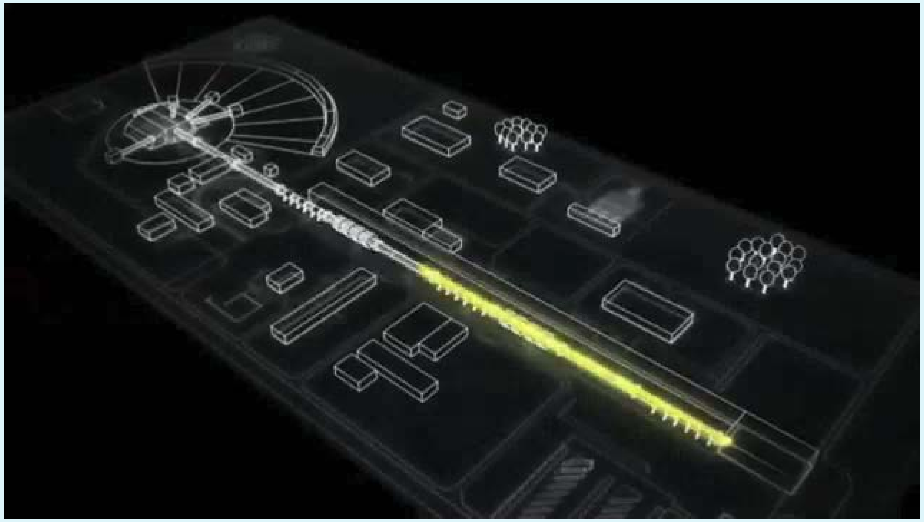
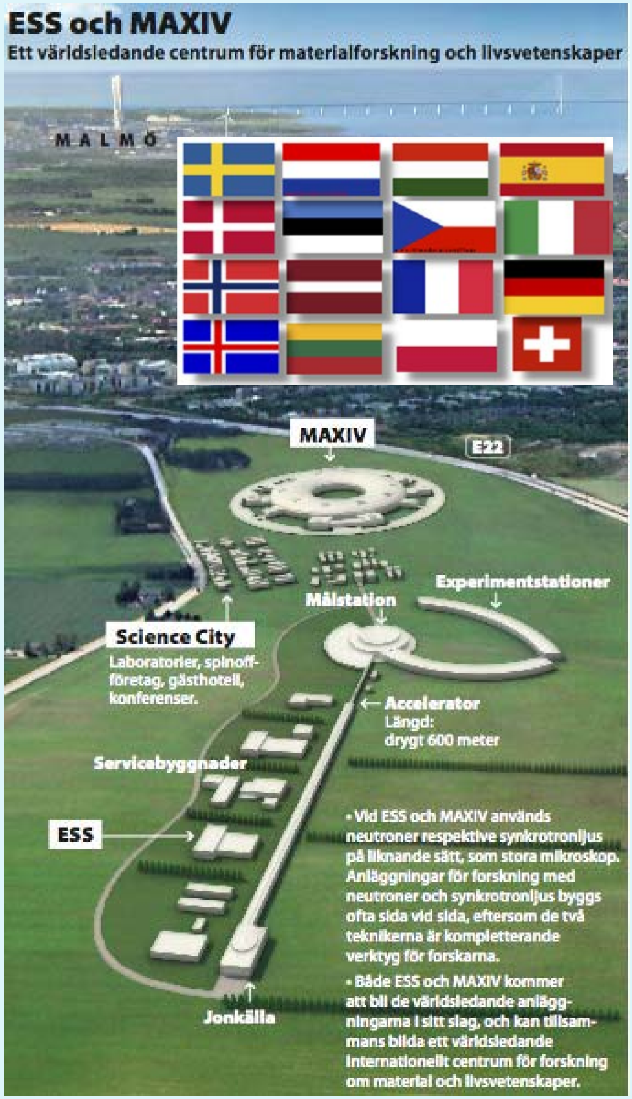
UPPSALA UNIVERSITET 1477

A lepton CP violation discovery experiment using a unique neutrino Super Beam



Using the ESS 2.5 GeV proton linac to generate a neutrino Super Beam



The European Spallation Source (ESS), which is being built in Lund, will have a **2.5 GeV 5 MW** superconduction linac to produce

1.25 x 10^{16} protons on target/second

= Power [W]/(Energy [eV]x1.6×10^{-19})

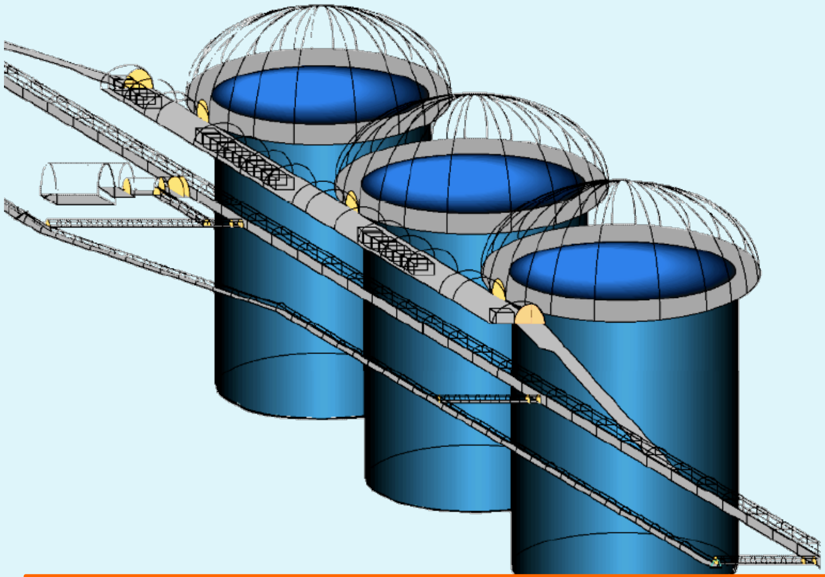
which is two orders of magnitude more than any other planned proton driver for neutrino beams

T2HK – JPARK to HyperKamiokande 30 GeV, 0.75 MW -> 1.6×10^{14} protons on target/second

LBNE – FNAL to Sanford Lab <u>60</u>-120 GeV, 0.7 MW –> 1.1×10^{14} protons on target/second

First beams 2019, **Full operation 2025**

Using a megaton water Cherenkov detector to measure the neutrinos



A "Hyperkamiokande" type detector to study;

•Neutrinos from accelerators (Super Beam)

but also

•Supernovae neutrinos (burst + "relics"),

•Solar Neutrinos,

•Atmospheric neutrinos,

•Geoneutrinos

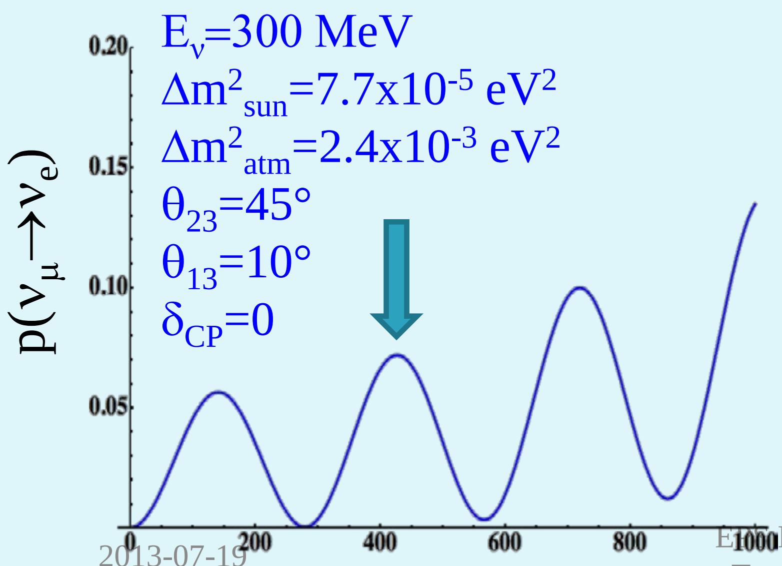
•Proton decay up to ~10^{35} years life time.

