Physics Opportunities with Future Proton Accelerators

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1 - Introduction and summary

We survey some of the physics opportunities that could be provided by possible developments and upgrades of the present CERN Proton Accelerator Complex [1], highlighting synergies between different experimental fields. We recall some of the principal physics objectives of LHC upgrades [2] and other possible experiments from 2010 onwards, and identify some key physics and technical inputs that will be needed to define ultimately a preferred scenario. We identify several key detector R&D items required to provide some of these technical inputs, mentioning also some key accelerator R&D topics.

Options for the LHC include an upgrade to optimize the useful LHC luminosity integrated over the lifetime of the accelerator, a project we term the SLHC, and a possible future energy increase of the LHC, a project we term the DLHC. The absolute and relative priorities of these options would depend on initial results from the LHC in around 2010.

We also consider options for providing Europe with a forefront neutrino oscillation facility, whose principal physics objective would be to observe CP or T violation in the lepton sector. This might be achievable either by a combination of superbeam and β-beam or a neutrino factory using stored muons, depending on physics and technical developments that may also become available around 2010.

We discuss how the CERN proton accelerator complex might be upgraded so as to accommodate optimally these two programmes.

Continuing research on topics such as kaon physics, collider and fixed-target physics with heavy ions, muon physics, other fixed-target physics and nuclear physics could form an interesting supplementary physics programme for optimizing the exploitation of CERN's proton accelerators, and are very complementary to the physics performed at the energy frontier.

2 – LHC luminosity upgrade

Achieving the nominal LHC luminosity of 10^{34} cm^{-2}s^{-1} with high reliability and efficient operation is vital for the correct exploitation of the large investment in the LHC and hence the CERN physics programme. However, this may well prove challenging, particularly in view of the ageing of the PS and the SPS.

We expect that the LHC luminosity will increase gradually with time, thanks to experience in its operation, incremental hardware improvements and consolidation. The luminosity may eventually reach a factor of two above the nominal luminosity, if the beams collide only in IP1 and IP5 and the bunch population is increased to the beam-beam limit. Increasing the LHC luminosity above this figure would require hardware changes in the LHC insertions and/or in the injector complex and in the LHC detectors [2]. We note in passing that an 8% increase in the LHC energy, which might be possible with the available LHC magnets, would permit improved studies of new heavy particles.

Many examples of the new physics accessible via a tenfold increase in the LHC luminosity to 10^{35} $cm^{-2}s^{-1}$ (SLHC), were given in [2].

They include :

- **Higgs physics** – Observation of rare Higgs decays as $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu$, detection of Higgs pair production and measurement of the Higgs self-coupling (see Fig. 1), and also more sensitive studies of strongly-coupled vector bosons in the case that no light Higgs boson is observed at LHC;
- **Electroweak measurements** – Improved multiple-gauge-boson production and precise measurements of the triple-gauge-boson couplings to the level of electroweak radiative corrections (see Fig. 2) ;
- **Searches for new physics** – Extending the mass reach for squarks and gluinos from about 2.5 TeV to about 3 TeV (see Fig. 3), the mass reach for a new Z' from about 5 TeV to about 6 TeV, and the scale for compositeness from 30 to 40 TeV.

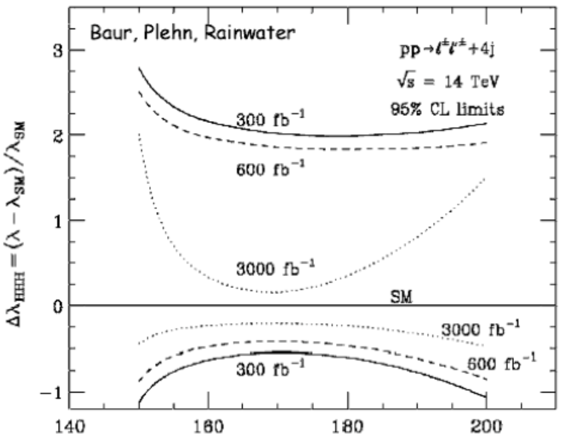

Figure 1- Limits achievable at the 95% CL for the deviation of the triple-Higgs coupling from the Standard Model value, $\Delta\lambda_{HHH}$, at the LHC and SLHC [3]. The allowed region is between the two lines of equal texture. The Higgs boson self-coupling vanishes for $\Delta\lambda_{HHH}$ = - 1.

