Status of neutrino mixing measurements and future searches for CP violation in the leptonic sector

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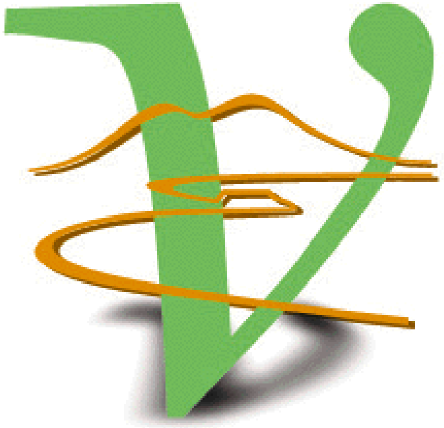


Outline

- Why the neutrinos are so important?
- A brief introduction to ν oscillations and their evidences
- Present knowledge of the mixing parameters
- The OPERA experiment
- The quest for θ_{13}: T2K and the reactor experiments
- Super-beams
- Beta-beams
- Neutrino Factories

Unique Role of Neutrino Mass

- Lowest order effect of new physics at short distances
- Tiny effect $(m_\nu/E_\nu)^2 \sim (0.1\mathrm{eV}/\mathrm{GeV})^2 = 10^{-20}$!
- Inteferometry
  - Need coherent source
  - Need interference (*i.e.*, large mixing angles)
  - Need long baseline

Nature was kind to provide all of them!

- "neutrino interferometry" (a.k.a. neutrino oscillation) a unique tool to study physics at very high scales
- Not entirely surprising (in *retrospect*) that neutrino mass was the first evidence for physics beyond standard model

The PMNS leptonic mixing matrix

If neutrinos have mass: $\left|\nu_l\right\rangle = \sum U_{li}\left|\nu_i\right\rangle$

Flavour e.s. Mass e.s.

For three neutrinos

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, *and* $s_{ij} = \sin\theta_{ij}$

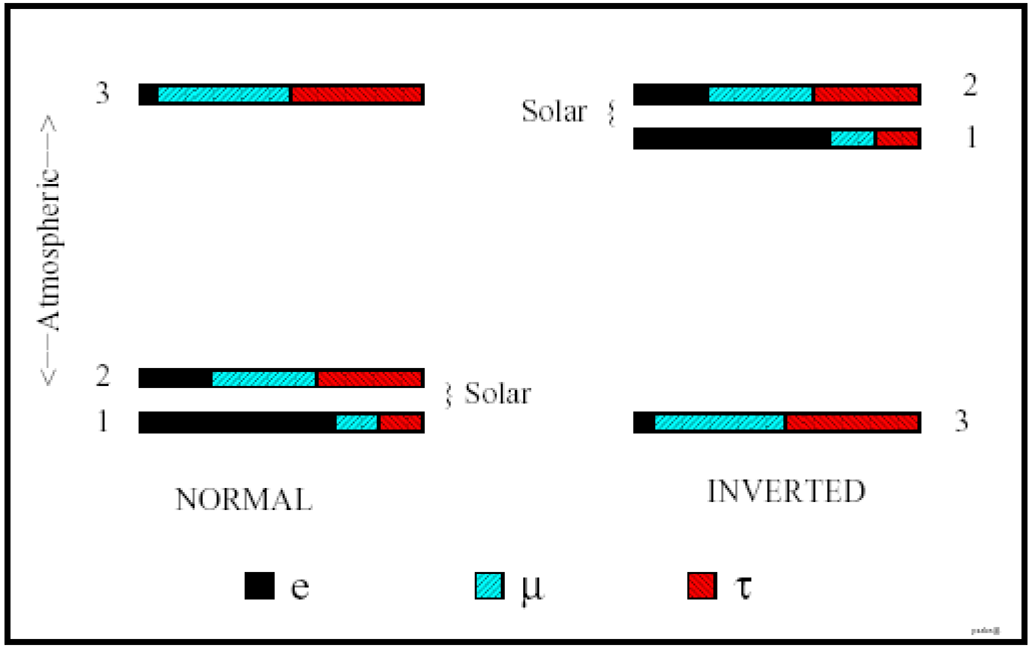
Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta}(L) = \sum_{k=1}^{3} \left|U_{\alpha k}\right|^2 \left|U_{\beta k}\right|^2 + 2\,\mathrm{Re}\sum_{\substack{k=1 \\ k>j}}^{3} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj}\boxed{L}}{\boxed{2E}}\right)$$

Fixed by nature Tuned by experiments

Notation

- Mixing parameters: $U = U\,(\theta_{12}, \theta_{13}, \theta_{23}, \delta)$ as for CKM matrix
- Mass-gap parameters: $M^2 = \Delta m^2_{12}\ ,\ \pm \Delta m^2_{23}$

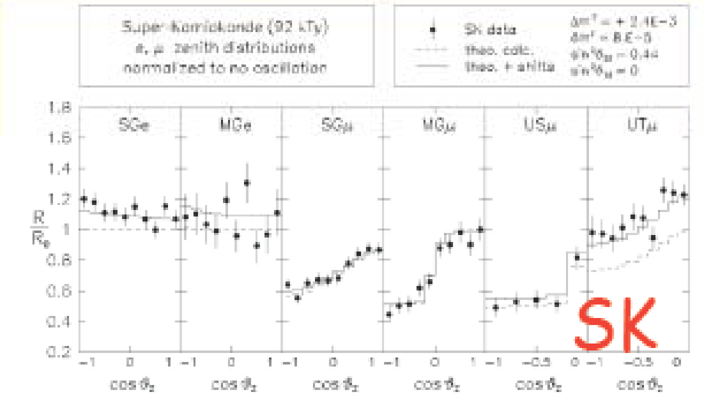


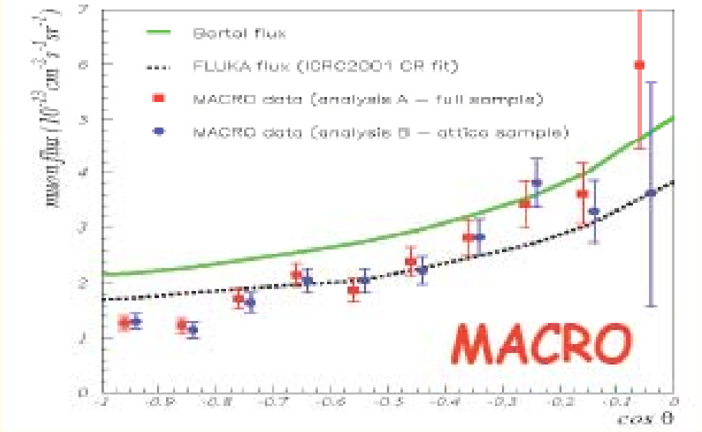
The absolute mass scale should be set by other measurements:

- β-decay
- 0ν2β-decay
- anisotropies in cosmic background radiation

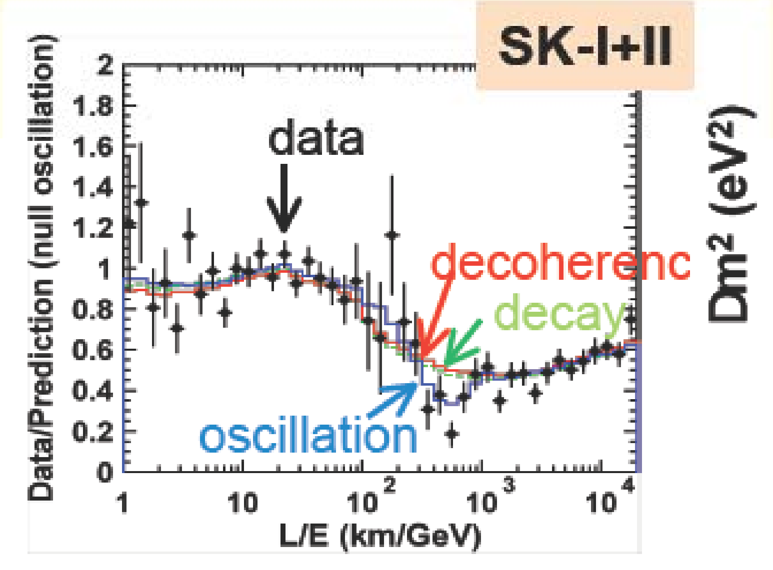
(Δm^2, θ_{23}) - driven oscillations in atmospheric neutrinos

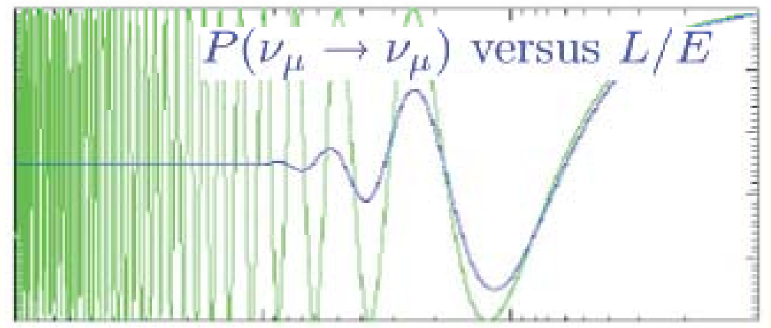
From zenith distortions…





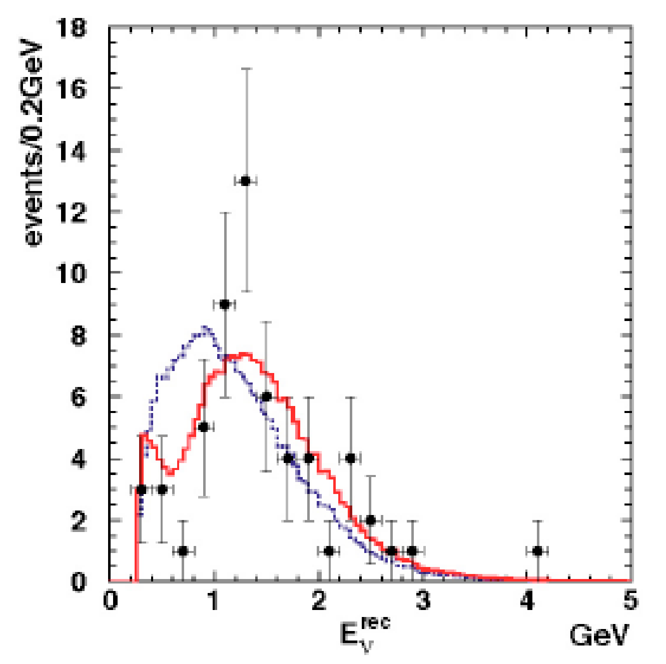
… to L/E osc. (half period)



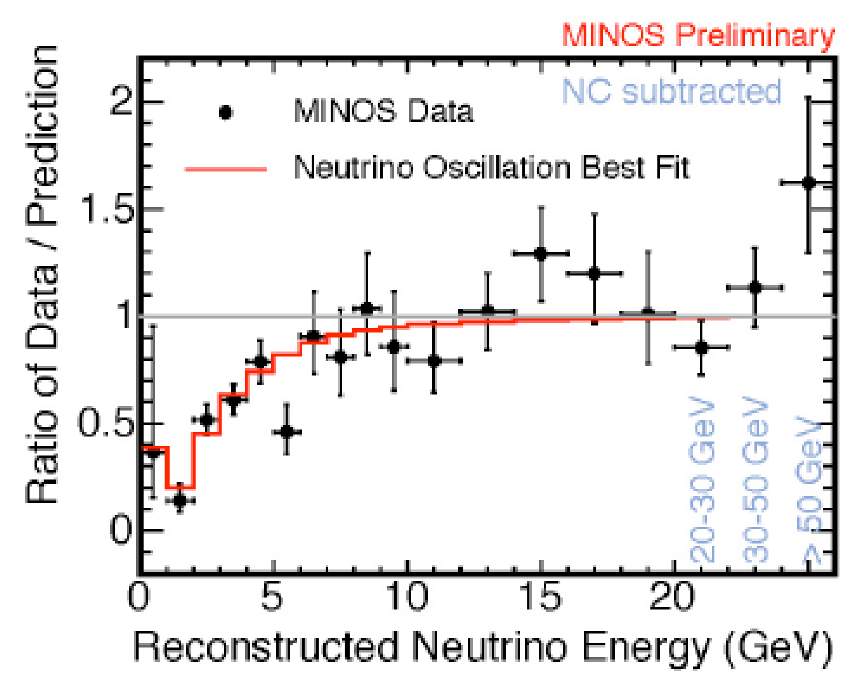


(Δm^2, θ_{23}) - driven oscillations in LBL accelerator neutrinos

Fixed L, half-oscillation period (dip) seen in E spectrum

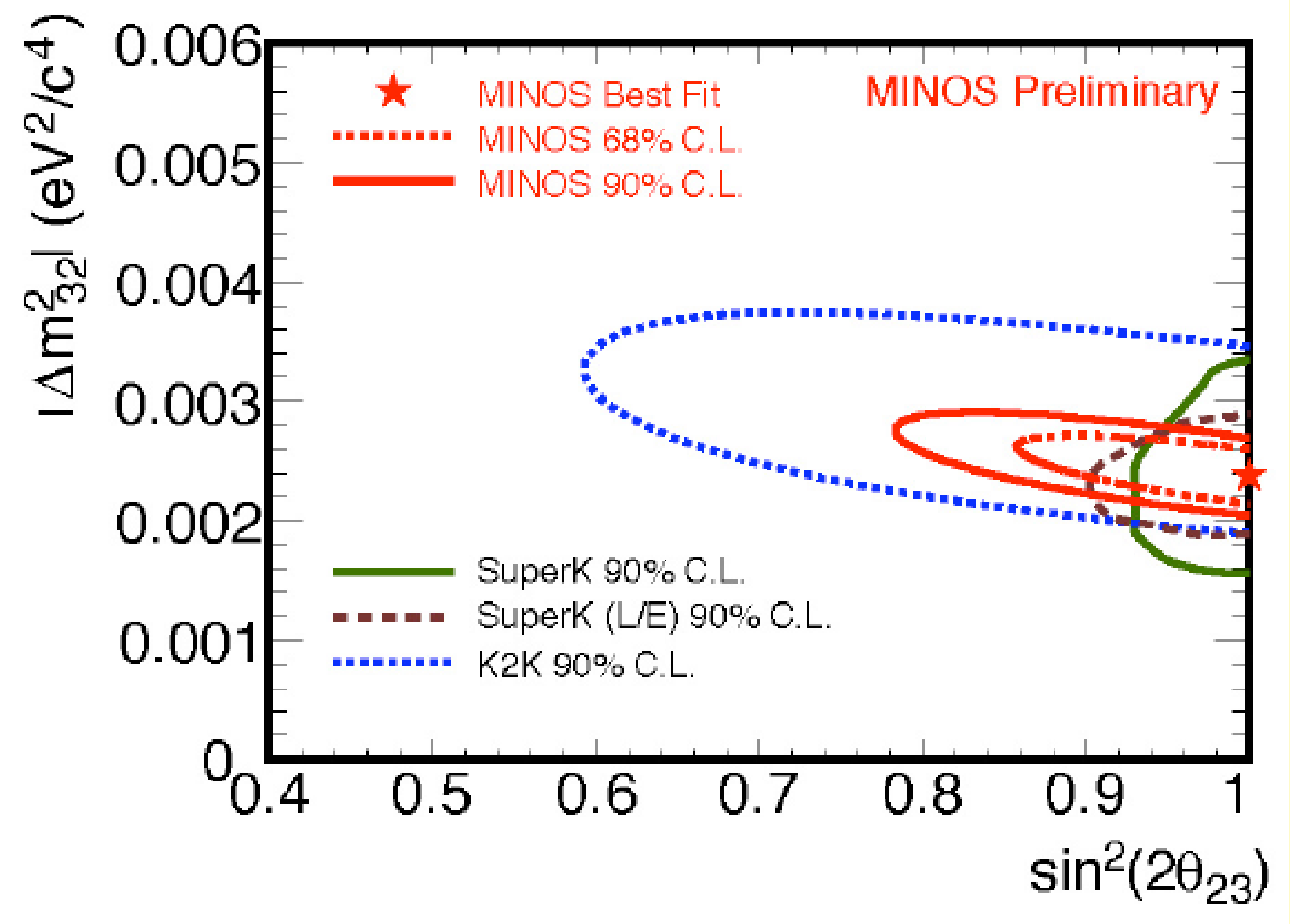


K2K final results



MINOS 2007 results

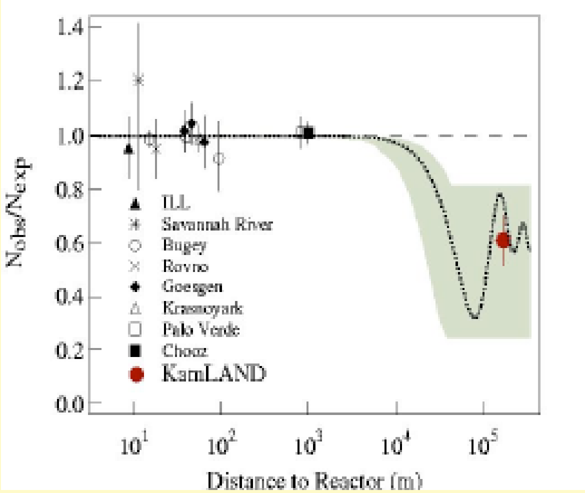
(Δm^2, θ_{23}) - complementarity of atmospheric/accelerator ν



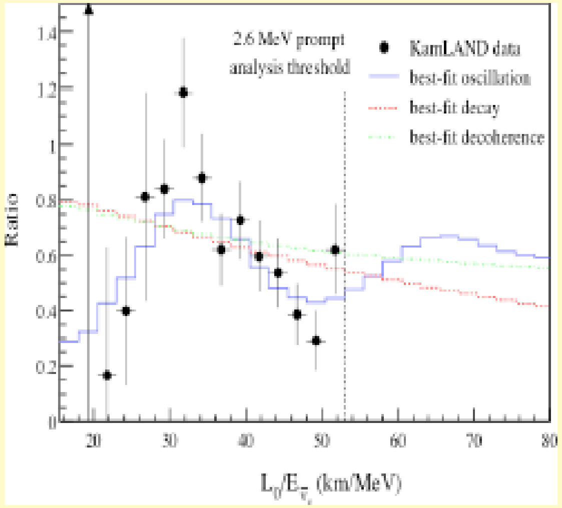
All results consistent with <u>muon flavor disappearance</u> and <u>no electron appearance</u> - hence, ***with*** **$\nu_\mu \rightarrow \nu_\tau$ oscillations***. Missing piece: direct observation of ν_τ appearance*

(δm^2, θ_{12}) - driven oscillations in LBL reactor neutrinos

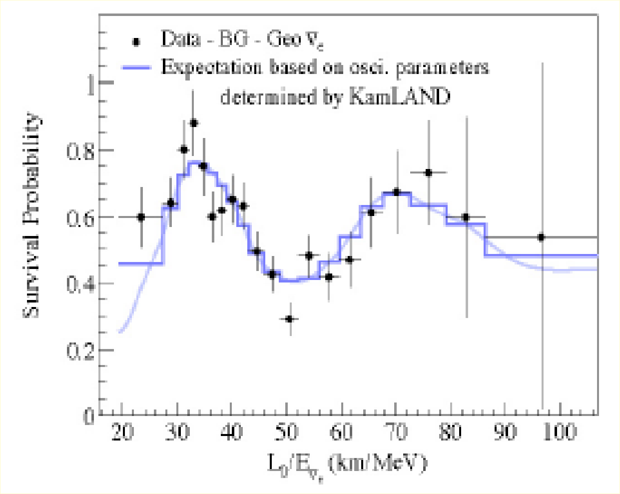
2002: electron flavor disappearance observed



2004: half-period of oscillation observed



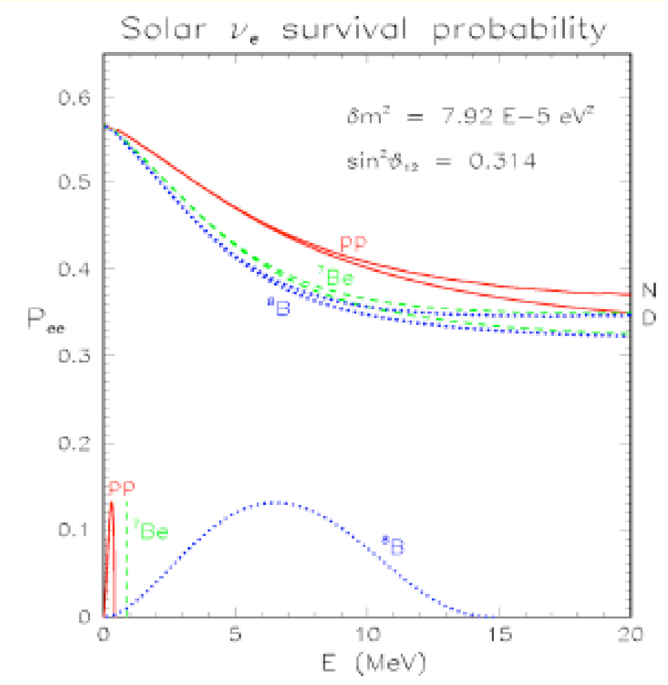
2007: one period of oscillation observed

