1 Theory

Useful formula:

$$p = 0.3 \cdot B \cdot V \cdot r \tag{1}$$

2 Results

2.1 Multiplicity

Of the 64 inelastic scattering events, 11 had two, 35 four, 13 six, and 5 eight outgoing charged particles, giving a total of 280 charged tracks from 64 events, giving an average charged multiplicity of $m_{\text{chg}} = 4.375$. This matches our expectations for $s \approx 47$ GeV^2.[5]
From this, the π^0 multiplicity is

$$m_0 = \frac{m_{\text{chg}}}{4} = 1.094$$

As at high energies, positive, negative and neutral pions are created in equal numbers,[5,6] we expected the multiplicity to be around 1.3 ± 0.3.
The other way we calculated the neutral pion multiplicity is to count the detected pair productions. We found 4 such events. The formula then reads

$$m_{\pi^0} = \frac{n_{\text{pp}} \cdot l}{2 \cdot n_{\text{inel}} \cdot \left((x_0 \cdot e^{-l/x_0} - 1) + l\right)} = 0.5026 \pm 0.0003, \tag{2}$$

where the error comes from the uncertainty of the measured length of (148.739 ± 0.085) we examined. This result is in disagreement with the first, and the reason is the low pair production count we recorded (quantifying this uncertainty would also give a much larger deviation for the multiplicity)

2.2 Neutrino momentum

The pion had an initial radius of 27.0 ± 0.9 cm, this gives a momentum of 120.1 ± 3.8 MeV/c. The track length was measured to be 79.3 ± 0.9 cm. The graph provided gave a corresponding 128.5 ± 5.9 MeV/c. Comparing the two values, we infer that the pion has indeed decayed while at rest in the laboratory frame.
Next, we measured the length of the μ track, and found it to be 0.597 ± 0.085 cm. From the graph again, a momentum of 27.64 ± 1.26 MeV/c was read, in fairly good agreement with the theoretical 29.8 MeV/c value.[5]

2.3 V0

We found two V_0-canditate events. It is important to note that the angle between the two produced particles in each case was close to 0°, so the possibility of these being pair productions is considerable.
On image 2898 we detected a primary vertex with 2 visible outgoing particles and one distant vertex of two particles with opposite charges (meaning it was a decay process) which is suspected to have come from the primary vertex. The distance of the two vertices was measured to be 137 cm.

2.3.1 The secondary vertex

The neutral particle decayed into two particles with an angle of $(0 \pm 0.1)°$ between them, this made the association to the primary vertex an easy task. We measured the two radii to be (56 ± 2) cm for the negative, 750 ± 50 for the positive particle. From Eqn. 1, in a coordinate system with the x-axis along the supposed V_0 path, we get

$$\begin{aligned} p_- &= ((249.2 \pm 8.9)\,\text{MeV/c}, \quad (0.22 \pm 0.22)\,\text{MeV/c}) \\ p_+ &= ((3337.1 \pm 222.7)\,\text{MeV/c}, \ (-2.92 \pm 2.92)\,\text{MeV/c}) \end{aligned}$$

The total V_0 momentum is then

$$|p_0| = (3586.21 \pm 222.89)\,\text{MeV/c} \tag{3}$$

2.3.2 A first look at the primary vertex

The primary vertex consists of the incoming proton, and two positively charged particles: particle 1 has a path with radius (2000 ± 200) cm and angle $(2 \pm 0.3)°$, particle 2 (1700 ± 100) cm and $(4.5 \pm 0.3)°$. Using the incoming beam as the direction of the x-axis and the positive quarter plane being the top right one, we can write down the momenta:

$$\begin{aligned} p_1 &= ((8893.4 \pm 889.8)\,\text{MeV/c}, \quad (310.6 \pm 56.0)\,\text{MeV/c}) \\ p_2 &= ((7540.7 \pm 444.2)\,\text{MeV/c}, \quad (-593.5 \pm 52.7)\,\text{MeV/c}) \\ p_0 &= ((3585.7 \pm 62.6)\,\text{MeV/c}, \quad (222.9 \pm 19.2)\,\text{MeV/c}) \end{aligned}$$

$$\Sigma p = ((20019.7 \pm 1019.1)\,\text{MeV/c}, \ (-220.3 \pm 79.3)\,\text{MeV/c})$$

The momenta of the three particles do not add up to the momentum of the incoming proton (23877 MeV/c in the x-direction), this offers two probable explanations to check first:

- Another neutral particle was created which was not detected, or
- One neutral particle was created that decayed into neutral particles very close to the primary vertex, and one of these decayed, showing up as a secondary vertex.

