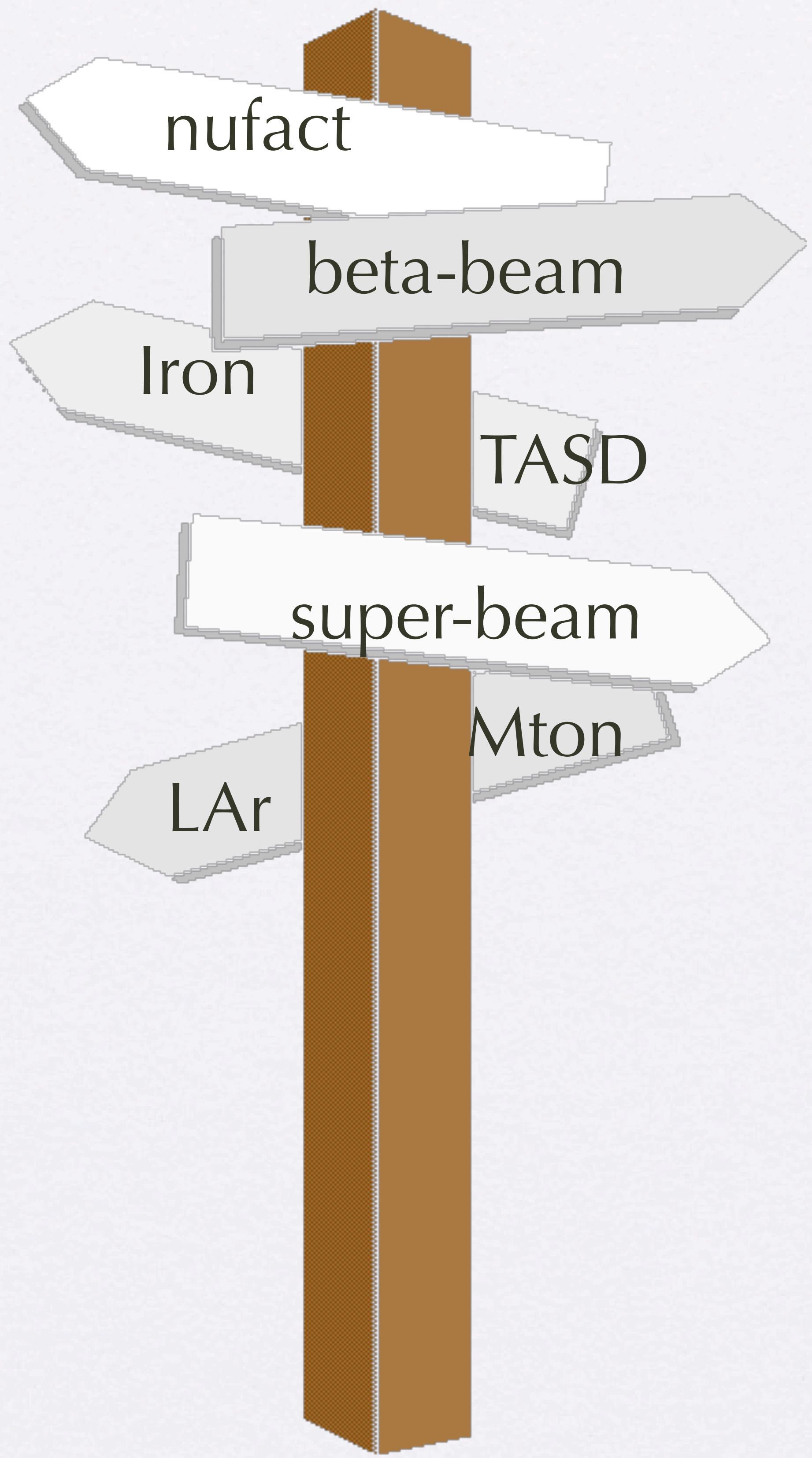
Neutrino factories and Beta Beams

J.J. Gómez-Cadenas
IFIC-CSIC-UV

Neutrino 08
Christchurch

Madrid & Chicago candidatures being prepared for Olympics

What are our candidates for a future neutrino physics facility?



We wish we knew!

International scoping study of a future
Neutrino Factory and super-beam facility

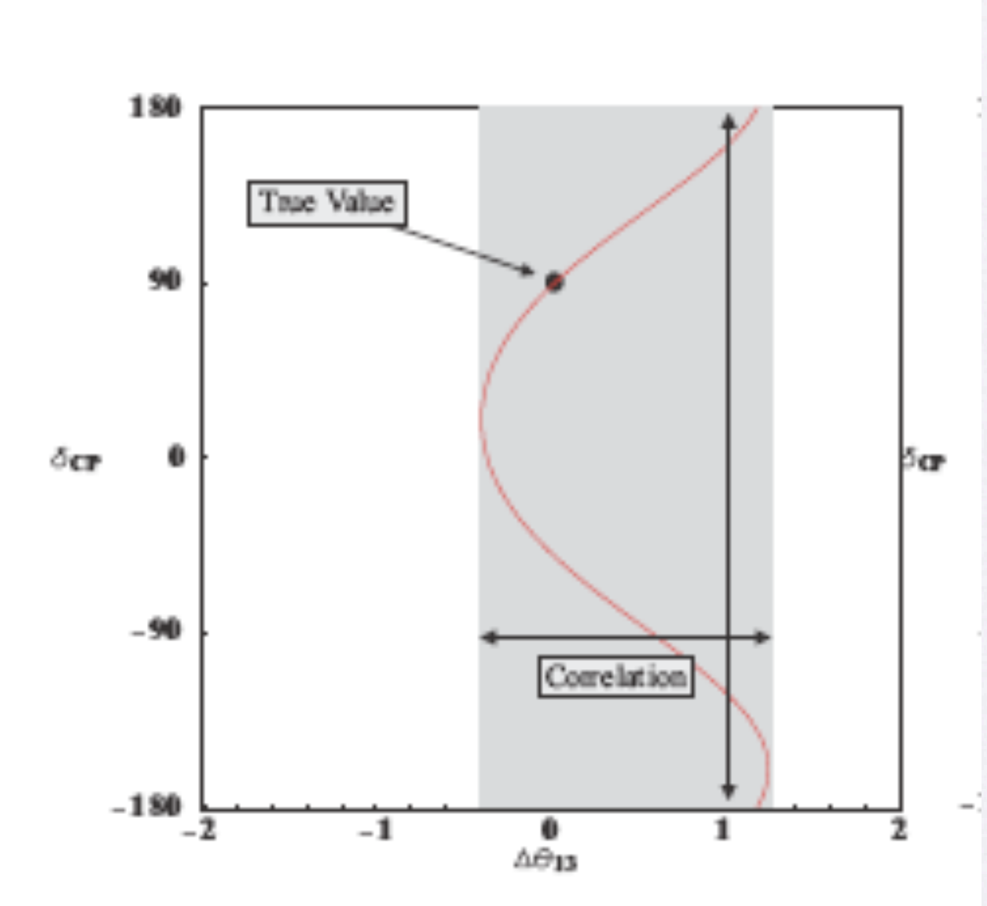
RAL-TR-2007-019

Physics at a future Neutrino Factory and super-beam facility

The ISS Physics Working Group

Measurement of $\sin^2\theta_{13}$: Correlations

$$P^{\pm}_{\nu_e\nu_\mu}(\theta_{13},\delta) \approx X_\pm \sin^2 2\theta_{13} + \left(Y^c_\pm \cos\delta \mp Y^s_\pm \sin\delta\right) \sin 2\theta_{13} + Z$$



At fixed E,L, the equation

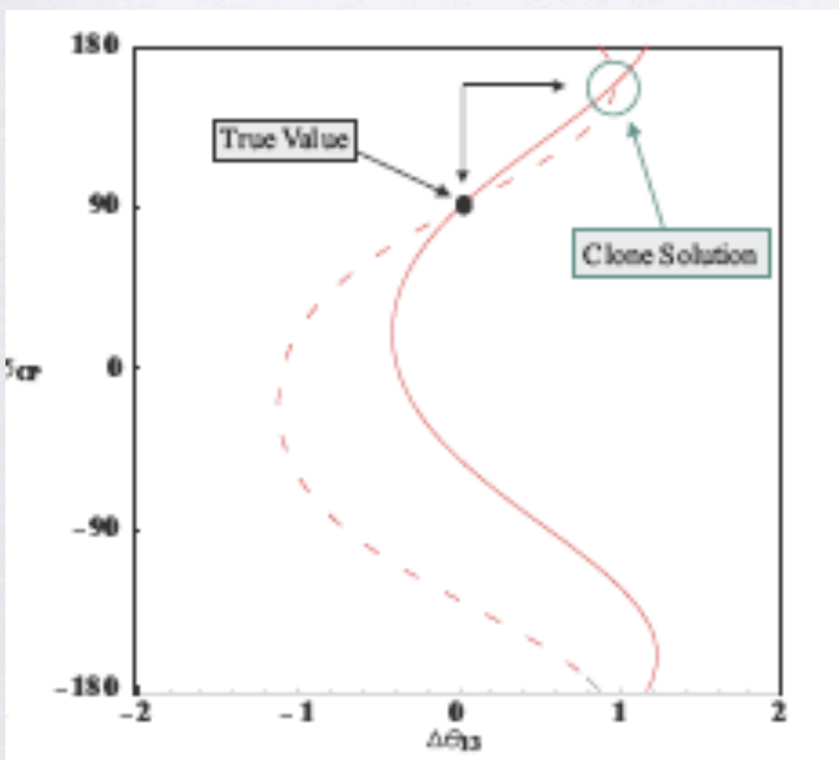
$$P_{\alpha\beta}(\bar{\theta}_{13},\bar{\delta}) = P_{\alpha\beta}(\theta_{13},\delta)$$

Has a continuum of solutions (the equiprobability curve).

J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez, and O. Mena, "On the measurement of leptonic CP violation," *Nucl. Phys.* **B608** (2001) 301–318,

Measurement of $\sin^2\theta_{13}$:Intrinsic degeneracy

$$P^{\pm}_{\nu_e\nu_\mu}(\theta_{13},\delta) \approx X_{\pm}\,\sin^2 2\theta_{13} + \left(Y^c_{\pm}\cos\delta \mp Y^s_{\pm}\sin\delta\right)\sin 2\theta_{13} + Z$$

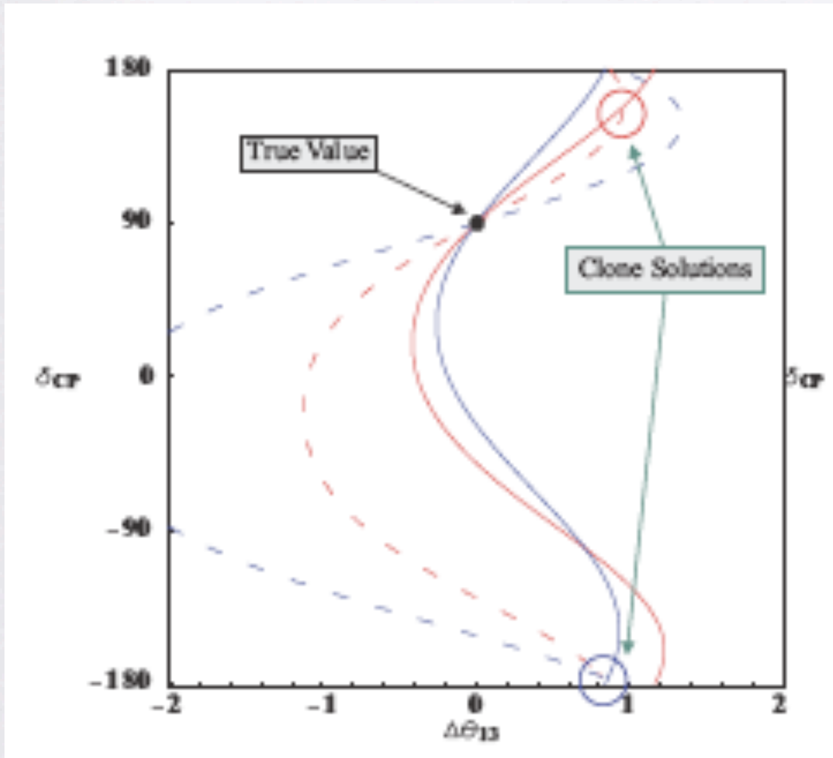


For neutrinos and antineutrinos at fixed E,L, the equation

$$P_{\alpha\beta}^{\pm}(\bar{\theta}_{13},\bar{\delta}) = P_{\alpha\beta}^{\pm}(\theta_{13},\delta)$$

has two intersections. The true solution and a clone of “ghost” ENERGY DEPENDENT solution

Solving Intrinsic degeneracy: Recipe 1



Neutrino beams are not monochromatic
Spectral analysis in detectors with good energy resolution allows to combine several “monochromatic” energies, each one with the clone in a different place

Use of two different baselines changes E/L by a very significant factor, separating dramatically the clones

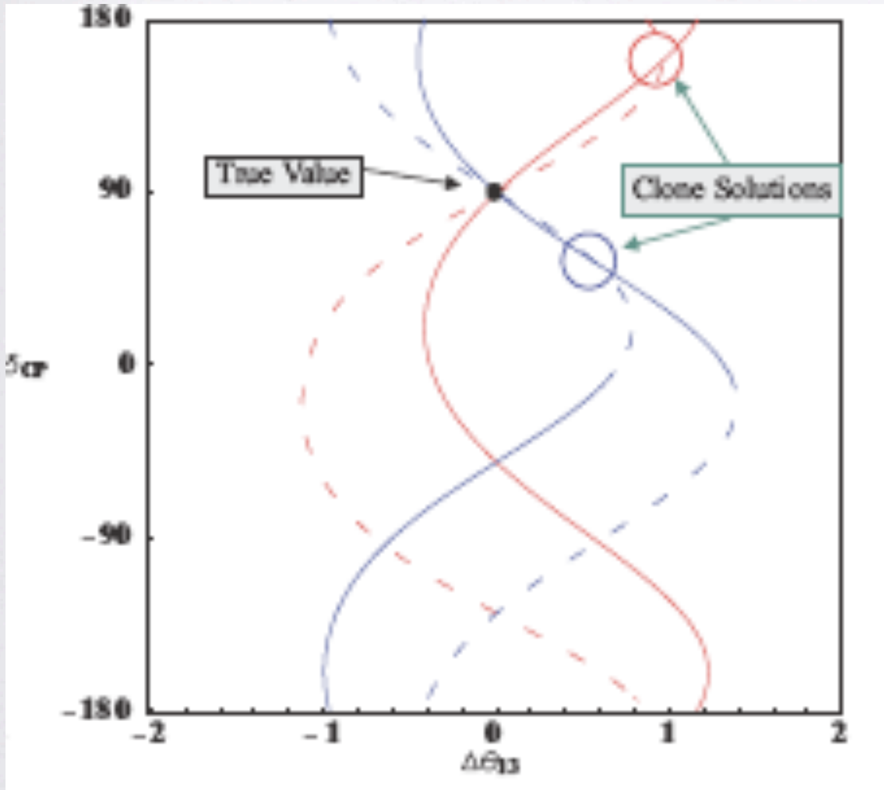
J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez, and O. Mena, “On the measurement of leptonic CP violation,” *Nucl. Phys.* **B608** (2001) 301–318,

P. Huber, M. Lindner, M. Rolinec, and W. Winter, “Optimization of a neutrino factory oscillation experiment,” hep-ph/0606119.

A. Donini and E. Fernandez-Martinez, “Alternating ions in a beta-beam to solve degeneracies,” *Phys. Lett.* **B641** (2006) 432–439, hep-ph/0603261.

A. Rubbia, “Neutrino factories: Detector concepts for studies of CP and T violation effects in neutrino oscillations,” hep-ph/0106088.

Solving Intrinsic degeneracy: Recipe 2



A. Donini, D. Meloni, and S. Rigolin, "Clone flow analysis for a theory inspired neutrino experiment planning," *JHEP* **06** (2004) 011, hep-ph/0312072.

Include other oscillation channels such as the "silver" channel

The Silver Channel at the Neutrino Factory

$$\mu^+ \rightarrow \begin{cases} e^+ \\ \bar{\nu}_\mu \\ \boxed{\nu_e \rightarrow \nu_\tau \rightarrow \tau^- \rightarrow \mu^-} \end{cases}$$

The oscillation probability is

$$\begin{aligned} P^{\pm}_{e\tau} = \; & X^{\tau}_{\pm} \sin^2(2\,\theta_{13}) \\ & - Y_{\pm} \cos\left(\delta \mp \frac{\Delta_{atm} L}{2}\right) \cos\theta_{13} \sin(2\,\theta_{13}) \\ & + Z^{\tau} + \ldots \end{aligned}$$

S. Rigolin, "Physics reach of beta-beams and nu-factories: The problem of degeneracies," *Nucl. Phys. Proc. Suppl.* **155** (2006) 33–37, hep-ph/0509366.

Discrete degeneracies

Two other sources of degeneracy.

1. Ignorance of the sign of Δm_{23}^2
2. Ignorance of the octant of θ_{23}

$$s_{atm} = \mathrm{sgn}(\Delta m_{23}^2)$$

$$s_{oct} = \mathrm{sgn}(\tan(2\theta_{23}))$$

These two discrete values assume the value ± 1

H. Minakata and H. Nunokawa, "Exploring neutrino mixing with low energy superbeams," *JHEP* **10** (2001) 001, `hep-ph/0108085`.

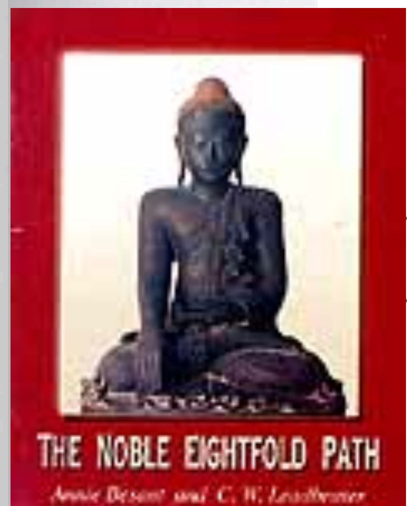
H. Minakata, H. Nunokawa, and S. J. Parke, "CP and T trajectory diagrams for a unified graphical representation of neutrino oscillations," *Phys. Lett.* **B537** (2002) 249–255, `hep-ph/0204171`.

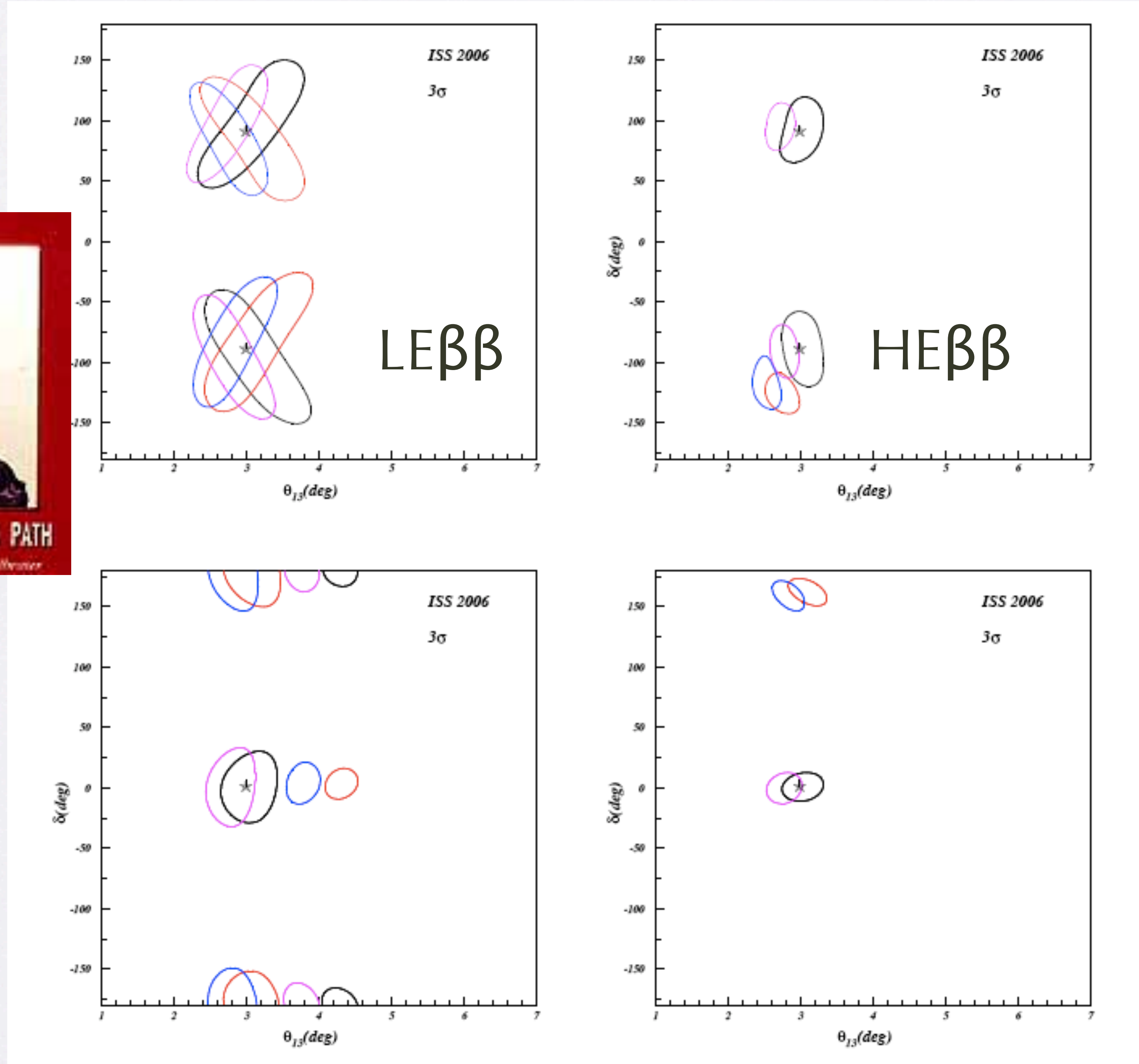
H. Minakata, H. Nunokawa, and S. J. Parke, "Parameter degeneracies in neutrino oscillation measurement of leptonic CP and T violation," *Phys. Rev.* **D66** (2002) 093012, `hep-ph/0208163`.

[211] G. L. Fogli and E. Lisi, "Tests of three-flavor mixing in long-baseline neutrino oscillation experiments," *Phys. Rev.* **D54** (1996) 3667–3670, `hep-ph/9604415`.

[212] V. Barger, D. Marfatia, and K. Whisnant, "Breaking eight-fold degeneracies in neutrino CP violation, mixing, and mass hierarchy," *Phys. Rev.* **D65** (2002) 073023, `hep-ph/0112119`.

