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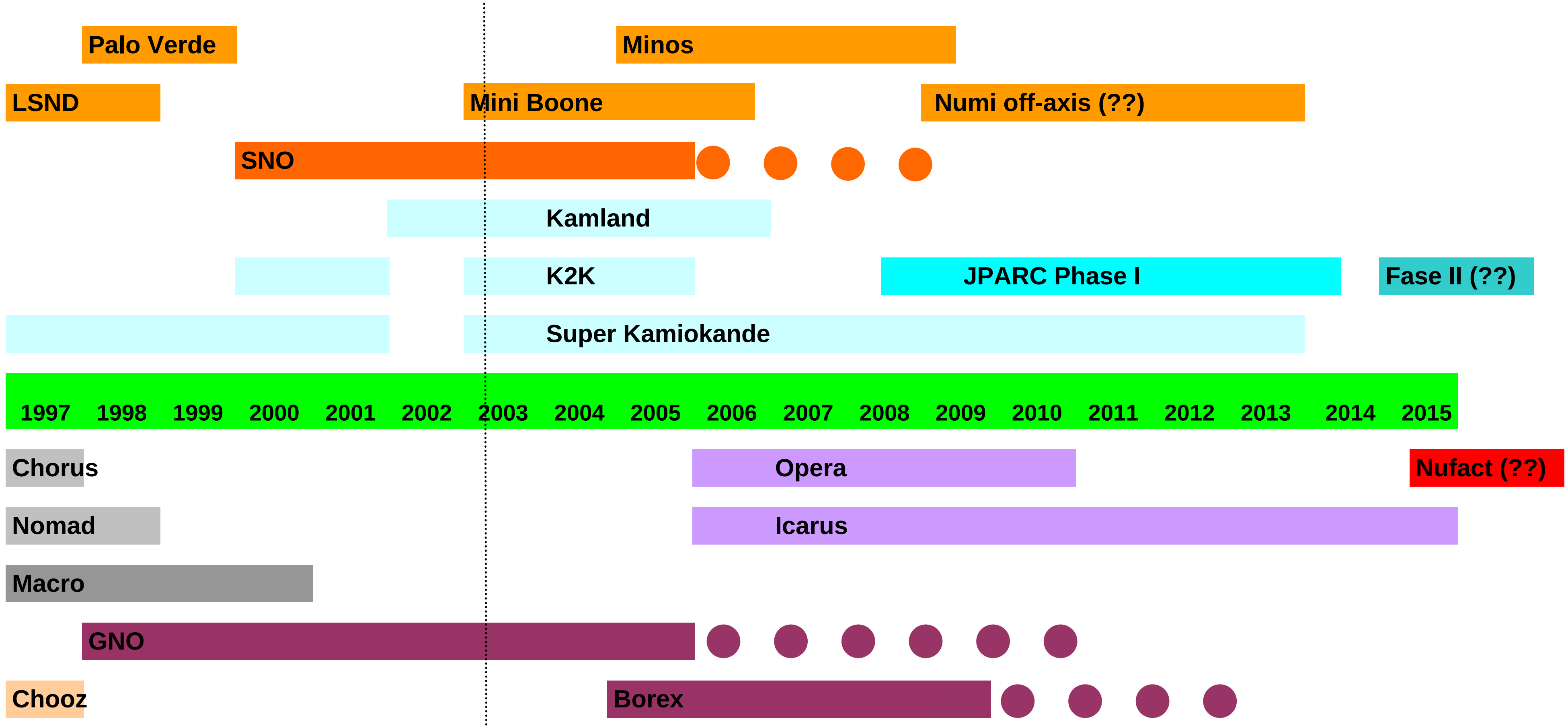
“Reach of Neutrino Factories, SuperBeam and BetaBeams ”

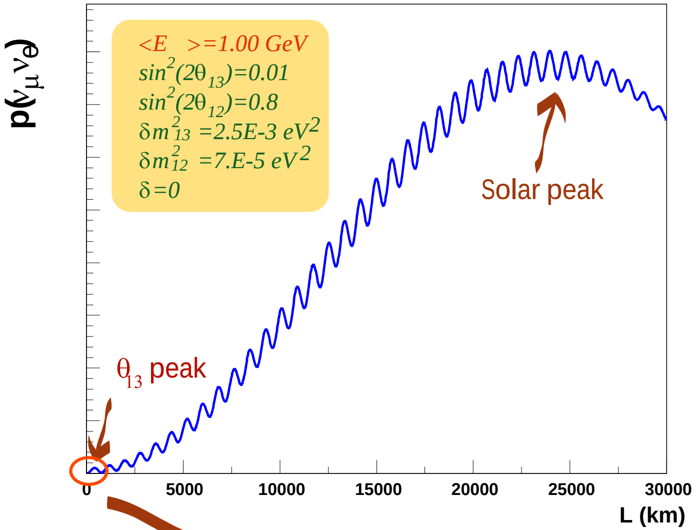
- **How and when.**
- **Description of the facilities.**
- **Physics reach and some comparison.**
- **Biased towards Europe.**
- **Normalized to 20 minutes.**

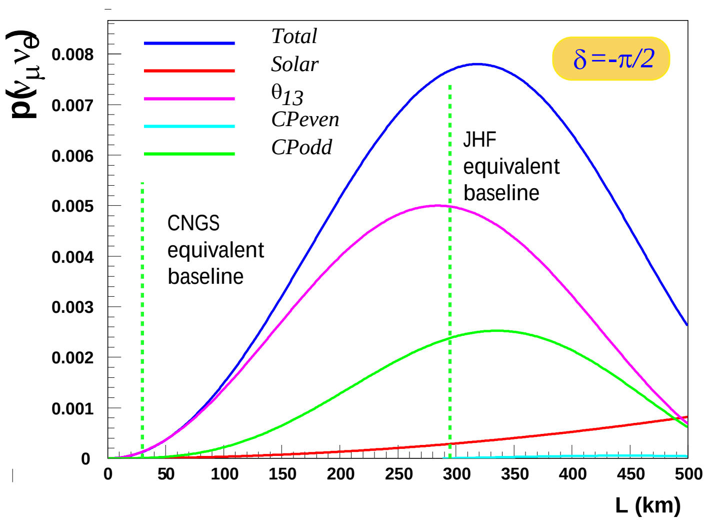
WIN 03, Lake Geneva, October 8^{th}, 2003

Neutrino Oscillation Experiments



Sub leading $\nu_\mu - \nu_e$ oscillations





$p(\nu_\mu \to \nu_e)$ developed at the first order of matter effects

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23} cos\delta - s_{12}s_{13}s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

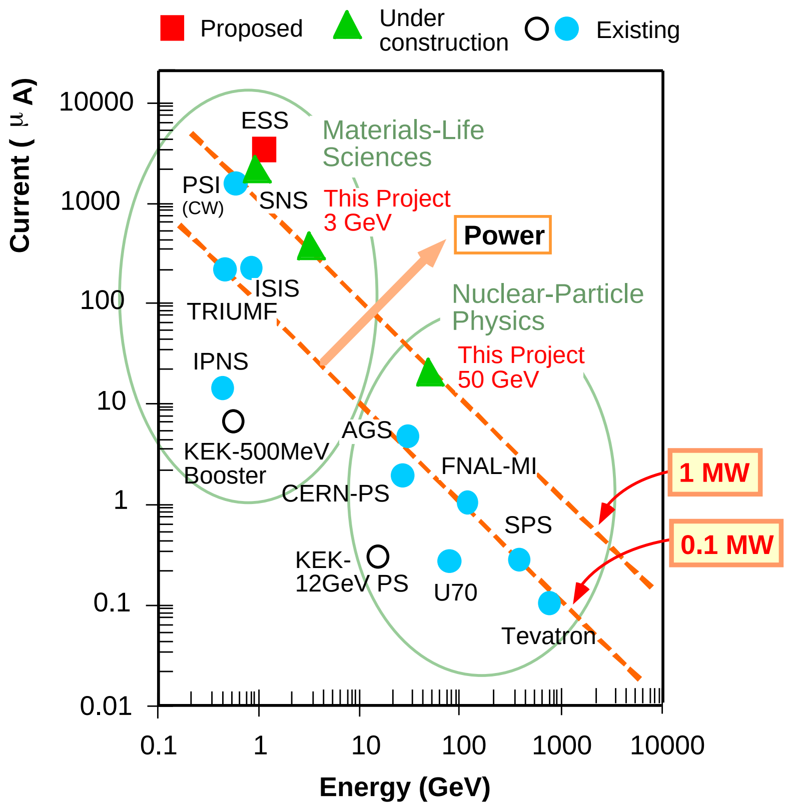
$$+ 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

$$- 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \quad \text{matter effect (CP odd)}$$

where $a = \pm 2\sqrt{2} G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho[g/cm^3] E_\nu [GeV] \quad [eV^2]$

After JPARC, in the standard scenario

- θ_{13}, discovery or precision measure
- Mass hierarchy
- **Leptonic CP violation**



Any major improvement of JPARC will be extremely expensive:

- The proton driver is a next generation machine
- The detector is 10 times bigger of the second biggest: Minos.
- The designed close detectors system is very ambitious.

THE θ_{13} DILEMMA

The knowledge of θ_{13} is necessary to guarantee the conditions to measure δ and to optimize the facility.

Waiting for the JPARC results (or Numi Off-Axis or Reactors) implies a 10 years delay.

If we wait and θ_{13} remains undetected we should consequently stop any further neutrino oscillation initiative (because of the cost).

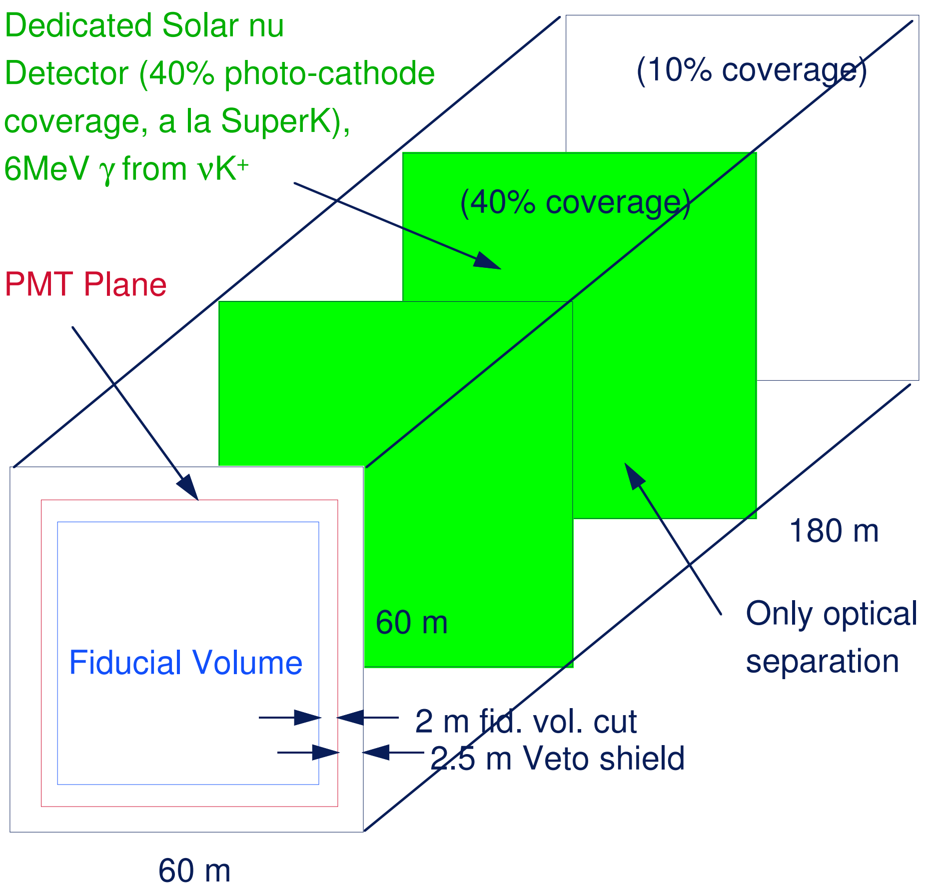
Any future initiative should have enough physics potential besides neutrino oscillations to justify the risk of starting the Leptonic CP violation searches without any guarantee.

