Neutrino Factories

Dario Autiero IPN Lyon
Lyon 4/3/2006 SFP
The next and the ultimate goals in neutrino oscillation physics:

- Proof for $\nu_\tau$ appearance in the atmospheric sector ($\nu_\tau \rightarrow \nu_\tau$ oscillations) (OPERA)
- Measurement of $\Delta m_{23}^2$ and $\theta_{23}$ (MINOS, OPERA)

- Precise measurement of $\Delta m_{23}^2$ and $\theta_{23}$ → is $\theta_{23}$ exactly $\pi/4$?
- Search the subleading $\nu_\mu \rightarrow \nu_e$ oscillations related to the still unknown parameter $\theta_{13}$
- Absolute mass values (cosmology, double beta)
- Determine if the mass hierarchy the same as for charged leptons (sign of $\Delta m_{23}^2$) through MSW matter effects

- Show CP violating effects (measure the phase $\delta$ in the mixing matrix) depends on the magnitude of $\theta_{13}$
- Precise measurement of all the oscillation parameters with resolution of degeneracies

Neutrino factories will be the ultimate tools for the determination of the neutrino mixing matrix and pattern of masses
The $\nu_{\mu} \rightarrow \nu_e$ channel at the L/E typical of the atmospheric neutrinos will be the main handle to study/measure in the future all these parameters.

The $\nu_{\mu} \rightarrow \nu_e$ oscillation probability has a complicated dependance on many factors introducing degeneracies ($\theta_{13}$, matter effects, CP violating phase $\delta$). To solve degeneracies many measurements/channels have to be combined

\[ \nu_{\mu} \rightarrow \nu_e \text{ in the full MNS scenario} \]

Taylor expansion around $\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2$ and $\sin^2 2 \theta_{13}$ for constant matter density:

\[ P(\nu_{\mu} \rightarrow \nu_e) = \sin^2 2 \theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \]

- $\sin 2 \theta_{13} \xi \sin \delta_{CP} \sin \Delta \frac{\sin[\hat{A}\Delta]}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$
  - $O_1$ (leading term)

- $-\alpha \sin 2 \theta_{13} \xi \cos \delta_{CP} \sin \Delta \frac{\sin[\hat{A}\Delta]}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$
  - $O_2$ ($\sim \sin \Delta$)

- $+\alpha \sin 2 \theta_{13} \xi \cos \delta_{CP} \cos \Delta \frac{\sin[\hat{A}\Delta]}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$
  - $O_3$ ($\sim \cos \Delta$)

- $+\alpha^2 \cos^2 \theta_{23} \sin^2 2 \theta_{12} \frac{\sin^2[\hat{A}\Delta]}{\hat{A}^2}$
  - $O_4$ (suppressed by $\alpha^2$)

$\xi \equiv \cos \theta_{13} \sin 2 \theta_{12} \sin 2 \theta_{23} \sim O(1)$

$\hat{A} \equiv 2 \sqrt{2} G_F n_e \frac{E}{\Delta m_{31}^2}$

$\Delta \equiv \frac{\Delta m_{31}^2 L}{4 E}$
The subleading $\nu_\mu \to \nu_e$ oscillation is a small effect.
The effect of $\delta$ (CP violation) is a second order effect with respect to $\theta_{13}$.
The smaller is $\theta_{13}$ the more difficult is to measure CP violation effects.

Need for intense and pure neutrino beams.

Conventional wide band neutrino beams:

- Target: $\pi^+, K^+$
- Magnetic lenses
- Decay tunnel:
  - $\pi^+ \to \mu^+ \nu_\mu$
  - $K^+ \to \mu^+ \nu_\mu$

Contaminations:
- $\nu_\mu$ (wrong sign parents): $O(5\%)$
- $\nu_e$ (Ke3 decays, $\mu$ decays): $O(1\%)$
- $\nu_\tau$ (Ds decays): $O(10^{-6})$

Beams are limited in intensity, and have an important $\nu_e$ contamination.

