Title page :

Title: Designing a particle physics experiment

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Feel free to include some UZH logo or whatever.

I thought I had time writing it on Wednesday, it turnt out to be Thursday evening afterall. I apologize for the slight delay. I have not read it through just yet, and it is quite late right now, so might ve included some wacky stuff. I have a dentist appointment tomorrow morning and will be in Zurich in the afternoon, so feel free to read it through if time in the meantime. And Alessandro, chief of Microsoft office pimp the report up with flare. (As of right now the layout is a mess)

@oliver@Ion please

-check for mistake and add if not sufficient or tell me to add whatever

-I am not sure if we need to include appendix with all the code

-The asymmetry of uncertainty in NLL part why?

Thank you, bless u with longevity.

To do list @alessandro please:

- do title page

-clean up the layout and adjust spacing

-adjust the fonts and etc.

-do the highlighted part, and delete the highlighted text after done

-page number

-proper table of content

-proper bibliography

- copy paste formulary see appendix

- do whatever to make it pretty

Grazias Mille tung tung tung tung sahur!

Table of content:

1. Introduction
   1. Motivation & Setup
   2. Project Objectives
2. Determination of average decay length of the Kaons

2.1) Methodology

2.2)Result

1. Simulation of Kaon Decay and Pion Kinematics

3.1)Simulation with infinitely narrow beam

3.2)Simulation with Beam Divergence

4) Detector optimization

4.1) Methodology

4.2) Results

5) Further notes and Conclusion

5.1)Simulation assumptions and limitations

5.2)Reproducibility and Code Structure

5.3)Conclusion

Appendix:

1. Formulary and values
2. Code structure overview
3. Bibliography
4. Introduction:

1.1)Motivation & Setup

The goal of the project is to perform a simulation to optimize the layout of an experiment designed to measure the decay of charged kaons (K+ ) into a charged pion (π+) and a neutral pion (π0):

K+→π++π0

The experimental setup consists of two detectors and utilizes a beam of K+. The first detector tags incoming kaons, while the second detects outgoing π+ and π0 . The second detector has a circular cross section with a 4-m diameter centered on the beam axis. Our goal is to determine the optimal distance between the two detectors that maximizes the number of events where both pion decay products are successfully detected downstream.

图表, 折线图

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Figure 1: Illustration of the setup

1.2)Project Objectives

The following secondary objectives outline the structure of the project, ultimately leading to our primary interest of identifying the optimal detector distance:

1. Extract the mean decay length of kaons from a set of mixed data containing both kaons and pions.
2. Generate random kaon decay vertexes and simulate the resulting pion momenta using two body decay kinematics.
3. Apply Lorentz transformation to boost the decay products from rest frame to lab frame.
4. Simulate both infinitely narrow divergent beam and one with angular divergence.
5. Identify the detector distance with maximal number of accepted events by counting intersection of pions’ trajectories with a given detector position.

The tasks were implemented as separate python modules/functions with shared random seed to ensure reproducibility. (for further information, refer to Appendix section ii)

1. Determination of average decay length of the Kaons

2.1) Methodology

The input data consists of a large sample of 105 measured decay lengths, drawn from a beam that composed of both kaons and pions. The composition is however known to be 84% pions and 16% kaons. Both particles decay exponentially with different decay lengths. For pions, the lab frame mean decay length is known to be =4.188km. Hence the value is taken as fixed, and decay length of Kaons, , is to be fitted.

We modeled the decay length distribution as a weighted sum of two exponential distributions :

Where .

To estimate , we minimized the negative log likelihood of PDF with respect to the sample decay lengths :

**scipy.optimize.minimize\_scalar** was used for computing the best fit kaon decay length. The uncertainties are computed from a likelihood scan, where the upper and lower bounds are the value for which the NLL increases by 0.5 above the minimum, corresponding to the 68% confidence interval.

2.2) Results

图表, 折线图

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Figure 2: Fitted with uncertainty

The resulting average decay length is:

One notices that the uncertainties are asymmetric due to the not quite quadratic shape of the NLL function around its minimum. ( why? Open for suggestion)

图表

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Figure 3: Fitted distribution overlaid onto histogram of decay lengths

We find that the fit agrees well with the plotted histogram, with the dominating long tail (very different decay lengths between charged and neutral pions) due to pions and the steep drop due to kaons.

Lastly, we shall compare our mean lifetime with the literature value. The momentum of the beam is unknown; however, the kaons and pions share the same magnitude of momentum:

Where , with being the speed of the respective particle and c the speed of light.

We also know that:

Plugging Eq.2.6 into Eq.2.3, and then Eq.2.3 into Eq.2.5 we obtain expression for mean Kaon lifetime:

Where mass of kaon , mass of pion , and mean pion lifetime .

Comparing this to literature value:

They values are compatible.

1. Simulation of Kaon Decay and Pion Kinematics

3.1) Simulation with infinitely narrow beam

In this section we shall discuss the methodology and results for the special case of the kaons traveling along the z-axis with no angular divergence, later in section 3.2 we shall consider the general case including angular divergence.

To simulate the position of kaon decays along the axis, the vertices are sampled from an exponential distribution based on the fitted mean decay length from the previous task:

The kaon decay is treated as a two-body process: K+→π++π0 . In the rest frame of the kaon, we can determine the energy and momentum of the pions by conservation of momentum and energy. The magnitude of momentum of the pions in rest frame is given by:

The computed values are then multiplied by isotropically generated directions using **scipy.stats.uniform\_direction.**

图表, 折线图

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Figure 4: Generated kaon decay vertices and pions’ velocities( hence momentum) with no angular divergence

The corresponding energy of the pion in kaon’s rest frame for the four-momenta is given by:

= –(3.3)

The four-momenta of the pion are then boosted using the special Lorentz transformation along z-axis:

–(3.4)

Where and refers to the factors for using and are obtained by:

Using fitted and known lifetime from previous task. We have thus obtained four-momenta of the pions in lab frame. All values obtained in this section are recorded for later use in detector optimization.

