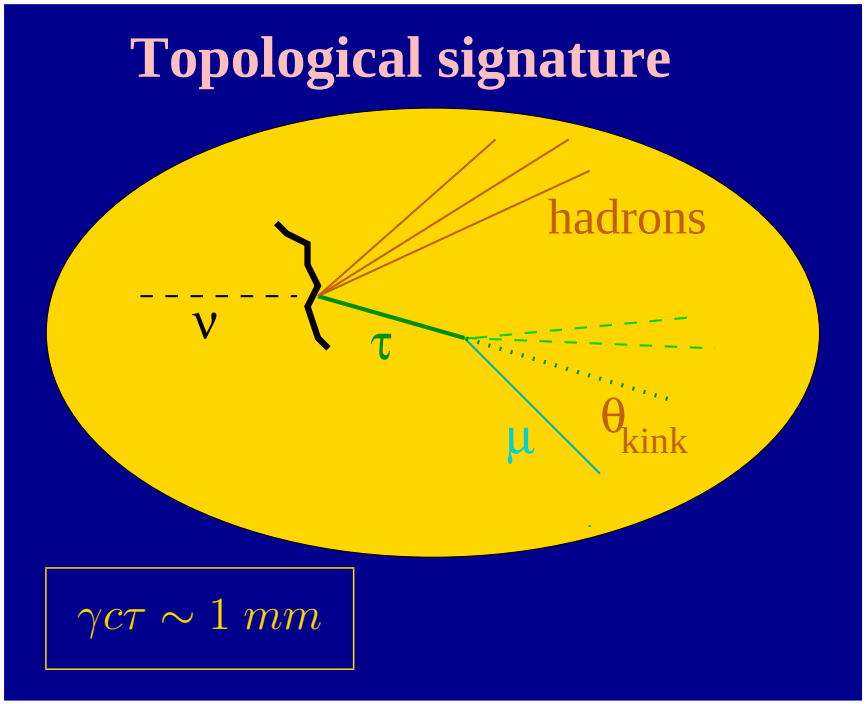
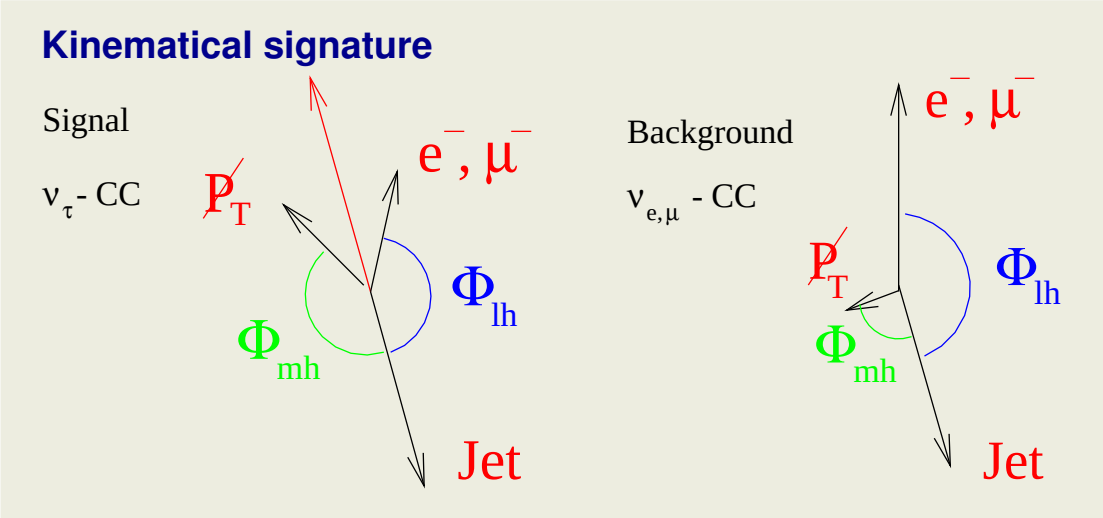
$\nu_\mu \longrightarrow \nu_\tau$ search at the CNGS





ν_τ appearance optimization

$$p(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \cdot \sin\left(1.27 \Delta m^2 L(km)/E(GeV)\right)$$
$$\Delta m^2_{atm} \simeq 2.5 \cdot 10^{-3}\ eV^2 \Rightarrow L(km) \simeq 500 \times E\,(GeV)$$

ν_τ appearance requires a proper optimization:

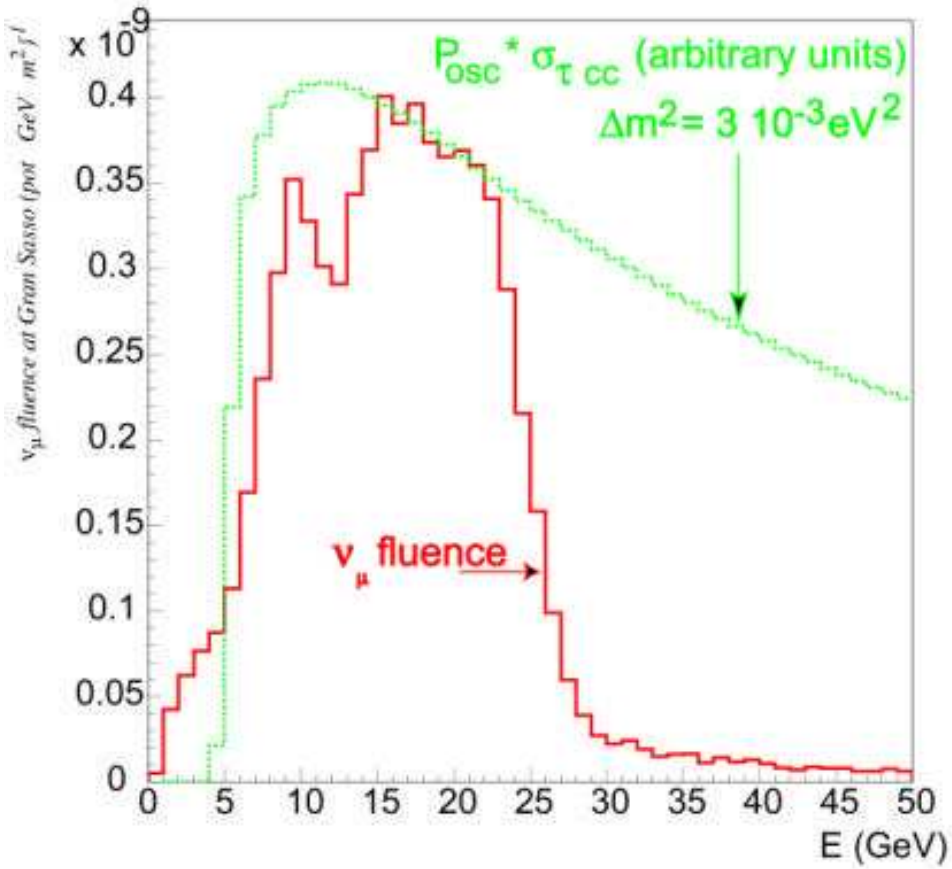
- Neutrinos have to oscillate
- ν_τ neutrinos have to produce a τ lepton

τ mass fix a threshold on neutrino cross section at 3.5 GeV.

CNGS: having a 450 GeV proton beam and a 735 km baseline, optimization accounting for:

- ν_τ cross section
- pion yield of 450 GeV protons (assuming perfect focussing)
- Opera τ detection efficiency

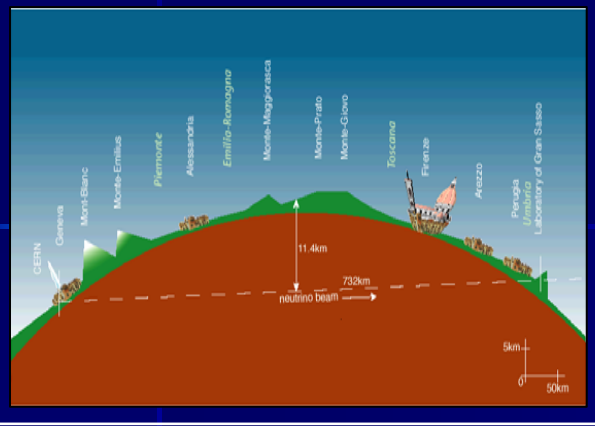
L=732 km; $\langle E_\nu \rangle \simeq 17$ GeV.



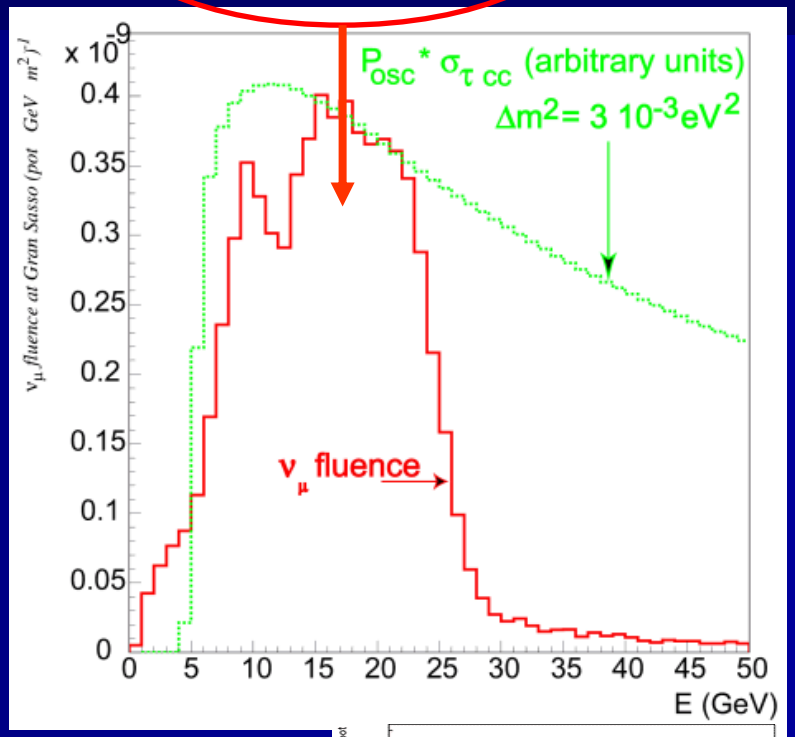
Neutrino energy at the first oscillation maximum: $\simeq 1.5$ GeV $\Rightarrow$

CNGS configuration very far from oscillation maximum !!!

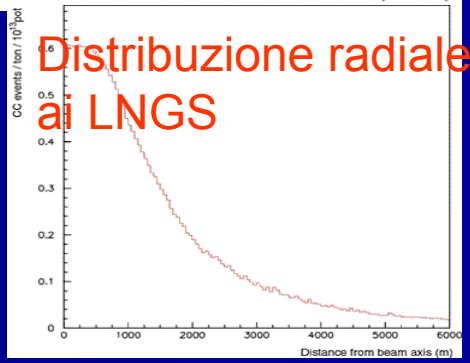
Il fascio CNGS (CERN to LNGS)



$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E) \sigma_{\nu_\tau}^{CC}(E) \varepsilon(E) dE$$

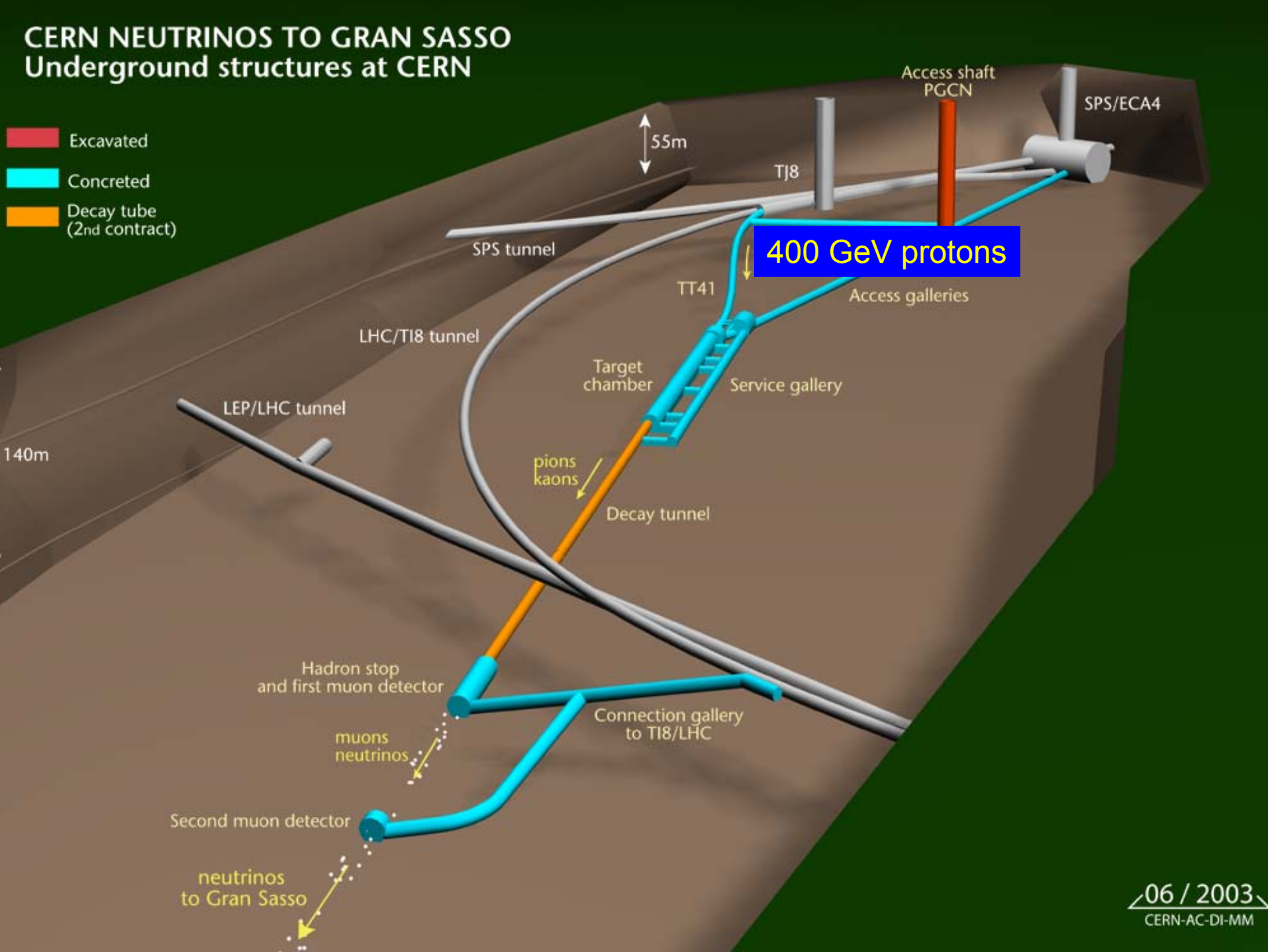


Caratteristiche del fascio	
L	732 km
$<E\nu_\mu>$	17 GeV
$L/<E\nu_\mu>$	43 km/GeV ← "Off peak"
$(\nu_e+\nu_e)/\nu_\mu$	0.87%
ν_μ / ν_μ	2.1%
ν_τ prompt	trascurabile