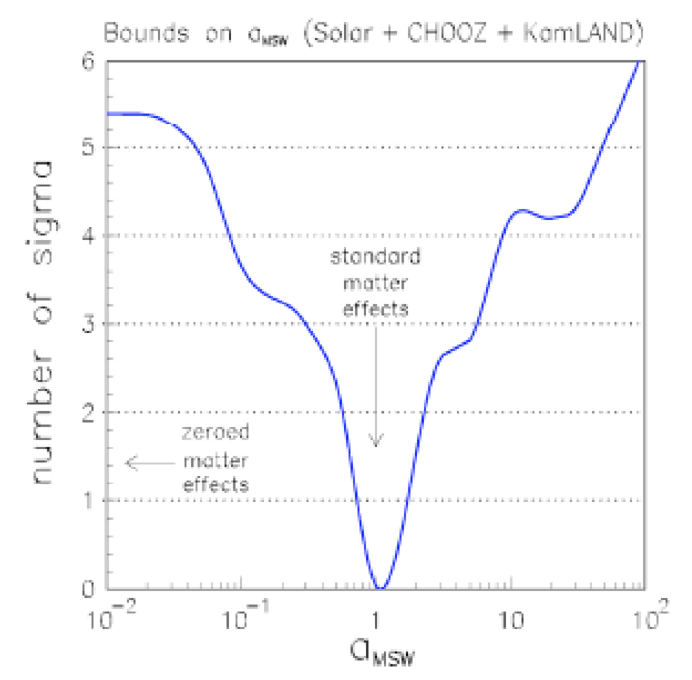


KamLAND

(δm^2, θ_{12}) - driven oscillations in solar neutrinos

Evidence for solar matter (MSW) effects $\propto G_F N_e$\
→ nonoscillatory pattern





Prog.Part.Nucl.Phys.57, 742 (2006)

- ***Borexino has performed the first real-time detection of sub/MeV solar neutrinos***
- with just 2 months of data **a clear ^{7}Be signal** is visible better results to come in the near future
    - (+ checks on day/night, seasonal or long term effects)
  - the central value is well in agreement with MSW/LMA

theoretical prediction with oscillations

49 ± 4 counts/day/100t

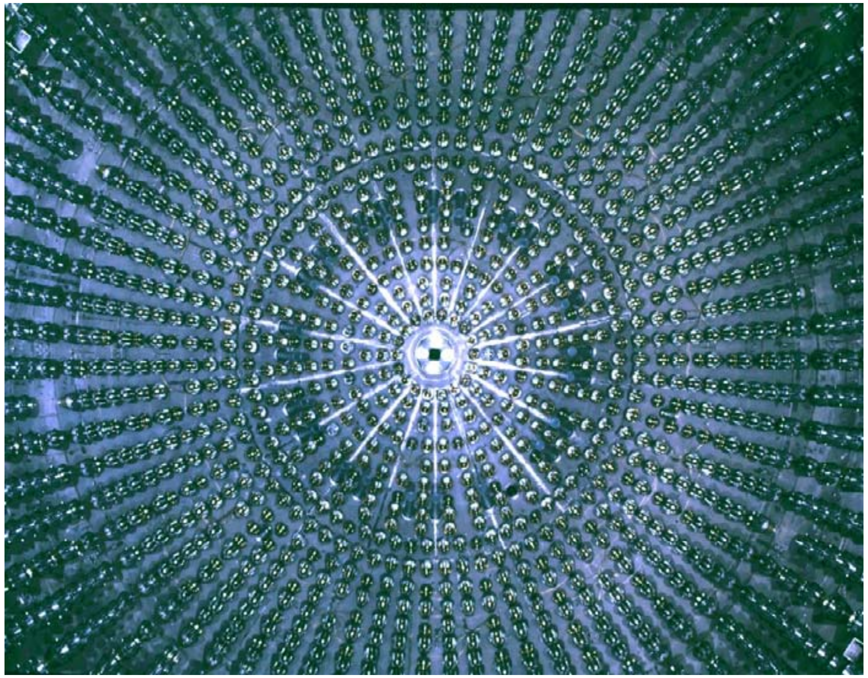
measured rate

47 ± 7_{stat} ± 12_{syst} counts/day/100t

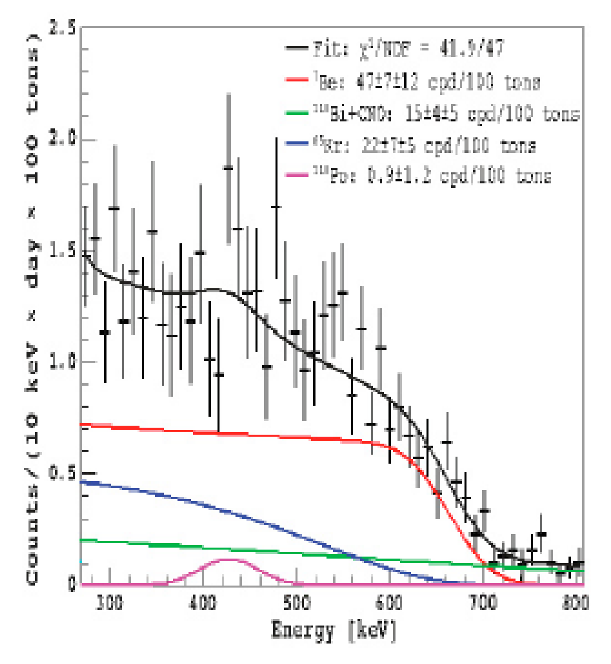
no oscillation expectation

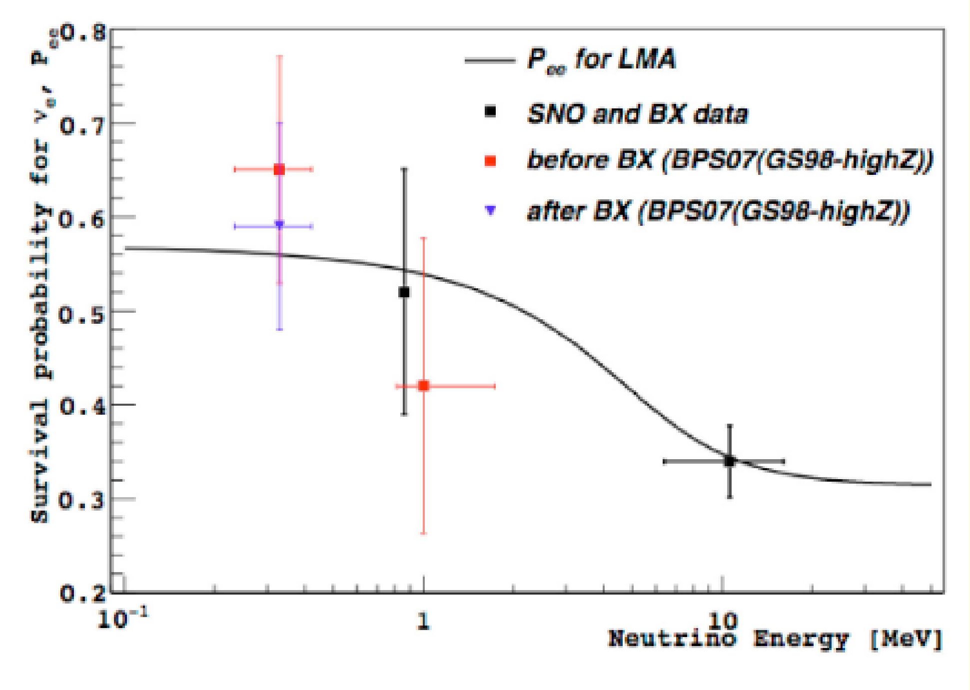
75 ± 4 counts/day/100t

- future scientific plans
  - pp, pep and CNO neutrinos fluxes
  - antineutrinos (earth, reactors, Sun)
  - supernova
  - neutrino magnetic moment



BOREXINO first results





Rate consistent with
MSW expectations
within latest SSM
(from A. Ianni, TAUP 2007)

^{7}Be rate = 47±7$_{stat}$±12$_{sys}$(max)

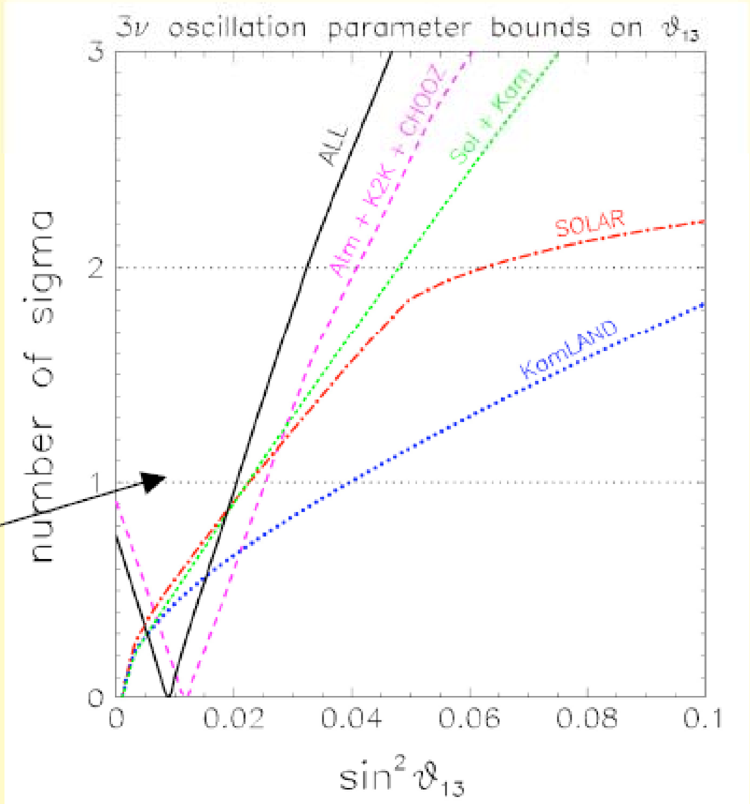
LMA yearly averaged: 49±4
No osc. : 75±4 (2.6σ excluded)

What about θ_{13}?

CHOOZ results:

For Δm^2 around 2.5×10^{-3} eV^2, get stringent upper bound on θ_{13}

Corroborated by subleading sensitivity to θ_{13} from all the other experiments - a nontrivial consistency check



Fogli et al., Prog.Part.Nucl.Phys.57, 742 (2006)

Grand total from full 3ν oscillation analysis (Bari group)

at 95% C.L. (2 standard deviations)

$$\begin{aligned}\delta m^2/\mathrm{eV}^2 &= 7.9 \pm 0.7 \times 10^{-5}\\ \Delta m^2/\mathrm{eV}^2 &= 2.6 \pm 0.4 \times 10^{-3}\\ \sin^2\theta_{12} &= 0.31^{+0.06}_{-0.05}\\ \sin^2\theta_{23} &= 0.45^{+0.16}_{-0.09}\\ \sin^2\theta_{13} &< 3.1 \times 10^{-2}\end{aligned}$$

2006, published

$$\begin{aligned}\delta m^2/\mathrm{eV}^2 &= 7.65 \pm 0.35 \times 10^{-5}\\ \Delta m^2/\mathrm{eV}^2 &= 2.4 \pm 0.3 \times 10^{-3}\\ \sin^2\theta_{12} &= 0.32^{+0.06}_{-0.04}\\ \sin^2\theta_{23} &= 0.45^{+0.16}_{-0.09}\\ \sin^2\theta_{13} &< 3.2 \times 10^{-2}\end{aligned}$$

2008, preliminary

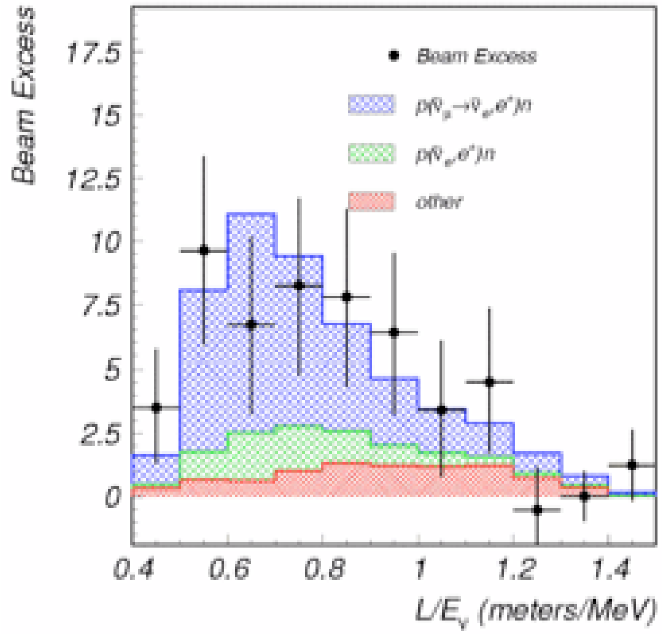
Small changes? Depends on viewpoint. For OPERA, reduction of best-fit **Δm^2** implies about -1.5 expected tau events.

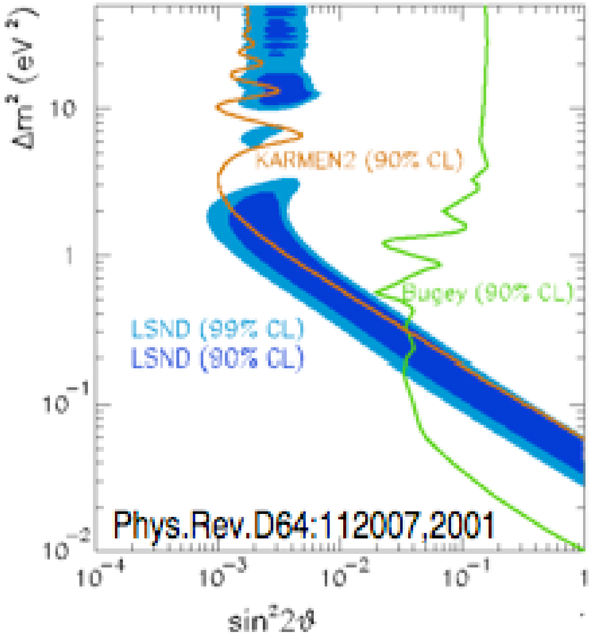
For another global analysis, see Strumia & Vissani, hep-ph/0606054

MiniBooNE was Prompted by the Positive LSND Result

LSND observed a (~3.8σ) excess of $\bar{\nu}_e$ events in a pure $\bar{\nu}_\mu$ beam: 87.9 ± 22.4 ± 6.0 events

Oscillation probability $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2 L/E)$





Phys.Rev.D64:112007,2001

The Karmen Exp. did not confirm the LSND oscillations but had a smaller distance.

LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν's.

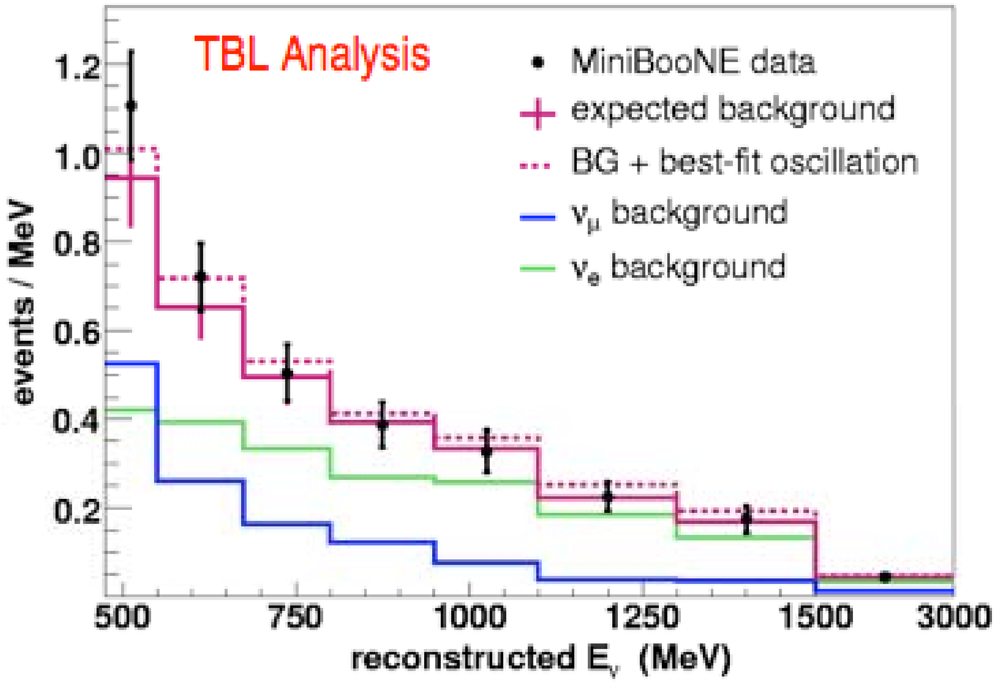
⇒ Models developed with 2 sterile ν's

or

Maybe one of the experiments is wrong.

MiniBooNE's task: Confirm or refute LSND.

MiniBooNE First Results (April, 2007)



Oscillation Search Region
$475 < E_\nu < 1250$ MeV

data: 380 ± 19 (stat) events

expectation: 358 ± 35 (sys) events

significance: 0.55 σ

Best Fit (dashed):

$(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ \text{eV}^2)$

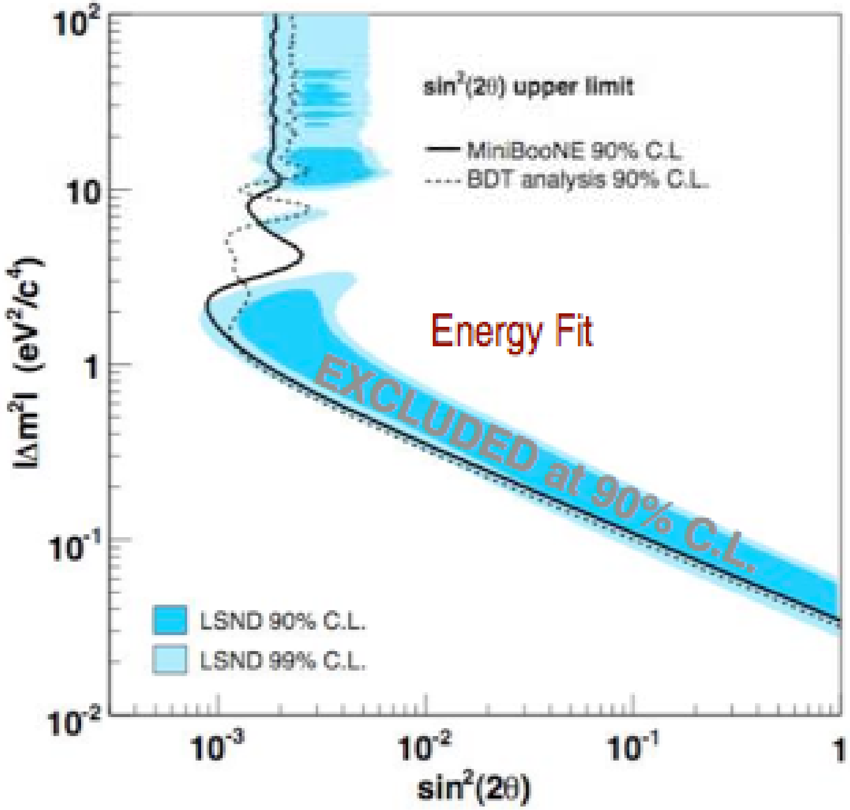
Probability of Null Fit: 93%

Probability of Best Fit: 99%

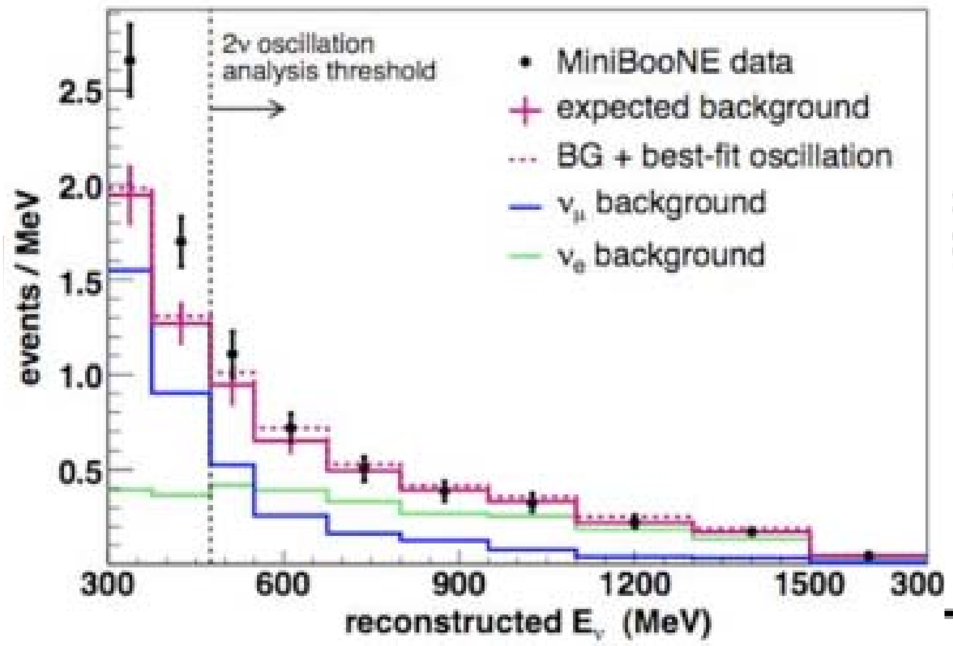
Data consistent with expected background

