Measuring Leptonic CP violation: Flux and cross-section issues

0. Introduction: precision measurements for leptonic CP violation and masss hierarchy

1. Future neutrino beam possibilities
   1.1 neutrino factory
   1.2 low energy superbeam and betabeam

2. The cross-section issues

3. Outlook

There are today THREE compelling and firmly established observational facts that the Standard Model fails to account for:

-- neutrino masses
-- the existence of dark matter
-- the baryon asymmetry of the universe

The fact that neutrino have masses and mix is established by neutrino oscillations

The neutrino masses offer a chance to explain the baryon asymmetry in the most natural way via

*** LEPTOGENESIS ***

by a combination of
-- fermion number violation (authorized by neutrino masses and GUT)
-- three families of neutrinos ==> leptonic CP violation
(authorized by the mixing of three families with large mixing angles)

Status of neutrino oscillations in a few words

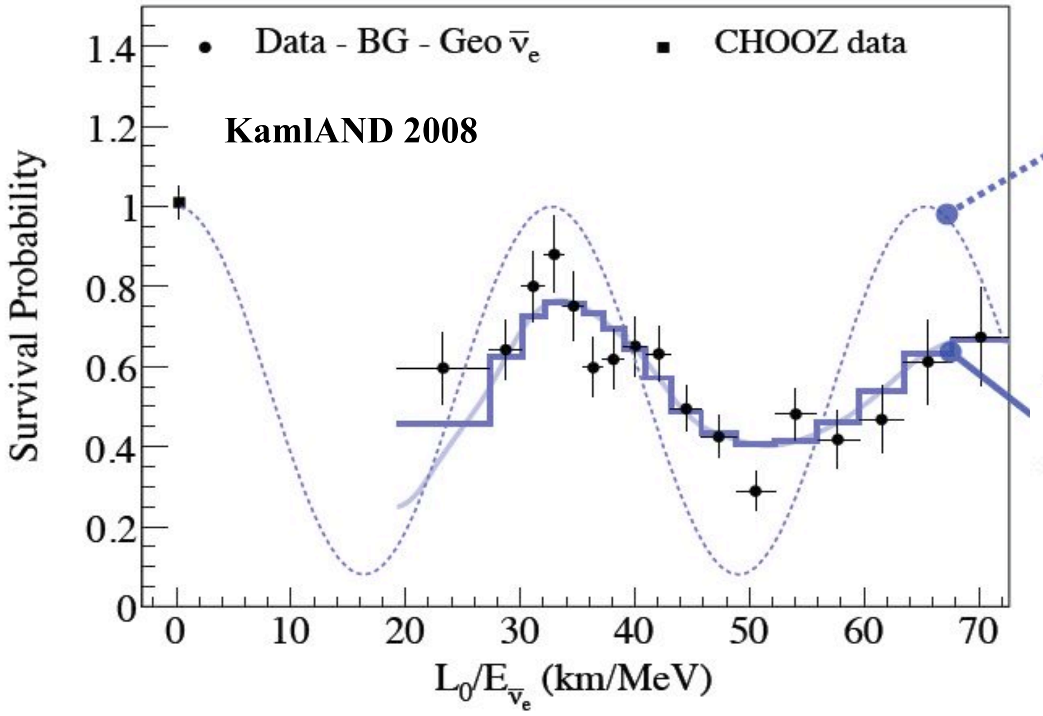
1. We know that there are three families of active, light neutrinos *(LEP)*
2. Solar neutrino oscillations are established *(Homestake+Gallium+SK+SNO +KamLAND)*
3. Atmospheric neutrino (ν_μ –>) oscillations are established *(IMB+Kam+SK+Macro+Sudan+K2K+MINOS)*
3. At that frequency, electron neutrino oscillations are small *(CHOOZ)*

4. Indication of possible higher frequency oscillation (LSND) not confirmed (miniBooNe) but MiniBoone itself is not without questions….

This allows a consistent picture with 3-family oscillations
preferred:
LMA: $\theta_{12} \sim 30^0$ $\Delta m_{12}^2 \sim 7\ 10^{-5} eV^2$, $\theta_{23} \sim 45^0$ $\Delta m_{23}{}^2 \sim \pm 2.5\ 10^{-3} eV^2$, $\theta_{13} <\sim 10^0$
with 3 unknown parameters
=> an exciting experimental program for at least 25 years *)
including leptonic CP & T violations

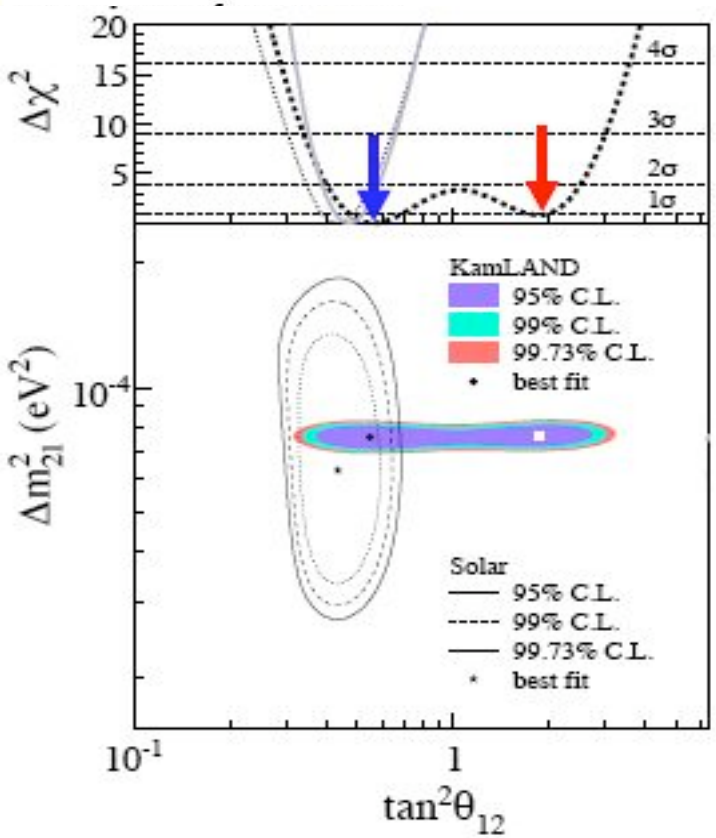
*) to set the scale: CP violation in quarks was discovered in 1964
and there is still an important program (K0pi0, B-factories, Neutron EDM, BTeV, LHCb..)
to go on for 10 years…i.e. a total of ~50 yrs.
and we have not discovered leptonic CP yet!

5. Several experiments are prepared/starting to go further:
OPERA, T2K, D-CHOOZ, NOvA, and the future program is being discussed!

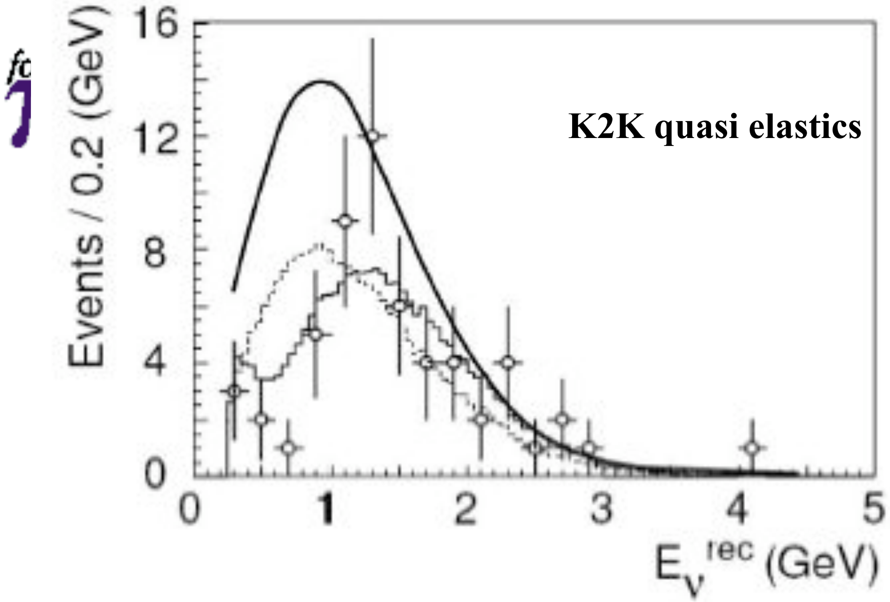


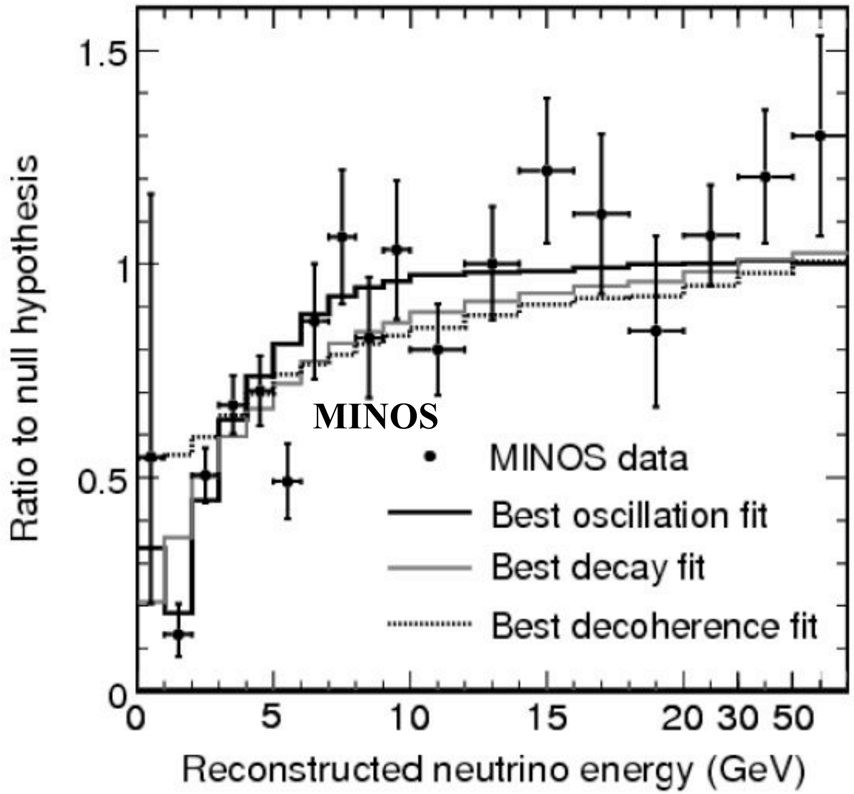
Oscillation pattern for a mono-energetic $\overline{\nu}_e$ at one baseline

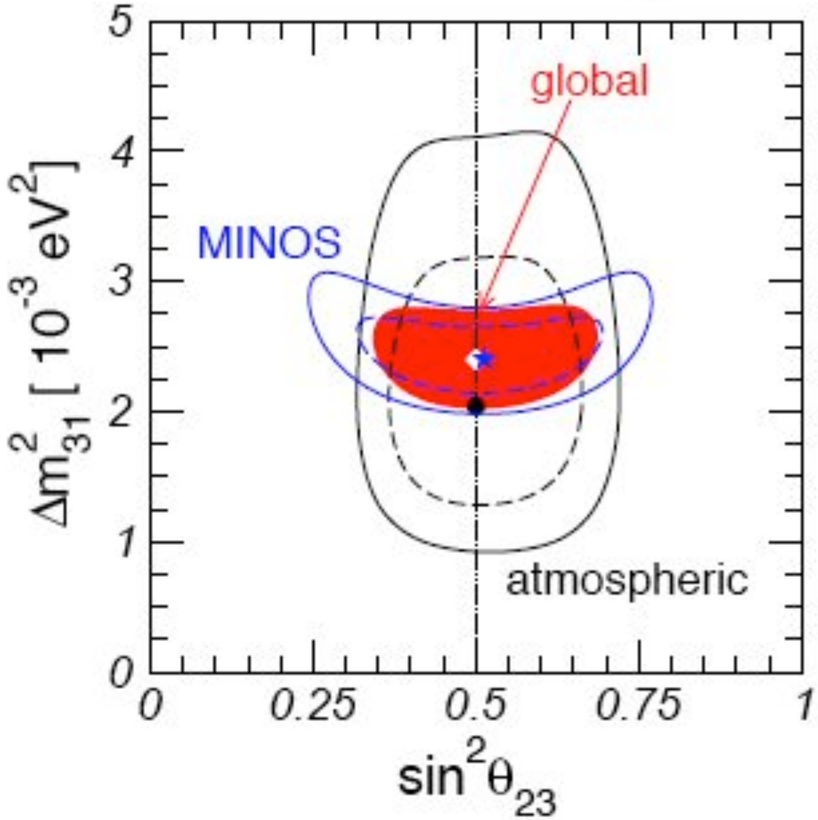
Best-fit oscillation



KamLAND+Solar: $\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}\,\mathrm{eV}^2 \qquad \tan^2\theta = 0.47^{+0.06}_{-0.05}$





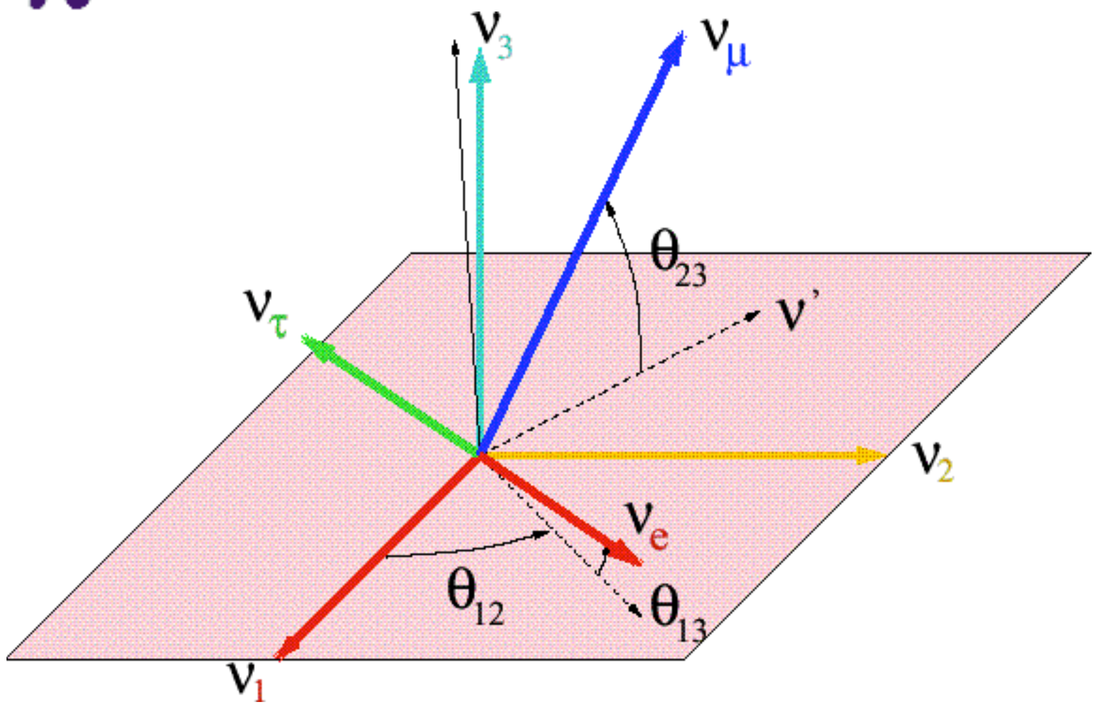


arxiv:0806.2237, 3.4×10^{20} pot

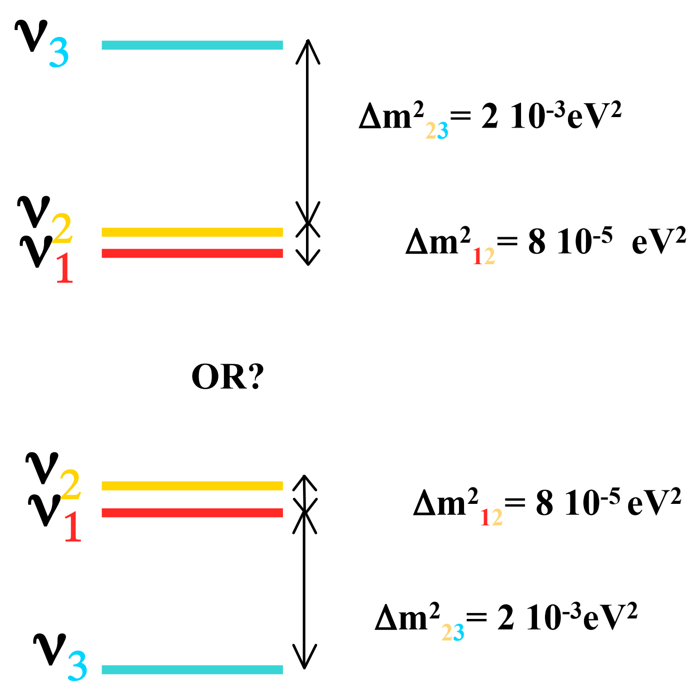
$$\sin^2\theta_{23} = 0.50^{+0.07}_{-0.06}$$

$$|\Delta m^2_{31}| = 2.40^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$$

