GDR TERASCALE
Lyon , April 2011

Search for massive
Active & Sterile Neutrinos
Experimental Status

Outline

1. Introduction on neutrino mass measurement
2. Introduction to neutrino oscillations
3. Active neutrinos oscillations
4. Beyond 3 neutrinos
5. Conclusions

Yves Déclais
Lyon1 University
CNRS/IN2P3/IPNL

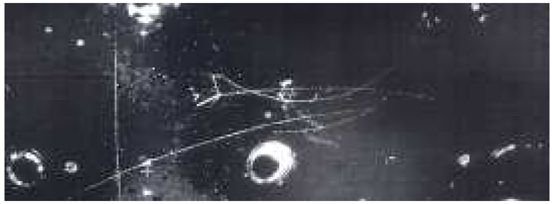
Neutrino properties

Postulated by Pauli in 1930 as a neutral and mass-less particle

- most abundant matter particle in the universe : $\sim 10^{10}$ * e,p,n
- smallest X section : huge experimental difficulties

- Weak interaction

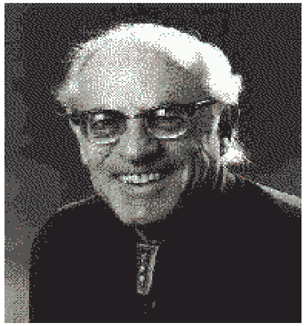
1973, A. Lagarrigue
Weak Neutral Current discovery



Same technique
as used in OPERA:
Emulsion Cloud Chmber

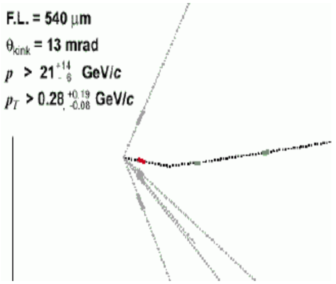
- 3 families

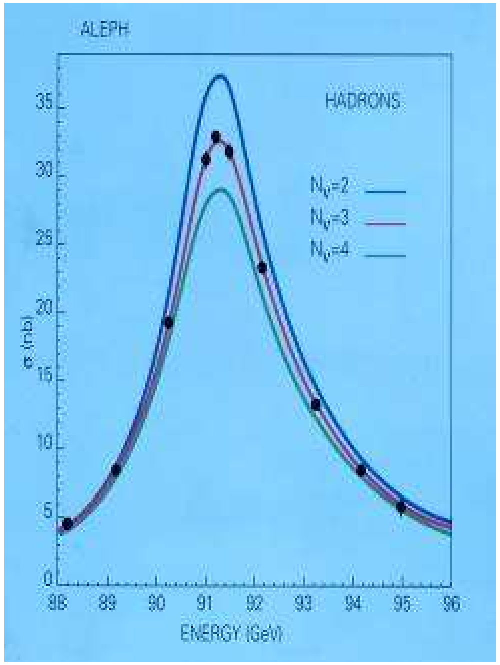
1956, F. Reines
ν_e discovery



1962, Lederman, Schwarz, Steinberger
ν_μ discovery

2001, K. Niwa
DONUT experiment
ν_τ direct detection



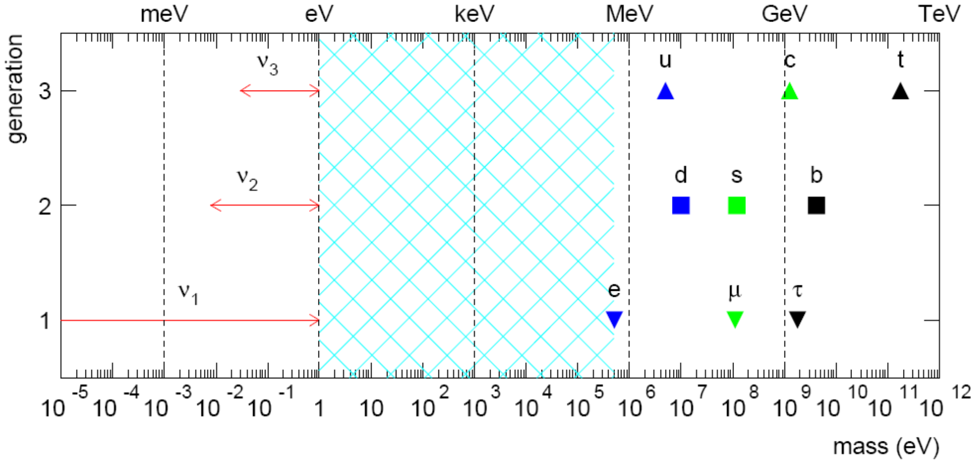


LEP result:
only 3 neutrinos coupled to the Z^0
($M_\nu < M_Z/2$)

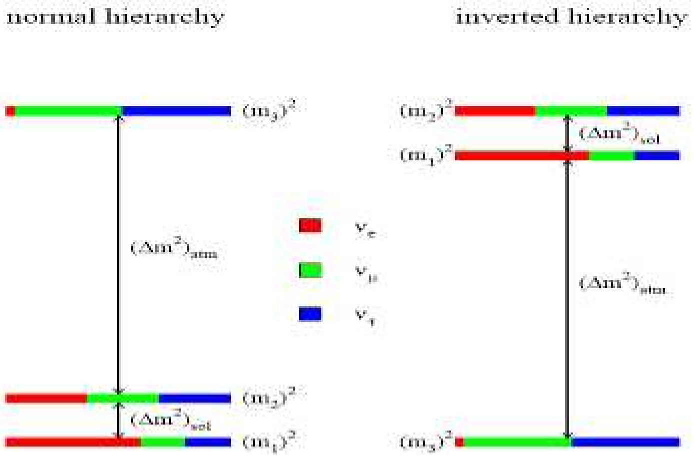
The long quest for massive neutrino observation

➔Why looking for massive neutrino
- hint for physics beyond the Standard Model
- Astrophysical & Cosmological consequences

Mass Scale



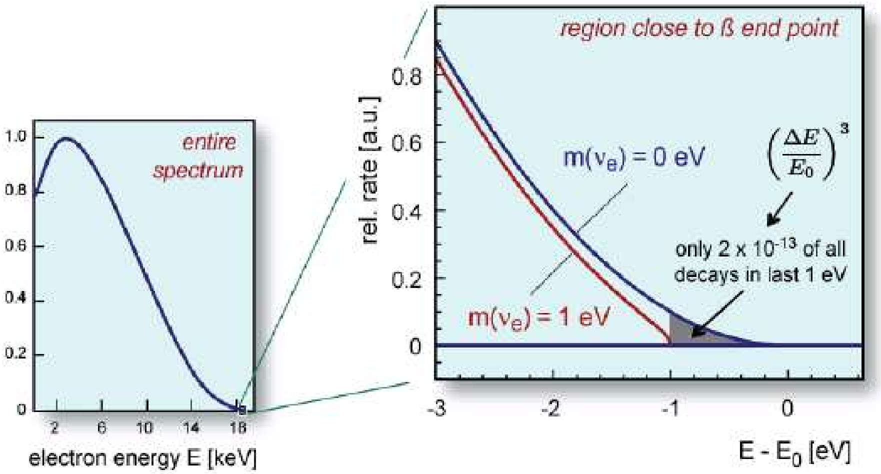
Mass hierarchy

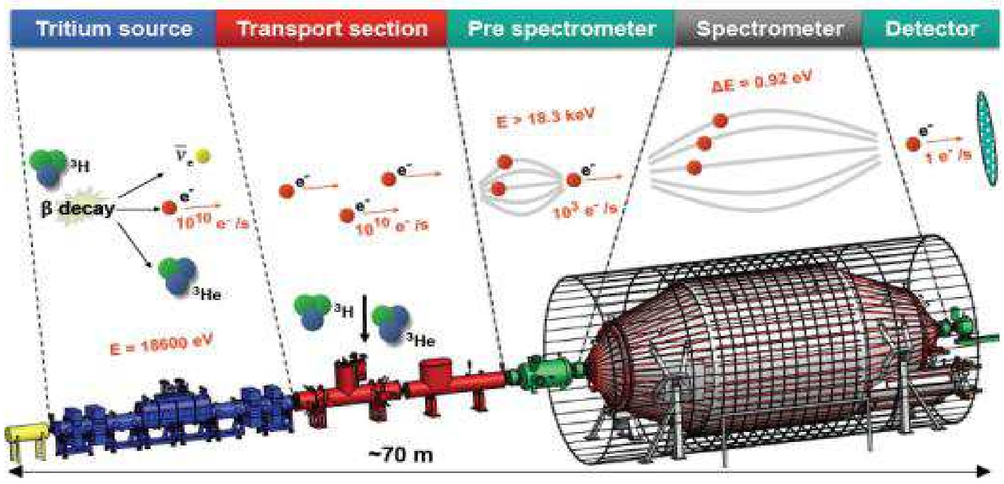


➔How to measure the mass of the neutrino

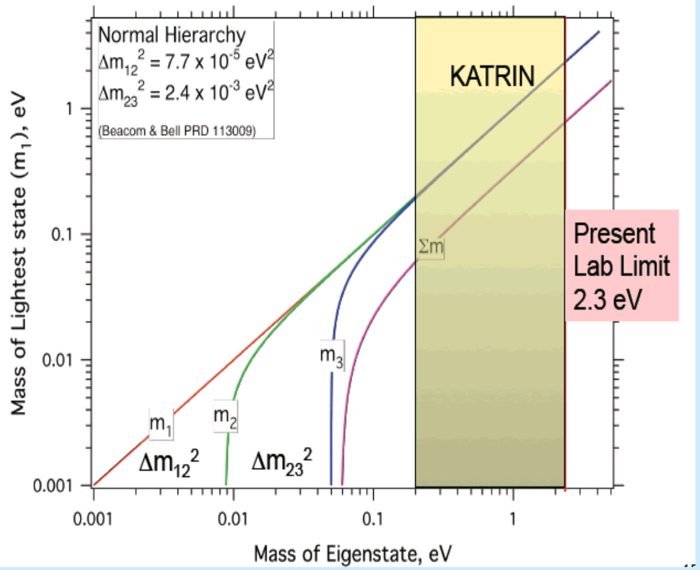
Absolute mass measurement
- precision measurement of decay kinematics (β decay, π+,τ)
- neutrino less double β decay
- constraints from Cosmology
- neutrino oscillation ← Only sensitive to mass differences

Direct measurement by kinematics





➔ Tritium β decay



➔ Pion decay

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

K. Assamagan et al.,
Phys. Rev. D53 (1996)
PSI (Villigen, CH)

$$m\nu_\mu < 0.19 \text{ Mev}$$

(limited by π mass accuracy)

➔ Tau decay

$$e^+ \, e^- \rightarrow \tau^+ \, \tau^-$$

(ALEPH @ LEP)

$$m\nu_\tau < 18.2 \text{ Mev}$$

Neutrinoless ββ decay

Non-conservation of leptonic number

Majorana neutrinos

$$\langle m_{ee}\rangle^2 = \frac{1}{\tau_{1/2}\; G_{0\nu}\, |M_{0\nu}|^2}$$

m_{ee} = Majorana mass

$G_{0\nu}\ |M_{0\nu}|^2$ = phase space & NME

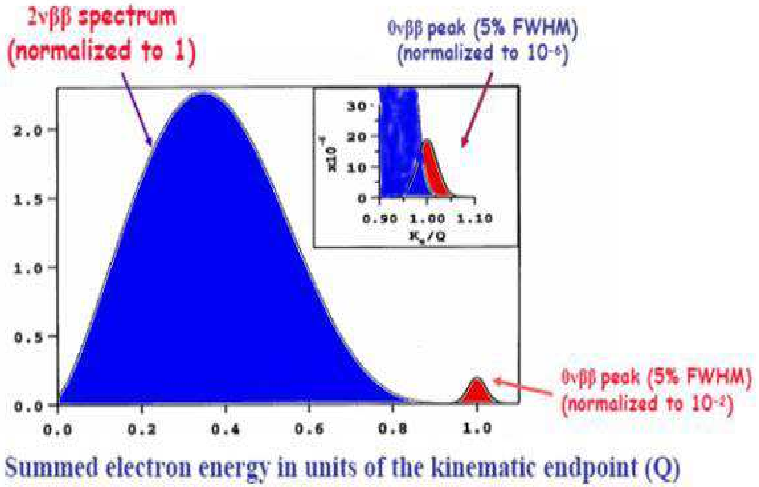
$S_{0\nu}$ = 0ν sensitivity

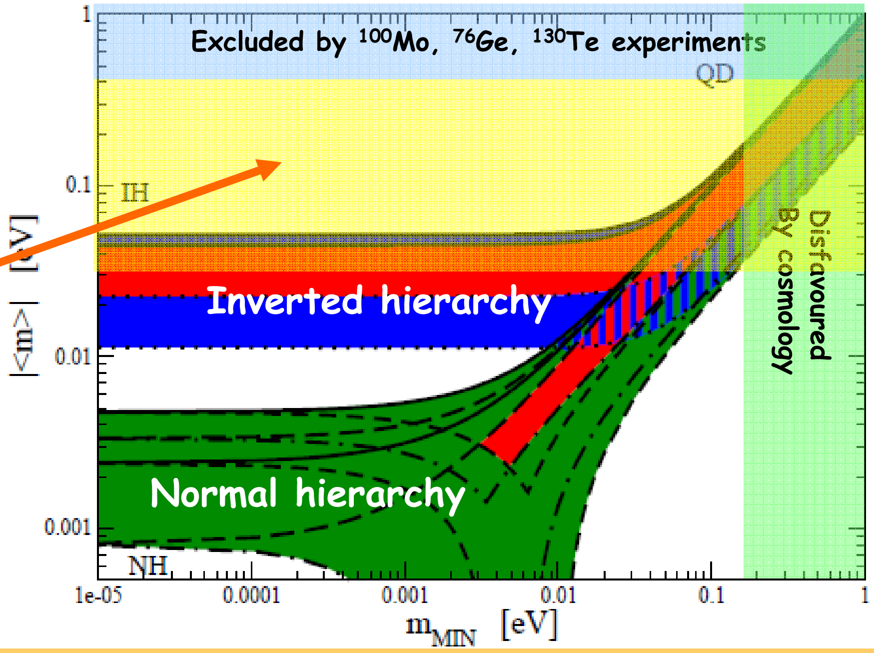
F_N = nuclear factor of merit

The knowledge of the mass hierarchy is needed from oscillation experiments

To be tested by new generation experiments:

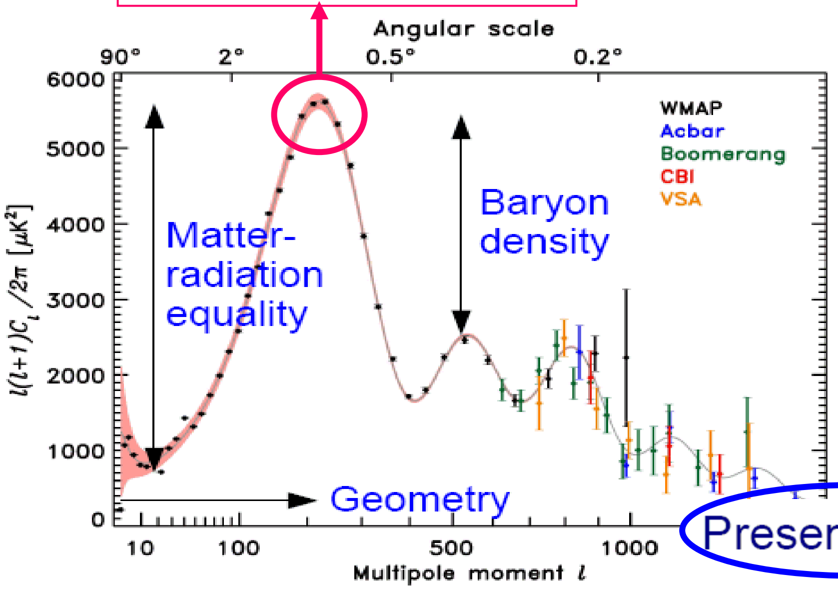
- CUORE: 200kg bolometers ^{100}Te
- GERDA: 18-40 kg ^{76}Ge
- Super-NEMO: 7-100kg ^{82}Se, ^{150}Nd
- SNO: 44 kg ^{150}Nd
- KamLAND: 400 kg ^{136}Xe





Constraints from Cosmology

Non standard 1st peak
➔ $\Sigma m_\nu > 0$



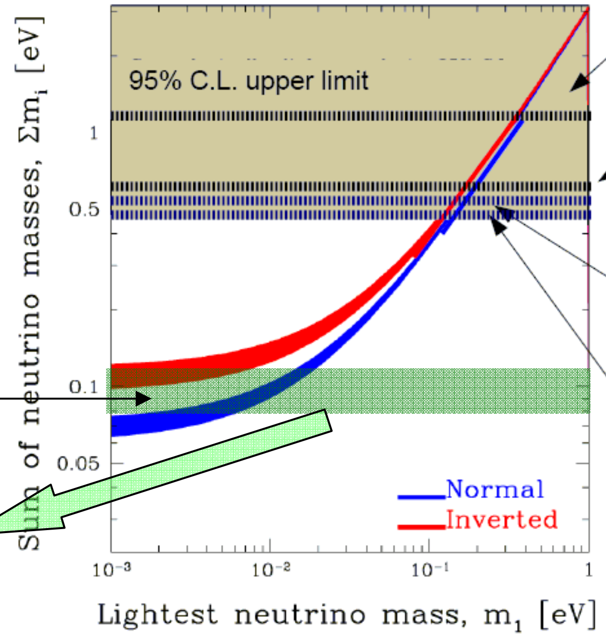
WMAP, 2006

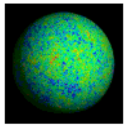
Temperature fluctuations from acoustic oscillations of the photon-Baryon fluid frozen on the last scattering surface

+

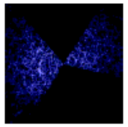
Large scale structure: Galaxy clustering, Cluster abundance, Gravitational lensing, Lyman-α

Present status..

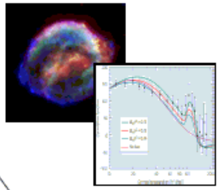




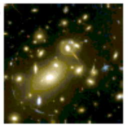
WMAP7 only
Komatsu et al. 2010



WMAP7+Galaxy clustering
Hannestad, Mirizzi, Raffelt
& Y^3W 2010



WMAP5+Galaxy
+SN+HST
Reid et al. 2009
(extended models)



WMAP5+Weak lensing
Tereno et al. 2008
Ichiki et al. 2008

Coming ...

Planck + Weak lensing (LSST)

This would require
~1% accuracy on the
theoretical predictions
of the matter power spectrum

Y. Wong, Neutrino 2010

Neutrino oscillations : Mixing Matrix

Neutrino mixing (Pontecorvo 1958; Maki, Nakagawa, Sakata 1962):

3 neutrinos framework:

- ➔ neutrinos are massive particles and they mix similarly to quarks;
- ➔ the flavour eigenstates (ν_e, ν_μ, ν_τ) are linear superpositions of the mass eigenstates ν_1, ν_2, ν_3 (eigenvalues m_1, m_2, m_3)

$$\boxed{|\nu_\alpha\rangle} = \sum_i \boxed{U_{\alpha i}}\boxed{|\nu_i\rangle}$$

$\alpha = e, \mu, \tau$ (flavor index)

$i = 1, 2, 3$ (mass index)

Uai= unitary mixing matrix

Today favorite parameterization of U: in terms of 3 mixing angles $\theta_{12}\, \theta_{23}\, \theta_{13}$ and one Dirac-like CP phase δ (two extra phases in case of Majorana neutrinos):

$$U_{MNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Cross Mixing}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

Θ_{13} gateway to leptonic CPV

Neutrino oscillations : Time evolution

Considering the **time evolution** of a flavour eigentstate ν_α produced at t = 0:

$$|\nu(t)\rangle = e^{i\mathbf{p}\cdot\mathbf{r}} \sum_k U_{\alpha k}\, e^{-iE_k t} |\nu_k\rangle \qquad E_k = \sqrt{p^2 + m_k^2}$$

The phases: $e^{-iE_k t}$ will be different if $m_j \neq m_k$

Appearance of the flavour $\nu_\beta \neq \nu_\alpha$ for t > 0

$$\mathcal{P}_{\alpha\beta}(L) = \sin^2(2\theta)\sin^2(1.267\Delta m^2 \frac{L}{E})$$

$$\mathcal{P}_{\alpha\alpha} = 1.- \mathcal{P}_{\alpha\beta}$$

L=ct [km] (distance among the source and the detector)

E [GeV] (neutrino energy)

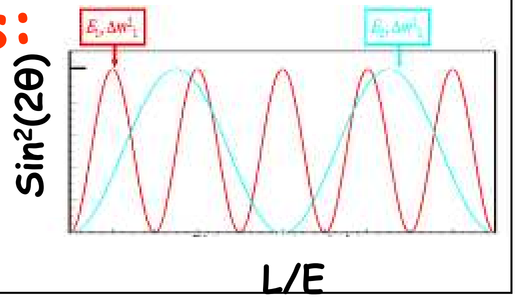
$\Delta m2$ [eV2]

Neutrino oscillations are not sensitive to the absolute mass scale

How to establish firmly neutrino oscillations:

and

- L/E pattern for neutrino
  ➔ Disappearance
- flavor change in the beam composition
  ➔ Appearance

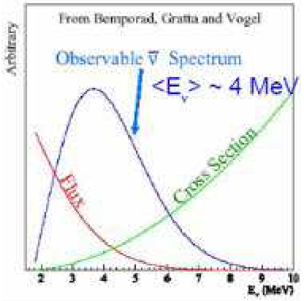


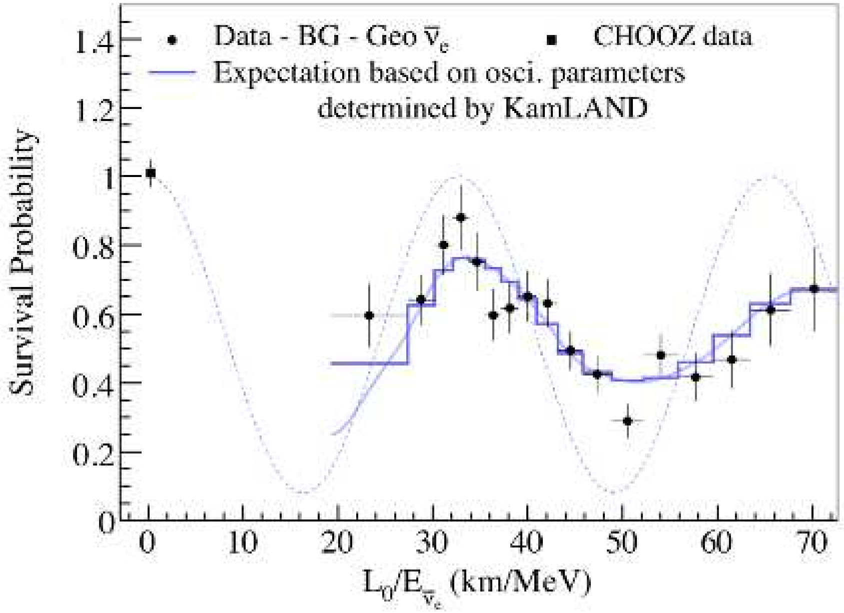
Solar sector robustness : L/E pattern

So called 'solar neutrinos Anomaly'

