Memo to SPSC (November 2009)

- The SPSC committee is interested in seeing some results from 2008 data, in particular on πK-atoms with improved precision after 2007.

Our colleague Valery Yazkov performed an express analysis of the 2008 data:

The offline software was tuned very carefully. For the analysis we used information from all detectors excluding the microdrift chambers and the W-plane of the scintillation fiber detector (SFD). This temporary simplification reduces the number of events that can be reconstructed with unambiguous matching of downstream tracks with upstream SFD hits (requirement of not more than two hits in the expected SFD region). This approach leads to the reconstruction of 42% of the total events.

Let us discuss the procedure of reconstruction in details.

The simplified procedure of the data treatment is based on extrapolation of the tracks to the target using tracks in the drift chambers after the magnet and the known magnet field map. The intersection points of tracks with the X and Y SFD planes give the expected X and Y coordinates of the hits in SFD (Figure 1). Due to multiple scattering, the region of the hits is around ± 10mm on average.

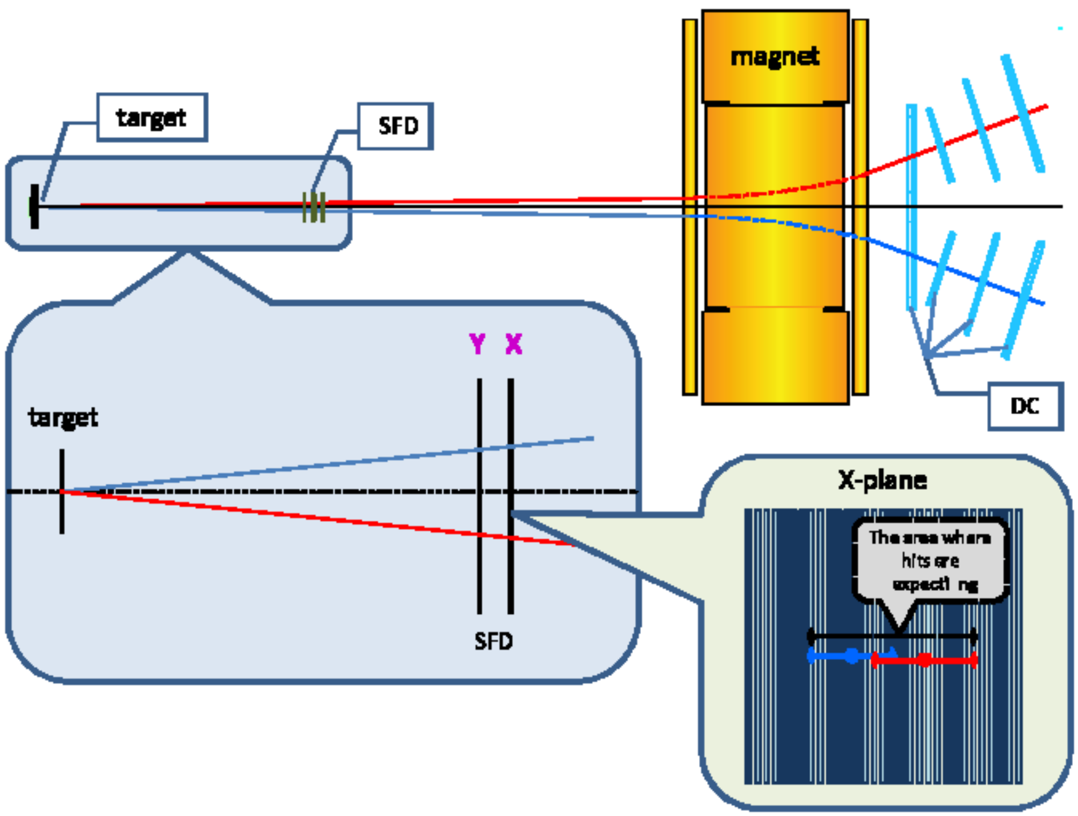

Figure 1.

The investigated events are characterized by small angles between particles. Therefore the regions of expected hits for the positive and negative particles are overlapping for most of the events. In the analysis one selects events with one or two X as well as Y SFD hits in this region. Such events represent 42% from the overall statistics.