The neutrino mixing matrix: 3 angles and a phase δ



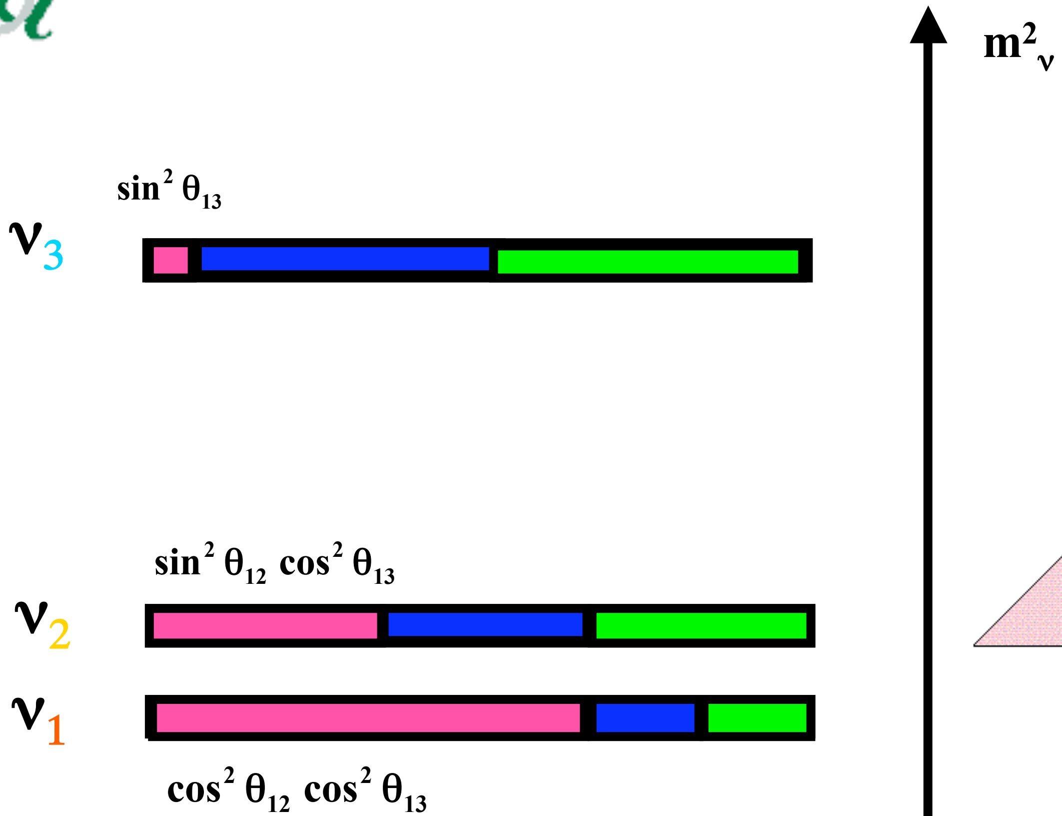
θ_{23} (atmospheric) = 45^0 , θ_{12} (solar) = 32^0 , θ_{13} (Chooz) < 13^0

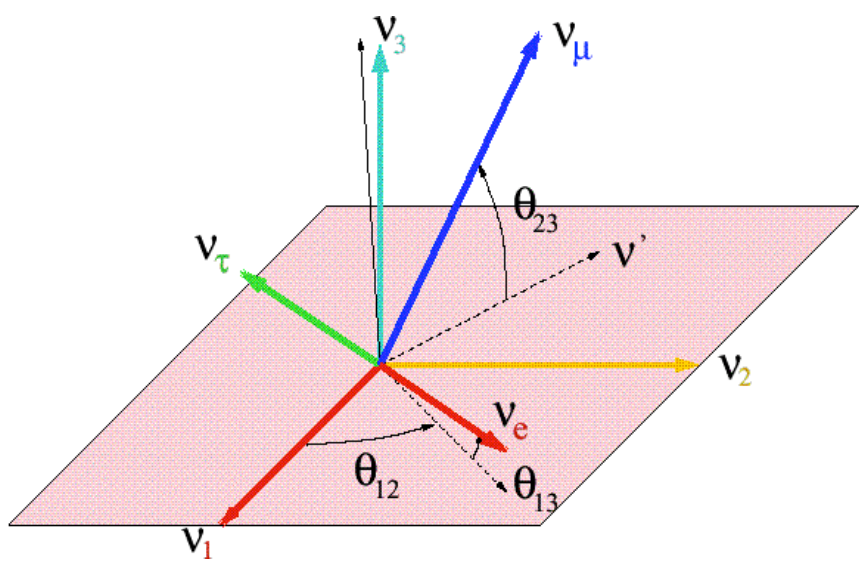


$$U_{MNS}: \begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

Unknown or poorly known
θ_{13} , phase δ , sign of Δm_{13}^2

neutrino mixing (LMA, natural hierarchy)





$$U_{MNS}: \begin{pmatrix} \sim\frac{\sqrt{2}}{2} & \sim-\frac{\sqrt{2}}{2} & \sin\theta_{13}\,e^{i\delta} \\ \sim\frac{1}{2} & \sim\frac{1}{2} & \sim-\frac{\sqrt{2}}{2} \\ \sim\frac{1}{2} & \sim\frac{1}{2} & \sim\frac{\sqrt{2}}{2} \end{pmatrix}$$

ν_e is a (quantum) mix of

ν_1 (majority, 65%) and ν_2 (minority 30%)

with a small admixture of ν_3 (< 13%) (CHOOZ)

Oscillation maximum $1.27\,\Delta m^2\ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}\ \mathrm{eV}^2$ **L = 500 km @ 1 GeV**

Solar $\Delta m^2 = 7\ 10^{-5}\ \mathrm{eV}^2$ **L = 18000km @ 1 GeV**

Consequences of 3-family oscillations:

I There will be $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_e$ oscillation at L_{atm}

$$P(\nu_\mu \leftrightarrow \nu_e)_{max} =\sim \tfrac{1}{2}\ \sin^2 2\theta_{13}\ + \ldots\ \text{(small)}$$

II There will be CP or T violation

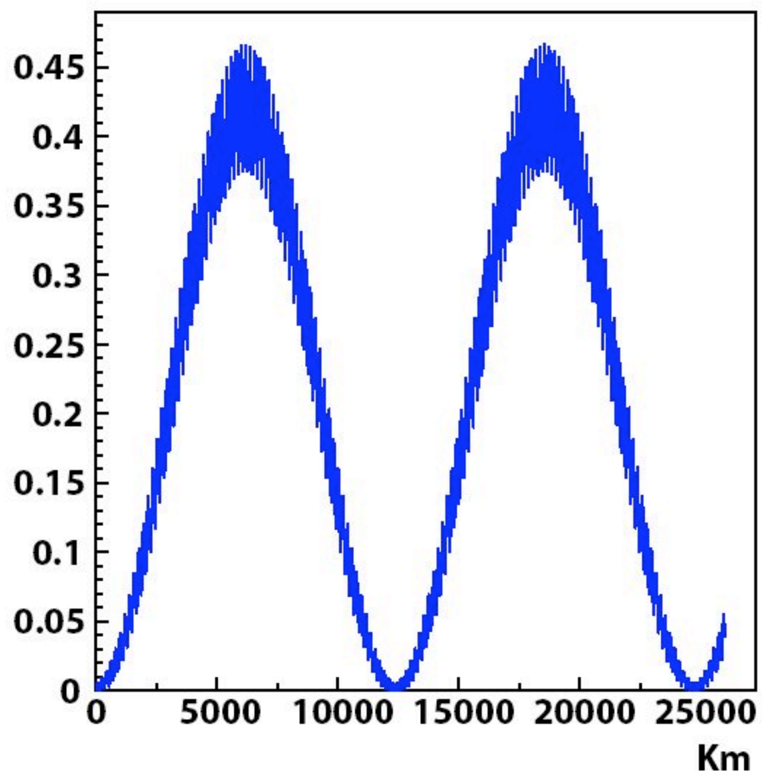
CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

T : $P(\nu_\mu \leftrightarrow \nu_e) \neq P(\nu_e \leftrightarrow \nu_\mu)$

III. we do not know if the neutrino ν_1 which contains more ν_e
is the lightest one (natural?)
or not.

Oscillations of 250 MeV neutrinos;

$P(\nu_\mu \leftrightarrow \nu_e)$



Three family oscillations look at $\nu_\mu \rightarrow \nu_e$ oscillation

Mezzetto

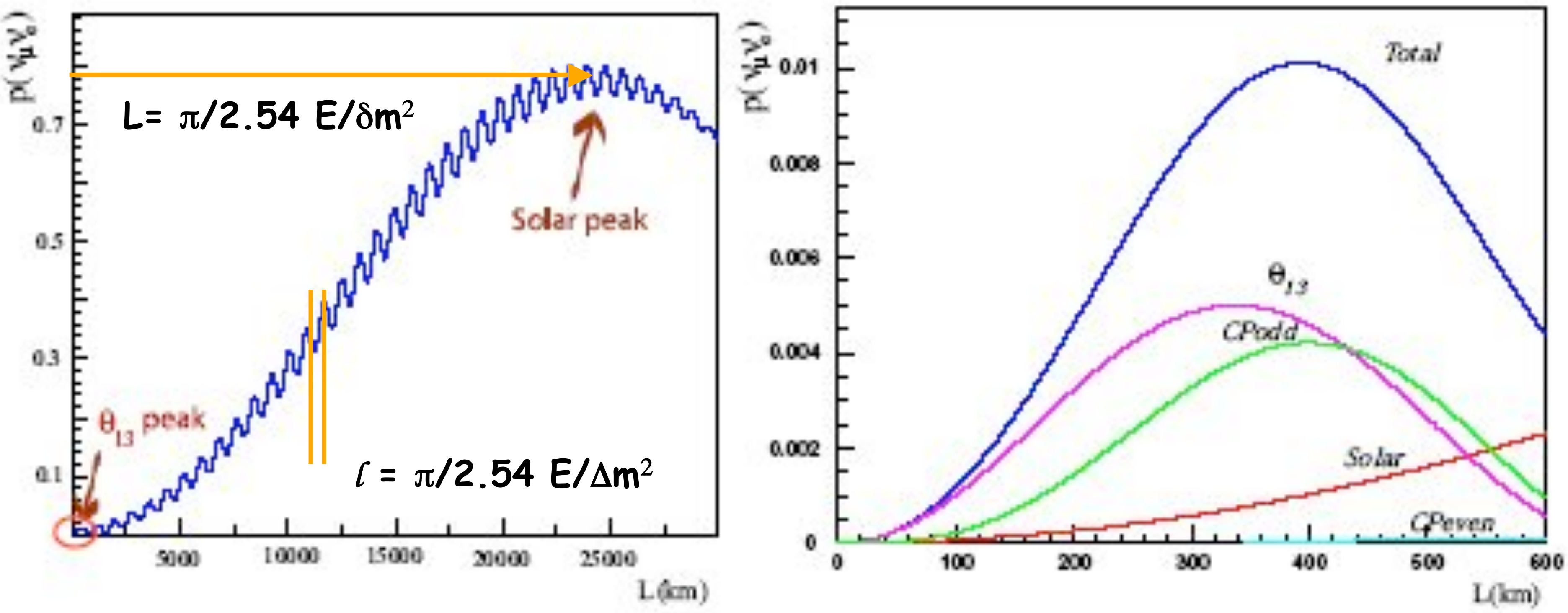


Figure 3: Sketch of $P(\nu_\mu \rightarrow \nu_e)$ as function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for $\delta_{CP}=0$ (left) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (right), where the different terms of eq. 4 are displayed. The following oscillation parameters were used in both cases: $\sin^2 2\theta_{13} = 0.01$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2, $\Delta m^2_{12} = 7 \cdot 10^{-5}$ eV^2.

$$p(\nu_\mu \to \nu_e) =$$

$$4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

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

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

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

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

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} = A_{CP} \;\alpha\; \frac{\sin\delta \;\; \sin(\Delta m^2_{12} L/4E) \;\; \sin\theta_{12} \sin\theta_{13}}{\sin^2 2\theta_{13} + \text{solar term}\ldots}$$

… need large values of $\sin\theta_{12}$, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

… need APPEARANCE … $P(\nu_e \to \nu_e)$ is time reversal symmetric (reactors or sun are out)

… can be large (30%) for suppressed channel (one small angle vs two large)

at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \to \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$

$$P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2\,A\,S\ \sin\delta$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2\,A\,S\ \sin\delta$$

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

… need large values of sin θ_{12}, Δm^2_{12} (LMA) but *not* large $\sin^2\theta_{13}$

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at wavelength at which 'solar' = 'atmospheric' and for $\nu_e \rightarrow \nu_\mu$, ν_τ

… asymmetry is opposite for $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$

T asymmetry for sin δ = 1

!

