2 Rare Kaon Decays at Brookhaven AGS

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Our research program at the Brookhaven National Laboratory's Alternating Gradient Synchrotron (AGS) focuses on rare kaon decays. Only at the AGS sufficiently intense low-momentum neutral and charged kaon beams are still available today. Experiment BNL E-865 finished data-taking in 1998, and the last results from the analysis of a high-statistics sample of rare semi-leptonic charged kaon decays are being presented. The KOPIO-experiment has been approved for funding by the U.S. National Science Foundation, and its planning concentrates now on the construction of detector prototypes and development of a suitable neutral kaon beam.

2.1 BNL E-865: a search for lepton flavor violation in K^+ decay

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The final results obtained by experiment E865 concern the search for the lepton flavor number violating (LFNV) decay $K^+ \rightarrow \pi^+\mu^+e^-$ ($K_{\pi\mu e}$), i.e. the decay for which the experiment was primarily set up. The proposal had aimed for a sensitivity level reaching down to a branching ratio below 10^{-11}. With finite neutrino masses established LFNV is no longer forbidden. The standard model extended to incorporate neutrino masses still predicts this decay to occur at an unobservably low level. Several extensions of the standard model, however, allow lepton family number violation at a much higher rate (as high as 10^{-10}). Hence, if the search for the decay is successful, it signals non-standard model physics, if not, parameters of the extension models are constrained. We can illustrate this taking the example of the extended technicolor model (ETC) [1], where the transitions between the leptons of different generations can be mediated by a horizontal ETC boson. Due to the similarity between $K_{\pi\mu e}$ decay and the familiar decay $K_{\mu 3}$ ($K^+ \rightarrow \pi^0\mu^+\nu_\mu$) the branching ratios can be compared to give an approximate mass of the ETC boson (M_H)

$$\frac{B(K_{\pi\mu e})}{B(K_{\mu 3})} = 16\frac{1}{\sin^2\theta_c}\left(\frac{g_H}{g}\right)^4\left(\frac{M_W}{M_H}\right)^4 ,$$

where θ_c is the Cabbibo angle, g and g_H are the weak and ETC coupling constants, and M_W is the mass of the W boson.

The existing limit on the branching ratio for $K_{\pi\mu e}$ of $2\cdot 10^{-10}$ [2] was lowered with E865's 1995/6 data to $2.8\cdot 10^{-11}$ [3]. The analysis of the 1998 data, which was the thesis project of Aleksey Sher [4] has by itself improved the limit to $2.2\cdot 10^{-11}$. A combination of all the above results then leads to $1.2\cdot 10^{-11}$ or, with $g_H \approx g$, to

$$M_H \approx 150\,\mathrm{TeV}\left[\frac{10^{-12}}{B(K_{\pi\mu e})}\right]^{1/4} \geq 80\,\mathrm{TeV}\ .$$

In order to reach this result a time-consuming and difficult analysis had to be brought to conclusion. One difficulty refers to the total amount data, which Aleksey Sher had to handle. During a period of seven months $1.5 \cdot 10^9$ K-decays were registered in the detector, corresponding to 500 Exabyte tapes with approximately 4.5 Gbyte each or 2 Tbyte of raw data. The first analysis step, which reduced the amount of data by about a factor of five, selected events with three charged tracks coming from a reconstructible vertex and took eight months on a cluster of Linux workstations at BNL working around the clock. This cumbersome part was followed by the selection of candidates based on the reconstructed momenta using kinematics, proper particle identification, the decay vertex and the event timing. The blind analysis philosophy was followed here, i.e. all conceivable sources of background were investigated first and criteria were developed to suppress them, before the small volume in the multi-parameter space, in which the real events were expected, the so-called *box*, was looked at.

Three types of background had to be dealt with:

- decays in which one or two of the products decayed, too, yielding the correct $K_{\pi\mu e}$ final particles, for example the K_τ decay sequence $K^+ \to \pi^+\pi^+\pi^-$; $\pi^+ \to \mu^+\nu_\mu, \pi^- \to e^-\bar{\nu}_e$,
- decays in which one or two of the decay products were misidentified, for example again K_τ with a π^- misidentified as an e^- and a π^+ as a μ^+, and
- accidental overlap of two kaon decays simulating a real decay.

