Future neutrino Facilities: the Neutrino Factory

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On behalf of the EUROnu and IDS-NF collaborations

Outline

- The neutrino puzzle:
  - today's picture
  - tomorrow's challenges

- Proposed future neutrino facilities:
  - super-beams
  - beta-beams
  - neutrino factory

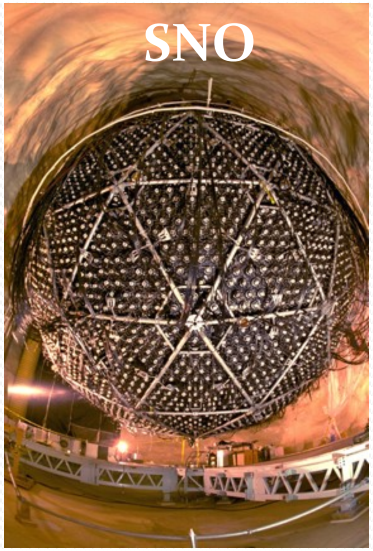
- The neutrino factory design study:
  - baseline, challenges and supporting R&D
  - next steps toward completion of the study

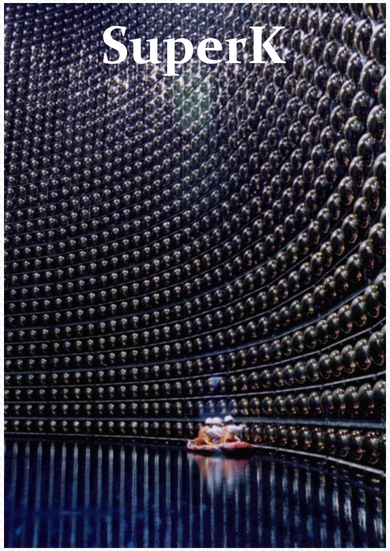
Today's picture (1/3)

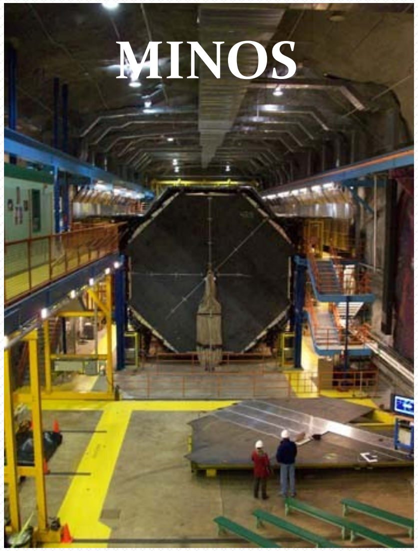
- "NEUTRINOS, they are very small.
  They have no charge and have no mass
  and do not interact at all…"
  Cosmic Gall by John Updike (1960).

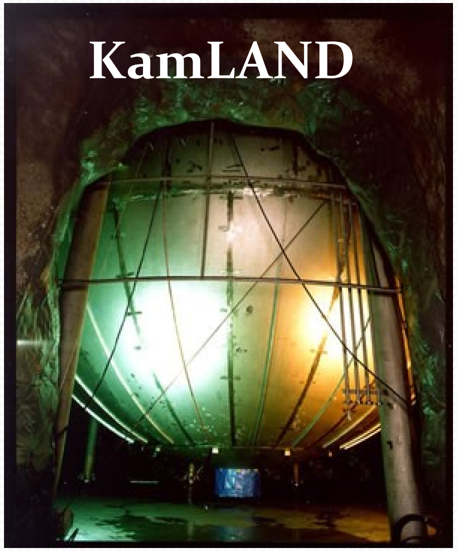
- In the Standard Model:
  - neutrinos belong to the lepton family and come in three flavours ν_e, ν_μ and ν_τ
  - have no charge, no mass and interact only via the weak interactions

- Experimental results:
  30+ years of solar, atmospheric, accelerator-based and reactor-based neutrino experiments have demonstrated that neutrinos can change flavour and have a mass.









Today's picture (2/3)

- Weak eigenstates versus mass eigenstates (PMNS matrix):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha 1/2} & 0 & 0 \\ 0 & e^{i\alpha 2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

3 mixing angles θij
1 CP violation phase δ
2 Majorana phases α_1 and α_2

- Oscillation probability (vacuum):

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\Sigma \mathrm{Re}[W_{\alpha\beta}{}^{ij}]\sin^2(\Delta m^2{}_{ij}L/4E) + 2\Sigma \mathrm{Im}[W_{\alpha\beta}{}^{ij}]\sin^2(\Delta m^2{}_{ij}L/2E)$$

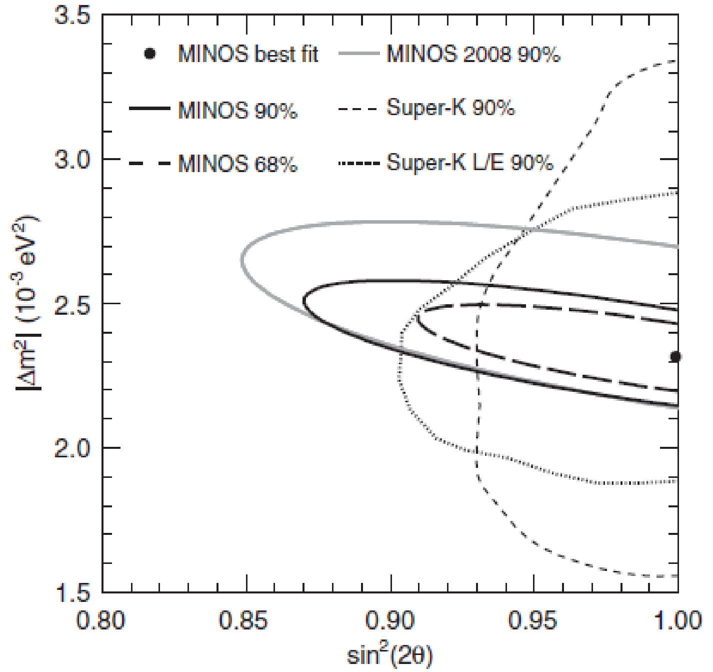
with $\Delta m^2{}_{ij} = m^2{}_i - m^2{}_j$ and $W_{\alpha\beta}{}^{ij} = U^*{}_{\alpha i}U_{\beta i}U_{\alpha j}U^*{}_{\beta j}$

