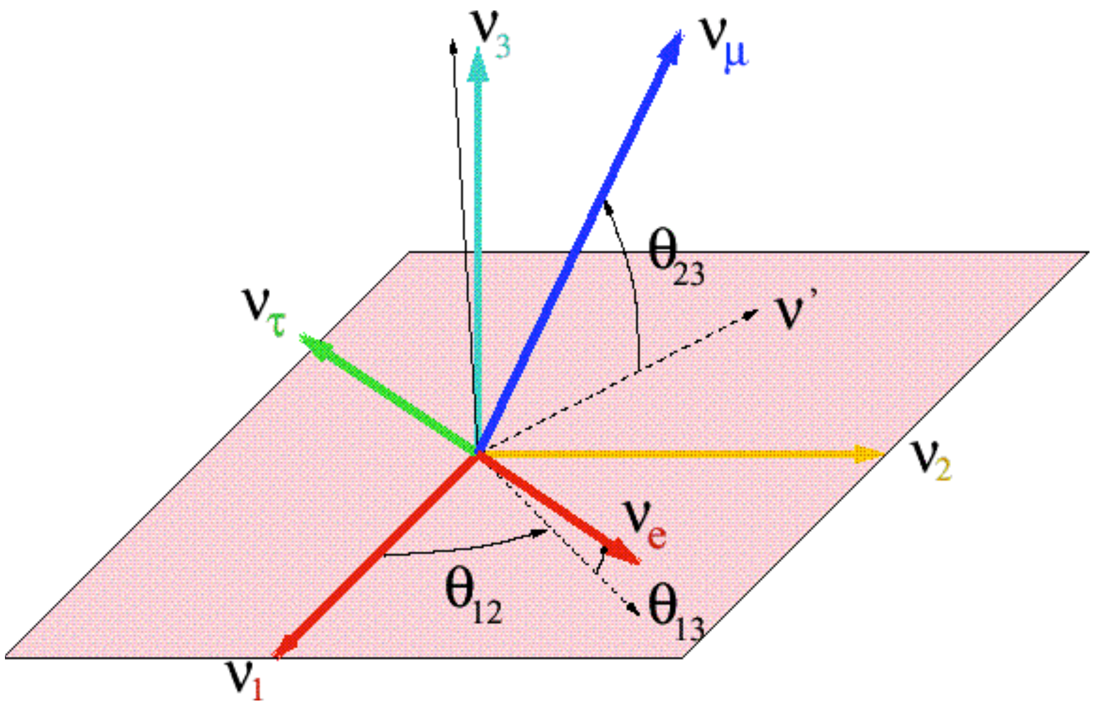
Neutrino Factory and Beta-beams

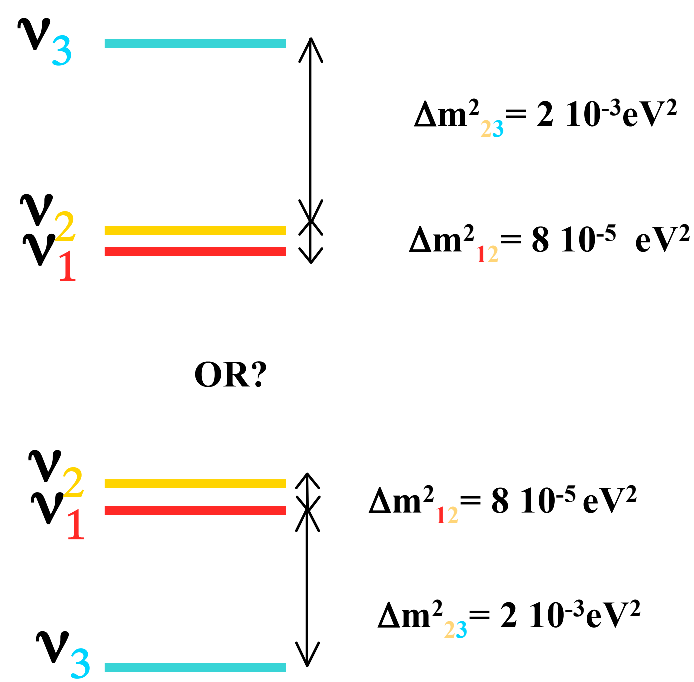
1. Motivation
2. Operation Principles
3. Neutrino factory the accelerator
4. Neutrino factory the detectors
5. Beta beam the accelerator
6. Beta beam the detectors
7. Overall comparison
8. Conclusions

Today: overview with lots of questions open
Tomorrow: more details on the accelerator (mostly NUFACT) and R&D

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 even after approved program:
θ_{13} , phase δ , sign of Δm^2_{13}

Motivations

Neutrinos can tell us much more than just 'we have mass!'

-- is CP violated in neutrino oscillations?
-- is the mixing angle θ_{13} small, very small, zero?
-- is the mass hierarchy 'natural' or 'bizarre'?
-- is the mixing angle θ_{12} really very close to pi/4?
-- is the mixing matrix unitary?
-- are there special relations between mixing angles and masses in neutrinos (as perhaps in quarks?)
-- can we measure the mixing parameters with the same precision as for quarks in order to test our theoretical ideas?

Motivations (II)

Conventional neutrino beams (from pion decay) have intrinsic limitations:

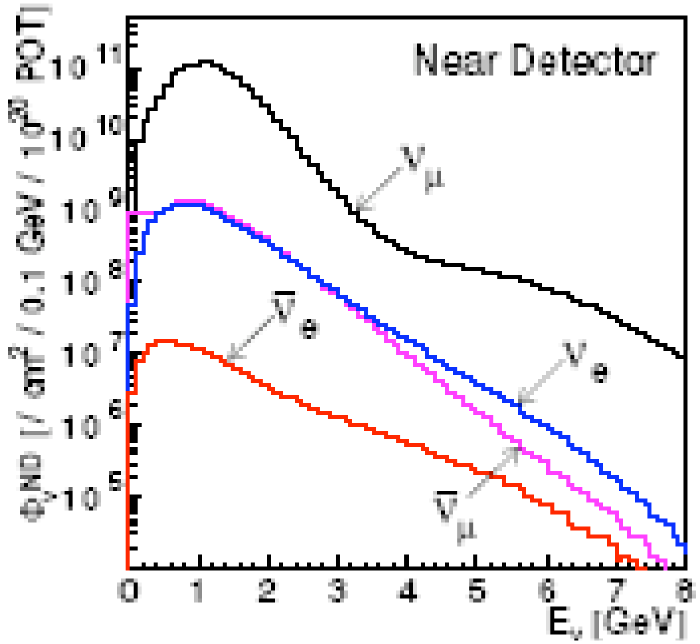
1. Exact shape and intensity of flux is not well known
Limited by knowledge of hadron production
compounded by delicacies of neutrino beam line

2. Neutrino cross sections are poorly known
and difficult to measure

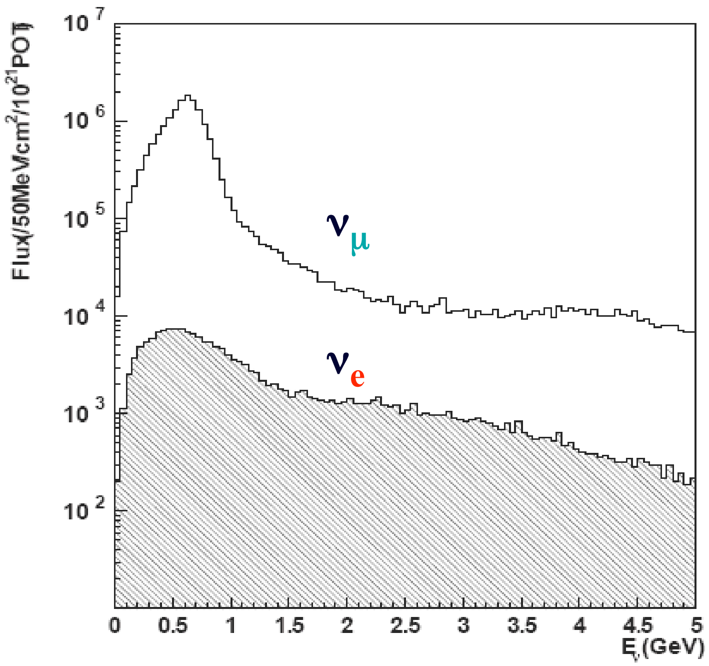
3. Near detectors measure flux times cross-sections
for the main component of the beam

4. Optimization capability is limited

→Experiments are limited at the ~5% level



K2K beam



T2K off axis Beam But anti-ν are also present!

Motivations (III)

THE CHALLENGE:

If *physics of flavour* due to symmetry GUT and/or family then

The quark- and lepton-mixing parameters must be related

For the theory of flavour to be developed measurements must be sufficiently precise to remove the model-builders freedom

Challenge to neutrino experimenters:

Measure neutrino-mixing parameters with a precision similar to the precision with which the quark-mixing parameters are known

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

Atmospheric $\Delta m^2 = 2.5\ 10^{-3}\ eV^2$ $L = 500$ km @ 1 GeV
Solar $\Delta m^2 = 7\ 10^{-5}\ eV^2$ $L = 18000$ km @ 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

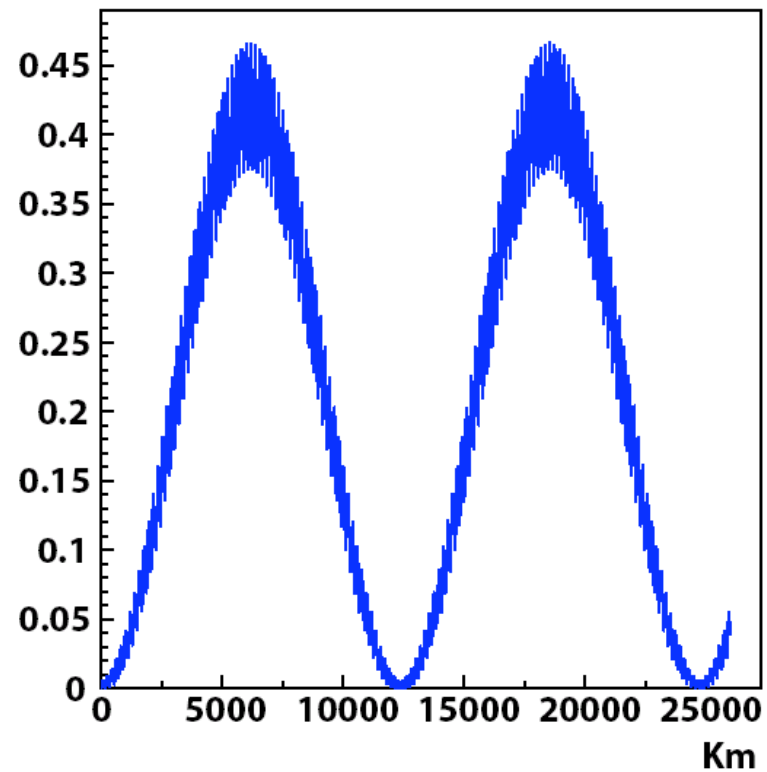
CP: $P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e) \neq P(\nu_\mu \leftrightarrow \nu_e)$