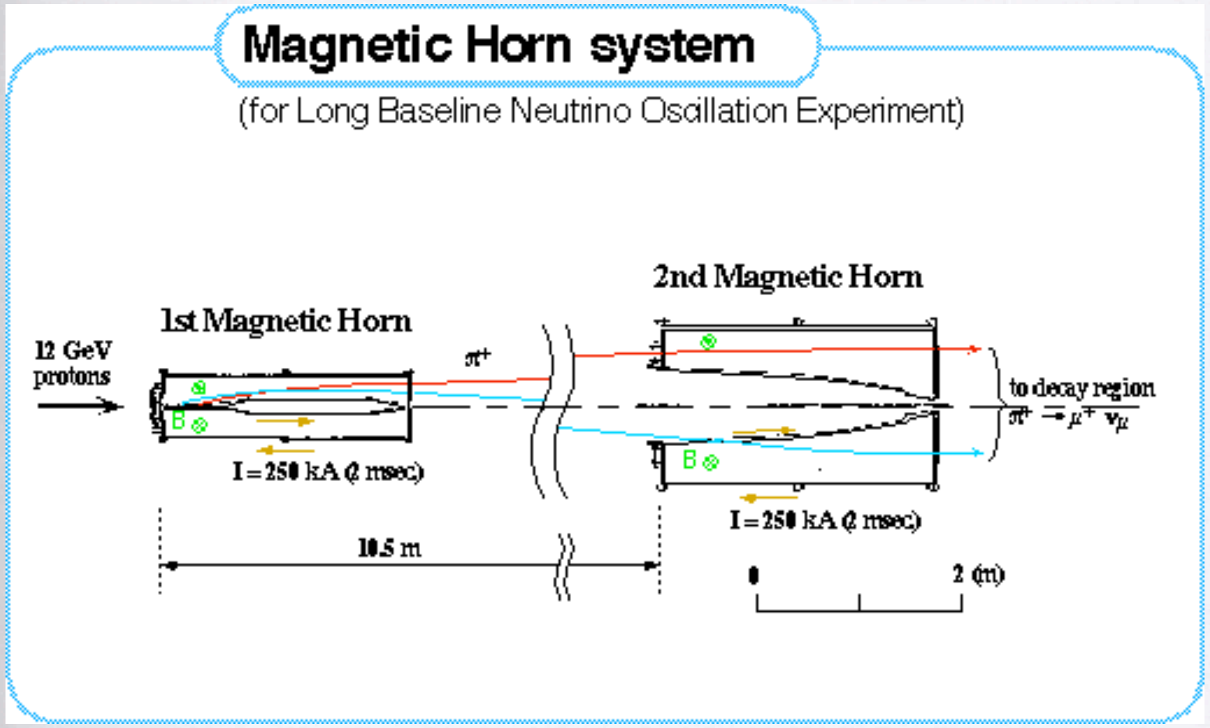
[213] E. K. Akhmedov, R. Johansson, M. Lindner, T. Ohlsson, and T. Schwetz, "Series expansions for three-flavor neutrino oscillation probabilities in matter," *JHEP* **04** (2004) 078, `hep-ph/0402175`.

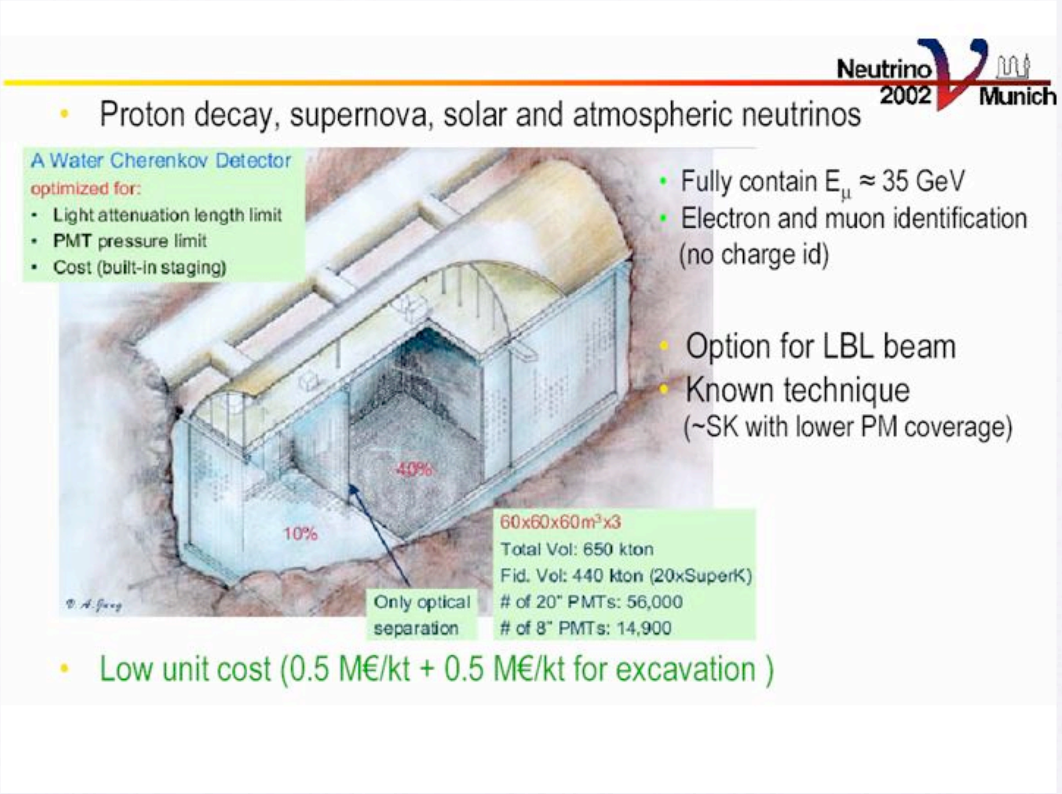


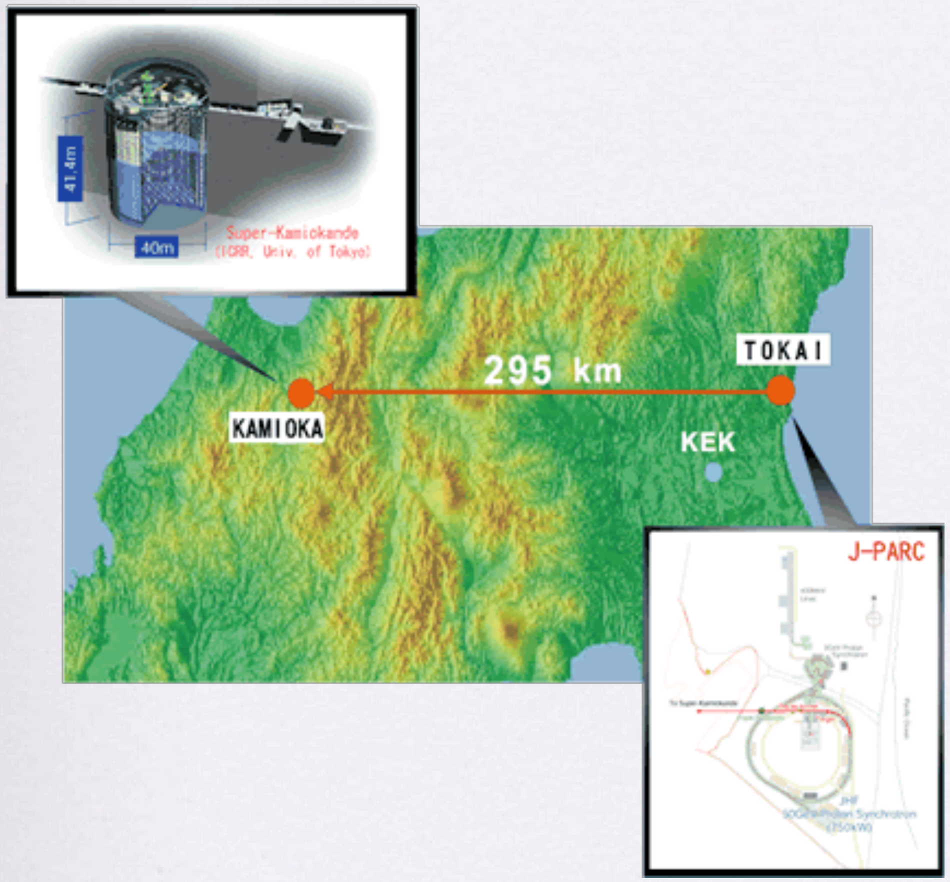


Three degeneracies (intrinsic, sign, octant) for $2^3 = 8$ combinations

Super Beams







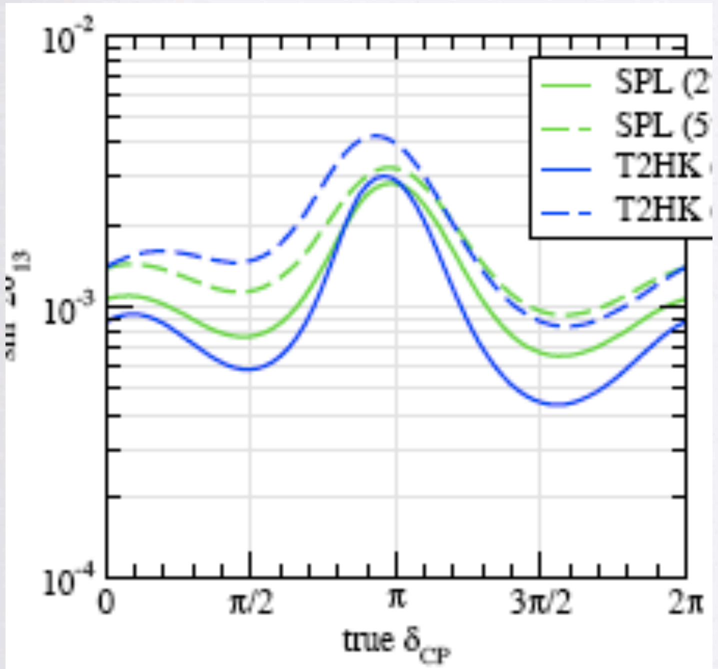
High power (1-4 MW)

Large detector

Narrow band beam

Energy near 1 GeV (QE range)

$$\sin^2 2\theta_{13} \rightarrow 4\times10^{-3}$$



J. E. Campagne, M. Maltoni, M. Mezzetto, and T. Schwetz, "Physics potential of the CERN-MEMPHYS neutrino oscillation project," hep-ph/0603172.

Better for δ near $\pi/2$, but strongly affected by

correlations and systematic errors

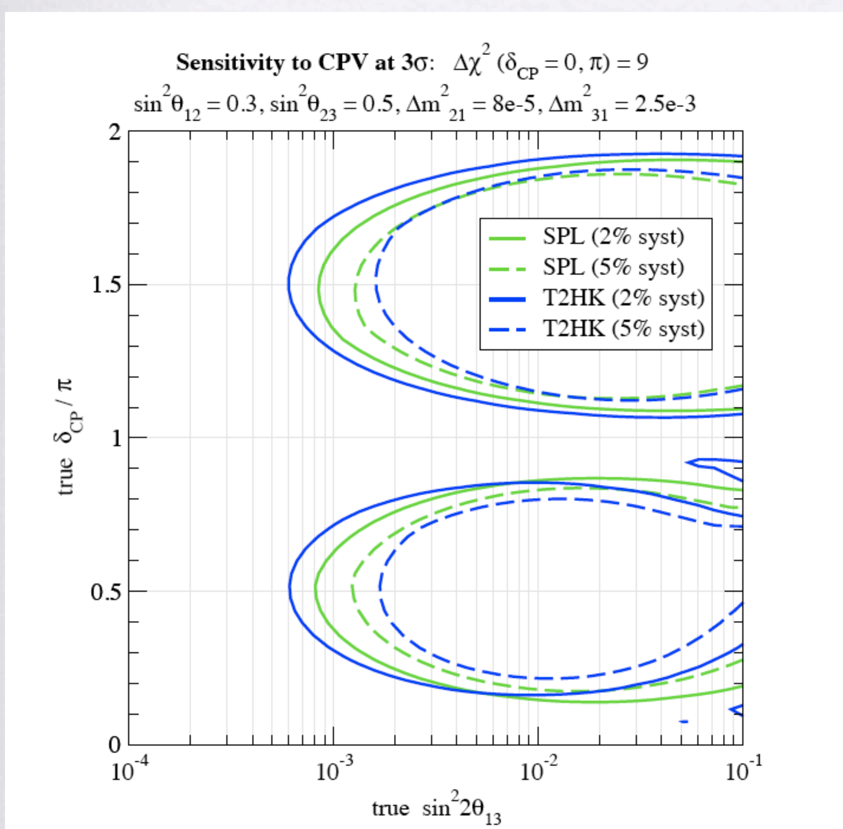
Understanding background systematics to the level of 2% is very challenging

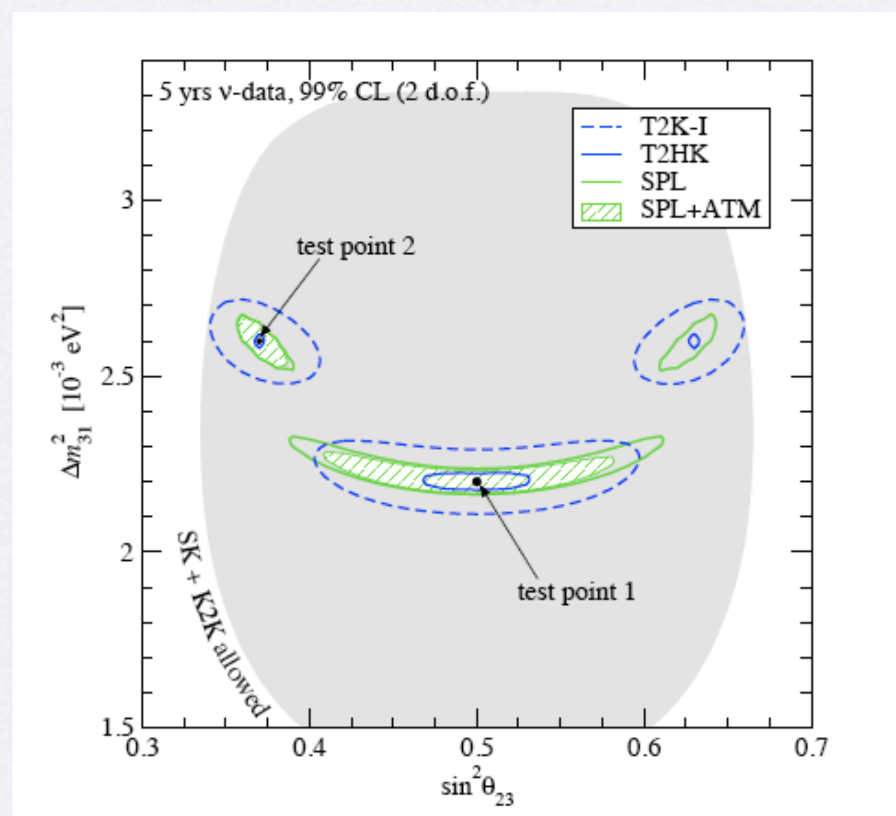
Excellent measurement of atmospheric parameters

Little sensitivity to mass effects

	True values	T2K	SPL	T2HK
Δm^2_{31}	$2.2\cdot10^{-3}$ eV^2	4.7%	3.9%	1.1%
$\sin^2\theta_{23}$	0.5	20%	22%	6%
Δm^2_{31}	$2.6\cdot10^{-3}$ eV^2	4.4%	3.0%	0.7%
$\sin^2\theta_{23}$	0.37	8.9%	4.7%	0.8%

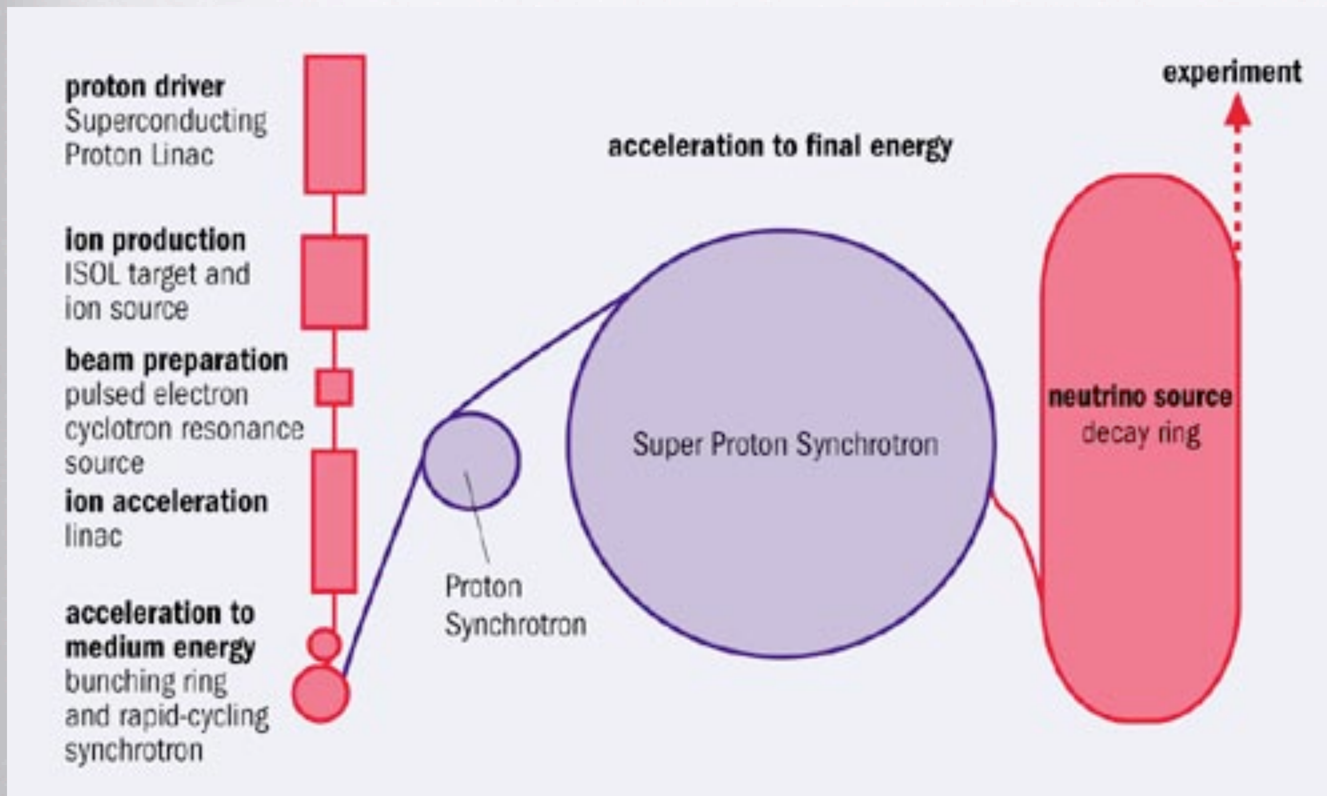
$$\max CPV \rightarrow 6-8\times10^{-3}$$

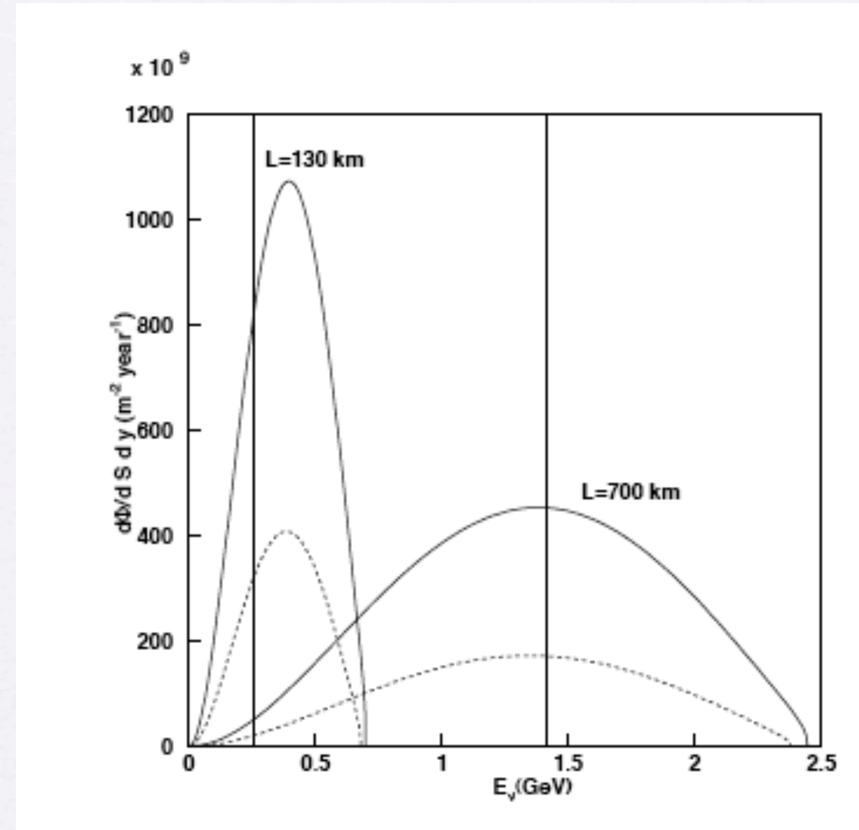


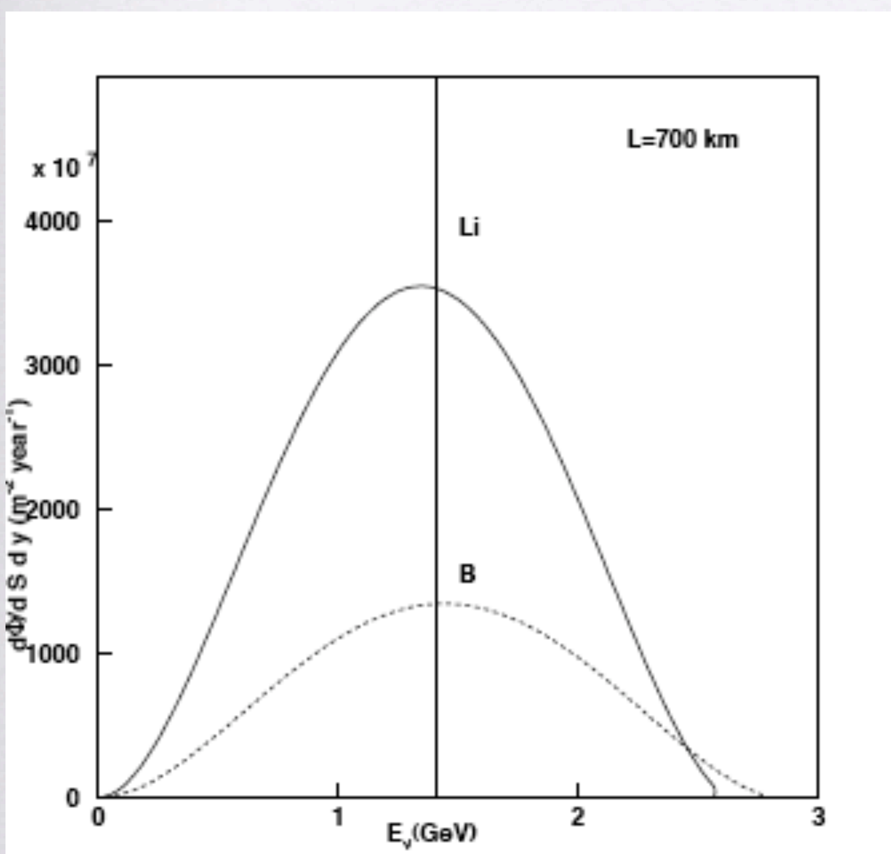


Beta Beam

P. Zucchelli, "A novel concept for a anti-nu/e / nu/e neutrino factory: The beta beam," *Phys. Lett.* **B532** (2002) 166–172.





