REVIEW OF KAON FACTORIES

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Abstract

A brief motivation, from the Particle Physics point of view, is given for a Kaon Factory. The facility requires a rapid cycling, multi GeV synchrotron, operating in fixed target geometry. The generic components of such a facility are discussed. The candidate Kaon Factory proposals are recalled, and their status reported. In conclusion, a more detailed presentation is made of the proposed Canadian KAON Factory at TRIUMF, and some of the findings of the recent Project Definition Study are presented.

Introduction

This presentation on Kaon Factories will be given from the rather biased point of view of an experimental particle physicist. I will begin by motivating a little the need for a Kaon Factory, since after all we have been familiar with the strange quark for over forty years [1], and one may wonder whether there remain secrets to be revealed. Next I would like to point out the pieces of accelerator that are assembled to make up the "generic" Kaon Factory, which in all cases aims for a fixed target, multi GeV, high current proton facility. There are a number of proposed candidate Kaon Factories, all with proposals in various stages of development. I will point out their features, and try to indicate, to the extent that I know, that status of the proposals. In conclusion I will spend some time presenting the TRIUMF KAON Factory proposal, which I believe at this moment could reasonably claim to be the most advanced candidate for a world Kaon facility.

Status of Particle Physics

Experimental Particle Physics is currently very successfully explained by what is known at the Standard Model (SM), which describes the weak, electromagnetic and strong interactions between quarks and leptons. It is a very elegant model, and works over a larger energy range (10^{17} eV), even if we limit ourselves to the range from the Lamb shift to 100 GeV. The electroweak theory [2] also works calculationally at more than the leading order. However the SM has a fairly large number of apparently arbitrary constants which have to be taken from experiment, and there is widespread belief that this cannot be the whole story. Currently there are many theoretical recipes for progressing beyond the SM, but none finds universal acceptance.

As experimentalists we desperately seek the missing players in the SM, most notably the top quark and the Higgs scalar. We make extremely precise measurements which may deviate slightly from the impressive calculational power of the SM, and provide clues about missing pieces or extensions. Also we look for evidence which does not fit within the framework of the SM, and thus may provide a clue for extensions. Roughly speaking these approaches represent the traditional three pronged attack outlined crudely in Table 1 - the energy frontier, detailed measurement, and rare processes which either fit in, or surprise us. Fortunately we have a clue as to where it may be most advantageous to look next. The SM predicts that certain cross sections will violate unitarity when collisions between building blocks approach 1 TeV. Clearly Nature is wiser, and will have no part of this nonsense, so something must be learned if the experiments can be performed unambiguously. This energy scale of 1 TeV is the driving force behind the SSC and LHC projects. A Kaon Factory cannot claim to provide access to the energy frontier however it affords the complementary possibilities of detailed measurements and the examination of rare processes.

Figure 1 shows the Kaon Factory at 30 GeV along with the SSC and LHC as points on the so-called "Livingston Plot". The collider points are placed at the equivalent beam energy which a machine would have to produce in order to achieve the same centre of mass energy using a fixed target geometry. It is clear that without the invention of colliding beams, the linearity of the plot from 1930 to the mid-sixties would, by now, be very badly bent!

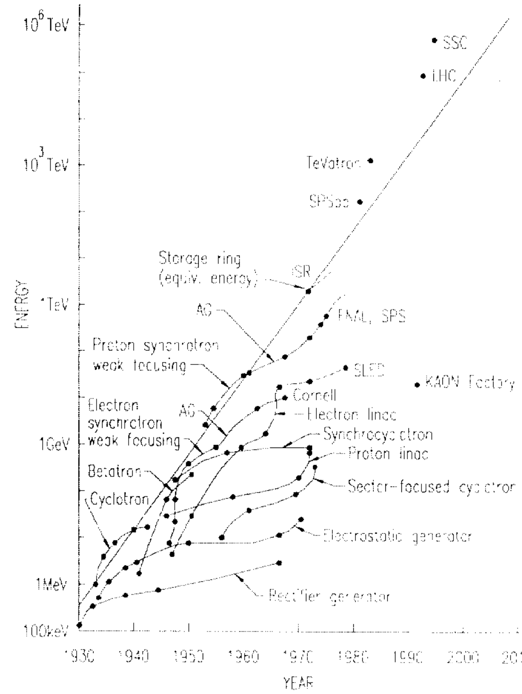

Figure 1. The Livingston Plot of the increase of maximum accelerator energy with calendar time. The new points show the KAON Factory, SSC and LHC.