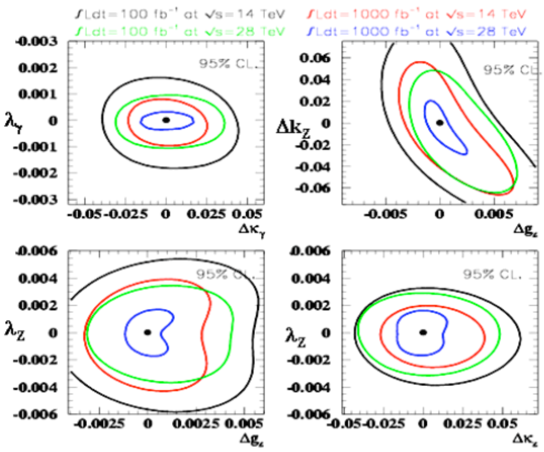

Figure 2 - Expected 95% C.L. constraints on triple-gauge-boson couplings [2]. The black (outer) contours correspond to 14 TeV and 100 fb^{-1} (LHC), the red to 14 TeV and 1000 fb^{-1} (SLHC) the green to 28 TeV and 100 fb^{-1} and the blue (inner) to 28 TeV and 1000 fb^{-1} (DLHC).

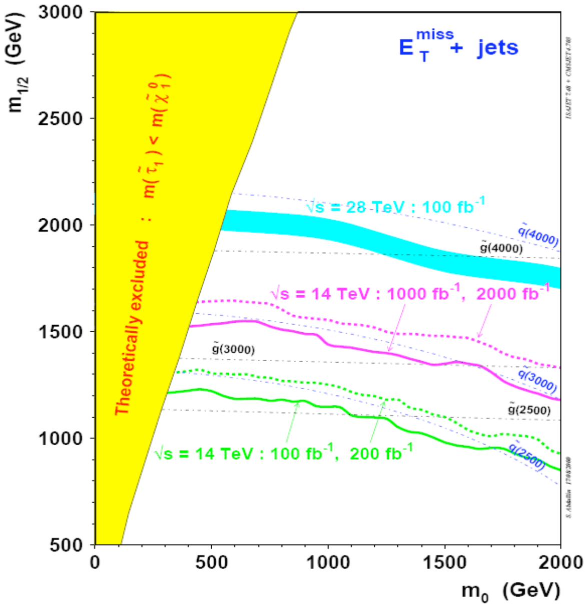

Figure 3 - Expected 5-σ discovery contours for supersymmetric particle masses in a typical model plane [2]. The various curves show the potentials of the LHC for luminosities of 100 fb^{-1} and 200 fb^{-1}, of the SLHC for 1000 fb^{-1} and 2000 fb^{-1}, and of the DLHC for 100 fb^{-1}.

Table 1 shows a brief summary of the comparison of the physics potentials of the basic LHC and the SLHC. We also give some examples of the physics reach of the DLHC and, for completeness, the physics reaches of a Linear Collider of 0.8 TeV and CLIC with 5 TeV.

Units are TeV (except W_LW_L reach)
∫Ldt correspond to 1 year of running at nominal luminosity for 1 experiment

PROCESS	LHC 14 TeV 100 fb^{-1}	SLHC 14 TeV 1000 fb^{-1}	DLHC 28 TeV 100 fb^{-1}	LC 0.8 TeV 500 fb^{-1}	CLIC 5 TeV 1000 fb^{-1}
Squarks	2.5	3	4	0.4	2.5
W_LW_L	2σ	4σ	4.5σ	6σ	90σ
Z'	5	6	8	8†	30†
Extra-dim (δ=2)	9	12	15	5-8.5†	30-55†
q*	6.5	7.5	9.5	0.8	5
Λ compositeness	30	40	40	100	400
TGC λ_γ (95%)	0.0014	0.0006	0.0008	0.0004	0.00008

† indirect reach (from precision measurements)

Table 1: The reach of LHC, SLC and DLHC are compared with a Linear Collider of 0.8 TeV and CLIC at 5 TeV [2].

Experimentation at SLHC will be more difficult due to the large increase in pile-up - by a factor of 5 to 10 - and to the large irradiation of the detectors. The physics reach will be the result of an optimization between the increase in integrated luminosity and the more challenging running conditions that will strain the performance of the detectors. The first LHC runs will give input on some parameters that are needed for the design of the upgraded SLHC detectors like neutron fluence, radiation damage and performances of the present detectors.