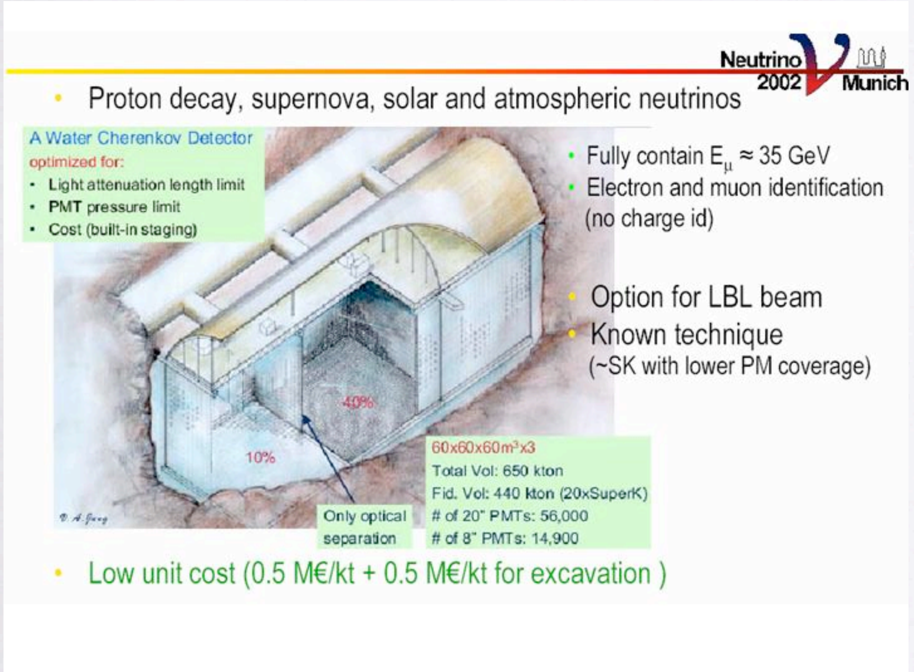


Ion	γ	$L(km)$	$\bar{\nu}_e$ CC	ν_e CC	$\langle E_\nu \rangle (GeV)$
He/Ne	100	130	28.9	32.8	0.39/0.37
He/Ne	350	700	62.0	55.	1.35/1.3
Li/B	100	700	5.0	4.9	1.3/1.4

M. Mezzetto, "Physics reach of the beta beam," *J. Phys.* **G29** (2003) 1771–1776, hep-ex/0302007.

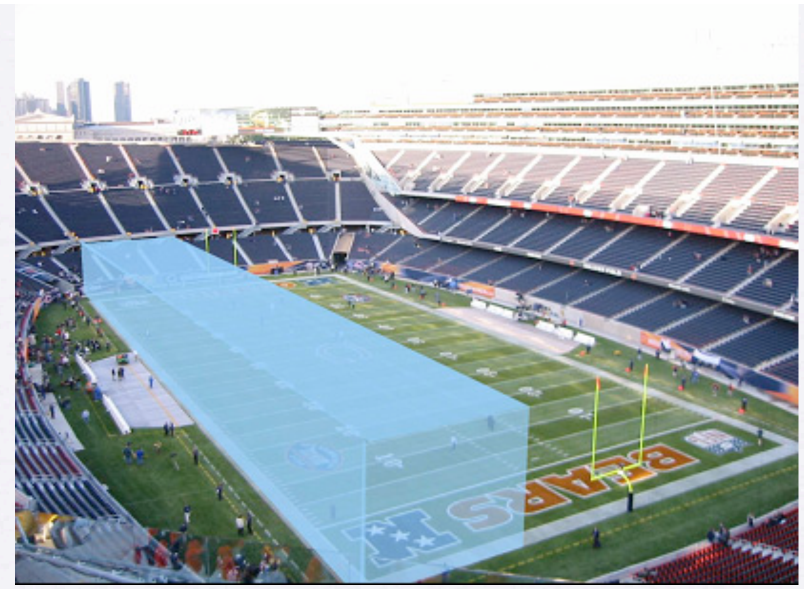
J. Burguet-Castell, D. Casper, J. J. Gomez-Cadenas, P. Hernandez, and F. Sanchez, "Neutrino oscillation physics with a higher gamma beta- beam," *Nucl. Phys.* **B695** (2004) 217–240, hep-ph/0312068.

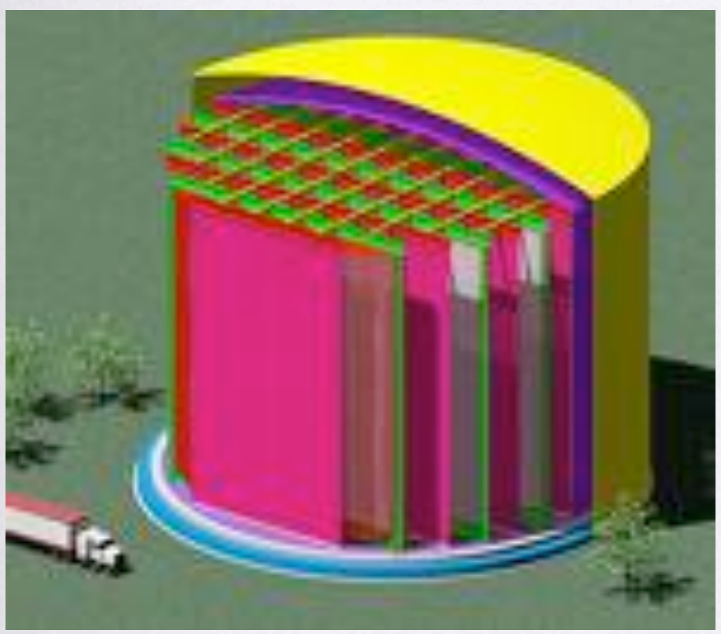
[712] C. Rubbia, "Ionization cooled ultra pure beta-beams for long distance nu/e → nu/mu transitions, theta(13) phase and CP- violation," hep-ph/0609235.



J. Burguet-Castell, D. Casper, J. J. Gomez-Cadenas, P. Hernandez, and F. Sanchez, "Neutrino oscillation physics with a higher gamma beta- beam," *Nucl. Phys.* **B695** (2004) 217–240, `hep-ph/0312068`.

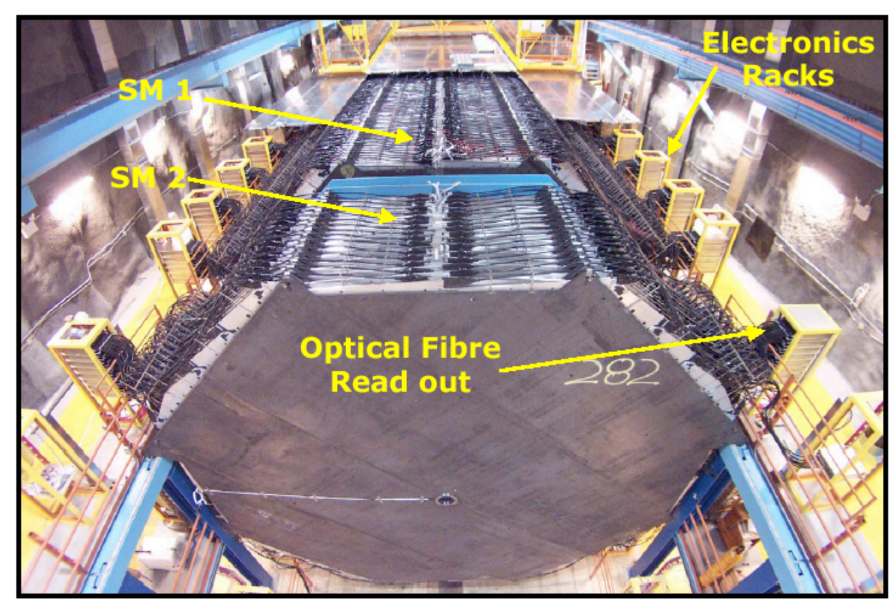
M. Mezzetto, "Physics reach of the beta beam," *J. Phys.* **G29** (2003) 1771–1776, `hep-ex/0302007`.



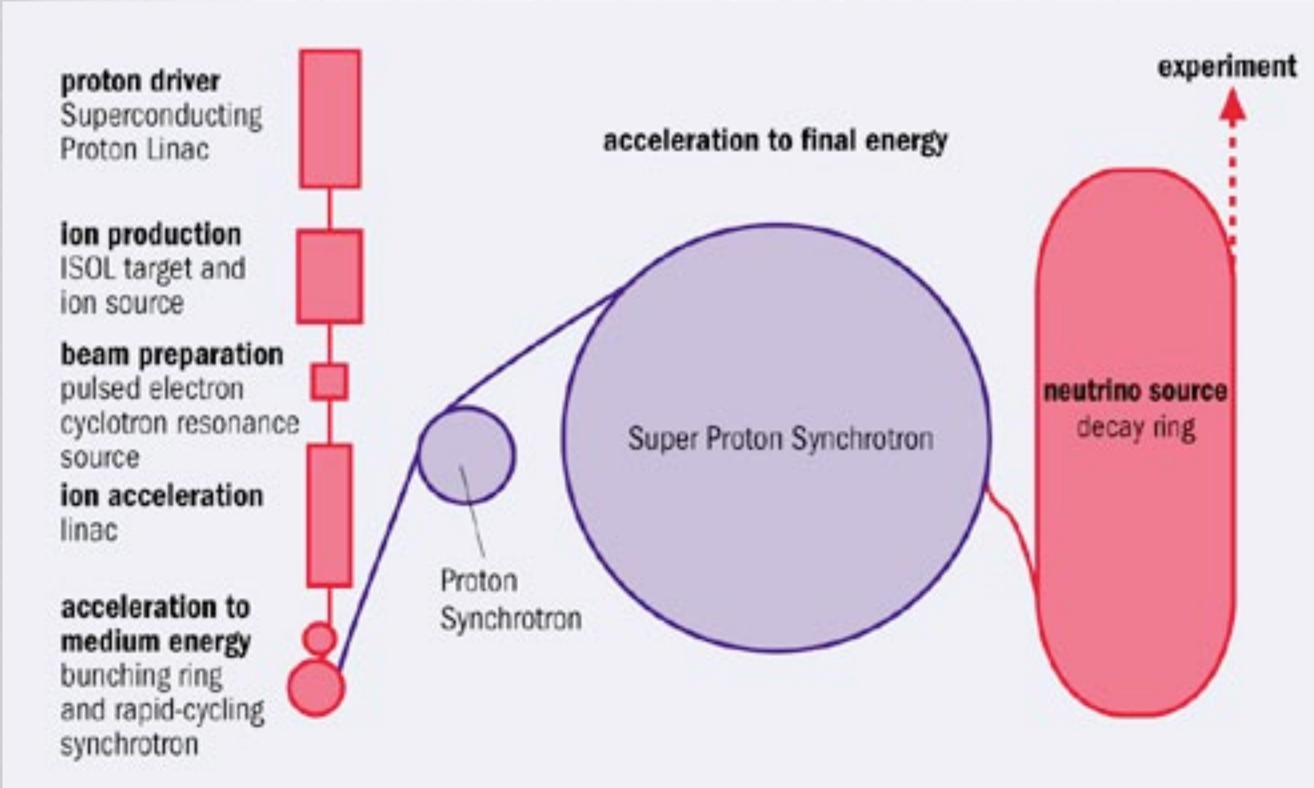


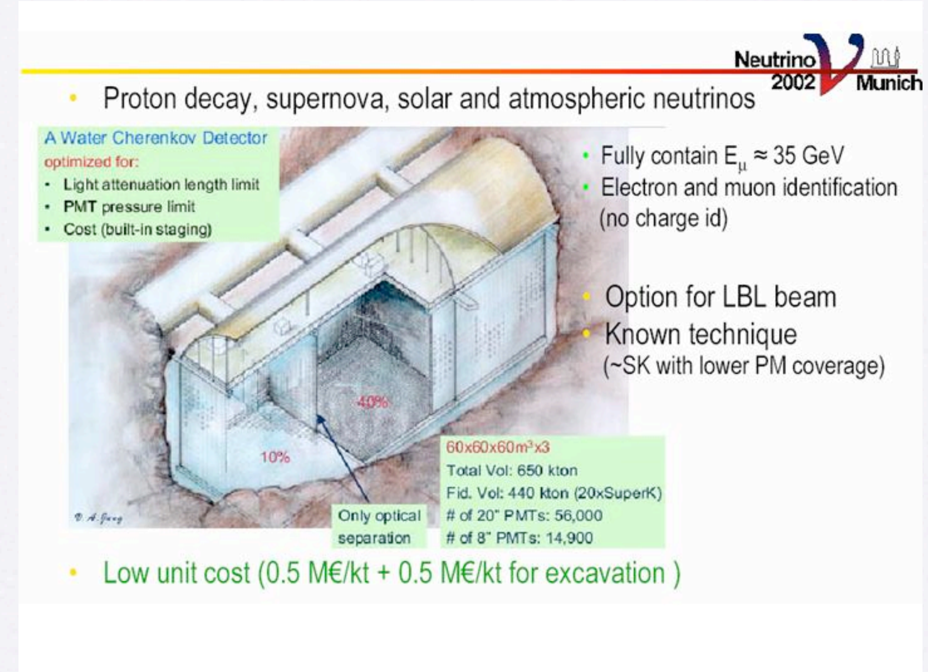
P. Huber, M. Lindner, M. Rolinec, and W. Winter, "Physics and optimization of beta-beams: From low to very high gamma," *Phys. Rev.* **D73** (2006) 053002, `hep-ph/0506237`.

C. Rubbia, "Ionization cooled ultra pure beta-beams for long distance nu/e → nu/mu transitions, theta(13) phase and CP- violation," `hep-ph/0609235`.

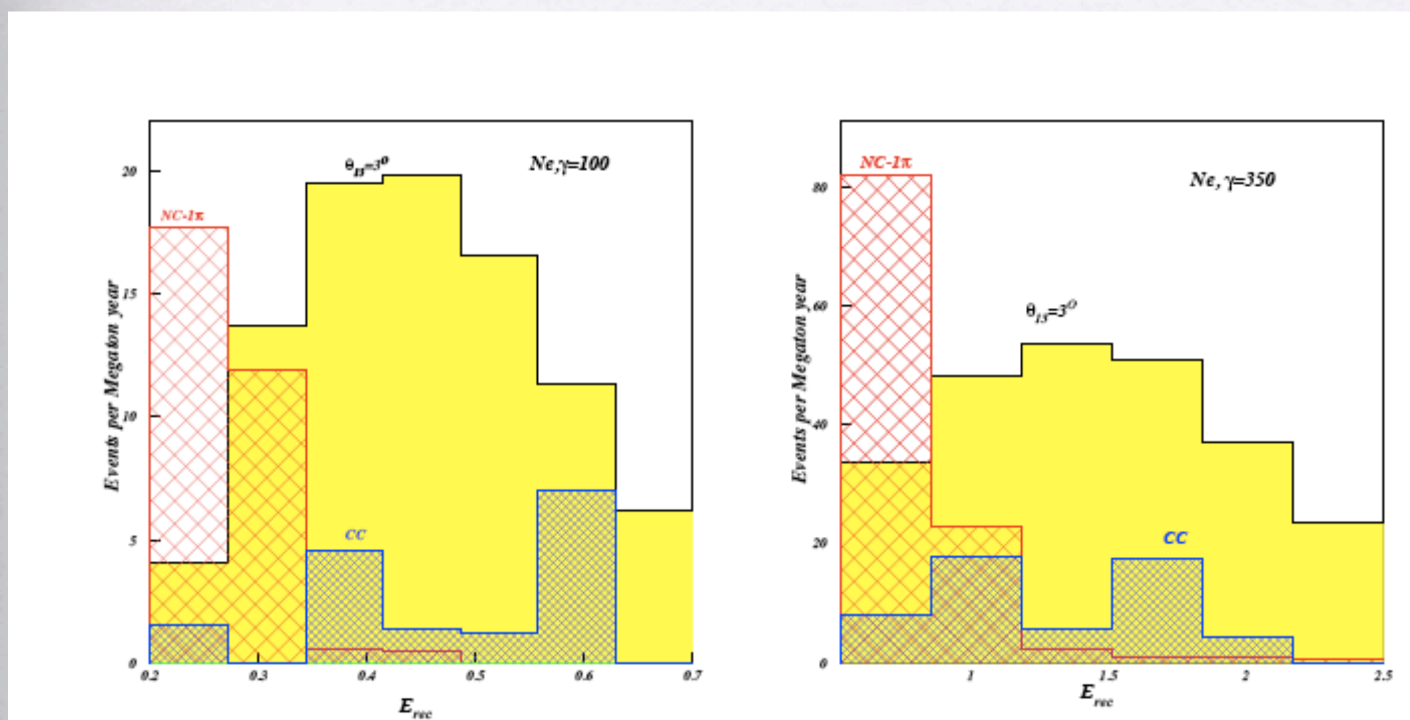


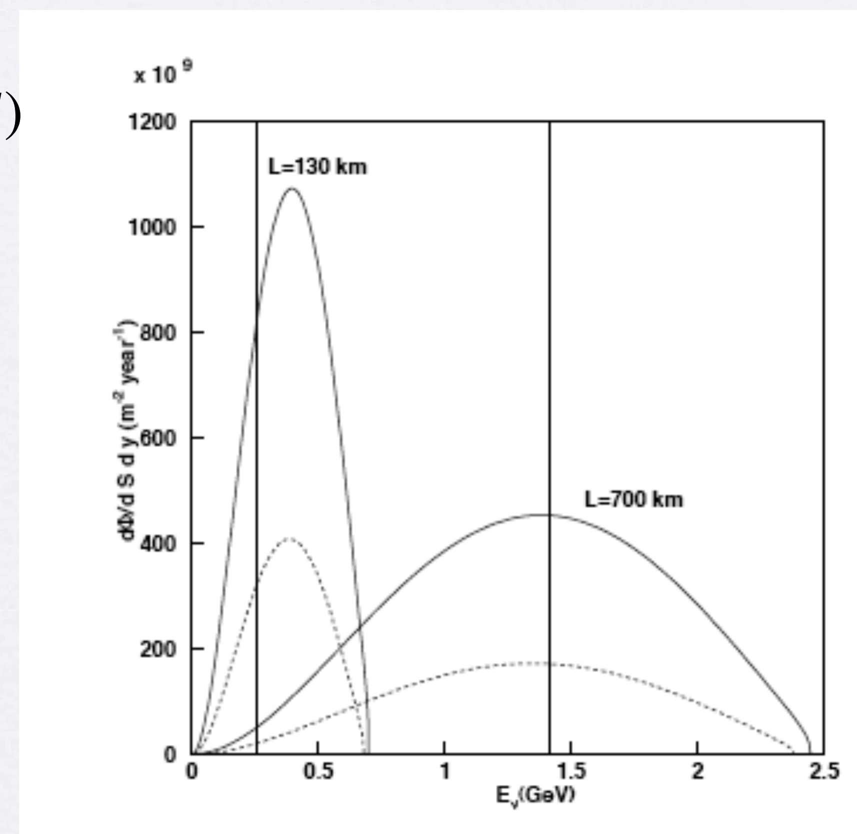
A. Donini *et al.*, "A beta beam complex based on the machine upgrades of the LHC," *Eur. Phys. J.* **C48** (2006) 787–796, `hep-ph/0604229`.