Recent results from LEP [3] and SLC [4] tell us that we have only three generations of quarks and leptons at our disposal experimentally. In figure 2 these constituents are shown along with the exchange particles of the SM. The vertical scale approximates the mass, and the horizontal scale is the charge. The existing and proposed accelerator facilities reveal that if all are built, then "all bases are pretty well covered". In addition, HERA, not shown, will be a factory for virtual photons, W's and Z's. At this stage in the development of Particle Physics one feels the need to be able to attack experimentally at all levels.

Why KAON?

The KAON Factory will be an intense source of strange quarks, bound in K-mesons. The obvious decays are either Cabibbo suppressed ($s \rightarrow u$) or forbidden ($s \rightarrow d$). The $s \rightarrow d$ transition is, however, allowed at second order in the weak decay, making decays like $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ especially interesting and for "technical reasons", particularly sensitive to the mass of the un-

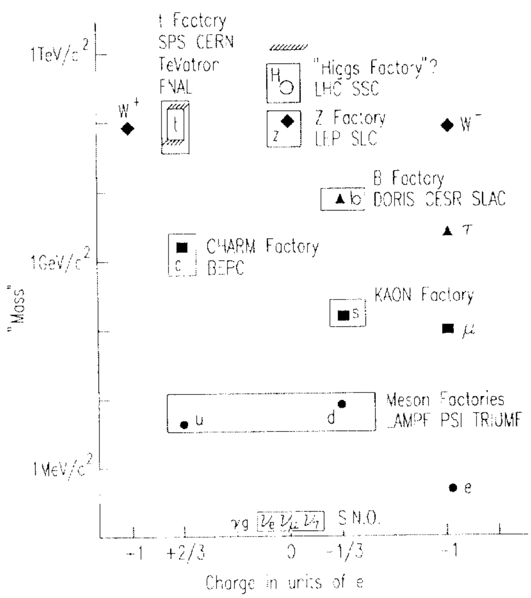

Figure 2. Nature's quarks, leptons, and exchange bosons arranged by increasing mass, in the various charge states. The present, and, possible future, facilities reveal that almost all specialised options are covered.

discovered top quark. This state of affairs comes about since it looks as if the mass of the top quark will be greater than that of the W boson [5]. CP violation has so far only been observed as a relatively rare process in K-decay. A copious source of kaons may make it possible to settle the explanation on the complex phase in the Kobayashi-Maskawa quark mixing matrix. The candidate theory of the strong interaction QCD, has a number of unanswered questions at the long distance scale (~ 10^{-13} cm) where quarks are bound into hadrons, i.e. the confinement scale. A better experimental understanding of the spectrum of hadrons may help what is theoretically a very difficult problem. The KAON Factory is an appropriate machine for these studies.

The program of Nuclear Physics can be very varied, with a rich variety of hadronic probes available. Therefore the KAON Factory has a complementary role to CBAF and RHIC in answering the question "What are the appropriate degrees of freedom in a nucleus?"

Why a Factory?

Why do we need a Factory? This question is simply answered in reference to rare processes. There is a need to detect and make measurements at branching ratios (10^{-11}— 10^{-12}). A good rule of thumb which makes this feasible is the target of being capable of measuring ratios of 10^{-10} in one hour. This forces experimental stop rates and beams of ~ 10^{8} per sec, which is SSC-like in rate if not multiplicity. Experimentally this will be a daunting task, but if we learn from the example of the Meson Factories and rare muon decays, then experimentalists have traditionally managed to rise to the occasion, and the limits have steadily decreased over the years, as techniques improve.

Towards a Generic Kaon Factory

We can begin the steps towards a Kaon Factory by examining the features of some of the existing accelerators at which kaon experiments have been performed. The CERN PS and the Brookhaven AGS both have energies of ~ 30 GeV, beam currents ~ 1μA, and repetition rates ~ 0.4Hz. The number of protons per pulse accelerated to top energy by these machines is (1-2) x 10^{13}.