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

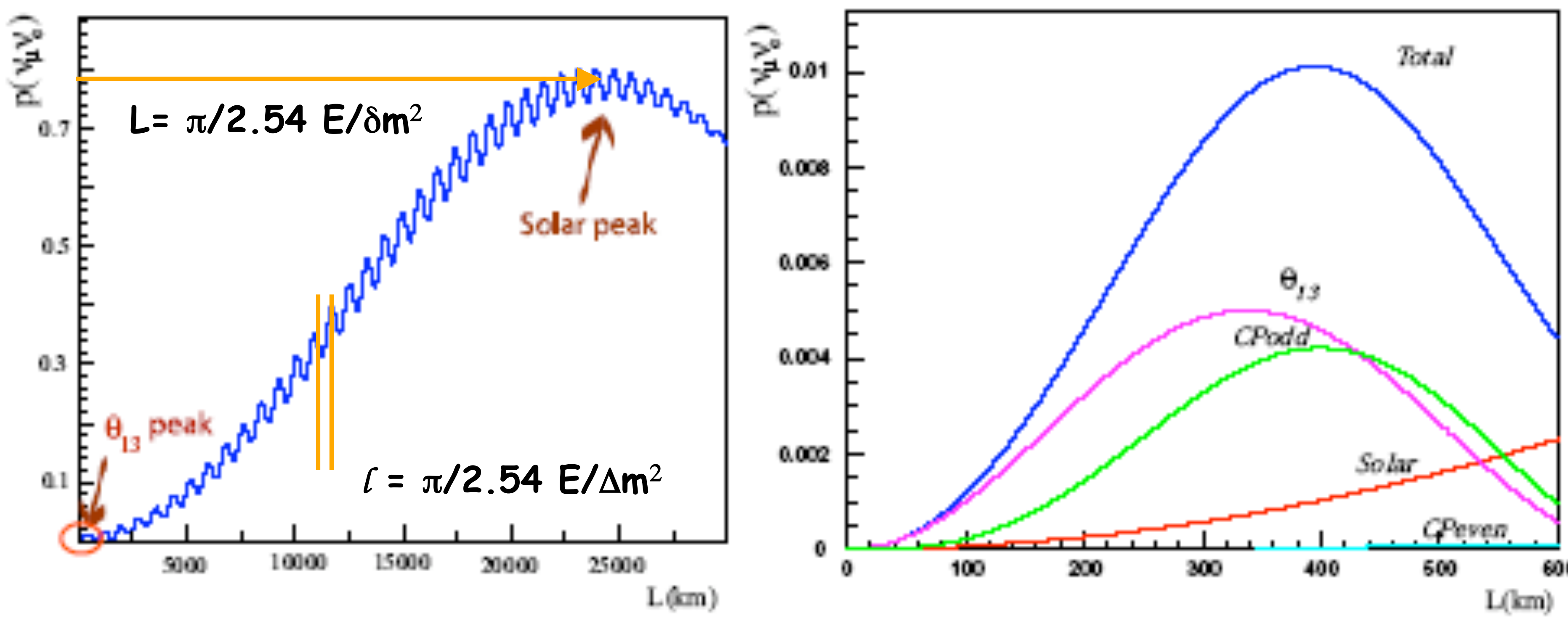


Figure 3: Sketch of $P(\nu_\mu \rightarrow \nu_e)$ as function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for $\delta_{CP}=0$ (left) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (right), where the different terms of eq. 4 are displayed. 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.

CP violation

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

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

… need APPEARANCE … $P(\nu_e \rightarrow \nu_e)$ is time reversal symmetric (reactor νs do not work)

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

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 $\nu_e \rightarrow \nu_\tau$

An interference phenomenon:

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

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

T asymmetry for sin $\delta = 1$

!

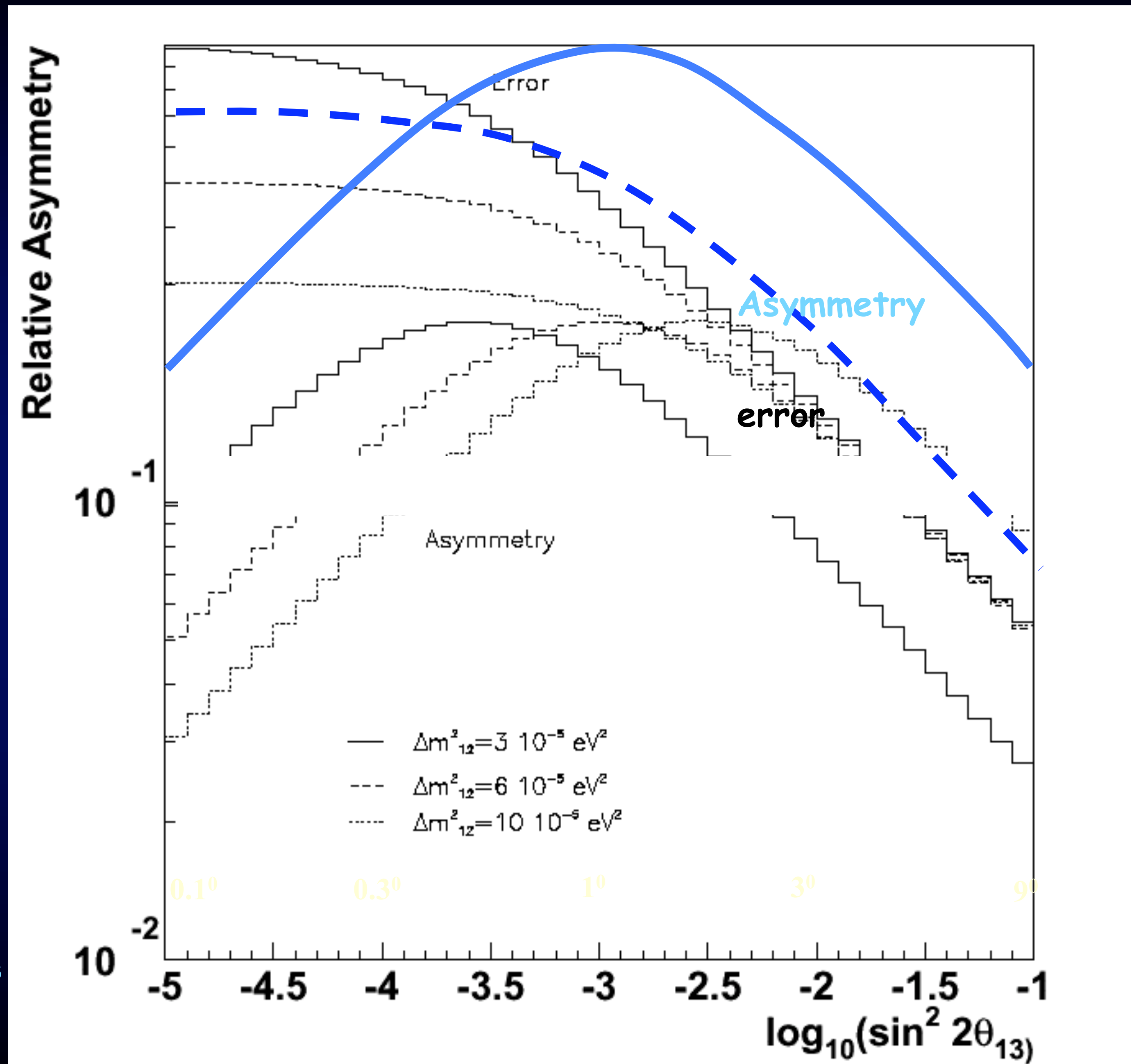
asymmetry is
a few %
and requires
excellent
flux normalization
(neutrino fact., beta beam
or
off axis beam with
not-too-near
near detector)

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.



Road Map

A Experiments to find θ_{13} :

search for $\nu_\mu \rightarrow \nu_e$

--in conventional ν_μ beam (MINOS, OPERA)

limitations: NC π^0 background, intrinsic ν_e component in beam

-- in reactor experiments

--Off-axis beam (JPARC-SK, NOvA, T2KK) or

--Low Energy WBB Superbeam (BNL/FNAL→ INO, SPL →Fréjus)

B Precision experiments to find CP violation

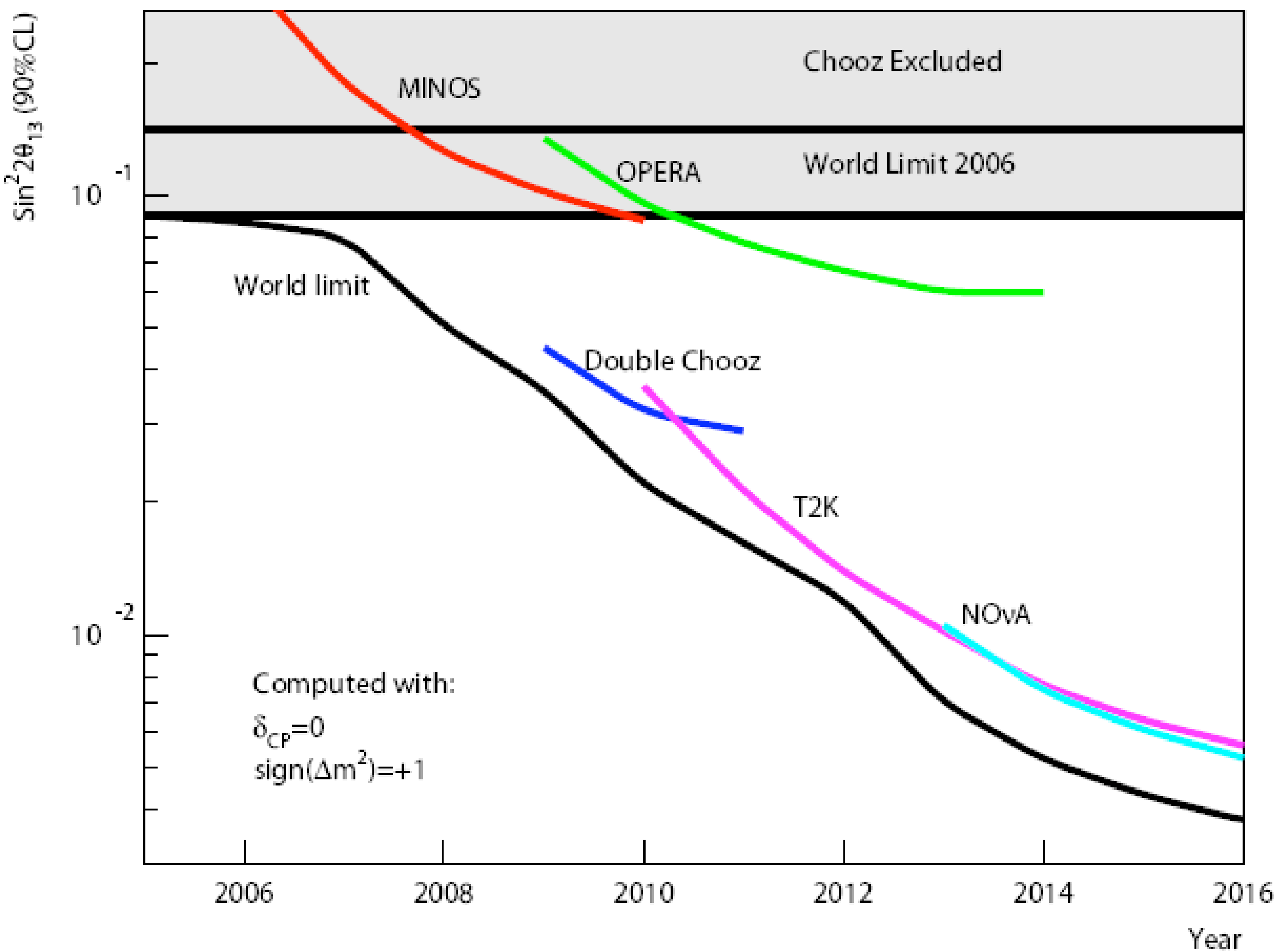
-- or to search further if θ_{13} is too small

-- beta-beam $^{6}He^{++} \rightarrow {}^{6}Li^{+++} \, \bar{\nu}_e \, e^-$ **and** $^{18}Ne^{10+} \rightarrow {}^{18}F^{9+} \, \nu_e \, e^+$

