LBL neutrino beams and experiments

See also arXiv:hep-ph/0106088

André Rubbia, ETH Zürich
(ICARUS Collaboration)

Special thanks to A. Bueno, M. Campanelli & S. Navas-Concha

NO-VE: International Workshop on "Neutrino Oscillations in Venice"

24th-26th July, 2001

Three family oscillation phenomenology

MNSP (Maki-Nagawa-Sakata-Pontecorvo) matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Neutrino oscillations phenomenology determined by 6 parameters:

3 angles θ_{12}, θ_{13}, θ_{23}

1 phase δ

2 independent Δm^2's

In addition, propagation through matter requires additional density parameter ρ of traversed medium (in fact, matter profile)

The target of next generation LBL ν experiments

- **Precise determination of Δm^2_{23} and Θ_{23}**
- **Stringent limit/precise measurement of Θ_{13}**
- **Determination of Δm^2_{23} sign**
- **Study matter effects**
- **First detection of $\nu_e \rightarrow \nu_\tau$ oscillations**
- **Over-constrain the oscillation parameters (matrix unitarity)**
- **Study the δ phase (CP/T violation effects in the leptonic sector)**

Looking at the θ_{13} term

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

for $\Delta m^2_{21}\,(L/4E_\nu) << 1$:

$$P(\nu_e \to \nu_\mu) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{32}\, L/4E_\nu)$$

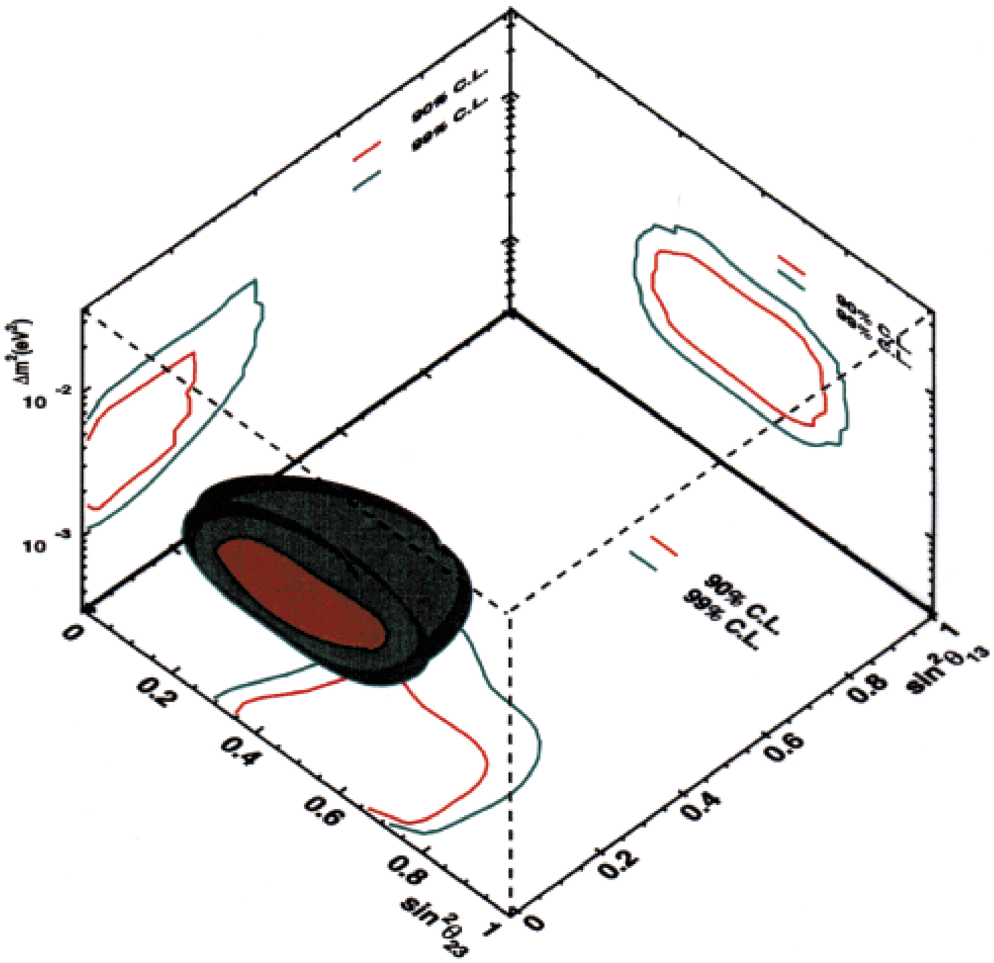
$$P(\nu_e \to \nu_\tau) \approx \sin^2 2\theta_{13} \cos^2\theta_{23} \sin^2(\Delta m^2_{32}\, L/4E_\nu)$$

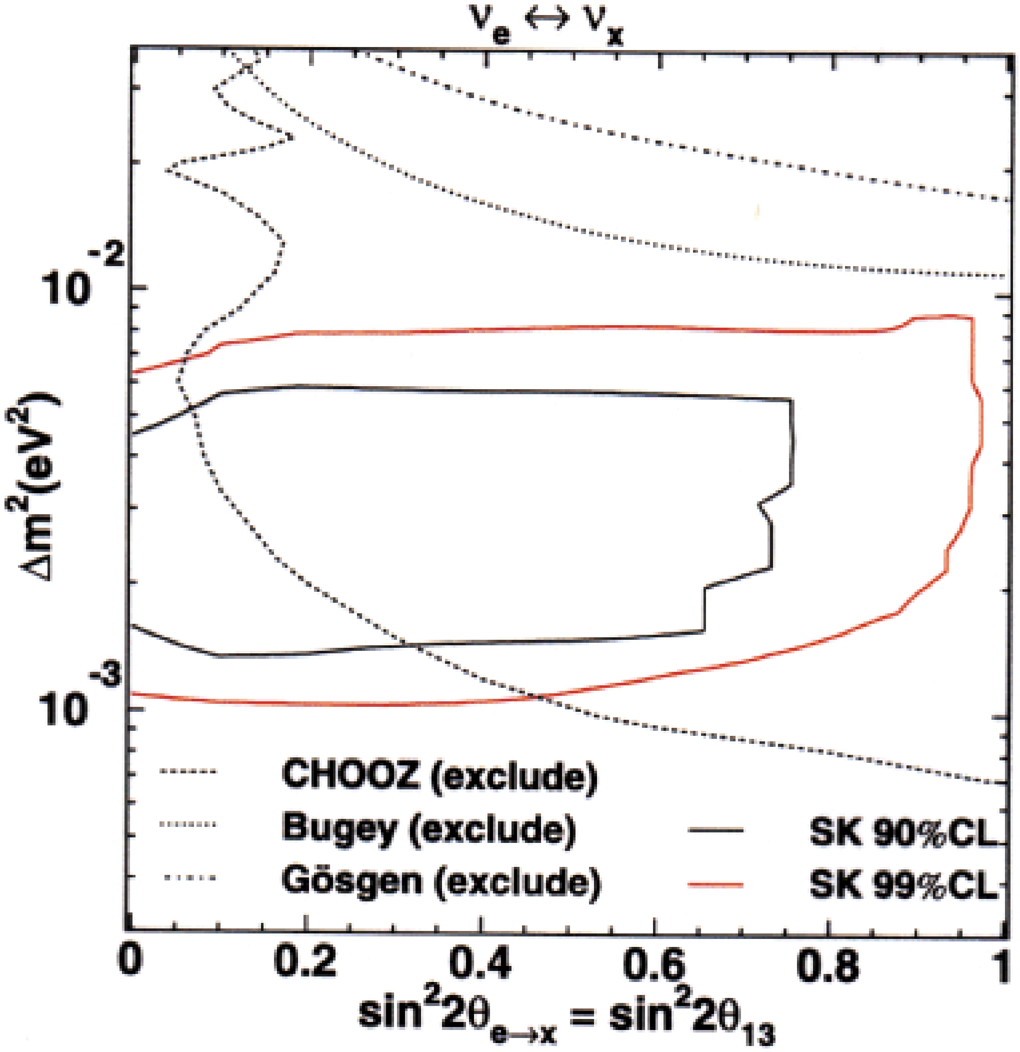
In contrast,

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \Delta^2_{32}$$

3 flavor mixing analysis of atmospheric

PRELIMINARY





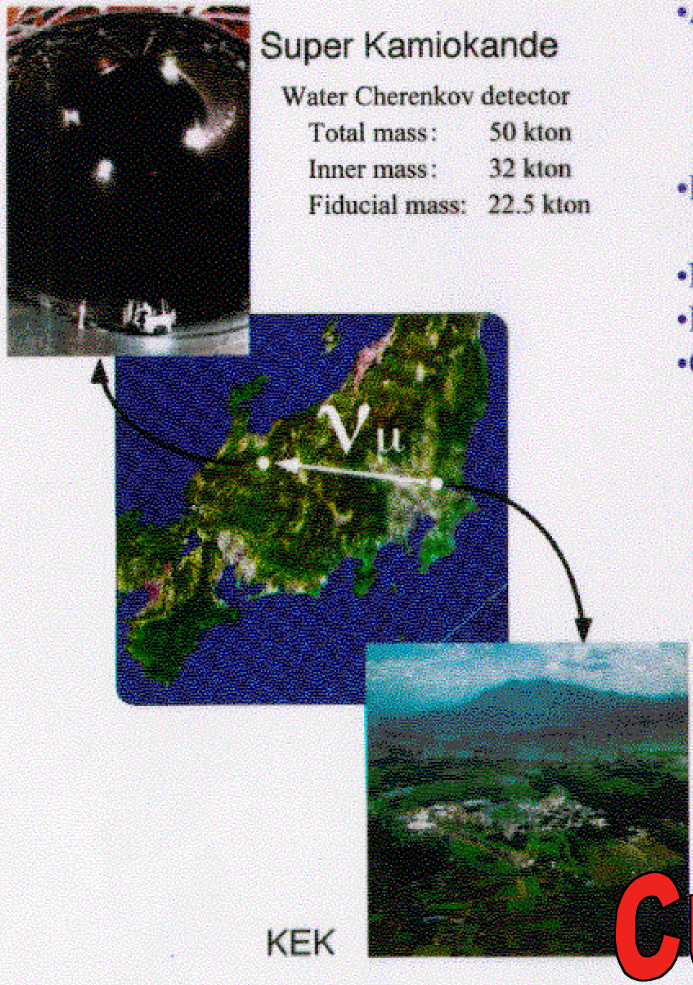
Atmospheric neutrinos analysis

K. Nakamura, NUFACT00, Monterey (USA), May 2000

Running or approved LBL neutrino beams

	K2K	**MINOS**	**CNGS** **(shared)**
E(GeV)	**12**	**120**	**400**
Pulse (10^{12}ppp)	6	40	92
Rate (Hz)	0.45	0.53	0.04
Power (MW)	**0.0052**	**0.41**	**0.22**
Pot (/yr)	**2×10^{19}**	**3.7×10^{20}**	**4.5×10^{19}** **($7.6\text{x}10^{19}$ dedicated)**

K2K (KEK-to-Kamioka)

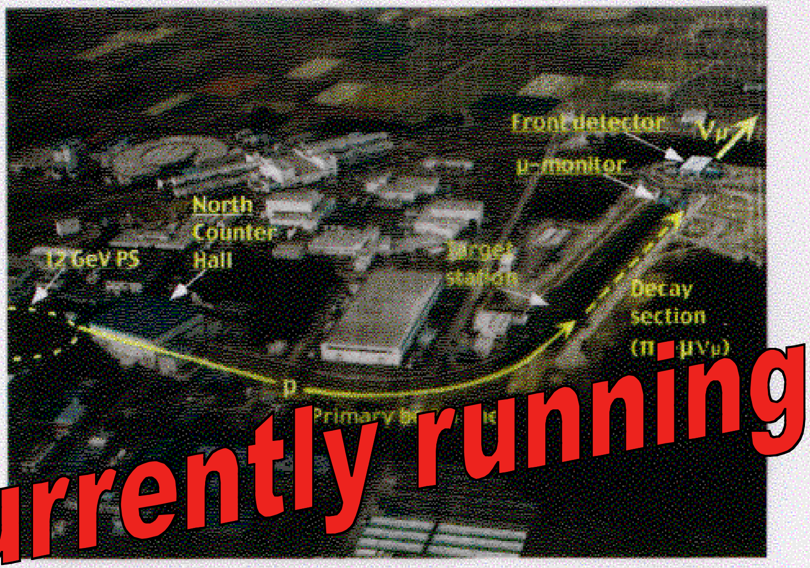


Super Kamiokande

Water Cherenkov detector

Total mass:	50 kton
Inner mass:	32 kton
Fiducial mass:	22.5 kton

- Accelerator: 12 GeV proton synchrotron
  - Beam intensity: 6×10^{12} protons / pulse
  - Repetition: 1 pulse / 2.2 sec
  - Pulse width: 1.1 μs (9 bunches)
- Horn-focused wide-band beam
  - Average neutrino energy: 1.4 GeV → $\nu_\mu - \nu_\tau$ disappearence
- Near detector: 300 m from the target
- Far detector (Super-Kamiokande): 250 km from the target
- Goal: 10^{20} protons on target



Currently running!

Naka~ - 03

K. Nakamura, Neutrino2000

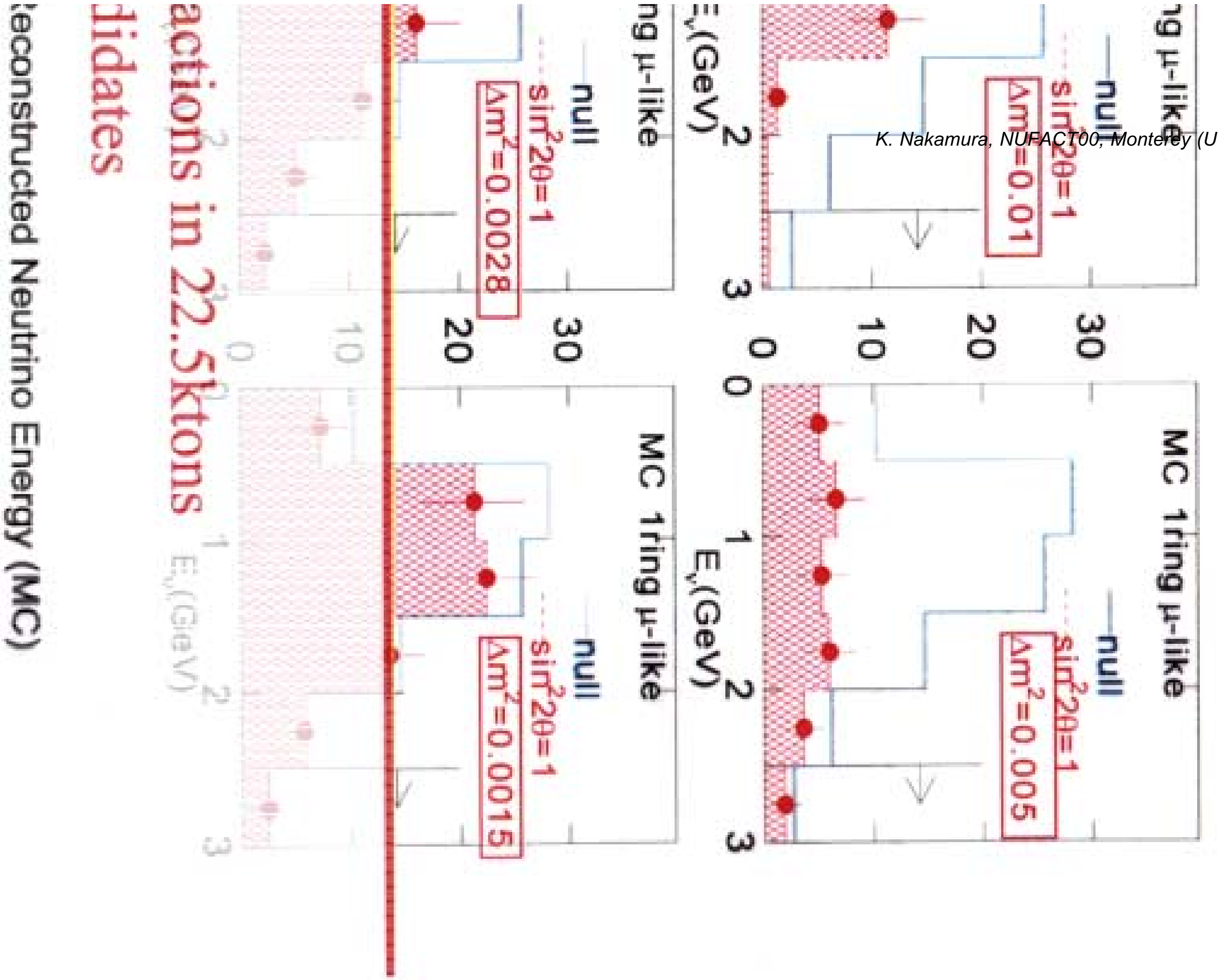
- *Results* *consistent* *with neutrino disappearance.*

- *More statistics needed.*

- *Final statistics:* *Expected 10^{20} pots*

- *Energy spectrum*

$$\Rightarrow \Delta m^2_{32}, \theta_{23}$$



K. Nakamura, NUFACT00, Monterey (USA), May 2000

NUMI

MINOS

Neutrino 2000
June 17, 2000
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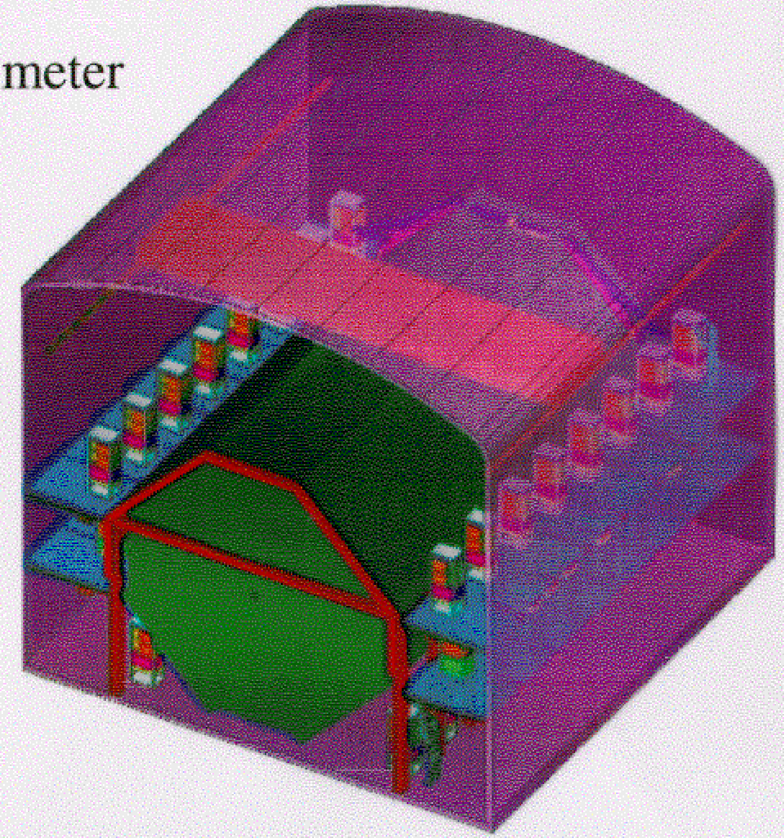
MINOS Far Detector

- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m^2 active detector planes
- Magnet coil provides $\langle B\rangle \approx 1.3T$
- 5.4kt total mass



Half of the MINOS Far Detector

Wojcicki -

S. Wojcicki, Neutrino2000

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Neutrino 2000
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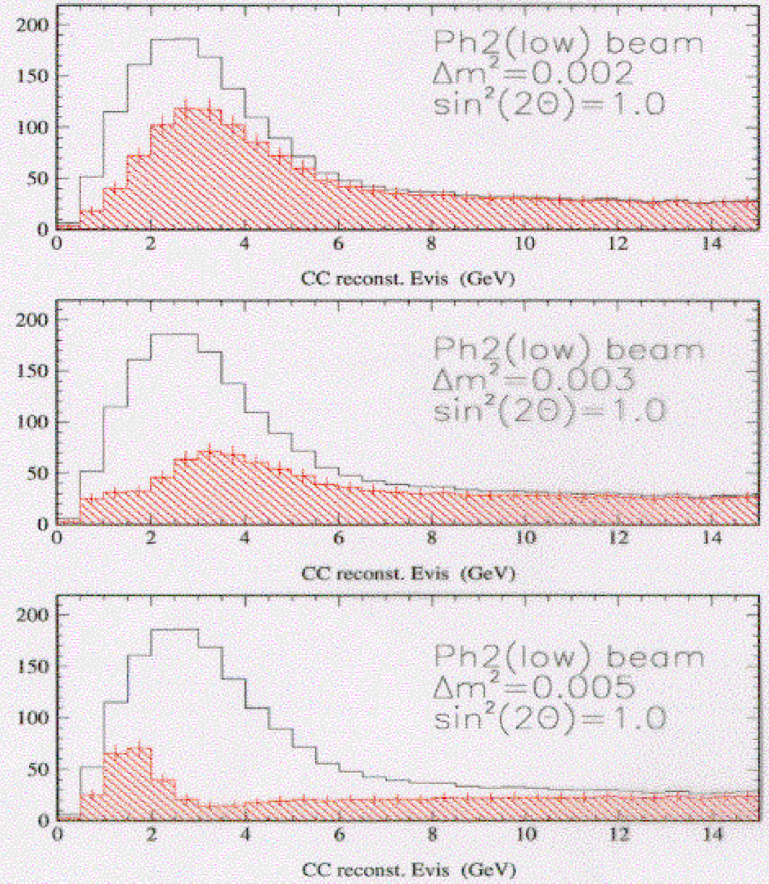
MINOS Energy Spectra



10 kt-yr Exposure

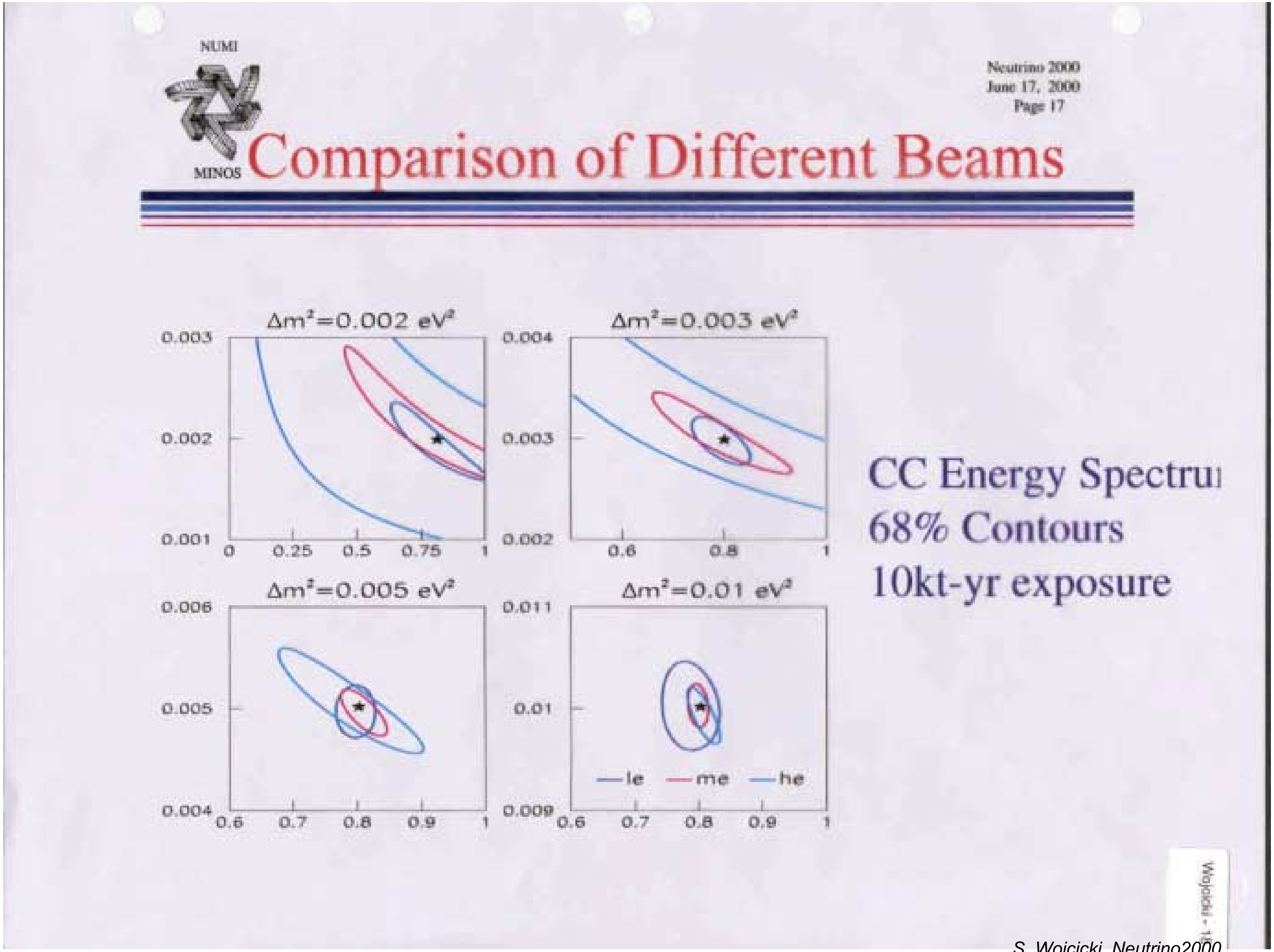
Solid lines - energy spectrum without oscillations

Dashed histogram - spectrum in presence of oscillations

⇒ $\Delta m^2_{32}, \theta_{23}$

Wojcicki - 17

S. Wojcicki, Neutrino2000



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Comparison of Different Beams

CC Energy Spectru
68% Contours
10kt-yr exposure

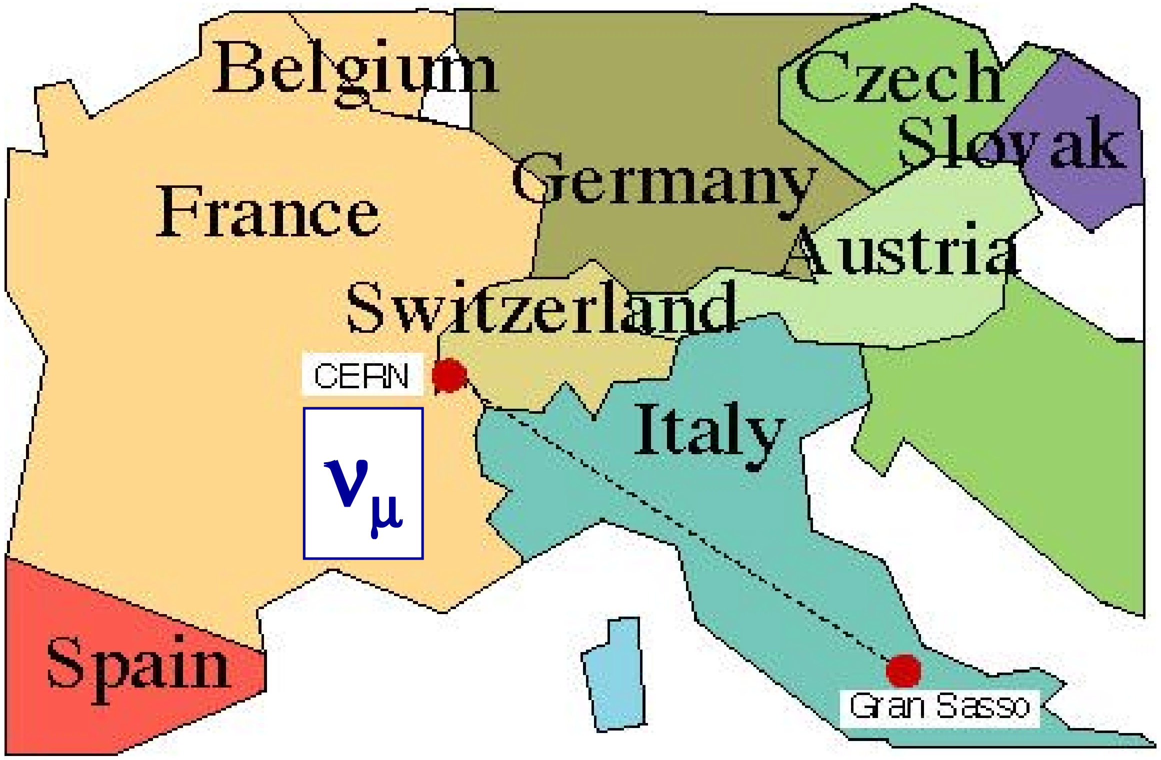
Wojcicki - 1

S. Wojcicki, Neutrino2000

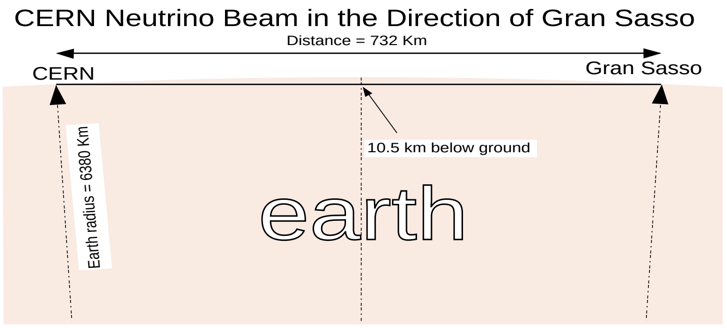
CNGS neutrino beam

The expected ν_e and ν_τ contamination of the CNGS beam are of the order of 10^{-2} and 10^{-7} respect to the dominant ν_μ.

CERN 98-02 - INFN-AE/98-05
CERN-SL/99-034(DI) - INFN/AE-99/05



ν_τ? ν_e?



