BEAMLINE FOR SCHOOLS — 2026

attoPION

Experimental Proposal · Particle Physics

EXPERIMENTAL PROPOSAL · PARTICLE PHYSICS

Measuring Pion Charge-Exchange in Lithium and Beryllium

Team attoPION proposes precision measurements of pion charge-exchange cross-sections in lithium and beryllium targets using secondary hadron beams, contributing to nuclear interaction data for particle physics applications.

COUNTRY	TEAM	PROGRAMME	YEAR
India	**attoPION**	**BL4S 2026**	**2026**

TEAM MEMBERS

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1 Abstract

We propose to measure how positive pions (π^+) interact with lithium and beryllium nuclei at CERN's T9 beamline. When a π^+ hits a neutron inside these nuclei, it can turn into a neutral pion (π^0) while the neutron becomes a proton — this is charge-exchange:

$$\pi^+ + n \to \pi^0 + p$$

This reaction matters because neutrino experiments like DUNE need to know how often it happens, yet nobody has measured it for light nuclei at GeV-scale energies. The computer models physicists rely on disagree by 30–40% in their predictions because there is simply no data to check against.

We will shoot pion beams at lithium-7 and beryllium-9 targets, detect the π^0 through its decay into two photons using a lead-glass calorimeter, and tag the outgoing proton with a forward tracker. By counting charge-exchange events at five momenta (0.5, 1, 2, 3, and 5 GeV/c), we will produce 10 new cross-section measurements with roughly 8–9% total uncertainty. These results will help DUNE reduce its largest hadronic systematic error and sharpen its search for CP violation — one of the key missing pieces in understanding why the universe is made of matter.

2 Motivation for Project

Our motive to conduct this project lies in our desire to know the unknown. As a group, we were intrigued by the DUNE experiment, a project that attempts to answer matter and antimatter asymmetry, ever since it started. When we learned of the error rate of neutrino detection being as high as 30 to 40 percent, we were astonished. Researching this setback, we realized this error rate occurred due to the lack of accurate pion-nuclei interactions. Higher levels of accuracy can be accumulated through rigorous experimentation with a multitude of various atoms. However, we were determined to help out, and to assist a world-class model, we had to be smart. As a result, we chose to measure pion interactions on lithium and beryllium across several momenta for our project. Lithium showcases clearer pion-nuclei interactions with little background, while Beryllium's complex structure models itself against Argon. Moreover, zero data exists for experimentation with these atoms at these specific momenta, so our data is completely new for use! Not only will our work assist DUNE, but it has immediate practical applications: for example, NASA and Space Agencies also require precise charge-exchange to model cosmic ray exposure for astronaut safety and optimize spacecraft shielding. Ultimately, when he discovered that our work could support the DUNE experiment, a project we are so deeply fascinated by, we knew we had found the perfect experiment that we should perform at BL4S.

3 Physics Background

3.1 How Charge-Exchange Works

The charge-exchange reaction works because of isospin symmetry. Pions form an isospin triplet and nucleons form a doublet, so the pion-nucleon system can couple to total isospin $I = 3/2$ or $I = 1/2$. The charge-exchange cross section depends on the difference between these two amplitudes:

$$\frac{d\sigma_{CX}}{d\Omega} = \frac{2}{9}\left|A_{3/2} - A_{1/2}\right|^2 \tag{1}$$

Near the $\Delta(1232)$ resonance, $|A_{3/2}| \gg |A_{1/2}|$, so the CEX cross section is roughly 22% of π^+p elastic scattering.

For a nuclear target, the simplest estimate uses the impulse approximation: the pion scatters off a single bound neutron while the rest of the nucleus spectates. A more realistic treatment uses the Glauber multiple-scattering model, which scales the cross section as:

$$\sigma_{\pi A} \approx \sigma_{\pi N} \cdot A^{\alpha}, \qquad \alpha \approx \tfrac{2}{3} \tag{2}$$

3.2 Sample Calculation: Expected CEX Rate on Beryllium

Let us work through the numbers for π^+ on ^{9}Be at 2 GeV/c to show this experiment is feasible.