-- Neutrino factory with muon decay storage ring

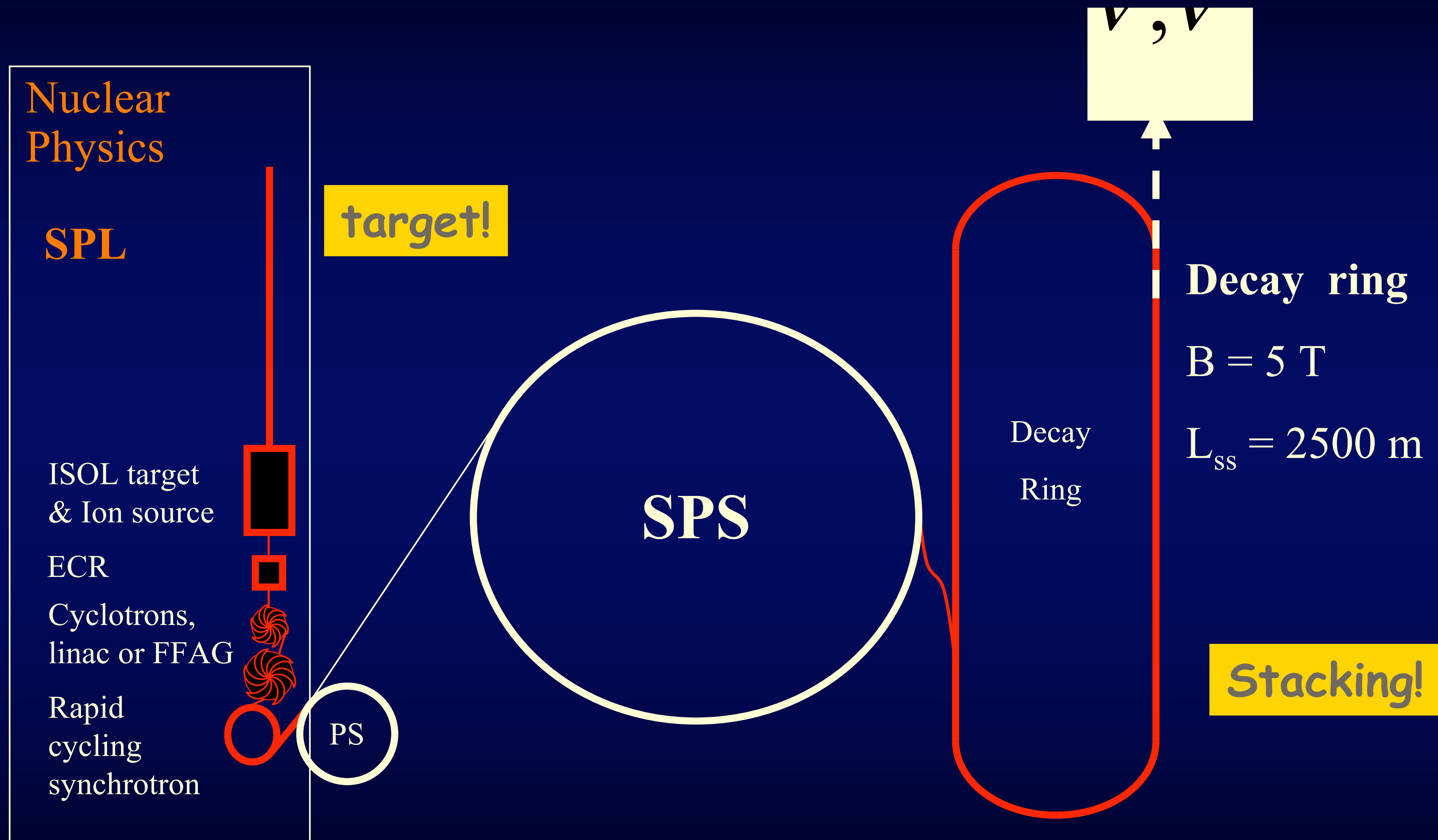
$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu$ **and** $\mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu$

fraction thereof will exist .


Chooz Excluded
MINOS
World Limit 2006
OPERA
World limit
Double Chooz
T2K
NOvA
Computed with:
$\delta_{CP}=0$
$sign(\Delta m^2)=+1$
$\sin^2 2\theta_{13}$ (90% CL)
10^{-1}
10^{-2}
2006
2008
2010
2012
2014
2016
Year

CERN: β-beam baseline scenario

neutrinos of E_{max}=~600MeV



$^{6}He^{++} \to {}^{6}Li^{+++} \bar{\nu}_e e^-$

$^{18}Ne^{10+} \to {}^{18}F^{9+} \nu_e e^+$

Same detectors as Superbeam !

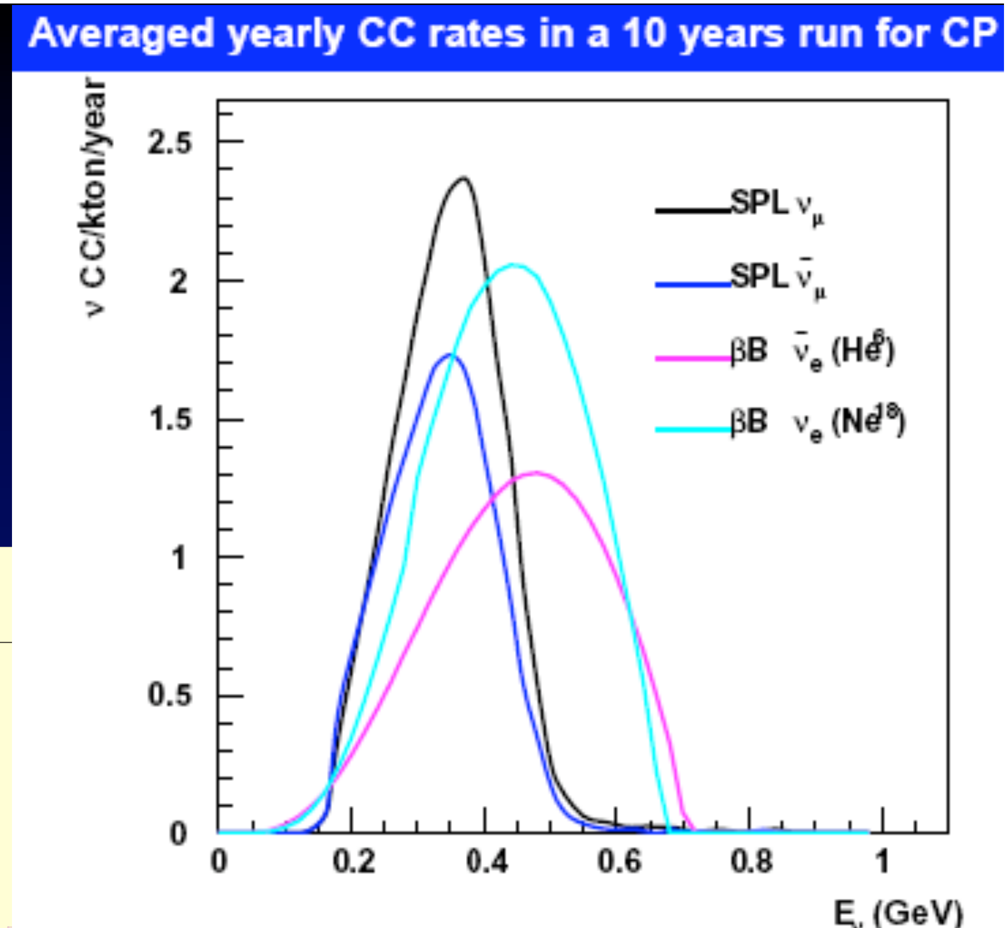
3.5 GeV SPL

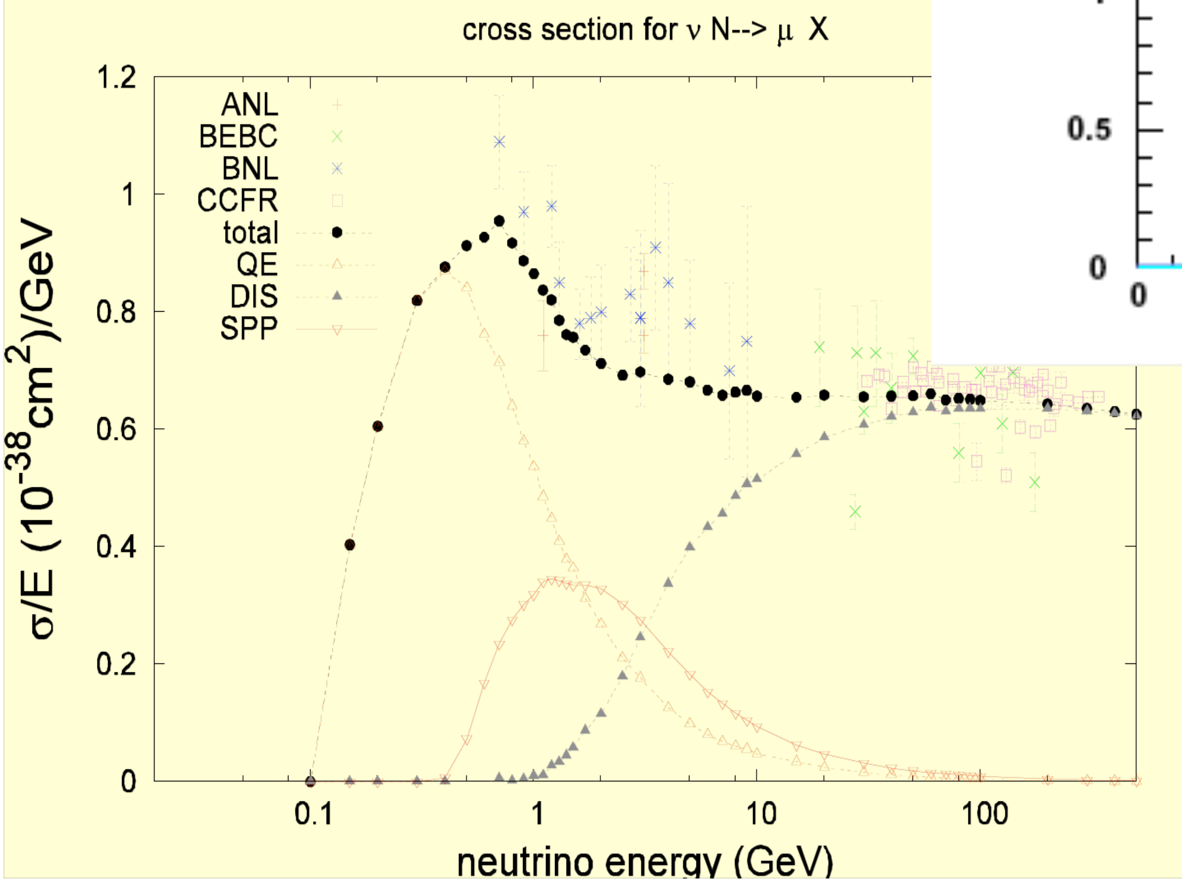
+

γ= 100 β–beam

End point is $E = 2\gamma Q$

Q= end point in center of mass, 3.5 MeV for ^6He





-- low proton energy:

no Kaons → ν_e background is low

--region below pion threshold

(low bkg from pions)

but:

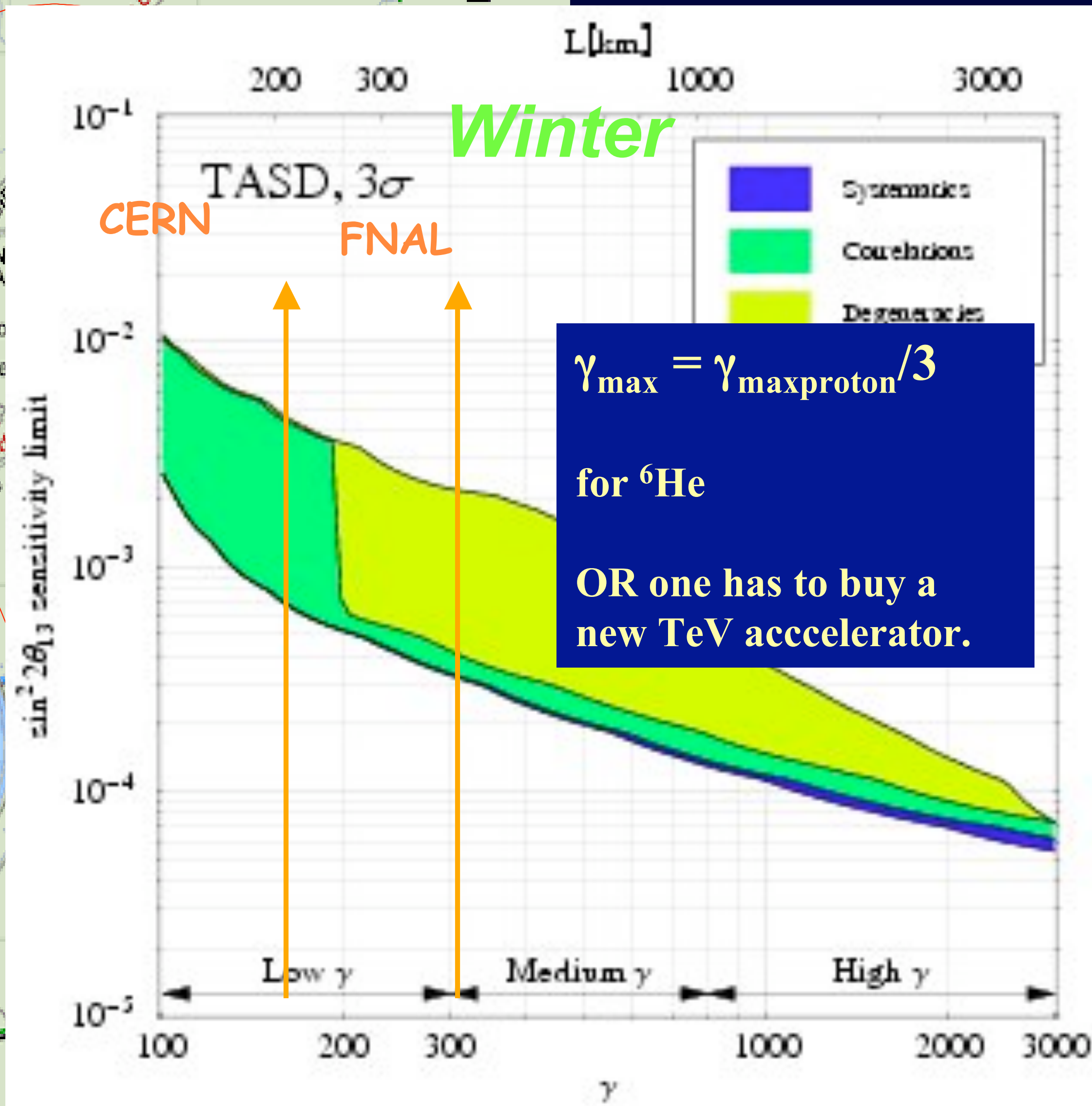
low event rate and

uncertainties on cross-sections

High gamma beta-beam increases sensitivity considerably

Beta-beam at FNAL?

(Hernandez, Gomez-Cadenas)

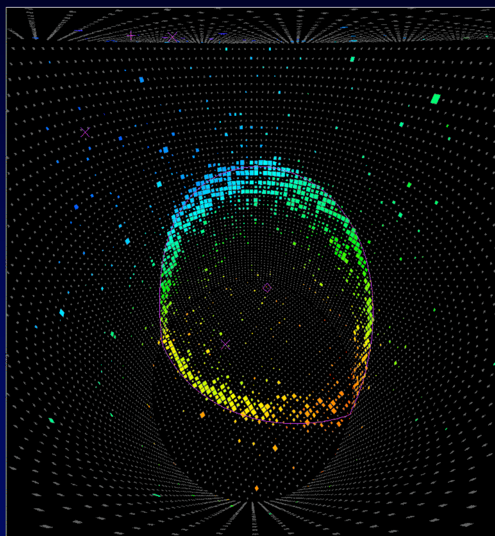


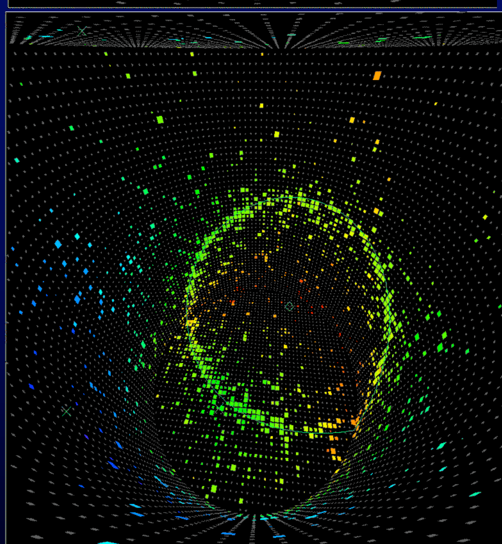
$\gamma_{max} = \gamma_{maxproton}/3$

for ^6He

OR one has to buy a new TeV acccelerator.

Combination of beta beam with low energy super beam





combines CP and T violation tests

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

(CP)

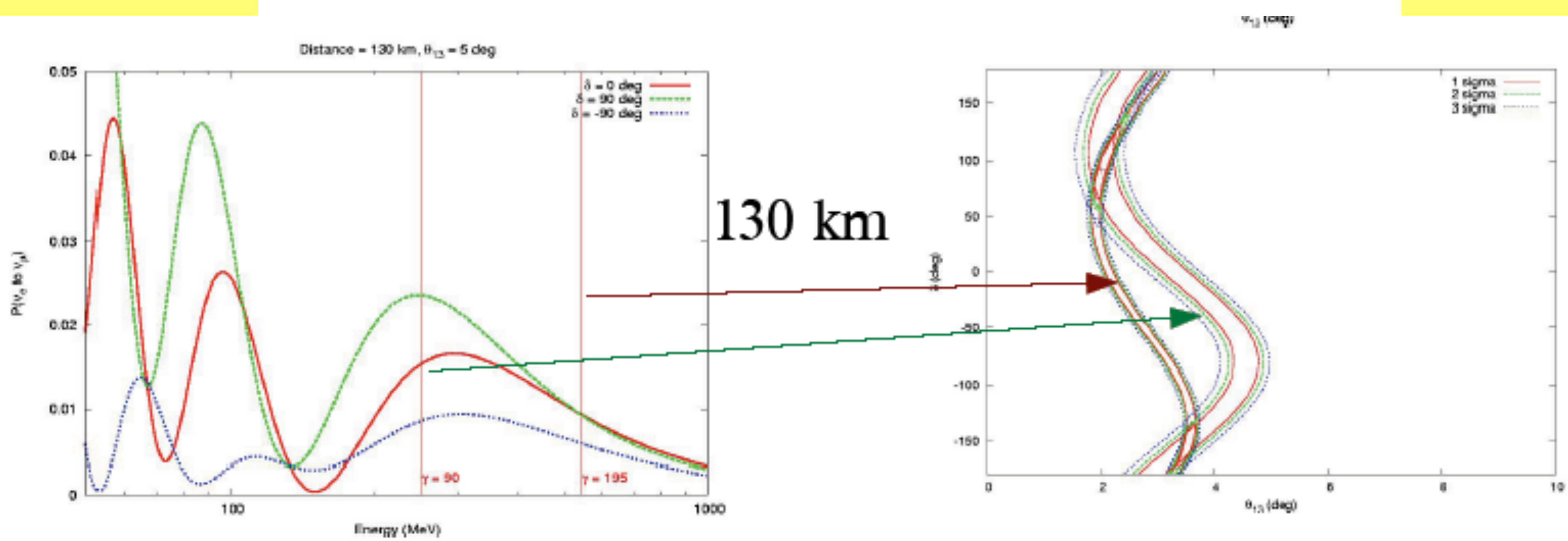
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ (β-) (T) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (π^-)

EC: A monochromatic neutrino beam

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

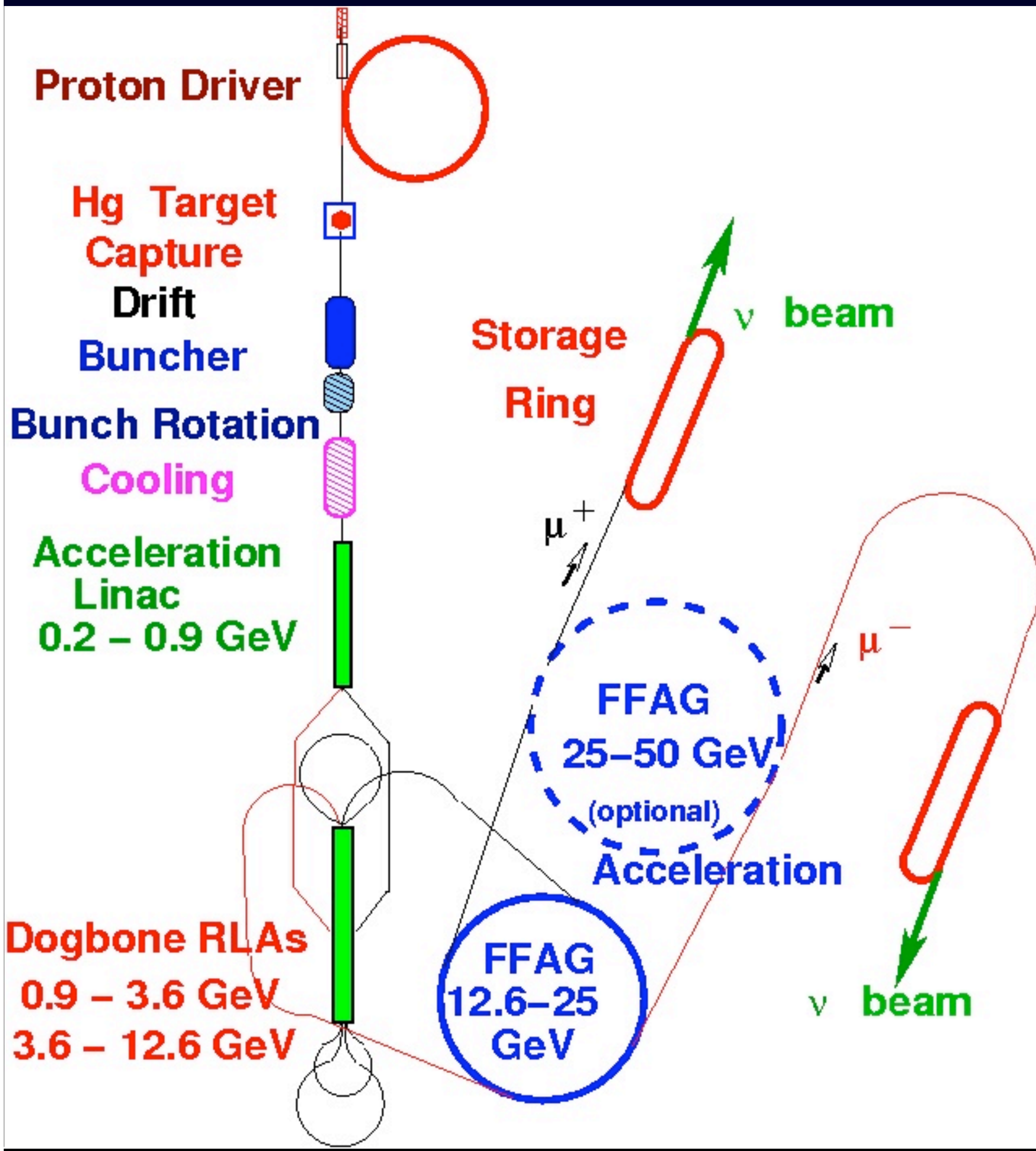
Burget et al

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



The Neutrino Factory

International Scoping Study « baseline »