CNGS beam characteristics

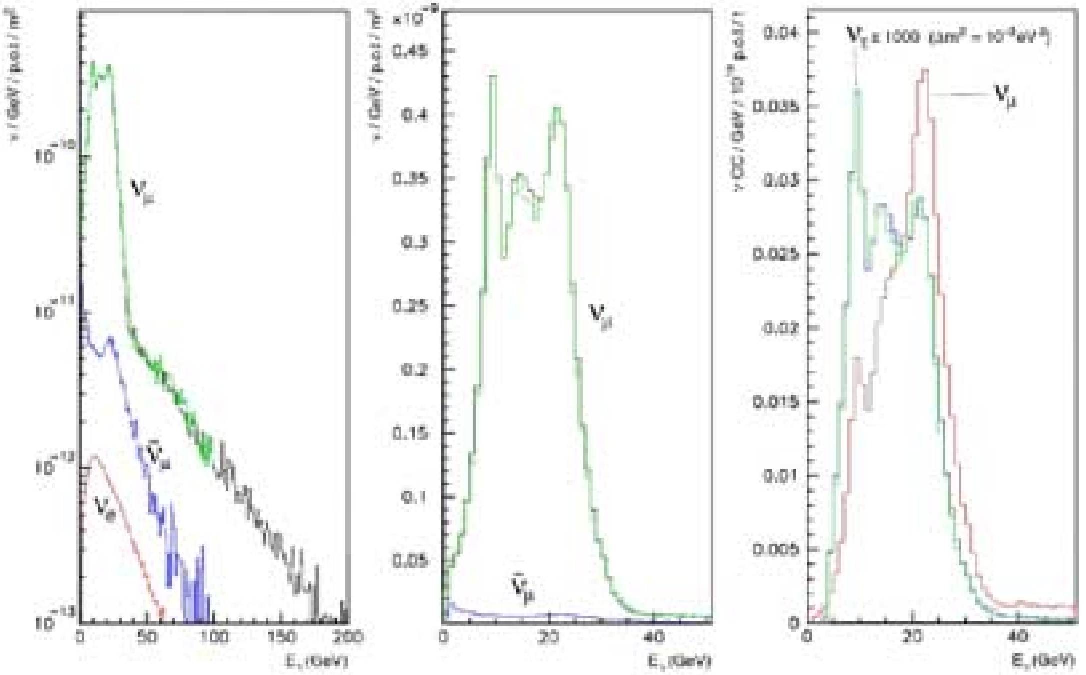
Nominal ν beam

ν_μ (m^{-2} / pot)	7.78×10^{-9}
ν_μ CC / pot / kton	5.85×10^{-17}
$\langle E \rangle_\nu$ (GeV)	17
$(\nu_e + \overline{\nu}_e) / \nu_\mu$	0.87 %
$\overline{\nu}_\mu / \nu_\mu$	2.1 %
ν_τ prompt	negligible

$\Rightarrow$ **Interactions with 1.8 kton target x 5 years**

~ 30000 ν NC+CC

~ 140 ν_τ CC (@full mixing, $\Delta m^2 = 2.5\times10^{-3}$ eV^2)



400 GeV primary protons

Shared SPS operation

200 days/year

4.5×10^{19} pot / year

CNGS event rates

- Primary protons: ***400 GeV; 4x2.3x10^{13} p/cycle; 26.4 s/cycle***
- Pots per year: ***4.5x10^{19} pots*** “shared”; ***200x0.75 days/year***
- 7.6x10^{19} pots/yr “dedicated”

Process	Rates (events/kton/year)
ν_μ CC	2450
$\bar{\nu}_\mu$ CC	49
ν_e CC	20
$\bar{\nu}_e$ CC	1.2
ν NC	823
$\bar{\nu}$ NC	17

No oscillations

- Optimized for $N_\tau \propto \int \phi_{\nu_\mu}(E) \times \sigma_{\nu_\tau}^{CC}(E) E^{-2} dE$

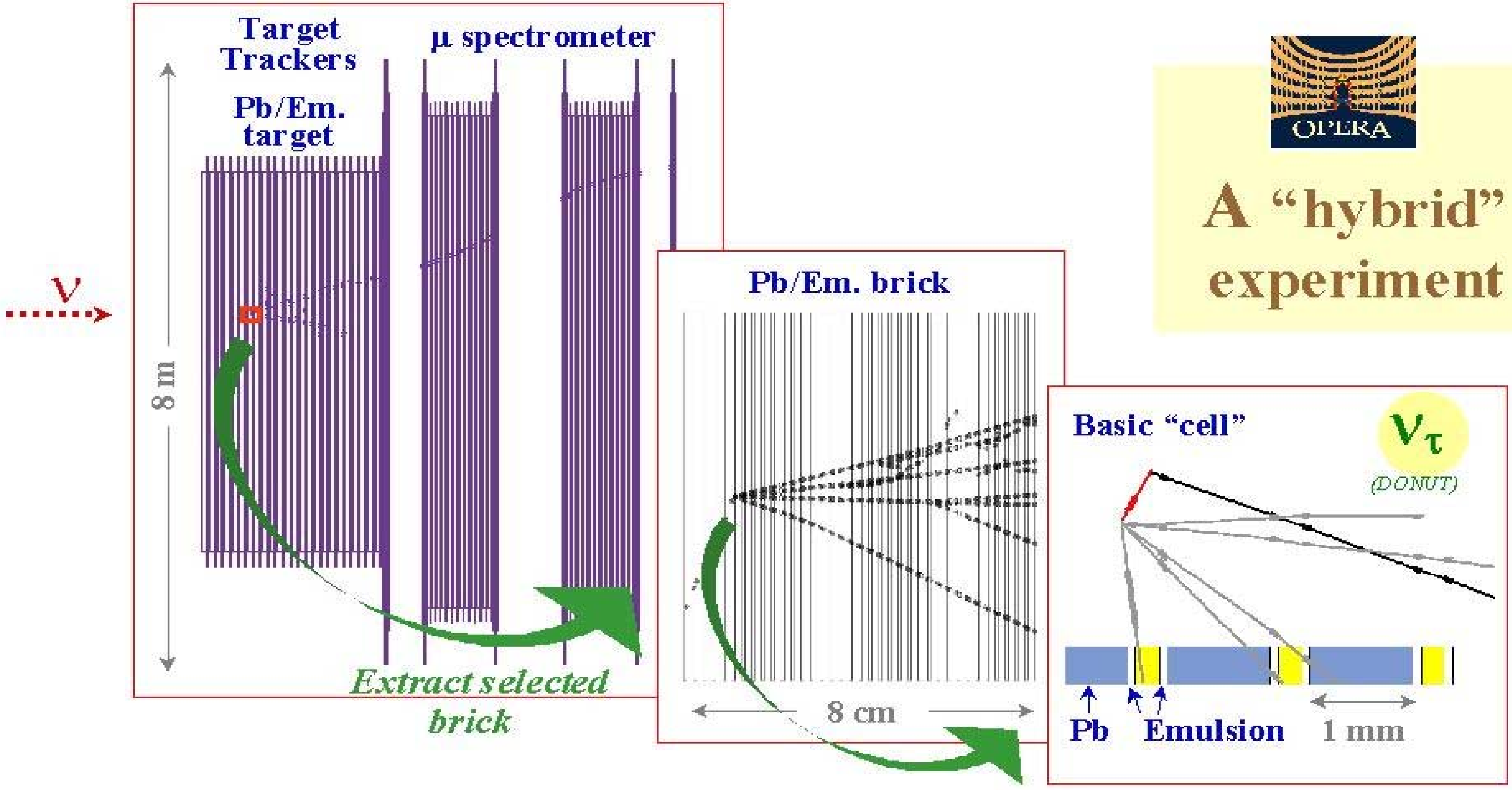
Δm^2 (eV^2)	Rates (events/kton/year)
1×10^{-3}	2.4
2.5×10^{-3}	15.1
3.5×10^{-3}	29.4
5×10^{-3}	58.6
1×10^{-2}	209.0

ν_τ CC event rates

CERN 98-02 - INFN-AE/98-05; CERN-SL/99-034(DI) - INFN/AE-99/05

The OPERA experiment

A "hybrid" experiment



Electronic detectors

→ select ν interaction brick

→ μ ID, charge and p

Emulsion scanning

→ vertex search

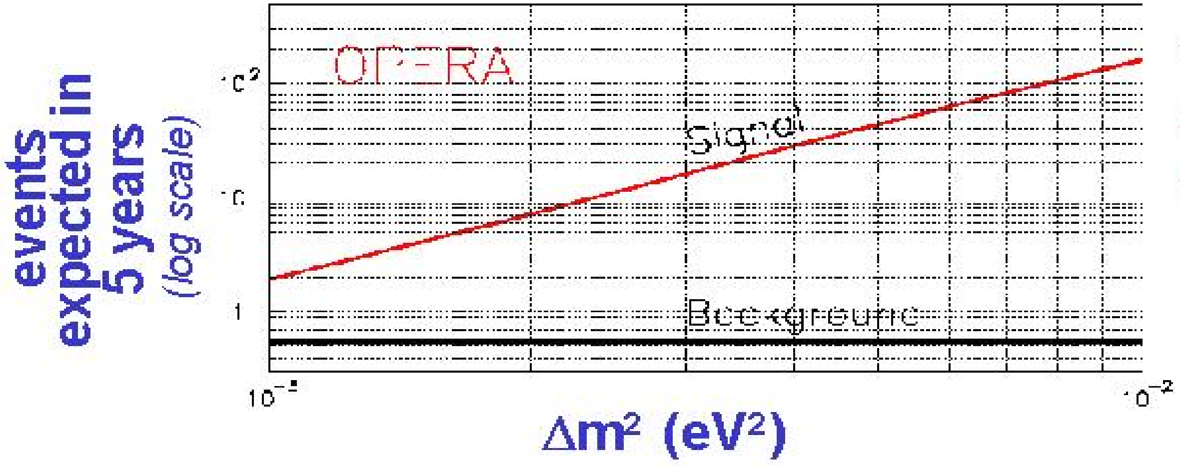
→ decay search

→ e/γ ID, kinematics

A. Ereditato, Now2000

Expected numbers of events

τ decay	**ν_τ events** Δm^2 (10^{-3} eV^2) 1.5	3.2	5.0	**b.g.**
e	1.7	7.7	18.5	0.19
μ	1.3	5.7	13.8	0.13
h	1.1	4.9	11.8	0.25
Total	**4.1**	**18.3**	**44.1**	**0.57**



- **Full mixing**
- **5 years with shared SPS operation (2.25×10^{20} pot)**
- **Average target mass = 1.8 kton**

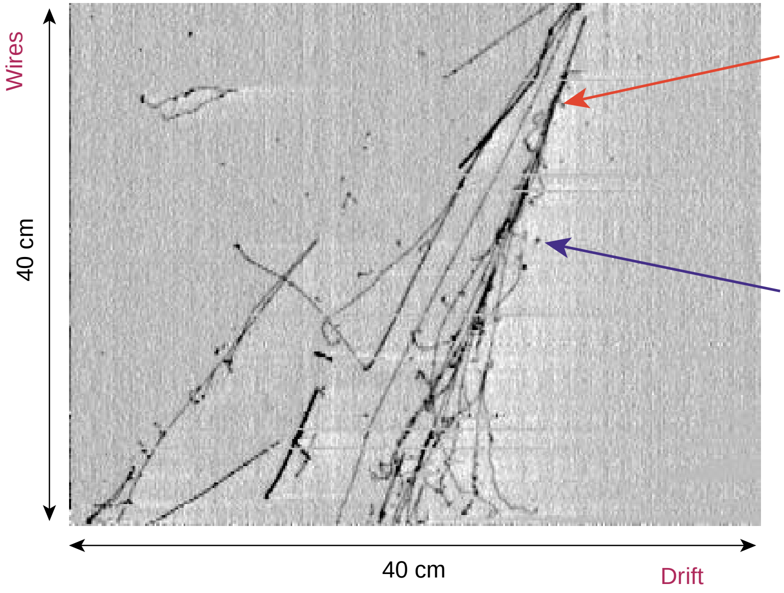
(accounting for mass reduction with time, due to brick removal for analysis)

- **Uncertainties on background and efficiencies accounted for in the following**

$$\Rightarrow \Delta m_{32}^2 \times \theta_{23}$$

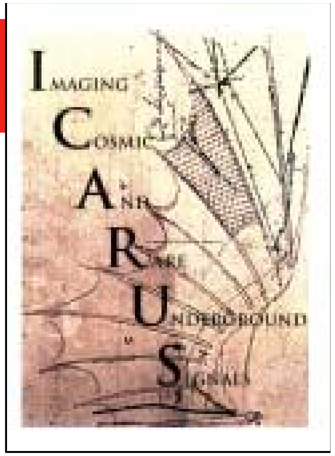
A. Ereditato, Now2000

The ICARUS experiment

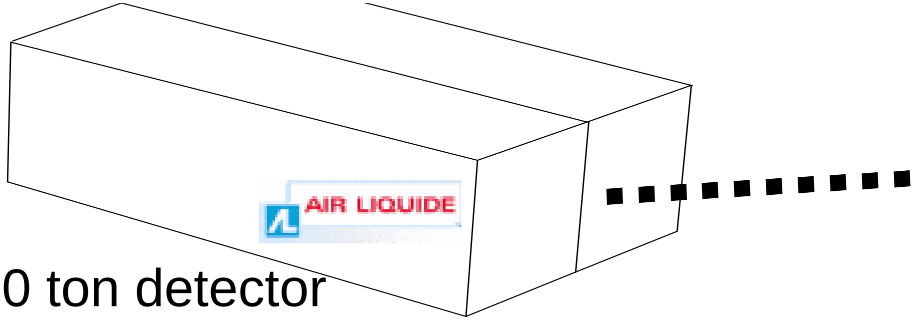


"Bubble" size
≈ 3 x 3 x 0.2 mm^3

Energy deposition measured for each point



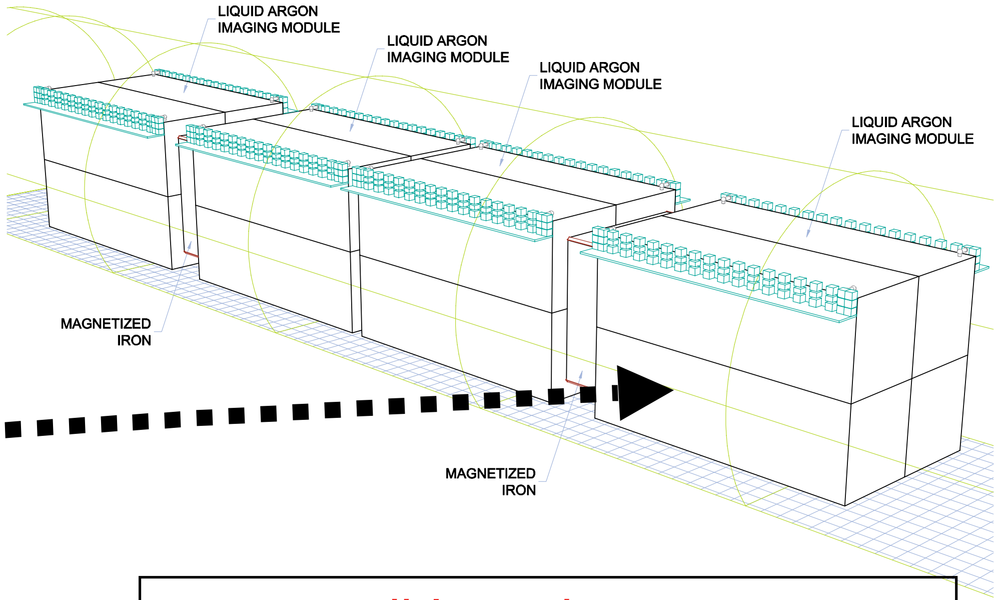
ICARUS T600 (approved)



600 ton detector

First test run in March 2001!
In LNGS Tunnel in 2002

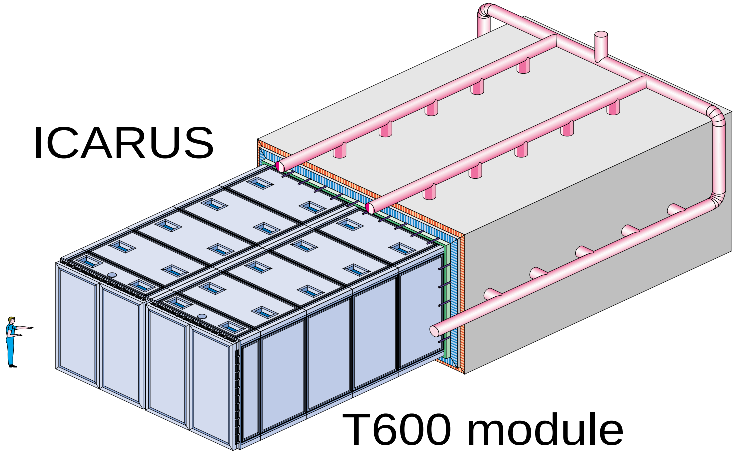
ICARUS multi-kton



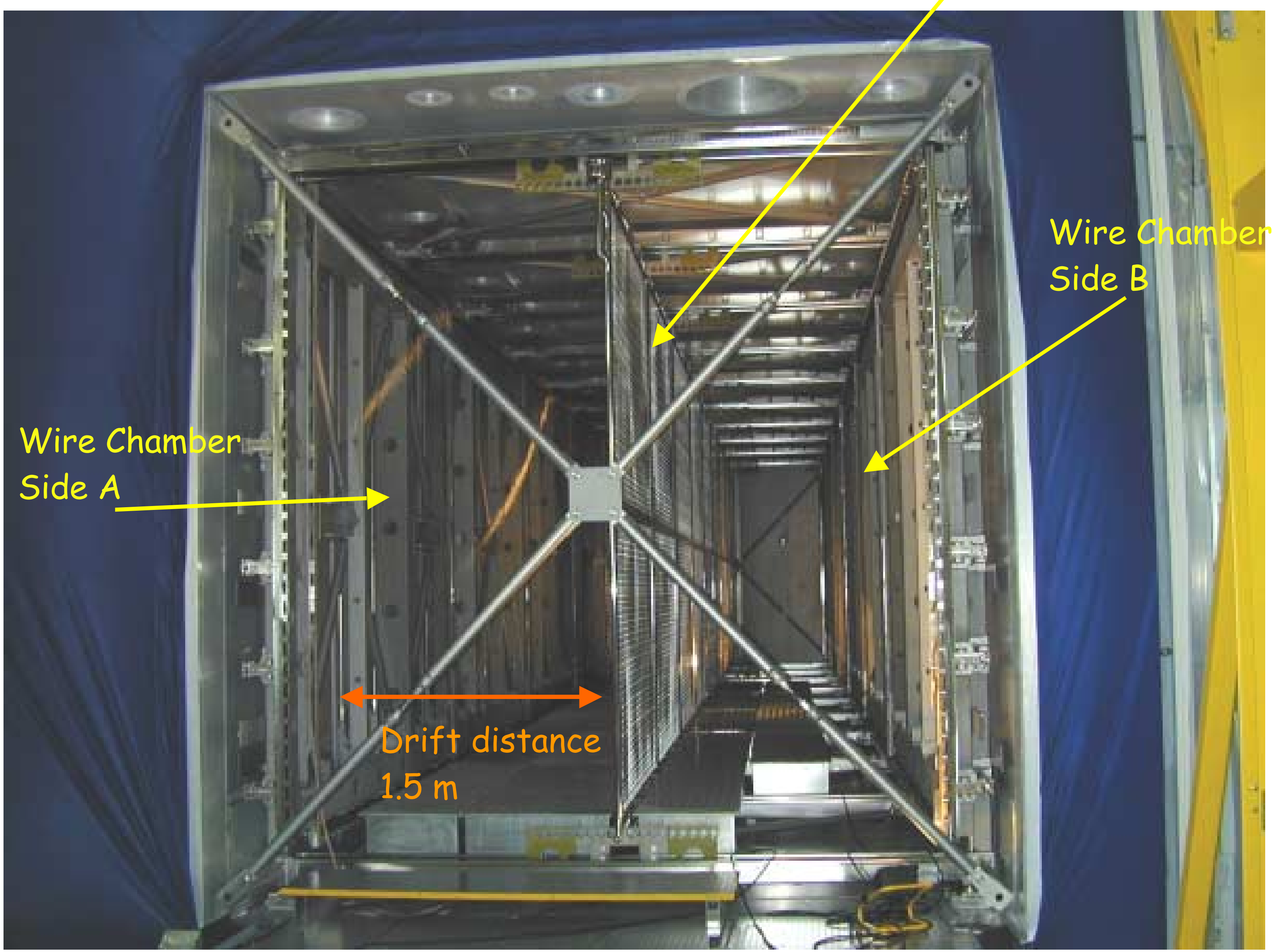
Two possible options:
A) n x T600
B) m x T1400 (better for physics)

The first ICARUS T600 prototype

- The T600 module is to be considered as a fundamental milestone on the road towards a total sensitive mass in the multi-kton range
  - ➜First piece of the detector to be complemented by further modules of appropriate size and dimension ⇒ *Goal is **to reach a multikton mass in LNGS tunnel in a most efficient and rapid way***
- It has a physics program of its own, immediately relevant to neutrino physics, though limited by statistics (see hep-ex/0103008)



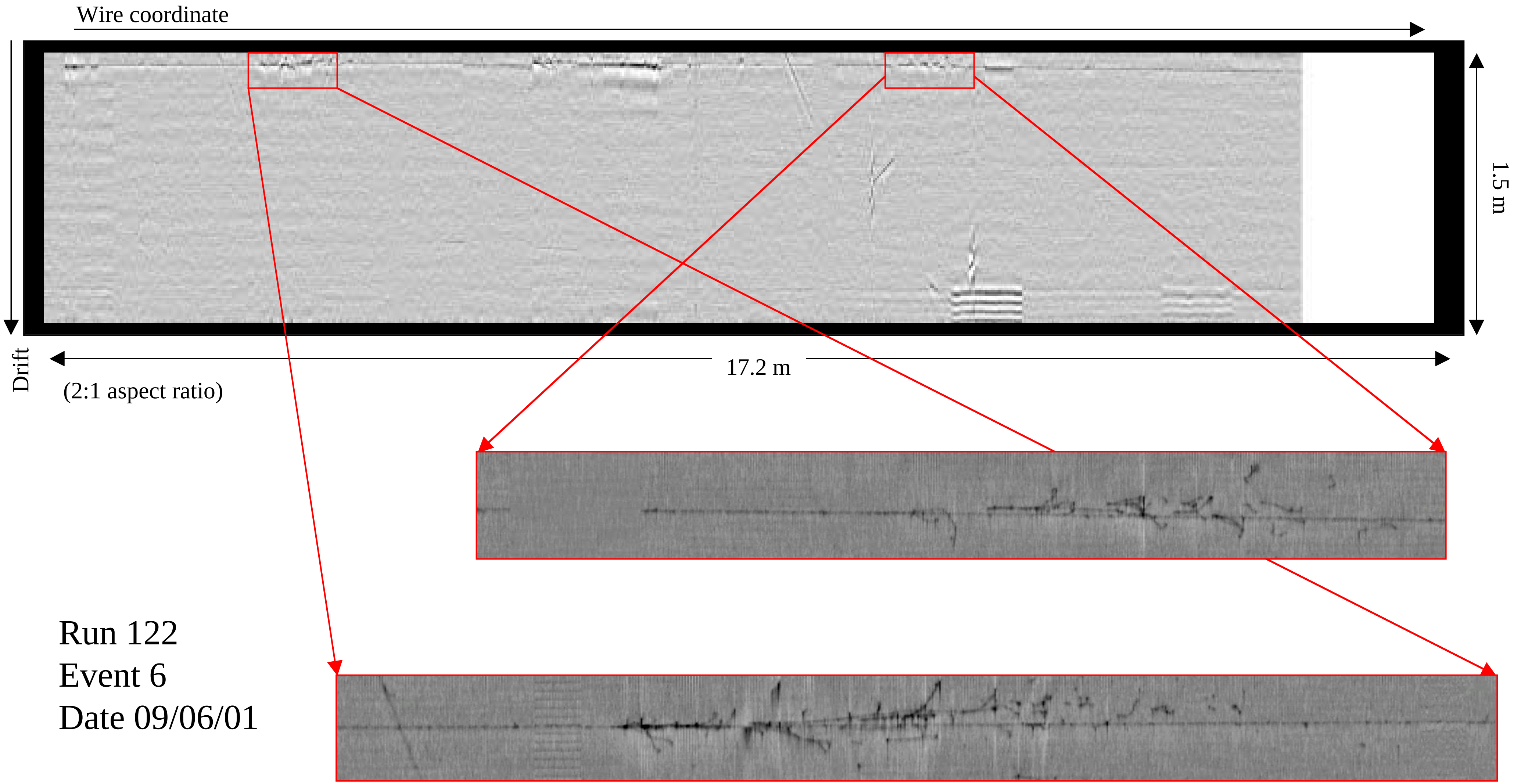
T600 - Completed Internal Half-Detector view



ICARUS T600 semimodule horizontal muon

60° Induction view

VERY PRELIMINARY

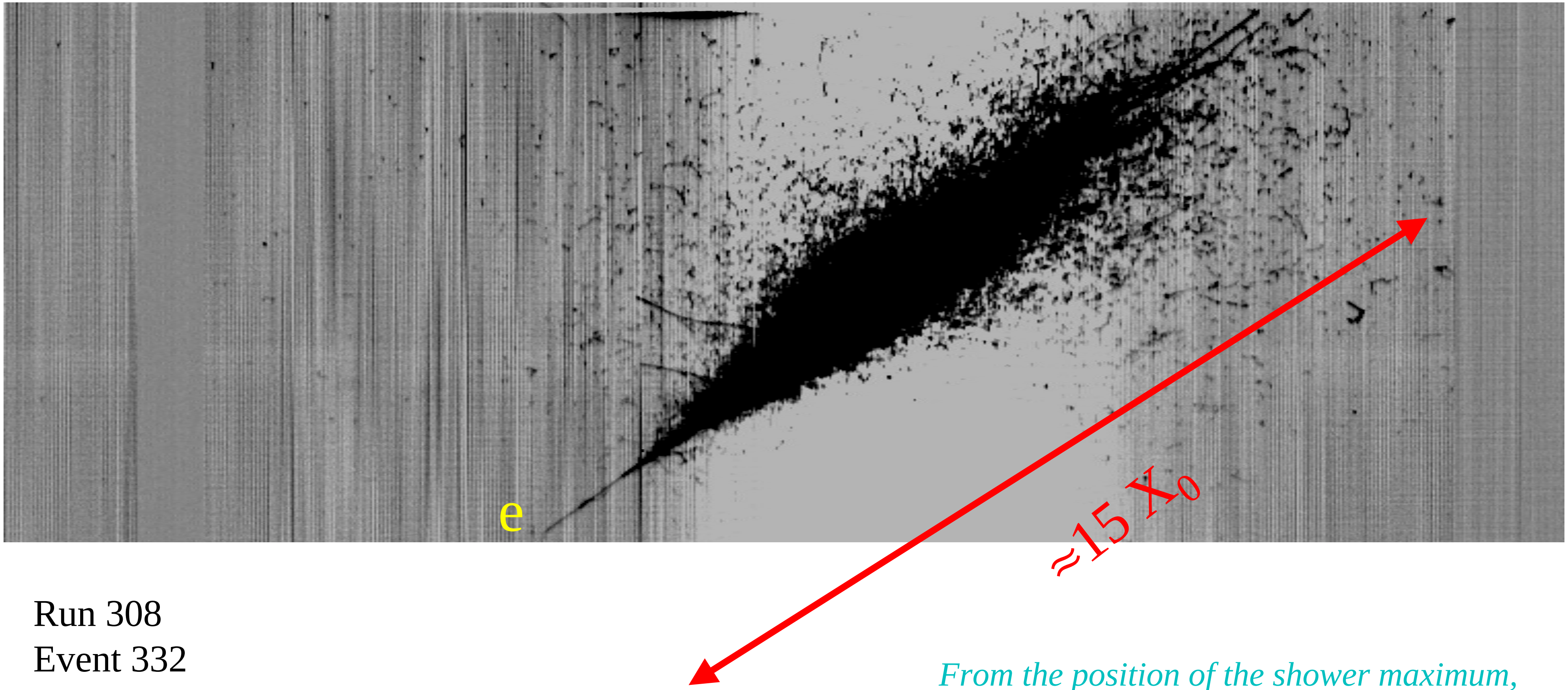


Run 122
Event 6
Date 09/06/01

ICARUS T600 high energy electron candidate

The entering track is consistent with the dE/dx deposition of a single electron. An e^+e^- pair from a converted photon would deposit twice as much energy.

VERY PRELIMINARY



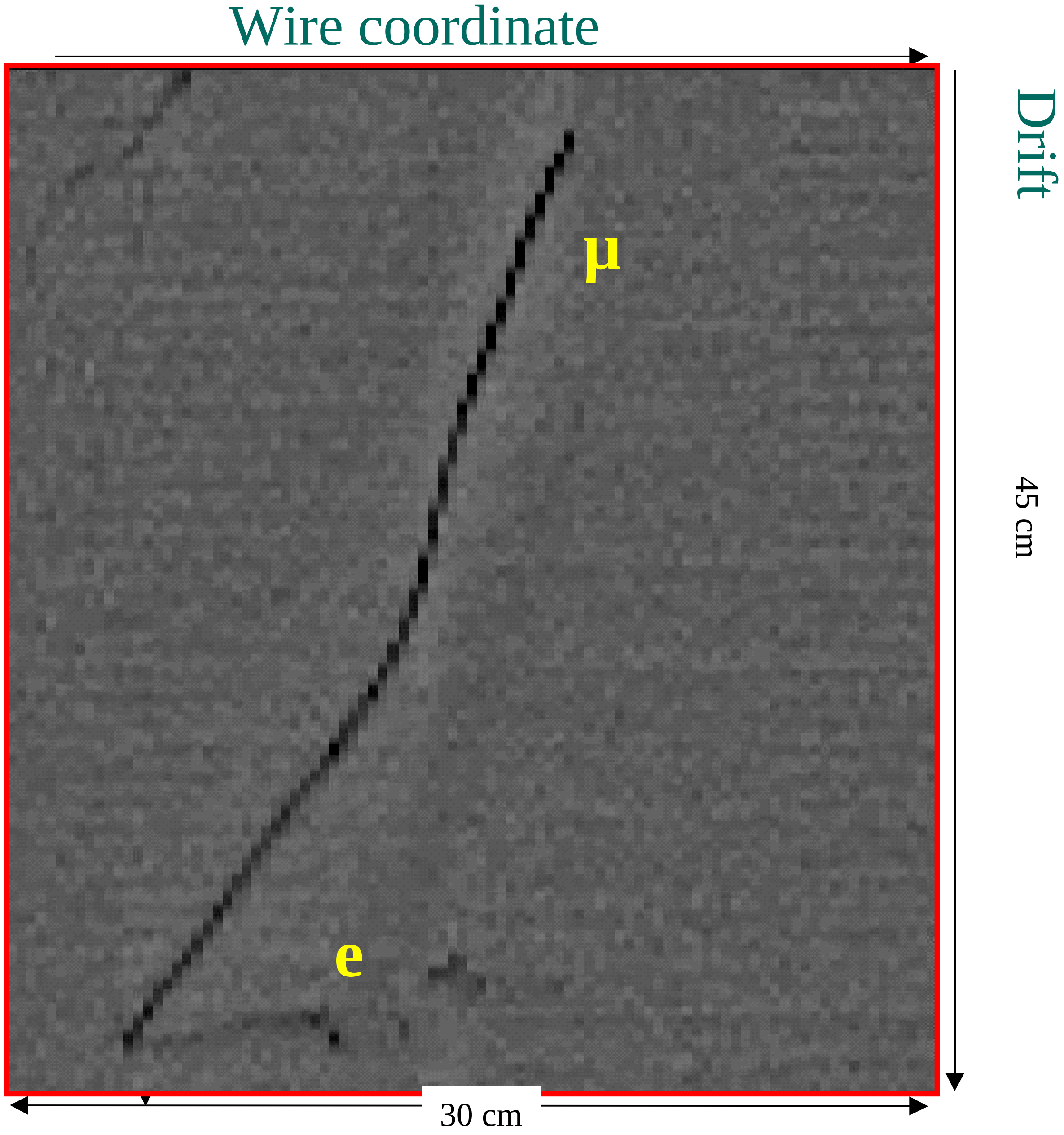
Run 308
Event 332
Date 21/06/01

From the position of the shower maximum, we can estimate the electron energy $E_e \approx$ 20 GeV

ICARUS T600 semimodule stopping muon

VERY PRELIMINARY

60° Collection view



Run 118
Event 11
Date 08/06/01

CNGS events in 4 kton, 5 years running

$\theta_{23} = 45°, \theta_{13} = 7°$

20 kton×year

	No osci	Δm^2_{23} (eV^2) 1×10^{-3}	Δm^2_{23} (eV^2) 3.5×10^{-3}	Δm^2_{23} (eV^2) 5×10^{-3}
ν_μ CC	54300	53820	49330	44910
$\bar{\nu}_\mu$ CC	1090	1088	1070	1057
ν_e CC	437	437	437	436
$\bar{\nu}_e$ CC	29	29	29	29
ν NC	17550			
$\bar{\nu}$ NC	410			
$\nu_\mu \to \nu_e$ CC	-	7	74	143
$\nu_\mu \to \nu_\tau$ CC	-	52	620	1250
$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	-	< 1	< 1	1
$\bar{\nu}_\mu \to \bar{\nu}_\tau$ CC	-	< 1	6	13

$\nu_\mu \rightarrow \nu_\tau$ oscillations in ICARUS 4 kton

- Analysis of the electron sample
  - → Exploit the small intrinsic ν_e contamination of the beam
  - → Exploit the unique e/π^0 separation
- Expected in 5 years @ CNGS and 4 ktons:

$$\nu_\mu \rightarrow \nu_\tau$$

$$\nu_\tau + N \rightarrow \tau + \mathrm{jet}; \quad \tau \rightarrow e\nu\nu$$

Charged current (CC)

$$Br \approx 18\%$$

$$\Delta m^2 = 3.5 \times 10^{-3} eV^2 \quad \Rightarrow \quad 110 \ \ events$$

Background:

$$\nu_e + N \rightarrow e + \mathrm{jet}$$

Charged current (CC)

$$470 \ \ \nu_e CC$$

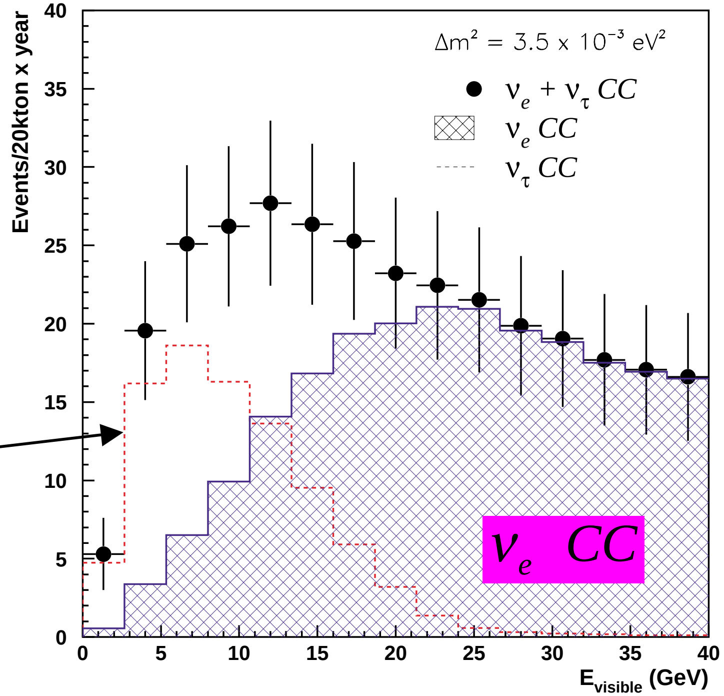
Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