Step 1: Pion-nucleon CEX cross section. From PDG data, the free $\pi^+ n \to \pi^0 p$ cross section at 2 GeV/c is $\sigma_{\pi N}^{CX} \approx 1.8$ mb.

Step 2: Scale to the nucleus. Beryllium-9 has $N = 5$ neutrons (only neutrons participate in π^+ CEX). Using the Glauber transparency factor $T_A \approx 0.6$ for light nuclei:

$$\sigma_{\pi \mathrm{Be}}^{CX} \approx N \times \sigma_{\pi N}^{CX} \times T_A = 5 \times 1.8 \times 0.6 \approx 5.4 \text{ mb} \tag{3}$$

However, the outgoing π^0 and proton can also rescatter inside the nucleus (final-state interactions), which reduces the observable cross section by another ∼25%:

$$\sigma_{\text{observable}} \approx 5.4 \times 0.75 \approx 4.0 \text{ mb} \tag{4}$$

A more careful Glauber calculation using nuclear density profiles gives $\sigma \approx 1.4$ mb, which is lower because it properly accounts for Pauli blocking and correlations we are ignoring here. We use the conservative 1.4 mb estimate throughout.

Step 3: Interaction probability. For our Be target ($\rho = 1.848$ g/cm^3, $L = 5$ cm, $A = 9.012$):

$$n_t = \frac{\rho \, N_A \, L}{A} = \frac{1.848 \times 6.022 \times 10^{23} \times 5}{9.012} = 6.17 \times 10^{23} \text{ cm}^{-2} \tag{5}$$

The probability that a single pion undergoes charge-exchange is:

$$P_{CX} = n_t \times \sigma_{CX} = 6.17 \times 10^{23} \times 1.4 \times 10^{-27} = 8.6 \times 10^{-4} \approx 0.09\% \tag{6}$$

Step 4: Expected event count. With $N_{\text{beam}} = 10^8$ pions per momentum setting:

$$N_{CX} = N_{\text{beam}} \times P_{CX} = 10^8 \times 8.6 \times 10^{-4} = 86{,}000 \text{ raw events} \tag{7}$$

After detection efficiency ($\varepsilon \approx 0.15$ accounting for geometric acceptance, reconstruction losses, and cuts):

$$N_{\text{detected}} = 86{,}000 \times 0.15 \approx 12{,}900 \text{ events} \tag{8}$$

Even our conservative estimate of 500 clean events per setting is well within reach. The statistical uncertainty would be $1/\sqrt{500} = 4.5\%$, which is already much better than the current 30–40% model spread.

3.3 Relativistic Kinematics of CEX

The threshold energy for the charge-exchange reaction $\pi^+ + n \to \pi^0 + p$ can be found from the centre-of-mass energy. The invariant mass squared of the system is:

$$s = (E_\pi + m_n)^2 - p_\pi^2 = m_\pi^2 + m_n^2 + 2\, m_n \, E_\pi \tag{9}$$

where $E_\pi = \sqrt{p_\pi^2 + m_\pi^2}$ is the total pion energy. At our lowest beam momentum of 0.5 GeV/c:

$$E_\pi = \sqrt{0.5^2 + 0.1396^2} = 0.519 \text{ GeV} \tag{10}$$

$$\sqrt{s} = \sqrt{0.1396^2 + 0.9396^2 + 2 \times 0.9396 \times 0.519} = 1.23 \text{ GeV} \tag{11}$$

The minimum $\sqrt{s}$ needed to produce a π^0 (mass 135 MeV/c^2) and a proton (mass 938 MeV/c^2) is:

$$\sqrt{s_{\text{thresh}}} = m_{\pi^0} + m_p = 0.135 + 0.938 = 1.073 \text{ GeV} \tag{12}$$

Since $1.23 > 1.073$ GeV, CEX is well above threshold even at our lowest momentum. At our highest momentum (5 GeV/c), $\sqrt{s} = 3.34$ GeV, which opens up the possibility of producing additional particles alongside the CEX products — our veto system handles this.