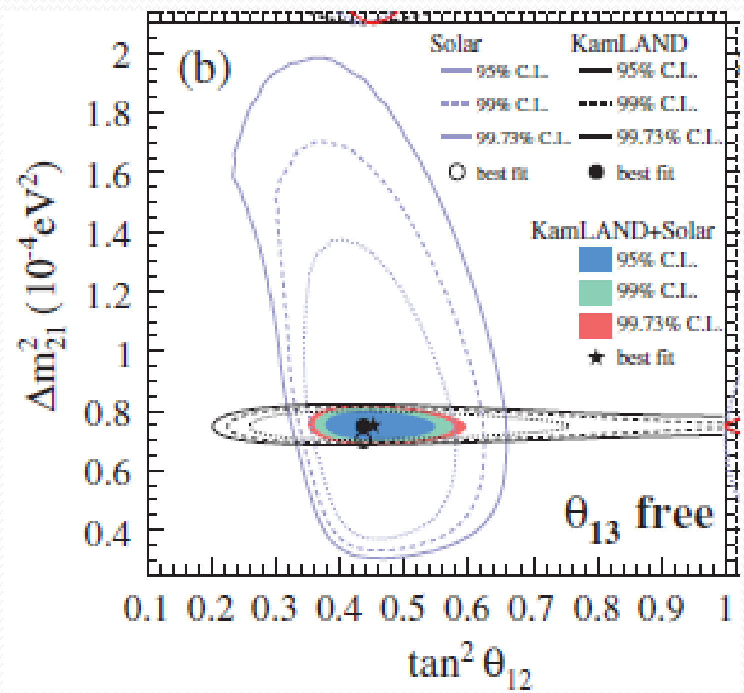
2 squared mass differences $\Delta m^2{}_{ij}$

- What has been measured:

P. Adamson *et al.* (MINOS Coll.)
Phys. Rev. Lett. 106, 181801 (2011)

A. Gando *et al.* (KamLAND Coll.)
Phys. Rev. D 83, 052002 (2011)





$|\Delta m^2|$ mixture of $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ and $\sin^2(2\theta)$ mixture of θ_{13} and θ_{23}.

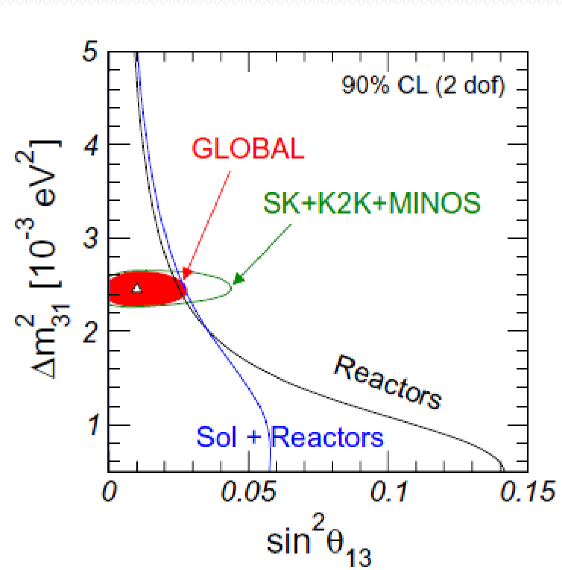
Solar/Reactor data fit depends on θ13.

Mixing angles: $\theta_{12} \sim 34°$(solar) and $\theta_{23} \sim 46°$ (atmospheric).

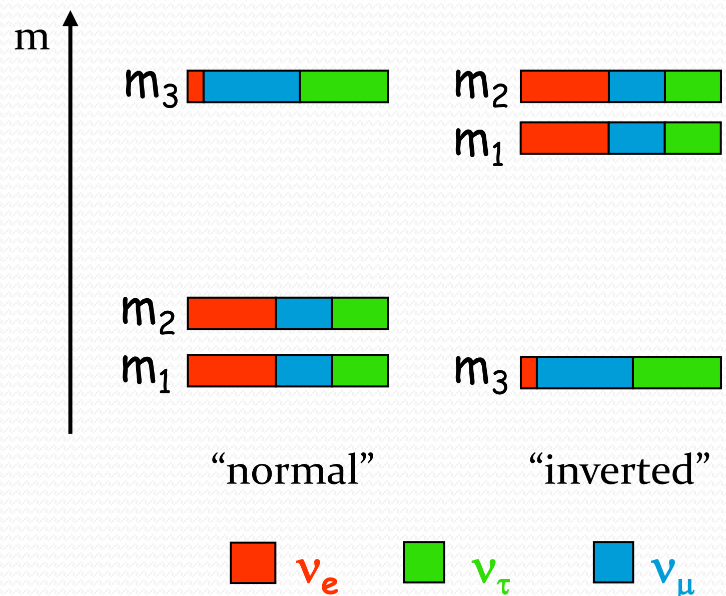
Mass difference $\Delta m^2_{12} \sim 8\text{x}10^{-5}$ eV² (reactor) and $|\Delta m^2_{23}| \sim 2.5\text{x}10^{-3}$ eV² (accelerator).

Tomorrow's challenges (1/1)

- We still don't know:
  - the value of the mixing angle θ_{13} ⟵ Future ν facilities
  - the sign of the squared mass difference Δm^2_{23} ⟵ ββ0ν exp. / Future ν facilities
  - the value of the CP violation phase δ ⟵ Future ν facilities
  - if ν and $\bar{\nu}$ are the same particle (Majorana) ⟵ ββ0ν exp.
  - the absolute neutrino mass ⟵ ββ0ν exp.



T. Schwetz *et al.*, New J. Phys. 13, 063004 (2011)



But also:
MINOS
OPERA
SuperK
Borexino
KamLAND
T2K → θ13 ≠ 0
Double-Chooz
Daya Bay
RENO…

Proposed facilities: super-beams (1/3)

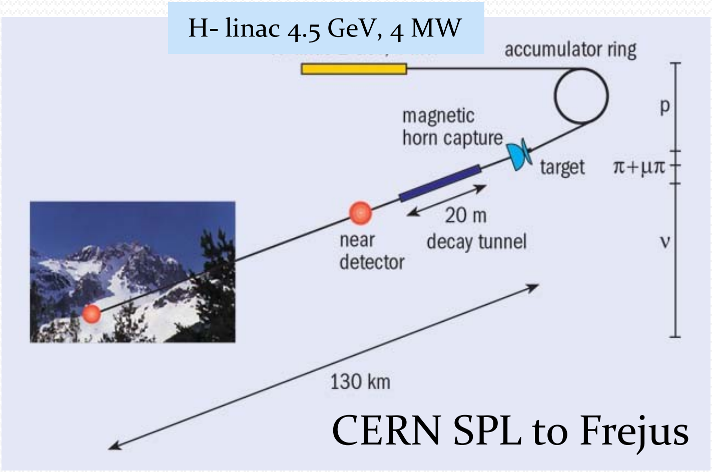
- Upgrade of a conventional neutrino beam:
  - ~98% ν_μ (or $\bar{\nu}_\mu$) produced by the decay of an intense pion beam

$$\begin{cases} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \end{cases}$$