$\nu_\mu \rightarrow \nu_\tau$ *oscillations (II)*

- Reconstructed visible energy spectrum of electron events clearly evidences excess from oscillations into tau neutrino

$$\Delta m^2_{32} \times \theta_{23}$$

signal

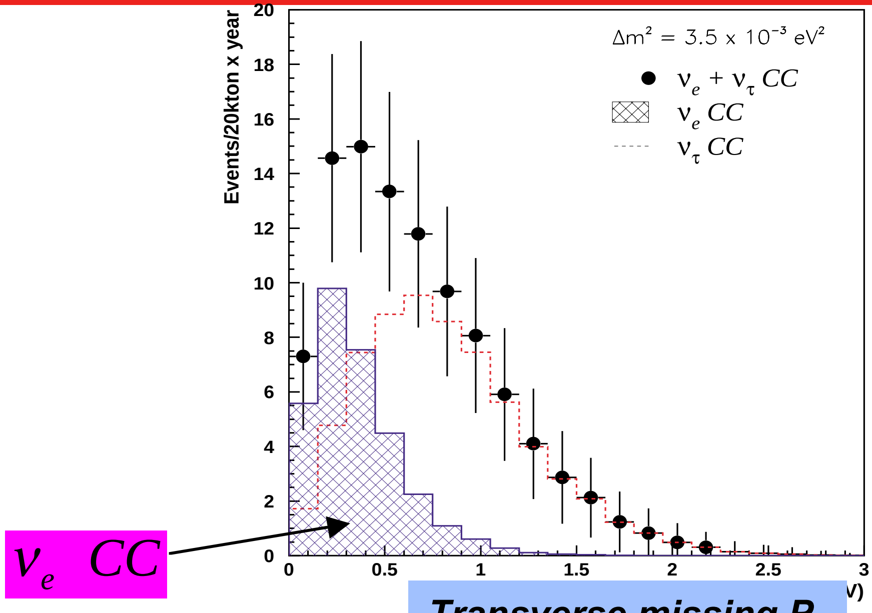


Reconstructed energy

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
Initial	100	437	29	9.3	71	111	779
Fiducial volume	88	383	25	8.2	64	97	686
One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522

$\nu_\mu \rightarrow \nu_\tau$ oscillations (III)

- Kinematical selection in order to enhance S/B ratio
- Can be tuned “a posteriori”
  depending on the actual Δm^2
- For example, with cuts listed below, reduction of background by factor 100 for a signal efficiency 33%



ν_e CC

Transverse missing P_T

Cuts	ν_τ Eff. (%)	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC $\Delta m^2 = 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 3.5 \times 10^{-3}$ eV^2	ν_τ CC $\Delta m^2 = 10^{-2}$ eV^2
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One candidate with momentum > 1 GeV	72	365	25	6.7	50	80	561
$E_{vis} < 18$ GeV	67	64	5	6.2	46	75	522
$P_T^e < 0.9$ GeV	54	31	3	5.0	38	60	421
$P_T^{lep} > 0.3$ GeV	51	29	2	4.7	35	56	397
$P_T^{miss} > 0.6$ GeV	33	4	0.4	3.1	23	37	257

Search for $\theta_{13}>0$

$\Delta m^2_{32}=3.5\mathrm{x}10^{-3}\ \mathrm{eV}^2;\ \sin^2 2\theta_{23}=1$

ICARUS 4kton
5 years @ CNGS

Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV

$\Delta m^2_{23} = 3.5\times 10^{-3}\ \mathrm{eV}^2,\ \theta_{23} = 45^o$

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC	$\nu_\mu \to \nu_\tau$ $\tau \to e$	$\nu_\mu \to \nu_e$	Total	Statistical significance
9	0.095	79	74	84	237	6.8σ
8	0.076	79	75	67	221	5.4σ
7	0.058	79	76	51	206	4.1σ
5	0.030	79	77	26	182	2.1σ
3	0.011	79	77	10	166	0.8σ

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2{}_{32}$$

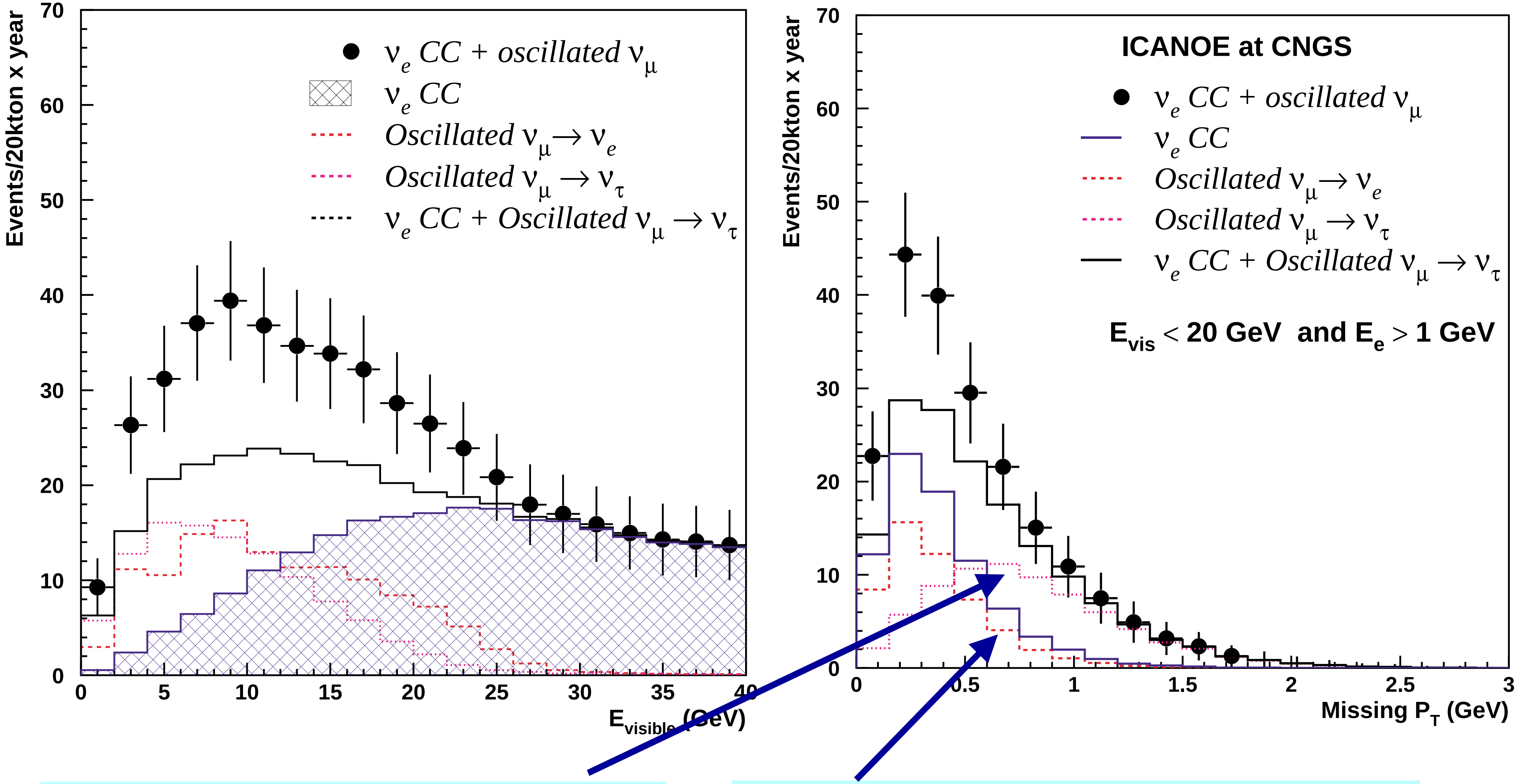
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2{}_{32}$$

$$\Rightarrow \Delta m^2_{32}, \theta_{23}, \theta_{13}$$

$\Delta m^2_{32}=3.5\times10^{-3}\ \text{eV}^2;\ \sin^2 2\theta_{23} = 1\ ;\ \sin^2 2\theta_{13} = 0.05$

Total visible energy

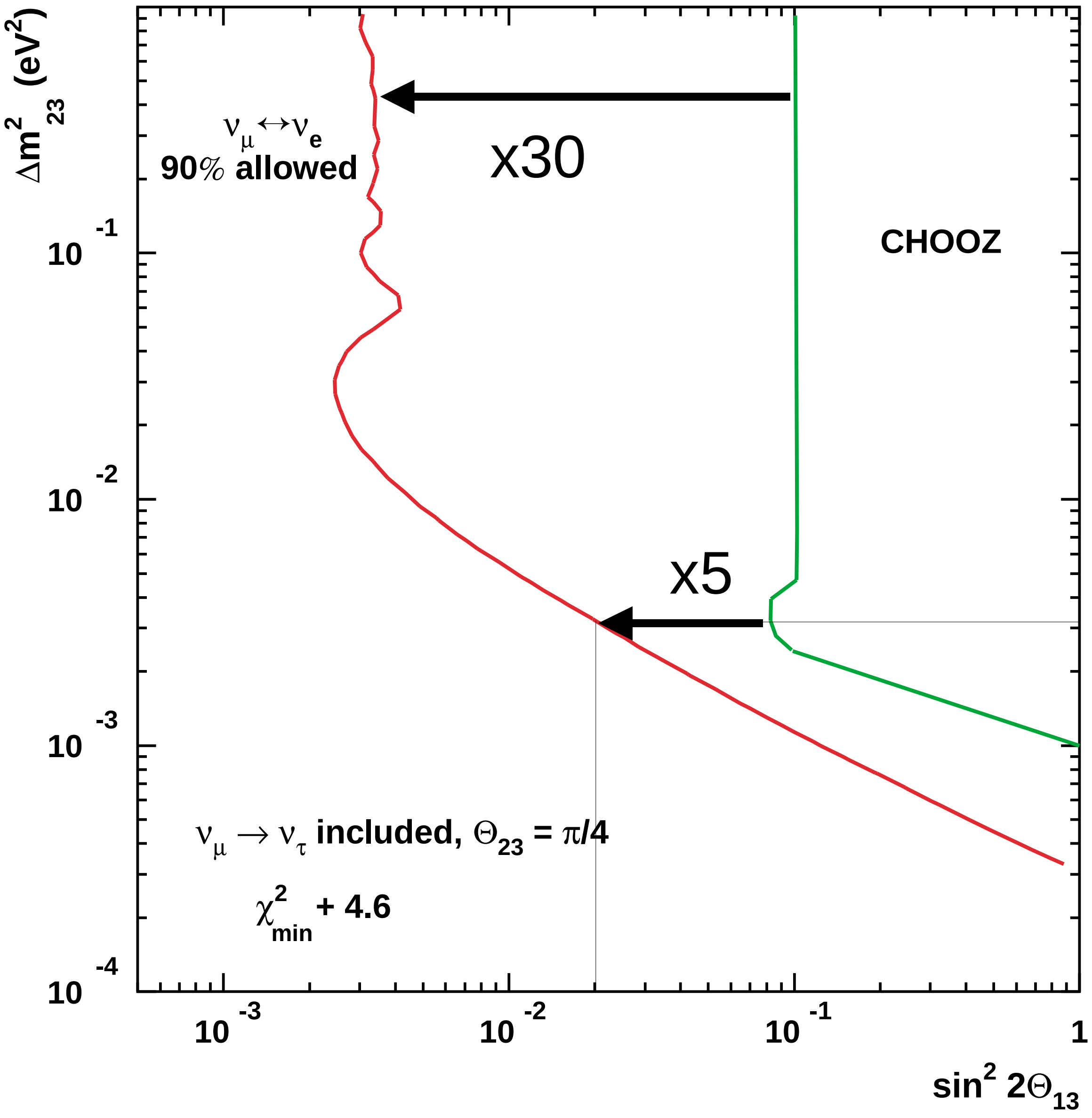
Transverse missing P_T



$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2{}_{32}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2{}_{32}$$

Sensitivity to θ_{13} in three family-mixing



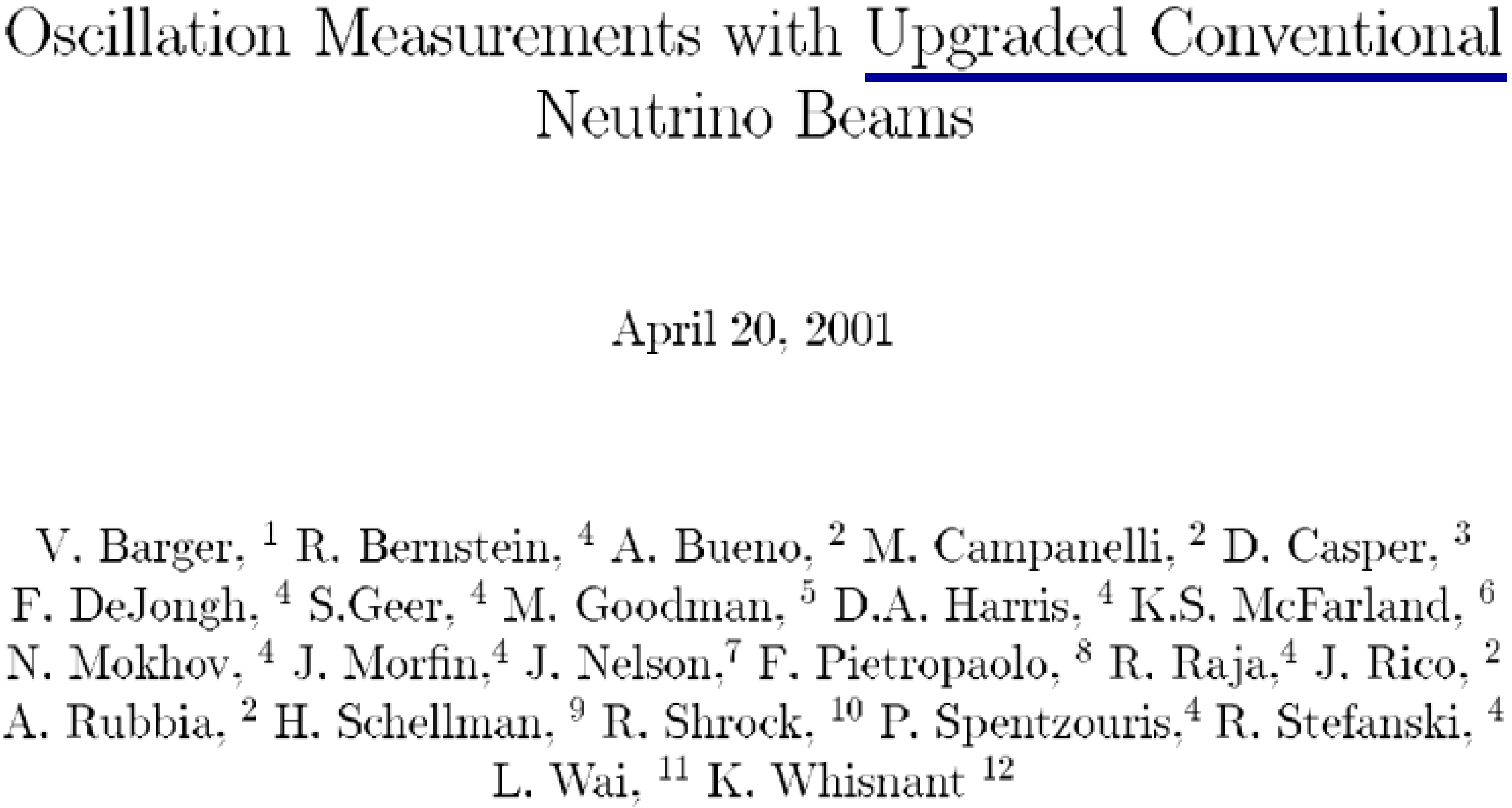
ICARUS 4kton
5 years @ CNGS

Sensitivity assuming both $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ at the same Δm^2 (i.e. three family mixing)

$$\sin^2 2\theta_{13} > 2\times 10^{-2}$$

$$for\ \ \Delta m^2_{32} = 3\times 10^{-3} eV^2$$

Study led by US working group:



Oscillation Measurements with Upgraded Conventional Neutrino Beams

April 20, 2001

V. Barger, [1] R. Bernstein, [4] A. Bueno, [2] M. Campanelli, [2] D. Casper, [3] F. DeJongh, [4] S.Geer, [4] M. Goodman, [5] D.A. Harris, [4] K.S. McFarland, [6] N. Mokhov, [4] J. Morfin,[4] J. Nelson,[7] F. Pietropaolo, [8] R. Raja,[4] J. Rico, [2] A. Rubbia, [2] H. Schellman, [9] R. Shrock, [10] P. Spentzouris,[4] R. Stefanski, [4] L. Wai, [11] K. Whisnant [12]

arXiv:hep-ph/0103052

The oscillation physics program at the Superbeams

Mostly $\pi^+ \rightarrow \mu^+ \nu_\mu$

$\nu_\mu \rightarrow \nu_e$	appearance
ν_μ	disappearance
$\nu_\mu \rightarrow \nu_\tau$	appearance (high energy)

Backgrounds for $\nu_\mu \rightarrow \nu_e$:

1. **Irreducible beam ν_e content (K and μ decays)**
2. **Electron misidentification**

*1. **Particle ID**: electron identification and measurement*

*2. **Near detector** : can help predict flux accurately*

Superbeams

	K2K	MINOS	CNGS (shared)	JHF	JHF Phase II	Upgraded Booster	Super-NUMI	Super-NGS
E(GeV)	12	120	400	50	50	16	120	360
Pulse (10^{13}ppp)	0.6	4	9.2	33		3		4
Rate (Hz)	0.45	0.53	0.04	0.29		15		1
Power (MW)	0.0052	0.41	0.22	0.77	4	1	1.6	2.3
Pot (/yr)	2×10^{19}	3.7×10^{20}	4.5×10^{19}	10^{21}	5×10^{21}		1.4×10^{21}	7×10^{20}

2000 ⇒ 2010

2008 and beyond

Comparison event rates Superbeams vs Nufactory

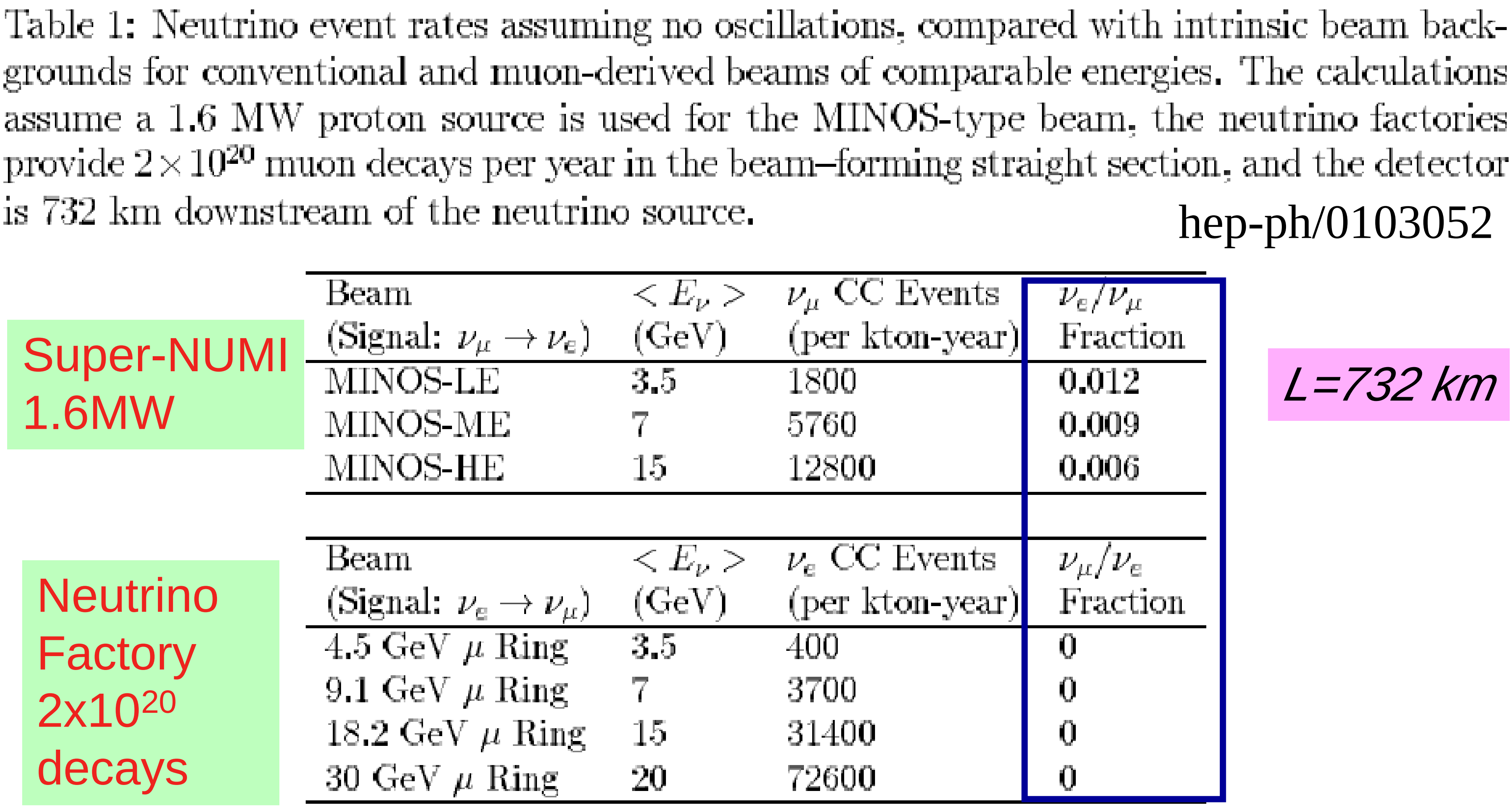


Table 1: Neutrino event rates assuming no oscillations, compared with intrinsic beam backgrounds for conventional and muon-derived beams of comparable energies. The calculations assume a 1.6 MW proton source is used for the MINOS-type beam, the neutrino factories provide 2×10^{20} muon decays per year in the beam–forming straight section, and the detector is 732 km downstream of the neutrino source.

hep-ph/0103052

Super-NUMI
1.6MW

Beam (Signal: $\nu_\mu \to \nu_e$)	$< E_\nu >$ (GeV)	ν_μ CC Events (per kton-year)	ν_e/ν_μ Fraction
MINOS-LE	3.5	1800	0.012
MINOS-ME	7	5760	0.009
MINOS-HE	15	12800	0.006

Neutrino
Factory
$2x10^{20}$
decays

Beam (Signal: $\nu_e \to \nu_\mu$)	$< E_\nu >$ (GeV)	ν_e CC Events (per kton-year)	ν_μ/ν_e Fraction
4.5 GeV μ Ring	3.5	400	0
9.1 GeV μ Ring	7	3700	0
18.2 GeV μ Ring	15	31400	0
30 GeV μ Ring	20	72600	0

L=732 km

Intrinsic beam background

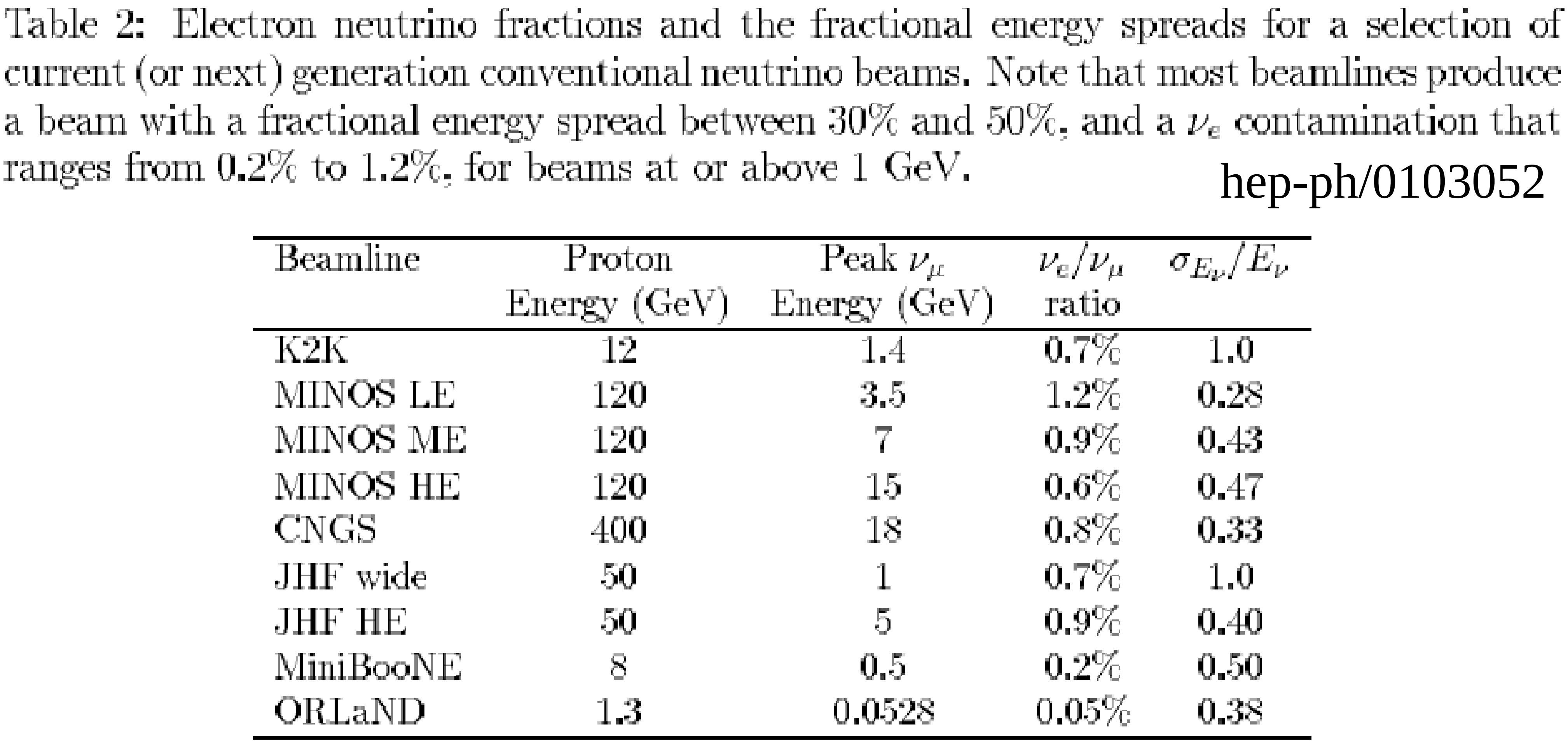


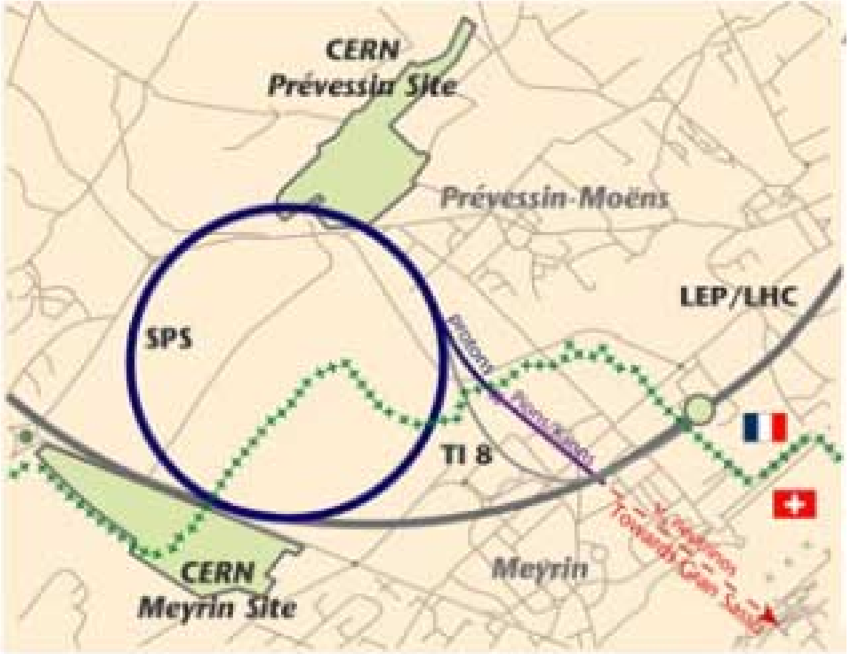
Table 2: Electron neutrino fractions and the fractional energy spreads for a selection of current (or next) generation conventional neutrino beams. Note that most beamlines produce a beam with a fractional energy spread between 30% and 50%, and a ν_e contamination that ranges from 0.2% to 1.2%, for beams at or above 1 GeV.

hep-ph/0103052

Beamline	Proton Energy (GeV)	Peak ν_μ Energy (GeV)	ν_e/ν_μ ratio	σ_{E_ν}/E_ν
K2K	12	1.4	0.7%	1.0
MINOS LE	120	3.5	1.2%	0.28
MINOS ME	120	7	0.9%	0.43
MINOS HE	120	15	0.6%	0.47
CNGS	400	18	0.8%	0.33
JHF wide	50	1	0.7%	1.0
JHF HE	50	5	0.9%	0.40
MiniBooNE	8	0.5	0.2%	0.50
ORLaND	1.3	0.0528	0.05%	0.38

Typ. at the level of 1% for multiGeV beams, assuming 5% error ⇒ natural limit ≈5×10^{-4}

Super-CNGS



	CNGS (shared)	Super-NGS
E(GeV)	**400**	**360**
Pulse (10^{13}ppp)	9.2	4
Rate (Hz)	0.04	**1**
Power (MW)	**0.22**	**2.3**
Pot (/yr)	**4.5×10^{19}**	**7×10^{20}**

⇒*Assume for simplicity,* ***Super-CNGS = 20xCNGS with same beam optics***

≈300 (48) ν_τ CC/kt/year @ $\Delta m^2=2.5(1.0)\times10^{-3}$ eV^2, full mixing

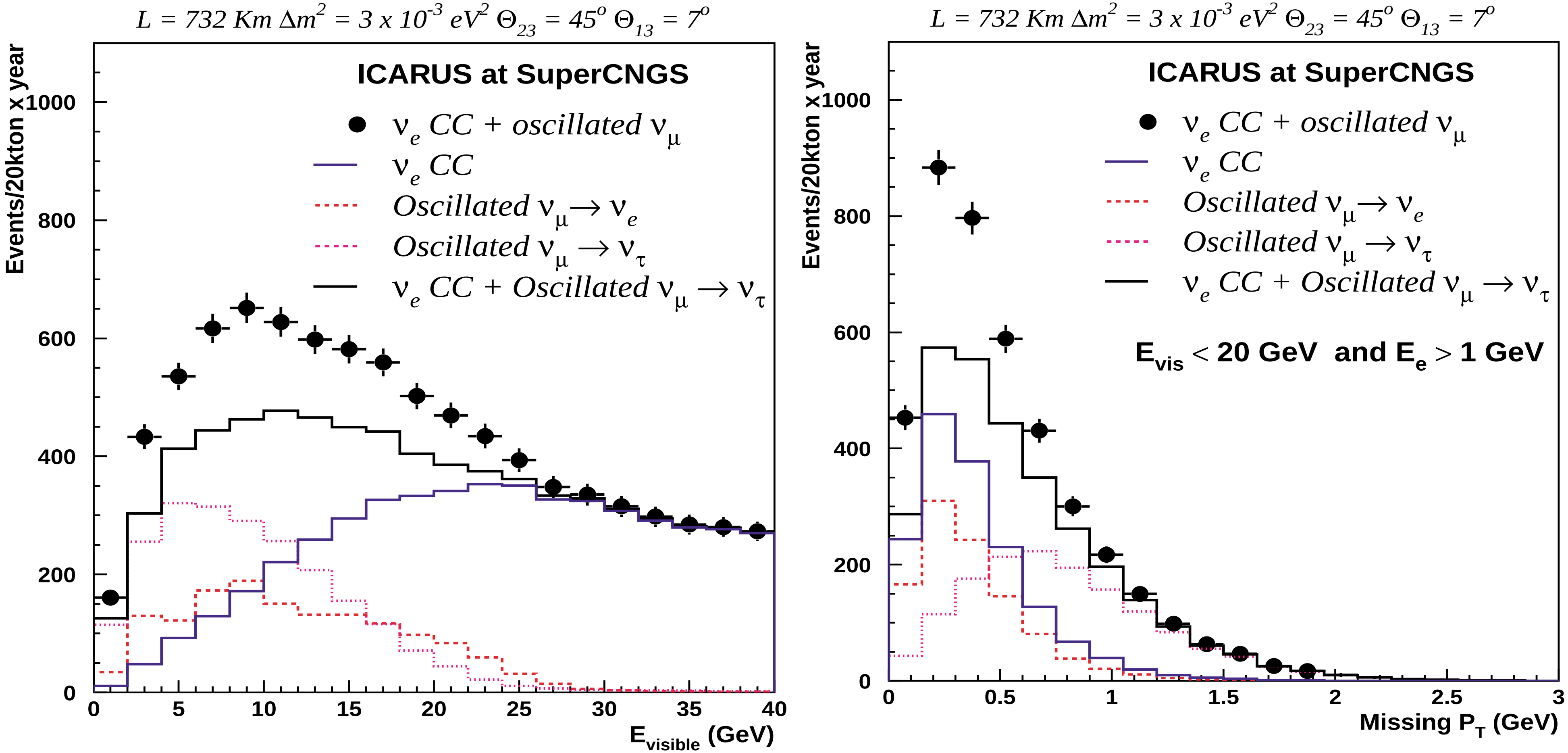
Also, with high proton yield, ***low energy beam*** optics optimizations become viable!