Need for new tools like
- Beta Beams or neutrino factories
- Neutrino purities and spectra not depending on hadronic physics uncertainties.
Neutrino factories: neutrino beams from muon decays

Pure beams
High intensity, sensible rates even on the opposite side of earth
Flux is very well known from muon decay kinematics

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]

CC interactions produce e+ and μ-.

The interesting signal, due to e- and μ+, must be identified by the sign of the charge of the emitted lepton.

Example:
Measure the $\nu_\mu \rightarrow \nu_e$ oscillation probability by looking at wrong sign muons in a magnetized iron calorimeter. Clean signature $10^{-4}$ bck

Typical parameters:
$10^{21}$ useful muon decays/year
$E_\mu = 50 \text{ GeV}, \ L = 3,000 \text{ km (CP violation)}$
Detector: 50 kt magnetized iron calorimeter
Wrong sign muons allow already to look for CP violation / matter effects

\[
P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) \over P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = A_{CP} \alpha \sin \delta \sin (\Delta m^2_{12} L/4E) \sin \theta_{12} \over \sin \theta_{13} + \text{solar term}...
\]

For CP violation matter effect must be subtracted. This should be possible with an uncertainty of order of 2%.

Optimal baseline 2500-3000 Km
An intense muon beam is required:

Muons are produced as tertiary beam, large phase space, must be strongly cooled.

Muons decay (2.2 μs) their manipulation and acceleration must be fast.

Similar technologies as for the muon collider but simpler.

Driver + Target + Pion capture section in common to superbeams.
Proton driver

- Superconducting Proton Linac, 2.2 GeV / [up to 4 GeV ?], 2 mA H- linear accelerator.
- Stripping injection into accumulator ring
- NuFact pulse: 2.8 ms duration (13 mA); rep. rate 50 Hz
- Bunching 1 ns with storage ring + compressor: 140 bunches
  Needed for next (phase rotation)

Energy: optimize π yield (HARP), production/capture/acceleration optimization
4 MW: will yield 10^{21} μ/year in storage ring
50 Hz: batches spacing must be > μ lifetime (1.1 ms); 4 MW upper limit (targetry/π-collector)
Target

Should stand 4 MW beam power (20% released in the target)
High radioactivity environment, thermal shock, cooling, lifetime, (item in common with superbeams)

Liquid mercury jet (L30cm, 20m/s, φ1cm)

Tantalum spheres 2mm, He cooling

mercury jet target in 15 T B-field
24 GeV proton beam
data taking 04/2007
Pion capture:
20 T superconductive solenoid
Target inside
Lifetime > 1 year
(rad. Hardness, replacement cost)

**HARP** (CERN PS214):
particle production on various targets
data 2001-2002, first results 2005

K2K thick target event display (proton, 12 GeV/c)

Double horn system, like in
present neutrino beams

Similar efficiency than solenoid
Lifetime 0.5 years (heat, radiation, stress
for pulsing)
After pion decay channel (30 m, 60 cm, 1.8 T, 85% of pion decay, E:0.-2. GeV)
Reduces $\Delta E/E$, necessary due to the small acceptance of the next RLA chain
Acceleration of low energy muons and deceleration of high energy muons, exploiting
phase-energy correlation, possible with a non relativistic beam

Muons produced with: large energy spread and small time spread

- RF frequency must vary along bunching channel
  Because High mom. bunches move faster than low

44MHz, 2MV/m  RF + solenoid focusing
bunch-to-bucket principle : a 180° piece (11ns)
of the muon bunch fits into the 44MHz bucket
50% of incoming $\mu$'s are captured ; $\Delta E$ 100-300MeV, channel length : 30m - 30 cavities
Muons ionization cooling:

Reduce transversal spread
Traditional cooling methods too slow

Liquid $H_2 \rightarrow dE/dx$

**TRANSVERSE**
- Competes with Coulomb Scattering
- Best with Hydrogen
- and Strong Focus

$\mathbf{p}_\parallel$ less $\rightarrow$ $\mathbf{p}_\perp$ less

Material

$\mathbf{p}_\parallel$ restored $\mathbf{p}_\perp$ still less

Acceleration

The cooling channel (200m) is a linear accelerator with liquid $H_2$ absorbers in 3 sections:

- 50m: $11 \times (4 \times 44\text{MHz cav.} + H_2\text{abs})$
- 30m: Accel 44MHz
- 110m: $25 \times (8 \times 88\text{MHz cav.} + H_2\text{abs})$

**MICE** (RAL): first data 2007
cooling demonstration 2009

RF cavity

H2 absorber

Tracker
Muon acceleration

5 GeV, 220 MHz, 4 passages

11-50 GeV

3-11 GeV

1 GeV, 220 MHz, 4 passages

Recirculating linacs RLA, muon survival 90%

Acceptance: $1.5\pi$ cm norm. transverse, $0.15\pi$ eV.s longitudinal, limited by cavities

R&D 200 MHz cavity. Acceptance no more limited by cavity, rather by arc/combiners design, and reaches $3\pi$ cm / $0.7\pi$ eV.s.

Reduces the necessity of phase rotation/cooling
LINAC + Recirculating Linear Accelerator (RLA) Very costly and rigid use.

Possible solution:

Fixed Field Alternating Gradient (FFAG). A new type of accelerator with B field shaped as \( r^k \): particles can be kept and accelerated over a range of energies of \( \sim \)factor 3. Like cyclotrons in the 50s but with modern magnet design technology.

The acceleration is fast because the B field has not to ramp up, particles moving to regions of higher field.

Allows for more turns (less RF)

But low frequency non superconducting RF

- \( \mu \)-acceleration: FFAG rings. Weak \( <E> \sim 1 \text{MV/m} \), acceleration distance to 20GeV is \( \sim 20 \text{km} \) \( \Rightarrow \) muon survival only \( \sim 50\% \).

- Advantage of FFAG:

  - very large acceptance transverse \( 3 \pi \text{cm norm.}, \text{longitudinal } 5 \pi \text{eV.s.} \) (no phase-rotation, no cooling). This ensures \( 0.3 \mu/p \) and \( 10^{20} \text{decay/MW-p/drift/year in } \mu \text{SR} \)

  - should be simpler (less R&D), and cheaper than RLA (no cooling section, FFAG is easier technology/construction).

Technological challenges: Injection and ejection
Muon acceleration: FFAG

A lot of progress in Japan with the development and demonstration of large acceptance FFAG accelerators.

Latest ideas in US have lead to the invention of a new type of FFAG ("non-scaling FFAG") in combination with strong focusing lattice, closer orbits, less aperture, interesting for more than just Neutrino Factories (e.g. from SPL to 20 GeV?) require a demonstration experiment (PRISM, electron prototype).

⇒ Perhaps US & Japanese concepts are merging to produce something better??
⇒ Neutrino factories could be cheaper and come sooner
- PRISM, 20MeV FFAG for muon phase rotation: 0.8MW super-beam for stopped-µ experiments at JHF, approved.

- **PRISM (Osaka)** will demonstrate scaling FFAG system with muon beam
  - construction completed in 2009
  - first phase (ring itself) funded (complete 2007)

- Pion capture section
- Decay section
- *Injection* ⇒ *R&D NuFact!*
- Phase rotation section
- *Xtraction* ⇒ *R&D NuFact!*
- $10^{11-12}$ muon/s

**FFAG** a ring instead of linac
  - reduced # of rf cavities
  - reduced rf power
  - compact
NuFACT Japan

FFAG based neutrino factory

JHF construction 2001-2006

• 50GeV ring : 4 bunches accelerated, $<I>=20\mu A$, $3 \times 10^{14}$ ppp, 0.4Hz, 1MW
• 8 bunches, bunch length ~6ns rms, spacing 0.5\mu s,
• There have been 4½ previous NF “feasibility” studies
  – 1 in Japan
  – 1 in Europe
  – 2½ in the U.S.
  • studies I, II, Ila

Costs evaluations

The Study of a European Neutrino Factory Complex, P. Gruber et al.,
CERN/PS/2002-080 (PP), CERN-NUFACT 122, December, 2002;
http://slap.web.cern.ch/slap/NuFact/NuFact/nf122.pdf
Neutrino Factory Studies in the US