The present inner tracking systems are designed to survive a maximum of 300 fb^{-1}, after which they will need to be replaced during a long shut-down with new devices. In the event of luminosity upgrade, they should also be capable of sustaining the increase in pile-up. Electronic technology evolution will bring benefits and should be adopted, but the associated power distribution is an issue requiring further study, as well as the integration of services in the existing space. Radiation-hard silicon sensors are being developed in the framework of the RD50 collaboration in conjunction with industrial partners. System design and the industrial production and qualification of many hundreds of square meters of silicon are challenges.

One important ingredient for the luminosity increase is the modification of the insertion quadrupoles to yield a β^* of 0.25 m, compared to the nominal 0.5 m. The new interaction regions have yet to be defined, and their layout may have significant implications for the experiments.
Another important ingredient for the luminosity increase and for the reduction of the pile-up is the reduction of the spacing between beam crossings at the SLHC. The upgrade of the electronics of the calorimeters and of the muon systems would depend strongly on this new spacing. The LHC experiments have expressed clear preferences for going to a spacing of 12.5 ns (one half of the present 25 ns) that could allow most of the front-end electronics for the calorimeter and muon system to continue running at 40 MHz. A spacing of 10 or 15 ns – which would avoid changes to the timing of the SPS - would be likely to require much more complex modifications to the front-end electronics of these subsystems. In the case of the tracking detector, new front-end electronics would be designed according to the new selected bunch spacing.

These technical challenges are already under study by the ATLAS and CMS Collaborations, together with the modifications to the Trigger and DAQ systems and to the radiation protection and shielding that would be required in any SLHC scenario. The R&D needed for this upgrade of the detectors has synergies with the EUDET program and ILC detector R&D in general, especially for items linked to the electronic technology evolution. The complex modifications to the detectors may cost a substantial fraction of their initial capital costs. The final choice of luminosity upgrade scenario will require a global optimization of the combined accelerator and detector expenses.

The definition and schedule of the preferred LHC luminosity upgrade scenario in 2010 will depend on results from the initial LHC running including physics results and assessment of the LHC running conditions. A common element in all the upgrade scenarios is Linac4. Higher-energy replacements for the PS Booster, PS and/or SPS are considered in some upgrade scenarios [3].

3 – LHC energy upgrade

Many scenarios for new physics at the LHC would benefit from an increase of a factor of two in the centre-of-mass energy at a luminosity of 10^{34} $cm^{-2}s^{-1}$ (DLHC). This is typically the case in scenarios with a new threshold in the multi-TeV range beyond the physics reach of the LHC at its nominal centre-of-mass energy of 14 TeV. Two examples are:

- LHC discovers supersymmetry in a scenario in which DLHC allows further studies/discoveries of heavy supersymmetric particles and/or the production of new gauge particles mediating supersymmetry breaking;
- LHC discovers that quarks are composite particles and the scale of the compositeness is in the range of DLHC.

Another example is illustrated in Figure 4.

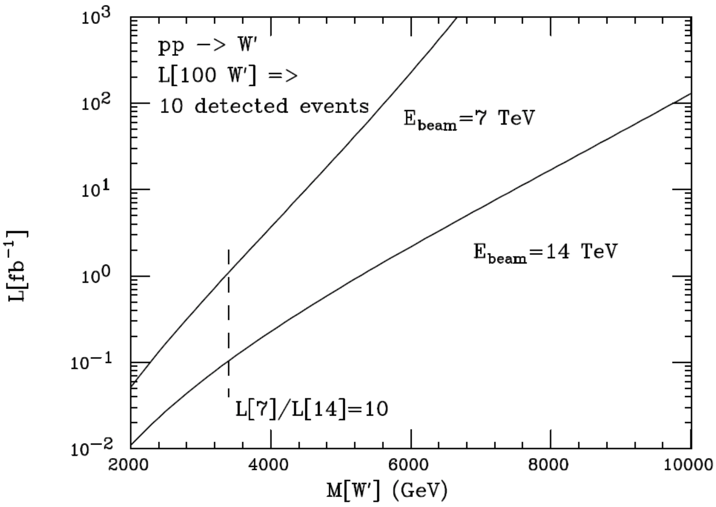

Figure 4 - An example of the interplay between the SLHC and the DLHC: at low mass ~ 2 TeV, the W′ cross section increases by a factor of 5, but the increase is much larger for a heavier W′. The DLHC would require only a few fb^{-1} to discover a W′ weighing 7 TeV, which would require 1000 fb^{-1} at the SLHC.