$\nu_\mu \leftrightarrow \nu_e$ oscillations (CNGS superbeam)

$\Delta m^2_{32}=3\text{x}10^{-3}$ eV^2; $\sin^2 2\theta_{23} = 1$; $\sin^2 2\theta_{13} = 0.05$

ICARUS 4kton @ LNGS

5 years @ super-CNGS



Fully exploit liquid Argon electron reconstruction capabilities!

Θ_{13} sensitivity (CNGS superbeam)

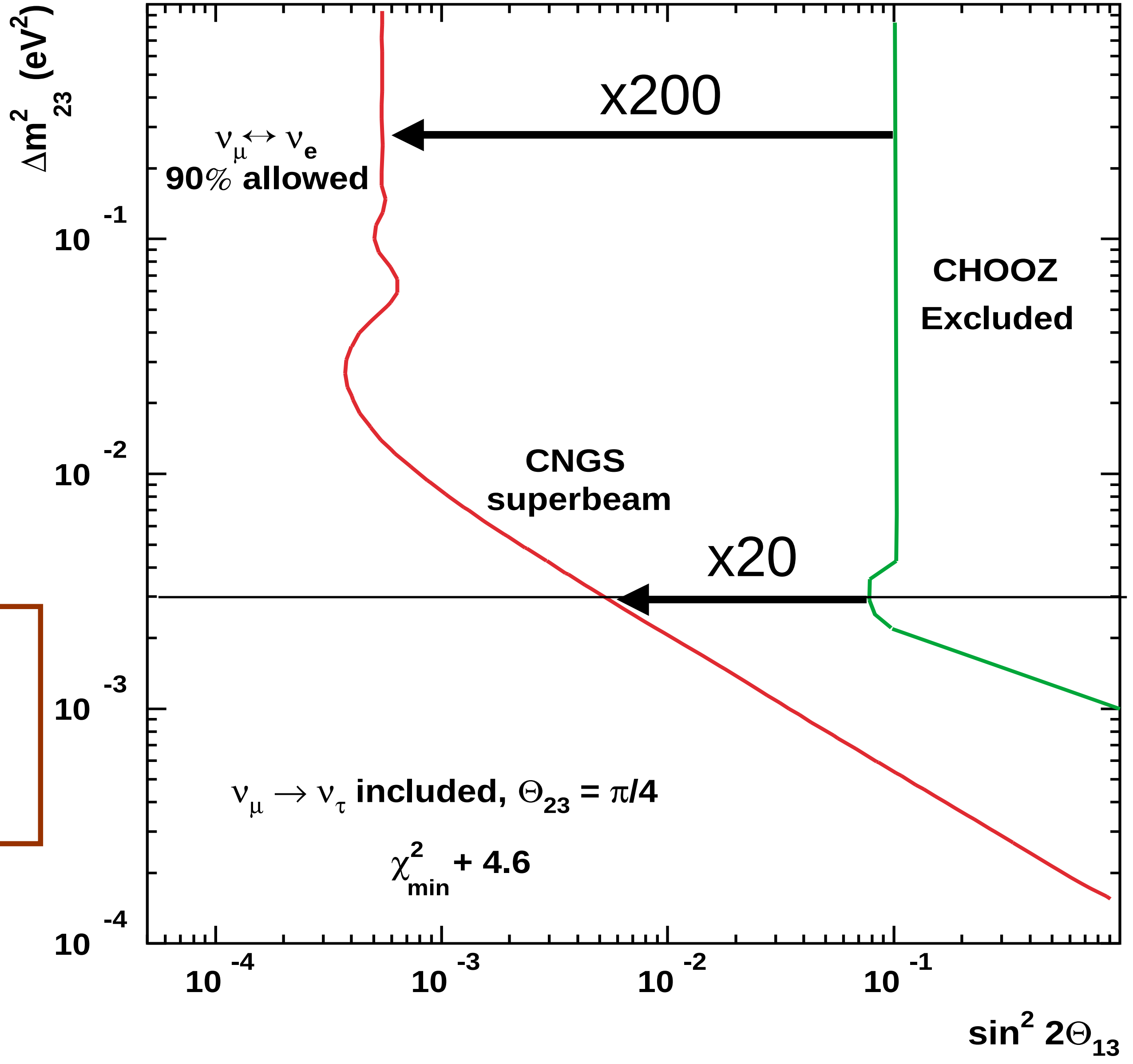
ICARUS 4kton

5 years @ super-CNGS

Sensitivity assuming both $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ at the same Δm^2 (i.e. three family mixing)

For $\Delta m^2_{23} = 3 \times 10^{-3}$ eV^2

$\sin^2 2\Theta_{13} < 5 \times 10^{-3}$



To parameterize different types of detectors

Exposure (statistical error of signal):

$$D \equiv M_{fiducial} \times \varepsilon_{signal} \times t_{data-taking} \left[kt \times years \right]$$

Background (statistical error of signal):

$$f_B \equiv background \quad fraction \ (relative \ \ to \ \ CC)$$

Background (systematic error of background):

$$\sigma\left(f_B \right) / f_B \equiv fractional \ uncertainty$$

A detector comparison

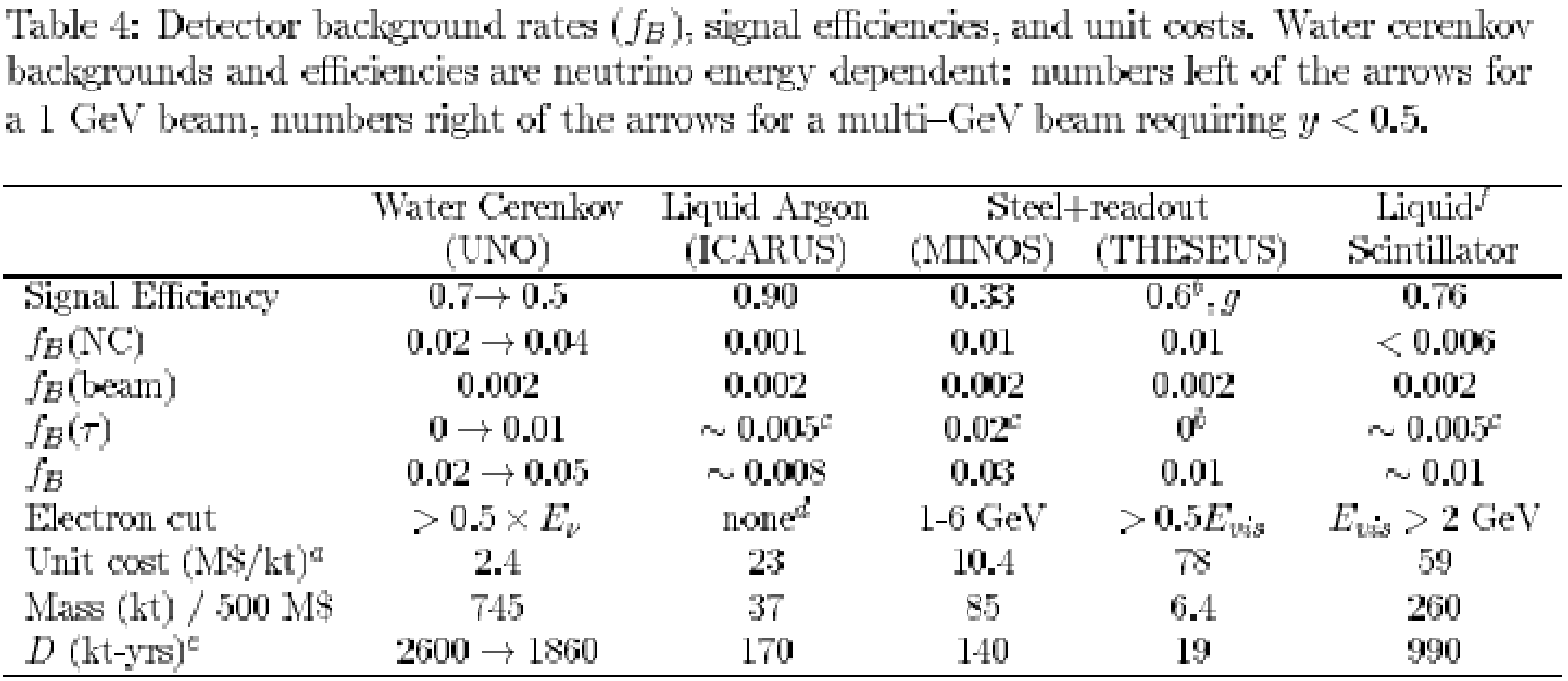


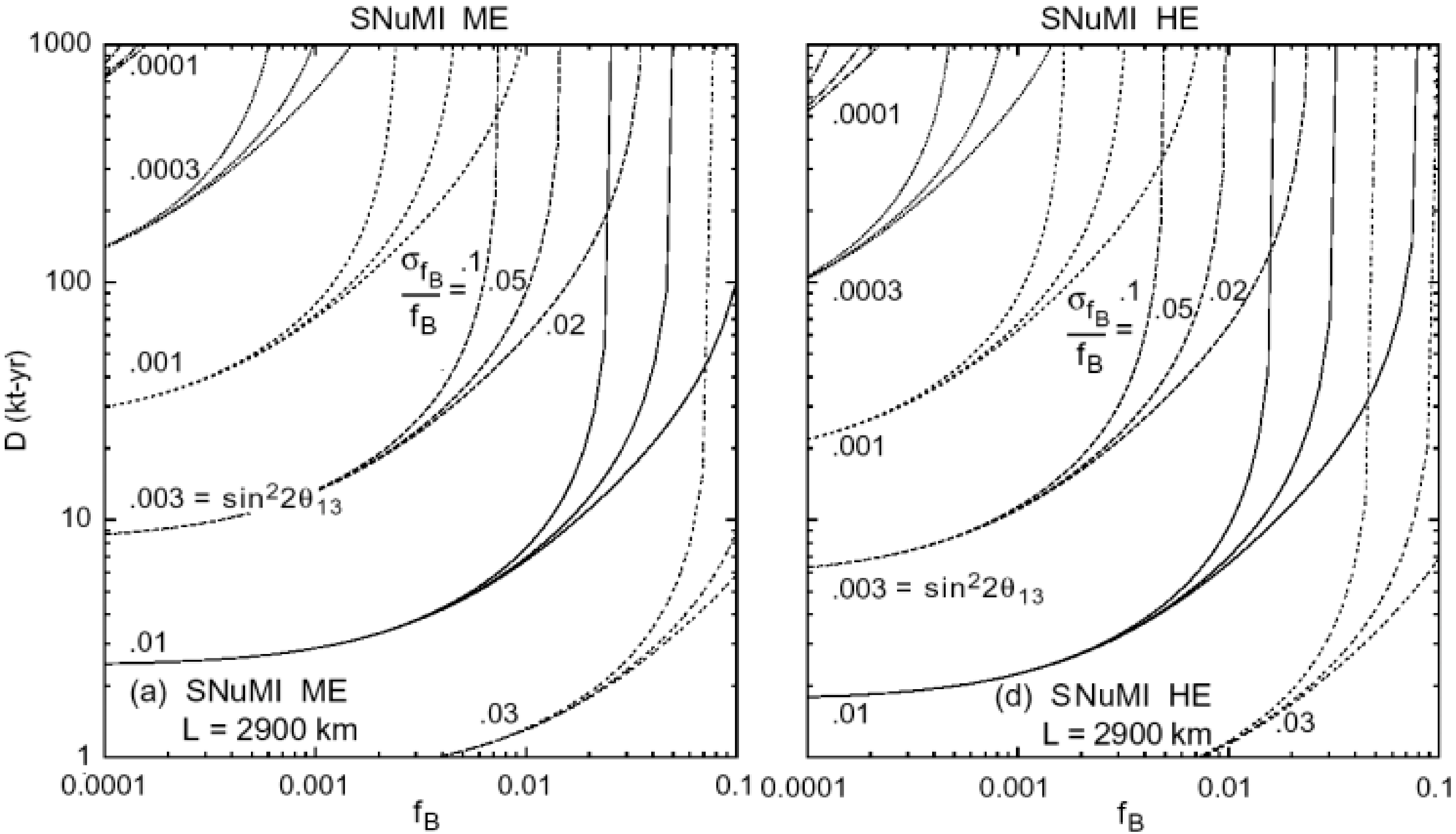
Table 4: Detector background rates (f_B), signal efficiencies, and unit costs. Water cerenkov backgrounds and efficiencies are neutrino energy dependent: numbers left of the arrows for a 1 GeV beam, numbers right of the arrows for a multi–GeV beam requiring $y < 0.5$.

	Water Cerenkov (UNO)	Liquid Argon (ICARUS)	Steel+readout (MINOS)	Steel+readout (THESEUS)	Liquid^f Scintillator
Signal Efficiency	$0.7 \to 0.5$	0.90	0.33	$0.6^{b}, g$	0.76
f_B(NC)	$0.02 \to 0.04$	0.001	0.01	0.01	< 0.006
f_B(beam)	0.002	0.002	0.002	0.002	0.002
$f_B(\tau)$	$0 \to 0.01$	$\sim 0.005^c$	0.02^c	0^b	$\sim 0.005^c$
f_B	$0.02 \to 0.05$	~ 0.008	0.03	0.01	~ 0.01
Electron cut	$> 0.5 \times E_\nu$	none^d	1-6 GeV	$> 0.5 E_{vis}$	$E_{vis} > 2$ GeV
Unit cost (M$/kt)^a	2.4	23	10.4	78	59
Mass (kt) / 500 M$	745	37	85	6.4	260
D (kt-yrs)^e	$2600 \to 1860$	170	140	19	990

hep-ph/0103052

1.6MW Super-NUMI

hep-ph/0103052



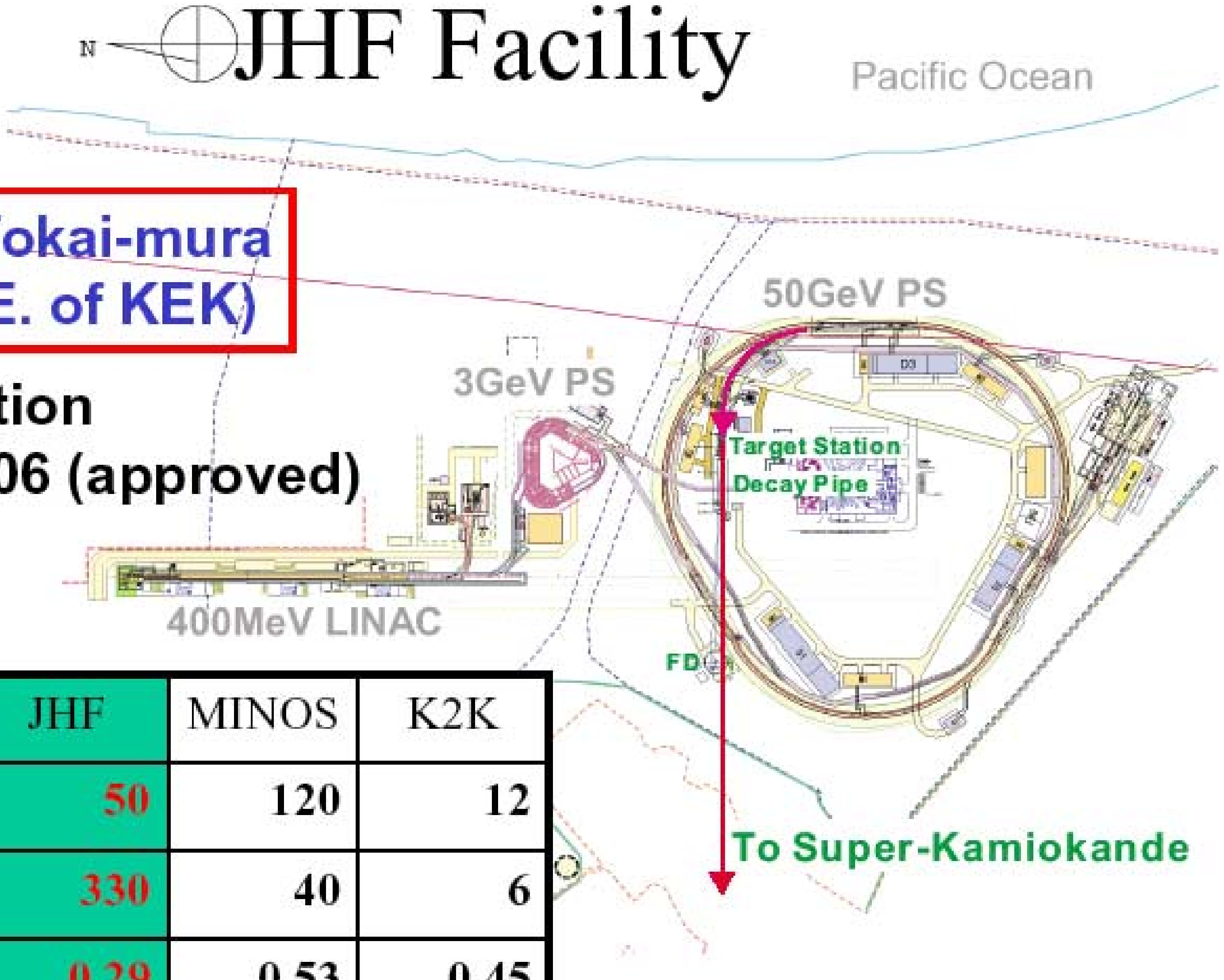
3σ above-background reach contours

JHF-Kamioka neutrino project

- L=295km, Eν=0.5~2 GeV
  - match to a Water Cherenkov detector (SK exists)
    - generally easy to build a larger detector
    - less NC π^0 background to $\nu_\mu \rightarrow \nu_e$
    - good ν energy reconstruction by QE interaction
    - good particle ID capability
  - small matter effect (difficult to see the sign of Δm_{23}^2, but easier to look for CP violation.)
  - match to a size of Japan with the existing facilities

Nakaya, NUFACT01

JHF Facility



JAERI@Tokai-mura
(60km N.E. of KEK)

Construction
2001～2006 (approved)

	JHF	MINOS	K2K
E(GeV)	50	120	12
Int.(10^{12}ppp)	330	40	6
Rate(Hz)	0.29	0.53	0.45
Power(MW)	0.77	0.41	0.0052

10^{21}POT(130day) $\equiv$ “1 year”

Nakaya, NUFACT01

Neutrino beam and detectors:

Kamioka

~1GeV ν beam

JAERI
(Tokaimura)

Super-K: 22.5 kt

Hyper-K: 1000 kt

0.77MW 50 GeV PS

4MW 50 GeV PS

(conventional ν beam)

Phase-I (0.77MW + Super-K)

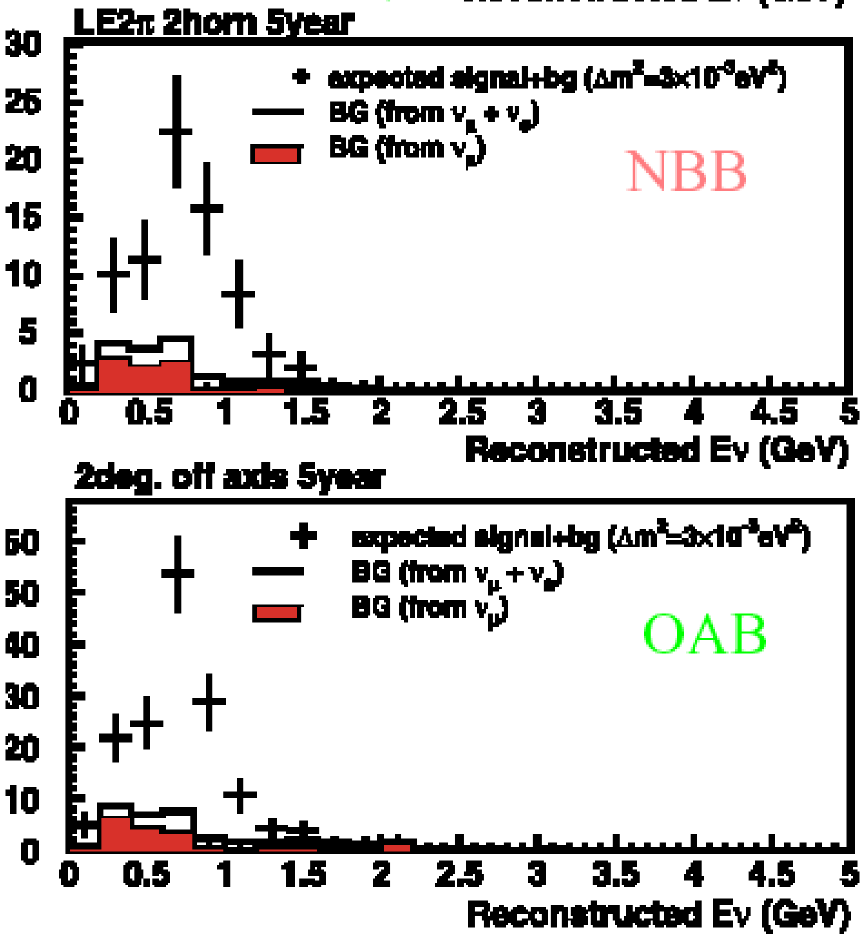
Phase-II (4MW+Hyper-K) ~ Phase-I **× 200**

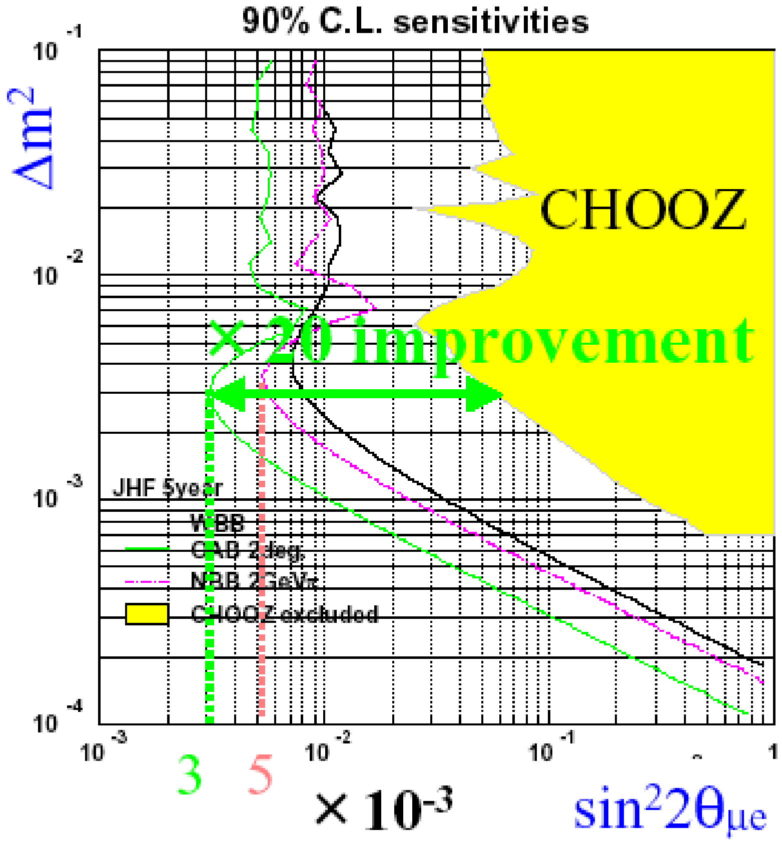
Nakaya, NUFACT01

ν_e appearance

Background rejection against NC π^0 is improved.

$\sin^2 2\theta_{\mu e}=0.05$ ($\sin^2 2\theta_{\mu e} \equiv 0.5\sin^2 2\theta_{13}$)



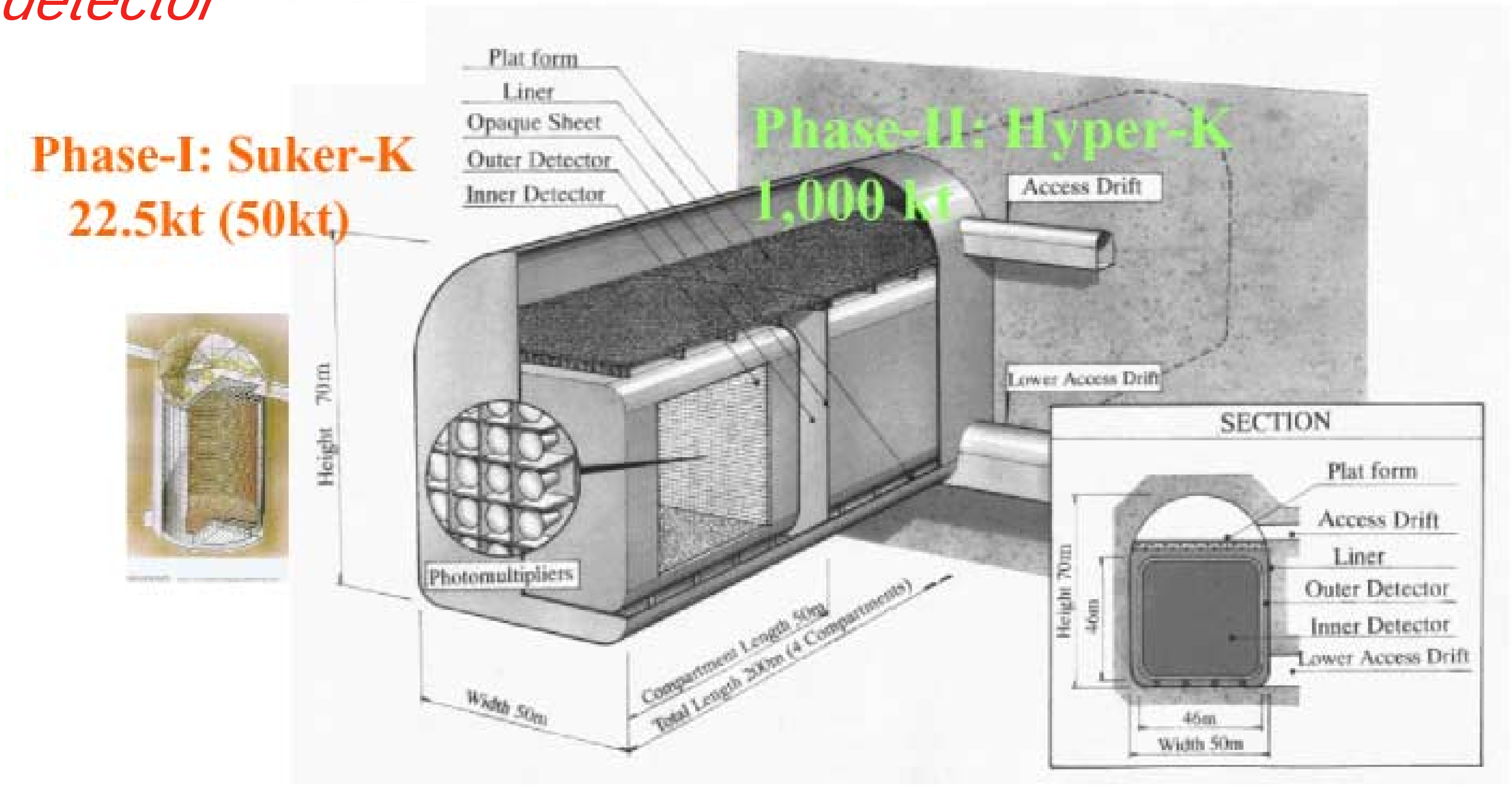


$$\sin^2 2\theta_{13} > 6\times10^{-3}$$

Ph2me, Ph2he from right
A.Para, hep-ph/0005012)

Nakaya, NUFACT01

Phase II: *upgraded 4MW machine coupled to Mton Water detector*



$$\sin^2 2\theta_{13} > 10^{-3}$$

Nakaya, NUFACT01

CP Violation Study

4 MW machine + 1000 kt Water
2 years ν and 6 years $\bar{\nu}$

- Compare $\nu_\mu \rightarrow \nu_e$ with $\overline{\nu_\mu} \rightarrow \bar{\nu}_e$

N(e+)

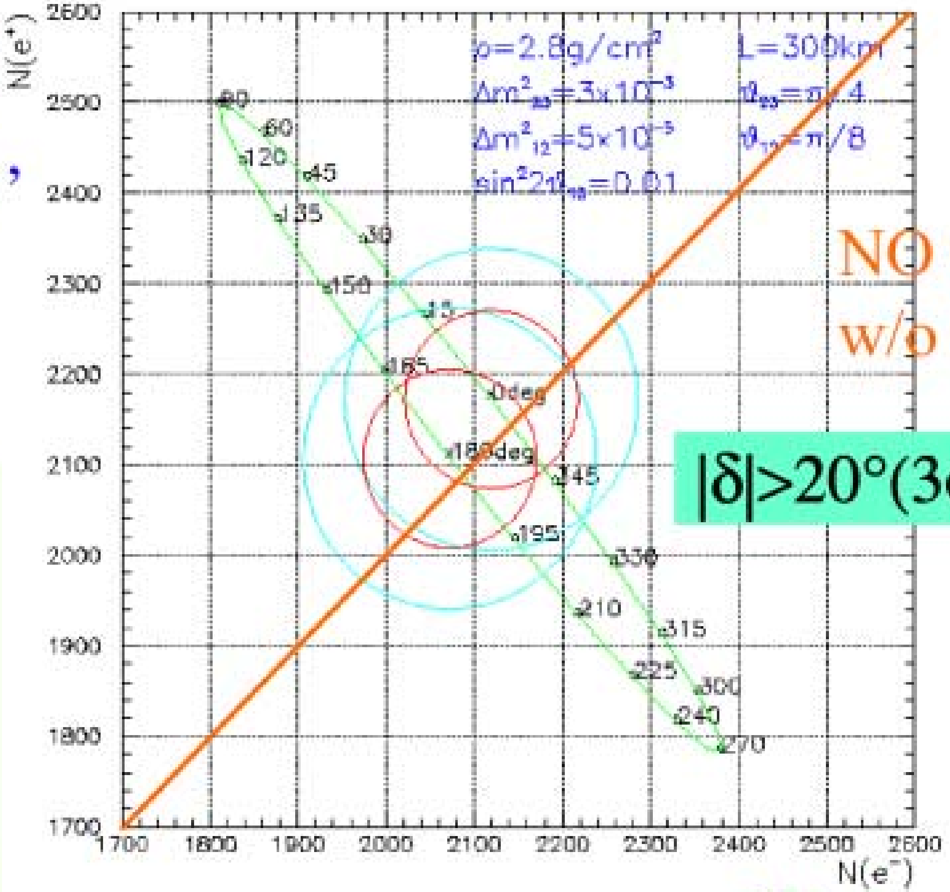
$\Delta m_{12}{}^2 = 5 \times 10^{-5} eV^2$,
$\Delta m_{23}{}^2 = 3 \times 10^{-3} eV^2$
$\sin^2 2\theta_{13} = 0.01$
$\theta_{23} = \pi/4$, $\theta_{12} = \pi/8$

