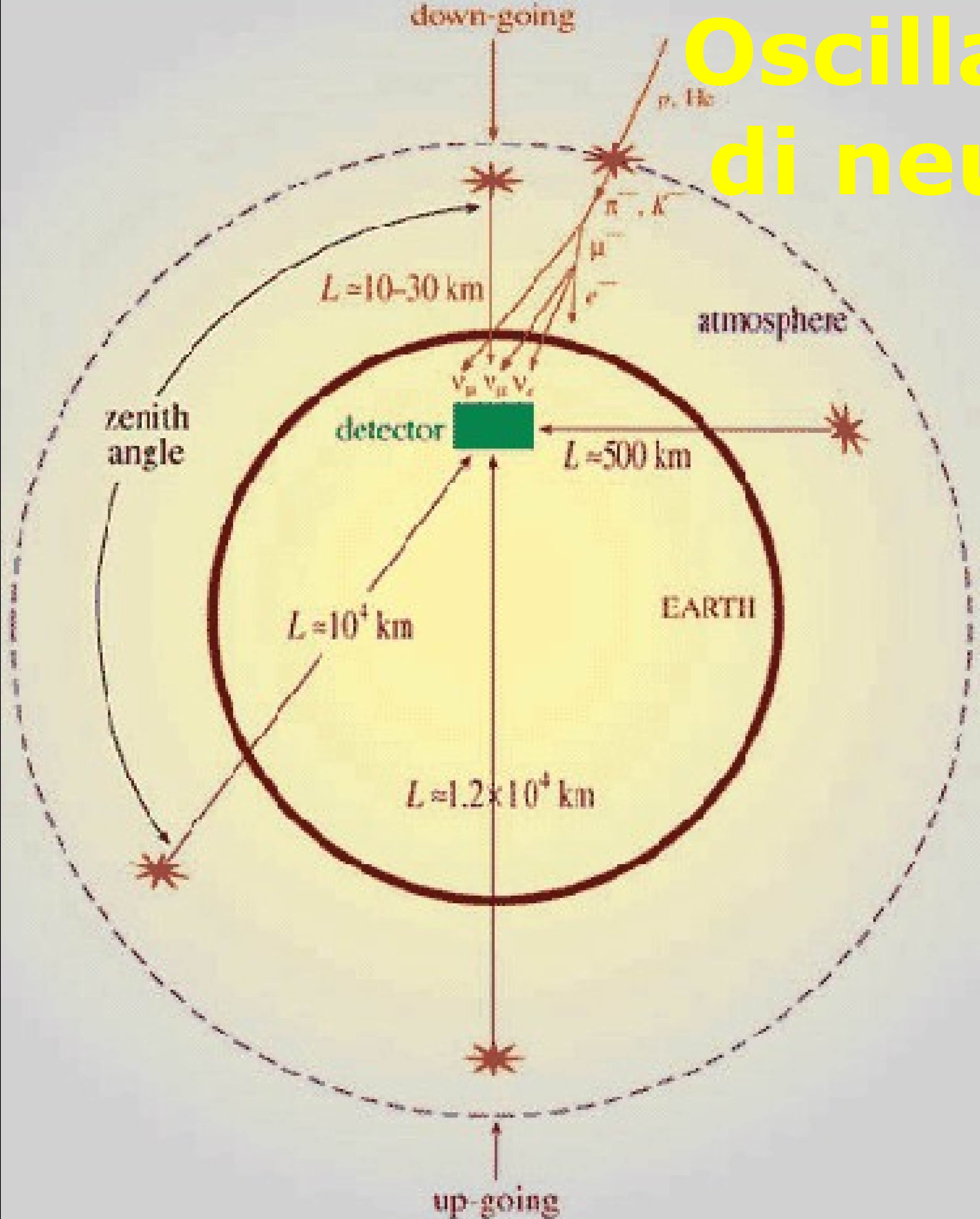
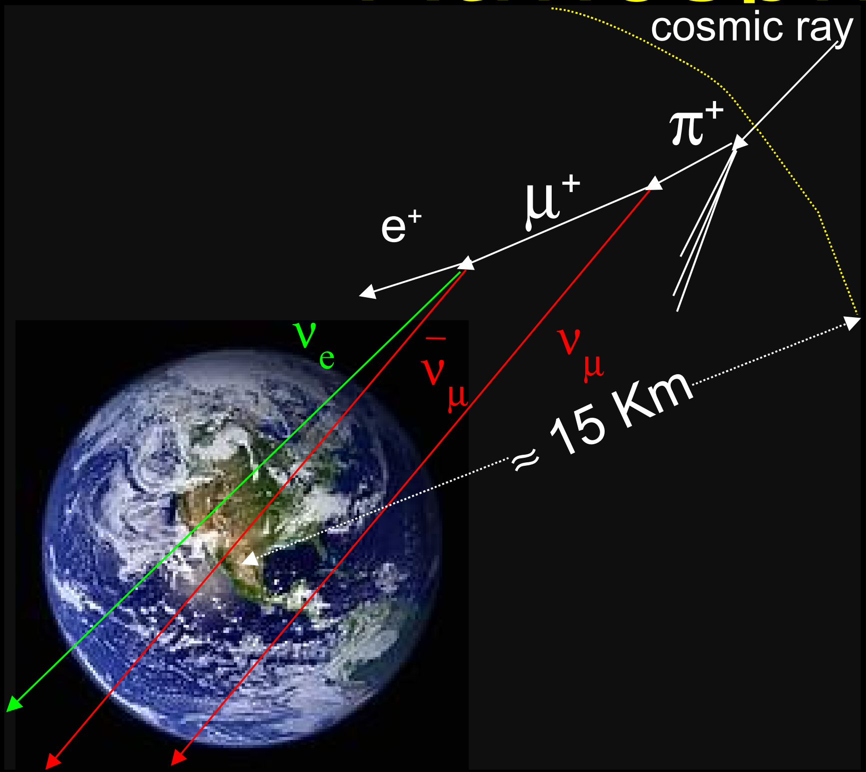
Oscillazioni di neutrini



L. Ludovici
INFN/Roma

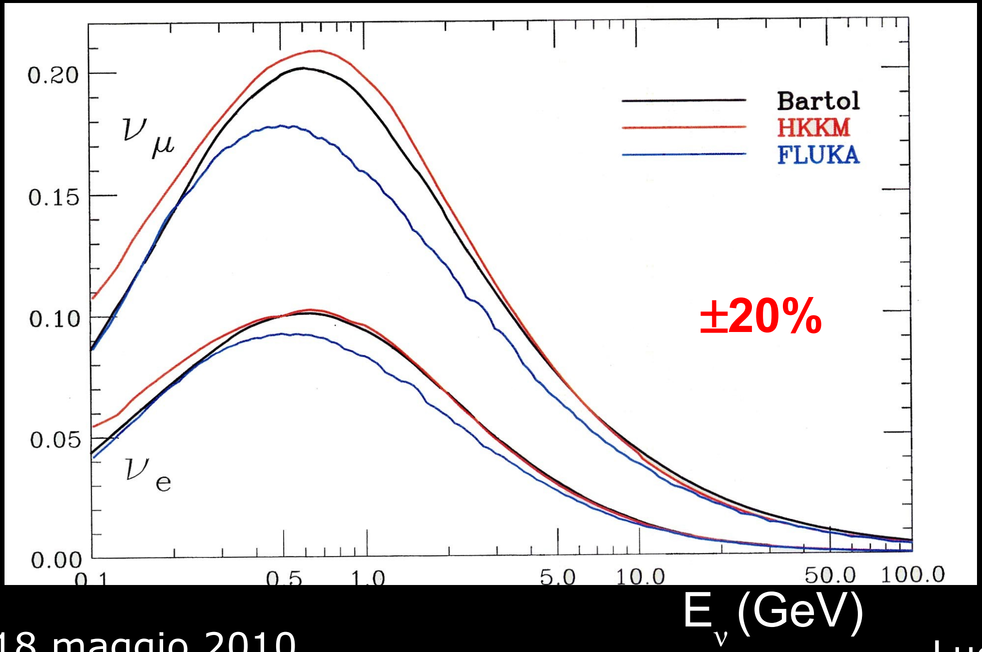
Pomeriggi Tematici
Roma, 12 maggio 2011

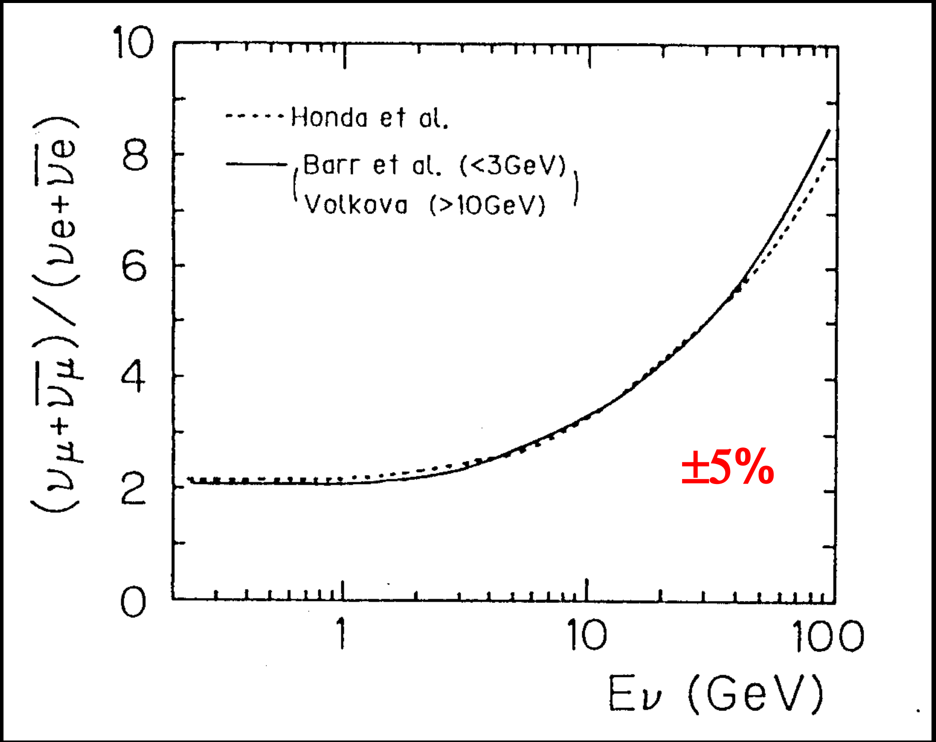
Atmospheric neutrinos



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\quad \hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- \nu_\mu \bar{\nu}_e$$

$$R(E) = \frac{(\nu_\mu + \bar{\nu}_\mu)}{(\nu_e + \bar{\nu}_e)} \xrightarrow[E <\approx 1\text{GeV}]{} 2$$





ν_μ/ν_e Ratio (of Ratios)

Kamioka mines (3000t)

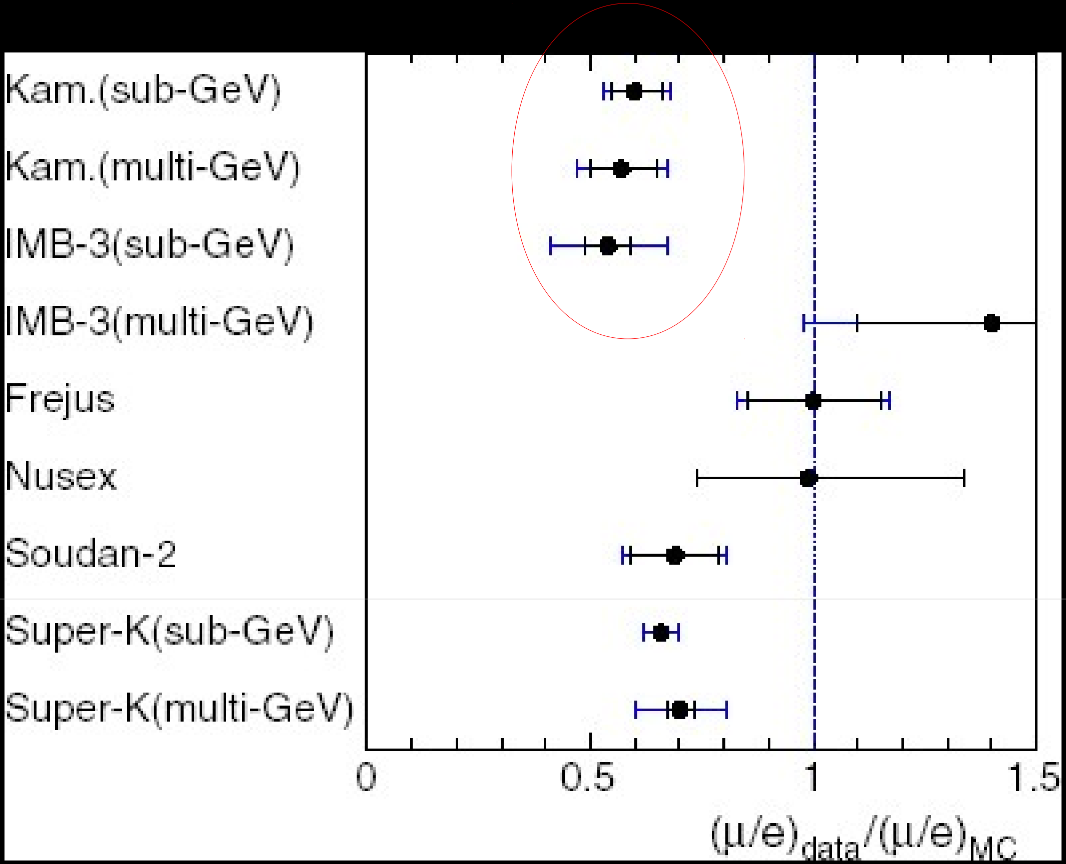
Morton salt mines (8000t)

Frejus (900t)

Mont Blanc (150t)

Soudan mines(960t)

Kamioka mines (50,000t)

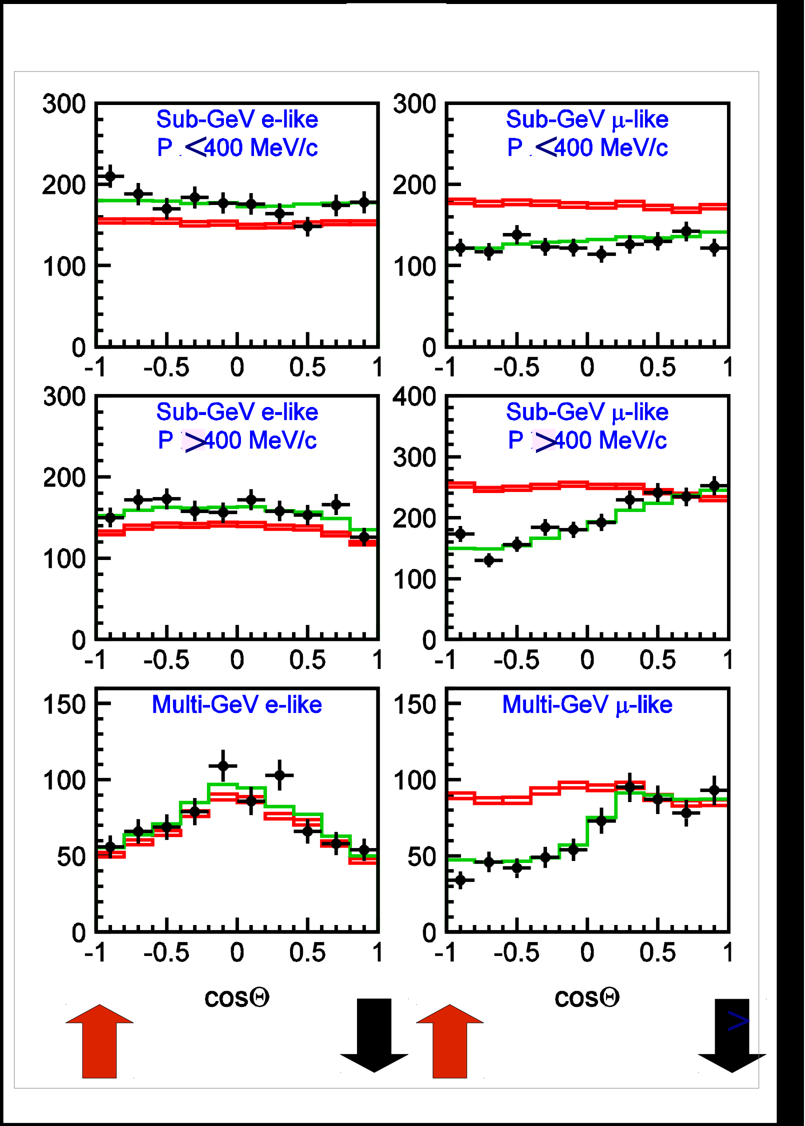


Prime (contrastanti) indicazioni

Prima indicazione del deficit di $\nu\mu$ dal rapporto $\nu\mu/\nu e$ (Kamiokande)

Indicazioni contrastanti negli anni '80

SK zenit angle dependence (1998)



“The data are consistent with two-flavor $\nu_{\mu} \rightarrow \nu_{\tau}$ oscillations with $\sin 2\theta > 0.82$ and $5 \cdot 10^{-4} < \Delta m^2 < 6 \cdot 10^{-3}$ eV^2 at the 90% confidence level.”