- **99-00** Neutrino Factory Feasibility Study I
  - Emphasized **Feasibility**, with complete Simulation
  - "Entry Level Performance" (≈ $0.2 \times 10^{20} \mu$/year/dec at 1 MW)

- **01-02** Neutrino Factory Feasibility Study II
  - Emphasized **Performance**
    - **Similar Cost**
    - 6 times **Performance of Study I**

- **03-04** Neutrino Factory Feasibility Study IIa
  - Emphasized **Cost Reduction**
  - Part of APS Neutrino Study (September 04)
    - **61 % cost of Study II**
  - Same flux, both charges:
    - **12 times Performance of Study I**
  - Meets original Physics Requirement

Flux Required for the Physics
Study 2a Schematic of 20 GeV Factory

- p Driver
- Hg Target (10%)
- Phase Rotation (17%)
- Cooling (21%)
- Pre-Acceleration
  - Acceleration (42%)
- RLA
- Storage Ring (8%)
- Neutrino Beam

R. Palmer
Progress towards Cost Reduction

Costs: **Study II was** $1500M + 400M*E/20$

Timescale: 2025

Ongoing (world) R&D: Proton driver, Targetetry, Collection, Cooling, FFAG

Reasonable goal: proton driver + 1 G €

<table>
<thead>
<tr>
<th>Component</th>
<th>Study 2</th>
<th>Now</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot Length (m)</td>
<td>328</td>
<td>166</td>
<td>51%</td>
</tr>
<tr>
<td>Acc Length (m)</td>
<td>269</td>
<td>35</td>
<td>13%</td>
</tr>
<tr>
<td>Acc Type</td>
<td>Induction</td>
<td>Warm RF</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Study 2</th>
<th>Now</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot Length (m)</td>
<td>108</td>
<td>33</td>
<td>30%</td>
</tr>
<tr>
<td>Acc Length (m)</td>
<td>54</td>
<td>37</td>
<td>21%</td>
</tr>
<tr>
<td>Acc Grad (MV/m)</td>
<td>16</td>
<td>12</td>
<td>66%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Study 2</th>
<th>Now</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vac Length (m)</td>
<td>3261</td>
<td>1094</td>
<td>34%</td>
</tr>
<tr>
<td>Tun Length (m)</td>
<td>1494</td>
<td>1094</td>
<td>49%</td>
</tr>
<tr>
<td>Acc Length (m)</td>
<td>288</td>
<td>102</td>
<td>35%</td>
</tr>
<tr>
<td>Acc Grad (MV/m)</td>
<td>16</td>
<td>8</td>
<td>50%</td>
</tr>
</tbody>
</table>

- **Phase Rotation**
- **Cooling Channel** (Linear channel → Ring)
- **Acceleration** RLA → FFAG
Study IIa (2004)

- FFAGs are introduced
- cost / GeV lower than RLA

Typical FFAG lattice data:

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>2.5-5</th>
<th>5-10</th>
<th>10-20</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of turns</td>
<td>6.0</td>
<td>9.9</td>
<td>17.0</td>
</tr>
<tr>
<td>No. of cells</td>
<td>64</td>
<td>77</td>
<td>91</td>
</tr>
<tr>
<td>D length (cm)</td>
<td>54</td>
<td>69</td>
<td>91</td>
</tr>
<tr>
<td>D radius (cm)</td>
<td>13.0</td>
<td>9.7</td>
<td>7.3</td>
</tr>
<tr>
<td>D pole tip field (T)</td>
<td>4.4</td>
<td>5.6</td>
<td>6.9</td>
</tr>
<tr>
<td>F length (cm)</td>
<td>80</td>
<td>99</td>
<td>127</td>
</tr>
<tr>
<td>F radius (cm)</td>
<td>18.3</td>
<td>14.5</td>
<td>12.1</td>
</tr>
<tr>
<td>F pole tip field (T)</td>
<td>2.8</td>
<td>3.6</td>
<td>4.4</td>
</tr>
<tr>
<td>No. of cavities</td>
<td>56</td>
<td>69</td>
<td>83</td>
</tr>
<tr>
<td>RF voltage (kV)</td>
<td>419</td>
<td>516</td>
<td>621</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>246</td>
<td>322</td>
<td>426</td>
</tr>
<tr>
<td>Decay (%)</td>
<td>6.4</td>
<td>6.8</td>
<td>7.7</td>
</tr>
<tr>
<td>Total cost (PB)</td>
<td>71.6</td>
<td>77.5</td>
<td>88.9</td>
</tr>
<tr>
<td>Cost per GeV (PB/GeV)</td>
<td>28.7</td>
<td>15.5</td>
<td>8.9</td>
</tr>
</tbody>
</table>
R Palmer, Muon collider studies 1992-