KamLAND:

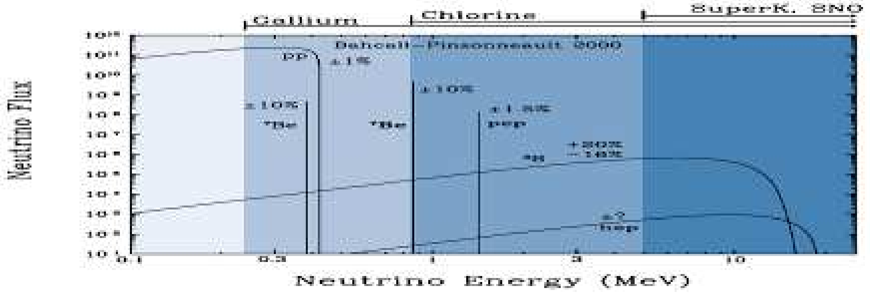
Reactor neutrino disappearance:
Baseline ~175 km

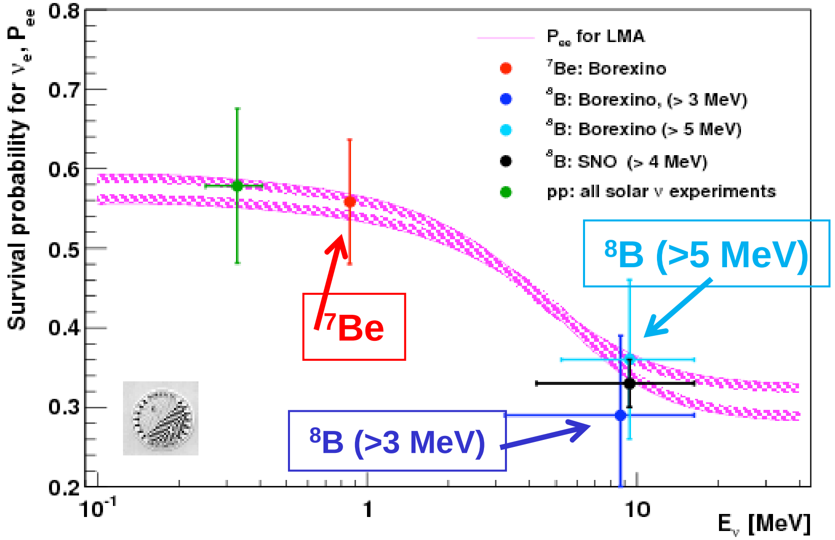




All solar neutrino experiments:

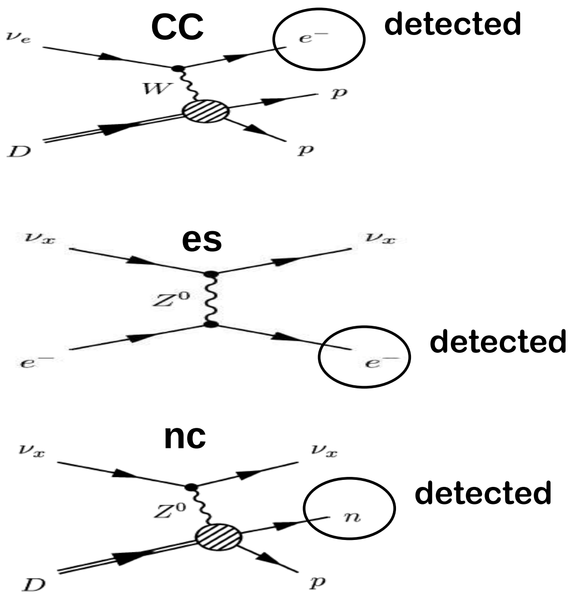
Survival probability :
The oscillation pattern is modulated by the matter effect (MSW)





Solar sector robustness : Appearance & Global fit

SNO



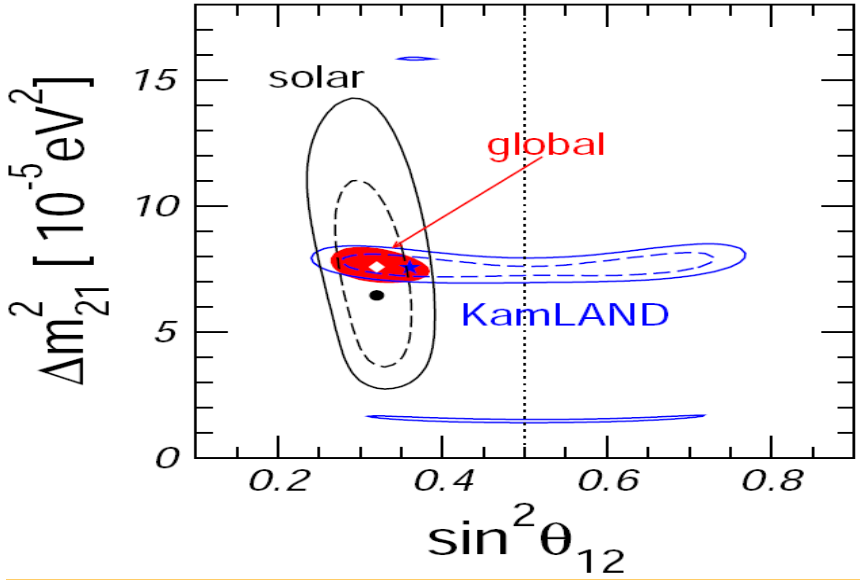
$\Phi_{cc}(\nu_e) = 1.76\ ^{+0.06}_{-0.05}(\text{stat.})\ ^{+0.09}_{-0.09}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$

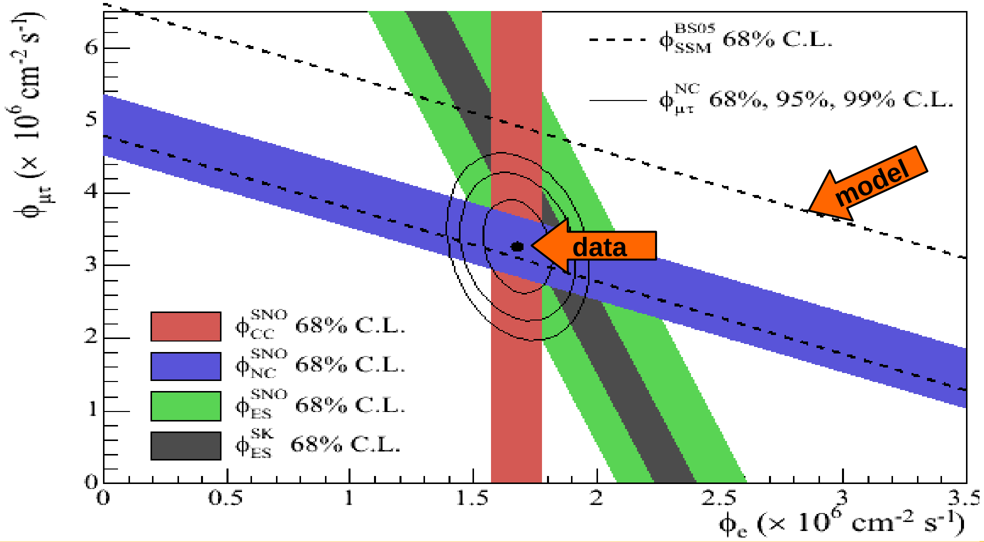
$\Phi_{es}(\nu_x) = 2.39\ ^{+0.24}_{-0.23}(\text{stat.})\ ^{+0.12}_{-0.12}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$

$\Phi_{nc}(\nu_x) = 5.09\ ^{+0.44}_{-0.43}(\text{stat.})\ ^{+0.46}_{-0.43}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$

$\Phi_e = 1.76\ ^{+0.05}_{-0.05}(\text{stat.})\ ^{+0.09}_{-0.09}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$

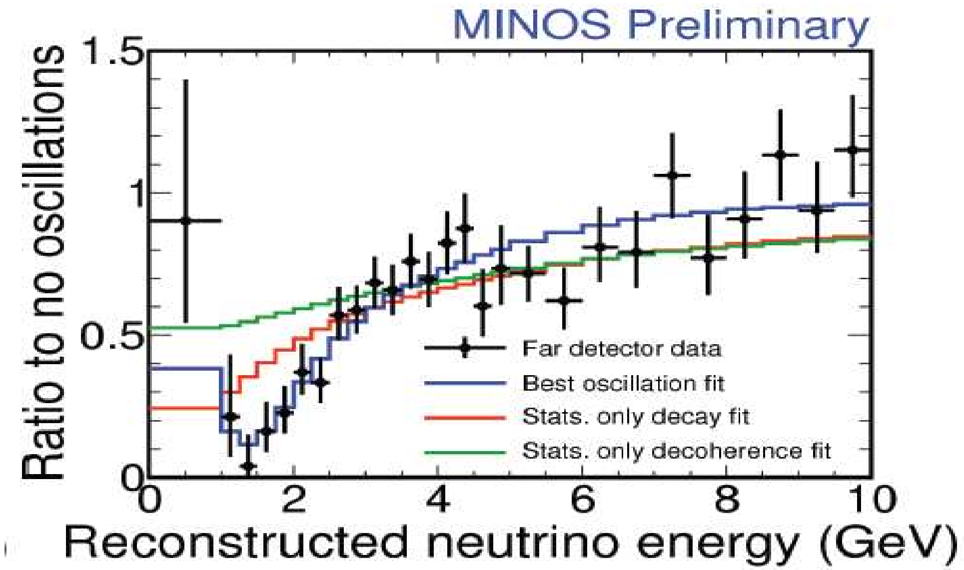
$\Phi_{\mu\tau} = 3.41\ ^{+0.45}_{-0.45}(\text{stat.})\ ^{+0.48}_{-0.45}(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$

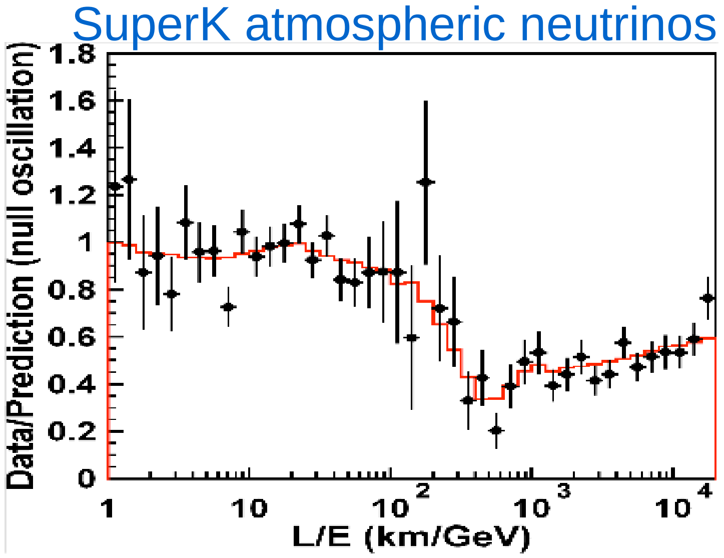




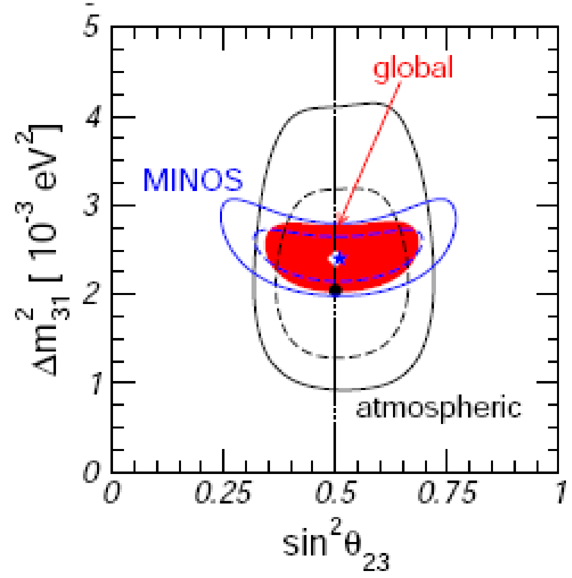
Atmospheric sector robustness : L/E pattern & Global fit

So called 'Atmospheric neutrinos Anomaly'

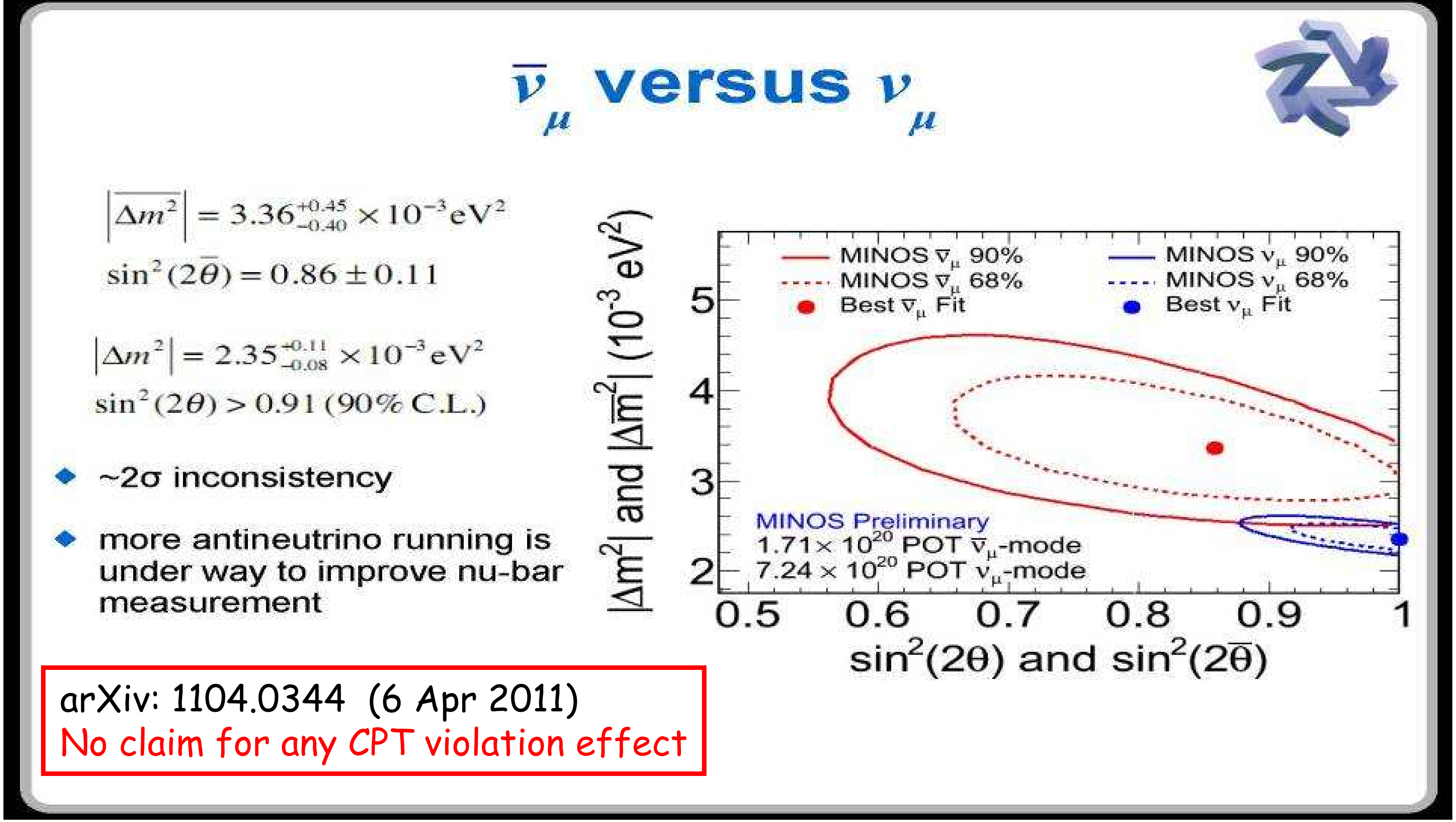




- $\nu_\mu \rightarrow \nu_\mu$ **measurement w/ 7.2×10^{20} POT.**
- **1986 events** observed
  for **2451 events** expected without oscillation.
  - Best fit with neutrino oscillations.
  - Decoherence disfavored: > 8σ
  - Pure decay disfavored: > 6 σ (7.8 σ if including NC)



CPT violation in the atmospheric sector ?



$\bar{\nu}_\mu$ versus ν_μ

$$|\overline{\Delta m^2}| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

$$|\Delta m^2| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

- ~2σ inconsistency
- more antineutrino running is under way to improve nu-bar measurement

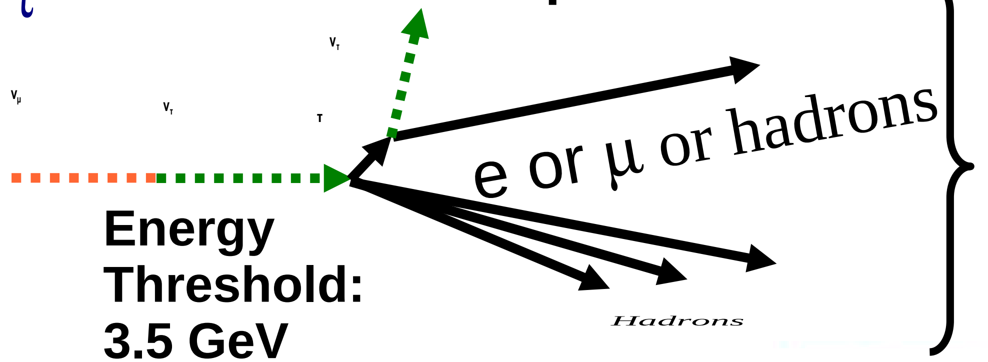
arXiv: 1104.0344 (6 Apr 2011)

No claim for any CPT violation effect

SuperK : similar oscillation parameters for neutrinos and anti-neutrinos (not based on an event by event analysis)

Wilkes 'Neutel 2011

ν_τ Events at Super-K

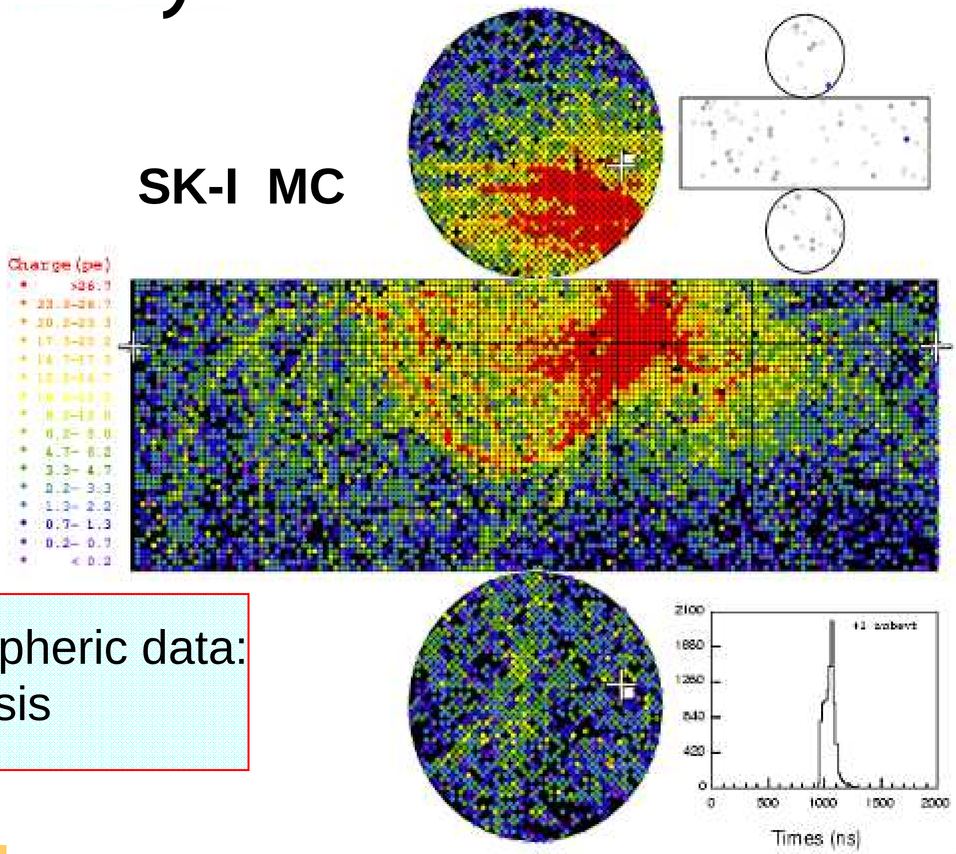


Energy Threshold: 3.5 GeV

- » Many light-producing particles
- » Most events are deep inelastic scattering (DIS) interactions

- » Complicated event topology makes identification of the leading lepton difficult
  - Use a Neural Network
- » Negligible primary flux
  - Observed tau events must be oscillation induced