Phys.Rev.Lett. 81 (1998) 1562
(3500+ citations)

Neutrino Physics and oscillation

1930	ν existence postulated	Pauli
1934	ν interaction theory and name	Fermi
1938	Solar ν flux calculation	Bethe
1946	Idea of ν chlorine detector	Pontecorvo
1956	ν interactions observed	Reines & Cowan
1957	Idea of ν oscillation	Pontecorvo
1958	Left-handed ν	Goldhaber
1962	2 ν's, ν_μ ,ν_e	Lederman, Schwartz & Steinberger
1968	Solar neutrino deficit	Davis
1973	ν NC interactions observed	Gargamelle
1975	τ and the third ν	Perl
1986	Solar deficit again, atmospheric(?)	Kamiokande
1987	ν from SN1987A	Kamiokande, IMB
1989	3 light neutrino families	LEP Collaborations
1991	Solar deficit again	Gallex, SAGE
1998	Atmospheric ν oscillation	Super-Kamiokande
2002	Solar ν oscillation confirmed	SNO, KamLand
2005	Atmospheric ν oscillation confirmed	K2K

CHARM

(1976-1983)

CHARM2

(1983-93)

CHORUS

(1991-1998)

K2K

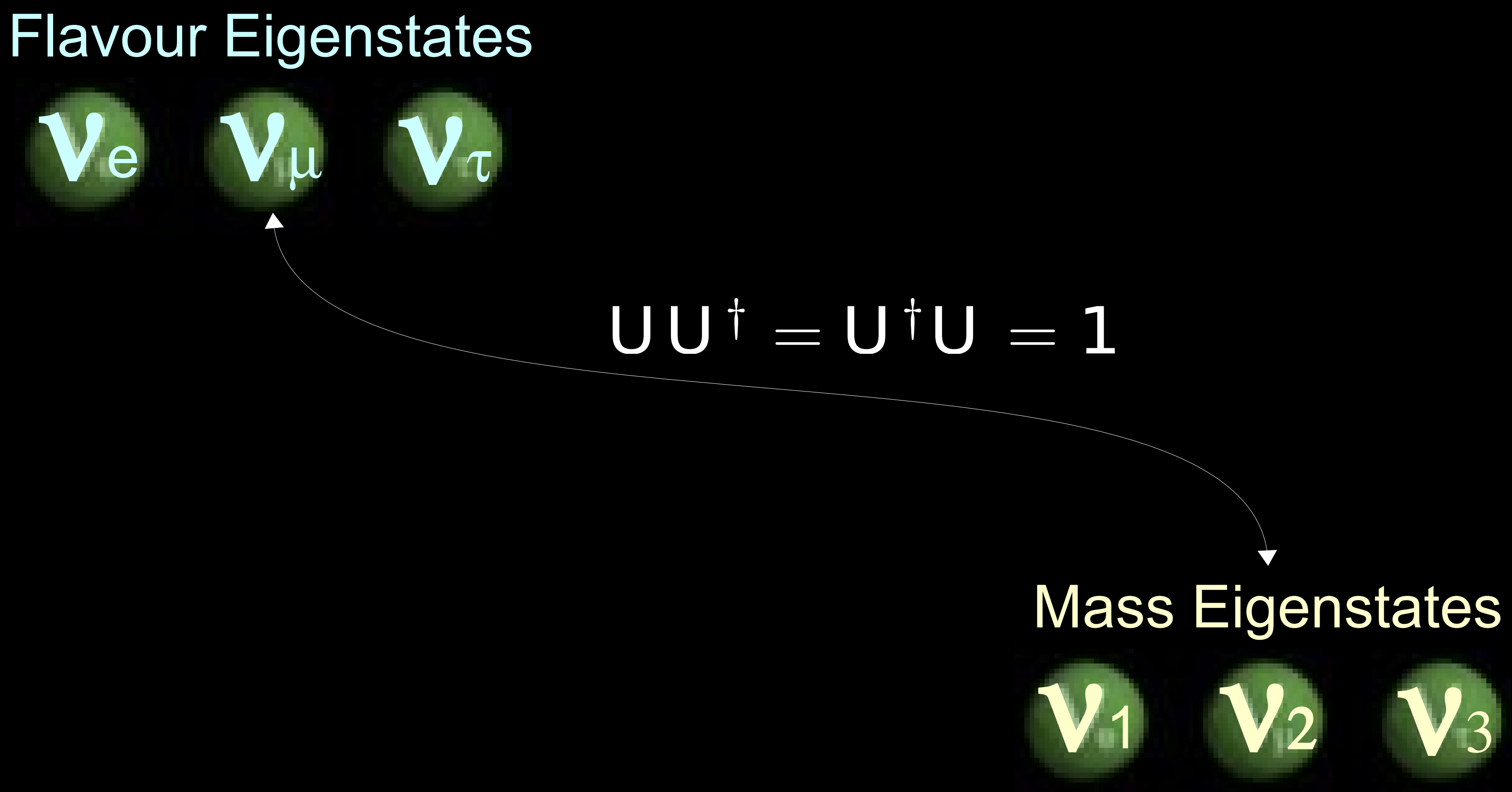
(1999-2004)

OPERA

(2007)

T2K

(2010)



Flavour Eigenstates

ν_e ν_μ ν_τ

$$\mathrm{U}\,\mathrm{U}^\dagger = \mathrm{U}^\dagger\mathrm{U} = 1$$

Mass Eigenstates

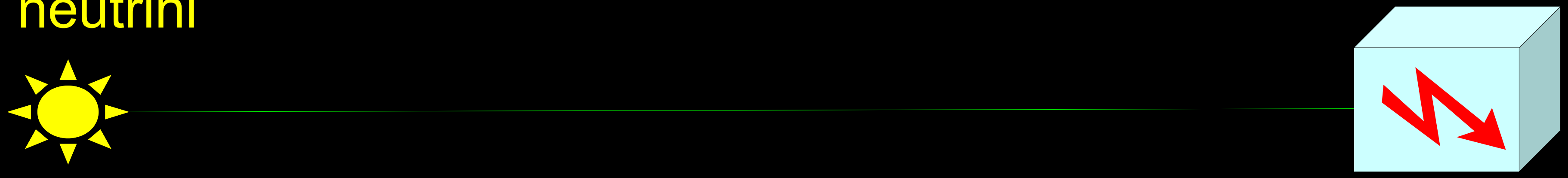
ν_1 ν_2 ν_3

$$|\,\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} \mathrm{U}_{\alpha i}\,|\,\nu_\alpha\rangle$$

sorgente di neutrini

propagazione

rivelatore



autostato α
di sapore definito

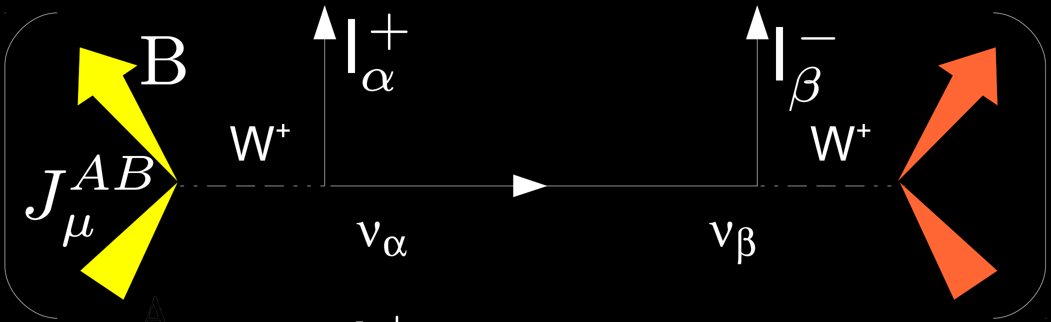
sovrapposizione di autostati di massa
→fasi differenti →interferenza

autostato β
di sapore definito

$$\pi^+ \rightarrow \mu^+ \nu$$

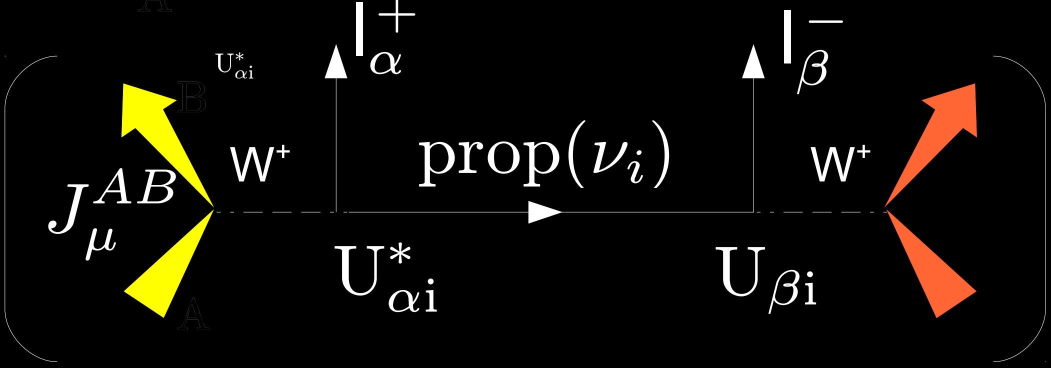
$$\nu_\tau N \rightarrow \tau^- N$$

$$\mathrm{Amp}$$



$$=$$

$$= \sum_i \mathrm{Amp}$$



Probabilità di oscillazione

$$\mathcal{P}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta}(L,E) = \sum_k |\mathrm{U}_{\alpha\mathrm{k}}|^2 |\mathrm{U}_{\beta\mathrm{k}}|^2 + 2\Re \sum_{k>j} \mathrm{W}_{kj}^{\alpha\beta\,(*)} e^{-i\frac{\Delta m^2_{kj}}{2E}}$$

$$\mathrm{W}_{kj}^{\alpha\beta} = \mathrm{U}^*_{\alpha\mathrm{k}} \mathrm{U}_{\beta\mathrm{k}} \mathrm{U}_{\alpha\mathrm{j}} \mathrm{U}^*_{\beta\mathrm{j}}$$

$$\begin{aligned}\mathcal{P}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta}(L,E) = \sum_k |\mathbf{U}_{\alpha k}|^2 |\mathbf{U}_{\beta k}|^2 + 2\sum_{k>j} \Re\{\mathbf{W}_{kj}^{\alpha\beta}\} \cos\left(\frac{\Delta m^2_{kj} L}{2E}\right) \\ \overset{+}{(-)} 2\sum_{k>j} \Im\{\mathbf{W}_{kj}^{\alpha\beta}\} \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)\end{aligned}$$

$$\begin{aligned}\mathcal{P}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta}(L,E) = \delta_{\alpha\beta} + 4\sum_{k>j} \Re\{\mathbf{W}_{kj}^{\alpha\beta}\} \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right) \\ \overset{+}{(-)} 2\sum_{k>j} \Im\{\mathbf{W}_{kj}^{\alpha\beta}\} \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)\end{aligned}$$

Probabilità per due famiglie

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \mathbf{U} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \mathbf{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad \Delta m^2 = m_2^2 - m_1^2$$

$$\mathcal{P}_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

Importante storicamente e nella pratica degli esperimenti di oscillazione
Approssimazione delle formule generali valida in molti casi

Formule approssimate

Esperimenti a distanze terrestri, con $\Delta m_{12} L/E \ll 1$, sono descritti solo da 3 parametri: θ_{23}, Δm_{12}, θ_{13} e da formule simili a quelle per 2 famiglie:

$$P(\nu_e \rightarrow \nu_\mu) \cong \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{23} = \sin^2 2\theta_{\mu e} \sin^2 \Delta_{23}$$

$$P(\nu_\mu \rightarrow \nu_\tau) \cong \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta_{23} = \sin^2 2\theta_{\mu\tau} \sin^2 \Delta_{23}$$

$$P(\nu_e \rightarrow \nu_\tau) \cong \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{23} = \sin^2 2\theta_{e\tau} \sin^2 \Delta_{23}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - (\sin^2 2\theta_{\mu\tau} + \sin^2 2\theta_{\mu e}) \sin^2 \Delta_{23}$$

$$P(\nu_e \rightarrow \nu_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{23}$$

Angoli di mixing efficaci:

$$\sin^2 2\theta_{\mu e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \cong 0.5 \sin^2 2\theta_{13}$$

$$\sin^2 2\theta_{\mu\tau} = \cos^4\theta_{13} \sin^2 2\theta_{23} \cong \sin^2 2\theta_{23}$$

$$\sin^2 2\theta_{e\tau} = \cos^2\theta_{23} \sin^2 2\theta_{13} \cong 0.5 \sin^2 2\theta_{13}$$

Parametrizzazione della matrice di mixing

$$\mathrm{U} = \mathsf{R}_{23}\mathsf{R}^{C}_{13}\mathsf{R}_{12}\mathsf{D}(\phi_2,\phi_3)$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}\begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}s_{13} & 0 & c_{13} \end{pmatrix}\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

atmosferici “terra incognita” solari ΔL=2

Still unmeasured:
CHOOZ limit:
$\sin^2(2\theta_{13})<0.15$ (90%CL)

SK, K2K, MINOS
$\sin^2(2\theta_{23})>0.92$ (90%CL)
$\Delta m^2_{23}=2.43\pm0.13 \times 10^{-3}$ eV^2

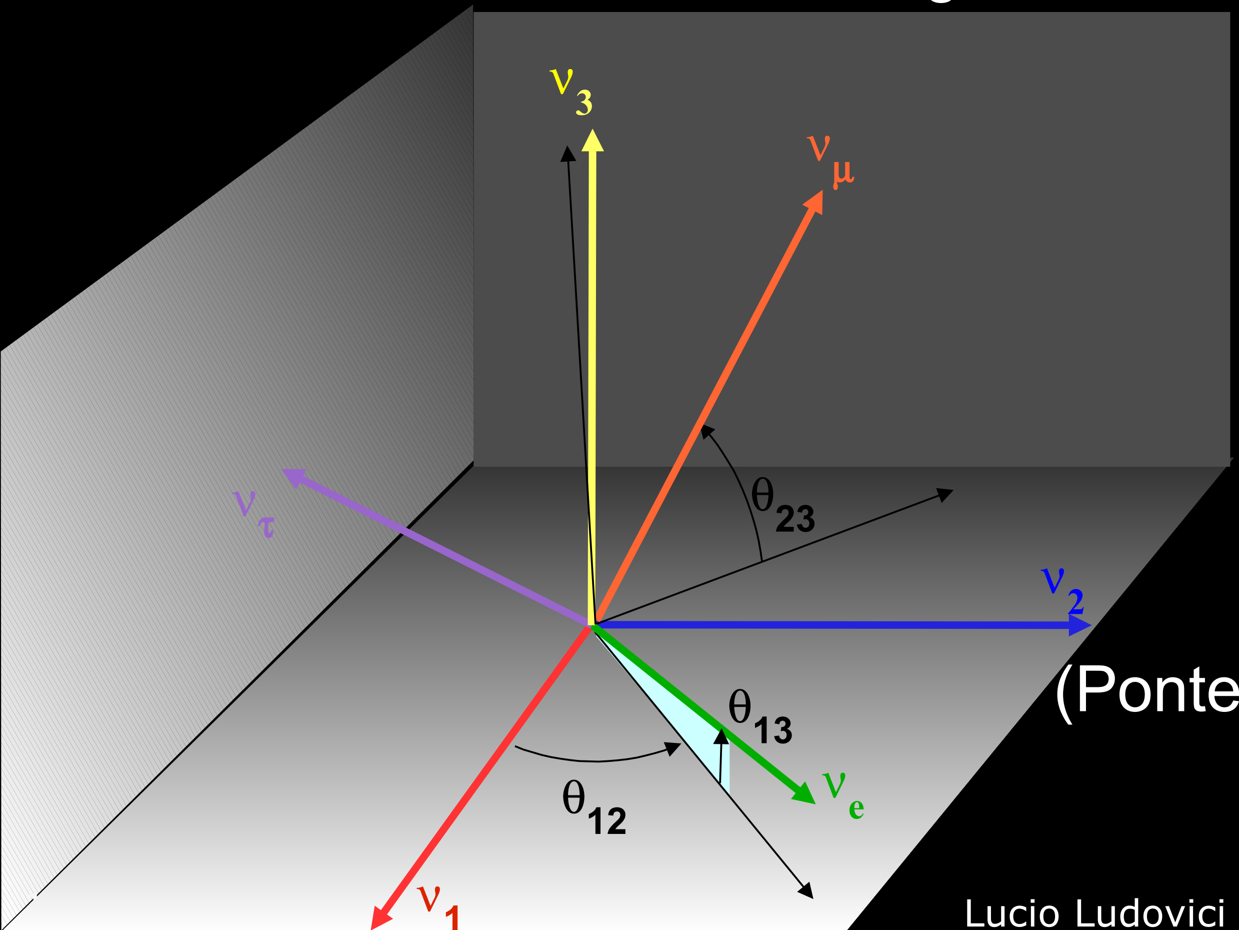
KAMLAND, SNO
$\sin^2(2\theta_{12})=0.87\pm0.03$
$\Delta m^2_{12}=7.59\pm0.20 \times 10^{-5}$ eV^2

Parametrizzazione della matrice di mixing

$$U = R_{23} R^{C}_{13} R_{12} D(\phi_2, \phi_3)$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i\phi_3} \end{pmatrix}$$

atmosferici “terra incognita” solari $\Delta L=2$



3 neutrini:

θ_{12} θ_{23} θ_{13} δ

(+ 2Δm^2 indipendenti)

Matrice PMNS
(Pontecorvo-Maki-Nakagawa-Sakata)

Violazione di CP leptonica

$$\mathcal{A}^{CP}_{\alpha\beta} = \frac{\mathcal{P}_{\nu_\alpha \to \nu_\beta} - \mathcal{P}_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}}{\mathcal{P}_{\nu_\alpha \to \nu_\beta} + \mathcal{P}_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}}$$

$$\mathcal{A}^{CP}_{\alpha\beta} = \frac{2\sum_{k>j} \Im\{\mathrm{W}^{\alpha\beta}_{kj}\} \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)}{\delta_{\alpha\beta} - 4\sum_{k>j} \Re\{\mathrm{W}^{\alpha\beta}_{kj}\} \sin^2\left(\frac{\Delta m^2_{kj} L}{4E}\right)}$$

Invariante di Jarskolg $J_{\alpha\beta;kj} = \Im\{\mathrm{U}^*_{\alpha\mathrm{k}} \mathrm{U}_{\beta\mathrm{k}} \mathrm{U}_{\alpha\mathrm{j}} \mathrm{U}^*_{\beta\mathrm{j}}\} = \pm\mathbf{J}$

Analogo all'area dei triangoli unitari in CKM: $\mathbf{J}^{\mathrm{CKM}} \approx 3 \cdot 10^{-5}$

$$\mathbf{J} = \frac{1}{4} \sin 2\theta_{12} \sin 2\theta_{23} \cos^2\theta_{13} \sin\theta_{13} \sin\delta \approx 0.23 \sin\theta_{13} \sin\delta$$

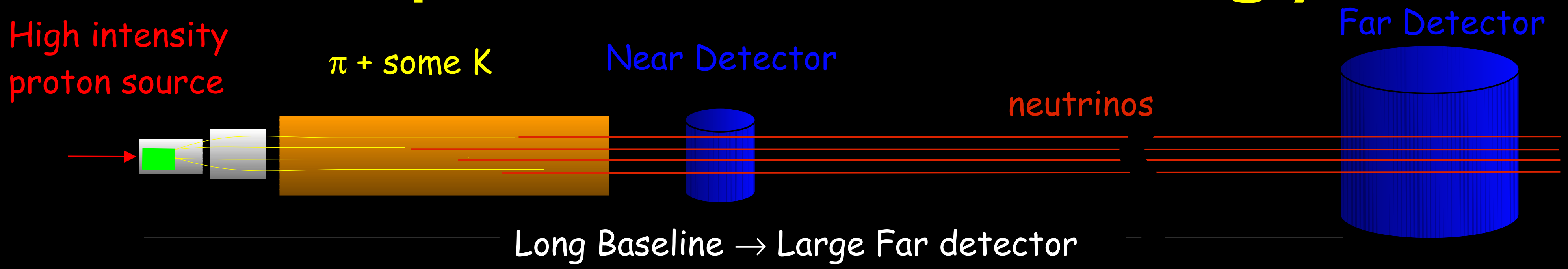
La possibilità di misurare $\cancel{\text{CP}}$L è legata al valore di θ_{13}