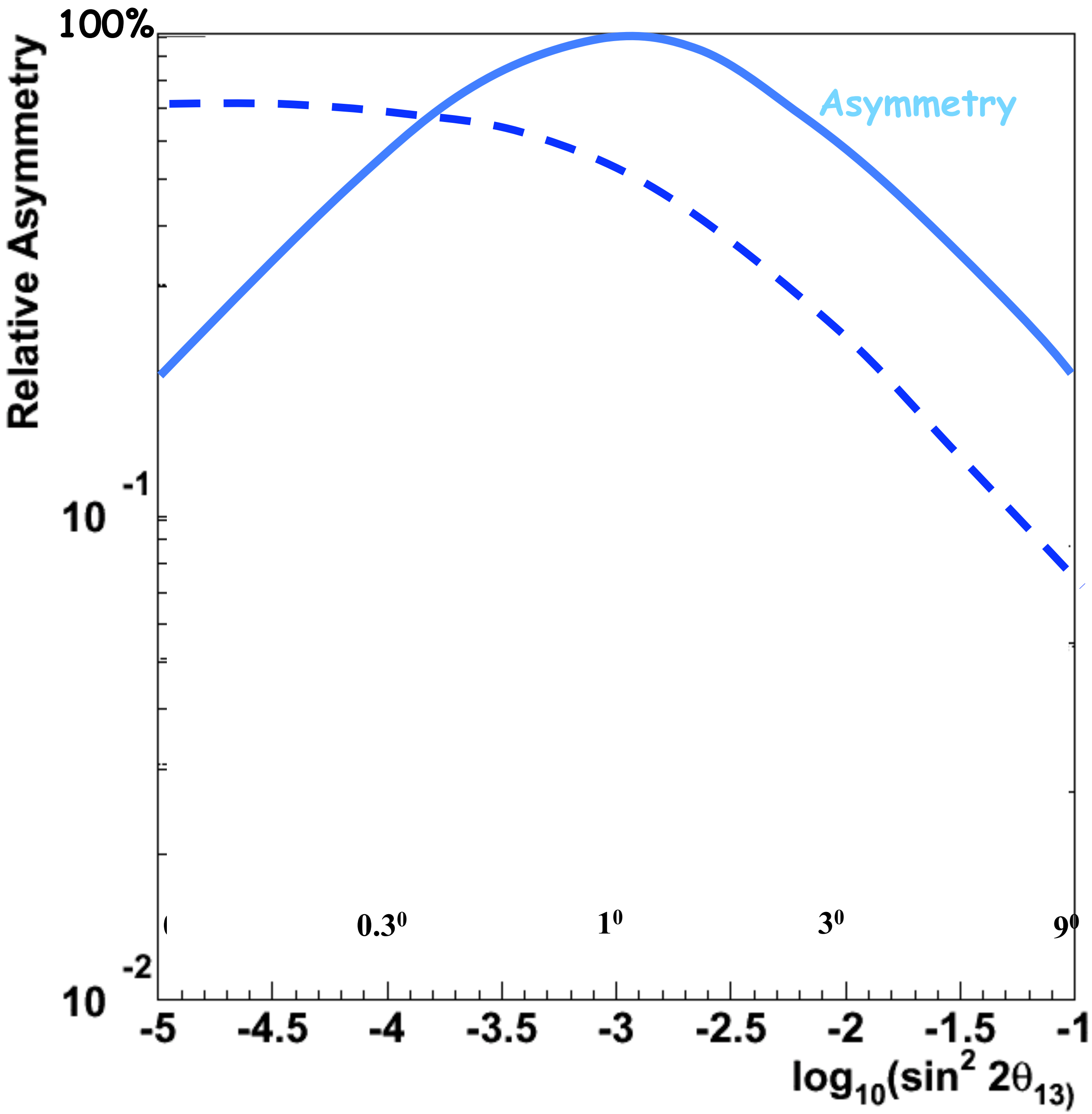
asymmetry is a few % and requires excellent flux normalization (neutrino fact., beta beam or off axis beam with not-too-near near detector)

NOTES:

1. sensitivity is more or less independent of θ_{13} down to max. asymmetry point

2. This is at first maximum! Sensitivity at low values of θ_{13} is better for short baselines, sensitivity at large values of θ_{13} is better for longer baselines (2d max or 3d max.)

3.sign of asymmetry changes with max. number.



The next generation (2009-2015+)

Reactor experiments D-CHOOZ, Daya Bay will measure $\bar{\nu}_e$ disappearance
-> no sensitivity to δ or matter effects
-> sensitive to $\sin^2 2\theta_{13}$

T2K will be sensitive to $\nu_\mu \rightarrow \nu_e$ appearance at low energy and short baseline (295 km, ~600 MeV) and may run antineutrino
-> little sensitivity to matter effects
-> sensitive to $\sin^2 2\theta_{13}$ and δ

NOvA will be sensitive to $\nu_\mu \rightarrow \nu_e$ appearance at mid-energy and baseline (810km, 2 GeV) and may run antineutrino
-> larger sensitivity to matter effects --> $\pm\Delta m^2_{13}$
-> sensitive to $\sin^2 2\theta_{13}$ and δ

Combination of the three may say something about $\{\theta_{13}, \delta, \pm\Delta m^2_{13}\}$

ONLY IF θ_{13} is large -- but then A_{CP} is small

These experiments will need to publish a quantity like $P(\nu_\mu \rightarrow \nu_e)\{L, E_\nu\}$

Typical measurement:

$$\frac{\{ N''(\nu_e N \to e X)''_{cuts} - Bkg \} \text{ (far det.)}}{\{ N''(\nu_\mu N \to \mu X)''_{other\ cuts} - Bkg \} \text{ (near det.)}} \times \frac{\Phi_{Near}}{\Phi_{Far}} \times \frac{\sigma(\nu_\mu N \to \mu X)_{other\ cuts}}{\sigma(\nu_e N \to e X)_{cuts}}$$

Thus, knowledge of $\sigma(\nu_\mu N) / \sigma(\nu_e N)$ will be necessary -- within cuts! --

--> physics understanding + implementation in Monte Carlo.

Even with assumption of lepton universality this is not a completely easy task

Lepton mass effect X nuclear effects --> uncertainties

Further in the future… (these projects are under discussion / study)

Fermilab to DUSEL (π,K ν_μ beam, 1300 km, 300kton WC or 50kton Larg)

T2K future projects (π,K ν_μ beam, 300-1000 km, 500kton WC or 100kton Larg)

CERN SPL + Beta-beam (π ν_μ beam, beta-decay ν_e beam)

Neutrino factory (μ decay ν_μ ν_e beam)

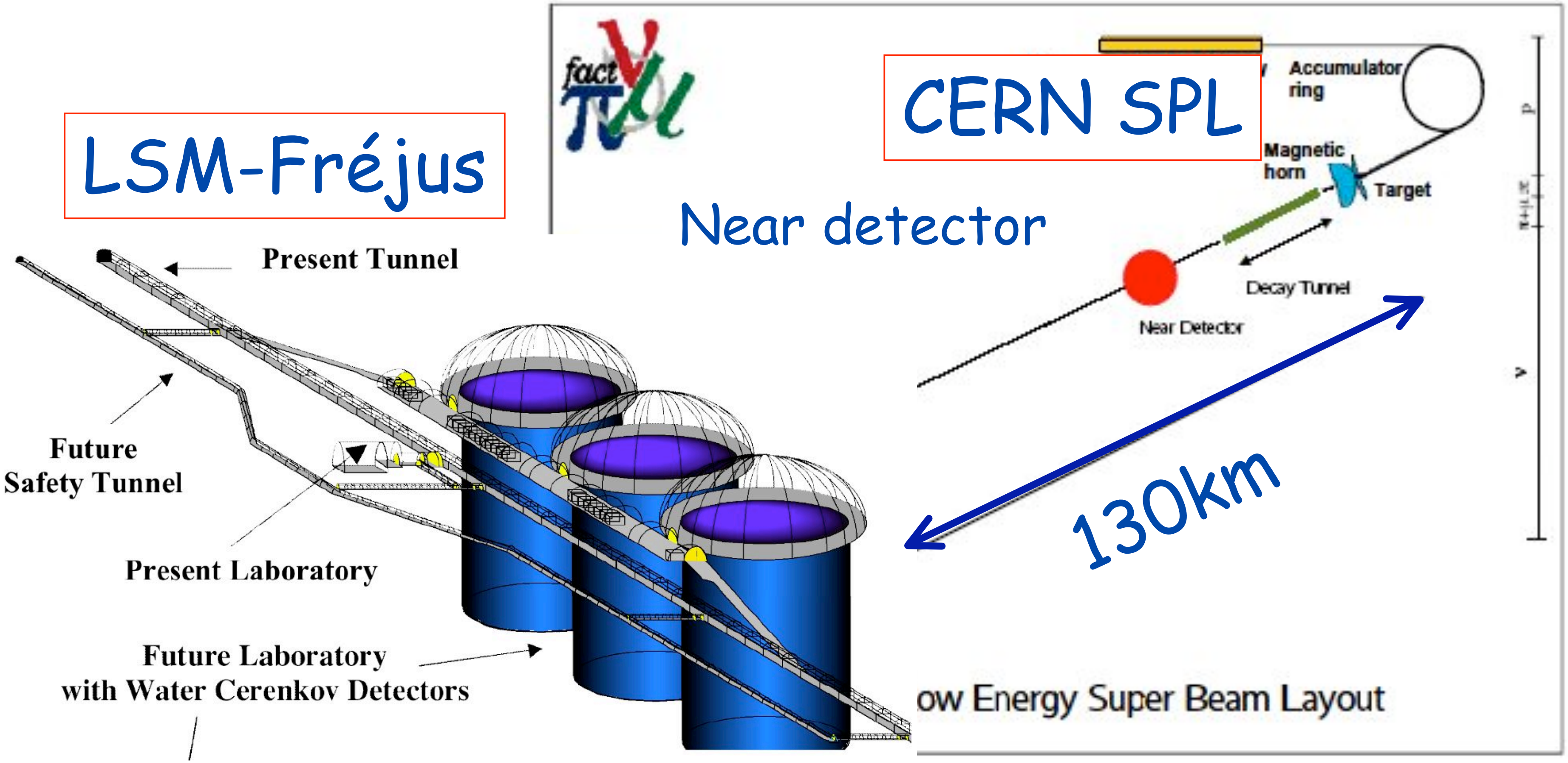
Three Possible Scenario Studied at NP08 Workshop

NP08 is **The 4th International Workshop on Nuclear and Particle Physics at J-PARC**

http://j-parc.jp/NP08

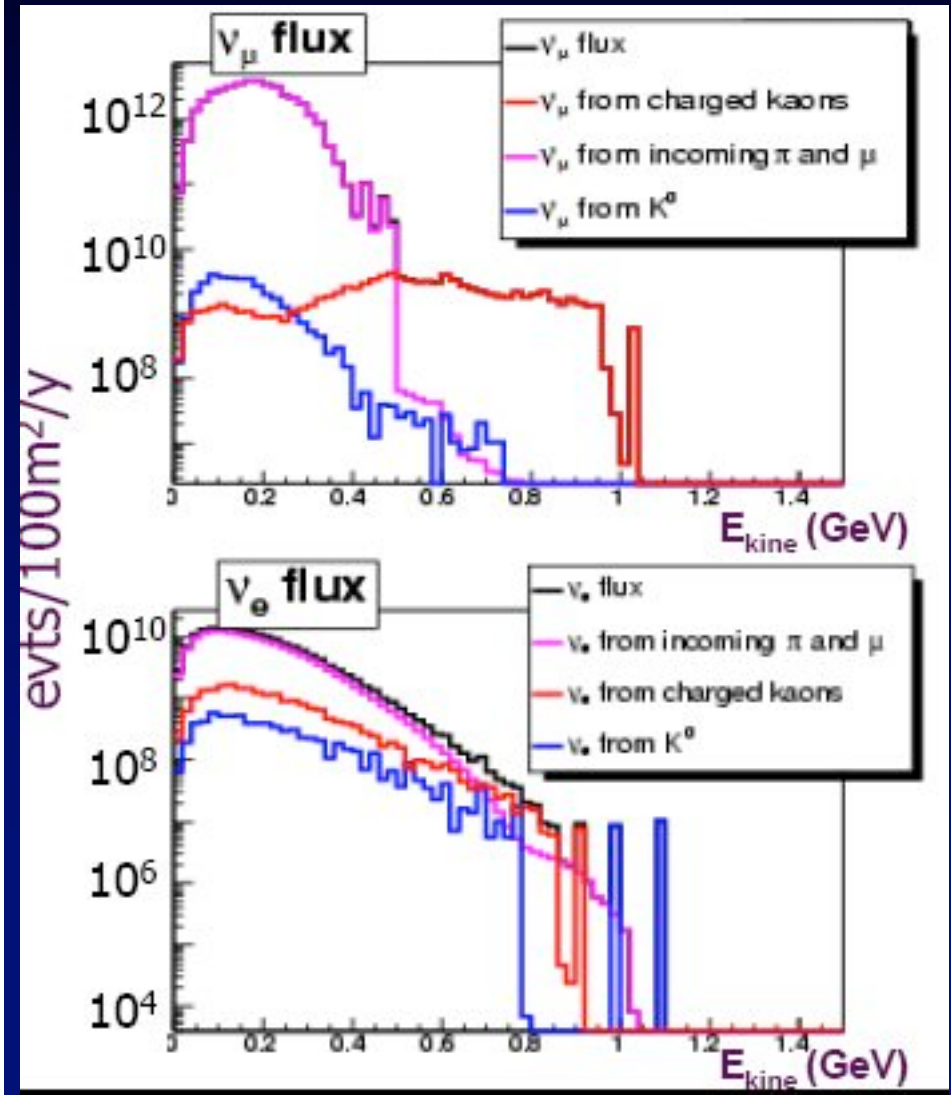
Future project	$\sin^2 2\theta_{13}$, sign (Δm^2_{13}) CP	methods
DCHOOZ (2010) DAYA BAY(2012)	0.03 - 0.01 no no 0.02-0.008 no no	Reactor + scintillator Near + far (1km) baselines up to 1.8km
T2K (2010) T2K+ (2020)	0.01 no no 0.001? Yes? ?	Near (scint. + TPC) Far (Water Ckov)50kt Far= 250-500 kt WC a/o 100kt Larg TPC?
3. NOvA (2012) 4. DUSEL (2017)	0.01 W/T2K no 0.001 Yes? ?	Active Scintillator WC, (TASD, Larg)?
5. CERN?(2022) -- SB to Frejus ? -- BB to Frejus ?	Combination allows 0.001 no yes	SB or BB + 500 kt WC
-- neutrino factory (2025)	0.0001 Yes Yes	muon decay beam magnetized Fe Mag Emulsions/Larg

Super-beams: SPL-Frejus



SPL (2.2 GeV) superbeam
20m decay tunnel
single open horn, L Hg target

Low energy --> low Kaon rate
better controlled ν_e
contamination

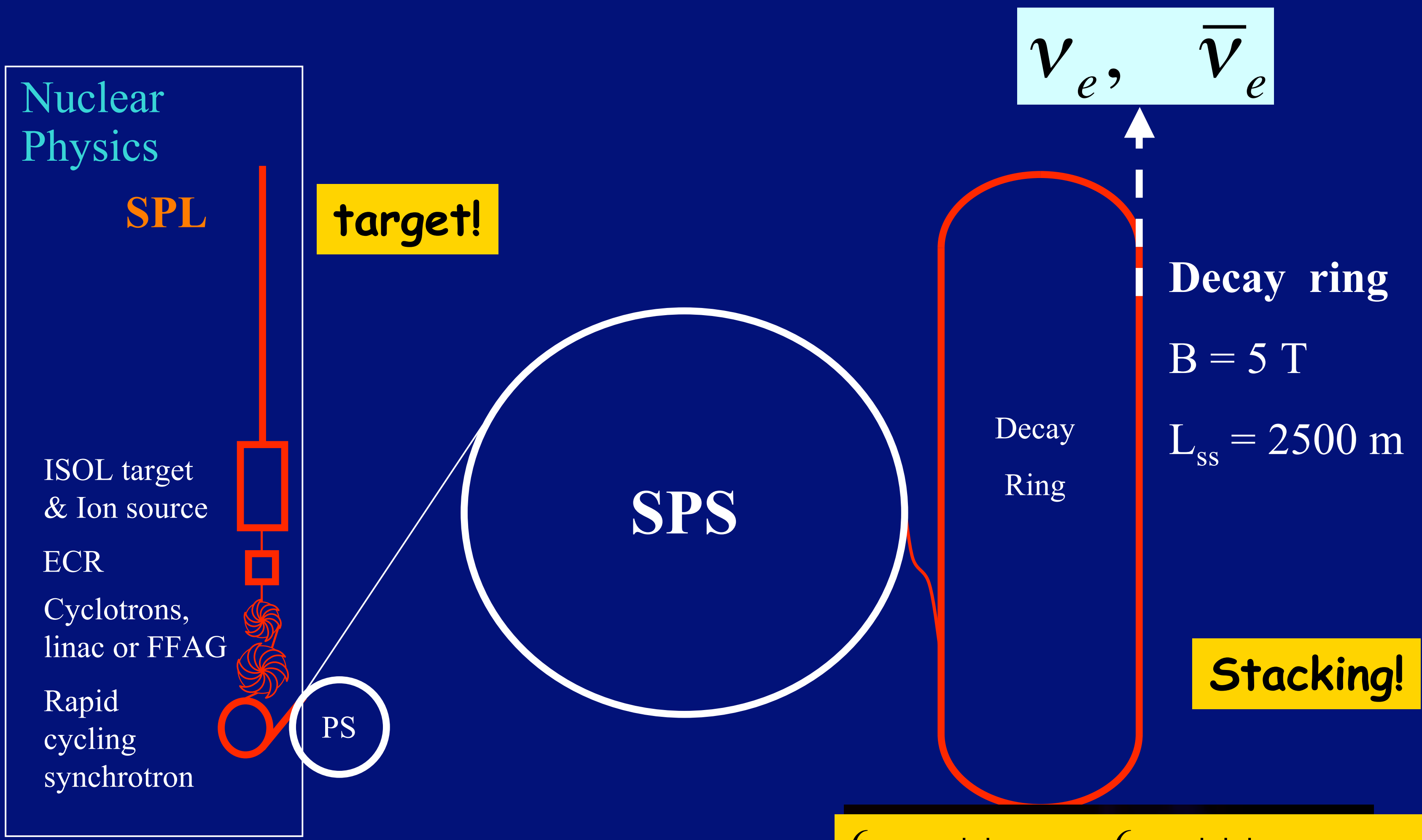


	positive focusing	
	Flux (/100m²/y)	Majoritary composition
ν_μ	3.89 10^{13}	π^+ (99%)
$\bar{\nu}_\mu$	3.19 10^{12}	π^- (99%)
ν_e	1.77 10^{11}	$\pi^+ \to \mu^+$(80%)
$\bar{\nu}_e$	1.24 10^{10}	K^0 (55%); $\pi^- \to \mu^-$(45%)

	negative focusing	
	Flux (/100m2/y)	Majoritary composition
ν_μ	1.42 10^{13}	π^- (98%)
$\bar{\nu}_\mu$	6.65 10^{13}	π^+ (99.5%)
ν_e	1.19 10^{11}	K^+ (50%);K^0 (30%) $\pi^+ \to \mu^+$(20%)
$\bar{\nu}_e$	1.87 10^{11}	$\pi^- \to \mu^-$(80%)