Asymmetry

$$\equiv \frac{N(e^+) - N(e^-)}{N(e^+) + N(e^-)}$$

$$\approx \frac{\sim 2000 - \sim 2000}{\sim 2000 + \sim 2000}$$

$$\approx 0.02$$



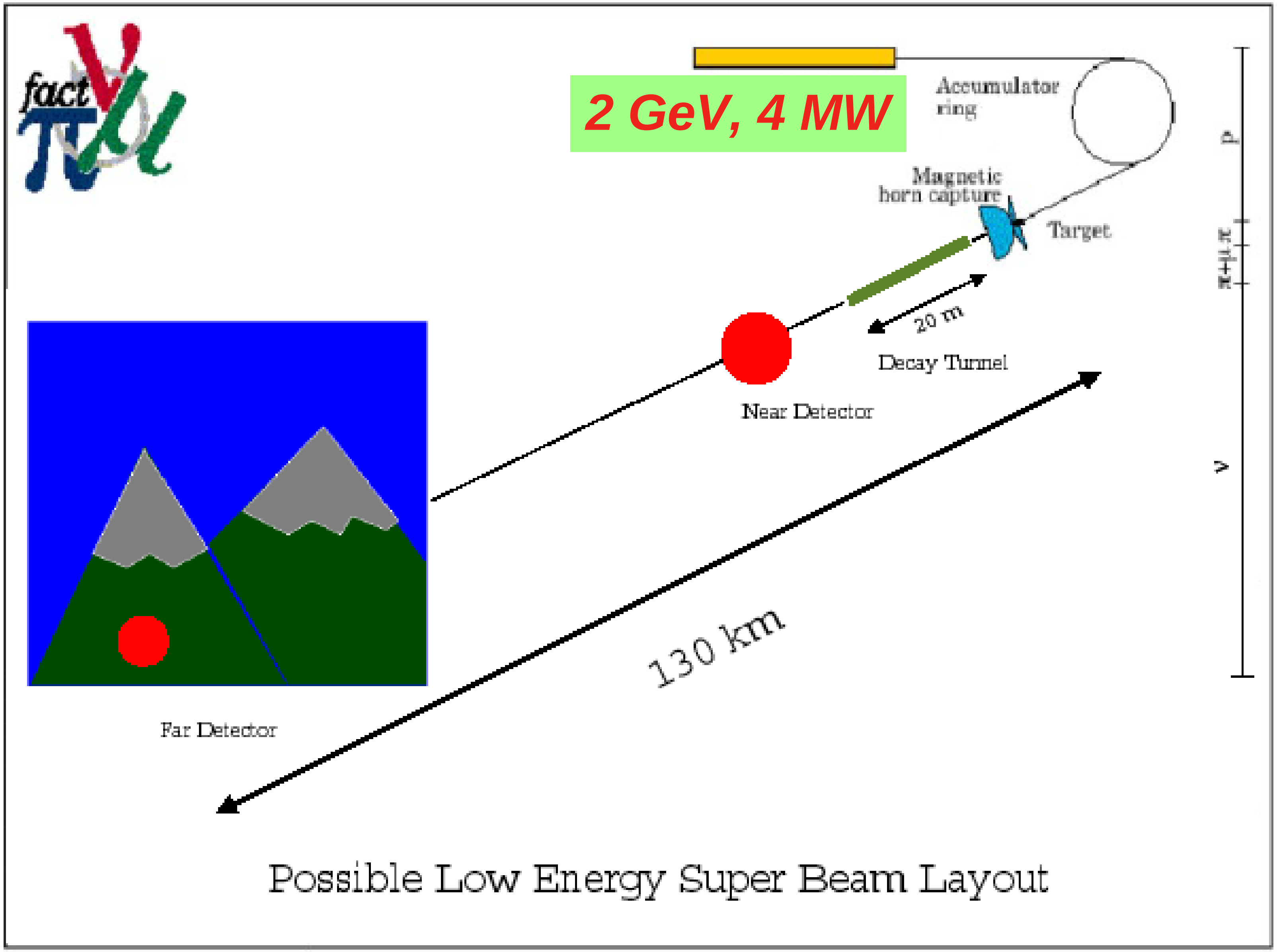
NO CP violation
w/o matter effect.

|δ|>20°(3σ discovery)

N(e-)

Nakaya, NUFACT01

CERN superbeam option: Requires the SPL (Superconducting Proton Linac)



Possible Low Energy Super Beam Layout

Mezzetto, NUFACT01

Three detectors scenario

Water Čerenkov detector á la SuperK (40% PMT coverage) with 40 kton fiducial mass

- $\epsilon_s \sim 70\%$ (from a full simulation + analysis)
- $f_B(\pi^0\ /e) \sim 0.002$ (full simulation + analysis using energy flow fitter to identify π^0)
- $f_B(\mu/e) \sim 0.001$ (full simulation)
- $f_B\ (\mathrm{Beam}) \sim 0.003$ (full simulation of beam)

f_B are normalized to the ν_μ CC rate

Liquid scintillator á la MiniBoone (10% PMT coverage) with 40 kton fiducial mass

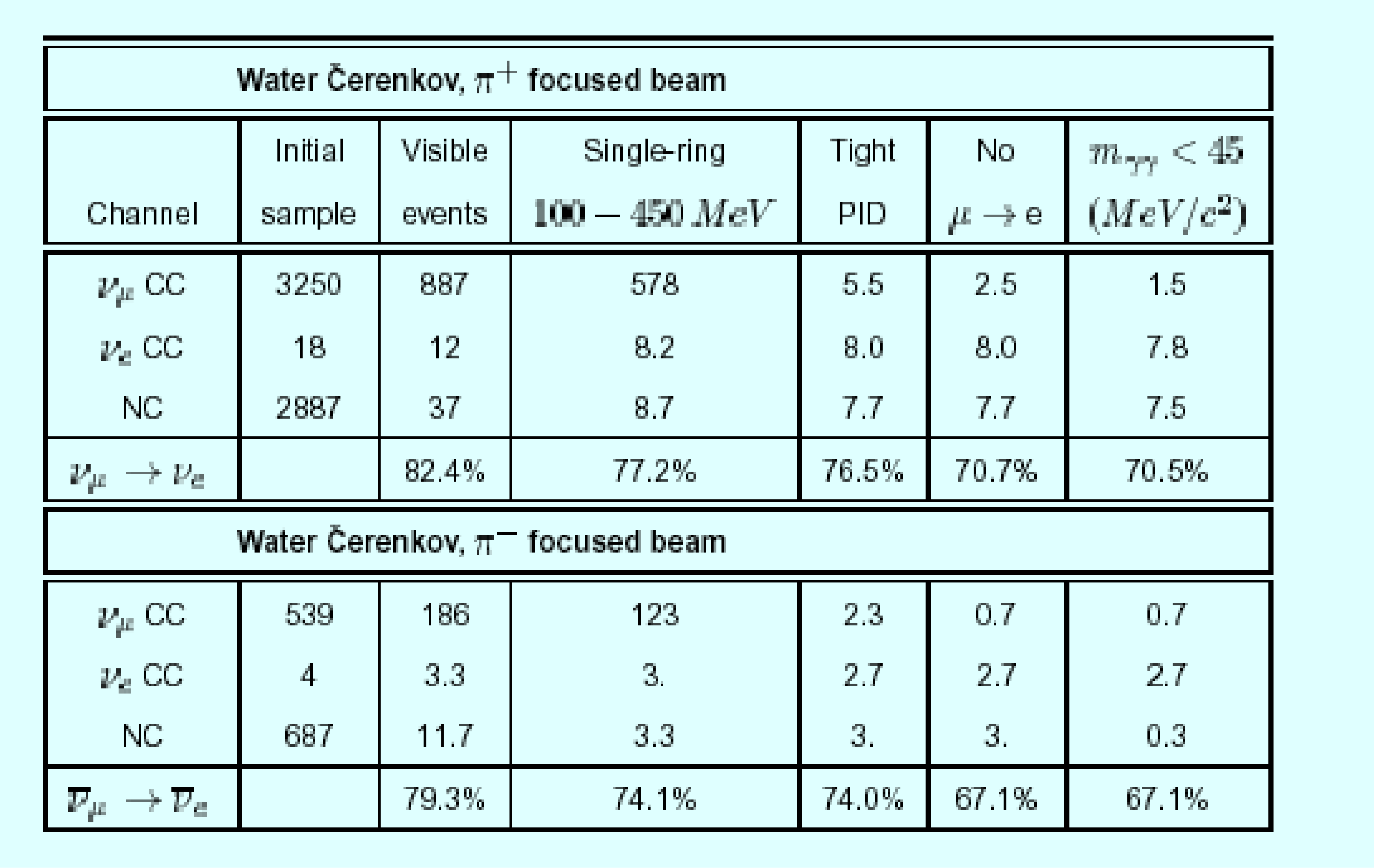
- $\epsilon_s \sim 50\%$ (using MiniBoone numbers)
- $f_B(\pi^0\ /e) \sim 0.001$ (using MiniBoone numbers)
- $f_B(\mu/e) \sim 0.001$ (using MiniBoone numbers)
- $f_B\ (\mathrm{Beam}) \sim 0.003$ (full simulation of beam)

Water Čerenkov detector á la SuperK with 400 kton fiducial mass

- Extrapolated from the 40 kton detector

Mezzetto, NUFACT01

Expected event rate for 200 kt x year exposure:



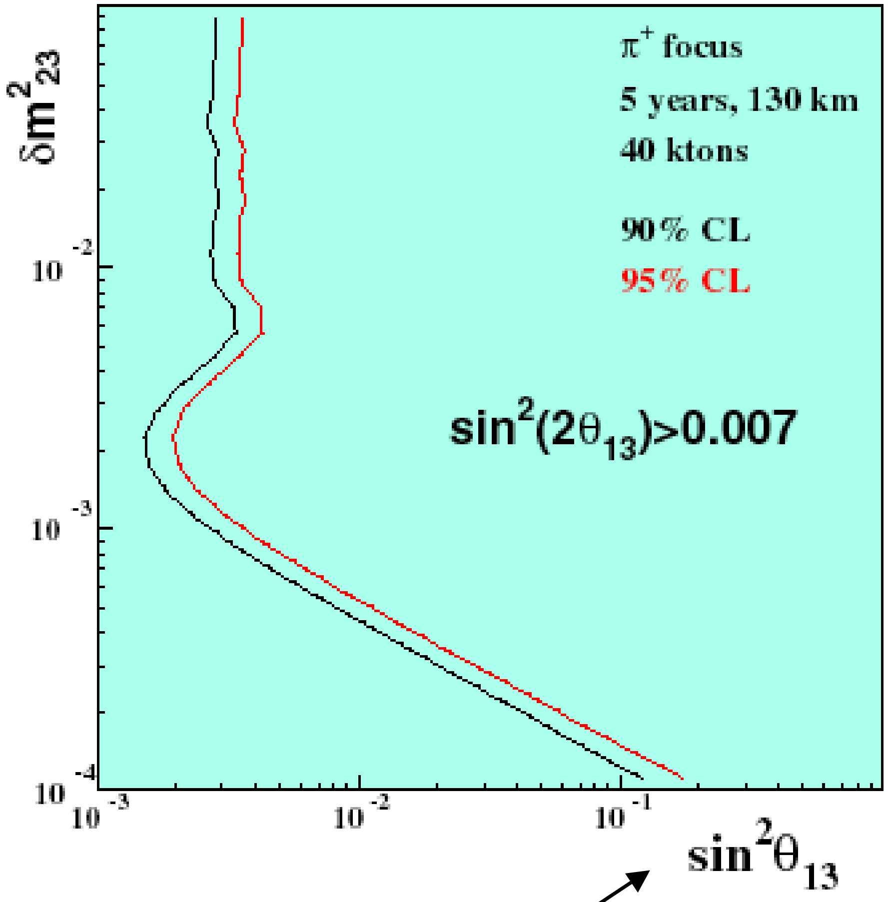
Water Čerenkov, π^+ focused beam						
Channel	Initial sample	Visible events	Single-ring $100 - 450\ MeV$	Tight PID	No $\mu \to$ e	$m_{\gamma\gamma} < 45$ (MeV/c^2)
ν_μ CC	3250	887	578	5.5	2.5	1.5
ν_e CC	18	12	8.2	8.0	8.0	7.8
NC	2887	37	8.7	7.7	7.7	7.5
$\nu_\mu \to \nu_e$		82.4%	77.2%	76.5%	70.7%	70.5%
Water Čerenkov, π^- focused beam						
ν_μ CC	539	186	123	2.3	0.7	0.7
ν_e CC	4	3.3	3.	2.7	2.7	2.7
NC	687	11.7	3.3	3.	3.	0.3
$\overline{\nu}_\mu \to \overline{\nu}_e$		79.3%	74.1%	74.0%	67.1%	67.1%

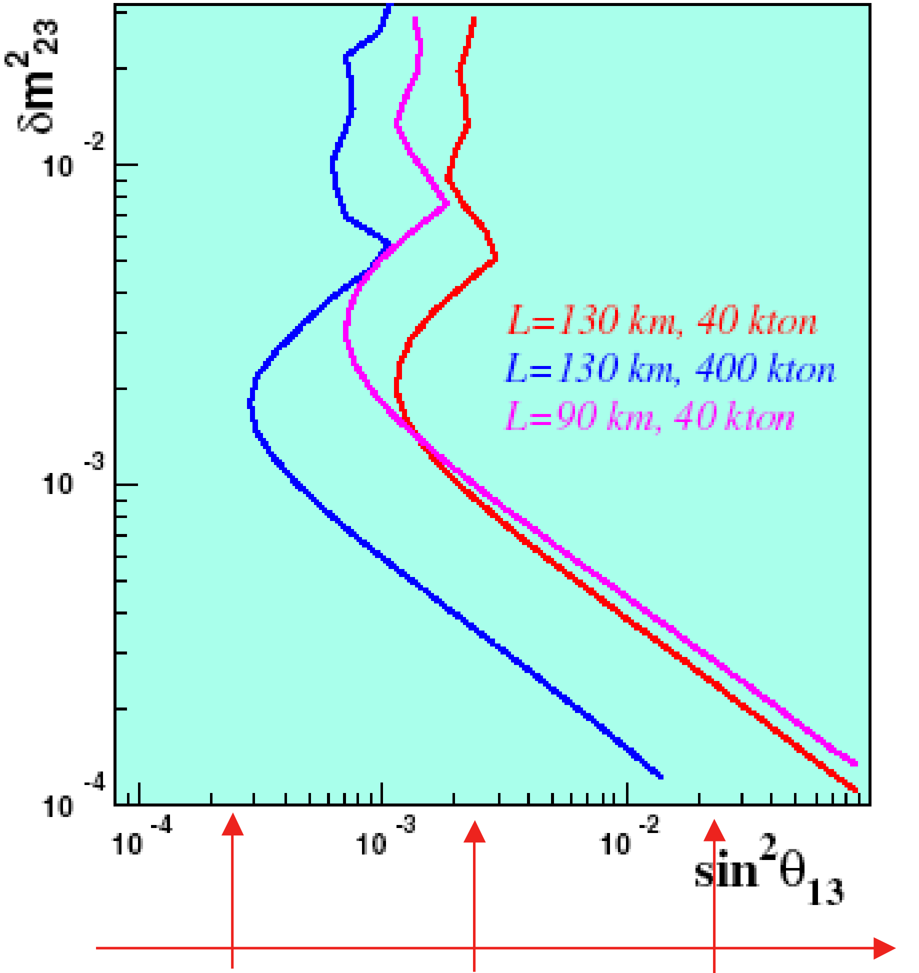
Mezzetto, NUFACT01

Sensitivity curves, 5 years running:

Mezzetto, NUFACT01

$$\sin^2 2\theta_{13} > 6\times10^{-3}\ \ (40kt)$$





10^{-3} 10^{-2} 10^{-1}

$\sin^2 2\theta_{13}$

Beware: $\sin^2 2\theta_{13} \approx 4\sin^2\theta_{13}$

The oscillation physics program at the NF

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

$\nu_\mu \to \nu_e$	appearance
ν_μ	disappearance
$\nu_\mu \to \nu_\tau$	appearance
$\bar{\nu}_e$	disappearance
$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance
$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance

Plus their charge conjugates with μ^+ beam

Ideal detector should be able to measure **12 different processes as a function of L and E_ν**

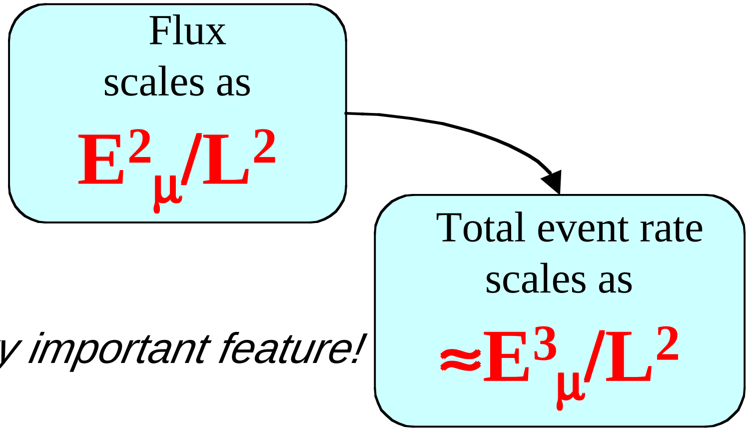
$$\begin{cases} \nu_\ell N \to \ell^- + hadrons \\ \bar{\nu}_\ell N \to \ell^+ + hadrons \end{cases} \qquad \begin{cases} \nu_\ell N \to \nu_\ell + hadrons \\ \bar{\nu}_\ell N \to \bar{\nu}_\ell + hadrons \end{cases}$$

1. ***Particle ID***: *charged lepton tags* ***incoming neutrino flavor***
2. ***Charge ID***: *sign of lepton charge tags* ***helicity*** *of incoming neutrino*
3. ***Energy resolution***: *Reconstructed event energy is* $E_\nu = E_l + E_{had}$
4. ***Various baselines L*** *could help for detector systematics*

The Neutrino Factory

$$\boxed{\mu^- \to e^- \bar{\nu}_e \nu_\mu \quad \text{or} \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu}$$

Roughly as many ν_e's as ν_μ's



Flux scales as **E^2_μ/L^2**

Total event rate scales as **$\approx E^3_\mu/L^2$**

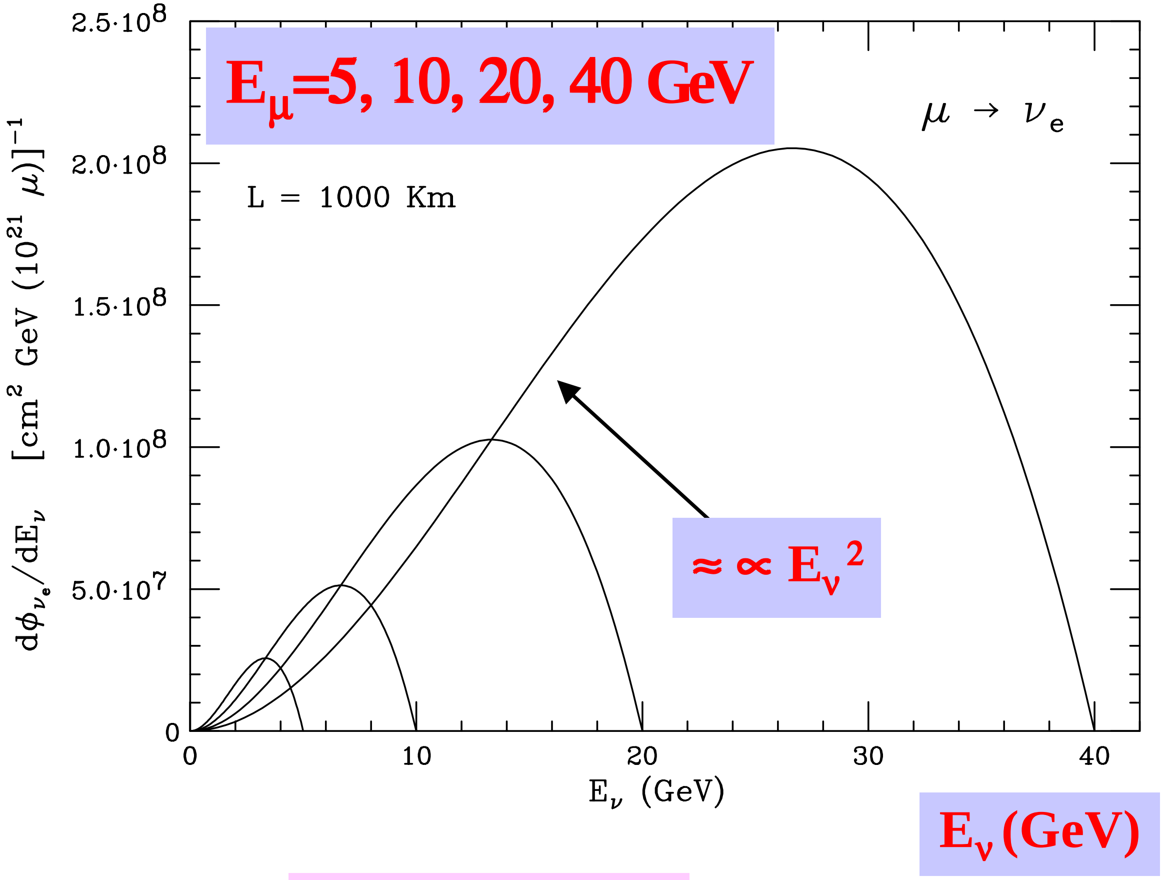
A very important feature!

The generally adopted consensus (see later) ⇒

high energy ν-factory

$$\boxed{E_\mu = O(30\text{GeV})}$$

P. Lipari, hep-ph/0102046



$$\frac{dN}{dx} \propto x^2(1-x) \qquad x \equiv E_\nu / E_\mu$$

Predicted event rates at a Neutrino Factory

FNAL-FN-692, Apr 2000

10^{20} μ^- decays

No oscillations assumed

Experiment		Baseline (km)	$\langle E_{\nu_\mu} \rangle$ (GeV)	$\langle E_{\bar{\nu}_e} \rangle$ (GeV)	N(ν_μ CC) (per kt–yr)	N($\bar{\nu}_e$ CC) (per kt–yr)
NuMI	Low energy	732	3	–	458	1.3
	Medium energy	732	6	–	1439	0.9
	High energy	732	12	–	3207	0.9
CNGS		732	17	–	2714	1.4
Muon ring	E_μ (GeV)					
	10	732	7.5	6.6	1400	620
	20	732	15	13	12000	5000
	50	732	38	33	1.8×10^5	7.7×10^4
Muon ring	E_μ (GeV)					
	10	2900	7.6	6.5	91	41
	20	2900	15	13	740	330
	50	2900	38	33	11000	4900
Muon ring	E_μ (GeV)					
	10	7300	7.5	6.4	14	6
	20	7300	15	13	110	51
	50	7300	38	33	1900	770

However, in addition to the increased neutrino flux, ambitious oscillation physics program requires detectors in the ***10’s kton*** *range to perform experiment with baselines* ***L≈1000’s km***

The goal: detect μ^+, μ^-, e^+, e^-, τ^+, τ^- and NC !

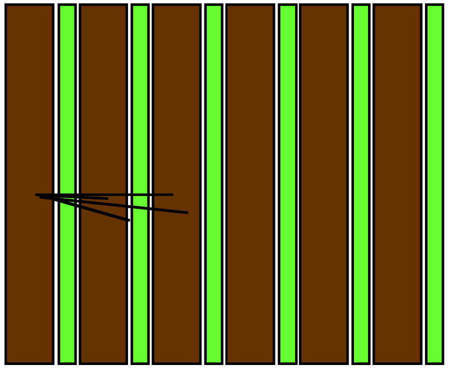
- **Particle ID**: ⇒ *via CC interactions*
  - → ***Muons***: ***straight-forward***, look for penetrating particles, but beware $\pi^\pm$,$K^\pm$ and charm decays
  - → ***Electrons***: ***harder***, look for large & "short" energy deposition, need good granularity for e/π^0 separation
  - → ***Taus***: ***hardest***, "kink" or kinematical methods (statistical separation), $\tau\rightarrow$hadrons$+\nu$ (Br≈60%) look like "NC"
- **Charge ID**: ⇒ *via magnetic analysis*
  - → ***Muons***: ***easy***, muon spectrometer downstream or fully magnetized target
  - → ***Electrons***: ***hardest***, need to measure significantly precisely the bending in B-field before start of e.m. shower
  - → ***Taus***: easy for $\tau\rightarrow\mu\nu\nu$ (Br≈18%), otherwise ***difficult***

⇒ *This has to be implemented on multi-kton detectors…*
various choices & optimizations considered.

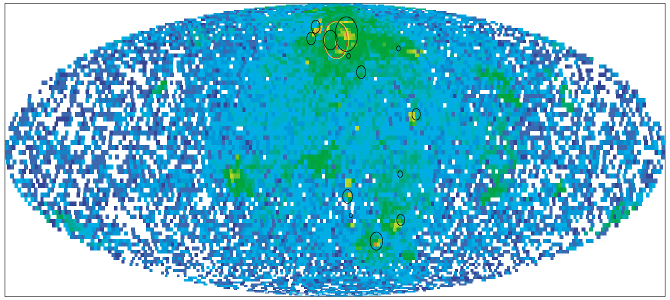
The typical detectors

- ✯ *See also arXiv:hep-ph/0106088*

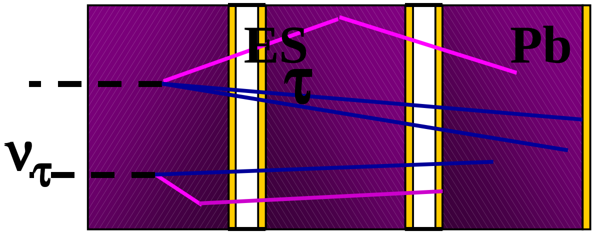
1. Magnetized iron-scintillator sandwich



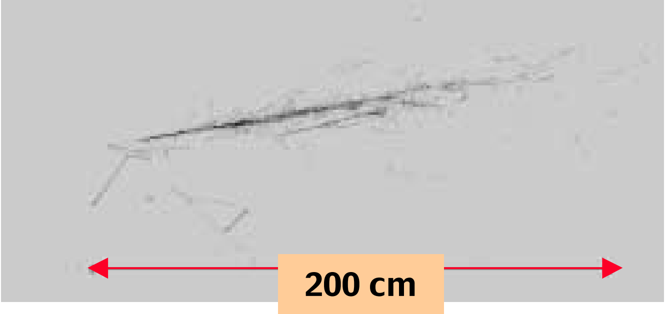
2. Large water Cerenkov



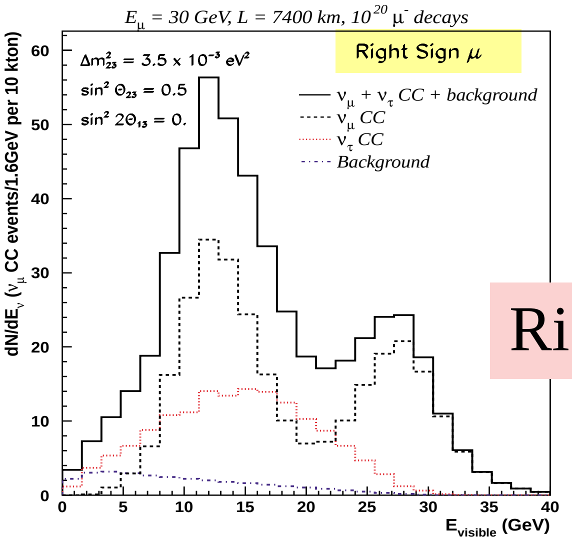
3. Emulsion/target sandwich



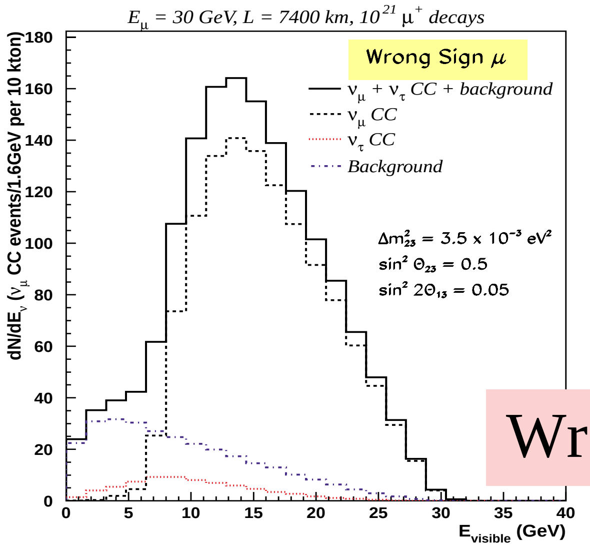
4. Liquid argon imaging TPC



Over-constraining the parameters (I)

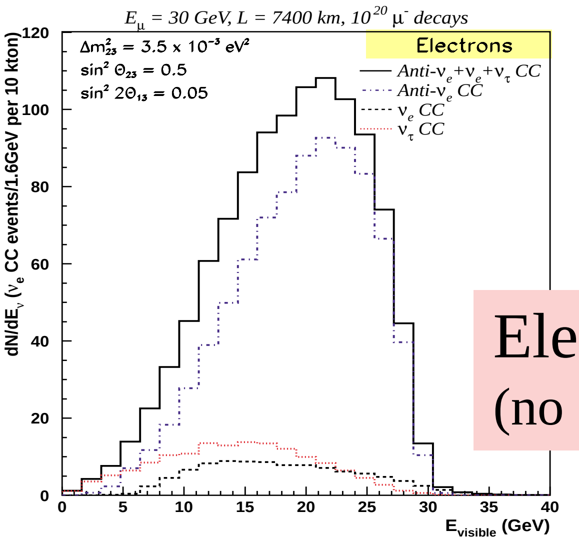


Right sign μ



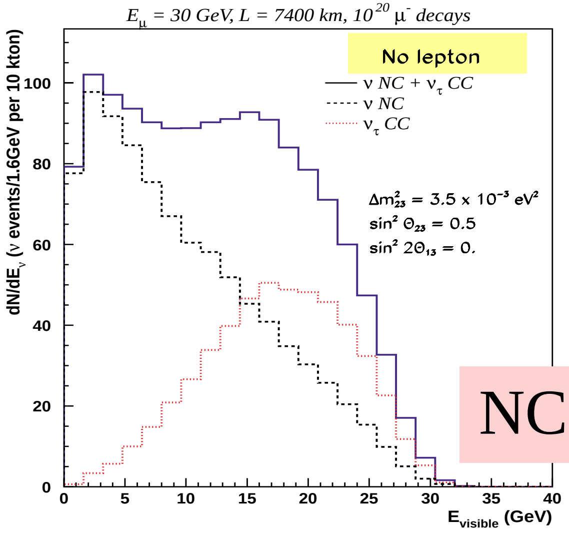
ICARUS-like 10kton

Wrong sign μ



Electrons

(no charge info)



NC-like

Combining all classes$\Rightarrow$ (over-constrained) sensitivity to all oscillations!