The events with 3 or more hits in any of the X or Y plane in the expected region will be treated by using the data from the micro-drift chambers and the SFD W plane. According to our preliminary estimates, the efficiency of the data treatment using the information from all detectors will be not higher than 80%.

One can also notice that the proton beam intensity during data taking is presently restricted by the numbers of hits in the SFD.

The software for offline reconstruction of the microdrift chambers and the SFD W-plane will be implemented in the common DIRAC software in November 2009. By March 2010 the tracking procedure will be modified to incorporate these two detectors. By June 2010, the 2008 data will be reprocessed including all detectors. The full processing of the 2009 data is expected for November 2010.

For the restricted event sample described above, the experimental distributions for $\pi^+\pi^-$, π^+K^- and $K^+\pi^-$ pairs over the longitudinal component Q_L of the pair CMS relative momentum are shown in Figures 2-4. These data are used in the following investigations. The corresponding distribution for $K^+\pi^-$ pairs from 2007 is much wider and the background higher as seen in Figure 5. (The background in the Q_L distribution of πK pairs is non-symmetrical due to the setup acceptance: K-mesons are preferably detected with lower momenta that in CMS correspond to the opposite orientation of the kaon momentum and the total momentum of the pair. The opposite slopes for π^+K^- and $K^+\pi^-$ are due to the definition $\vec{Q} = \vec{p}_+ - \vec{p}_-$.)

In 2007, in comparison to 2008, the information from the SFD X-plane was not recorded. Therefore, the already published results in the article "Evidence of πK-atom with DIRAC" (Physics Letters B 674 (2009) 11) were obtained by using only downstream detectors in the event reconstruction. In such an approach, pairs from the πK atom breakup (atomic pairs) are reconstructed showing a peak at zero pair CMS relative momenta with RMS (width) of 2.9 MeV/c, 2.6 MeV/c and 0.96 MeV/c in the X, Y and L projection, correspondingly. The atomic pairs were extracted from the Q_L distribution (Figure 5), which was obtained by applying a cut of $Q_T < 8$ MeV/c (transversal component).

Incorporating the X and Y planes of SFD into the 2008 data processing reduces the momentum widths of the reconstructed atomic pairs to 1 MeV/c for the X and Y projections (Q_X and Q_Y) and to 0.9 MeV/c for the longitudinal projection (Q_L). Such a significant improvement in the transverse component resolution allows to apply a much tighter cut of $Q_T < 4$ MeV/c. In Figure 6, an illustrative distribution of the background over Q_T shows an almost linear dependence. This means that a change of the Q_T cut from 8 to 4 MeV/c reduces the background by 4. This can be seen by comparing Figure 4 with 5. Moreover, the Coulomb peak in Figure 4 is narrower due to the better Q_T resolution.

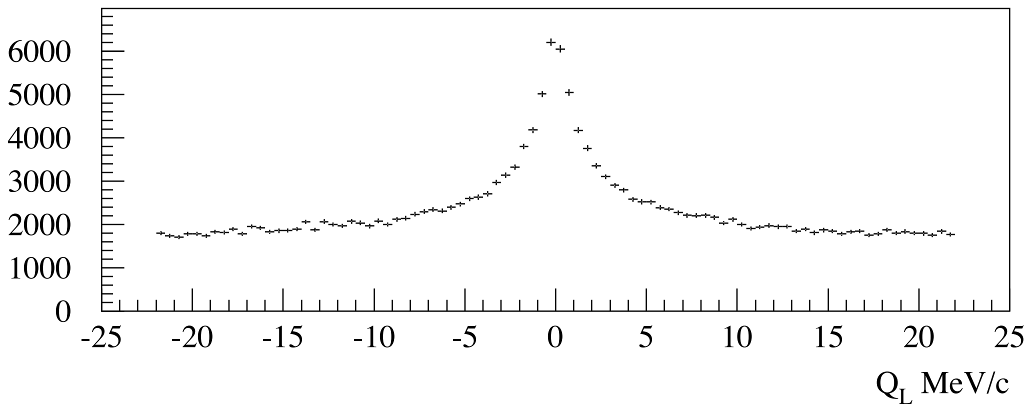

Figure 2: Q_L-distribution for $\pi^+\pi^-$ pairs from 2008 data.