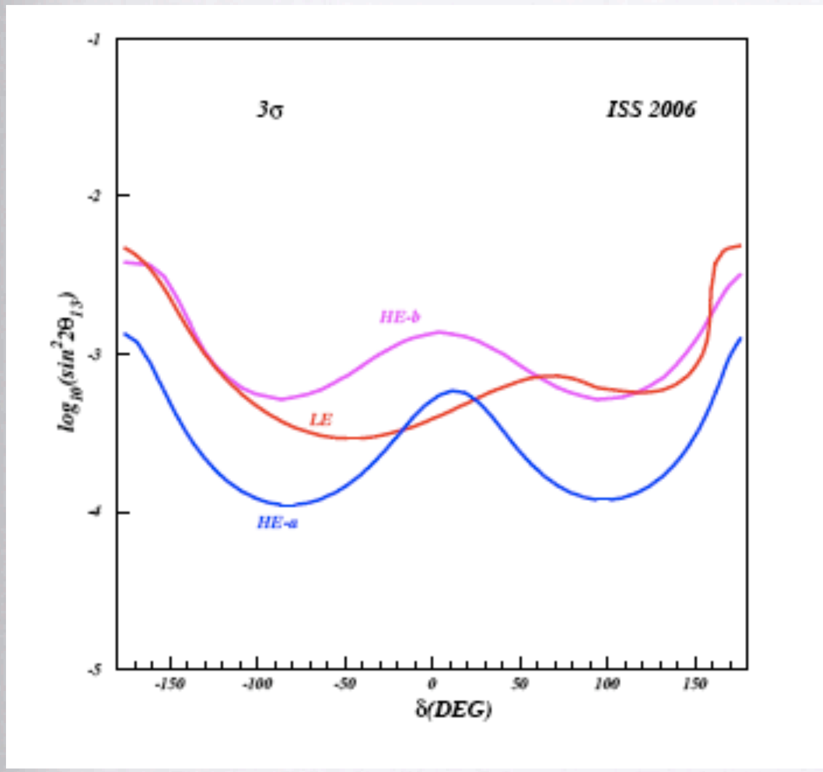


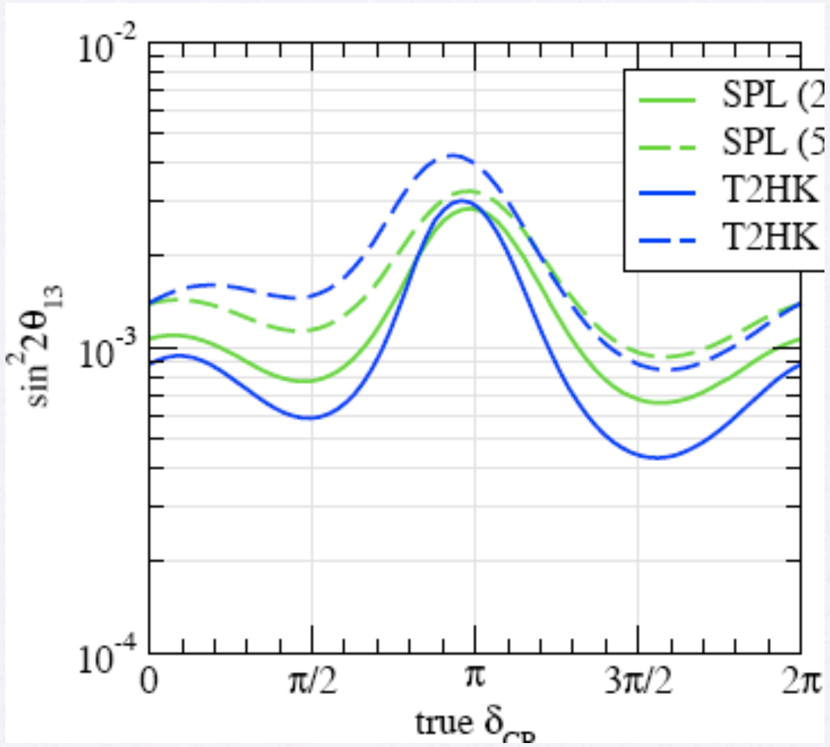
$$\nu_e \to \nu_\mu \to \mu(CC,QE)$$

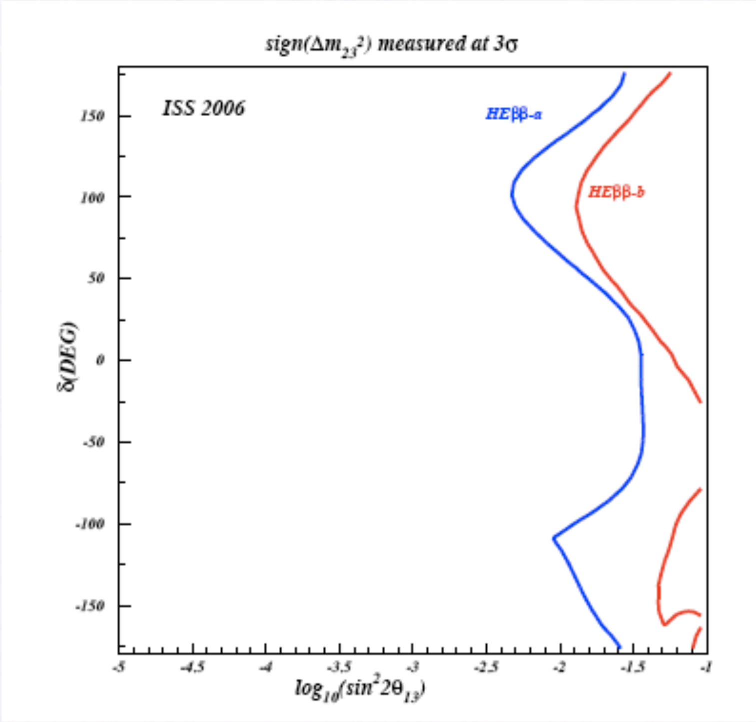


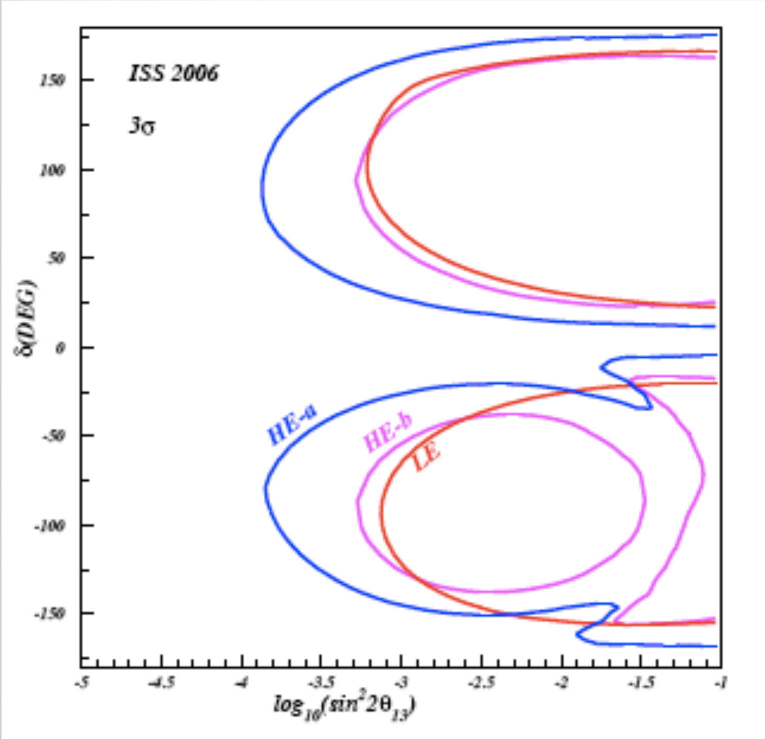


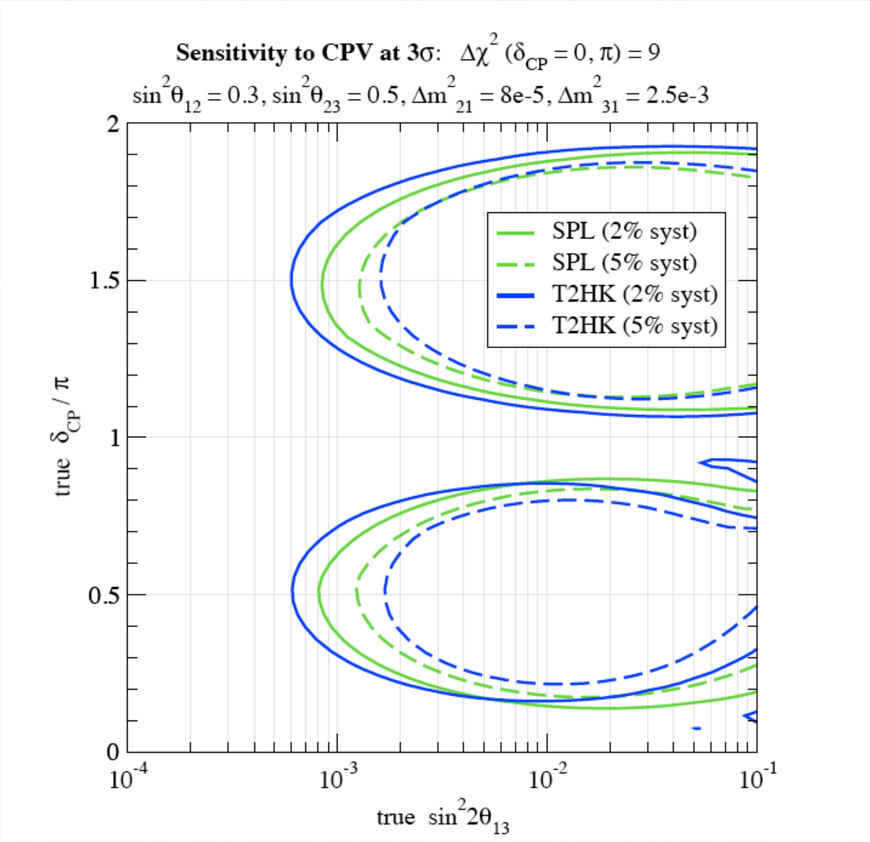
$$\nu_e(NC) \to 1\pi(\Delta)$$









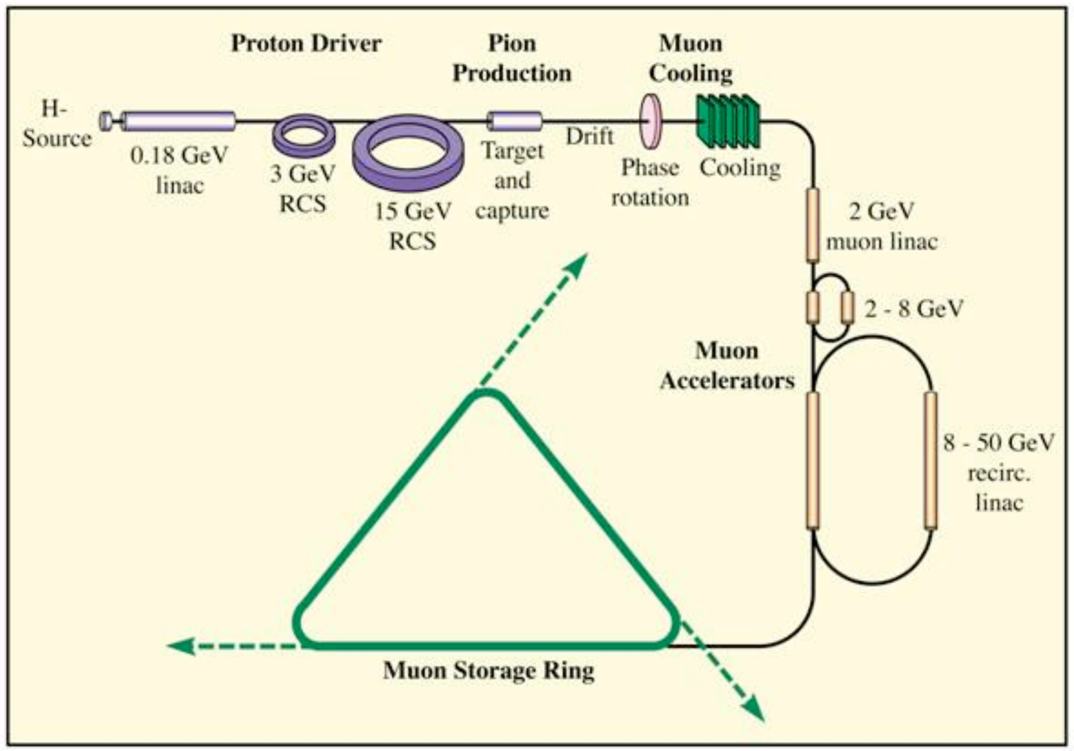


Outperforms super-beam both in reach for θ13,δ and sensitivity to ME

Sensitivity to ME spoiled by sign(matter) ambiguity. This can be solved by combining with atmospheric data

A HE- bbeam with a Mton class detector and using atmospherics has an excellent physics case

The neutrino factory



Neutrino Factory at RAL

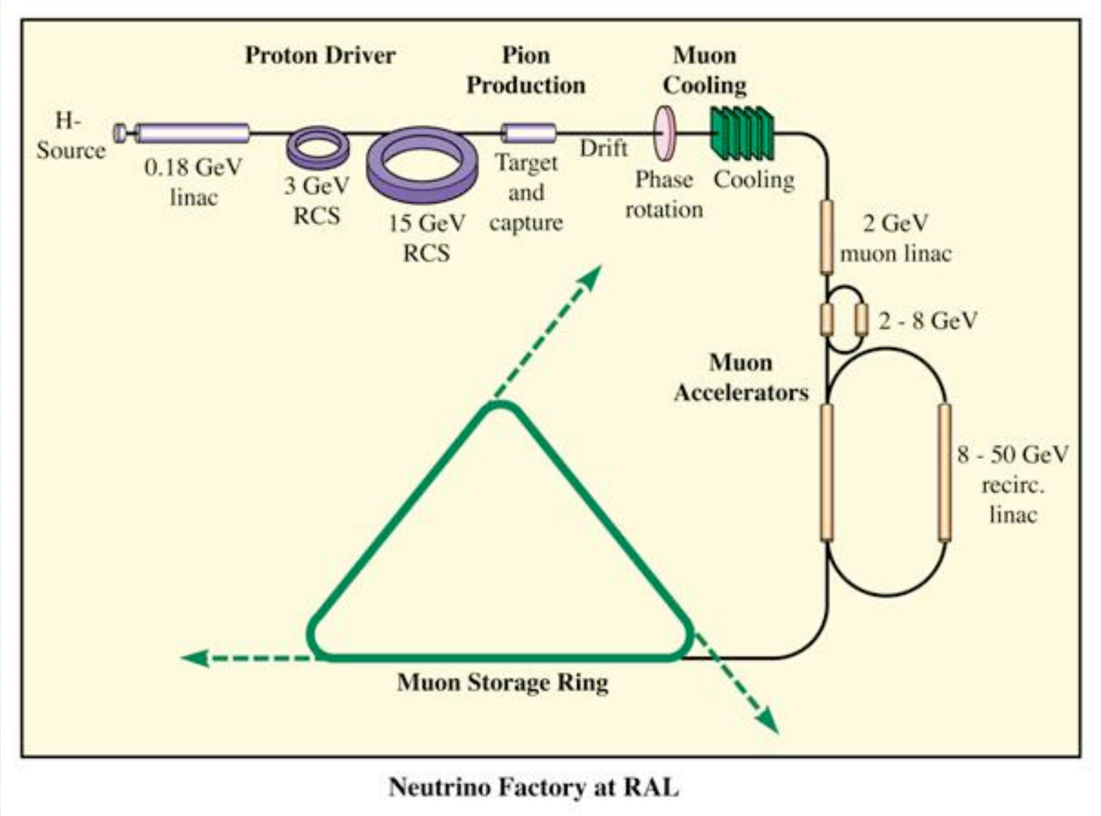
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

Table 13: Oscillation processes in a Neutrino Factory.

S. Geer, "Neutrino beams from muon storage rings: Characteristics and physics potential," *Phys. Rev.* **D57** (1998) 6989–6997, `hep-ph/9712290`.

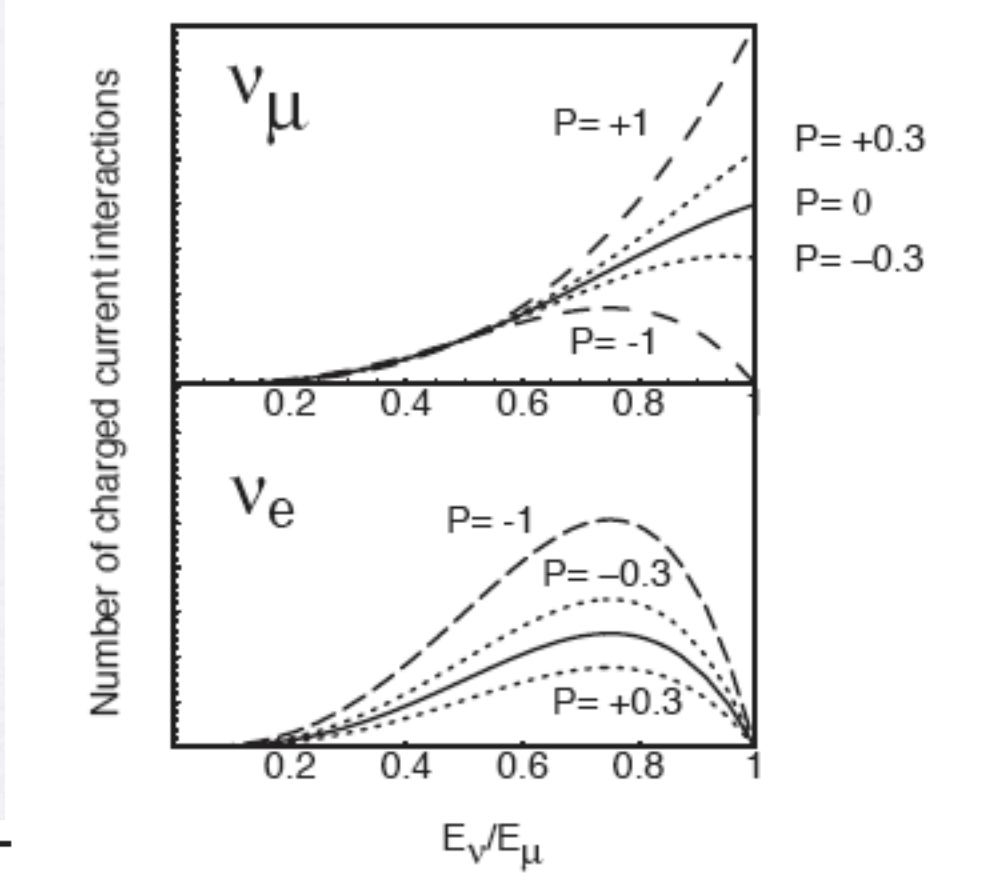
A. De Rujula, M. B. Gavela, and P. Hernandez, "Neutrino oscillation physics with a neutrino factory," *Nucl. Phys.* **B547** (1999) 21–38, `hep-ph/9811390`.

The “standard” neutrino factory



Neutrino Factory at RAL

25-50 GeV stored energy muons



Baseline (km)	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_\mu + \nu_e$ NC	ν_μ(signal)
732	3.5×10^7	5.9×10^7	3.1×10^7	1.1×10^5
3500	1.2×10^6	2.4×10^6	1.2×10^6	1.0×10^5
7332	1.2×10^5	5.1×10^5	2.1×10^5	3.8×10^4

$\bar{\nu}_\mu + N \longrightarrow \boxed{\mu^+} + X$ CC

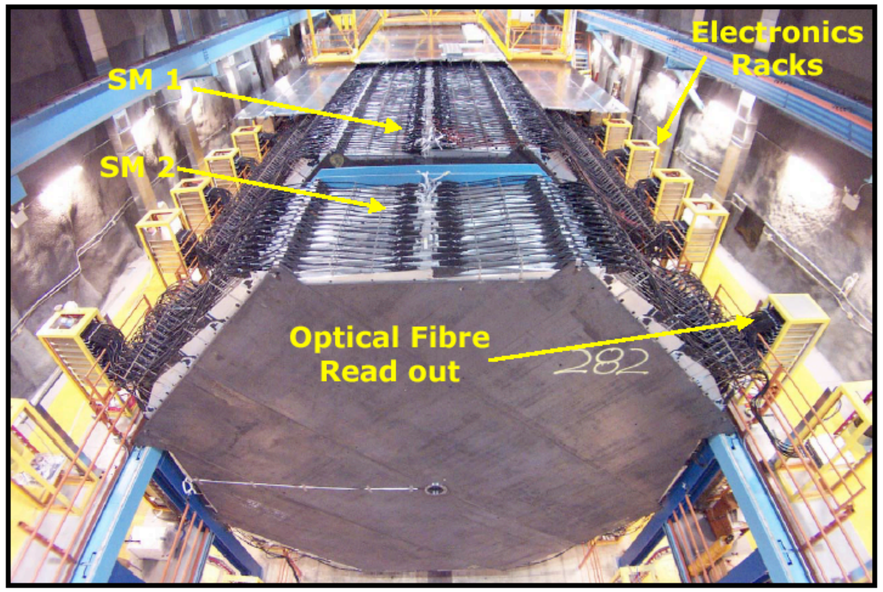
right sign muon

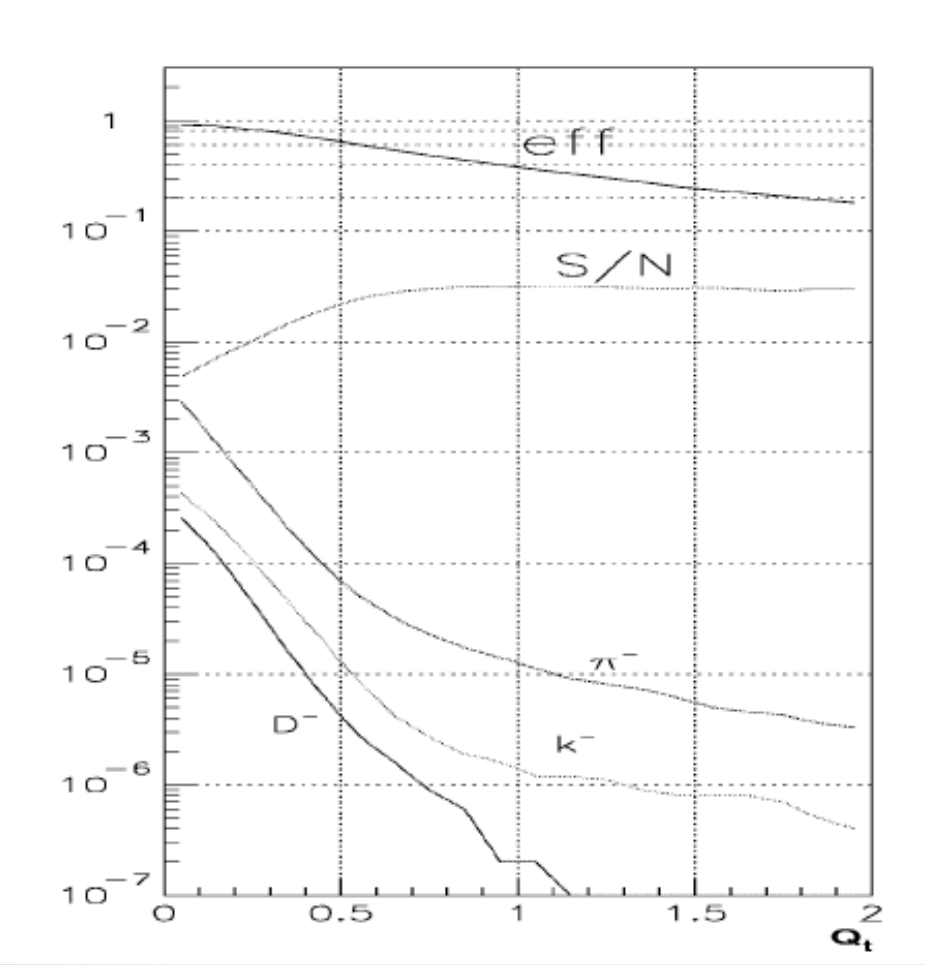
$\bar{\nu}_\mu + N \longrightarrow \bar{\nu}_\mu + X$ NC

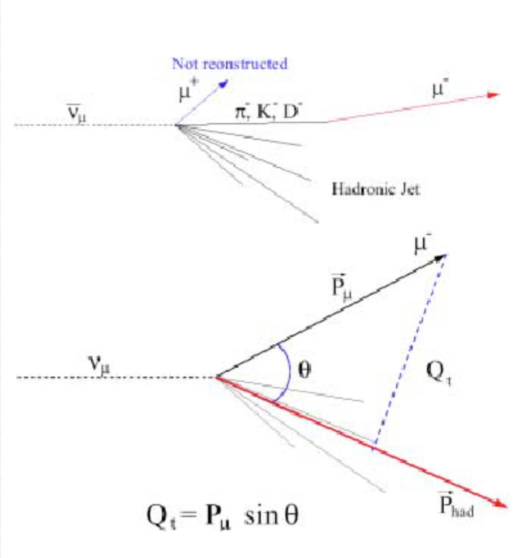
$\nu_e \overset{\text{osc}}{\sim} \nu_\mu$

