A New Method for Beam Particle Identification at the COMPASS Experiment

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Why do we need beam particle identification?

- COMPASS hadron beam consists of different particles (mainly π and $\mathbf{K}$)
- One needs to know the particle for physics analysis

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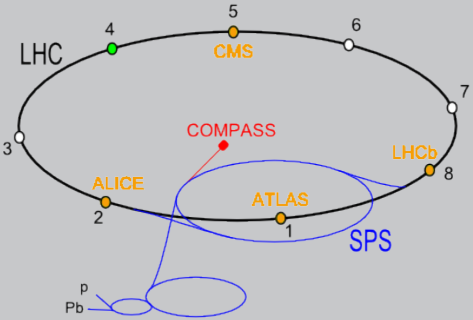
Why do we need a new method?

- COMPASS hadron beam is divergent
- Method used so far does not work for divergent beams

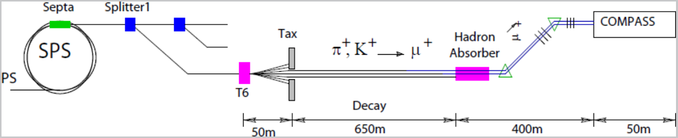
Outline

COMPASS in General

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



The M2 Beamline



Different Beams possible for COMPASS

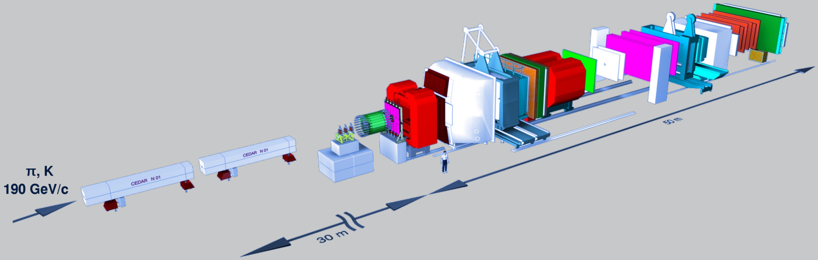
- positive Hadron (mainly Proton)
- negative Hadron
- Muon (μ^+, μ^-)

Here: negative hadron beam @ 190 GeV/c

- 97% π^-,
- 2.4% $\mathbf{K}^-$,
- few $\bar{\mathbf{p}}$

The COMPASS Spectrometer

- Two-stage spectrometer
- Large angular acceptance
- Broad kinematical range



The COMPASS Muon Program

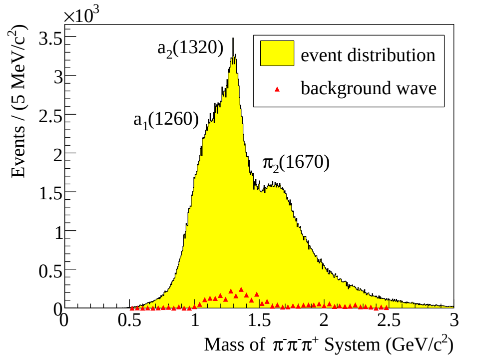
- Generalised Parton Distributions (GPD)
- Transverse Momentum Dependent Distibutions (TMD)
- Fragmentation Functions
- Gluon Polarisation

The COMPASS Hadron Program

- Mesonspectroscopy
- Baryonspectroscopy
- Central Production ($\longrightarrow$ Glueballs)
- Polarisabilities (π, $\mathbf{K}$)
- Primakoff
- Drell-Yan

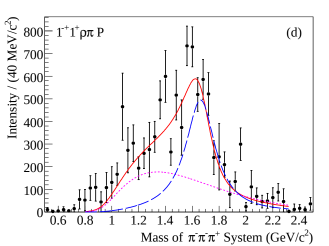
Example: 3π analysis

Observation of a $\mathbf{J^{PC} = 1^{-+}}$ exotic resonance in diffractive dissociation of $\mathbf{190\,GeV/c}\ \pi^-$ into $\pi^-\pi^-\pi^+$, PRL **104**, 241803 (2010)