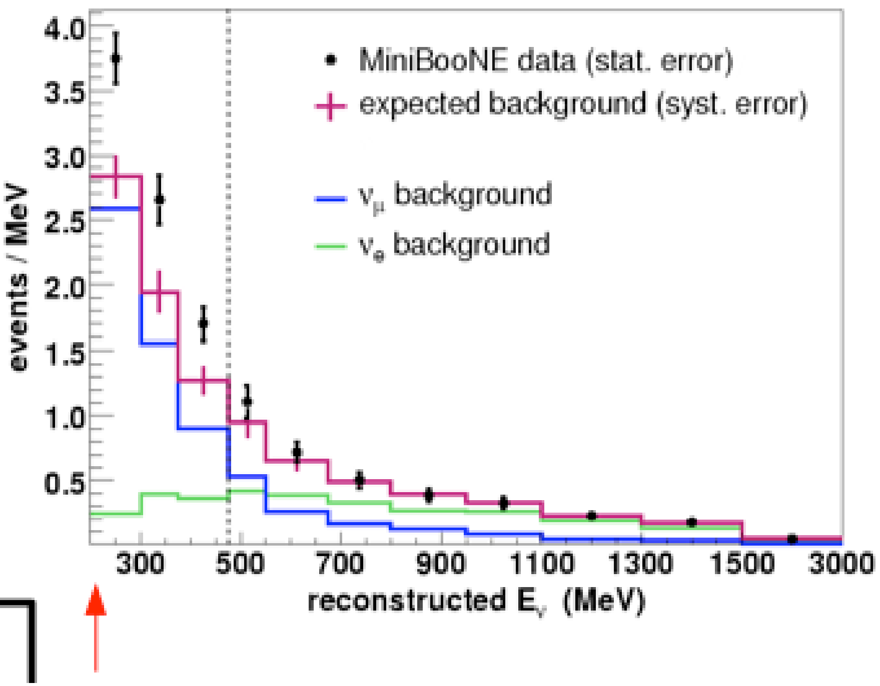
⇒ Inconsistent with a $\nu_\mu \rightarrow \nu_e$ oscillations

Exclude region in parameter space:



Phys. Rev. Lett. 98, 231801 (2007),





96 ± 17 ± 20 events above background, for 300< Ev QE <475 MeV

Deviation: 3.7 σ

Investigating the low E excess (E < 475 MeV)

Opened bin from 200- 300 MeV.

Excess persists below 300 MeV

Future plans

- Run MiniBooNE in anti-neutrinos for several more years to make oscillations search in anti-neutrino mode.
  - Statistics are less but background are smaller and somewhat different.
  - Provides another low *E* data set and directly checks LSND.

- Constrain further the systematic errors in the analysis of NuMI beam events. This tests properties if the detector with a different beam.

- SciBooNE experiment can test properties of the Booster neutrino beam with different detector. Will provide new data on ν cross sections.

- Study exotic scenarios (*e.g.* extra dimensions – Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005-) that could explain low E excess.

- MicroBooNE
  - New proposed experiment to put a 70 ton Liquid Argon detector near MiniBooNE
    - High ν_e efficiency down to low energies
    - ***Can tell electron from gamma events***
    - Nearly free of background from misidentified particles

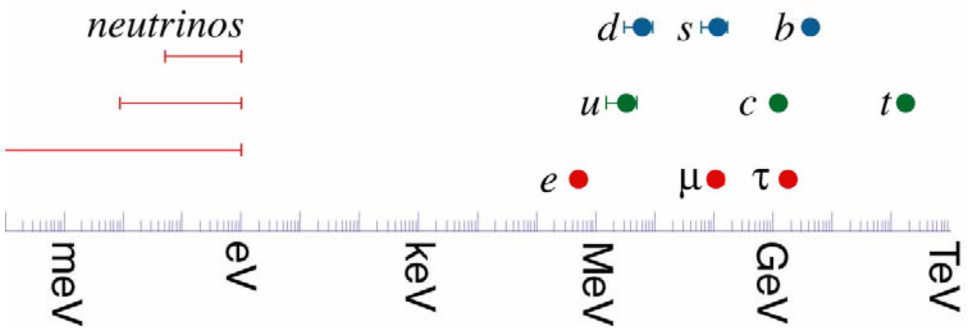
What we learned

- Lepton Flavor is not conserved
- Neutrinos have tiny mass, not very hierarchical
- Neutrinos mix a lot

the first evidence for

demise of the Minimal Standard Model

Very different from quarks



What still we have to observe or measure with higher precision

- The source of atmospheric oscillations (detect τ appearance)
- Three angles (θ_{12}, θ_{13}, θ_{23})
- Two mass squared differences (Δm^2_{12}, Δm^2_{23})
- The sign of the mass squared difference Δm^2 ($\pm\Delta m^2_{23}$)
- One CP phase (δ)
- The absolute masse scale
- Are neutrino Dirac or Majorana particles (or both)?
- Are there more - sterile - neutrinos?

All the underlined items can be studied with LBL experiments

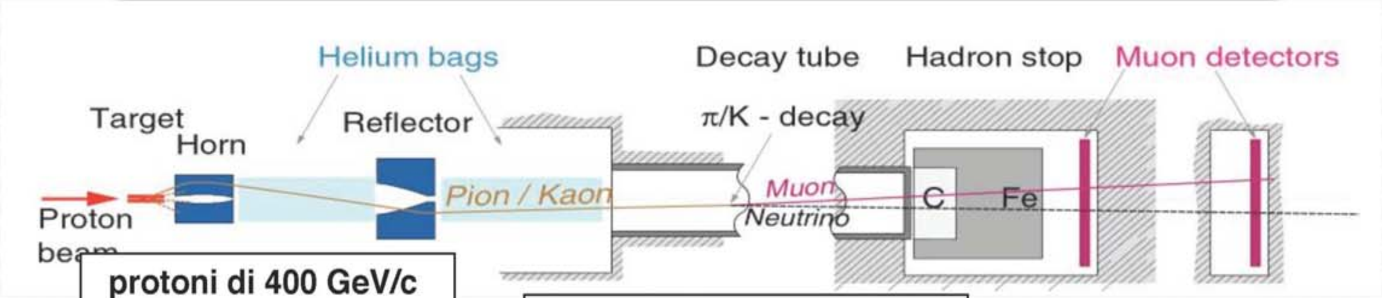
Discovery

Precision meas.

The source of atmospheric oscillations

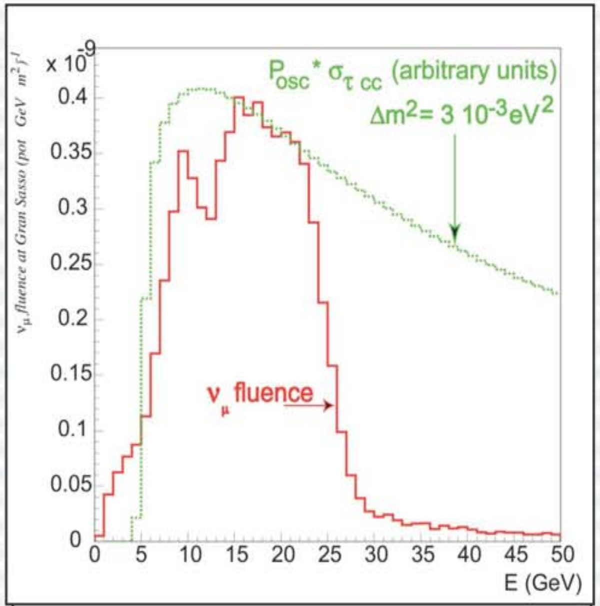
The OPERA experiment at LNGS

CNGS : neutrini dal CERN al Gran Sasso

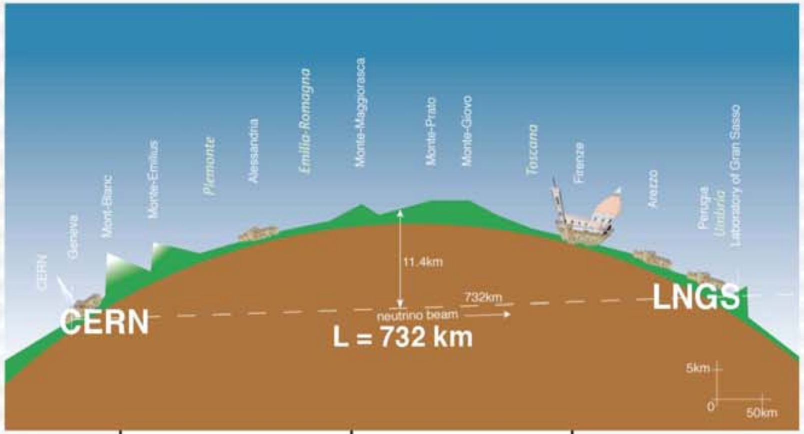


protoni di 400 GeV/c su bersaglio di grafite

decadimento in volo di π e k in un tunnel lungo 1 km



fascio progettato per massimizzare il rate di interazione di ν_τ a LNGS



$<E\nu_\mu>$	17 GeV
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	< 1%
$\bar{\nu}_\mu / \nu_\mu$	4%
ν_τ *prompt*	trascurabile

OPERA @ LNGS

INFN: 54 FTE - sez. AQ, BA, BO, LNGS, LNF, NA, SA, PD, RM1

BRUSSEL, ITEP, JINR, BERN UN., NEUCHATEL, ZURIGO, LYON UN.-IPNL, HAIFA, METU ANKARA, AICHI UN,TOHO UN,KOBE UN., NAGOYA UN., UTSONOMYA, LAPP (ANNECY), MUNSTER UN., IHEP(PECHINO), BERLINO, HAGEN, DESY, ROSTOK, STRASBURGO, ORSAY, ZAGABRIA

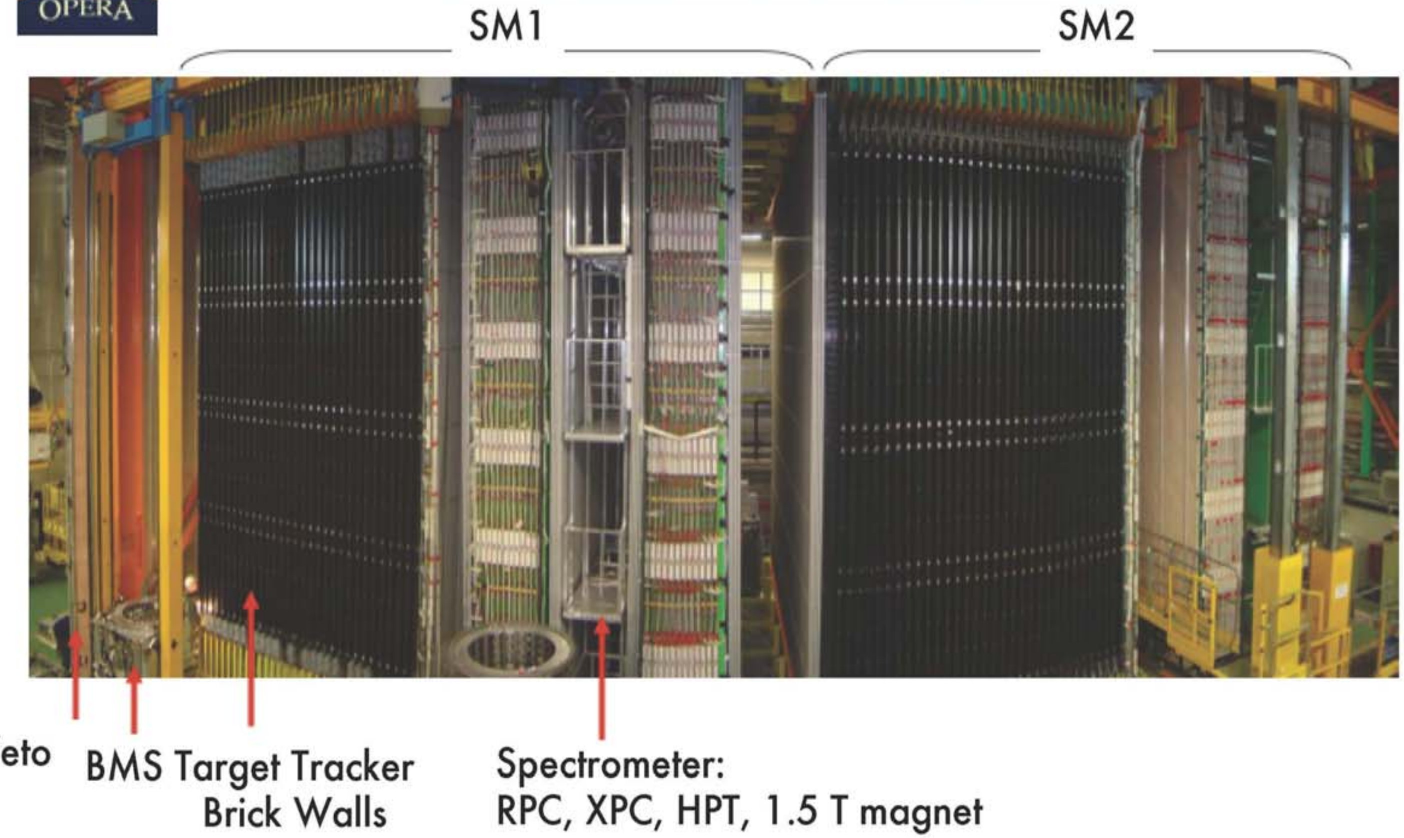
Aims

- Direct observation of ν_τ appearance in the CNGS ν_μ beam due to $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations
- sub-leading $\nu_\mu \rightarrow \nu_e$ oscillations

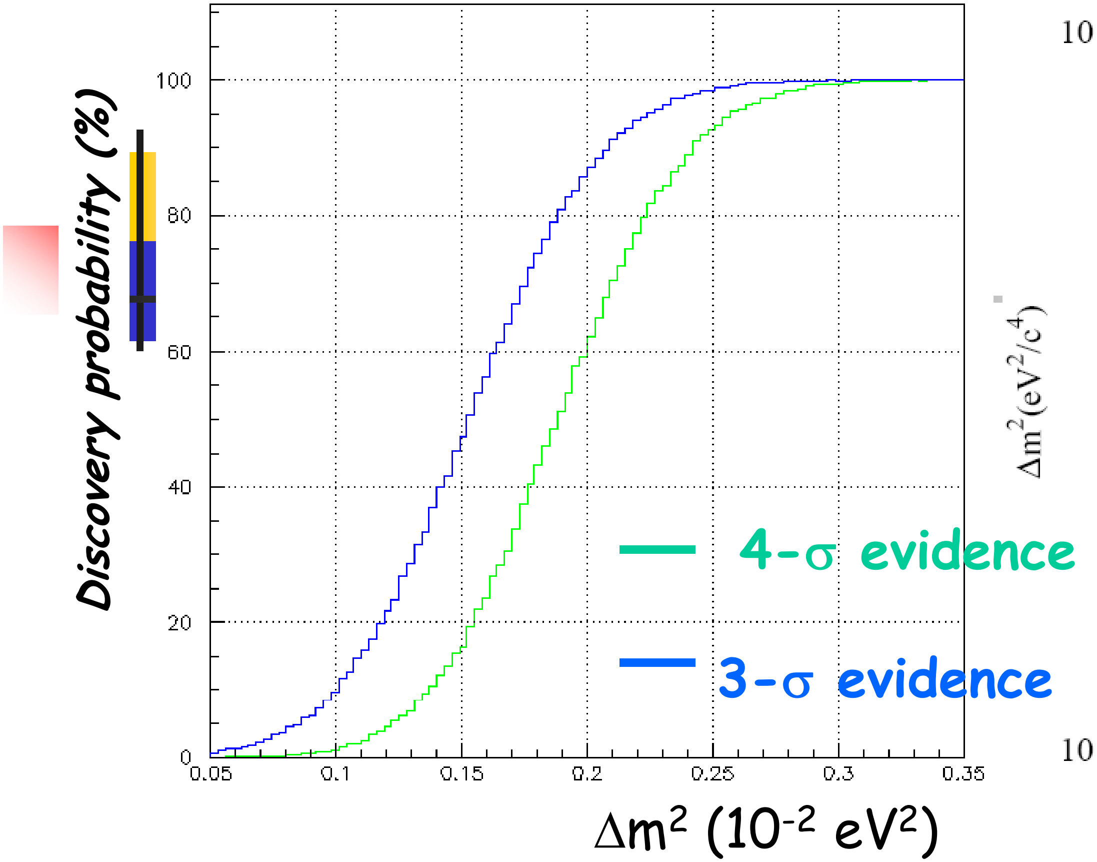
Milestones

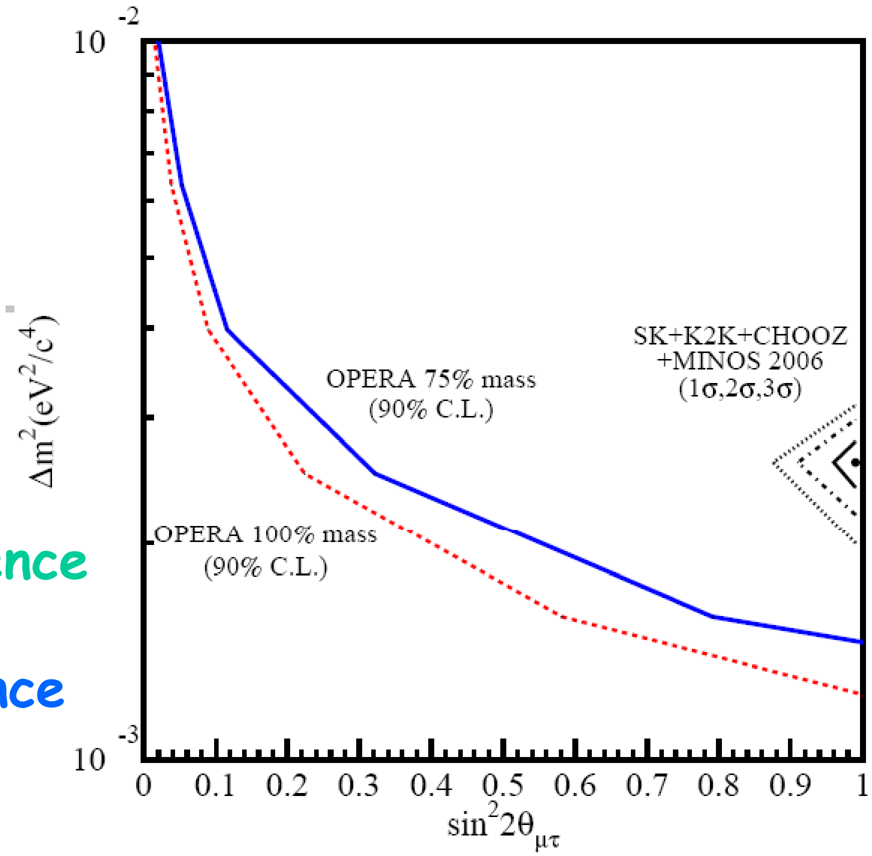
- 2002 Start of detector construction
- Mar 2003 First spectrometer completed
- Mar 2005 Second spectrometer completed
- May 2006 electronic detectors commissioning
- Aug 2006 First CNGS technical run, 0.76 x10^{18} integrated p.o.t. 319 ν-interactions in the rock + mechanical structures (300 expected)
- Oct 2006 Start of brick production - Very short CNGS run - 29 ν-events (no emulsions)
- Oct 2007 New CNGS physics run with 40% target- Only 0.82 x10^{18} p.o.t delivered- 38 neutrino interactions detected in the target
- Apr 2008 112000 bricks produced and installed (73% target)
- Jun 2008 New CNGS run (SPSC schedule) - 30 10 x^{18} p.o.t. expected in 147 days of SPS run

The OPERA detector



Target: 1.35t Lead+Emulsion (25% reduction wrt proposal 154 k bricks,)
112 k bricks produced+installed (73%) .