The detector [5] resided in a 6 GeV/c unseparated K^+ beam and featured a high resolution magnetic charged particle spectrometer with four large multi-wire proportional chambers, two of them built by us in Zürich, a finely segmented electromagnetic calorimeter of shashlyk type, a muon range filter equipped with proportional tubes, and two large atmospheric pressure gas Čerenkov counters within the spectrometer magnets. Calorimeter and Čerenkov counter information was used for e versus π discrimination. Only 0.2 event from these two types of backgrounds were expected in the signal region. In order to reach this prediction extensive Monte Carlo simulations were necessary, with the experimentally and independently determined detector efficiencies properly adapted to the high rate running conditions of 1998. The acceptance for $K_{\pi\mu e}$ events and the two monitor decays from pre-scaled minimum bias trigger events K_{Dal} ($K^+ \to \pi^+\pi^0$; $\mu^+\pi^0\nu_\mu$; $e^+\pi^0\nu_e$; $\pi^+\pi^0\pi^0$; $\pi^0 \to e^+e^-\gamma$) and K_τ had to be calculated. Figures 2.1 and 2.2 illustrate how well the simulation represents the measured quantities.

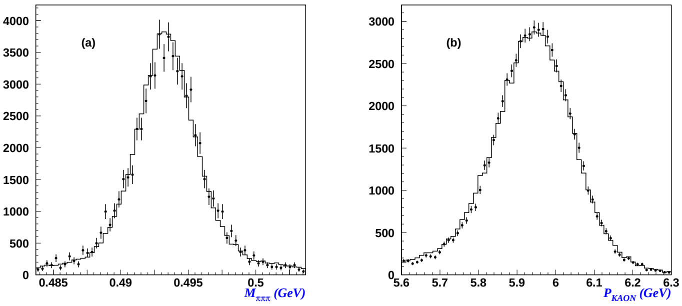


Figure 2.1: *Distributions of (a) 3π invariant mass and (b) K^+ momentum for K_τ (see text). Full histograms: simulation; crosses: measured data.*

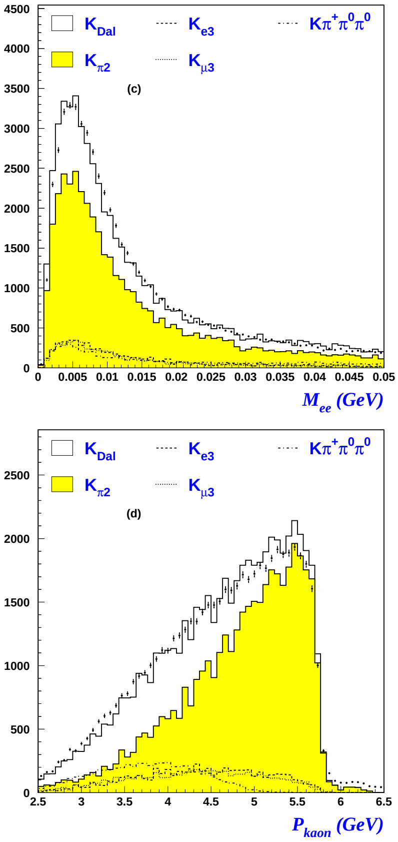


Figure 2.2: *Distributions of (top) e^+e^- - invariant mass and (bottom) K^+ momentum for K decays into e^+e^- pairs. Full histograms: simulation; crosses: measured data.*

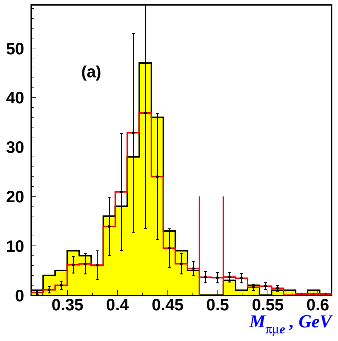


Figure 2.3:
*Three particle invariant mass for $K_{\pi\mu e}$ candidates. The signal region (*box*) is indicated. Full histogram: predicted background from misidentified K_τ and K_{Dal} decays and accidental background; crosses: measured data.*

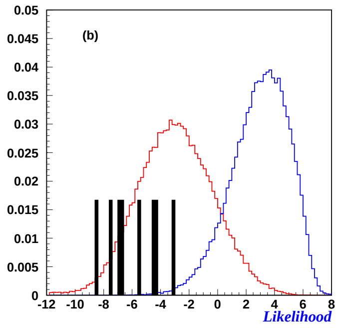


Figure 2.4:
Expected log-likelihood distributions for signal (blue curve) and background (red curve) events. The position of the eight events found in the K^+ mass window are indicated.