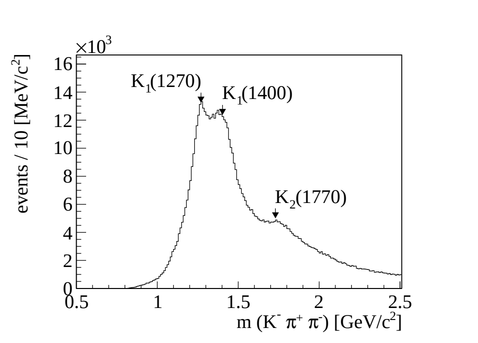
π^-Pb $\rightarrow \pi^-\pi^-\pi^+$Pb

Partial Wave Analysis performed



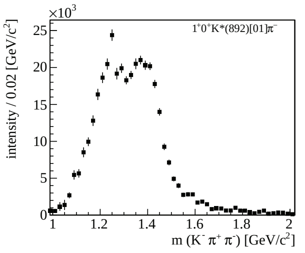
Example: $\mathbf{K}\pi\pi$ analysis

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



$\mathbf{K}^-\mathbf{p} \rightarrow \mathbf{K}^-\pi^+\pi^-\mathbf{p}$

$\rightarrow$ detect beam Kaon



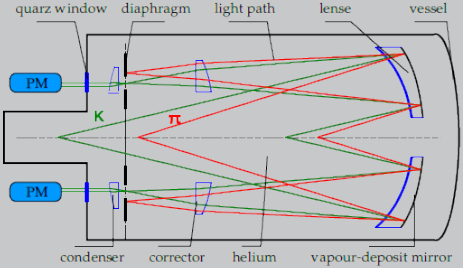
CEDARs at COMPASS

- CEDAR = ČErenkov Differential counters with Acromatic Ring focus manual"
- Two CEDARs at COMPASS beamline about 30 m upstream of the target

How does a CEDAR work?

- Fast charged particles emit Čerenkov light with angle θ

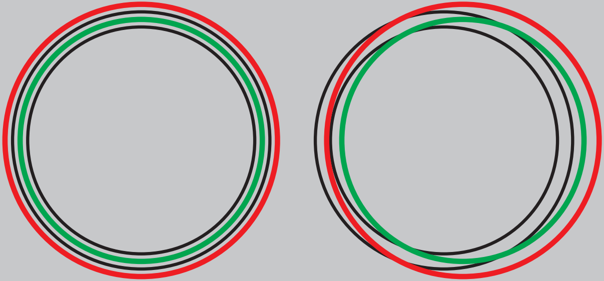
$$\cos(\theta) = \frac{1}{n\beta}$$



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

Influence of Beam Divergence

- Kaon ring leaves acceptance, pion ring enters



⇒ Multiplicity method does not work for divergent beams

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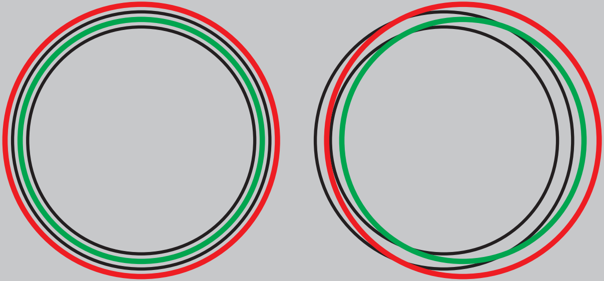

⇒ Multiplicity method does not work for divergent beams

Goal

Find a better method to take divergence into account

General Idea

- Look at PMT response for Kaon and Pion seperately
- Take beam divergence into account
- Identify beam particles using likelihoods

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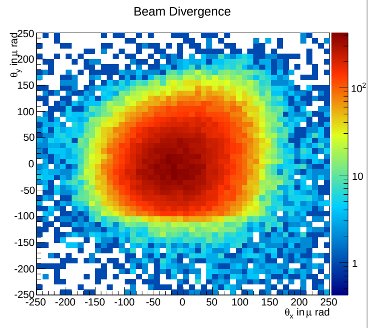
5 steps to take

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

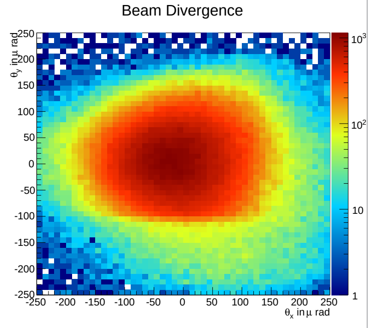
Step 1: Measure beam divergence

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

Events with 8 of 8 PMTs



Events with at least 6 of 8 PMTs



Step 2: Create a pure Kaonsample and a pure Pionsample

Create a Kaonsample and a Pionsample

- Kaonsample

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

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

- Pionsample

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

  - 3 outgoing particles with correct charge
  - Primary vertex inside the target
  - Small angle to beam direction
  - Similar momenta

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

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

Example: Probability that a particle with divergence θ_x, θ_y that produces a signal in PMT **i** is a Kaon

$\rightarrow$ Use Bayes' Theorem:

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

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

Step 3 continued

We know that Pions and Kaons have the same divergence distribution:

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

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

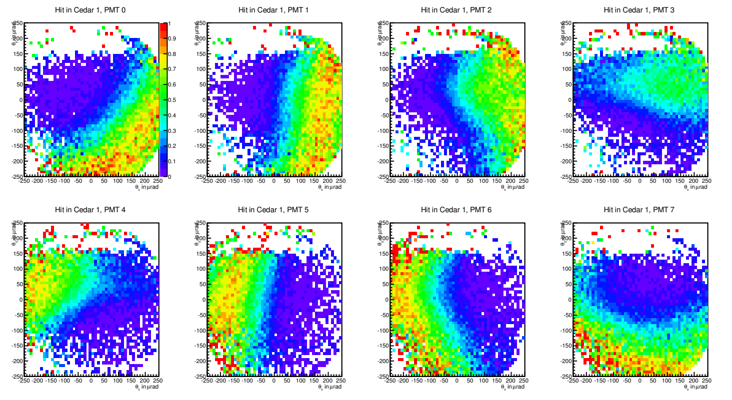
factor $\frac{\mathbf{P}_{\theta_x,\theta_y}(\text{Beam})}{\mathbf{P}^{\mathbf{i}}_{\theta_x,\theta_y}(\text{Signal})}$, thus

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

Also calculate

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

$P^i_{xy}(\text{Signal}|\text{Pion}) \propto P^i_{xy}(\text{Pion}|\text{Signal})$



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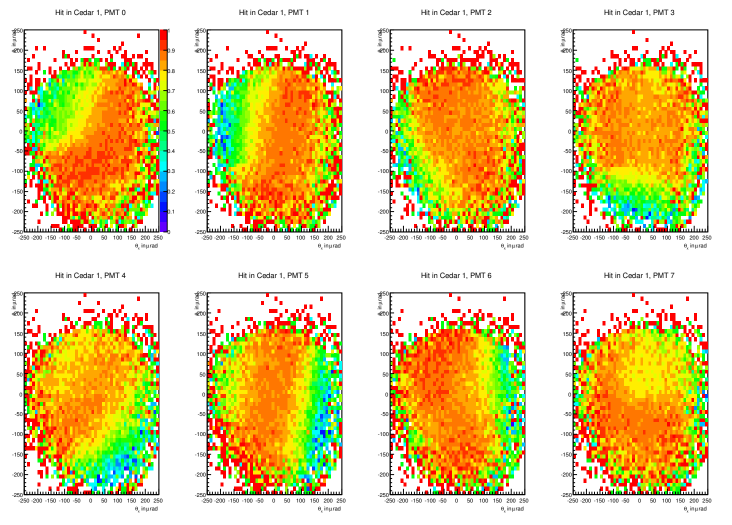


Step 4: Calculate likelihoods from probabilities

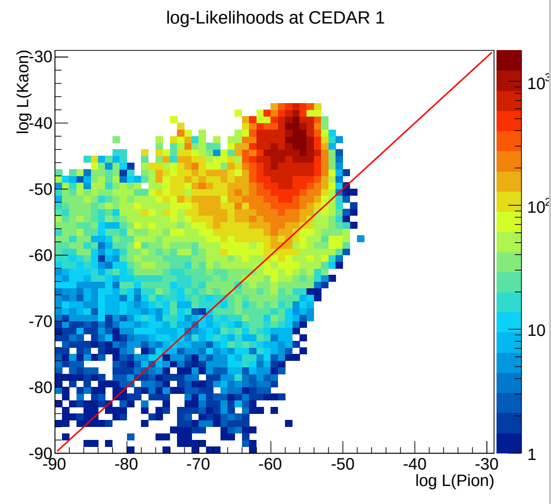
To obtain the log likelihood just add logarithms of probabilities

$$\mathbf{log\,L(}\mathrm{Kaon}\mathbf{)} = \sum_{i=1}^{8} \mathbf{log\,P}^{i}_{\theta_x,\theta_y}(\mathrm{Kaon}|\mathrm{Signal}) \cdot \eta^{i} + \sum_{i=1}^{8} \mathbf{log\,P}^{i}_{\theta_x,\theta_y}(\mathrm{Kaon}|\overline{\mathrm{Signal}}) \cdot (1 - \eta^{i})$$

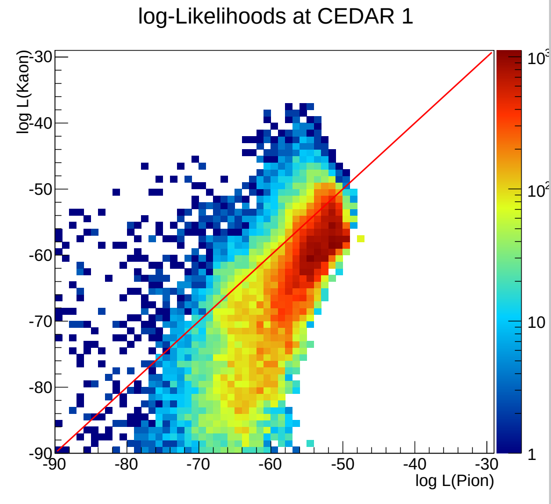
Where:

$$\eta^{i} = \begin{cases} 1 & \text{Signal in PMT i} \\ 0 & \text{no Signal in PMT i} \end{cases}$$