CERN: β-beam baseline scenario

neutrinos of E_{max}=~600MeV



$${}^{6}_{2}He^{++} \rightarrow {}^{6}_{3}Li^{+++} \, \bar{\nu}_e \, e^-$$

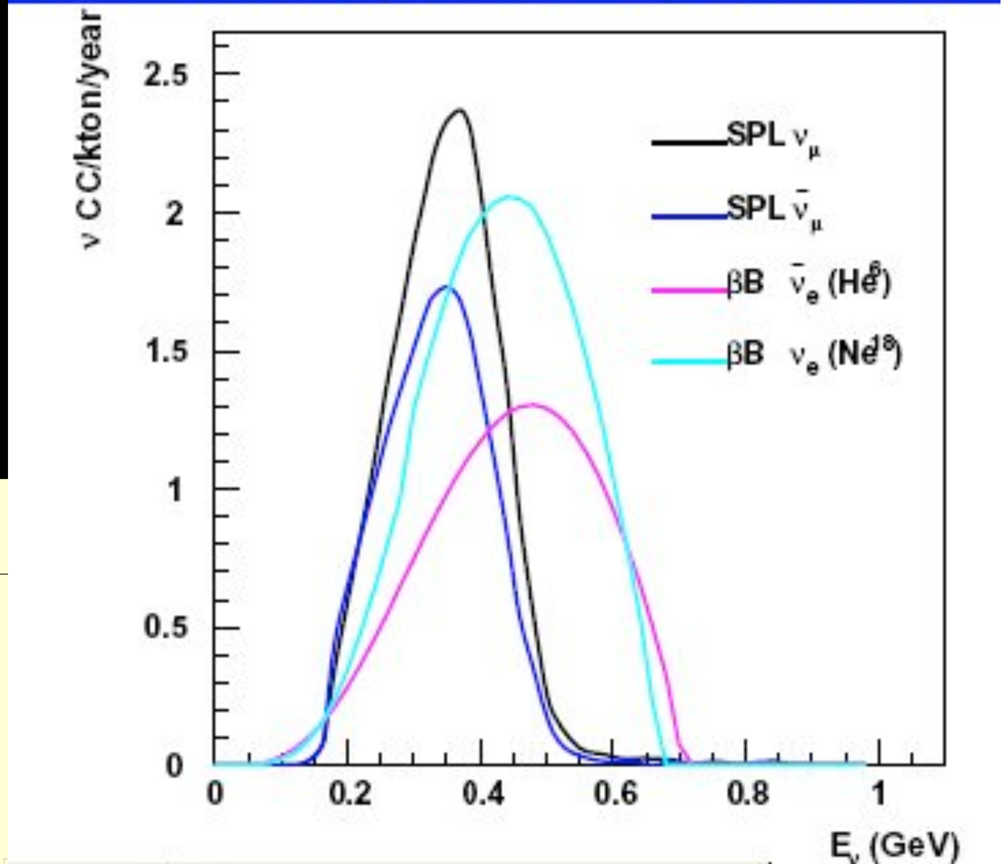
$${}^{18}_{10}\mathrm{Ne} \rightarrow {}^{18}_{9}\mathrm{F} \, \nu_e \, e^+$$

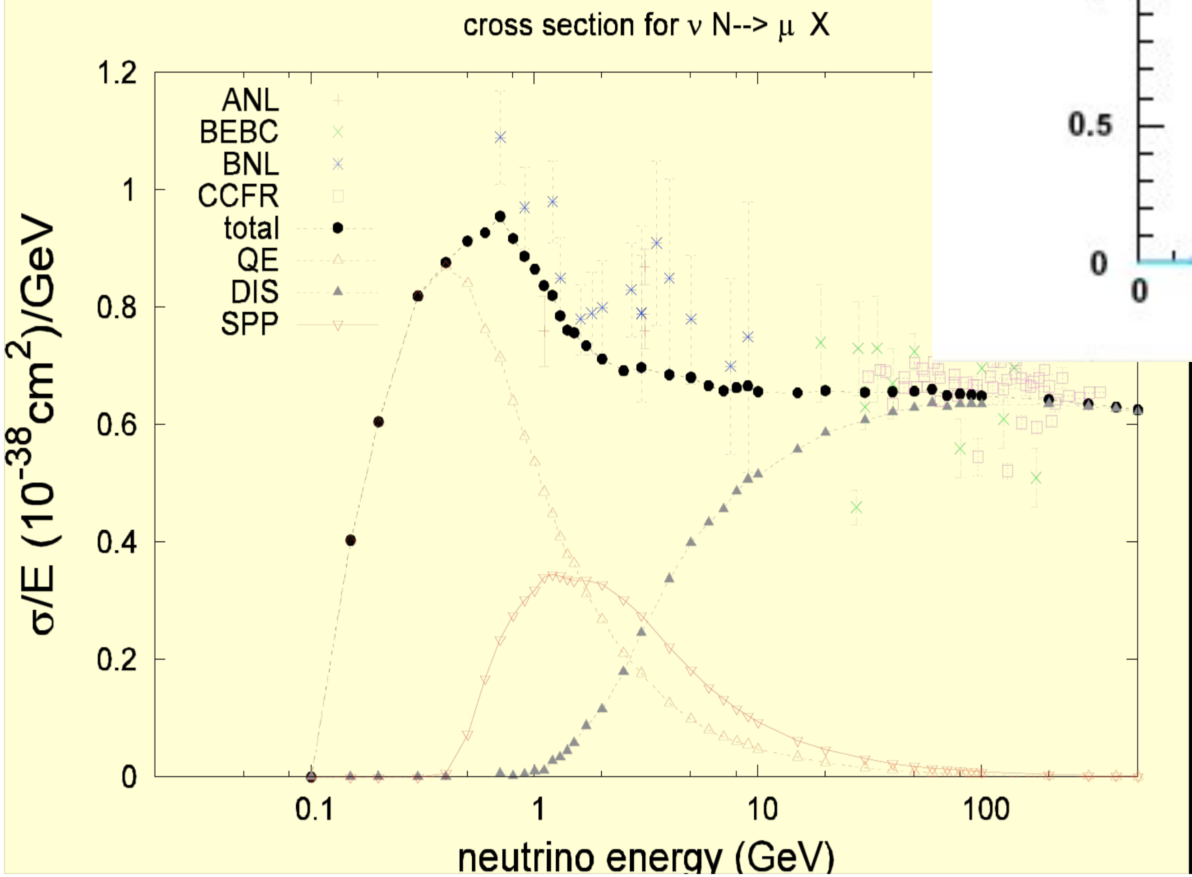
Same detectors as Superbeam !

3.5 GeV SPL

$\gamma = 100$ β–beam

Averaged yearly CC rates in a 10 years run for CP

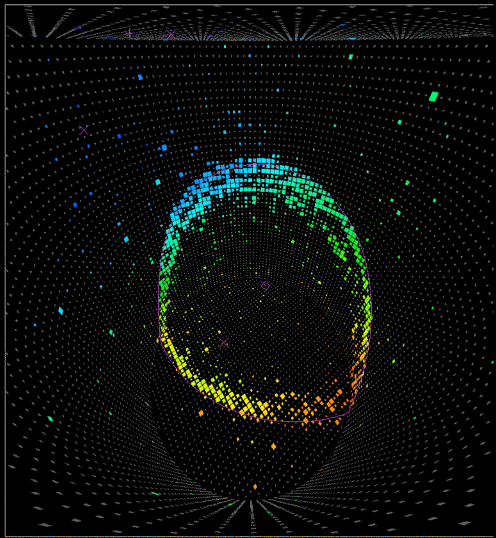


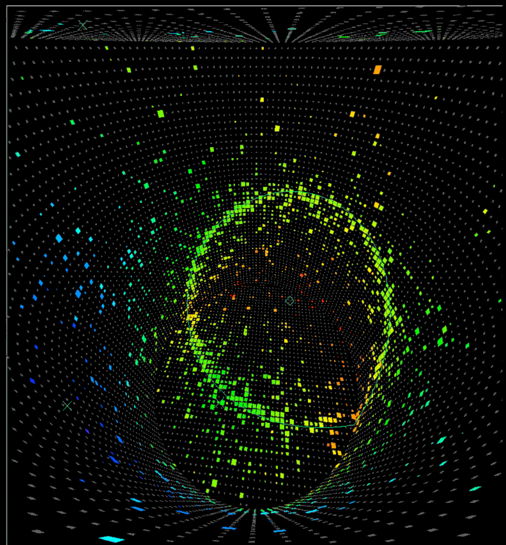


-- low proton energy:
no Kaons → ν_e background is low
--region below pion threshold
(low bkg from pions)

but:
low event rate and
uncertainties on cross-sections

Combination of beta beam with super beam





combines CP and T violation tests

$\nu_e \rightarrow \nu_\mu$ $(\beta+)$ **(T)** $\nu_\mu \rightarrow \nu_e$ (π^+)

(CP)

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $(\beta-)$ **(T)** $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (π^-)

Eurisol baseline Study

CERN site
-- could benefit from PS2
Max. γ_{ion} in CERN SPS is 450 GeV Z/M_{ion}
γ = 150 for ^{6}He,
γ = 250 for ^{18}Ne ==> $E_{\nu} \sim$ 600 MeV

$E_{\nu}^{max} = 2.\ Q_0.\ \gamma_{ion}$

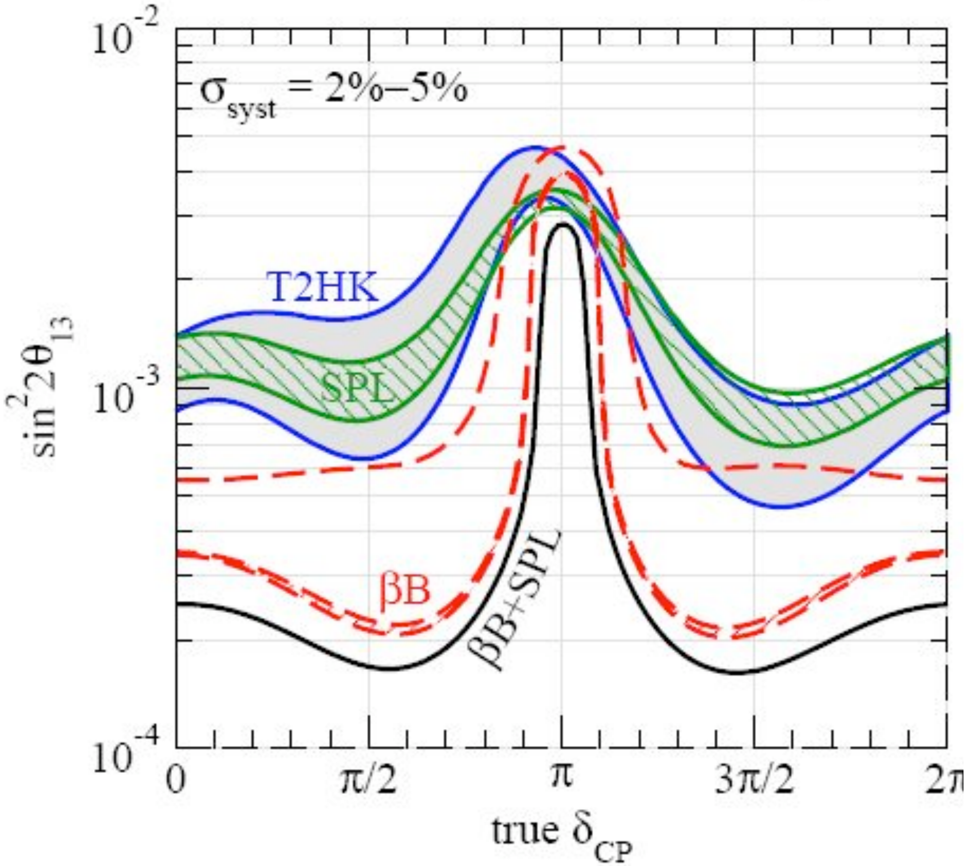
2.9×10^{18} /yr anti-ν_e from ^{6}He
Or 1.1×10^{18} /yr ν_e from ^{18}Ne

race track (one baseline) or triangle (2 base lines)
so far study CERN--> Fréjus (130km)

longer baseline ~ 2-300km would be optimal
+ moderate cost: ion sources, 450 GeV equiv. storage ring (O(0.5M€))
+ no need for 4MW target

3σ sensitivity to $\sin^2 2\theta_{13}$

10 year exposure



issues:

-- ^{18}Ne flux?
-- low energy
--> cross-section accuracy?
(assume 2%)
-- energy reconstruction OK
-- near detector concept?

sensitivity $\sin^2 2\theta_{13}$ ~2-5 10^{-4}

combine SPL(3.5 GeV) + βB
==> improves sensitivity by T violation!

J-E. Campagne et al. hep/ph0603172

near detector constraints for CP violation

ex. beta-beam or nufact:

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

Near detector gives ν_e diff. cross-section*detection-eff *flux   and ibid for bkg

BUT: need to know ν_μ and $\bar{\nu}_\mu$ diff. cross-section* detection-eff

with small (relative) systematic errors.