Players

Facility	Momentum	Power	Baseline	Events	Bacgkr.
Super Beams firing to a 20x SuperKamiokande like detector					
BNL AGS	28 GeV/c	1 MW	2500 or 2990 Km	1115	126
JPARC Phase II	50 GeV/c	4 MW	295 Km	8237	1378
CERN SPL	2 GeV	4 MW	130 Km	3137	454
Beta Beams firing to a 20x SuperKamiokande like detector					
			$\overline{\nu}_e$	348	0.5
			ν_e	3358	198
Neutrino Factories				40582	112

Event numbers are ν_e appearance at the Chooz limit ($\sin^2 2\theta_{23} = 0.12$), $\delta = 0$, 5 yrs running. JPARC phase II and Nufact are taken from P. Huber, EPS 2003.

UNO/HyperK detector



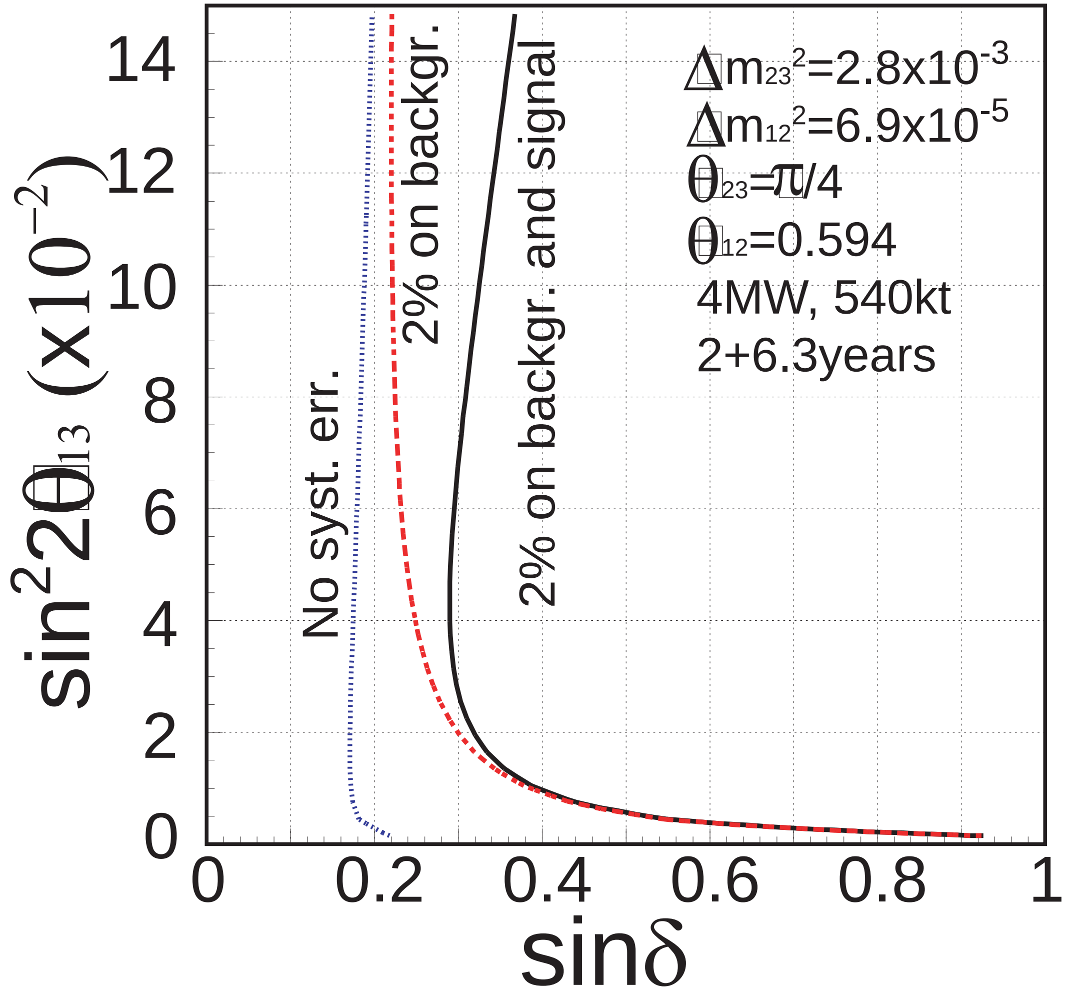
- Fiducial volume: 440 kton: 20 times SuperK.
- 60000 PMTs (20") in the inner detector, 15000 PMTs in the outer veto detector.
- Energy resolution is poor for multi track events but quite adequate for sub-GeV neutrino interactions.
- Quoted at 500M$ (including excavation). Timescale: 10 years.

The

killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.

SuperBeams - JPARC phase 2

T. Kobayashi, J.Phys.G29:1493(2003)



Upgrade the proton driver from 0.75 MW to 4 MW

Upgrade SuperKamiokande by a factor $\sim 20 \Longrightarrow$ HyperKamiokande

Both upgrades are necessary to address leptonic CP searches.

Systematics at 2% are tight

4 MW at 50 GeV/c are tight

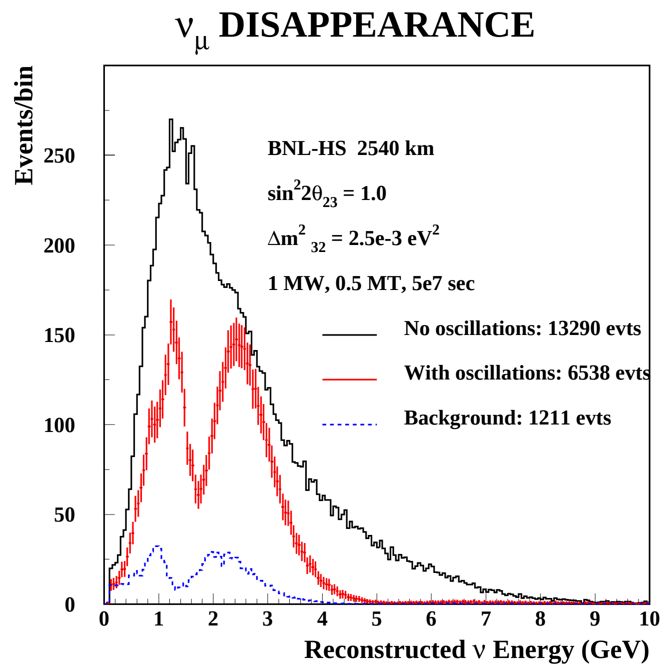
Target and optics at 4 MW are tight and will require some compromise

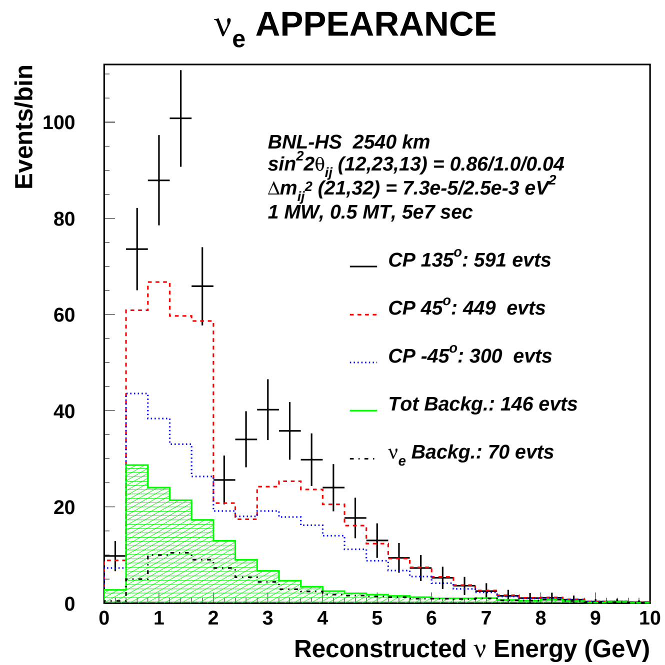
SuperBeams - BNL

- The very far detector detects the first and the second oscillation maximum.
- The comparison of the two maxima can allow the detection of θ_{13} , δ and sign(Δm^2), without the need of an antineutrino run.
- An original and powerful method to extract the mixing matrix parameters

HOWEVER

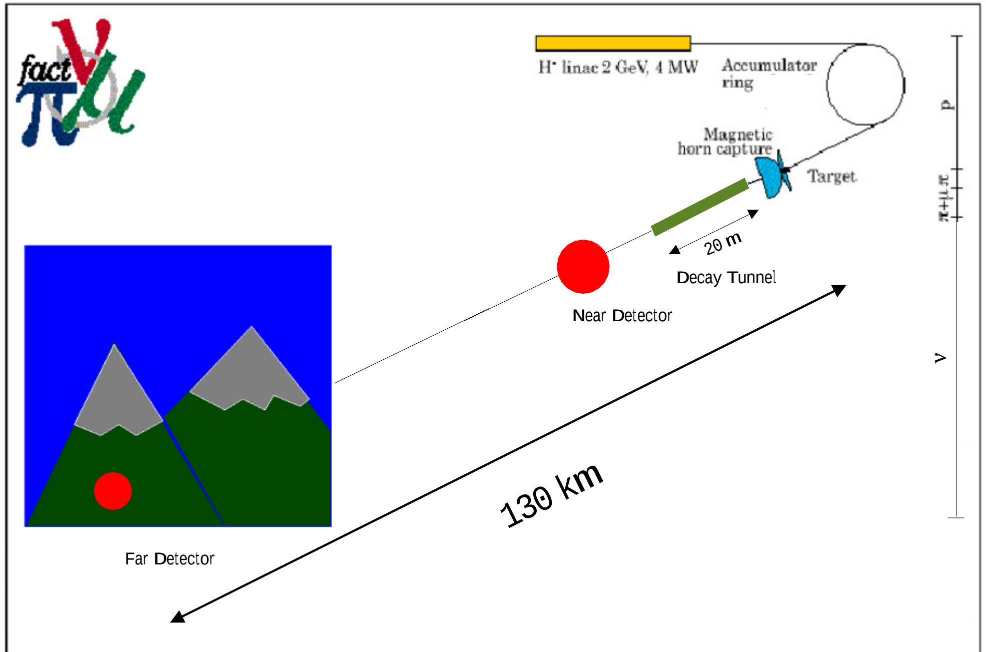
- The very long baselines wastes the most critical parameter of SuperBeams: statistics
- The spectrum analysis requires good control of energy reconstruction in a critical energy range for Water Cerenkov detector and for the cross section knowledge
- First maximum neutrinos are pion daughters while second maximum neutrinos are kaon daughters.



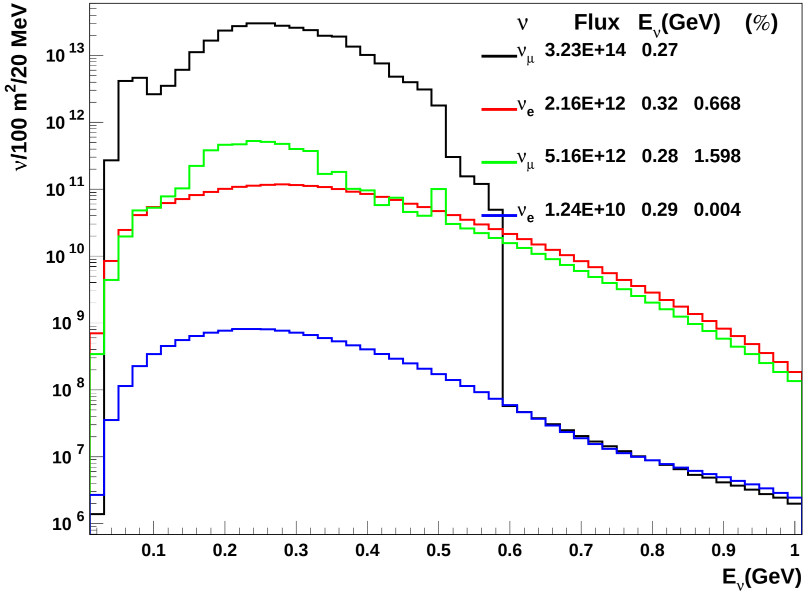


SuperBeams - SPL ν beam at CERN

A feasibility study of the CERN possible developments



Possible Low Energy Super Beam Layout



Flux intensities at 50 km from the target

Flavour	Absolute Flux $(\nu/10^{23}\mathrm{pot/m^2})$	Rel. Flux (%)	$\langle E_\nu \rangle$ (GeV)
ν_μ	$3.2 \cdot 10^{12}$	100	0.27
$\overline{\nu}_\mu$	$2.2 \cdot 10^{10}$	1.6	0.28
ν_e	$5.2 \cdot 10^{9}$	0.67	0.32
$\overline{\nu}_e$	$1.2 \cdot 10^{8}$	0.004	0.29

Interesting features of a low energy conventional neutrino beam.