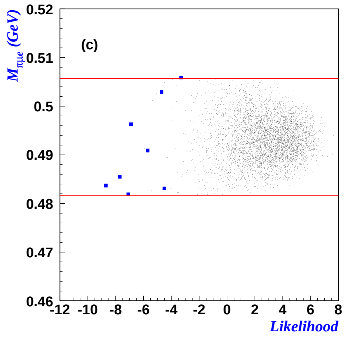


Figure 2.5:
Three particle invariant mass versus log-likelihood. Points: Monte Carlo generated signal events; squares: measured data.

The most problematic background source turned out to be accidental coincidences, e.g. from the decay $K^+ \to \pi^+\pi^0$; $\pi^0 \to e^+e^-\gamma$ with detected π^+ and e^- and a μ^+ from the beam halo or another decay, which survived the selection criteria. The analysis of the side bins in the event timing distributions and of those events, to which the reconstruction assigned a kaon momentum above 6.9 GeV/c led to an expectation of 8.2 ± 1.9 such events in the *box* (see Fig. 2.3). Eight events were indeed found, when the *box* was opened, to all of which the maximum likelihood analysis assigned a low probability to be signal events (see Fig. 2.4 and Fig. 2.5).
The flexibility of the E865 apparatus allowed also to obtain high statistics event samples on other rare final states, where existing data were scarce, namely:

- $\mu^+e^+e^-\nu_\mu$
- $e^+e^+e^-\nu_e$ ($K_{\ell\nu\gamma^*}$)
- $\pi^+\pi^-e^+\nu_e$ (K_{e4})
- $\pi^0e^+\nu_e$ (K_{e3})
- $\pi^+e^+e^-$
- $\pi^+\mu^+\mu^-$.

Several publications have appeared concerning these decay branches in the past, the last two in 2003 [6; 7]. The analysis of the K_{e4} data (400'000 events) allowed to measure low energy s-wave $\pi\pi$ scattering phase shifts and K-decay form factors with high precision, from which a new value for the s-wave $\pi\pi$ scattering length was extracted [6]. These results are often cited, because they provide stringent constraints for chiral QCD perturbation theory (ChPT) parameters. In a dedicated low intensity run in 1998 we also collected 70'000 K_{e3} events to afford a precise measurement of the branching ratio for this decay, which along with that for the analogous decay of the neutral kaon is the primary source for the determination of the CKM quark mixing matrix element V_{us}. In our experiment the π^0 was detected via its Dalitz decay $\pi^0 \to e^+e^-\gamma$ and the K_{e3} branching ratio was measured relative to the sum of all other decays involving π^0 [7]. We have reported on the significance of this result for testing unitarity relations in CKM-matrix [8] last year.

[1] E. Farhi, and L. Susskind, Phys. Rep. **74**, 277 (1981).

[2] A.M. Lee *et al.*, Phys.Rev.Lett.**64**, 165 (1990).

[3] R. Appel *et al.* (E865-coll.), Phys.Rev.Lett.**85**, 2450 (2000).

[4] *An improved limit on the decay* $K^+ \to \pi^+\mu^+e^-$*,*
Aleksey Sher, PhD. Thesis, University of Zürich, 2003;
http://www.physik.unizh.ch/people/truoel/e865/sherthesis.pdf.

[5] *A large acceptance, high resolution detector for rare* K^+*-decay experiments,*
R. Appel *et al.* (E865-coll.), Nucl.Instr.Meth.**A479**, 349 (2002).

[6] *High statistics measurement of* K_{e4} *decay properties,* S. Pislak *et al.* (E865-coll.), Phys.Rev.**D67**, 072004-1 (2003); Phys.Rev.Lett.**87**, 221801-1 (2001).

[7] *High statistics measurement of the* $K^+ \to \pi^0e^+\nu_e$ (K^+_{e3}) *branching ratio,*
Alexandre Sher *et al.* (E865-coll.), Phys.Rev.Lett.**91**, 261802-1 (2003).

[8] H. Abele *et al.*, Eur.Phys.J.**C33**, 1 (2004).

