High Energy Physics

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Abstract

This work focuses on the determination of particles produced in high-energy pion-proton interactions in the SLAC bubble chamber at Stanford university. 10.3 ± 0.1 GeV pions (π^+) incident upon a liquid hydrogen proton pool interact with hydrogen atoms (stationary p) via the strong interaction to produce multiple outgoing particles of unique masses and momenta. Charged particles travelling throughout liquid hydrogen ionize the electrons off of the surrounding atoms, superheating the hydrogen and forming visible ionization tracks, much like a cloud chamber. In the presence of a magnetic field of $\mathbf{B} = 15.5 \pm 0.1\text{kG}\ \hat{\mathbf{z}}$, these particles curve by the Lorentz force law, therefore allowing the observation of charge type. The goal of this experiment was to analyze two imaged processes[1] in hopes of determining all particles produced in the interactions: consulting a Beth-Bloche figure, calculating momentum conservation, invariant masses, neutral particle decays, and invoking quantum number symmetries. This was taken out using image analysis software developed by the University of Toronto physics department, called 'Traxis'. It was found that, for the first event, $\pi^+ p \to \Xi^* K^* \pi^+ K^+$ and $\Xi^* \to \Xi^- \pi^+,\ K^* \to K^+ \pi^-$ for the neutral particle decays, where all momenta, invariant masses, and quantum numbers were conserved. For the second event, $\pi^+ p \to \pi^+ \pi^+ K^* \Lambda^0$ and $\Lambda^0 \to \pi^- p$ (this proton scatters via $pp \to pp$ later), $\pi^+ \to \mu^+ \nu_\mu$ (for one pion), where all momenta, invariant masses, and quantum numbers were also conserved. It was found that the corresponding neutral particle lifetimes could not be comparitavely analyzed qualitatively with the image. Laboratorical improvements such as Traxis limitations, error analyses, and mistakes were also discussed.

Summary of Theory, Procedures, and Results

A bubble chamber works by ionization. When charged particles pass through superheated liquid hydrogen, the surrounding atoms are ionized. The ionization condenses the liquid, forming visible drops, and thus tracks form when charged particles pass through the chamber. At the SLAC Stanford bubble chamber, 10.3 ± 0.1 GeV π^+ pions are incident upon stationary protons of the hydrogren, allowing for strong interactions to take place. In the presence of a magnetic field of 15.5 ± 0.1 kG, such charged particles curl according to the Lorentz force law, $\mathbf{F} = q\mathbf{v} \times \mathbf{B}$ which crosses to a radial force. It was found by examining electron curls that $\mathbf{B}$ points out of the image, therefore making negative particles curl clockwise and positive particles anticlockwise.

Many methods were utilized to attempt to quantify the particles involved in the interactions. The first was consulting the Beth-Bloche equation for particles travelling in liquid hydrogen, given as a figure[1] which required interpolation for every momentum, track length, and ionization energy $\dfrac{dE}{dx}$ value. Though momentum and track length values were given via Traxis calculations, $\dfrac{dE}{dx}$ ionization energies were measured by an 'optical density' in Traxis, which was a measurement of the black pixels making up the track (higher energy tracks had darker, thicker lines), and converting to $\dfrac{dE}{dx}$ units by a known factor given by the incident π^+ energy and optical density. This step proved quite simple for event 1, but involved some guessing for some particles during the event 2 analysis. The second method was by using momentum conservation at each vertex, which was done by measuring the angles between tracks and summing x and y components of momentum before and after the vertex. The third method was by invoking the invariant mass expression, which, similar to that of momentum conservation, also accounted for energy conservation. This was given by the contraction between the contravariant and covariant total momentum 4-vector:

$$M^2_{\text{INV}} = P^{\mu}_{\text{TOT}} P_{\mu\,\text{TOT}} \tag{1.1}$$
$$= (E_{\text{TOT}})^2 - \mathbf{P}_{\text{TOT}} \cdot \mathbf{P}_{\text{TOT}} \tag{1.2}$$
$$= \left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \mathbf{p}_i\right)^2 \tag{1.3}$$