ν beam:

- $\langle E_{\nu_\mu} \rangle \simeq 0.25$ GeV
- ν_e production by kaons largely suppressed by threshold effects.

ν_e in the beam come only from μ decays.

$$\pi^+ \longrightarrow \mu^+\nu_\mu, \quad \mu^+ \downarrow e^+\nu_e\overline{\nu}_\mu$$

$\Rightarrow$ they can be predicted from the measured ν_μ CC spectrum both at the close and at the far detector **with a small systematic error of $\sim 2\%$.**

Detector Backgrounds

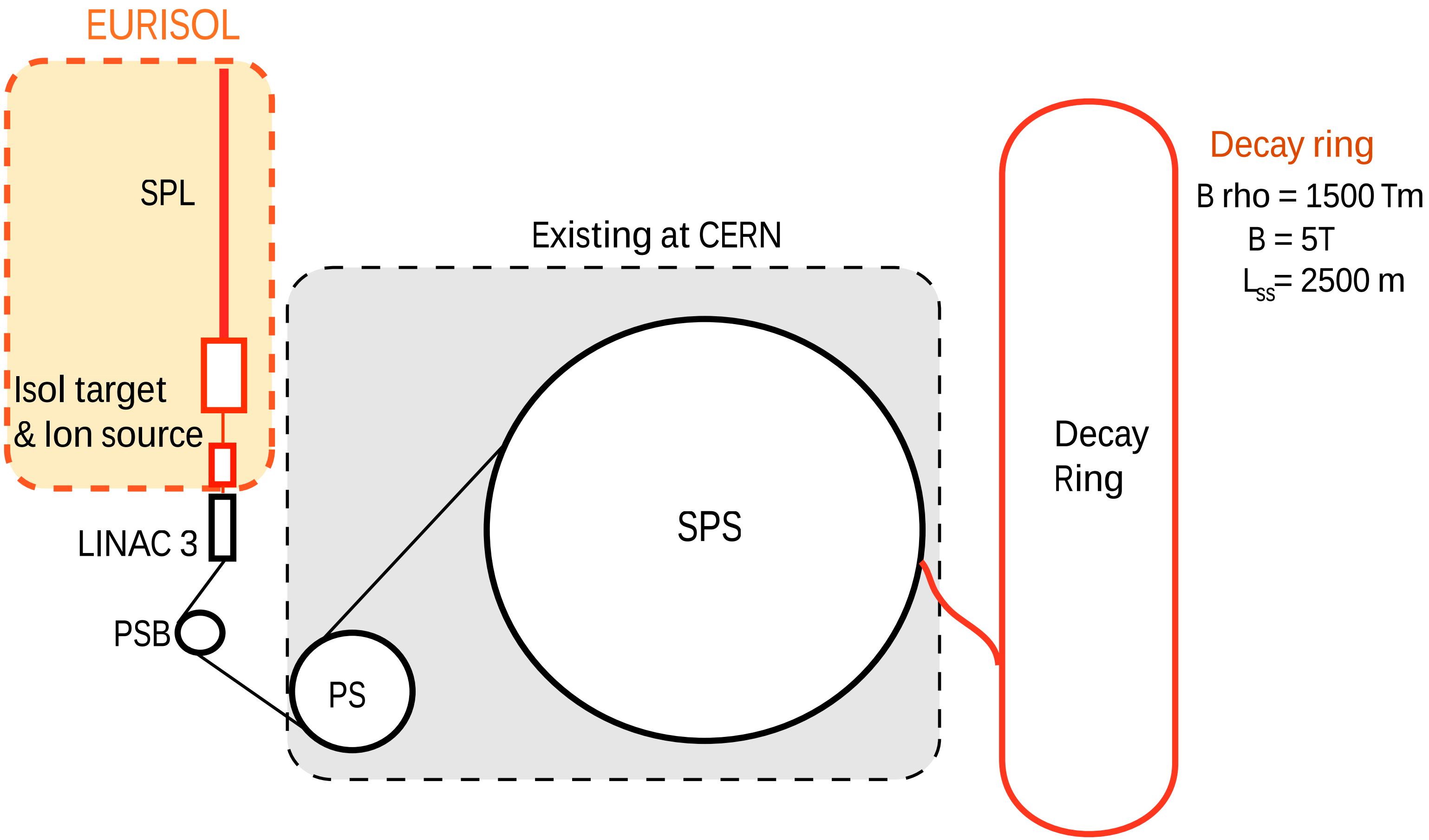
- Good e/π^0 separation following the large $\pi^0 \rightarrow \gamma\gamma$ opening angle
- Good e/μ separation in a Čerenkov detector because μ are produced below or just above the Čerenkov threshold.
- Charm and τ production below threshold.

Less exiting aspects of a low energy neutrino beam

- Cross sections are small $\Rightarrow$ large detectors are necessary in spite of the very intense neutrino beam.
- $\overline{\nu}_\mu$ production is disfavored for two reasons:
  - Smaller π^- multiplicity at the target.
  - $\overline{\nu}_\mu/\nu_\mu$ cross section ratio is at a minimum (1/5).
- Visible energy is smeared out by Fermi motion

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

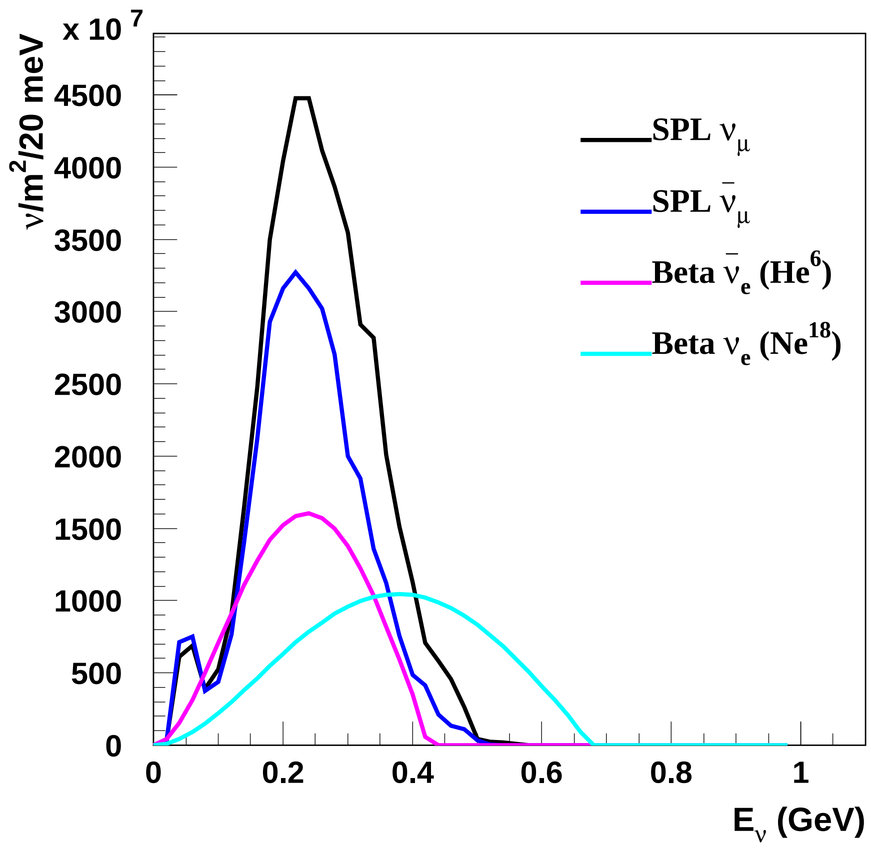
M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam



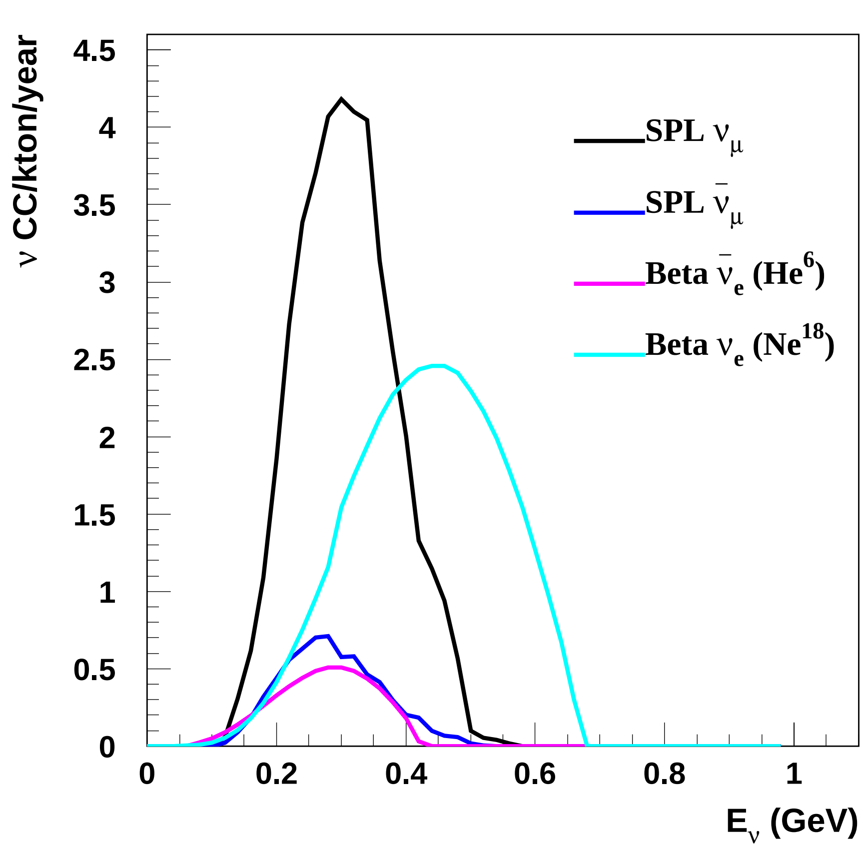
- 1 ISOL target to produce He^{6}, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- The 4 targets could run in parallel, but the decay ring optics requires:

$$\gamma(Ne^{18}) = 1.67 \cdot \gamma(He^{6}).$$

Fluxes



CC Rates



	Fluxes @ 130 km $\nu/m^2/yr$	$< E_\nu >$ (GeV)	CC rate (no osc) events/kton/yr	$< E_\nu >$ (GeV)	Years	Integrated events (440 kton $\times$ 10 years)
SPL Super Beam						
ν_μ	$4.78 \cdot 10^{11}$	0.27	41.7	0.32	2	36698
$\overline{\nu}_\mu$	$3.33 \cdot 10^{11}$	0.25	6.6	0.30	8	23320
Beta Beam						
$\overline{\nu}_e$ $(\gamma = 60)$	$1.97 \cdot 10^{11}$	0.24	5.2	0.28	10	28880
ν_e $(\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36	39.2	0.43	10	172683

Distinctive features of the Beta Beam

Just one neutrino flavour in the beam. No intrinsic contamination.

In the proposed scheme the $\overline{\nu}_e$ channel is completely background free!