On a time-scale longer than the SLHC, the DLHC is another option for a future major accelerator at the high-energy frontier that should be assessed in light of the early LHC physics results, along with the ILC and CLIC.

The detector R&D needed for the DLHC is smaller than that required for the SLHC and one could in principle use ATLAS and CMS with only small modifications. However, on the time scale of a DLHC project, the present detectors will require the replacement of aged/old subdetectors using the new technologies, e.g., electronics and DAQ, that will then be available. There should be synergy with the detector R&D for the SLHC.

The DLHC accelerator would require a substantial long-term effort in the development of new magnet technologies, in order to double the bending field. There should be synergy with the R&D on high-field magnets for the SLHC collision insertions. Some of the scenarios for upgrading CERN's proton accelerator complex would have particular relevance if the DLHC were to be envisaged: for example, the DLHC would require a chain of higher-energy injectors.

4 – Neutrino physics

Neutrinos have provided the first clear experimental evidence for physics beyond the Standard Model, and there are many important outstanding issues to be addressed by future accelerator neutrino experiments. These include the magnitude and hierarchy of neutrino masses, the magnitude of the third neutrino mixing angle θ_{13} and the possibility of CP or T violation in neutrino oscillations, as well as the overall verification of the assumed theoretical framework.

The magnitude and hierarchy of neutrino masses will be addressed by neutrinoless double-β decay experiments, cosmological measurements and accelerator experiments on neutrino oscillations, though these issues are unlikely to be resolved before 2015. The magnitude of θ_{13} is being addressed by a series of oscillation experiments, including Double-Chooz and OPERA in Europe, MINOS and perhaps NOνA in the US, T2K in Japan and perhaps another reactor experiment in the US, Japan, China or Brazil. As seen in the Figure 5, Double-Chooz may reach a sensitivity to $\sin^2 2\theta_{13} \sim 2.10^{-2}$ by 2010, and the world sensitivity may reach $\sin^2 2\theta_{13} \sim 5.10^{-3}$ by 2015. Theory currently does not provide useful guidance on the magnitude of θ_{13}. None of the projects discussed for the next ten years have any significant sensitivity to the CP-violating phase δ in the simplest 3-generation mixing scheme.

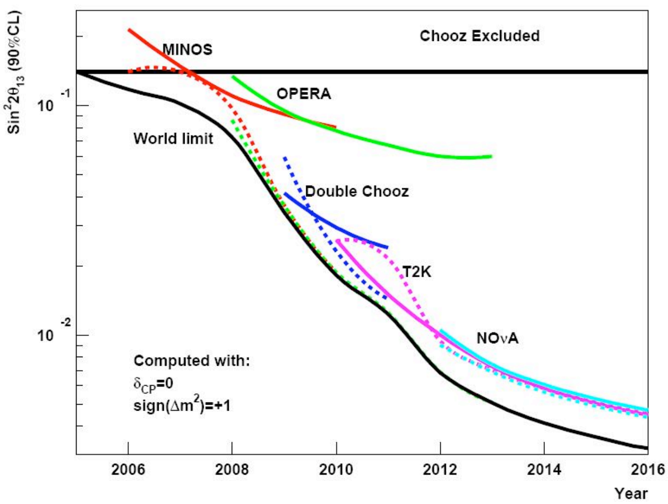

Figure 5 – Estimate of the possible future evolution of the experimental sensitivity to θ_{13} [4].

A forefront programme of precision neutrino oscillation physics, including the observation of leptonic CP violation, would be a very interesting goal for CERN. As seen in Figure 6, if $\sin^2 2\theta_{13}$ is larger than about 10^{-2}, it may be possible to measure δ using a 'conventional' superbeam in combination with a γ =100 β-beam [6] and a megaton water Cerenkov detector at a distance of 100 to 200km. However, a neutrino factory with distant magnetized detectors at one or possibly two very long baselines may be needed to measure δ and determine unambiguously the oscillation parameters, especially if $\sin^2 2\theta_{13}$ is less than about 10^{-2}. One of the goals of the of the International Scoping Study launched, in particular, by the EU-funded network BENE [6] of CARE, is the evaluation of the relative merits of a neutrino factory, a superbeam and a low-γ β-beam for large values of $\sin^2 2\theta_{13,}$ taking into account systematic uncertainties.