One of the most important parameters which determines the beam intensity of these accelerators is the energy of injection into the synchrotron. In a regime where there are no real aperture and image force problems the tune shift induced by space charge effects in a bunch is given by $\Delta\nu \propto N/\beta^2\gamma^3$ [6] where N

is the number of protons per bunch $\quad \beta = \sqrt{1-\left(\frac{m}{T+m}\right)^2} \quad$ and

$\gamma = 1+T/m$, with T the kinetic energy of the protons at injection. Over the years the energy of injection at the CERN PS has been raised from 50 MeV to 800 MeV, and from 50 MeV to 200 MeV at the Brookhaven AGS. This suggests that the injection energy at a Kaon Factory should be as high as is practically possible, probably ~ 1 GeV.

The energy of 30GeV is adequate to produce kaons copiously and also gives a reasonable yield of antiprotons. There is not therefore great incentive for increasing the machine energy. However to provide access to a new range of physics it seems reasonable to aim for at least an hundred-fold increase in beam current to ~100 μamp. This level of current yields ~ 6 x 10^{14} protons per sec, and if the accelerated charge per pulse is to be kept to a level close to current experience, i.e. ~ 6 x 10^{13}, then it is immediately clear that a rapid cycling machine ~10 Hz is required. The voltage demands from the RF for a 30 GeV 10 Hz machine are much higher (~ 2 MV) than in the older slow cycling synchrotrons. In addition there will be a significant frequency swing (~ 20%) in order to accommodate injection energies < 1 GeV. A resolution to these problems is provided by the insertion of a Booster synchrotron of a few GeV between the injector and the main synchrotron. The smaller Booster must cycle faster, ~ 50 Hz, in order to fill up the circumference of the main ring. A further advantage of this arrangement is the shrinking of the aperture ($\varepsilon^* = \beta\gamma\varepsilon$) of the high energy machine. With this type of arrangement the circulating currents in the accelerators can be kept to $\lesssim$ 3A, which is a level not far removed from existing operational experience.

The operation of the complex is significantly simplified if a dc collector ring is added before the main ring, here the Booster pulses may be assembled before acceleration. Also a dc stretcher ring following the main accelerator removes a number of technical tasks which would otherwise have to be executed in the 30GeV ring, most notably the provision of a dc slow spill over 1/10 second for electronic experiments. This requirement places stringent demands on the stretcher ring for magnetic field stability (10^{-5}), vacuum (10^{-9} Torr) and low loss extraction (< 0.2%).

The picture of our generic Kaon Factory, shown in figure 3, is completed by the addition of injection into the Booster via the stripping of H^- ions. This enables multiturn injection into the same region of phase space providing a high space charge per pulse. The transfer between storage rings and accelerators is performed at the bucket-to-bucket level and is achieved with the aid of kicker magnets in the various rings.

No part of this combination of accelerators and storage rings extends into regions of operation which are not already explored in accelerator physics. However the major concern must be loss of beam. Traditionally losses in synchrotrons are in the range of a few per cent; with the two orders of magnitude increase in beam, this level will produce an intolerable activation problem. The major challenge then in the Kaon Factory is the control, monitoring and response to beam loss, particularly in the high energy rings where one is dealing with 3MW of beam power.

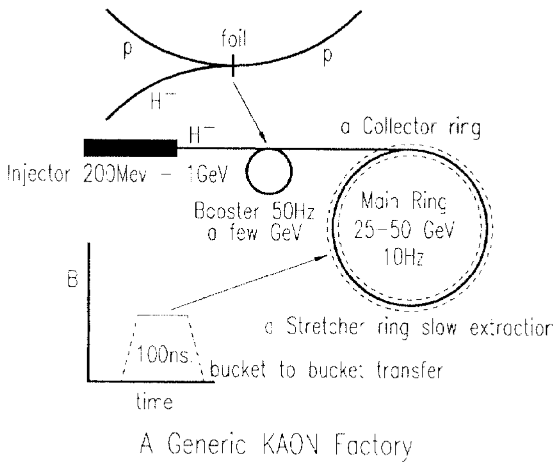

Figure 3. The components which make up the generic Kaon Factory.