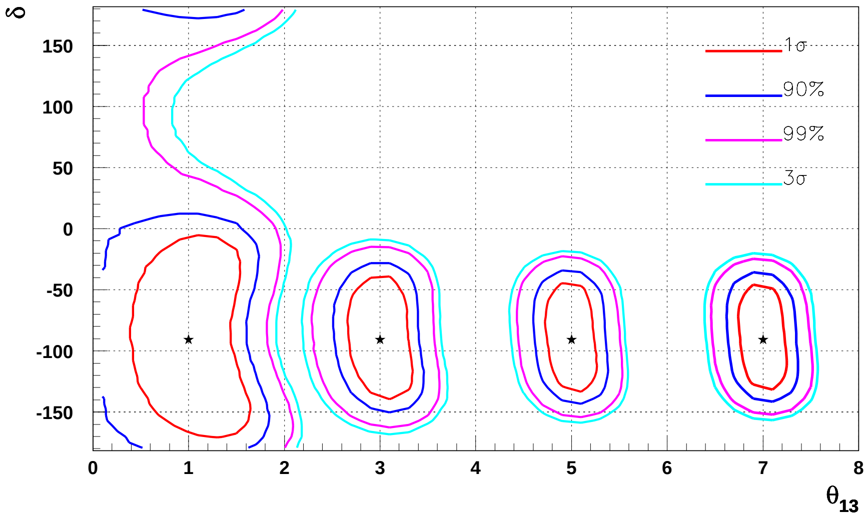
Neutrino fluxes are completely defined by the beta decay properties of the parent ion and by the knowledge of the number of ions in the decay ring. This assures very small systematic errors and a powerful measure of neutrino cross-sections in the close detector.

The ν_e and $\overline{\nu}_e$ beams allow for the disappearance channel with a very good control of the systematics, with a direct access to θ_{13} .

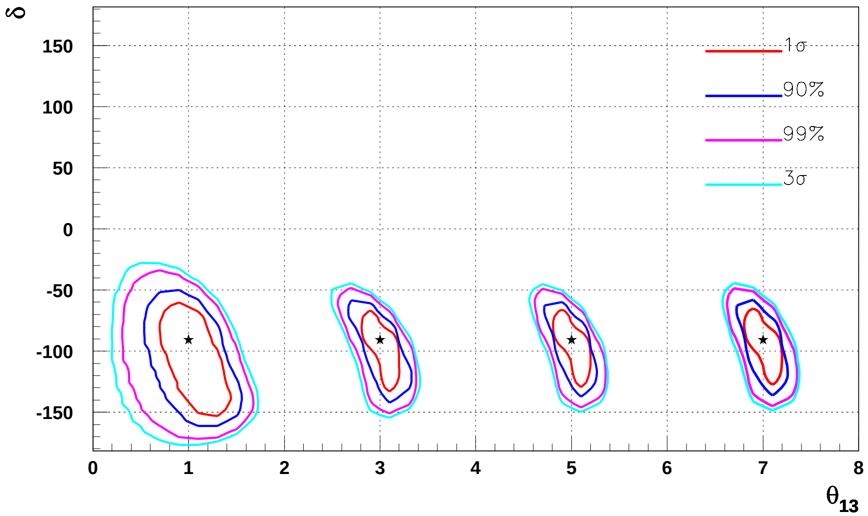
When combined with the ν_μ and $\overline{\nu}_\mu$ SPL beams, the ν_e and $\overline{\nu}_e$ Beta Beams allow for CP, T, and CPT searches.

Beta Beam - Super Beam synergy: CP sensitivity

SUPER BEAM ONLY



SUPER BEAM + BETA BEAM

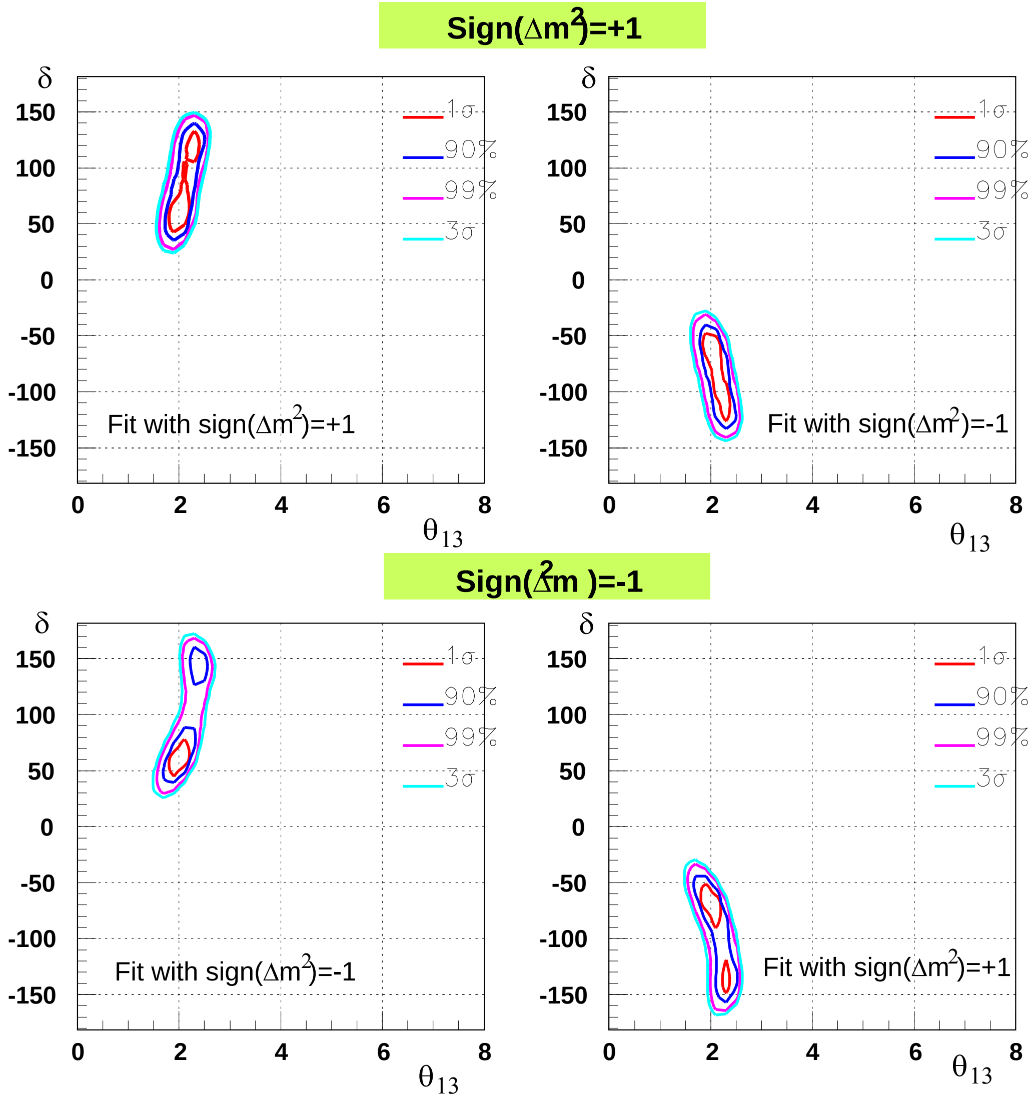


$\delta m^2_{12} = 7 \cdot 10^{-5}\ eV^2, \quad \theta_{13} = 1^\circ, \quad \delta_{CP} = \pi/2$

10 yrs (4400 kton/yr)	SuperBeam		Beta Beam	
	ν_μ	$\overline{\nu}_\mu$	$\overline{\nu}_e$ (He^6)	ν_e (Ne^{18})
	(2 yrs)	(8 yrs)	$\gamma = 60$	$\gamma = 100$
CC events (no osc, no cut)	36698	23320	28880	172683
Total oscillated	1.7	33.3	0.5	198.3
CP-Odd oscillated	-25.5	16.9	-13.4	88.8
Beam backgrounds	141	113	/	/
Detector backgrounds	37	50	1	396
Statistical Error	13.4	13.6	1.5	24.4
Error on θ_{23}	2.1	1.7	0.5	9.5
Error on δm^2_{12}	2.8	1.9	0.3	18.2
Total Error	13.9	14.6	1.8	34.0

The sign(Δm^2) ambiguity

Being the matter effect terms negligible, the sign(Δm^2) ambiguity makes the sign$(sign\Delta m^2 \times \delta)$ undetectable, but doesn't degrades the overall resolution.

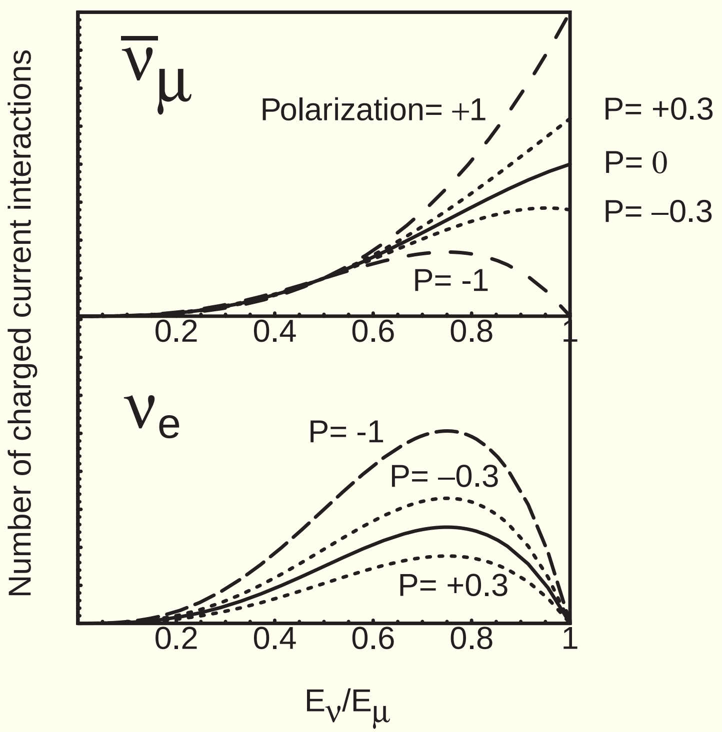


Introducing Neutrino Factories

- The dream beam of every neutrino physicist.
- The first case in which the whole neutrino production chain, including proton acceleration, is accounted on the budget of the neutrino beam construction.
- Beam intensities predicted to be two orders of magnitude higher than in traditional neutrino beams.
- No hadronic MonteCarlos to predict neutrino fluxes.
- Oscillated events N_{osc} at a distance L:

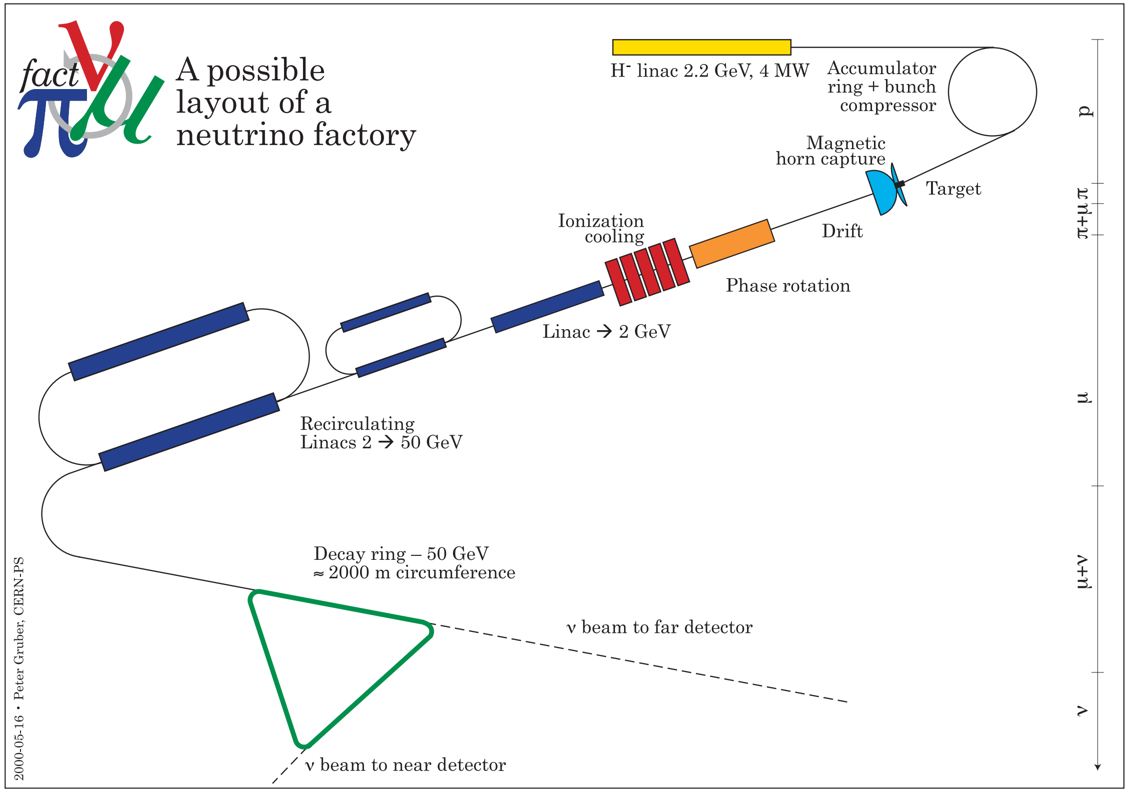
$$N_{\rm osc} \sim {\rm Flux} \times \sigma_\nu \times P_{\rm osc} \sim \frac{E_\nu^3}{L^2} \sin^2 \frac{L}{E_\nu} \propto E_\nu$$