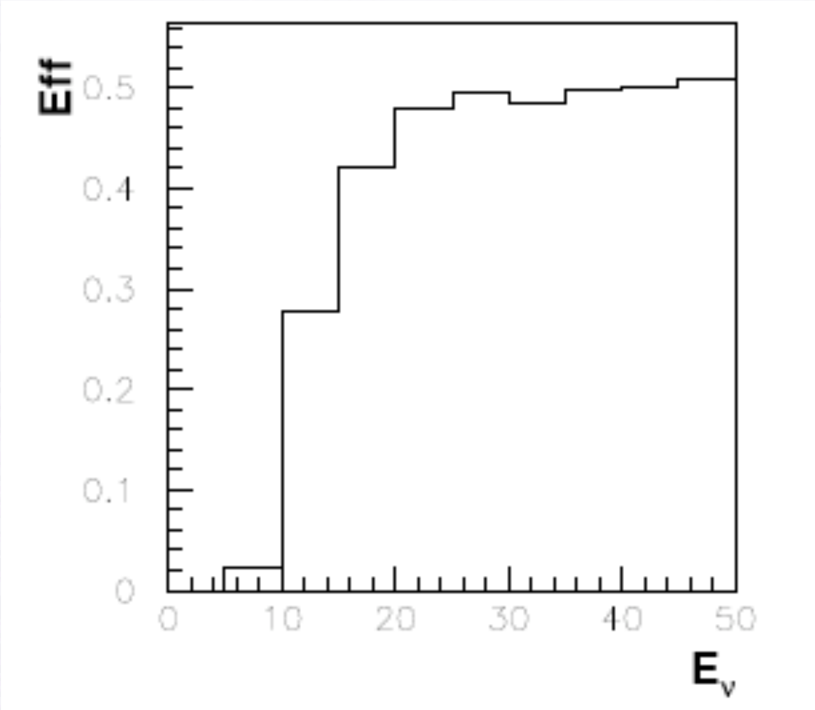
$\nu_\mu + N \longrightarrow \boxed{\mu^-} + X$ SIGNAL

wrong sign muon



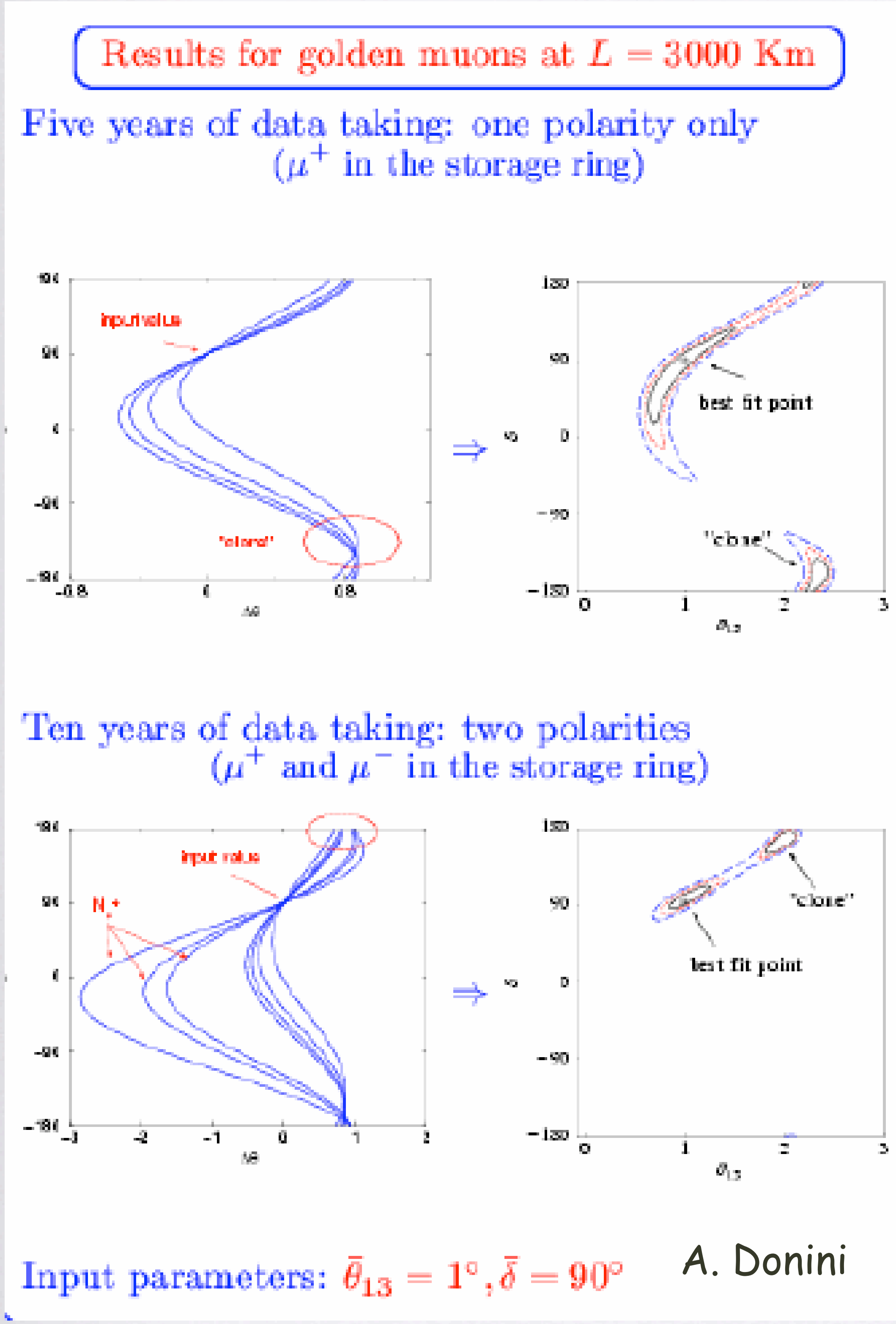






A. Cervera *et al.*, "Golden measurements at a neutrino factory," *Nucl. Phys.* **B579** (2000) 17–55, hep-ph/0002108.

Nufact and degeneracies



A. Donini

The Golden muon measurement is affected by degeneracies, given the high energy of the neutrino factory

This results in first oscillation peak to be at some 3000 km, were matter effects are already very strong

It was understood since the beginning that the optimal performance of the nufact required to break degeneracies

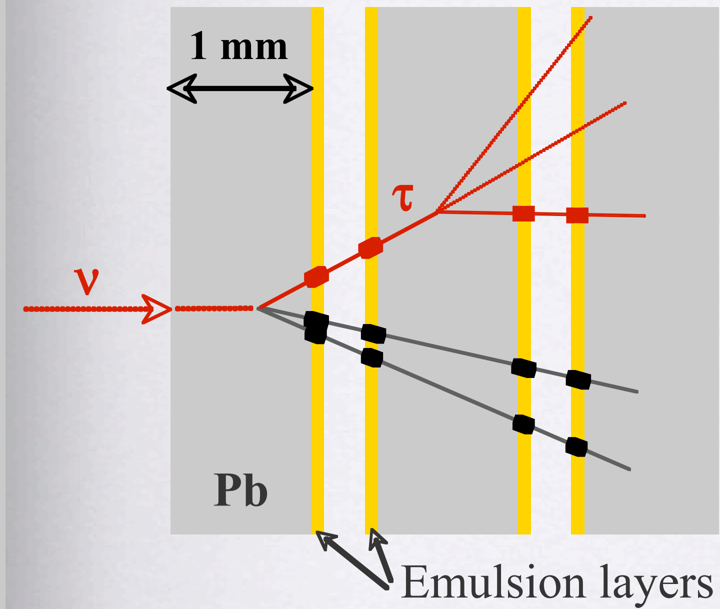
This requires:

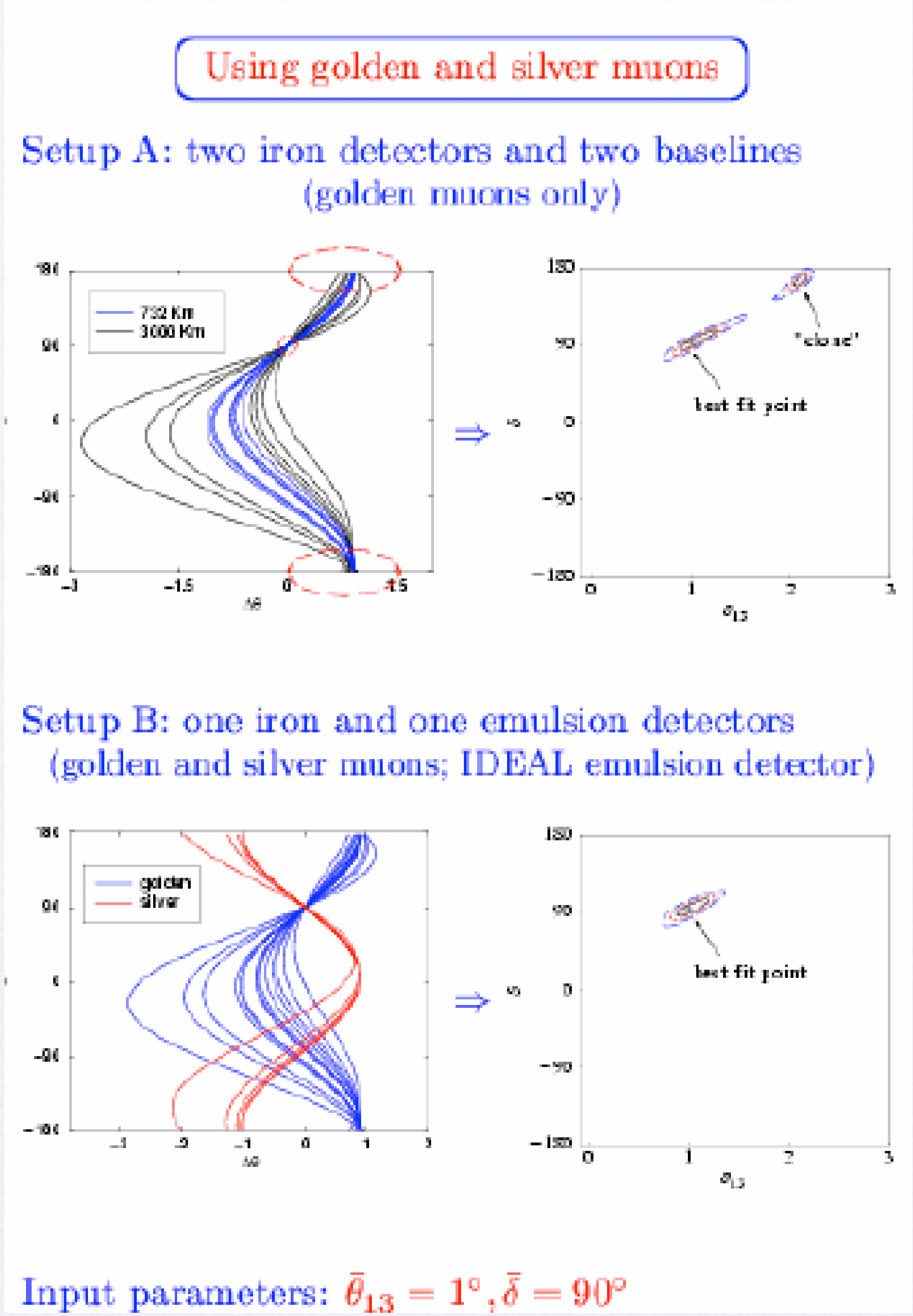
a) An improved detector

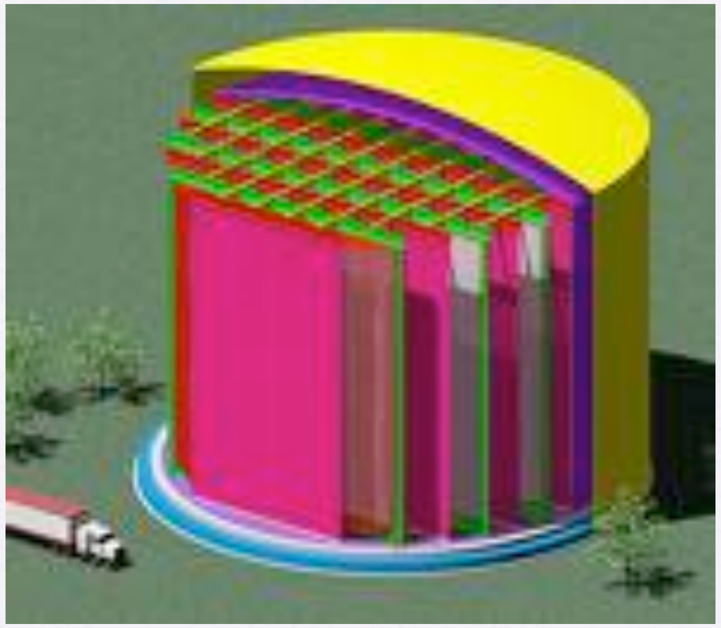
b) Two baselines

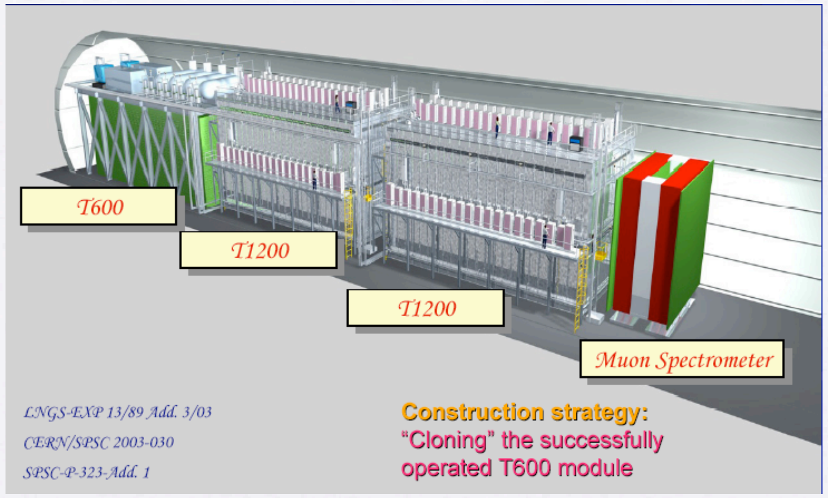
c) Combination with other channels

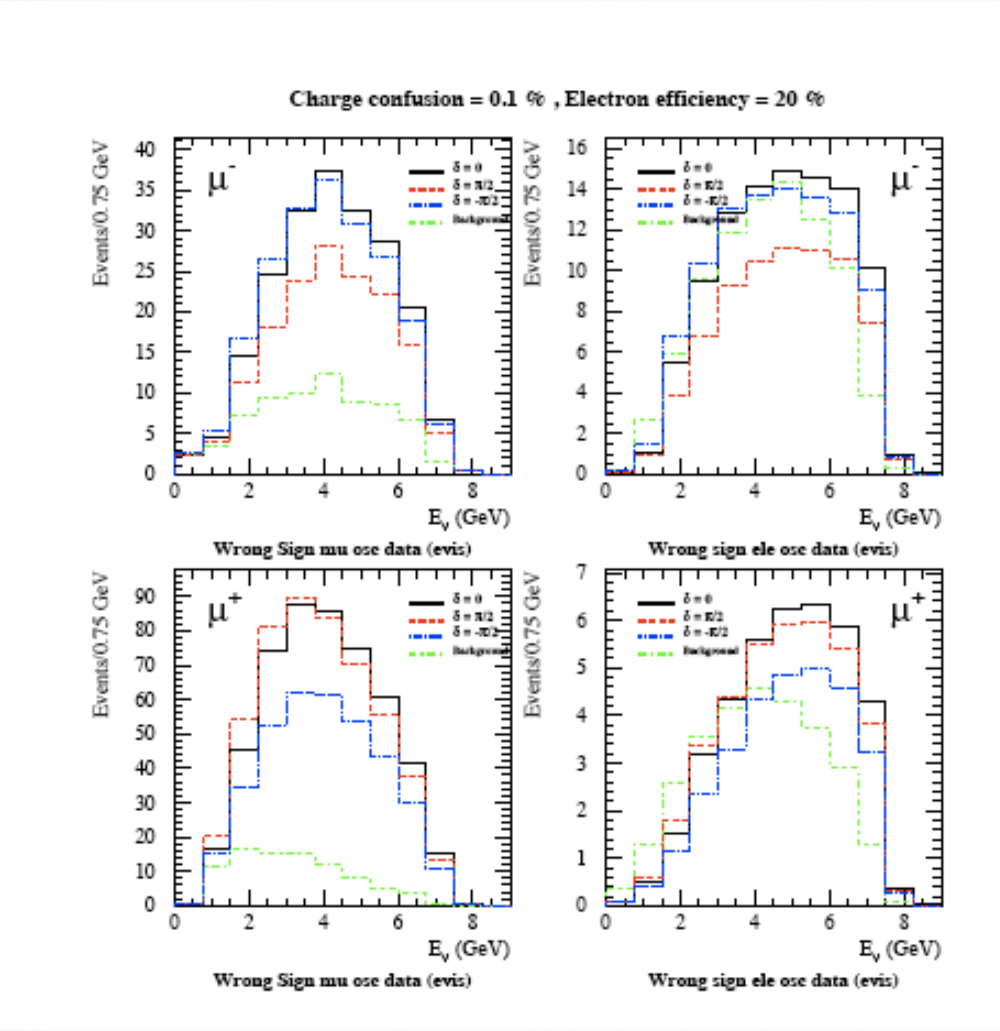
Silver channels

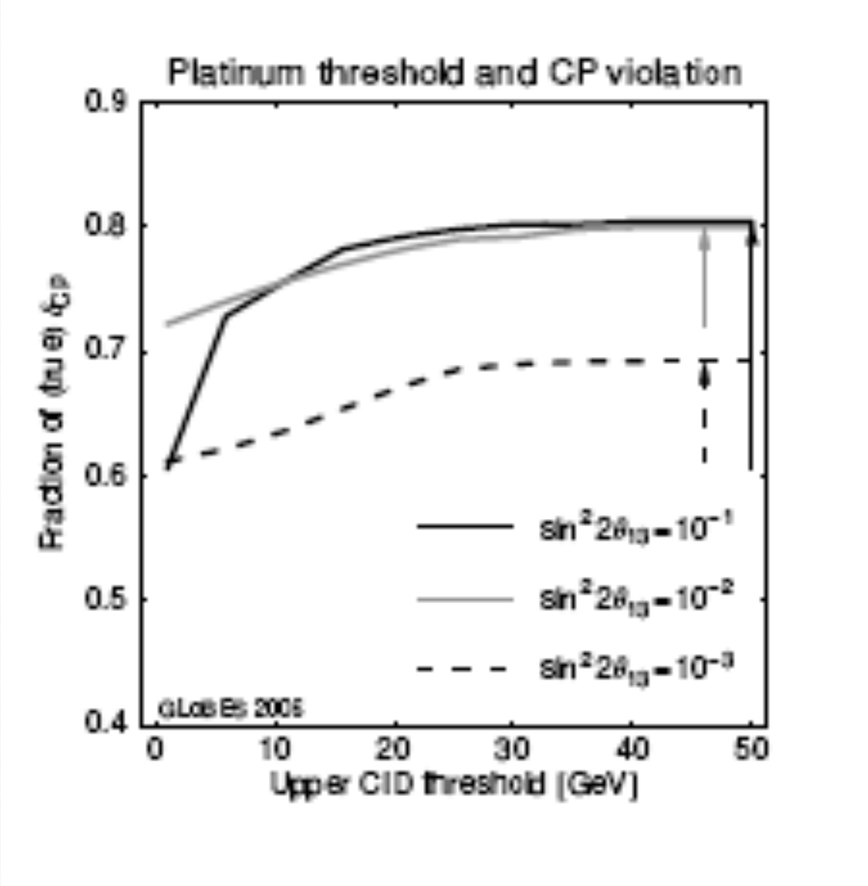







T600
T1200
T1200
Muon Spectrometer
LNGS-EXP 13/89 Add. 3/03
CERN/SPSC 2003-030
SPSC-P-323-Add. 1
Construction strategy:
"Cloning" the successfully
operated T600 module


Charge confusion = 0.1 % , Electron efficiency = 20 %
Events/0.75 GeV
E_ν (GeV)
Wrong Sign mu osc data (evis)
Wrong sign ele osc data (evis)
Wrong Sign mu osc data (evis)
Wrong sign ele osc data (evis)

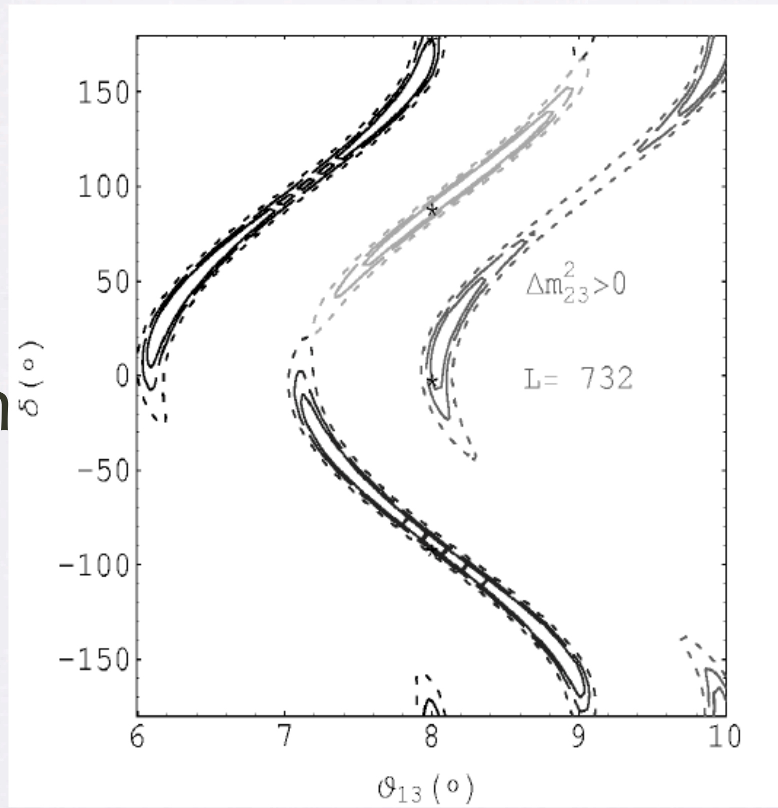

Platinum threshold and CP violation
Fraction of (μ, θ) f_{CP}
Upper CID threshold [GeV]
$\sin^2 2\theta_{13} = 10^{-1}$
$\sin^2 2\theta_{13} = 10^{-2}$
$\sin^2 2\theta_{13} = 10^{-3}$
GLoBES 2005

No magic baseline for nufact

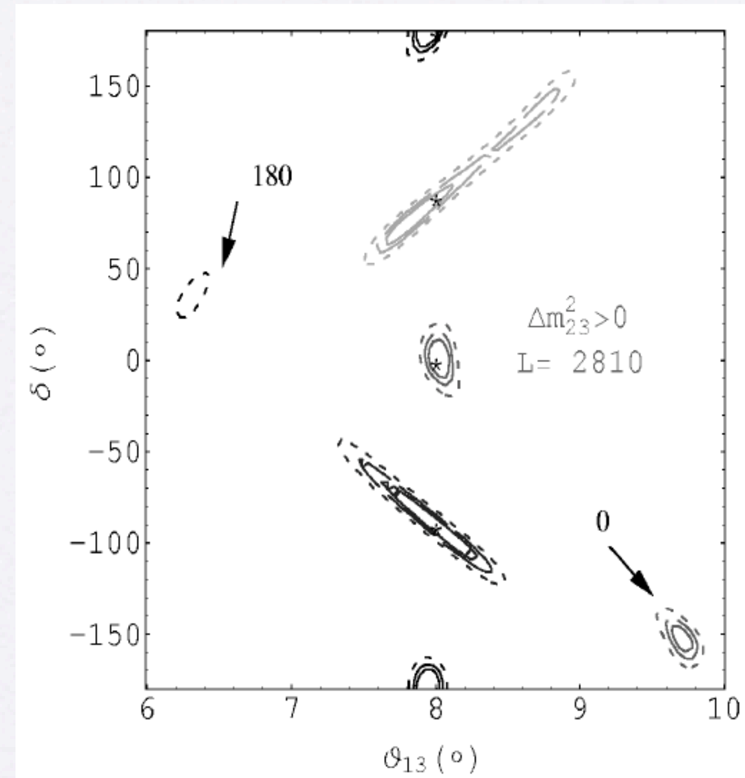
On the measurement of leptonic CP violation