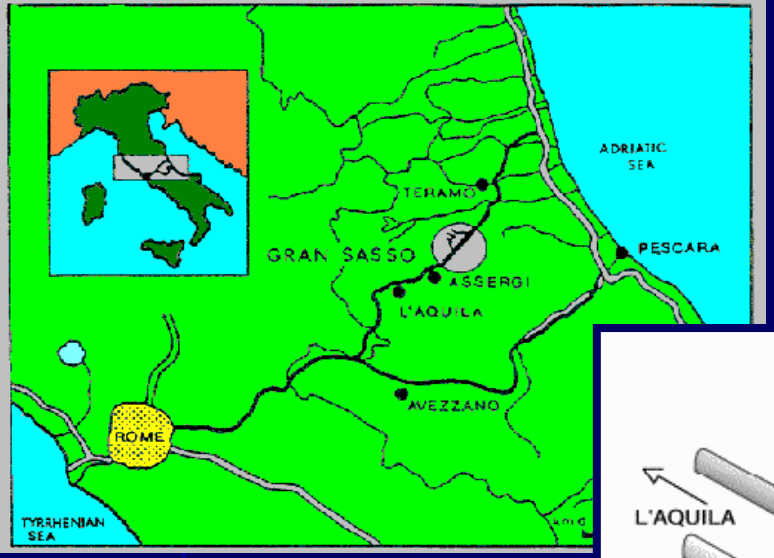


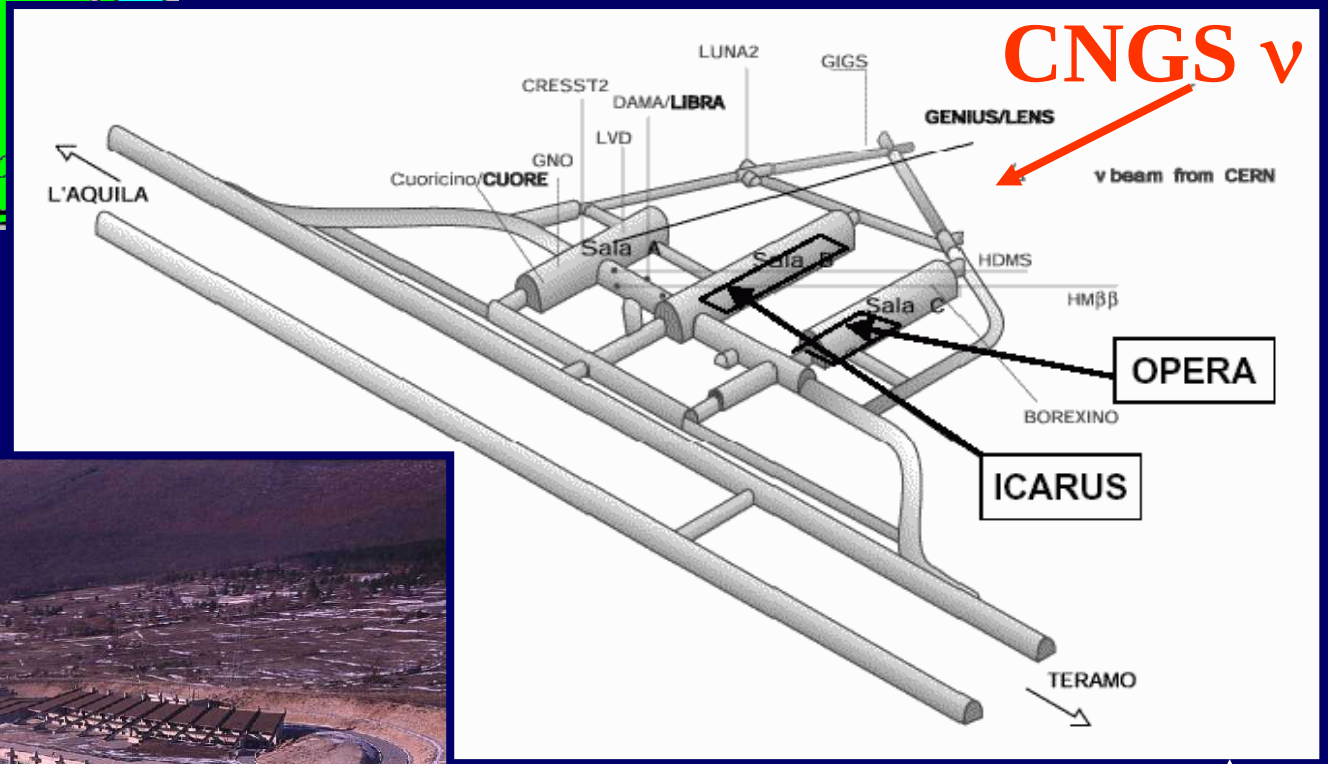
Event rate per OPERA (a 4.5 10^{19}/anno, 200 giorni/anno):

6200 ν_μ CC+NC/anno, 19 ν_τ CC/anno @ 2 10^{-3} eV^2


CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
Access shaft
PGCN
SPS/ECA4
55m
TI8
SPS tunnel
400 GeV protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
Connection gallery
to TI8/LHC
muons
neutrinos
Second muon detector
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM

I Laboratori LNGS (Italia, 900 m a.s.l.)





Lab esterni

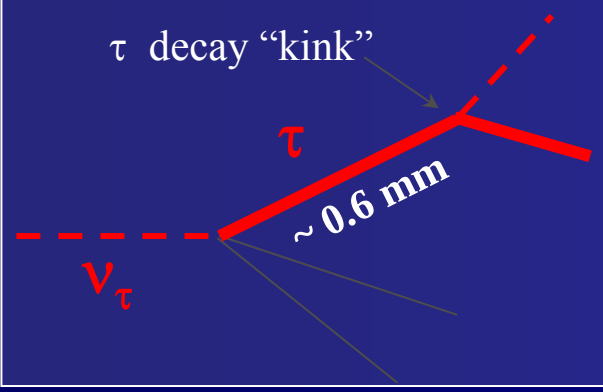
Lab Underground

1400 m di roccia sovrastante: cosmici ridotti di un fattore 10^6 rispetto alla superficie. Bassa radioattività ambientale

OPERA ≡ Oscillation Project with Emulsion tRacking Apparatus

Obiettivo primario:

osservazione diretta del leptone τ prodotto in interazioni ν_τ^{CC}



Risoluzioni dell'ordine di *O(1 mm)*

$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E, \Delta m^2) \sigma_{\nu_\tau}{}^{CC}(E) \varepsilon(E) dE$$

Massa dell'ordine di *O(1 kton)*
per $\Delta m^2 = O(10^{-3}\ eV^2)$

ECC (Emusion Cloud Chamber)

Experimental signature of the ν_τ appearance

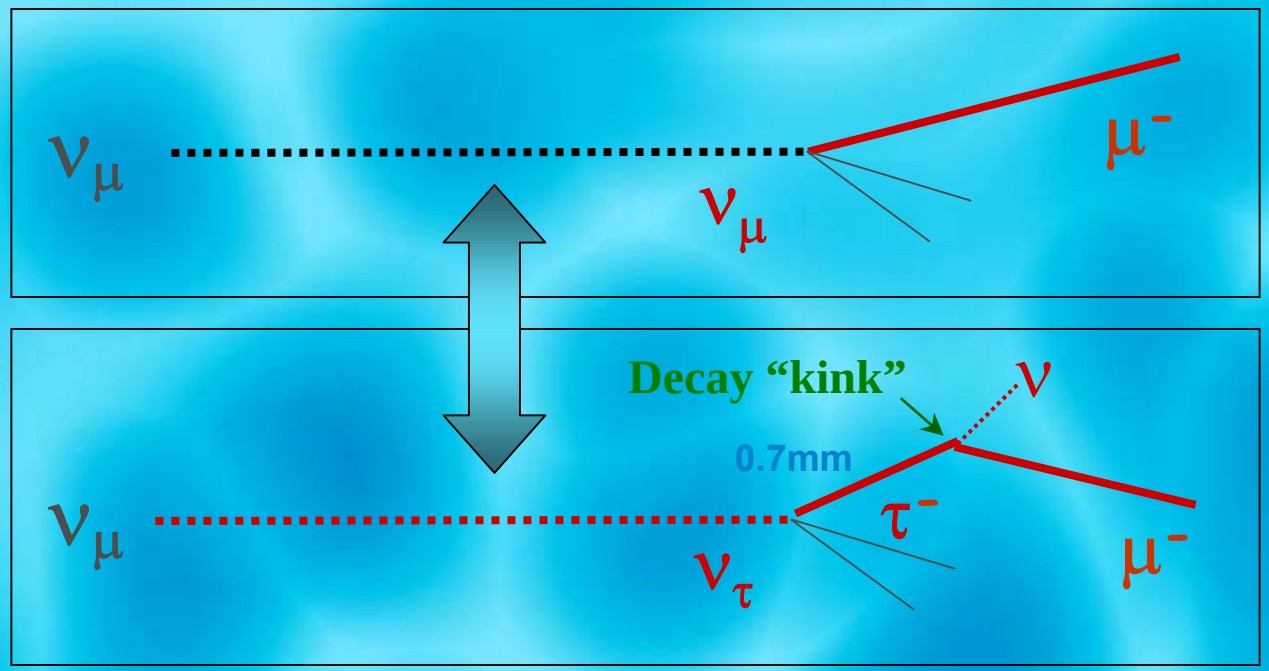
CC interaction

$\nu_\mu \sim \nu_\tau \rightarrow \tau^- + X$

oscillation

$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	B. R. ~ 17%
$h^- \ \nu_\tau \ n(\pi^o)$	B. R. ~ 50%
$e^- \ \nu_\tau \ \bar{\nu}_e$	B. R. ~ 18%
$\pi^+ \ \pi^- \ \pi^- \ \nu_\tau \ n(\pi^o)$	B. R. ~ 14%

The challenge is to distinguish ν_τ interactions from ν_μ interactions

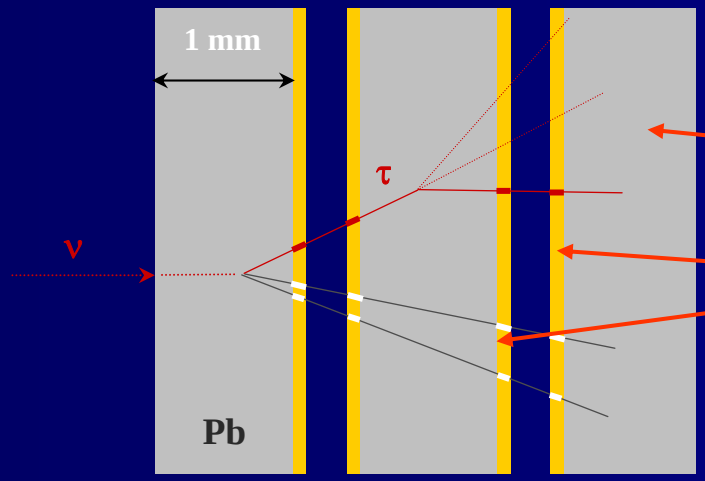


Topology selection:

⇓

kink signature

Emulsion Cloud Chamber

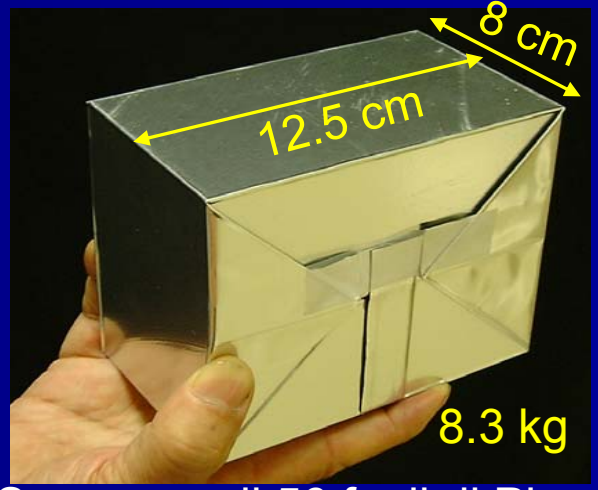


ECC ≡ sequenza di fogli Pb/emulsione

Pb: massa
Emulsion: tracking

Permette di avere grandi masse in strutture modulari

l'unità di base ECC è il "BRICK"



Sequenza di 56 fogli di Pb + 56 fogli di emulsione ($10X_0$ ok per misure di *p* e pID)

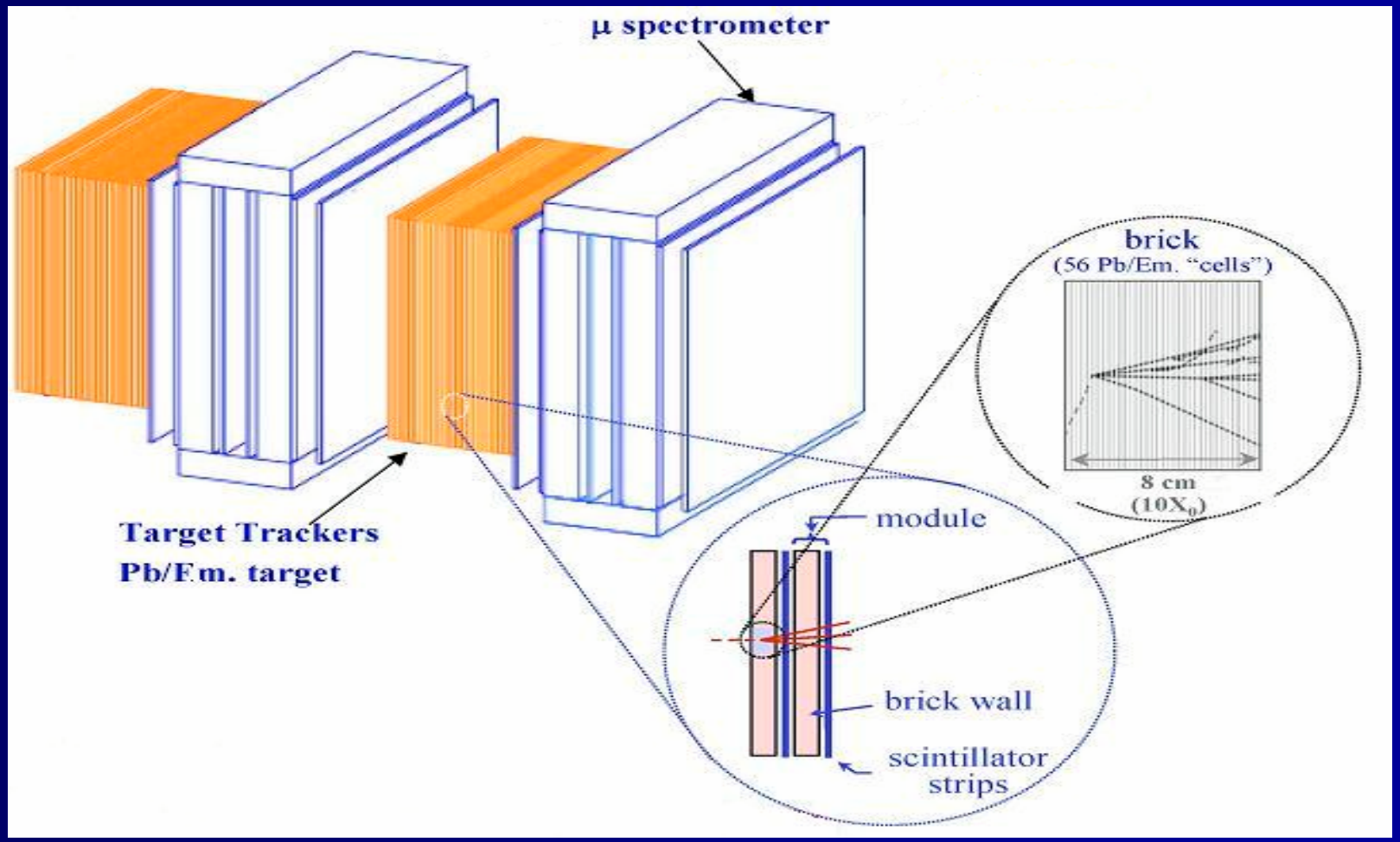
Layout generale del rivelatore

Rivelarore ibrido (elettronica + emulsioni) con struttura modulare:

2 supermoduli = 2*(31 walls + 1 spettrometro)

↳ 31 walls = 31*(56*64 bricks + 1 scintillator tracker plane)