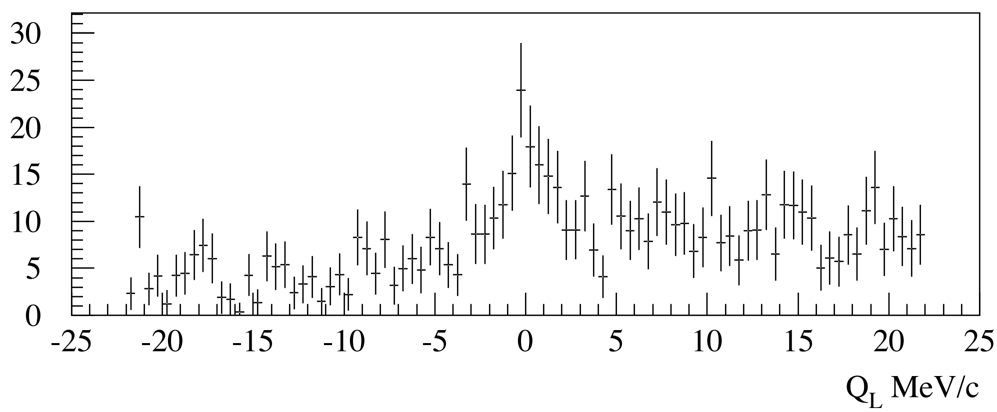

Figure 3: Q_L-distribution for π^+K^- pairs from 2008 data.

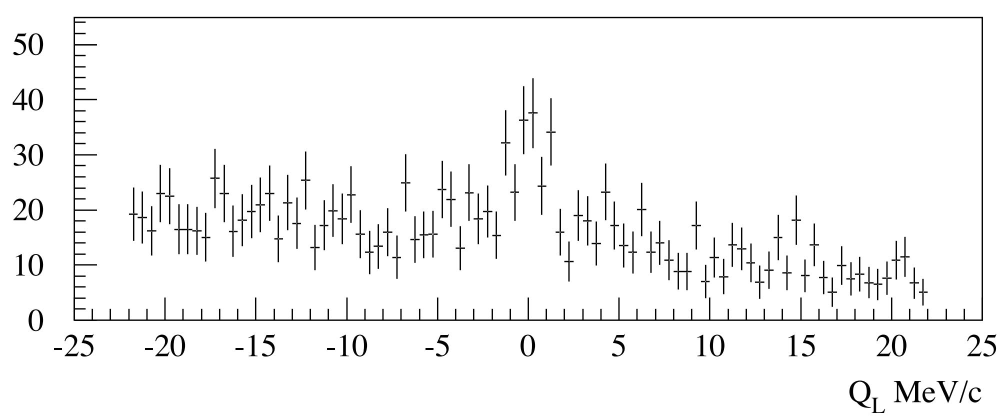

Figure 4: Q_L-distribution for $K^+\pi^-$ pairs from 2008 data.

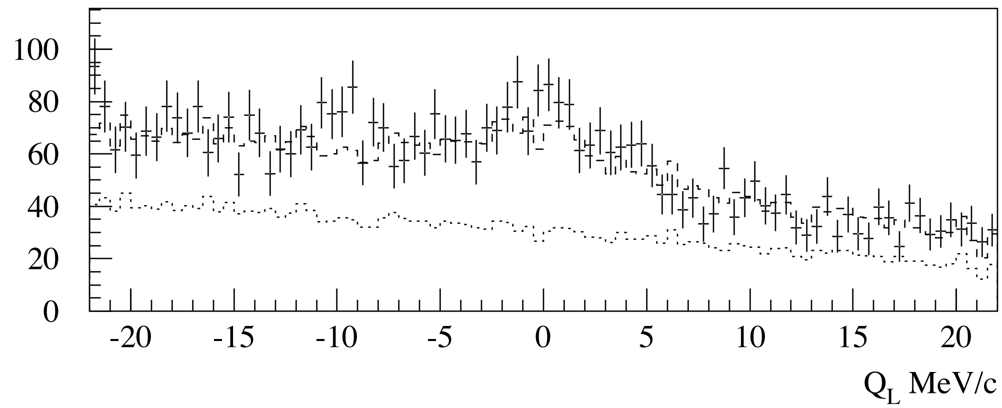

Figure 5: Q_L-distribution for $K^+\pi^-$ pairs from 2007 data.