All these other measurements require the **detector to be shielded by ~1000 m rock from cosmic ray muons**

The MEMPHYS detector of the FP7 LAGUNA project;
•Fiducial mass: 440 kt in 3 cylinders 65x65 m
•Readout: 3x81k 12" PMTs, 30% geom. cover.
•Order of magnitude cost : 700 MEuro

The optimal base line for CP violation measurements and the depth and distance from ESS/ Lund of different mines in Scandinavia

With the newly measured high value of ca 0.1 for $\sin^2 2\theta_{13}$ the maximum sensitivity to CP violation is at the second oscillation maximum – all other earlier planned experiments have their detector at the first oscillations maximum

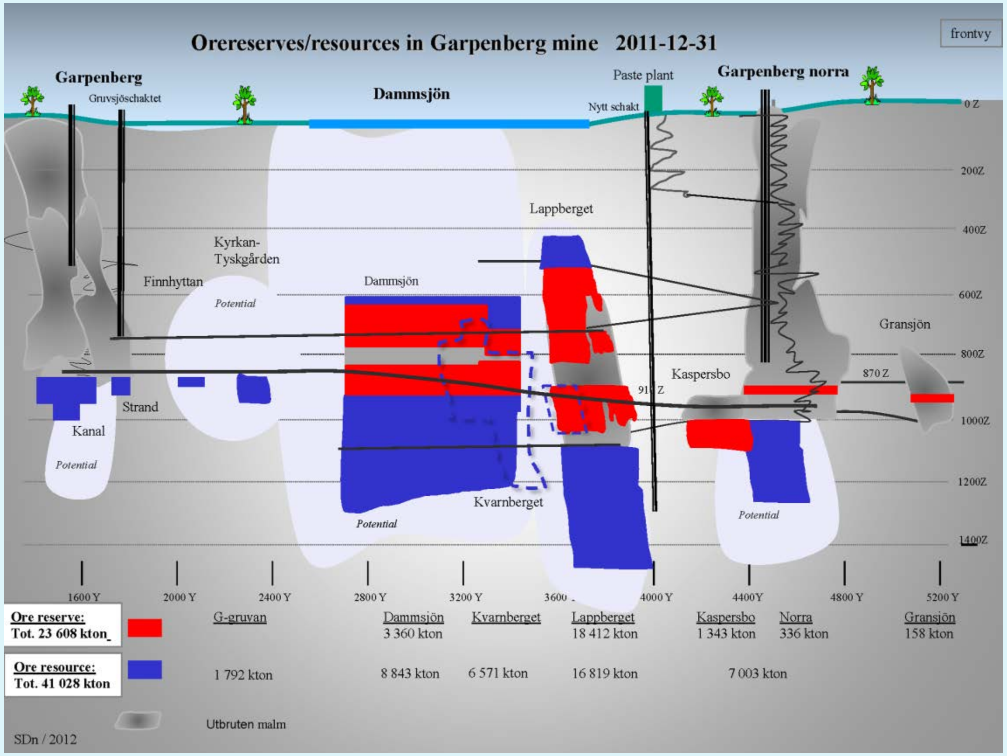


Garpenberg Mine

Distance from ESS Lund **540 km**

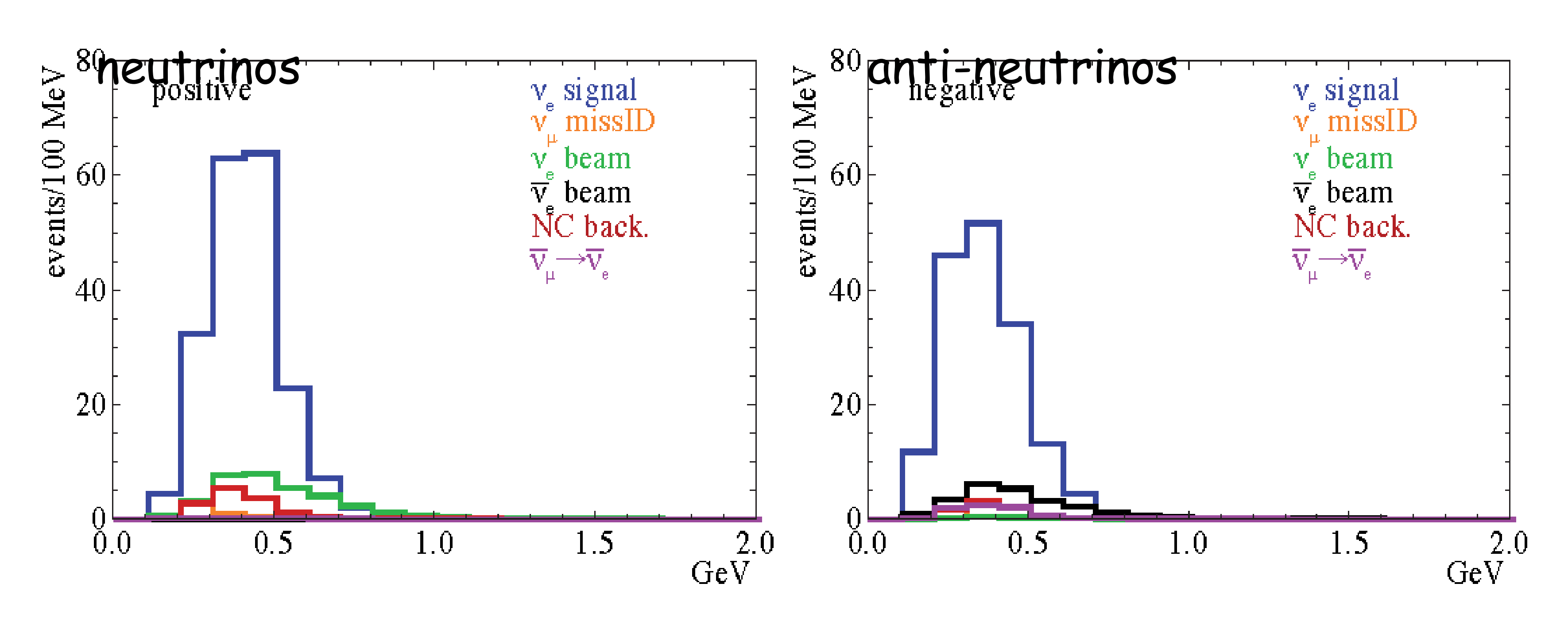
Depth 1232 m
Truck access tunnels
Two ore hoist shafts

A new ore hoist schaft is planned to be ready i 3 years, leaving the two ex shafts existing free for other uses

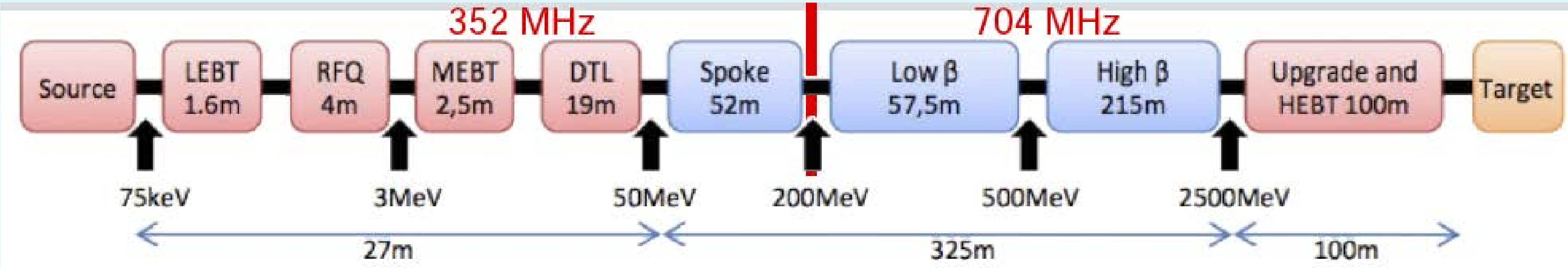


Normalized energy spectra for electron neutrinos and anti-neutrinos

as detected in a MEMPHYS type detector after 2 years of neutrino running (left) plus 8 years of antineutrino running (right) with a baseline length of 540 km and 2.0 GeV protons for the ν_μ->ν_e oscillation signal (blue) and background sources (other colors)



How can the ESS linac be used as a proton driver for a neutrino Super Beam, maintaining spallation neutron production unchanged?



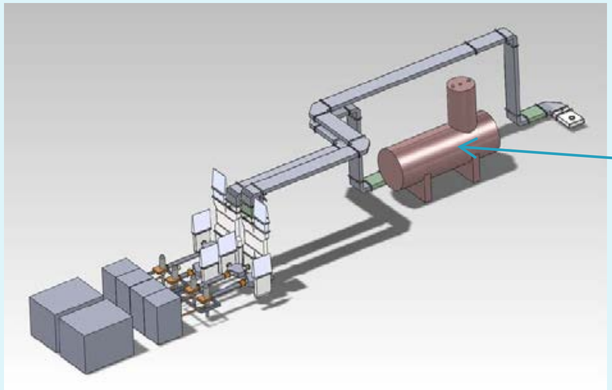
The average RF power needs to be doubled

For the simultaneous acceleration of 14 linac pulses per second for neutron physics and 14 pulses for neutrino physics the **average power of the linac will have to be doubled from 5 MW to 10 MW**, requiring a corresponding doubling of the output power from the linac RF sources.

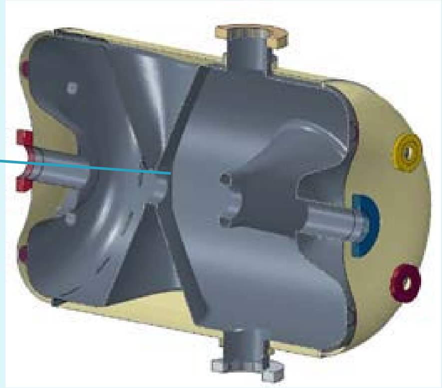
The cost for this doubling of order 100 MEuro will be the dominant cost for the linac modification project. Modulators, amplifiers and power transfer equipment should be designed for the doubled average power of the linac already during the build-up phase.