  - search for $\nu_\mu \rightarrow \nu_e$ oscillations.
  - high intensity (proton driver > 1 MW) and low-energy (E_ν < 5 GeV).
- On-axis ($E_\nu \propto p_\pi$):
  - CERN SPL to Frejus - 4 MW – 4.5 GeV protons – 130 km – $E_\nu \sim 0.3$ GeV.
  - LBNE - 2.3 MW – 60-120 GeV protons – 1300 km – $E_\nu \sim 0.5$ -5 GeV.

EUROν WP2

- Off-axis (E_ν same at a given angle but ν flux smaller):
  - T2K upgrade – ~1.7 MW – 295 km (T2HK)
    E_ν = 0.6 GeV at 2.5° off-axis.

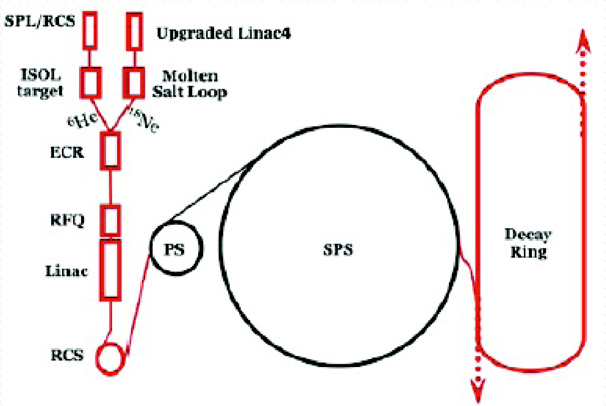


Proposed facilities: beta-beams (2/3)

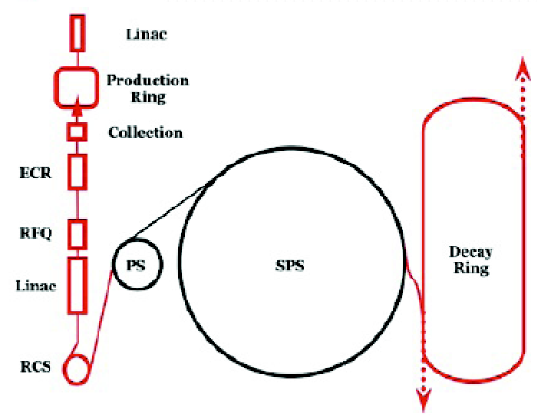
- Uses the decay of a stored beam of beta-unstable ions:
  - pure ν_e (or $\bar{\nu}_e$) beam
  - search for $\nu_e \rightarrow \nu_\mu$ oscillations.
  - $E^{\nu}_{max} = \gamma_L Q_\beta$ (γ_L = Lorentz boost - Q_β beta spectrum end-point)

EUROν WP4

- Low-Q (baseline) concept:
  - $^{6}He \rightarrow {}^{6}Li + e^- + \bar{\nu}_e$ (Q_β = 3.50 MeV)
  - $^{18}Ne \rightarrow {}^{18}F + e^+ + \nu_e$ (Q_β = 3.42 MeV)
  - CERN to Frejus ~ 130 km.



- High-Q (alternative) concept:
  - $^{8}Li \rightarrow 2\,{}^{4}He + e^- + \bar{\nu}_e$ (Q_β = 12.96 MeV)
  - $^{8}B \rightarrow 2\,{}^{4}He + e^+ + \nu_e$ (Q_β = 13.92 MeV)
  - CERN to Gran-Sasso or CERN to Canfranc ~700 km.



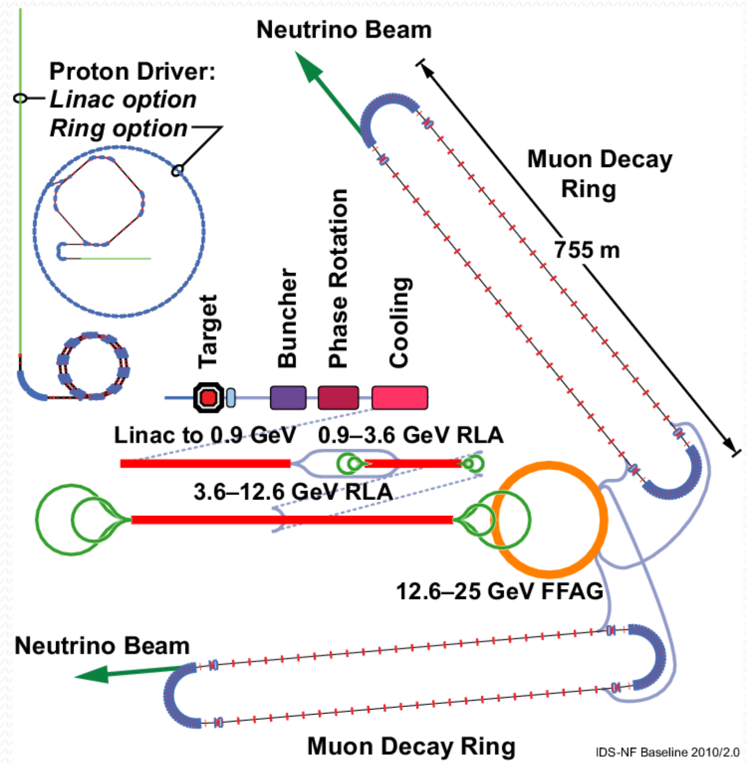
Proposed facilities: neutrino factory (3/3)

- Uses the decay of a stored muon beam:
  - 50% ν_μ ($\bar{\nu}_\mu$) - 50% $\bar{\nu}_e$ (ν_e) beam from $\mu^\pm \rightarrow e^\pm + \nu_e$ ($\bar{\nu}_e$) + $\bar{\nu}_\mu$ (ν_μ)
  - search for $\nu_e \rightarrow \nu_\mu$ oscillations
  - exploit other channels $\nu_\mu \rightarrow \nu_x$ and $\nu_e \rightarrow \nu_x$, $x = e, \mu, \tau$
  - 4 MW - 10^{21} ν/year - $E_\nu > 20$ GeV
  - 2500-5000 km and 7000-8000 km baselines
- Accelerator systems:
  - proton driver and annexes
  - target system
  - front-end system (buncher, rotator, cooler)
  - muon acceleration
  - decay rings

An essential milestone for a muon collider.