which is a Lorentz invariant quantity (the same in any reference frame) and is invariant regardless if evaluated before or after the interaction vertex. By invoking this expression, the masses of neutral particles were determined (measuring momenta, consulting the Beth-Bloche figure, substituting corresponding particle masses[2],[3], and measuring the opening angle), and the masses of missing particles were determined (the K^* in event 2). Lastly, particles were determined by using the quantum number symmetries: baryon number, strangeness, charge, quark color. For instance, if one strange neutral baryon (combination of three quarks) was produced and two positive mesons (combination of two quarks) were outgoing, it can be concluded that a missing neutral anti-strange baryon had to have been produced.

Tracks were measured by placing track markers in the center of every track, labelling the start 's' and end 'e' before calculating track momentum. Errors were taken directly from Traxis and did not require scaling (see below). For improperly drawn arcs, the formula $2\pi R - \ell$ was used to calculate the true arc length, where R was circle radius and ℓ the long track length. Optical density could not be calculated because the track markers were not overlaid with a curve. Optical density correlation factors were measured by computing O for the incident π^+ and observing that 10.3 ± 0.1 GeV correponds to 0.24 ± 0.05 on the $\frac{dE}{dx}$ scale. Then $Of = \frac{dE}{dx}$, where f is the corresponding unit conversion. f for event one was measured to be $(3.5 \pm 0.6) \times 10^{-4}$ MeV, and f for event two was observed to be $(2.5 \pm 0.4) \times 10^{-4}$ MeV (units of O are cm^{-1}). The same value could not be taken for both events because both images were capture with different cameras. The invariant masses and momentum conservation calculations for event one were very straightforward and are all recorded in the notebook. For event two, though, momentum did not appear conserved at the primary vertex when the invariant mass was calculated, so a missing particle was postulated. Momentum conservation had to be forced at the vertex in order to determine the mass of the postulated missing particle, which was a K^* (it was originally thought that one π^+ was a K^+ to conserve strangeness, but the missing particle corresponded to a lower mass which did not exist in particle form, thus assumptions were changed and the K^* mass was calculated), and this was done by determining the intersection between the expected invariant mass (the incident $\pi^+ p$) and the variable invariant mass. Altogether, all mass calculations, uncertainties, and intersections were taken out using the Desmos graphing calculator, since this was quicker and more simple than defining hundreds of unique variables in Python and coding each individual propagation.

The error propagation formulas that were used to calculate error are located on page 94 of the lab notebook. At first, it was thought that the errors given by Traxis (which were only due fitting procedure) may have been too small, so a scaling was considered depending on the magnitude of the measurement. Adjusting errors via scaling would therefore account for resolution uncertainty, human measurement uncertainties, and the systematic error given from the true particle location. Eventually, it was found that scaling errors actually produced a great overestimate in uncertainties (that is, $x \pm 0.5x$), and instead it was chosen to leave the given uncertainties from Traxis unscaled. The problem with obtaining too large of errors, especially when interpolating particle type, momentum or mass, is that too many particles overlap with the error, hence making it difficult to discern the appropriate particle. For instance, when calculating the Λ^0 mass, it was found to be 1100 ± 30 MeV, within the range of the proper mass (1115 MeV). If the error was scaled, 1100 ± 200 would overlap with the mass of the Σ^0 (1192 MeV). If the Σ^0 were to decay, the corresponding invariant mass would not be conserved, even though the Λ^0 and Σ^0 have the same (uds) quark content. Therefore it is better to keep errors relatively small, but not underestimated, as to not to interpolate (/'guess') the wrong particle. Furthermore, this is how errors could negatively affect the obtained measurements and thus the outcome of the experiment.