RF power source tests

A prototype 352 MHz spoke cavity for the ESS linac will be tested in the **FREIA Laboratory at Uppsala University** already as from July 2014 in a cryostat at 14 Hz pulse frequency and at the full instantaneous power required for ESS proton acceleration, which is 350 kW. For the generation of the 352 MHz power both a tetrode amplifier and a solid state amplifier will be tried out. As part of the EUROSB project, **the amplifier pulse frequency will be raised to 28 Hz**, thus doubling the average power to the cavity. The influence of this higher power on the operation of the cavity and on the capacity to cool the cavity itself and, in particular, its RF coupler will be studied.



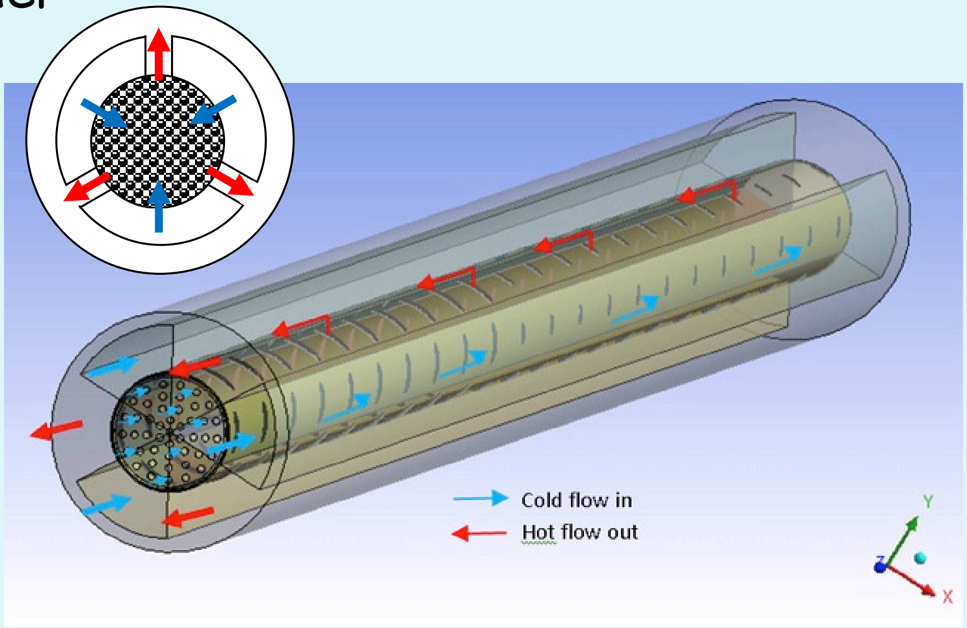
Lay-out of the 352 MHz RF source, wave guides and test cryostat in the FREIA hall



ESS Spoke 352 MHz Accelerating Cavity

The Target

A challenging part of this project is the **target** to be hit by the 5 MW proton beam to produce the pions needed for the neutrino beam production. The use of classical monolithic solid targets is impossible for this application because of the absence of efficient cooling. One design which is under investigation is a **packed bed of titanium spheres cooled with cold helium gas**. It needs to be investigated whether the pulsed beam will generate vibrations in the spheres, which could be transmitted to the packed bed container and beam windows and cause degradation of the spheres where they are in contact with each other.

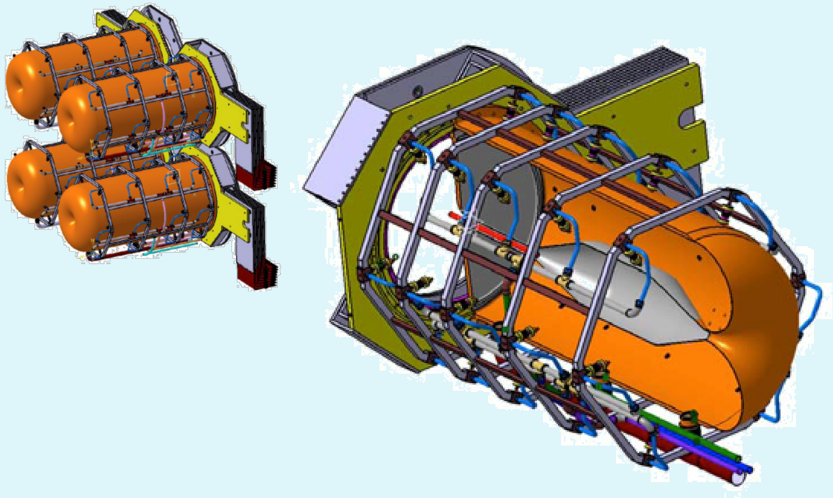


Tests of such a target are planned **using the HiRadMat high intensity proton irradiation facility at CERN**.

The Neutrino Horn

A key element for generating a neutrino beam is the hadron collector, also called **neutrino horn**, used to focus in the forward direction the charged pions produced in the proton-target collisions

A pulsed power supply able of providing the very high current (~350 kA) to be circulated inside the horn at the required pulse rate has not been produced so far and thus needs to be prototyped.



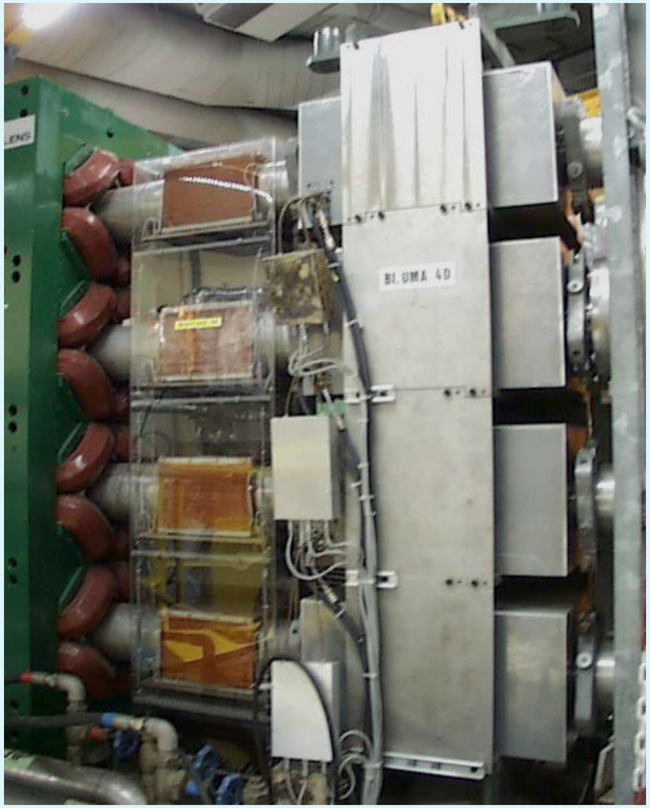
Furthermore, the time duration of this high current pulse can only be of a few microsecond to not overheat the horn. This implies that the ESS pulse length of ca 3 milliseconds has to be shortened by ca 1000 times using a **storage ring** in which the whole 3 ms long pulse is accumulated by multi(1000)-turn injection and then ejected in one turn. To obtain a 1.5 μs pulse the ring should have a **450 m circumference.**

H^- accleration, injection and compression

During the 3 ms long period of injection in the storage ring the large stored positive charge will **repel the successively arriving negatively positive protons**. To alleviate this problem one must **inject H^- ions** and strip off the electrons from the H^- ions at the moment when they enter the stored circulating beam.

The proposed plan for simultaneous H^- acceleration is to have one 3 ms long 50 mA **H^- pulse accelerated in the 70 ms long gap between to proton (H^+) pulses**.

The large stored charge also causes **space charge problems** and beam blow-up in the compressor storage ring, which can be alleviated by dividing up the ring on four rings. This is a trick already used for the CERN PS Booster ring.

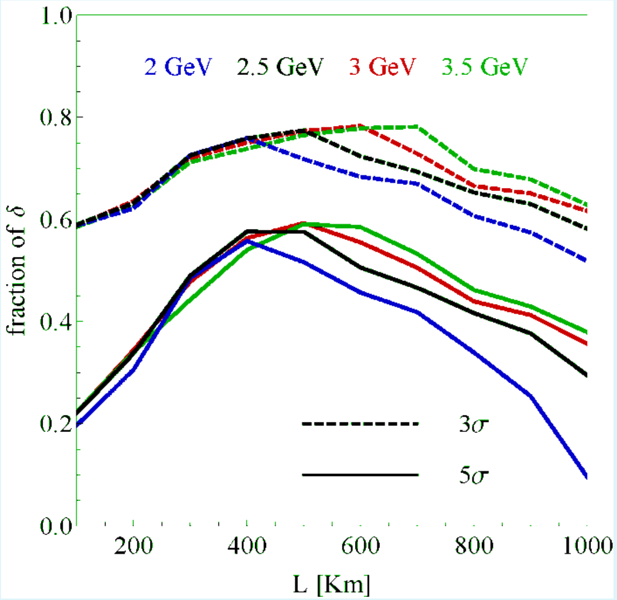


The 4 rings of the CERN PS Booster

Which is the optimal base line for the ESS SuperBeam for CP violation discovery?