R&D and feasibility study activities:
US (FNAL, BNL):
CERN: http://muonstoragerings.web.cern.ch/muonstoragerings/
U.K.: http://hepunx.rl.ac.uk/uknf/
Japan: http://www-prism.kek.jp/nufactj/

Nufact conferences on a yearly base:

- Lyon 1999
- Monterey 2000
- Tsukuba 2001
- London 2002
- Columbia Univ. 2003
- Osaka 2004
- Frascati 2005

International scoping study: http://www.hep.ph.ic.ac.uk/iss/

CERN 22/9/05
KEK 23/1/06
RAL 24/4/06
Irvine 21/8/06

- Discussion of results at NUFAC'T06 Irvine 24/8
- ISS report september 2006
- Proposal for full design study 2007
- 2010 Conclusions of design study
ISS GOALS

✓ Compare the different approach which have been taken in the feasibility studies and converge on a common one optimal and cost effective. Common design effort

✓ Evaluate the physics case for a second-generation super-beam, a beta-beam facility and the Neutrino Factory and to present a critical comparison of their performance

✓ Establish the cost and performance of the overall facility including the detector/baseline options as well

✓ Participants:

ECFA/BENE working groups  (incl. CERN) (funded by CARE)
Japanese Neutrino Factory Collaboration
US Neutrino Factory and Muon collider Collaboration
UK Neutrino Factory Collaboration (also part of BENE)
others (e.g. India INO collaboration, Canada, China, Corea ...)

Strong points of NF

High flux and purity

High energy (better knowledge of cross sections, energy spectra for detected neutrinos, tau production)

High flux+energy allow for long baselines (matter effects, hierarchy)

Large variety of channels if charge determination, electron id, tau id:

\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]  
Atm neutrino osc.

a) right-sign muons

b) wrong-sign muons

c) electrons/positrons

d) positive \( \tau \)-leptons

e) negative \( \tau \)-leptons

f) no leptons

\[ X_2 (\mu^+ \text{ stored and } \mu^- \text{ stored}) \]

Sensitivity to very small values of \( \theta_{13} : \sin^2 2\theta_{13} \sim 10^{-5} \)

Only way to access CP violation for small \( \theta_{13} : \sin^2 2\theta_{13} < 10^{-2} \)

Complete resolution of degeneracies

determination of mass hierarchy

<table>
<thead>
<tr>
<th>Beam</th>
<th>( E_v ) (GeV)</th>
<th>Flux (v/m²/yr)</th>
<th>L (km)</th>
<th>CC (v/kton/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNGS</td>
<td>17.7</td>
<td>( 3.5 \times 10^{11} )</td>
<td>730</td>
<td>2448</td>
</tr>
<tr>
<td>T2K1(2)</td>
<td>0.7</td>
<td>( 1.9 \times 10^{11} ) (1.2 \times 10^{12})</td>
<td>295</td>
<td>95 (570)</td>
</tr>
<tr>
<td>SPL</td>
<td>0.27</td>
<td>( 4.78 \times 10^{11} )</td>
<td>130</td>
<td>31.1</td>
</tr>
<tr>
<td>Beta B</td>
<td>0.36</td>
<td>( 1.88 \times 10^{11} )</td>
<td>130</td>
<td>24.5</td>
</tr>
<tr>
<td>NUFACT</td>
<td>30</td>
<td>( 2.4 \times 10^{12} )</td>
<td>3000</td>
<td>17700</td>
</tr>
</tbody>
</table>
Long Future / “Next 30 years”

Ability to observe non-zero $\theta_{13}$ versus time

Fermilab
Proton driver study report’
http://protondriver.fnal.gov/
Physics cases

1) Large $\theta_{13}$: $\sin^2 2\theta_{13} > 0.01$
   (Physics case for NuFact at all? vs. Superbeams?)