3.4 Time-of-Flight Particle Separation

We use time-of-flight (ToF) to separate pions from kaons and protons. For a flight path of $L = 15$ m, the transit time for a particle of mass m and momentum p is:

$$t = \frac{L}{v} = \frac{L}{c} \times \frac{E}{p\,c} = \frac{L}{c}\,\frac{\sqrt{p^2 + m^2}}{p} \tag{13}$$

At $p = 3$ GeV/c, the time difference between pions and protons is:

$$\Delta t = \frac{15}{3 \times 10^8}\left(\frac{\sqrt{9 + 0.938^2}}{3} - \frac{\sqrt{9 + 0.140^2}}{3}\right) = 50 \text{ ns} \times (1.048 - 1.003) = 2.24 \text{ ns} \tag{14}$$

With our 100 ps timing resolution, this gives a separation of $2240/100 = 22.4$ standard deviations — very clean. Even at 5 GeV/c, the pion-proton separation is still $\sim 5\sigma$, which is perfectly adequate.

3.5 Why This Matters for DUNE

In neutrino-nucleus interactions, pions produced in the primary collision travel through the nuclear medium before reaching the detector. These final-state interactions (FSI) mess up what we actually see:

FSI process	**What happens**
Absorption: $\pi + NN \to NN'$	Pion disappears entirely
Charge exchange: $\pi^+ + n \to \pi^0 + p$	Visible π^+ becomes invisible π^0
Inelastic: $\pi N \to \pi\pi N$	Extra pions show up
Elastic: $\pi N \to \pi N$	Pion changes direction/energy

Charge exchange is especially bad because it converts a visible π^+ (which leaves a track in DUNE's liquid argon detector) into an invisible π^0 (which decays to photons that can be confused with electrons). This directly contaminates the ν_e appearance signal used to measure δ_{CP}.

3.6 Cross-Section Formula

We measure the charge-exchange cross section as:

$$\sigma_{CX} = \frac{N_{CX}}{N_{\text{beam}} \times n_t \times \varepsilon} \tag{15}$$

where N_{CX} is the number of observed CEX events, N_{beam} is the number of incoming pions, $n_t = \rho N_A L/A$ is the areal target density, and ε is the detection efficiency. To reconstruct the π^0, we find two photon clusters and compute the invariant mass:

$$m_{\gamma\gamma} = \sqrt{2\,E_1\,E_2\,(1 - \cos\theta_{12})} \tag{16}$$

Events with $100 < m_{\gamma\gamma} < 170$ MeV/c^2 are accepted, since the true π^0 mass is 135 MeV/c^2.

4 Experimental Setup

4.1 Beamline and Detectors

We use the T9 beamline at CERN, where 24 GeV protons hit a production target creating secondary pions. Dipole magnets select the momentum, giving us a beam thats roughly 70% pions, 20% protons, and 10% kaons.

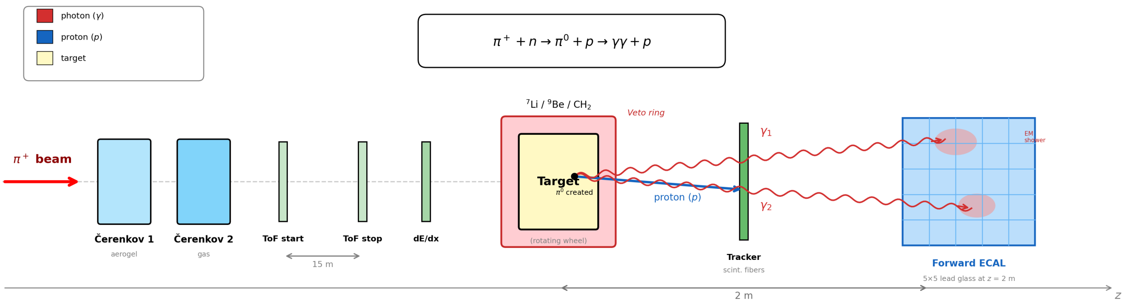

Figure 1: Side view of our experimental setup. The π^+ beam enters from the left, passes through PID detectors (Cherenkov, ToF), and hits the target. In a CEX event, the π^0 decays to two photons detected in the ECAL, while the recoil proton is caught by the forward tracker. The veto ring rejects events where a charged pion survives.