2.2 KOPIO: a study of the CP-violating rare decay $K^0_L \to \pi^0\nu\overline{\nu}$

in collaboration with:
Brookhaven National Laboratory, University of Cincinatti, INR Moscow, KEK, Kyoto University of Education, Kyoto University, University of New Mexico, INFN University of Perugia, Stony Brook University, Thomas Jefferson National Accelerator Facility, TRIUMF/UBC, University of Virginia, Virginia Polytechnic Institute $\&$ State University, and Yale University.

The aim of the experiment as formulated in the proposal and detailed in the technical design report [1], a measurement of the branching ratio of the decay $K^0_L \to \pi^0\nu\overline{\nu}$ with a single-event sensitivity around 6×10^{-13} (corresponding to $\approx 50 \pm 20$ observed events for the SM prediction), remains unchanged.

The combined MECO/KOPIO project at BNL is part of the US National Science Foundations (NSF) Major Research Equipment (MRE) program and funding of construction and operation will start in October 2005. Until that date some USD 6 million will be available for planning and design activities.

Within the Standard Model the $K^0_L \to \pi^0\nu\overline{\nu}$ decay amplitude is directly proportional to the CP-violating phase in the CKM matrix. In contrast to the interpretation of the value of ϵ'/ϵ theoretical uncertainties can be neglected. Whereas the Standard Model makes no quantitative prediction for this phase the comparison with the result obtained in the B-meson sector would allow a sensitive test of the Standard Model.

The KOPIO-experiment will use an intense low momentum, time structured K^0_L beam available only at the AGS. This way the momentum of the kaon can be determined from the time of flight which will allow the full reconstruction of the π^0 mass and momentum in the K^0_L center-of-mass system. Kinematical cuts and an elaborate veto counter system are designed to nearly eliminate all background from K^0_L decay modes with additional π^0 or charged particles. The observation of about 40 to 50 events (at SM prediction level) with a signal to background ratio of 2:1 would correspond to a measurement of the area of the CKM unitary triangle with an accuracy of about 10% .

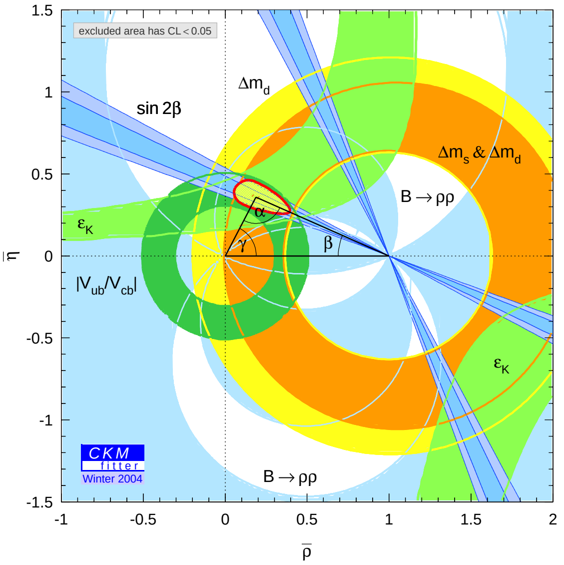
Our group has taken on the responsibility for the design and construction of the charged particle veto counters, which are of crucial importance for a variety of background sources, e.g. from $K^0_L \to \pi^-e^+\gamma\nu_e$ and $K^0_L \to \pi^-\pi^+\pi^0$. The energy of the PSI $\pi^\pm$ beams is ideally suited for testing prototypes, a program which we started in 2000.

2.2.1 CP violation in the quark sector: SM and beyond

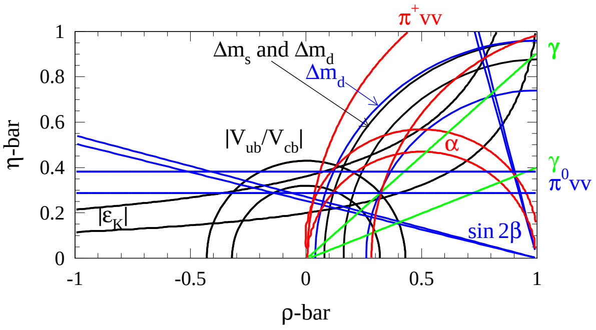
Within the SM CP violation in the quark sector arises from a single complex phase in the CKM mixing matrix [2]. In the Wolfenstein parametrisation the violation results from a non-zero value of the parameter η which manifests itself in two CKM elements:

$$\begin{array}{lllll} V_{ub} & = & |V_{ub}|e^{-i\beta} & = & A\lambda^3(\rho - i\eta) \\ V_{td} & = & |V_{td}|e^{-i\gamma} & = & A\lambda^3(1-(1-\lambda^2/2)(\rho+i\eta)) \;\approx\; A\lambda^3(1-\rho-i\eta) \end{array}$$