J. Burguet Castell[a], M.B. Gavela[b,1], J.J. Gómez Cadenas[a,c2], P. Hernández[c,3] O. Mena[b,4]

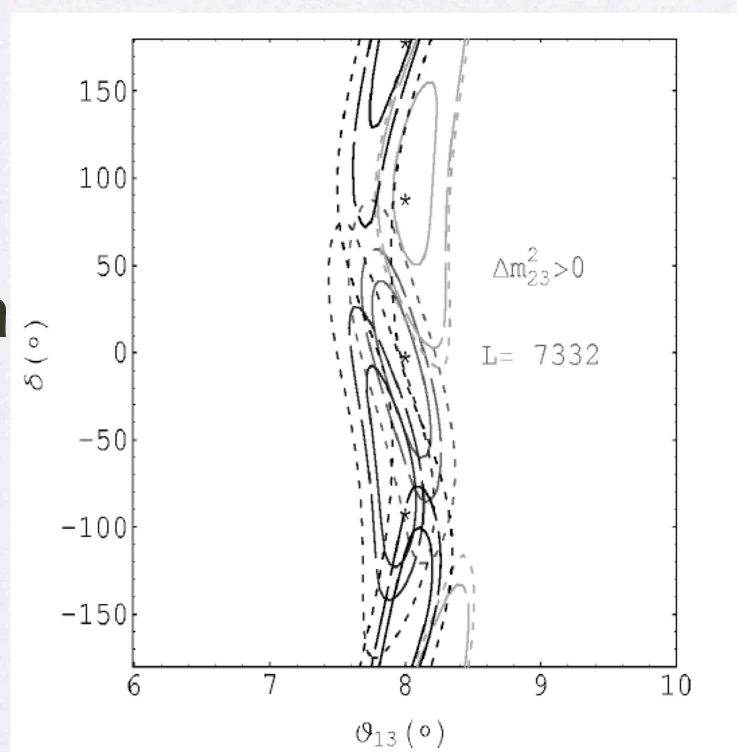
750km

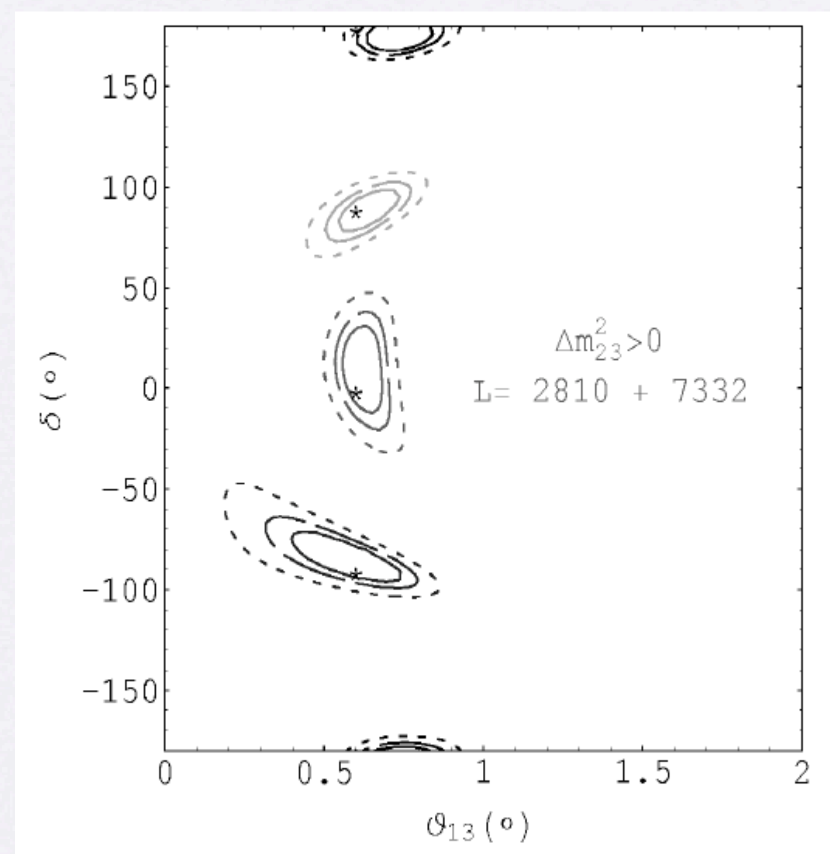


3000km



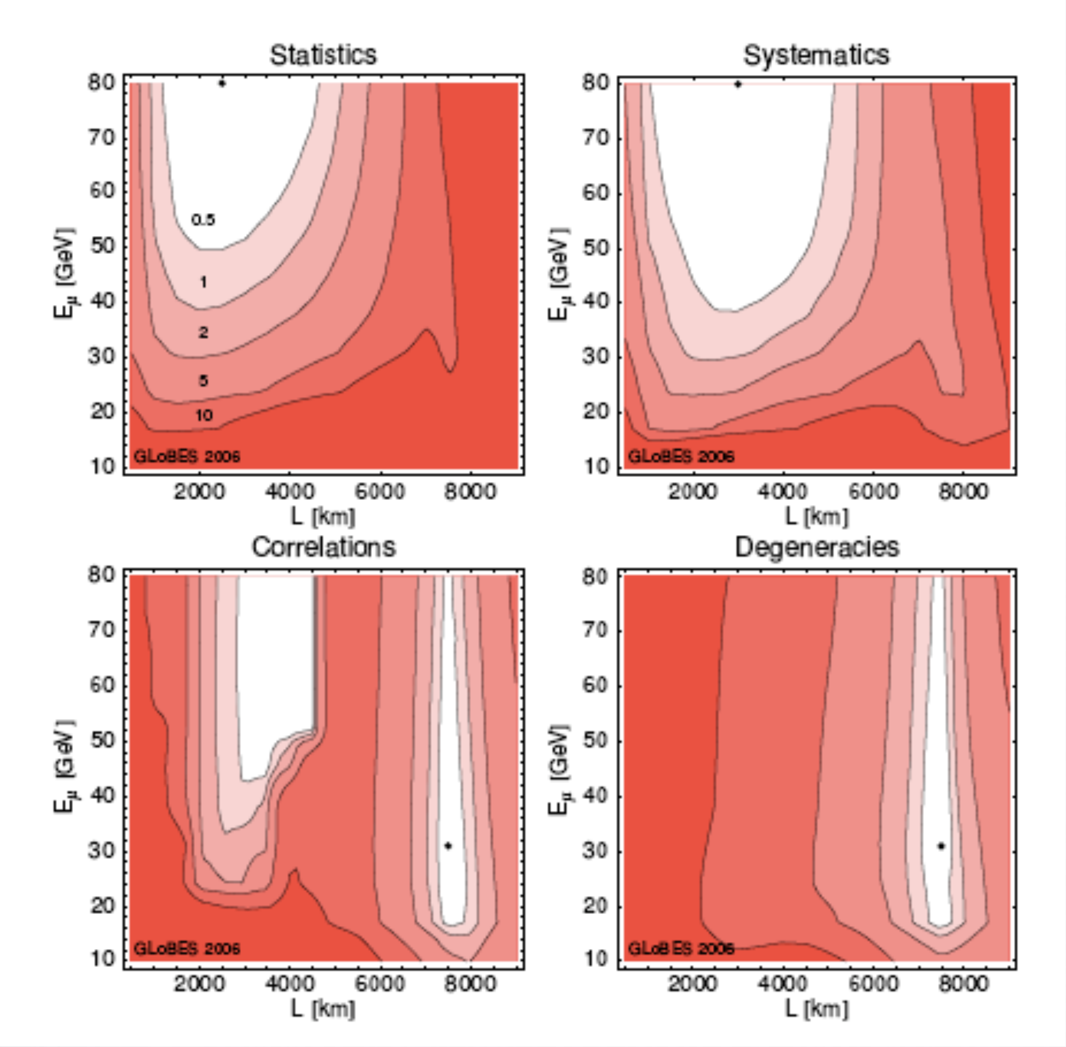
7500 km

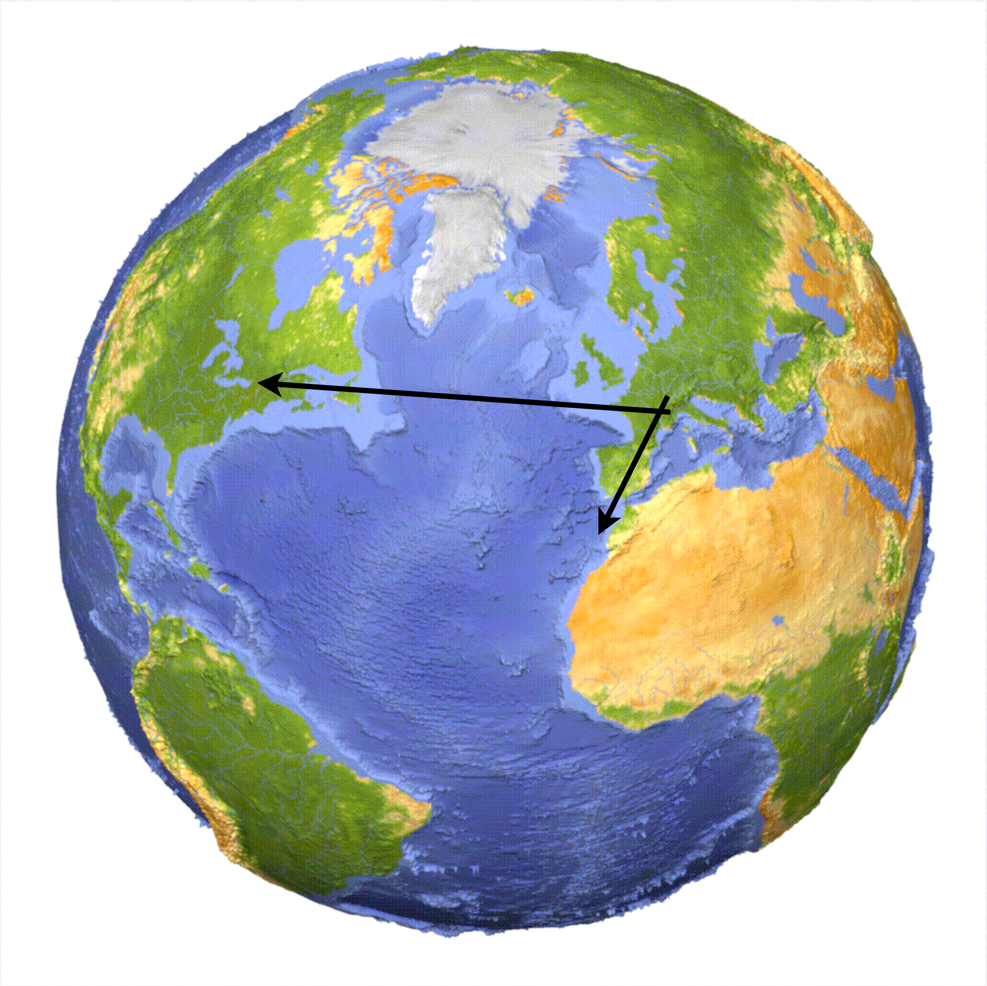




Or maybe yes...

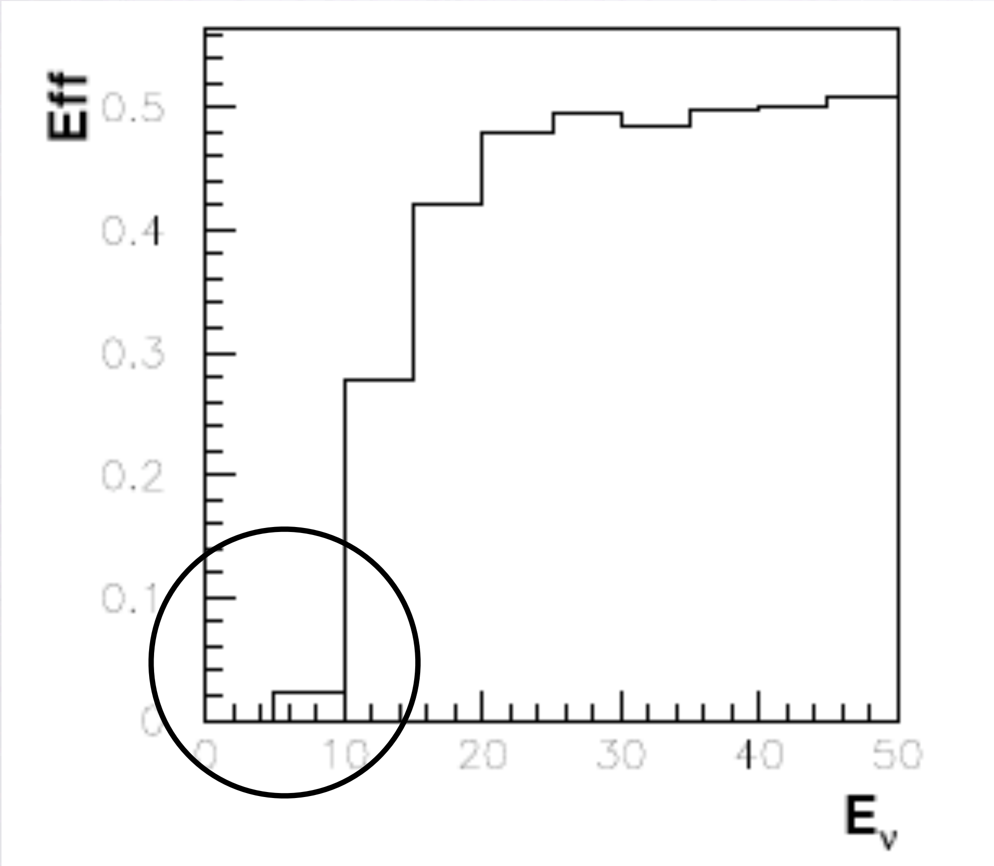
Two baselines seem to be a must for optimal performance:
"near": 3000-4000 km, for CP violation
"MB": 7500 km for matter effect and maximum sensitivity to $\sin^2\theta_{13}$

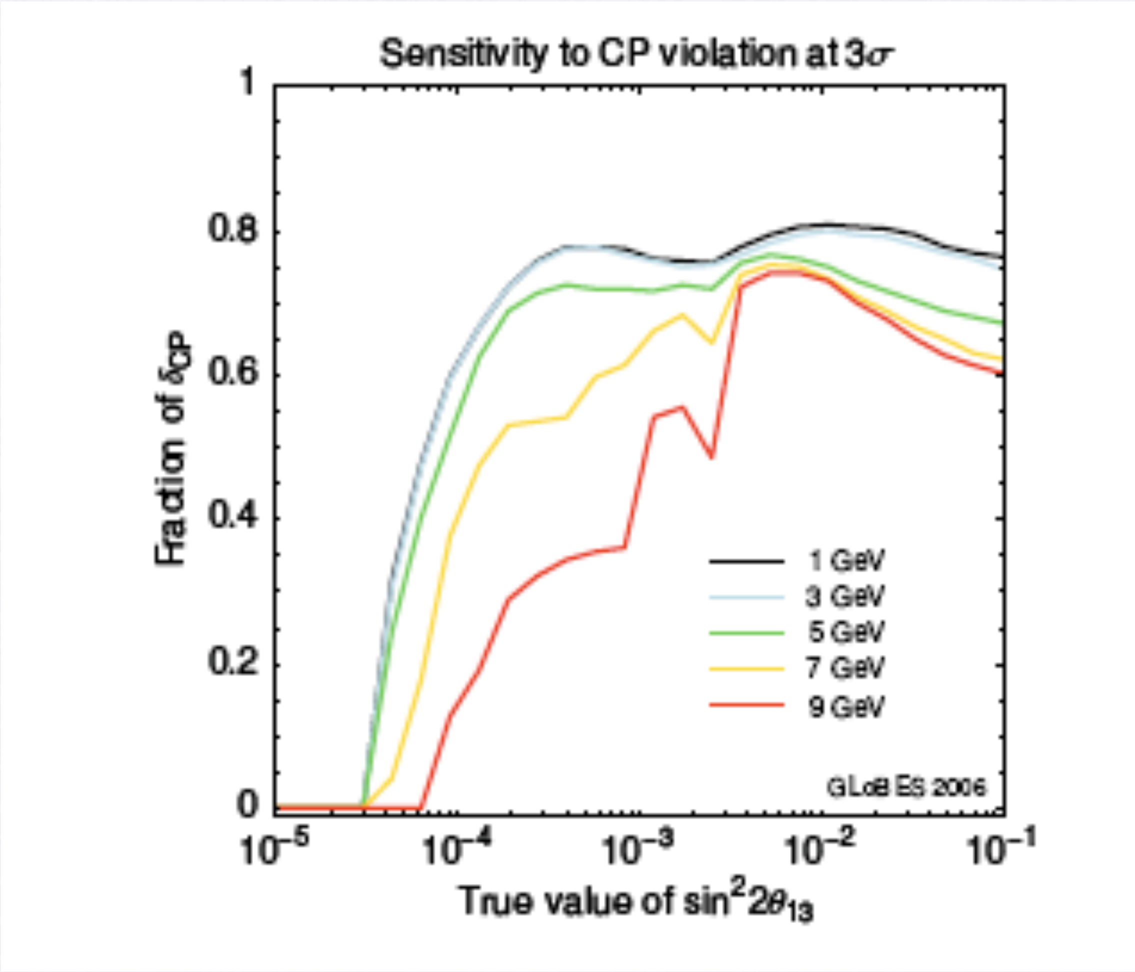




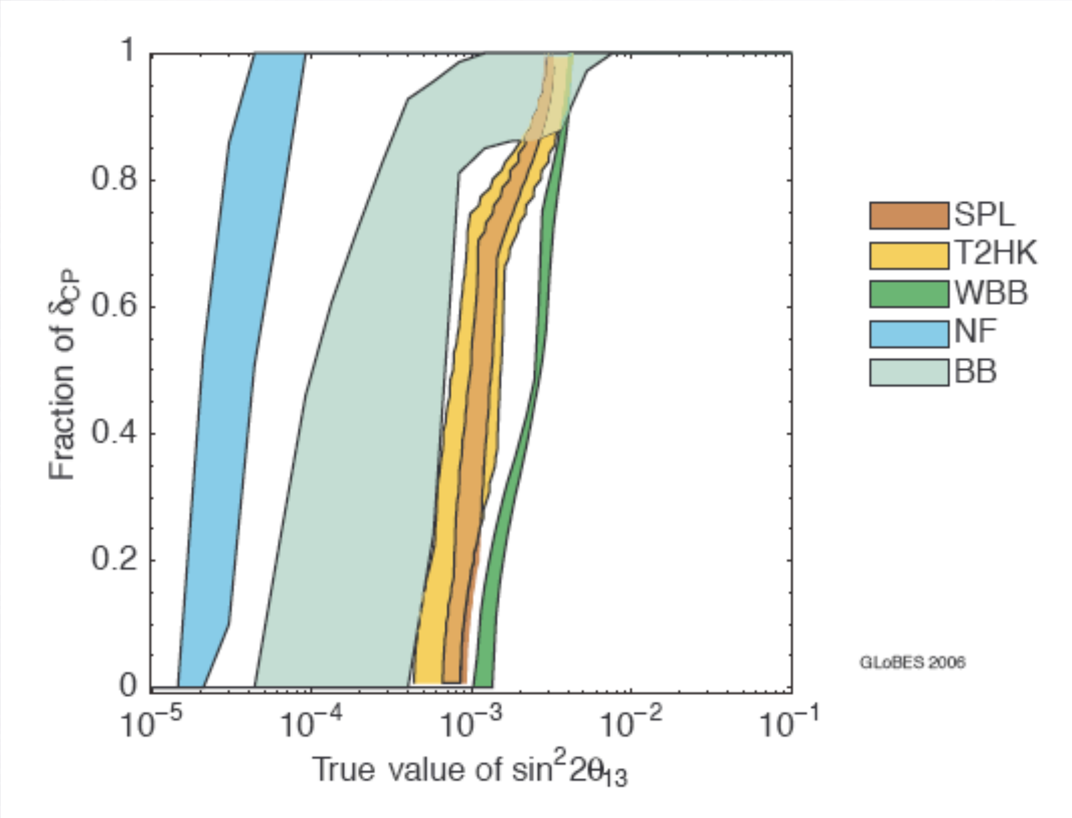
[43] P. Huber and W. Winter, "Neutrino factories and the 'magic' baseline," *Phys. Rev.* **D68** (2003) 037301, hep-ph/0301257.

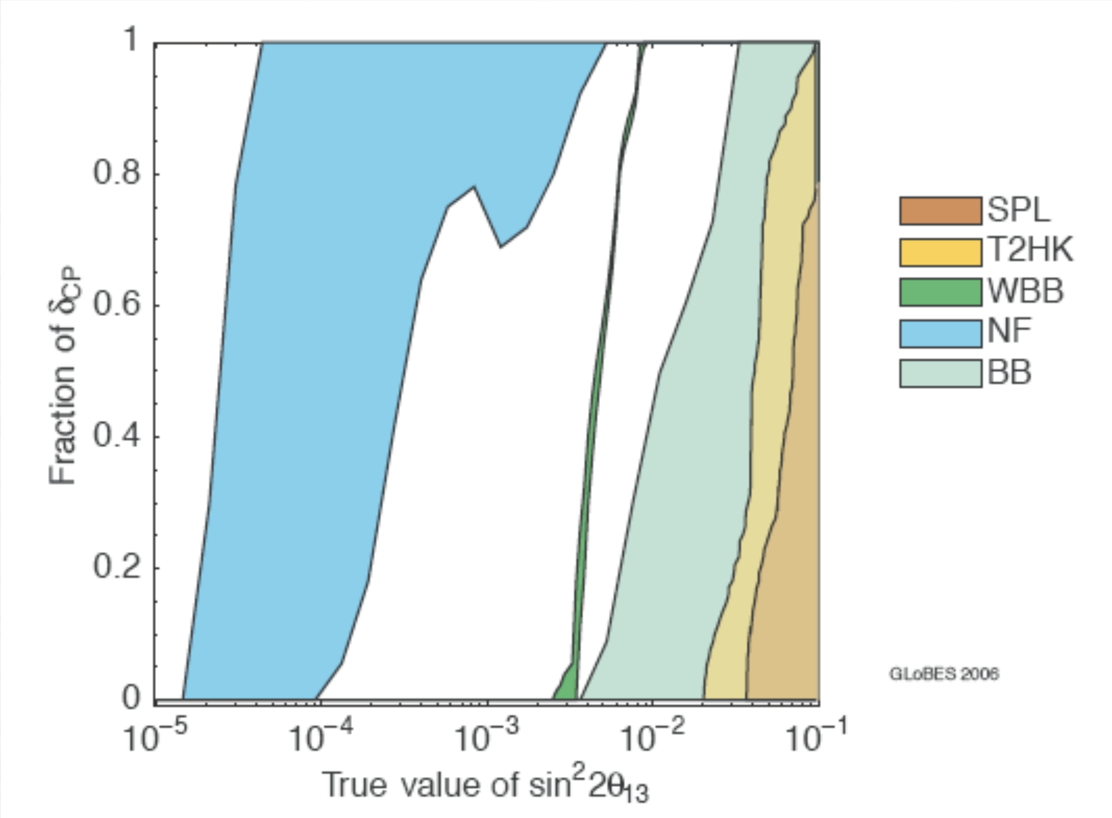
An improved detector

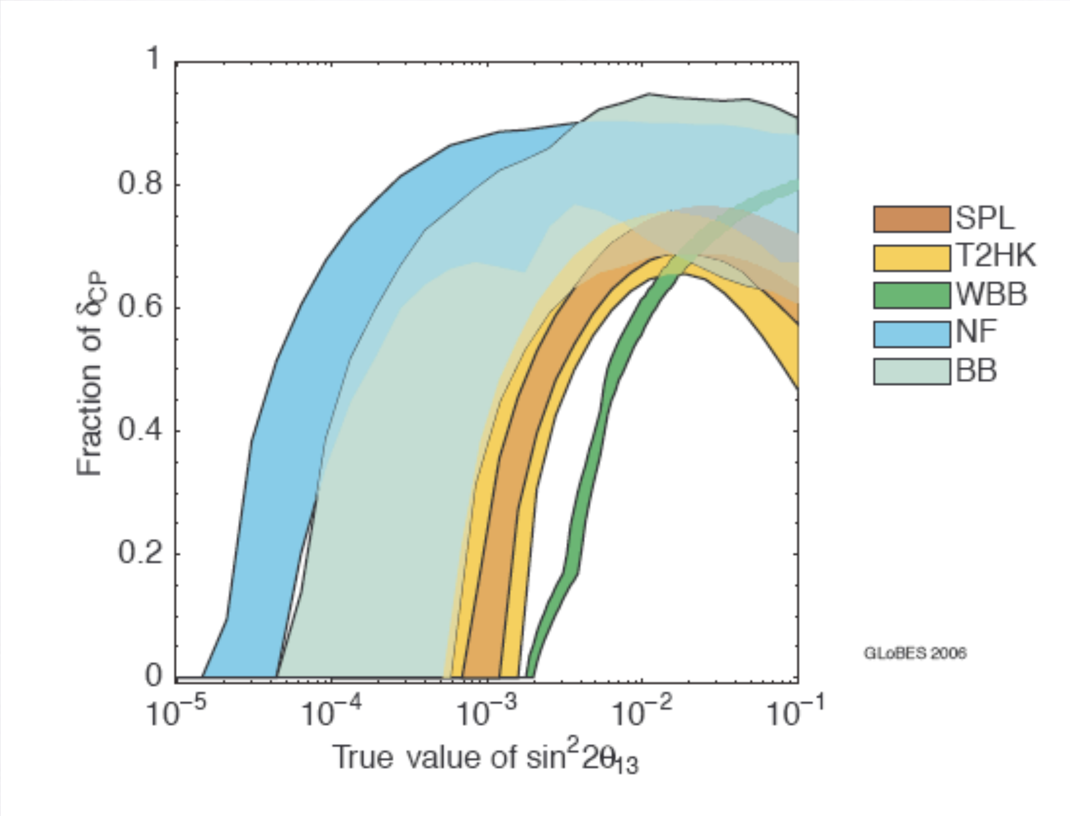




And the winner is...