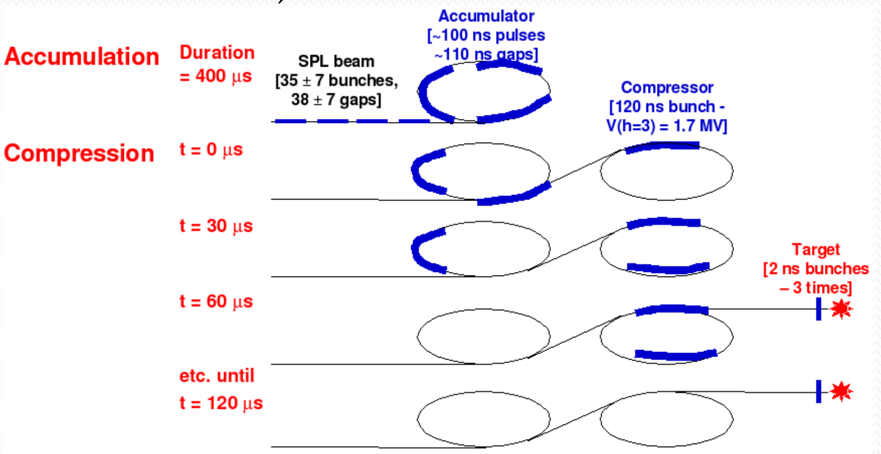
EUROν WP3

The International Design Study for the Neutrino Factory



Proton driver and annexes: CERN scenario (1/3)

- CERN SPL-based proton driver:
  - H$^-$ linac
  - bunch frequency 352.2 MHz
  - repetition rate 50 Hz
  - high-speed chopper < 2 ns (including rise and fall time)



- Option 1:
  - 2.25 MW (2.5 GeV) or 4.5 MW (5 GeV)
  - 1.1x10^{14} protons/pulse
  - average pulse current 20 mA
  - pulse duration 0.9 ms

- Option 2:
  - 5 MW (2.5 GeV) and 4 MW (5 GeV)
  - 2x10^{14} protons/pulse (2.5 GeV) and 1x10^{14} proton/pulse (5 GeV)
  - average pulse current 40 mA
  - pulse duration 1 ms (2.5 GeV) and 0.4 ms (5 GeV)

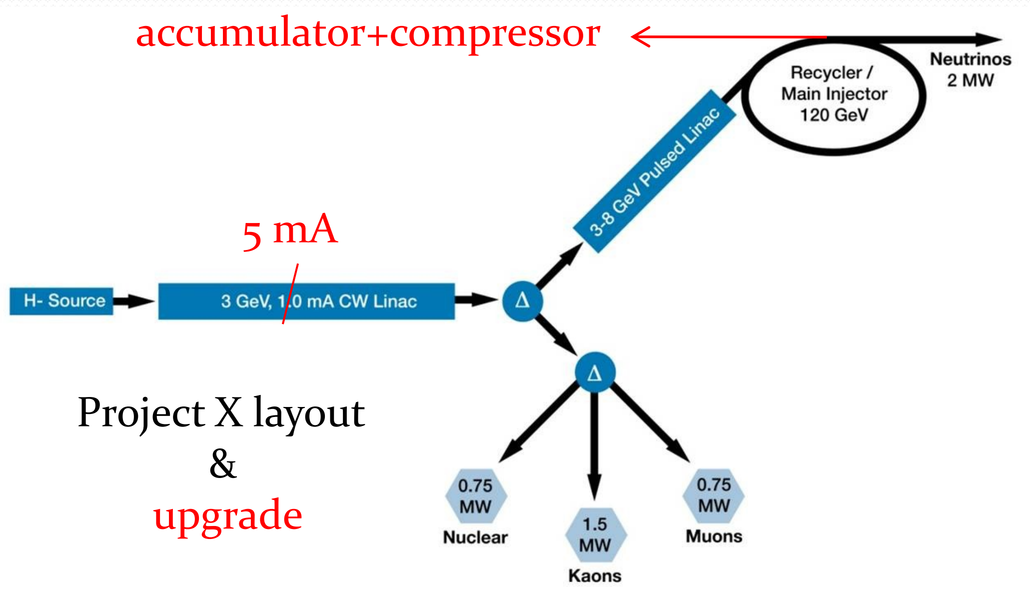
- Status:
  - beam instabilities in the accumulator investigated for 3 bunches
  - accumulator and compressor rings MADX lattices available
  - accumulator and compressor rings elements listed for the costing

Proton driver and annexes: Fermilab scenario (2/3)

- Fermilab Project X-upgrade-based proton driver, 4 MW at 8 GeV:
  - increase the CW linac average current to 5 mA
  - need to increase pulsed linac duty factor to ~10% (Project X is ~5%)
  - need to increase number of particles per linac bunch
  - add an accumulator and a compressor ring

- Accumulator :
  - ~250 m circumference
  - 14 bunches ~100 ns long
  - 1.3 x 10^{13} protons/bunch
  - stripping with foil or laser