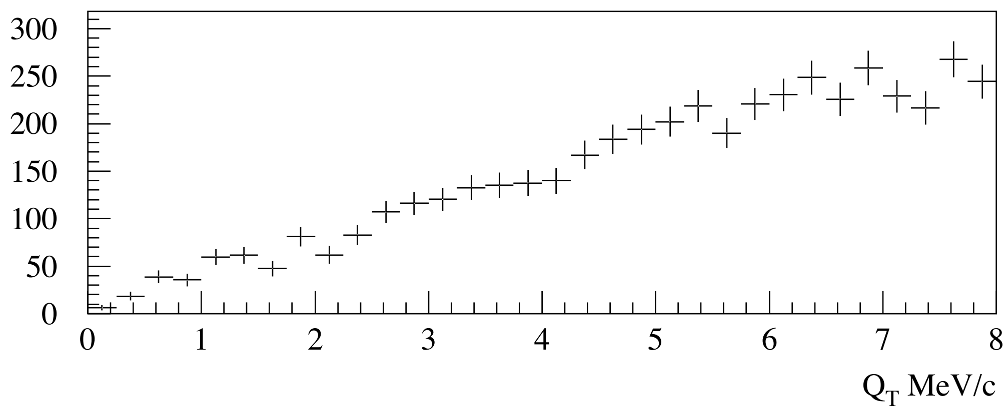

Figure 6: Q_T-distribution for $K^+\pi^-$ background pairs from 2007 data.

- Could you give an estimate of the significance of the πK signal from these 2008 data?
- Could you provide numbers for the expected overall significance of the πK signal at the end of 2009 and an estimate of how much more running is needed in 2010 to reach 5 sigma?

1. In the current analysis the background of Coulomb and non-Coulomb pairs was obtained from the experimental accidentals. In all tables below however, the statistical error of the accidentals was excluded under the assumption that the background will be simulated in the ongoing analysis.

2. In the Tables 1-4 the first rows show the following quantities: the number of produced atoms (N_A)[1], obtained in a model-independent way from the number of Coulomb pairs observed in the reduced event sample (42%); the expected number of atomic pairs (n_A)[2], determined from N_A and the calculated breakup probability, assuming the πK-atom lifetime predicted by theory; observation significance $n_A/Error$. The 2009 data for these rows correspond to the data collected till the end of September. In the second rows the same quantities are given for the case of a better event reconstruction

[1] N_A is the number of atoms generated in proton-nuclear interactions.

[2] n_A is the number of "atomic pairs" which are free $\pi^+\pi^-$ ($K^+\pi^-$ or π^+K^-) pairs generated in atom breakup due to interaction with a target matter.

efficiency of 63% expected by taking into account also the microdrift chambers and the SFD W-plane. For these rows it is assumed that in 2009 data will be collected with the current rate till the end of run, 23 November 2009. In addition, a further improvement in the microdrift chamber precision will allow to reconstruct about 80% of all events. The corresponding results are presented in the third table rows.

Table 1: Predictions for $K^+\pi^-$ with the Nickel target

	2008 + 2009		
reconstruction efficiency	N_A	n_A	$n_A/Error$
42%	158	49	2.41 ± 0.42
63%	274	85	3.17 ± 0.55
80%	348	108	3.55 ± 0.62

Table 2: Predictions for π^+K^- with the Nickel target

	2008 + 2009		
reconstruction efficiency	N_A	n_A	$n_A/Error$
42%	97	30	1.88 ± 0.28
63%	168	52	2.56 ± 0.39
80%	213	66	2.83 ± 0.43

Table 3: Predictions for πK pairs of both signs with the Nickel target

	2008 + 2009			2008 + 2009+2010
reconstruction efficiency	N_A	n_A	$n_A/Error$	$n_A/Error$
42%	255	79	3.06 ± 0.37	3.79 ± 0.46
63%	442	137	4.07 ± 0.49	5.15 ± 0.62
80%	561	174	4.54 ± 0.55	5.74 ± 0.70

Table 4: Prediction for πK pairs of both signs
with the Platinum target (2007) and Nickel target (2008+2009)

	2007 + 2008 + 2009
reconstruction efficiency	$n_A/Error$
42%	3.82 ± 0.35
63%	4.67 ± 0.45
80%	5.08 ± 0.51

3. From the results above it is obvious that a significant observation of πK-atoms can only be achieved after running in the year 2010. At this point it should be emphasized

that the aim of the experiment is not only to observe πK-atoms, but to measure their lifetime and to extract important πK-scattering lengths.