1. Production of pions by high power proton accelerator (4 MW) Proton energy 5-15 GeV

2. Pt-> PL transfer and pion decay to muons

3. Muon phase rotation and bunching

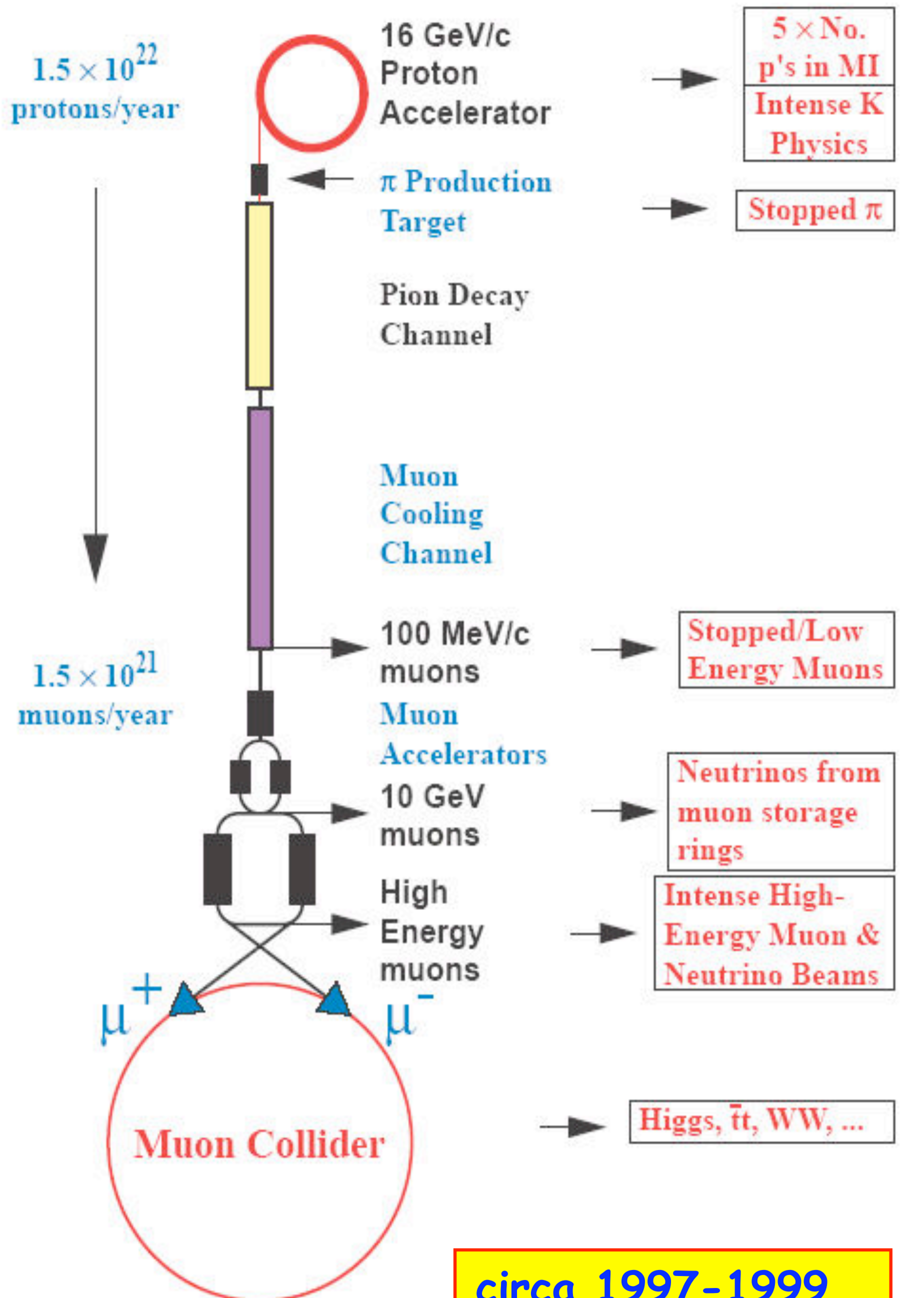
4. Muon cooling

5. Muon acceleration in large acceptance device

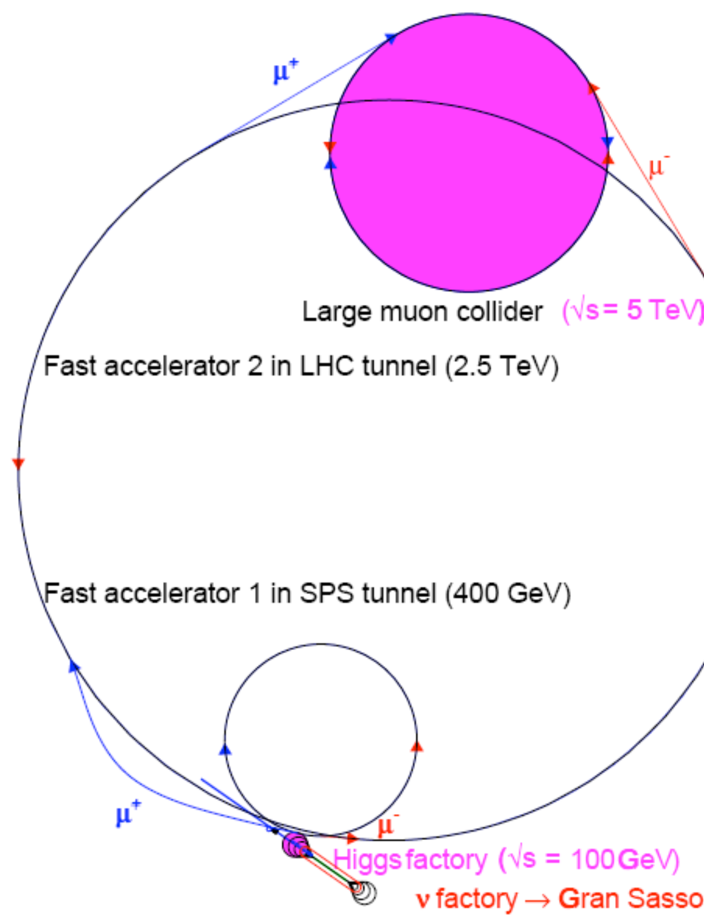
6. Muon storage at 20-50 GeV in decay ring

7. Neutrinos of $E\nu \le E\mu$

Intense K physics
Intense Low-E muons
Neutrino Factory
Higgs(es) Factory(ies)
Energy Frontier -> 5 TeV



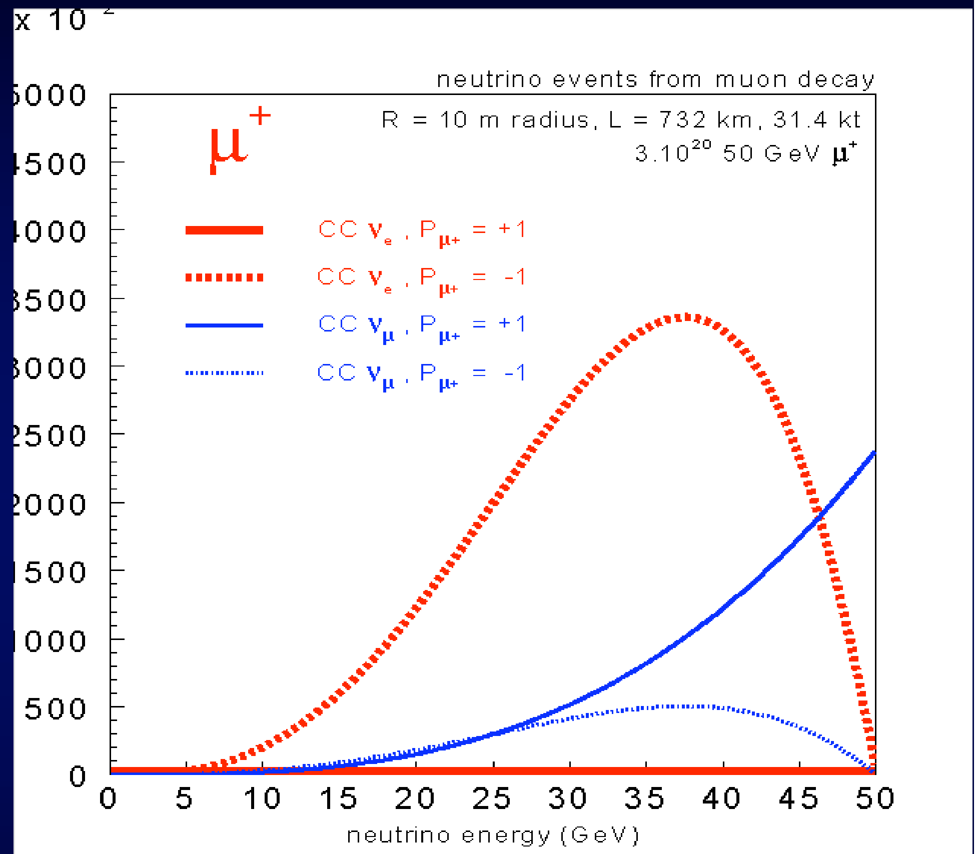
circa 1997-1999
US, Europe, Japan



Possible layout of a muon complex on the CERN site.

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

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 $\nu_\mu\ e^- \rightarrow \mu^-\ \nu_e$ in near expt.

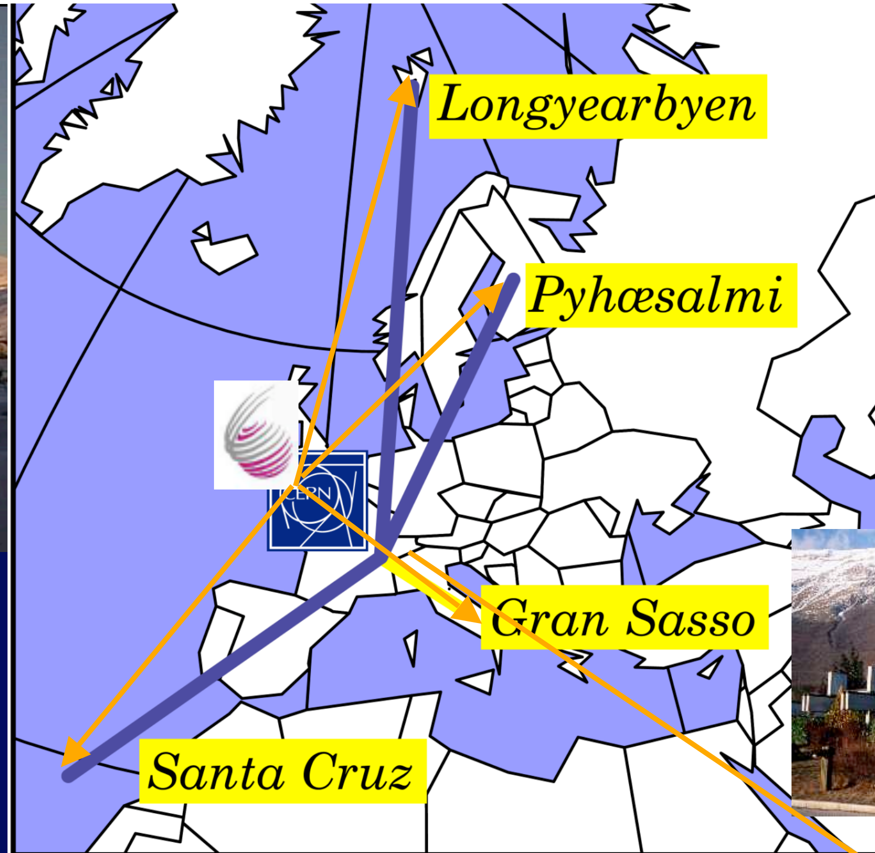
-- in **triangle or racetrack ring,**
muon polarization precesses and averages out
(preferred, -> calib of energy, energy spread)