→knowledge of cross-sections (relative to each-other) required
→knowledge of flux!

interchange role of ν_e and ν_μ for superbeam experimental signal= signal cross-section X efficiency of selection + Background

$$\sigma_{sig} = \sigma \times \varepsilon + B$$

need to know this:

$$\frac{\sigma_{sig}^{\nu_e} / \sigma_{sig}^{\nu_\mu}}{\sigma_{sig}^{\bar{\nu}_e} / \sigma_{sig}^{\bar{\nu}_\mu}}$$

this is not a totally trivial quantity as there is somethig particular in each of these cross-sections:

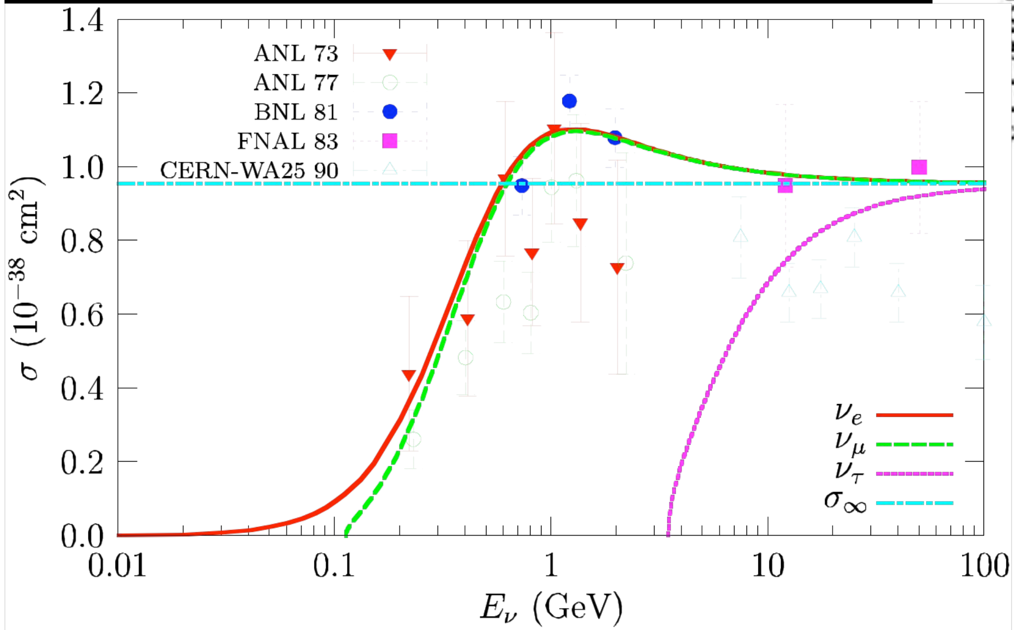
for instance the effects of muon mass as well as nuclear effects are different for neutrinos and anti-neutrinos

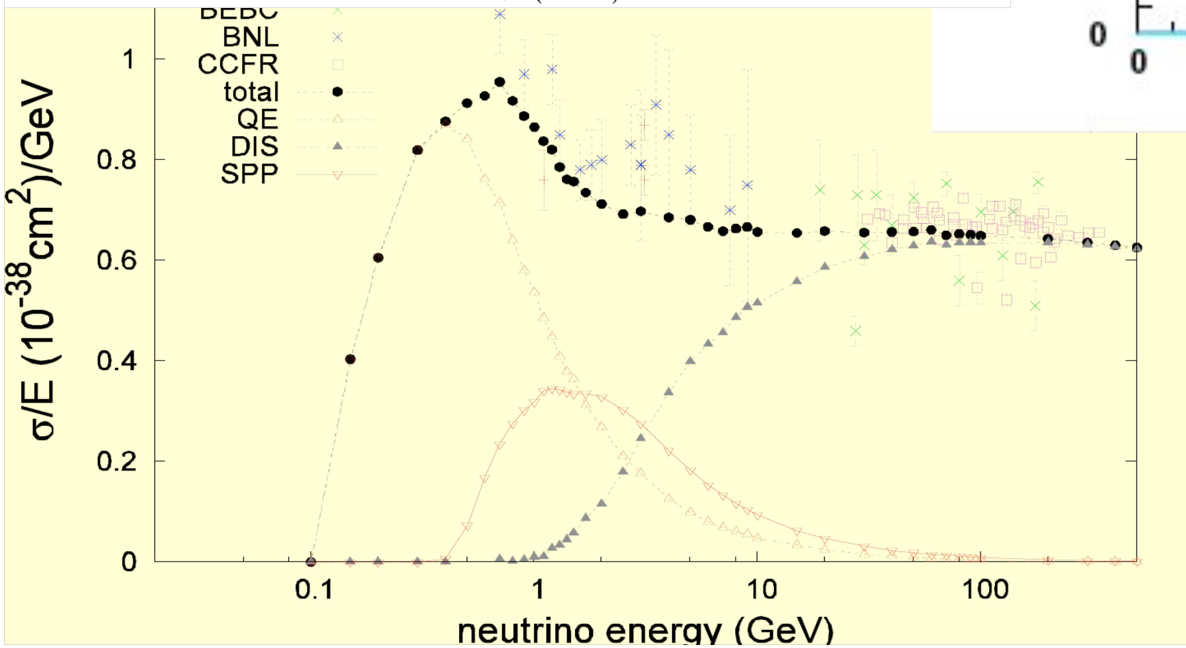
while e.g. pion threshold is different for muon and electron neutrinos

and of course the fluxes... but the product flux*σ_{sig} is measured in the near detector

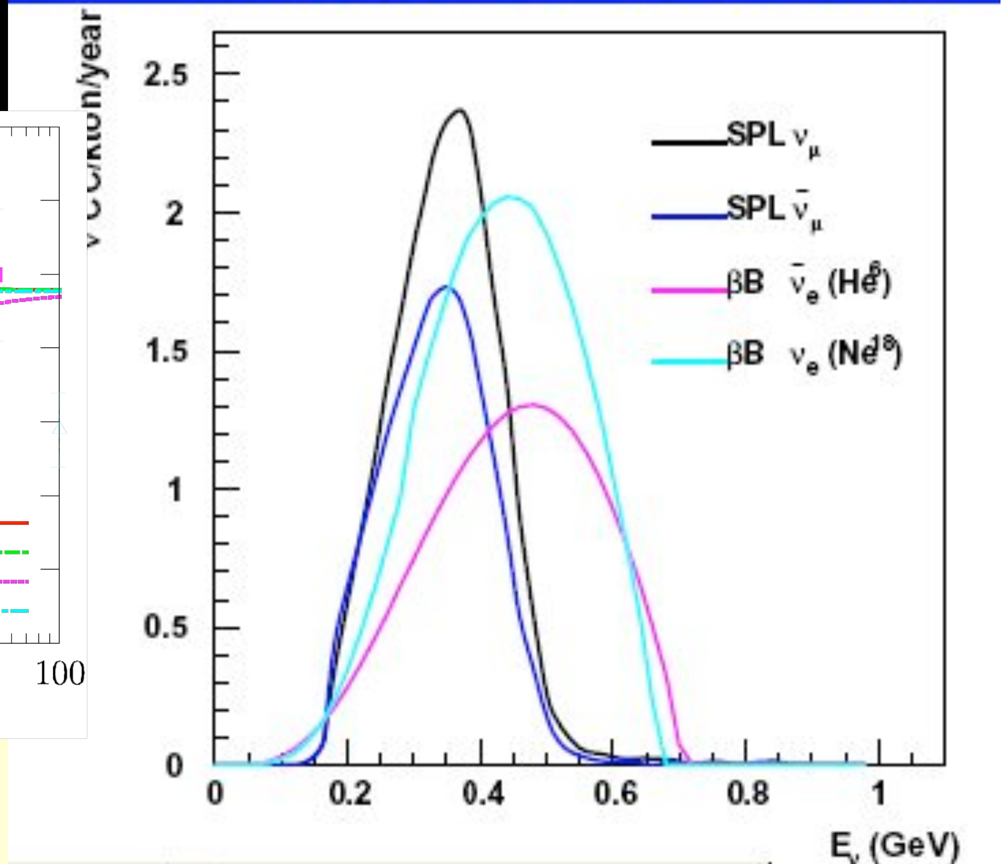
3.5 GeV SPL

$\gamma = 100$ β–beam





Averaged yearly CC rates in a 10 years run for CP



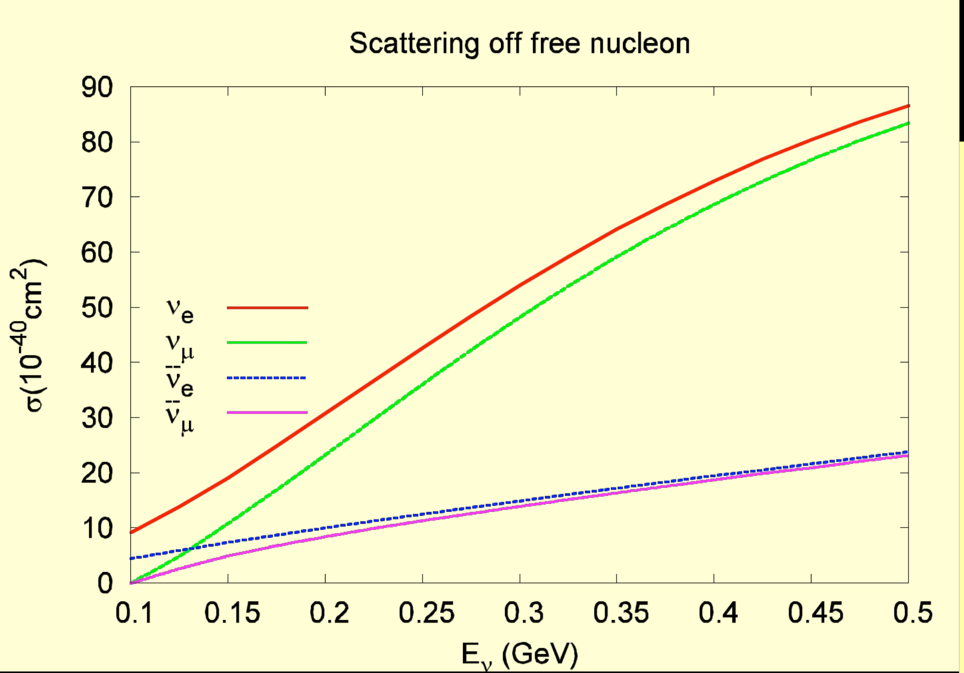
-- low proton energy:
no Kaons → ν_e background is low
--region below pion threshold
(low bkg from pions)

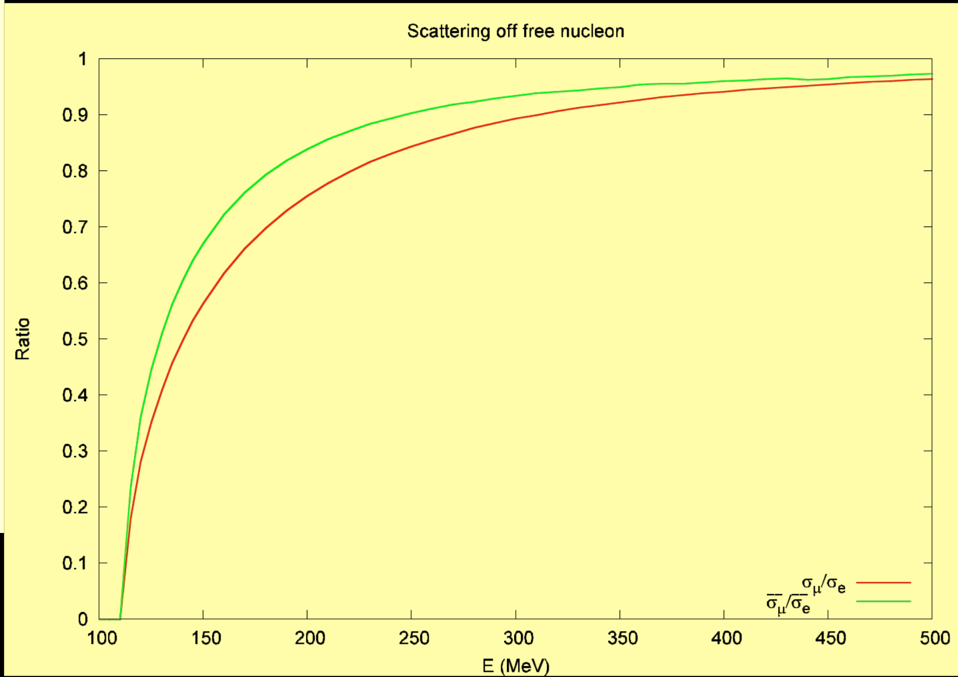
but:
low event rate and
uncertainties on cross-sections

Uncertainties in the double ratio (Sobczyk et al)

1. problem comes from compound of
Fermi motion and binding energy
with the muon mass effect.

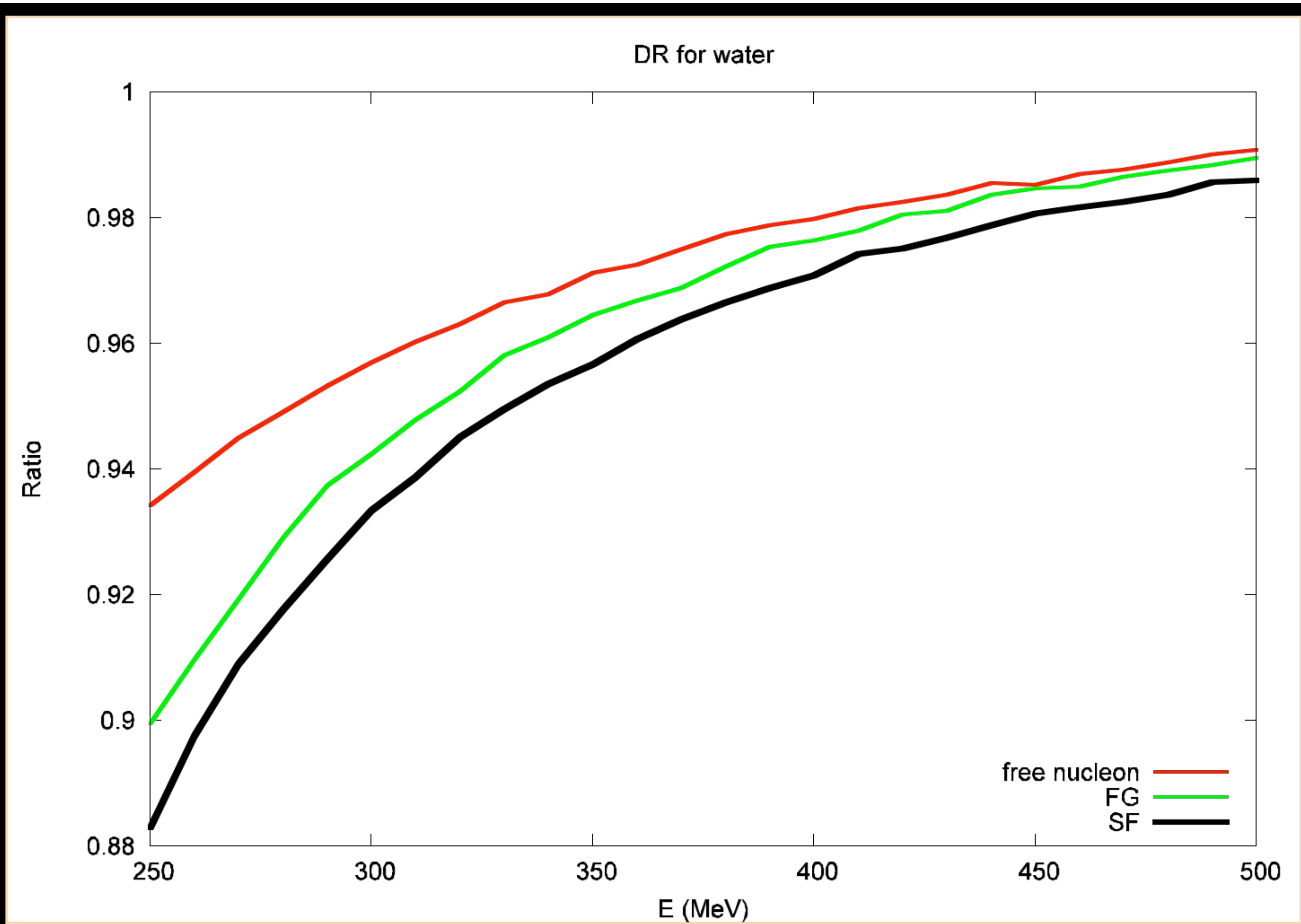
$$R \equiv \frac{\sigma(\nu_\mu)}{\sigma(\nu_e)}, \qquad \bar{R} \equiv \frac{\sigma(\bar{\nu}_\mu)}{\sigma(\bar{\nu}_e)}$$





the double ratio calculation is very insensitive to variations of parameters … but

$$DR \equiv \frac{\dfrac{\sigma(\nu_\mu)}{\sigma(\nu_e)}}{\dfrac{\sigma(\bar{\nu}_\mu)}{\sigma(\bar{\nu}_e)}}$$



at 250 MeV (first maximum in Frejus expt) prediction varies from 0.88 to 0.94 according to nuclear model used. (= +- 0.03-0.05?)