An important parameter to be determined is the optimal neutrino beam baseline length, **determining the choice of the mine where to install the detector**.

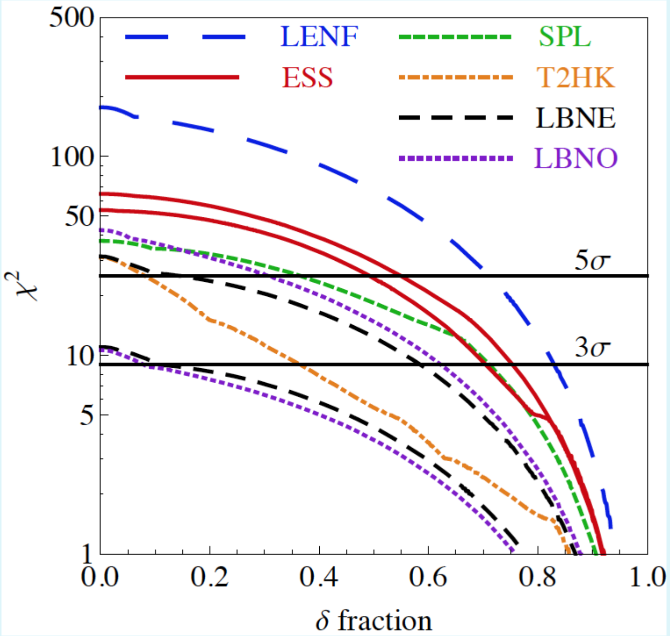
Below is plotted for different proton energies the potential for CP violation and neutrino mass hierarchy discoveries with EUROSB, measured as the fraction of the full CP violation angular range within which neutrino CP violation can be discovered, versus the baseline length.



The fraction of the full δ_{CP} range 0°-360° within which CP violation can be discovered as function of the baseline length in km for different proton linac energies from 2 to 3.5 GeV.
The lower (upper) curves are for CP violation discovery at 5σ (3σ) significance. (Enrique Fernandez)

ESS SuperBeam Physics Performance - CP Violation

The simulation software developed by the EUROnu project has been used to make first evaluations of the potential for CP violation discovery with EUROSB and the other planned neutrino experiments. The figure below shows the physics performance of the ESS SB as compared to the other proposals in terms of the χ^2 **for CP violation discovery as function of the fraction of the full δ range 0°-360° within which CP violation can be discovered.**



LENF – Low Energy Neutrino Factory
ESS – European Spallation Source to Garpeneberg 2 GeV protons (360/540 km, 5 MW, 500 kt WC)
SPL – Super Proton Linac to Canfranc 4.5 GeV protons (650 km, 4MW,500 kt WC)
T2HK – JPARK to HyperKamiokande 30 GeV protons (295 km, 0.75 MW, 500 kt WC)
LBNE – FNAL to Sanford Lab 60-120 GeV protons (1300 km, 0.7 MW, 10/35 kt LAr)
LBNO – SPS CERN to Pyhäsalmi 400 GeV protons (2300 km, 20 kt/200 kt LAr)

All simulations made with 5%/10% systematic errors for the signal/background and for 10 years running time

(Enrique Fernandez)

CONCLUSIONS

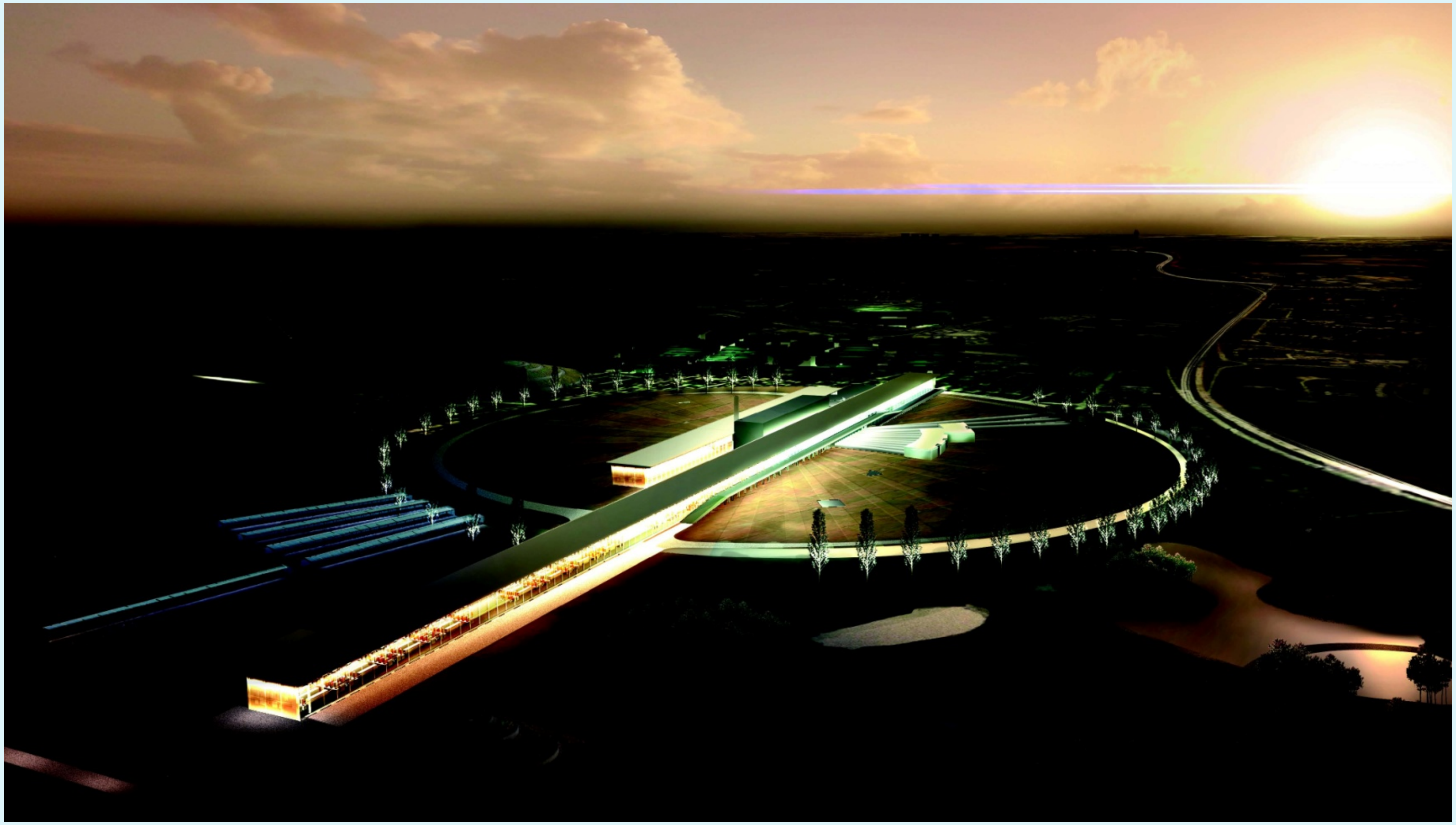
We propose the utilisation of the ESS linac to build a physics competitive and cost effective neutrino Super Beam facility.

The technical feasibility of this project will be studied in detail with the help of computer simulations and prototype tests.

The strong synergy between the use of the ESS linac for spallation neutron production and the proposed, simultaneous use for neutrino beam production presents a **possibility to create a neutrino Super Beam experiment of would leading potential for CP violation discovery**.

The MEMPHYS neutrino detector will also enable a rich variety of other measurements involving atmospheric and cosmic neutrinos.

A discovery of CP violation in the leptonic sector will have strong cosmological implications opening new possibilities to comprehend the matter/anti-matter asymmetry in Universe. Preliminary studies give very promising results compared to other neutrino facility proposals in Europe and elsewhere in the world.