Conferma agli acceleratori delle oscillazioni degli atmosferici

Δm^2 L/E

Long Baseline

Experimental Strategy



High intensity proton source

π + some K

Near Detector

neutrinos

Far Detector

Long Baseline → Large Far detector

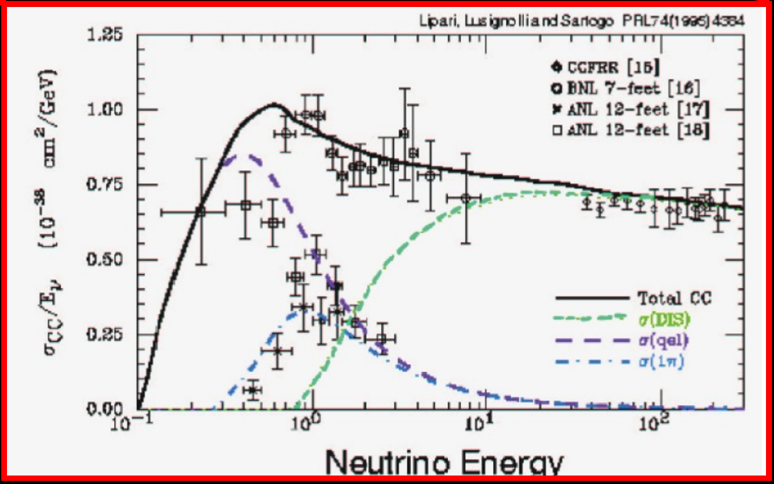
$\Phi_\nu(E)$

Event rate

Event rate

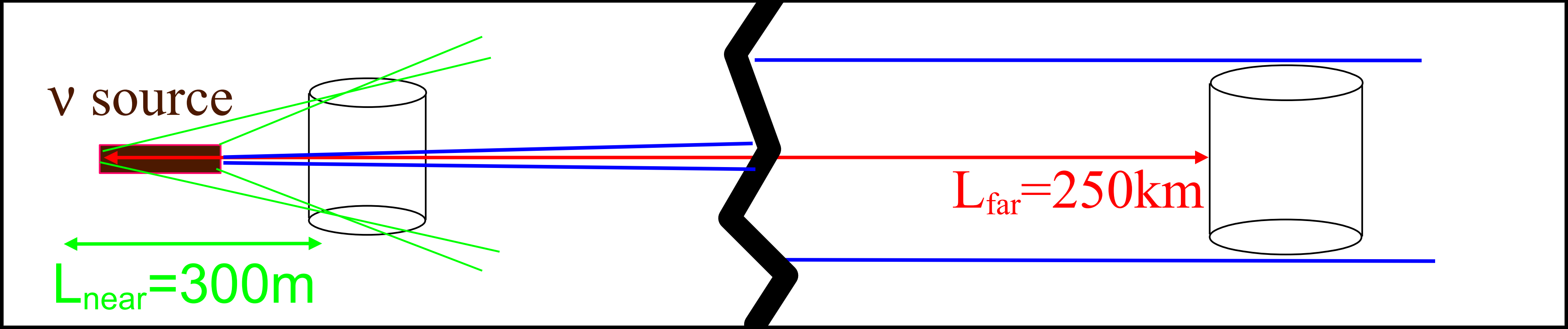
$$\sigma(E) \times \Phi_\nu^{near}(E) \Leftrightarrow \sigma(E) \times \Phi_\nu^{far}(E)$$

Beam monitoring
Beam simulation
Hadroproduction experiments


Lipari, Lusignolli and Sartogo PRL74(1995)4384

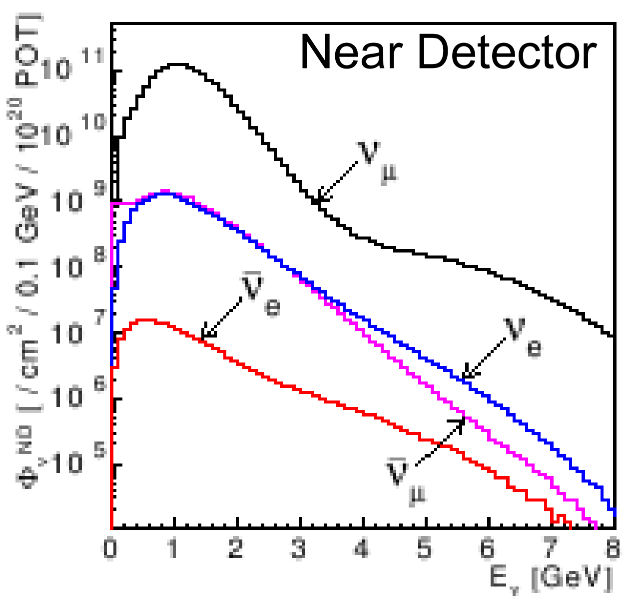
Near Detector cross-section studies
Old experiments: ...
Current experiments: MiniBooNE SciBooNE
Future experiments: MINERvA,...

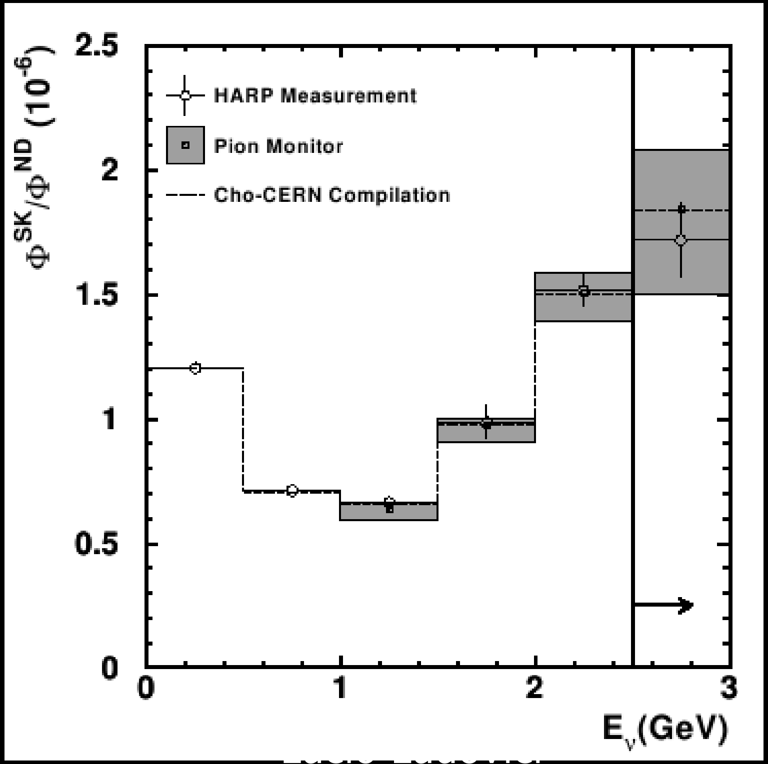
Far/Near Ratio

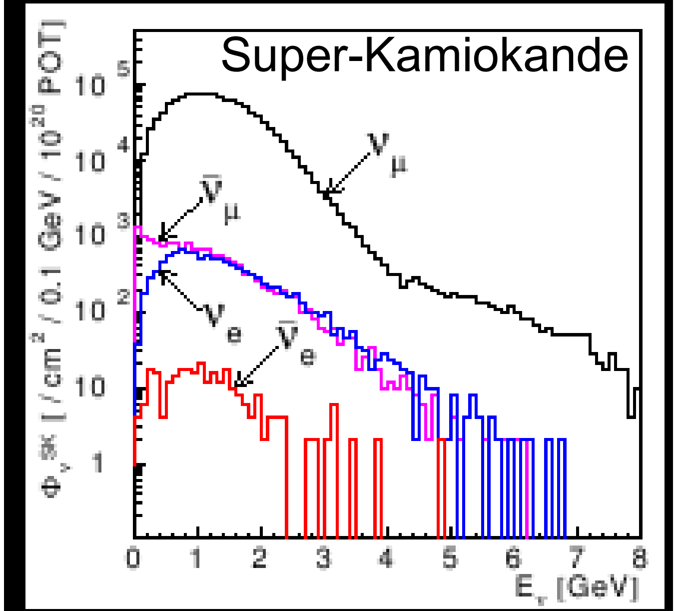


Extended neutrino source
Near vs Far solid angle

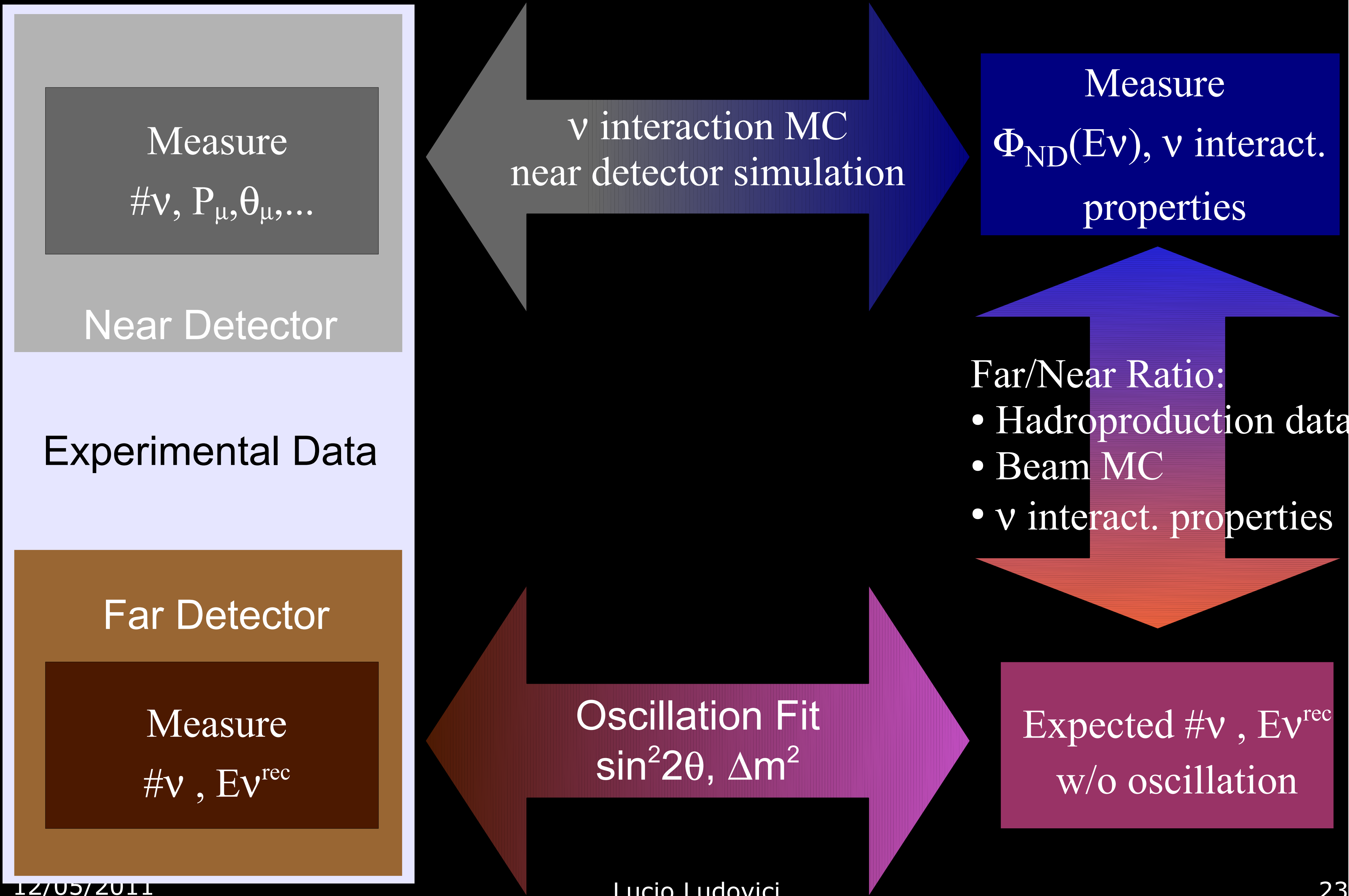
$R_{N/F}(E_\nu) \neq (L_{near}/L_{far})^2 \sim 10^{-6}$







Analysis Strategy



Measure

#ν, P_μ,θ_μ,...

Near Detector

Experimental Data

Far Detector

Measure

#ν , $E\nu^{rec}$

ν interaction MC
near detector simulation

Measure

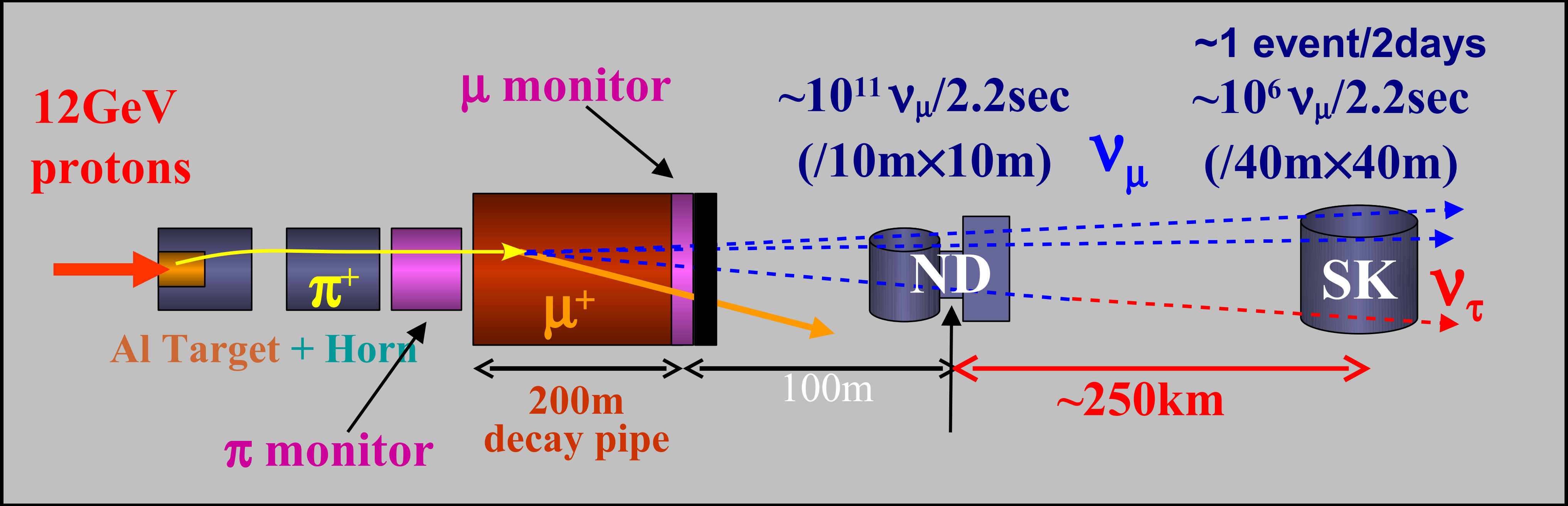
$\Phi_{ND}(E\nu)$, ν interact. properties

Far/Near Ratio:
- Hadroproduction data
- Beam MC
- ν interact. properties

Oscillation Fit
$\sin^2 2\theta$, Δm^2

Expected #ν , $E\nu^{rec}$
w/o oscillation

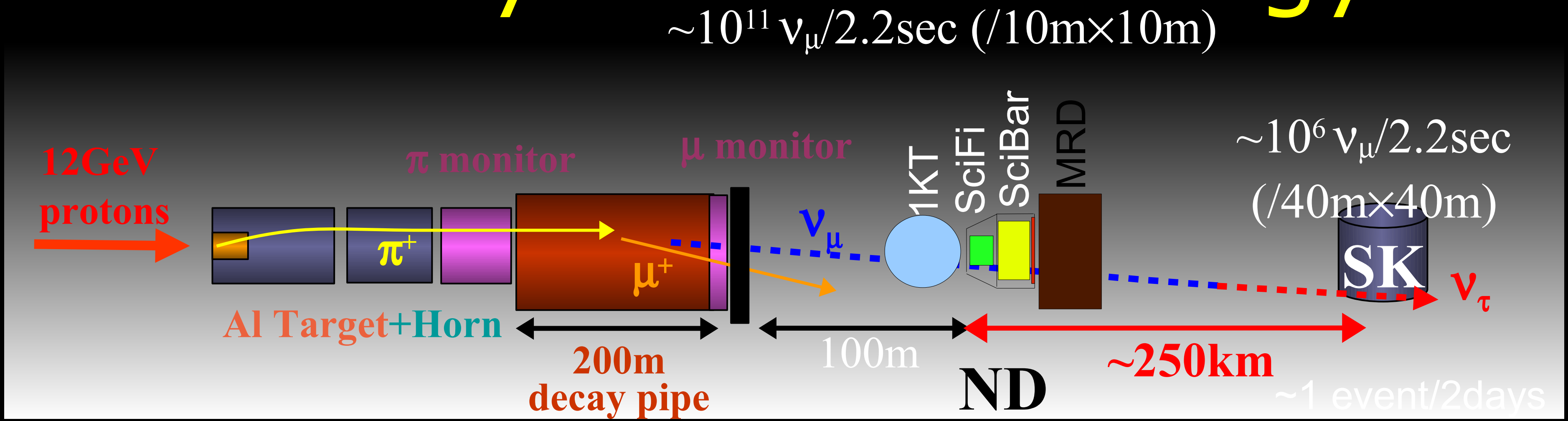
K2K Conceptual Layout



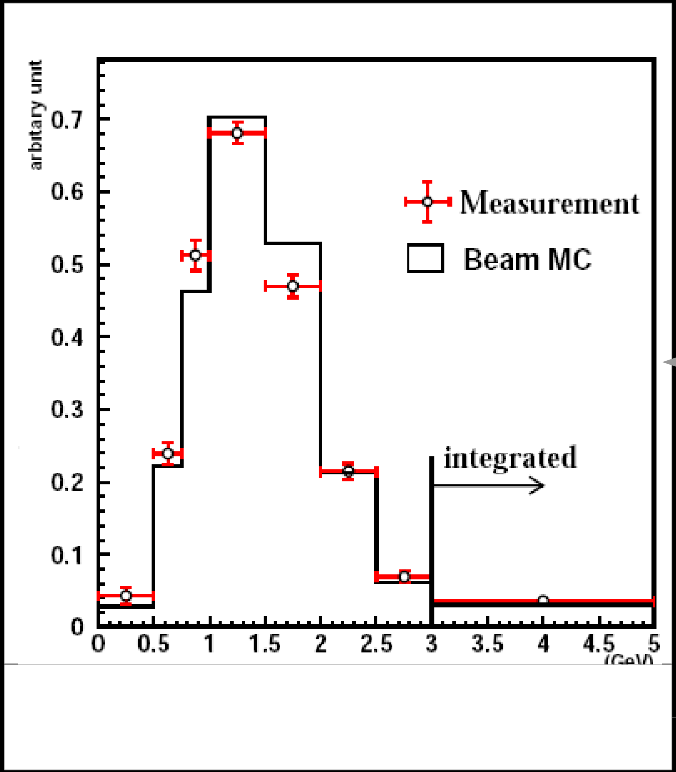
Signature of neutrino oscillation

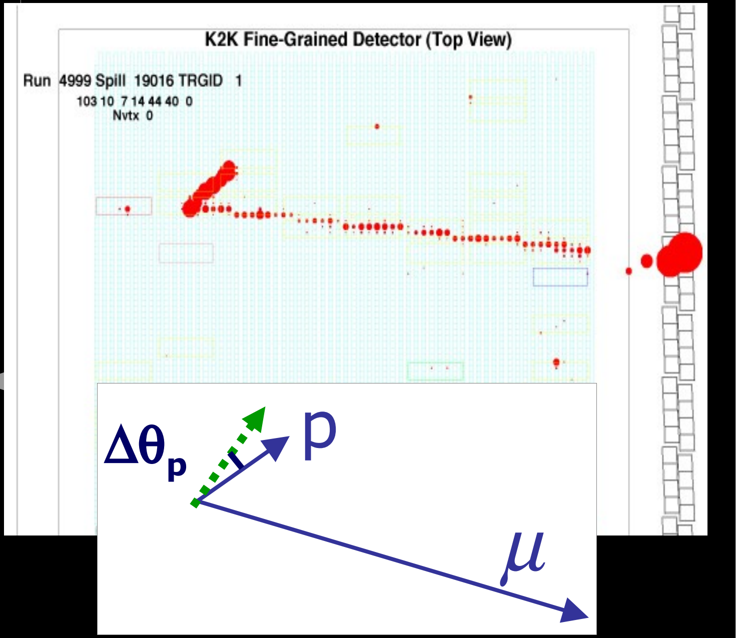
1. Reduction of ν_μ events
2. Distortion of ν_μ energy spectrum