  N_{osc} increases linearly with the beam energy. Optimal energy: as high as possible.
- Neutrino beams from muon decays contain ONLY two types of neutrinos of opposite helicities ($\overline{\nu}_e\ \nu_\mu$ or $\nu_e\ \overline{\nu}_\mu$). **It is possible to search for $\nu_\mu \to \nu_e$ transitions characterized by the appearance of WRONG SIGN MUONS, without intrinsic beam backgrounds.**



The basic concept of a neutrino factory (the CERN scheme)

- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: "phase rotation" and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating Linear Accelerators.
- Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.
- **GOAL: $\geq 10^{20}$ μ decays per straight section per year**



Detector

Iron calorimeter

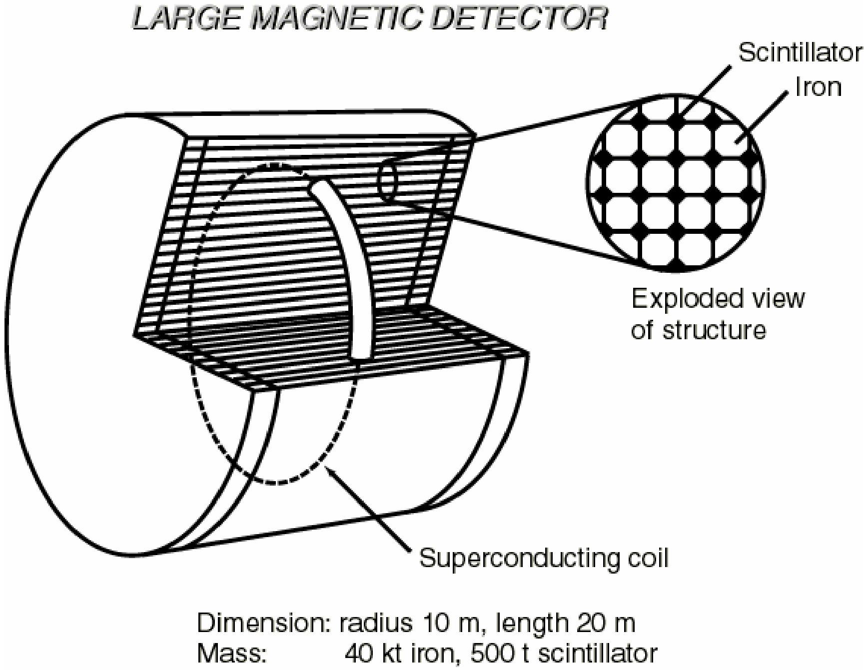
Magnetized

Charge discrimination

B = 1 T

R = 10 m, L = 20 m

Fiducial mass = 40 kT



Also: L Arg detector: magnetized ICARUS
Wrong sign muons, electrons, taus and NC evts

Events for 1 year

Baseline	$\bar{\nu}_\mu$ CC	ν_e CC	signal ($\sin^2\theta_{13}$=0.01)	
732 Km	3.5×10^7	5.9×10^7	1.1×10^5	
3500 Km	1.2×10^6	2.4×10^6	1.0×10^5	(cf 40 in JHF-SK)

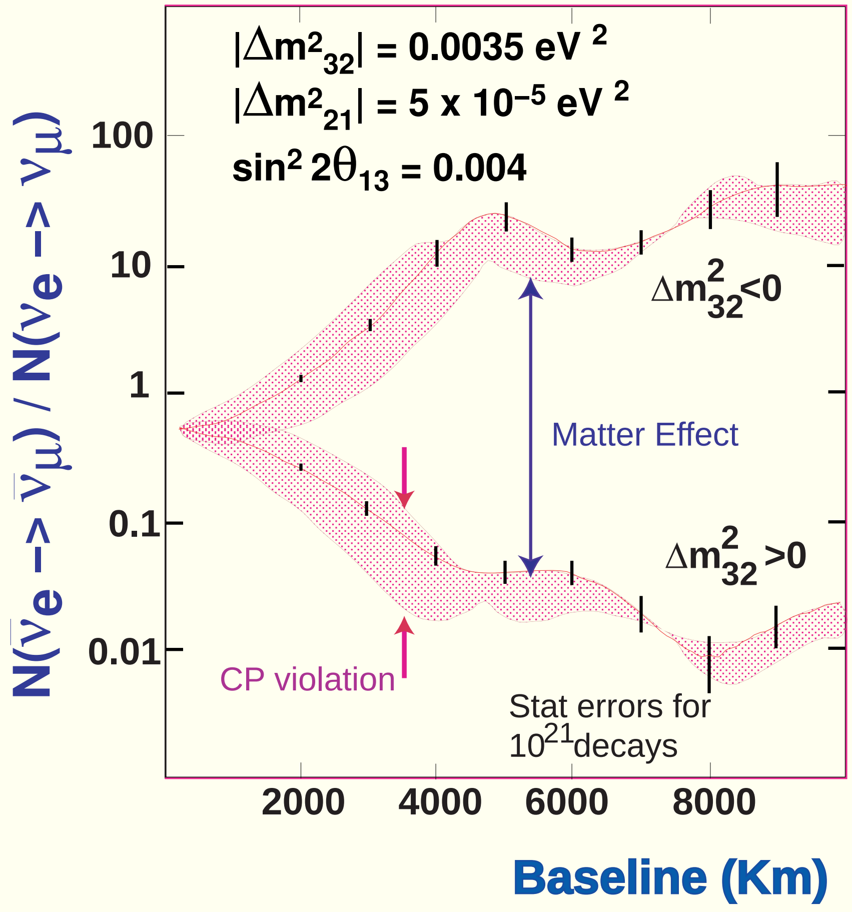
Alain Blondel, Venice, March 2003

Can genuine CP effects be separated from matter effects?

Genuine CP-odd, δ driven effects can be decoupled from matter effects, but paying a high price:

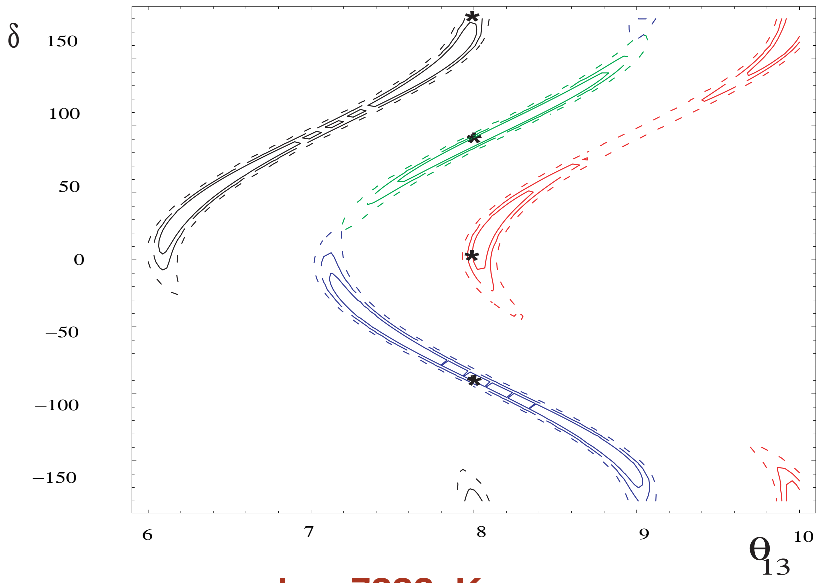
1. The experiment must be run at a baseline much shorter than the optimal one.
2. A strong correlation between δ and θ_{13} .
3. The experimental result is affected by the incertitude on the other parameters of the mixing matrix and by the incertitude on the matter density along the beam line.

From V. Barger et al., hep-ph/0003184.

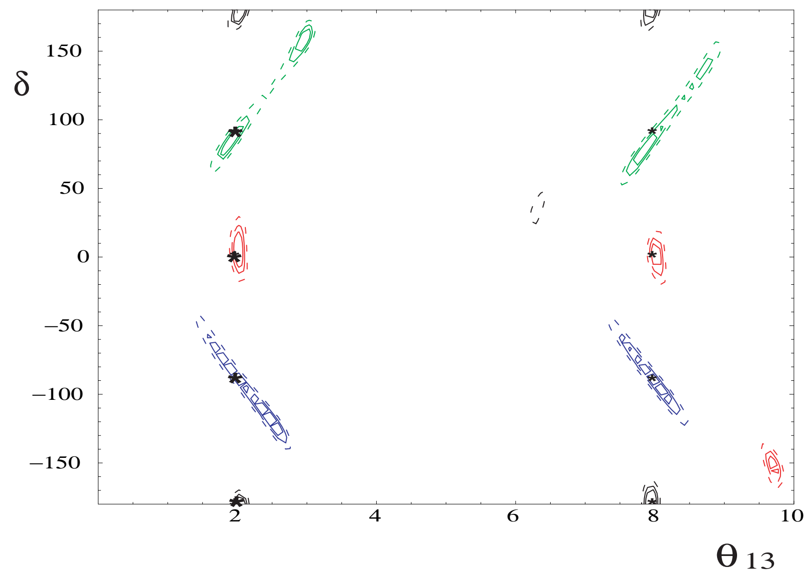


Simultaneous fits at δ e θ_{13} (from Nucl.Phys. B608(2001)301)