European Hadron Facility (EHF) [7]

The original proposal in 1987 was based on a 1.2 GeV Linac, a 9 GeV Booster, and a 30 GeV, 100 μamp main ring cycling at 12.5 Hz. This proposal has been "adopted' by the National Laboratory at Legnaro in Italy. The current planning is to build a 50 Hz pre-booster synchrotron which would receive protons from a new 650 MeV linac and raise their energy to 1.2 GeV in addition to having heavy ion capabilities. There would also be a "pre-holding" ring in the same tunnel, which could also serve as a cooler ring for radioactive heavy ions produced in an ISOL target. A proposal for these small rings is in the pipeline, and in a sense represents a step wise approach to a KAON Factory.

The Moscow KAON Factory [8]

This facility would be built at the Institute for Nuclear Research of the Academy of Sciences of the U.S.S.R. located near Moscow. A Meson Factory based on 600 MeV 500 μA Linac is nearing completion. The addition of a 7.5 GeV Booster and a main ring at 45 GeV cycling at 6.5 Hz to give 125 μamp of beam current for slow extraction will make the conversion to kaon physics. Technically the proposal was approved in 1987, money exists for prototype work, and it is anticipated that construction will begin in 1994.

Los Alamos Advanced Hadron Facility [9]

The LAMPF proposal opted for somewhat higher energies and lower currents, shifting the physics emphasis towards processes demanding higher momentum incident beams, e.g. the Drell-Yan production of muon pairs off nuclear targets. The injector complex was based upon two Linacs, one of 1.6 GeV followed by a second at 2.2 GeV. The final 6 Hz synchrotron produced an energy of 60 GeV with 25 μA of beam current. The NSAC review placed the completion of CBAF and the building of RHIC ahead of the LAMPF proposal. The mesa geography of the Los Alamos site calls for considerable ingenuity in the placement of projected facilities and studies are now considering 100 GeV and 50 μamp. In the meantime there is a certain retrenchment behind a 1.6 GeV Linac feeding a compressor ring with an emphasis on neutrino and spallation neutron physics.

The Japanese Hadron Facility Phase I [10]

The JHP will be located at KEK and is a joint proposal from the Institute of Nuclear Science and KEK. In the Phase I the project concentrates on a 1 GeV H^- Linac with an average current of 400 μamp feeding a compressor/stretcher ring. Three major experimental areas are planned, a Meson Area for πμ and ν work, a Neutron Area using a Spallation neutron source, and an Exotic nuclei facility which could well supply the world's first Radioactive Beam. The Linac can also inject into the 12 GeV KEK Synchrotron, where a new high current experimental area is being commissioned. The proposal for Phase I was submitted in 1988 and is being processed.

The Brookhaven AGS

The operating conditions of this thirty year old machine are derived from a 200 MeV Linac which feeds the main 28 GeV synchrotron cycling at 0.4 Hz to provide 1 μA of slow extracted beam. The charge in the machine is ~ 1.6×10^{13} p/pulse. An extensive and productive program of experiments on rare kaon decays is supported at the laboratory. An improvement program is nearing completion. This will insert a 7.5 Hz Booster synchrotron of 1.5 GeV between the Linac and main ring [11]. The intensity will be limited by the space charge tune shift of $\Delta\nu = .35$ at the Booster injection, but an overall factor of four increase to 6×10^{13} p per pulse will raise the slow extracted current to 4 μA. The project should be completed in March 1991. There is a proposal for the addition of a Stretcher ring but this is not approved.

FNAL Main Injector [12]

As part of a series of upgrades to the TeVatron Collider at FNAL a new Main Injector is proposed. The machine would be ~ 120 GeV in energy, cycle at .26 Hz, and have ~ 3×10^{13} protons per pulse with a spill time of 1.9s. This machine is a copious producer of K°s in the energy range 15 GeV < E < 50GeV, yielding a rate in this energy bin of ~ 3×10^7 per sec. This facility would have significant advantages in examining K° decays where the efficient reconstruction of π°s is an essential feature to suppress backgrounds. The energy spectrum of K°s is harder than that derived from 30 GeV protons, giving an improved resolution by the usual factor $^1/\sqrt{E}$. In addition the Lorentz boost to the decay products makes high geometrical efficiency easier to achieve. In the recent HEPAP Review this Main Injector was given the highest priority because of the unique opportunity of TeVatron collisions. When built it will offer the specialised possibilities for K° physics.

The TRIUMF KAON Factory [13]

The TRIUMF KAON Factory is a 30 GeV facility with 100μamp of beam current. The components, and their function are listed below.