The decay $K_L^0 \to \pi^0\nu\overline{\nu}$ has major contributions from penguin and box diagrams with up-type quarks in the intermediate state. Since the transition amplitude scales with the quark mass the top contribution dominates by far and $A(K_L^0 \to \pi^0\nu\overline{\nu}) \propto V_{td}^*V_{ts} - V_{ts}^*V_{td} \propto i\eta$. As a result $B(K_L^0 \to \pi^0\nu\overline{\nu}) \propto \eta^2$. The corresponding charged decay mode does not require CP violation but gives a circular constraint around $\rho = 1.3, \eta = 0$: $B(K^+ \to \pi^+\nu\overline{\nu}) \propto (\rho - 1.3)^2 + \eta^2$.



Present situation (95% confidence regions)



Possible situation in 2010

Figure 2.6: *The constraints from various K and B decays on the Wolfenstein parameters $\overline{\rho}$ and $\overline{\eta}$. Results from the CKMfitter working group*[2].

Ultimately these two decay modes together will give a complete picture of CP violation in the K system with negligible theoretical uncertainties. Figure 2.6 shows how various observables in K and B decays contribute to our knowledge of $\overline{\eta} \equiv (1-\lambda^2)\eta$ and $\overline{\rho} \equiv (1-\lambda^2)\rho$.

Physics beyond the SM generally allows additional CP-violating phases [3] and as a result the SM description with a universal set of Wolfenstein parameters for K and B would break down. It is very fortunate that we may expect significant improvements in the experimental constraints in both areas during the next decade so that meaningful tests can be made.

A recent theoretical analysis [4] links the observed $B \to \pi\pi$ rates using SU(3) flavour-symmetry and plausible dynamical assumptions to the $B \to \pi K$ rates and determines the CKM angle γ in accordance with the usual fits. The analysis of the $B \to \pi K$ system in the SM yields good agreement with the experimental picture, with the exception of those observables that are significantly affected by electroweak penguins, thereby suggesting new physics (NP) in this sector. Indeed, a moderate enhancement of these topologies and a large CP-violating NP phase allows then to describe any currently observed feature and to predict the CP-violating $B_d \to \pi^0 K_S$ observables. In the specific scenario where NP enters only through Z^0 penguins, one obtains a link to rare K and B decays, where the most spectacular NP effects are an enhancement of the $K_L \to \pi^0\nu\bar{\nu}$ rate by one order of magnitude with $B(K_L \to \pi^0\nu\bar{\nu}) \approx 4B(K^+ \to \pi^+\nu\bar{\nu})$.

[2] `http://www.slac.stanford.edu/xorg/ckmfitter/ckm_results_winter2004.html`

2.2.2 The KOPIO experiment

The decay $K_L^0 \to \pi^0 \nu \overline{\nu}$ will be distinguished from other more likely decay modes on the basis of the following signature:

- Two photons are observed with a common vertex inside the decay region and an invariant mass equal to m_{π^0}.
- No simultaneous charged particles or additional photons are observed.
- The energy $E^*_{\pi^0}$ of the reconstructed π^0 in the K_L^0 rest frame (using the K^0 time of flight through the beam line) and the photon energy sharing do not coincide with the regions populated by the background of the decay $K^0 \to 2\pi^0$ remaining after test 2.