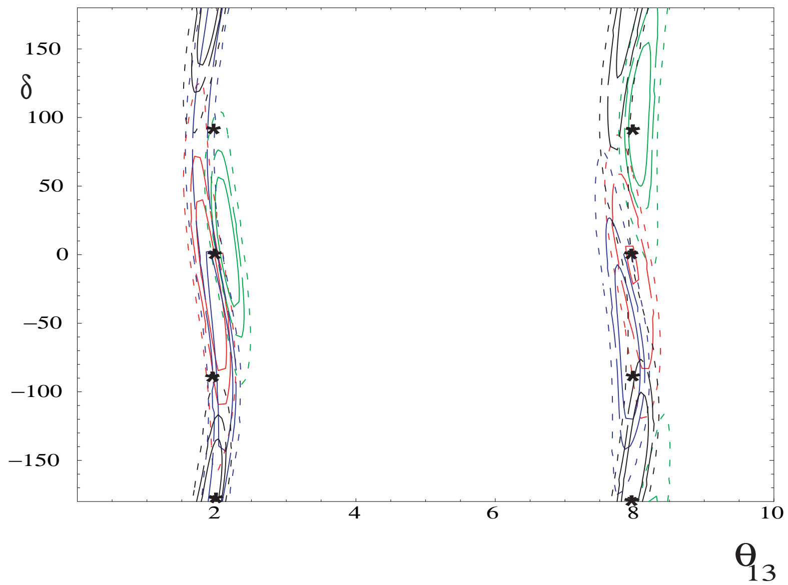
L = 732 Km



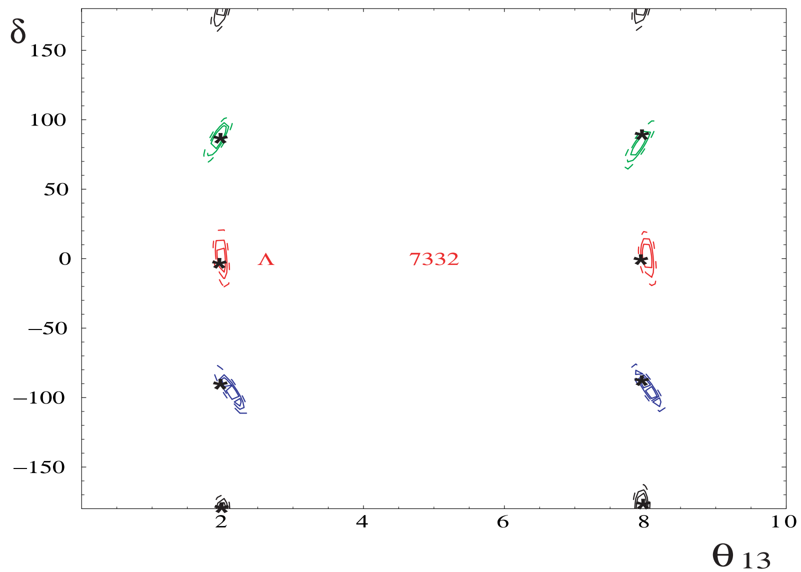
L = 2810 Km



L = 7332 Km

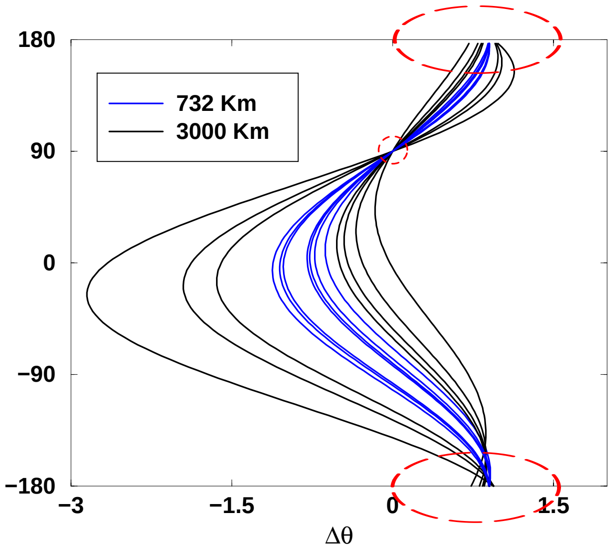


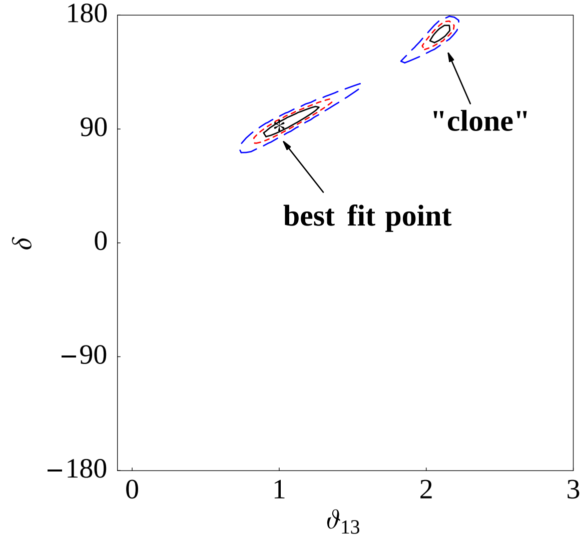
L = 2810 Km + L = 7332 Km

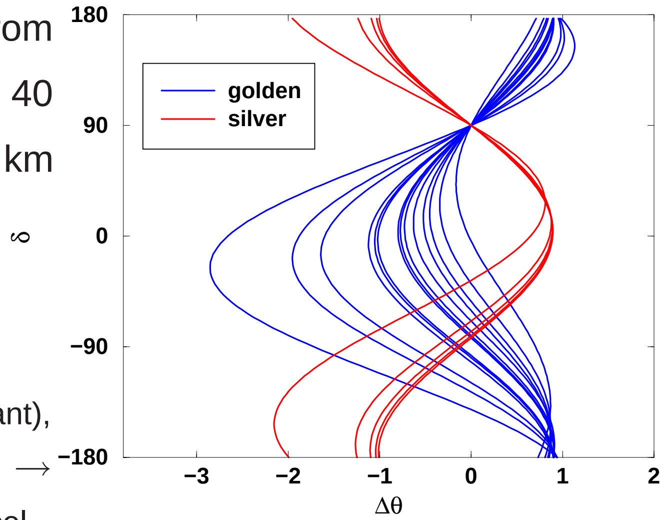


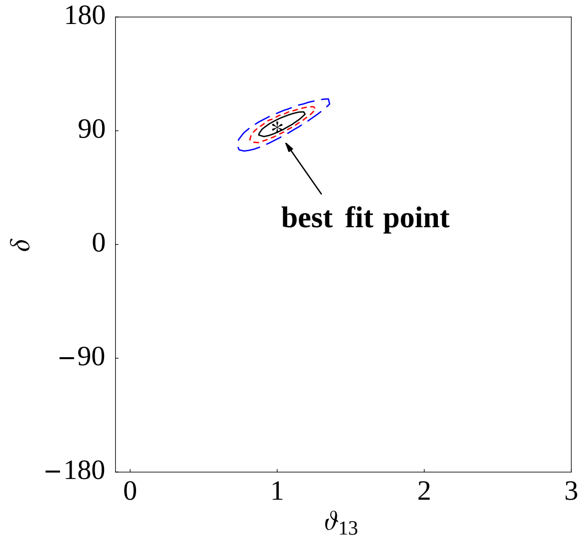
The δ, θ_{13} degereracy is better cured by the silver channel .

- From D. Autiero et al., hep-ph/0305185
- $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$ oscillations have opposite sign dependence from the δ term [a]
- This behavior better solves the δ-θ_{13} ambiguities.
- $\nu_e \rightarrow \nu_\tau$ oscillations can be detected by an Opera like or an Icarus like detectors.
- Computation for a detector twice as big as Opera (4 kton), at 732 km from Nufact (CERN-LNGS), coupled to a 40 kton iron magnetic detector at 2810 km (Cern-Canary Islands).





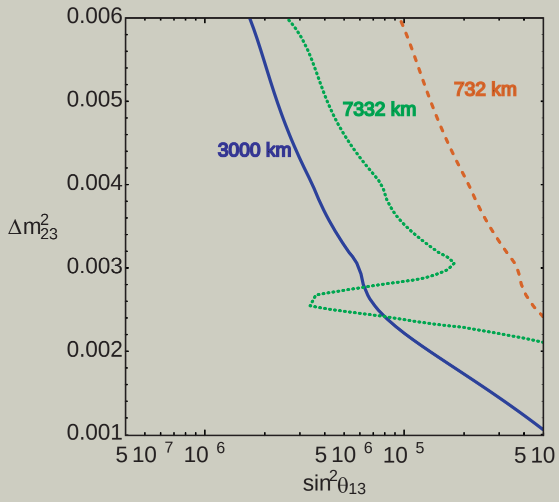




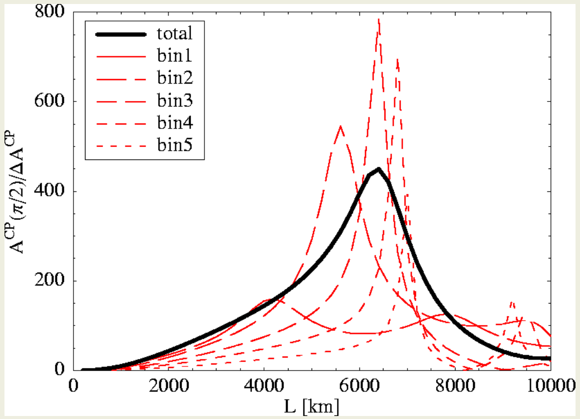
[a] That can easily derived considering that $p(\nu_e \rightarrow \nu_e)$ cannot violate CP (is T invariant), being 1-$p(\nu_e \rightarrow \nu_e)$ =$p(\nu_e \rightarrow \nu_\tau)$ +$p(\nu_e \rightarrow \nu_\mu)$, the δ terms of the last two terms must cancel.

Precision measurements at the Neutrino Factories

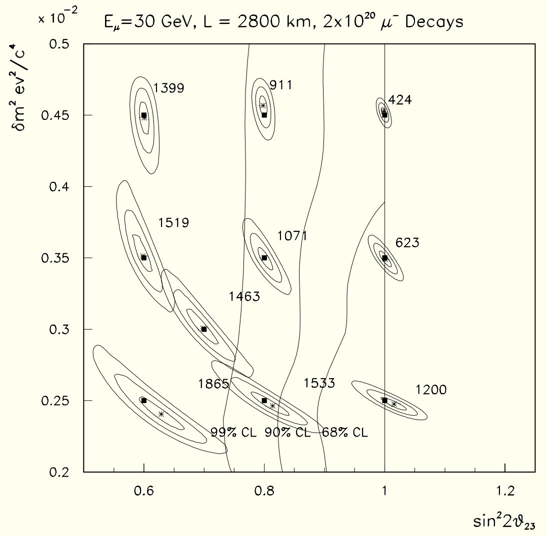
Improve up to 4 orders of magnitude the Chooz sensitivity on θ_{13}



Measure the Δm^2_{23} sign



Measure the atmospheric parameters at 1%.

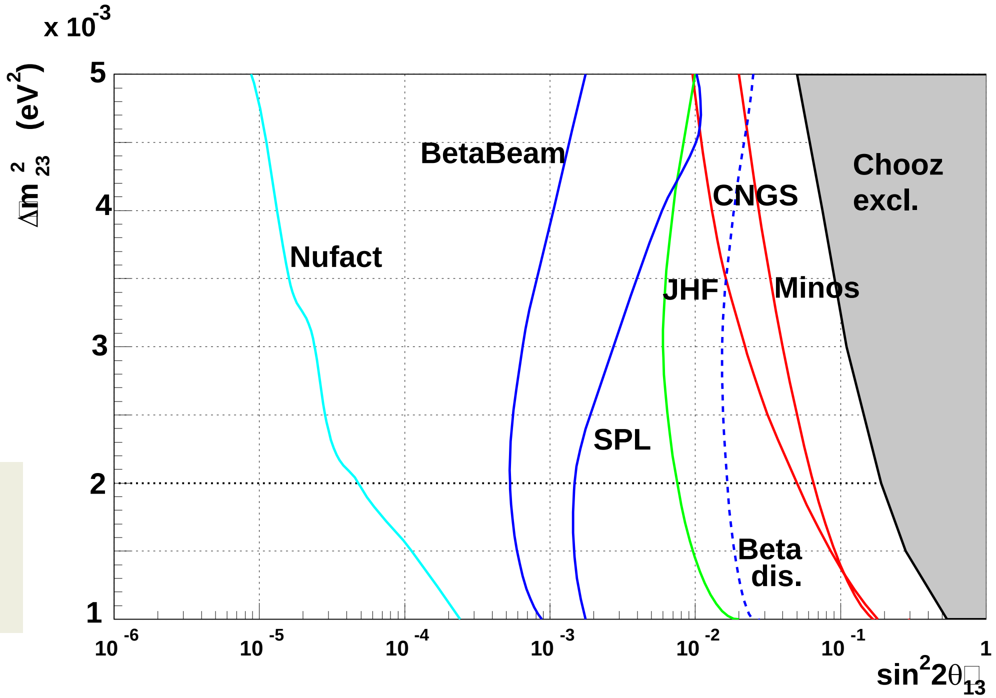


Sensitivities and some comparison

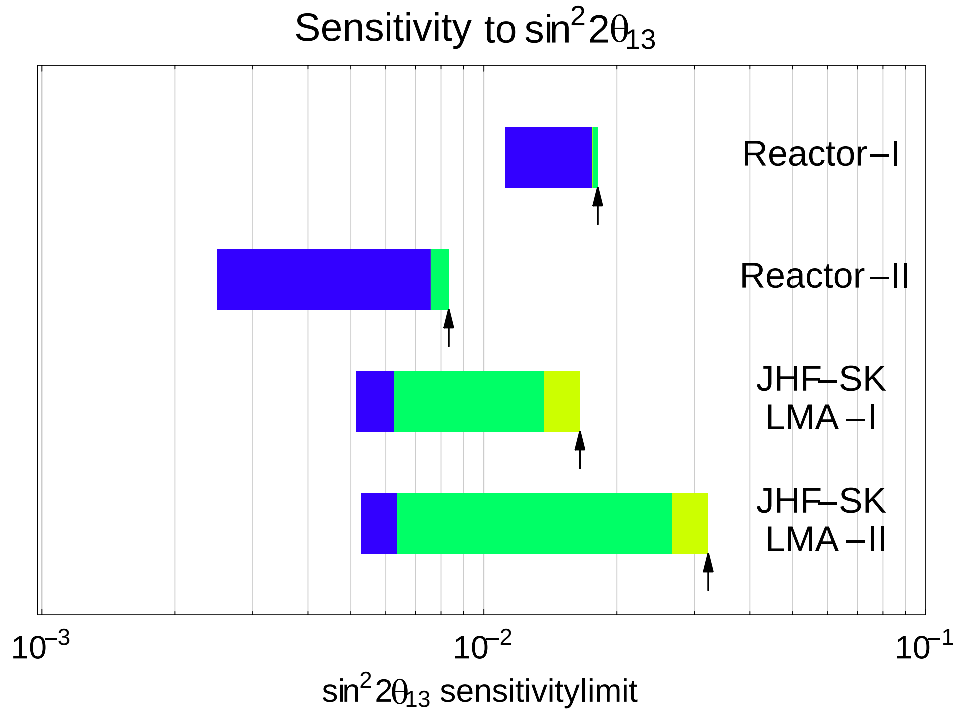
Disclaimer:

- A common agreement on what are the significant plots for the comparison is missing.
- A stable, common agreement on the input parameters and their errors is missing.
- Different groups often have different assumptions on statistical methods, treatment of systematic errors, experimental conditions, effects of parameter degeneracies.
- So it's not guaranteed that I will compare apples with apples.