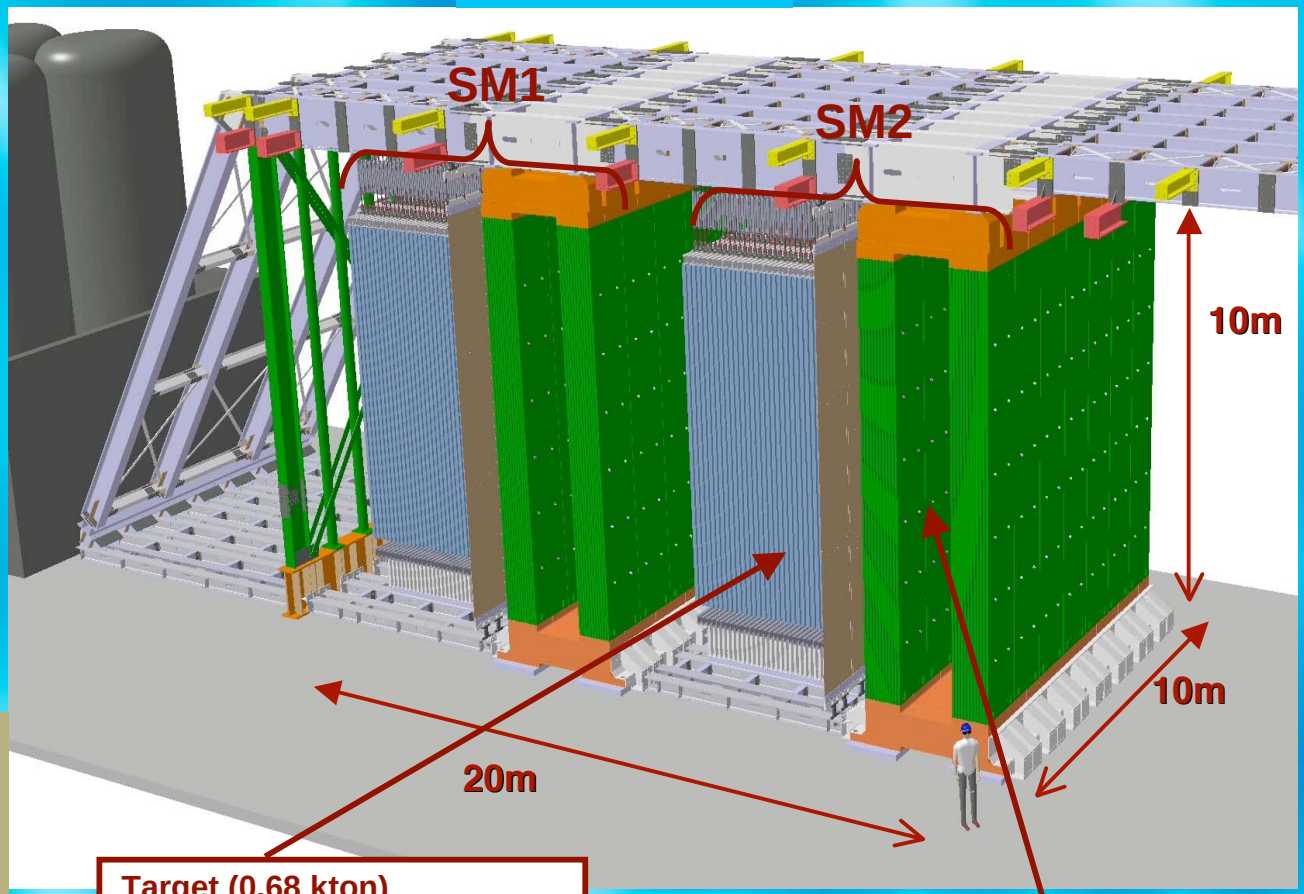
Massa totale = 1766 tons, # di bricks = 206336



OPERA Detector Design

LNGS Hall C

Installation started in
May 2003
First observation of the CNGS neutrinos on
August 18th, 2006
First observation of the CNGS neutrinos in emulsion on
October 2th, 2007



Target:1350 tons

5 year running @ 4.5 10^{19}

- 22,000 neutrino interactions
- ~110 ν_τ interactions
- ~11 ν_τ identified
- <1 event of background

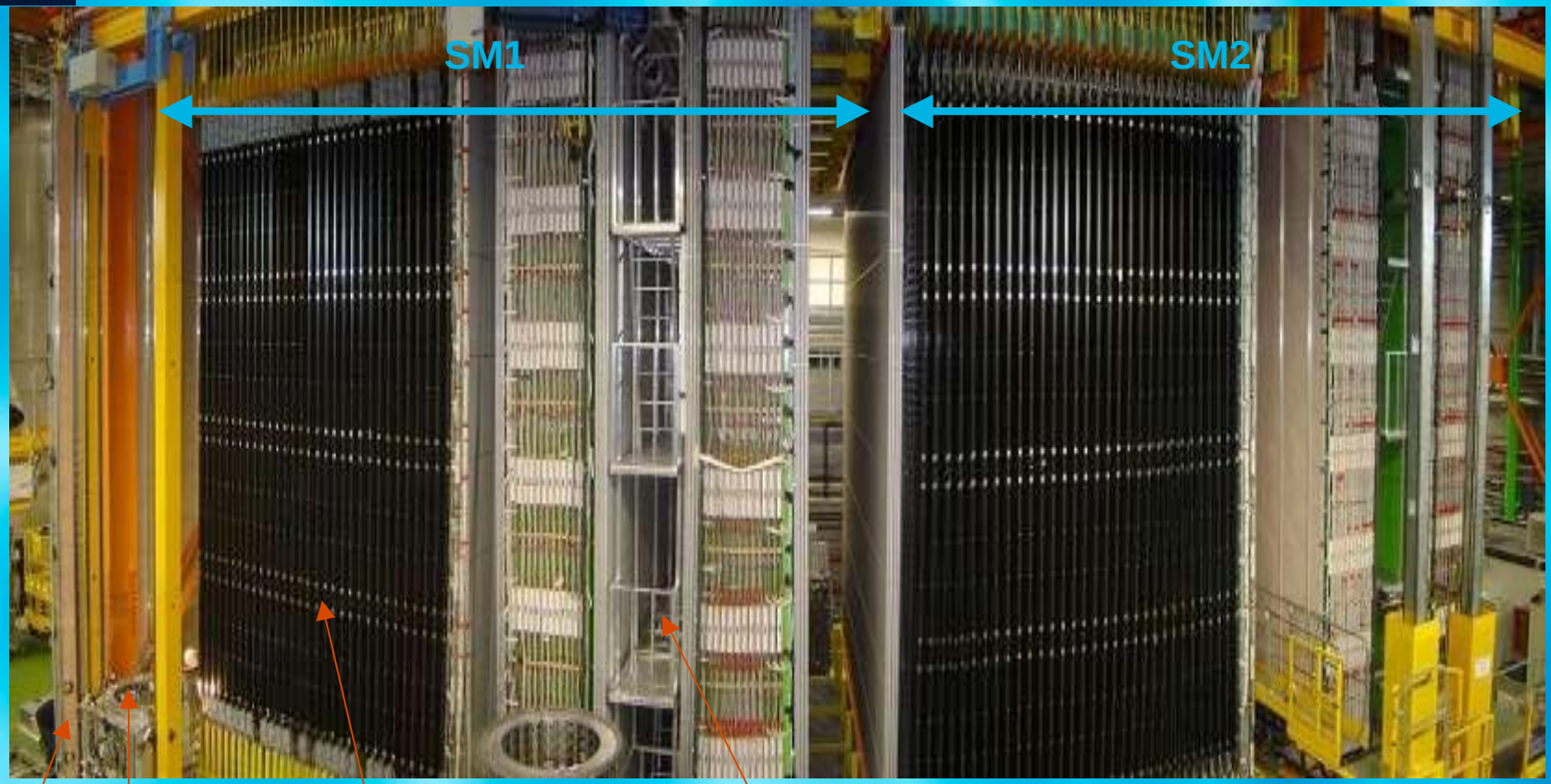
Target (0.68 kton)

29 lead/emulsion brick walls, alternated to scintillator planes, (T T) to select the brick containing neutrino interaction

Muon Spectrometer

Magnet equipped with 22 RPC planes: ID muons , charge and momentum measurement

OPERA Detector Today



Target (29 walls) +
Target Tracker (6.7*m*)^2

Spectrometer:
XPC, HPT, RPC, magnet

BMS

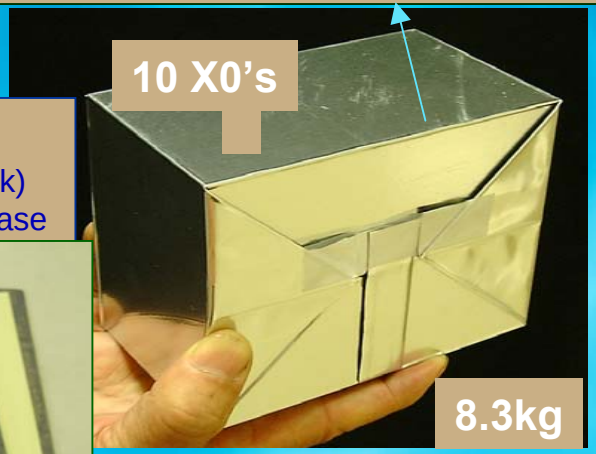
Veto

Detector today: electronics fully instrumented and tested
Brick filling is in progress, > 110000 bricks have already been inserted
75% target: SM1 full, SM2 at 50%

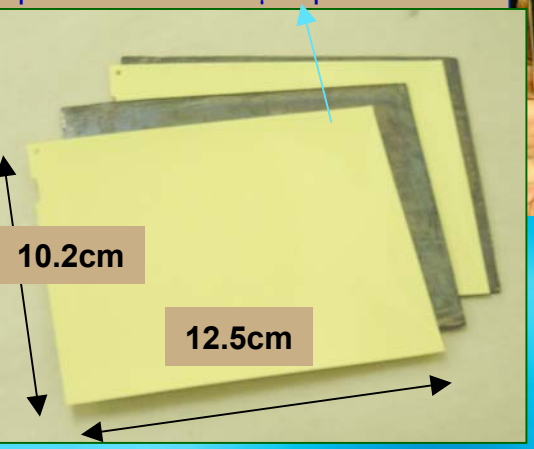
Brick Target

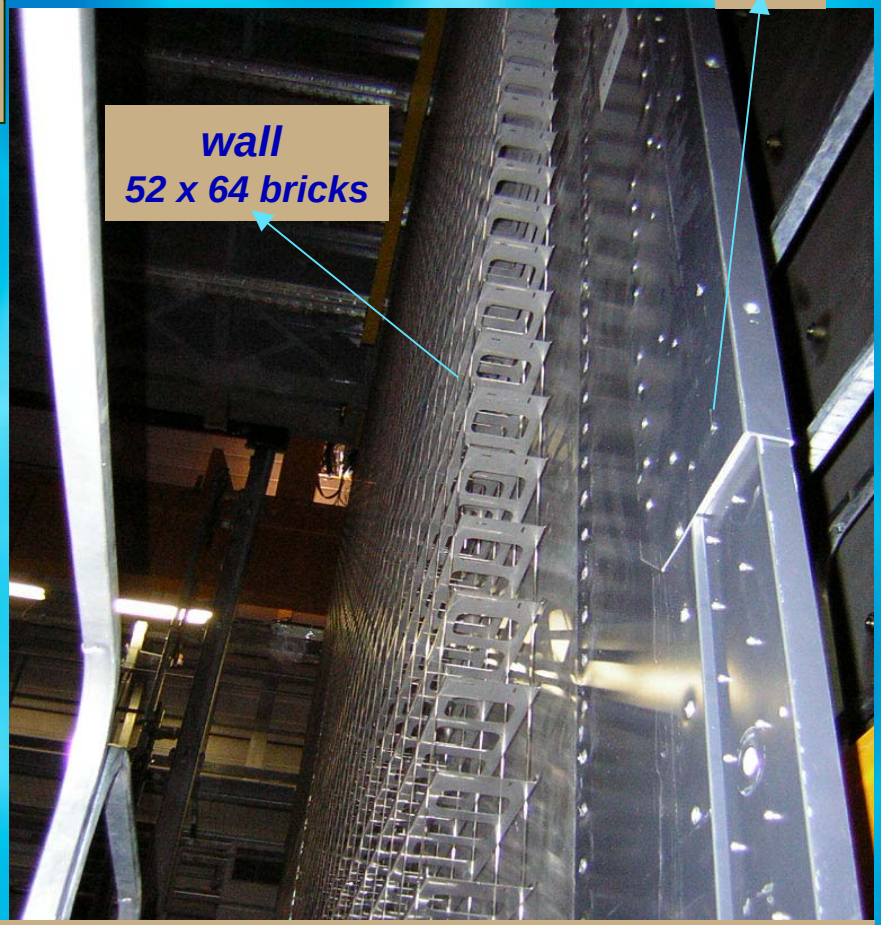
- **Micro-metric space resolution (emulsion) + target mass (lead)**
- **Compact and modular structure**

***Brick* (basic unit)**
56 Pb plates + 57 emulsion films



Emulsion film
2 emulsion layers (44 μm thick) poured on a 200 μm plastic base

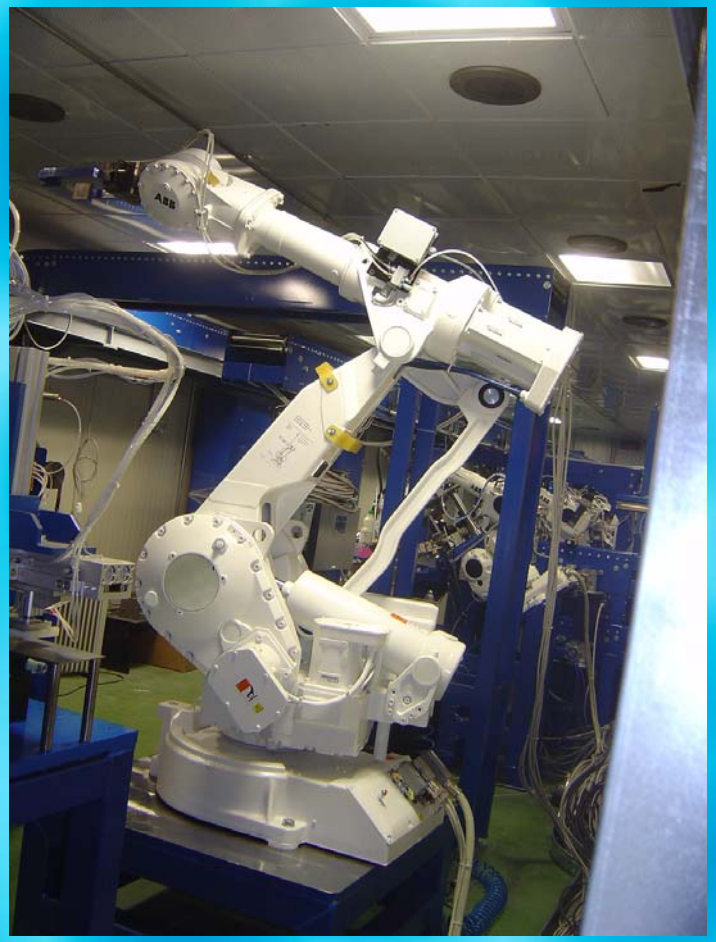




CS doublet (connection T T- brick)
two double refreshed emulsion films,vacuum packed and glued onto the bottom of each brick