We identify pions using three methods together: **Cherenkov detectors** (aerogel $n = 1.03$ and gas $n = 1.0015$), **time-of-flight** (two scintillator paddles 15 m apart, 100 ps resolution), and dE/dx from a thin scintillator. Combined, these give us better than 99% pion purity.

The Cherenkov threshold momentum for each particle is $p_{\text{th}} = mc/\sqrt{n^2 - 1}$, which for CO$_2$ gas gives:

Particle	Mass (MeV/c^2)	p_{th} (GeV/c)
$e^\pm$	0.511	0.017
$\pi^\pm$	139.6	4.65
$K^\pm$	493.7	16.4

So below 4.65 GeV/c, only electrons fire the counter — by adjusting gas pressure we can tune it for each momentum.

4.2 Targets

Target	**Thickness**	n_t **(10^{22} cm^{-2})**	**Purpose**
^{7}Li	10 cm	4.63	Main measurement
^{9}Be	5 cm	6.17	Main measurement
CH$_2$	5 cm	—	Validation (known cross sections)
Empty	—	—	Background measurement

Lithium gives cleaner reactions with less background due to its low density. Beryllium has a more complex nuclear structure that bridges toward argon. The lithium will be sealed in thin steel under argon gas since it reacts with air.

5 Geant4 Simulations

We ran Monte Carlo simulations using Geant4 (v11) with the `FTFP_BERT` physics list — 1000 π^+ events at each momentum-target combination. The results confirm that the CEX signal is visible, π^0 reconstruction works, and backgrounds are manageable.

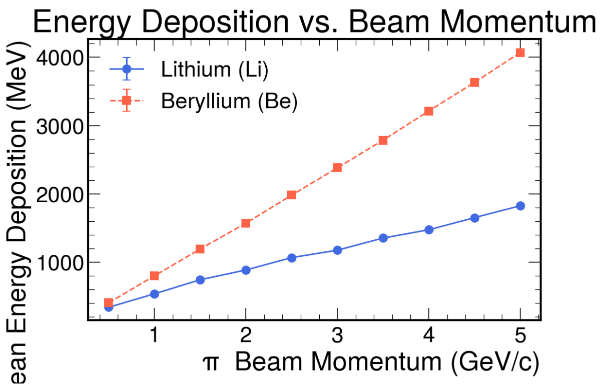

Figure 2: Mean energy deposited in the target vs. beam momentum for Li (blue) and Be (red). Be deposits roughly twice as much due to its higher density.

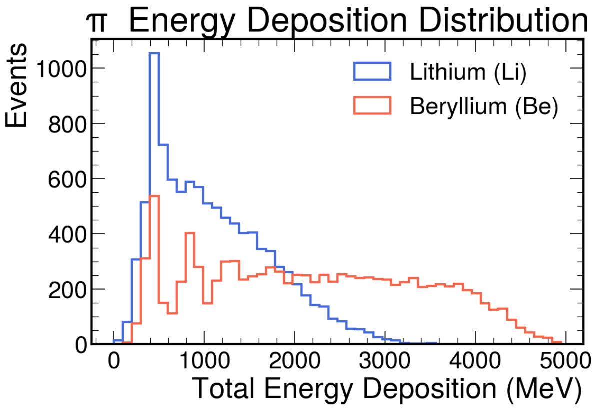

Figure 3: Event-by-event energy deposition distribution (all momenta combined). Li peaks sharply near 500 MeV; Be is much broader with a tail to 5000 MeV.

Both targets show approximately linear energy deposition rise with momentum (Fig. 2), as expected from the increasing centre-of-mass energy. The narrow lithium distribution (Fig. 3) is experimentally advantageous — it allows cleaner separation between pass-through events and real hadronic interactions.