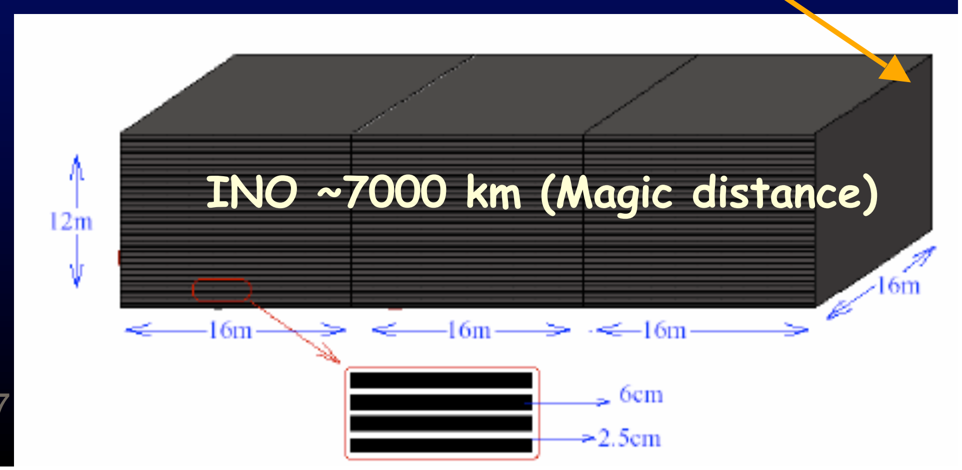
Similar comments apply to beta beam, except spin 0
→ Energy and energy spread have to be obtained
from the properties of the storage ring
(Trajectories, RF volts and frequency, etc…)

μ polarization controls ν_e flux:

μ^+ -X> ν_e in forward direction


Hammerfest bibliotek - Trond Remme


Longyearbyen
Pyhæsalmi
CERN
Gran Sasso
Santa Cruz


INO ~7000 km (Magic distance)
12m
16m
16m
16m
16m
6cm
2.5cm

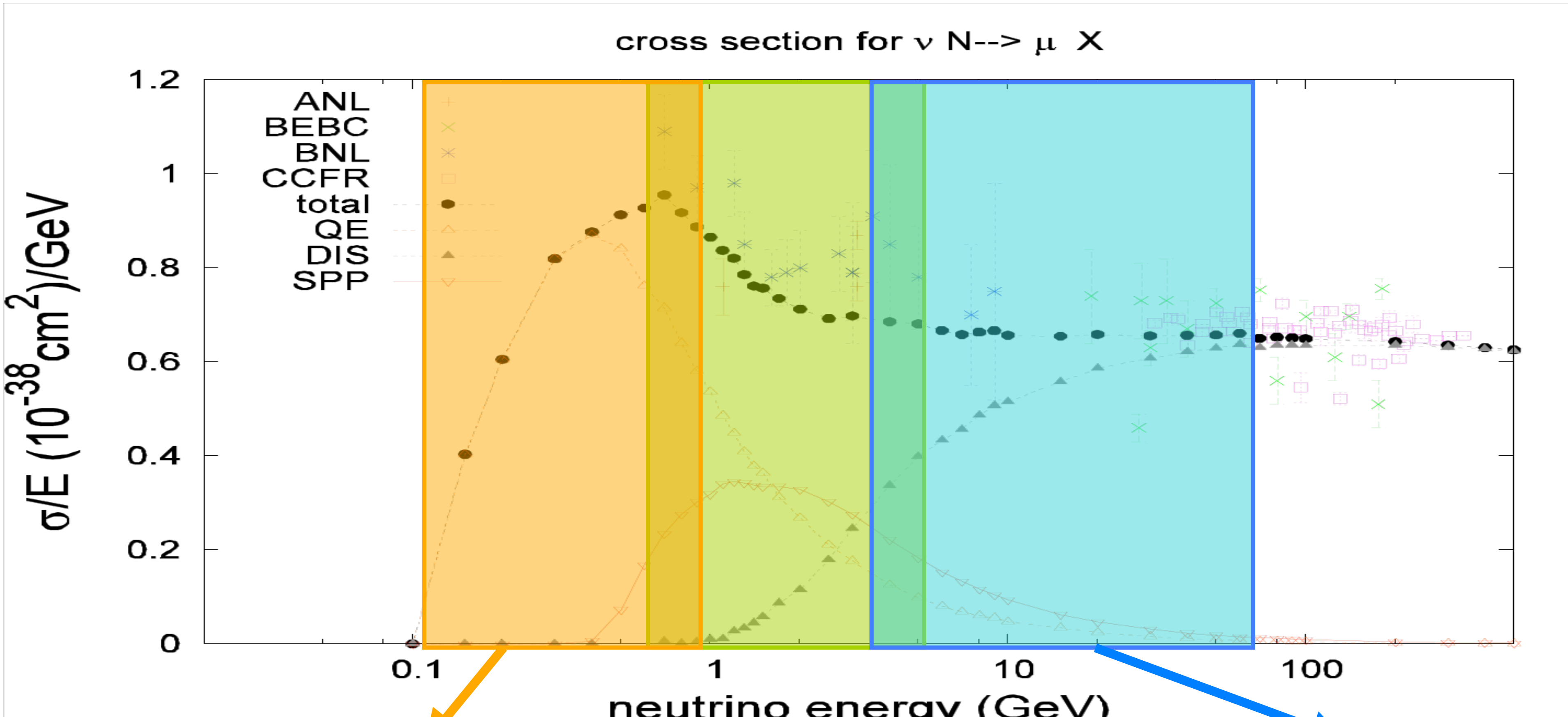
DETECTORS

Superbeam & beta-beam: Non-MAGNETIC

Beta beam ^{18}Ne: $\nu_e \rightarrow \nu_\mu$	T violation	Superbeam π^+: $\nu_\mu \rightarrow \nu_e$
CP violation	CPT	CP violation
Beta beam ^{6}He: $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	T violation	Superbeam π^+: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Nu-Fact: MAGNETIC

$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$	reaction	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	CC	Disappearance
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	CC	Appearance ('platinum' channel)
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$	CC	Appearance (atmospheric oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	CC	Disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	CC	Appearance: 'golden' channel
$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	CC	Appearance: 'silver' channel
$\nu \rightarrow \nu_s$	$\bar{\nu} \rightarrow \nu_s$	NC	Global disappearance, sterile neutrinos



Low energy region:
QE dominates

Low energy super beam
(T2K, T2HK, T2KK, Frejus)
Low energy beta-beam
(CERN baseline scenario)

WATER CHERENKOV (Mton)

Mid-energy region:
QE+ 1π + $n\pi$

Super beam
(Numi off, T2KK, CNGS+)
high Energy beta-beam
(CERN highQ or SPS+)

WATER CHERENKOV (Mton)
TASD (NOvA), Larg TPC

High-energy region:
DIS

Neutrino Factory

Magnetized Iron
Emulsion

large magnet around:
emulsion, TASD, Larg

Magnetized Iron calorimeter

(baseline detector, Cervera, Nelson)

$B = 1.7$ T $\Phi = 15$ m, $L = 25$ m

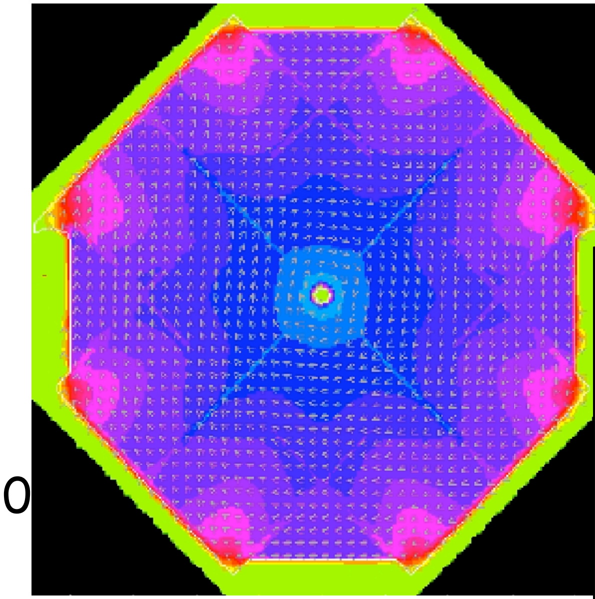
t(iron) =4cm, t(sc)=1cm

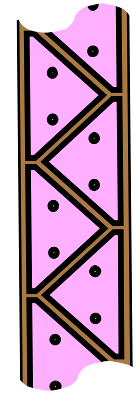
Fiducial mass = 100 kT

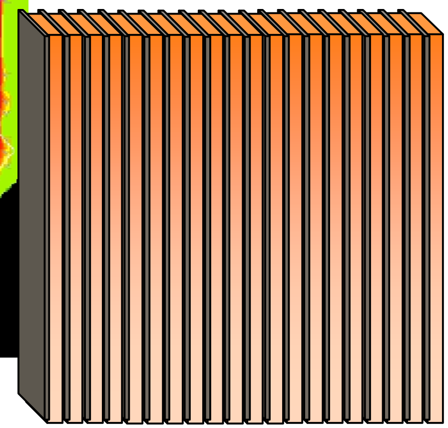
Charge discrimination down to 1 GeV

very similar to MINOS/NOvA/ND280

ex. detector: sci. fi. detector with multipixel APD readout



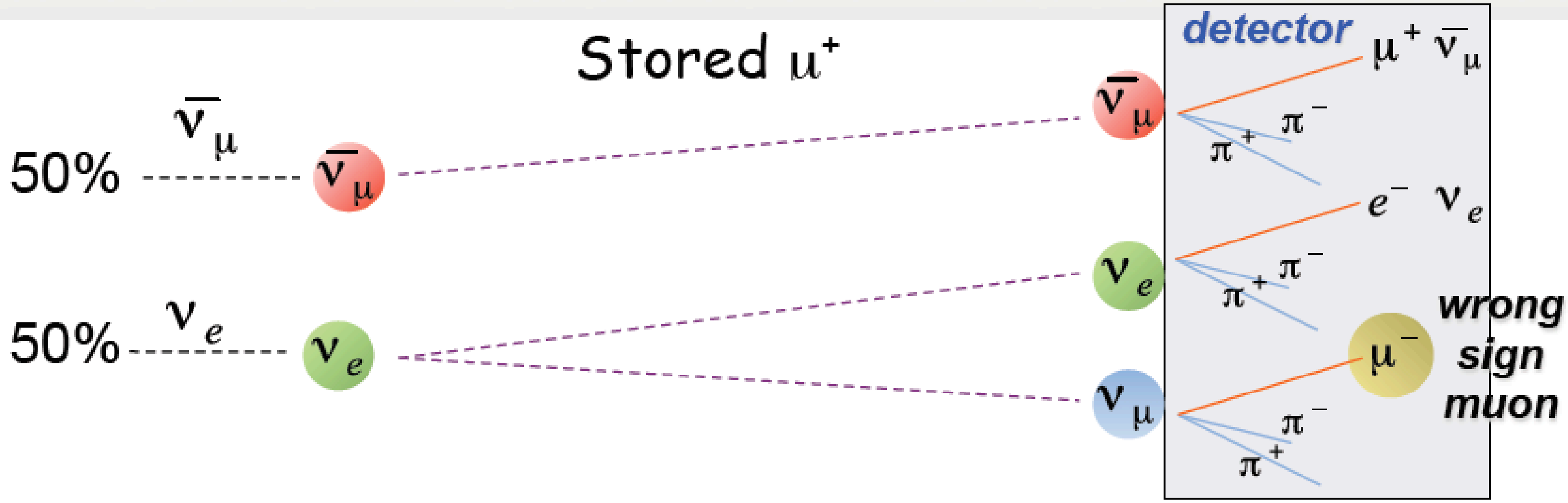




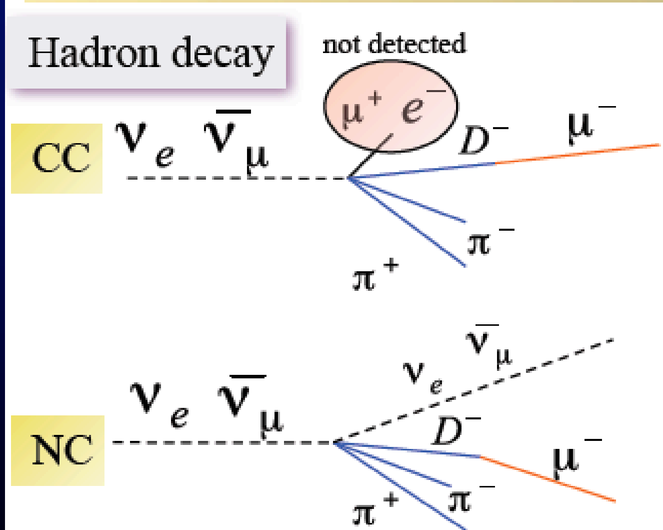
Event rates for 10^{21} muon decays for 50 GeV beam