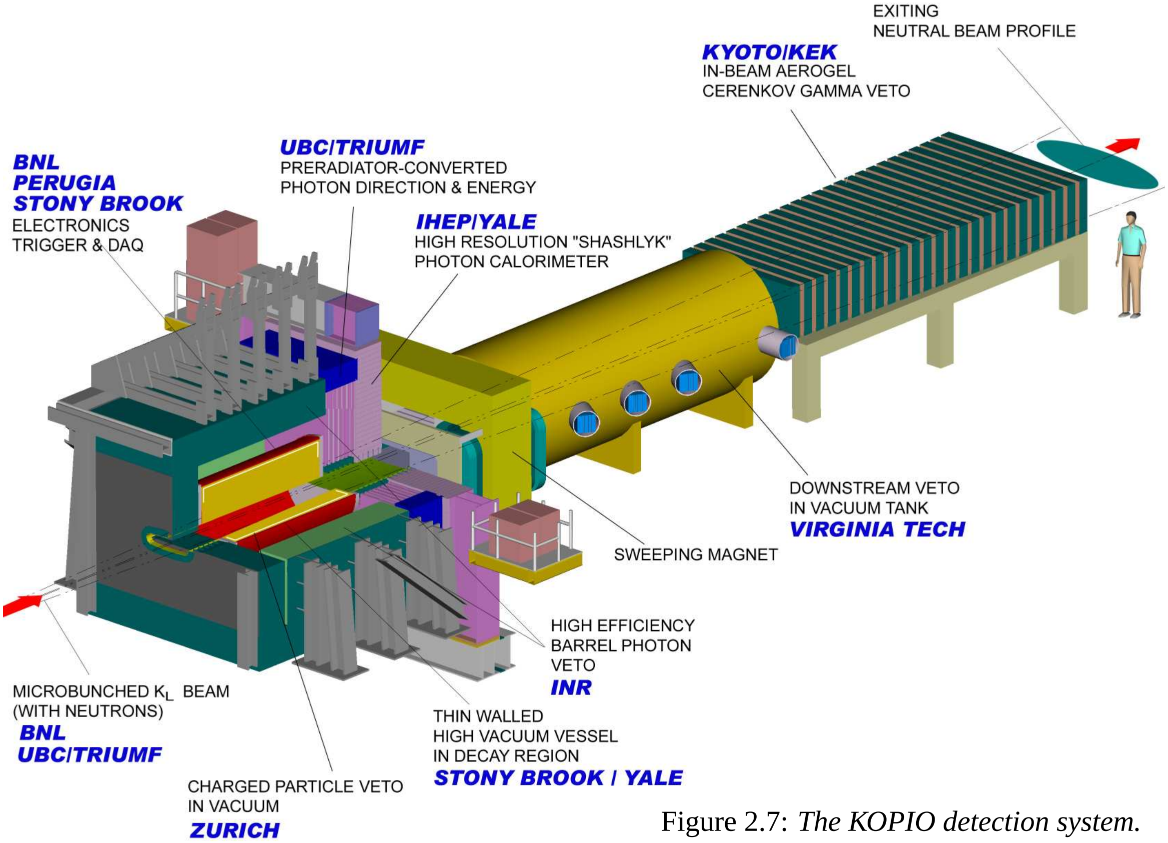


Figure 2.7: *The KOPIO detection system.*

Figure 2.7 shows the planned setup. The π^0 detector consists of a highly segmented pre-radiator followed by an electromagnetic calorimeter. All remaining detectors serve as veto counters for charged particles and photons. Particularly problematic are the detectors for particles and photons moving along the beam which contains $O(10^{11})$ s^{-1} neutrons. Charged particles are bend out of the beam with the help of a sweeping magnet situated right behind the π^0 detector.

The Zürich group took over the responsibility for the main charged-particle veto system situated directly around the decay region. Additional veto systems situated further downstream should detect charge particles escaping through the beam pipe. The purpose of the charged-particle veto systems is the efficient identification of background processes in which an apparent $\pi^0 \to 2\gamma$ decay inside the decay volume is accompanied by charged particle emission. Examples of such background processes are, (i) $K_L^0 \to \pi^+\pi^-\pi^0$, (ii) $K_L^0 \to e^+\pi^-\nu\gamma$ in which the positron creates a second photon through Bremsstrahlung or annihilation in flight, (iii) $K_L^0 \to e^+\pi^-\nu$ again followed by $e^+ \to \gamma$ whereas the

π^- creates a photon through $\pi^- p \rightarrow \pi^0 n$. In all cases two particles with opposite electrical charge emerge. The events may also produce signals in other detector elements, like the barrel veto system.

As discussed already in the proposal simulation shows that **detection efficiencies** of 99.99% or better are required to keep these backgrounds below a few events in the final sample. Our 2001 studies at PSI[5] have shown that the **dead layer** in front of the veto system (which includes wrapping material and possibly a window separating the detector from the high-vacuum decay region) should be kept below 20 mg/cm^2 and that a **detection threshold** of $\approx$ 75 keV (corresponding to $\approx$ 0.3 mm scintillator thickness) should be reached. Minimising dead material in front of the detector mainly helps to reduce the inefficiency for π^- caused by nuclear reactions.