- Compressor:
  - at entrance ~ 50 ns bunches
  - debunch in ~ few ns bunches



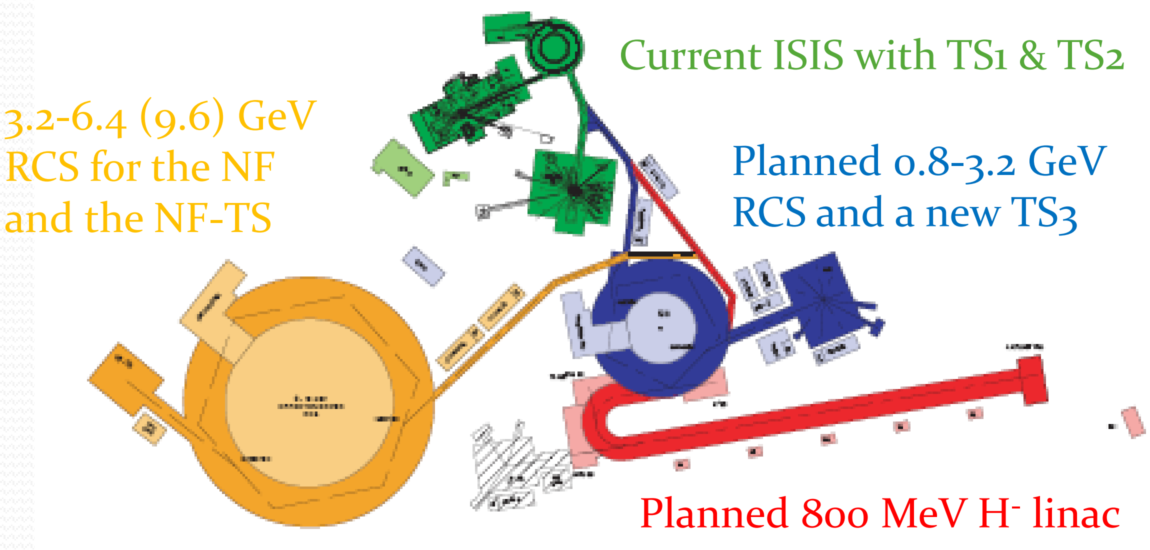
- Challenges and task:
  - stripping foil survival or laser technique demonstration
  - instabilities/space charge studies
  - beam size and angle at target optimization

Proton driver and annexes: RAL scenario (3/3)

- Upgrade of the RAL neutron spallation source ISIS, 2-5 MW at few GeV:
  - could be shared between a short pulse-spallation neutron source and the neutrino factory
  - requires an additional RCS or FFAG booster (to bring the proton beam to the necessary energy and perform appropriate bunch compression)

- Status:
  - lattice and high-intensity studies for a ~3.3 GeV booster synchrotron and beam lines
  - 800 MeV high-intensity linac design
  - RCS and FFAG lattice studies for a main ring accelerator

- R&D needs:
  - high-power front-end (FETS)
  - RF systems
  - stripping foils
  - diagnostics
  - kickers

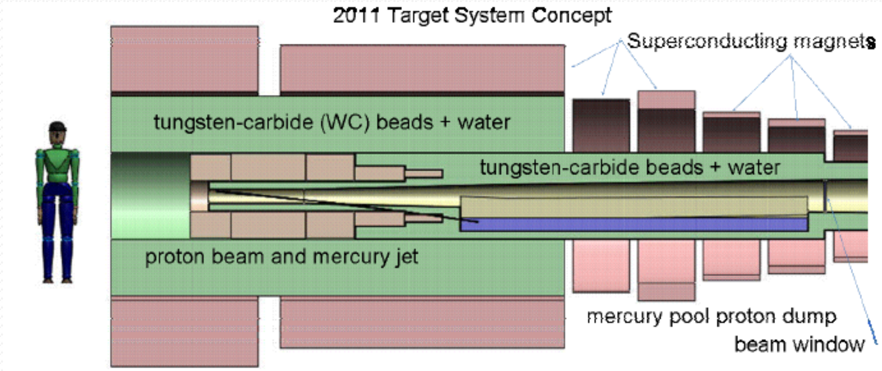


Target system: baseline (1/2)

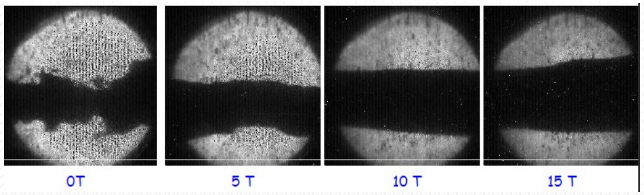
- Hg-jet target scheme:
  - pions capture in 20 T solenoid field followed by an adiabatic taper to 1.5 T

- Previous design (Interim Design Report – March 2011):
  - simulations (MARS15 & FLUKA) results showing high levels of energy deposition in the magnets (~2.4 MW need to be dissipated in the shielding)
  - both the Hg-jet and proton beam disrupt the Hg pool (need splash mitigation)

- Redesign:
  - better shielding of the SC magnets from radiation
  - splash mitigation options under study
  - mechanical support being improved



- R&D:
  - MERIT (2007) validated 4 MW proton beam operation in Hg



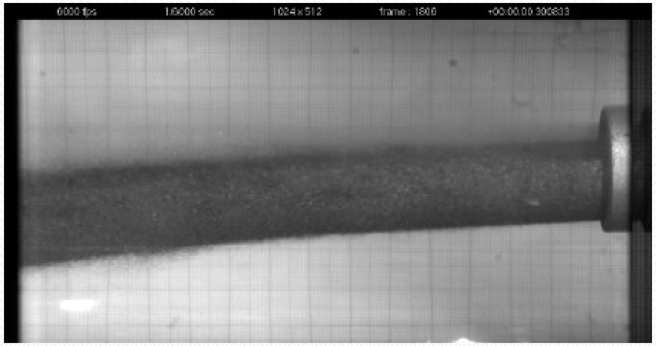
24 (14) GeV beam with different PS spill

- Tasks:
  - define target station infrastructure, including outer shielding, remote handling, Hg cooling loop, beam windows and beam dump

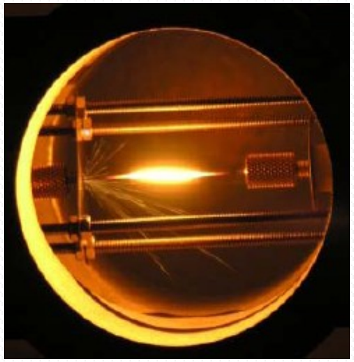
Target system: alternatives (2/2)

- Target systems under consideration as a mitigation option:
  - a metal-powder jet
  - a system of solid tungsten bars that are exchanged between pulses

- Metal-powder jet:
  - test rig at RAL with 100 kg W powder (grain size < 250 μm) ~20 min continuous operation
  - coherent free flow jet P ~ 2 bars
  - validation of results with simulations