The πK-atom lifetime measurement precision as a function of the accuracy of its breakup probability W_{break} are estimated and presented in Table 5. The πK-atom lifetime $\tau_{\pi K\text{-atom}} = 3.7\cdot 10^{-15}$ s is taken from theory predictions. The accuracy of the W_{break} measurement is mainly determined by the uncertainty in the determination of the atomic pair number n_A. The first row of Table 5 presents this accuracy in numbers of standard deviations and in percentage. The third row shows the relative errors (upper and lower errors of τ averaged) of the value for $|a_{1/2} - a_{3/2}|$, where $a_{1/2}$ and $a_{3/2}$ are the s-wave πK scattering lengths with isospin 1/2 and 3/2, respectively.

Table 5: Lifetime and scattering length measurement precision as a function of measured breakup probability accuracy

Measurement accuracy	5σ (20%)	6σ (17%)	6.5σ (15%)
$\tau_{\pi K\text{-atom}}$ (s)	$(3.7\ {}^{+60\%}_{-43\%})\cdot 10^{-15}$	$(3.7\ {}^{+51\%}_{-38\%})\cdot 10^{-15}$	$(3.7\ {}^{+46\%}_{-32\%})\cdot 10^{-15}$
$\delta_{av}\lvert a_{1/2} - a_{3/2}\rvert$	26 %	23 %	20 %

- If the 2008 data confirm the factor of 6 reduction in πK rate compared with your FRITIOF prediction, do you have some understanding of the origin of this discrepancy?

As mentioned above, up to now only 42% of all the 2008 data are available for a preliminary analysis. The Coulomb enhancement in the production of $\pi^+\pi^-$, π^+K^- and $K^+\pi^-$ pairs is detected (see Figures. 2-5). From these data the following numbers of produced atoms are derived model-independently:

$$N_A^{\pi^+\pi^-} = 8000 \pm 190, \quad N_A^{K^+\pi^-} = 70 \pm 24, \quad N_A^{K^-\pi^+} = 45 \pm 18.$$

The errors in the atom numbers include the statistical errors in the accidental background used for simulating Coulomb and non-Coulomb pairs. The measured ratio of $\pi\pi$ to πK atom is

$$\rho = N_A^{\pi^+\pi^-} / \left(N_A^{K^+\pi^-} + N_A^{K^-\pi^+}\right) = 70 \pm 18\,.$$

The corresponding ρ value given in the DIRAC-Addendum (CERN-SPSC-2004-009/ SPSC-P-284 Add.4) was found by means of the FRITIOF-6 generator and is equal to 12. How did we obtain this ratio?

The production cross section for any atom is given by

$$\frac{d\sigma_{nlm}^{A}}{d\vec{p}_A} = (2\pi)^3 \frac{E_A}{M_A} \left|\psi_{nlm}(0)\right|^2 \left.\frac{d\sigma_s^0}{d\vec{p}_1\, d\vec{p}_2}\right|_{v_1 = v_2},$$

where p_A, E_A and M_A are the momentum, energy and mass of the atom in the lab system, respectively; $\left|\psi_{nlm}(0)\right|^2 = p_B / \pi n^3$ is the square of the atomic wave function (without taking into account strong interaction between the particles forming the atom, i.e. pure

Coulomb wave function), calculated at the origin for an atom with principal quantum number n and orbital angular momentum $l = 0$; p_B is the Bohr momentum of the particles forming the atom; $d\sigma_s^0 / d\vec{p}_1 d\vec{p}_2$ is the double inclusive production cross section for pairs from short-lived sources not considering Coulomb final state interaction; p_1, p_2 and v_1, v_2 are momenta and velocities in the lab system of particles forming the atom. The accuracy of the above formula is about 1%.