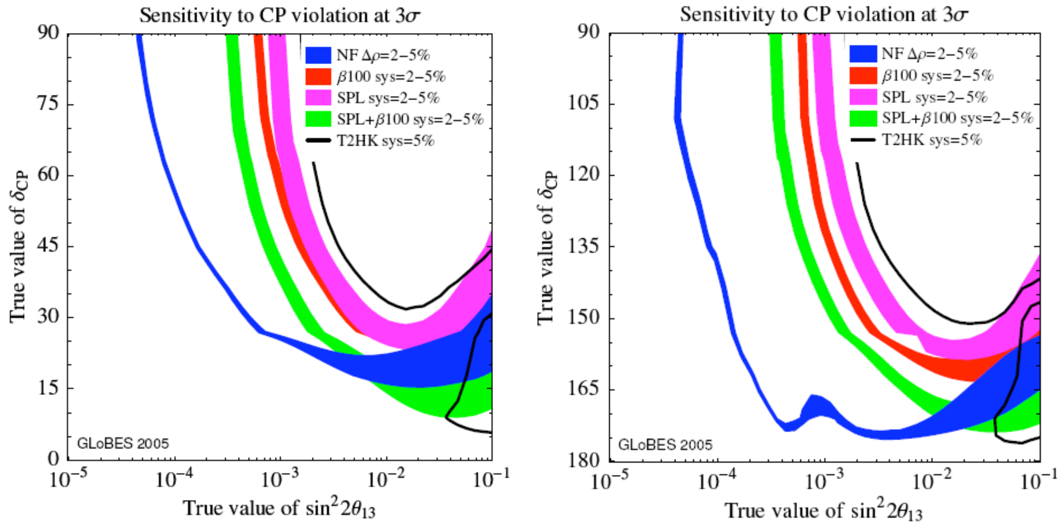

Figure 6 – Provisional estimates of the sensitivities of various proposed neutrino facilities to the CP-violating phase δ in the simplest three-generation model of neutrino mixing [5]. The black line assumes that JPARC delivers 4 MW for 8 years to Hyper-Kamiokande, a megaton water Cerenkov detector. The magenta line is the SPL superbeam running for 10 years aimed at a 440 kton water Cerenkov detector at a distance of 130 km, the red line is the γ=100 β-beam aimed at the same detector and the green line is a combination of the two. The blue line is the neutrino factory optimized for small values of θ_{13}, aiming at detectors 3000 and 7000 km away. The thickness of the lines shows the effect of varying the systematic errors related to cross sections or matter effects within the indicated ranges. A definitive version of this comparison is a deliverable of the International Scoping Study [7].

Also under consideration are higher-γ β-beam options with a longer baseline, that, while sensitive to small values of $\sin^2 2\theta_{13}$, would require an upgrade of the SPS to higher energy, or acceleration of the radioactive ions in the decay ring. In the latter case, it has been suggested that this post-acceleration capability could also be used to increase the energy of particle injection into the LHC.

The detectors considered for the beta-beam/superbeam combination are a megaton Water Cherenkov or a very large (100kton) Liquid Argon TPC. The detectors considered for a Neutrino Factory must be magnetized. There are concepts based on the iron-scintillator sandwich, liquid argon TPC, and emulsion tracker technologies. These detectors would weigh several dozen kilotonnes each, and would provide complementary measurements. A significant amount of R&D on detector technology will be necessary to reduce the costs of such large detectors and to establish their technical feasibility.

Extensive R&D is required for either the superbeam/ β-beam or the neutrino factory option. The β-beam would require less than half a megawatt of proton beam power, but would in addition require a new low-energy storage and acceleration stage in the CERN accelerator complex. The prospects of achieving the required ion intensities are currently under study and require R&D. On the other hand, the superbeam and the neutrino factory would require a 4 MW proton driver such as the SPL (whose energy optimization will require input from HARP) accompanied by an accumulator ring. The target area would be very demanding: aspects of it are currently being addressed via the MERIT experiment at nTOF. In the case of the neutrino factory, R&D on cooling is currently under way in the MICE experiment in the UK, whereas a proton bunch compressor ring, recirculating linacs or non-scaling FFAGs to accelerate rapidly muons to about 20 GeV and the corresponding storage ring would require further R&D projects.

The R&D for a γ = 100 β-beam is being addressed within the EURISOL framework, with conclusions to be available in 2010. The requirements for a combined superbeam and β-beam facility, including the megaton detector, will be defined better in the same time frame. Meanwhile, neutrino factory R&D is being assessed via the International Scoping Study. This is expected to lead, in 2007, to a proposal to the EU to fund a design study that should deliver a Conceptual Design Report in 2010.