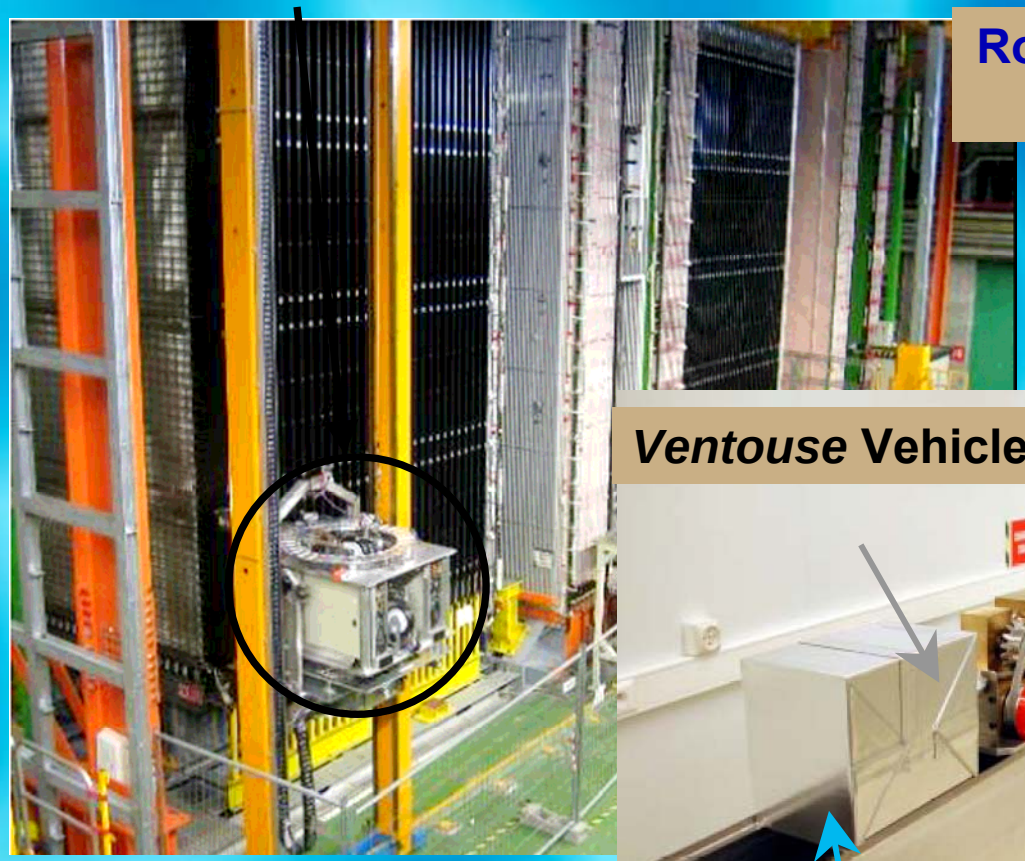
Total target mass : ~ 1800 t
(~200000 bricks, 12M emulsions and Pb plates)

Brick Assembly Machine

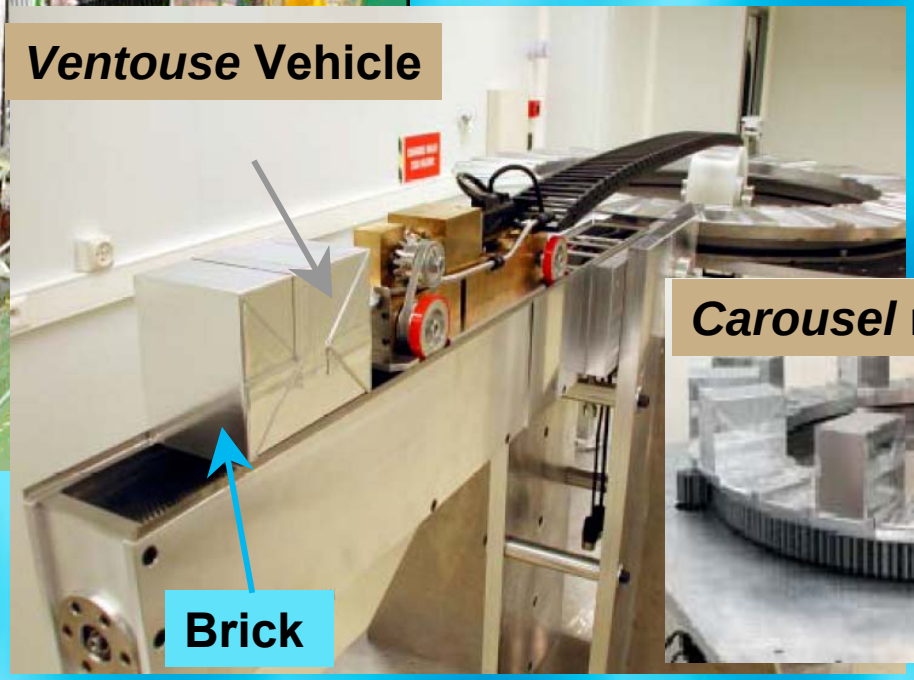


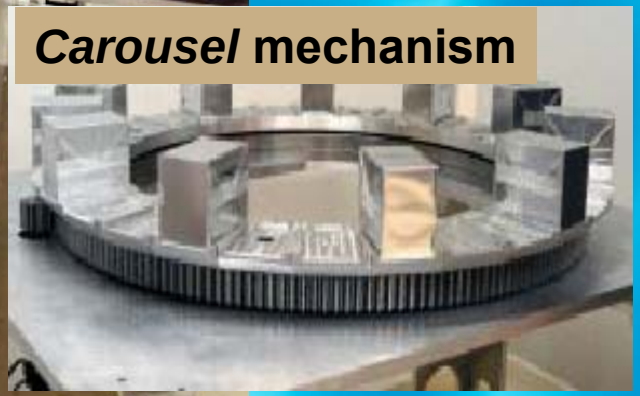
Robots will pile up bricks at a rate of ~ 800 bricks/day

Brick Manipulator System

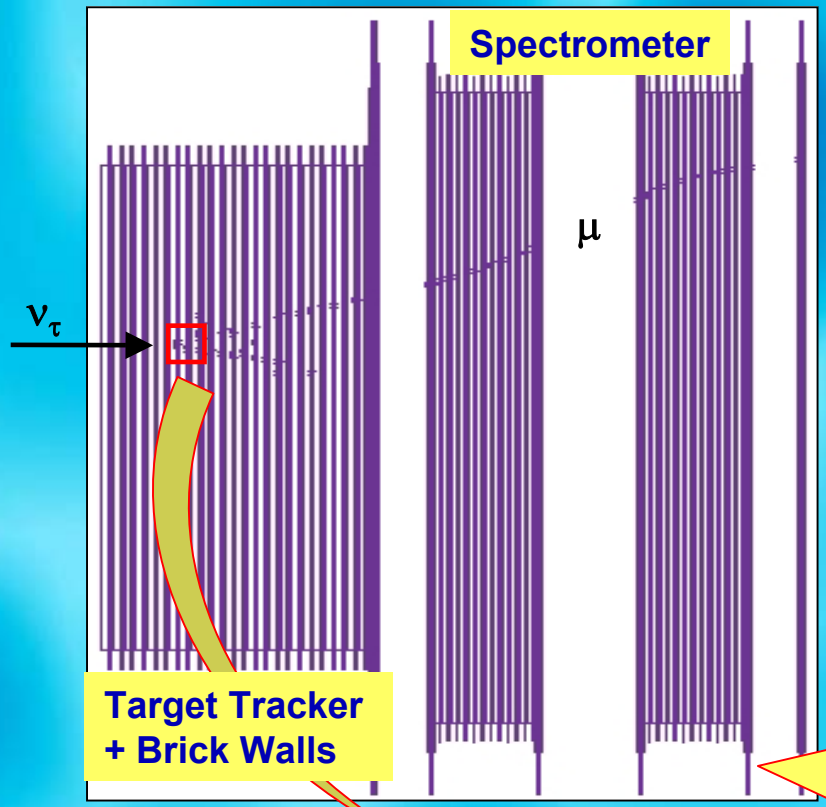


Robot for brick insertion (target filling) and removal (during run)



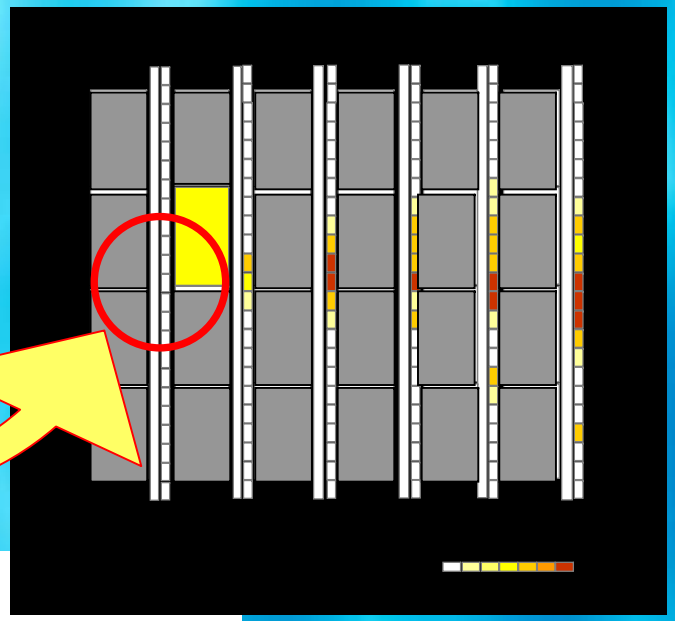


OPERA running



On-line analysis of electronic data

Brick finding algorithm



The selected brick is removed from the target and, after CS measurement, exposed to cosmic rays (alignment). Emulsions are developed and sent to scanning stations/labs

Event location
Decay search
Particle ID and kinematics
Event classification

LNGS: Development Facility

Line for the automated emulsion development

5 development chains ready

Maximum rate:
~ 50 bricks/day
(16 hours)

Automated microscopes for nuclear emulsions

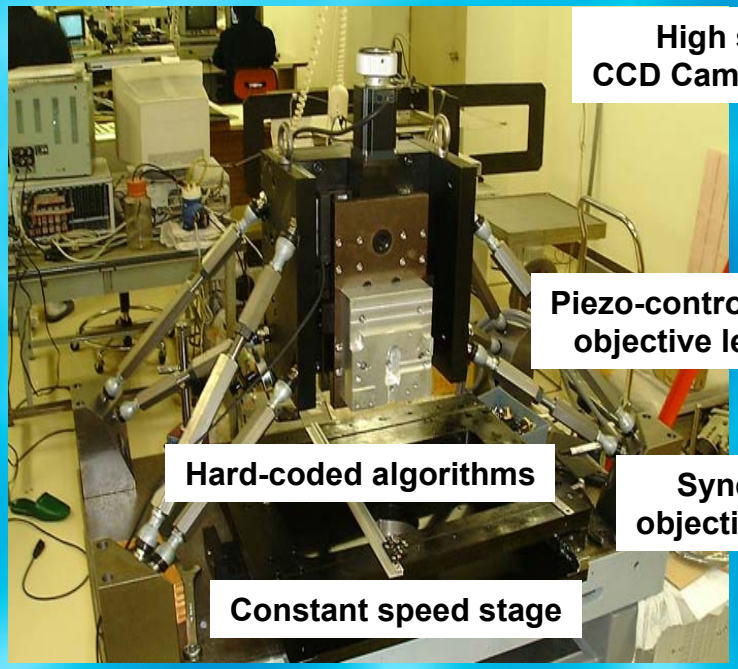
~ 30 bricks will be daily extracted from target and analyzed using high-speed automatic systems

European Scanning System

S-UTS (Japan)

scanning speed ~ 20 cm^2/h

Customized commercial optics and mechanics + asynchronous DAQ software



High speed CCD Camera (3 kHz)