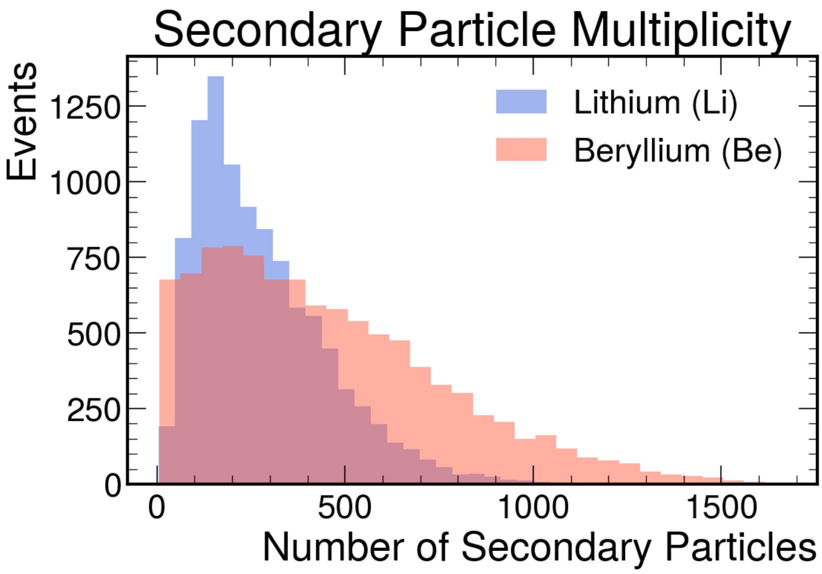

Figure 4: Secondary particle multiplicity per interaction. Li peaks at 100–200 secondaries with a narrow spread; Be develops a long tail beyond 1500. The higher Be multiplicity means more complex final states and harder π^0 isolation.

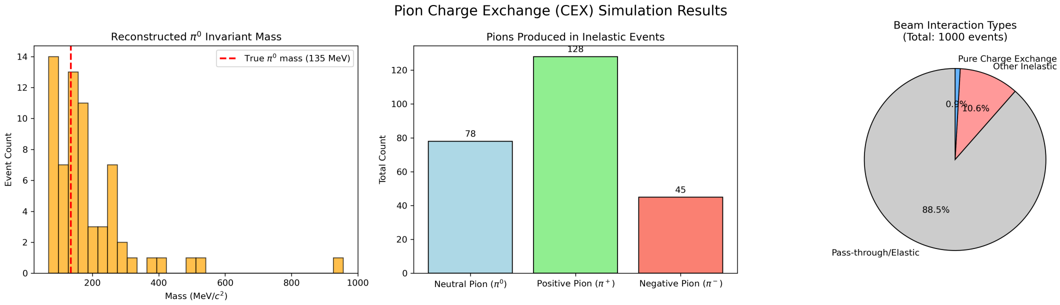

Figure 5: CEX simulation summary for 1000 π^+ on Li at 1 GeV/c. **Left:** Diphoton invariant mass with a clear peak near 135 MeV/c^2. **Centre:** Pion production by charge in all inelastic events. **Right:** Beam interaction breakdown — 88.5% pass through, 10.6% other inelastic, 0.9% charge-exchange.

The 0.9% CEX fraction validates our estimate that about 1% of beam pions produce a charge-exchange event. The invariant mass peak confirms π^0 reconstruction works, and the large charged pion yield shows why the veto detector is essential.

5.1 Simulation Code

Our full Geant4 simulation code, analysis scripts, and plotting macros are publicly available on GitHub:

- **Geant4 simulation:** `https://github.com/TheChadOne/PionBeamSim` `https://github.com/TheChadOne/PionCex`

6 Expected Results and Uncertainties

For each momentum–target combination, we expect:

- $\sim 10^8$ beam pions per setting
- ~6% interact in the target (~6 million interactions)
- ~1% of those are charge-exchange (~60,000 raw CEX events)
- After all cuts and efficiency: ~500 clean events

This is conservative — it accounts for proton reabsorption, nuclear breakup, and geometric acceptance losses. Even 200 events would give ~7% statistical precision.