θ_{13} sensitivities (I)



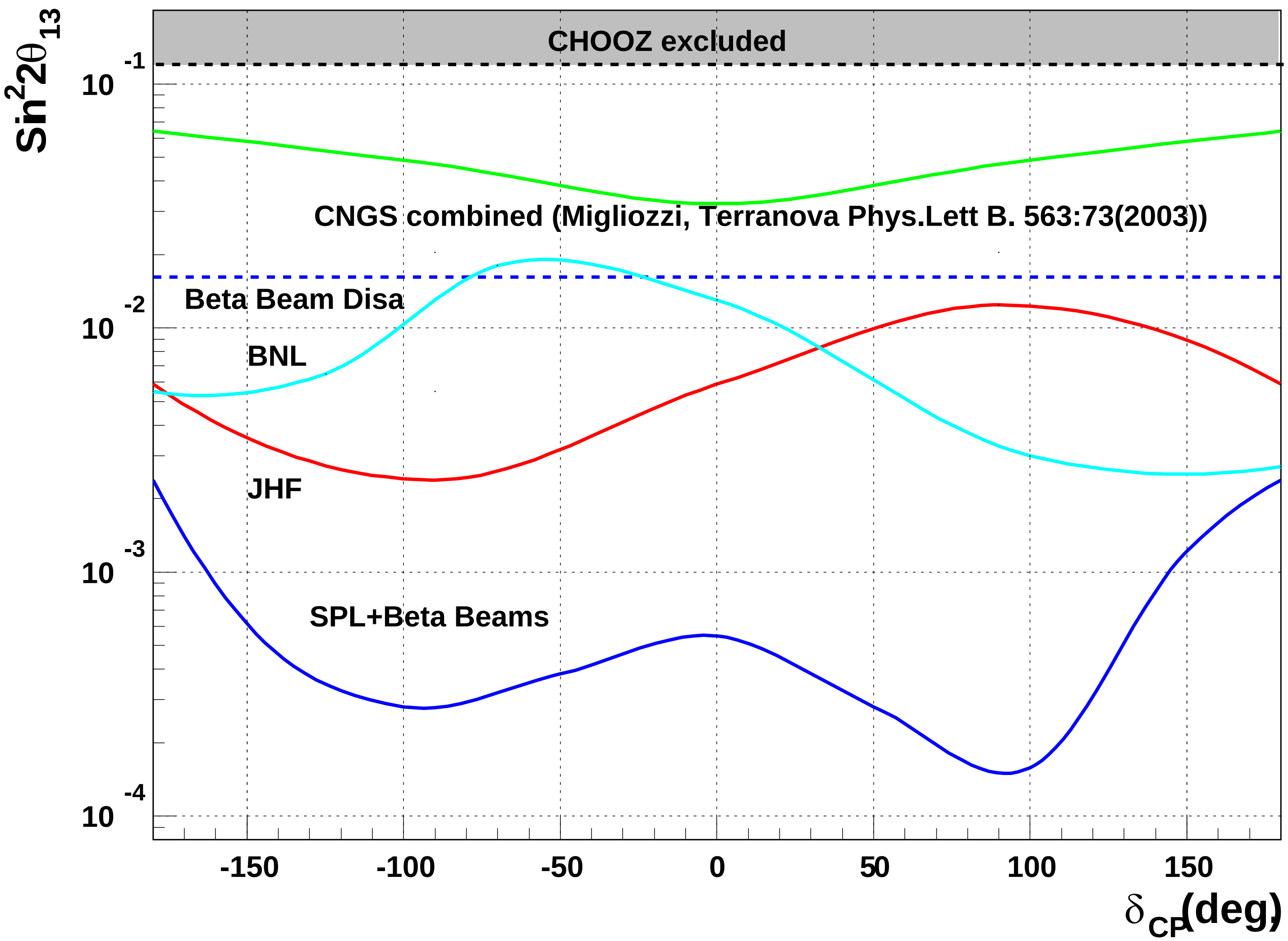
The sensitivity plots drawn above the Chooz result assume $\delta = 0$.



Sensitivity bars computed integrating out δ don't contain the full information (plot from Lindner et al. Nucl.Phys. B665:487-519 (2003)).

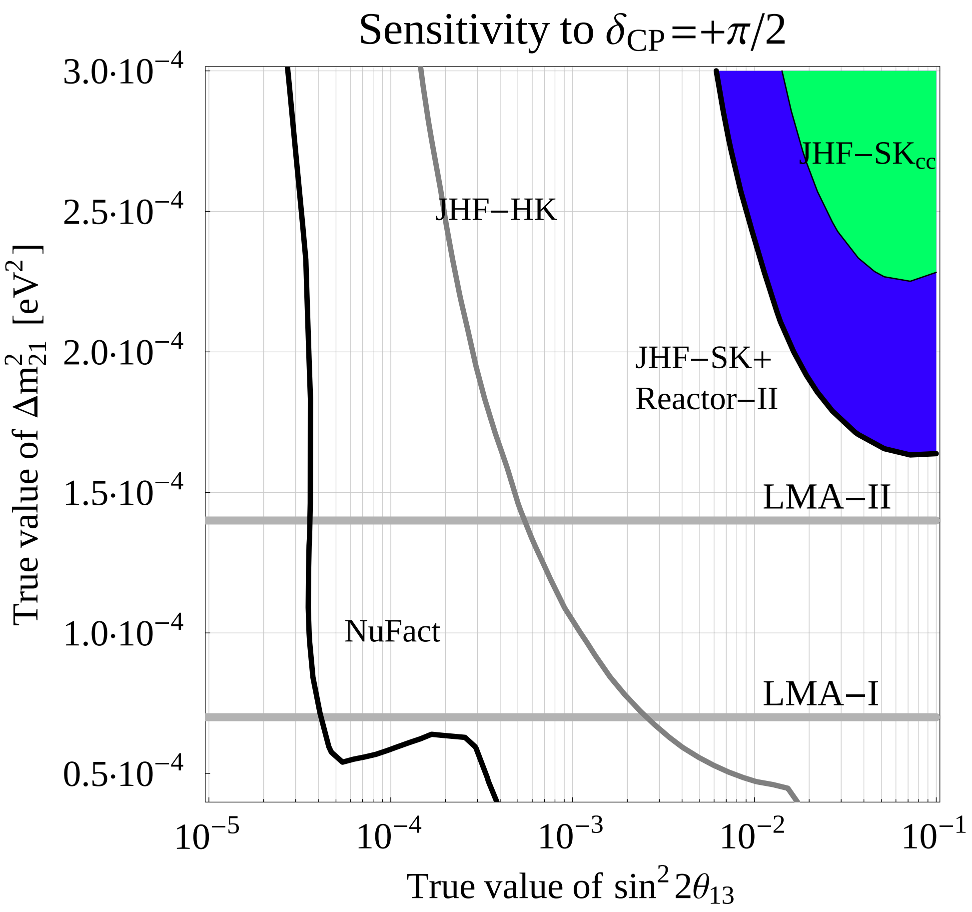
θ_{13} sensitivities (II)

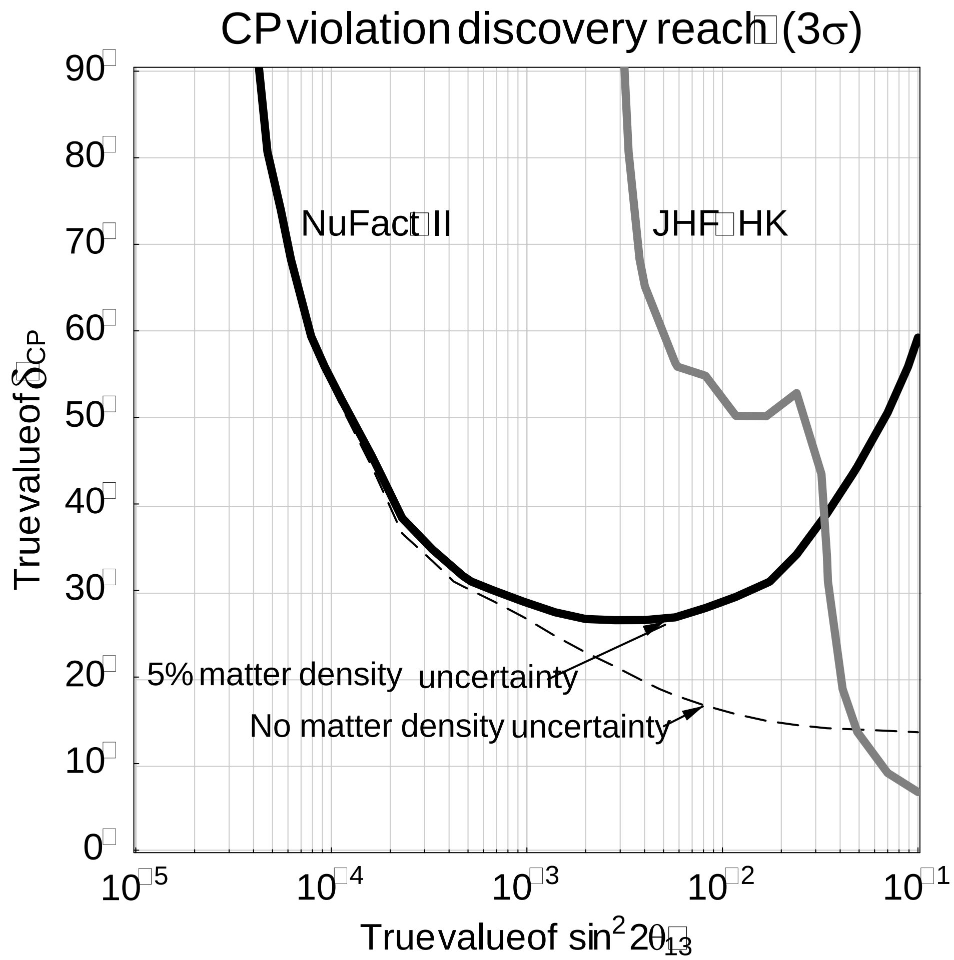
More satisfactory are θ_{13} vs δ plots. The following is computed for $\Delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2.



δ sensitivity: Nufact vs HyperK.