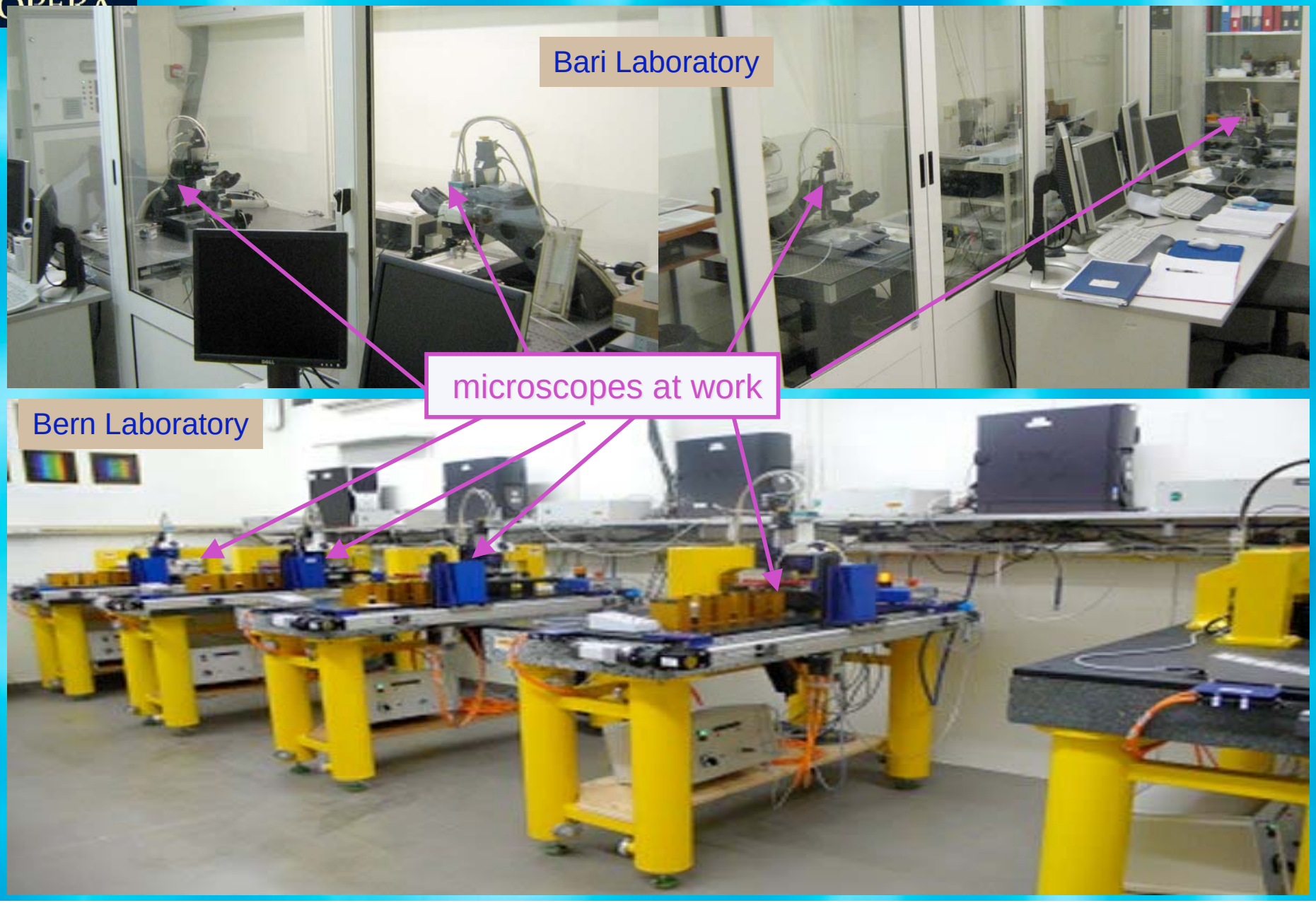
Piezo-controlled objective lens

Hard-coded algorithms

Synchronization of objective lens and stage

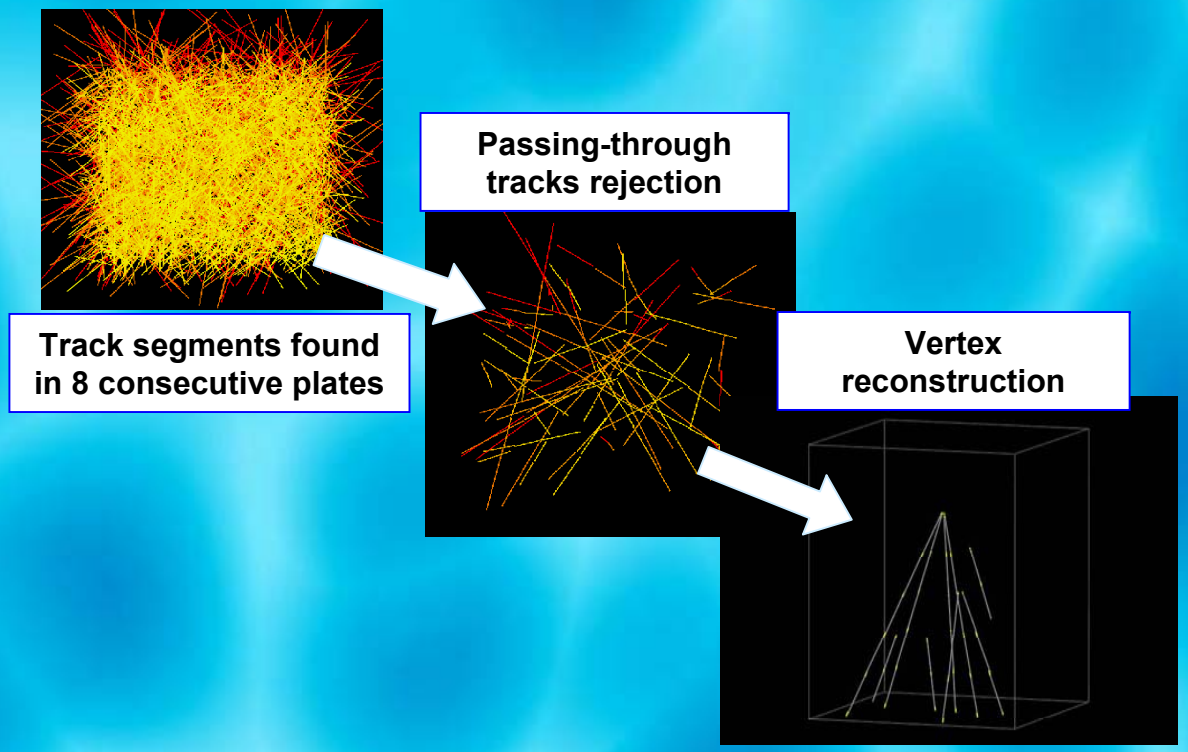
Constant speed stage

Scanning Laboratories



Automated Vertex Search

1) Cosmic alignment
2) Scan Back
3) Vertex analysis



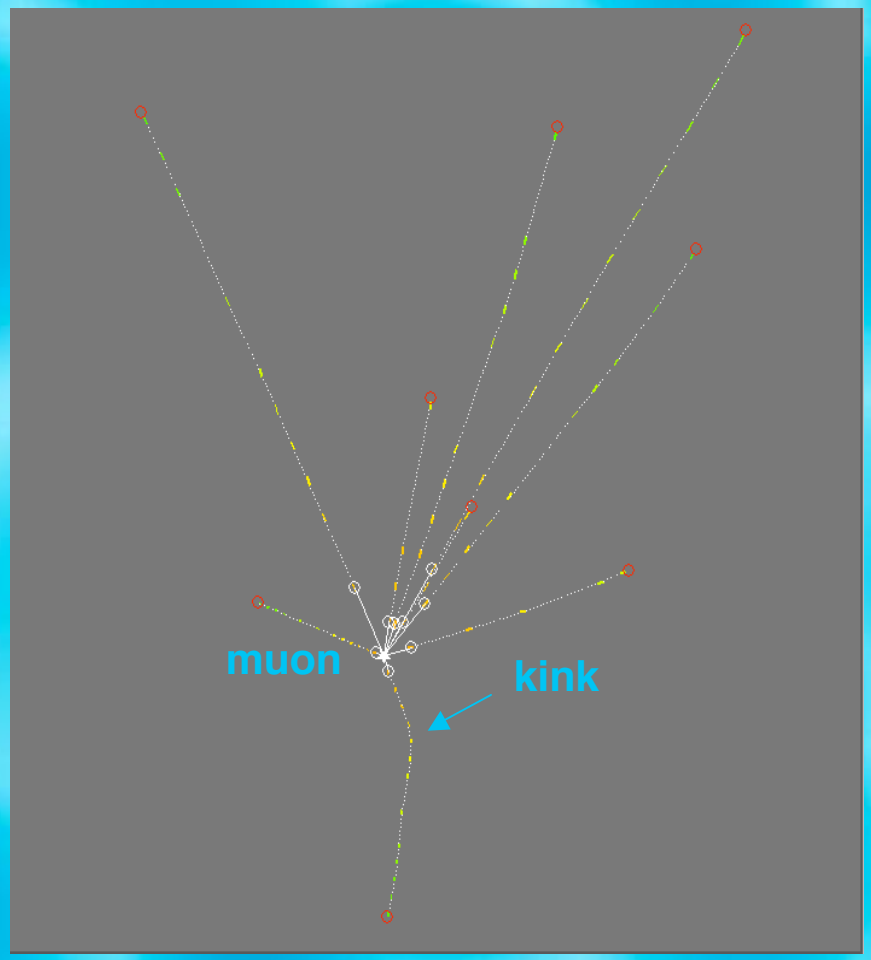
Oscillazioni $\nu_\mu \leftrightarrow \nu_\tau$: segnale atteso

	signal (Δm^2=1.9x10^{-3}eV^2)	signal (Δm^2=2.4 x10^{-3}eV^2)	signal (Δm^2=3.0x10^{-3}eV^2)	BKGD
OPERA 1.8 kton fiducial	6.6	10.5	16.4	0.7
+ brick finding + 3 prong decay	8.0	12.8	19.9	1.0
Background reduction	8.0	12.8	19.9	0.8

Full mixing, 5 anni di running, 4.5x10^{19} pot/anno

Event 180400976

PRELIMINARY



Tracks	TX	TY	P GeV	IP (μm)	
1	0.026	-0.097	-	5.7	kink
2	-0.024	0.019	>20	1.2	mu
3	0.045	0.197	$2.3^{+3.2}_{-0.9}$	1.7	
4	0.024	0.203	$4.5^{+22.8}_{-2.1}$	2.6	
5	0.100	0.051	$4.5^{+22.8}_{-2.1}$	7.9	
6	-0.047	0.199	$2.5^{+7.0}_{-1.1}$	2.9	
7	0.073	0.152	$3.0^{+7.9}_{-1.2}$	8.8	
8	0.085	0.254	$1.6^{+4.3}_{-0.7}$	10.3	
9	0.074	0.201	$1.8^{+6.0}_{-0.8}$	4.6	
10	0.114	0.010		9.0	e-pair
11	0.132	-0.001		18.1	

Secondary Vertex

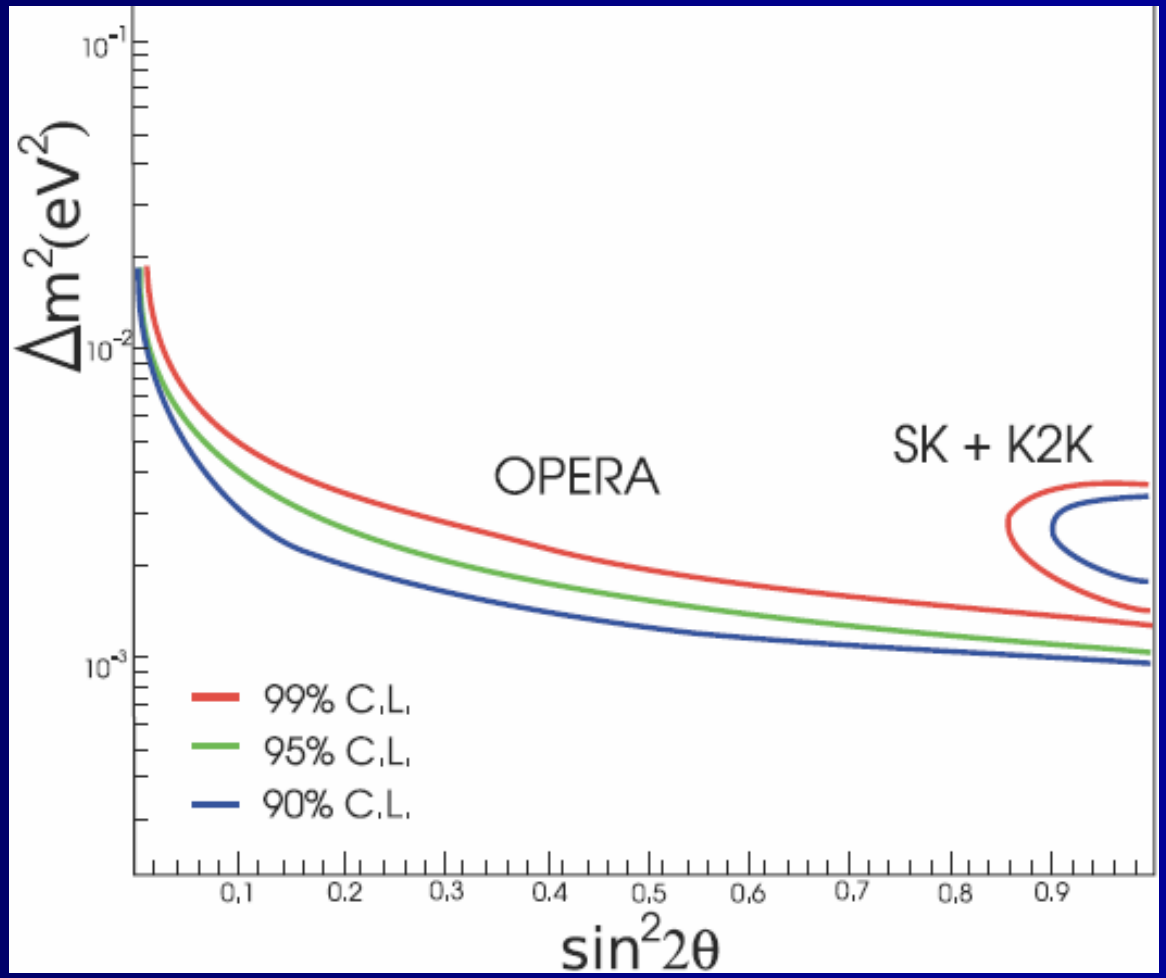
Daughter momentum = $1.9^{+0.7}_{-0.4}$

θ_{kink} = 0.031 rad

Flight length = 5901 μm

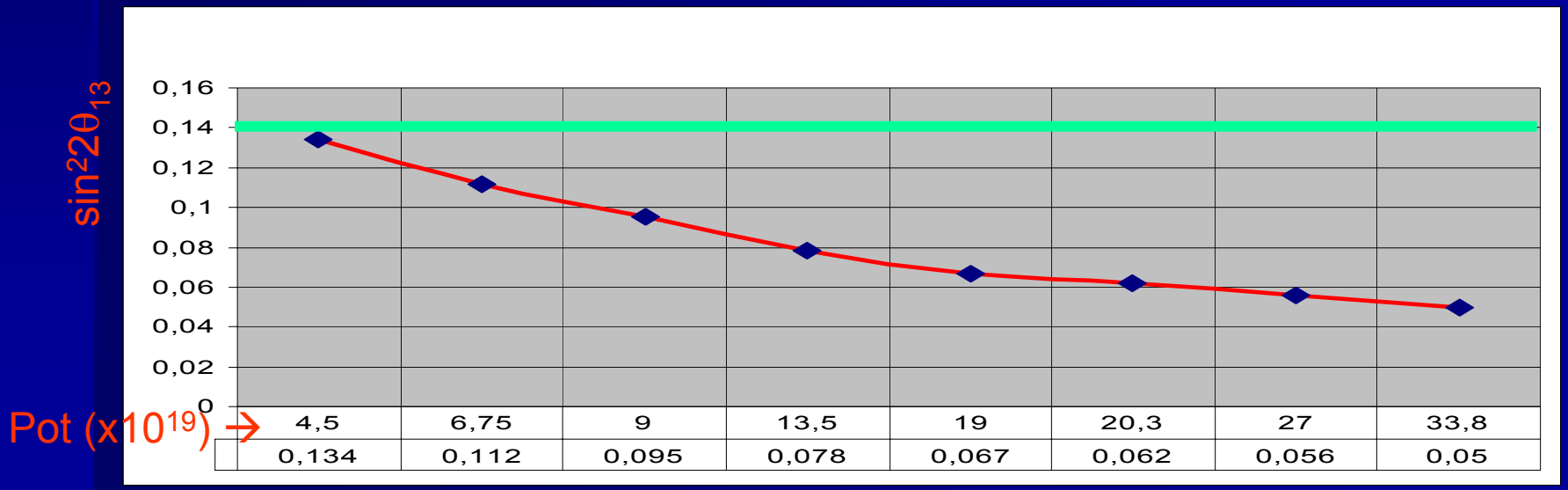
P_T = 59 MeV

Se venisse confermata l'ipotesi nulla?



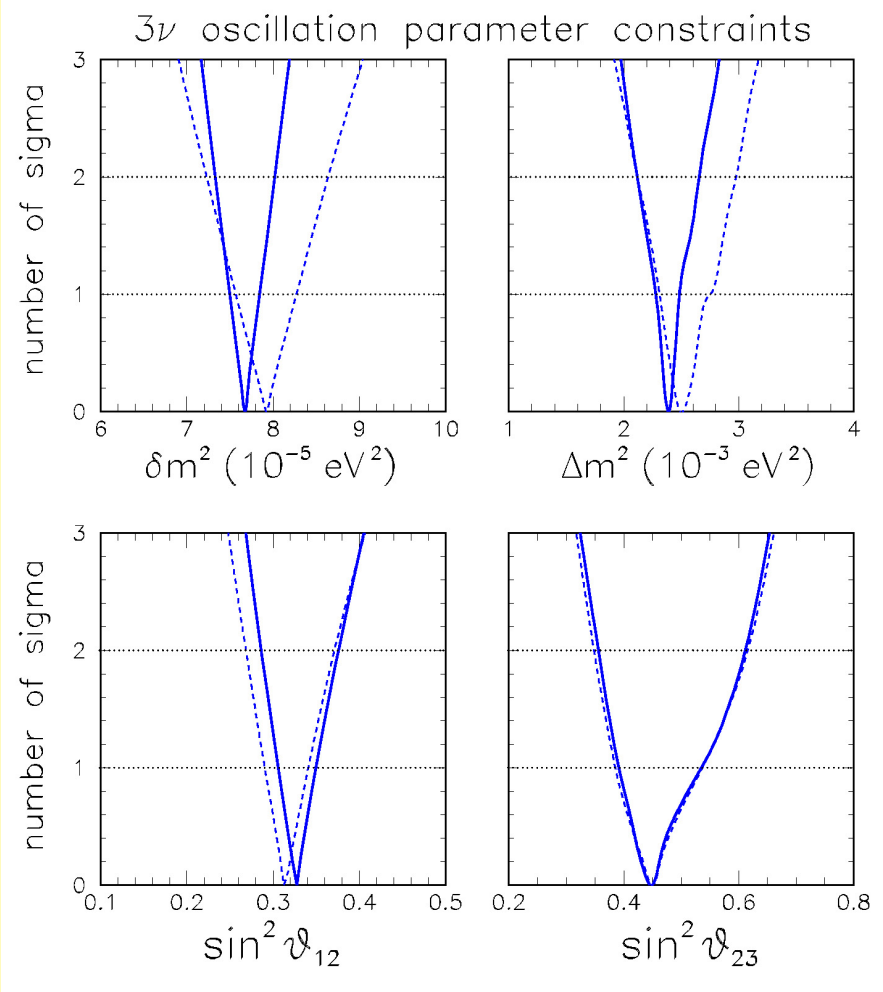
OPERA ed il canale $\nu_\mu \leftrightarrow \nu_e$

- Buona eID capability→ possibile analisi $\nu_\mu \leftrightarrow \nu_e$
- Fondi principali:
  - ν_e del fascio (contributo dominante)
  - π^0 misidentificati in ν_μ^{NC} o ν_μ^{CC} con il muone non identificato
  - $\tau \rightarrow e$ dalle oscillazioni $\nu_\mu \rightarrow \nu_\tau$



Visible progress from 2006 (dashed) to 2008 (solid)

"Solar" neutrinos



"Atmospheric" neutrinos

2008 parameter summary at 2σ level (95 % CL)

$$
\begin{aligned}
\delta m^2/\mathrm{eV}^2 &= 2.38 \pm 0.27 \\
|\Delta m^2|/\mathrm{eV}^2 &= 7.66 \pm 0.35 \\
\sin^2\theta_{12} &= 0.326\,^{+0.05}_{-0.04} \\
\sin^2\theta_{23} &= 0.45\,^{+0.16}_{-0.09} \\
\sin^2\theta_{13} &< 3.2 \times 10^{-2}
\end{aligned}
$$

(Addendum to hep-ph/0608060, in preparation)

This is what <u>we know</u>.