Baseline	$\bar{\nu}_\mu$ CC	ν_e CC	ν_μ signal ($\sin^2\theta_{13}=0.01$)	
732 Km	10^9	2×10^9	3.4×10^5	(J-PARC I→ SK = 40)
3500 Km	4×10^7	7.5×10^7	3×10^5	

Golden: signal and backgrounds



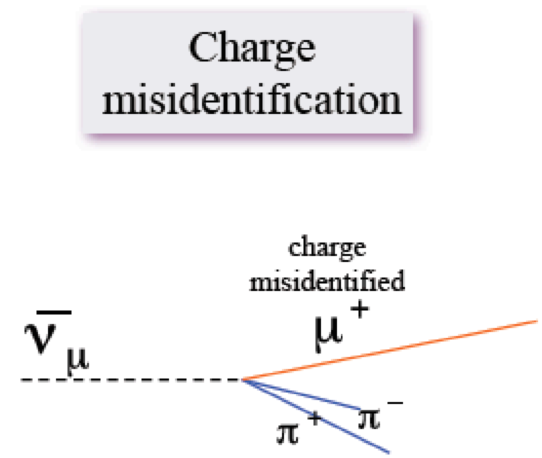
Backgrounds



μ^-

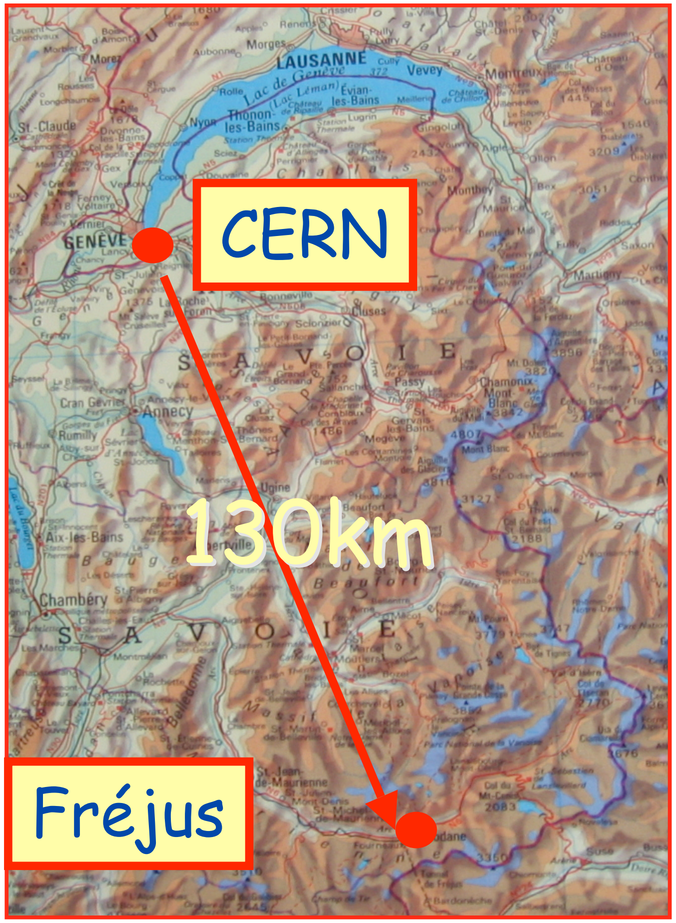
in the final state

no other lepton detected !!!

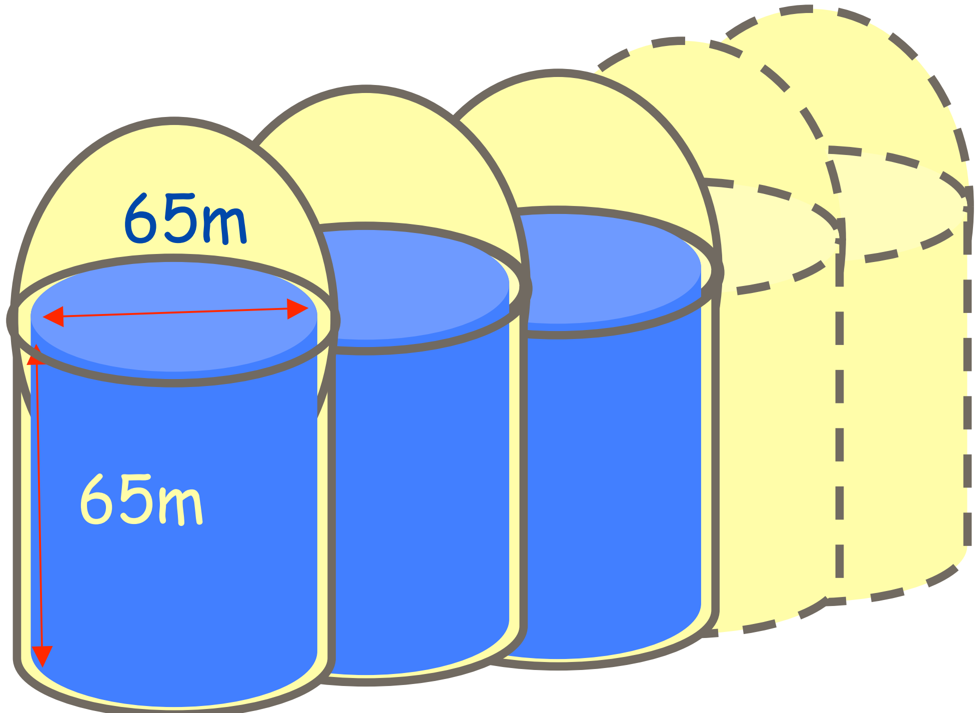


The MEMPHYS Project

Beta-beam detectors are similar to super-beam detectors



4800mwe



Water Cerenkov modules at Fréjus

CERN to Fréjus

Neutrino Super-beam and Beta-beam

Excavation engineering pre-study has been done for 5 shafts

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.

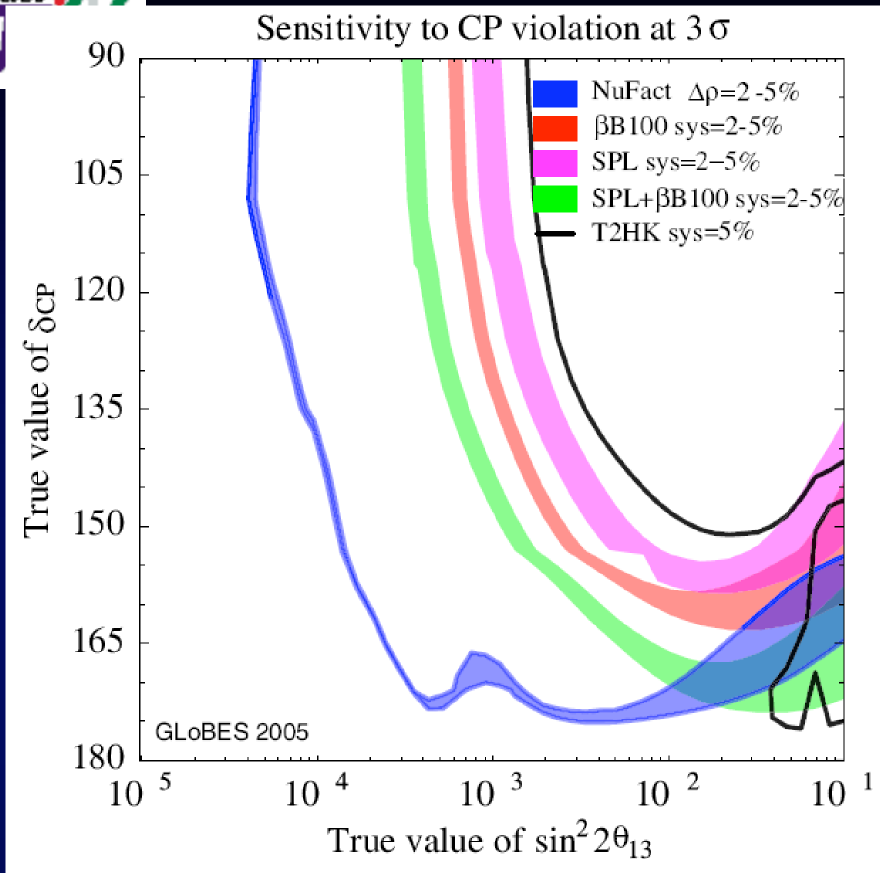
-- T2HK from LOI: 1000kt , 4MW beam power,
6 years anti-neutrinos, 2 years neutrinos.
systematic errors on background and signal: 5%.

-- 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%.

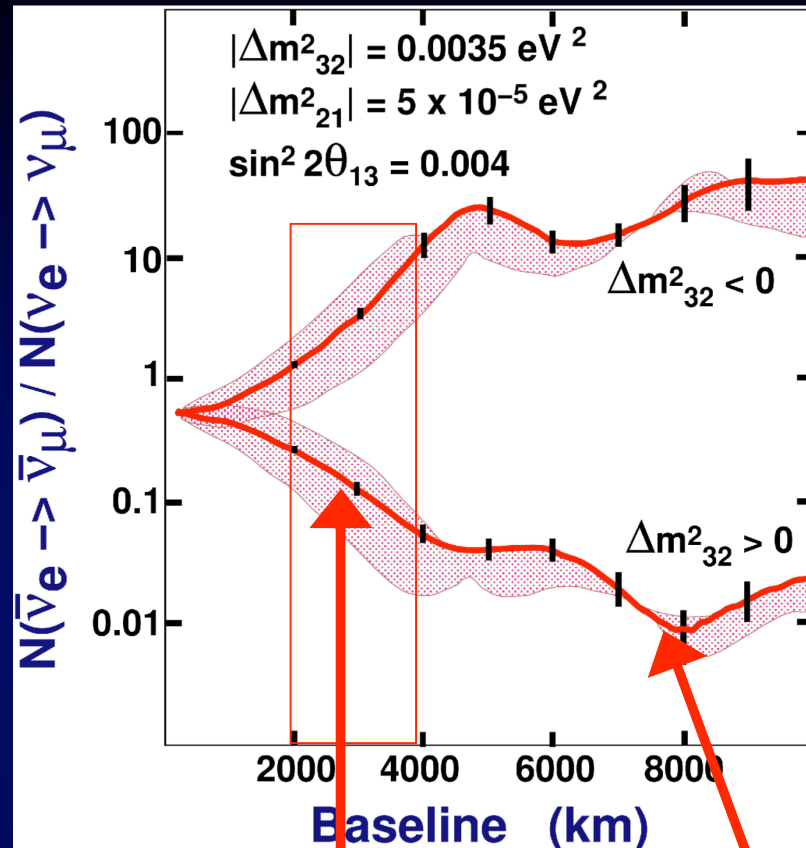
--NUFACT 3.1 10^{20} μ^+ and 3.1 10^{20} μ^+ per year for 10 years
100 kton iron-scintillator at 3000km and 30 kton at 7000km (e.g. INO) (old type!)
The matter density errors of the two baselines (uncorrelated): 2 to 5%
The systematics are 0.1% on the signal and 20% on the background, uncorrelated.

all correlations, ambiguities, etc… taken into account

What do we learn?



matter effect for NUFACT is very large



optimal baseline For CP

Magic baseline

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 outperforms anyone

4. for large values of θ_{13} systematic errors dominate:
Matter effects for NUFACT,
cross-sections errors for low energy beta-beams and superbeams.

This is because CP asymmetry is small!