Of course other options are also possible, but we are hoping to find the event to be one of these two types.

2.3.3 Determining V_0

Unfortunately, we cannot conclude much from the secondary vertex, situated (138 ± 1) cm away from the

Name	Mass (MeV)	Decays into	Fraction
Λ	1115.7	$\mathrm{p}\,\pi^-$	63.9%
K^0_S	497.6	$\pi^+\,\pi^-$	69%
K^0_L	497.6	$\pi^\pm\,e^\mp\nu_\mathrm{e}$ $\pi^\pm\mu^\mp\nu_\mu$	40.6% 27.0%
Σ^0	1192.6	$\Lambda\,\gamma$	100%
Ξ^0	1314.9	$\Lambda\,\pi^0$	99.5%

Table 1: Possible neutral particles[4]

Figure 1: First primary vertex examined.

primary vertex, showing the path of two particles which leave the chamber. We assume that the V_0 particle decayed into two charged particles and nothing else, as the overall momentum already matches what we expect, thus a possible neutral particle would have a pro- or retrograde motion, and we regard this as unlikely. Looking at Table 1, we see 3 possible scenarios:

- V_0 is a Λ particle, another neutral particle left the primary vertex undetected; the secondary vertex contains a proton and a pion,
- instead of a Λ, a K^0_S was created, which decayed into a pair of pions,
- A Σ^0 was created at the proton-proton collision, which then decayed within a few picometers, resulting in a Λ baryon which decayed into a proton and a pion, and a photon.

We can calculate the mass of the V_0 for these scenarios:

$$m_{\mathrm{V}_0}(\mathrm{p},\,\pi^-) = (1103.2 \pm 1028.3)\,\mathrm{MeV}$$
$$m_{\mathrm{V}_0}(\pi^+,\,\pi^-) = (532.8 \pm 2132.2)\,\mathrm{MeV}$$

The uncertainty is tremendous in both cases. We decided for the proton-pion case after comparing the relative errors. This means the V_0 was a Λ baryon.

2.3.4 Primary vertex revisited

The overall missing momentum of the system (the incoming proton has a momentum of 23895 MeV/c, hitting a stationary proton) is

$$p_\mathrm{missing} = ((7743.0 \pm 994.5)\,\mathrm{MeV/c}, (282.9 \pm 76.9)\,\mathrm{MeV/c})$$

It turns out that the simplest proposition for the missing momentum, the Σ^0 particle, would explain this missing momentum. To see this, check the conservation laws:

- Baryon number: the Σ^0 (uds) gives 1, this means one of the created charged particles must be a baryon, the other one a meson.
- Strangeness: Σ^0 has $S = -1$, the barion or the meson should have a $\bar{\mathrm{s}}$ quark.
- Flavours: the barion and the meson should have 3 u, 1 d, 1 $\bar{s}$ quarks.

Overall, one of the created particles is a proton, the other a positively charged Kaon (K^+, $\mathrm{u}\bar{\mathrm{s}}$). To check our proposition, we look at the energy conservation:

- The initial energy is $23895 + 938 = 24833$ MeV.
- $E(p_1,\, p^+) = (8948.1 \pm 884.3)$ MeV if we assume p_1 belongs to a proton,
- $E(p_2,\, K^+) = (7580.1 \pm 441.9)$ MeV,
- $E(p_\mathrm{missing}, \Sigma^0) = (7543.2 \pm 981.3)$ MeV,

giving an overall energy of (24071.4 ± 1392.9) MeV, which matches the initial energy. Switching the proton and kaon tracks yields (24077.6 ± 1394.4) MeV, also a valid result, thus we cannot uniquely assign the two final particles to tracks.

To sum up our results, we explain the event as a $\mathrm{p}\,\mathrm{p} \to \mathrm{p}\,\mathrm{K}^+\,\Sigma^0$, $\Sigma^0 \to \gamma\,\Lambda$ collision, where we detected $\Lambda \to \mathrm{p}\,\pi^-$.