Injector - The TRIUMF H^- cyclotron which routinely provides 150μA beams at energies up to 520 MeV acts as the injector. H^- ions will be extracted at 452 MeV.

A-Accumulator - This d.c. ring at 452 MeV accumulates the 23 MHz cw beam from the cyclotron over 20 ms periods. Multiple turn injection is achieved by charge exchange.

B-Booster Synchrotron - This acceleration operates at 50 Hz and accelerates the beam from 452 MeV to 3 GeV. The RF system must accommodate a large frequency sweep 46-61 MHz. The circumference is 216 m (4.5x that of the cyclotron).

C-Collector ring - This d.c. ring 1078 m in circumference collects 5 Booster pulses.

D-Driver synchrotron. This is the main synchrotron which cycles at 10Hz and provides the energy gain from 3 GeV to 30 GeV. The circumference of the Driver is 1078m. Fast extraction is provided from this machine. The frequency sweep of the Driver is small, ~3%, but the RF voltage is high, ~2550kV.

E-Extender ring - This d.c. ring is a 30 GeV stretcher which provides a slow spill for electronic experiments.

The transfer between the rings is performed on a "bucket-to-bucket" basis using kicker magnets. The lattice design of both synchrotrons is such that the transition energy is driven above the top energy of the ring, thus avoiding the potential beam loss in passage through transition. Figure 4 shows the layout of the accelerator complex and the experimental areas. It also shows sections through the tunnels which house the Booster and Main rings.

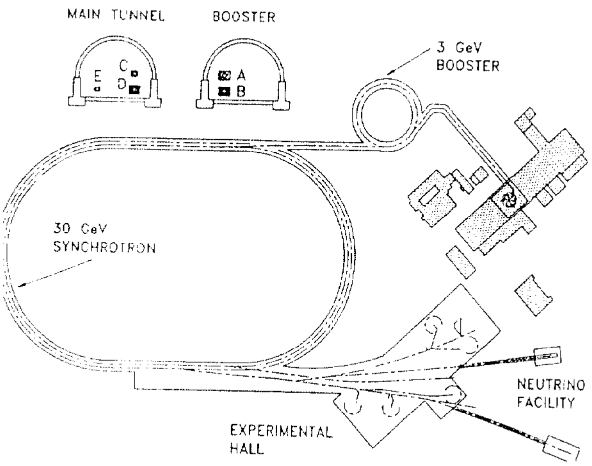

Figure 4. The layout of rings and experimental halls of the TRIUMF KAON Factory. Also shown are tunnel crosssections.

The Project Definition Study at TRIUMF [14]

At the end of February 1990 the 18 month Project Definition Study was completed. This was an $11M study of many aspects of the KAON Factory, and was jointly funded by the Provincial Government of British Columbia and the Federal Government of Canada.

The study had a number of components:

(i) Accelerator design
(ii) Building and testing of prototypes - mostly from the Booster.
(iii) Civil engineering and supply of conventional services.
(iv) Science workshops - where the science case was revisited.

In addition there were impact studies on Canadian Industrial Capability, the Economic Benefits from Construction and Operation, the Environment, and the Legal consequences. A further important aspect was the delegation which sought International Participation in the project. Roughly speaking the aim of the work was to provide the Federal Government with an updated and more accurate cost of the capital construction and operating costs, and to provide a reasonably sound estimate of what contributions, in kind, could be anticipated from International collaborators.

The Project Definition Study produced a number of design changes from the 1985 proposal. The most important of these were the following.

1. The main ring and experimental hall are in a new location, which assures the possibility for future expansion in the experimental facilities and provides adequate space for service buildings.

2. A racetrack lattice has been selected for the CD and E rings. This gives much more space in the straight sections for an efficient slow extraction system from the E ring. It also leaves open the possibility of inserting Siberian snakes into the Driver Synchrotron for the acceleration of polarised protons.

3. The E ring remains in the same tunnel as the C and D rings, but is displaced from them by ~4m. This allows the insertion of shielding between the rings at the extraction section.

4. The Booster magnet excitation is now sinusoidal at 50 Hz, only a 20% increase in RF voltage was required over the original dual frequency scheme, making the new arrangement simpler and more cost-effective. The Driver excitation remains dual frequency.