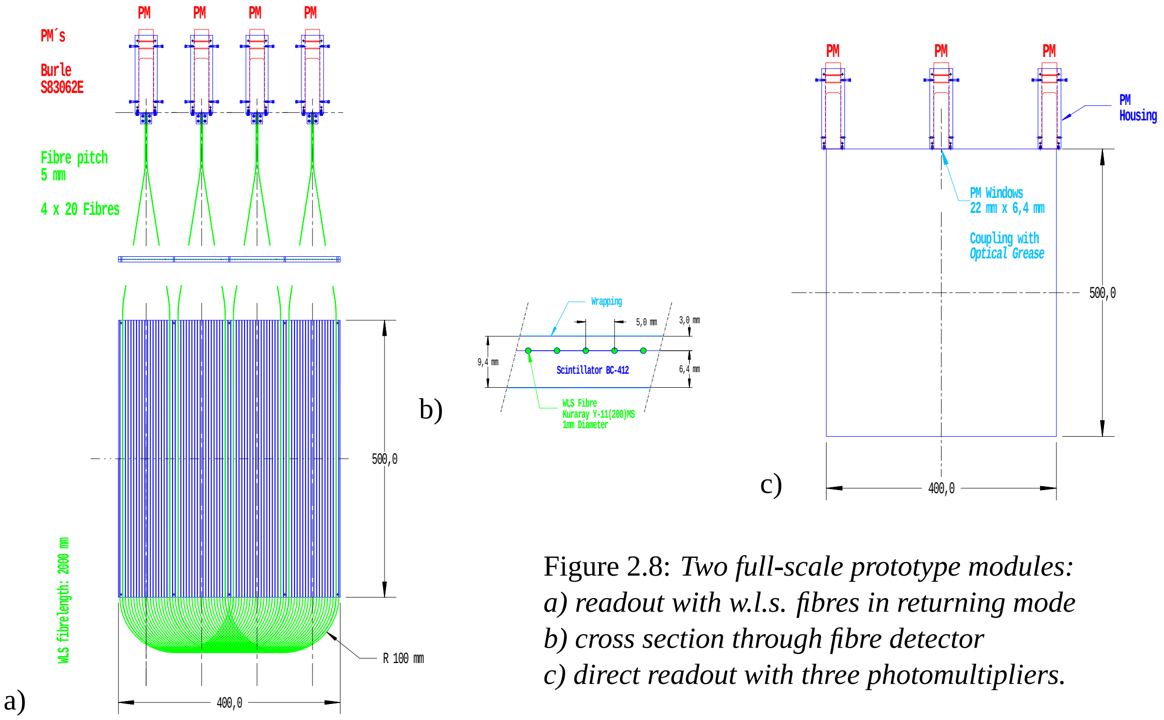


Figure 2.8: *Two full-scale prototype modules:*
a) readout with w.l.s. fibres in returning mode
b) cross section through fibre detector
c) direct readout with three photomultipliers.

During a two weeks beam period at PSI in July 2003 full-scale (400 mm x 500 mm) prototypes of the two light-collection schemes of interest were studied (see Fig.2.8). In addition prototypes for the downstream charged particle veto system and for the scintillator planes of the pre-radiator detector were tested. All measurements were done with 500 MeV/c π^-. Two xy MWPC's were used to determine the impact position on the scintillator.

In Table 2.1 the observed photoelectron yields are compared with our 2002 results for elements with dimensions 200 x 250 mm^2. As can be seen from the table direct readout may give almost ten times more photoelectrons for a given energy deposit then observed with embedded wavelength shifting fibres. Our new results with full-scale prototypes indicate that it should be possible to reach a threshold of $\approx$ 10 keV with a $\pm 5\%$ homogeneity over the detector surface. For this reason direct readout was chosen in our present design (see Fig. 2.9).