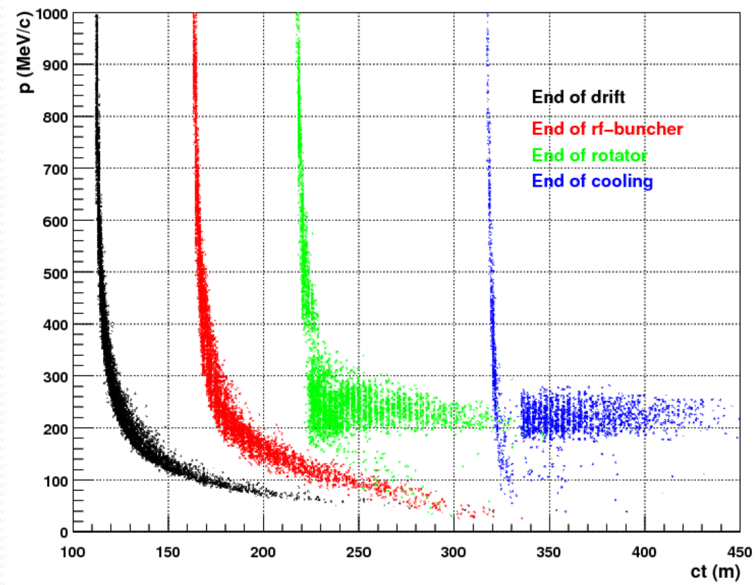
- Solid target:
  - shock study using high-currents in thin W (Ta) wires
  - results in agreement with LS-DYNA simulations
  - preliminary target change system engineering underway



- Future R&D:
  - flow improvement with mitigation of flux breakdown or phase separation for the powder target
  - irradiation study for tungsten powder and tungsten pebble bed at the CERN HiRadMat facility

Front-end: purpose (1/3)

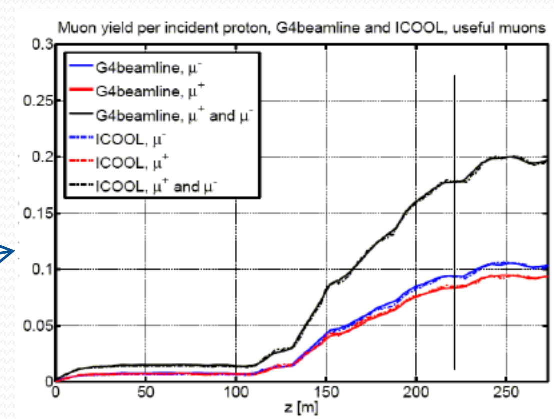
- Buncher:
  - slices the beam in a muons train of alternated signs
  - 320-234 MHz RF
  - 3.4 – 9.7 MV/m gradient
  - 0° phase



- Rotator:
  - reduces the particle energy inside the bunch train
  - 230-202 MHz RF
  - 13 MV/m gradient
  - 5° phase

- Cooler:
  - use absorbers (reduces p_μ) alternated with RF cavities (restores $p_\mu{}^L$)
  - 201 MHz RF
  - 15 MV/m gradient
  - 1 cm LiH absorbers windows
  - 35° phase

$100 < p_\mu < 300$ MeV/c
$\varepsilon_T = 30$ mm
$\varepsilon_L = 150$ m

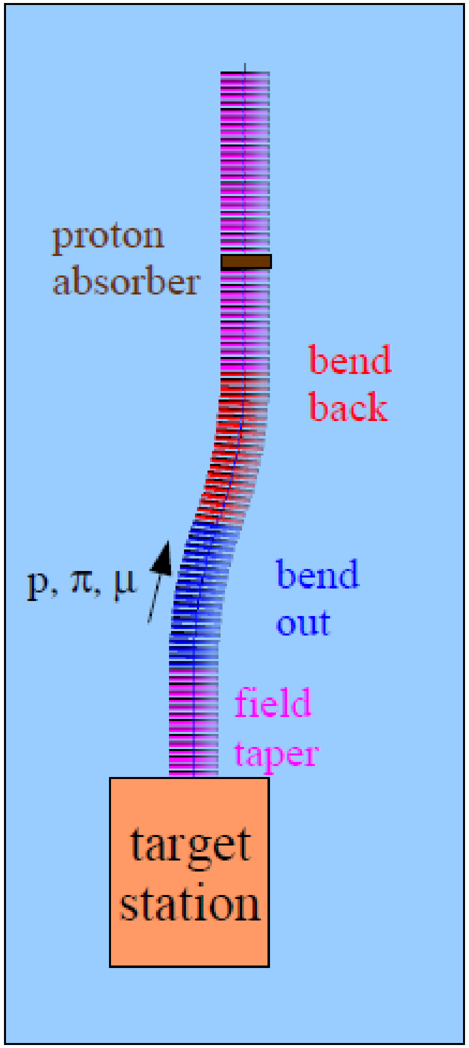


Front-end: status (2/3)

- Revised (IDR) lattice optimization - need to get rid early of the unwanted particles:
  - proton absorber for low-momentum protons
  - chicane for high-momentum particles.
  - transverse collimation.

- Started to take the reference lattice parameters for:
  - engineering study
  - costing exercise

- Remaining tasks:
  - determine realistic operational RF gradient limits (R&D @MTA)
  - assess and mitigate energy deposition from particle losses
  - optimize lattice matching sections
  - develop engineering design for magnets, RF and absorbers

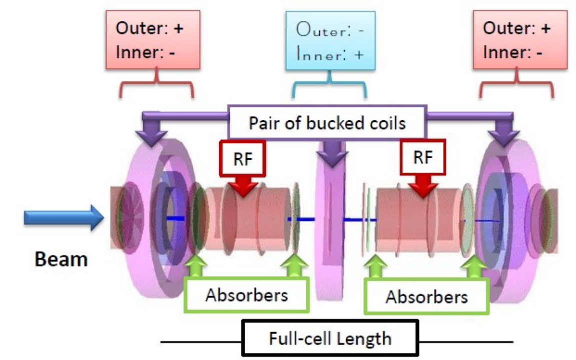


MICE: PoP of muon ionization cooling, hoping for results to come before 2014.

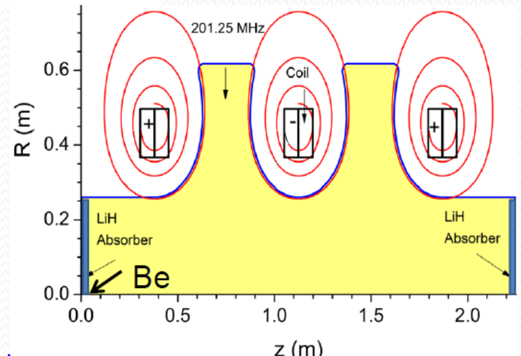
Front-end: alternatives (3/3)

- The RF cavities sit in high gradient (9-16 MV/m) high (~ 3T) magnetic field increasing the risk of breakdown as suggested by experiments performed at the Fermilab Muon Test Area (MTA).