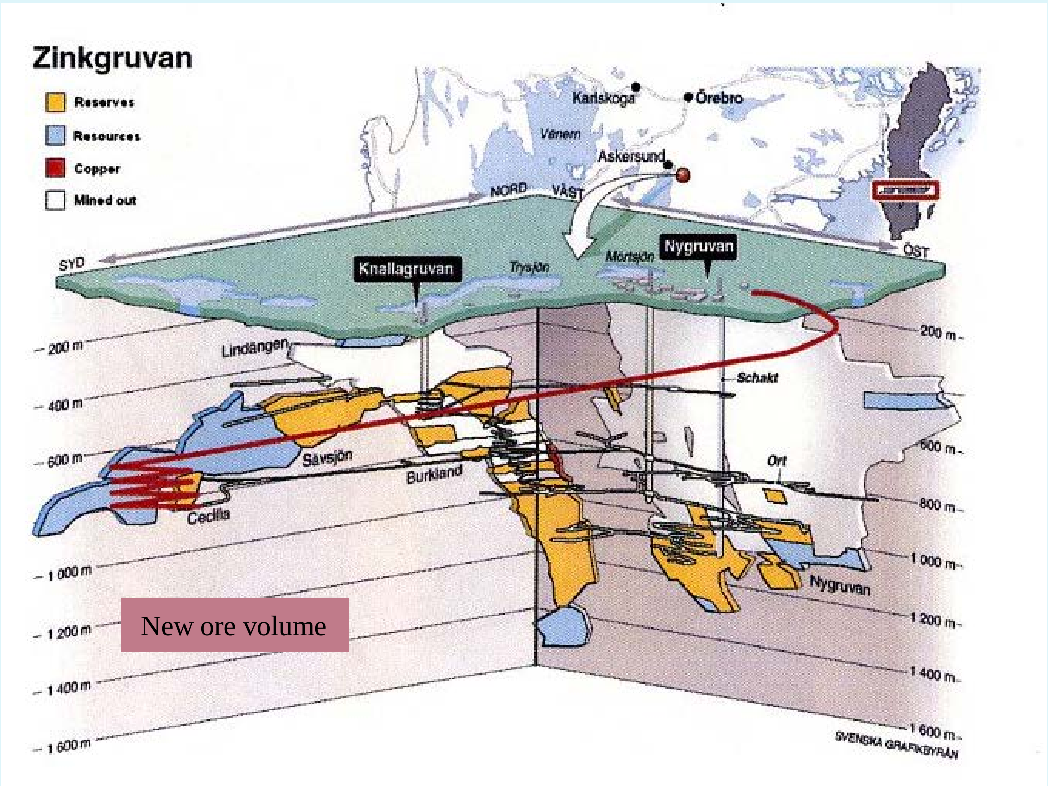
Back-up slides

Zinkgruvan mine

Distance from ESS Lund **360 km**

Depth 1200 m
Access tunnel 15 km
Ore hoist shaft 7m/s 20 tons
Personnel hoist shaft

2 km long tunnel planned
for new ore volume –
3 Memphys cavities could be
built adjacent to this tunnel.
Extension of access tunnel and
second hoist shaft needed.



Shorter pulses also needed for the ESS neutron application

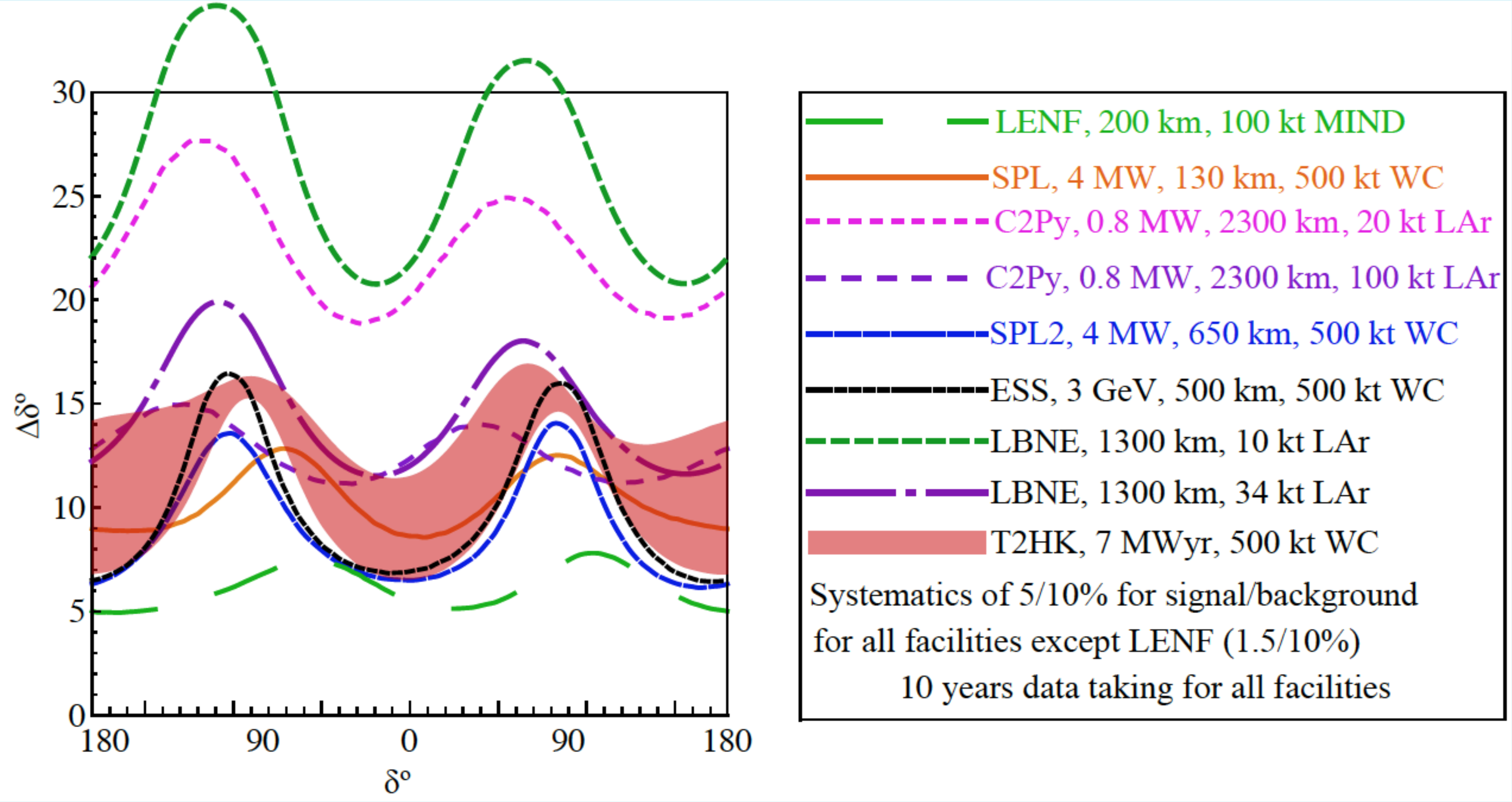
It is of significant interest to note that **spallation neutron users** of the ESS have expressed a **keen interest in having shorter neutron pulses** than 3 ms. For neutrons the optimal pulse length would be of the order of **100 µs**.

It would not be possible for economical reasons to have an accumulator ring with a circumference large enough (of order 30 km) to produce such pulses by single turn extraction.

However, with the system of 4 rings each of ca 450 m circumference **pulses of about 100 µs length can be obtained by multi-turn extraction**.

This option has already been discussed within the ESS and the synergy between the two uses opens the perspective of **sharing the investment and operation costs for the H^- beam and the accumulator** with the spallation neutron users.

Physics Performance for Future SB projects



(Enrique Fernandez)

δ_{CP} resolution versus the δ_{CP} angle.

Selection of the mine where to install MEMPHYS

A preliminary study of the geological parameters and existing mining infrastructures will be made of the few mines located within the range 200-550 km from the ESS site. Once the optimal baseline length has been obtained from the improved calculations, the final choice among these mines can be made **on the basis of the optimal baseline length, the geological parameters and the existing mining infrastructures**.

The selected mine will then be studied in detail collecting geological and rock mechanics information by making **core drillings, core logging, rock strength testing and rock stress measurements of the surrounding rock at 1000 m depth** in different directions and 500 m distance from active mining activities.

Once a suitable location for the neutrino detector underground halls, which should have a total volume of 600’000 m^3, has been determined, a design of the **geometry of and construction methods for the underground halls** will be made based on the measured strength and stress parameters of the rock.

Estimates of investment costs

The price of a **CERN-SPL based Super Beam** has been estimated to be of the order of **1 050 MEUR** (650 MEUR for the SPL, 200 MEUR for the accumulator and 200 MEUR for the target station).

A principal goal of the EUROSB project is to demonstrate that the ESS linac can also be used to produce a SB. If so, about 550 MEUR can be saved, compared to the cost of the SPL-SB project, assuming that about 100 MEUR will be needed for the ESS linac modifications to produce a SB beam. Furthermore, if the accumulator is built in common with the ESS neutron community, its cost 200 MEUR could be shared with the neutron users community.

The total estimated cost for a ESS neutrino beam is of order 400 MEUR, to be compared to the order 1050 MEUR required to build such a beam from scratch.

The price of the **MEMPHYS** neutrino detector has been estimated in the LAGUNA project to be **around 700 MEUR**.

The current EUROSB Feasibility Study Team

The **Strasbourg group** is, in view of their participation in the EUROnu Super Beam Design Study, oriented principally towards the **target/horn station** and the **Super Beam optimizations**. The CNRS has as partners the **University of Madrid** and the **UK-STFC** which will contribute with their expertise in neutrino phenomenology and physics performance simulations (Madrid) and in proton target technology (UK-STFC).