Neglecting Coulomb interaction in the final state, the double inclusive cross section has the form

$$\frac{d\sigma_s^0}{d\vec{p}_1 d\vec{p}_2} = \frac{1}{\sigma_{inel}} \frac{d\sigma}{d\vec{p}_1} \frac{d\sigma}{d\vec{p}_2} R\left(\vec{p}_1, \vec{p}_2\right),$$

where $d\sigma / dp_1$ and $d\sigma / dp_2$ are the inclusive cross sections of single particles, σ_{inel} is the total inelastic cross section of hadron production and $R\left(\vec{p}_1, \vec{p}_2\right)$ is the correlation function due to strong interaction in the final state.

Thus, the ratio of $\pi\pi$ and πK atom production depends on the ratio of the inclusive cross sections and the ratio of the correlation functions. By simulating the experiment, it was shown that FRITIOF-6 describes correctly the experimental inclusive cross section of p, π^+, π^- and K^+ for 24GeV/c proton-nucleus interaction at emission angles of 3.8° – 7.3°. The DIRAC setup angle range is 4.7° – 5.7°. The p, π^+, π^-, K^+ and K^- lab momentum spectra for the angles 5° and 6.15° are presented in Figures 7-11. The production cross section from FRITIOF-6 for K^- exceeds the experimental one by a factor of about 1.5. As the yield of $K^-\pi^+$ atoms in the DIRAC aperture is smaller than the one of $K^+\pi^-$ by a factor of 1.8, the ρ value cannot be higher than 14.

Thus, the observed discrepancy between the measured value of ρ (although so far with large errors) and the one obtained by using the FRITIOF-6 generator is presumably arising from an incorrect generator description of the correlation function R for $\pi\pi$ and πK pairs at small relative momentum.

The FRITIOF predictions might be improved by tuning its numerous parameters if the inclusive cross sections and inclusive spectra of different resonances were known. Unfortunately, the experimental information on resonance production is very limited not only for the *pNi* interaction at 24 GeV/*c*, but even for pp interactions. For example, there are no data on the ω, η, η', K^{*0} and Δ production. This implies that the ρ ratio can only be determined from DIRAC measurements.

To understand where the generator gets its correlation function at small Q one needs experimental data on numerous resonance production for *pNi* or at least pp interactions at 24 GeV/c. Unfortunately such experimental data are either absent or very restricted.

We can see from Figures 7-11 that - for the initial proton momentum 24 GeV/c and the angular interval of DIRAC – Fritiof-6 describes the inclusive cross-sections better than Fritiof-7. Therefore, Fritiof-6 was used to calculate the ρ value.

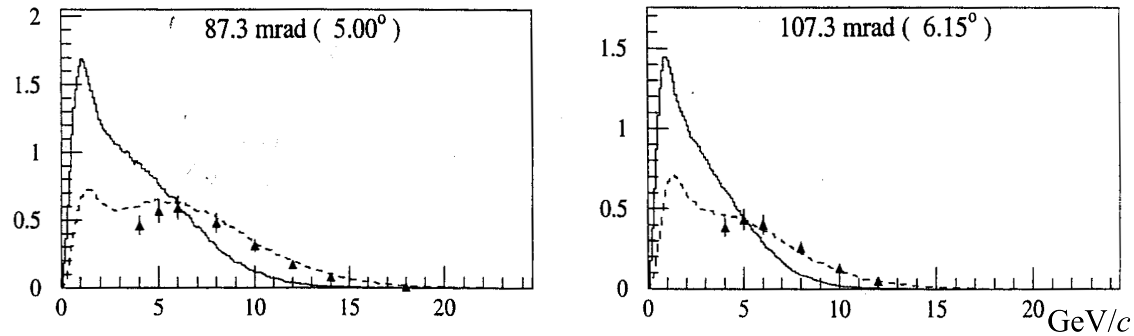

Figure 7: Comparison of the experimental inclusive yield of p from pAl interaction at 24 GeV with the simulated one in FRITIOF-7 (solid line) and FRITIOF-6 (dashed line).