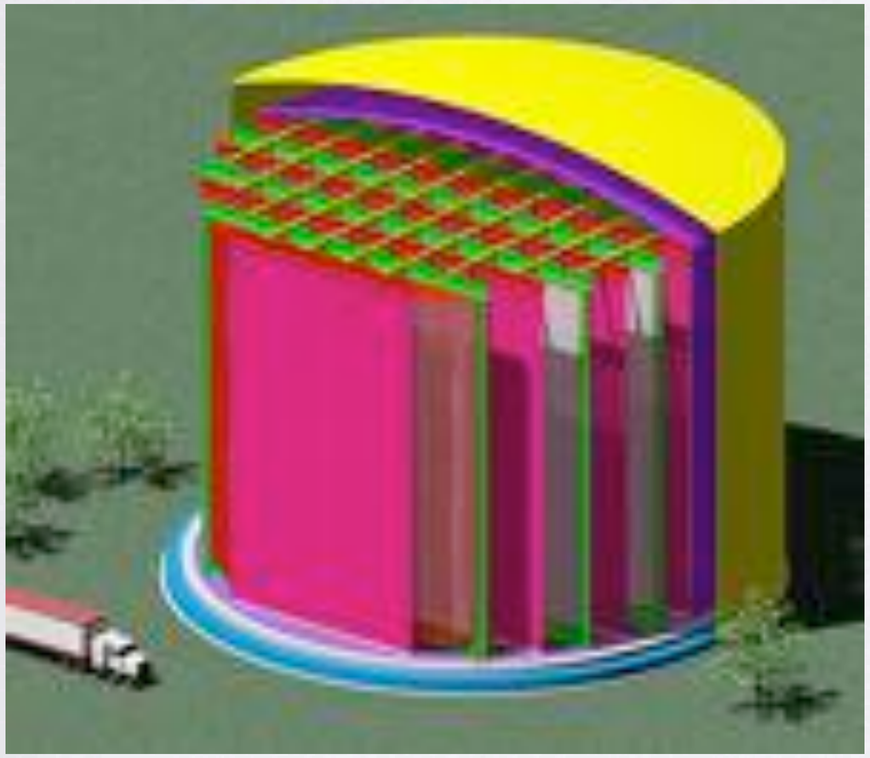


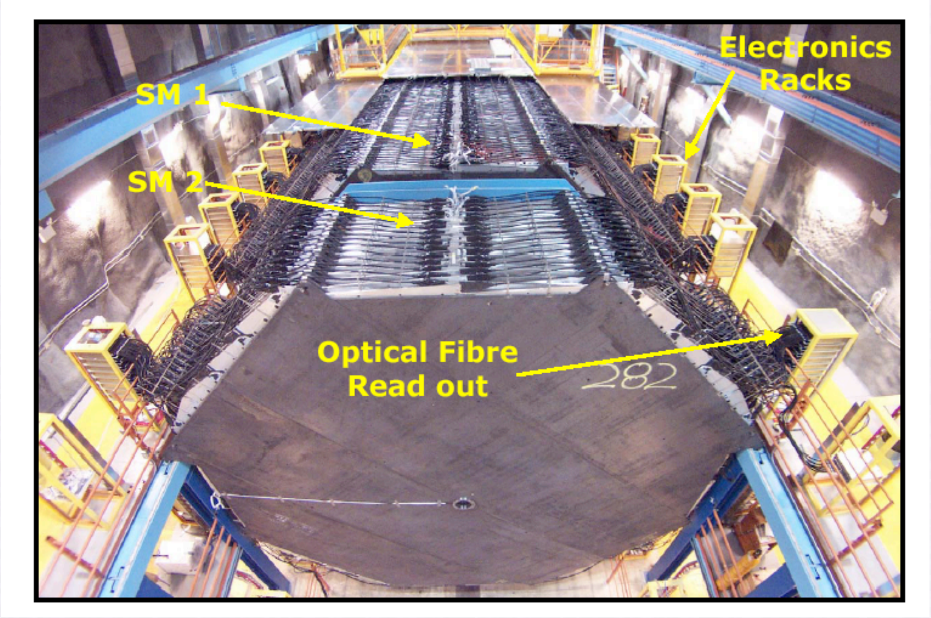


A neutrino factory with two baselines and improved detector reaches best sensitivity

Engineering and detector challenges not trivial

Two baselines can also improve beta-beam and super-beam

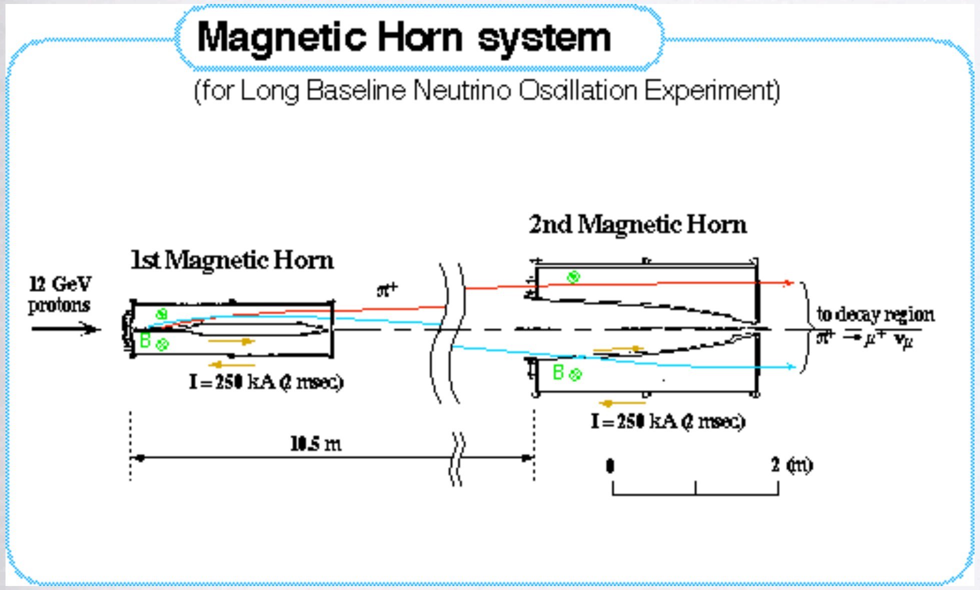


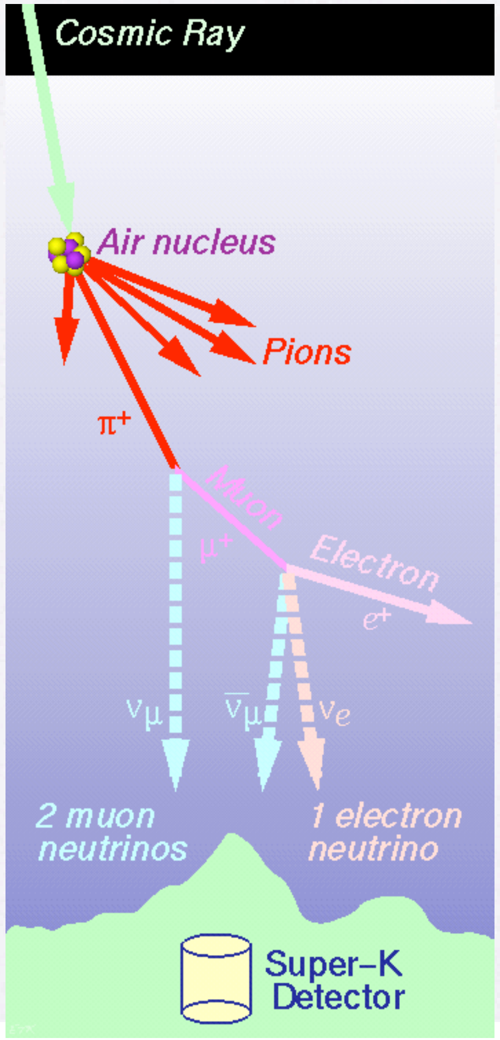

Electronics
Racks
SM 1
SM 2
Optical Fibre
Read out
282

Which Road to take?

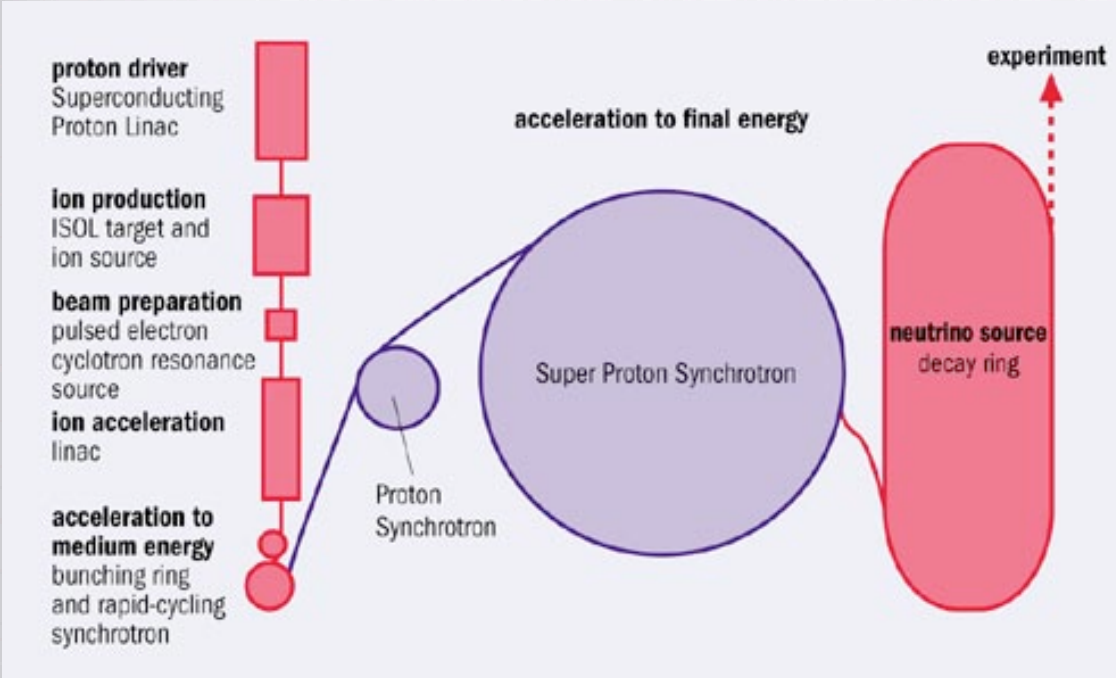
Build a Mton detector?

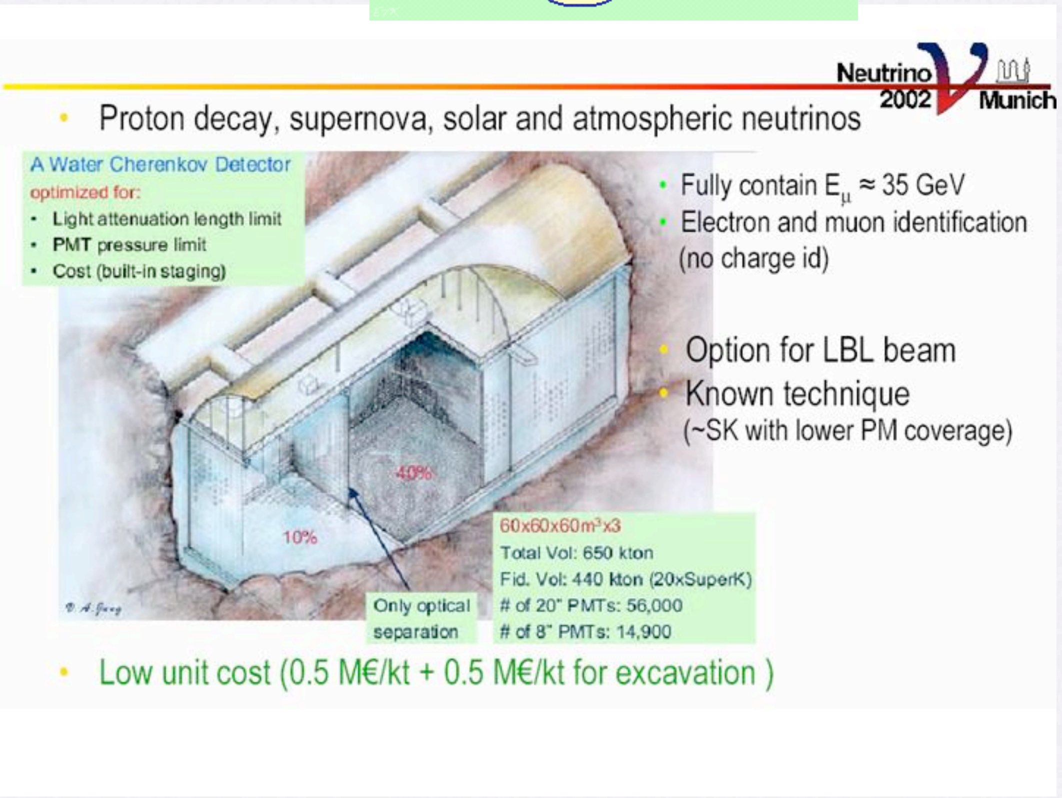
$$\nu_\mu \rightarrow \nu_e$$





$$\nu_e \rightarrow \nu_\mu$$

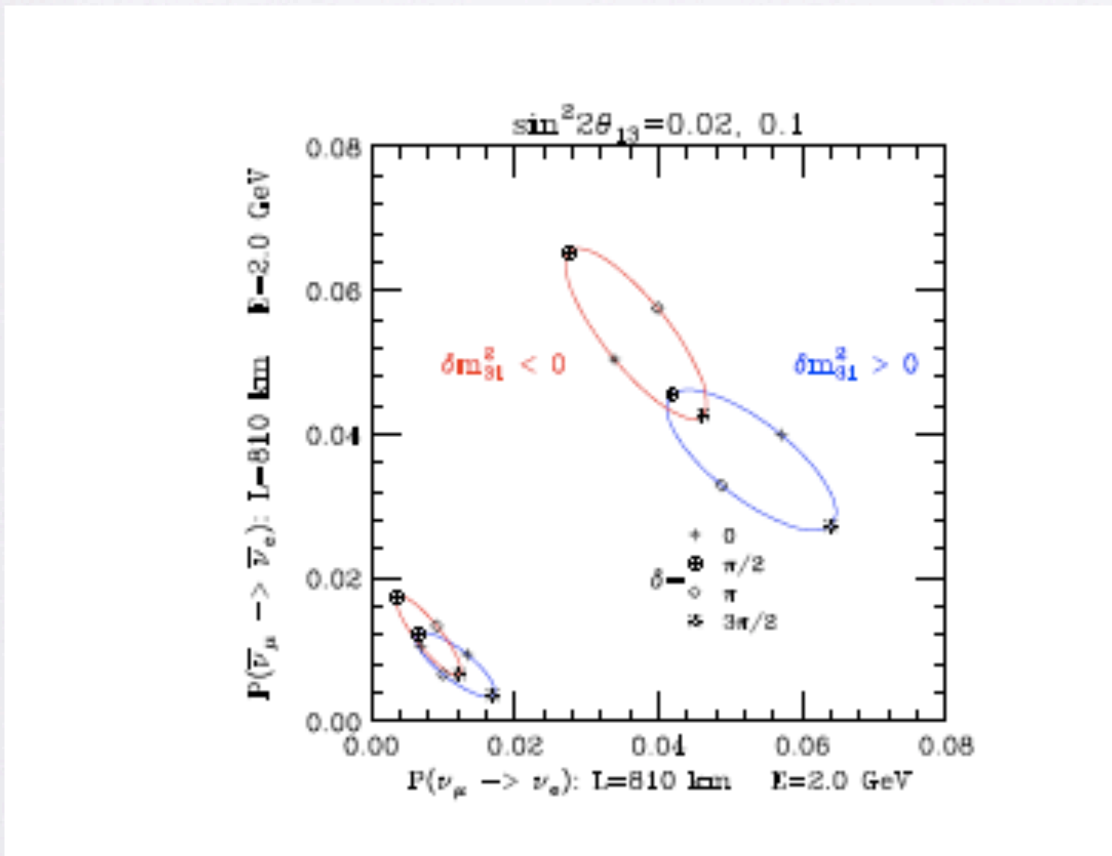


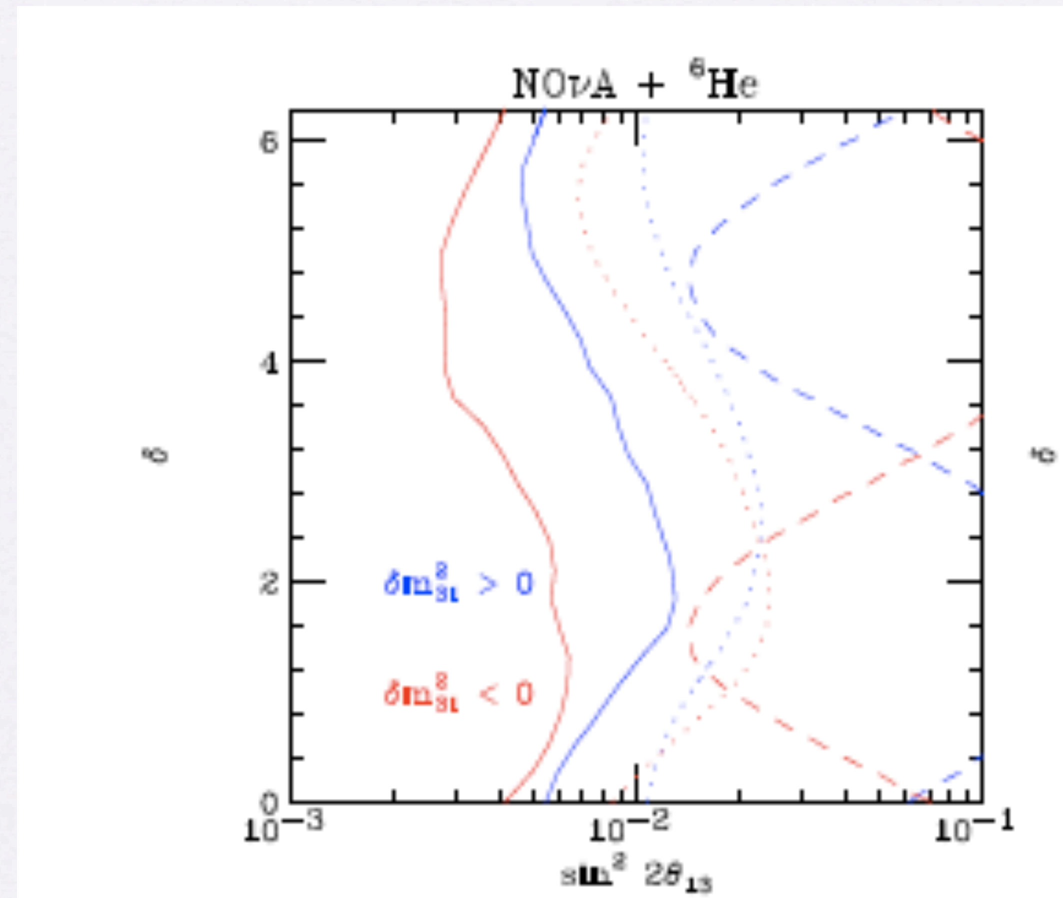


Combine Super-Beam and Beta-Beam in one facility?

Combining CPT-conjugate Neutrino channels at Fermilab

Andreas Jansson[1], Olga Mena[2], Stephen Parke[1] and Niki Saoulidou[1]



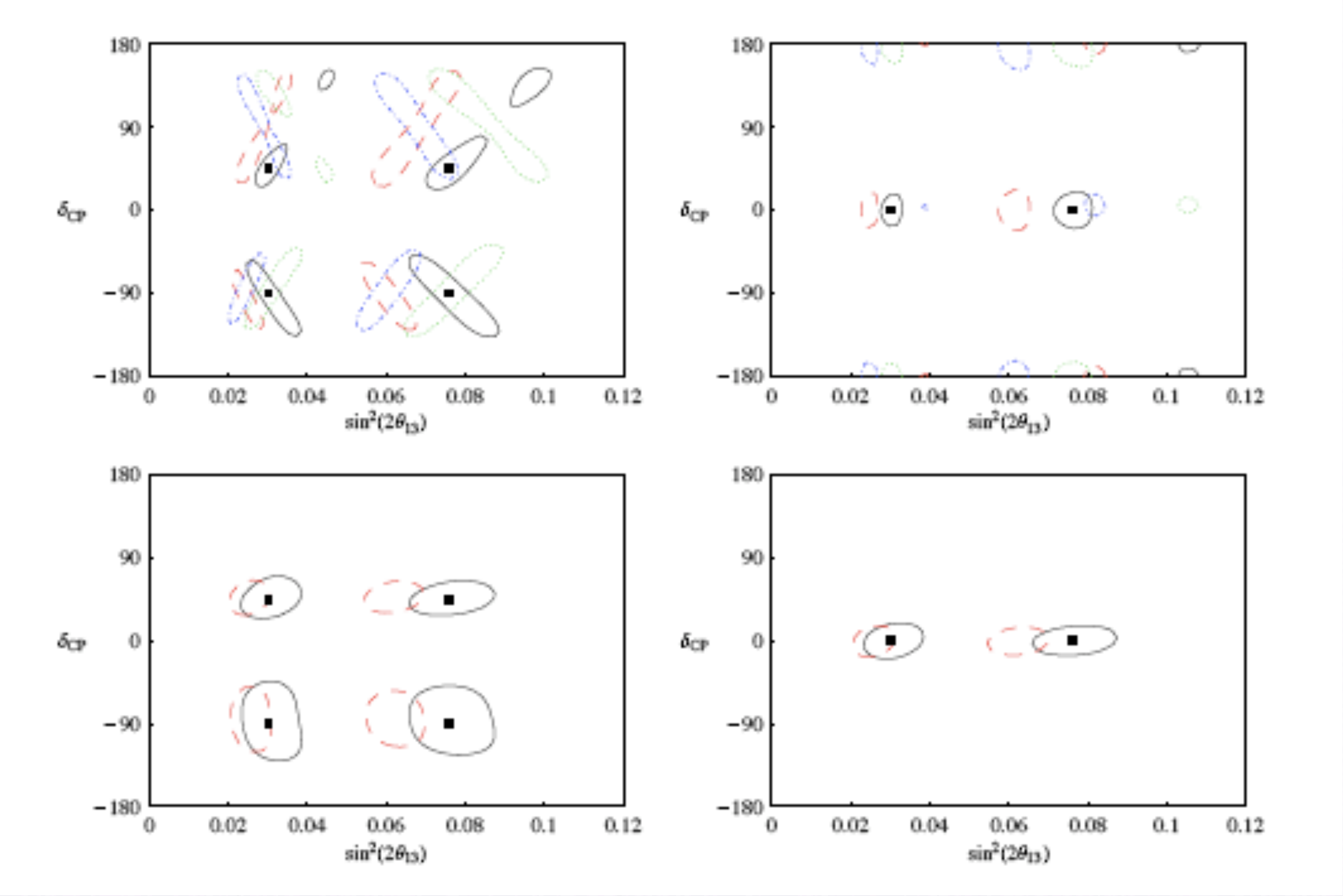


Using CPT conjugated channels for optimal sensitivity to mass hierarchy

Combine two ions at a fixed baseline to solve degeneracies?