SK-I MC



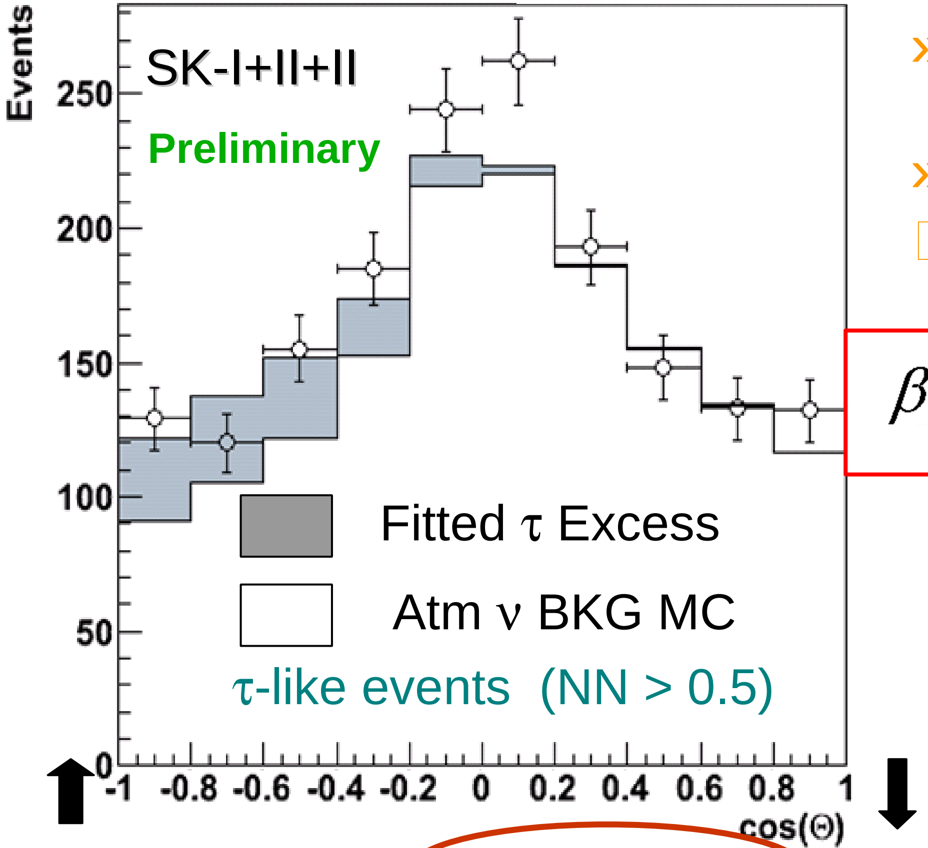
GOAL : Detect ν_τ events in SK atmospheric data: test the “no tau appearance” hypothesis

Fit Results

Wilkes 'Neutel 2011

If no τ appearance , β = 0

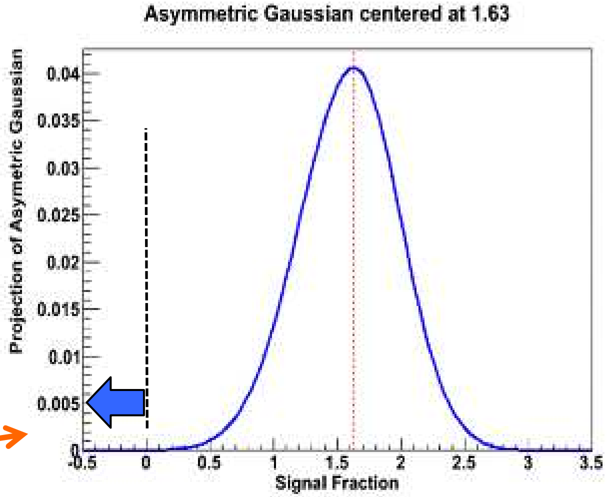
$$Data = \alpha(\gamma) \times bkg + \boxed{\beta}(\gamma) \times signal$$



- » Tau signal clearly appears in upward-going region
- » DIS fits to +1 σ
- ☐ τ normalization fit is 1.63 × expectation

$$\beta = 1.63 \pm 0.35_{(stat)} \, {}^{+0.10}_{-0.08}\,(sys) \, {}^{+0.02}_{-0.22}\,(3\,flav)$$

Preliminary

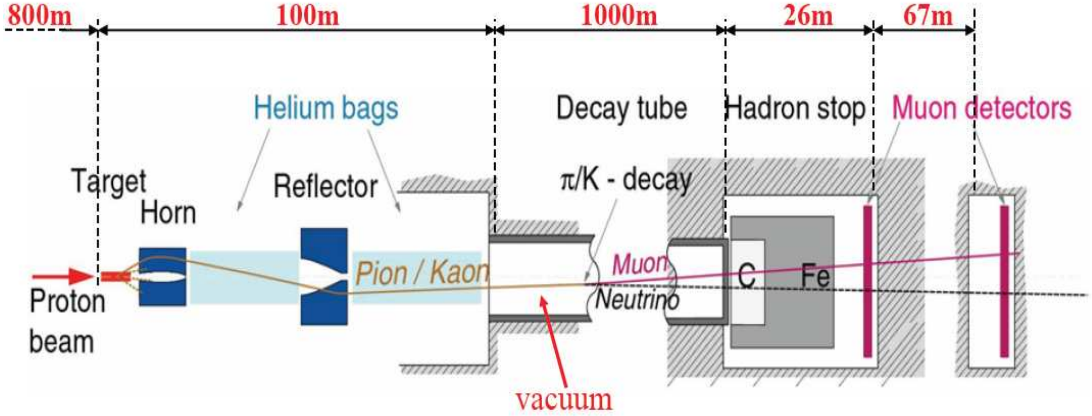


(This corresponds to 213.6 τ Events)

Measure of significance: Area under asymmetric Gaussian centered at β=1.63, for β < 0 (= no τ appearance)

SK data are ***inconsistent*** with ***no*** τ appearance at 3.8σ

CNGS (CERN Neutrino To Gran Sasso) beam



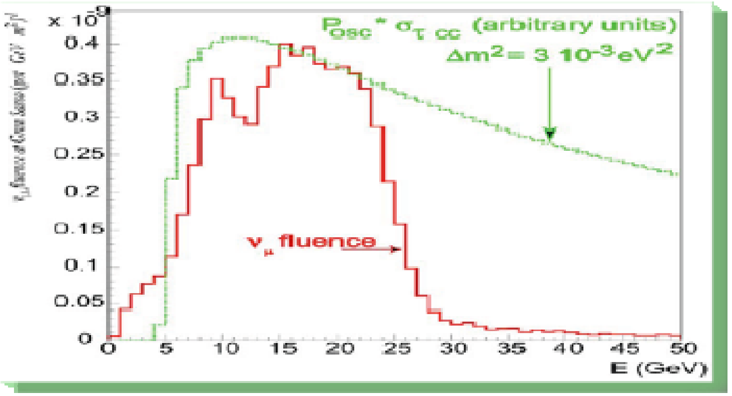
- Protons from SPS: 400 GeV/c
- Cycle length: 6 s
- 2 extractions separated by 50 ms
- Pulse length: 10.5 ms
- Beam intensity: 2.4 10^{13} proton/extr.

$<E\ (\nu_\mu)>$	17 GeV
L	730 km
L/E	43 Km/GeV
$(\nu_e + \overline{\nu}_e)/\nu_\mu$ cc	0.87%
$\overline{\nu}_\mu / \nu_\mu$ cc	2.1%
ν_τ prompt	negligible

Peak at
L/E=515 Km/GeV

P_{osc}~1.7 10^{-2}

Flux optimized to produce
the max. number of $\nu\tau$ CC



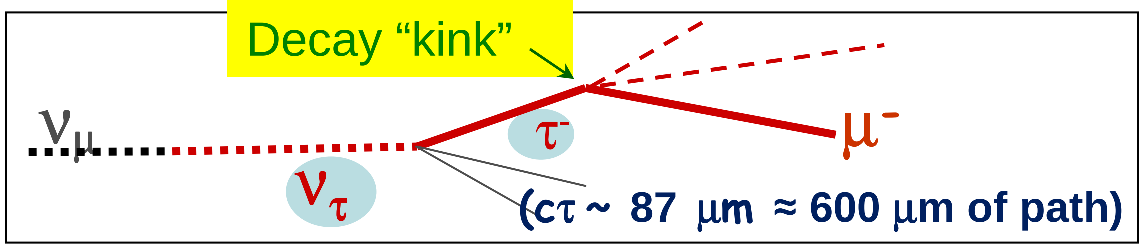
Principle of topological τ detection

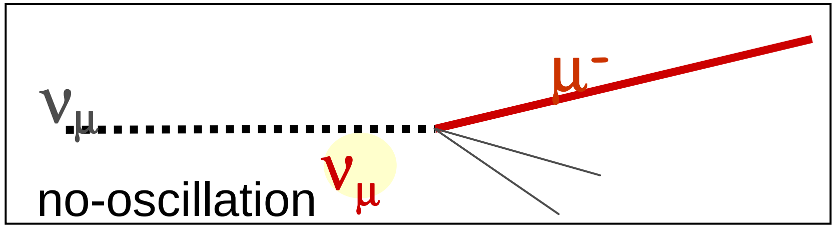
ν_τ CC interaction:

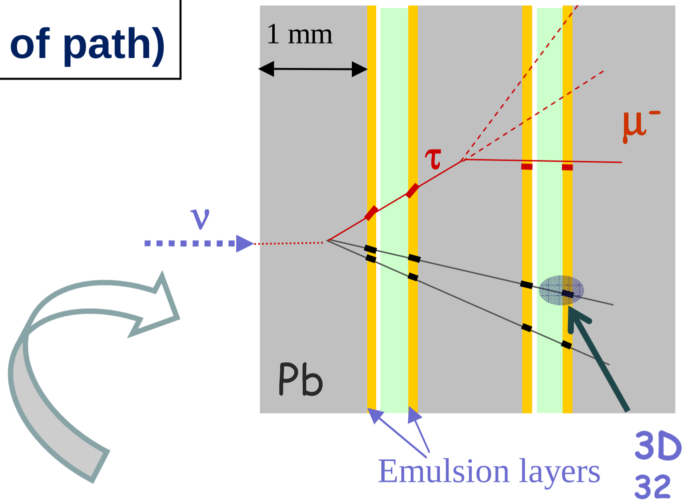
$\nu_\mu \Rightarrow \nu_\tau + N \rightarrow \tau^- + X$

oscillation

$\tau^- \rightarrow$	$\mu^-\ \nu_\tau\ \overline{\nu}_\mu$	B. R. ~ 17%
	$h^-\ \nu_\tau\ n(\pi^o)$	B. R. ~ 49%
	$e^-\ \nu_\tau\ \overline{\nu}_e$	B. R. ~ 18%
	$\pi^+\pi^-\pi^-\ \nu_\tau\ n(\pi^o)$	B. R. ~ 15%







3D tracking:
32 grains/100μm

2 conflicting requirements:

✓Target mass O(kton)
(low ν interaction cross-section)

✓High granularity : signal identification
background rejection

⇨ **ECC** (Emulsion Cloud Chamber) concept:
thin metal plates interleaved with
nuclear photographic emulsions on films

OPERA statistics : Signal & Background

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
All	BR*eff = 10.6%	10.4	0.75

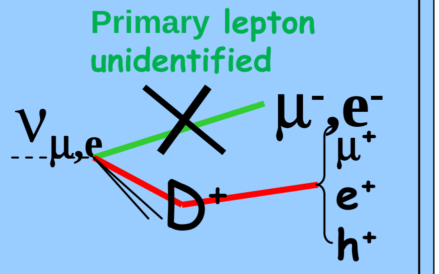
- 5 years of nominal beam ($4.5\ 10^{19}$ pot/year)
- $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$

(number of signal events $\propto (\Delta m^2)^2$)

➔ B/S ~ 0.072

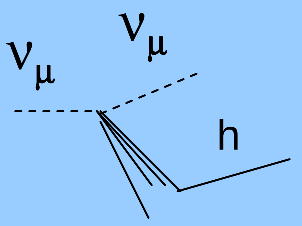
Background components:

Production of charmed particles
in CC interactions
(all decay channels)

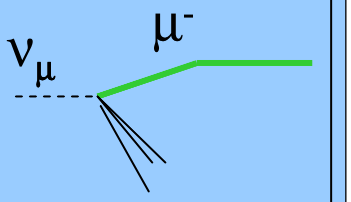


Hadronic interactions in lead:
Bkgd :
- $\tau \to h$
- $\tau \to \mu$

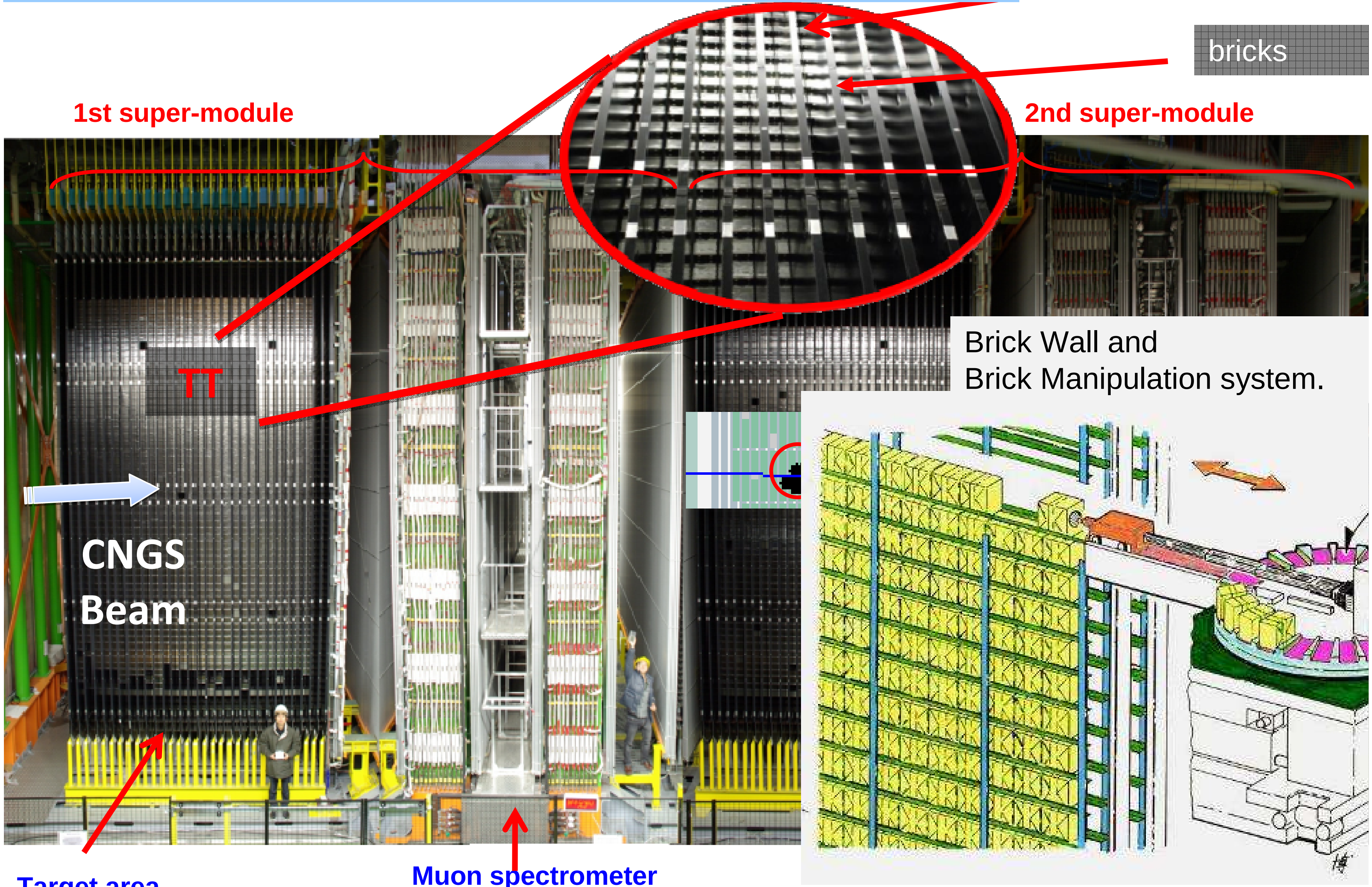
(if hadron misid. as muon)



Coulombian large angle scattering of muons in lead
(Bkgd. to $\tau \to \mu$)

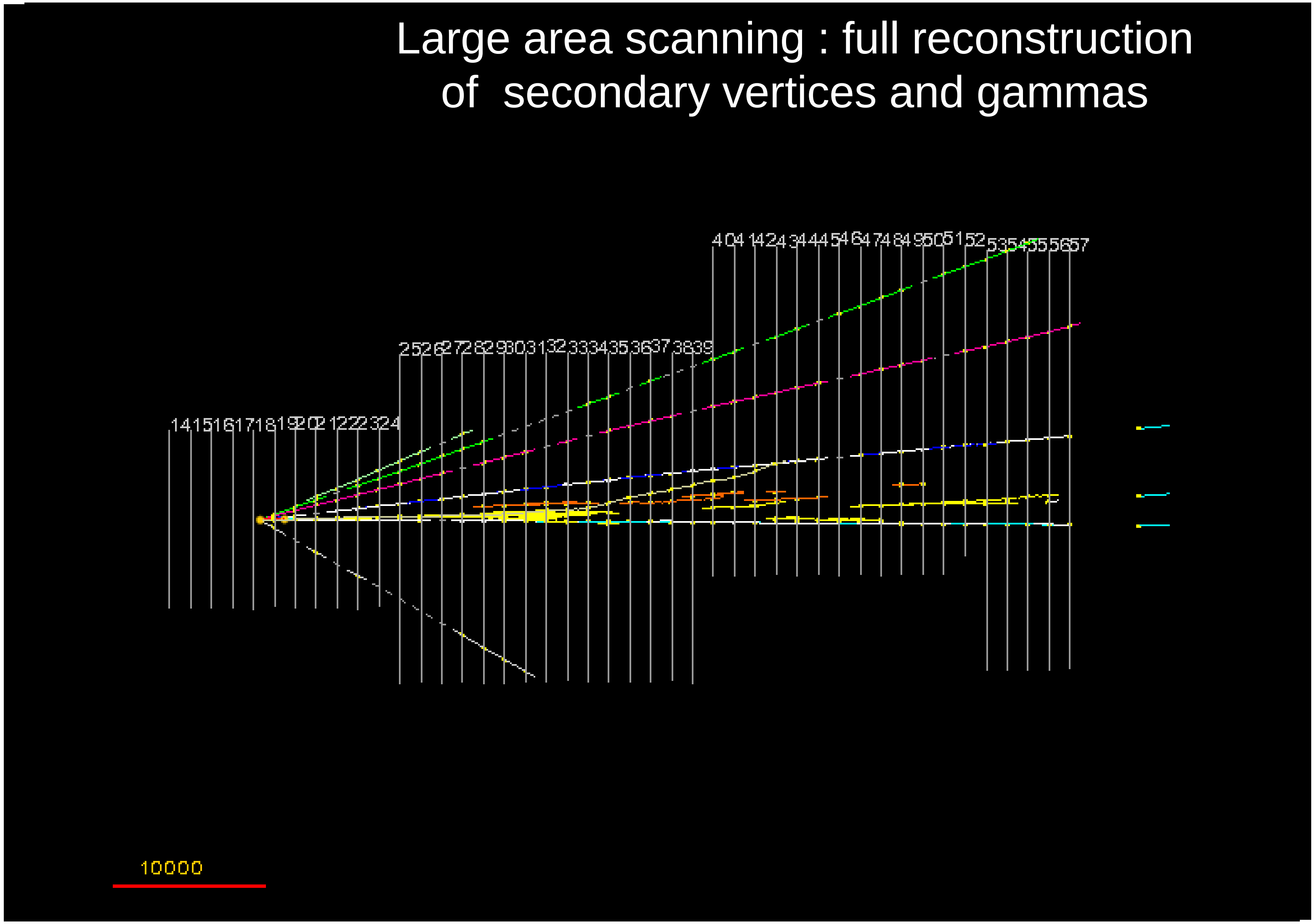


Brick extraction by the brick manipulator system)



Brick Wall and
Brick Manipulation system.

From CS to vertex location



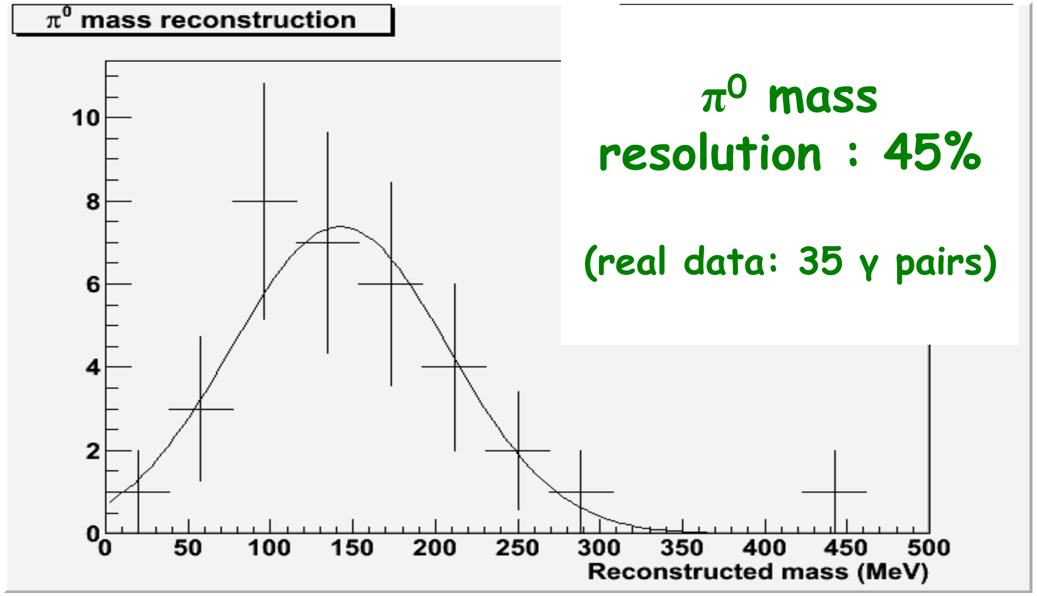
Large area scanning : full reconstruction of secondary vertices and gammas

Kinematical measurements

Selected tracks can be followed (scan-forth) for kinematical measurements

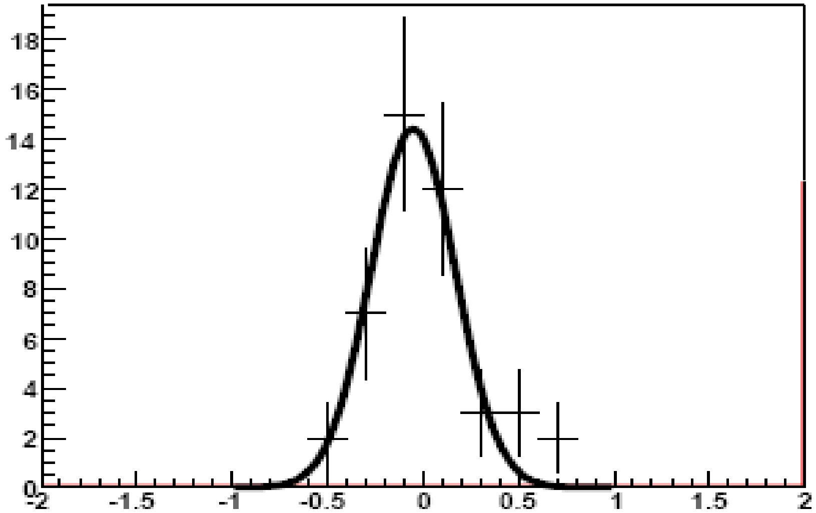
EM shower energy measured
by Shower Shape analysis
and Multiple Scattering method

Momentum measurement
by Multiple Coulomb Scattering
in the lead/emulsion film sandwich
and comparison with electronic
detector measurements