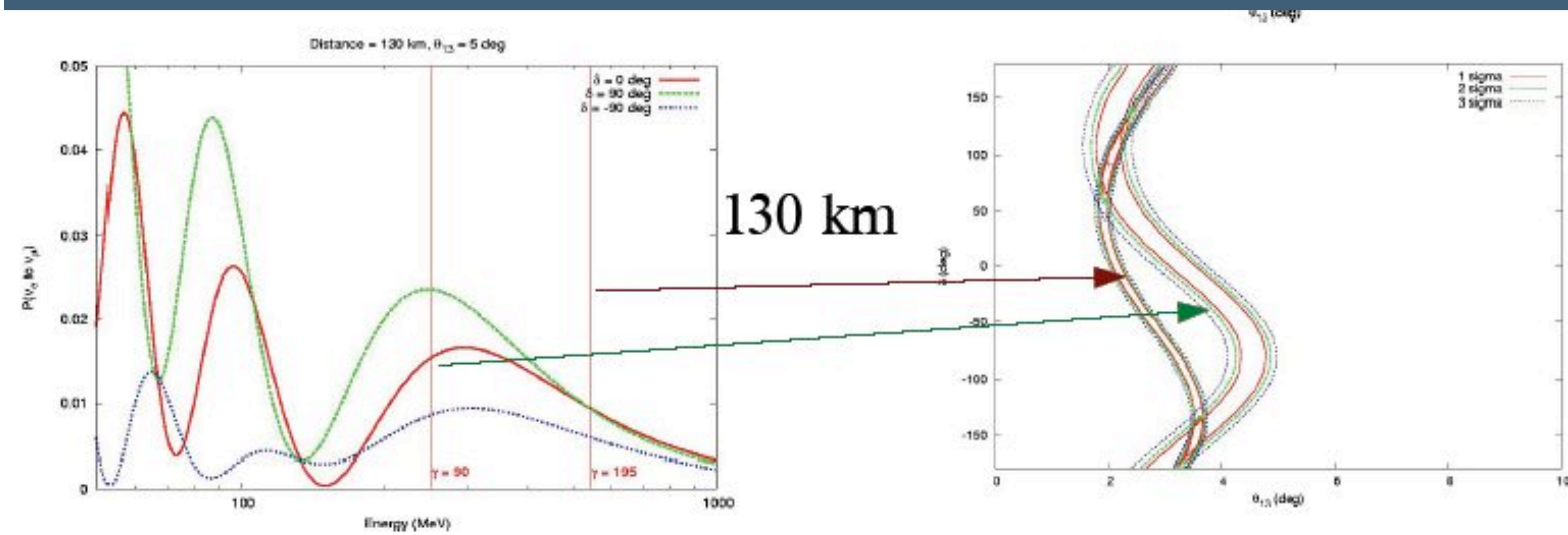
Hope to improve results with e.g. monochromatic k-capture beam

EC: A monochromatic neutrino beam

Electron Capture: $N+e^- \rightarrow N'+\nu_e$

Decay	$T_{1/2}$	BR_ν	EC/ν		B(GT)	E_{GR}	Γ_{GR}	Q_{EC}	E_ν	ΔE_ν
$^{148}Dy \rightarrow {}^{148}Tb^*$	3.1 m	1	0.96	0.96	0.46	620		2682	2062	
$^{150}Dy \rightarrow {}^{150}Tb^*$	7.2 m	0.64	1	1	0.32	397		1794	1397	
$^{152}Tm2^- \rightarrow {}^{152}E_T{}^*$	8.0 s	1	0.45	0.50	0.48	4300	520	8700	4400	520
$^{150}Ho2^- \rightarrow {}^{150}Dy^*$	72 s	1	0.77	0.56	0.25	4400	400	7400	3000	400

This has been advocated as a good way to perform oscillation measurements…

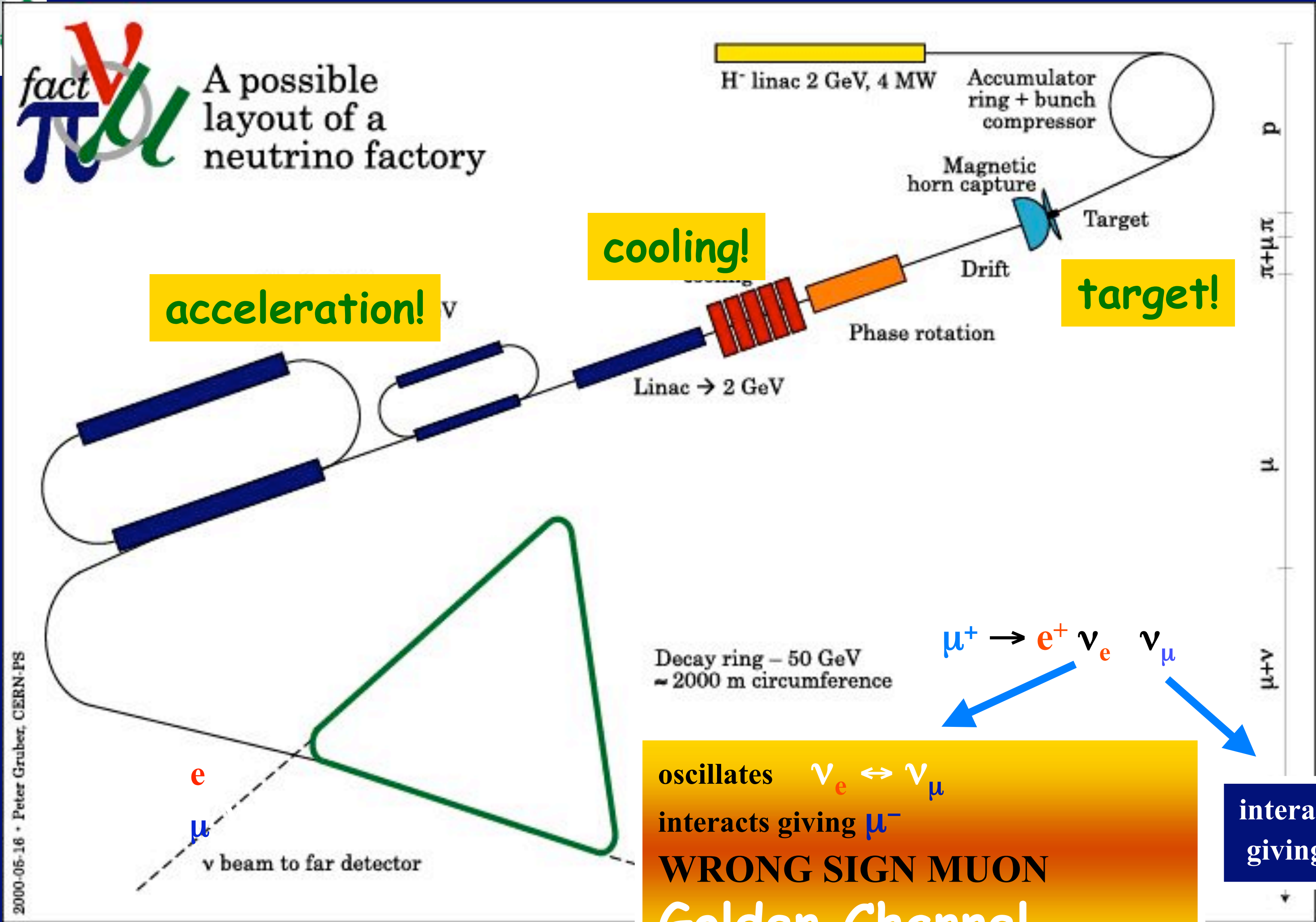


Electron Capture: $N+e^- \rightarrow N'+\nu_e$

Unfortunately the rate of decay of these isotopes is very long,
and the number of stored ions correspondingly lower
==> intensities likely to be too small for oscillation experiments.

The possibility to have a tuneable monochromatic beam for cross-section measurements in a near detector remains tentalizing.

-- Neutrino Factory -- CERN layout --

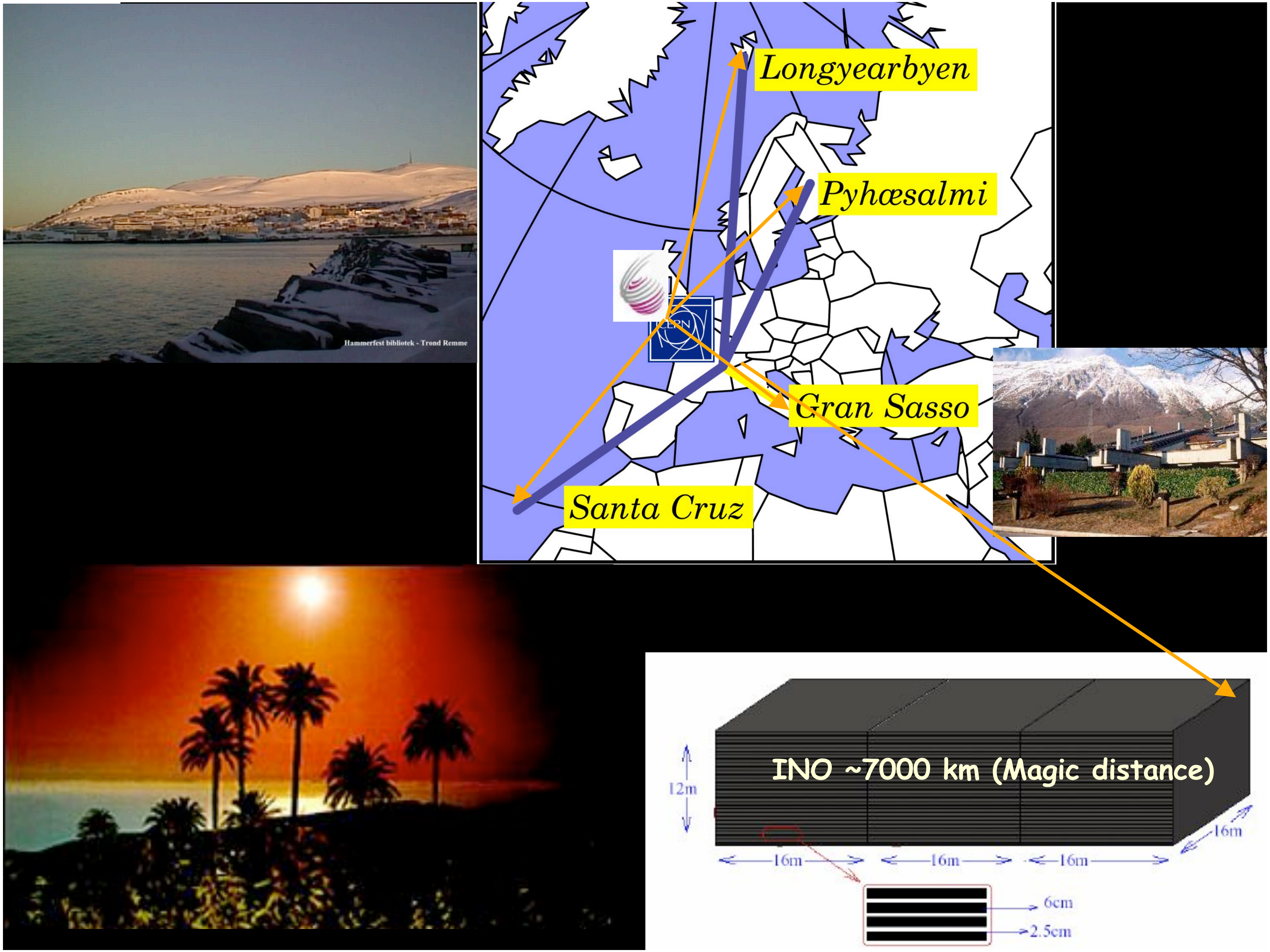


$\mu^+ \rightarrow e^+ \nu_e \;\; \nu_\mu$

oscillates $\nu_e \leftrightarrow \nu_\mu$
interacts giving μ^-
WRONG SIGN MUON
Golden Channel

interacts giving μ^+

also (unique) $\nu_e \leftrightarrow \nu_\tau$ Silver channel


Hammerfest bibliotek - Trond Remme
Longyearbyen
Pyhæsalmi
Gran Sasso
Santa Cruz
INO ~7000 km (Magic distance)
12m
16m
16m
16m
16m
6cm
2.5cm

Neutrino fluxes $\mu^+ \to e^+ \nu_e \nu_\mu$

ν_μ/ν_e ratio reversed by switching μ^+/μ^-
$\nu_e\ \nu_\mu$ spectra are different
No high energy tail.

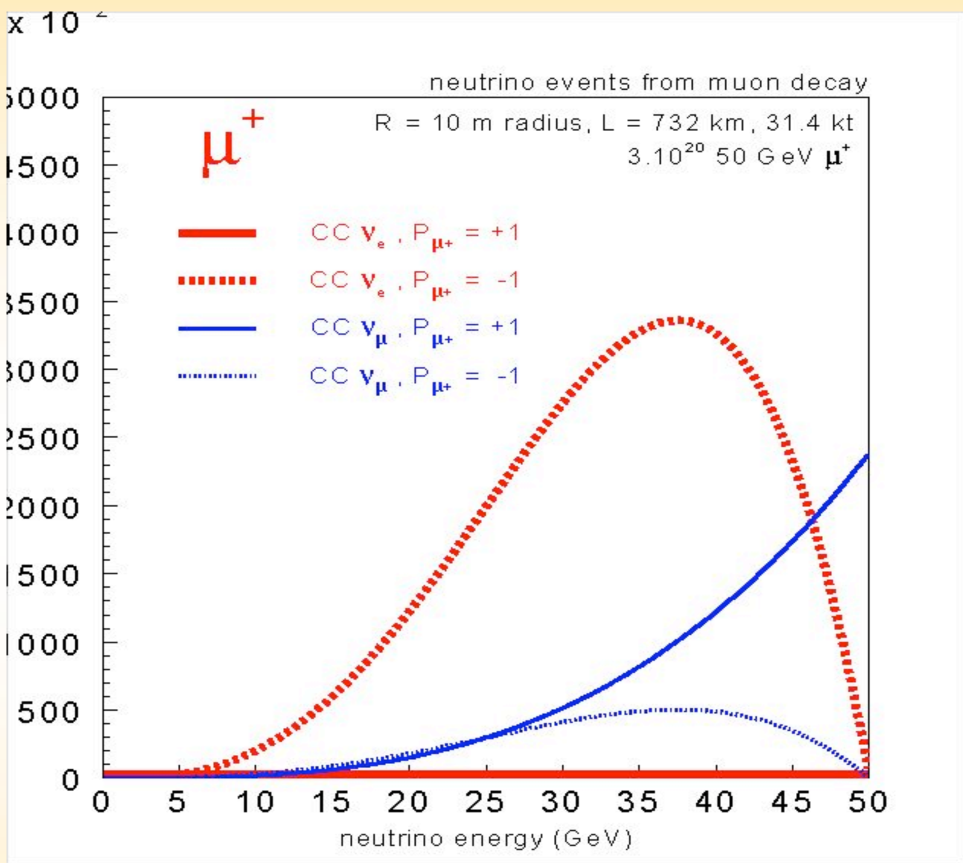
Very well known flux ($\pm 10^{-3}$)

-- $E\&\sigma_E$ calibration from muon spin precession

-- angular divergence: small effect if $\theta < 0.2/\gamma$,

-- absolute flux measured from muon current
or by $\nu_\mu\, e^- \to \mu^-\ \nu_e$ in near expt.