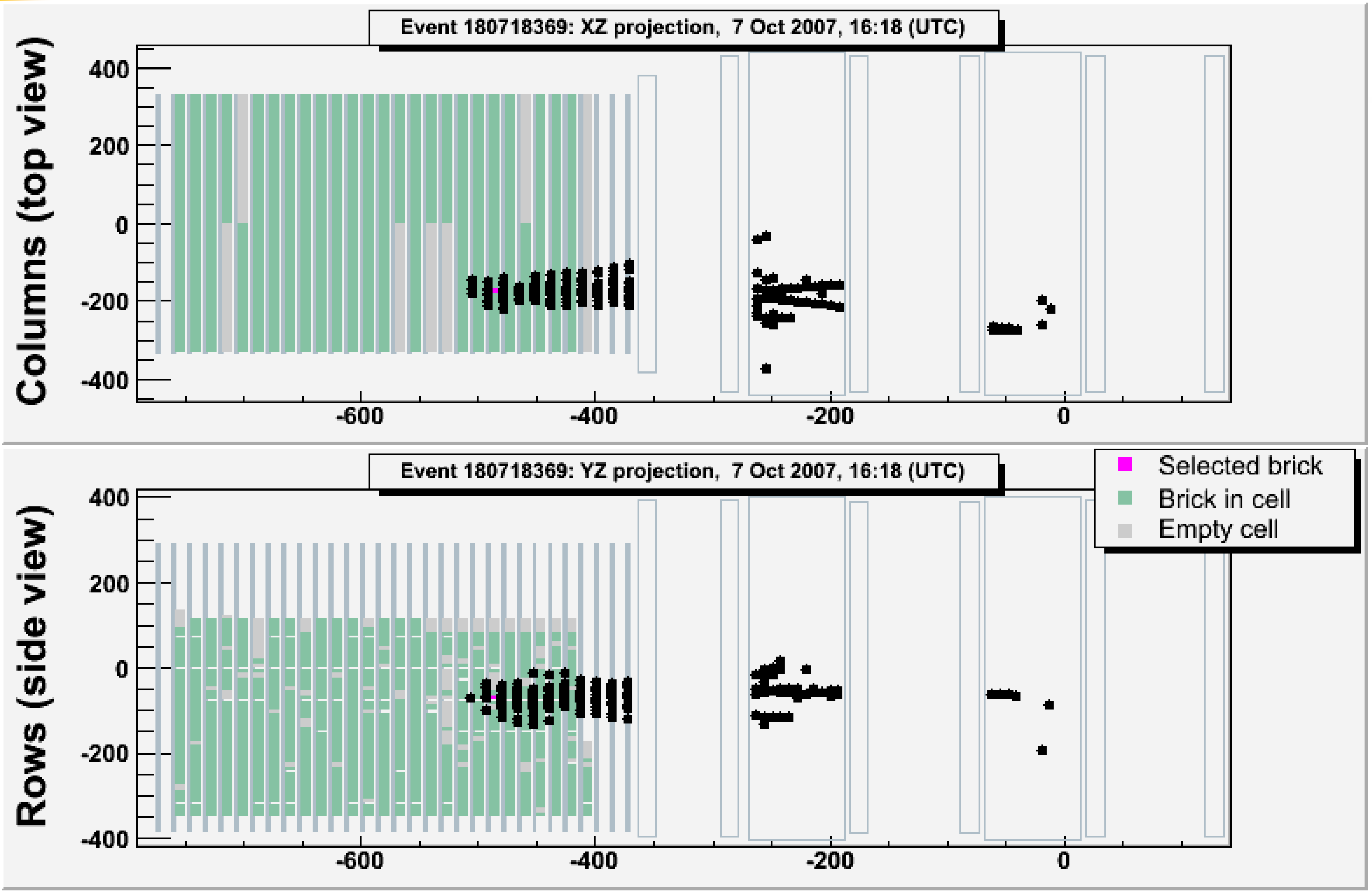


τ^- Decay channels	Signal ÷ $(\Delta m^2)^2$ – Full mixing		Background: Charm Hadron interaction Muon scattering
	Δm^2 = 2.5 x 10^{-3} eV^2	Δm^2 = 3.0 x 10^{-3} eV^2	
$\tau^- \to \mu^-$	2.9	4.2	0.17
$\tau^- \to e^-$	3.5	5.0	0.17
$\tau^- \to h^-$	3.1	4.4	0.24
$\tau^- \to$ 3h	0.9	1.3	0.17
ALL	10.4	15.0	0.76

Report on Charm candidate

F. Di Capua
on behalf of Napoli group

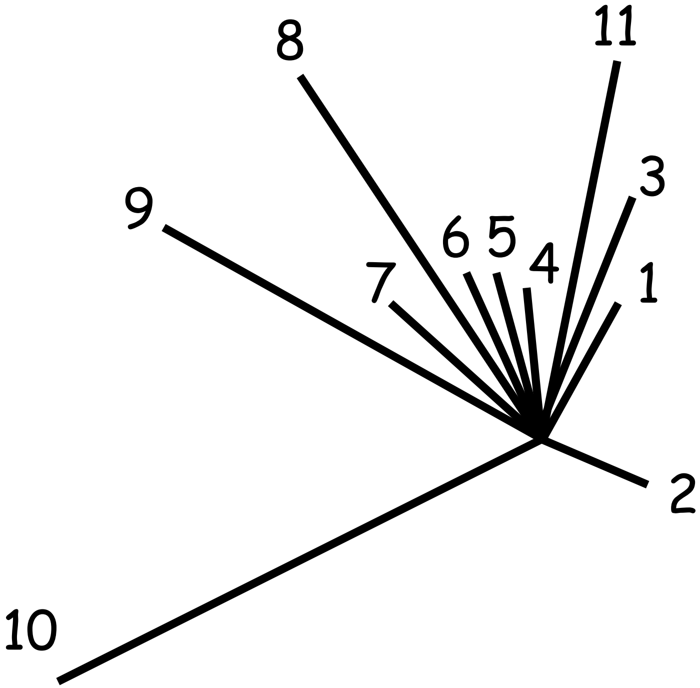
Event 180718369



Event classified as CC

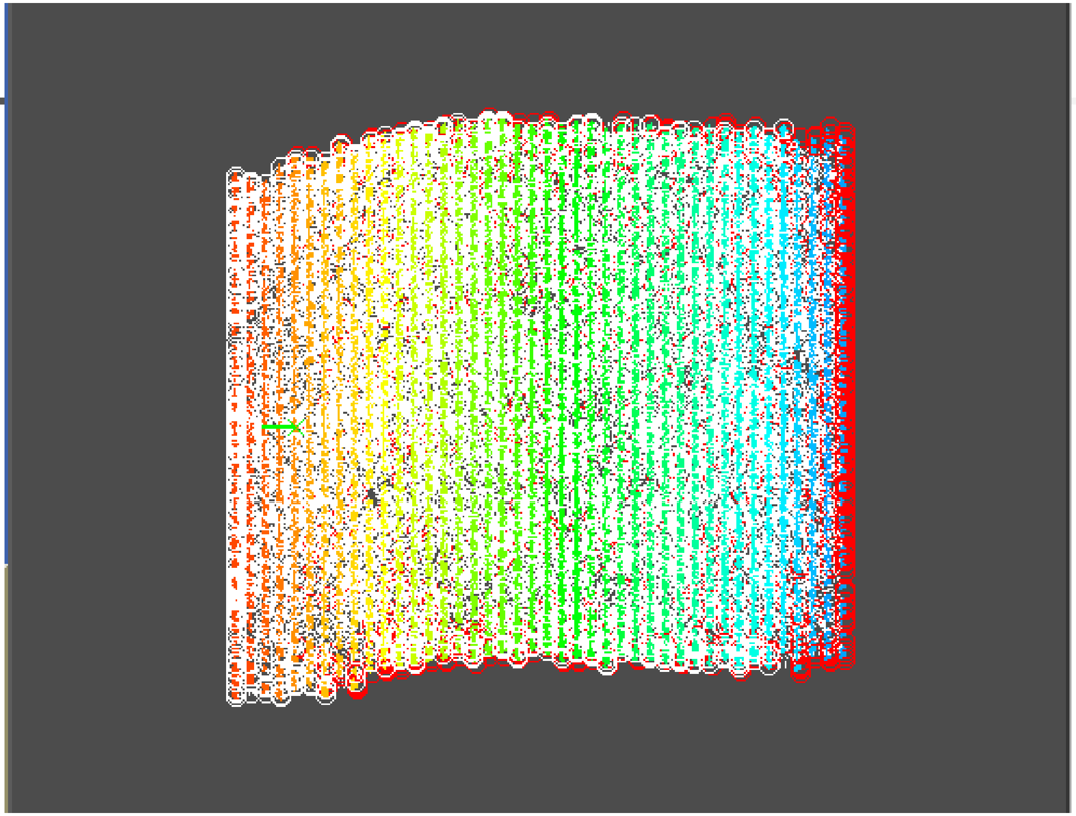
Manual check in pl 19

Very nice view of 11 tracks crossing at same point

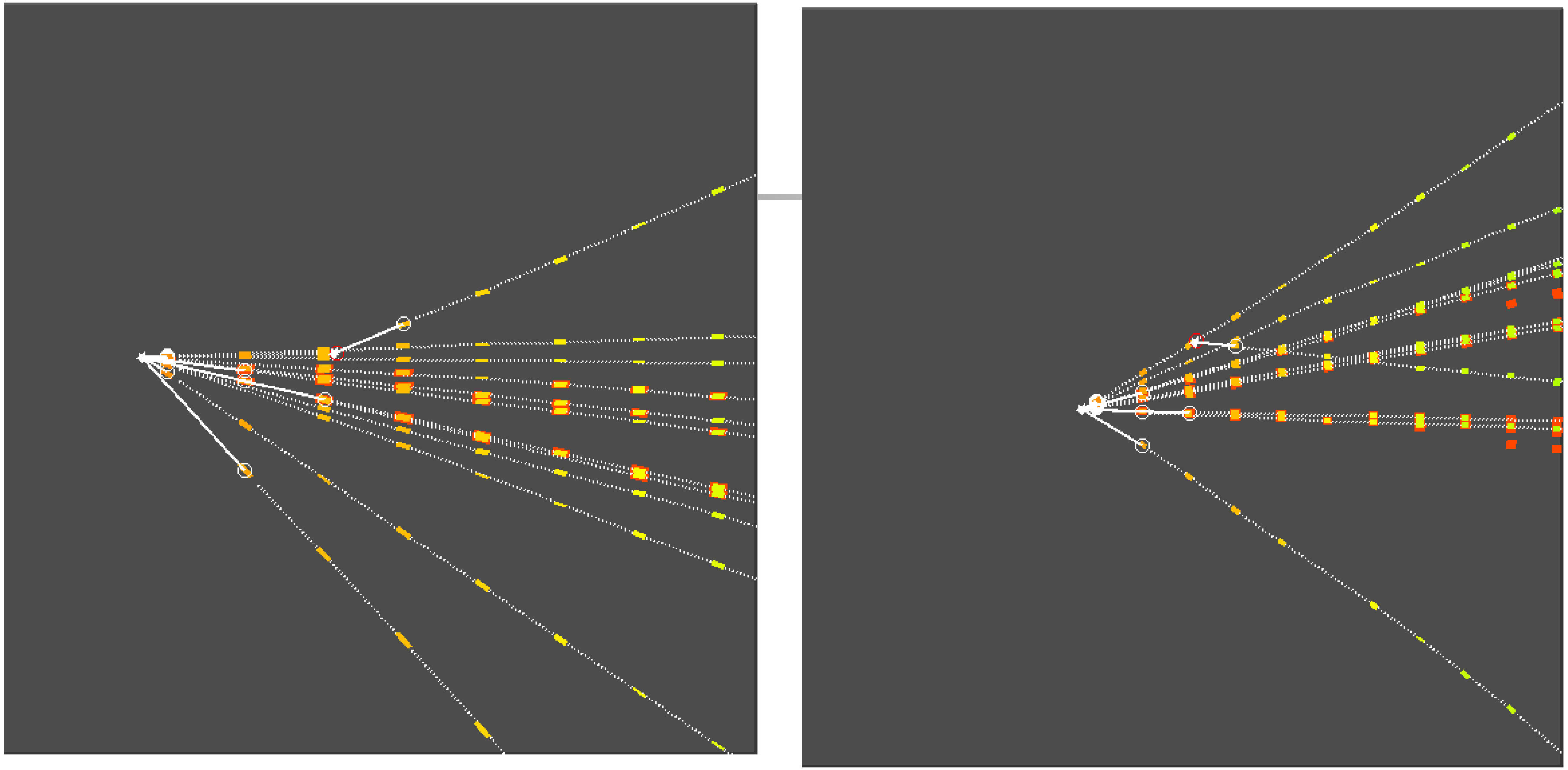


Trk	TX	TY	
1	0.009	0.037	SB
2	0.049	-0.015	
3	-0.033	0.067	SB
4	-0.010	0.031	
5	-0.027	0.045	SB
6	-0.033	0.067	SB
7	-0.076	0.068	SB
8	-0.081	0.133	
9	-0.184	0.109	
10	-0.305	-0.132	
11	0.005	0.142	

Volume scan: vertex reconstruction



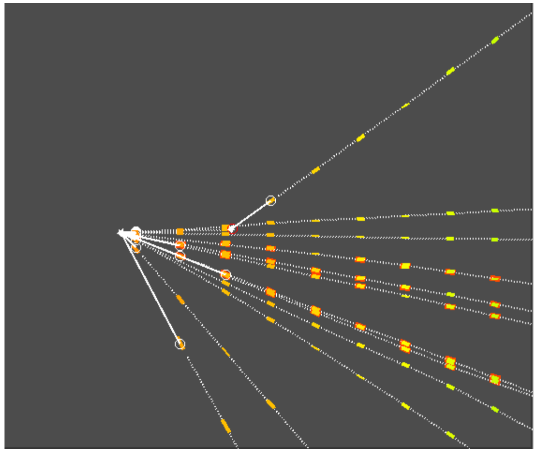
1cm^2 from plates 15 to 57



High multiplicity 1ry vertex and 2ry interaction

Track from decay is a SB track!!!