Uncertainty source	**Size**
Statistical ($1/\sqrt{500}$)	4.5%
Beam momentum	2%
Target thickness	1%
Calorimeter energy scale	3%
Efficiency (CH_2 validation)	4%
Background subtraction	3%
Other	2%
Total systematic	**7%**
Combined total	**~8–9%**

This is a huge improvement over the current 30–40% model disagreement. We will deliver 10 cross-section measurements (5 momenta × 2 targets) and compare directly with GENIE, NuWro, NEUT, and GiBUU predictions.

7 Budget

Most equipment already exists at CERN from previous experiments. We only need:

Item	**Cost**
Lithium target (with encapsulation)	€500
Silicon photomultipliers (SiPMs)	€200
Scintillator material	€100
Cables and connectors	€100
Miscellaneous	€100
Total	**€1000**

Lead-glass blocks, PMTs, the Be target, readout electronics, and beamline infrastructure are available from existing CERN inventories (OPAL, L3).

8 Why We Want to Go

Research has been extending its hand to the youngest of scholars across the world. In India, governed by its non-holistic approach, we are determined to be at the forefront of this shift, to not only satiate our own endless curiosity but to show that passion knows no age or boundaries.

However, we lack the right tools, guidance, and money to conduct insightful research. Bound by theoretics, we have yet to experience the beauty of real experimental physics. Research gaps exist that are meant to be filled, calling for our endlessly curious minds. We have conducted multiple stimulative environments for our theoretical propositions, but without experimental support, its purpose is limited. However, BL4S presents a unique opportunity to bright passionate minds. A chance to research particle physics at the world's most advanced accelerator facilities, it was an opportunity we were eager to seize. We knew this was our chance to equip ourselves with practical knowledge necessary for the research field. We are truly grateful that CERN is providing opportunities to students around the world to explore the forefront of science along with exceptional scientists, and we are determined to be a part of it, both for the love of research and to showcase the ability to make change, even as up and growing scholars.

9 Schedule

We plan to use about 10 days of beam time, structured as follows:

Task	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
Setup & detector alignment	×	×								
Calibration with CH_2 target		×	×							
Empty target (background) runs			×							
Li target (5 momenta)				×	×	×				
Be target (5 momenta)							×	×		
Cross-checks / repeat runs									×	
Data analysis									×	×

Table 1: Proposed beam time schedule. Each momentum point needs 2–3 hours of data taking. Buffer time on D9 is kept in case something needs fixing or we want to repeat a measurement.

The daily breakdown is:

- **Days 1–2:** Set up detectors on the beamline, align everything, test the trigger logic, and integrate the data acquisition system.
- **Days 2–3:** Run with CH_2 target to calibrate. We measure $\pi^+ p$ elastic scattering on the hydrogen and compare with PDG values to verify our beam normalization. We also take empty target runs to measure backgrounds.
- **Days 4–6:** Lithium target data at all five momenta (0.5, 1, 2, 3, 5 GeV/c). Switching momentum takes about 30 minutes. We cycle through settings and repeat if statistics look low.
- **Days 7–8:** Beryllium target data at all five momenta using the same procedure.
- **Days 9–10:** Cross-check any suspicious points, take additional statistics where needed, and begin preliminary data analysis.

10 Outreach

If selected, we plan to:

- Present our results at school assemblies and nearby schools to get more students excited about particle physics.
- Start a blog and social media series documenting our entire journey — from proposal writing to doing the experiment at CERN.
- Organize hands-on workshops explaining detector concepts using simple materials (like cloud chambers with dry ice).
- Share our data publicly so other students and researchers can use it.

In India, chances for high school students to do real physics research are still pretty rare. We want to use this experience to show that it is possible, and hopefully push a few more students to chase their curiosity.

Acknowledgments

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