Baseline optimization

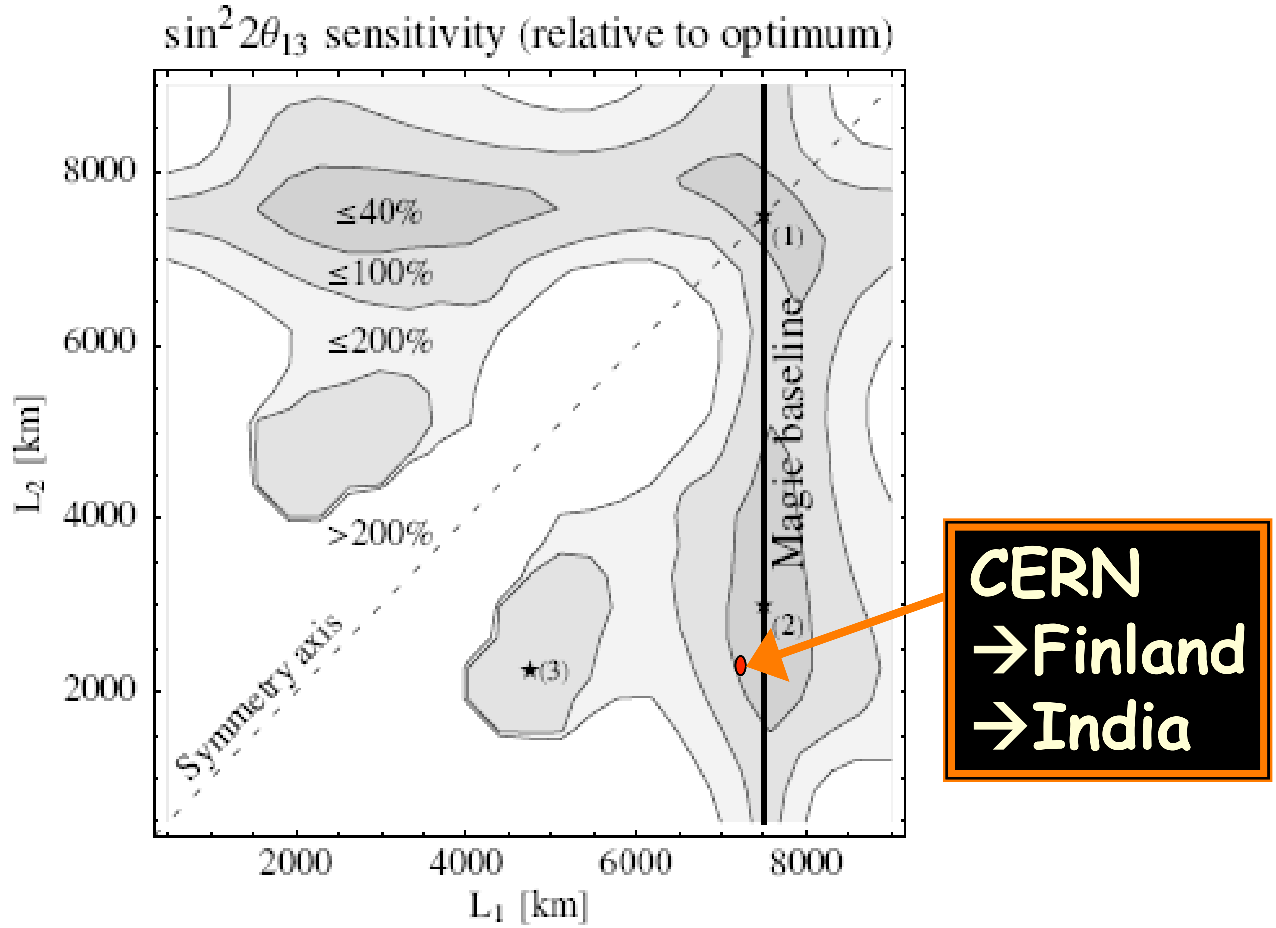
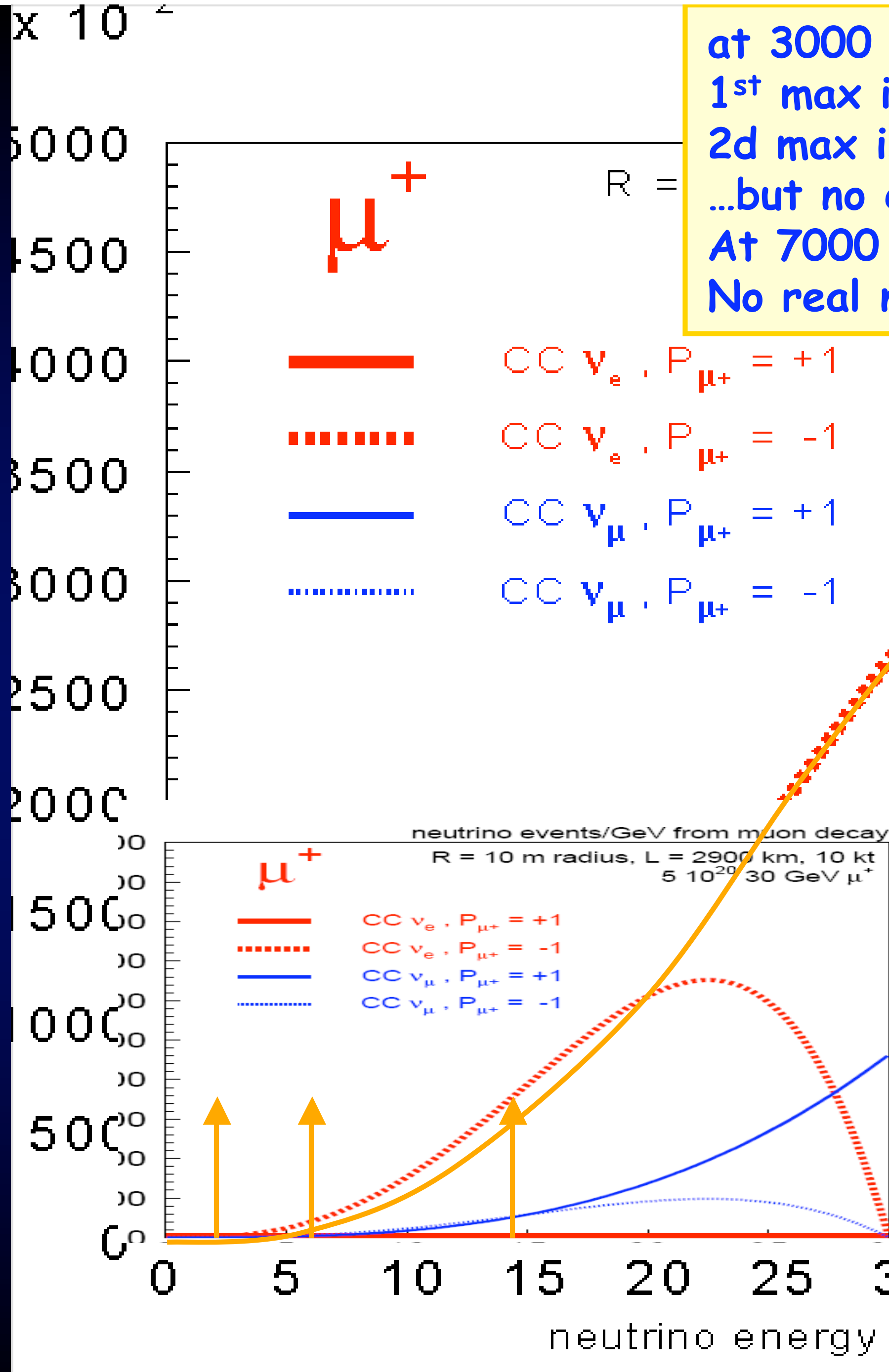
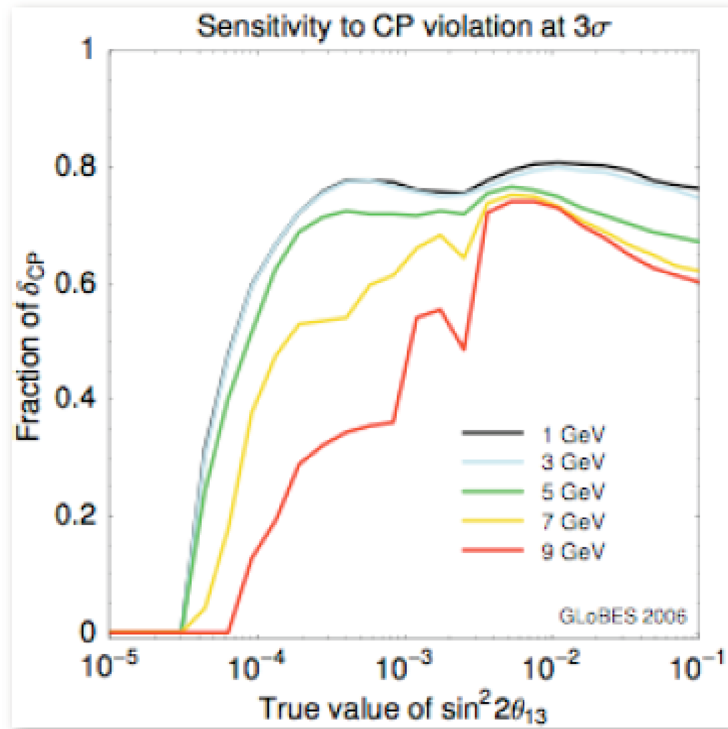


Figure 95: The $\sin^2 2\theta_{13}$ sensitivity limit relative to the optimum value of $5.9 \cdot 10^{-5}$ at $L_1 = L_2 \simeq 7\,500$ km. It is plotted at the 3σ confidence level as function of the baselines L_1 and L_2 heading from the 50 GeV Neutrino Factory towards two 25 Kton detectors. The sensitivity limit includes full correlations and degeneracies. The true parameters for this figure are $\Delta m^2_{31} = 3 \cdot 10^{-3}\,\mathrm{eV}^2$, $\theta_{23} = \pi/4$, $\Delta m^2_{21} = 7 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\sin^2\theta_{12} = 0.28$. Figure taken from [41].



at 3000 km,
1^{st} max is at 6 GeV
2d max is at 2 GeV
...but no events down there...
At 7000 km 1st max is at 14 GeV
No real need to go over 20 GeV muon energy



Initial comparison

Beta-beam

1. Low energy, even with 1 TeV proton accelerator, E<2-3 GeV no taus, no matter resonance

2. Pure ν_e or anti-ν_e
Well known flux
Non-magnetic detectors
Combination of superbeam required (?) for ν_μ cross section measts

3. Accelerator issues:
Ion production (need 10^{19}- 10^{21}/year)
High intensity, activation of accelerator
Storage and duty factor

4. Performance: low E BB is inferior.
High E BB is very competitive for CP at large θ_{13}
Not for universality test, matter effect

Neutrino-factory

1. High energy E>=15 GeV
taus, matter resonance

2. ν_e and anti-ν_μ simultaneously
Well known flux
Magnetic detectors
Low energy threshold difficult
Golden channel $\nu_e \sim \nu_\mu \rightarrow \mu^- X$ + CC
Electron charge difficult

3. Accelerator issues:
4 MW Target station
Cooling (RF in magnetic field)
Acceleration, beam monitoring

4. Performance: High E nufact
Will outperform at small θ_{13} for CP, universality test, matter effect, precision.

Initial comparison

Beta-beam

5. Technological readiness:
More recent!
Beta-beam not competitve without new concepts (see later) that need to be developped.
Activation in accelerator needs solution

6. Detector
Baseline is Water Cherenkov
"just needs money" R&D on phototubes!
Liquid Argon, TASD not demonstrated for very large masses

Neutrino-factory

5. Technological readiness:
Design and ideas are now mature. Unknowns regard RF Volts in magnetic field and power on target.
Cooling, target and accelerator demos are underway

6. Detector
Baseline is Magnetized iron
+ emulsion target for taus
"just needs money" +
R&D on photosensors
Liquid Argon, TASD not demonstrated for very large masses
in magnetic volume!

7. COST
1G€ for Mton detector + similar for accelerator with sharp dependence on ion energy.

7. COST
ISS cost = 1.4 G$ accelerator + 300M$ for far detector
All costs “unloaded”

Both projects cost about 2 G€ ~ “ILC/4”.
This is 5-10X more than NOνA or T2K