The CS confirmation is a very good validation of the topology



Kink analysis

2ry Vertex Impact Parameter

Parent track	1.70 μm
Daughter track	3.76 μm

Parent track slopes

Plate	TX	TY
19	0.005	0.139
20	0.005	0.141
21	0.008	0.147

Daughter track first segment

TX=0.113 TY=-0.028

θ_{kink}=0.204 rad

1ry Vertex position

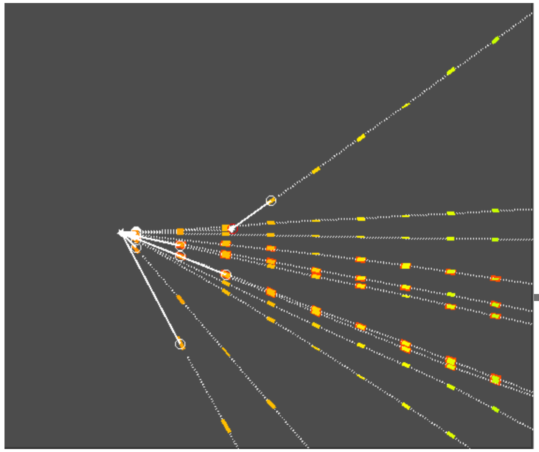
X=60338.0 Y=67065.0 Z=-422.7

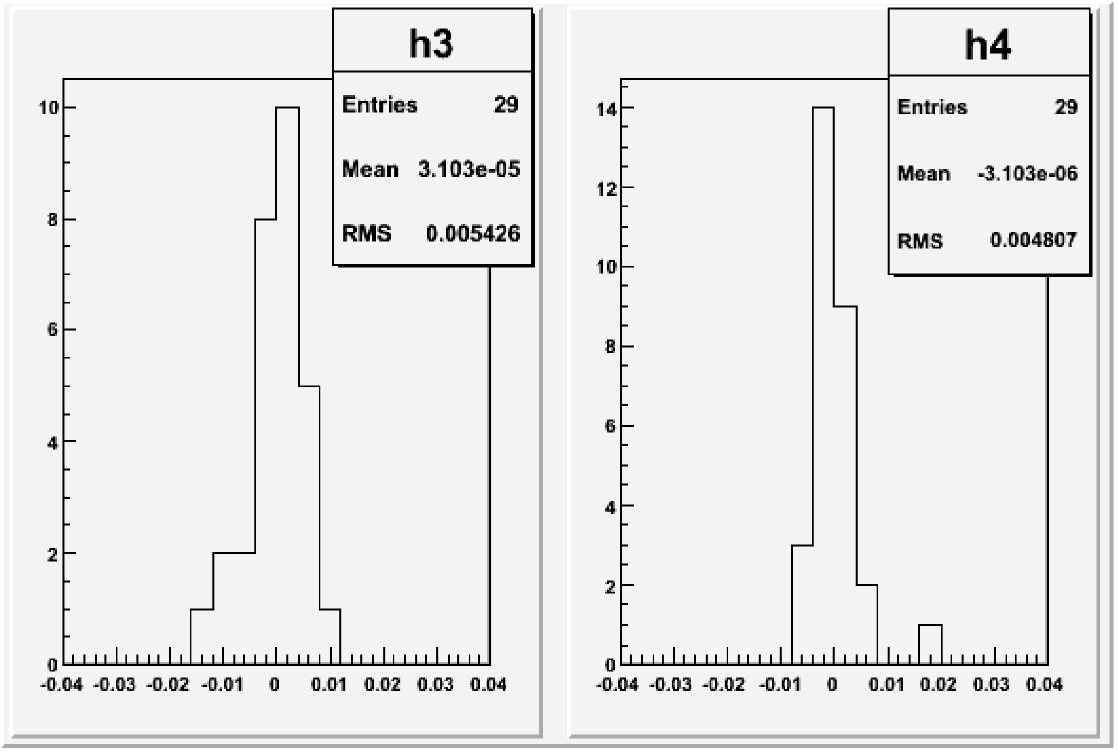
2ry Vertex position

X=60356.1 Y=67526.9 Z=2824.3

Flight length=3247.2μm

Kink analysis

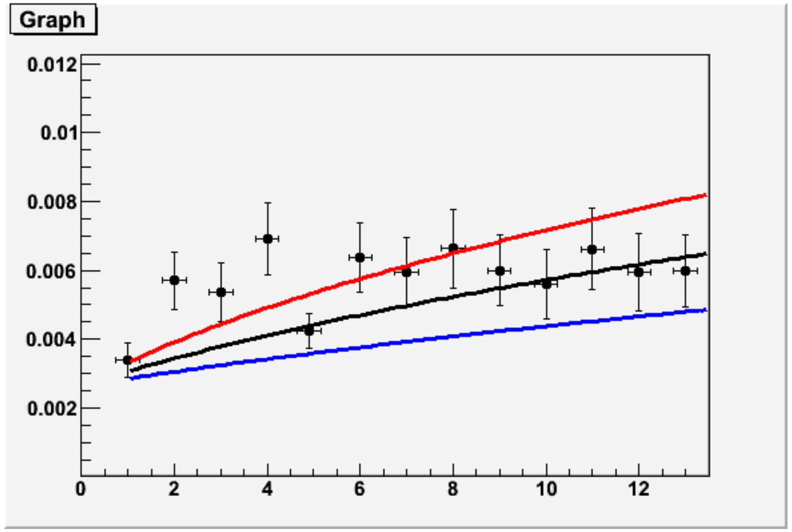


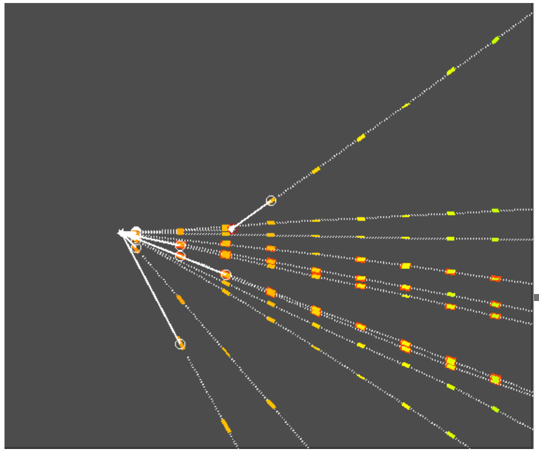


Daughter slopes wrt to average slope

Daughter momentum

$P=3.9^{+1.7}_{-0.9}$ GeV





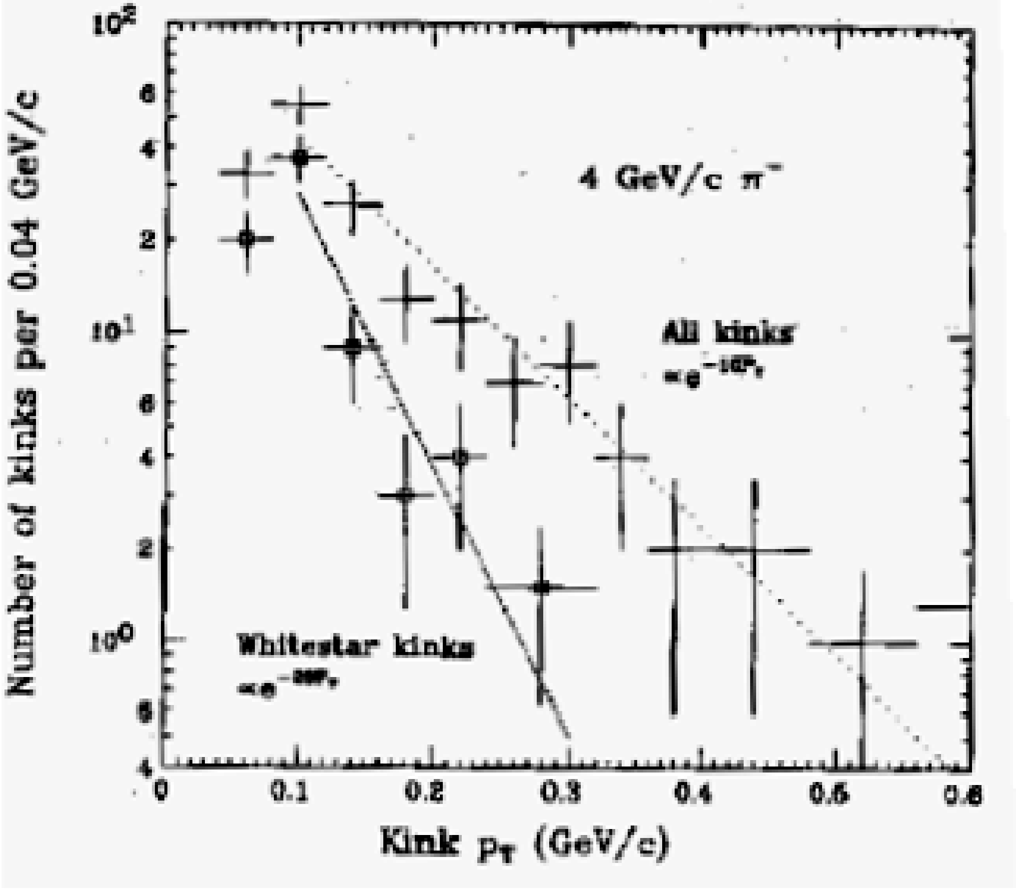
Kink analysis

Daughter track transverse momentum

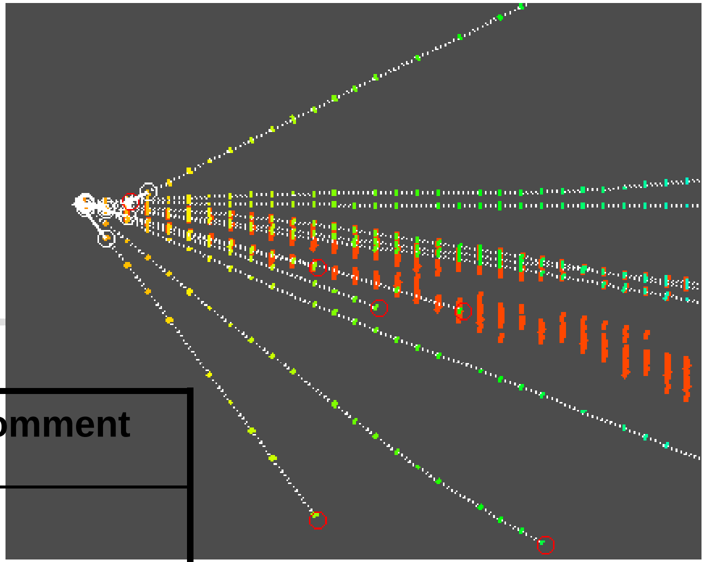
P_T=796 MeV

P_T^{MIN}=606 MeV (90% CL)

hadronic Kink (KEK measurement)



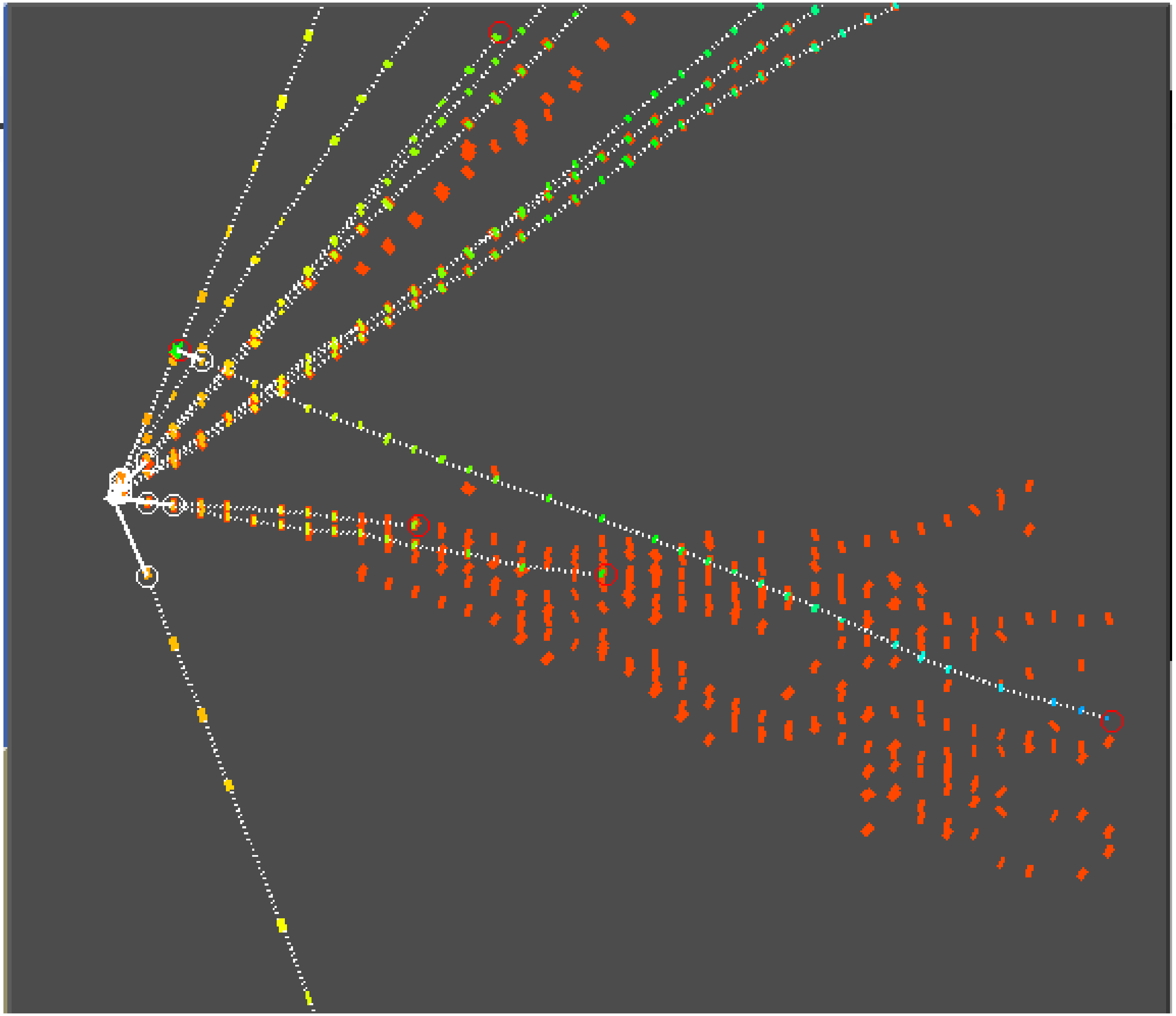
1ry vertex analysis

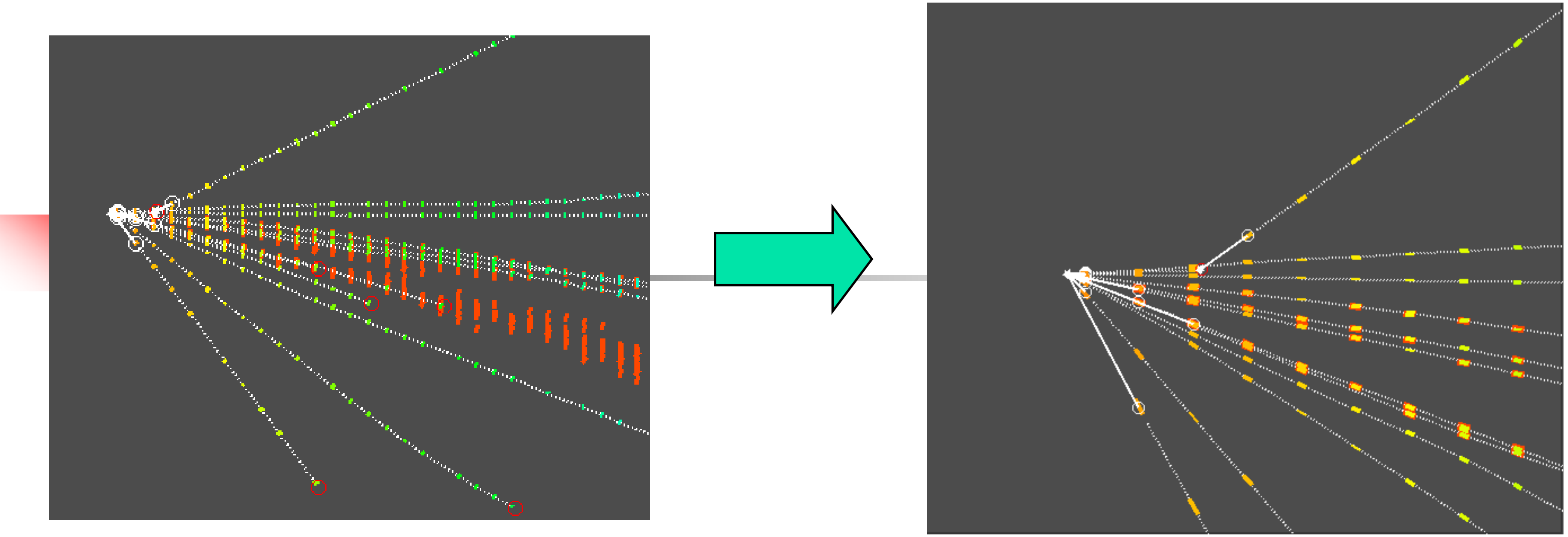


Trks	TX	TY	IP	Momentum(GeV)	Comment
1	0.005	0.036	3.30	$1.7^{+0.5}_{-0.3}$	
2	0.005	0.139	1.01	-	parent
3	0.002	0.064	6.64	>20.0	SB
4	-0.021	0.064	7.15	$2.1^{+0.7}_{-0.4}$	SB
5	-0.029	0.046	2.83	>8.4	SB
6	-0.031	0.064	7.32	$2.4^{+0.8}_{-0.5}$	SB
7	-0.076	0.068	4.19	$1.8^{+1.6}_{-0.6}$	SB
8	-0.089	0.141	6.88	$2.5^{+1.4}_{-0.7}$	
9	-0.183	0.106	5.39	$0.7^{+0.2}_{-0.1}$	
10	-0.297	-0.143	19.17	$0.7^{+0.3}_{-0.1}$	
11	-0.067	0.008	7.26	$3.5^{+3.6}_{-1.2}$	e-pair
12	-0.069	0.005	16.80	$2.0^{+3.1}_{-0.8}$	e-pair

E^{ν}_{vis}>50 GeV

shower





Conclusion

A charm candidate is found

Muon track is difficult to be reconstructed in the electronic detector, but strong indication there is combining emulsion-electronic information

Further study will be done on charm daughter slopes, attempt to reduce error on momentum estimation (training for much more important decays)

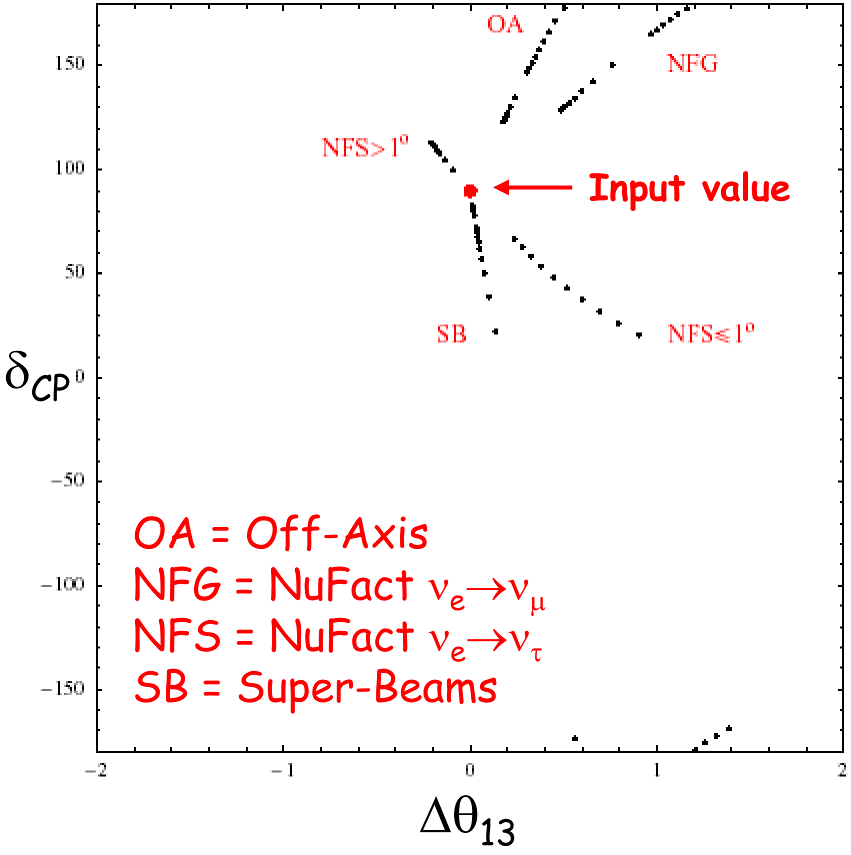
The full event look like good for particle physic books: kink, high multiplicity, electromagnetic shower

The quest for θ_{13}

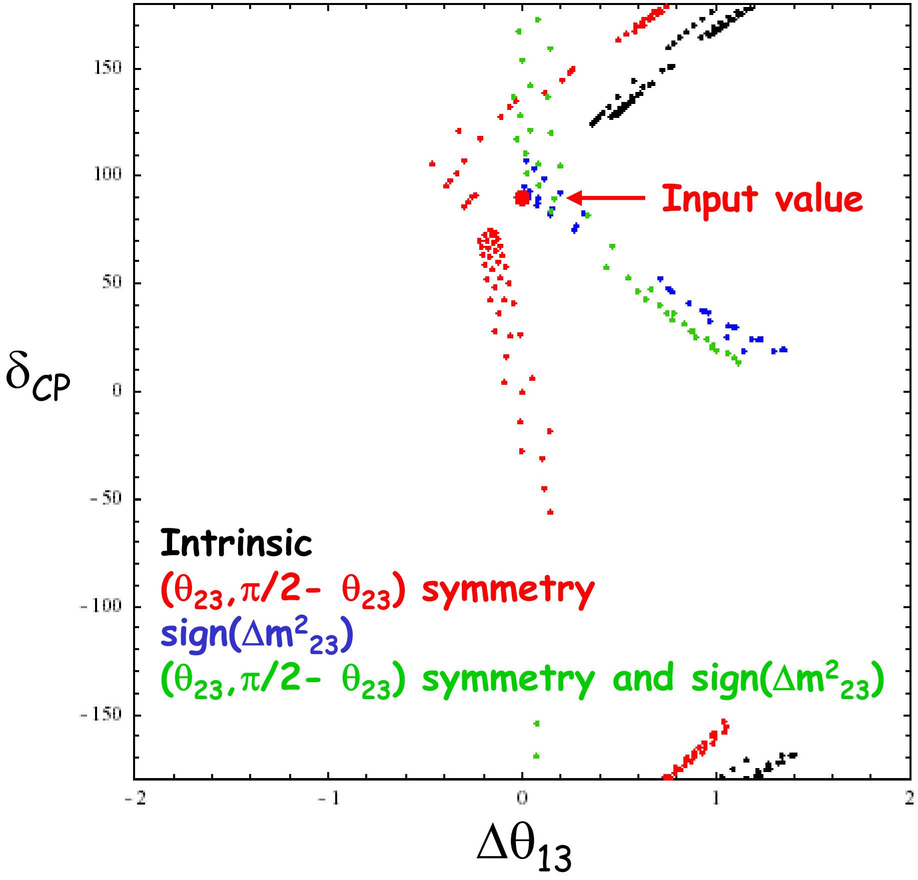
- T2K
- Reactor experiments

The problem of degeneracies

Intrinsic degeneracies
for different scenarios



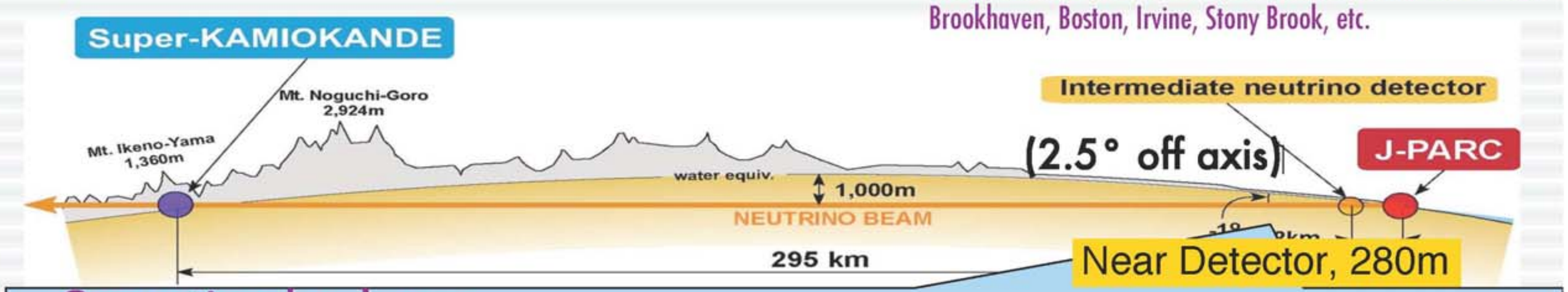
Eightfold degeneracies



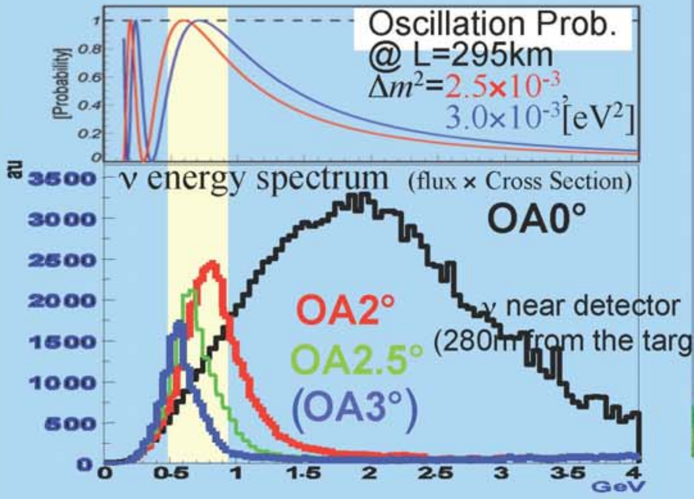
T2K : J-PARC ν beam to SK

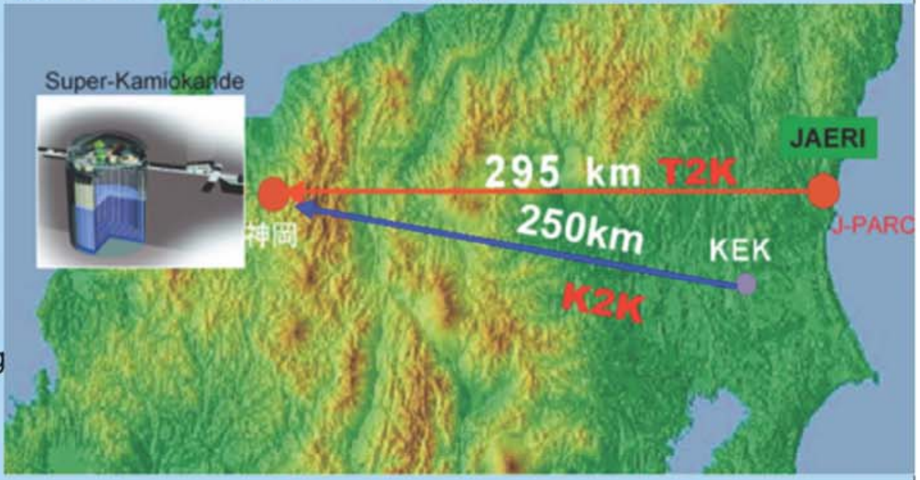
INFN: 2.9 FTE sez. PD, BA, RM1, NA

KEK, ICRR Tokyo, Kyoto Un., Tokyo Un., TRIUMF, IHEP Pechino, Saclay, INR, Barcellona Un., Ginevra Un., RAL, Imperial College, Brookhaven, Boston, Irvine, Stony Brook, etc.