Alternating ions in a β-beam to solve degeneracies

A. Donini[a] E. Fernández-Martínez[a]

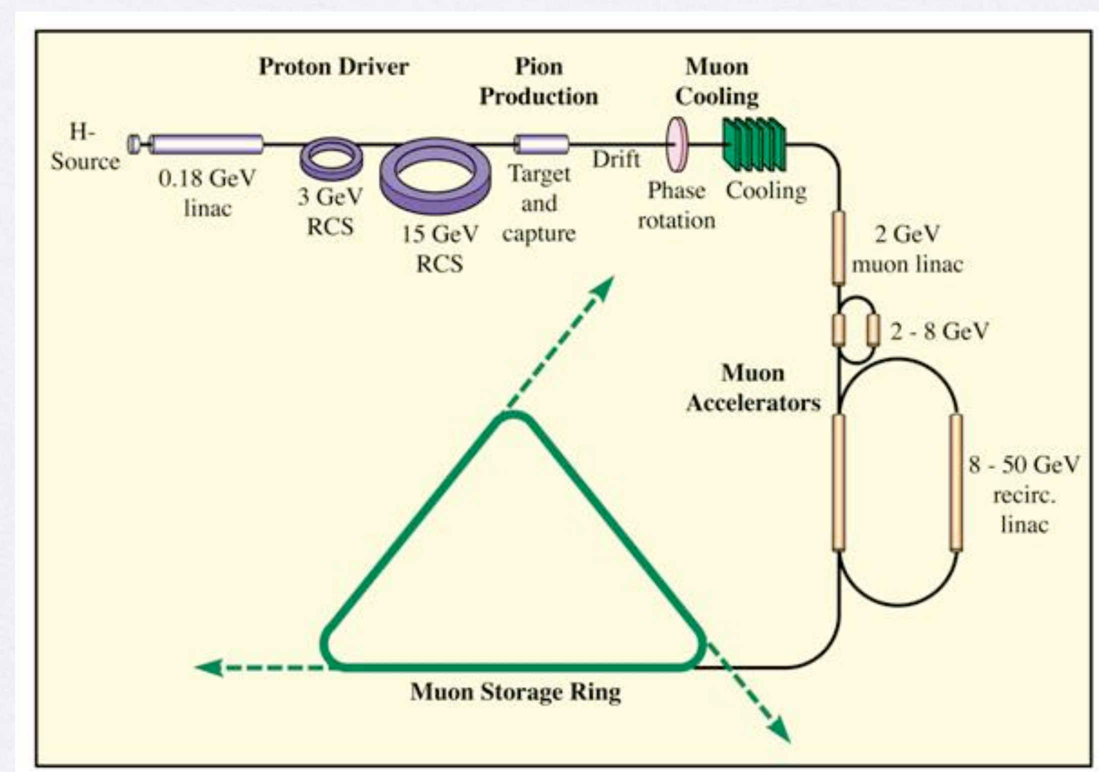


A low energy nufact?

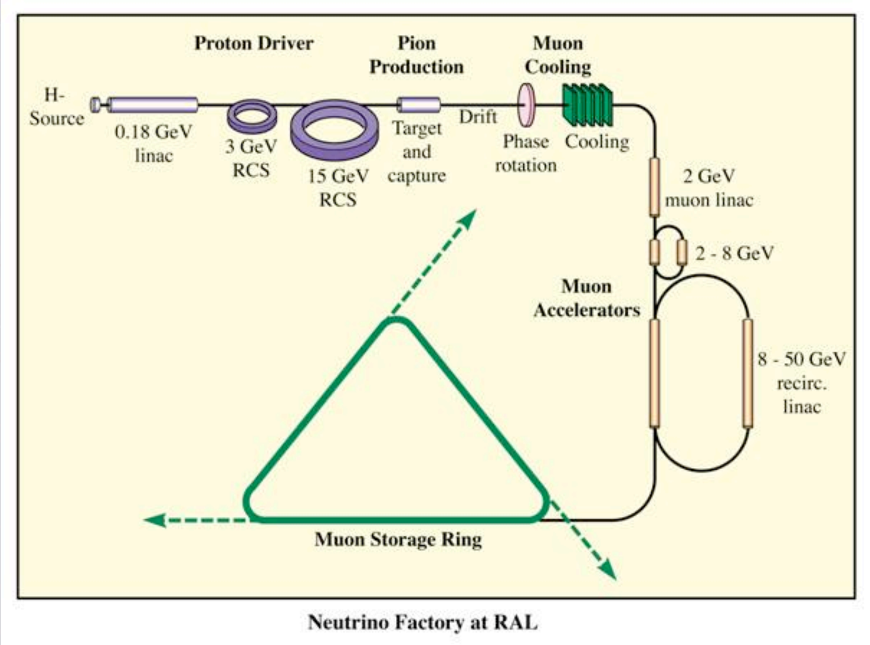
Alan Bross, Malcolm Ellis, and Steve Geer*
Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, USA

Olga Mena†
INFN - Sez. di Roma, Dipartimento di Fisica, Universitá di Roma "La Sapienza", P.le A. Moro, 5, I-00185 Roma, Italy

and Silvia Pascoli‡
IPPP, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom



Neutrino Factory at RAL

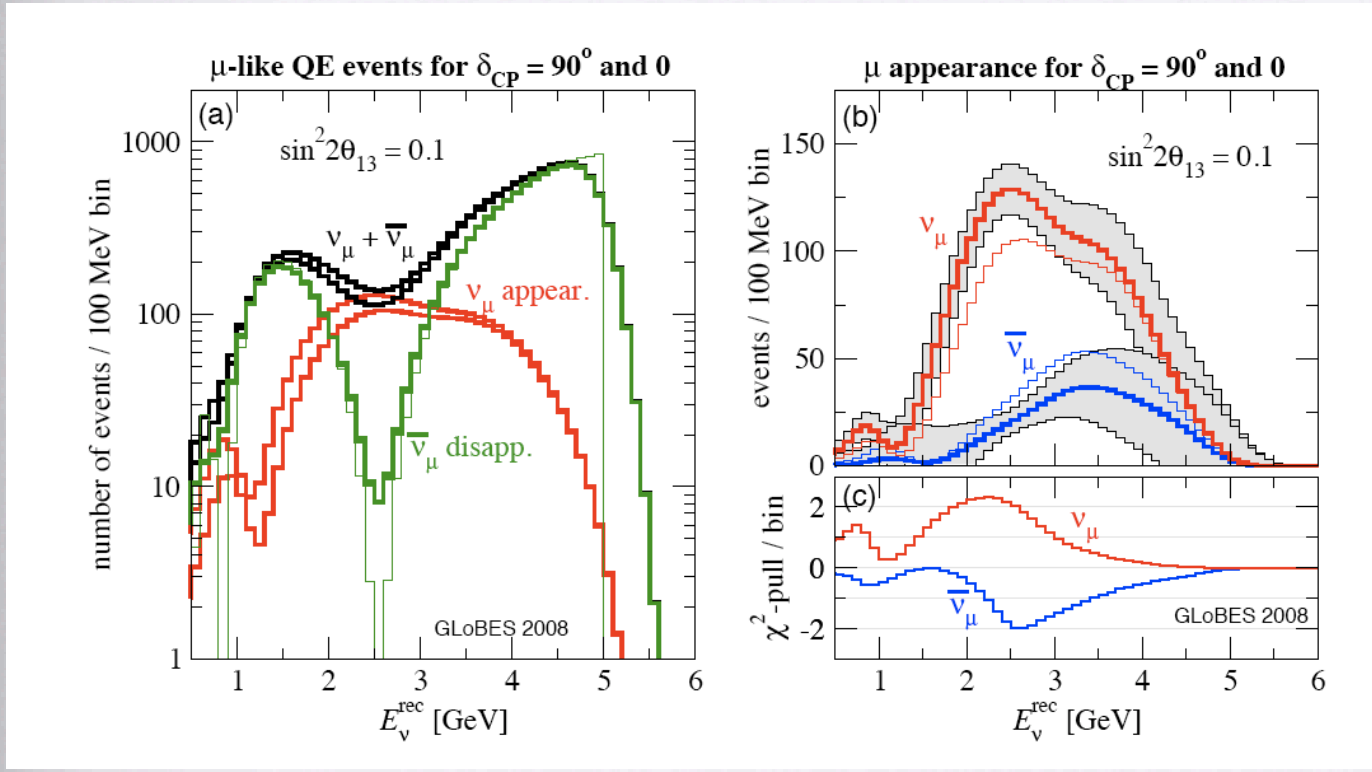


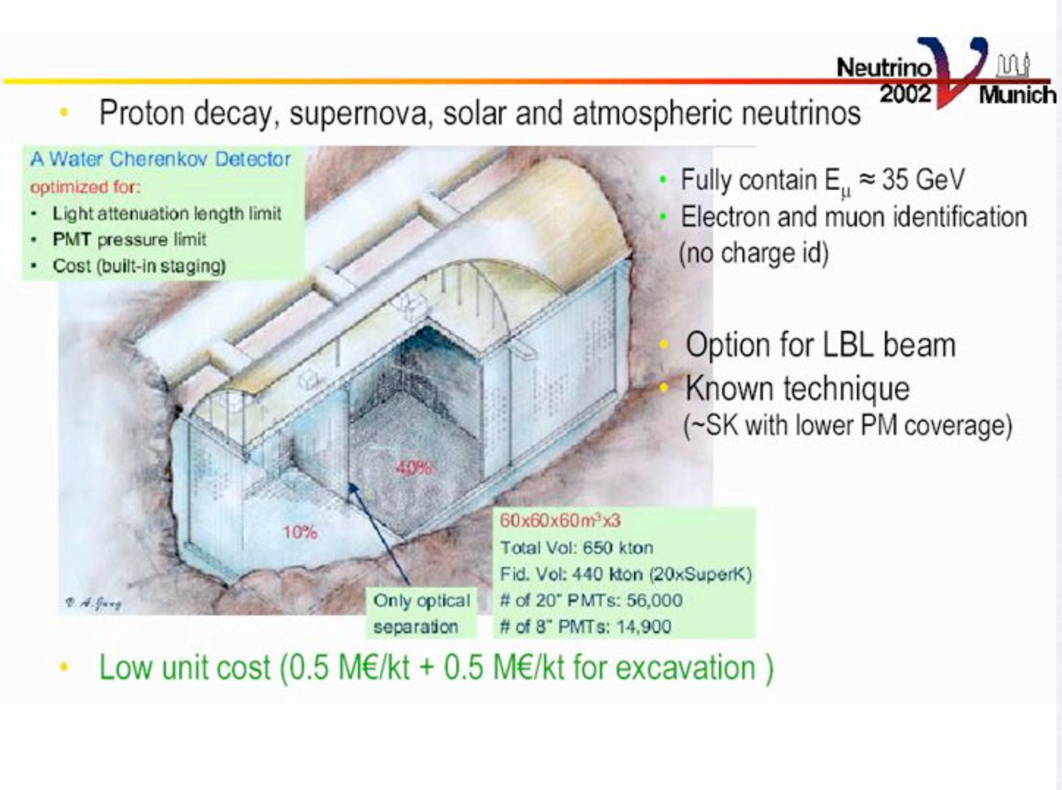
A low energy nufact with non magnetic detectors?

A low energy neutrino factory with non-magnetic detectors

Patrick Huber[1,2,*] and Thomas Schwetz[1,†]

E=5 GeV

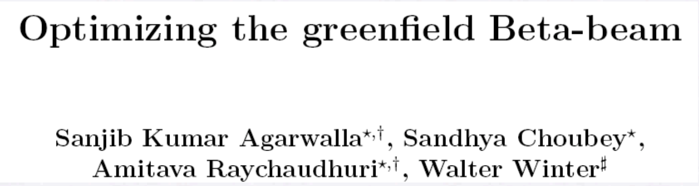




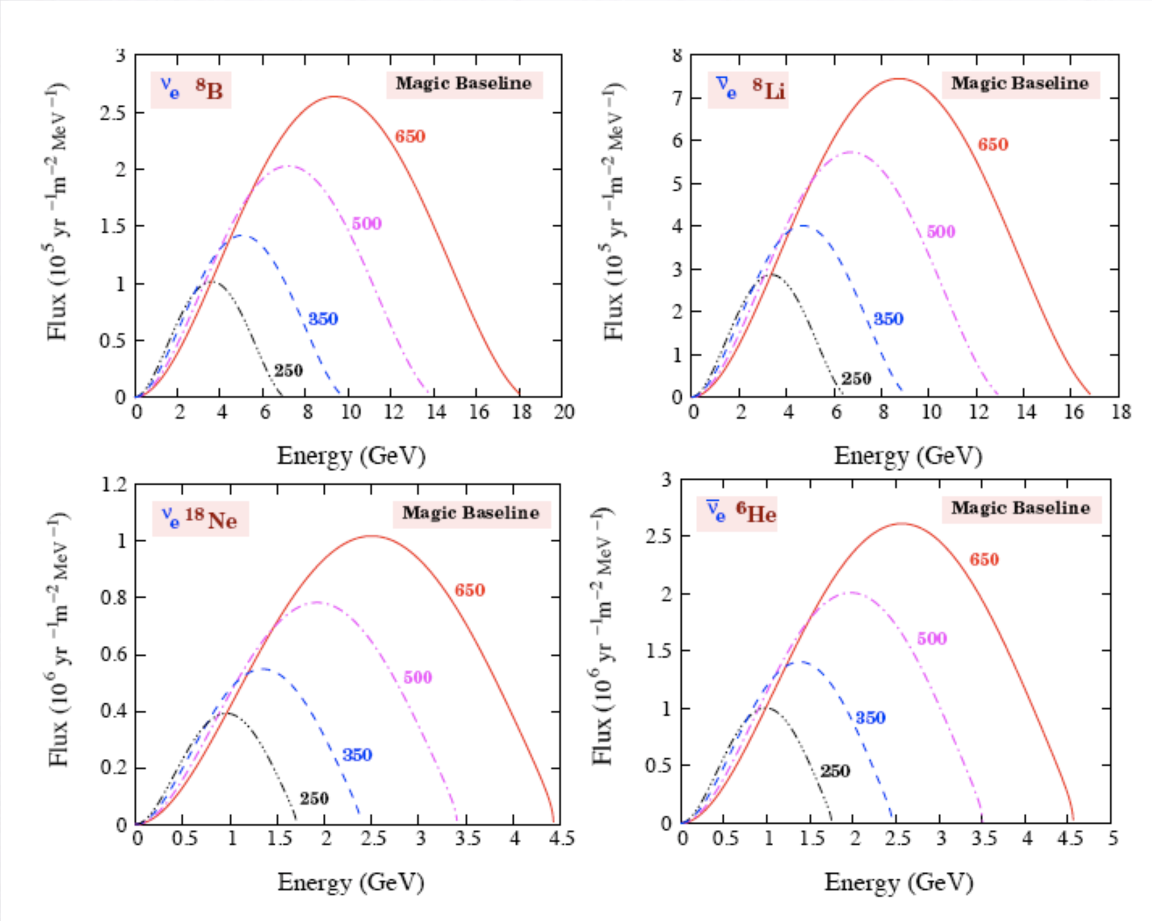
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ In peak

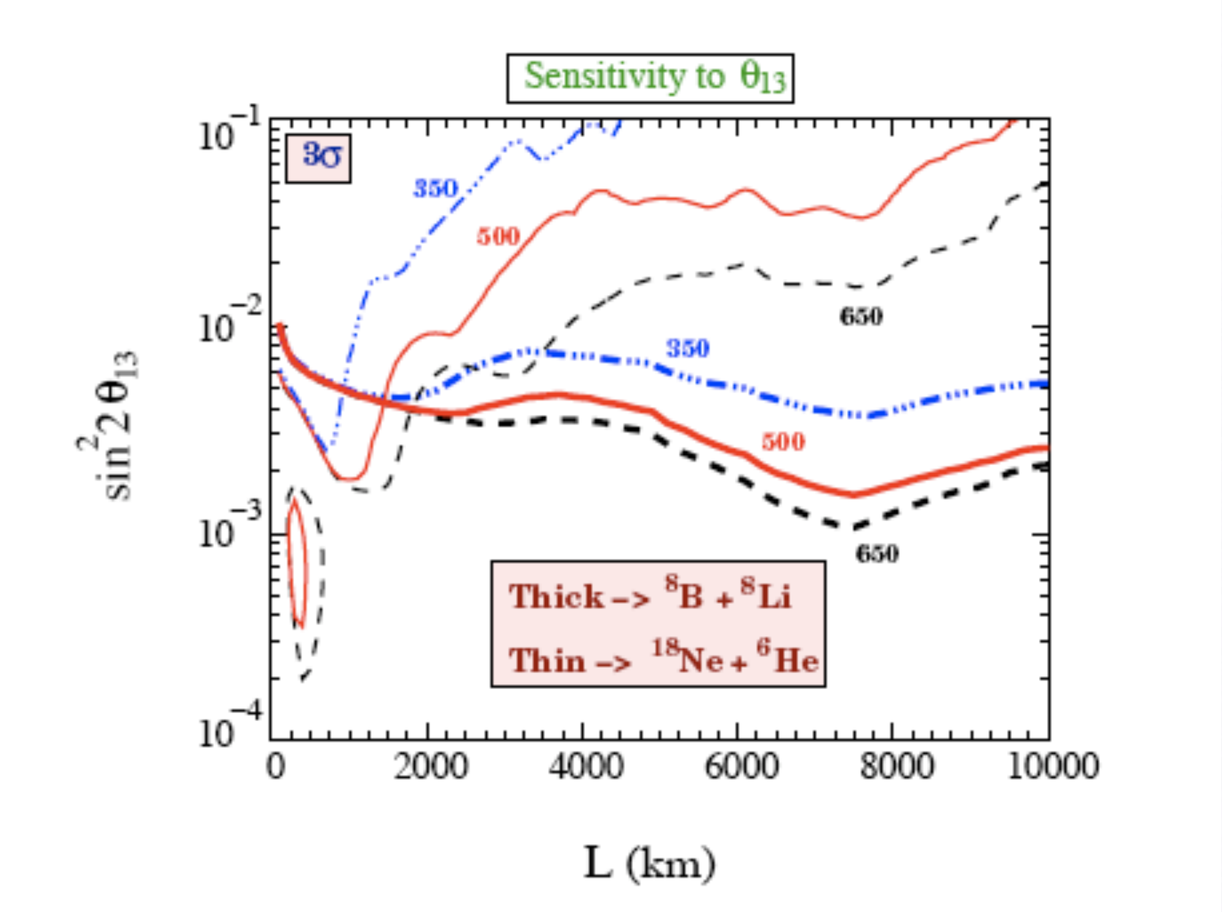
Gd doping tags n thus $\bar{\nu}_\mu$

Two baselines, two ions beta-beam?


Optimizing the greenfield Beta-beam

Sanjib Kumar Agarwalla*,†, Sandhya Choubey*, Amitava Raychaudhuri*,†, Walter Winter♯



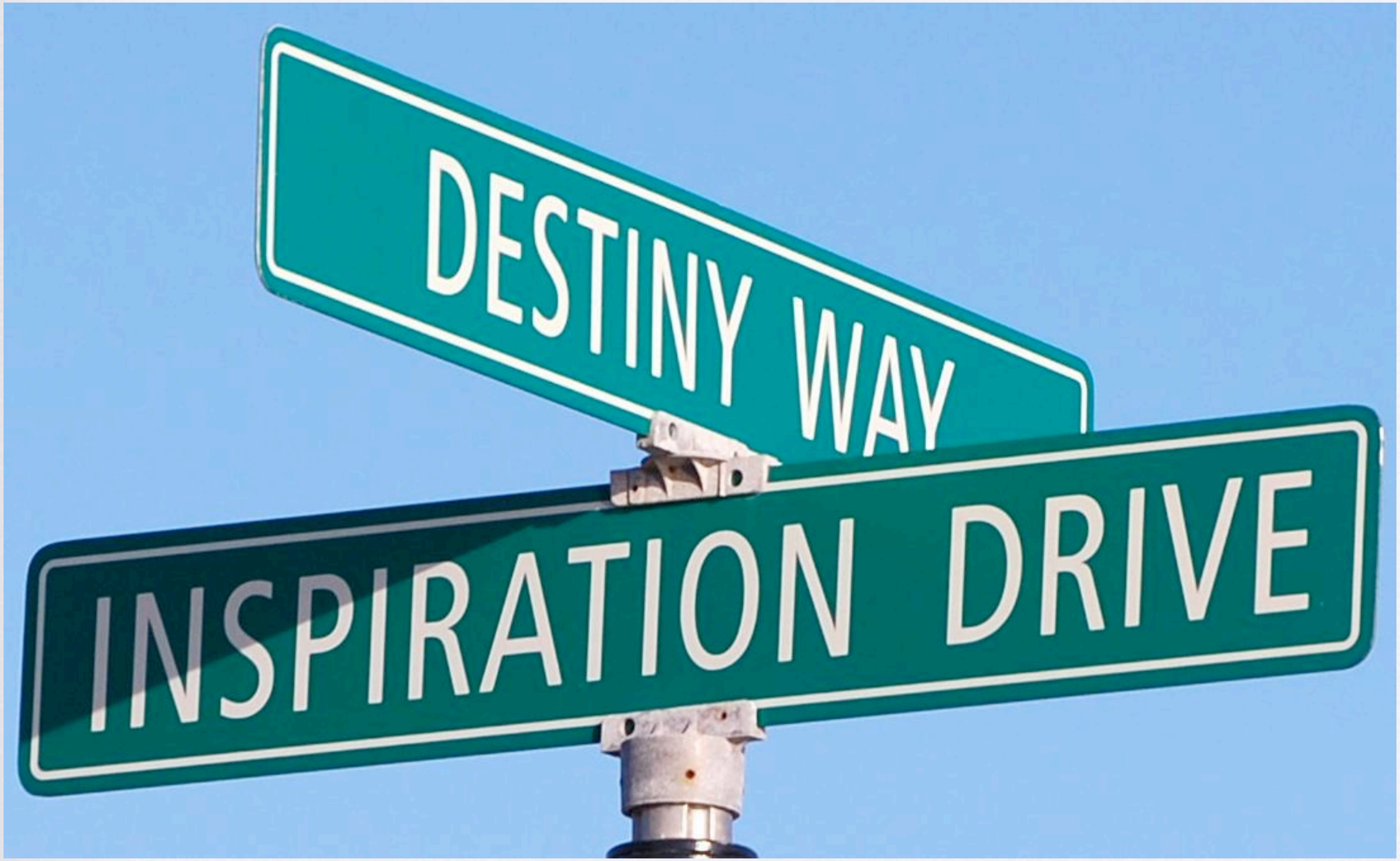


Sensitivity similar to a neutrino factory?

Too many combinations?

dreaming too big?

I hope we choose well




08
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Wg2: neutrino scattering
S. Boyd - Y. Hayato - K. McFarland
Wg3: accelerator physics
R. Garoby - D. Li - M. Meddahi - T. Uesugi
Wg4: muon physics
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And also NEUTRINO SUMMER SCHOOL_Benasque & Valencia_June 9-27