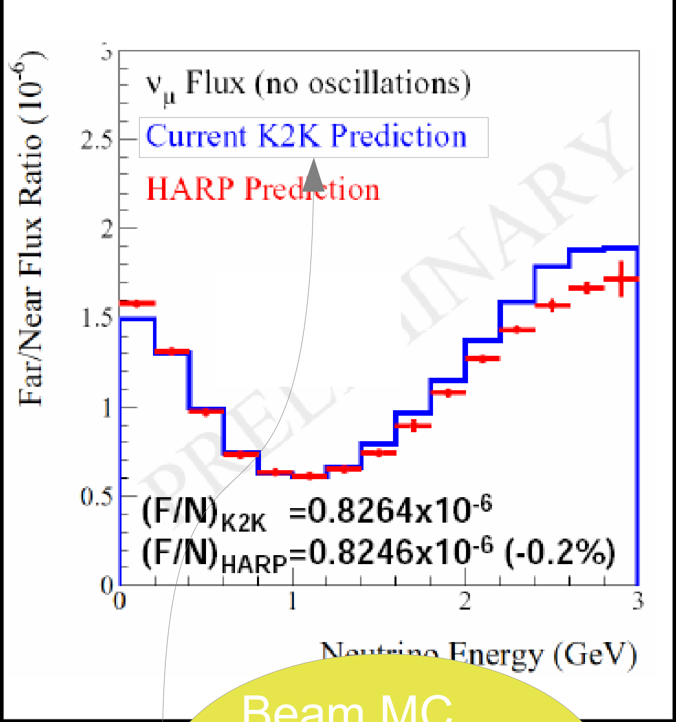
K2K Layout and Strategy



Combined (1KT,SciFi,SciBar) fit of Pμ,θμ distributions



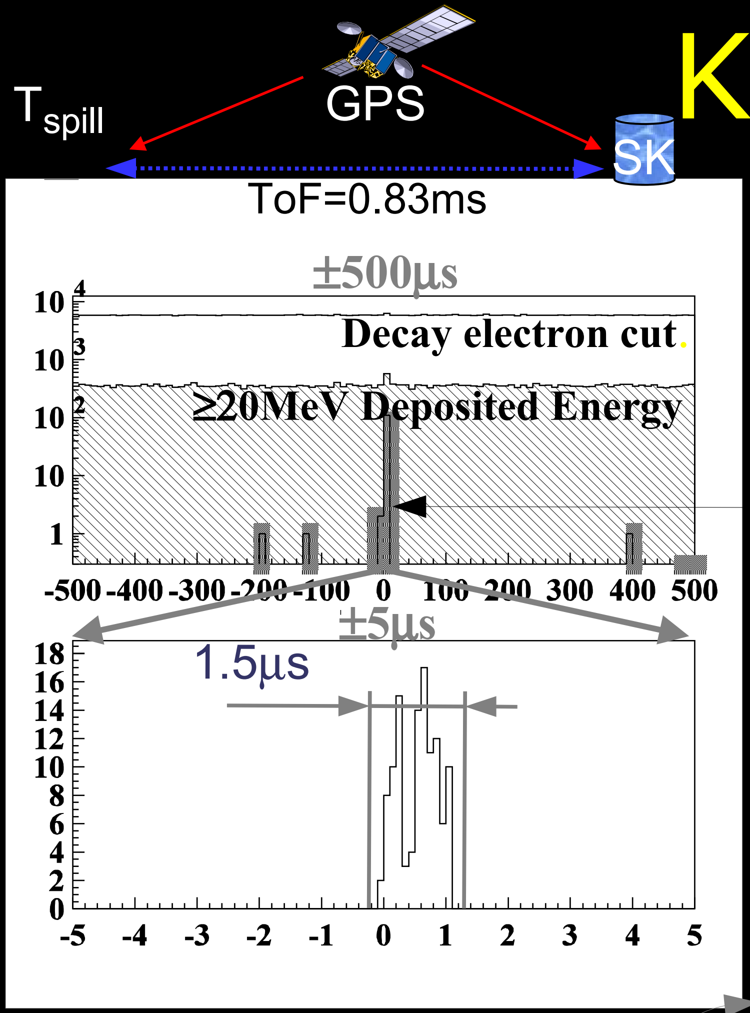




Beam MC
PIMON
Hadronic models
Hadropr. exp.

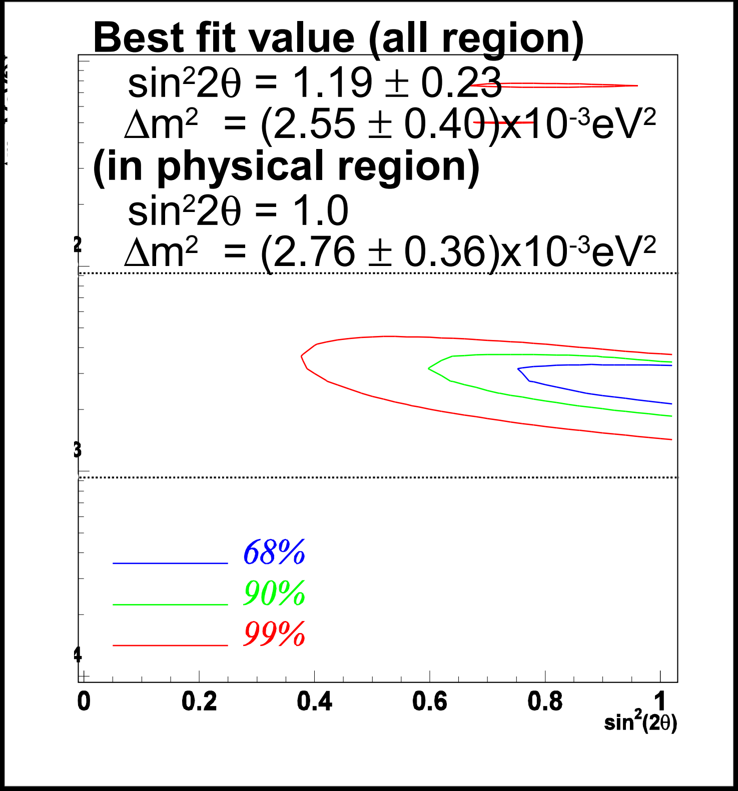
Far detector flux

K2K Result



No Activity in Outer Detector
Event Vertex in Fiducial Volume
More than 30MeV Deposited Energy

No Oscillation
0.003%
4.2σ



Best fit value (all region)
$\sin^2 2\theta = 1.19 \pm 0.23$
$\Delta m^2 = (2.55 \pm 0.40) \times 10^{-3} eV^2$
(in physical region)
$\sin^2 2\theta = 1.0$
$\Delta m^2 = (2.76 \pm 0.36) \times 10^{-3} eV^2$

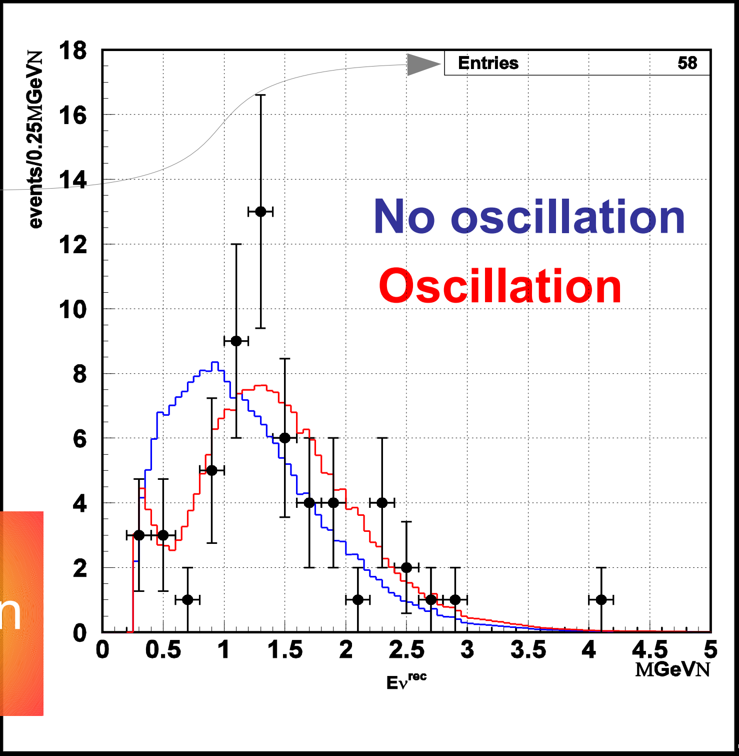
$$E_\nu^{rec} = \frac{(m_N - V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$

K2K	DATA	MC
FC 22.5kt	112	155.9
1-Ring	67	99.0
1-R μ-like	58	90.8
1-R e-like	9	8.2
Multi Ring	45	56.8

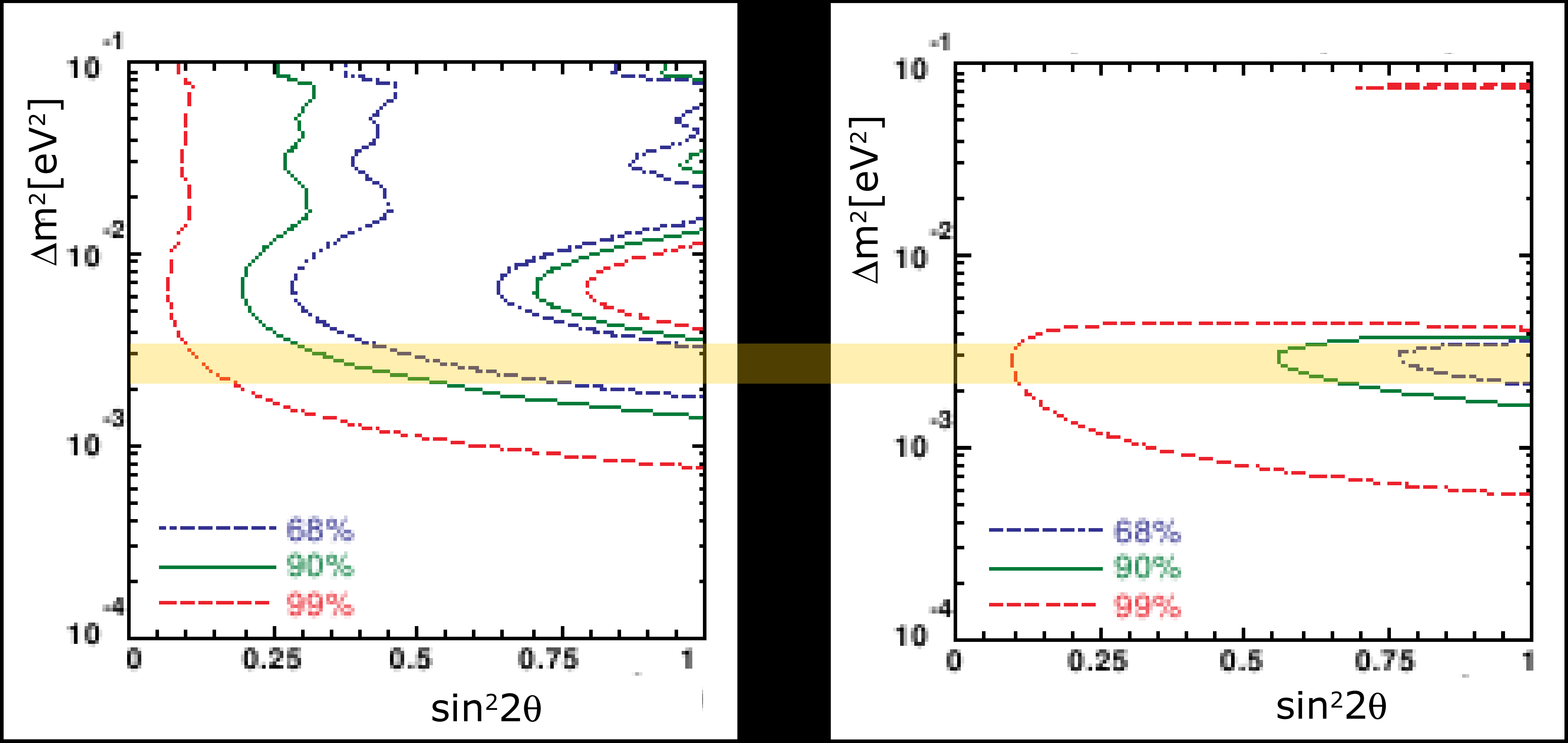
+11.5 (7.4%)
-10.2 (6.5%)

Absolute Deficit
3.1σ

Shape Distortion
2.8σ



Disappearance & Shape

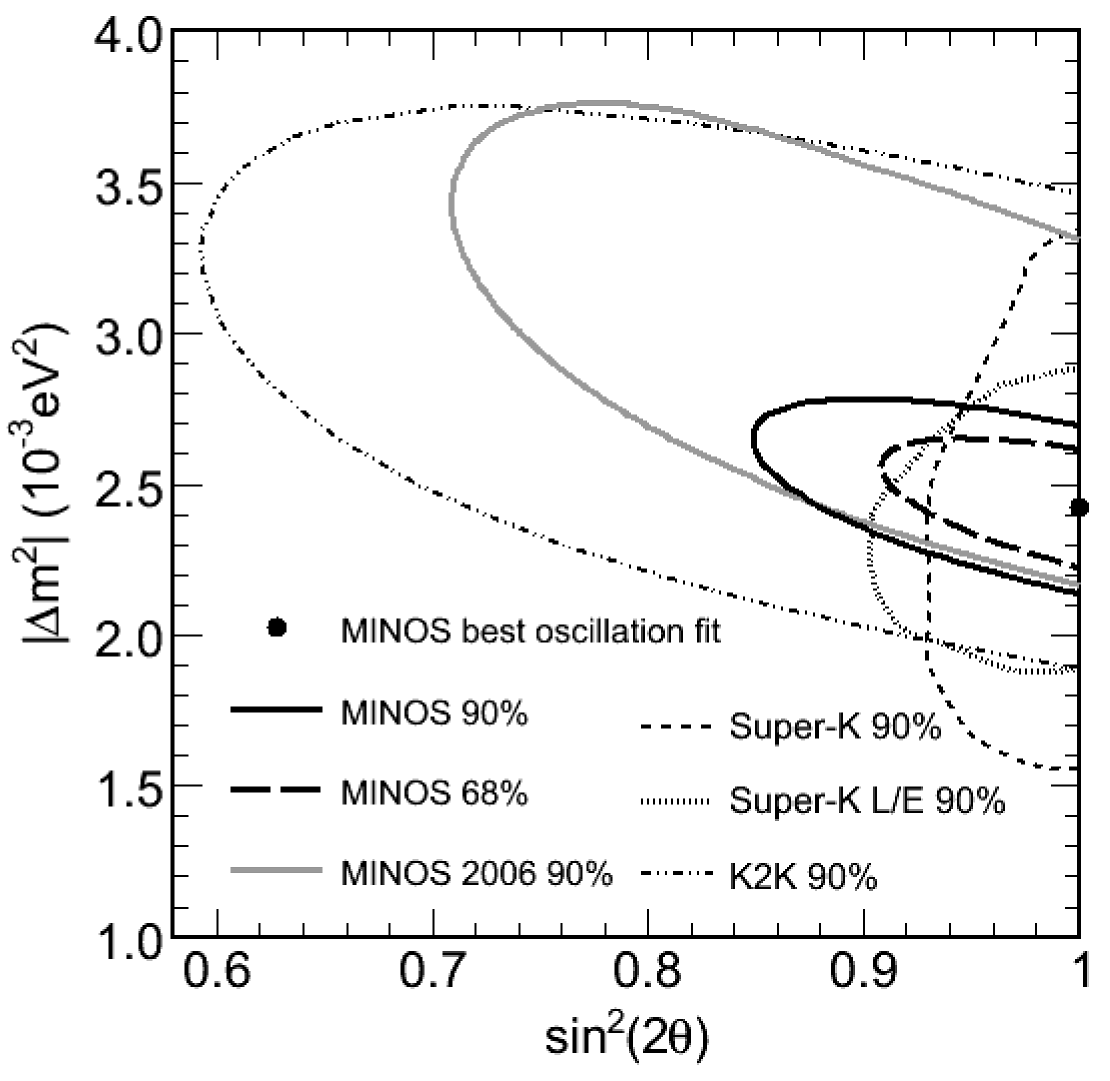


ABSOLUTE DEFICIT

ENERGY SPECTRUM DISTORTION

Allowed regions from ν_μ disappearance and distortion of E_ν spectrum are consistents

Minos (Fermilab→Soudan)



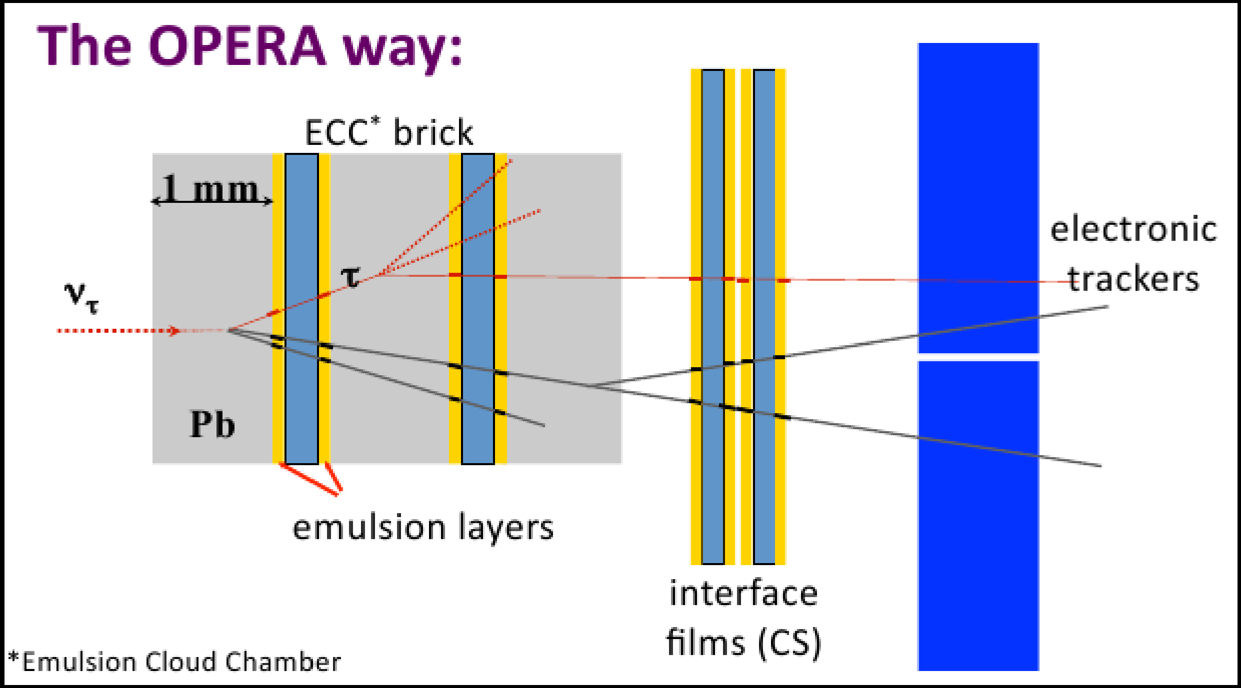
OPERA: $\nu_\mu \rightarrow \nu_\tau$ appearance

$$N_\tau \propto M_D \int \Phi_{\nu_\mu}(E) P_{\nu_\mu \rightarrow \nu_\tau}(E, \Delta m^2) \sigma_{\nu_\tau}(E) \epsilon(E) dE$$