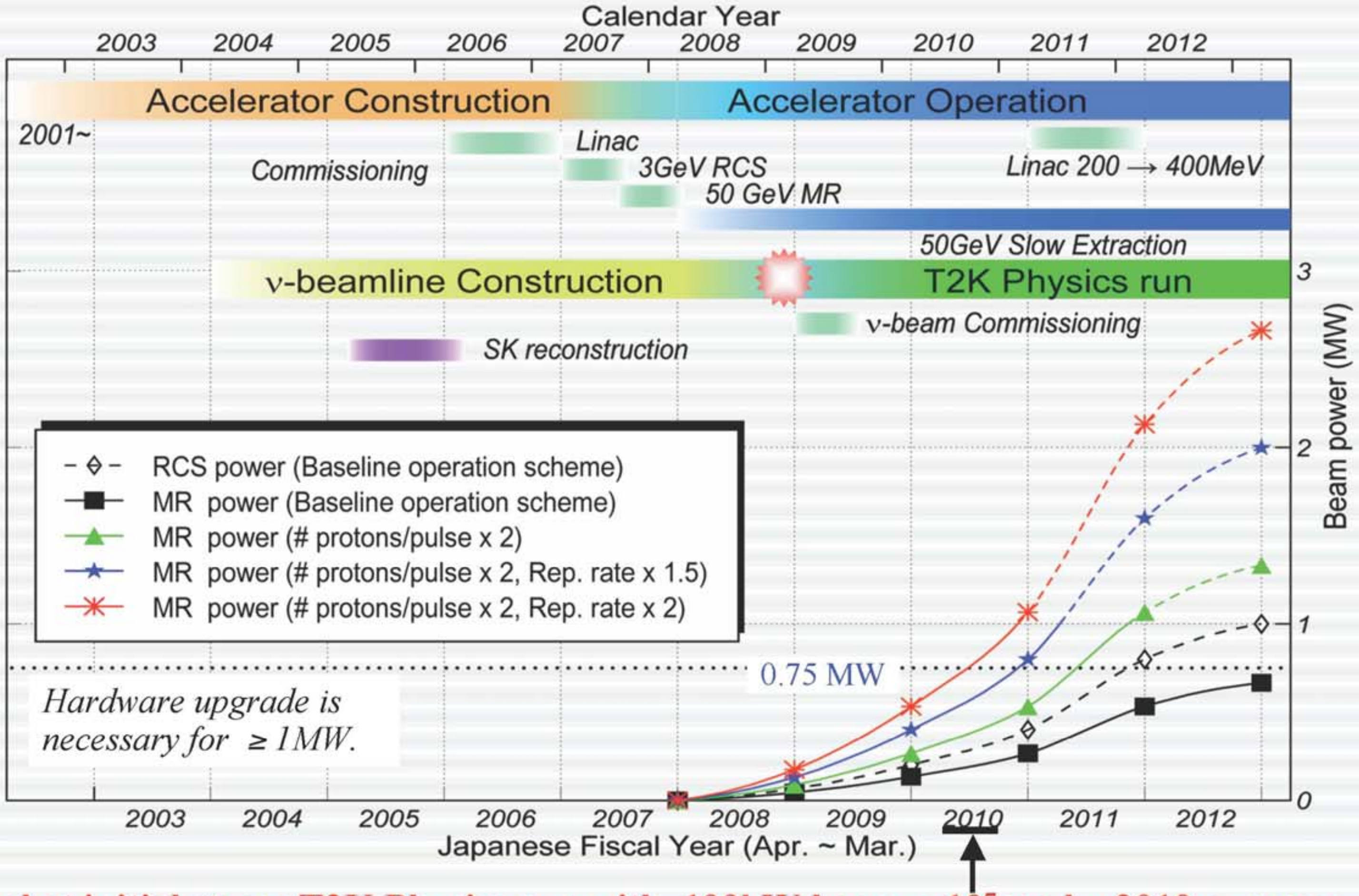
- **Conventional ν_μ beam:**
  - **protons + graphite target → pions**
  - **π^+ or π^- focused selectively**
  - **decay : $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \nu_\mu$**
- **Pseudo-Monochromatic beam by Off-Axis method** (ref. BNL E899)





Slides by M. Mezzetto

J-PARC Schedule



Hardware upgrade is necessary for ≥ 1MW.

Goal at initial stage: T2K Physics run with 100kW beam × 10^7 sec by 2010 summer.

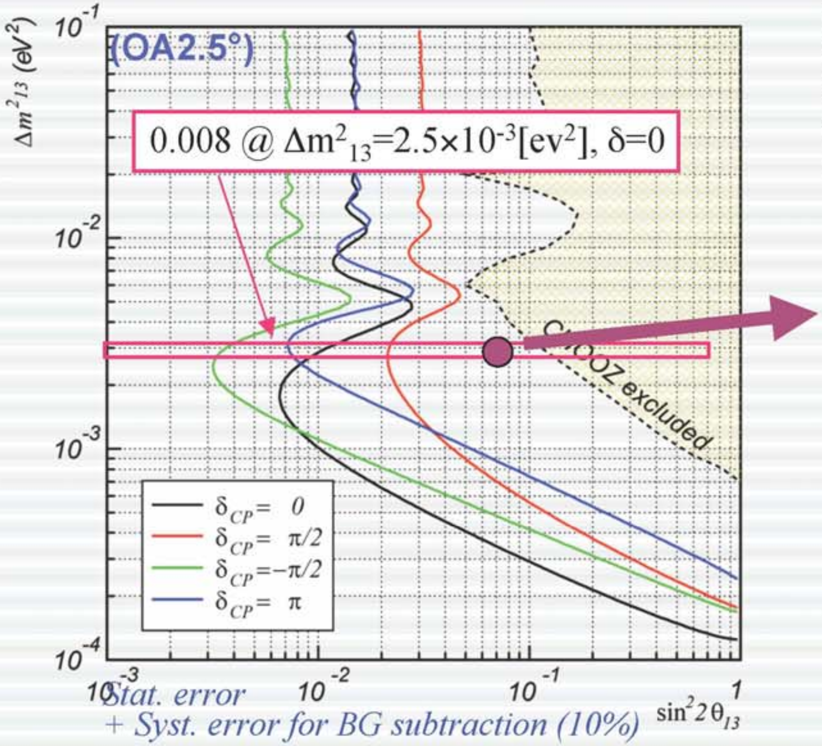
Physics sensitivity

- ν_e appearance

T2K 90%CL sensitivity

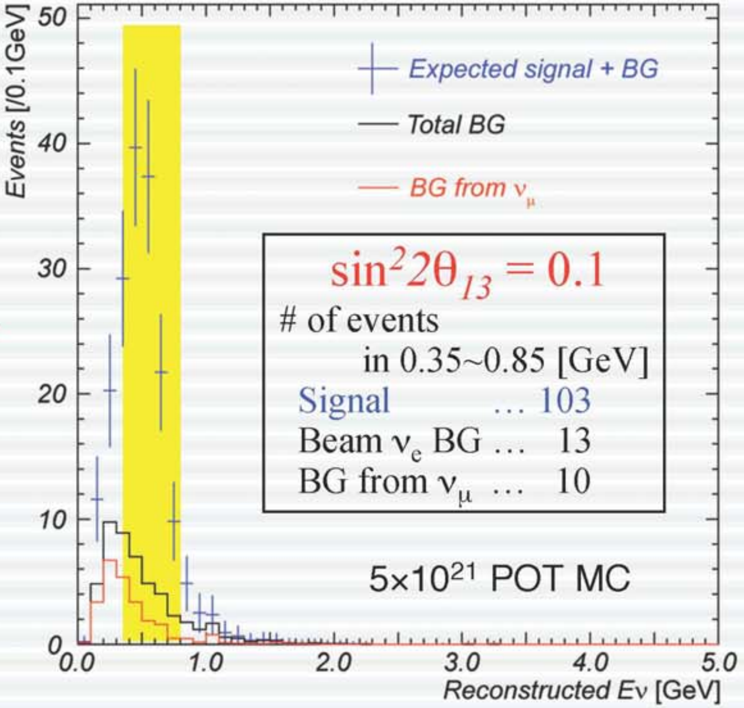
$\sin^2 2\theta_{23} = 1.0$ is assumed

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



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

Eνe @ SK ($\sin^2 2\theta_{13} = 0.1$, $\Delta m^2=2.5\times10^{-3}$)



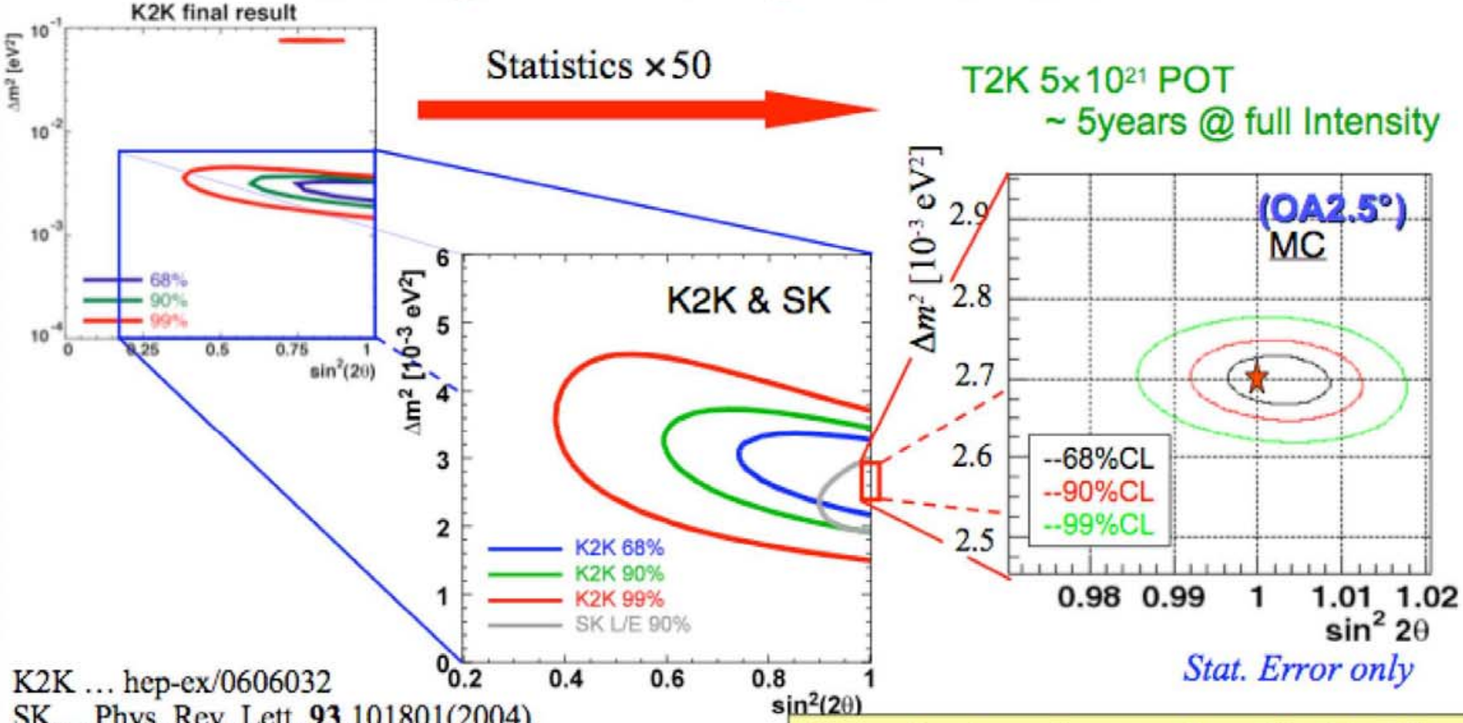
$\sin^2 2\theta_{13} = 0.1$

# of events
in 0.35~0.85 [GeV]

Signal	… 103
Beam ν_e BG	… 13
BG from ν_μ	… 10

Physics sensitivity (cont'd)

- ν_μ disappearance : $P(\nu_\mu \rightarrow \nu_\mu)=1-\sin^2\theta_{23}\sin^2(1.27\,\Delta m^2_{23}L/E)$
  - Goal : $\delta(\sin^2 2\theta_{23})\sim 0.01$, $\delta(\Delta m^2_{23}) < 1\times 10^{-4}$ [eV^2]



Statistics ×50

T2K 5×10^{21} POT
~ 5years @ full Intensity

Stat. Error only

K2K … hep-ex/0606032
SK… Phys. Rev. Lett. **93**,101801(2004)

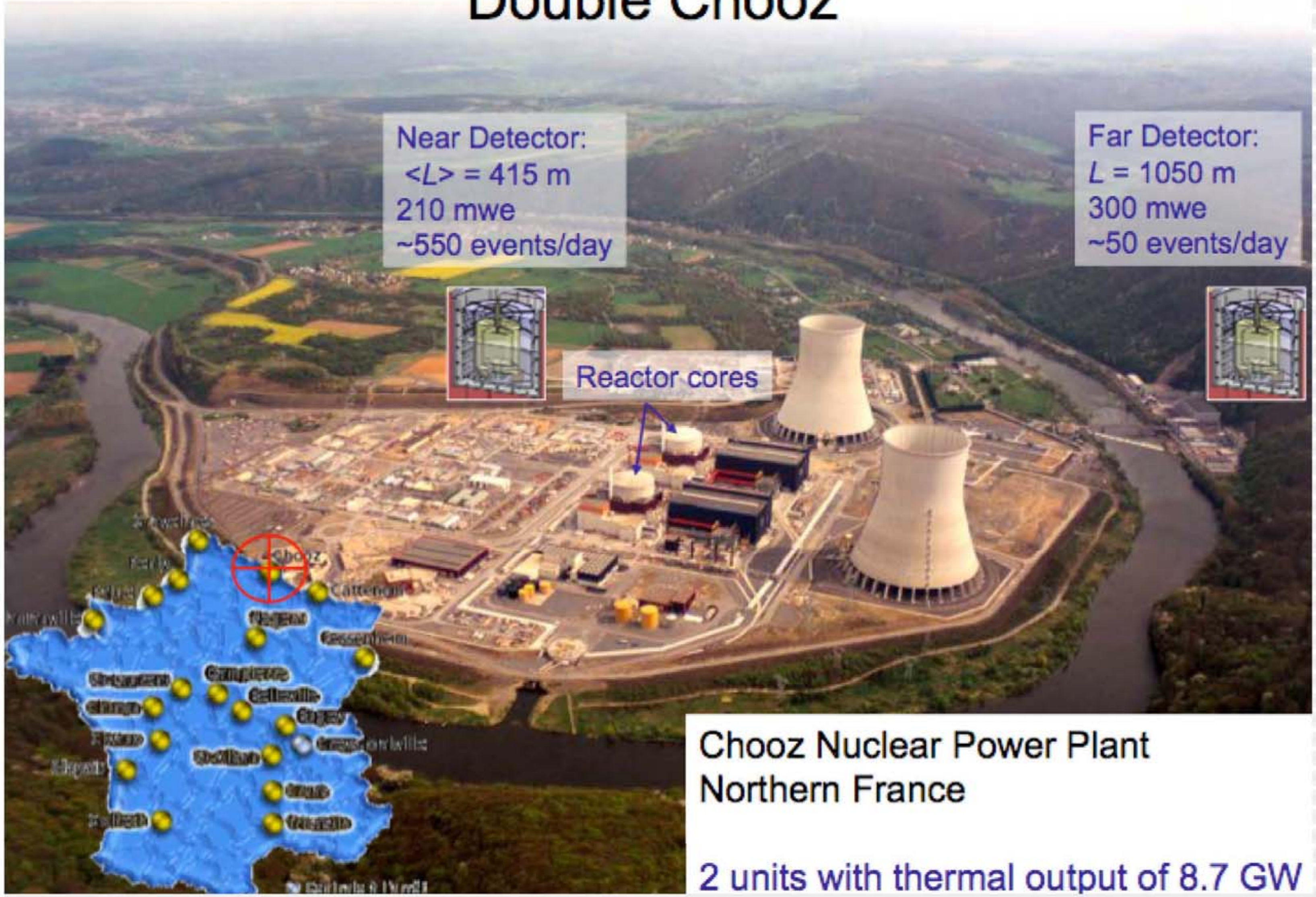
Note: Systematic error from the Far/Near Ratio:
$\delta(\sin^2 2\theta_{23})\approx 0.03$, $\delta(\Delta m^2_{23})\approx 1\times10^{-4}$
(much larger than the stat. error)

On the quest for Θ_{13} : reactor vs accelerator experiments

- Θ_{13} measurements from reactors suffer from correlation with Δm^2_{32}
- Accelerator experiments are affected by degeneracies, ambiguities & other correlations in addition (uncertainty on Θ_{23} , uncertainty in CP violating phase delta)

A precise measurement of Θ_{13} by reactors and accelerators could resolve some degeneracies
Or, a null result at reactors, would show the way to LBL experiments

Double Chooz



Near Detector:
<L> = 415 m
210 mwe
~550 events/day

Far Detector:
L = 1050 m
300 mwe
~50 events/day

Reactor cores

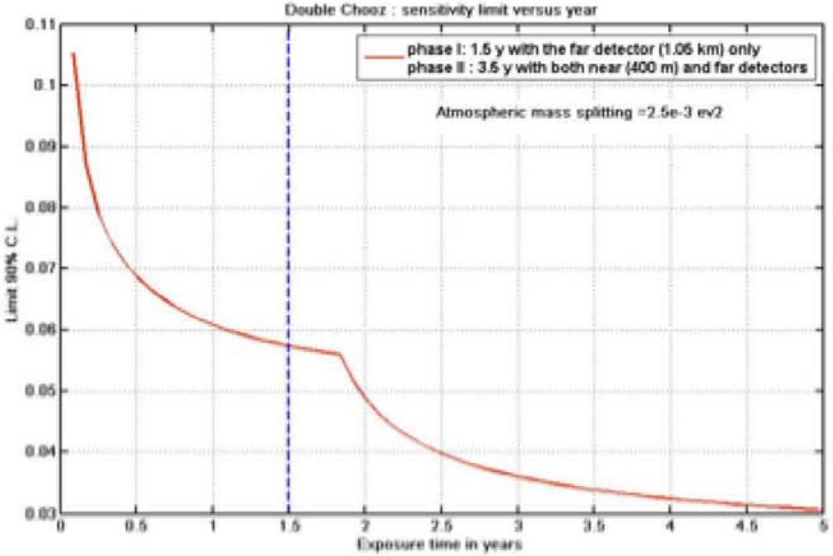
Chooz Nuclear Power Plant
Northern France

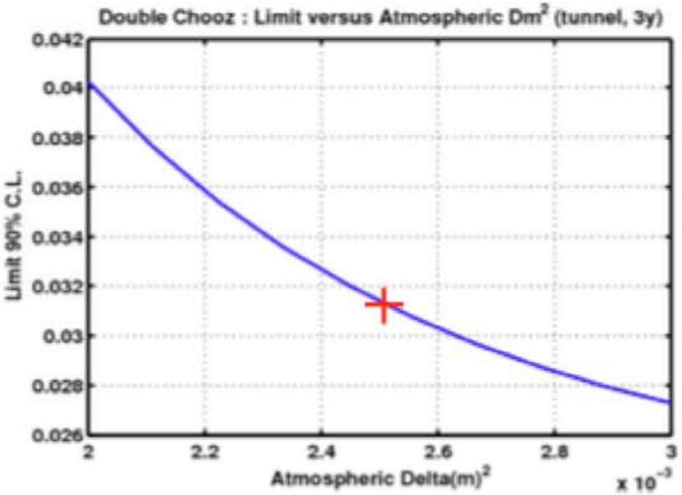
2 units with thermal output of 8.7 GW

Harris, La Thuile2008

Schedule and sensitivity

- Detector installation to start in May 2008
- FD data-taking starting mid-2009
- $\sin^2 2\theta_{13} < 0.06$ after 1.5 years





- ND data-taking starting mid-2010
- $\sin^2 2\theta_{13} < 0.03$ after an additional 3 years
- Can surpass the CHOOZ limit within 6 months

Global Systematic error <0.5% (Chooz 3%)