We note that all the possible major future options for neutrino physics at CERN could be based on Linac4 and the SPL. The γ = 100 β-beam would benefit from an upgraded PS that would address space-charge limitations. In addition, a higher energy β-beam would be facilitated by a higher-energy replacement for the SPS.

5 – Other physics

5.1 – Kaon physics

The chain of CERN proton accelerators provides the possibility of pursuing a very competitive and cost effective program in kaon physics at present, and future upgrades of the proton complex would allow the community to plan for next-generation experiments.

The most interesting subject addressed by current kaon experiments is the study of rare kaon decays. In particular, the highest priorities in kaon decay experiments are studies of the $K \to \pi\nu\nu$ decay modes, both neutral and charged. These flavour-changing neutral decays are particularly interesting because they are precisely calculable loop processes in the Standard Model, which may well get significant corrections from extensions such as supersymmetry, and complement measurements of B mesons, as seen in Figure 7.

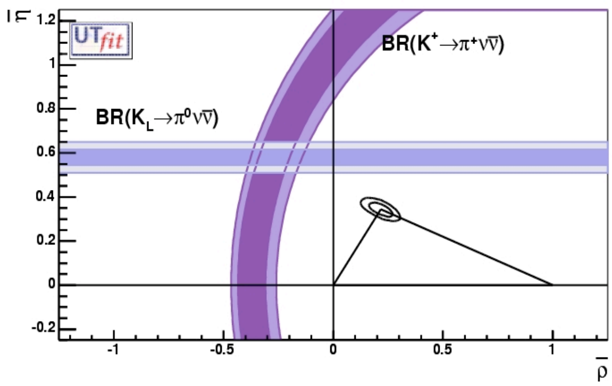

Figure 7 – The potential impacts of $K \to \pi\nu\nu$ measurements compared to a present fit to the Cabibbo-Kobayashi-Maskawa unitarity triangle, which are largely derived from measurements of B decays [8].

Projects to measure these decays in the United States have been cancelled, but the neutral mode may be measured at KEK and JPARC, and the P-326

(NA48/3) proposal aims to measure the charged mode at the SPS. The latter would start taking data in 2009/2010, with the objective of obtaining around 80 events by about 2012, assuming the Standard Model branching ratio. This would provide a constraint on flavour mixing independent of those being provided by B mesons. The NA48/3 apparatus could also be modified to obtain about 30 $K_L \rightarrow \pi^0 \nu\nu$ events if the branching ratio is similar to that predicted in the Standard Model, and a substantial fraction of the SPS proton intensity is used to produce neutral kaons. In addition, if the apparatus' tracker is retained, it could also be used to measure the $K_L \rightarrow \pi^0 e^+ e^-$ and $K_L \rightarrow \pi^0 \mu + \mu^-$ modes. These measurements could be completed by about 2016.

Follow-up measurements with greater accuracy would be very important if any of these first-generation experiments finds a possible discrepancy with the Standard Model prediction based on B physics measurements. This would require Giga-Hertz kaon rates, for instance a sequel to P-326 using a separated kaon beam originating from a 4 MW 50 GeV proton beam such as could be provided by a rapid-cycling replacement for the PS. This could obtain over 1000 $K^+ \rightarrow \pi^+ \nu\nu$ events per year, assuming the Standard Model branching ratio.

It is important to stress that the crucial parameter for the quality of a kaon experiment is the machine duty cycle, which should be as close to 100% as possible. The duration of the flat top for slow extraction may be limited by the power consumption of the warm magnets. The energy of the proton beam is not the primary concern for the design of a rare kaon decay experiment provided it is high enough to produce kaons efficiently.

5.2 – Muon physics

In future, the headline question in muon physics may become the possible existence of flavour-violating $\mu \rightarrow e$ transitions [9]. This would be the case, in particular, if the LHC reveals new physics at the TeV scale, such as supersymmetry.

An experiment with sensitivity to $\mu \rightarrow e\,\gamma$ decay at the level of 10^{-13} is being prepared at PSI, whereas a proposed search for anomalous $\mu \rightarrow e$ conversion on nuclei at BNL has recently been cancelled. If $\mu \rightarrow e\,\gamma$ decay is found at PSI, follow-up searches for $\mu \rightarrow eee$ and anomalous $\mu \rightarrow e$ conversion will be high priorities, but the interest of the latter would be strong even if the PSI experiment does not detect $\mu \rightarrow e\,\gamma$ decay. A programme in muon physics is planned for JPARC, but not yet funded. We note that R&D and prototyping for a possible muon physics facility is currently being conducted by the PRIME collaboration on a site-independent basis. This project should be ready by 2010 for a decision whether to site it at JPARC or elsewhere.