It was always attempted to measure the track from forward to backwards, but sometimes Traxis would not draw a proper arc making it impossible to calculate ionization energy (optical density), and in switching 's' and 'e' points, reference angles could not be calculated accordingly. This led to having to guess some particles, especially the ones whose tracks had larger momenta (radii). For instance, the high energy π^+ was guessed to be a K^+ initially, until it was found that it had to be a π^+ to conserve the invariant mass. Traxis would not draw the proper line over the curve, hence no length or optical density could be calculated, and therefore the particle had to be guessed.

Similarly, Traxis' optical density calculations were sometimes inconsistent, as the images had some dark spots, some images were darker than others, and hence mostly overestimated the ionization energy of the particle. This was not too complicated to fix, since instead the optical density could be visually interpolated and compared with surround particles with a known O value.

This experiment was quite straightforward, however it is important to note how this lab can be improved. One thing not mentioned above was the inability to determine accurate particle lifetimes of decaying neutral or charged particles. This was because straight lines cannot be measured in Traxis - Traxis can only measure curved lines made up of 3 tracks markers minimum, not straight lines. Therefore straight particle distances could not be accurately measured and hence have their lifetimes calculated. However, their mean lifetimes were taken[3] and the expected distances were calculated usinig the given momentum and mass values, then they were compared qualitatively to the image. Eventually, it was concluded that particle lifetimes could not be verified.

All interaction or decay results were compared with the expected branching ratios found on the particle data group database[2]:

$$\Gamma_i(K^*(700) \to K^+\pi^-) = 100\%$$
$$\Gamma_i(\Xi^*(1530) \to \Xi^-\pi^+) = 100\%$$
$$\Gamma_i(\pi^+ \to \mu^+\nu_\mu) = 99.99\%$$

To conclude, by utilizing momentum, invariant mass, and quantum number conservation, it was found that the event one interactions were $\pi^+p \to \Xi^*K^*\pi^+K^+$ and $\Xi^* \to \Xi^-\pi^+$, $K^* \to K^+\pi^-$ for the neutral particle decays, where all momenta, invariant masses, and quantum numbers were conserved. Similarly, for event two, $\pi^+p \to \pi^+\pi^+K^*\Lambda^0$ and $\Lambda^0 \to \pi^-p$ (this proton later scatters via $pp \to pp$ later), $\pi^+ \to \mu^+\nu_\mu$ (for one pion), where all momenta, invariant masses, and quantum numbers were also conserved. All measured values and angles are located in Table 1 for events one and two. Momentum conservation, invariant mass conservation can be deduced from these (note that, the K^* measurements and ν_μ measurements on event 2 were derived, not measured, so that momentum will be conserved). Figures 1 and 3 depict the interpolations made via the Beth-Bloche figure while determining the type of particles involved in the interaction, while Figures 2 and 4 depict sample leading-order $\langle f|\, S-1\,|i\rangle$ matrix elements $\mathcal{O}(g^2)$ Feynman diagrams (there are always more than one) for the interactions and decays along with their proceeding primary interaction type (strong, weak, or electromagnetic). See Appendix 1.