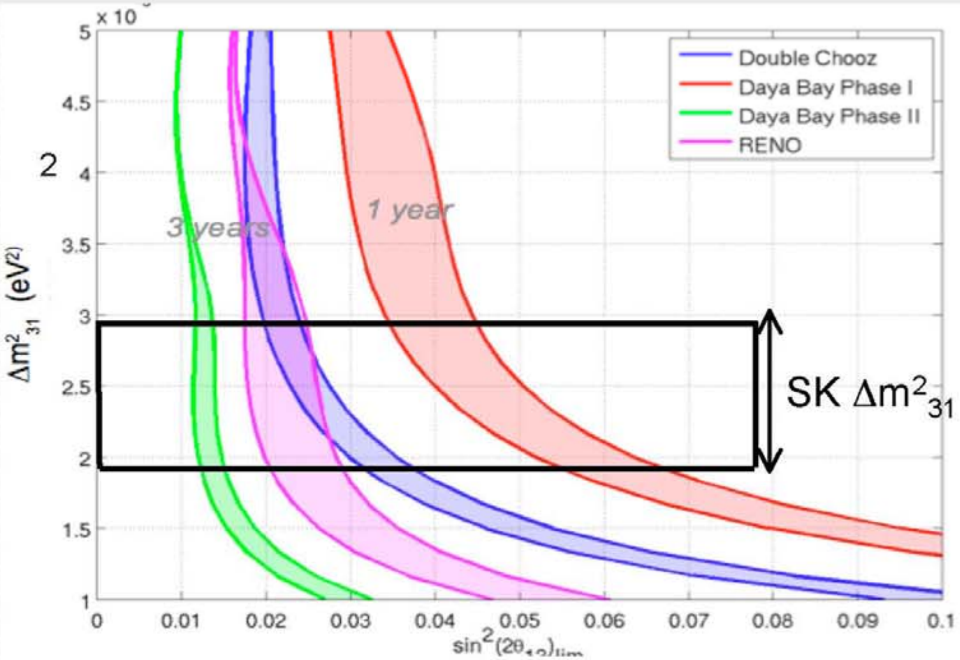
Reactor ν experiments

Reactor	Estimated start date	GW-t-yr (yr)	90% CL $\sin^2 2\theta_{13}$ sensitivity	For Δm^2 (10^{-3} eV^2)	Far event rate
Double Chooz	Mar 2009 (far) 2010 (near)	75 (1) 300 (1+3)	0.07 0.03	2.5	18,000/yr
Daya Bay	2010	3500 (3)	0.01	2.5	70,000/yr 110,000/yr (after 2010)
RENO	Late 2009	750 (3)	0.03	2.5	35,000/yr

Harris, La Thuile2008

(Mention's talk, GLoBES workshop 07)

Sensitivity Comparison



Best constraint

$\sigma_{rel} = 0.38$ %

$\varepsilon_{elt} = 10^{-4}$

Worst constraint

$\sigma_{rel} = 0.6$ %
$\sigma_{pwr} = 3.0$ %
$\sigma_{abs} = 3.0$ %

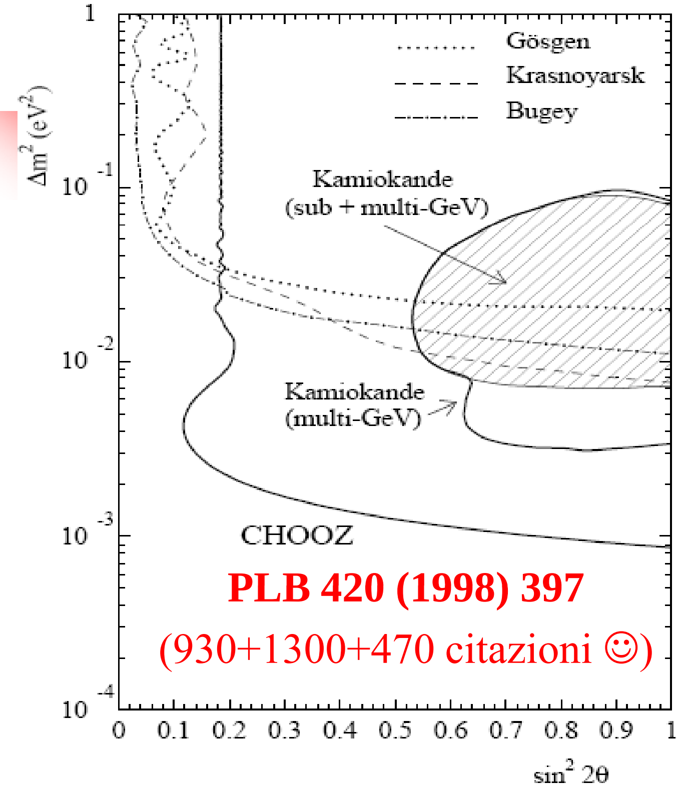
→ 3 first generation experiments: **Double Chooz**, **RENO** sensitivity ~ 0.02 to 0.03 (depending on sytematics, Δm^2 value, and backgrounds) and **Daya Bay Phase I** with sensitivity ~ 0.04 to 0.05 (1 year) ~ 0.03 to 0.035 (3 years)

- A second generation experiment: **Daya Bay** with forseen sensitivity ~ 0.01.

→ To go below 0.01 with reactor experiments seems difficult.

SuperBeam, βBeam, NuFact

La reinterpretazione dei dati di Chooz

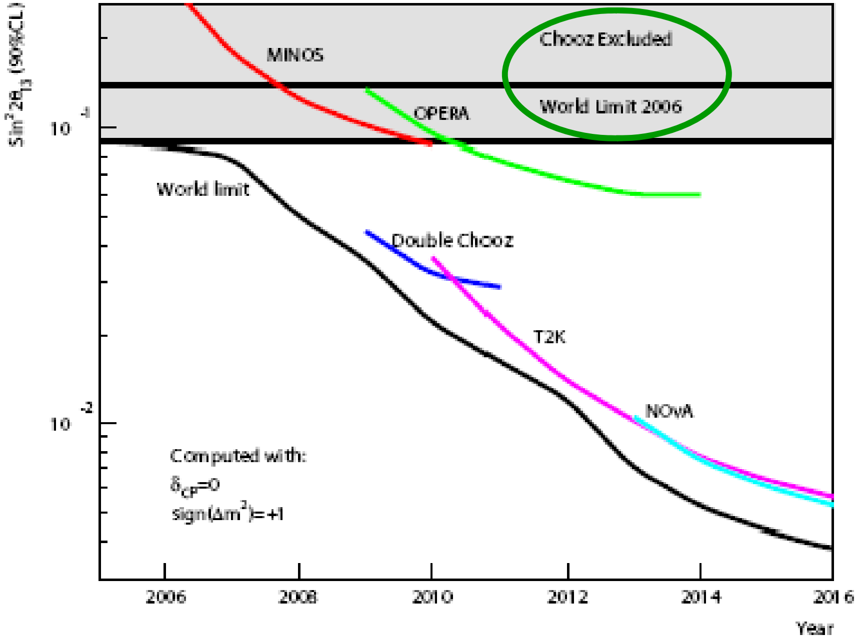


PLB 420 (1998) 397

(930+1300+470 citazioni ☺)

La rilevanza di questa re-interpretazione e' legata al valore "non troppo piccolo" (≈1/30) di:

$$\boxed{\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|}$$



$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} \;\simeq\;& \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
& - \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
& + \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

$$\Delta \equiv \Delta m^2_{31} L/(4E) \qquad \hat{A} \equiv 2\sqrt{2} G_F n_e E/\Delta m^2_{31}$$

Se ϑ_{13} >3°

$$\begin{aligned} P_{\nu_\mu\rightarrow\nu_e} \simeq\ & \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\ & - \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & + \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\ & + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \end{aligned}$$

O(10^1)xMINOS/NUMI

O(10^2) x MINOS/NUMI

O(10^3) x MINOS/NUMI

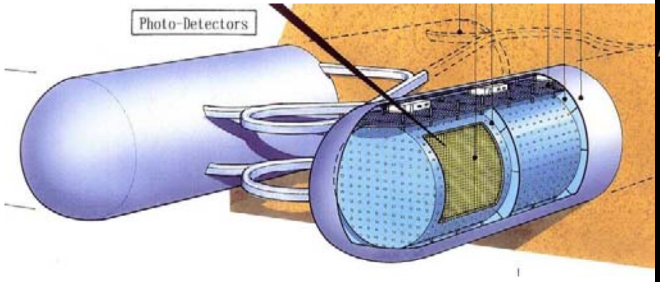
O(10^1) x MINOS/NUMI	Sorgenti convenzionali: T2K, NOVA, Modular etc.
O(10^2) x MINOS/NUMI	Ai limiti dell'utilizzo dei Superbeam: T2HK. Ideale per le sorgenti non convenzionali (Neutrino Factories, Beta-beams)
O(10^3) x MINOS/NUMI	Sorgenti non-convenzionali: Neutrino factories

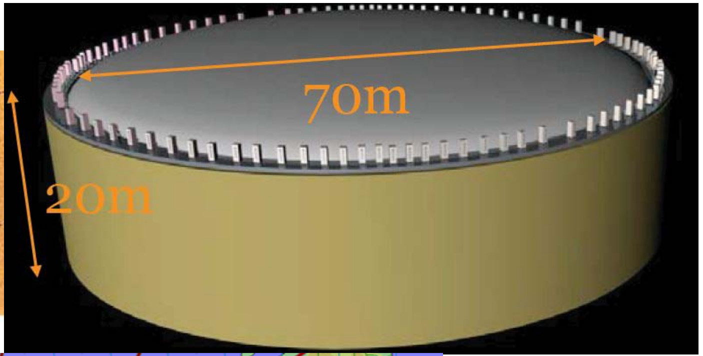
Se ϑ_{13} <3° le sorgenti convenzionali sono sostanzialmente inutilizzabili

Superbeams

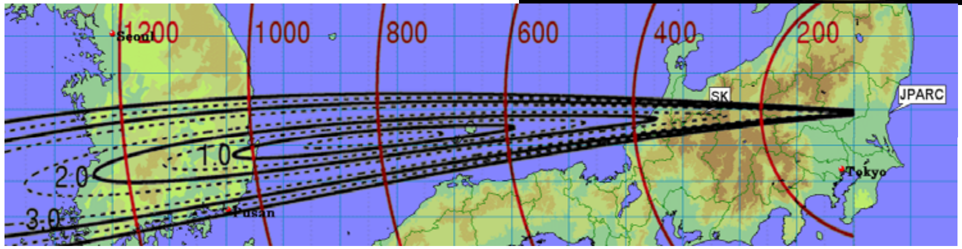
La piu' ambiziosa estensione della tecnica tradizionale basata sul decadimento in volo del π fino a potenze di 2-4 MW

Caratteristiche: osservazione delle oscillazioni $\nu_\mu \rightarrow \nu_e$ e anti-ν_μ $\rightarrow$anti-ν_e (stato finale: elettroni). Rivelatori a bassa densita': Water Cherenkov $\mathcal{O}$(1000) kton, Liquid Argon $\mathcal{O}$(100kton), scint.liquido.

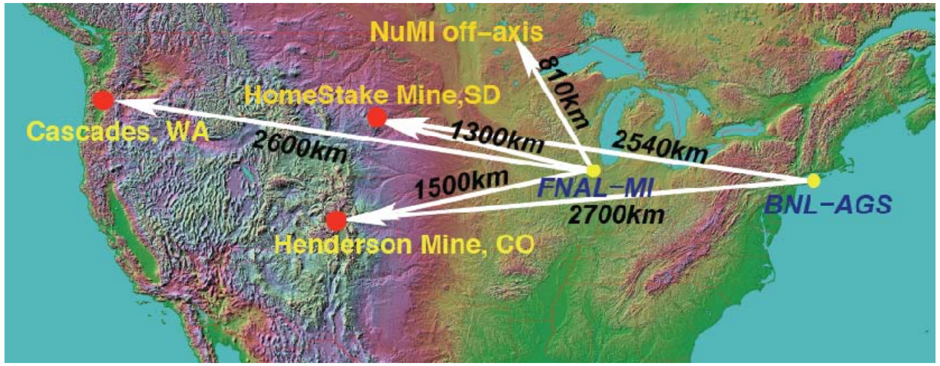


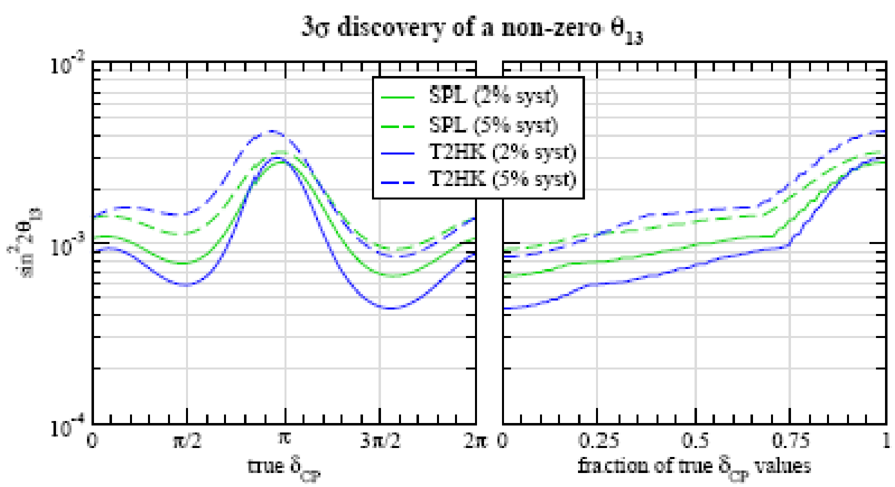


Narrow band approach (T2HK, SPL–To–Frejus / MEMPHIS, two far detectors @ T2KK)

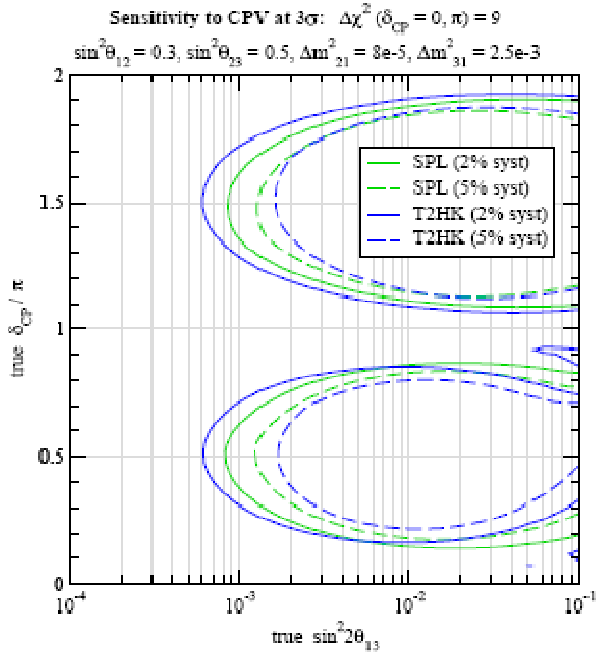


Wide band approach (FNAL/BNL to DUSEL)




3σ discovery of a non-zero θ_{13}

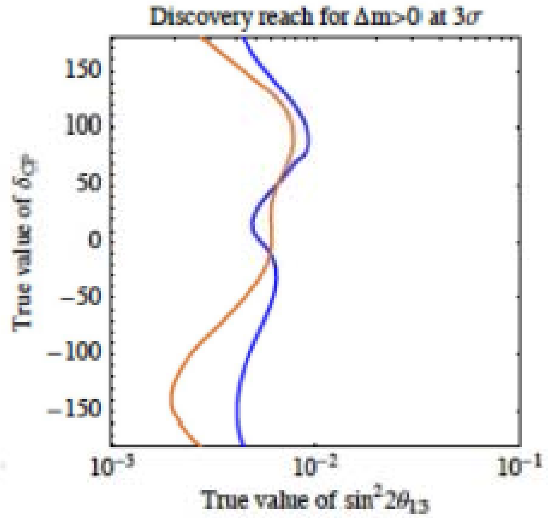
Le sistematiche sperimentali costituiscono il caveat piu' pesante per questa opzione (P.Huber M.Mezzetto, T.Schwetz, arXiv:0711.2950v2)


Sensitivity to CPV at 3σ: $\Delta\chi^2 (\delta_{CP} = 0, \pi) = 9$

$\sin^2\theta_{12} = 0.3$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{21} = 8e\text{-}5$, $\Delta m^2_{31} = 2.5e\text{-}3$

S.F.King et al., "The ISS physics report" arXiv:0710.4947

- Narrow band a baselines di 100-300 km: fornisce la migliore precisione su δ ma non ha praticamente sensibilita' sul sign Δm^2
- Wide band a 1000-2000 km. Performance su CPV peggiori ma una certa sensibilita' alla gerarchia di massa dei neutrini
- La conoscenza dei flussi e delle sezioni d'urto alle basse energie (0.5-3 GeV) ha un ruolo cruciale
- Rivelatori di questo tipo sono multipurpose (proton-decay, supernovae, atm neutrinos). Gli atmosferici aiutano ad alti θ_{13} (v.dopo)


Discovery reach for Δm>0 at 3σ

M.Diwan et al. hep-ph/0608023

Il contributo dei neutrini atmosferici

Multi-GeV ν_e:
impossibile
distinguere il segno
del leptone.
Perturbazioni nel rate
inclusivo

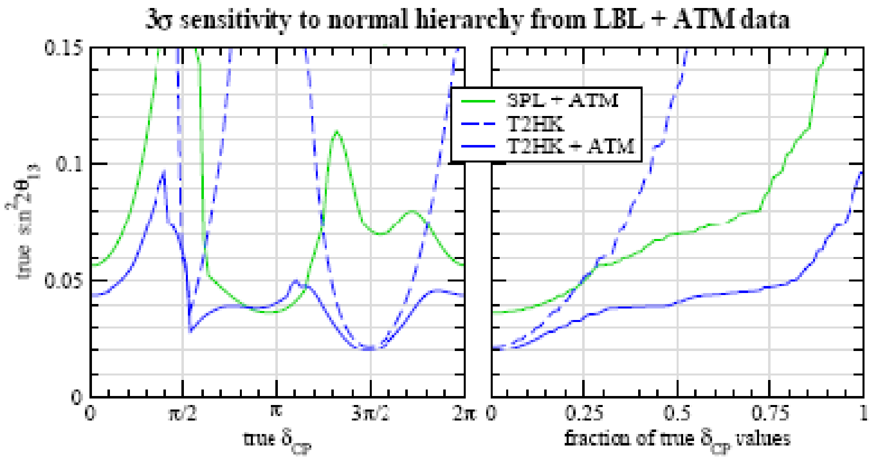
(Water Cherenkov)

Risonanza MSW

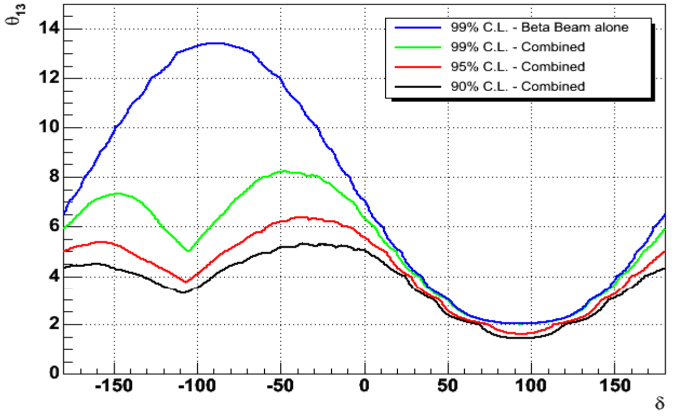
$$E_R = \pm \Delta m_{31}^2 L_{magic} \ \cos 2\theta_{13}/4\pi$$

$$\Gamma_R = |\Delta m_{31}^2| L_{magic} \ \sin 2\theta_{13}/2\pi$$

Multi-GeV ν_μ:
segno osservabile
in riv. magnetizzati
(NuFact, high-E
BetaBeam)



J.Campagne et al., JHEP 0704 (2007) 003



A Donini et al. EPJ C53 (2008) 599

F.Terranova @ NuFact07, Okayama

Sub-GeV ν_e: ~ $\cos^2\theta_{23}$ sensibilita'
all'ottante di θ_{23} (Water Cherenkov)

$$\epsilon_e^{sub} \equiv \frac{N_e}{N_e^0} - 1 \approx \left(r \cos^2\theta_{23} - 1\right) \langle P_{21}^{2\nu} \rangle \,.$$

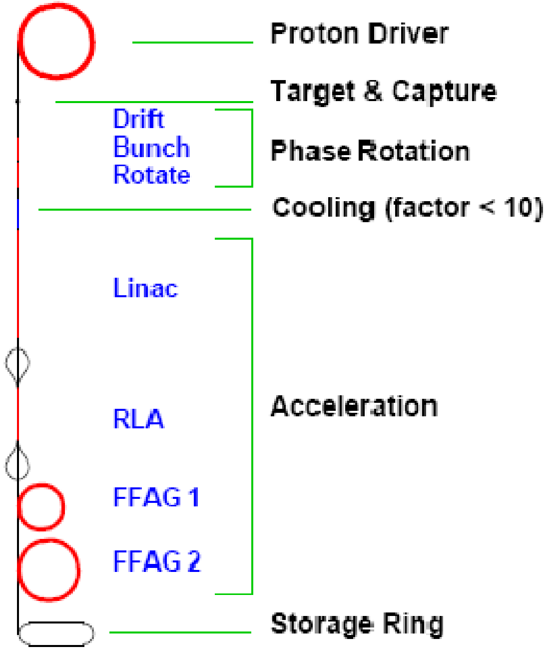
Neutrino Factories

La piu' ambiziosa tra le tecniche non-convenzionali. Originariamente considerata un by-product dell'R&D per i muon collider: oggi riottimizzata per la fisica del neutrino J.S.Berg et al., PR ST Accel.Beams 9 (2006) 011001

Neutrini prodotti dal decadimento in volo dei muoni e non dei pioni. Non vi e' fondo intrinseco dai decadimenti dei K e la violazione di CP viene osservata in appearance dei ν_μ ("wrong sign muons")

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

μ^- (μ^+) decay in (ν_μ , $\overline{\nu}_e$) (($\overline{\nu}_\mu$, ν_e)).