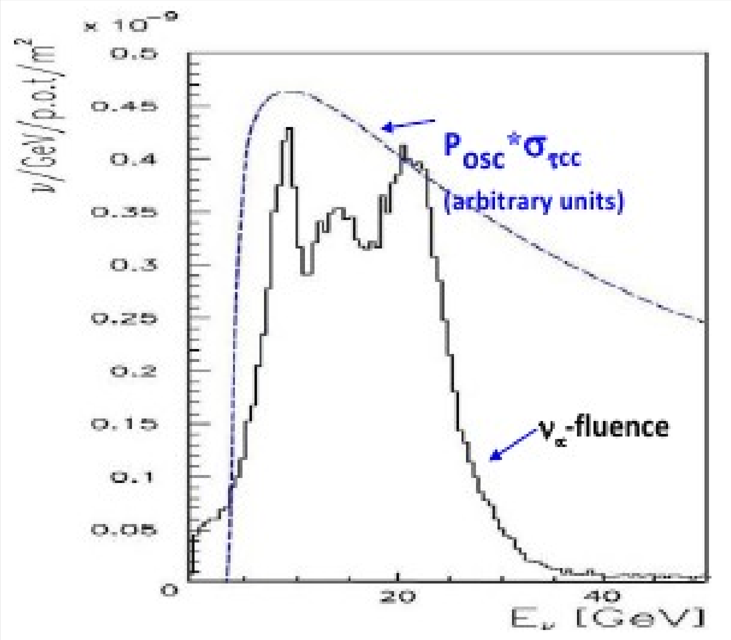
Small interaction probability: large detector mass ≈1kT

Small signal/background: high resolution ≈1μm

Cross-section threshold: large energy ≈20GeV



*Emulsion Cloud Chamber



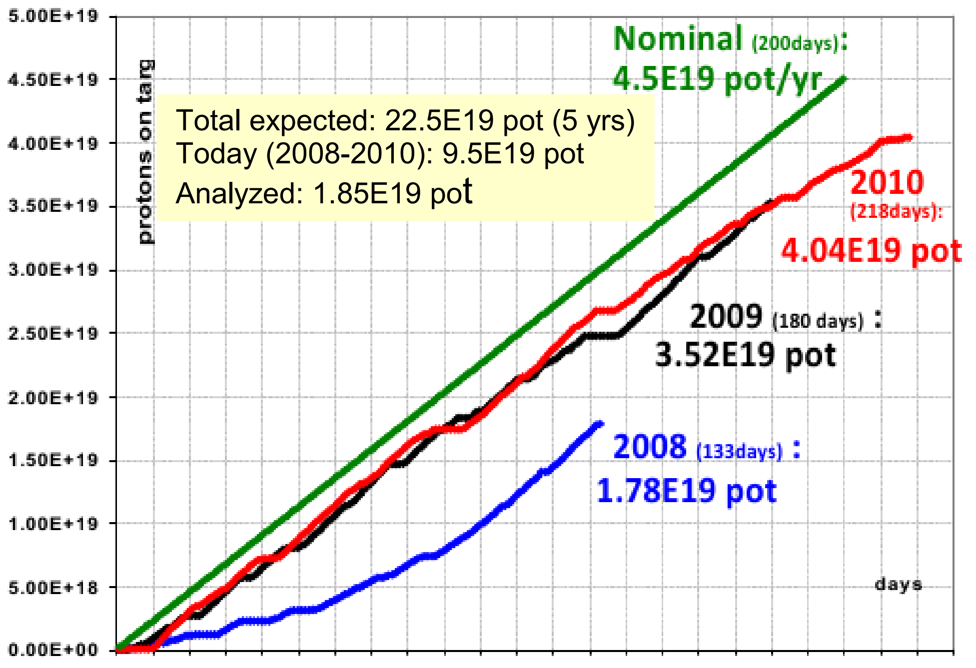
Tau lepton

Impact Parameter cτ ~87μm

Track length cτγ ~1mm

The CNGS beam

<En>	17.7 GeV
L	730 km
$(N\nu_e+N\bar{\nu}_e)/N\nu_\mu$	0.87%
$N\nu_\mu/N\bar{\nu}_\mu$	2.1%
Prompt ν_τ	Negligible



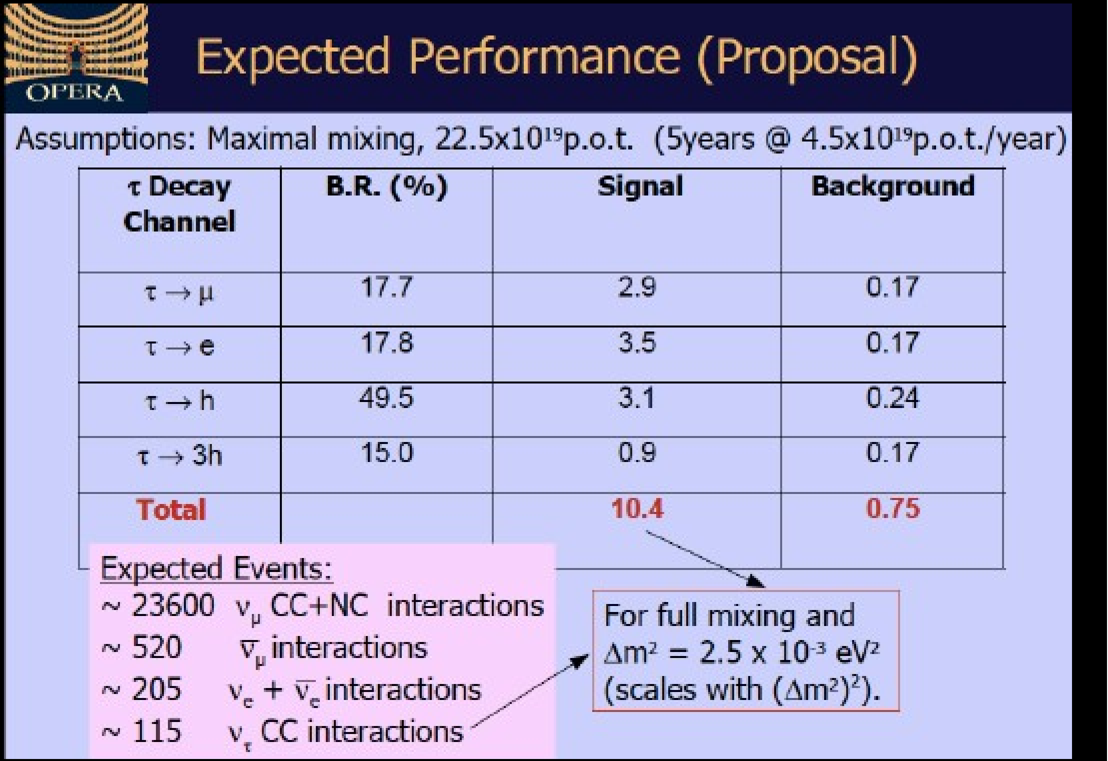
Nominal (200days): 4.5E19 pot/yr

Total expected: 22.5E19 pot (5 yrs)
Today (2008-2010): 9.5E19 pot
Analyzed: 1.85E19 pot

2010 (218days): 4.04E19 pot

2009 (180 days) : 3.52E19 pot

2008 (133days) : 1.78E19 pot



Expected Performance (Proposal)

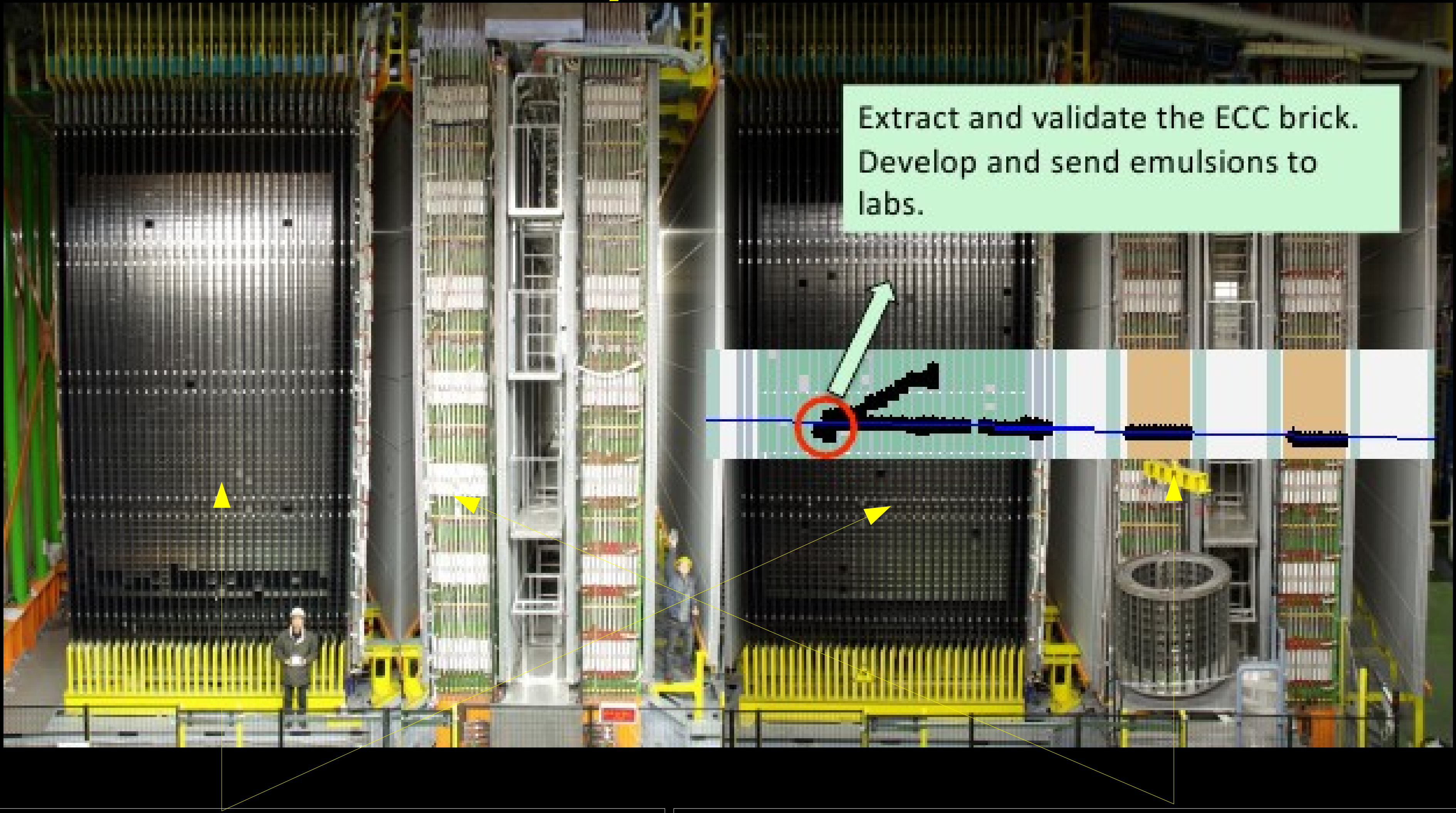
Assumptions: Maximal mixing, 22.5×10^{19}p.o.t. (5years @ 4.5×10^{19}p.o.t./year)

τ Decay Channel	B.R. (%)	Signal	Background
$\tau\to\mu$	17.7	2.9	0.17
$\tau\to e$	17.8	3.5	0.17
$\tau\to h$	49.5	3.1	0.24
$\tau\to 3h$	15.0	0.9	0.17
Total		10.4	0.75

Expected Events:
~ 23600 ν_μ CC+NC interactions
~ 520 $\bar{\nu}_\mu$ interactions
~ 205 $\nu_e + \bar{\nu}_e$ interactions
~ 115 ν_τ CC interactions

For full mixing and $\Delta m^2 = 2.5\times10^{-3}$ eV^2 (scales with $(\Delta m^2)^2$).

OPERA Hybrid Detector



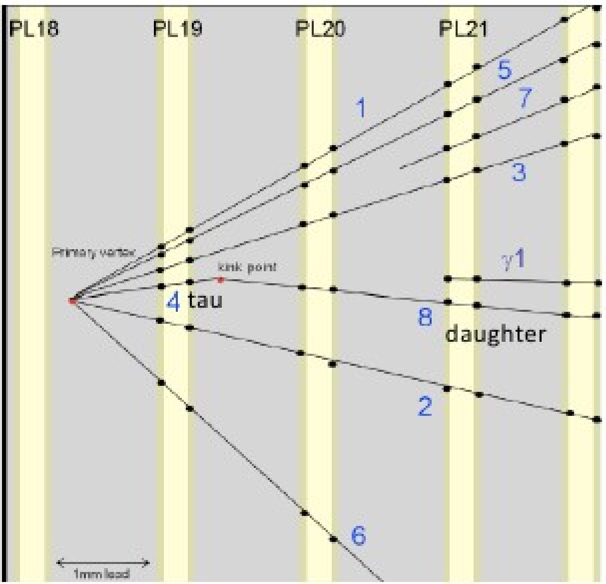
Extract and validate the ECC brick. Develop and send emulsions to labs.

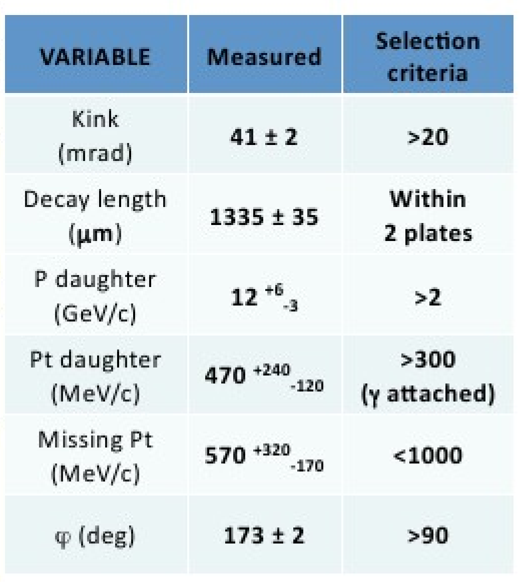
TARGETS
Target tracker (scintillators)
Lead/Emulsion Bricks (75,000x2)
Target mass~1.25 kt

MUON SPECTROMETERS
Iron + RPCs
Precision Tracker: 6 drift tubes planes

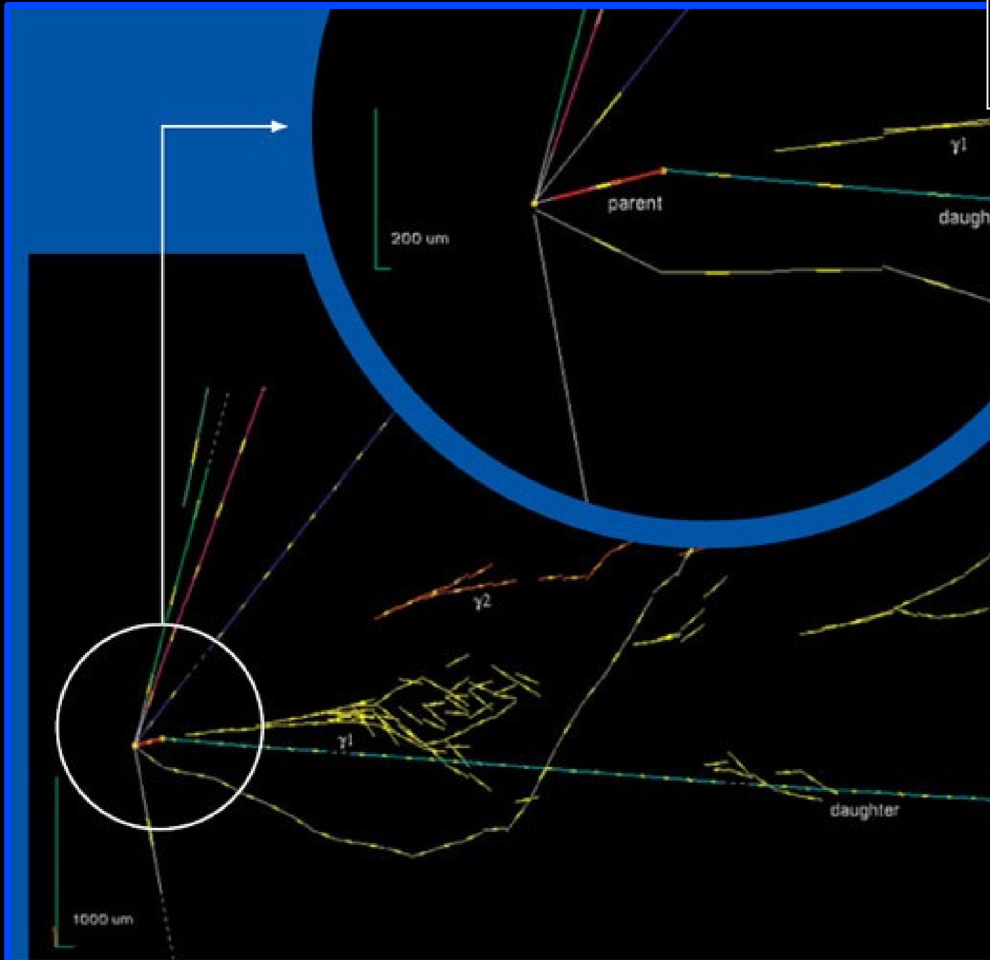
Phys. Lett. B691 (2010) 138

Event number 9234119599, 22 August 2009, 19:27 (UTC)





VARIABLE	Measured	Selection criteria
Kink (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	Within 2 plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt daughter (MeV/c)	470^{+240}_{-120}	>300 (γ attached)
Missing Pt (MeV/c)	570^{+320}_{-170}	<1000
φ (deg)	173 ± 2	>90



Probability of backg. fluctuation (only 1prong)

4.5%

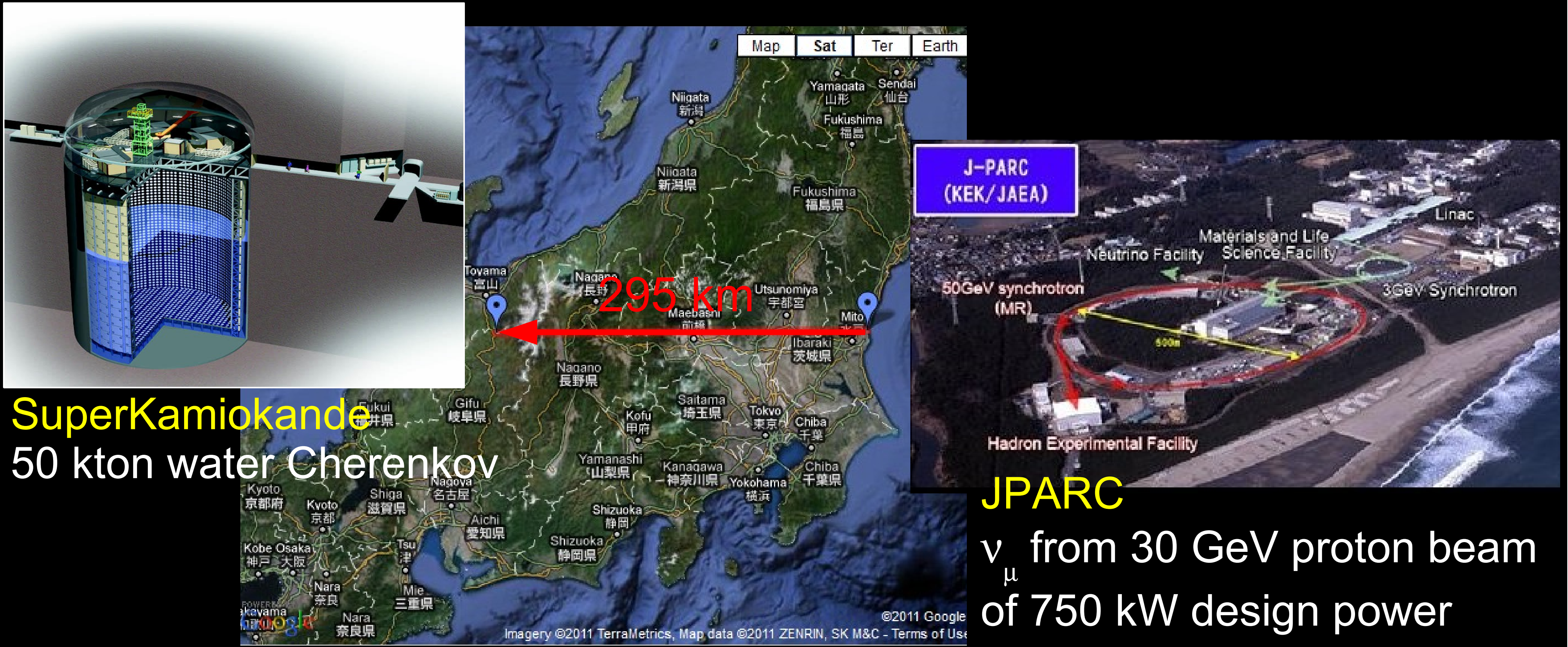
(1.8%)