We also note that intense muon beams incident on a fixed target may provide an opportunity to look for $\mu \rightarrow \tau$ transitions in deep-inelastic scattering.

The construction of a high-intensity, low-energy proton driver for either neutrino and/or nuclear physics would provide CERN with a scientific opportunity to host a world-leading muon physics facility.

5.3 – Other fixed-target physics

The COMPASS detector is well suited for a continuing physics programme after 2010. The COMPASS collaboration plans to propose in 2006 an extension of its present approved programme, aiming at the measurement of generalized parton distribution functions via deeply-virtual Compton scattering and hard meson-exchange processes. The modified apparatus could be prepared between 2007 and 2009 and take data between 2010 and 2015.

A fixed-target programme to study further aspects of charm and charmonium production as a continuation of the NA60 programme is also under consideration.

5.3 – Heavy-ion physics

The ALICE experiment at the LHC envisages a comprehensive programme of physics which is expected to last until around 2017, whereas the RHIC programme is expected to terminate around 2012. ALICE plans to explore different beam types and energies as well as increase the luminosity as far as possible. The first Lead-Lead run is expected in 2008, to be followed by further Lead-Lead runs in the following two running years, at least. ALICE also plans continuous proton-proton running and requests some proton-ion running in 2010 or later, which would be necessary to isolate better the collective effects in ion-ion collisions. Running with low-mass ions is also requested. The collaboration plans to install a jet calorimeter by 2010, as well as improved particle identification and forward detectors. During the following five years, runs at lower energies and with more ion-ion and proton-ion combinations will be requested, as well as proton-proton running.

An increase in the Lead-Lead luminosity to 5.10^{27} $cm^{-2}s^{-1}$ would enable good measurements to be made of Υ, Υ' and Υ'' production as well as γ-jet correlations. In order to gather sufficient statistics, the ALICE collaboration would like to run for three or four years at this enhanced luminosity. Obtaining this would increase in luminosity would require combatting pair production and electron capture, and rapid turnarounds and refills would also be desirable.

A critical point in the quark-hadron phase diagram is thought to be accessible to fixed-target heavy-ion experiments at the SPS, but its signatures are uncertain. It is expected that data would be needed over a range of energies, with good luminosity. The possible step-wise suppression of J/ψ production would be one objective, as well as charm production studies. In order to establish a baseline for nuclear absorption, studies of both proton-ion and light-ion collisions would be desirable.

This programme could be addressed using an NA60-like dimuon spectrometer. Other research topics would include studies of low-mass lepton pairs (in the ρ region, to understand better the possible effects of chiral-symmetry restoration), the observed enhancement of intermediate-mass dimuon production (which is thought to be thermal, rather than due to charm production) and the search for fluctuations in particle yields in narrow ranges of effective temperature and baryon chemical potential (which could be a signal for the critical point of the QCD phase transition). A possible scenario would include runs in the period from 2010 to 2013, including Pb-Pb, Cu-Cu and Pb-Be collisions. If the SPS+ were to become available, runs with Pb-Pb or U-U at the highest possible beam energy would also be interesting.

5.4 – Nuclear Physics

The evolution of experimental nuclear physics towards ever more complex experiments, combined with the need for large beam power for the generation of highly exotic isotopes, will in the future require a laboratory infrastructure for nuclear physics similar to that required for high-energy physics. Nuclear physics is closer to applied sciences than particle physics, but the subject is driven by a drive to explore the unknown, and is in its nature a fundamental science. This, together with the potential synergies at the infrastructure level, generates large common ground between the subjects.

CERN currently has a forefront research programme in nuclear physics, based on ISOLDE and nTOF. The on-line isotope separation technique perfected at ISOLDE provides a uniquely broad range of isotopes with fast change-overs, which in turn provide many interesting physics opportunities. As seen in Figure 8, these include studies of *nuclear structure*, e.g., of light nuclei with extended neutron haloes and of the break-down of the shell model far from stability with a transition from order to quantum chaos in nuclear spectroscopy, studies in *nuclear astrophysics*, e.g., of the s- and r-processes as well as light nuclei, *probes of the Standard Model and its possible extensions*, e.g., via measurements of beta transitions that bear upon Kobayashi-Maskawa unitarity, and *applications* to solid-state physics and the life sciences. nTOF also provides unique opportunities, e.g., for measuring neutron cross sections and for fission studies. A community of about 600 nuclear physicists is currently using these facilities at CERN.