π^0 mass resolution : 45%

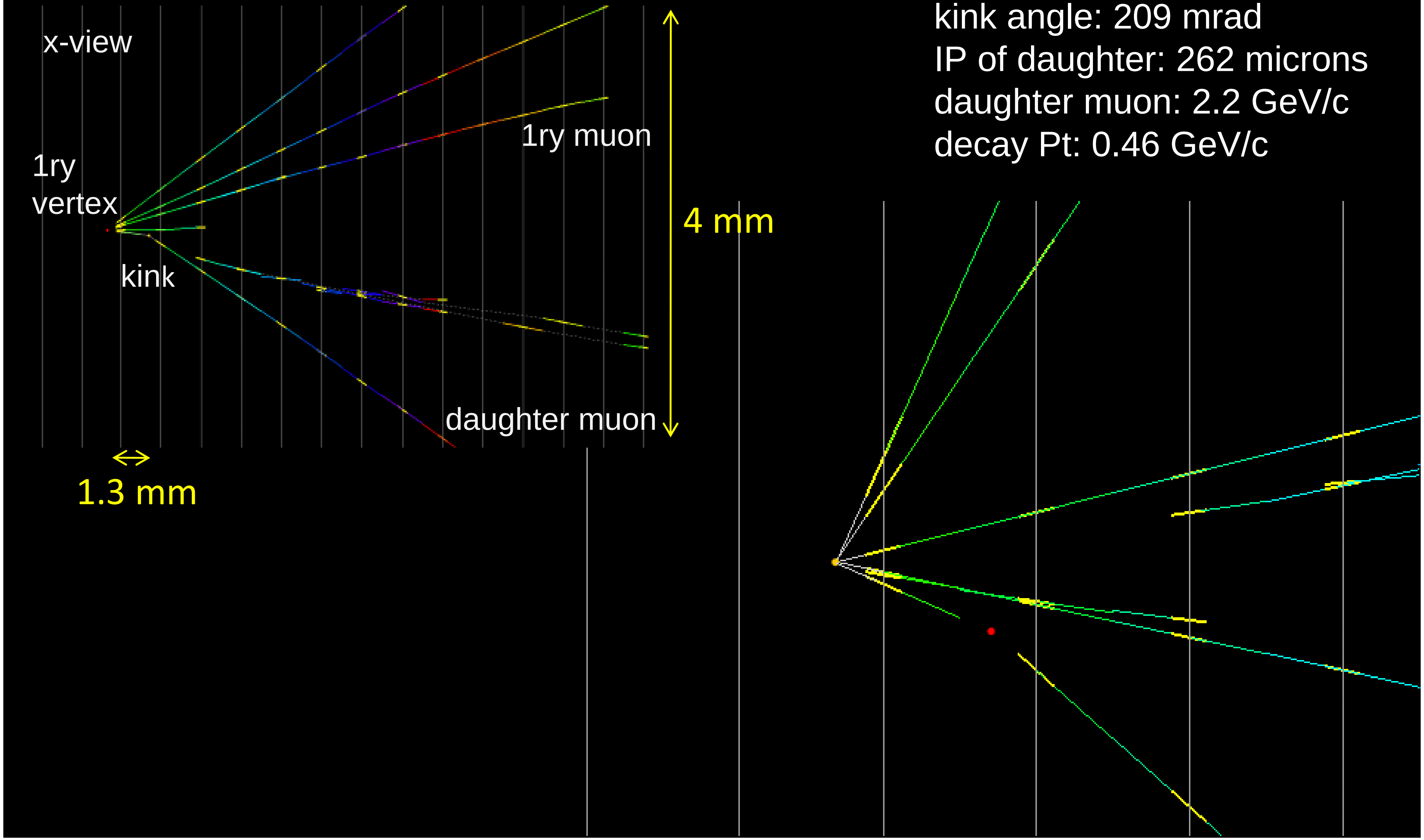
(real data: 35 γ pairs)



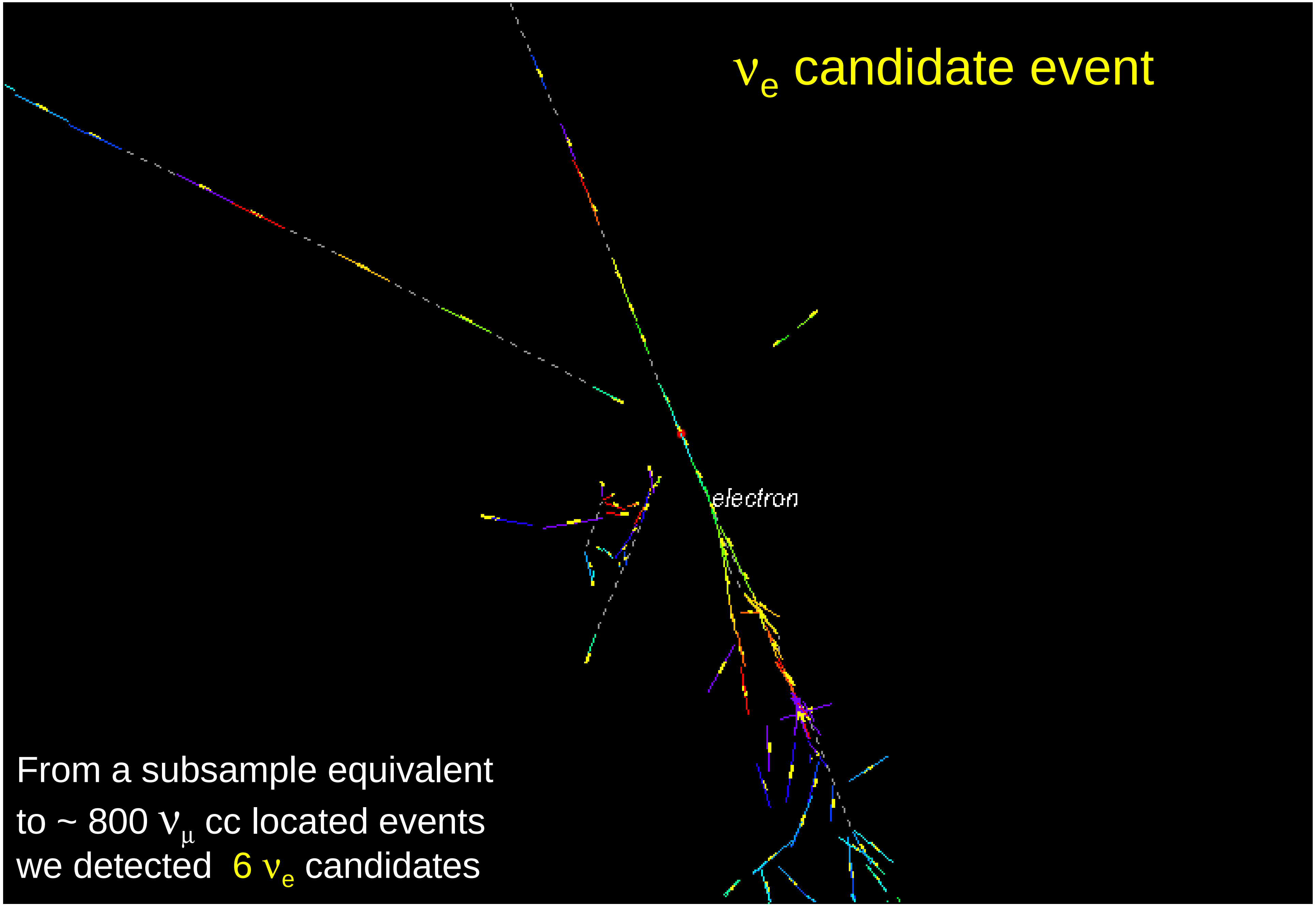
$(P_{mcs}-P_{spectro}) / P_{spectro}$

Charm candidate event (dimuon)

flight length: 1330 microns
kink angle: 209 mrad
IP of daughter: 262 microns
daughter muon: 2.2 GeV/c
decay Pt: 0.46 GeV/c

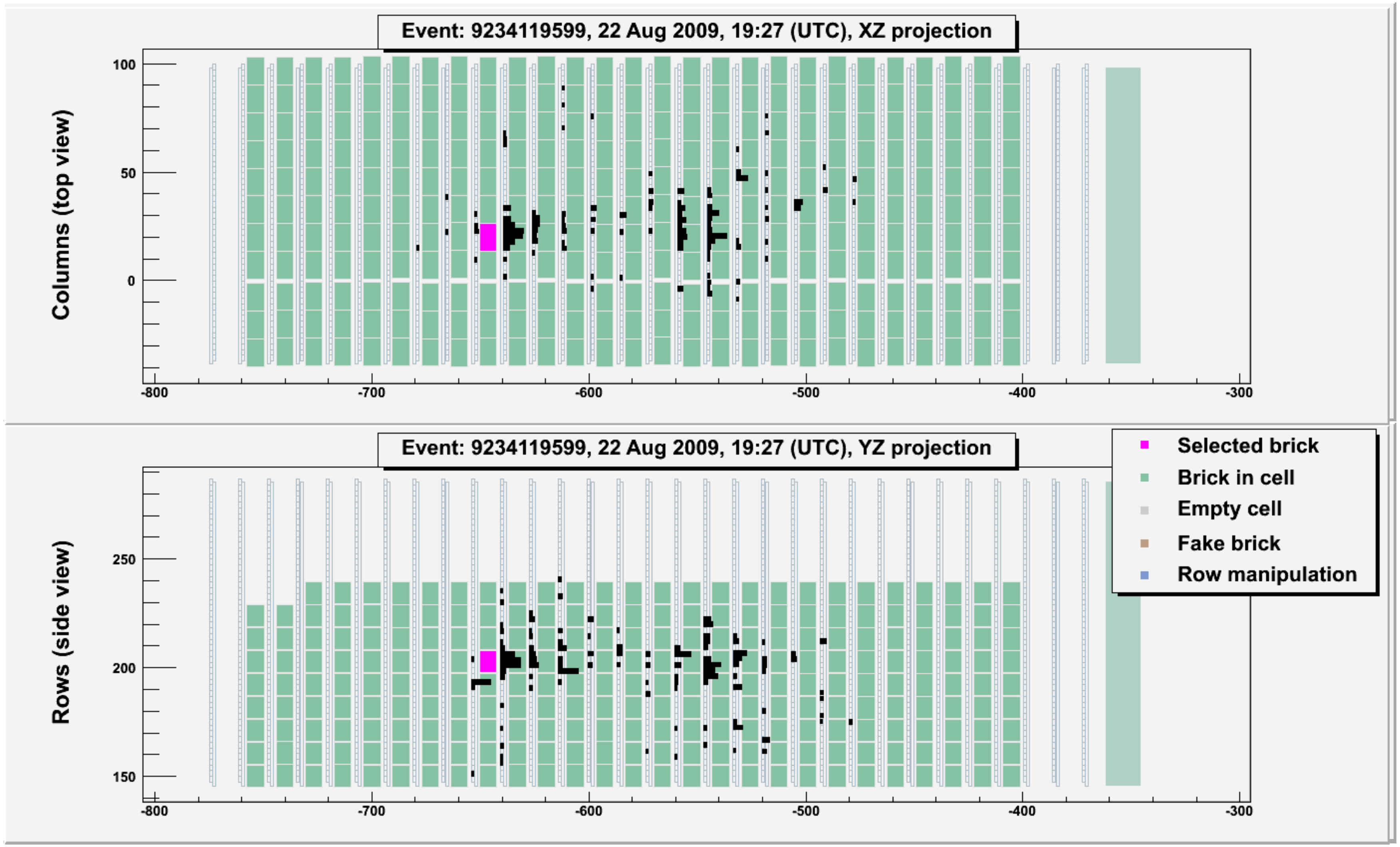


ν_e candidate event



From a subsample equivalent
to ~ 800 ν_μ cc located events
we detected 6 ν_e candidates

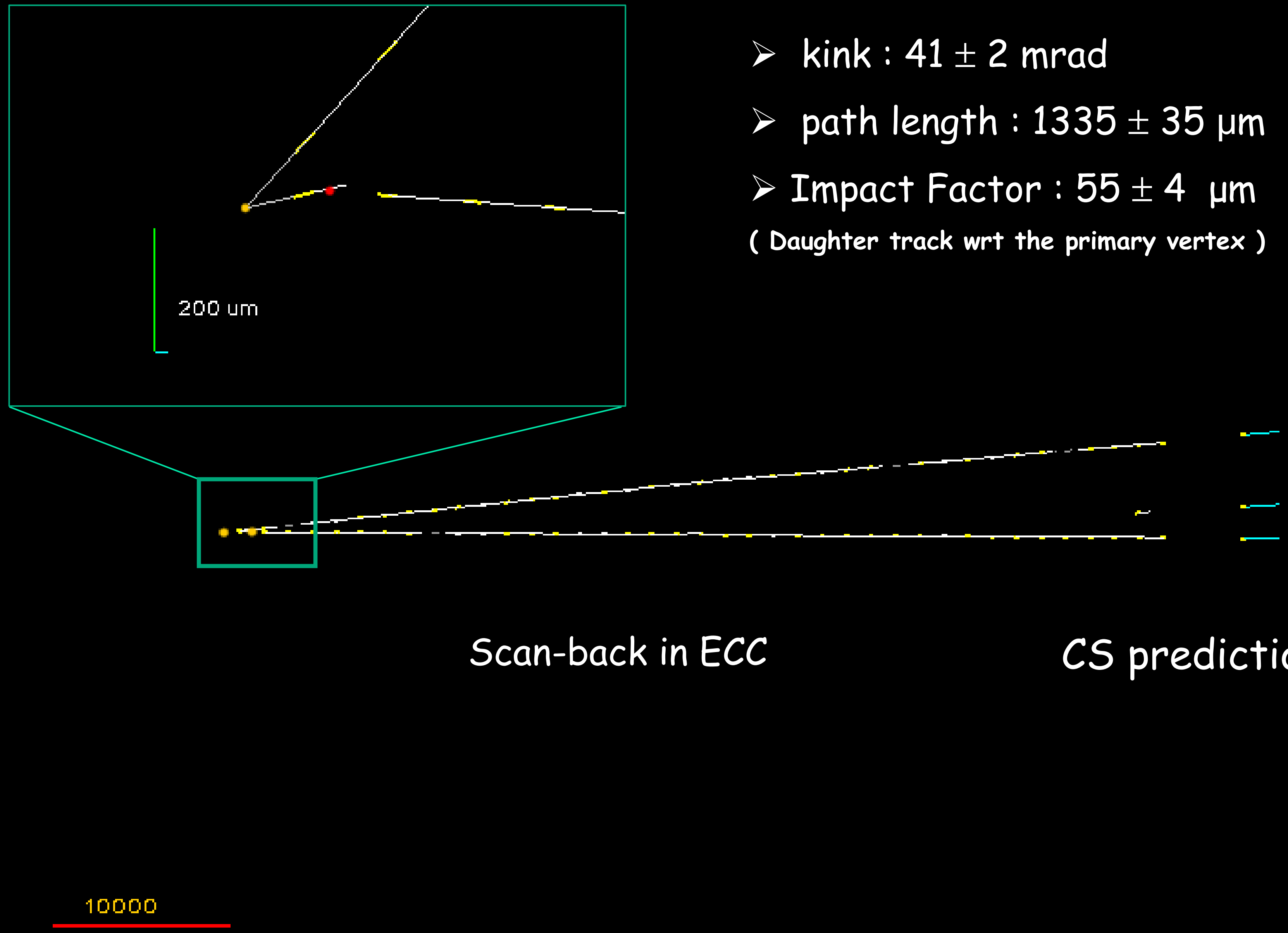
Muon less event 9234119599, recorded on 22 August 2009, 19:27 (UTC) (as seen by the electronic detectors)



Secondary vertex found during the-scan back procedure

- kink : 41 ± 2 mrad
- path length : 1335 ± 35 µm
- Impact Factor : 55 ± 4 µm

(Daughter track wrt the primary vertex)

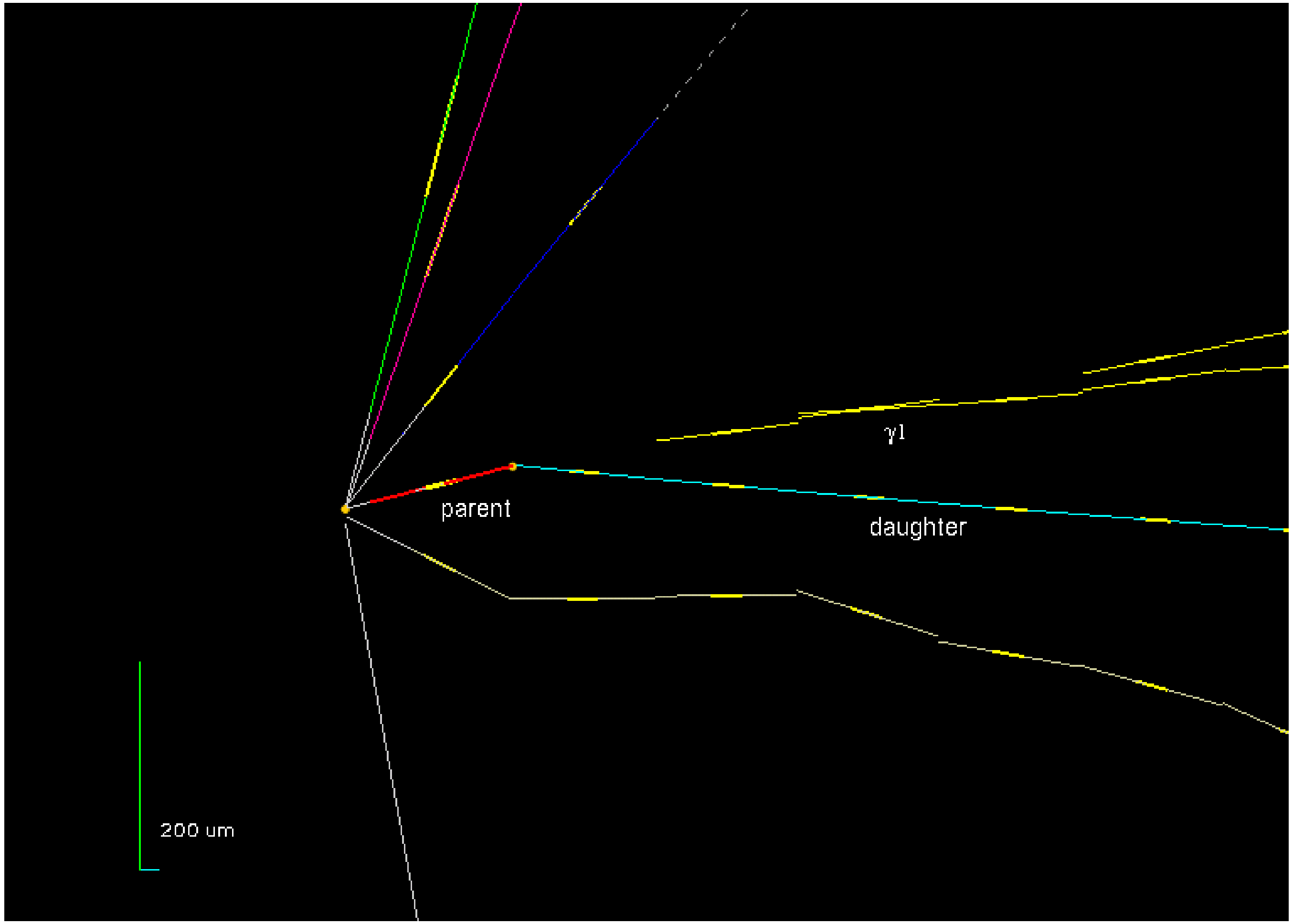


Scan-back in ECC

CS predictions

Event reconstruction (zoom)

careful visual inspection of the films behind/in-front the secondary vertex:
→ no "black" or "evaporation" tracks. Support topological hypothesis of a particle decay



Conclusions for OPERA

We have observed 1 ν_τ interaction candidate with the τ decaying into a single hadron:

One swallow
does not make spring

Background expectations

- single hadron mode only — 0.018 ± 0.007 (syst) ➡ 1.8 % , 2.36 σ
  - 0.011 events (reinteractions)
  - 0.007 events (charm)
- all decay modes (total Background): — 0.045 ± 0.020 (syst) ➡ 4.5 % , 2.01 σ

1-prong hadron, 3-prongs + 1-prong μ + 1-prong *e* :

Significance

Probability to observe 1 event due to a background fluctuation

With only 1 event in OPERA
we obtained the same significance
as SuperK (2006)

Third matrix : θ_{13} search

Les expériences *réacteurs* ne sont sensibles qu'à $\sin^2 2\Theta_{13}$

Formalisme avec *l'effet matière*

$$P_{\nu_\mu \to \nu_e} \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 [(1-A)\Delta]}{(1-A)^2}$$

$$\Delta = \frac{\Delta m^2_{13} L}{4E}$$

$$\pm\, \alpha \sin\theta_{13} \sin\delta_{CP} \sin\Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{(1-A)}$$

$+\nu$

$-\bar{\nu}$

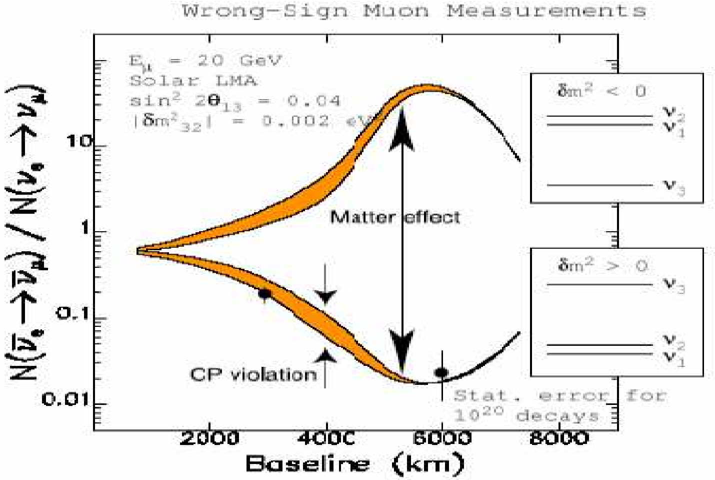
La *nouvelle physique* est contenue dans ce terme

$$\alpha = \frac{\Delta m^2_{21}}{|\Delta m^2_{13}|} \sim 2\ 10^{-2}$$

Un autre cadeau du ciel !