Concerning

What <u>we would like to know</u>

- Hierarchy (normal or inverted)
- CP in the ν sector
- θ_{13} mixing

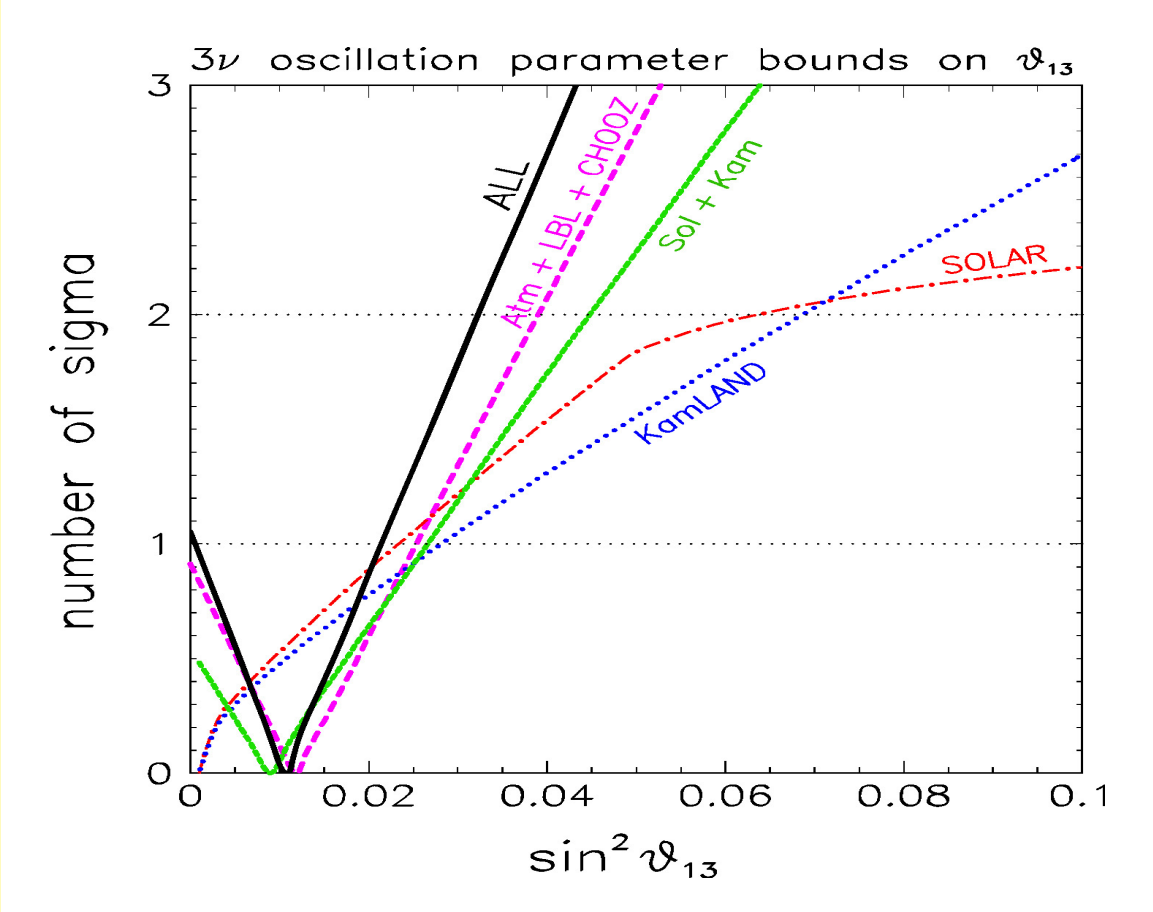
Some aspect is currently "hidden" below **1σ** C.L.

A recent example:

slight preference for

$\sin^2\theta_{13} \sim 0.01$

from the combination of solar +reactor 2008 data
(green curve in the figure)

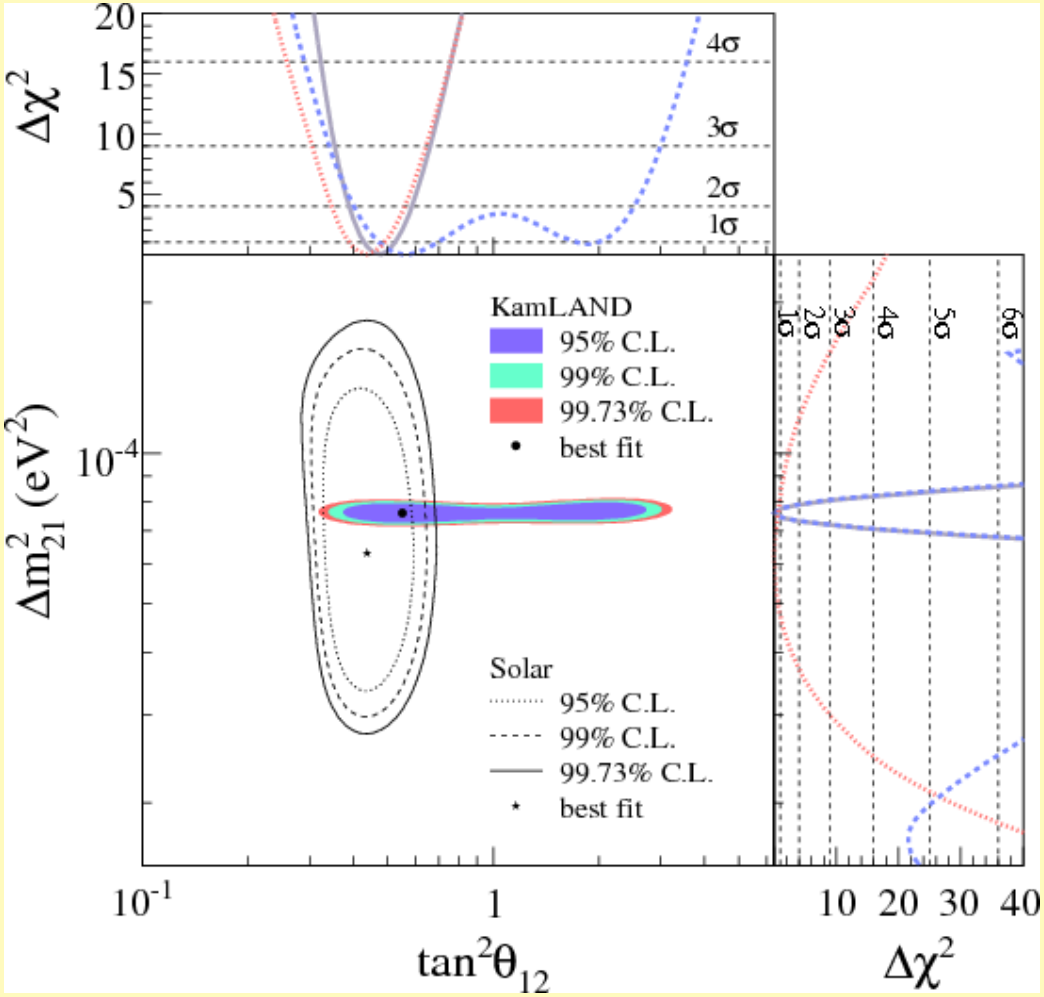


Reason:

Slight disagreement between

- Solar data (SNO dominated)
- KamLAND data (at $\theta_{13} = 0$)

when the two best-fits are compared in the usual plane (m^2_{12}, $\tan^2\theta_{12}$)

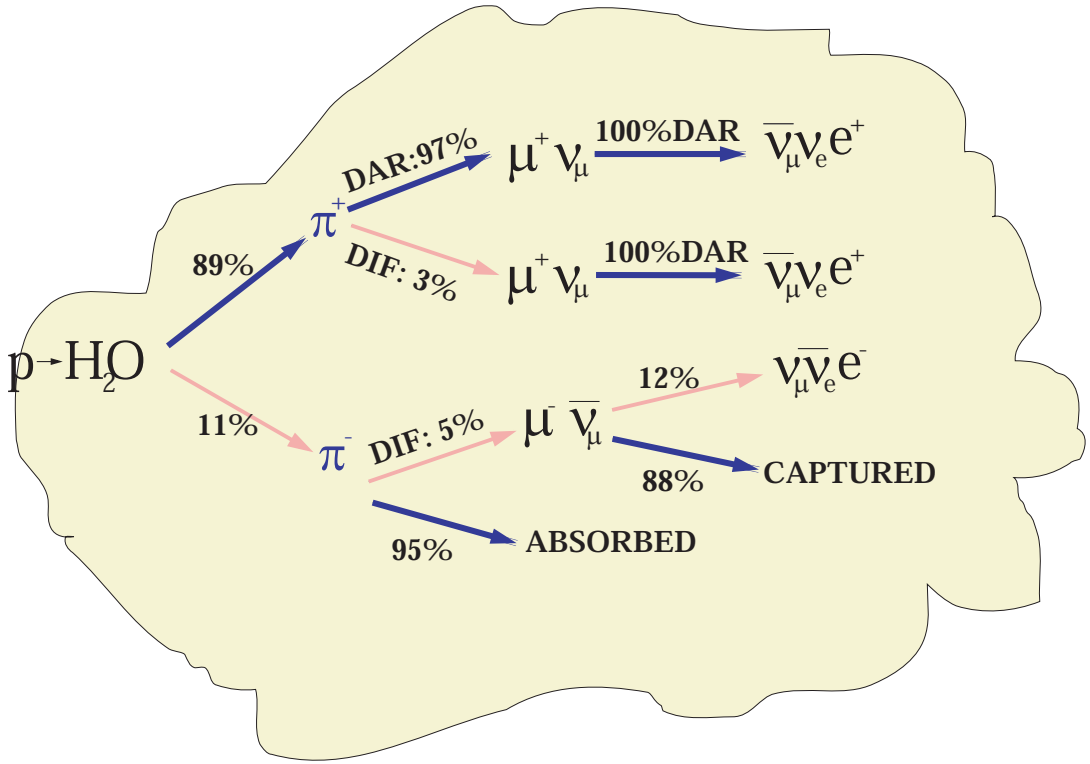


[figure taken from the official Kamland site (2008)]

LSND experiment at the Los Alamos Meson Physics Facility (LAMPF)

Neutrino Source High intensity (1mA) low energy (800 MeV) p beam into stop target

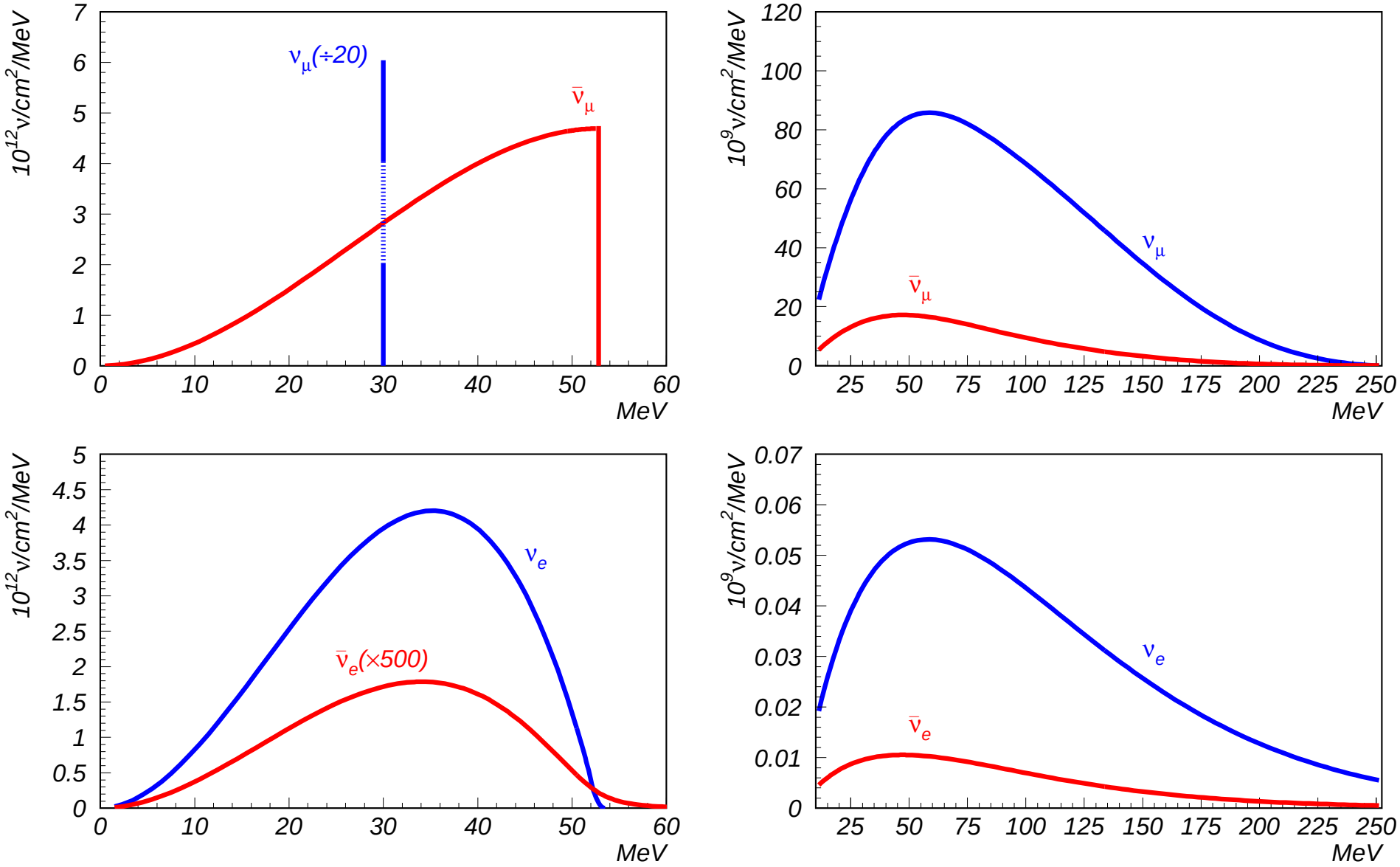
Look for $\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$ oscillation from decay at rest (DAR) neutrino flux and for $\nu_\mu \longrightarrow \nu_e$ oscillation from decay in flight (DIF) neutrino flux.