3.2)Simulation with Beam Divergence

In this section, the model is extended to simulate a more realistic kaon beam with finite angular divergence. Specifically, the kaon’s direction is randomly sampled from a narrow cone around the z-axis, where the polar angle is drawn from a multivariate Gaussian profile with a standard deviation of . The azimuthal angle is sampled uniformly from [0,2, and the corresponding direction vector is constructed in spherical coordinates.

In previous section the kaons move along the z-axis. Now after boosting the pion’s four-momenta into lab frame, each resulting vector is rotated so that the kaon’s direction aligns with the sample direction.

The rotation is implemented by a rotational matrix that aligns the z-axis with the kaon’s new direction vector. The same then was applied to the pions’ four-momentum. Again, all values obtained in this section are recorded for later use.

图表

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Figure 5: Generated kaon decay vertices and pions’ velocities( hence momentum) with small angle divergence

4) Detector optimization

4.1) Methodology

The downstream detector is modeled as a 4 meter in diameter circular disk centered on the z-axis. Decay behind the detector is assumed to not trigger events. A detection event is considered valid if the pions intersect with the disk. To identify an optimal distance between the detectors, the simulation run multiple times for varying distances. At each trial distance, the number of detection events was registered.

To maximize the number of detection events **scipy.optimize.minimize\_scalar** was used to find the distance z that minimizes the negative number of accepted events.

The method is applied to both the non-divergent and divergent beam modeled in part 3.

4.2) Results

|  |  |
| --- | --- |
|  | Ideal z in meter |
| Non-divergent Beam | 442.58 |
| Divergent Beam | 420.19 |

Table 1: Optimal z of divergent and non-divergent beams

The result matches our expectation, as a finite divergence would cause a lost in number of events should the disk be too far away. That is the rapid loss due to divergence of the beam outweighs the gain from increased decay probability further downstream.

5) Further notes and Conclusion

5.1)Simulation assumptions and limitations

Several simplifications were made in our simulation:

-The pions won’t further decay

-The charged and neutral pions were roughly treated the same

-The secondary interaction of pions such as scattering were neglected

-All detectors were modeled to have full efficiency

-The kaon beam’s energy was assumed to be uniform

These assumptions simplified our analysis, however for a more accurate model/simulation they should be taken into consideration.

5.2)Reproducibility and Code Structure

All steps were implemented in Python with random sampling via a stored entropy file. This should ensure full reproducibility. (For further detail, refer to Appendix section ii)

5.3)Conclusion

The analysis confirmed that the estimated kaon lifetime aligned closely with the literature value. Furthermore, it was found that introducing beam divergence slightly reduces the optimal distance for the detector. Thus, we conclude our analysis on optimized experiment layout for kaon decay.

Appendix

A.i) Formulary and Values

All value from Zyla, P.A.; et al. (Particle Data Group) (2020). "Review of Particle Physics". Progress of Theoretical and Experimental Physics. 2020 (8)

List all the formulary here

2

(this one is copied here cuz it mentiond in biblio..)

A.ii)

**Everything is currently in a private GitHub repo**

* All scripts in the ./scripts folder
* Data used in the report can be found in ./data/value\_cache.json
* Package management trivialized thanks to uv

**Reproducibility**

* Code adopts [SPEC 7](https://scientific-python.org/specs/spec-0007/), meaning it uses numpy Generator instances
* To reproduce the values, run ./scripts/generate.py with the seed found in ./data/entropy (which it does by default)
* If that file is not found, it will save it to that location (by default, can be changed by command line arguments)

**Code structure overview**

**Common.py:**

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**find\_dec\_length.py: Estimates the kaon decay length by fitting an NLL model to a mixed decay dataset.**

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**experiment\_simulation.py: Simulates kaon decay using two-body kinematics and Lorentz boosts.**

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**intersection.py: Determines whether decay products intersect with the detector and performs distance optimization.**

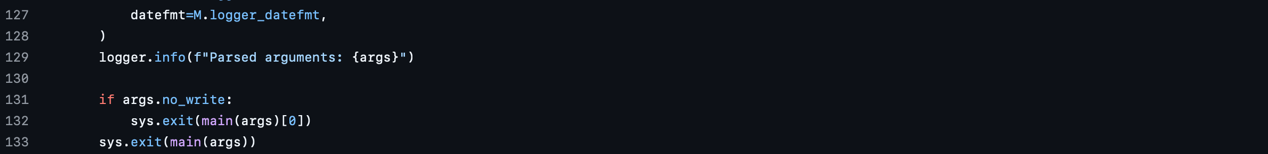
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**generate\_plots.py: Produces plots for NLL curve and decay length histogram.**

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**generate.py: Simulation regeneration with shared entropy for reproducibility.**

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**Aiii)** Bibliography

Figure 1 source: Designing a particle physics experiment Data analysis 2025 – Group project III Patrick Owen, Olaf Steinkamp April 8, 2025

**1** source: https://en.wikipedia.org/wiki/Particle\_decay#Two-body\_decay

**2** source: https://en.wikipedia.org/wiki/Particle\_decay#Two-body\_decay