Kaonsample


log-Likelihoods at CEDAR 1
log L(Kaon)
-30
-40
-50
-60
-70
-80
-90
-90
-80
-70
-60
-50
-40
-30
log L(Pion)
10^3
10^2
10
1

Pionsample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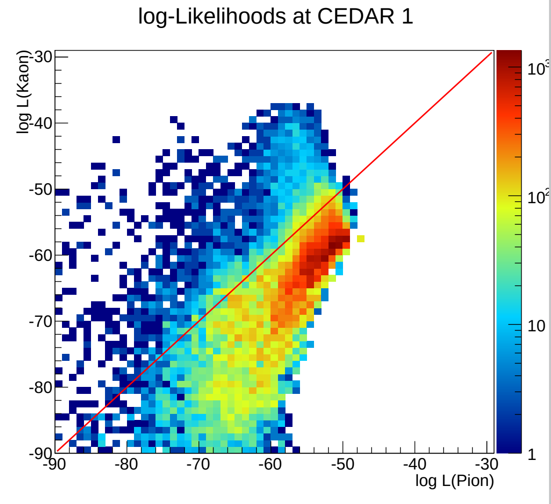
Beamsample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-60
-50
-40
-30
log L(Pion)
10^3
10^2
10
1

Step 5: Use likelihoods to identify particles

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

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

- Tune **A** and **B** due to efficiency/purity.
- Preliminary choice: $\mathbf{A = B = 0.1}$ in the following slides, equivalent to $\mathbf{P^i(}\text{Kaon}\mathbf{) = 1.01 \cdot P^i(}\text{Pion}\mathbf{)}$ (and vice versa)

Comparing Likelihood ID and Majority ID

82723 Events $\Rightarrow$ 1985 Kaons expected (2.4%)

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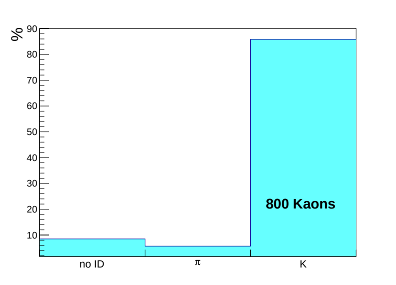
Likelihood ID for Majority Kaons

932 Majority Kaons (1.1%)



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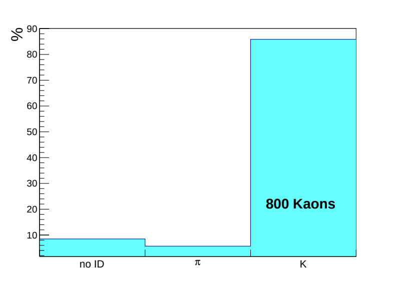
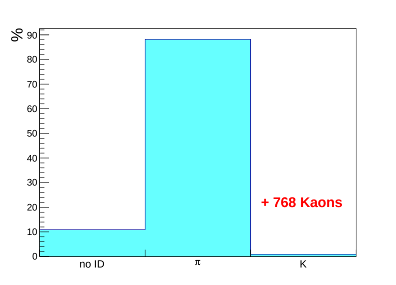


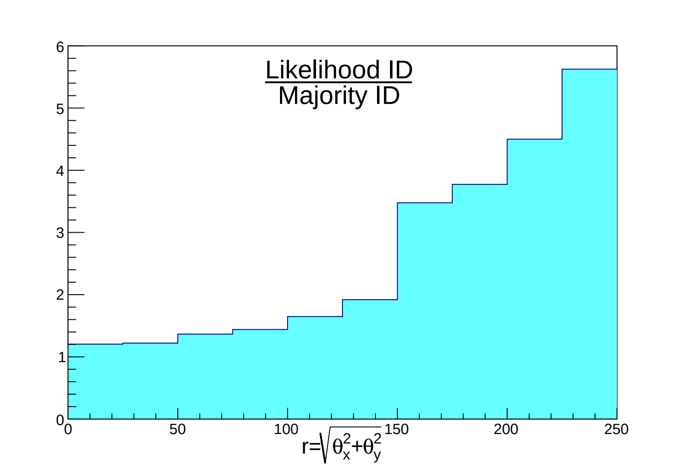
Likelihood ID for Majority Pions

81791 Majority Pions (98.9%)



⇒ doubles the number of Kaons

Where are the additional Kaons?



Summary

- COMPASS hadron beam consists of 97% Pions and 2.4% Kaons
- Pions and Kaons have to be identified for analyses
- Majority method identifies 45% of the Kaons
  - Problems with divergent beams
- Likelihood method improves identification for divergent beams
  - Identifies 80% of the Kaons