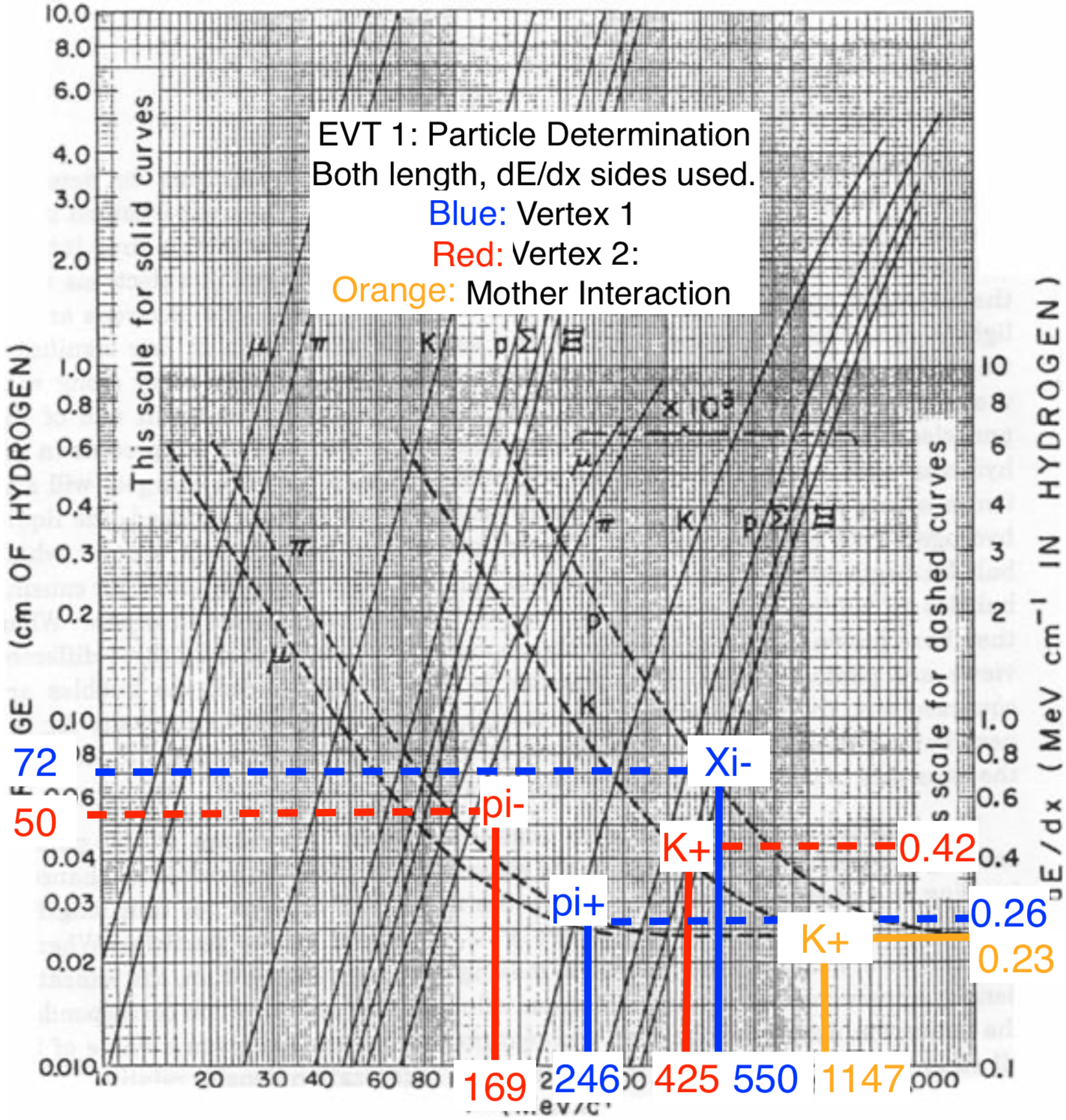
Bibliography

[1] Krieger. P, et al. (rev. 2014) 'High Energy Physics, Lab Manual'. University of Toronto Advanced Undergraduate Laboratory.