- $\overline{\nu}_e$flux is $\overline{\nu}_e/\overline{\nu}_\mu$(DAR) = $7.8 \cdot 10^{-4}$
- Oscillated $\overline{\nu}_e$events have a maximum energy of 52.8 MeV.
- No electron from ν_e above 36 MeV ($\nu_e^{12}C \longrightarrow e^{-}\ {}^{12}N$)
- No electron with a correlated γ above 20 MeV ($\nu_e^{12}C \longrightarrow e^{-}n^{11}N$)

DAR FLUXES

DIF FLUXES



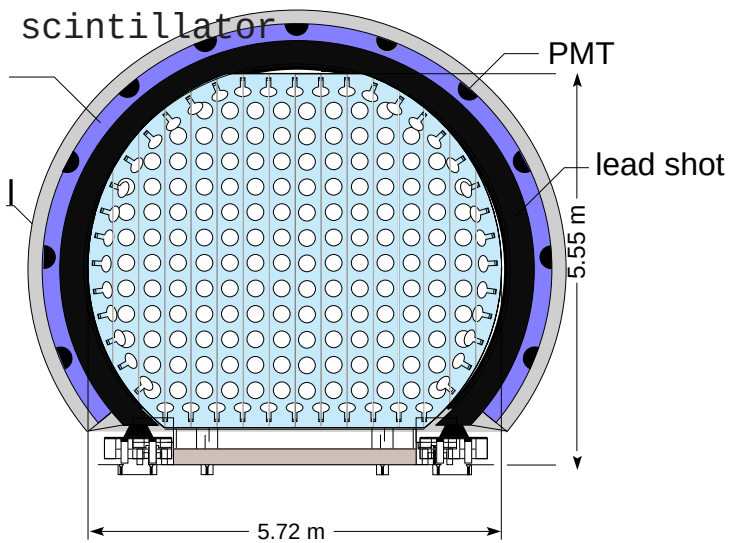
Liquid Scintillator Neutrino Detector

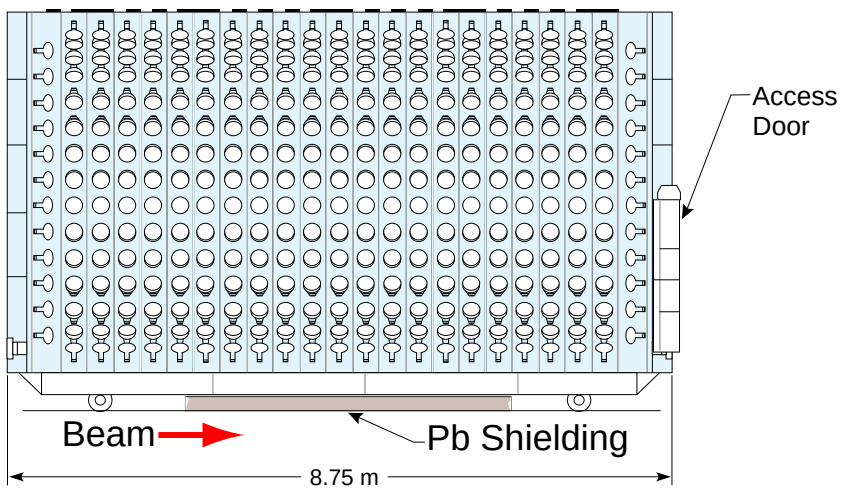
of Dilute Mineral Oil

nkov light (n=1.47): threshold+direction
tillation : energy
nkov/scintillation: particle identification

central detector: 1220x8" PMT
(25% surface coverage)
mineral oil (CH2) doped with
0.031 g/l of b-PBD .

veto detector: 292x8" PMT,
passive shield: ~2 Kg/cm2

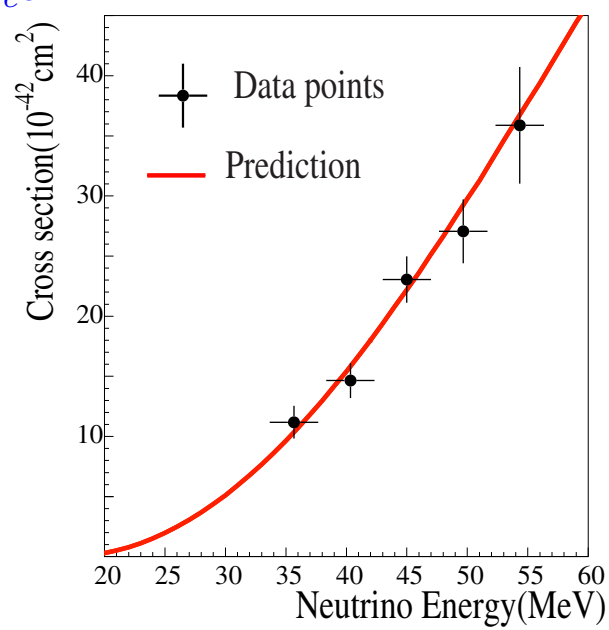




DATA TAKING

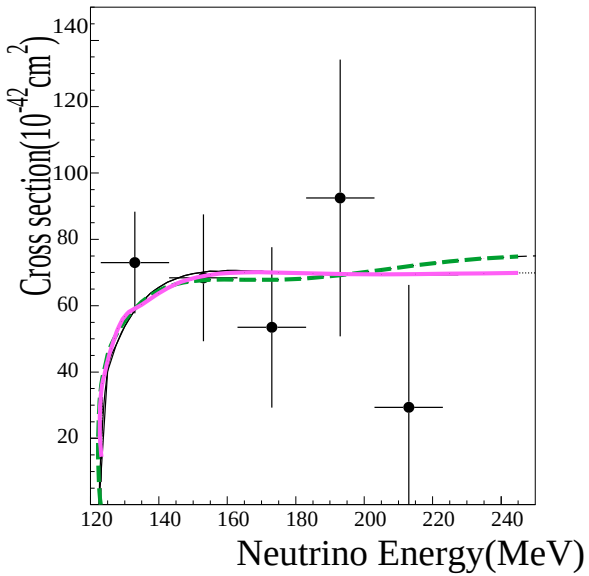
YEAR	COULOMBS	
1993	1787	
1994	5904	First DAR paper: ”Candidate events ..” (PRL 75(1995)2650)
1995	7081	Second DAR paper: “Evidence for ...”, (Ph.Rev.C 54(1996)2685 and PRL 77(1996)3082 ”
		DIF paper: ” Results on ...”, (PRL 81(1998)1774 and Ph.Rev.C 58(1998)2489)
1996	3790	Water tank substituded with high Z target.
1997	7181	Preliminary results at Neutrino 1998
1998	3154	End of data taking 21 dec 1998

$\nu_e$detected and flux measured by $\nu_e^{12}C \rightarrow^{12} N_{gs}e^-$ and $\nu_e e^- \rightarrow \nu_e e^-$



$\overline{\nu}_\mu$flux known at 7% through the results of a subsidiary experiment.

ν_μ detected and flux measured by $\nu_\mu^{12}C \rightarrow^{12} N_{gs}\mu^-$



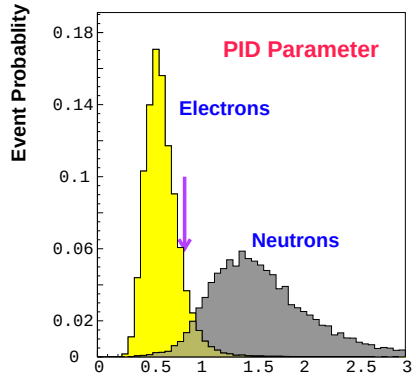
DAR OSCILLATION SEARCH

prompt positron signal, energy range.

$$\overline{\nu_e} p \rightarrow e^+ n$$

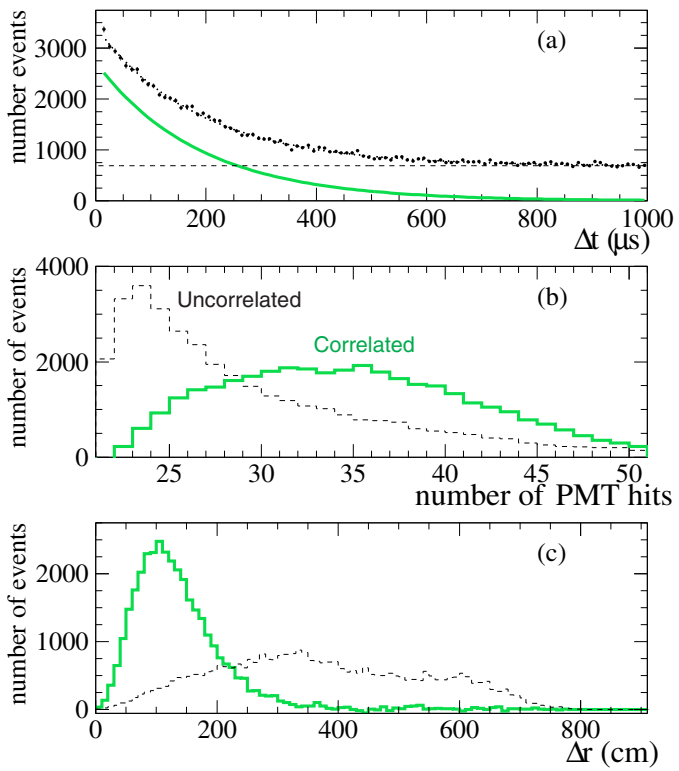
$$n + p \underset{\tau \simeq 186\ \mu s}{\longrightarrow} d + \gamma(2.2\ MeV)$$

delayed correlated photon.

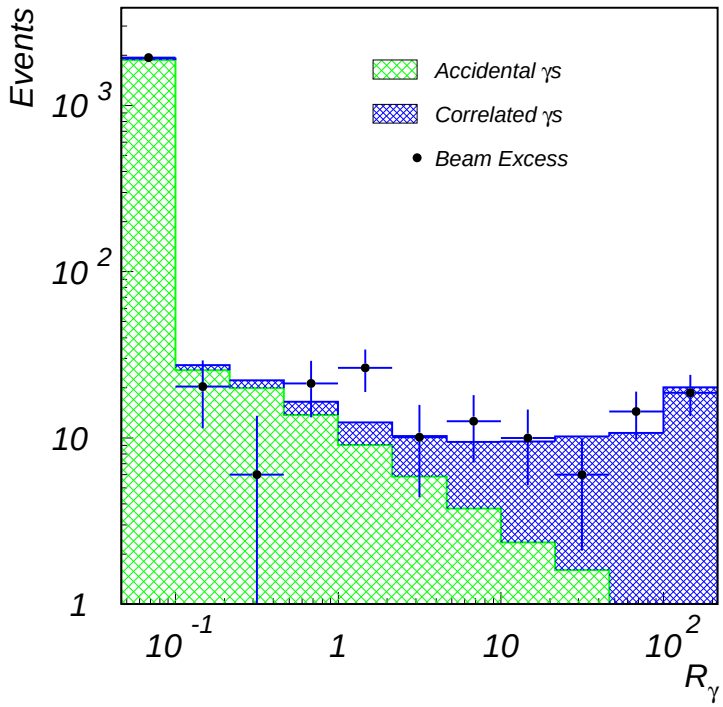


1. Particle identification through position, direction, #PMT (e^- calibration through Michel e^- from CR μ decays)
2. CR veto through veto on detector activity before and after the trigger.
3. Correlated γ through likelihood function $\mathcal{R}$ (built with CR muons and/or MC)
4. Energy range: $20 \leq E_e \leq 60$ or $36 \leq E_e \leq 60\ MeV$ (golden sample).

Overall $\overline{\nu}_e$detection efficiency: 22%



EXCESS OF $\overline{\nu_e}$ EVENTS



BACKGROUNDS

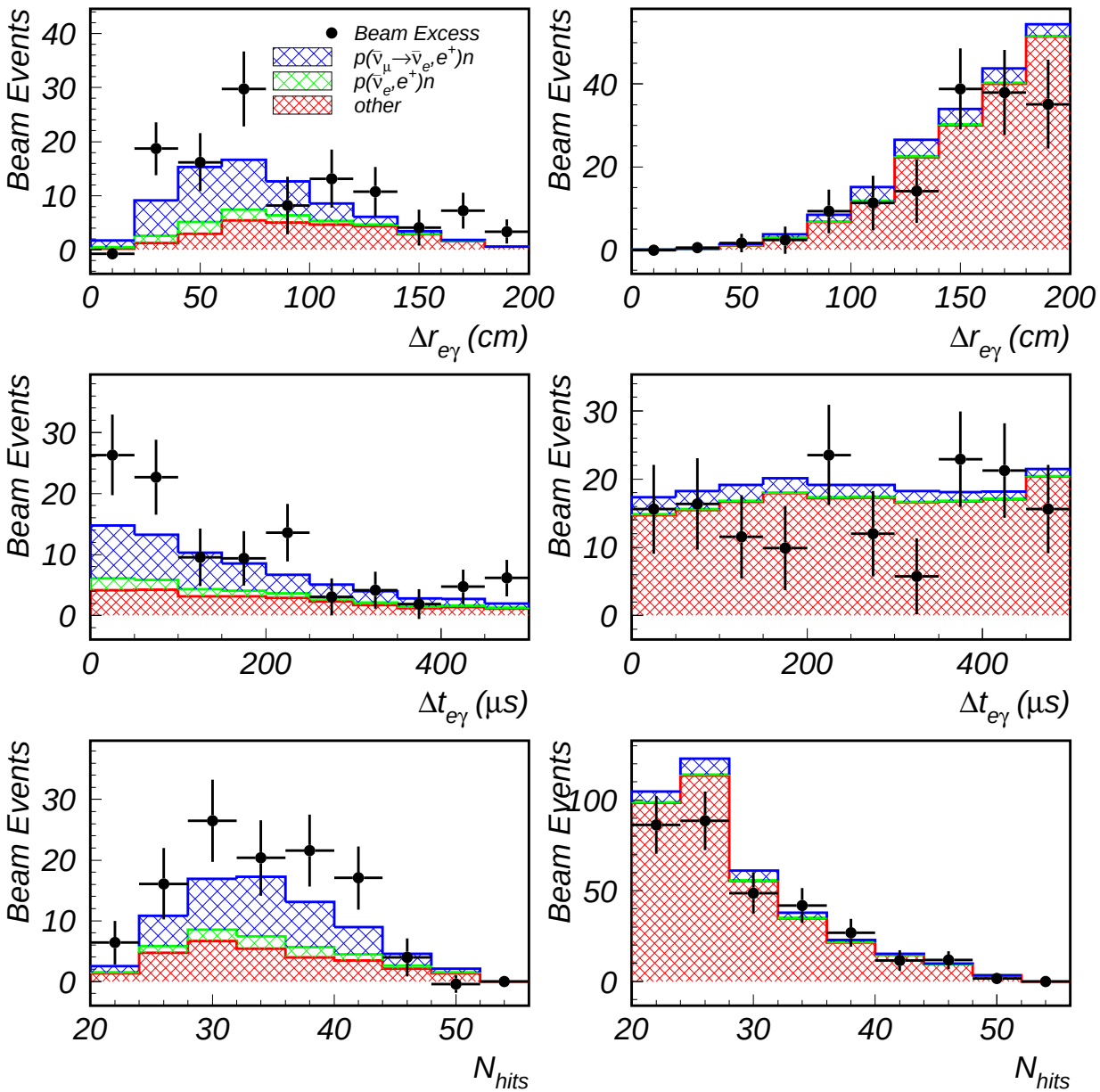
1. Cosmic Rays. Measured in beam off data (beam-off/beam-on$\simeq 13$, $\rightarrow$ good statistical accuracy for background subtraction).
2. Beam interactions with a random γ (measured)
3. Genuine $\overline{\nu}_e$and $\overline{\nu}_\mu$with a correlated γ. Studied via MC simulations.