Statistical significance

2.01 σ

(2.36 σ)

T2K (Tokai to Kamioka) experiment



SuperKamiokande
50 kton water Cherenkov

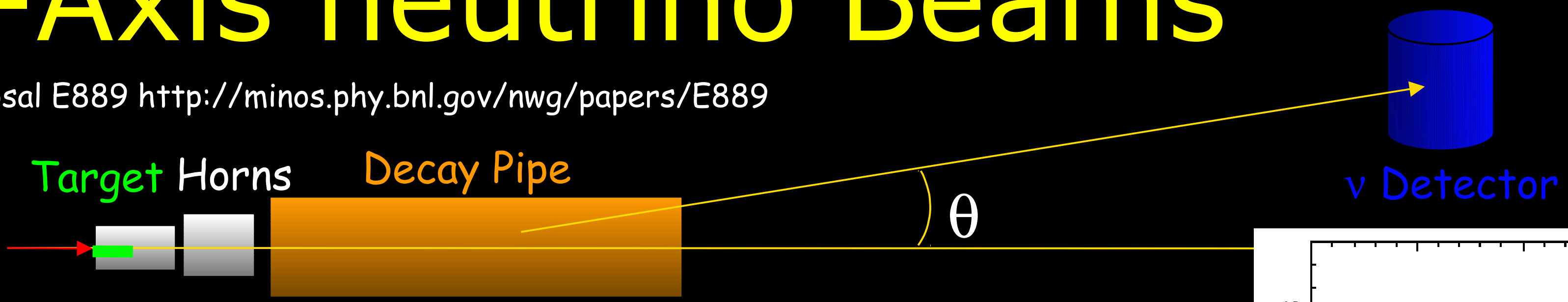
JPARC
ν_μ from 30 GeV proton beam of 750 kW design power

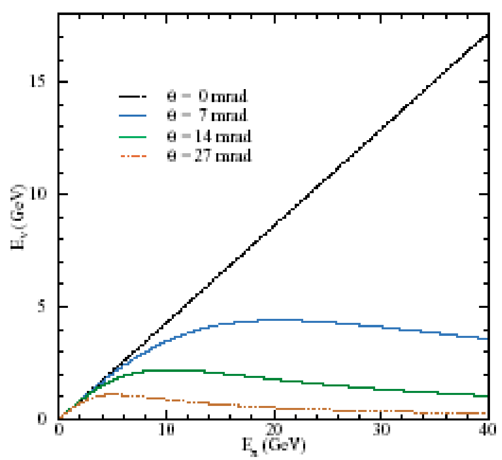
Goals

1. ν_e appearance (θ_{13} "discovery")
2. ν_μ disappearance (θ_{23},Δm^2_{23} precise measurement)

Off-Axis neutrino Beams

BNL proposal E889 http://minos.phy.bnl.gov/nwg/papers/E889





$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2\,(E_\pi - p_\pi\cos\theta)} \qquad \Phi_\nu = \frac{1}{4\pi L^2}\,\frac{m_\pi^2}{(E_\pi - p_\pi\cos\theta)^2}$$

$E_\pi \gg m_\pi$, and $\theta \ll 1$

$$\frac{m_\pi^2 - m_\mu^2}{m_\pi^2\,(1+\gamma_\pi^2\theta^2)}\,E_\pi \qquad \frac{1}{\pi L^2}\left(\frac{E_\pi}{m_\pi}\right)^2\frac{1}{(1+\gamma_\pi^2\theta^2)^2}$$

Much higher flux than old-style NBB.

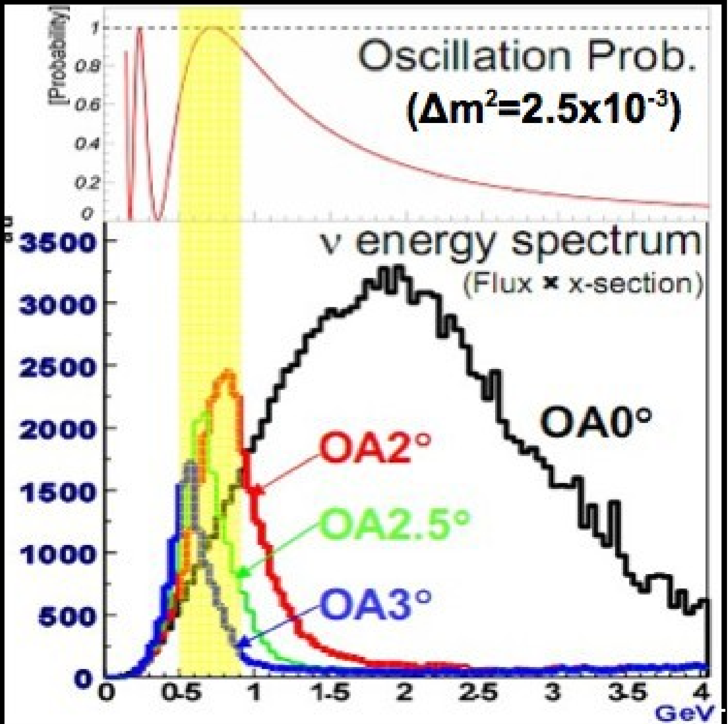
Strong cut-off of HE tail: reduced NCπ^0 bckg.

Reduced ν_e contamination.

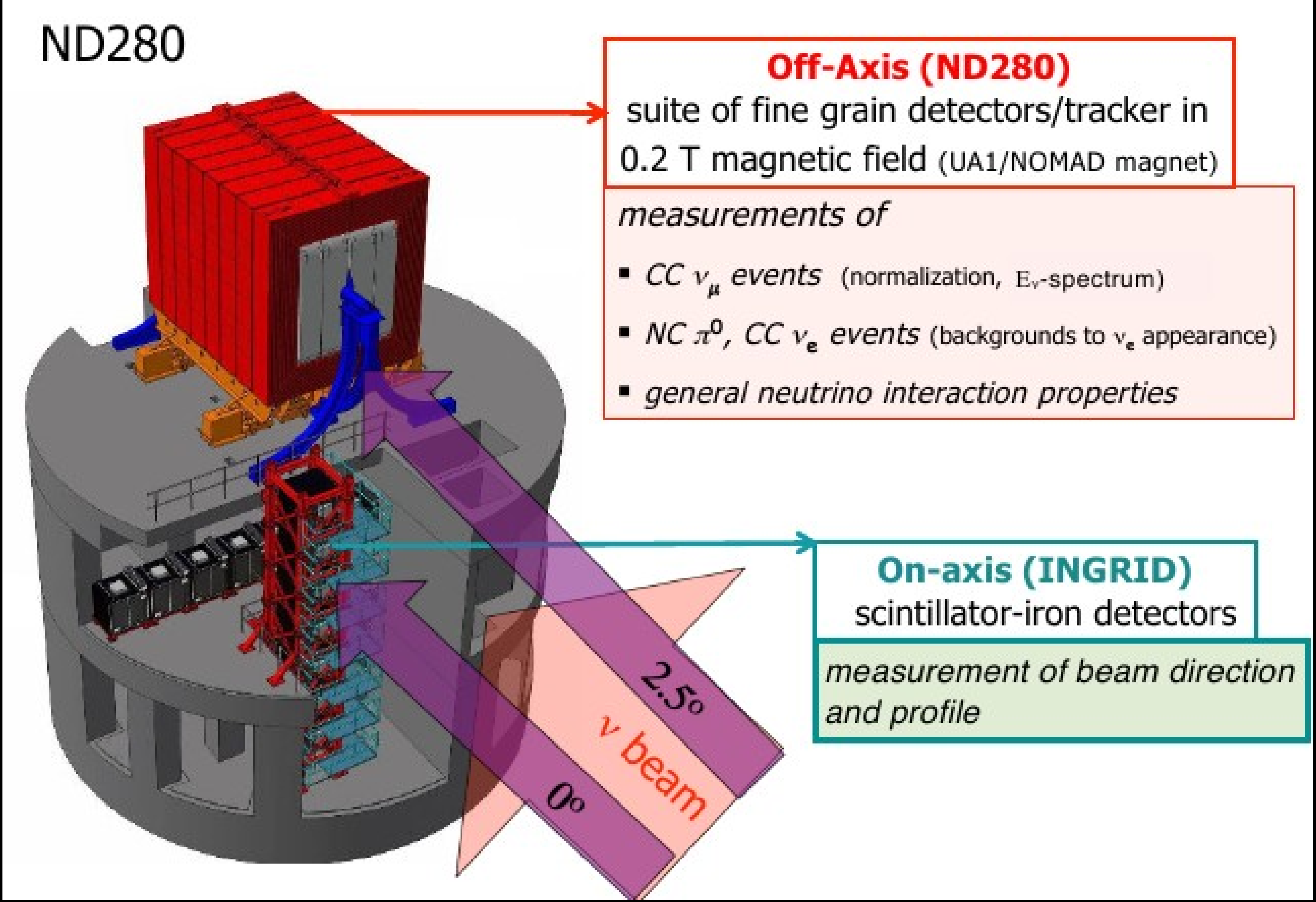
Tune energy to maximise sensitivity:

$$\Delta = 1.27 \cdot \Delta m^2(\mathrm{eV}^2) \cdot L(\mathrm{Km}) \,/\, E(\mathrm{GeV})$$

Beam energy almost fixed by geometry



T2K Near Detector: ND280



Off-Axis (ND280)
suite of fine grain detectors/tracker in
0.2 T magnetic field (UA1/NOMAD magnet)

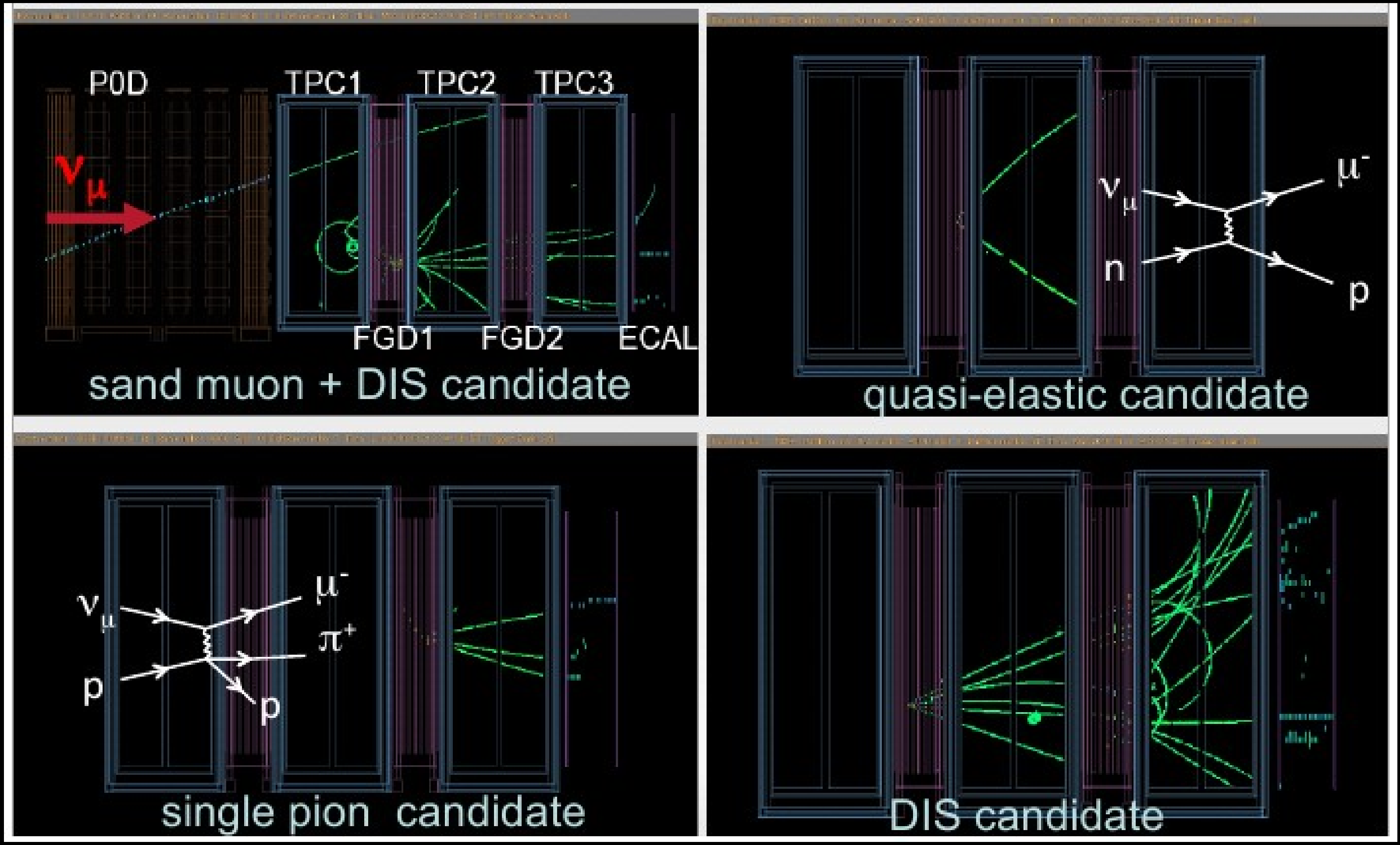
measurements of

- *CC ν_μ events* (normalization, E_ν-spectrum)
- *NC π^0, CC ν_e events* (backgrounds to ν_e appearance)
- *general neutrino interaction properties*

On-axis (INGRID)
scintillator-iron detectors

measurement of beam direction and profile

ND280 events



sand muon + DIS candidate

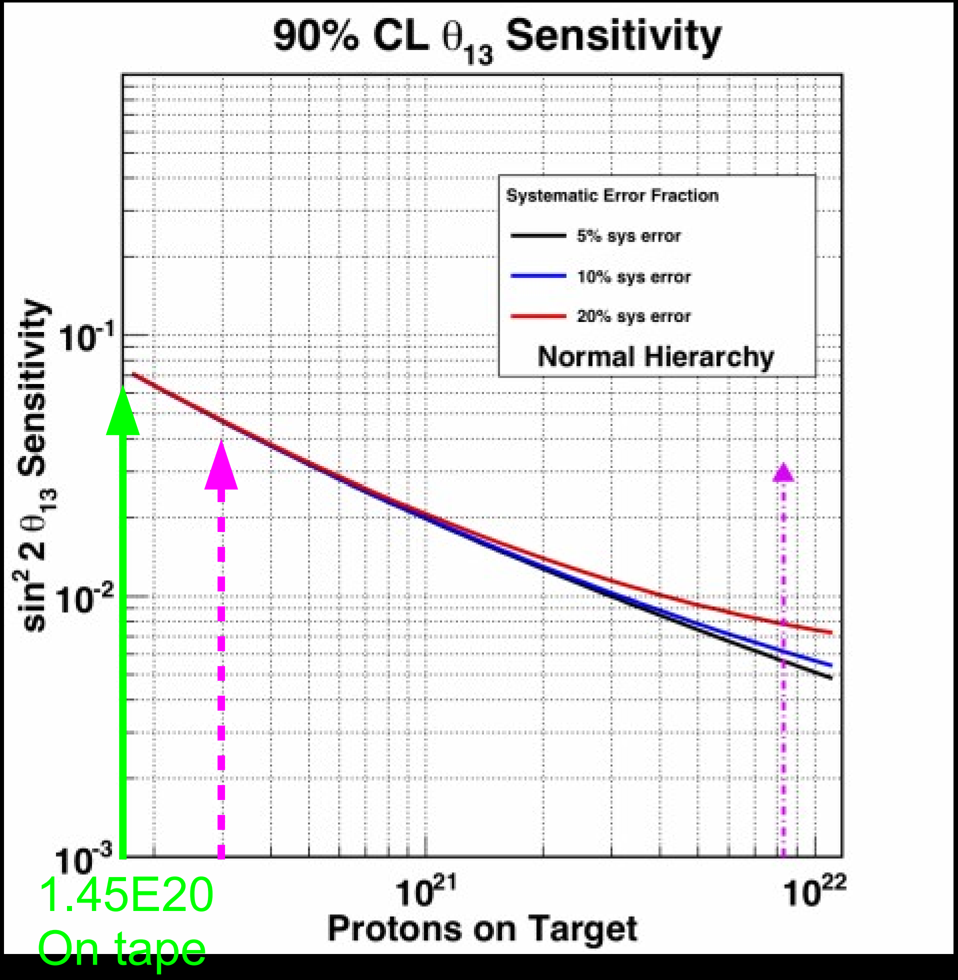
quasi-elastic candidate

single pion candidate

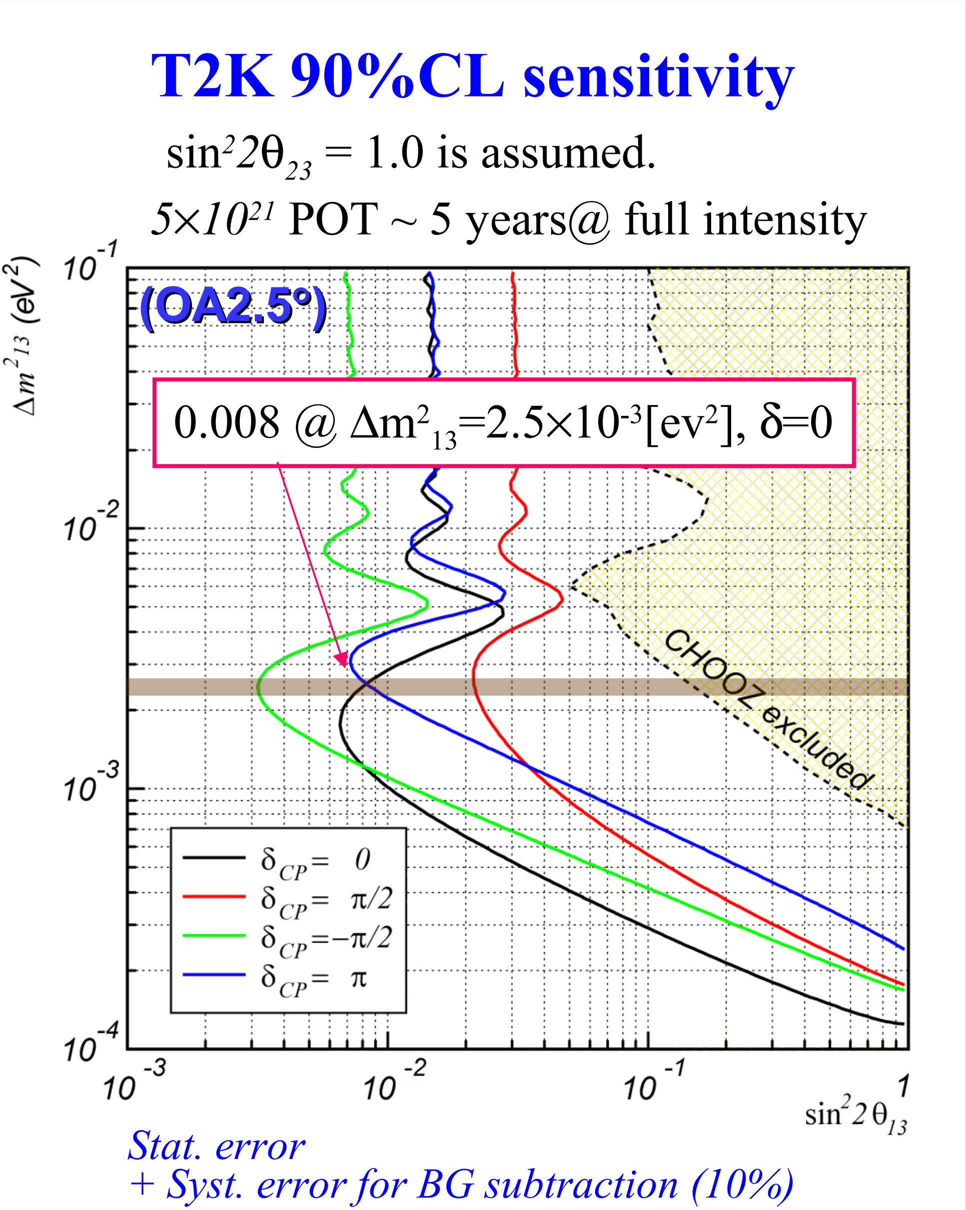
DIS candidate

T2K θ_{13} sensitivity

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2(1.27\,\Delta m^2_{23}L/E)$$



1.45E20
On tape



T2K 90%CL sensitivity

$\sin^2 2\theta_{23} = 1.0$ is assumed.