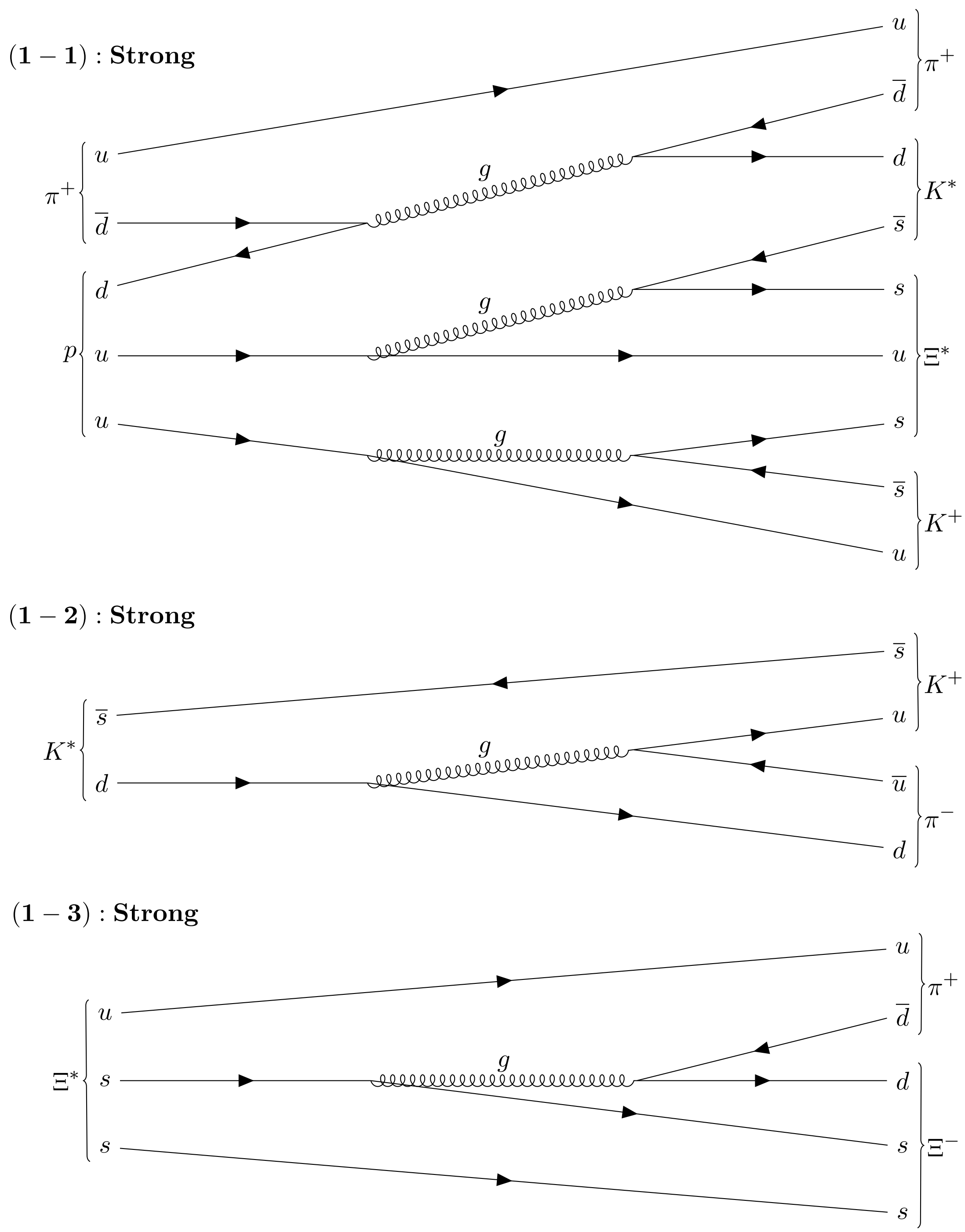
[2] Particle Data Group (Summary Tables). https://pdg.lbl.gov/2023/tables/contents_tables_baryons.html.

[3] Griffiths. D, (2008) 'Introduction to Elementary Particles; 2nd rev. version'. Wiley Publishing, New York, NY.