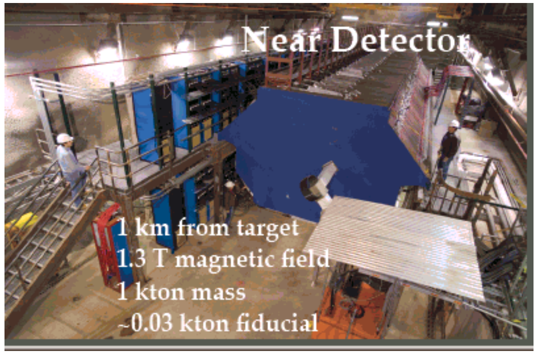
Effet matière:

$$A = 2\sqrt{2} G_F n_e \frac{E}{\Delta m^2_{3}}$$

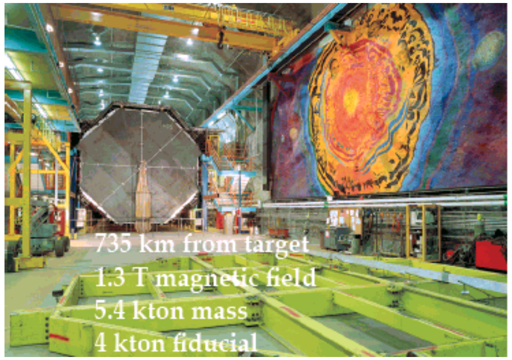


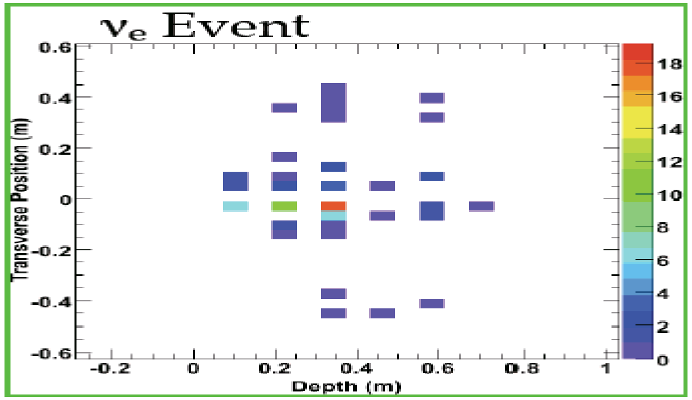
Permet de définir la hiérarchie des masses

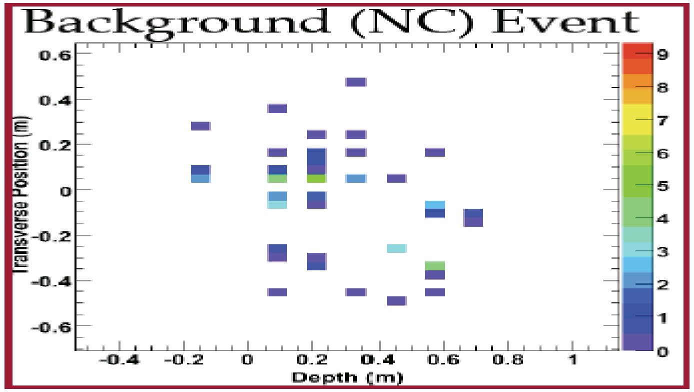
υ_e Appearance in MINOS


Near Detector

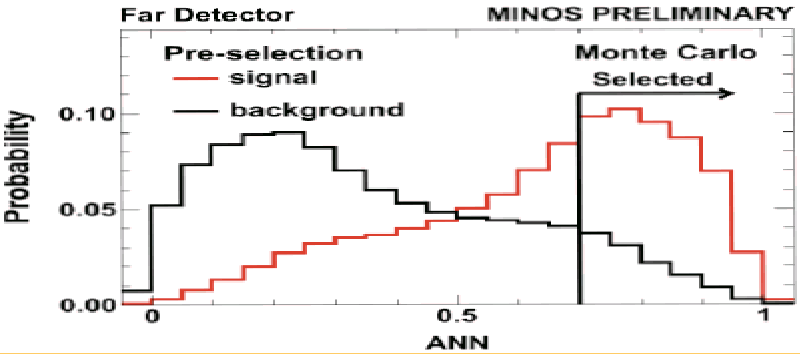
1 km from target
1.3 T magnetic field
1 kton mass
~0.03 kton fiducial


735 km from target
1.3 T magnetic field
5.4 kton mass
4 kton fiducial

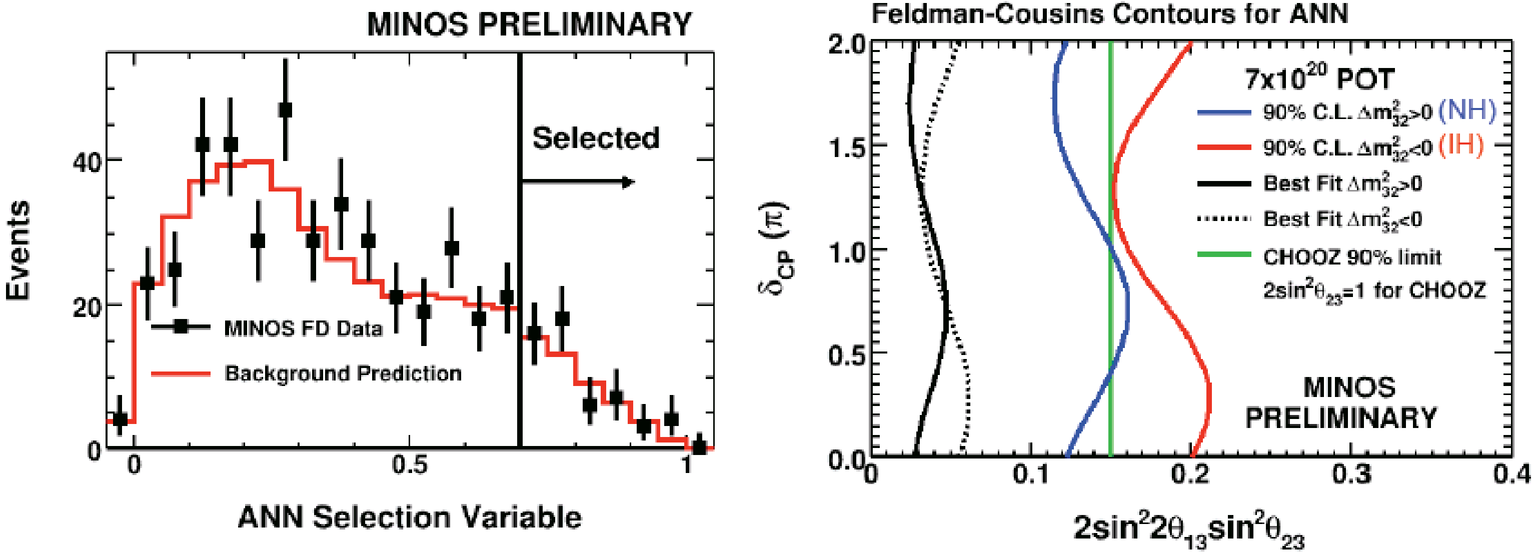




- ANN uses 11 variables
- Most important plotted
- Select ANN > 0.7



ν_e Appearance in MINOS



$$\text{Assuming } \theta_{23} = \pi/4,\ \delta_{\rm CP} = 0,\ |\Delta m^2_{32}| = 2.43 \times 10^{-3}$$

$$\text{Normal Hierarchy}: \quad \sin^2(2\theta_{13}) < 0.12\ (90\%\text{C.L.})$$

$$\text{Inverted Hierarchy}: \quad \sin^2(2\theta_{13}) < 0.20\ (90\%\text{C.L.})$$

Better than CHOOZ for the Normal Hierarchy

A. Rubbia
Neutel 2011

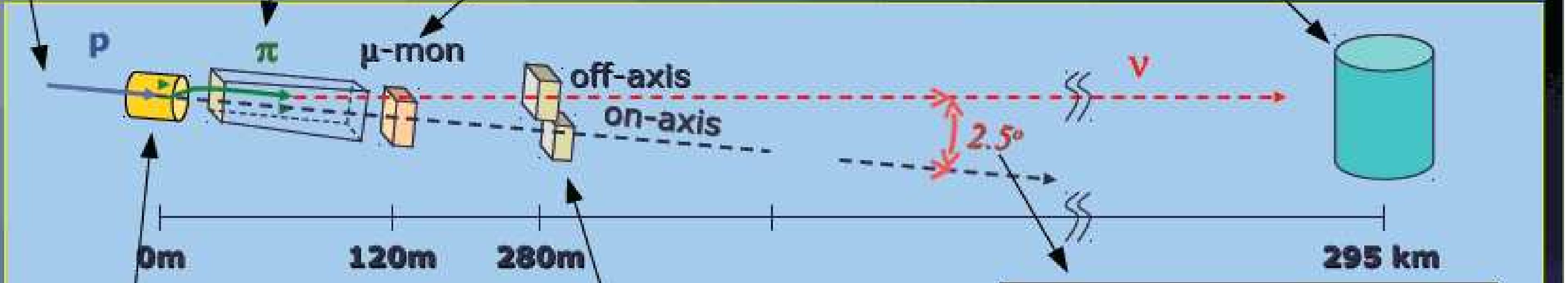
T2K Overview

30 GeV proton beam from J-PARC Main Ring (MR)

Pions decay in ≈100m decay volume

MUMON monitor measures muons from pion decay

Off-axis at 295 km, Super-Kamiokande (SK) water cherenkov detector measures oscillated flux



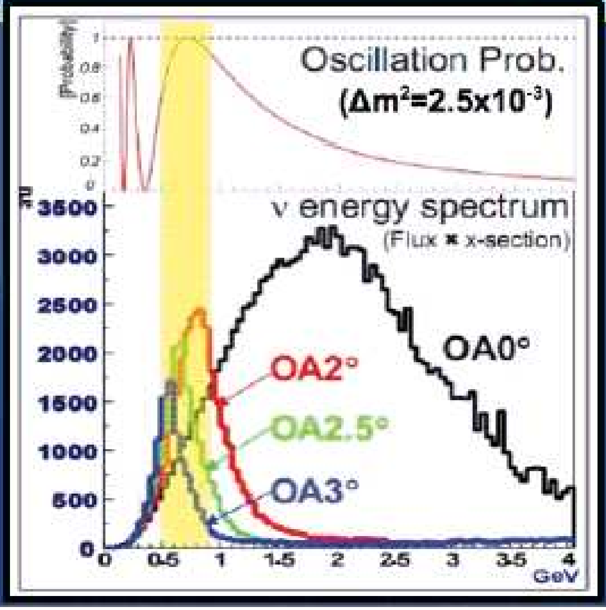
Beam on 90 cm graphite target

3 magnetic horns focus positively charged hadrons

At 280 m, on-axis INGRID detector measures neutrino rate, beam profile

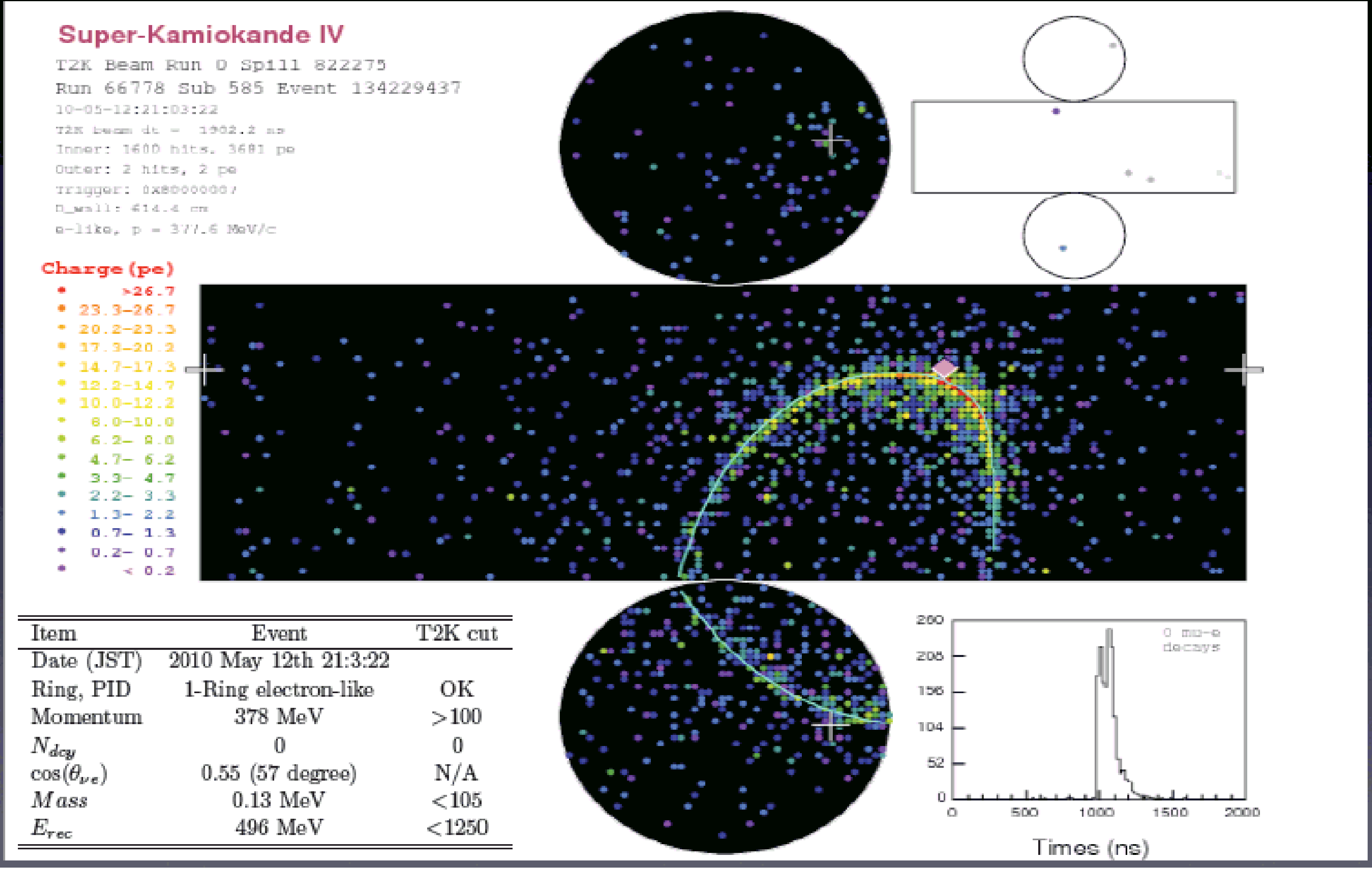
Off-axis ND280 detector measures spectra for various neutrino interactions

Beam peaked at 1st max E≈600 MeV



T2K ν_e CC signal candidate (2010a)

Signal candidate event passing all cuts



```
T2K Beam Run 0 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt =  1902.2 ns
Inner: 1600 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 377.6 MeV/c
```

Item	Event	T2K cut
Date (JST)	2010 May 12th 21:3:22	
Ring, PID	1-Ring electron-like	OK
Momentum	378 MeV	>100
N_{dcy}	0	0
$\cos(\theta_{\nu e})$	0.55 (57 degree)	N/A
$Mass$	0.13 MeV	<105
E_{rec}	496 MeV	<1250

Expected #SK events

Run 2010a : 3.23 10^{19} pot

Source	Estimated number
Beam ν_μ (CC+NC)	0.13
Beam $\bar{\nu}_\mu$ (CC+NC)	0.01
Beam ν_e (CC)	0.16
Total background	**0.30 ± 0.07 (syst.)**
Total sig.+background	**1.20 ± 0.23 (syst.)**

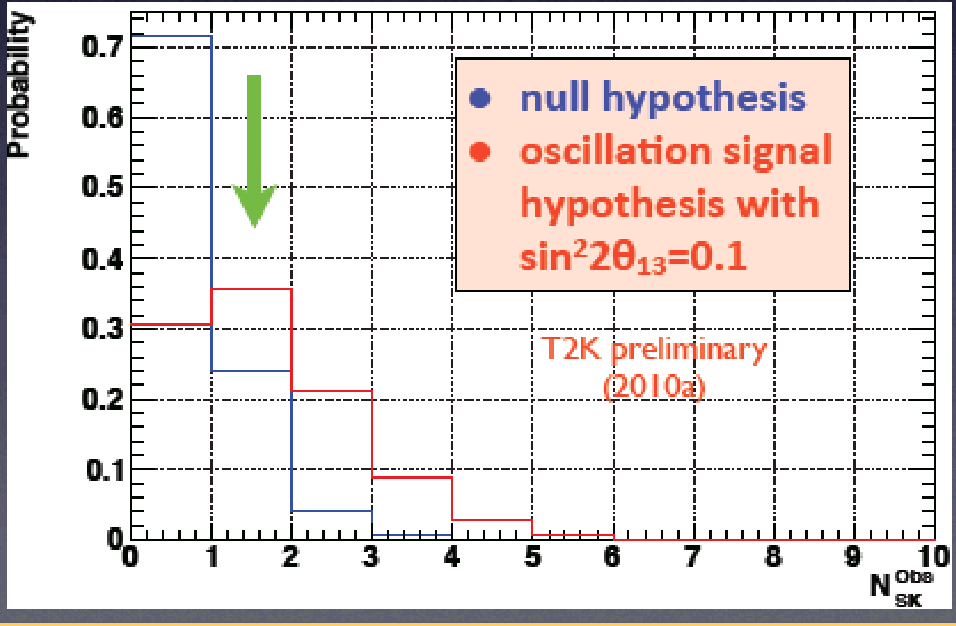
- #events normalized to p.o.t. and corrected for ND280 ν_μ CC measured normalization
- Assumed oscillation parameters for signal:

$\Delta m^2_{23} = 2.4 \cdot 10^{-3} \text{eV}^2$

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

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

$\delta_{CP} = 0$



T2K preliminary (2010a)

~29% probability to observe >=1 event when expected average = 0.3 event

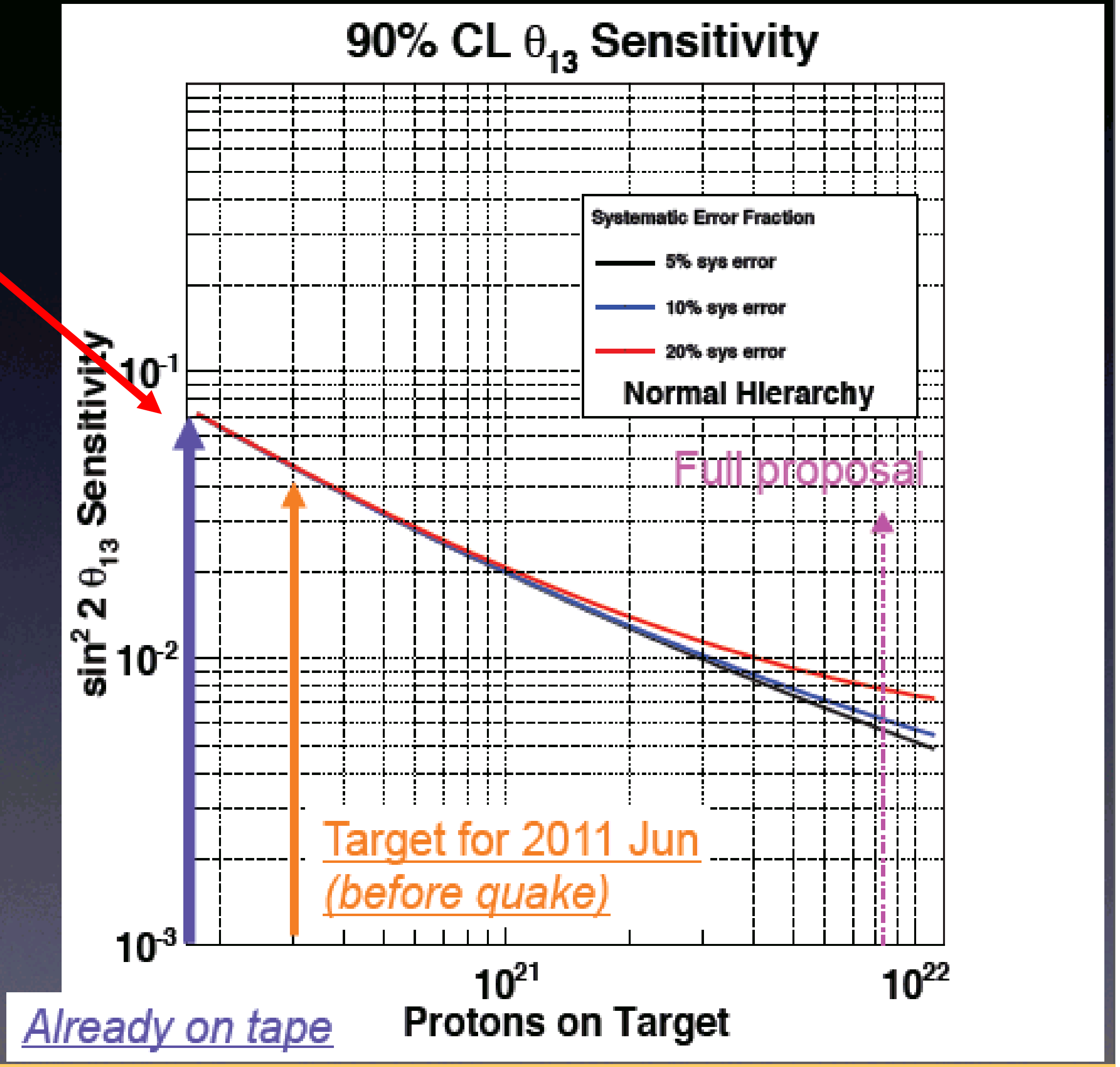
1 data candidate!

$N_{SK}^{obs} = 1$

Prospects for updated results

- 1.45x10^{20} p.o.t. on tape = 73kW*1e7 s = 4.5x(2010a)
- Aim at 3x10^{20} p.o.t. = 150kW*1e7 s by July 2011 (quake→??)
- Analysis improvements underway
  - New NA61 results → Systematic error uncertainty from hadron production will be reduced.
  - Spectrum measurement in ND and near/far ratio to reduce model dependence

Signal sensitivity vs p.o.t.