2) Small $\theta_{13}$: $10^{-4} < \sin^2 2\theta_{13} < 10^{-2}$
   (NuFact's "golden age"?)

3) "Zero" $\theta_{13}$: $\sin^2 2\theta_{13} \ll 10^{-4}$
   (What physics can be done? What does that mean?)

(Huber/POFPA report)

For large $\theta_{13}$ systematic errors dominate

Neutrino factory!
(or higher gamma beta beam)

Beta beam? Superbeam-Upgrade? $\nu$-factory?
Degeneracy

When one measures the $\nu_\mu \rightarrow \nu_e$ oscillation probability for neutrinos and antineutrinos, $P=\text{constant}$ yields curves in the plane $(\theta_{13}, \delta)$

The curve for neutrinos and antineutrinos will meet in two points (intrinsic clone)
The ignorance of sign of $\Delta m^2_{23}$ can be compensated by a change in $\delta$
Is $\theta_{23}$ smaller or greater than $45^\circ$ ?, reabsorbable by a shift in $(\theta_{13}, \delta)$

The result is an eigth-fold degeneracy

It can be resolved by repeating measurements at different energies/baselines (e.g. iron at 3000 and 7500 Km) or studying another transition like $\nu_e \rightarrow \nu_\tau$ (the silver channel at neutrino factories) which has opposite CP behavior than $\nu_\mu \rightarrow \nu_e$
The Emulsion Cloud Chamber (ECC)
for $\nu_e \rightarrow \nu_\tau$ appearance at $\nu$ Factories

Wrong sign taus

- $\nu_e \rightarrow \nu_\mu$ (golden events) \textbf{and} $\nu_e \rightarrow \nu_\tau$ (silver events) to reduce $\theta_{13} - \delta$ ambiguities
- Pb as passive material, \textbf{emulsion as sub-\mu m precision tracker:} unique to observe $\tau$ production and decay
- 1.8 kton OPERA target mass
  $\rightarrow$ ~ 4 kton at $\nu$ Factory
- Search for $\tau$-decay only
  in events with a “wrong sign” muon:
  x 2 increase of scanning power required
- Hybrid experiment: emulsion + electronic detectors
- OPERA as a “milestone” for the technique
Golden + Silver vs « Double Golden »

Double Golden

Golden + Silver
Is it possible to build a magnetized « electronic bubble chamber » at the tens Kton scale?
Liquid Argon TPC + magnetic field: measurement of charge, electron, muons, taus: The complete detector for Neutrino Factories
R&D going on, large LAr detectors interesting also for astroparticle physics
A. Rubbia, Nufact05

Large mass LAR TPC (up to 100 Kton)
LNG tank
Amplification in gas phase

With SC solenoid
High T SC?
Global comparisons: $\delta_{CP} - \theta_{13}$

- The Nufact sensitivities are mainly based on the old iron calorimeter study, with the addition of the silver channel for degeneracies.
- These studies should be redone in order to consider globally all the channels and compare in a fair way with study is old (5 years). It should be revisited in order to make a fair comparison with $\beta$-beam.

For large $\theta_{13}$, systematic errors dominate. The picture is not clear yet: ongoing studies.

For small $\theta_{13}$, Nufact and High $\gamma$ $\beta$-beam (350) outperforms all others.

The third option should be Low $\gamma$ $\beta$-beam + Super-beam.
Conclusions:

The NF are a unique (ultimate) tools providing pure neutrino beams of high intensity and high energy and allowing the study of a large variety of channels, with ultimate sensitivities and performance. It is the only way to be sensitive at small $\theta_{13}$

Behind NF there are a strong international community and important R&D and analysis activities involving theorists, experimentalists and machine people in EU, US and Japan. It will be a world project with $O(1 \text{ Geur})$ cost and timescale 2020-2025

The ISS will allow to improve the design and R&D efforts coherently and to perform a global optimization and performance comparisons with other options

The decision on NF, like for other options, will come after T2K phase I results