Taken from P. Huber talk at EPS 2003, Aachen



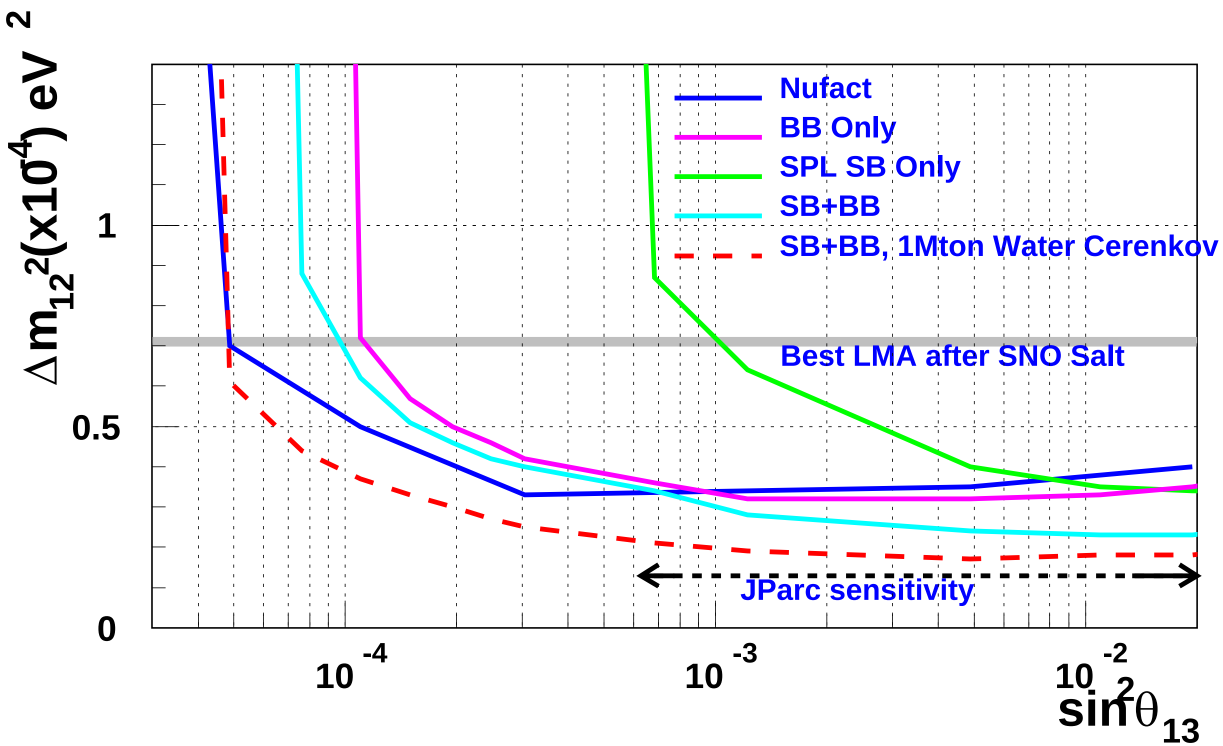


δ sensitivity: Nufact vs SPL SuperBeam + Beta Beam.

CP sensitivity: parameter space where max CP ($\delta = \pi/2$) can be separated from no CP ($\delta = 0$) at 99%CL.

Nufact sensitivity as computed in J. Burguet-Castell et al., Nucl. Phys. B **608** (2001) 301:

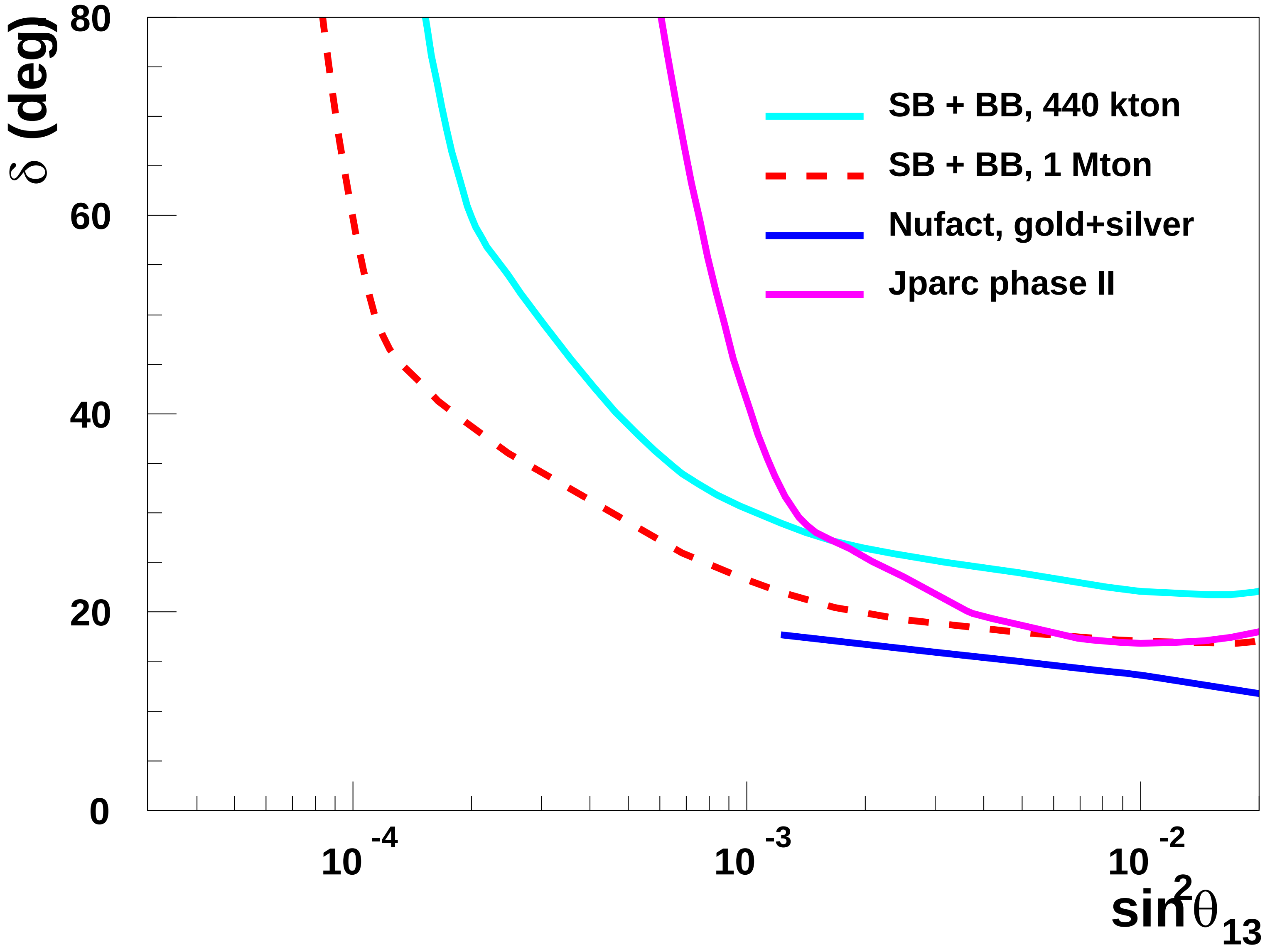
- 50 GeV/c μ.
- $2 \cdot 10^{20}$ useful μ decays/year.
- 5+5 years.
- 2 iron magnetized detectors, 40 kton, at 3000 and 7000 km.
- Full detector simulation.



δ sensitivity: Nufact vs SPL SuperBeam + Beta Beam.

Minimum value of δ at 3σ from zero as function of θ_{13} . $\Delta m^2_{12} = 7 \cdot 10^{-3}$ eV^2.

Nufact curve is silver+gold, preliminary, courtesy of O. Mena. Its extension below 2° is under investigation.



Super(Beta)Beams vs. Nufact

Super(Beta)Beams

- Negligible matter effects: can be run at the optimal baseline.
- Negligible matter effects: reduced correlations between θ_{13} and δ
- Limited by the statistics (and by the intrinsic backgrounds).
- Very difficult to measure sign(Δm^2).
- No critical R&D required for the construction of the facilities.

Neutrino Factories

- Very large statistics and reduced intrinsic backgrounds.
- Leptonic CP violation is in competition with matter effects.
- Can address all the remaining unknowns in neutrino oscillations at their ultimate sensitivity.
- R&D required in many items of the acceleration scheme.

Synergy and not competition

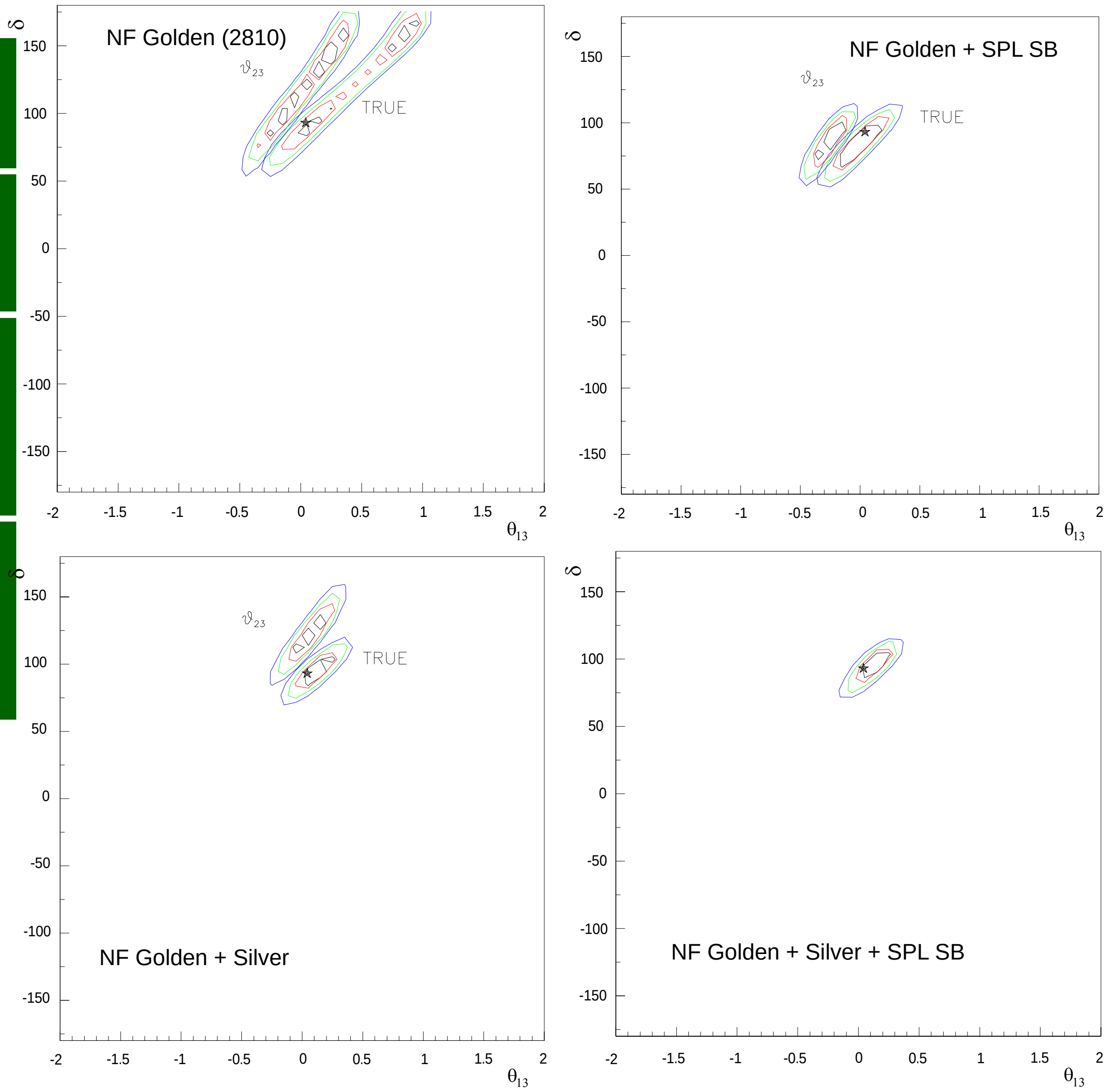
The cost and the time scale of the two facilities are different.

Their approach is completely complementary.

Super(Beta)Beams are needed to eliminate any parameter degeneracy in case $\theta_{13} < 2°$.

The synergy of the two approaches must be used to reach the ultimate sensitivity to the leptonic CP violation.

Plot taken from A. Donini, hep-ph0310014, golden is a magnetic detector of 40 kton at 2810 km, silver is an emulsion detector of 4 kton at 732 km, SPL SB is the CERN SPL SuperBeam fired to a 400 kton Cerenkov detector at 130 Km.



Conclusions

- The neutrino oscillation roadmap predicts several tens years to be completed in the simplest scenario.
- Leptonic CP violation searches require accelerators, detectors and cooperation at scales unknown to the neutrino physicists.
- A working group on physics at the future neutrino beams is active in Europe, sponsored by ECFA and the novel EU network BENE. The conveners are Pilar.Hernandez@cern.ch and Mauro.Mezzetto@pd.infn.it, the web page is **http://axpd24.pd.infn.it/nowg**