The **Uppsala group** is, in view of its involvement in the ESS proton linac, oriented principally towards the **proton linac** and towards the investigation of possible **detector sites** and the surveillance of the **design study of the detector underground hall**. The Uppsala team has four partners, **ESS** with its detailed knowledge of, and management responsibilities for, the ESS linac, **CERN** with its experience of developing the SPL proton linac project and an accumulator ring for a neutrino beam to the Fréjus site, **Stockholm KTH** with its expertise in neutrino phenomenology and **Lund University** with is experience of particle detector construction.

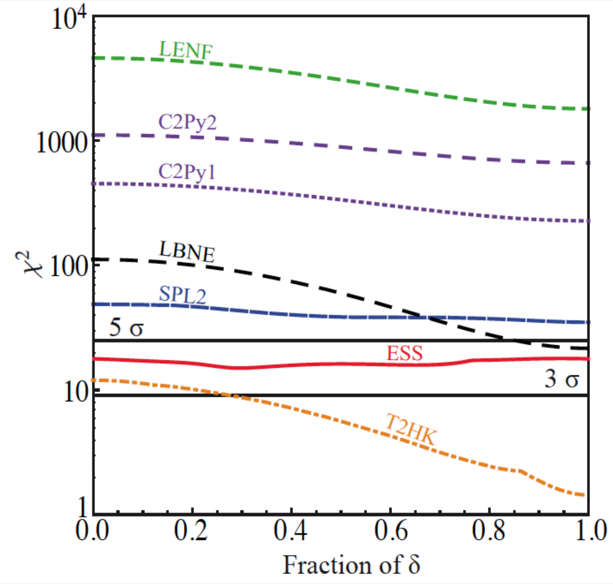
New collaborators are most welcome to join in!

Metrics of ESS SB for Snowmass

- **Science goals**
  - discovery potential: **yes, unique potential for CPV, potential for MH together with several other experiments**
  - physics topics and parameter sensitivity: **CPV and δ_{CP}**
  - is science unique? **yes, the uniquely high ESS proton driver flux (10^{23} protons/year) provides uniquely high CPV sensitivity**
  - are there other competing experiments? **yes, T2HK (with lower proton flux) and NF (with significantly longer time schedule)**
  - complementarity with other experiments? **yes, ESS SB has lower neutrino energy 200-500 MeV and shorter base line ca 500 km**
- **R&D requirements**
  - ready for proposal or construction: **conceptual proposal 2013, proposal 2015, start of construction 2016**
  - limited R&D sufficient (1-2 years): **yes, for the detector**
  - long-term R&D required (> 2 years): **yes, for the neutrino beam**
  - synergies with other experiments? **yes, with the ESS spallation-neutron scientific program (linac and accumulator in common)**
- **Cost categories (indicate separately categories for US contribution and total project cost, no precise estimates needed)**
  - < $5M ($) - minor construction (below threshold for project reporting)
  - < $50M ($) - e.g. Daya Bay-like, less than LBNE underground option
  - $50-300M ($$) - e.g. NOvA, mu2e, IceCube-size
  - > $300M ($$$) - e.g. LBNE-I
  - > $1B ($$$$) - e.g. LBNE-II, NuFact, beta beams: **costs of order $300M for ESS linac upgrade and accumulator to be shared with the neutron users, of order $200M for the target and of order $700M for the detector - any US contribution would be most welcome**
- **Synergies**
  - with other experiments? **yes, with LNBO, LBNE, T2HK, PINGU**
  - with other fields and frontiers? **yes, with astroparticle physics, proton life time, geophysics**
- **US collaborations and leadership**
  - US leadership? **no**
  - US based experiment/facility? **no**
  - opportunity for international engagement? **yes, enlarged international engagement most welcome and needed**
  - continued international collaboration? **no, but building on earlier experience made in EUROnu, LAGUNA and others**
- **Timeline and projected schedule: tied to the ESS schedule - ESS is already approved and construction is starting this year**
  - R&D timeline: **2013-2016**
  - construction time: **2016-2023**
  - data taking and science program duration: **2023-2033 (may be continued beyond 2033 with further scientific programs)**

The Neutrino Mass Hierarchy

The figure below shows the physics performance of ESS SB as compared to other proposals in terms of the **χ^2 for Neutrino Mass hierarchy determination as function of the fraction of the full δ range 0°-360° within which CP violation can be discovered.q**

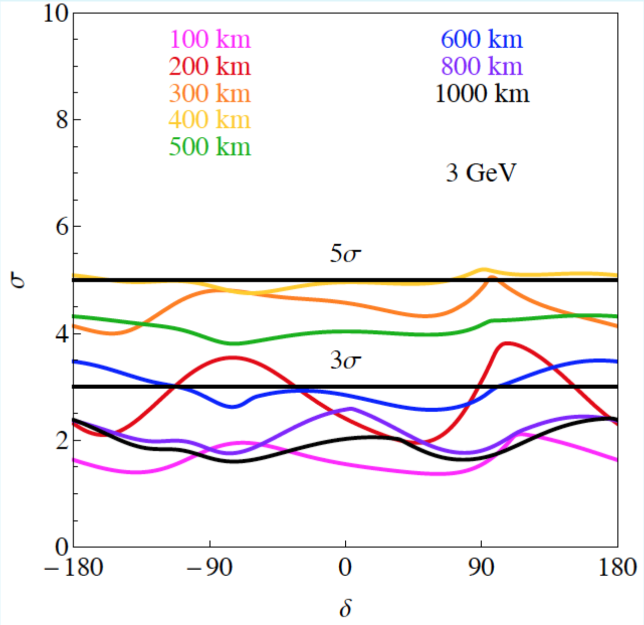


Mass hierarchy performance versus the fraction of δ_{CP} parameter**.**
LENF, C2Py1, C2Py2, SPL2, ESS, T2HK and LBNE stand for
Low Energy Neutrino Factory (2000 km, 100 kt MIND),
CERN to Pyhasalmi (SPS, 2300 km, 20 kt resp. 200 kt LAr),
SPL to Canfranc (650 km, 500 kt WC),
ESS Super Beam (400 km, 500 kt WC),
T2HK Japan project and
LBNE USA long baseline, respectively.

(Enrique Fernandez)

For these first evaluations, the target, horn and decay tunnel parameters, had **not been optimized** for the ESS proton driver energy of 2.5 GeV. Inclusion of **atmospheric neutrinos** in the mass hierarchy determination will certainly also improve the physics reach of this project.