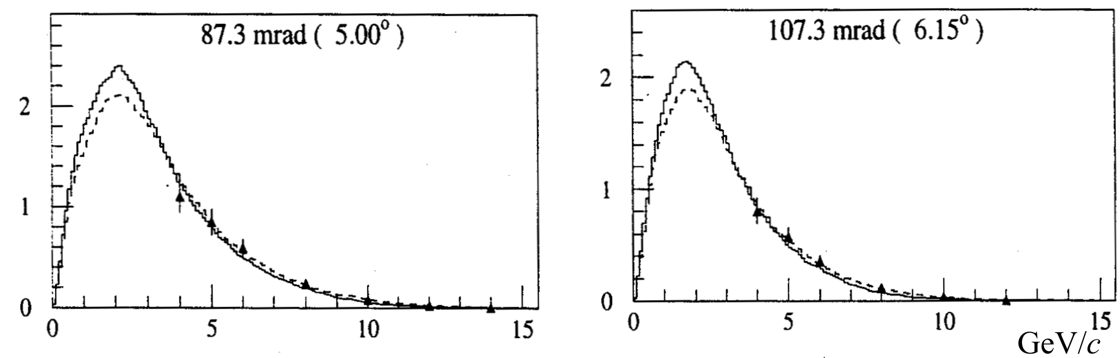

Figure 8: Comparison of the experimental inclusive yield of π^+ from pAl interaction at 24 GeV with the simulated one in FRITIOF-7 (solid line) and FRITIOF-6 (dashed line).

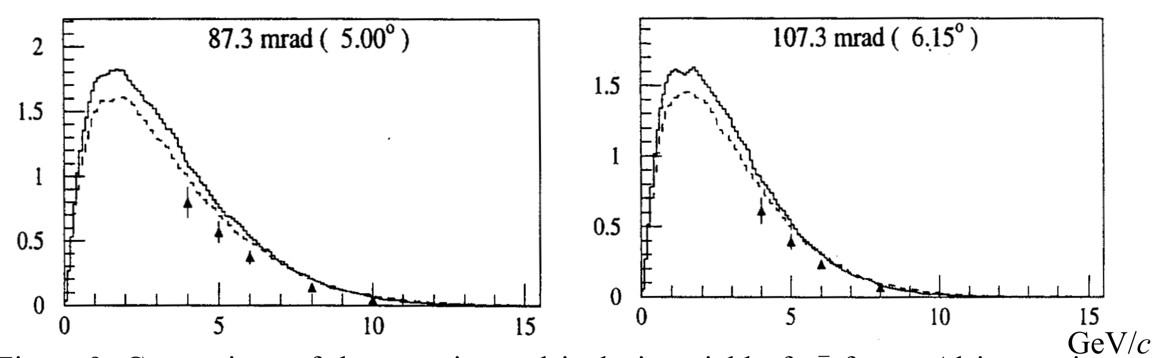

Figure 9: Comparison of the experimental inclusive yield of π^- from pAl interaction at 24 GeV with the simulated one in FRITIOF-7 (solid line) and FRITIOF-6 (dashed line).

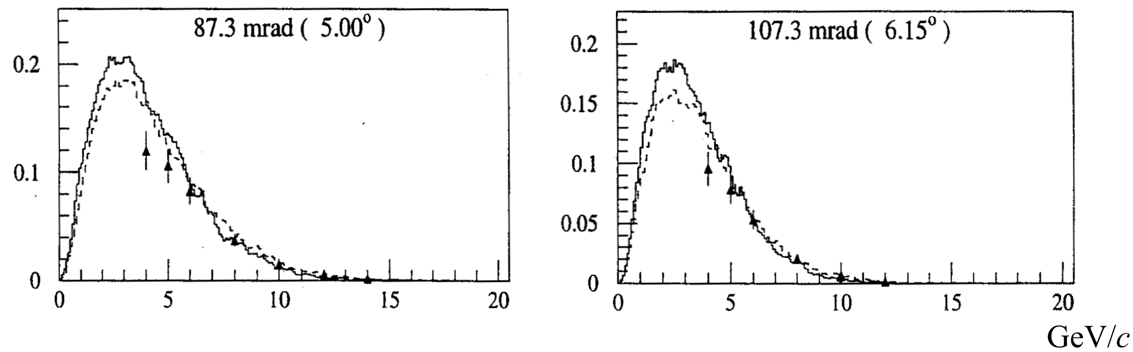

Figure. 10: Comparison of the experimental inclusive yield of K^+ from pAl interaction at 24 GeV with the simulated one in FRITIOF-7 (solid line) and FRITIOF-6 (dashed line).