5×10^{21} POT ~ 5 years@ full intensity

(OA2.5°)

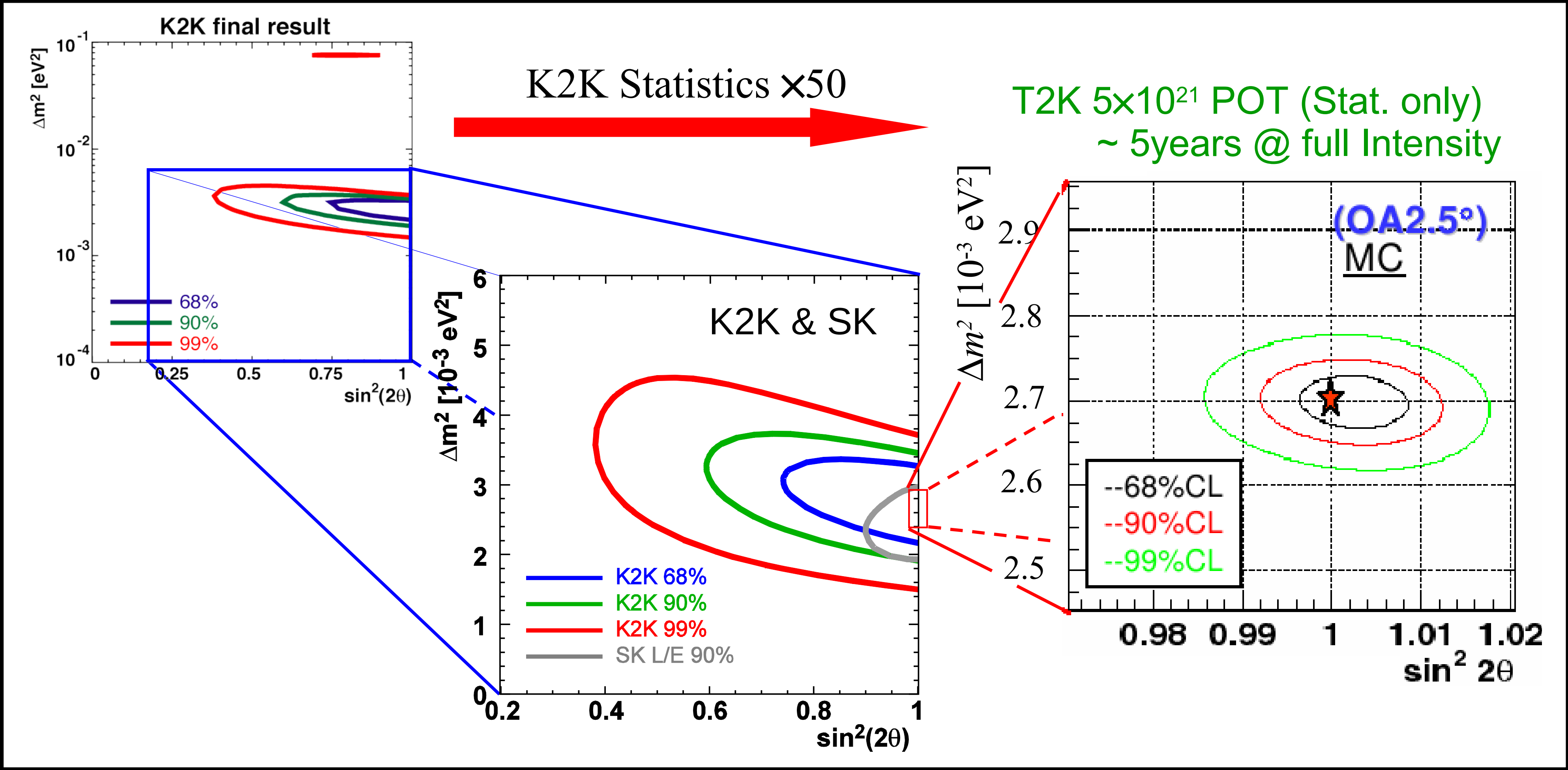
0.008 @ $\Delta m^2_{13}=2.5\times10^{-3}$[ev²], $\delta=0$

Stat. error
+ Syst. error for BG subtraction (10%)

T2K ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1-\sin^2 2\theta_{23}\sin^2(1.27\,\Delta m^2_{23}L/E)$$

Sensitivity: $\delta(\sin^2 2\theta_{23}) \sim 0.01$, $\delta(\Delta m^2_{23}) < 1\times10^{-4}\ [\mathrm{eV}^2]$



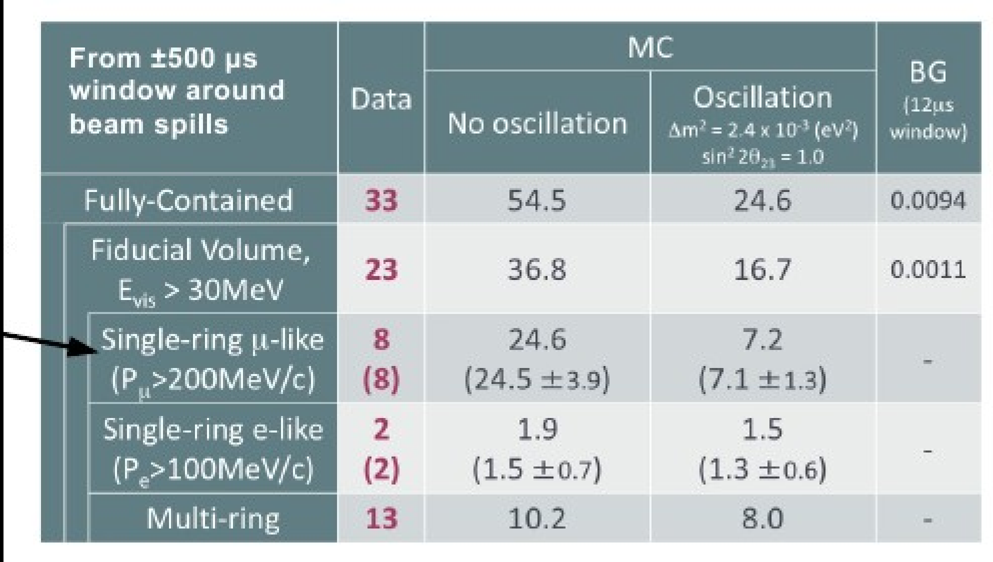
K2K Statistics ×50

T2K 5×10²¹ POT (Stat. only)
~ 5years @ full Intensity

T2K Preliminary Results

Jan-June 2010 (2010a): 3.23E19 pot
(w.r.t. 1.45E20 already on tape)

Consistent with oscillation parameters measured by SK, K2K,MINOS



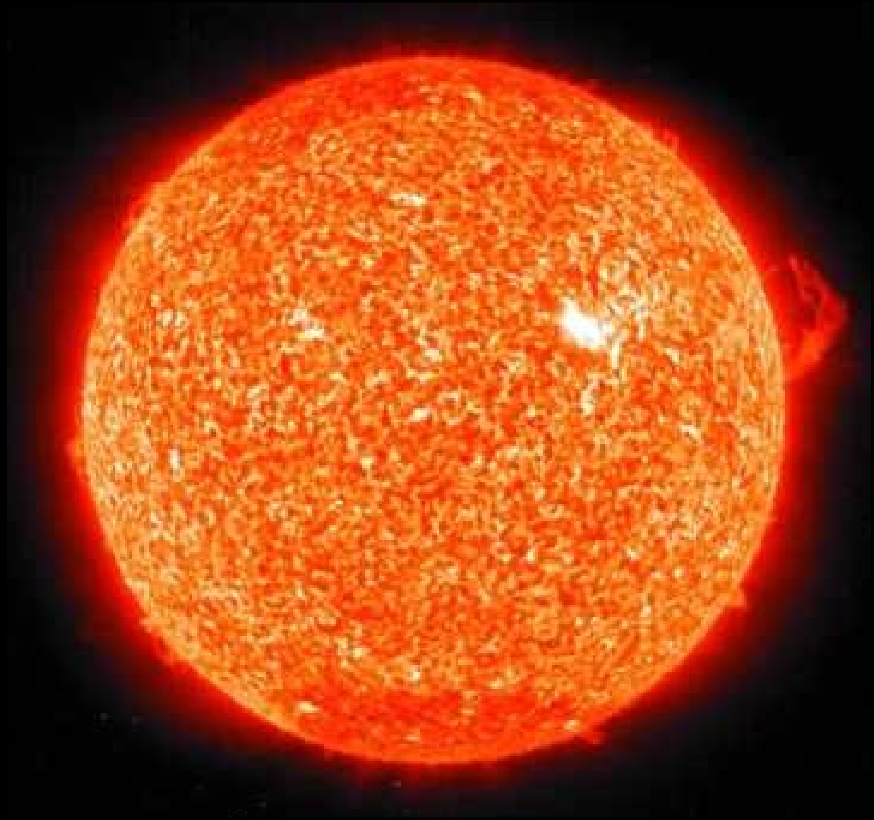
From ±500 μs window around beam spills	Data	MC		BG (12μs window)
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$	
Fully-Contained	33	54.5	24.6	0.0094
Fiducial Volume, $E_{vis} > 30$MeV	23	36.8	16.7	0.0011
Single-ring μ-like (P_μ>200MeV/c)	8 (8)	24.6 (24.5 ±3.9)	7.2 (7.1 ±1.3)	-
Single-ring e-like (P_e>100MeV/c)	2 (2)	1.9 (1.5 ±0.7)	1.5 (1.3 ±0.6)	-
Multi-ring	13	10.2	8.0	-

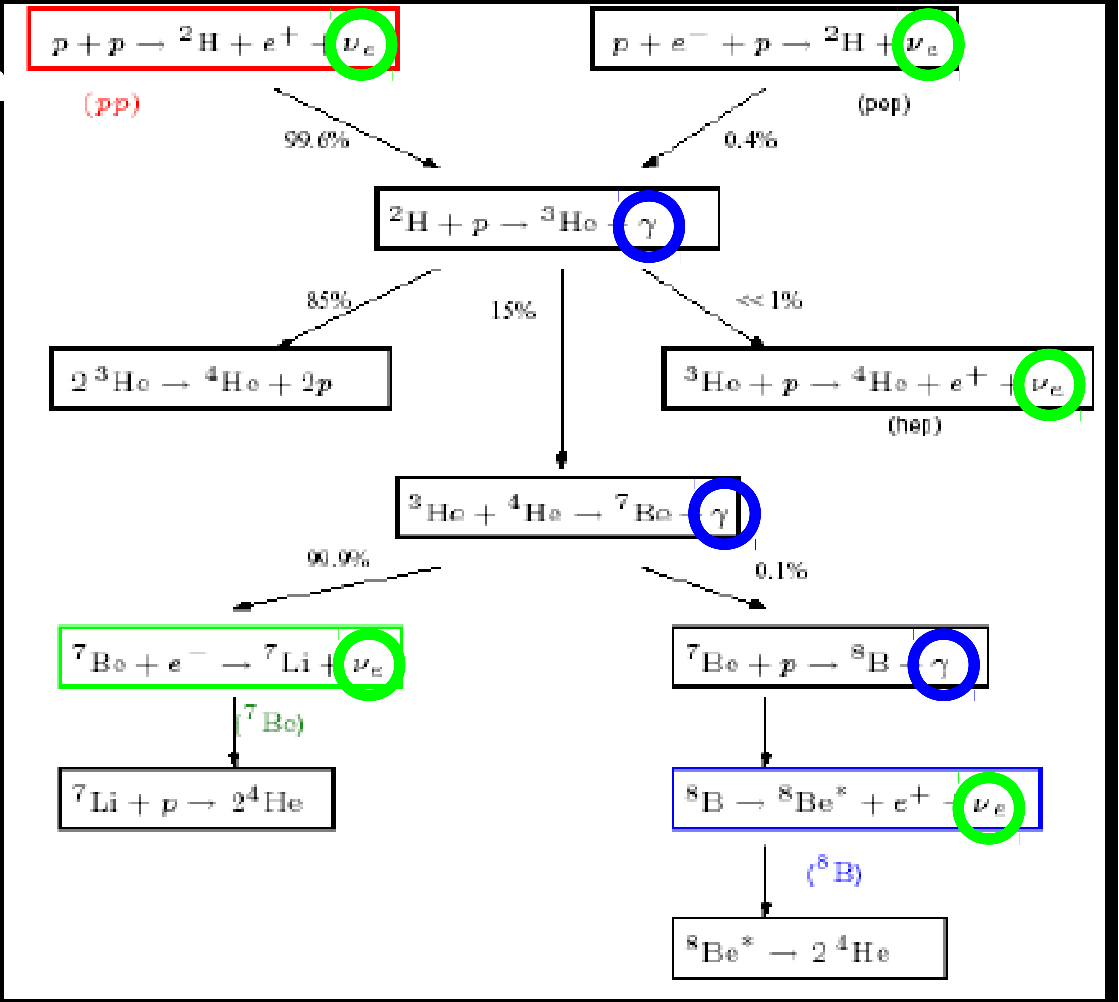
observed ν_e candidates surviving all cuts: 1

expected background events (θ_{13}=0): 0.30±0.07

Neutrino from the Sun

The Standard Solar Model (SSM) predicts the power radiated by the Sun from fusion reactions in its core





98.5% of the Sun power comes from the pp reaction: $4\,p \to 4\mathrm{He} + 2e^+ + 2\nu_e + 26.7$ MeV

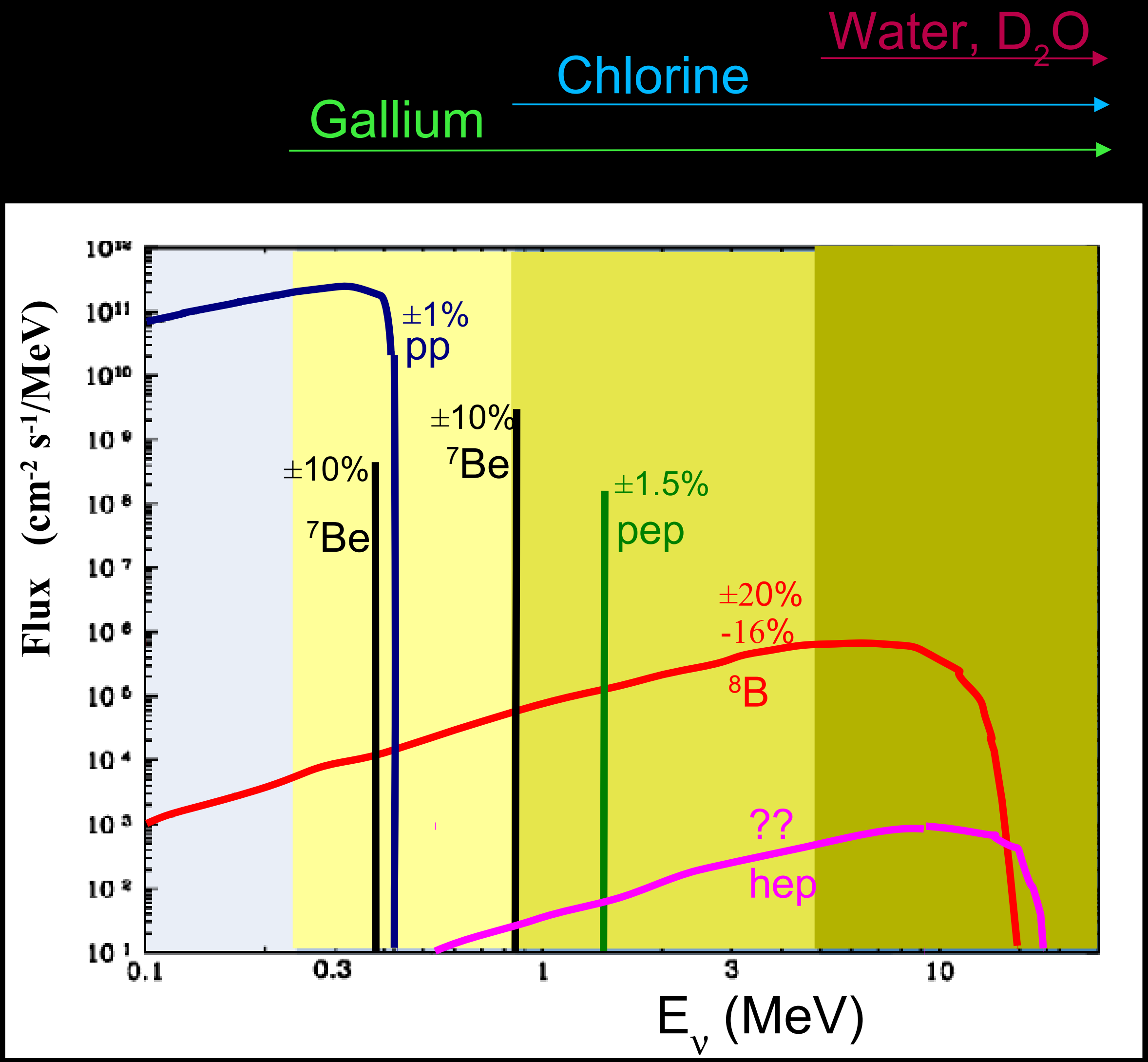
$L_\odot = 3.9\ 10^{26}\ \mathrm{Js^{-1}}$

$D = 1.5\ 10^{11}\ \mathrm{m}$

$Q = 26.7\ \mathrm{MeV} = 4.3\ 10^{-12}\ \mathrm{J}$

$$\Phi_\odot = 2L_\odot / Q \cdot (1/4\pi D^2) \approx 6.5\ 10^{10}\ \mathrm{cm^{-2}\ s^{-1}}$$