5. The perpendicularly biased ferrite tuned cavity (Los Alamos) was selected as the reference cavity for the Booster. This cavity has the capability of operating at higher volts resulting in fewer cavities.

An extensive program of prototypes was put in place during the study, in many instances the work and tests have continued, and results are still being realised. Several of the projects are presenting detailed results in poster sessions at this conference. I will highlight briefly below the major items which are closely related to the machine.

R.F. Booster Cavity [15]. The d.c. biased Los Alamos cavity was rebuilt, and the tuner redesigned to test the operation and response of the cavity to the biased ferrite at 50 Hz. The system has achieved the frequency sweep of 46-61 MHz.

Magnet design. A Booster Dipole, laminated for 50 Hz operation, and 3.0m long has been built but not yet tested. The field range is 0.27T - 1.12T and the uniformity requirement is < 200 ppm over an aperture of ±5cm. An approximation to a Booster Quadrupole will eventually be completed with redesigned coils. It is important to be able to measure how the magnets "track" with rapid cycling operation.

Power Supplies. A test setup has produced a dual frequency waveform which can be used on tests with the prototype magnets.

Kicker Magnets. A pulse forming network was assembled from components borrowed from CERN. It operated at 80KV and 50Hz with pulses 200-700 nsecs long. It was used to test the 30Ω, 10 cell decay line kicker module which was built. A 1 MHz chopper which creates a 110 ns gap in the A ring for subsequent kicker operation by removing 3 and then 2 cyclotron pulses, has been built and tested at low voltage [16]. A full scale prototype is nearing completion.

Vacuum. A 3.5m section of ceramic vacuum vessel for a Booster Dipole was designed at Rutherford Appleton Lab and has been built in industry. It is also equipped with an R.F. shield.

H^- Extraction. An R.F. Deflector cavity operating at 18KV excites the $\nu_r = 3/2$ resonance. This is backed up by a D.C. Deflector which moves the H^- into a series of magnetic channels. A prototype D.C. Deflector was installed in the cyclotron and tested in April this year [17]. Separated turns were observed, although the H^- did not exit the cyclotron.

Controls. An object oriented methology has been used to design a "generic" control system of the KAON Factory. This design is to a large extent independent of the eventual hardware choice.

Production Target. A "bare" rotating target was designed and built, and is currently under test in a TRIUMF extraction line. A water cooled and driven rotating target was tested for lifetime and reliability.

Systems integration. This study looked in detail at the installation of components in the tunnel using a transporter device. It also considered the supply of services to these components.

Status of the TRIUMF KAON Proposal

The final proposal was handed to the Federal Government of Canada on 24 May. The Provincial Government of British Columbia has already approved an approximately $100M contribution to the conventional construction. The International Negotiating team has indicated to the Federal Government that contributions to the accelerator, in kind, in the region of $200M are possible, most notably from the U.S., West Germany, and Japan.

It is anticipated that a decision will be made in the Fall of this year, so at the moment we wait patiently, but optimistically.

Acknowledgements

I would like to thank the organisers of this meeting, especially G. Plass, for their kind invitation to give this review. A lot of what I know abouot Kaon Factories I have learned from my colleagues in the Project Definition Study of the TRIUMF KAON Factory, many of whom presented their work at this meeting.

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Table I

Energy Frontier	Detailed Measurements	Rare and Forbidden Processes
Δ	$g_\mu \neq g_\beta$	$\tau \cdot \theta$ puzzle
N*Y*	Hadron spectroscopy	$\pi^+ \to e^+ + \nu$
$\nu_\mu \neq \nu_e$	Ω^-, colour QCD	$\pi^+ \to \pi^\circ e^+ \nu$
DIS e-p	quark-parton model	$\mu^- \to e^- + \gamma$
J/x	Neutral currents	$K^\circ_L \to \pi^+ \pi^-$
τ	Weak-EM Interference	$K^+ \to \pi^+ \nu \bar{\nu}$
υ	Charm spectroscopy	LF violation
W/Z, top	jets: QCD:	p-decay
LEP II	LEP precision tests	Rare Z decays
HERA	$M_Z \Gamma_Z N_\nu$	
↑	↑	↑
Discoveries here	Consolidation here	Surprises/early warnings here

KAON Factory's role