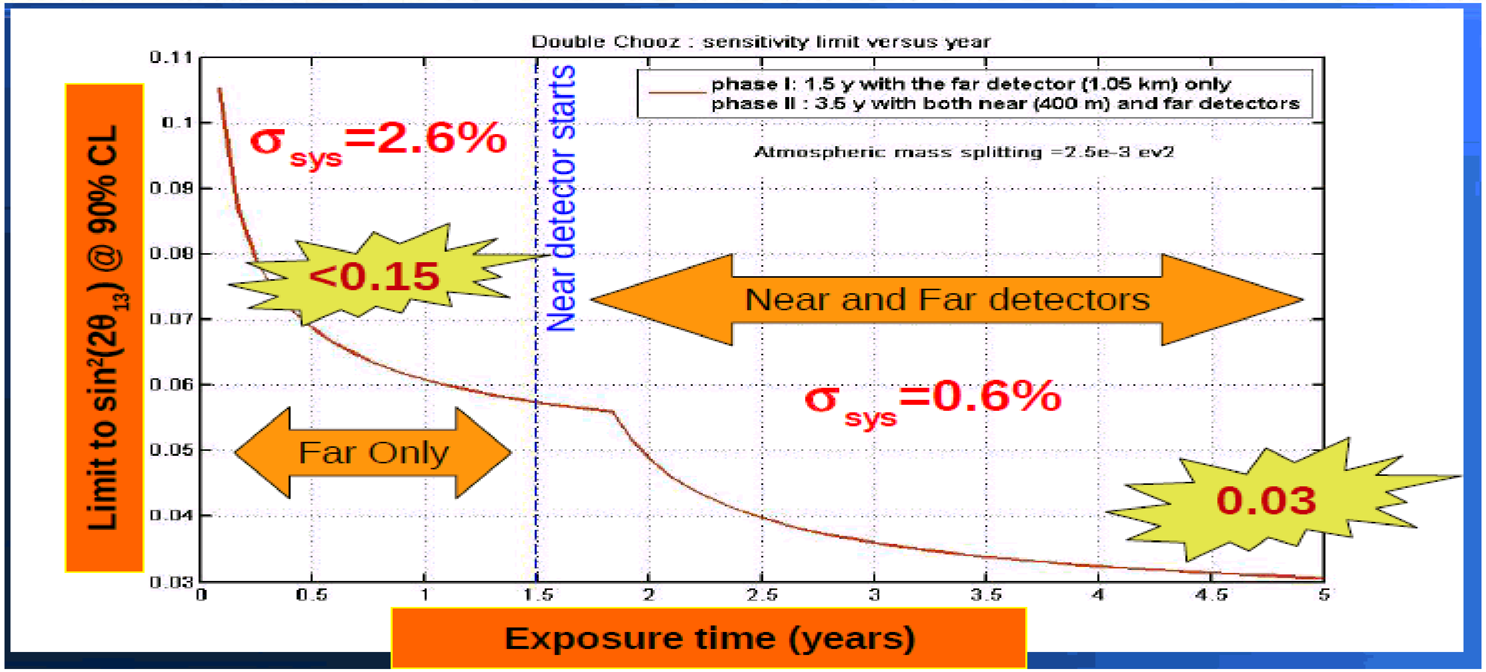


Θ_{13} dedicated reactor experiments

Chooz Reactors
Power: 8.5GWth
(N4s: very powerful)

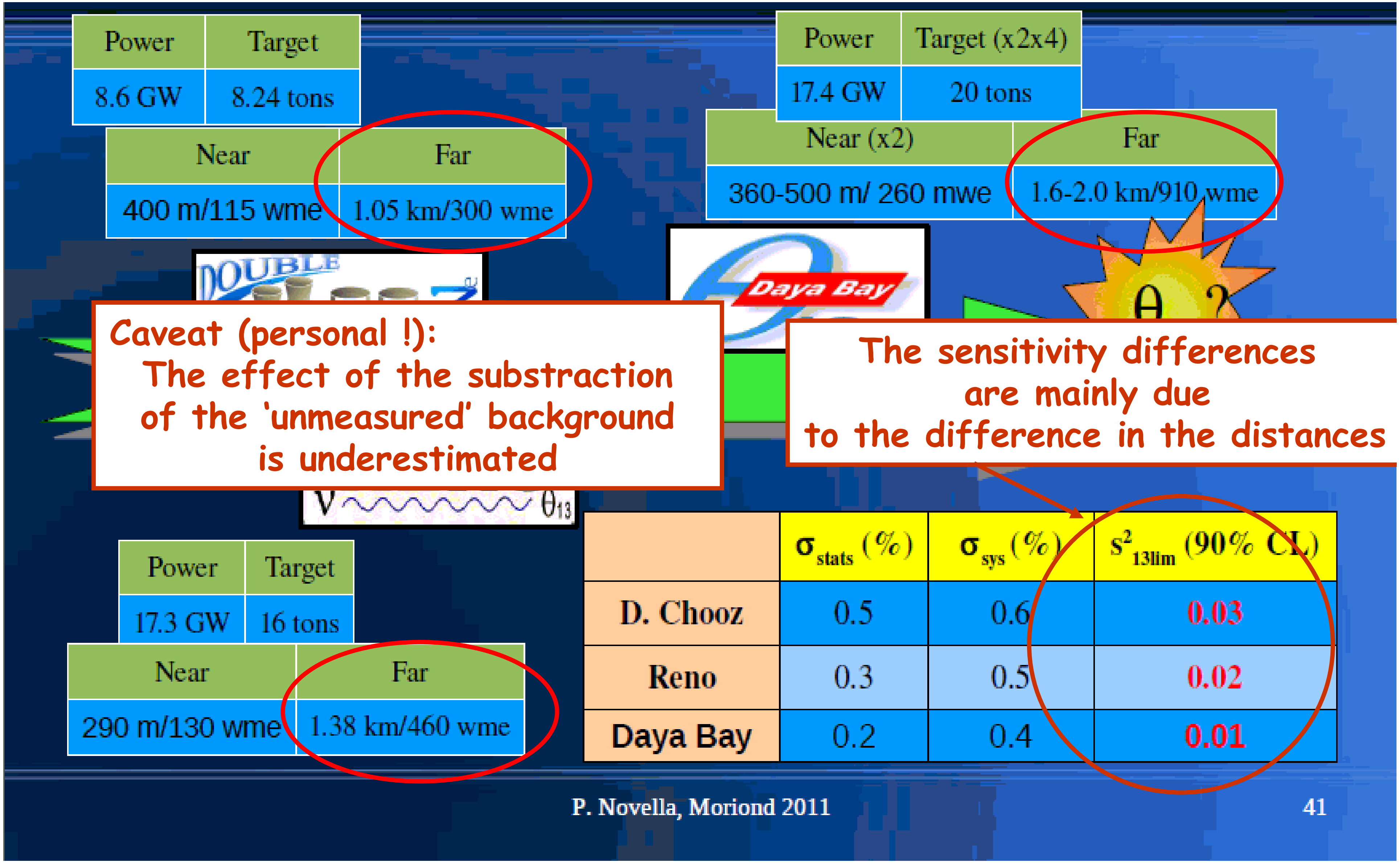
Near
<L> 400m
400ν/day
120mwe
Target: 8.2t
End of 2012

Far
<L> 1050m
50ν/day
300mwe
Target: 8.2t
March 2011



Θ_{13} dedicated reactor experiments

3 'carbon copy' experiments …



Power	Target
8.6 GW	8.24 tons

Near	Far
400 m/115 wme	1.05 km/300 wme

Power	Target (x2x4)
17.4 GW	20 tons

Near (x2)	Far
360-500 m/ 260 mwe	1.6-2.0 km/910 wme

Power	Target
17.3 GW	16 tons

Near	Far
290 m/130 wme	1.38 km/460 wme

	σ_{stats} (%)	σ_{sys} (%)	s^2_{13lim} (90% CL)
D. Chooz	0.5	0.6	0.03
Reno	0.3	0.5	0.02
Daya Bay	0.2	0.4	0.01

P. Novella, Moriond 2011

41

Caveat (personal !):
The effect of the substraction
of the 'unmeasured' background
is underestimated

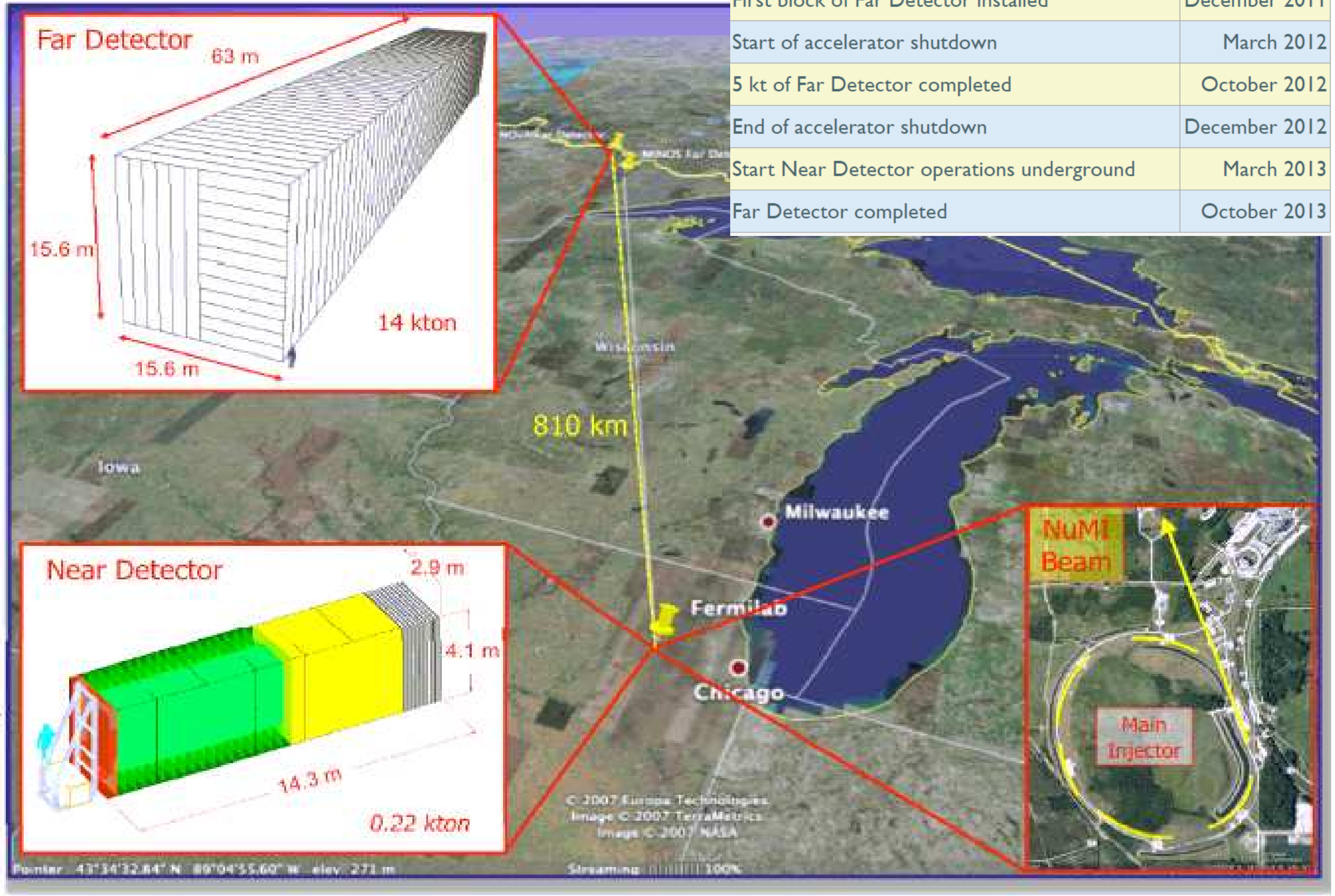
The sensitivity differences
are mainly due
to the difference in the distances

NOvA Overview

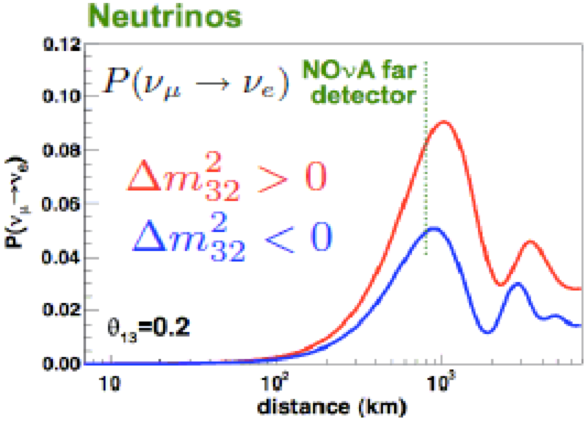
NuMI Off-Axis ν_e Appearance

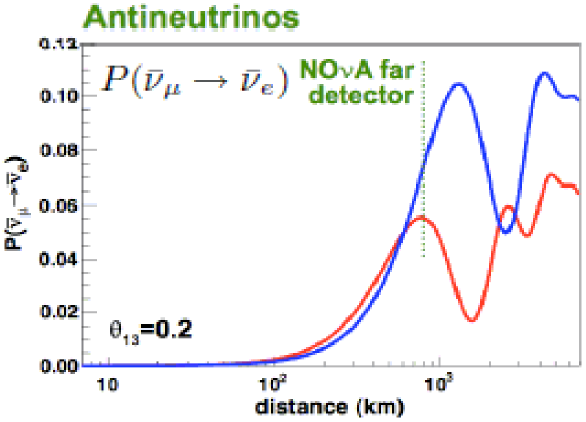
NDOS first beam neutrino	December 2010
NDOS fully commissioned	June 2011
First block of Far Detector installed	December 2011
Start of accelerator shutdown	March 2012
5 kt of Far Detector completed	October 2012
End of accelerator shutdown	December 2012
Start Near Detector operations underground	March 2013
Far Detector completed	October 2013

- 810 km baseline from Fermilab to Ash River, in northern MN
- 700 kW NuMI neutrino beam
- Near and Far detectors placed 14 mrad off the NuMI beam axis
- Search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations to:
  - Measure θ_{13}
  - Determine the neutrino mass hierarchy
  - Constrain δ_{CP}



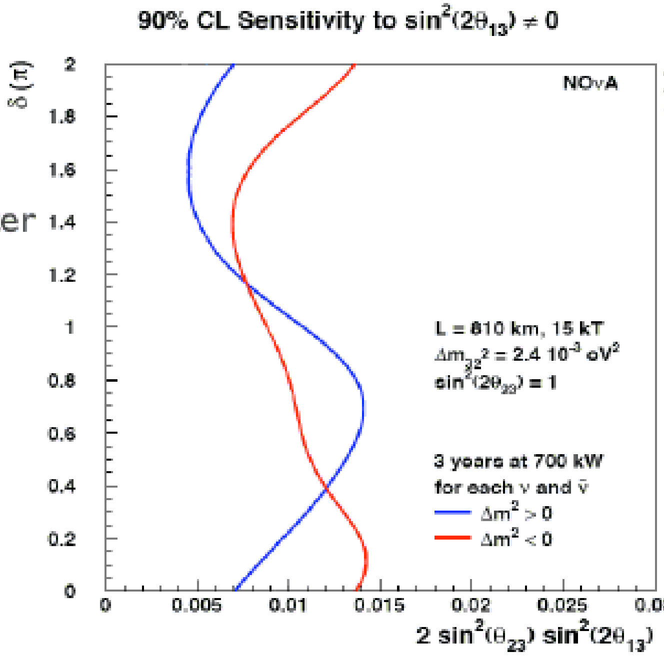
NOvA Physics Reach

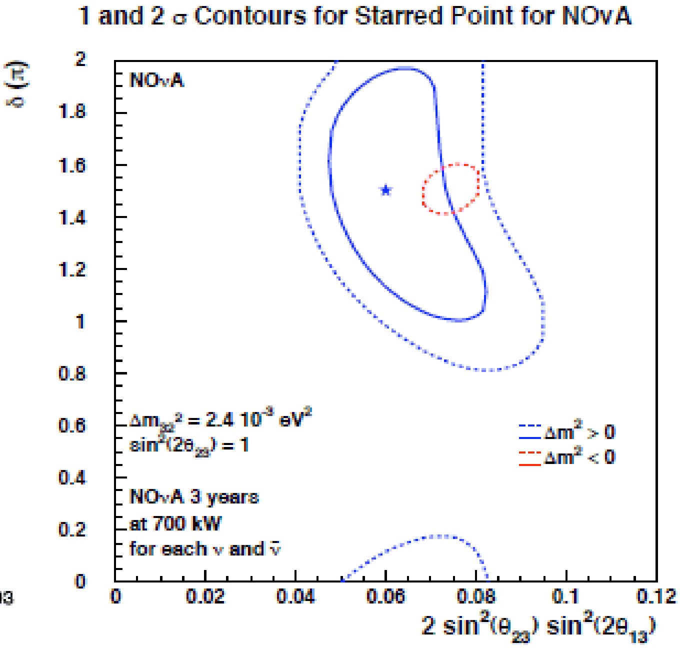

Neutrinos


Antineutrinos

- NOvA plans to run for 3 years in neutrino and 3 years in antineutrino mode
- Take advantage of large matter effects => 30% enhancement/suppression of oscillation probability (11% in T2K)

- NOvA's sensitivity to θ_{13} is one order of magnitude better than the limit from CHOOZ ($\sin^2 2\theta_{13} < 0.15$, 90% CL)
- NOvA may also begin to constrain the δ_{CP} parameter space


90% CL Sensitivity to $\sin^2(2\theta_{13}) \neq 0$


1 and 2 σ Contours for Starred Point for NOvA

Conclusions on Active neutrino oscillations

Evidence for massive neutrinos is only provided through the observation of neutrino oscillations

- Solar sector: fully validated (L/E & Appearance)
- Atmospheric sector :
  - ✓ unambiguous L/E distribution from MINOS & SuperK
  - ✓ Appearance signal existing → stronger signal needed from OPERA
- cross mixing (θ_{13}, δ_{cp}) : gateway for CP violation and mass hierarchy
  → on-going experiments : MINOS, T2K, Reactors, NOvA

Still some anomalies flying around …
suggesting the presence of sterile neutrinos ??!!

G_a Anomaly (Giunti, NeuTel 2011)

Gallium Radioactive Source Experiments

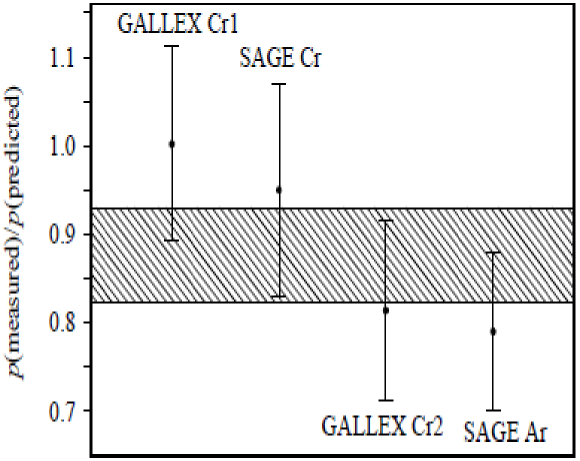
When a test leads to a discovery

Tests of the solar neutrino detectors GALLEX (Cr1, Cr2) and SAGE (Cr, Ar)

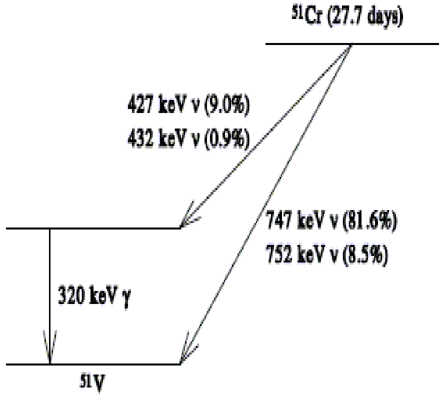
Detection Process: $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

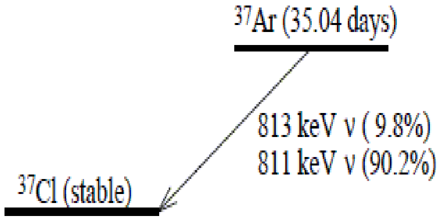
	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
B.R.	0.8163	0.0849	0.0895	0.0093	0.902	0.098



[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]



[SAGE, PRC 59 (1999) 2246, hep-ph/9803418]

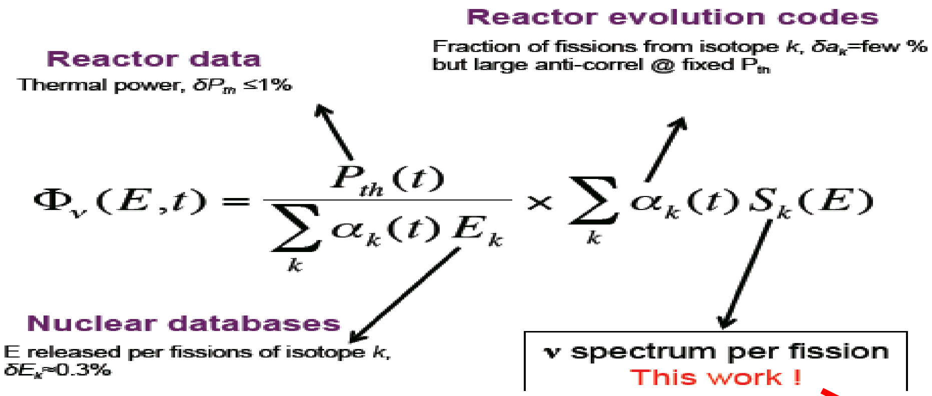


[SAGE, PRC 73 (2006) 045805, nucl-ex/0512041]

Weighted mean

$$\boxed{R_{\mathrm{Ga}} = 0.86 \pm 0.05}$$

The Reactor Antineutrino Anomaly (1) : (RNA pour les intimes …)



Reactor data
Thermal power, $\delta P_{th} \leq 1\%$

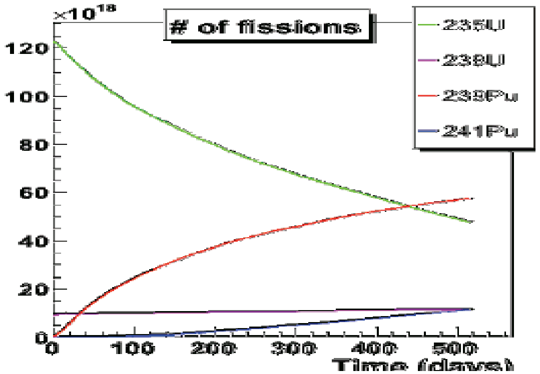
Reactor evolution codes
Fraction of fissions from isotope k, $\delta\alpha_k$=few %
but large anti-correl @ fixed P_{th}

$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

Nuclear databases
E released per fissions of isotope k,
$\delta E_k \approx 0.3\%$

ν spectrum per fission
This work !