Mass hierarchy determination for different base lines

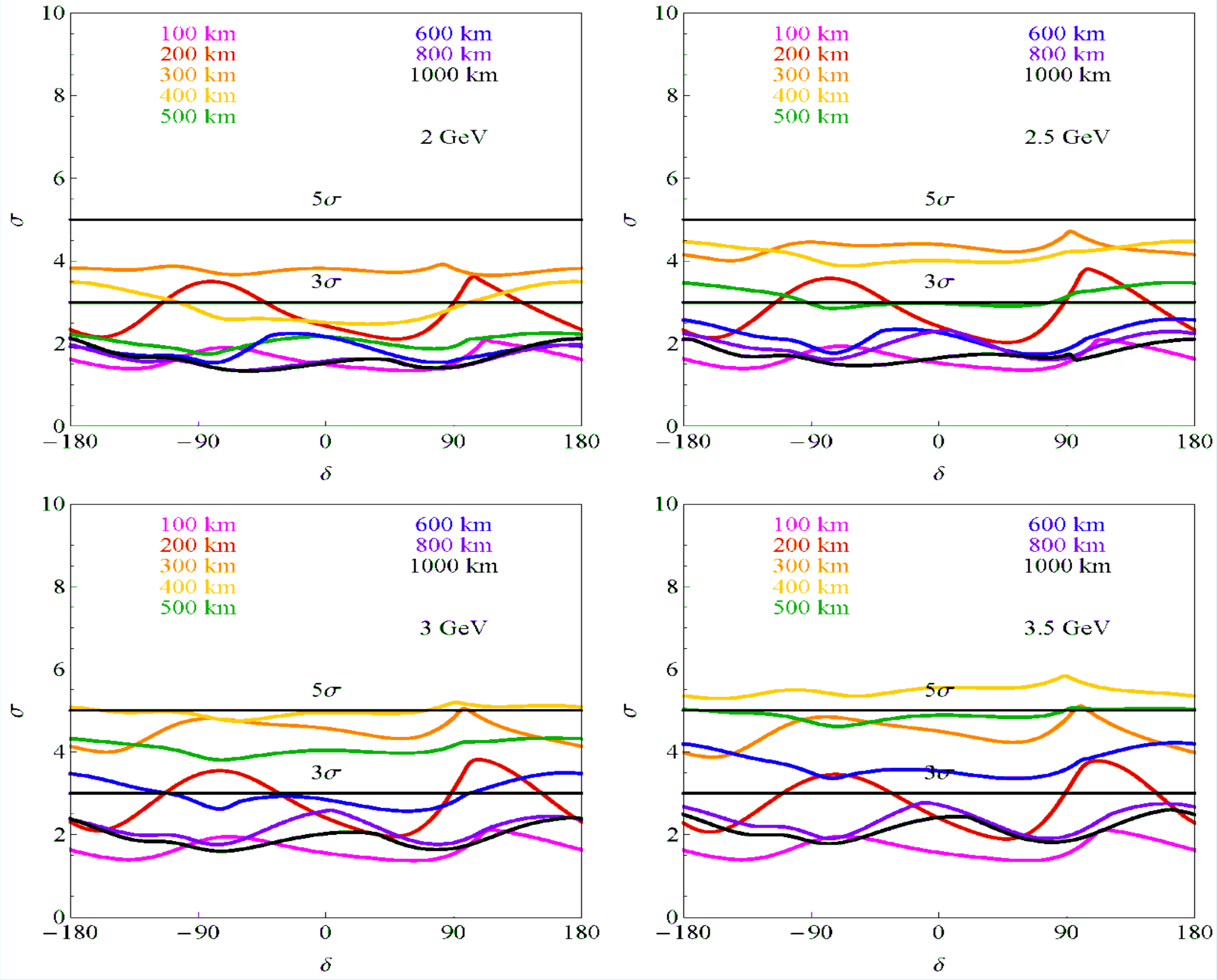


The significance in mass hierarchy determination as function of δ_{CP} for different base line lengths

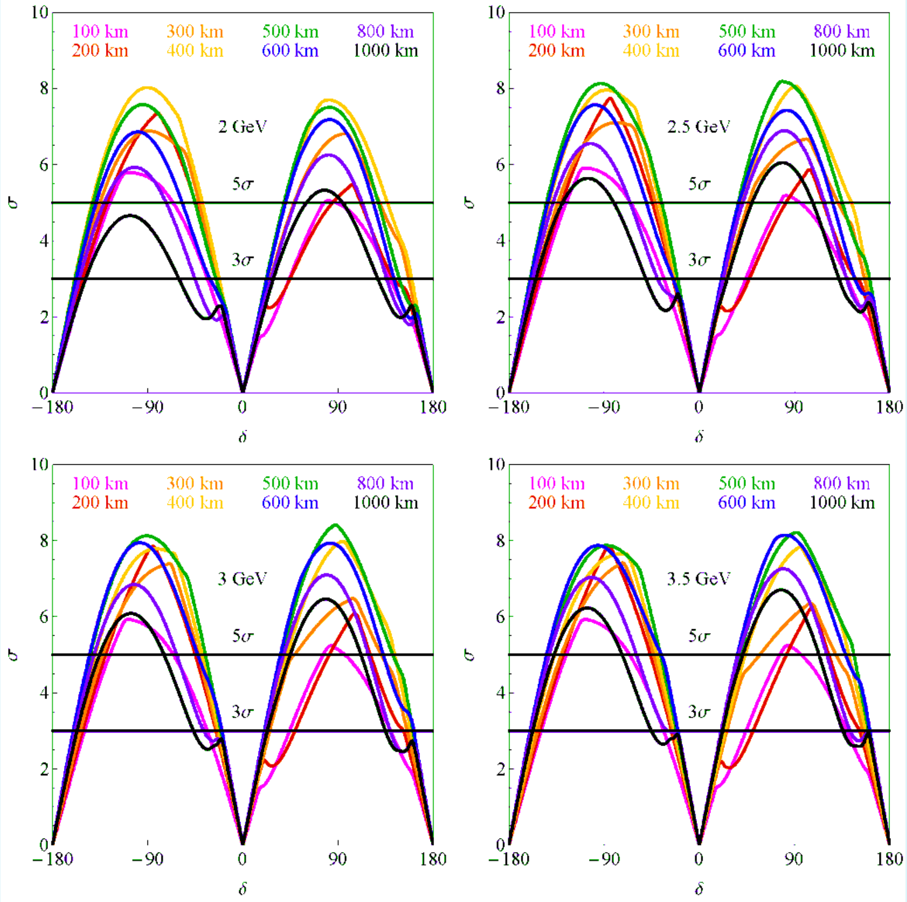
(Enrique Fernandez)

Measurements with atmospheric neutrinos will further improve this performance

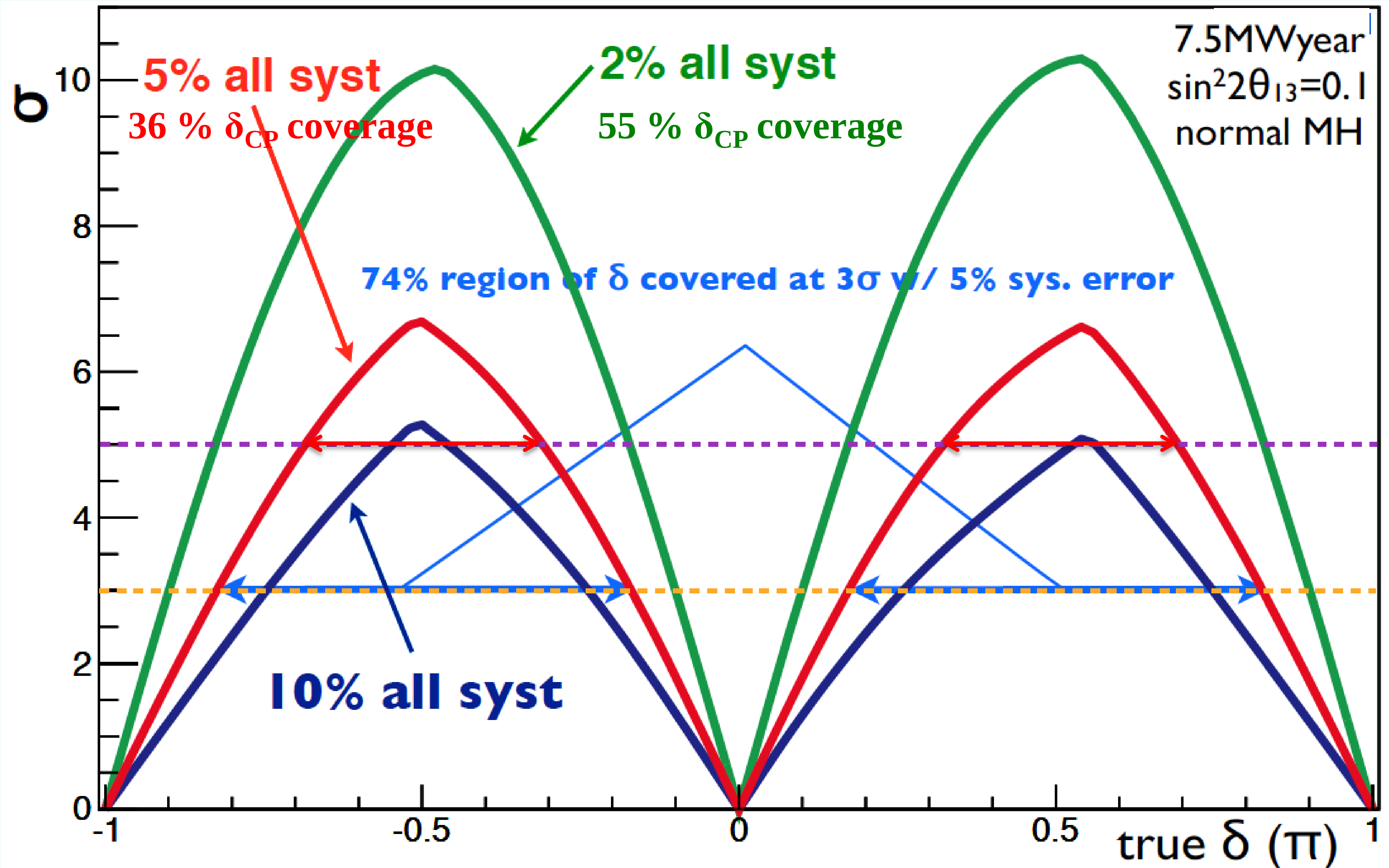
Mass hierarchy determination for different proton energies and different base lines