-- in triangle ring,
muon polarization precesses and averages out
(preferred, -> calib of energy, energy spread)



Similar comments apply to beta beam, except spin 0
→ Energy and energy spread have to be obtained from the properties of the storage ring
(Trajectories, RF volts and frequency, etc…)

μ polarization controls ν_e flux:

μ^+ -X> ν_e in forward direction

A revealing comparison:

A detailed comparison of the capability of observing CP violation was performed by P. Huber (+M. Mezzetto and AB) on the following grounds

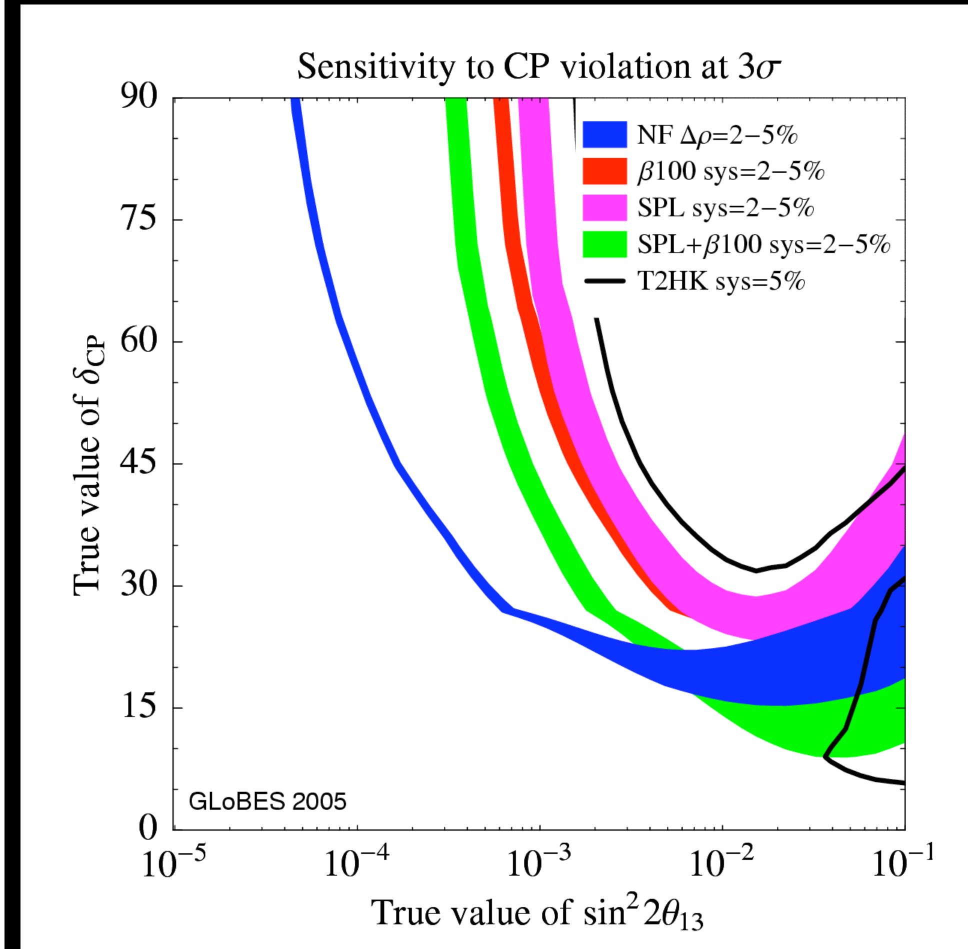
-- GLOBES was used.

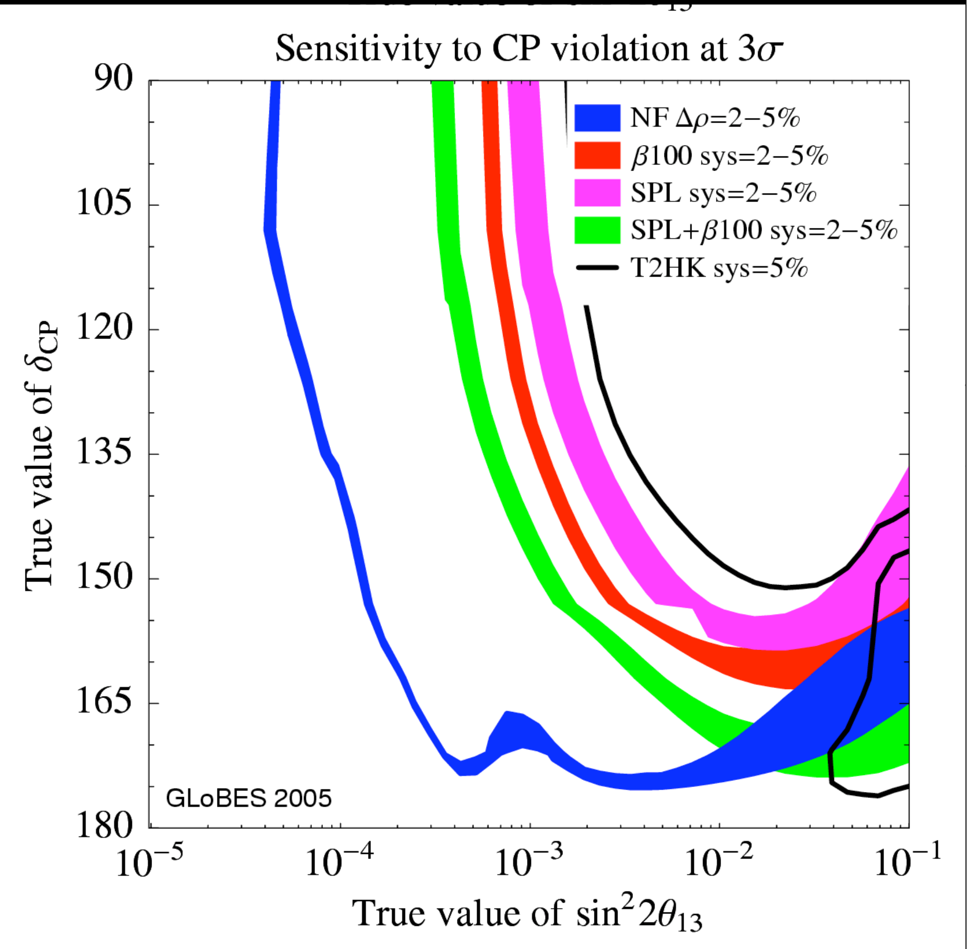
-- T2HK from LOI: 1000kt , 4MW beam power,
6 years anti-neutrinos, 2 years neutrinos.
systematic errors on background and signal: 5%.

-- The beta-beam 5.8 10^{18} He dk/year 2.2 10^{18} Ne dk/year (5 +5yrs)
The Superbeam from 3.5 GeV SPL and 4 MW.
Same 500kton detector
Systematic errors on signal efficiency (or cross-sections) and bkgs are 2% or 5%.

--NUFACT 3.1 $10^{20}\mu^+$ and 3.1 $10^{20}\mu^+$ per year for 10 years
100 kton iron-scintillator at 3000km and 30 kton at 7000km (e.g. INO).
The matter density errors of the two baselines (uncorrelated): 2 to 5%
The systematics are 0.1% on the signal and 20% on the background, uncorrelated.

all correlations, ambiguities, etc… taken into account

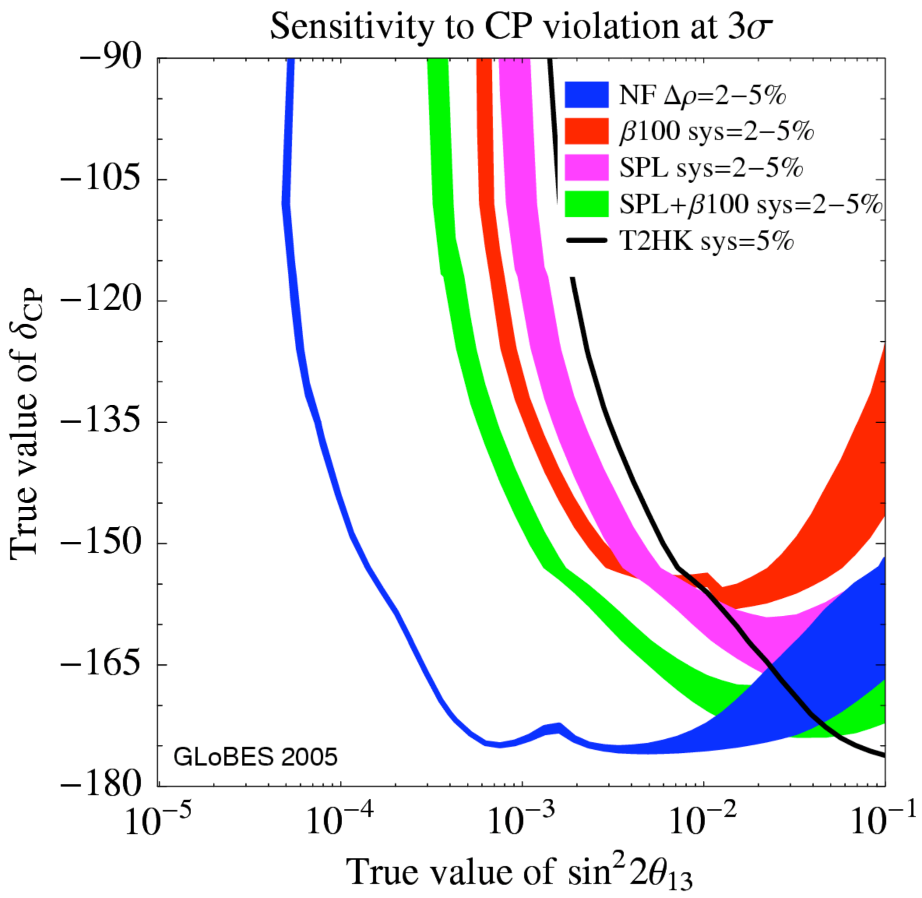


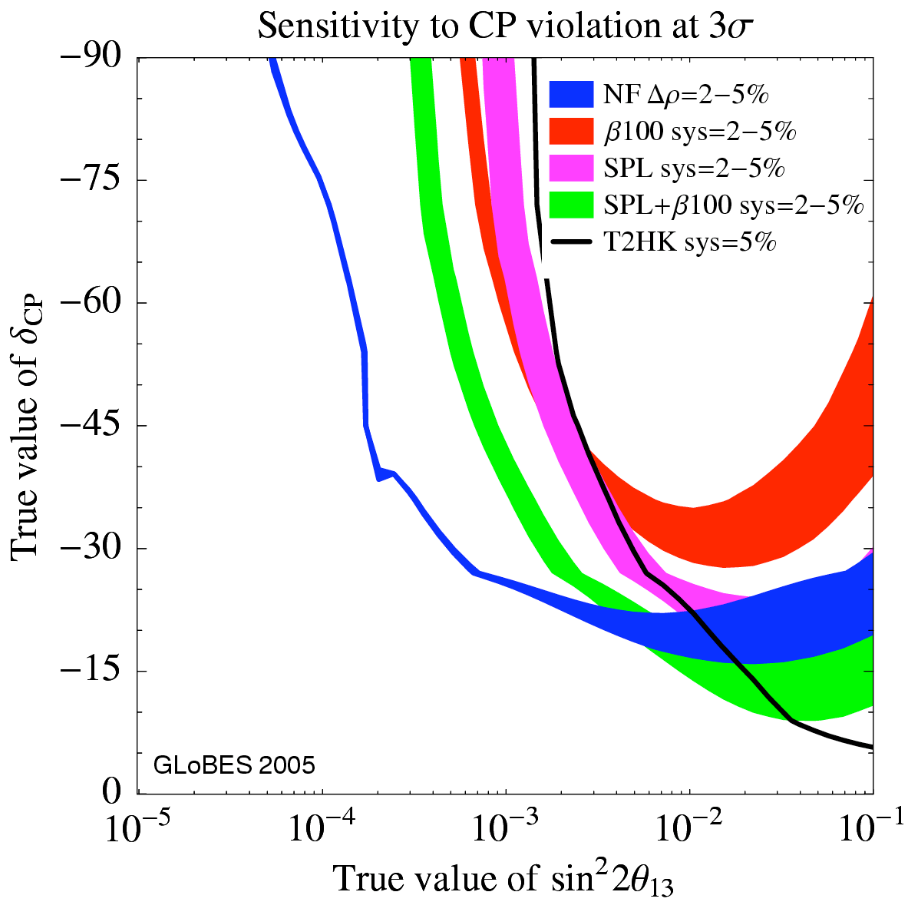


$\delta \in [0^0 - 90^0]$

$\delta \in [90^0 - 180^0]$

NB: 3sigma = 6^0 means that +-1 sigma = +-3.5^0

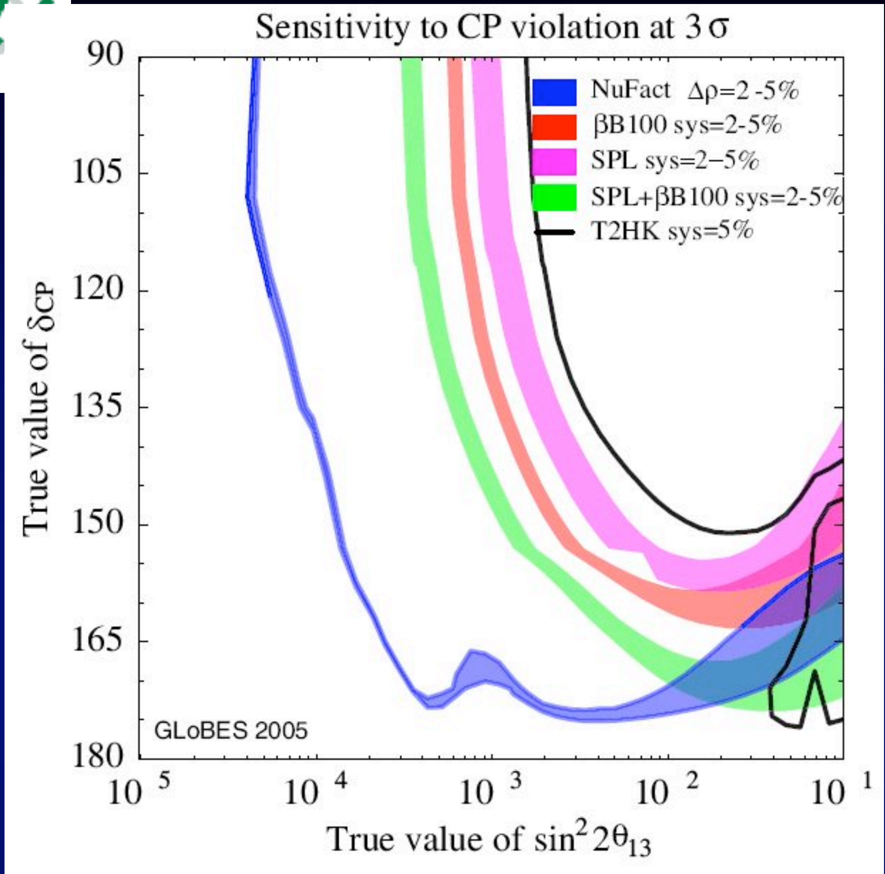




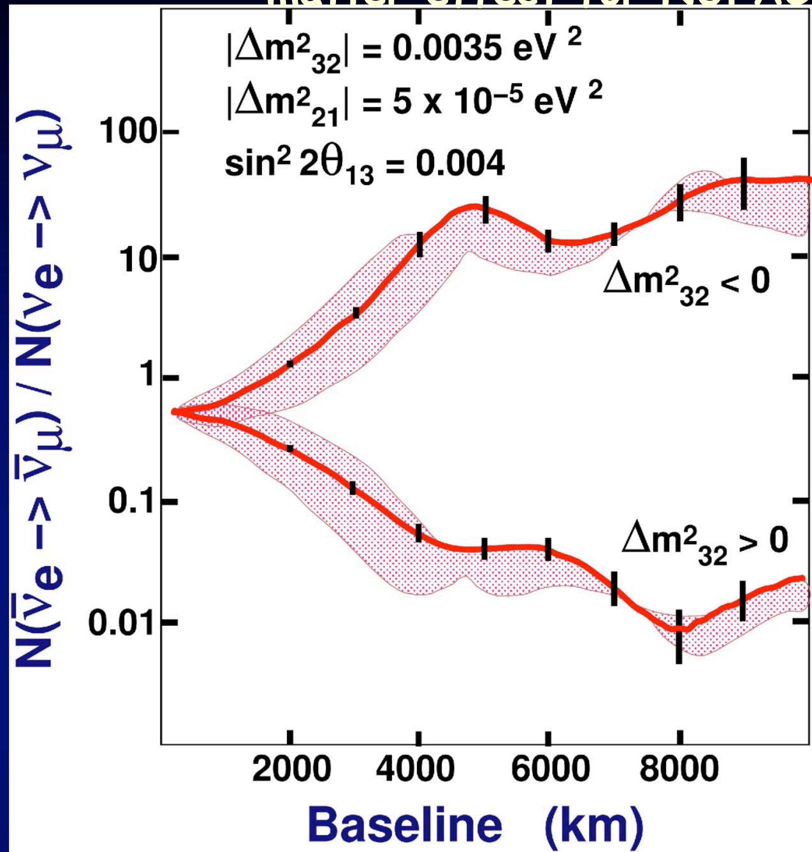
$\delta \in [180^0 - 270^0]$

$\delta \in [270^0 - 360^0]$

What do we learn?



matter effect for NUFACT



1. Both (BB+SB+MD) and NUFACT outperform e.g. T2HK on most cases.

2. combination of BB+SB is really powerful.