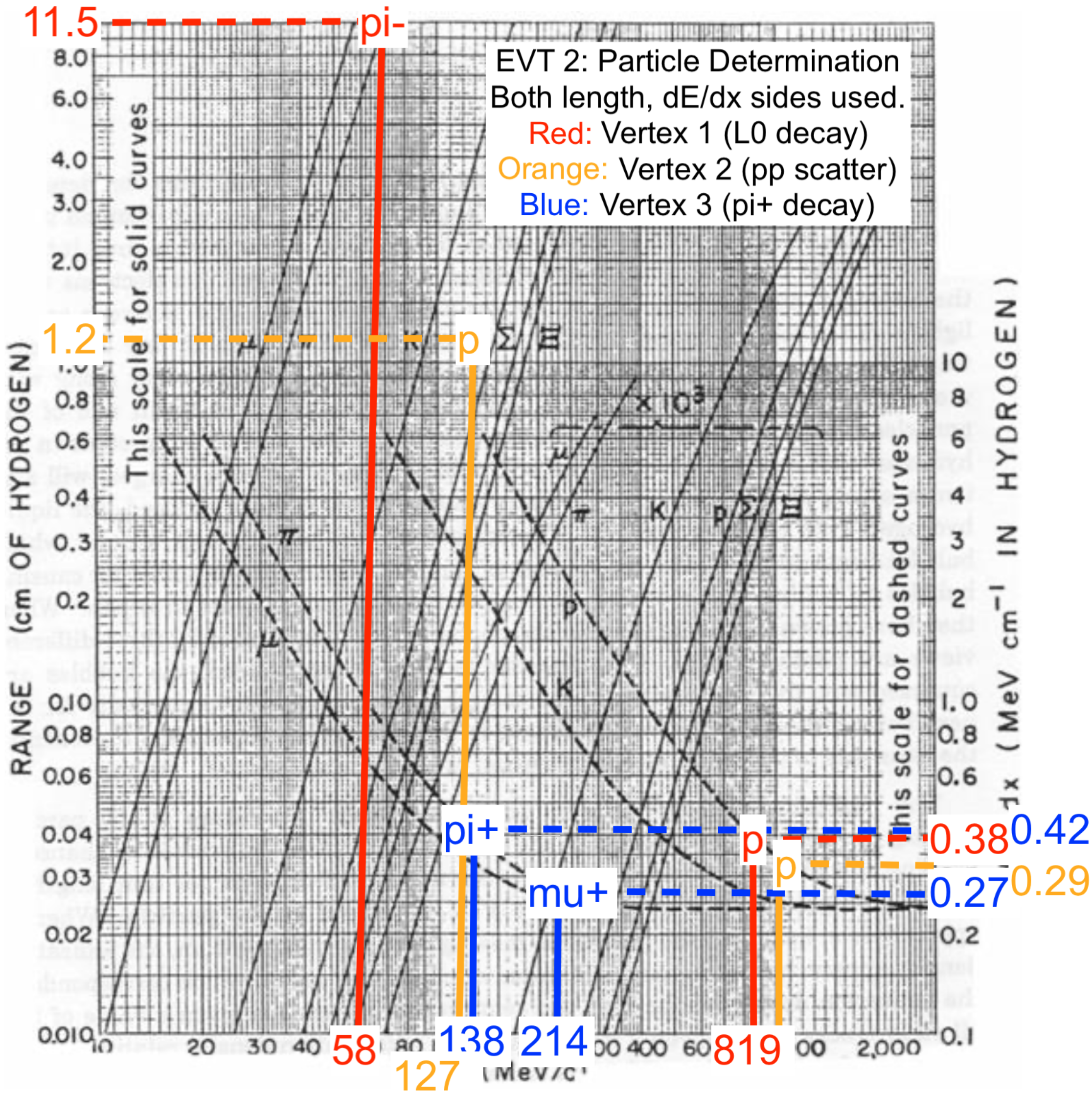
Appendix I - Figures and Tables



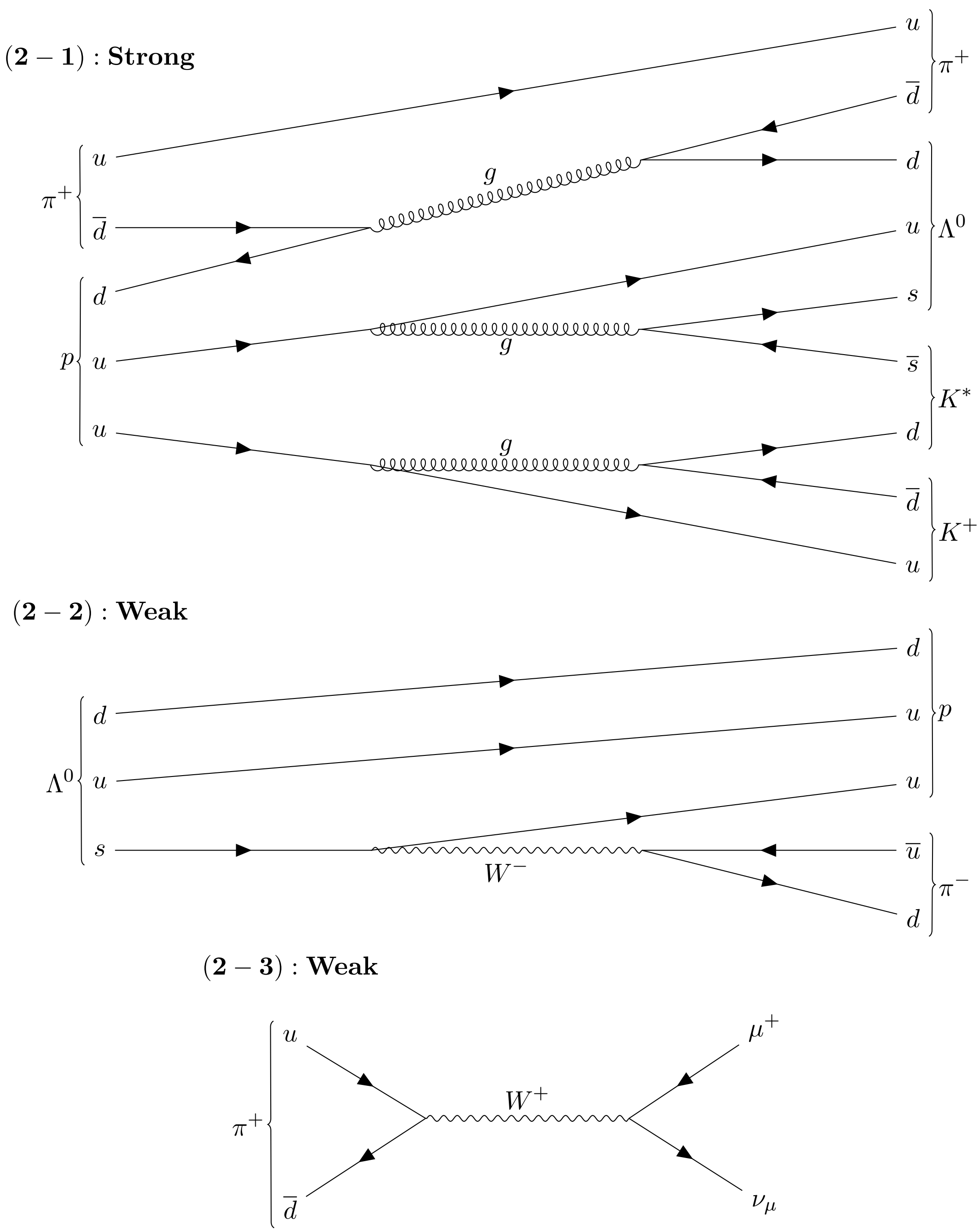
[Figure 1] Particle interpolation for particle determination via the Beth-Bloche curves, completed for event 1.



[Figure 2] Sample first-order Feynman diagrams for the interactions observed in event 1. In (1-1) we note the interaction with takes place at the primary mother vertex, the production of the pion, kaons, and xi baryons. In (1-2) we write the decay of the $K^*(700)$ meson into the positive kaon and negative pion. Lastly in (1-3) the decay of the $\Xi^*(1530)$ baryon into the negative xi and positive pion. All three of these interactions take place via the strong interaction, gluon exchange between quarks. Observe that strangeness, charge, baryon number, and quark flavours are all conserved.



[Figure 3] Particle interpolation for particle determination via the Beth-Bloche curves, completed for event 2.