The remaining decisions are on the detector thickness and the type of photomultiplier or possibly Geiger-mode avalanche photodiode. As can be seen from Tab. 2.1 3 mm thick counters still give 200 photoelectrons for minimum-ionising particles so 1-2 mm thickness should be sufficient. Reducing the thickness results in less sensitivity to neutrons and photons and in less dynamic range which in turn improves the double-pulse resolution. Reducing the thickness also reduces the cathode

Table 2.1: *Photoelectron (p.e.) yields of various light collection schemes.*
Scintillator: BC-412 by BICRON, photomultipliers: Burle 83062E (Ø 22 mm).

	size [cm^2]	thickness [mm]	version		wrapping	nr. of PMT's	p.e.	p.e. in 10 mm
w.l.s. fibers			fiber	geometry				
	20x25	2x6.4	Bicron[a]	straight[c]	Tyvek[d]	4	110	90
		⋮	Kuraray[b]	⋮	⋮	⋮	130	110
	40x50	6.4+3.0	⋮	returning[c]	VM2000[e]	⋮	115	125
direct readout			width of windows	grease				
	20x25	6.4	10 mm	no	black paper	4[f]	130	200
		⋮	⋮	⋮	Tyvek[d]	⋮	260	400
	40x50	⋮	⋮	⋮	⋮	4[g]	130	200
		⋮	22 mm	⋮	⋮	⋮	220	340
		⋮	⋮	yes	⋮	⋮	410	640
		⋮	⋮	⋮	VM2000[e]	⋮	520	810
		3.0	⋮	⋮	⋮	⋮	200	670
		6.4	⋮	⋮	⋮	3[g]	500	780
		⋮	⋮	⋮	⋮	2[g]	330	520

[a] BCF-92MC
[b] Y-11(200)MS
[c] read from both ends
[d] DuPont trademark
[e] radiant mirror film produced by 3M
[f] mounted at opposite sides
[g] mounted at one side

area required. As a result the newly-developed Geiger-mode photodiodes become an interesting alternative to photomultipliers. These devices are presently available with an area of 3 × 3 mm^2 and an effective efficiency (geometric times quantum efficiency) around 20%. Contrary to photomultipliers significant improvements can be expected in the near future. Advantages are much smaller dimensions, lower price (so one can afford more of them), ease of operation and immunity to magnetic field. Compared to standard APD's they do not require large electronic amplification which makes them both faster and less noisy.

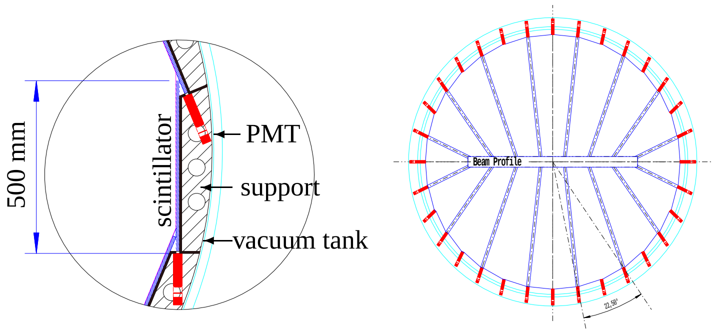


Figure 2.9:
Present design of the main charged-particle veto system.
Left: sector of a cross section perpendicular to the beam. Along the beam there would be ≈ 10 modules with overlap to avoid dead space.
Right: endcap detectors.

[1] *Rare Symmetry Violating Processes, KOPIO section*, Technical design report submitted to the National Science Foundation to construct the MECO and KOPIO experiments, June 2001; available at *http://www.physik.unizh.ch/people/truoel/kopio/kopiotdr.pdf*.
The proposal (1999) is available at *http://pubweb.bnl.gov/people/rsvp/proposal.ps*

[2] *Flavour physics and CP violation in the SM*, A. Buras, Proceedings of KAON 2001, eds. F. Constantini, G. Isidori and M. Sozzi, (Frascati Physics Series Vol.XXVI), pp. 15-43.

[3] *Flavour physics and CP violation beyond the SM*, A. Masiero, Proceedings of KAON 2001, eds. F. Constantini, G. Isidori and M. Sozzi, (Frascati Physics Series Vol.XXVI), pp. 45-58.

[4] A.J. Buras, R. Fleischer, S. Recksiegel, and F. Schwab, Preprint CERN-PH-TH-2004-020, TUM-HEP-540-04, MPP-2004-14, hep-ph/0402112 (February 2004).

[5] KOPIO Technical Note TN027, *Measurements on the response of plastic scintillator to charged pions at 185-300 MeV/c*, H. Kaspar, P. Robmann, A. v.d.Schaaf, S Scheu, P. Truöl, J. Egger, M. Blecher, 31 October 2001.