$k = {}^{235}\mathrm{U}, {}^{238}\mathrm{U}, {}^{239}\mathrm{Pu}, {}^{241}\mathrm{Pu}$



Th. A. Mueller et al: arXiv:1101.2663

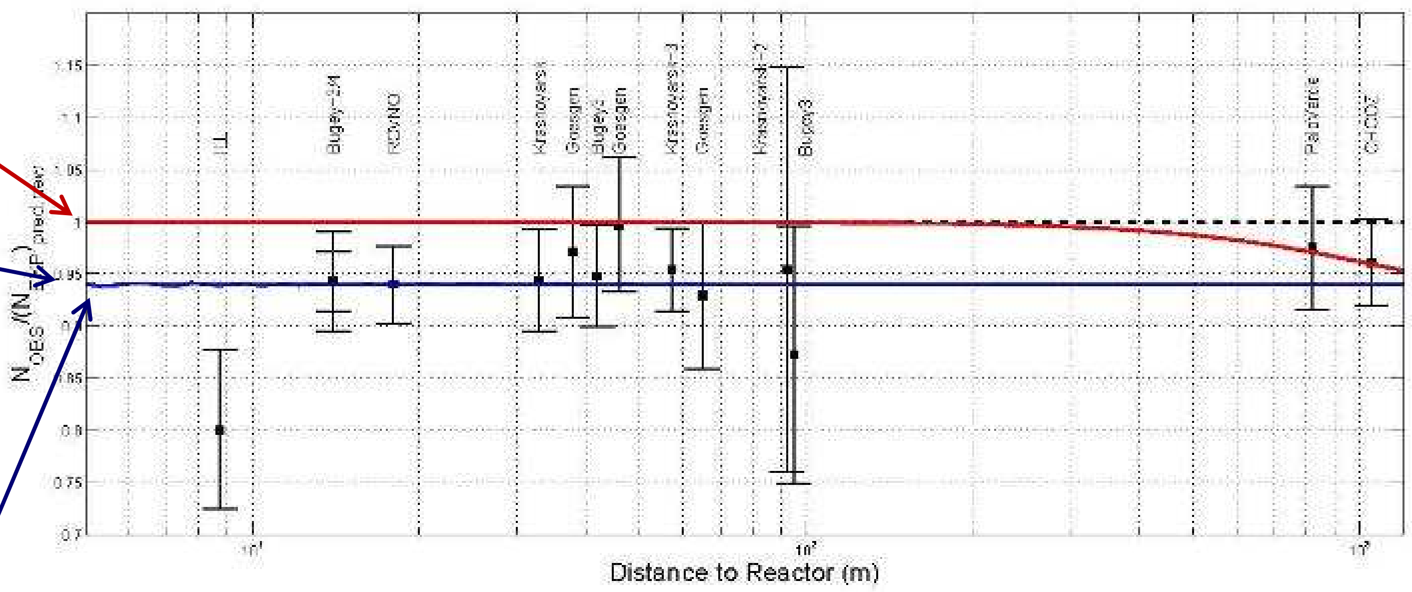
$\Phi_\upsilon \rightarrow + 3\%$

Assuming oscillation with $\sin^2 2\theta_{13} = 0.06$

Assuming $\theta_{13} = 0$ and suppression due to sterile neutrino with $\sin^2 2\theta_{14} \sim$ and $|\Delta m^2| > 1.5$ eV²

Observed/Predicted = 0.937 ± 0.027

For < 100m.



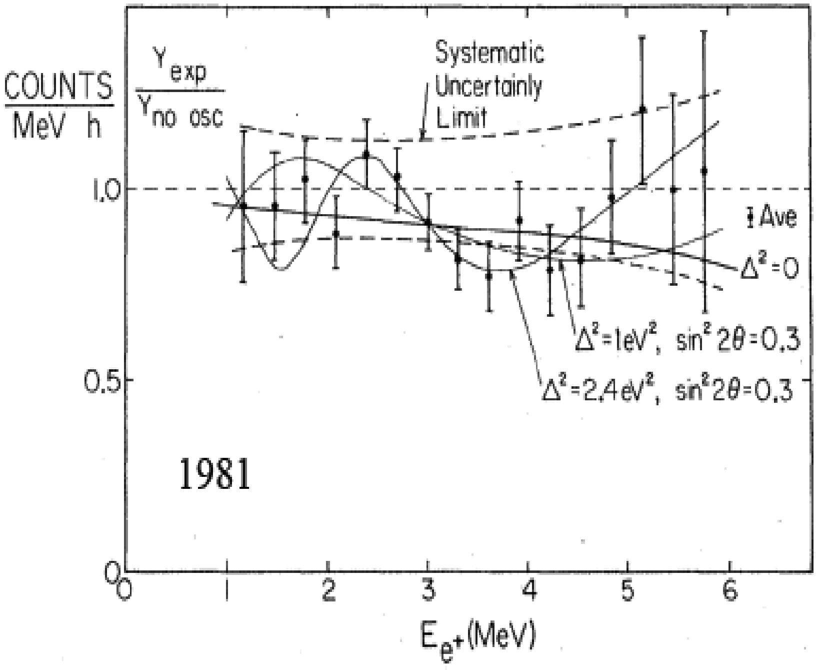
G. Mention et al: arXiv:0179257

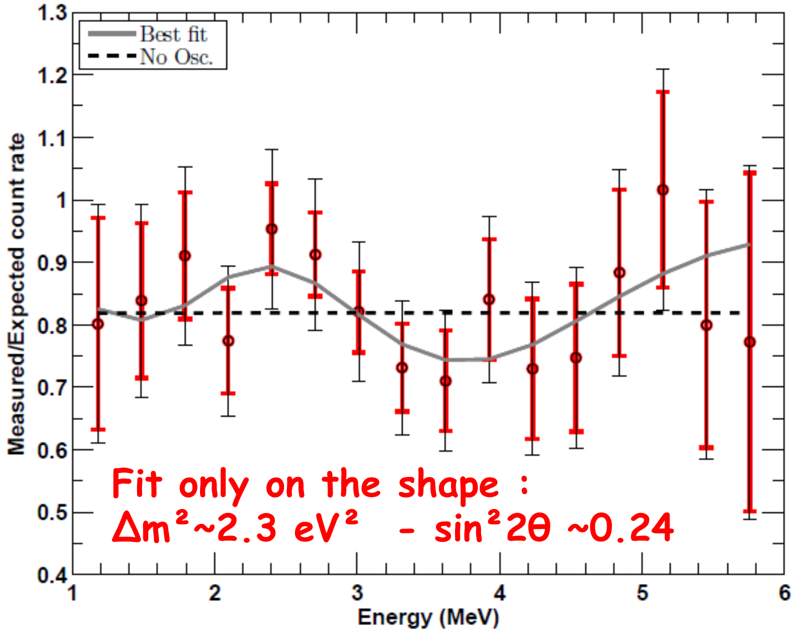
The Reactor Antineutrino Anomaly (2) : ILL ν experiment 'revisited'
G. Mention et al: arXiv:017925

- Reactor at ILL with **almost pure** ^{235}**U**, with **compact core**
- Detector **8.76(?) m** from core. Any bias?

A. Hoummada et al, Appl. Rad. Isot. V46, 1995

- Reanalysis in 1995 by part of the collaboration to account for overestimation of flux at ILL reactor by 10%... Affects the rate only





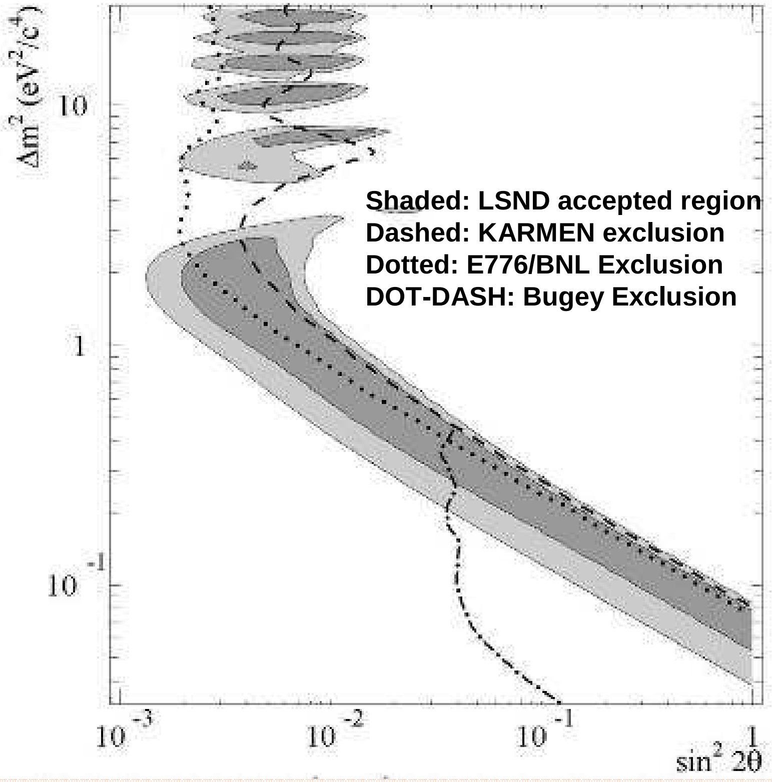
Fit only on the shape : $\Delta m^2 \sim 2.3\ eV^2$ - $\sin^2 2\theta \sim 0.24$

- Large errors, but a striking pattern is seen by eye ?

LSND (1996)

Measurement of muon antineutrino to electron antineutrino conversion at LAMPF facility:

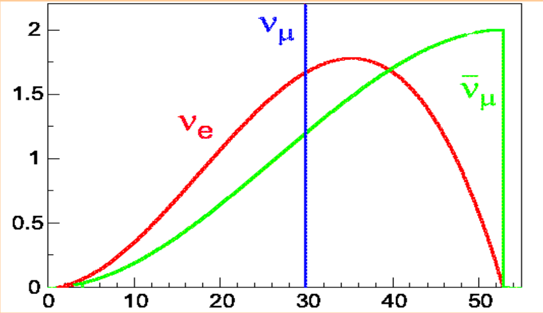
Excess of $51.8^{+18.7}_{-16.9} \pm 8$ events.



Shaded: LSND accepted region
Dashed: KARMEN exclusion
Dotted: E776/BNL Exclusion
DOT-DASH: Bugey Exclusion

LAMPF
Beam stop

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

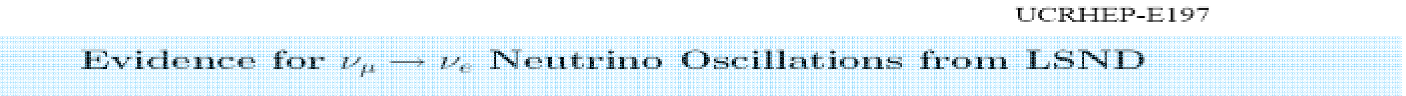



LA-UR-96-1582

Evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations from the LSND Experiment at LAMPF

Nucl-ex-9605003v

Discarded

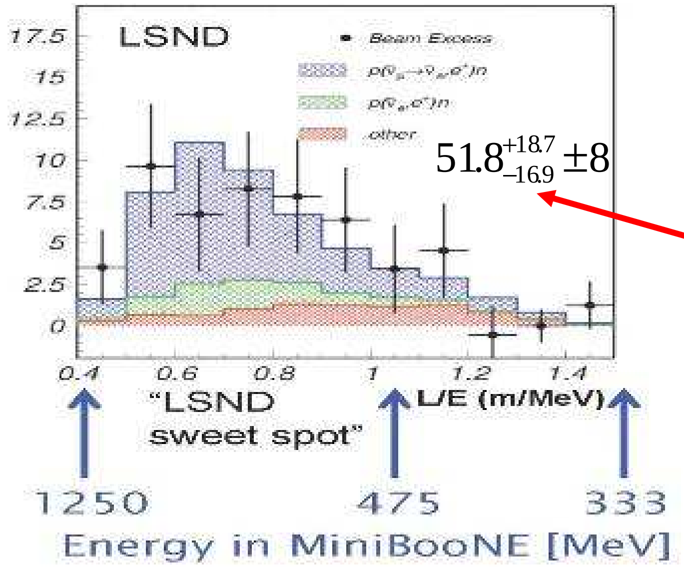

UCRHEP-E197

Evidence for $\nu_\mu \to \nu_e$ Neutrino Oscillations from LSND

Nucl-ex-9709006v

LSND (1996) & MiniBooNE (2009)

R. Van de Water Nu2010



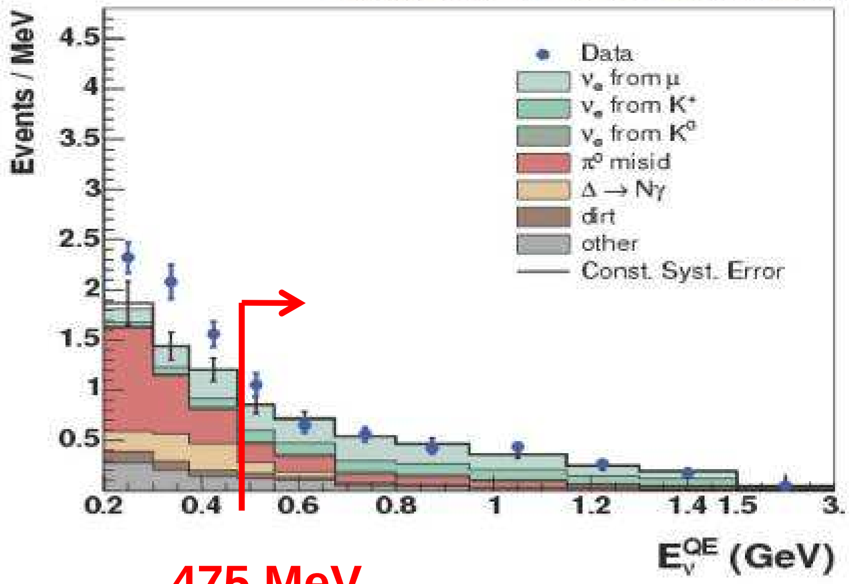
$51.8^{+18.7}_{-16.9} \pm 8$

Excess compatible between LSND & MiniBooNE

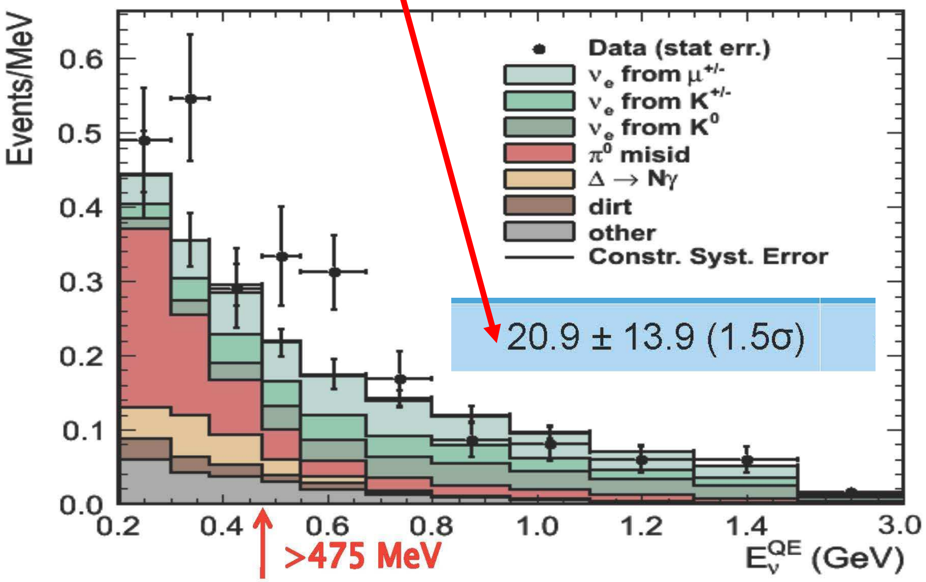
$$\nu_\mu \to \nu_e$$

$$\bar{\nu}_\mu \to \bar{\nu}_e$$

Published PRL 102,101802 (2009)



475 MeV



20.9 ± 13.9 (1.5σ)

>475 MeV

Is there a coherent pattern for sterile neutrino effects

Antineutrino	Neutrino
Reactor Neutrino Anomaly	Ga experiments Source Anomaly
LSND/MiniBooNE	nothing

- ν_e disappearance experiments:

$$\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2\left(1-|U_{e4}|^2\right) \simeq 4|U_{e4}|^2$$

- ν_μ disappearance experiments:

$$\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2\left(1-|U_{\mu4}|^2\right) \simeq 4|U_{\mu4}|^2$$

- $\nu_\mu \to \nu_e$ experiments:

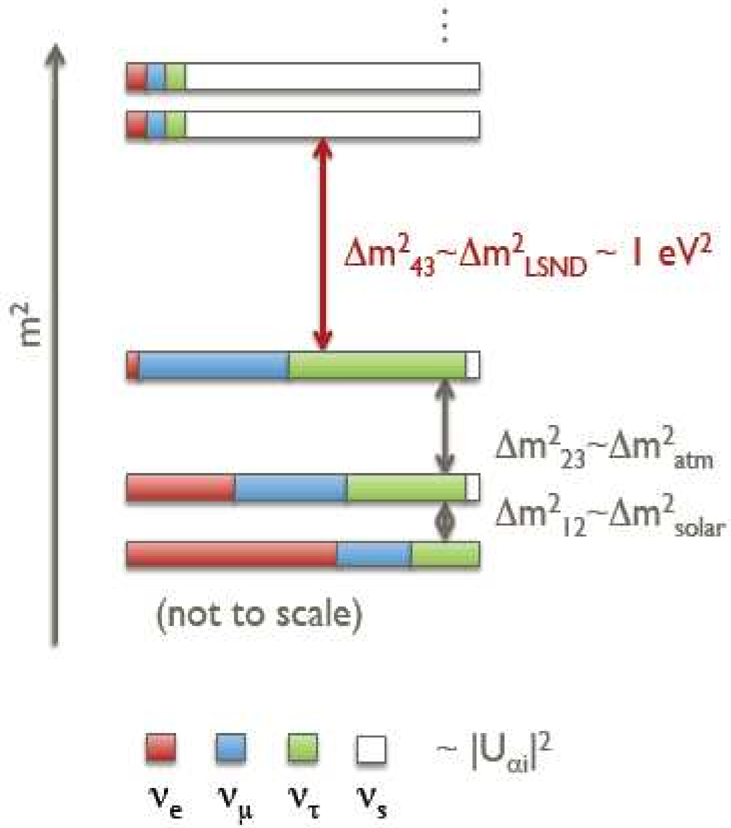
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$

- Upper bounds on $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ $\Longrightarrow$ strong limit on $\sin^2 2\vartheta_{e\mu}$

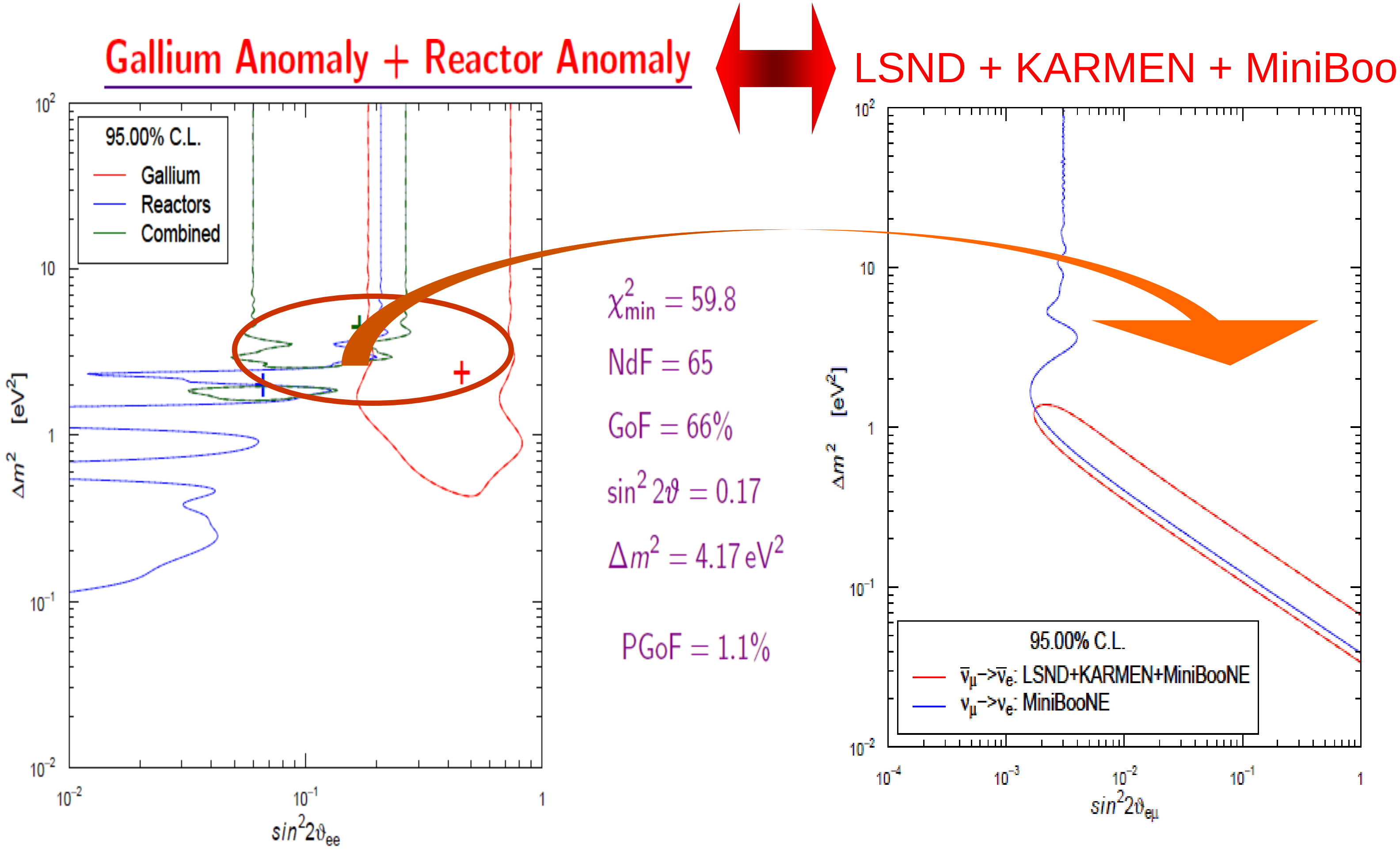
[Okada, Yasuda, Int. J. Mod. Phys. A12 (1997) 3669-3694, arXiv:hep-ph/9606411]

[Bilenky, Giunti, Grimus, Eur. Phys. J. C1 (1998) 247, arXiv:hep-ph/9607372]