[Figure 4] Sample first-order Feynman diagrams for the interactions observed in event 2. In (2-1) we note the interaction with takes place at the primary mother vertex, the production of the pion, kaons, and lambda baryons, proceeding via the strong interaction. In (2-2) we write the decay of the Λ^0 baryon into the proton and negative pion, proceeding via the weak interaction. Lastly in (2-3) the decay of the π^+ into the positive (anti)muon and the muon neutrino, proceeding via the weak interaction. Observe that charge and baryon number are both conserved in all interactions, however that strangeness is not conserved in (2-2) (weak interaction does not conserve strangeness and quark colour), quark flavour is not conserved in (2-2) and (2-3), however muon lepton number is conserved in (2-3) as expected, assuming the neutrino does not oscillate.

Event [Obs.], f Factor	Track (Particle)	Momentum (MeV)	Length (cm)	Angle to Incident Particle ($^\circ$)	Optical Density $(\mathrm{cm})^{-1}$	dE/dx (MeV cm^{-1})
1-1	$K^+_{(1)}$	1150 ± 90	72 ± 5	7.2 ± 0.1	700 ± 70	0.23 ± 0.05
[Pri.]	π^+	7900 ± 600	135 ± 10	1.5 ± 0.2	790 ± 80	N/A
	K^*	580 ± 9	N/A	14 ± 2	N/A	N/A
	Ξ^*	787 ± 8	N/A	15 ± 2	N/A	N/A
1-2	π^-	170 ± 10	50 ± 10	5.37 ± 0.08	N/A	N/A
[K^*]	$K^+_{(2)}$	430 ± 30	28 ± 2	20.97 ± 0.04	1500 ± 200	0.5 ± 0.1
1-3	π^+	250 ± 20	15 ± 1	13.36 ± 0.08	740 ± 80	0.26 ± 0.05
[Ξ^*]	Ξ^-	550 ± 40	73 ± 6	5.4 ± 0.3	N/A	N/A
(3.5 ± 0.6)e-4						
2-1	$\pi^+_{(1)}$	4000 ± 300	61 ± 5	15.9 ± 0.3	N/A	N/A
[Pri.]	$\pi^+_{(2)}$	140 ± 10	11.1 ± 0.9	26 ± 3	1700 ± 200	0.42 ± 0.08
	Λ^0	850 ± 70	N/A	20.8 ± 0.1	N/A	N/A
	K^*	700 ± 200	N/A	8.8 ± 0.1	N/A	N/A
2-2	π^-	58 ± 4	11.5 ± 9	52.5 ± 0.2	1500 ± 200	0.36 ± 0.07
[Λ^0]	$p_{(1)}$	820 ± 60	12.5 ± 0.9	7.4 ± 0.4	1600 ± 200	0.39 ± 0.08
2-3	μ^+	210 ± 20	18 ± 1	2.3 ± 0.4	1200 ± 100	0.29 ± 0.06
[π^+]	ν_μ	41 ± 7	N/A	9 ± 3	N/A	N/A
2-4	$p_{(2)}$	920 ± 70	40 ± 3	4.61 ± 0.04	1200 ± 100	0.29 ± 0.05
[pp]	$p_{(3)}$	127 ± 8	1.2 ± 0.1	99.3 ± 0.7	1500 ± 100	0.38 ± 0.07
(2.5 ± 0.4)e-4						

[Table 1] List of acquired measurements from the Traxis analysis of particle paths. See discussion for detailed enquiries on uncertainty choices and comments on the event 2 momentum conservation. This table includes the measured momentum, track length, angles, optical density, dE/dx values, and the f optical density conversion factors for each event, along with all errors. Any 'N/A' in a column indicates that the value was unable to be calculated, whether that be a Traxis limitation, the track cannot be directly observed, or a limitation while invoking the Beth-Bloche charts shown in Figures 1 and 3. The observation of the event is listed in the first column underneath the event name, where '1-x' indicates a measurement on the photo 10-164-0872 and '2-x' indicates a measurement on the photo 20-254-0810.