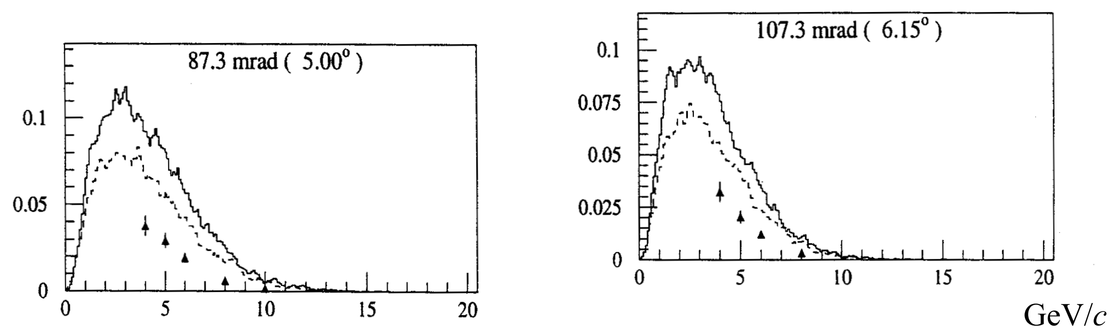

Figure 11: Comparison of the experimental inclusive yield of K^- from pAl interaction at 24 GeV with the simulated one in FRITIOF-7 (solid line) and FRITIOF-6 (dashed line).

- We are asked for full details of the factor 1.6 reduction in spills compared with what was approved.

Here is the answer of the Proton Synchrotron group leader Rende Steerenberg:

In 2001-2003 we ran shorter super cycles because CNGS was not yet operational. Now they are and they require a substantial amount of cycles in the super cycles. The remaining time slots have to be distributed to the other users (DIRAC, T7 Irradiations, T9/T10/T11, nTOF, AD, Fixed target physics in SPS and the LHC beam for tests).

One additional problem is that since the start of 2007 we can no longer share the beam from a single cycle between T7 irradiations and the north branch (T9/T10/T11). Instead we now need to produce their beams on separate cycles. We therefore program now 4 cycles for EASTA and EASTC, where in the past we could do the same with only 2 cycles. The reason for this is that the so called MNP23 magnet that was replaced several times was finally replaced by another magnet (MCB) not allowing simultaneous operation of the north and south branch.

Some details.

At present the situation is the following:

The typical day super cycle is 46.8 sec in which DIRAC get 5 cycles
a 1 cycle every 9.36 seconds
The typical night super cycle is 45.6 sec in which DIRAC get 5 cycles
a 1 cycle every 9.12 seconds

If we would have the MNP23 and could split the north branch we could have replaced one EASTA and one EASTC by two EASTB's which would result in the following:
The typical day super cycle is 46.8 sec in which DIRAC could get 7 cycles
a 1 cycle every 6.7 seconds
The typical night super cycle is 45.6 sec in which DIRAC could get 6 cycles
a 1 cycle every 7.6 seconds
The later gets close to what DIRAC had in 2001-2003 (16.4 / 2.5 = 1 cycle every 6.6 second)

In addition to the accelerator problems, DIRAC spent in 2008 about three months for implementing and tuning new electronics as you were informed in previous messages. Since September 2008, the new electronics is fully operational and satisfies all DIRAC demands.

There is request in the DIRAC ADDENDUM [CERN-SPSC-2004-009, SPCS-P-284, Add.4, 21 April 2004] on the page 82 on the beam time needed for the experiment. The estimation "of the beam time is based on the $A_{2\pi}$ statistics collected in 2001-2003 and on the assumption that we will use 2.5 spills from super-cycle." From the letter of R. Steerenberg it is obvious that DIRAC requested one spill every 6.6s. From the same letter it follows that DIRAC in fact had one spill every 9.24s in 2008-2009 or a factor 1.4 less than in the ADDENDUM.

DIRAC@CERN, November 2009