A. Bueno et.al. , Nucl.Phys.B589 (2000) 577

Over-constraining the parameters (II)

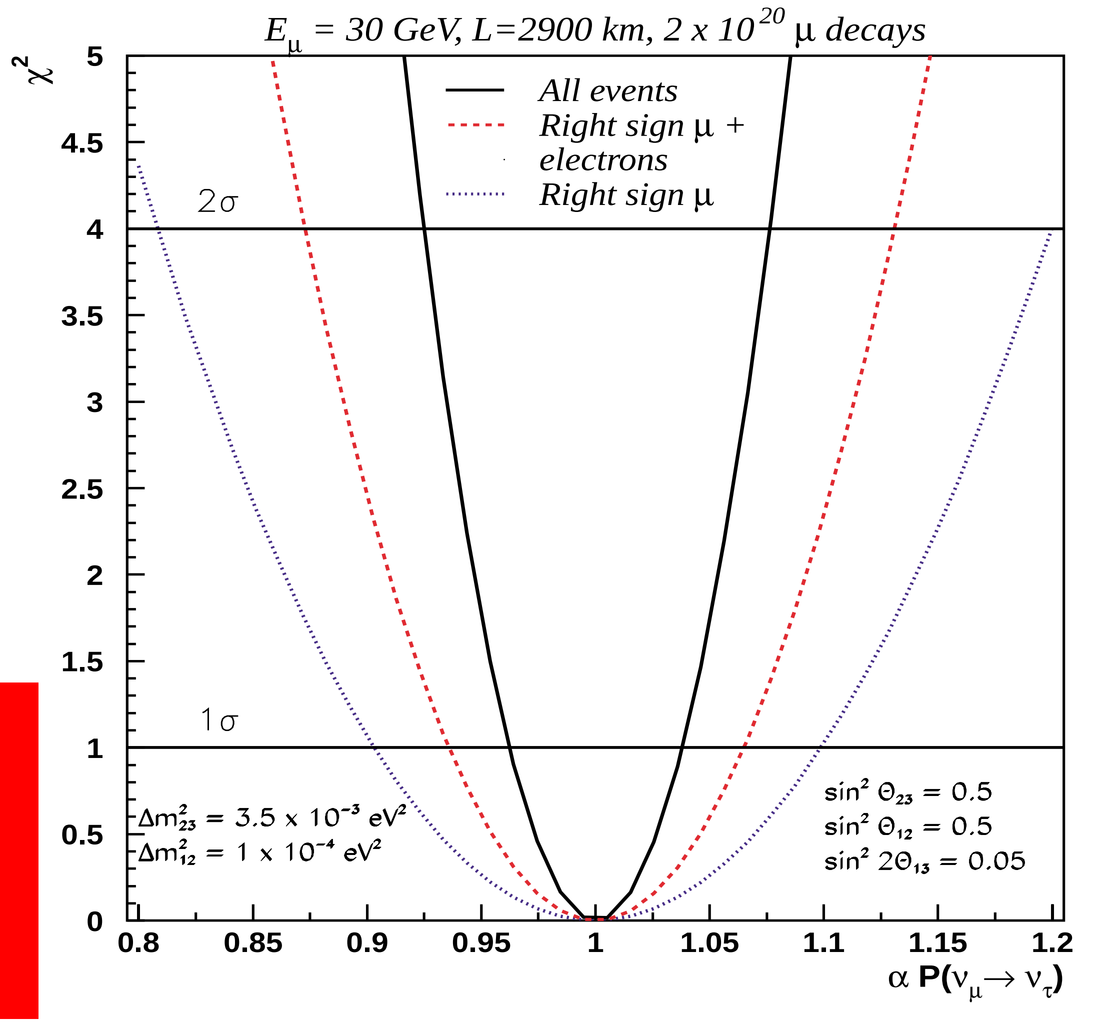
- Check consistency between different observed oscillation processes

- Proof/rule out the existence of sterile neutrinos

- **First observation of $\nu_e \rightarrow \nu_\tau$**

Ability to detect
τ appearance is crucial

ICARUS-like 10kton



A. Bueno et.al. , Nucl.Phys.B589 (2000) 577

Measurement/limit on Θ_{13}

Wrong sign muons are the ideal way to detect $\nu_e \rightarrow \nu_\mu$ oscillations

$$\sin^2 2\theta_{13} > 10^{-4}$$

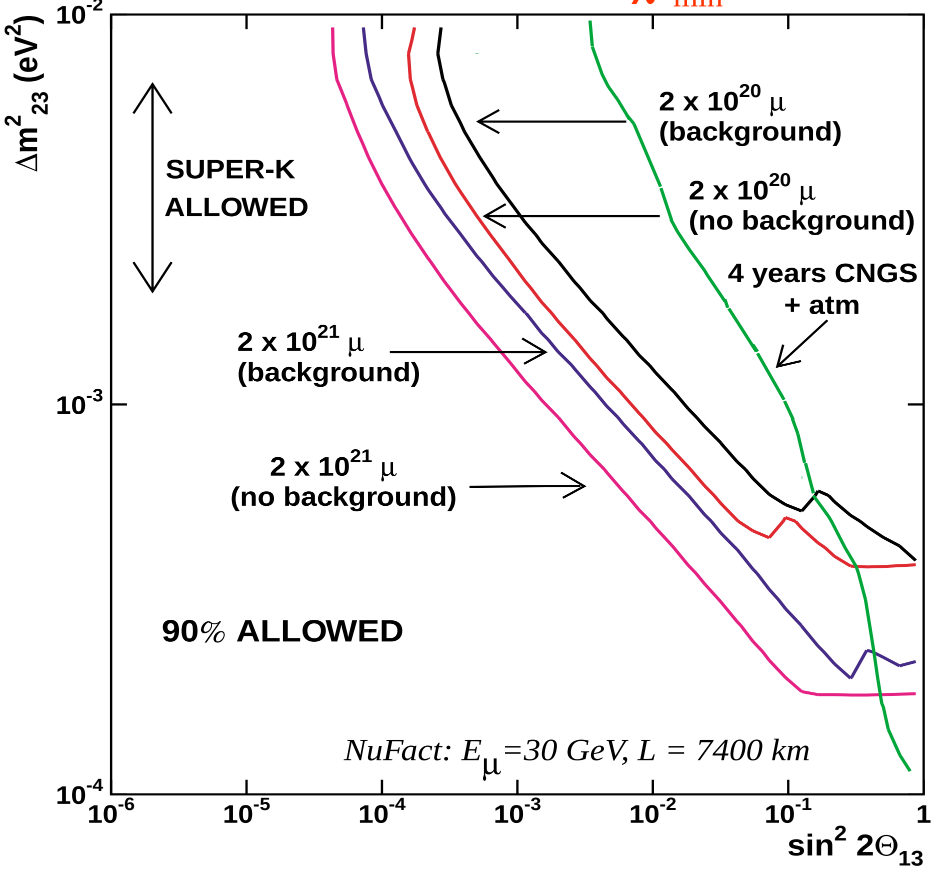
ICARUS-like 10kton
E=30 GeV

Assuming $\Delta m^2_{23} > 0$ ⇨ *Matter enhanced ν oscillation* ⇨better measurement at longer distances

$\delta(\sin^2 2\Theta_{13})=15\%$ (L=2900 km)
$\delta(\sin^2 2\Theta_{13})=10\%$ (L=7400 km)

for $\sin^2 2\Theta_{13} = 0.05$

90% contour obtained as $\chi^2_{min} + 4.6$



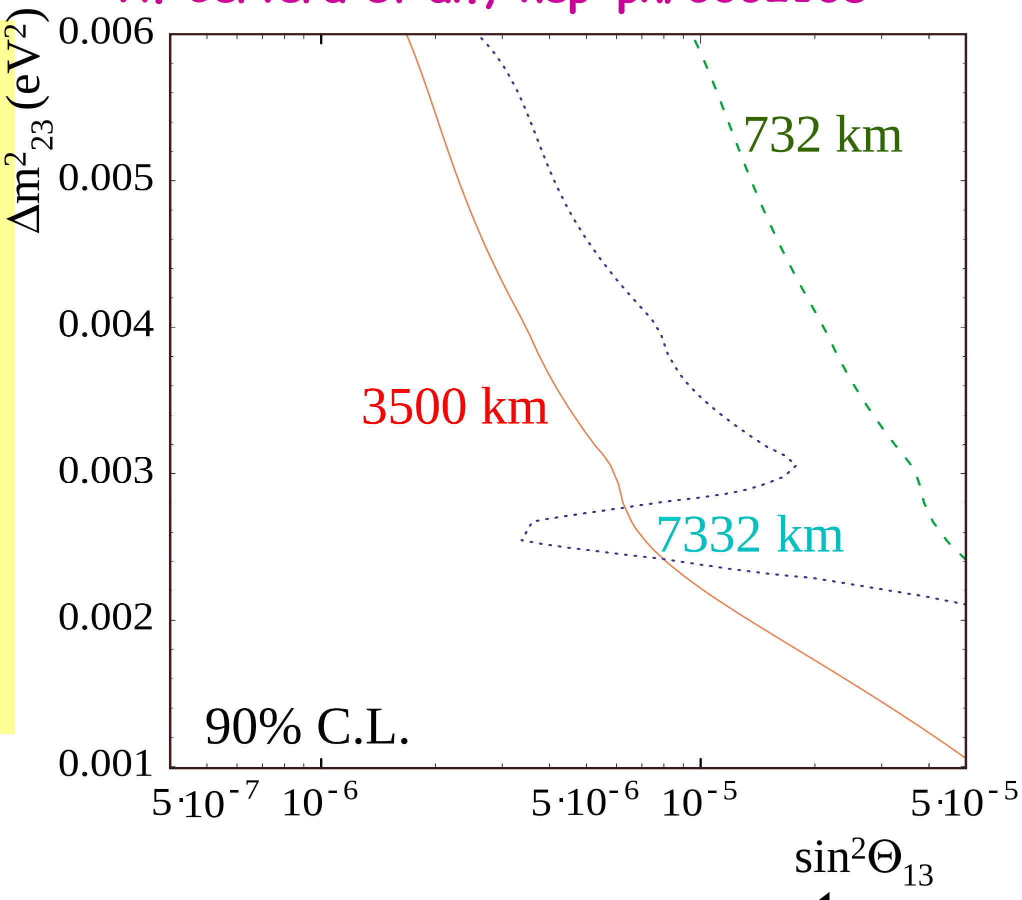
A. Bueno et.al. , Nucl.Phys.B589 (2000) 577

Ultimate sensitivity on Θ_{13}

- — 40 kT Fe-Scintillator detector
- — $E_\mu = 50$ GeV
- — 10^{21} μ decays
- — **Include background and detector efficiencies**
- —**Tight cuts to suppress backgrounds (e.g. charm)**

$$\sin^2 2\theta_{13} >\approx 10^{-5}$$

A. Cervera et al., hep-ph/0002108



Beware: $\sin^2 2\theta_{13} \approx 4\sin^2\theta_{13}$

Observing effects related to the δ-phase

Optimizing the search for a complex phase in the leptonic mixing matrix far from trivial

- A priori, the effect depends on L and E in a complicated way (In vacuum, the scaling of the effect with L/E can help an intuitive understanding of the oscillation behavior)

- Measurement precision depends on practical limits on machine power, maximal energy/flux, detector mass

The choice of the baseline is critical: at the time of the Neutrino Factory, there will be already experiments located at a distance of 250 km from JHF and 730 km from CERN and FNAL; if new sites are really needed, due to physics considerations, that would require major new investments for sites and detectors.

$\nu_e \rightarrow \nu_\mu$ *oscillation probability*

Following the conventional formalism for leptonic mixing, CP-/T-violating effects are observed in ***appearance transitions involving the first family***. Therefore, transitions between electron and muon flavors are clearly favored.

These probabilities are composed of three terms:

Independent of δ

$$P(\nu_e \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) =$$

$$4c^2_{13}[\sin^2 \Delta_{23} s^2_{12} s^2_{13} + c^2_{12}(\sin^2\Delta_{13} s^2_{13} s^2_{23} + \sin^2\Delta_{12} s^2_{12}(1-(1+s^2_{13})s^2_{23}))]$$

$$-1/2 c^2_{13} \sin^2\theta_{12} s_{13} \sin^2\theta_{23} \cos\delta[\cos^2\Delta_{13} - \cos^2\Delta_{23} - 2\cos^2\theta_{12} \sin^2\Delta_{12}]$$

$$+1/2 c^2_{13} \sin\delta \sin 2\theta_{12} s_{13} \sin^2\theta_{23}[\sin^2\Delta_{12} - \sin^2\Delta_{13} + \sin^2\Delta_{23}]$$

CP-even

CP-odd

Beat of frequencies

To fix numbers

Unless otherwise specified, we assume following parameters:

$$\Delta m_{32}^2 = 3\times 10^{-3} eV^2,$$

$$\Delta m_{12}^2 = 1\times 10^{-4} eV^2,$$

$$\sin^2\theta_{23} = 0.5,$$

$$\sin^2\theta_{12} = 0.5,$$

$$\sin^2 2\theta_{13} = 0.05$$

Consistent with atmospheric data and LMA solar data (assuming maximal mixing).

Looking for effects of δ!

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

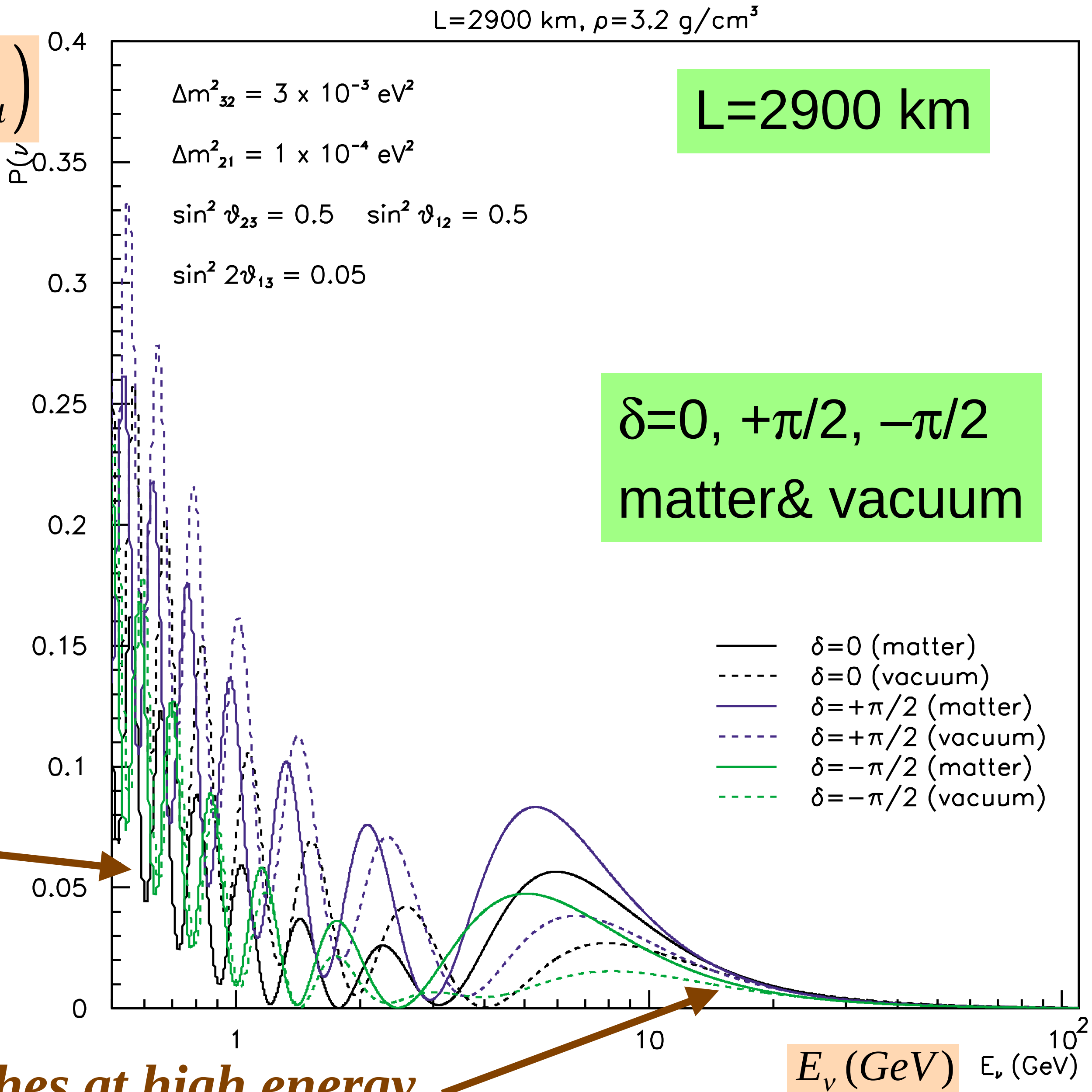
Effect "largest" when beat of three sin-functions:

$\Delta m^2_{21}\,(L/4E_\nu)\approx 1$

&

$\Delta m^2_{32}\,(L/4E_\nu)>1$

⇒L/E of "solar" !



L=2900 km

δ=0, +π/2, –π/2

matter& vacuum

$E_\nu\,(GeV)$

Effect vanishes at high energy

André Rubbia, ETH/Zürich, NOVE, 7/26/01

The effect is

For a complex mixing matrix (in vacuum)

$$P(\nu_e \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4c^2_{13}[\sin^2 \Delta_{23} s^2_{12} s^2_{13} + c^2_{12}(\sin^2\Delta_{13} s^2_{13} s^2_{23} + \sin^2\Delta_{12} s^2_{12}(1-(1+s^2_{13})s^2_{23}))]$$

$$-1/2c^2_{13}\sin^2\theta_{12} s_{13}\sin^2\theta_{23}\cos\delta[\cos^2\Delta_{13} - \cos^2\Delta_{23} - 2\cos^2\theta_{12}\sin^2\Delta_{12}]$$

$$+1/2c^2_{13}\sin\delta\sin 2\theta_{12} s_{13}\sin^2\theta_{23}[\sin^2\Delta_{12} - \sin^2\Delta_{13} + \sin^2\Delta_{23}]$$

1. A ***precision measurement of the transition probability*** can yield information on the ***δ-phase*** *provided we know all other parameters very precisely*!

   OR

2. We can try to ***directly measure a difference of probability between neutrinos or antineutrinos*** (T or CP-violation)

$$\begin{tikzcd}
\nu_e \to \nu_\mu \arrow[r, leftrightarrow] \arrow[d, bend right, leftrightarrow] & \nu_\mu \to \nu_e \arrow[d, bend left, leftrightarrow] \\
\bar{\nu}_e \to \bar{\nu}_\mu \arrow[r, leftrightarrow] & \bar{\nu}_\mu \to \bar{\nu}_e
\end{tikzcd}$$

In fact

In vacuum

$$\Delta CP = \Delta T =$$

$$2\cos\theta_{13}\sin\delta\,\sin 2\theta_{12}\,\sin 2\theta_{13}\,\sin 2\theta_{23}\times$$

$$\sin(\Delta m^2_{12}\,L/4E_\nu)\,\sin(\Delta m^2_{13}\,L/4E_\nu)\,\sin(\Delta m^2_{23}\,L/4E_\nu)$$

1. *Only depends on* $\sin\delta$

   and

2. *Only depends on* L/E_ν

Comment with respect to θ_{13}

$P(\nu_e \rightarrow \nu_\mu)=$

$$4c^2_{13}[\sin^2\Delta_{23}s^2_{12}\mathbf{s^2_{13}}+c^2_{12}(\sin^2\Delta_{13}\mathbf{s^2_{13}}s^2_{23}+\sin^2\Delta_{12}s^2_{12}(1-(1+s^2_{13})s^2_{23}))]$$

$$-1/2c^2_{13}\sin^2\theta_{12}\mathbf{s_{13}}\sin^2\theta_{23}\cos\delta[\cos^2\Delta_{13}-\cos^2\Delta_{23}-2\cos^2\theta_{12}\sin^2\Delta_{12}]$$

$$+1/2c^2_{13}\sin\delta\sin2\theta_{12}\mathbf{s_{13}}\sin^2\theta_{23}[\sin^2\Delta_{12}-\sin^2\Delta_{13}+\sin^2\Delta_{23}]$$

$$\left.\begin{array}{l}\Delta CP = \Delta T \propto \sin\theta_{13} \\ P \propto \sin^2\theta_{13}\end{array}\right\} \frac{\Delta CP}{\sqrt{P}} \propto \frac{\sin\theta_{13}}{\sqrt{\sin^2\theta_{13}}} \quad \textit{independent of} \quad \theta_{13}$$

This is true as long as

1. we have events in the detector
2. we can neglect the second term in the probability

   (cannot be done for $\theta_{13} \rightarrow 0$)

Matter effects

$$\sin^2 2\theta_m(D) = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\pm \frac{D}{\Delta m^2} - \cos 2\theta\right)^2}$$

$$\lambda_m = L \times \sqrt{\sin^2 2\theta + \left(\pm \frac{D}{\Delta m^2} - \cos 2\theta\right)^2}$$

+ for neutrinos
– for antineutrinos

where

$$D(E_\nu) = 2\sqrt{2} G_F n_e E_\nu \approx 7.56 \times 10^{-5} \quad eV^2 \left(\frac{\rho}{gcm^{-3}}\right)\left(\frac{E}{GeV}\right)$$

For example, for neutrinos:

Resonance: $D \approx \Delta m^2 \cos 2\theta \quad \Longrightarrow \quad \sin^2 2\theta_m(D) \approx 1$

Suppression: $D > 2\Delta m^2 \cos 2\theta \quad \Longrightarrow \quad \sin^2 2\theta_m(D) < \sin^2 2\theta$

Mixing in matter smaller than in vacuum

Effect tends to become “visible” for L > ≈1000 km

A way to rescale probabilities...

$$p \equiv P\left(\nu_e \to \nu_\mu\right) \times E_\nu^2 / L^2$$

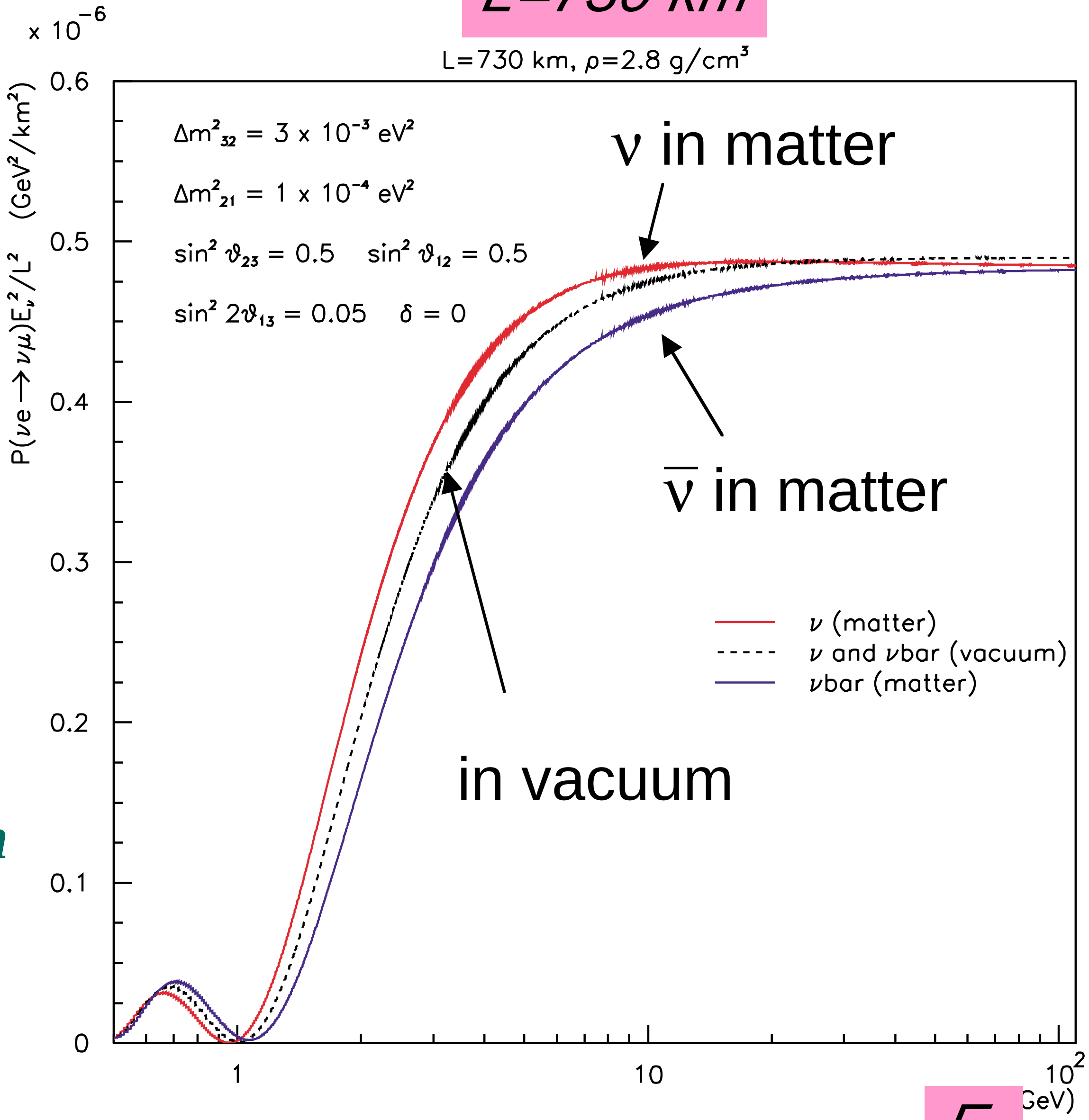
probability

Approximate E_ν-dependence of NF ν-spectrum

Flux attentuation with distance

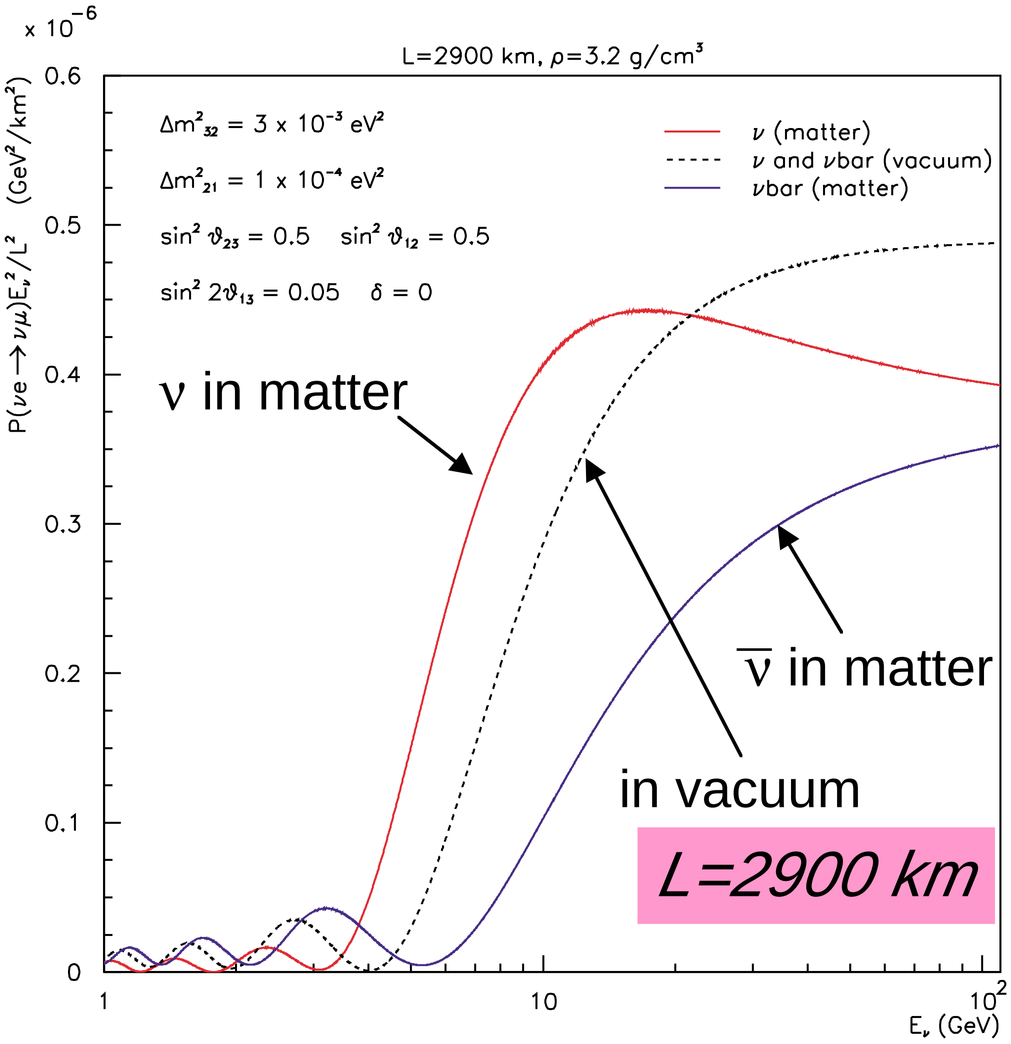
1. *p→const when E_ν →∞*
2. *It* ***correctly “weighs” the probabilities with the E_ν dependence of the NF ν spectrum***
3. *p can be* ***directly compared at different baselines***

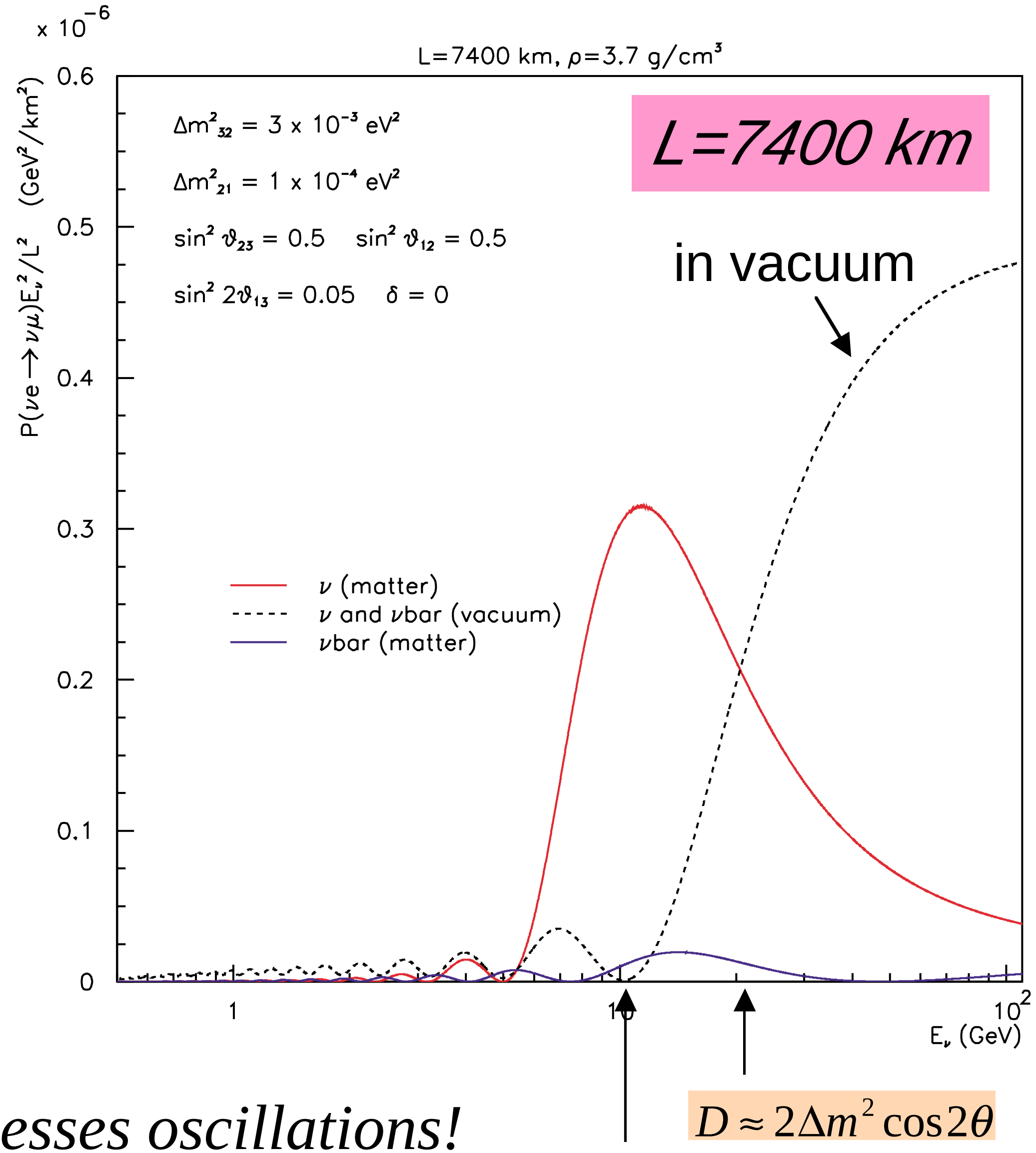
L=730 km



E_ν

Behaviour at larger distances...





$D \approx 2\Delta m^2 \cos 2\theta$

$D \approx \Delta m^2 \cos 2\theta$

At large distances, matter effect suppresses oscillations!

So what about the effects of δ?