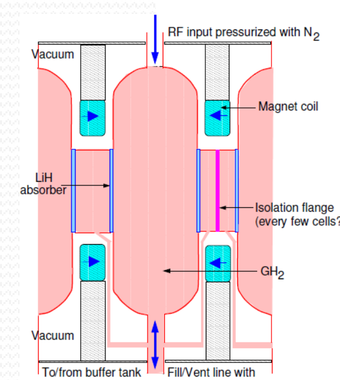
- Bucked coil lattice:
  - reduced magnetic field in the RF
  - 2 x 1.80 (or 2.10) m long cooling cell
  - G4MICE results comparable to the International Scoping Study (ISS-2006)



- Magnetically insulated lattice:
  - E⊥B field in the cavity
  - similar performance to the ISS study
  - tolerance to coil misalignment < 2 mm
  - multipactoring and power-consumption issues

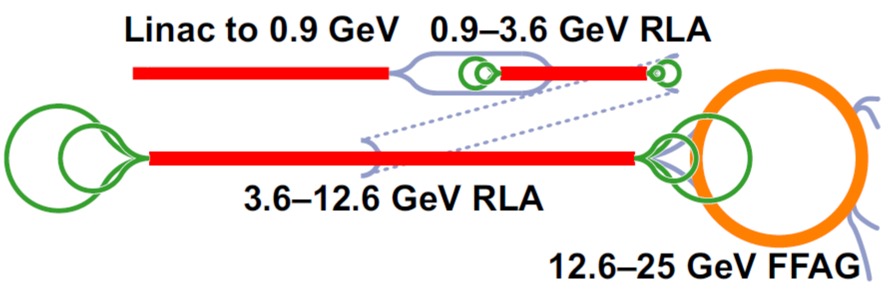


- High-pressure (HPRF) lattice:
  - cavity filled with high-pressure H_2 gas
  - use LiH absorbers for muon cooling
  - study of windows material, thickness and pressure
  - test with a gas-filled cavity done at the MTA



Acceleration system: Linac and RLAs (1/2)

- Acceleration system components:
  - 1 linac for low-energies (below 0.9 GeV)
  - 2 RLAs allowing multiple passes
(to 12.6 GeV)
  - final acceleration to 25 GeV in a FFAG



- Linac:
  - short (3 m, 3.8 MV/m), medium (5 m, 5.1 MV/m) and long (8 m, 6.4 Mv/m) cells made of SC RF and solenoids
  - focusing with solenoids (better for low-energy, large emittance beams)
  - increase acceleration rate by moving toward crest

- RLA:
  - dogbone shape provide greater separation at switchyard (over racetrack)
  - made of SC RF and quadrupoles
  - inject into linac center
  - 4.5 passes per linac

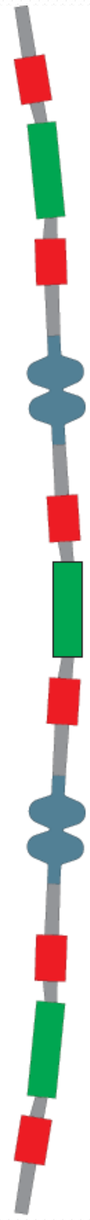
- Tasks:
  - validation of the switchyard design
  - complete lattice design (matching sections, injection, overall layout)
  - track through all subsystems with realistic errors
  - complete the engineering design for all the components (magnets, RF…)

Acceleration system: FFAG (2/2)

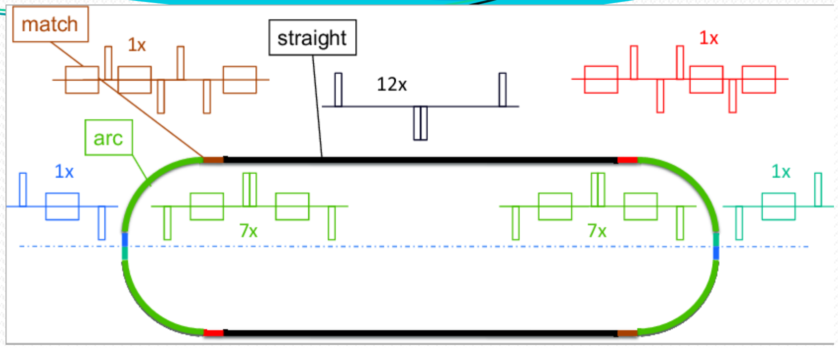
- Linear non-scaling FFAG:
  - single arc with large energy acceptance
  - consists entirely of identical FDF triplets
  - almost all drifts contain SC cavities or injection/extraction hardware

- Injection/Extraction:
  - kickers shared for both muons signs
  - inject from inside/extract to outside
  - slightly bigger magnet apertures in injection/extraction regions

- Tasks:
  - finalize the chromatic correction scheme
  - determine optimal longitudinal phase space matching
  - design matching to upstream and downstream systems
  - complete 6D tracking with errors
  - design main components (magnets, RF, injection/extraction)
  - make cost comparison with equivalent RLA solution.



Decay rings (1/1)



- Design criteria:
  - 2 racetrack shaped rings
  - 3 x train of ~50 bunches, 25 GeV
  - muons decay in straight which is a large fraction of the circumference
  - store both muon signs simultaneously
  - beam divergence from the lattice at most 0.1/γ
  - 1609 m circumference, 599 m straights
  - tilt angles of 36° (7500 km detector) and 18° (4000 km detector)
  - depths of 440 m and 240 m respectively
  - β is 150 m in the straights and 13 m in the arcs.

- Beam diagnostic:
  - polarimeter to measure decay electrons (beam energy and energy spread)
  - in-beam devices for divergence measurements (Cherenkov with He gas or Optical Transition Radiation)
  - challenging to get to the desired precision (natural 1/γ is 4 mrad)

- Tasks:
  - design the injection system
  - assess needs for chromatic corrections and beam abort scheme
  - design study of diagnostics and specifications
  - consider whether beam abort is necessary
  - design means to measure neutrino flux spectrum at far detectors.

Next step toward completion of the study (1/)

- March 2011 publication of the Interim Design Report (IDR) documenting in details the neutrino factory design study.