Golden channel: search for $\nu_e \longrightarrow \nu_\mu$ ($\overline{\nu}_e \longrightarrow \overline{\nu}_\mu$) transitions by detecting wrong sign muons.

Default detector: 40-100 kton iron magnetized calorimeter (Minos like)

Silver channel: search for $\nu_e \longrightarrow \nu_\tau$ transitions by detecting ν_τ appearance.

Ideal detectors: $4\times$ Opera or 10 Kton LAr detector.

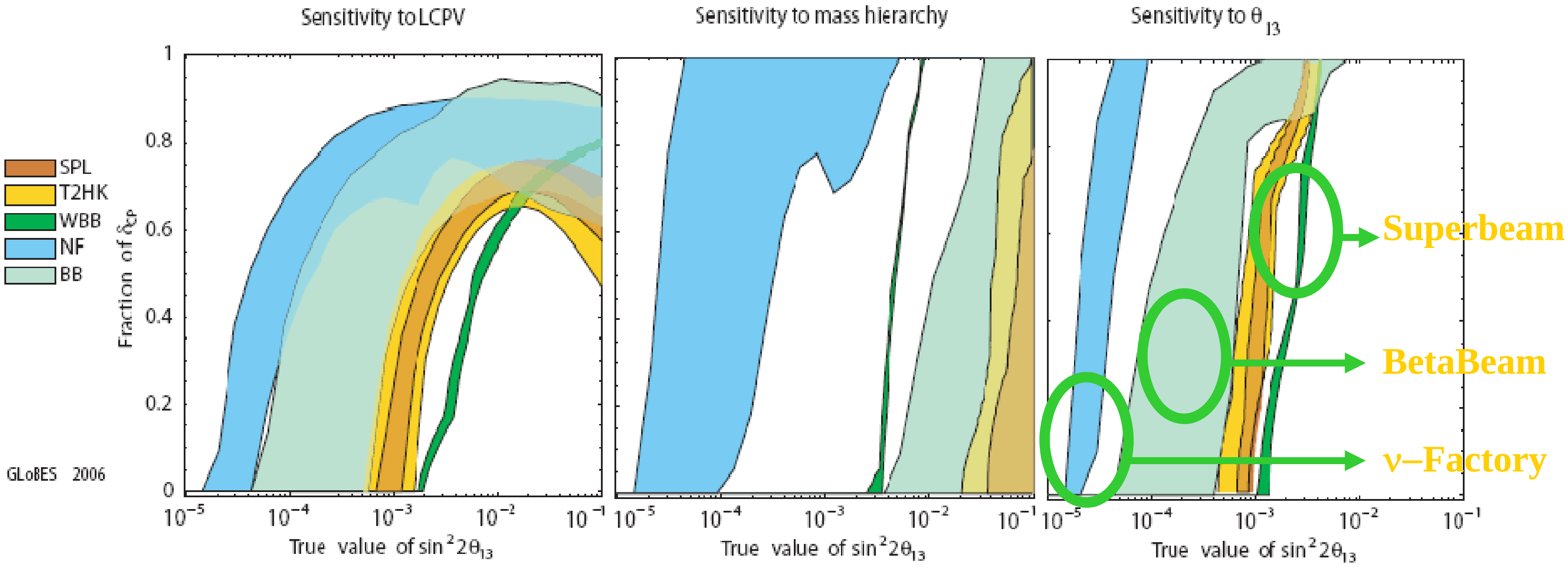
La fisica alle Neutrino Factories e’ sostanzialmente diversa da quella dei superbeam

Gli stati finali sono puramente muonici: rivelatori densi e sale sperimentali simili a quelle del Gran Sasso

Le energie sono >10 GeV (dominano DIS e RES), le baseline sono grandi (L=3000 km) e sono grandi gli effetti di materia

Il fondo dominante e’ dagli anti-ν_μ CC: wrong charge rejection $<10^{-3}$

Grazie alle alte energie+flussi e all’assenza di fondi intrinseci rappresenta al momento la facility di gran lunga piu’ performante



Una (ragionevole) inversione di tendenza: rivelatori piu' sofisticati per ridurre il costo esorbitante della facility di fascio

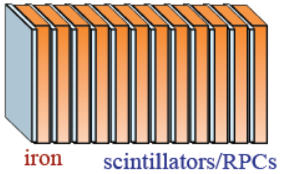
- Utilizzo l'appearance del τ per risolvere le degenerazioni nei parametri (OPERA-like) D.Autiero et al., EPJC 33 (2004) 243
- Abbassare i tagli in E_μ P.Huber et al., PRD 74 (2006) 073003, A.Cervera @Nufact07, Okayama
- Low energy neutrino factory S.Geer et al, PRD 75 (2007) 093001, A.Bross et al.,arXiv:0709.3889.
- Identificazione degli elettroni P.Huber et al., PLB (2007) 655

Baseline option →

MIND 25xMINOS

Magnetised Iron Neutrino detector

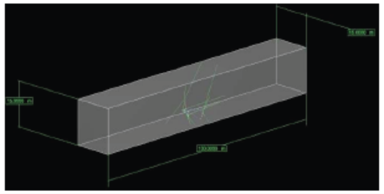
100 Kton



TASD NOvA + B

Totally active Scintillating Detector

25 Kton

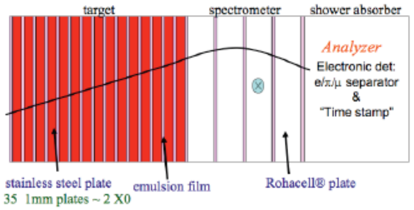


(M)ECC (2-7)xOPERA (+ B)

(Magnetised) Emulsion Cloud Chamber

4-15 Kton

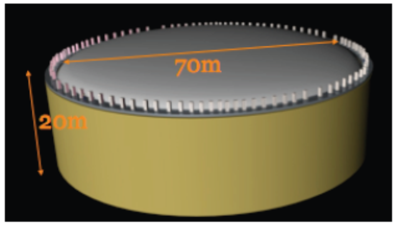
MECC cell



GLACIER

Giant Liquid Argon Charge Imaging ExpeRiment

100 Kton

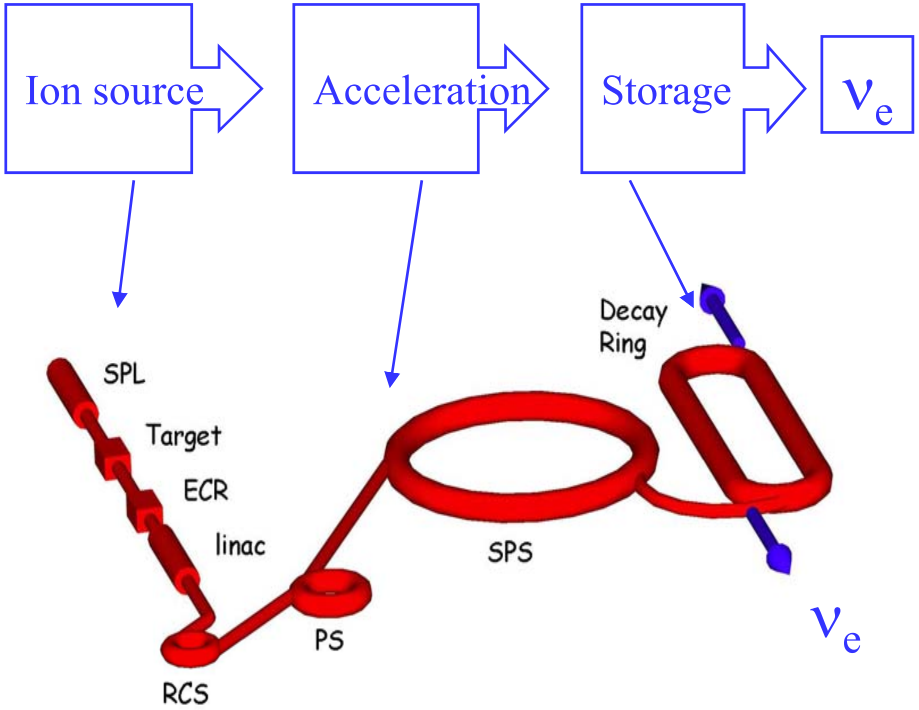


$\vec{B}$ in aria su enormi volumi!

Un’interessante alternativa: i Beta Beam

$$\text{proton} \xrightarrow{\text{target}} \text{isotope}$$

$$\hookrightarrow \text{isotope}^{*} + e^{+} + \nu_e$$

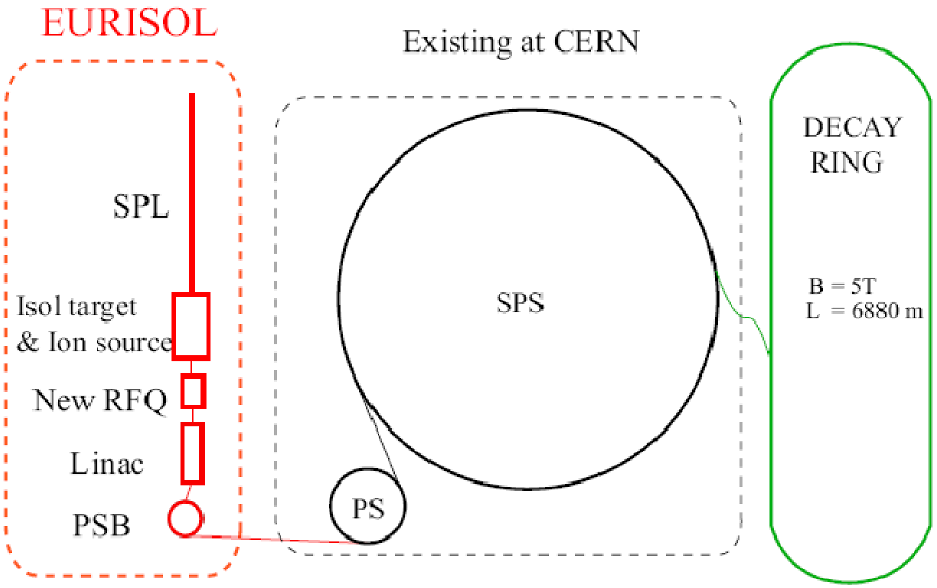


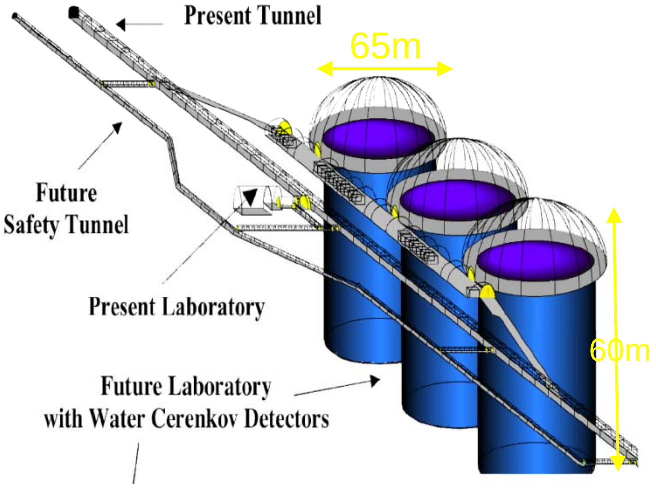
- Works in ν_μ appearance mode but only one flavor is present in the initial state: Ideal condition at t=0 !!
- It makes estensive use of current technologies (ISOL technique for ion production, existing accelerators at CERN or Fermilab)
- Main drawback: $q/m \ll q/m_\mu$… we mainly work with low-energy neutrinos (sub GeV if we use ^{18}Ne, ^{6}He and the SPS as terminal booster)

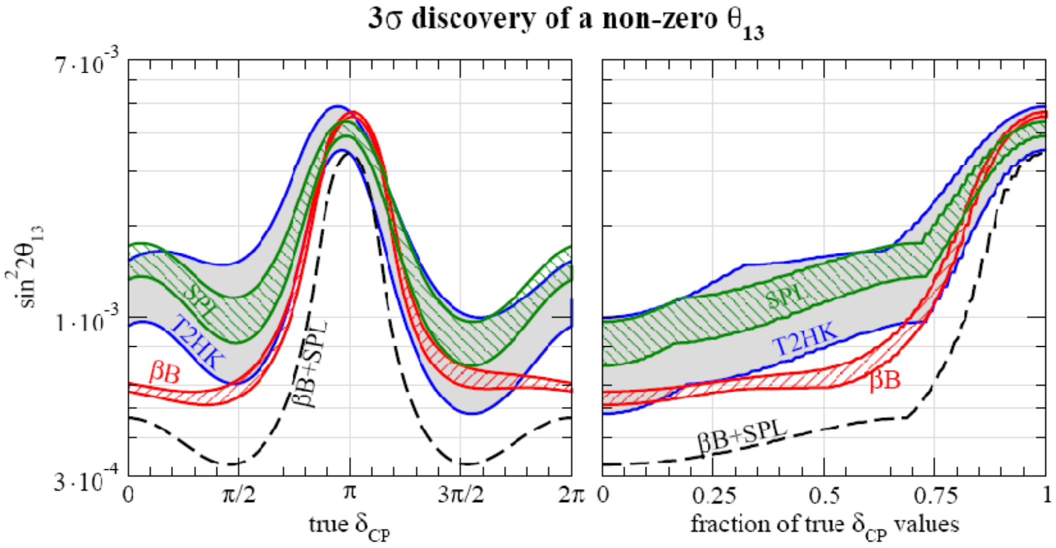
THE EURISOL BASELINE DESIGN

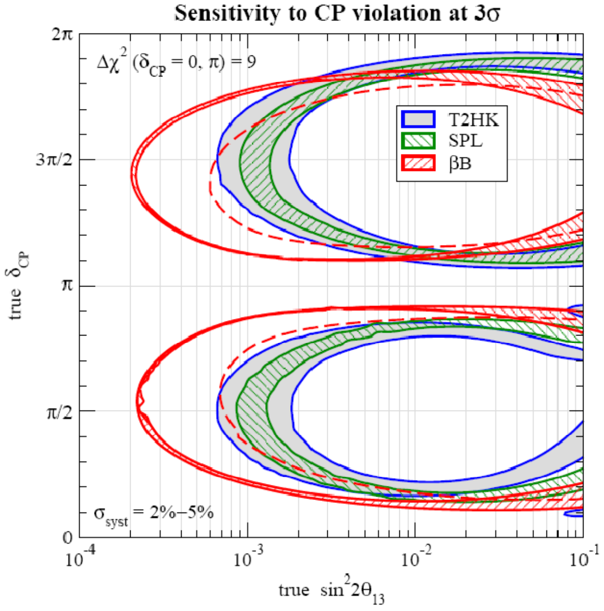
Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

M. Lindroos et al., see http://beta-beam.web.ch/beta-beam







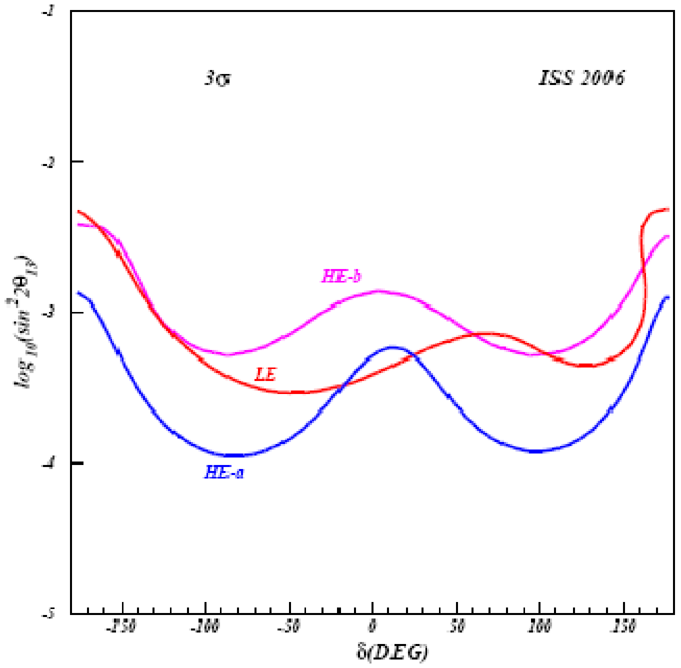


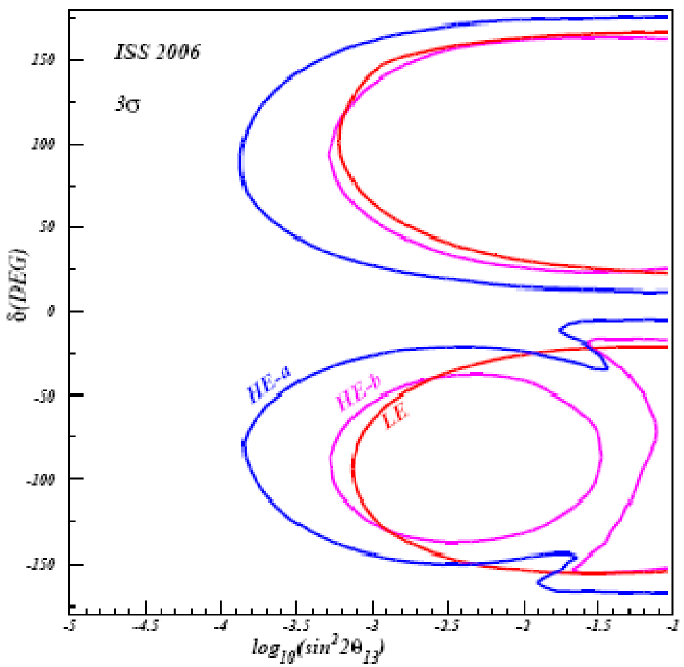
Una tecnica versatile: molte varianti proposte (high-E BB, electronic capture J.Bernabeu et al., JHEP 0512 (2005) 14 , uso di rivelatori ad alta densita’ etc.) e alcuni punti fermi.

La principale debolezza dei Beta Beam e’ la bassa energie degli ioni:

- Utilizzare un booster a piu’ alto gamma: J.Burguet-Castell et al., NPB 695 (2004) 217, NBP 725 (2005) 306, F.Terranova et al., EPJC 38 (2004) 69, P.Huber et al., PRD73 (2005) 053002
- Utilizzare ioni a piu’ alto Q^2: C.Rubbia et al. NIM A568 (2006)

Ma finora nessuno ha dimostrato che i flussi ottenibili siano confrontabili con l’opzione baseline.





↗ Ambiguita’ dovuta al sign di Δm^2

Qualche considerazione finale

- ✓ La generazione di esperimenti post-T2K sembra lontana (>2015) e sicuramente gli investimenti per le sorgenti non convenzionali sono inadeguati. Ma questo e' perfettamente comprensibile (ignoranza su ϑ_{13}, costi >500 M€ etc.)
- ✓ La situazione rischia di cambiare rapidamente nei prossimi 4-5 anni in caso di segnale da parte di T2K, Double Chooz, Daya-Bay, Nova etc. e <u>probabilmente ci sara' una brusca accelerazione</u>
- ✓ In Europa, dovremo essere pronti a rispondere almeno ad alcune domande:
  - Se ϑ_{13} >3°, un superbeam da' la garanzia di chiudere la matrice di mixing leptonica? Vale l'enorme investimento per costruire il laboratorio sotterraneo?
- ✓ In caso di risposta negativa dobbiamo essere consapevoli che:
  - La Neutrino Factory offre al momento la migliore chance di fare fisica di precisione sulla PMNS ma i costi e la durata dell'R&D sono incerti
  - I Beta-Beam offrono una buona sinergia con il CERN e potrebbero essere un'opzione praticabile in Europa. L'R&D e' meno challenging di una NF ma, almeno nell'opzione baseline, le performance di fisica sono "un po' troppo vicine ai Superbeam" per prendersi il rischio di una sorgente non-convenzionale.

Rispetto a 5 anni fa (Kamland results) oggi abbiamo una buona conoscenza delle performance di fisica di queste facility. Ma credo che le risposte alle domande chiave arriveranno dagli acceleratoristi e non dai fisici del neutrino.

Ringraziamenti

- E. Lisi, L. Patrizii, F. Terranova per aver utilizzato alcune delle loro trasparenze presentate alla Commissione 2 dell'INFN