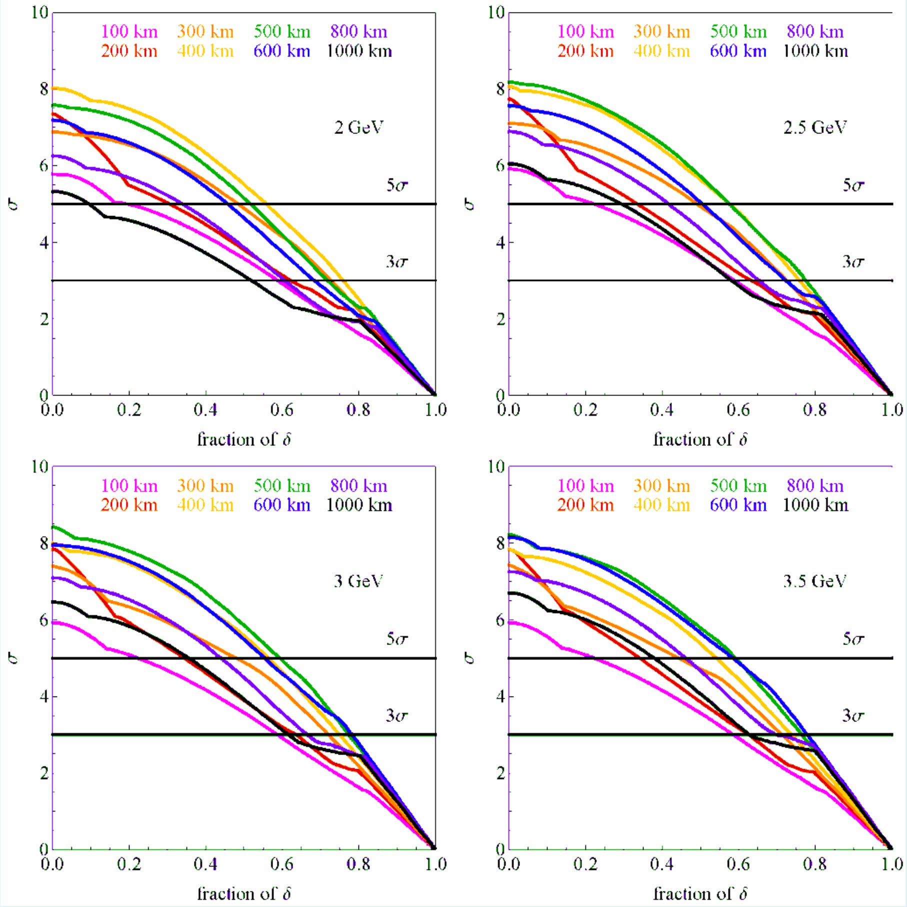
The signifiance in terms of number of standard deviations with which CP violation could be discovered for δ_{CP}-values from -180 to +180 degrees



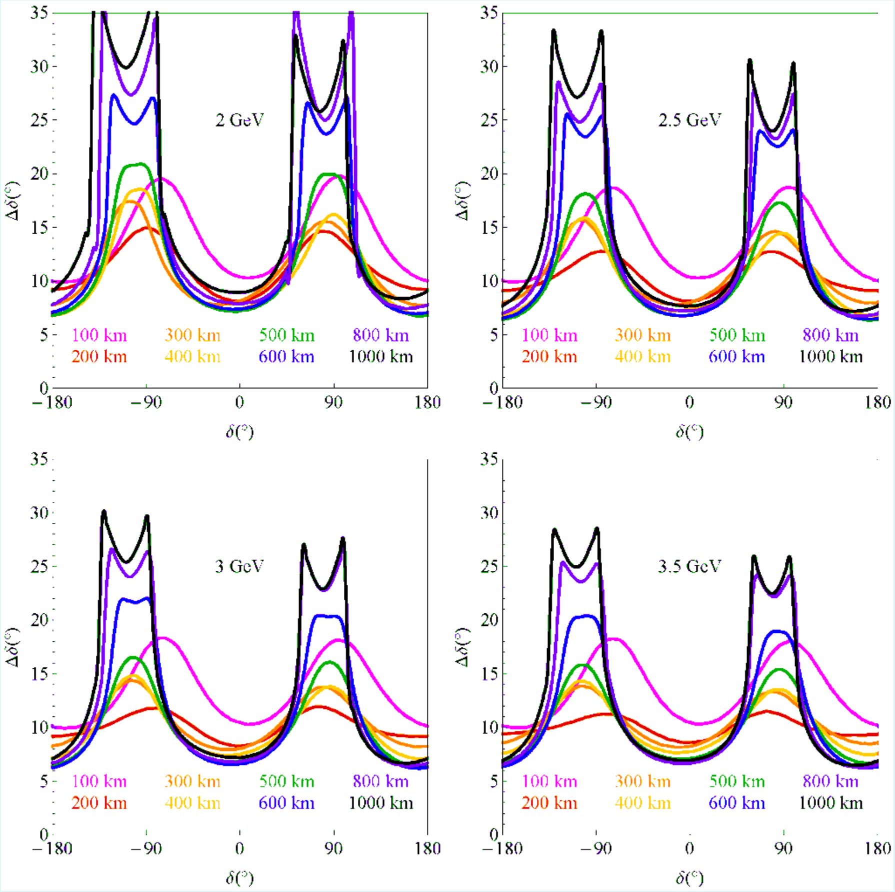
Hyper-Kamiokande Physics Opportunities: Exploring CP Violation with the Upgraded JPARC Beam



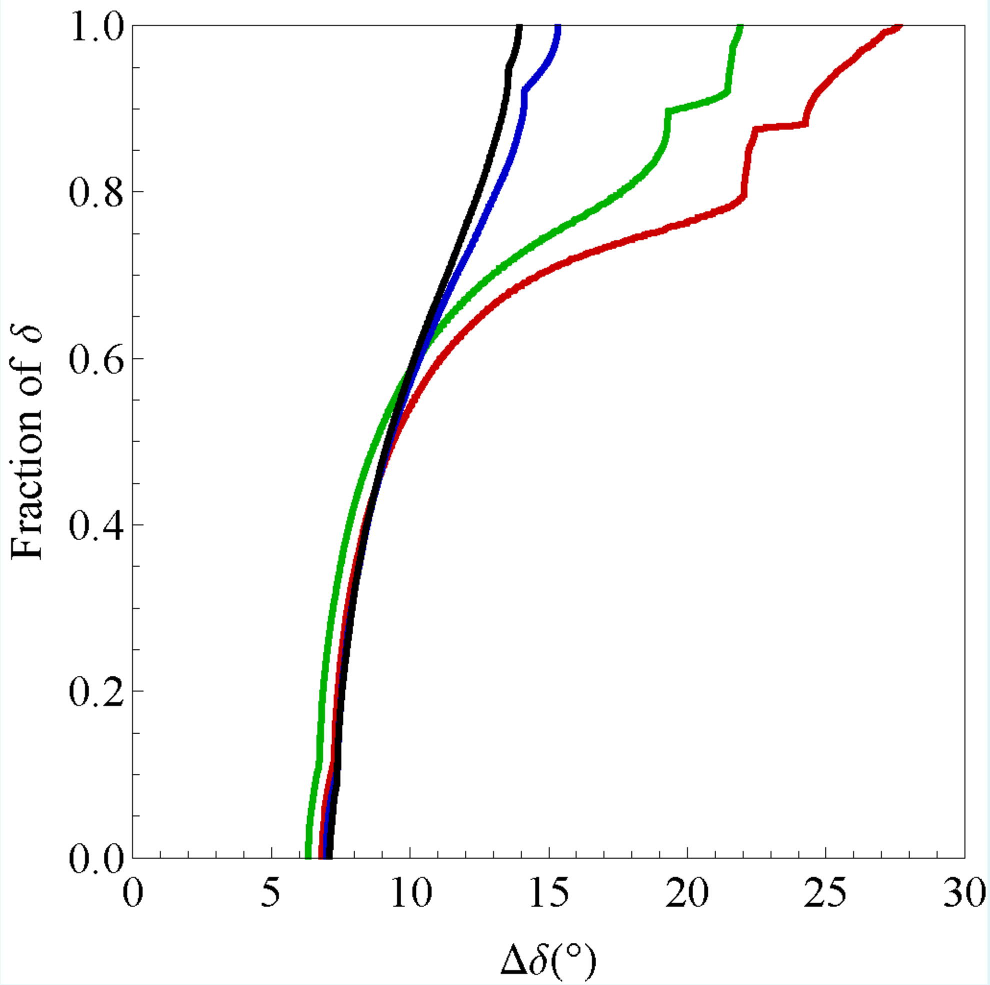
The signicance in terms of number of standard deviations with which CP violationcan be discovered as function of the fraction of the full δ_{CP} range for different proton energies and base lines



The resolution with which the δ_{CP} angle can be measured as function of δ_{CP} for different energies and base lines



The fraction of all possible true values of δ_{CP} as a function of the 1 σ error in the measurement of δ_{CP} . A CP fraction of 1 implies that this precision will be reached for all possible CP phases, wheras a CP fraction of 0 means that there is only one value of δ_{CP} for which the measurement will have that precision.



EUROSB
red = 540 km 2 GeV
green = 540 km 2.5 GeV
blue = 360 km 2 GeV
black 360 km 2.5 GeV

The fraction of all possible true values of δ_{CP} as a function of the 1 σ error in the measurement of δ_{CP} . A CP fraction of 1 implies that this precision will be reached for all possible CP phases, wheras a CP fraction of 0 means that there is only one value of δ_{CP} for which the measurement will have that precision.