International Design Study for the
Neutrino Factory

IDS-NF-020

Interim Design Report

The IDS-NF collaboration

March 26, 2011

134 authors, 47 institutes:

Bulgaria	University of Sofia
France	IPHC Strasbourg
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India	HCRI Allahabad, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Universita di Napoli Federico II, Universita di Padova and INFN Padova, Sezione INFN Roma Tre
Japan	Kyoto University RRI, University of Osaka, Tokyo Metropolitan University
Spain	UAM and IFT Madrid, UV/CSIC and IFIC Valencia
Russia	INRR Moscow
Switzerland	CERN, University of Geneva
UK	Brunel University, Daresbury Laboratory, Glasgow University, Imperial College London, IPPP Durham, Oxford University, Rutherford Appleton Laboratory, Sheffield University, Warwick University
USA	Brookhaven National Laboratory, Fermi National Laboratory, Jefferson Laboratory, Laurence Berkeley National Laboratory, University of Mississippi, Michigan State University, Muons Inc., Northwestern University, Oak Ridge National Laboratory, Princeton University, University of California at Riverside, Stony Brook University, University of South Carolina, Virginia Polytechnique Institute, University of California at Los Angeles

https://www.ids-nf.org/wiki/FrontPage/Documentation/IDR

Next step toward completion of the study (2/)

- Review of the neutrino factory design study:
  - the European Committee for Future Accelerators (ECFA) Review Panel was mandated to review the EUROnu Mid-term Report and the IDS-NF Interim Design Report (IDR)

Review meeting at STFC, Darebury, May 5-6, 2011.

  - review was presented at the ECFA-EPS joint session (Grenoble, 23 July 2011)
  - review report ECFA/11/273 published in November 2011
  - report summary given to the CERN council in December 2011

- Toward the Reference Design Report (RDR):
  - develop a complete and technically feasible design having the required performance
  - carry out the end to end tracking of the entire facility to validate performance estimate
  - perform a cost estimate for the whole facility

Goal is to publish the RDR by the end of 2012/2013.

THANKS !!!

For your attention

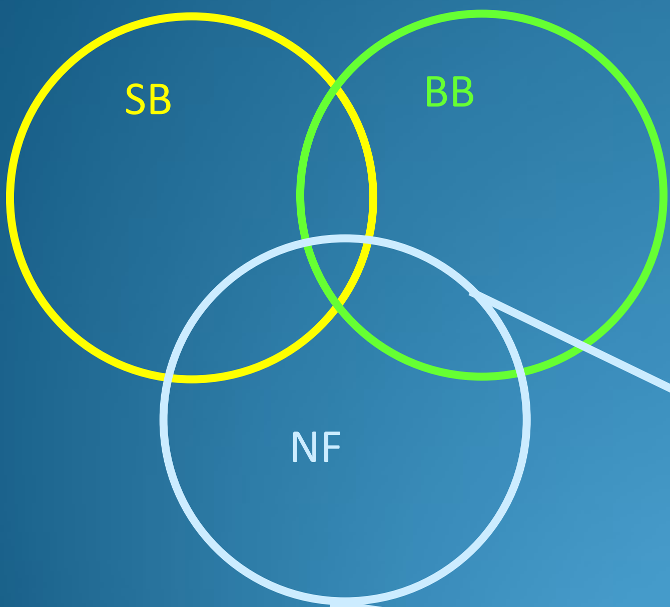
&

To my EUROnu & IDS-NF colleagues for the help providing material.

BACKUP SLIDES

IDS-NF and EUROnu structures:

EURONu



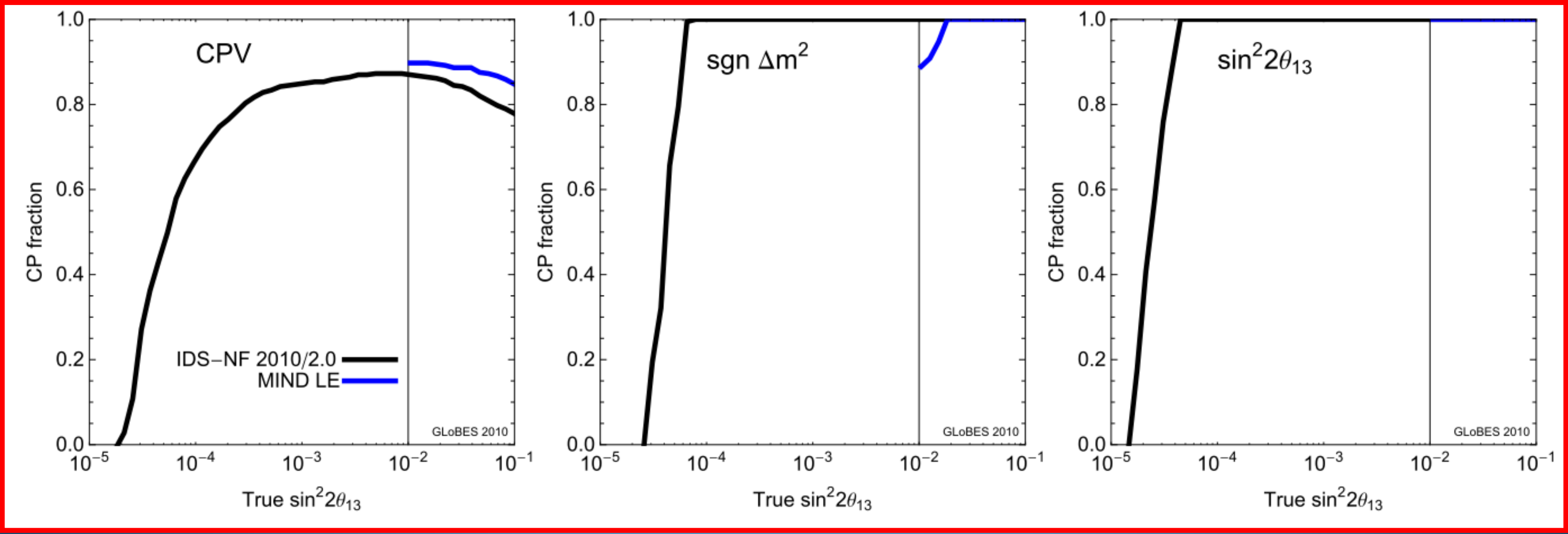
IDS-NF

- The Americas
  - Canada
  - USA
- Asia
  - Japan
  - India
  - (in the future: China …)
- Europe
  - EUROnu

Neutrino factory physics potential:

Channel multiplicity:

Stored $\mu^- \to e^- \nu_\mu \bar{\nu}_e$	
Disappearance	**Appearance**
$\bar{\nu}_e \to \bar{\nu}_e \to e^+$	$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+$ $\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+$
$\nu_\mu \to \nu_\mu \to \mu^-$	$\nu_\mu \to \nu_e \to e^-$ $\nu_\mu \to \nu_\tau \to \tau^-$



Discovery potential at 3σ for CP violation (left), mass hierarchy (middle) and $\sin^2\theta_{13}$(right).