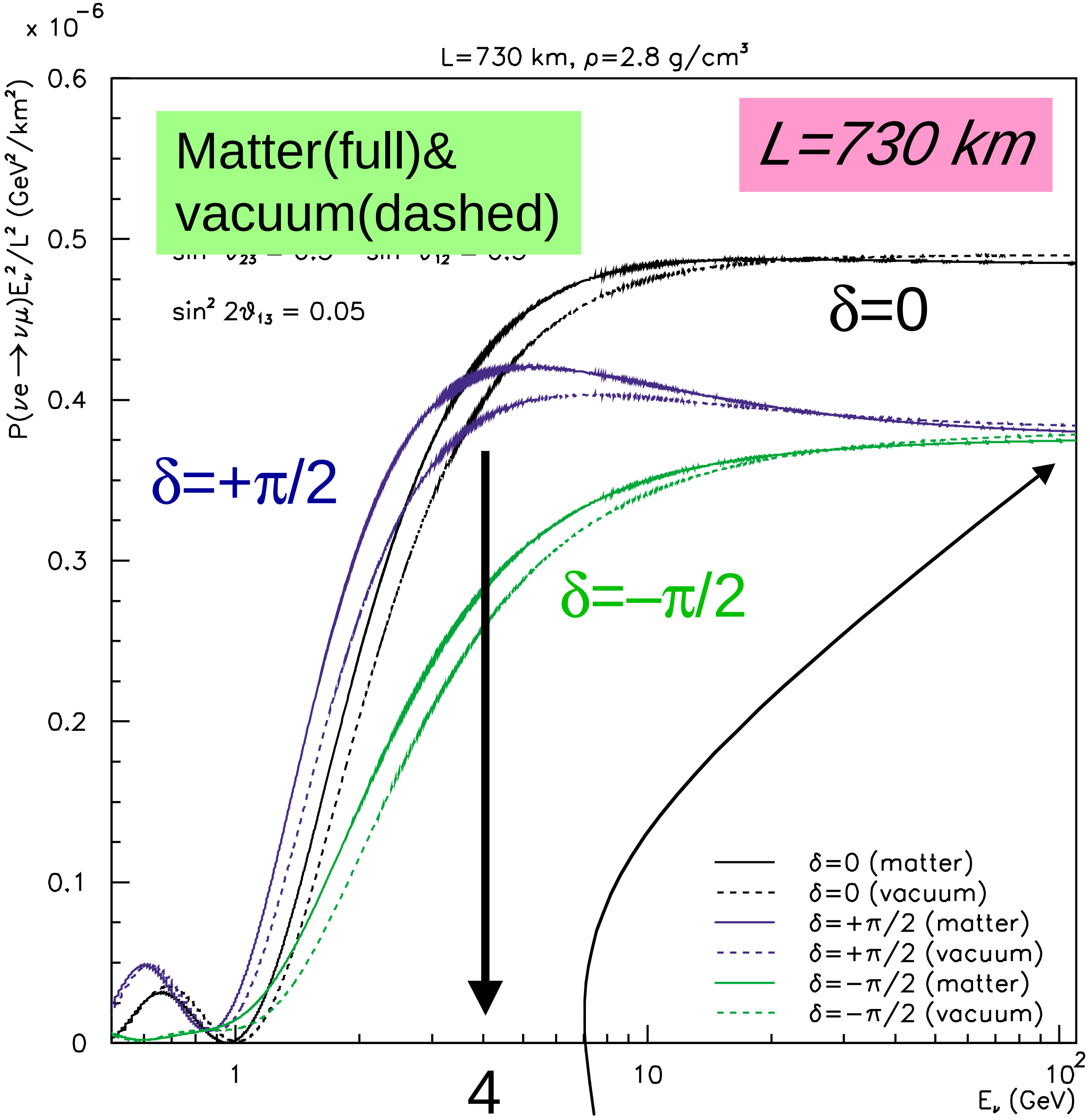
$$P\left(\nu_e \to \nu_\mu\right) \times E_\nu^2 / L^2$$

1. The E_ν^2 term takes into account that the NF likes to go to high energy $\Rightarrow$ damps the part $\Delta m^2_{21}\,(L/4E_\nu) \approx 1$

2. At “high energy”, i.e. $\Delta m^2_{21}\,(L/4E_\nu) << 1$ & $\Delta m^2_{32}\,(L/4E_\nu) << 1$, there is no more oscillation

$\Rightarrow$ **change of $\boldsymbol{\delta}$ = change of $\boldsymbol{\theta_{13}}$!!!**

3. At “high energy”, the CP-effect goes like $\cos\delta \Rightarrow$ cannot measure sign of δ



$$P\left(\nu_e \to \nu_\mu, \delta = \frac{\pi}{2}\right) - P\left(\nu_e \to \nu_\mu, \delta = 0\right) \propto \cos\delta$$

So where is the compromise in L/E?

We must compromise at "medium" energy to

1. This means $\Delta m^2_{21}(L/4E_\nu) \ll 1$

& $\Delta m^2_{32}(L/4E_\nu) \approx 1$

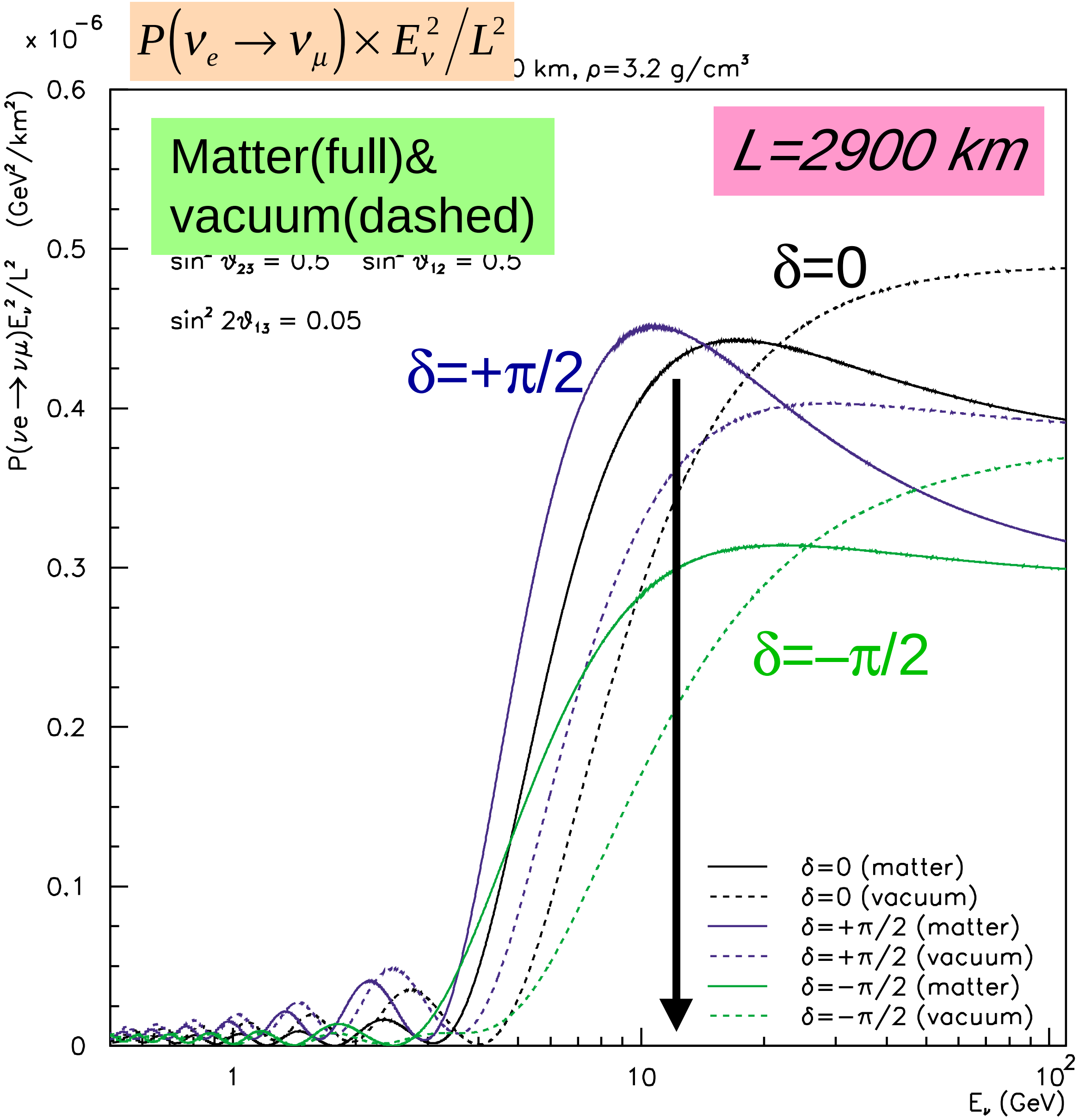
2. To gain from the E_μ^3 *behavior of the NF*

3. To guarantee the possibility to disentangle δ *from* θ_{13}

$$\Rightarrow \quad \frac{L}{E_\nu} \approx \frac{4\pi}{2\Delta m^2_{32}}$$

¥E$_{\nu,MAX}$ ˉ 2 GeV for L=732 km

¥E$_{\nu,MAX}$ ˉ 8 GeV for L=2900 km



If L/E_ν is fixed, what should be L and E_ν ?

The magnitude of the CP effect (given by J) is known to be unaffected by matter

$$J = \cos\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}/8$$

Our "choice-point" for CP is at the fixed L/$E_{\nu,\max}$ given by: $E_{\nu,\max} = \dfrac{2\times 1.27 \times \Delta m^2 L}{\pi}$

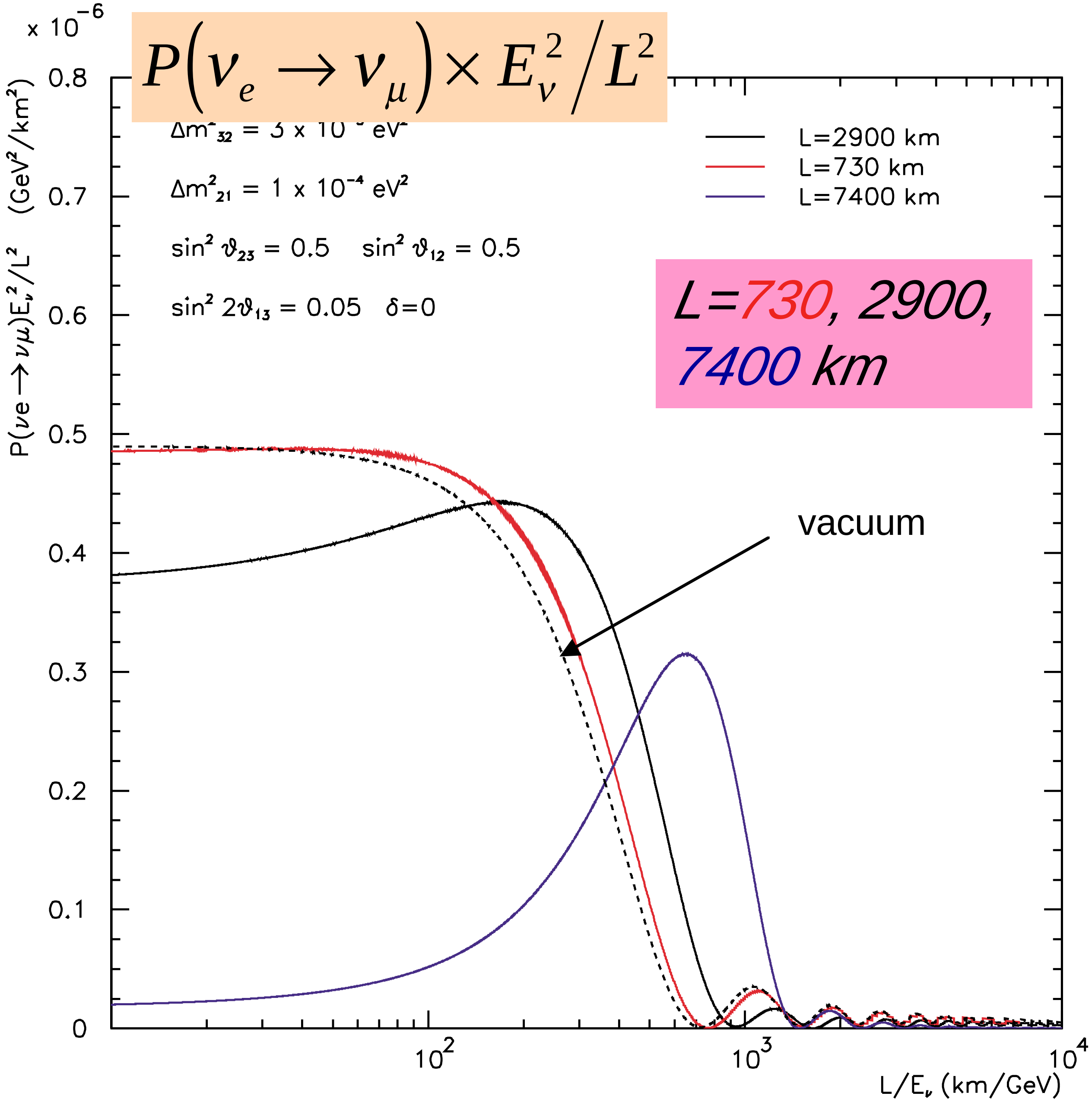
When the neutrino energy becomes close to the MSW resonance, the effective oscillation wavelength increases, hence the CP effect at a fixed distance L becomes less visible.

Hence, we gain until the MSW resonance region and then loose.

$$2\sqrt{2}G_F n_e E_\nu < \Delta m^2 \cos 2\theta \quad \Rightarrow \quad 2\sqrt{2}G_F n_e \frac{2\times 1.27\Delta m^2 L}{\pi} < \Delta m^2 \cos 2\theta$$

$$L < \frac{\pi \cos 2\theta}{2\times 1.27 \times 7.56 \times 10^{-5} \quad eV^2 \left(\dfrac{\rho}{gcm^{-3}}\right)} \approx \frac{1.5\times 10^4\, km}{\left(\dfrac{\rho}{gcm^{-3}}\right)} \approx 5000 km$$

Dependence of probability in matter on L/E$_\nu$



$$P\left(\nu_e \to \nu_\mu\right) \times E_\nu^2 / L^2$$

L=730, 2900, 7400 km

The "scaling" with L/E$_\nu$ of the probabilities is violated when E$_{\nu,max}$ > E$_{\nu,\ resonance}$, due to matter effects.

The longest baseline is clearly disfavored!

$$L / E \ \ (km / GeV)$$

How to experimentally observe the δ-phase?

- $\Delta\delta \equiv P(\nu_e \rightarrow \nu_\mu; \delta=\pi/2) - P(\nu_e \rightarrow \nu_\mu; \delta=0)$

Compares oscillation probabilities as a function of E_ν measured with wrong-sign muon event spectra, to MonteCarlo predictions of the spectrum in absence of CP violation

- $\Delta CP(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; \delta)$

Compares oscillation probabilities measured using the appearance of ν_μ and $\bar{\nu}_\mu$, running the storage ring with a beam of stored μ^+ and μ^-, respectively. Matter effects are dominant at large distances

- $\Delta T(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\nu_\mu \rightarrow \nu_e; \delta)$

Compares the appearance of ν_μ and ν_e in a beam of stored μ^+ and μ^-. As opposite to the previous case, matter effects are the same, thus cancel out in the difference

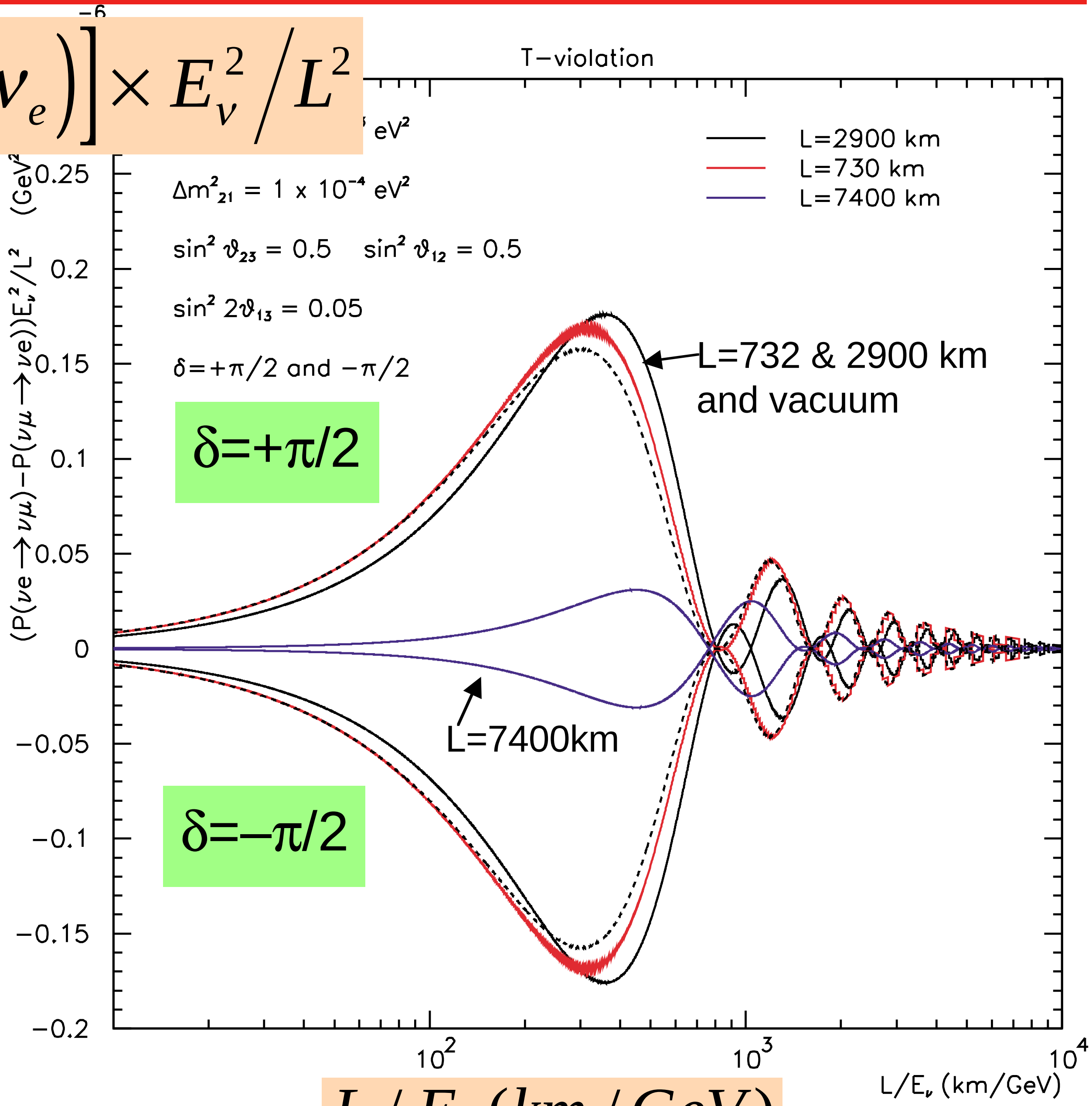
- $\Delta\bar{T}(\delta) \equiv P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu; \delta) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e; \delta)$

Same as previous case, but with antineutrinos. This effect is usually matter-suppressed with respect to the neutrino case.

The ΔT dependence on L/E$_\nu$

$$\left[P\left(\nu_e \to \nu_\mu\right) - P\left(\nu_\mu \to \nu_e\right)\right] \times E_\nu^2 / L^2$$

- ❖The effect as function of L/E is the approximately the same at L=732 or 2900 km and in vacuum.
- ❖The dependence to the δ-phase is reduced by matter at L=7400 km

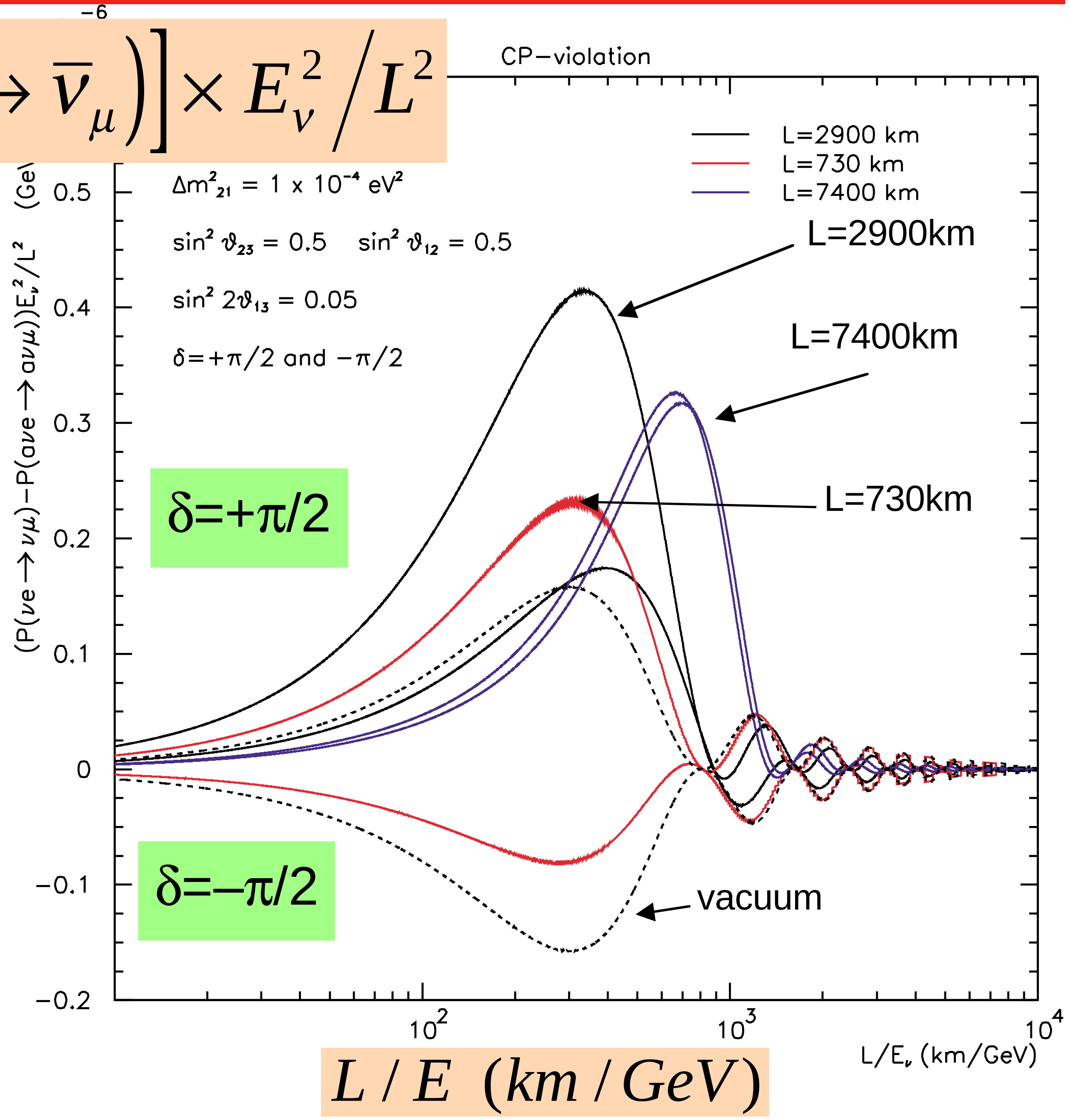


$$L/E \;\; (km/GeV)$$

The ΔCP dependence dependence on L/E$_\nu$

$$\left[P\left(\nu_e \rightarrow \nu_\mu\right) - P\left(\bar{\nu}_e \rightarrow \bar{\nu}_\mu\right)\right] \times E_\nu^2 / L^2$$

- ❖Matter introduces a large asymmetry, independent of δ
- ❖The dependence to the δ-phase is reduced by matter at L=7400 km



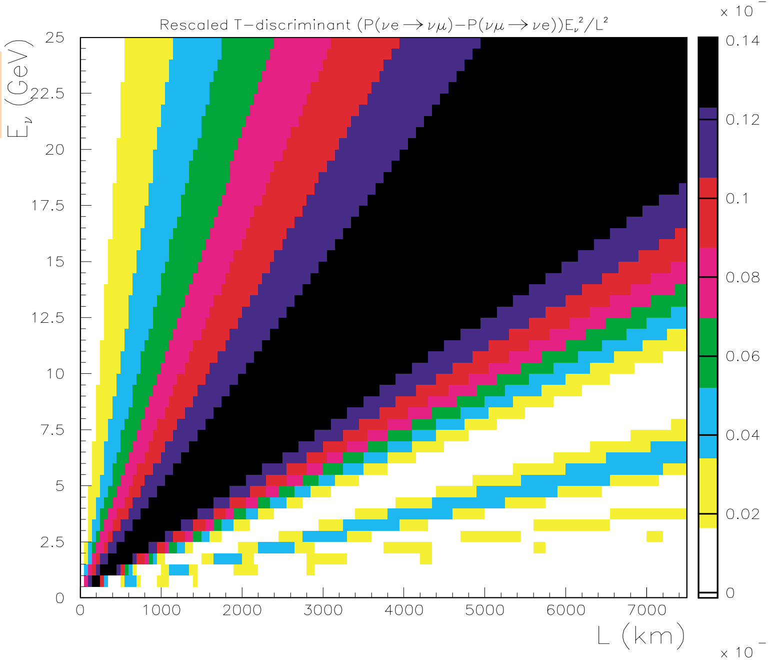
Effects of matter on ΔT

E$_\nu$ *(GeV)*

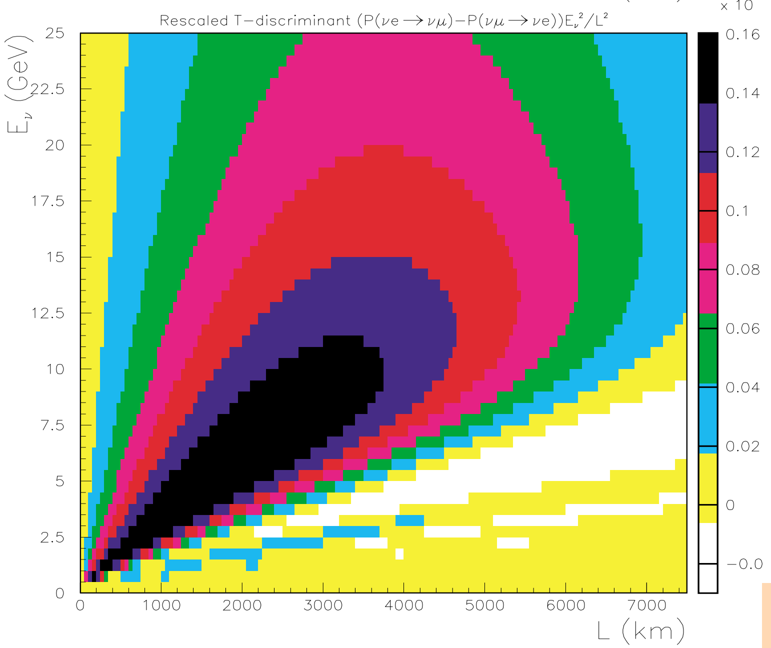
The cut-off of the scaled T-violating term in matter for L≈4000 km destroys L/E scaling. It is useless to go above this distance for T-and CP- violation studies

The above considerations have nothing to do with the necessity of subtracting fake-CP violation due to matter ν-$\bar{\nu}$ asymmetry!

They affect both ΔT and ΔCP.



Vacuum



Matter

L (km)

Measuring ΔT

The comparison of $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ oscillation probabilities offers a direct way to highlight a complex component in the mixing matrix, independent of matter and other oscillation parameters.

This measurement is not directly accessible at a neutrino Factory with a conventional detector due to the large ν_e background in the beam. It would add a considerable improvement to the physics reach of a Neutrino Factory

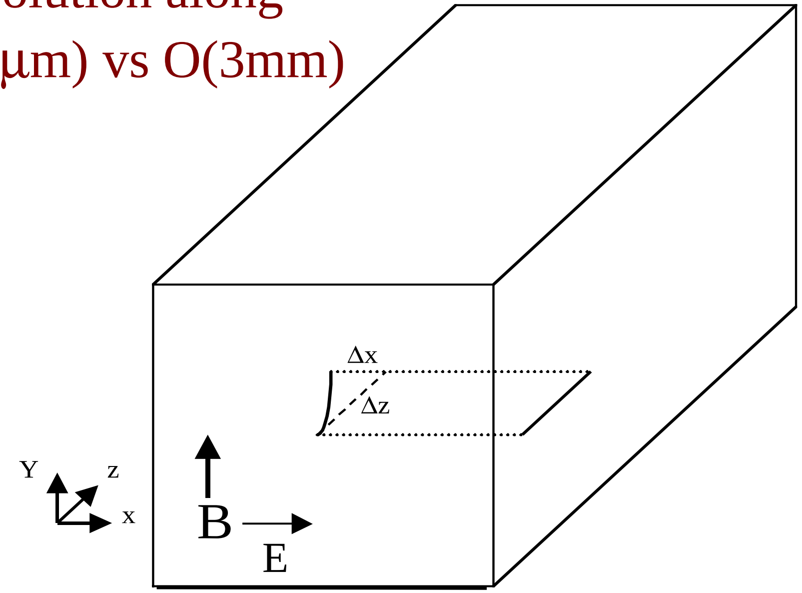
Two methods have been proposed to solve the problem of beam ν_e background :

- **Beam polarization** **(not very effective; see A.Blondel, A.Bueno, M.Campanelli, A.Rubbia, Monterey NUFACT 00 proceedings)**
- **Electron charge**

MC simulation for electron charge

MC simulations of electrons in a magnetic field have been performed assuming a magnetized liquid argon imaging TPC (Magnetized ICARUS-like detector)

Magnetic and electric fields are perpendicular to exploit the better resolution along drift (O(300 μm) vs O(3mm) wire pitch)



Purities obtained (for 10% efficiency) are encouraging, but clearly require high fields

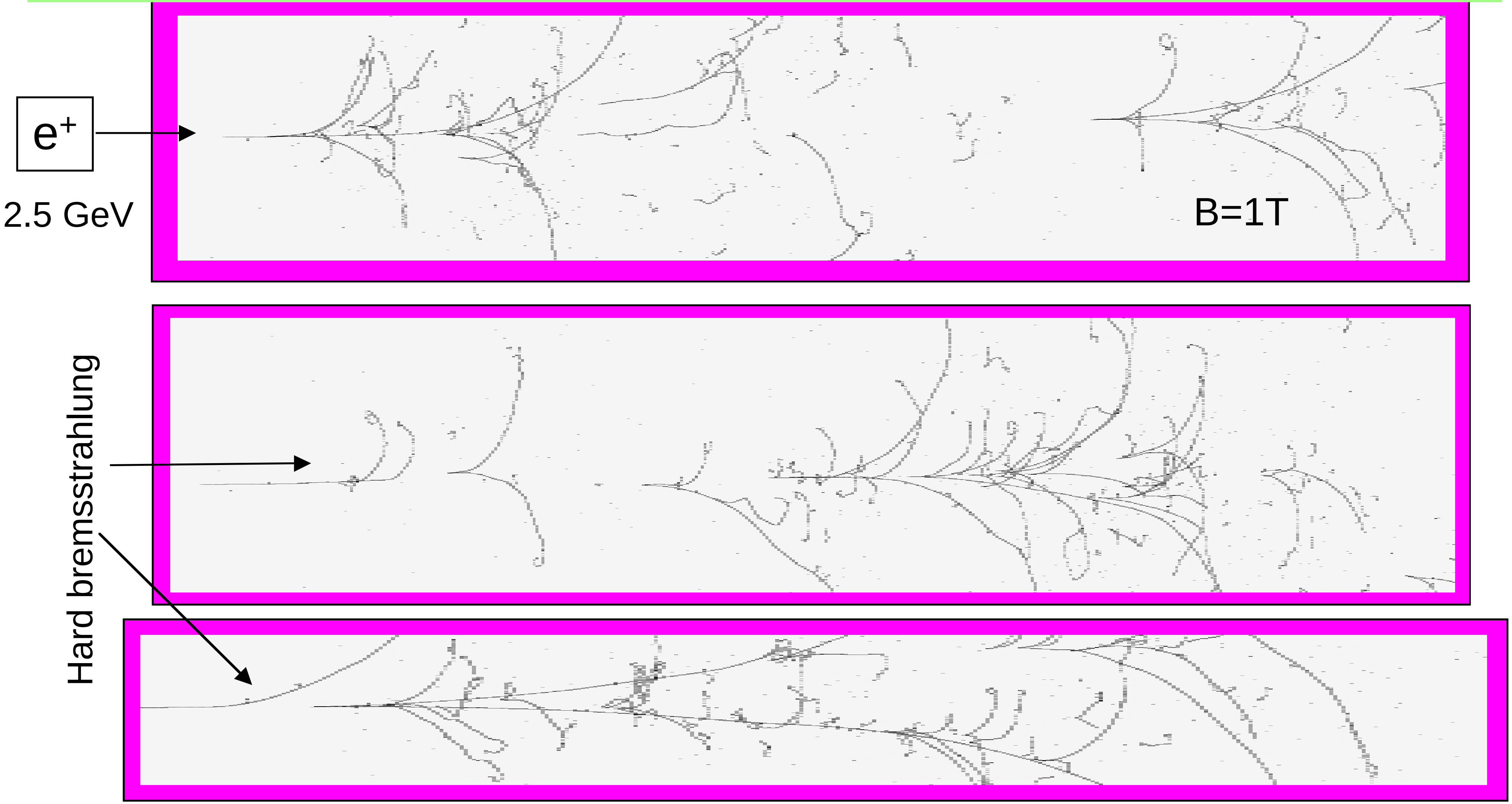
E_e=5 GeV

B field (T)	Charge confusion (%)
0.2	35
0.5	15
1.0	3

Actual R&D (imaging in B-field) and electron test beams required…

On the possibility to measure the electron charge

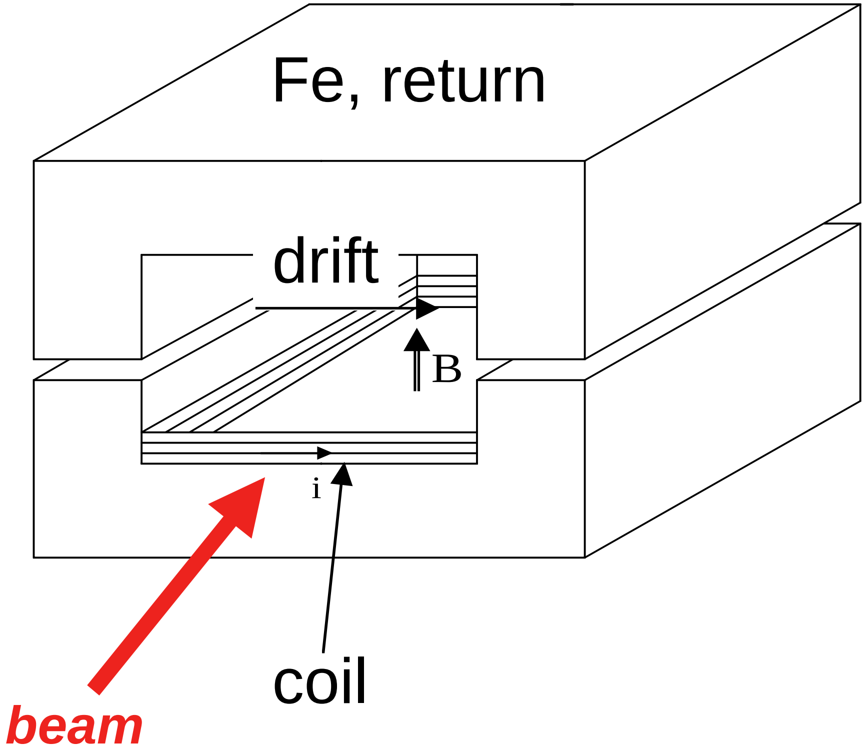
This appears to be only practically conceivable for electron energies $<\approx 5$ GeV



A large magnet ?