3. for $\sin^2 2\theta_{13}$ below 0.01 NUFACT as such outperforms anyone

4. for large values of θ_{13} systematic errors dominate.
Matter effects for NUFACT, cross-sections for low energy beams.
This is because we are at first maximum or above. → CP asymmetry is small!

Consequences -2

4. for large values of θ_{13} systematic errors dominate.

Matter effects for NUFACT, cross-sections for low energy beams.

This is because we are at first maximum or above, → CP asymmetry is small!

for NUFACT:

→ work on understanding systematic errors on matter effect

→ try to reach second maximum by lowering the muon detection threshold

→ try to achieve wrong sign electron detection

for superbeam/betabeam:

→must have a near detector concept that demonstrates ability to measure detection and efficiency with high precision

→going to second maximum requires a different baseline X 3

cf: project in Corea for T2HK baseline, or NUMI 2d max (farther off-axis)

not easy to achieve for both Superbeam and Beta-beam for NUFACT:

→ work on systematic errors on matter effect

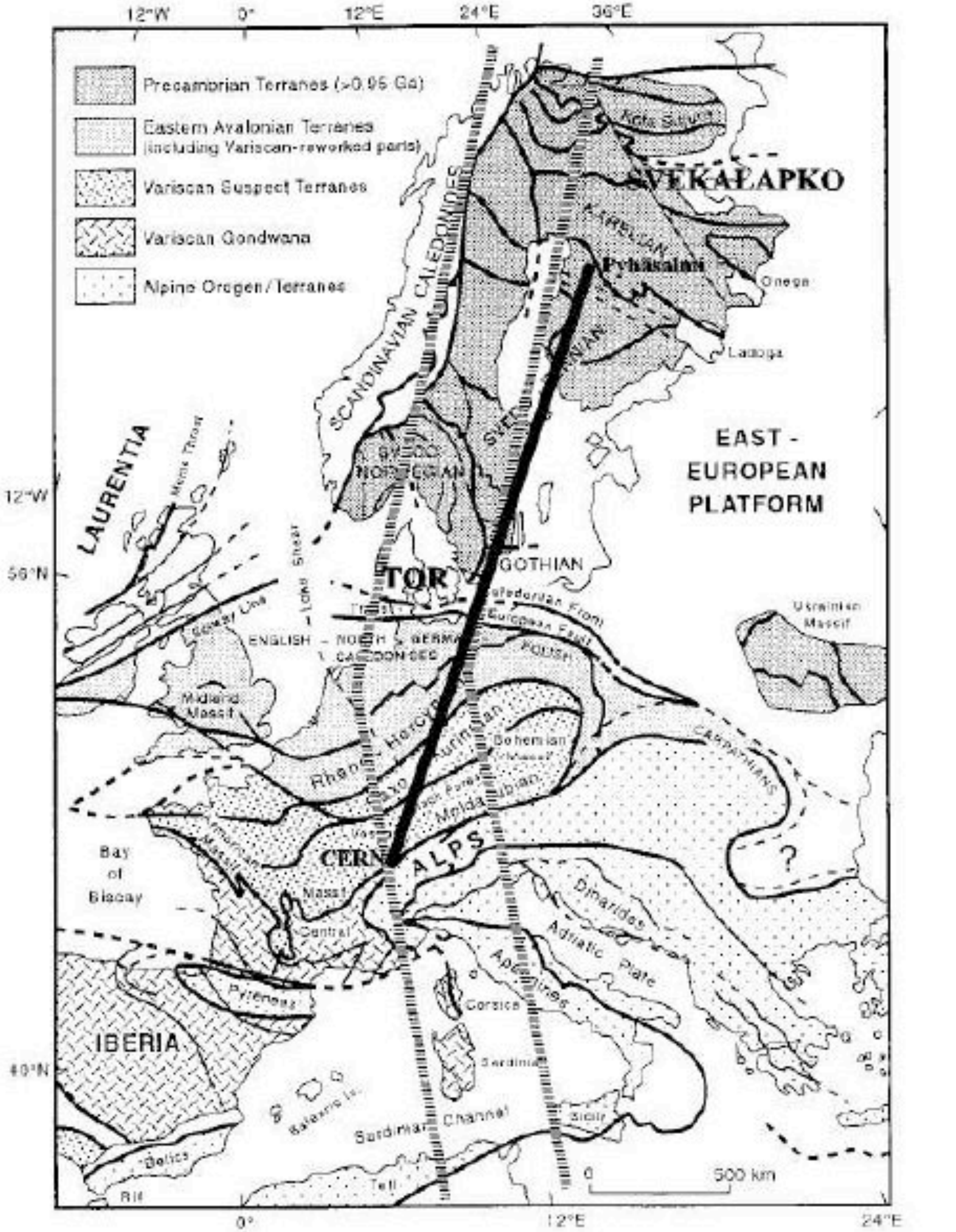
A preliminary study was made by

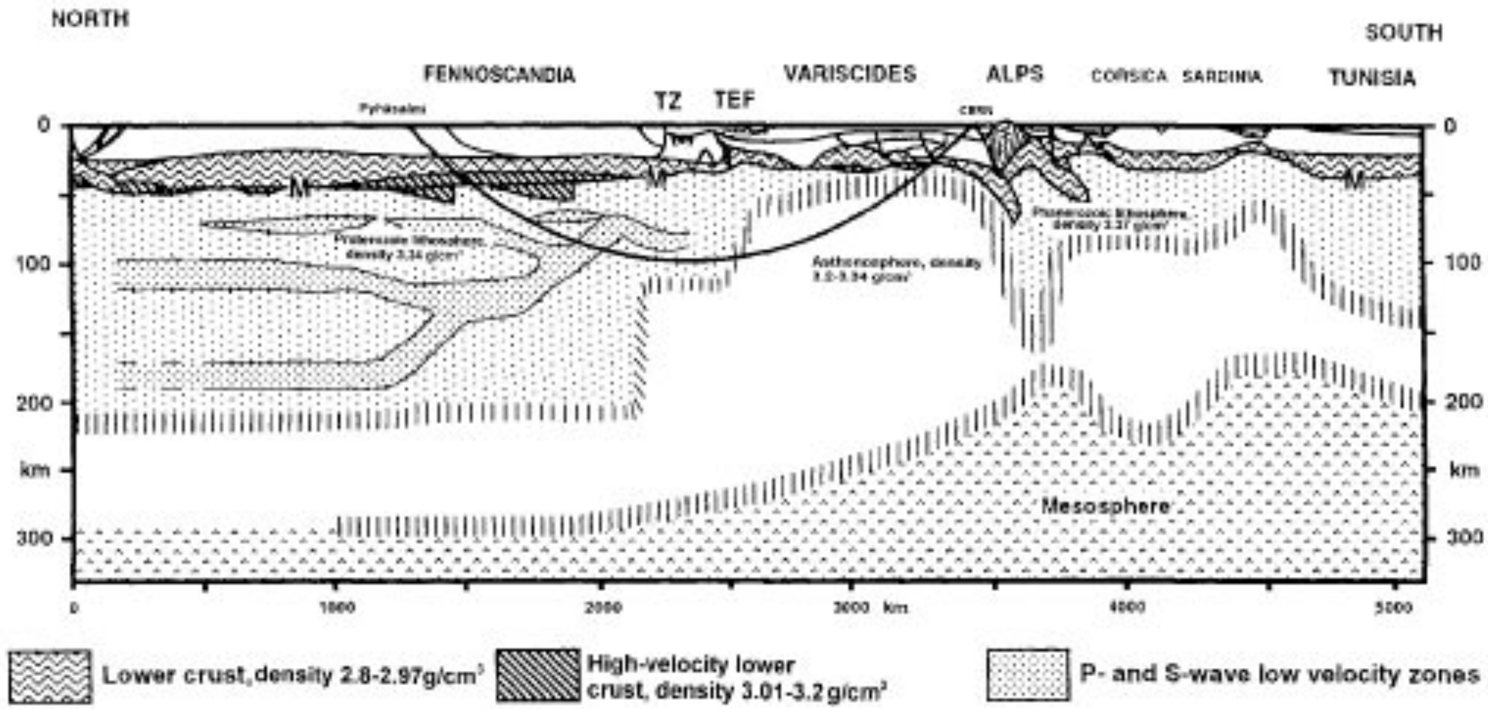
E. Kozlovskaya, J. Peltoniemi, J. Sarkamo,

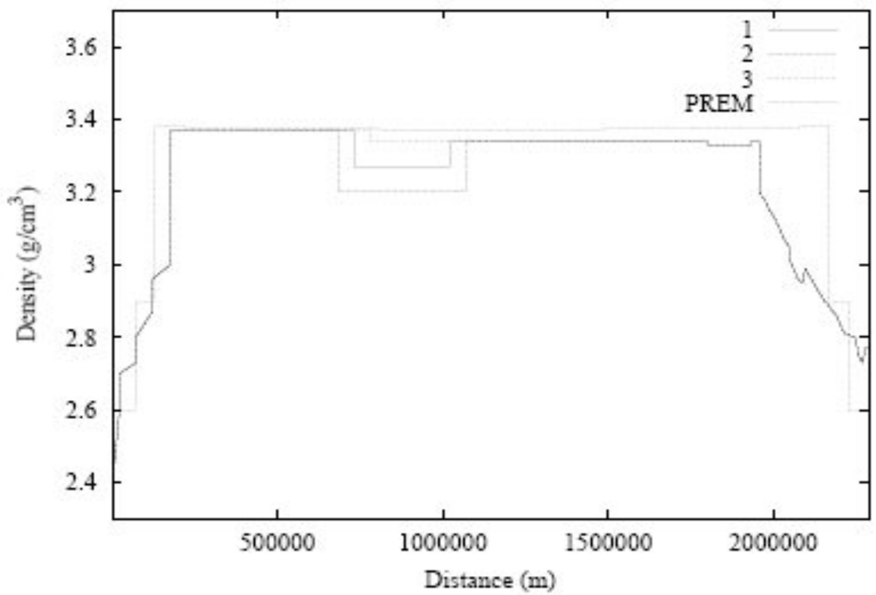
The density distribution in the Earth along the CERN-Pyhäsalmi baseline and its effect on neutrino oscillations. CUPP-07/2003

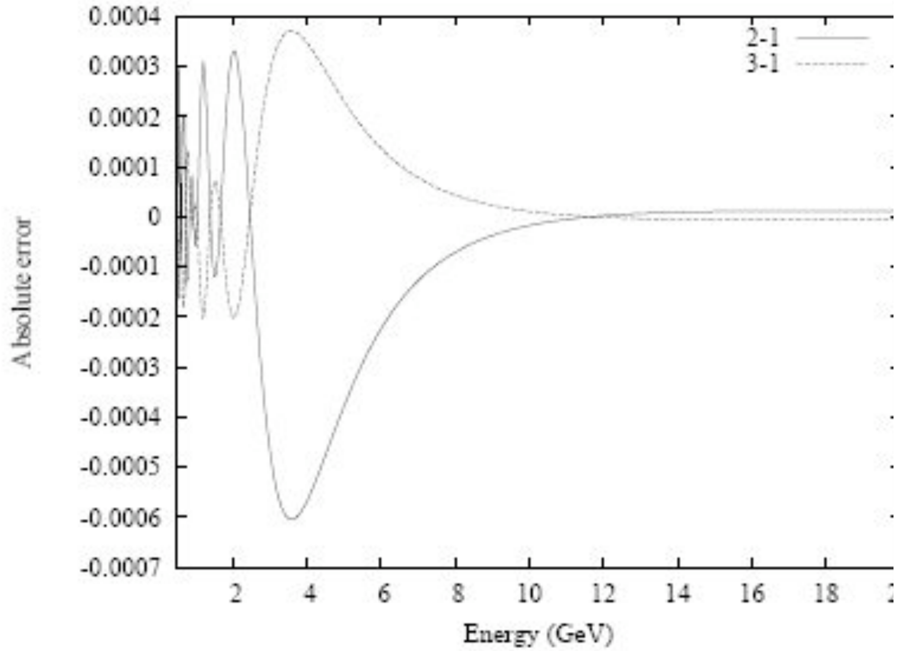
→the uncertainties on matter effects are at the level of a few%

J. Peltoniemi




NORTH
SOUTH
FENNOSCANDIA
TZ
TEF
VARISCIDES
ALPS
CORSICA
SARDINIA
TUNISIA
Mesosphere
km
0
100
200
300
1000
2000
3000 km
4000
5000
Lower crust, density 2.8-2.97g/cm³
High-velocity lower crust, density 3.01-3.2 g/cm³
P- and S-wave low velocity zones


1
2
3
PREM
Density (g/cm³)
Distance (m)
3.6
3.4
3.2
3
2.8
2.6
2.4
500000
1000000
1500000
2000000


2-1
3-1
Absolute error
Energy (GeV)
0.0004
0.0003
0.0002
0.0001
0
-0.0001
-0.0002
-0.0003
-0.0004
-0.0005
-0.0006
-0.0007
2
4
6
8
10
12
14
16
18

Conclusions

conclusions

There is a wealth of information in the $\nu_\mu \rightarrow \nu_e$ channel and its variations with antineutrinos or $\nu_e \rightarrow \nu_\mu$

The knowledge of $\sigma(\nu_\mu N) / \sigma(\nu_e N)$ will be necessary -- within cuts! --
→physics understanding + implementation in Monte Carlo.
First studies indicate that the theoretical knowledge may be at the level of 3-5% for the low energy (<500 MeV) region.
Pion threshold should be studied as it is different for e and μ

The measurement of this ratio is very challenging in conventional neutrino beams… since the ν_e flux is only <~% of the total.
Its knowledge requires hadroproduction experiments (i.e. NA61) performed with high precision especially for the kaon content.

In the future the ν_e cross section may be precisely meaasureable
In the beta beam
-- especially with monochromatic electron capture isotopes