3 V0 #2

In our second V_0 event, we have a primary vertex with 4 visible outgoing particles, and the secondary vertex is (18.8 ± 0.5) cm away from the primary one. With the notation on Figure 2 and labeling the positively charged secondary vertex particle as 5, the other one 6, we measured

$$\begin{aligned}
r_1 &= (47 \pm 3)\ \mathrm{cm},\\
r_2 &= (3300 \pm 500)\ \mathrm{cm},\\
r_3 &= (300 \pm 20)\ \mathrm{cm},\\
r_4 &= (490 \pm 20)\ \mathrm{cm},\\
r_5 &= (320 \pm 20)\ \mathrm{cm},\\
r_6 &= (62 \pm 3)\ \mathrm{cm},\\
\measuredangle_{5,6} &= (0.0 \pm 0.1)^\circ,\\
\measuredangle_1 &= (54 \pm 1)^\circ,\\
\measuredangle_2 &= (0.0 \pm 0.5)^\circ,\\
\measuredangle_3 &= (-5.0 \pm 0.5)^\circ,\\
\measuredangle_4 &= (-5.0 \pm 0.5)^\circ.
\end{aligned}$$

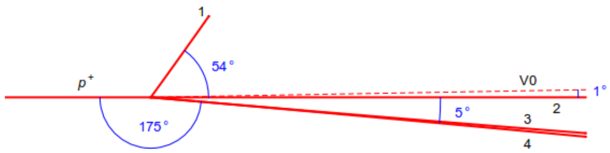

Figure 2: Second V_0 event.

From these values, the momenta are

$$
\begin{aligned}
p_1 &= ((122.9 \pm 8.4)\,\mathrm{MeV/c}, & (169.2 \pm 11.0)\,\mathrm{MeV/c})\\
p_2 &= ((14683.0 \pm 2225.2)\,\mathrm{MeV/c}, & (0.0 \pm 128.1)\,\mathrm{MeV/c})\\
p_3 &= ((1329.7 \pm 88.8)\,\mathrm{MeV/c}, & (-116.3 \pm 14.0)\,\mathrm{MeV/c})\\
p_4 &= ((2171.9 \pm 88.9)\,\mathrm{MeV/c}, & (-190.0 \pm 20.5)\,\mathrm{MeV/c})\\
p_0 &= ((1699.4 \pm 90.1)\,\mathrm{MeV/c}, & (29.7 \pm 14.9)\,\mathrm{MeV/c})
\end{aligned}
$$

$$p_{\mathrm{m}} = ((3870.0 \pm 2230.5)\,\mathrm{MeV/c}, \quad (107.5 \pm 131.8)\,\mathrm{MeV/c})$$

The missing momentum is within the uncertainty of the V_0 momentum p_0, therefore it is satisfactory to assume the direct creation of a Λ or K^0. The bubble density of the tracks leaves electrons as highly unlikely participants of the V_0 decay. Investigating the different scenarios (neglecting the neutrino momentum and mass):

- $m_{V_0}(\pi^+, \pi^-) = (371.6 \pm 587.7)$ MeV,
- $m_{V_0}(p, \pi^-) = (1081.1 \pm 199.4)$ MeV,
- $m_{V_0}(\mu^+, \pi^-) = (357.7 \pm 610.6)$ MeV,
- $m_{V_0}(\pi^+, \mu^-) = (300.6 \pm 723.7)$ MeV.

The most realistic result is for the case of the p π^- pair. Thus the secondary vertex is the decay of a Λ or Ξ^0 baryon (as both masses fall within the uncertainty interval), and the former might have come from the primary vertex itself, or from a decay of a Σ^0 or Ξ^0.
As for the primary vertex, due to the relatively large uncertainties, we cannot assign particles uniquely to each track. It is interesting to note, though, that if we assume the V_0 is a Λ baryon, the other strange particle (4) is a meson (K^+), particle 1 a π^+, particle 2 a proton, particle 3 a π^-, the overall energy is (20575.0 ± 2225.3) GeV, significantly below 24833 GeV meaning we need another neutral particle to satisfy energy conservation. We can, however, add a π^0 with a $\approx 200 - 300$ MeV due to the relatively large error in p_m. As a simple example, assigning p_0 and $p_m - p_0$ to the Λ and π^0, $E = (22751.2 \pm 3083.9)$ GeV, resolving the energy deficit. Thus this is a valid scenario, satisfying all relevant conservation laws.

References

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