3 active + n sterile neutrino states



Partial fit



Gallium Anomaly + Reactor Anomaly

LSND + KARMEN + MiniBooNE

$\chi^2_{\min} = 59.8$

NdF = 65

GoF = 66%

$\sin^2 2\vartheta = 0.17$

$\Delta m^2 = 4.17\,\mathrm{eV}^2$

PGoF = 1.1%

3+1 Schemes

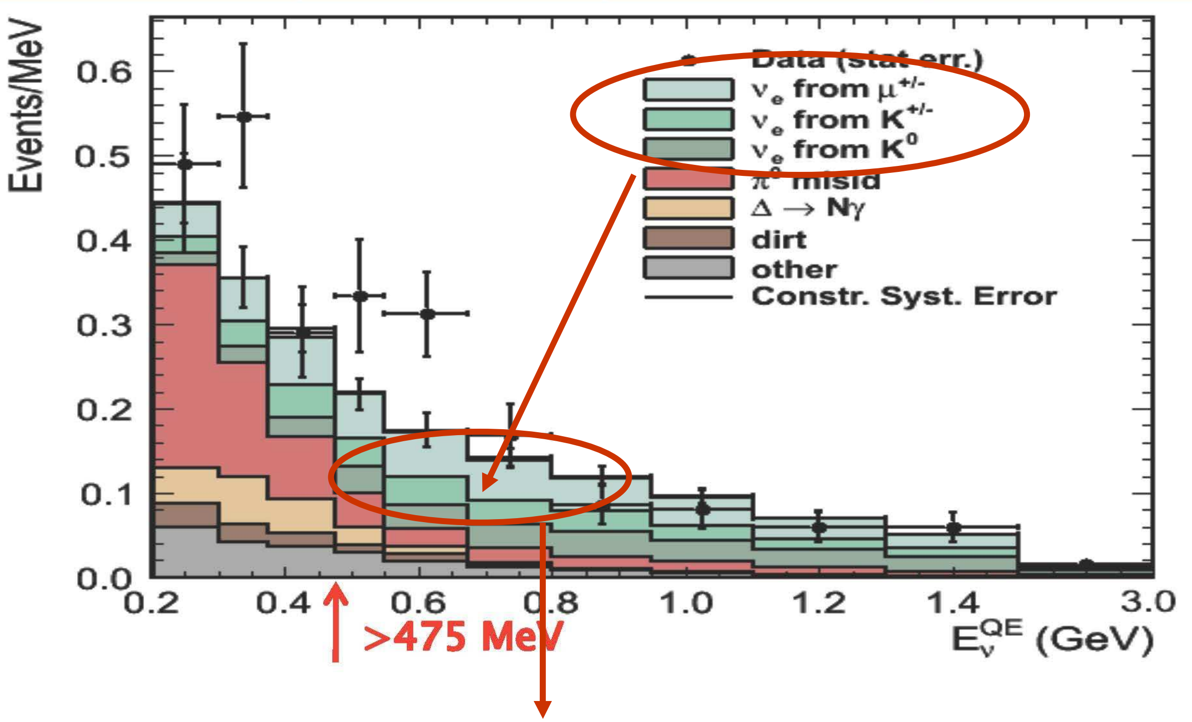
GoF = 32%

PGoF = 0.89%

- Tension between LSND + KARMEN + MiniBooNE $\bar\nu_\mu \to \bar\nu_e$ and MiniBooNE $\nu_\mu \to \nu_e \Longrightarrow$ CP Violation?
- 3+2 $\Longrightarrow$ CP Violation OK [Sorel, Conrad, Shaevitz, PRD 70 (2004) 073004, hep-ph/0305255; Maltoni, Schwetz, PRD 76, 093005 (2007), arXiv:0705.0107; Karagiorgi et al, PRD 80 (2009) 073001, arXiv:0906.1997]
- 3+1+NSI $\Longrightarrow$ CP Violation OK [Akhmedov, Schwetz, JHEP 10 (2010) 115, arXiv:1007.4171]

Partial fit : example

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$



This part correspond to ν_e abundance in the beam: the fit does not take into account their 'disappearance'

Global fit without Ga experiments

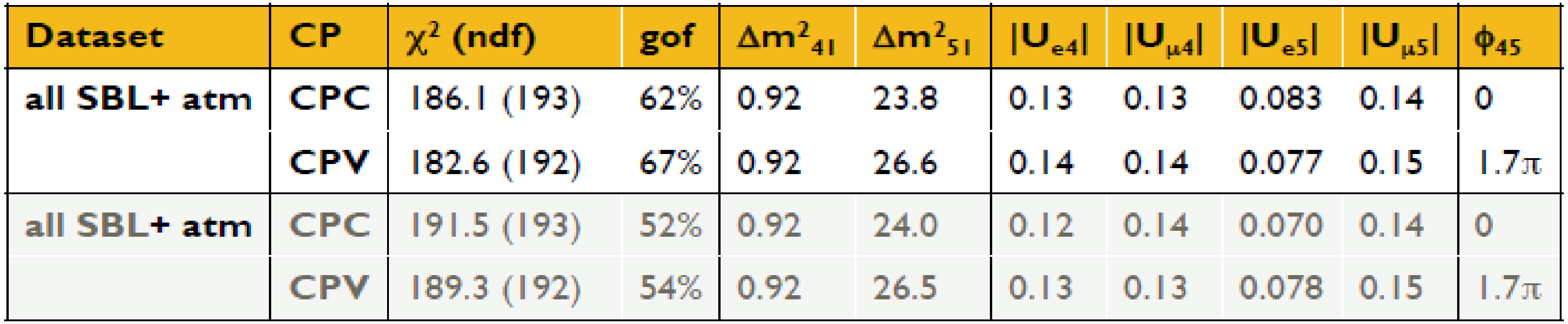
- Appearance and disappearance constraints

Excess:
LSND
MiniBooNE($\bar{\nu}$)

No excess:
KARMEN
NOMAD

Excess?:
NuMI at MiniBooNE (small)
MiniBooNE(ν) (low E)

No deficit:
CCFR
CDHS
Bugey
CHOOZ
atmospheric



Dataset	CP	χ^2 (ndf)	gof	Δm^2_{41}	Δm^2_{51}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	ϕ_{45}
all SBL+ atm	CPC	186.1 (193)	62%	0.92	23.8	0.13	0.13	0.083	0.14	0
	CPV	182.6 (192)	67%	0.92	26.6	0.14	0.14	0.077	0.15	1.7π
all SBL+ atm	CPC	191.5 (193)	52%	0.92	24.0	0.12	0.14	0.070	0.14	0
	CPV	189.3 (192)	54%	0.92	26.5	0.13	0.13	0.078	0.15	1.7π

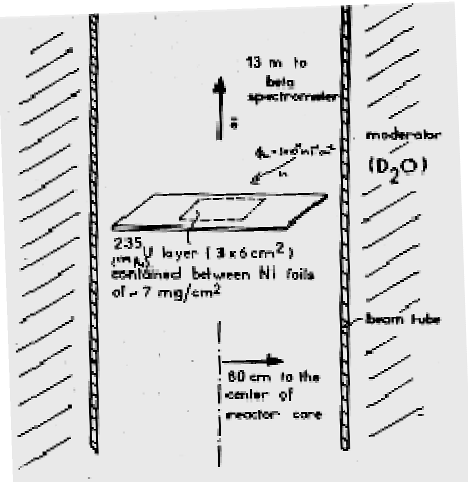
OLD: PRD 80 073001 (2009)
NEW: includes updated MiniBooNE antineutrino appearance dataset, and new reactor flux predictions

G. Karagiorgi, LAGUNA meeting

About Reactor Neutrino Anomaly (1) : new neutrino flux

-Derived from the β spectrum measured

by irriadiating fissile material with thermal neutrons : ^{235}U, ^{239}Pu, ^{241}Pu



SCHEMATIC VIEW OF THE TARGET SITE

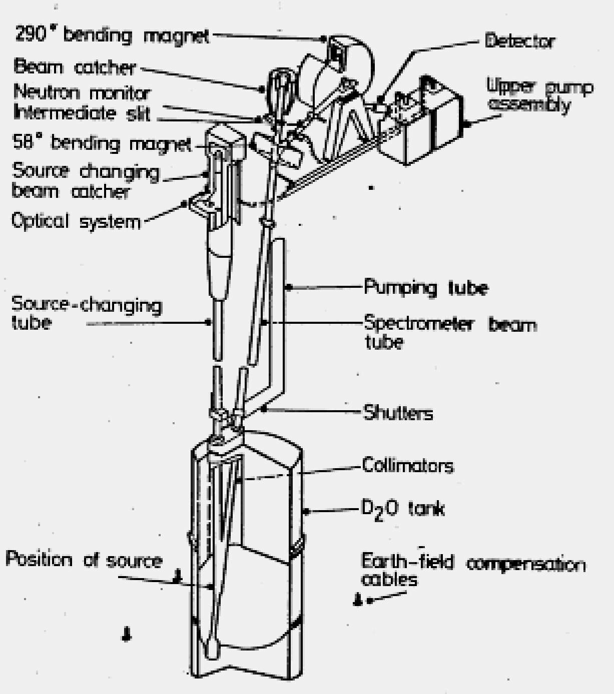


Fig 1

The conversion-electron spectrometer "BILL" (ILL)

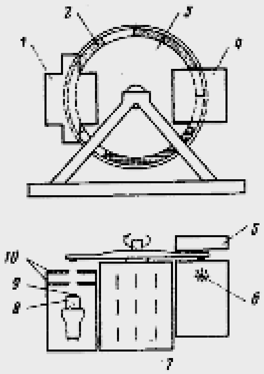


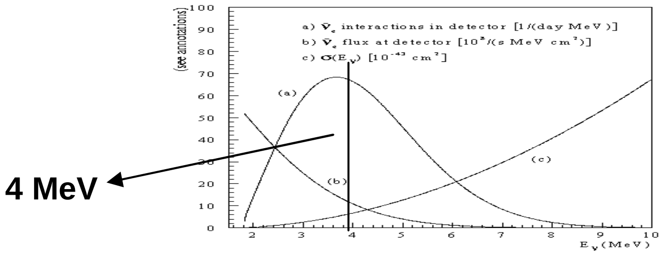
FIG. 1. Diagram of experimental apparatus: 1—β spectrometer, 2—targets, 3—disk of Plexiglas, 4—paraffin block moderator, 5—reflector of paraffin, 6—^{252}Cf source, 7—combination shielding, 8—main detector, 9—transmission detector, 10—diaphragms.

Huge background:
Dedicated run for substraction

Ref:

1) K. Schreckenbach et al , Phys. Lett. B 99, (1981)251
2. F. Von Feilitzsch et al. , Phys. Lett. B 118, (1982)162
3) A. A. Borovoi et al. , Sov. J. Nucl. Phys. 37(6), (1983)801
4. K. Schreckenbach et al , Phys. Lett. B 160, (1985)325
5) K. Schreckenbach et al, Weak and electromagnetic interactions in nuclei ed. H.V. Klapdor (Springer, Berlin, 1986) p. 759
6) K. Schreckenbach et al , Phys. Lett. B 218, (1989)365
7) T.A. Mueller et al, (2011) 1101.2663

^{235}U results comparison @ 4 Mev



	1981 Schreckenbach Ref 1	1982 Von Feilitzsch Ref 2	1983 Borovoi Ref 3	1985 Schreckenbach Ref 5	2011 Mueller Ref 7
N_β /Mev/fission @ 4 Mev	0.154 $\Delta^* = 6.5\ 10^{-2}$		0.183	0.164	
N_υ /Mev/fission @ 4 Mev	0.265 $\Delta^* = 6.5\ 10^{-2}$	0.274 $\Delta^* = 5.9\ 10^{-2}$	0.315	0.283 $\Delta^* = 3\ 10^{-2}$	0.288 $\sigma = 2.3\ 10^{-2}$

* Accuracy @90% C.L.

Data points dispersion :

- **between ILL measurements : 6 10^{-2} ➔ 2 σ**
- **including Borovoi : 18 10^{-2}**

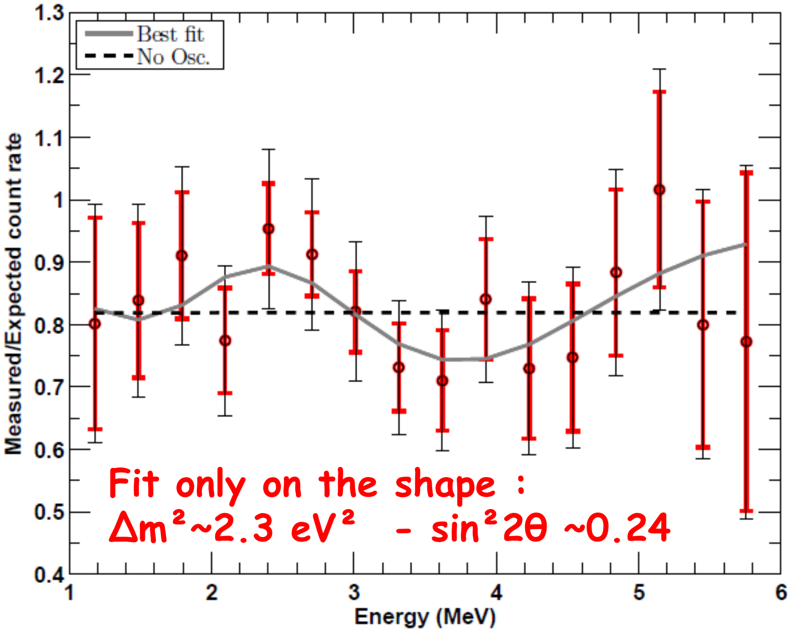
Weighted mean from ILL measurements : 0.276 υ /Mev /fission

Using the *weighted mean* the *anomaly* mostly vanish

(as for source measurements with Ga detectors)

About Reactor Neutrino Anomaly (2) : ILL neutrino experiment

a) Energy spectrum modulation



Fit only on the shape :
$\Delta m^2 \sim 2.3$ eV² - $\sin^2 2\theta \sim 0.24$

- Large errors, but a striking pattern is seen by eye ?

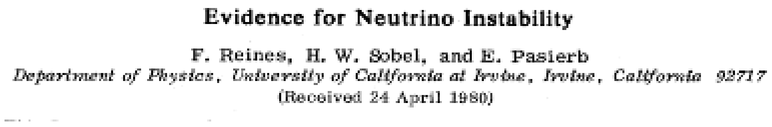
Not statistically significant:
Flattening can be obtained by playing with the detector energy response

b) Normalization discrepancy still not understood:

ongoing studies :
checking the distance and the experiment simulation

About Reactor Neutrino Anomaly (3) : ILL neutrino experiment

c) Mostly used to disprove νd result from Reines



Evidence for Neutrino Instability

F. Reines, H. W. Sobel, and E. Pasierb

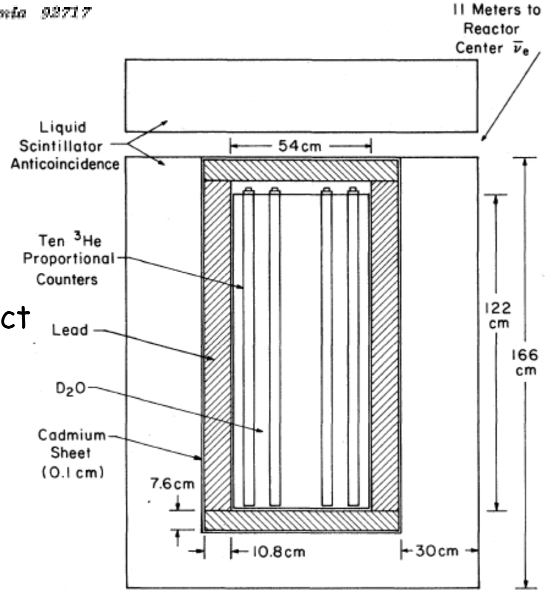
Department of Physics, University of California at Irvine, Irvine, California 92717

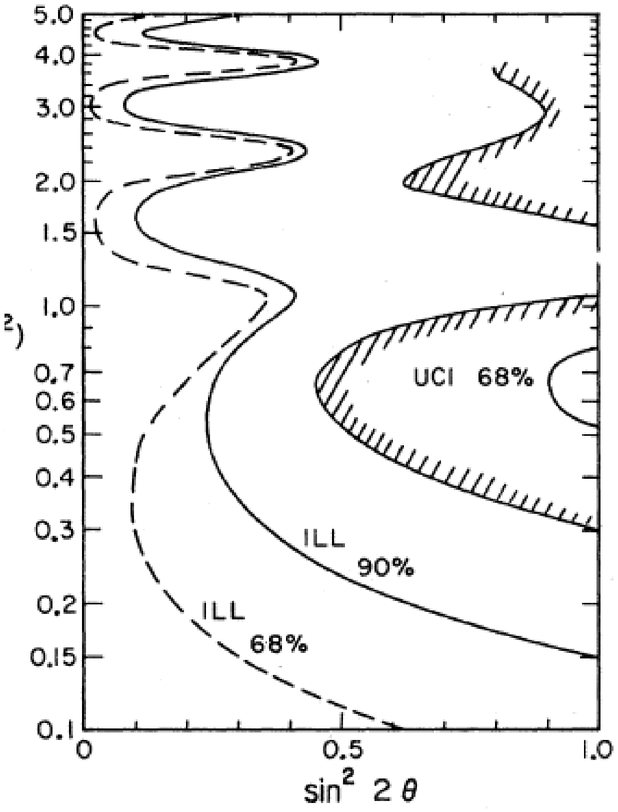
(Received 24 April 1980)

$$\bar{\nu}_e + d \begin{cases} n + n + e^+ & (ccd) \\ n + p + \bar{\nu}_e & (ncd) \end{cases}$$

$R = (ccd/ncd)_{meas} \, / \, (ccd/ncd)_{expect}$

$R_{SRP} = 0.62 \pm 0.16$ (1980)





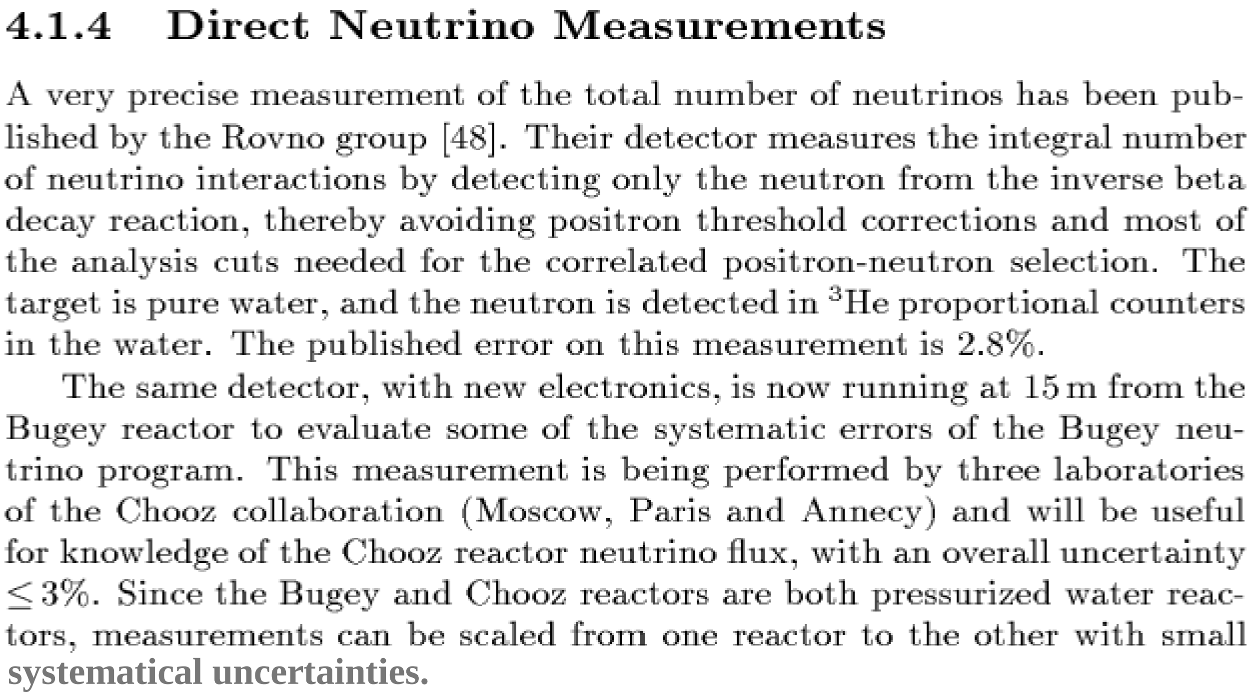
Optimizing the νd detector

		Background	Signal
Single neutron (ncd)	SRP	346.0 ± 2.7	63.8 ± 4.1
	BUGEY	25.3 ± 0.7	37.7 ± 2.0
Double neutrons (ccd)	SRP	49.7 ± 1.0	3.66 ± 1.67
	Bugey	1.4 ± 0.2	2.45 ± 0.48

$R_{Bugey} = 0.96 \pm 0.23$ (1995)

About Reactor Neutrino Anomaly (3) : θ_{13} limit from CHOOZ

CHOOZ proposal :

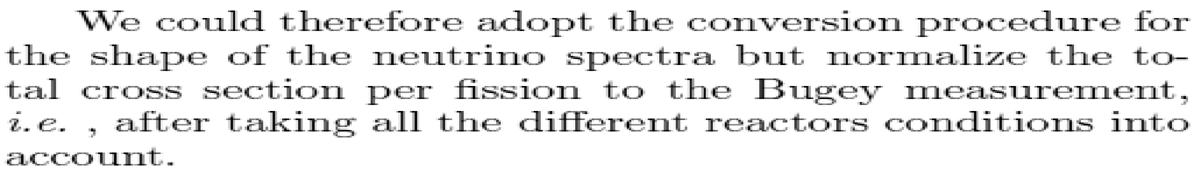


4.1.4 Direct Neutrino Measurements

A very precise measurement of the total number of neutrinos has been published by the Rovno group [48]. Their detector measures the integral number of neutrino interactions by detecting only the neutron from the inverse beta decay reaction, thereby avoiding positron threshold corrections and most of the analysis cuts needed for the correlated positron-neutron selection. The target is pure water, and the neutron is detected in ^{3}He proportional counters in the water. The published error on this measurement is 2.8%.

The same detector, with new electronics, is now running at 15 m from the Bugey reactor to evaluate some of the systematic errors of the Bugey neutrino program. This measurement is being performed by three laboratories of the Chooz collaboration (Moscow, Paris and Annecy) and will be useful for knowledge of the Chooz reactor neutrino flux, with an overall uncertainty $\leq 3\%$. Since the Bugey and Chooz reactors are both pressurized water reactors, measurements can be scaled from one reactor to the other with small systematical uncertainties.

CHOOZ publi :



We could therefore adopt the conversion procedure for the shape of the neutrino spectra but normalize the total cross section per fission to the Bugey measurement, *i.e.* , after taking all the different reactors conditions into account.

The CHOOZ result is obtained
by comparing the measured flux at 15m @ Bugey (Bugey4 , 1.4%) and at 1km
➔ Substracting automatically the sterile component … if any !

Conclusions

➢ Active ν oscillations are nicely established:

- ✓ ν are massive → extension of the standard model
- ✓ cross mixing studies may open the way for new physics

➢ Intriguing situation when trying to correlate some

- ✓ this does not demonstrate the existence of sterile ν
- ✓ simple test and experiments should be conducted before launching huge and expensive program …