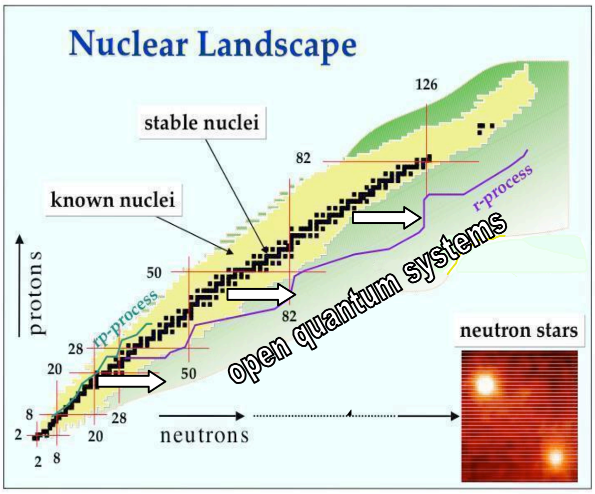

Figure 8 – Outline of the nuclear landscape, highlighting open research areas such as studies of processes relevant to astrophysics, and the breakdown of the shell model.

The ISOLDE community is integrated within the EURISOL initiative, which is planning two phases for developing new facilities. In the first phase, it is proposed to upgrade the present REX-ISOLDE facility to accelerate radioactive isotopes up to 10 MeV/u. This extension, HIE-ISOLDE, of the present ISOLDE programme should be completed by 2011, and would benefit from Linac4 and an upgrade of the PS booster to increase its frequency. We note in passing that nTOF would also benefit from Linac4.

In the second phase, EURISOL proposes a major new low-energy proton accelerator operating at 1 to 4 GeV, providing by 2015 100kW beams on three separate targets, one of which could yield the ^{6}He and ^{18}Ne needed for a beta-beam facility. There would also be a 5 MW beam incident on a spallation neutron target. The facility would deliver a radioactive ion beams up to 100 MeV/u from all target stations from a common linac.

We note the potential synergies with the rest of the CERN programme, e.g., with neutrino physics. The concept of the β-beam has been made possible by ISOLDE, and the proton driver for EURISOL might also to serve as a driver for a neutrino superbeam or a neutrino factory. In this case, a global optimization of its energy should be undertaken.

5.5 – Other physics projects

A recent workshop on flavour physics in the LHC era included the intriguing suggestion to make a highly competitive measurement of the CP-violating deuteron electric dipole moment with an accuracy ~ 10^{-29} e.cm using a 1.5 GeV/c storage ring [10]. This idea could be implemented at CERN by sending polarized deuterons into the LEIR ring for accumulation and bunching, before transferring them into a dedicated ring for experimental runs that would each last several hours. *A priori*, there is no obvious incompatibility with using LEIR to provide heavy ions for the LHC, so this interesting project might have good synergies with CERN's approved programmes.

On a very different scale, there have been two expressions of interest in colliding electrons at an energy around 70 GeV with a proton and/or heavy-ion beam in the LHC (eLHC). The QCD Explorer suggestion is to use an electron beam accelerated by a CLIC module, which would be an interesting synergy with a possible CERN Lepton Facility. More recently, the idea of reinstalling an electron ring in the LHC tunnel has been resurrected. We note that this project would also require the construction of a new lepton injector chain, since that used for LEP has now been dismantled and partly reused for other activities such as CTF3. These projects would have great interest for QCD studies, but their values for studying new physics remain to be evaluated.

Suggestions have also been made to use the LHC for electron-ion collisions. Such a project would have interest for relativistic heavy-ion physics, serving to probe parton saturation and the possible existence of the colour-glass condensate. This could be done with, in principle, more clarity than would be possible with the ion-ion or proton-ion collisions at the LHC. These would provide key physics input for such an electron-ion project, which would collide electrons with energies around 70 GeV with LHC ion beams. These energies are far beyond the capabilities of the eRHIC project at BNL, which envisages colliding 5 to 10 GeV electrons with 250 GeV protons and 100 GeV/A nuclei, in the period up to 2020.

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