An interesting possibility, ***to be further understood****, is the creation of the B-field over the large volume encompassing the LAr with the help of a very large solenoid*

$$\vec{B} \perp \vec{v}_{drift} \perp \vec{p}$$



Joule Power (non-superconducting):

$$P = \rho \frac{2(a+b)hB^2}{md\mu_0{}^2}$$

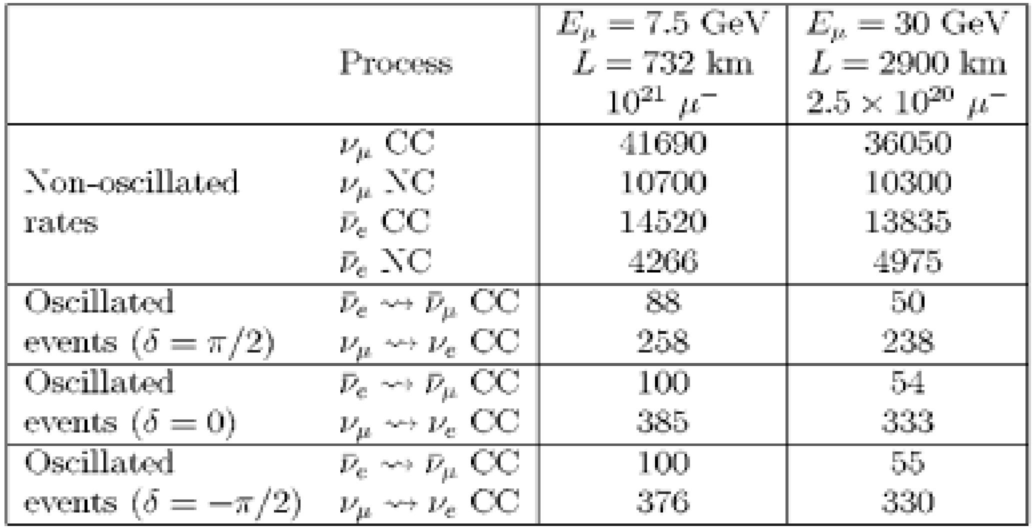
d=coil thickness, m=#windings, h=height, a=width, b=length

Parameter	
Argon volume	$8 \times 8 \times 16 m^3$
Argon mass	1.4 kton
Magnetic field	1.0 T
Current	2000 A
Conductor length	150 km
Resistance	1 Ω
Dissipated power	4 MW
Iron mass	5 kton

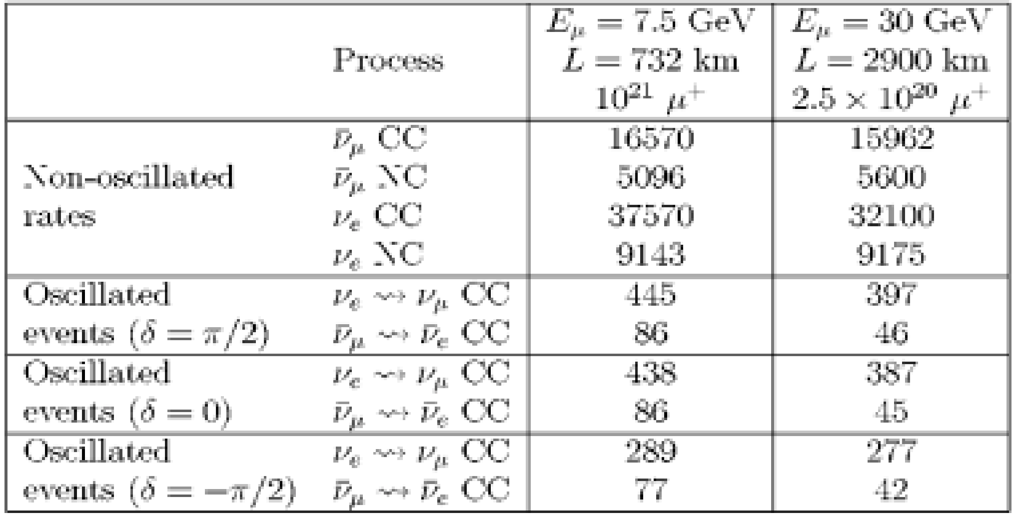
The proof that it could work

In order to prove L/E scaling, and explore the physical reach in practical examples, we have studied in detail two cases with a 10 kton detector:

- L= 732 km, E_μ = 7.5 GeV, 10^{21} μ decays for ΔCP and ΔT
- L=2900 km, E_μ = 30 GeV, 2.5×10^{20} μ decays for ΔCP only



	Process	$E_\mu = 7.5$ GeV $L = 732$ km 10^{21} μ^-	$E_\mu = 30$ GeV $L = 2900$ km 2.5×10^{20} μ^-
Non-oscillated rates	ν_μ CC	41690	36050
	ν_μ NC	10700	10300
	$\bar{\nu}_e$ CC	14520	13835
	$\bar{\nu}_e$ NC	4266	4975
Oscillated events ($\delta = \pi/2$)	$\bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$ CC	88	50
	$\nu_\mu \rightsquigarrow \nu_e$ CC	258	238
Oscillated events ($\delta = 0$)	$\bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$ CC	100	54
	$\nu_\mu \rightsquigarrow \nu_e$ CC	385	333
Oscillated events ($\delta = -\pi/2$)	$\bar{\nu}_e \rightsquigarrow \bar{\nu}_\mu$ CC	100	55
	$\nu_\mu \rightsquigarrow \nu_e$ CC	376	330



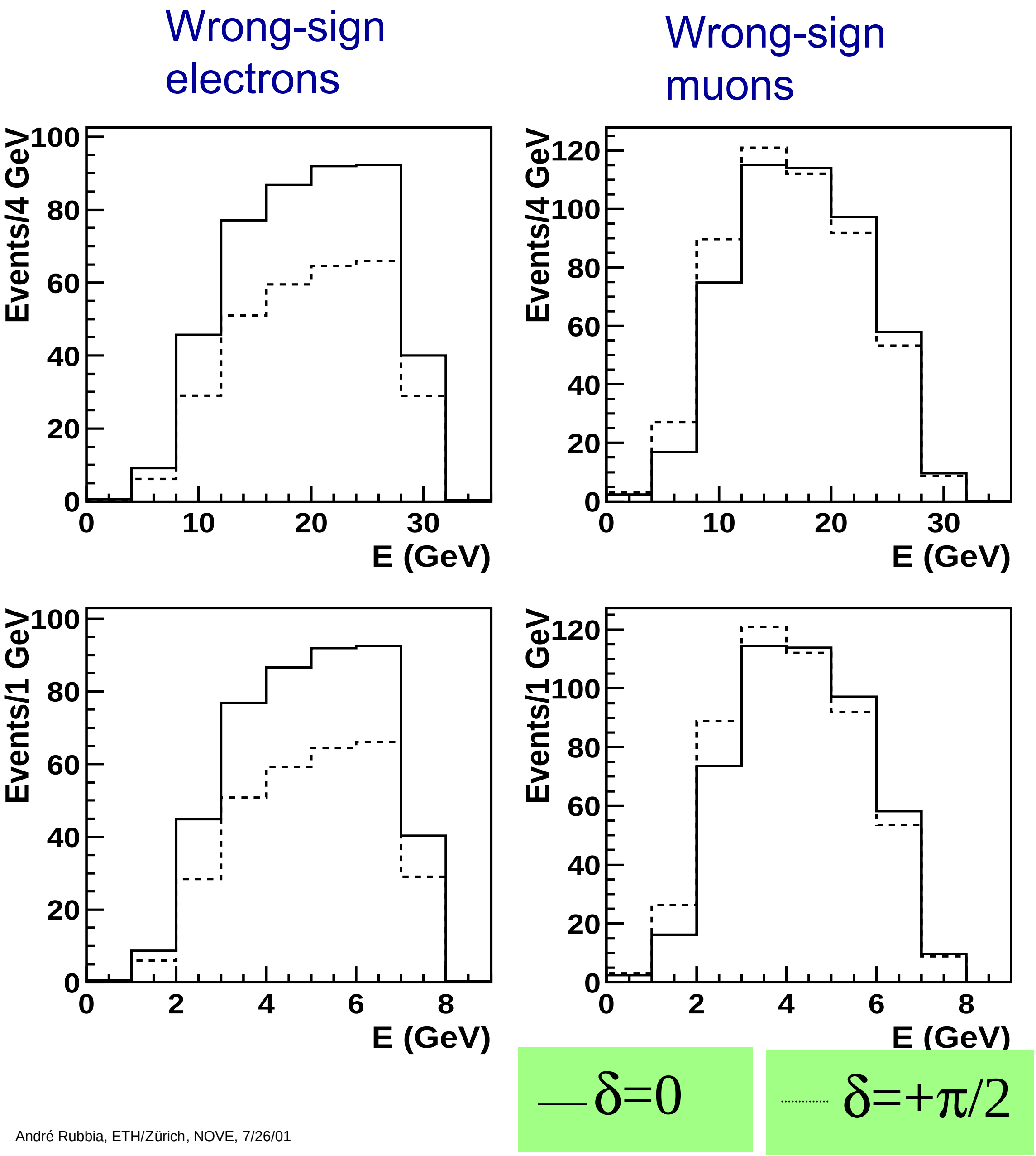
	Process	$E_\mu = 7.5$ GeV $L = 732$ km 10^{21} μ^+	$E_\mu = 30$ GeV $L = 2900$ km 2.5×10^{20} μ^+
Non-oscillated rates	$\bar{\nu}_\mu$ CC	16570	15962
	$\bar{\nu}_\mu$ NC	5096	5600
	ν_e CC	37570	32100
	ν_e NC	9143	9175
Oscillated events ($\delta = \pi/2$)	$\nu_e \rightsquigarrow \nu_\mu$ CC	445	397
	$\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$ CC	86	46
Oscillated events ($\delta = 0$)	$\nu_e \rightsquigarrow \nu_\mu$ CC	438	387
	$\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$ CC	86	45
Oscillated events ($\delta = -\pi/2$)	$\nu_e \rightsquigarrow \nu_\mu$ CC	289	277
	$\bar{\nu}_\mu \rightsquigarrow \bar{\nu}_e$ CC	77	42

τ→e background: another reason to require low energies!

Assume BG rejection factor for electrons O(10^{-3}) for 20% efficiency

L/E scaling

10 kton detector



L=2900 km,
E_μ=30 GeV

$L/E_\mu \approx 100$ km/GeV

10^{21} μ decays

L=732 km,
E_μ=7.5 GeV

$L/E_\mu \approx 100$ km/GeV

2.5×10^{21} μ decays

Identical L/E's yield identical effects !

André Rubbia, ETH/Zürich, NOVE, 7/26/01

Direct extraction of the oscillation probabilities (I)

- ✰ From the visible energy distributions of the collected events, one can extract the oscillation probabilities

$$P_i\left(\nu_e \to \nu_\mu\right) \equiv \frac{N_i(ws\mu) - N_i^0(ws\mu)}{\varepsilon_i(p_\mu > p_\mu^{cut})N_i^0(e)}$$

μ⁺ decays

$N_i(ws\mu) =$ number of wrong-sign muon events in the ith bin of energy

$N_i^0(ws\mu) =$ number of background events

$\varepsilon_i(p_\mu > p_\mu^{cut}) =$ efficiency of the muon threshold cut in that bin

$N_i^0(e) =$ number of electron events in absence of oscillations

Similar quantity can be defined for μ⁻ decays

Direct extraction of the oscillation probabilities (II)

- Similar quantities for measuring electron appearance

$$P_i\left(\nu_\mu \to \nu_e\right) \equiv \frac{N_i(wse) - N_i^0(wse)}{\varepsilon_e(1 - p_{conf})N_i^0(rs\mu)}$$

μ⁻ decays

$N_i(wse) = \text{number of wrong-sign electron events in the ith bin of energy}$

$N_i^0(wse) = \text{number of background events}$

$\varepsilon_e = \text{efficiency for charge identification of electrons}$

$N_i^0(rs\mu) = \text{number of right-sign muon events in absence of oscillations}$

Similar quantity can be defined for μ⁺ decays

Direct extraction of the oscillation probabilities (III)

- ✯ Binned discriminants for extraction of CP/T effects

For every energy bin *i*:

$$\Delta_{\mathrm{CP}}(i) \equiv P_i(\nu_e \rightarrow \nu_\mu) - P_i(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$$

$$\Delta_{\mathrm{T}}(i) \equiv P_i(\nu_\mu \rightarrow \nu_e) - P_i(\nu_e \rightarrow \nu_\mu)$$

$$and \quad similar \quad for \ \overline{\Delta}_{\mathrm{T}}(i) \quad for \ \ antineutrinos$$

- ✯ For checking matter-effects, we can define

$$\Delta_{\mathrm{CPT}}(i) \equiv P_i(\nu_\mu \rightarrow \nu_e) - P_i(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$$

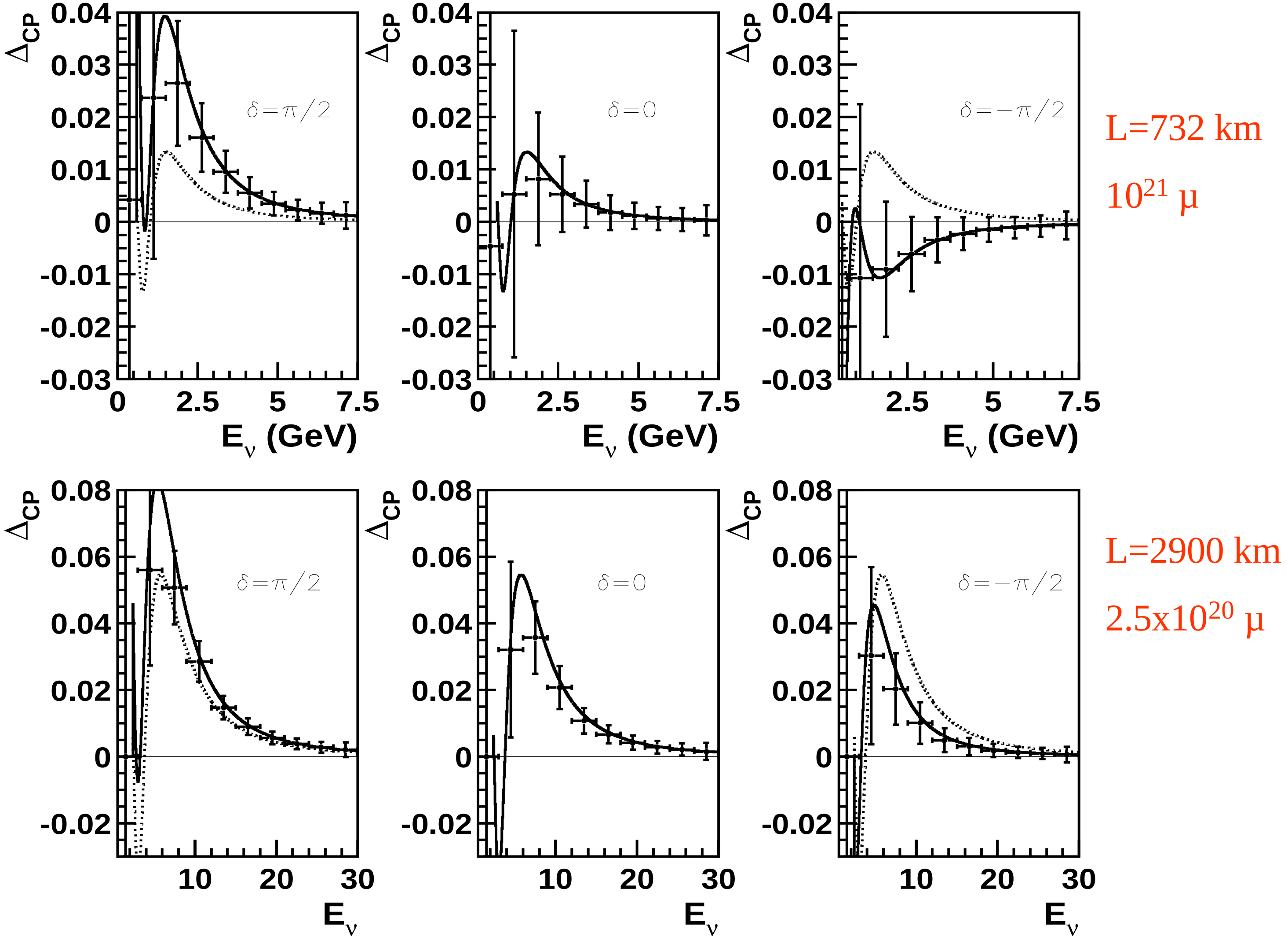
Binned CP violation discriminant

10 kton detector

The $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation probabilities obtained from wrong-sign muons.

Will be different from zero due to matter effects, even for δ=0

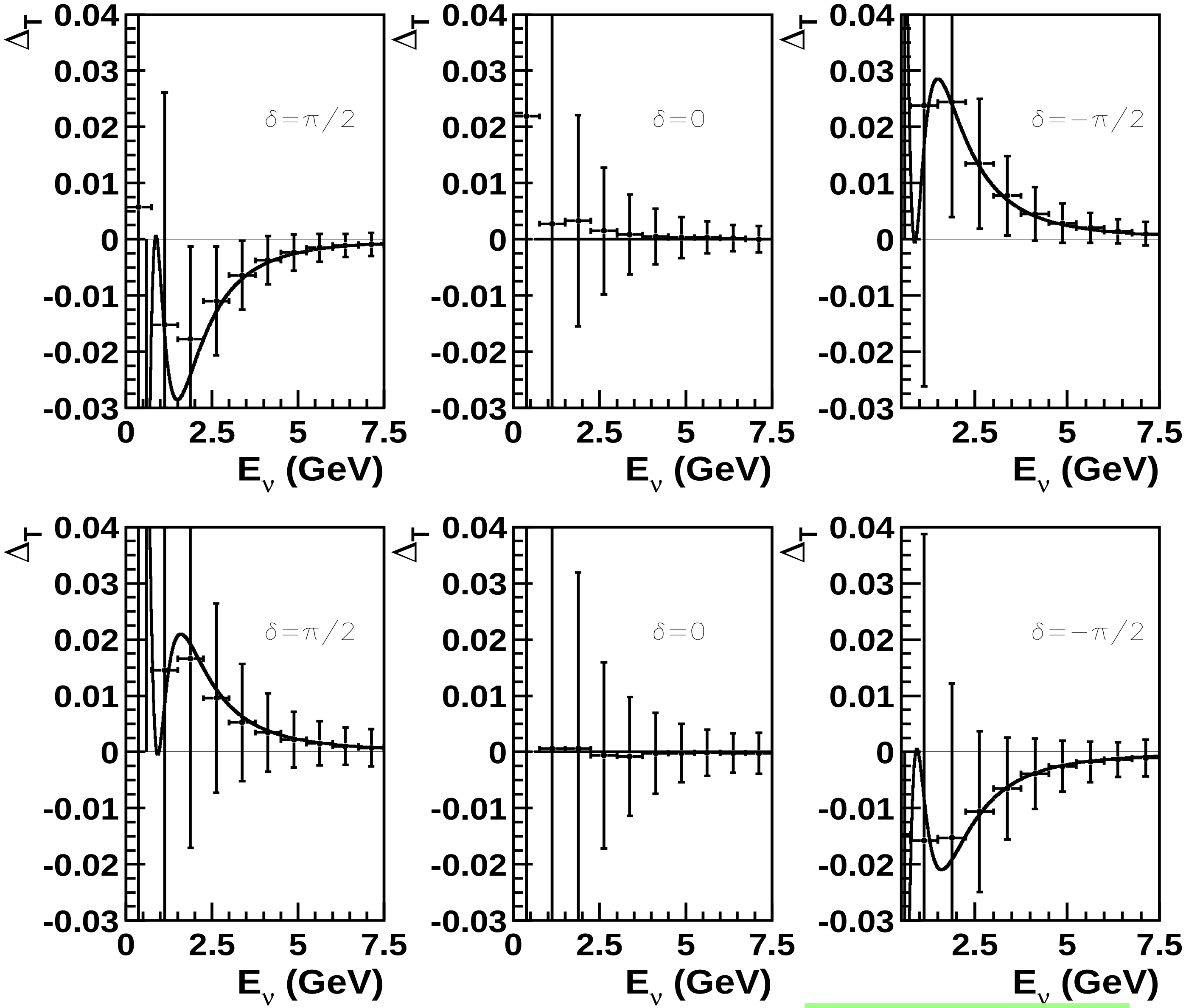
At L=732 km, matter effects are smaller, and large negative values of δ can reverse the sign of ΔCP



Expected statistical errors only

Binned ΔT discriminant

The difference in probability for wrong-sign muons and wrong-sign electrons is a direct proof of T-violation. Matter effects are the same, and cancel out in the difference.



10 kton detector

L=732 km

10^{21} μ decays

Expected statistical errors only

Defining sensitivities to the δ-phase

- One can define χ^2-significance of the effects to set sensitivity contours

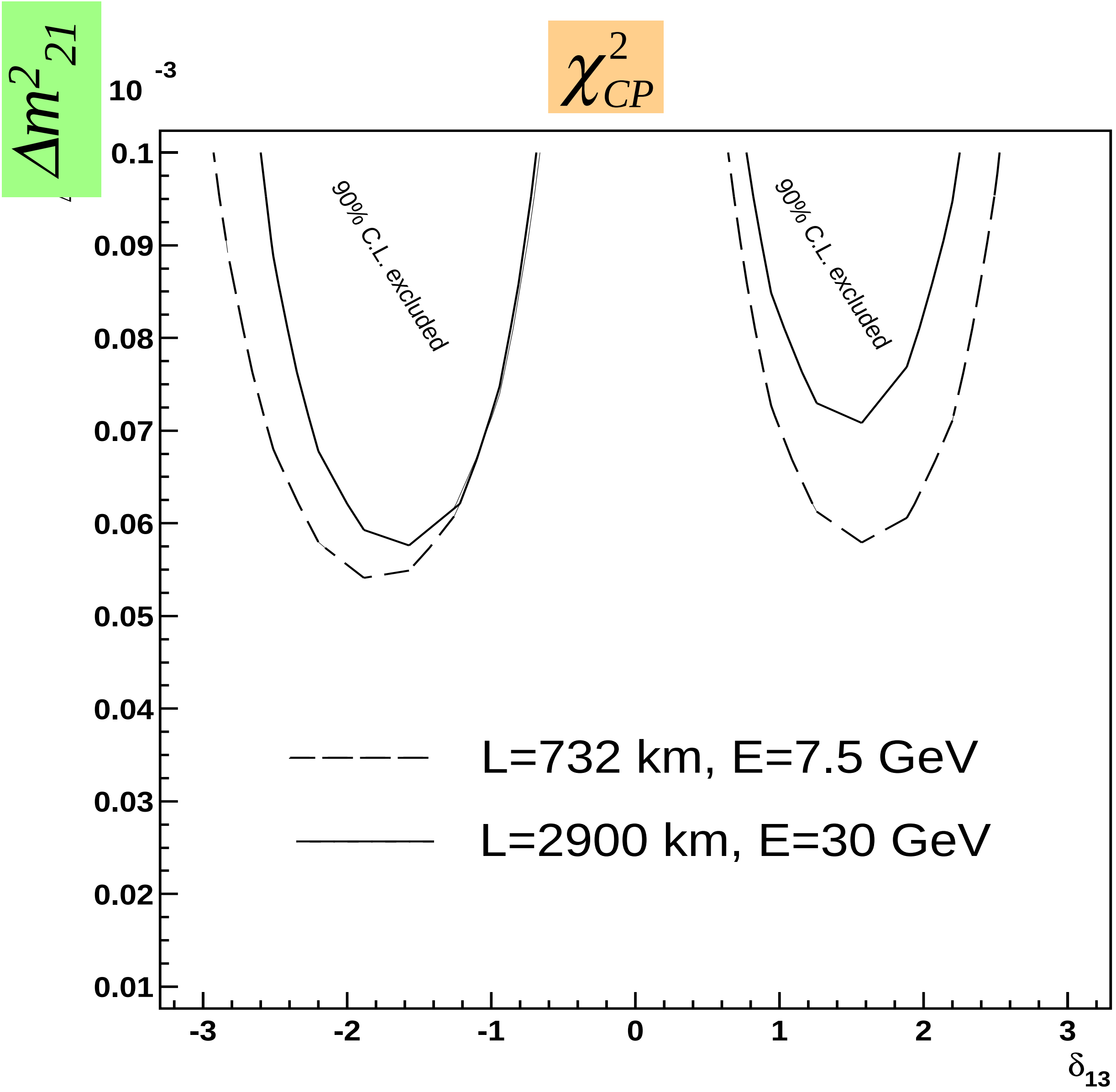
For CP-discriminant:

$$\chi^2_{CP} \equiv \sum_i \frac{\left(\Delta_{\mathrm{CP}}(i,\delta) - \Delta_{\mathrm{CP}}(i,\delta=0)\right)^2}{\left(\sigma\left(\Delta_{\mathrm{CP}}(i,\delta)\right)\right)^2}$$

For T-discriminant:

$$\chi^2_{T} \equiv \sum_i \frac{\left(\Delta_{\mathrm{T}}(i,\delta) - \Delta_{\mathrm{T}}(i,\delta=0)\right)^2}{\left(\sigma\left(\Delta_{\mathrm{T}}(i,\delta)\right)\right)^2} + \sum_i \frac{\left(\overline{\Delta}_{\mathrm{T}}(i,\delta) - \overline{\Delta}_{\mathrm{T}}(i,\delta=0)\right)^2}{\left(\sigma\left(\overline{\Delta}_{\mathrm{T}}(i,\delta)\right)\right)^2}$$

L/E_μ scaling at work for direct CP measurement

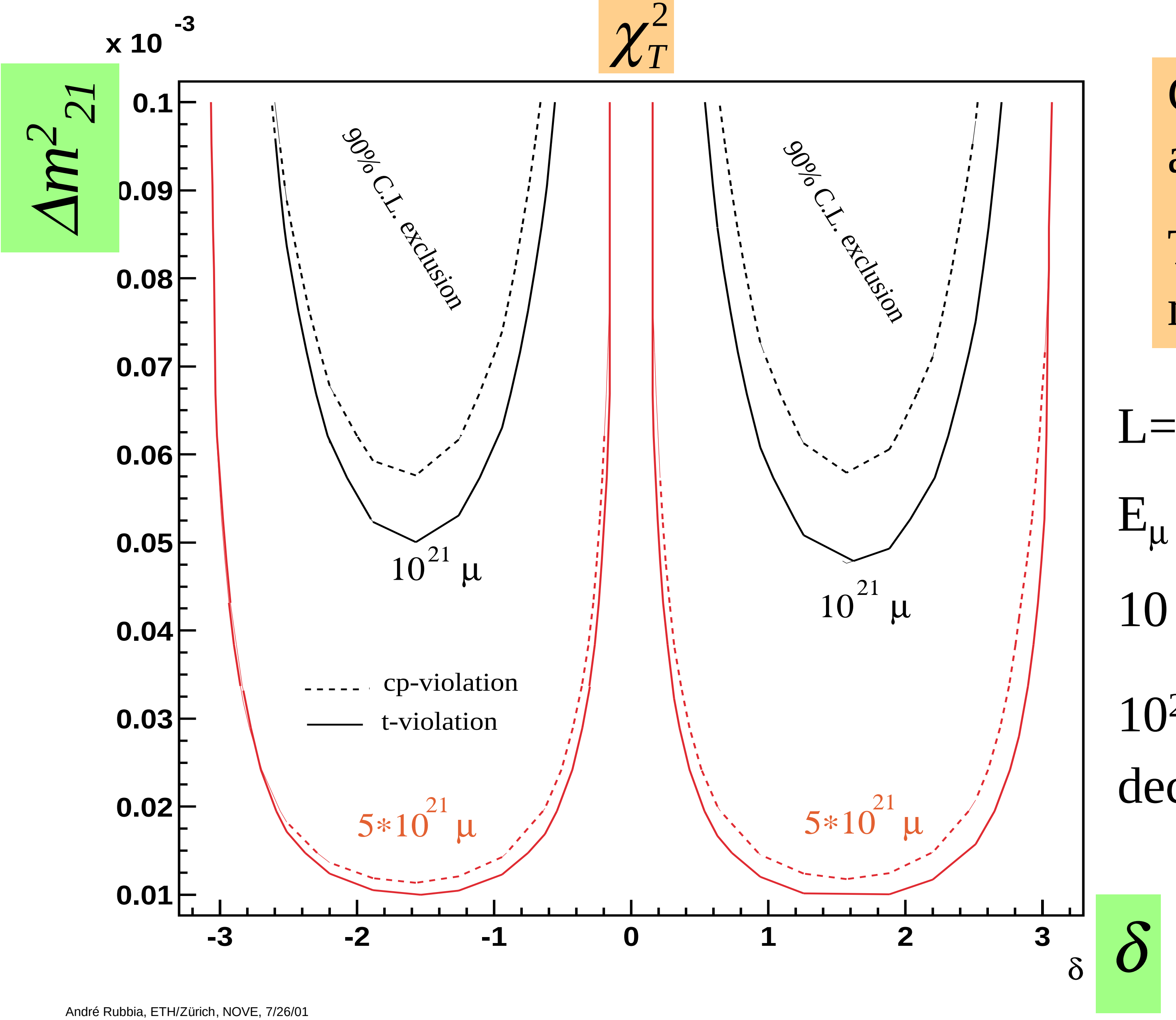


90% contours in the Δm^2_{12}-δ plane, obtained translating the probability differences into $\Delta\chi^2$

The sensitivity for the two cases is similar, proving the validity of the L/E_μ scaling at constant machine power. Actually, the shorter distance is even better due to the smaller influence of matter effects

Direct T-violation measurements sensitivity

χ^2_T



CP violation
and

T-violation
measurements

L=732 km

E_μ = 7.5 GeV

10 kton detector

10^{21} and 5×10^{21} μ
decays

André Rubbia, ETH/Zürich, NOVE, 7/26/01

Conclusion

- The current round of LBL experiments will be a ***confirmation*** of the SuperKamiokande results.
- The ***next discovery*** will come from the exploration of the so-called θ_{13} ***angle***, the connection between Sun and atmospheric oscillations.
  - → This is a challenging task
  - → It requires new high intensity beams, i.e Superbeams
- In case of Superbeams, one has to take into account
  - → intrinsic beam backgrounds
  - → detector-associated backgrounds
- One can hope to explore the ***δ-phase,*** but only if θ_{13} and solar LMA solution allow it…
  - → One approach is the JHF(phase II)-HyperK(1Mton) detector
  - → Our preferred approach relies on the cleanliness of the neutrino factory coupled to a detector capable of ***measuring the electron charge***. This would add a ***considerable improvement*** of a NF for CP and T violation studies.