Spettro dei neutrini solari



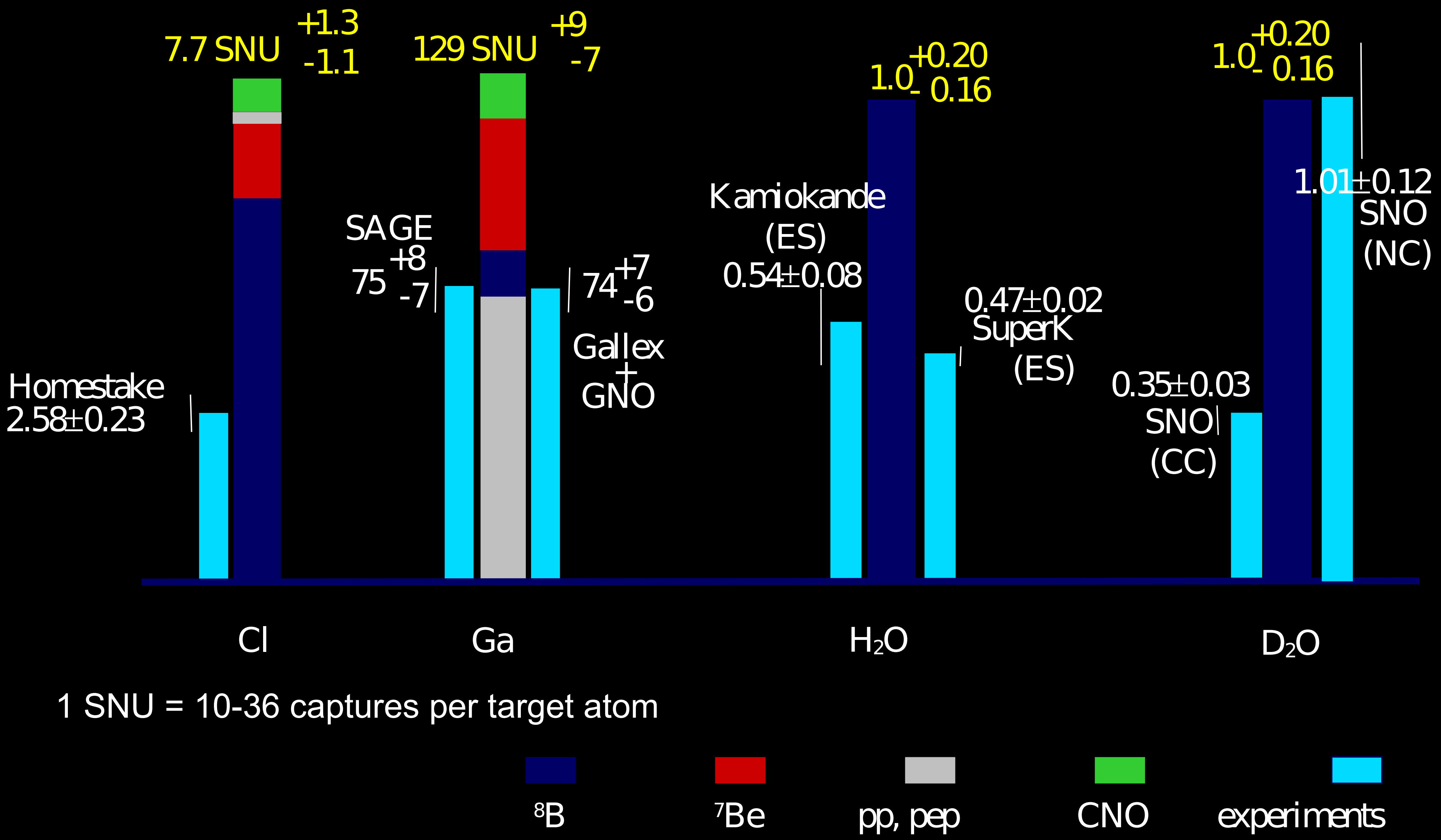
Chlorine
Homestake
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Gallium
SAGE, Gallex,GNO
$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Water
Kamiokande, SuperK
$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)

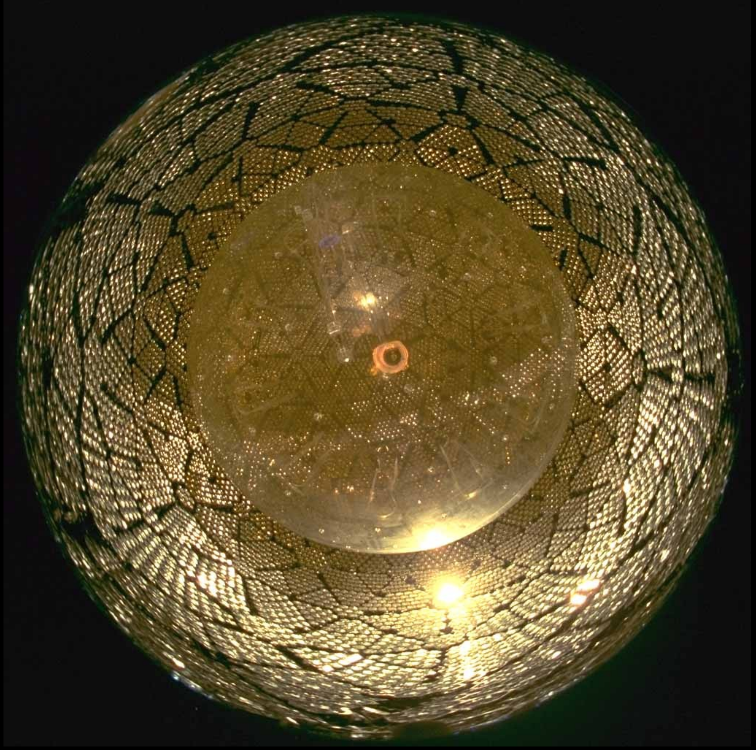
D_2O
SNO
$\nu_x + e^- \rightarrow \nu_x + e^-$ (ES)
$\nu_e + d \rightarrow p + p + e^-$ (CC)
$\nu_x + d \rightarrow n + p + \nu_x$ (NC)

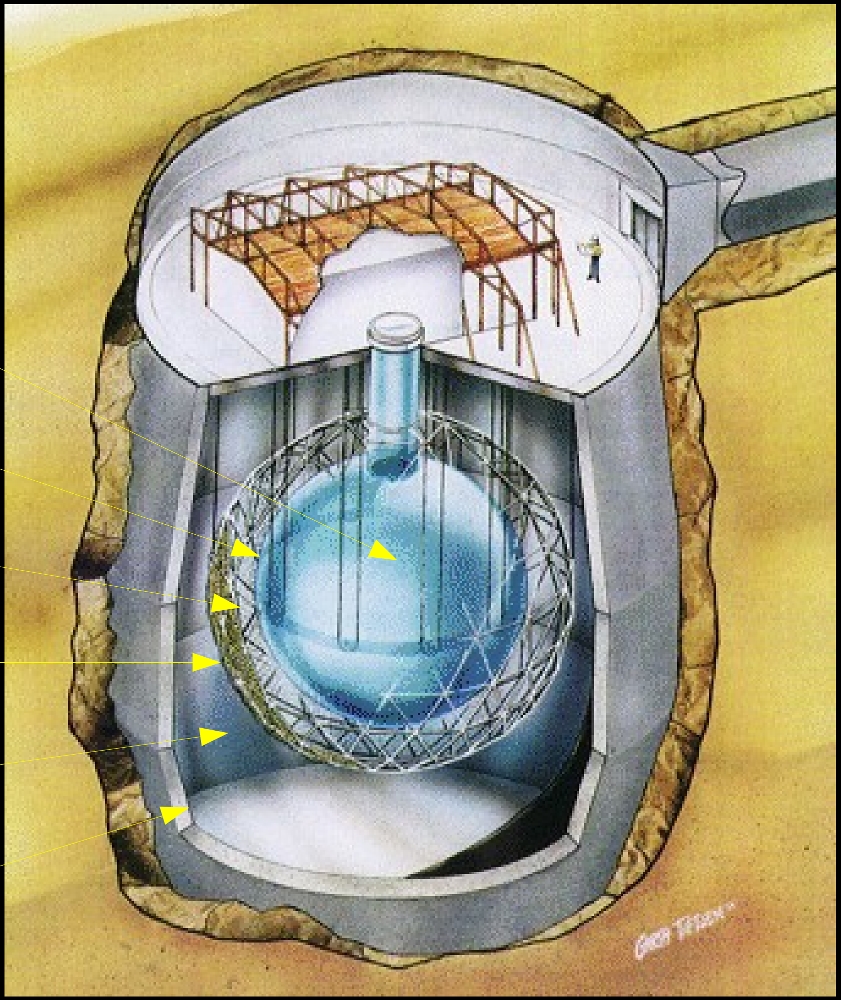
Misure del flusso dei neutrini solari



1 SNU = 10-36 captures per target atom

Sudbury Neutrino Observatory (SNO)





1000 tonnes D_2O

12 m Diameter Acrylic Vessel

1700 tonnes Inner Buffer H_2O

9500 PMTs, 60% coverage

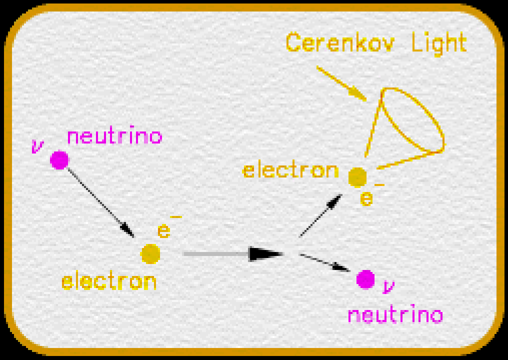
5300 tonnes Outer Shield H_2O

Urylon Liner and Radon Seal

Neutrino interactions in SNO

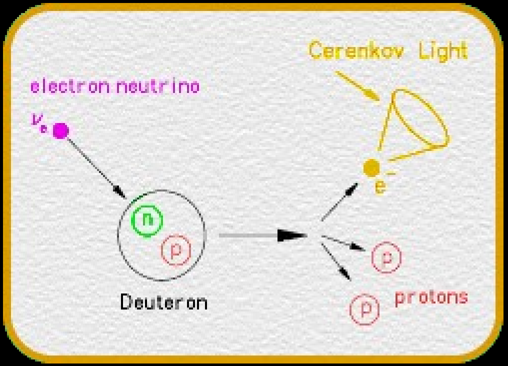
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- In SNO (D_2O) as in SK (H_2O)
- Mainly ν_e but also ν_μ,ν_τ (1:6)
- Strong Θ_ν sensitivity



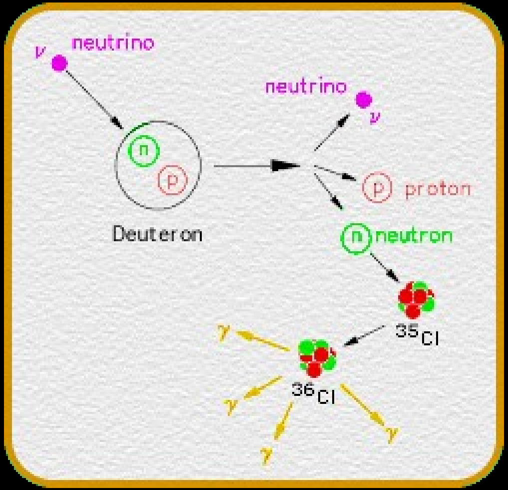
CC $\nu_e + d \rightarrow p + p + e^-$

- Good energy measurement
- ν_e only
- Weak directionality: $\propto 1-1/3\cos(\Theta_\nu)$



NC $\nu_x + d \rightarrow n + p + \nu_x$

- Equally sensitive to all ν
- Measure the total ^8B flux



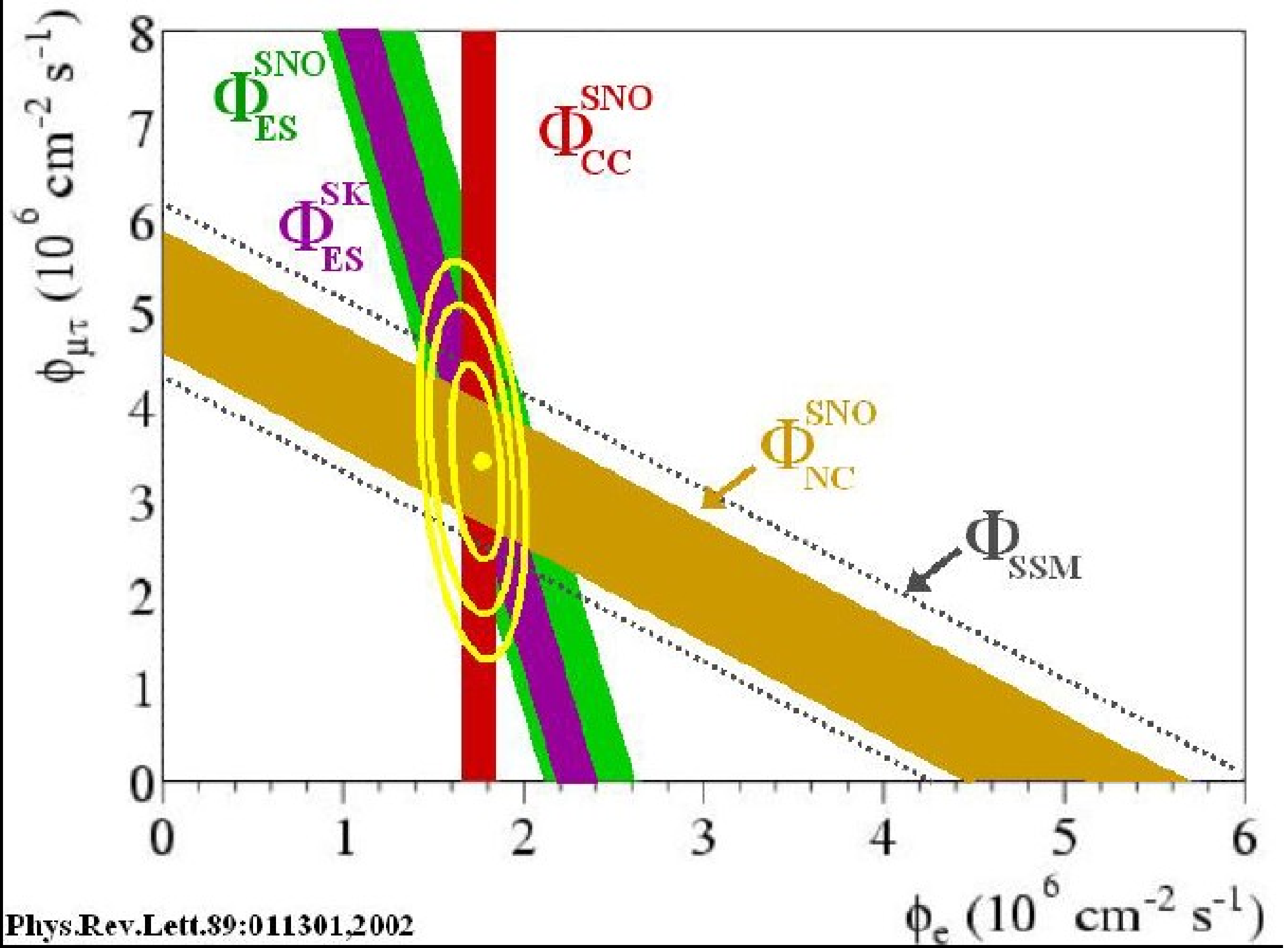
SNO: total flux as expected from SSM

- NC rate as expected from SSM (all neutrinos)
- CC rate (only ν_e) is 0.31 SSM
- ES rate is consistent with Super-Kamiokande and oscillation into ν_μ, ν_τ

$$\Phi_{CC} = 1.59^{+0.10}_{-0.11} \cdot 10^{-6} cm^{-2} s^{-1}$$

$$\Phi_{ES} = 2.21^{+0.33}_{-0.28} \cdot 10^{-6} cm^{-2} s^{-1}$$

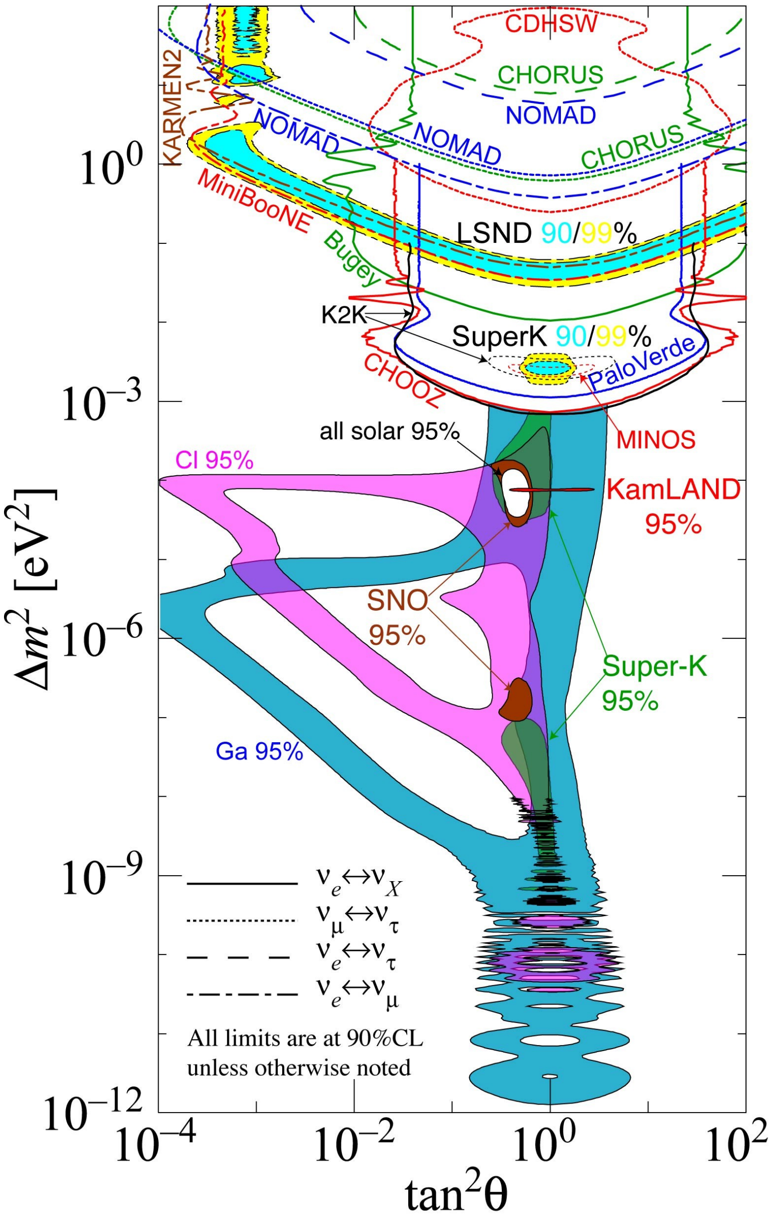
$$\Phi_{ES} = 5.21 \pm 0.47 \cdot 10^{-6} cm^{-2} s^{-1}$$



Phys.Rev.Lett.89:011301,2002

Neutrino differents from ν_e coming from the Sun ! (2002)

Oscillation data overview



http://hitoshi.berkeley.edu/neutrino

Decades of experimental and theoretical efforts !

That's all folks ?!

> “There is nothing new to be discovered in physics now.
> All that remains is more and more precise measurement.”

Kelvin, c. 1900