Selection	Beam-On Events	Beam-Off Background	ν Background	Event Excess	Probability
$R_\gamma > 1$	205	106.8 ± 2.5	39.2 ± 3.1	$59.0 \pm 14.5 \pm 3.1$	7.8×10^{-6}
$R_\gamma > 10$	86	36.9 ± 1.5	16.9 ± 2.3	$32.2 \pm 9.4 \pm 2.3$	1.1×10^{-4}
$R_\gamma > 100$	27	8.3 ± 0.7	5.4 ± 1.0	$13.3 \pm 5.2 \pm 1.0$	1.8×10^{-3}

Events with $20 \leq E_e \leq 60\ MeV$, $R_\gamma > 10$:

Analysis	Excess Events	Oscillation Probability
Present Analysis (1993-1998)	$87.9 \pm 22.4 \pm 6.0$	$(0.264 \pm 0.067 \pm 0.045)\%$
Previous Analysis (1993-1995)	$51.0^{+20.2}_{-19.5} \pm 8.0$	$(0.31 \pm 0.12 \pm 0.05)\%$

Excess events fit oscillated event characteristics:



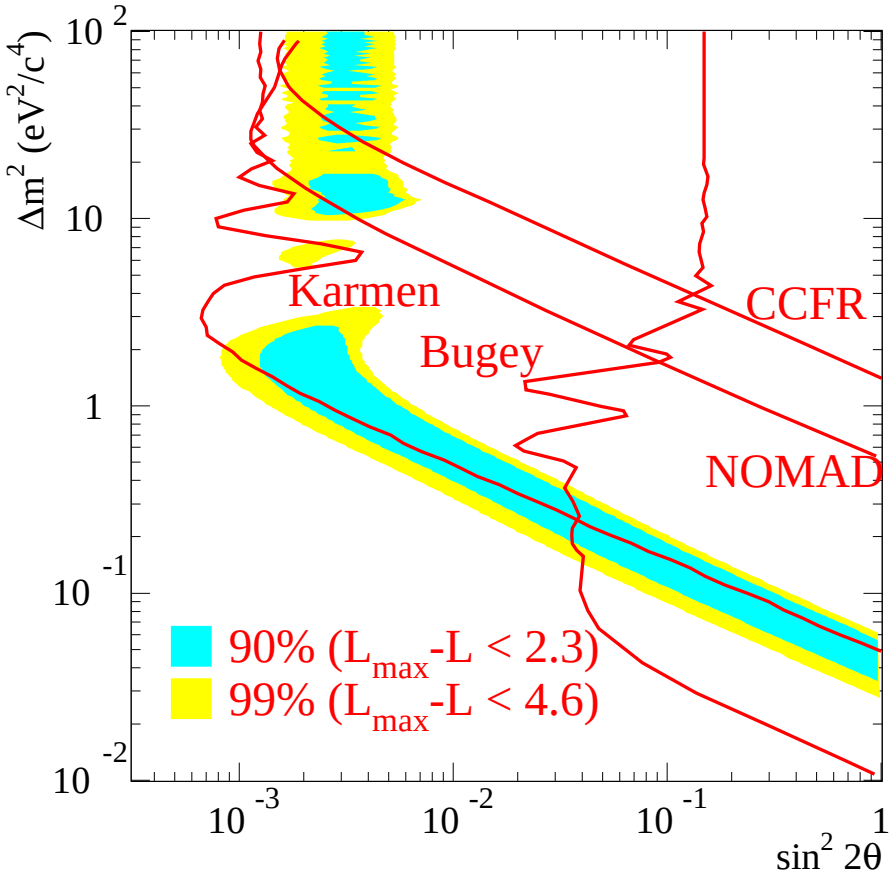
While don't fit backgrounds:

- Fit the excess with the μ^- background: it must be multiplied by 8.6 and χ^2 is 2.2 units worse than oscillation fit
- π^-

  DIF backgrounds studied with a special trigger during 1995, in order to increase sensitivity to muons associated to small activity: it resulted compatible with the MC predictions.

SIGNAL PLOT

- Global $\overline{\nu}_\mu - \overline{\nu}_e$ and $\nu_\mu - \nu_e$ analysis (DAR + DIF).
  5697 candidate events with $20 < E_\nu < 200$ MeV.
- 3600 bins in 4 variables: the energy, the likelihood R_γ, the angle respect the beam direction ($\cos\theta_b$) and the path length L
- Systematics included: neutrino flux $\times$ detection efficiency $= 10\%$.
- Bidimensional $(sin^2(2\theta), \Delta m^2)$ grid, selecting $\Delta\chi^2 = 2.6(90\%)$ and $4.5(99\%)$ above the minimum.
- The other exclusion curves in the plot are built with several different statistical methods!.



KARMEN EXPERIMENT

Performed at ISIS neutron spallation facility at RAL.

The detector (56 t), is at 17 m, 90^0, from the beam stop. Beam current is 0.2 mA.

The time structure of the beam permits a separation between neutrinos from μ^+ DAR and those from π decay (both DAR and DIF).

KARMEN 1: 1990-1995, 9120 Coulombs. Seen 171 events, expected 140 from cosmic rays and beam backgrounds. Beam excess $= 31 \pm 17$ (2.4σ), delayed event seen but prompt positron do not exhibit time and energy distribution from oscillations. A lower limit on oscillation probability: $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) < 4.25 \cdot 10^{-3}$ $(90\% CL)$ was set.
Also performed a search for $\nu_\mu \rightarrow \nu_e$ oscillation, with a 90% CL limit of $2 \cdot 10^{-2}$ on the probability.

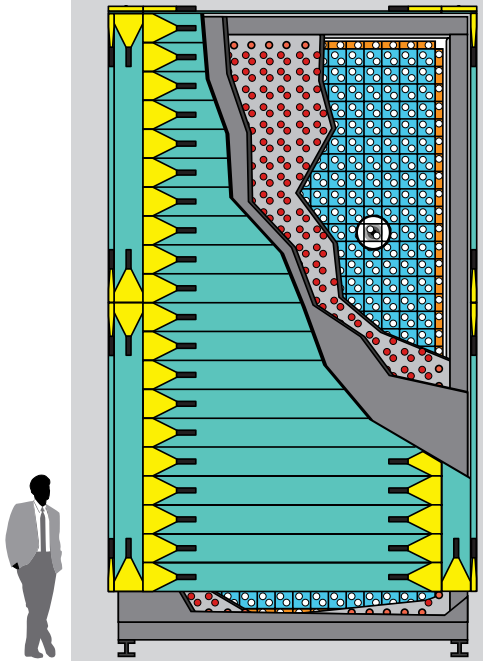
UPGRADE (KARMEN 2): new 300 m^2 active veto layer surrounding the iron blockhouse (4λ)

- throughgoing or stopping muons can be off-line vetoed
- Cosmic background suppression reduced by a factor 43.

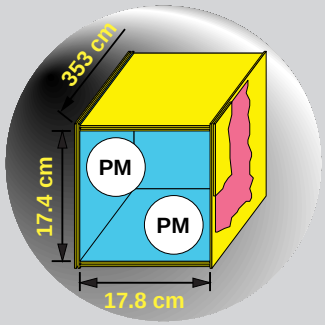
KARMEN DETECTOR

56t liquid scintillator calorimeter

96% active volume



OUTER VETO 1	NE110
PASSIVE SHIELD	20 cm
INNER VETO	96
SEGMENTED CENTRAL DETECTOR	16x32
3" PHOTOMULTIPLIER	
ACRYLIC GLASS	



Gd_2O_3 PAPER + AIR GAP

3.2m x 5.9m x 3.5m

$$\Delta E/E = \frac{11.5\%}{\sqrt{E(MeV)}} \quad (\Leftrightarrow 80\ pe/MeV)$$

$\sigma t = 0.4ns$
$\sigma x = 6.0cm$

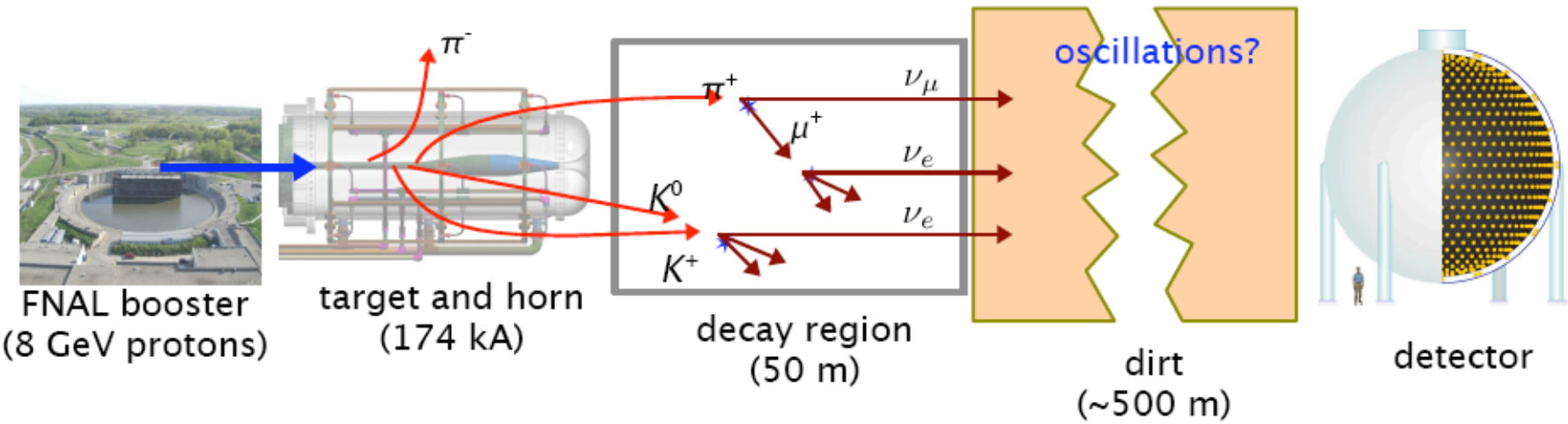
17.05.98

Reconciling LSND with Particle Physics and Cosmology

- Two light sterile neutrinos and low-energy seesaws? (hep-ph/0305255, hep-ph/0608147)
- Sterile neutrino and CPT invariance violation? (hep-ph/0308299)
- Sterile neutrino and large extra dimensions? (hep-ph/0504096)
- Heavy sterile neutrino decay? (hep-ph/0505216)
- Mass varying neutrinos? (hep-ph/0509163)
- Lorentz invariance violation? (hep-ph/0606154)
- Quantum decoherence? (hep-ph/0603028)
- Cosmological lepton asymmetry? (hep-ph/9508275, astro-ph/0608206)
- Inflationary models with low reheating temperature? (astro-ph/0403323)
- Extra neutrino couplings to massless bosons? (astro-ph/0404585)
- Non-standard ($w \neq -1$) dark energy equation of state? (astro-ph/0505551)
- ...

Generally requires to give away or introduce something fundamental

The MiniBooNE design strategy...must make ν_μ

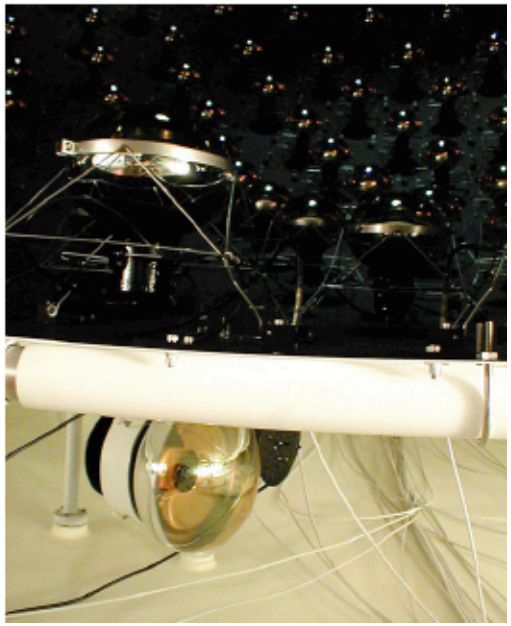


- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:

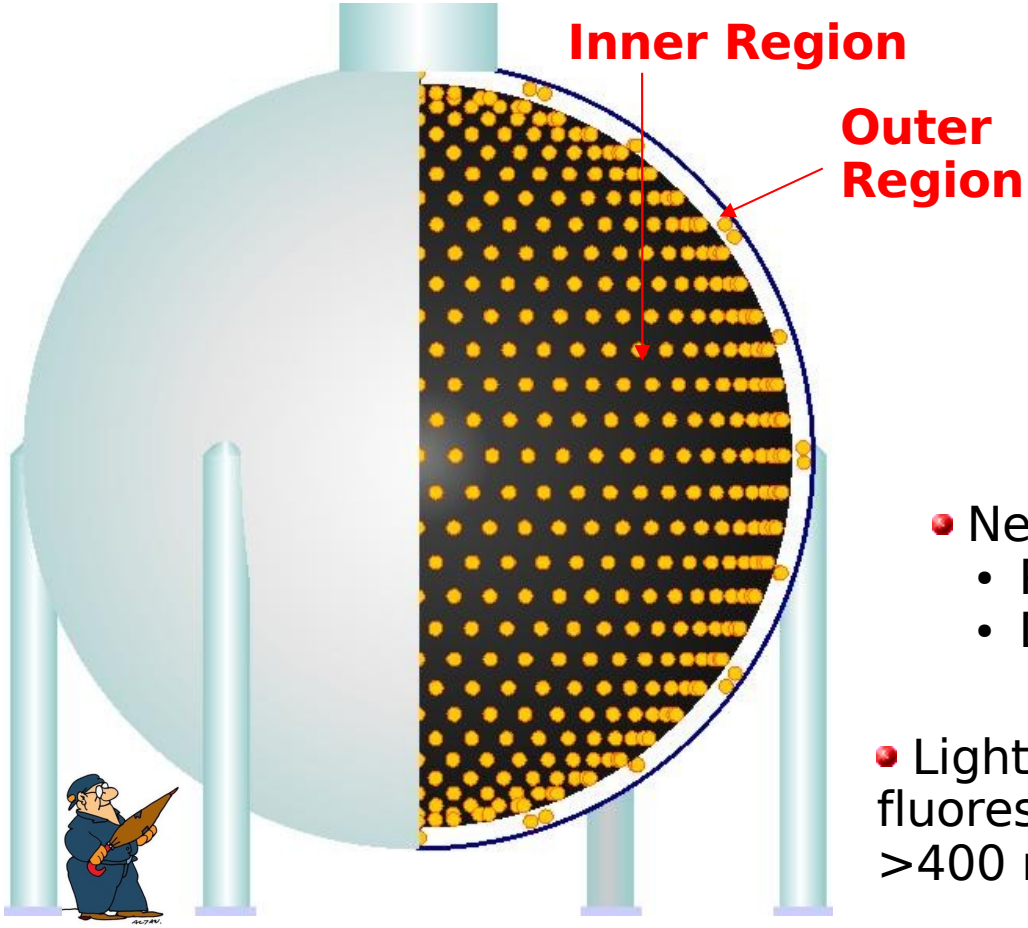
  MiniBooNE: (0.5 km) / (0.8 GeV)

  LSND: (0.03 km) / (0.05 GeV)
- 5.58×10^{20} P.O.T. total; up to 5×10^{12} p/pulse at up to 4 Hz

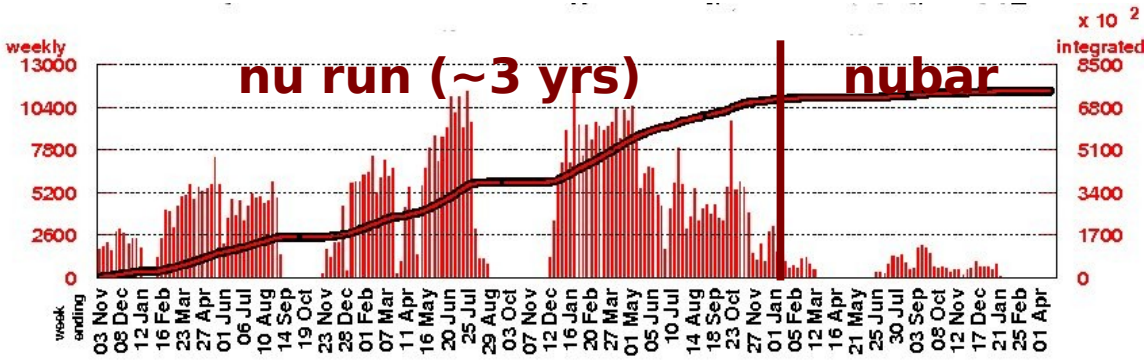
$$\nu_\mu = 93.5\%,\ \nu_e = 0.5\%,\ \bar{\nu}_\mu = 6\%$$



Neutrino Detector



- 12 m in diameter sphere filled with 800 t of undoped mineral oil
- Light tight inner region with 1280, 20 cm diam., PMTs (10% coverage)
- 240 PMTs in veto region (>99.9% veto efficiency)
- Neutrino interactions in oil produce:
  - Prompt, ring-distributed, Cerenkov light
  - Delayed, isotropic, scintillation light
- Light transmission affected by: fluorescence, scattering, absorption (>20m for >400 nm light)

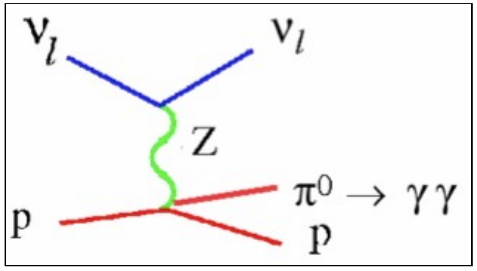


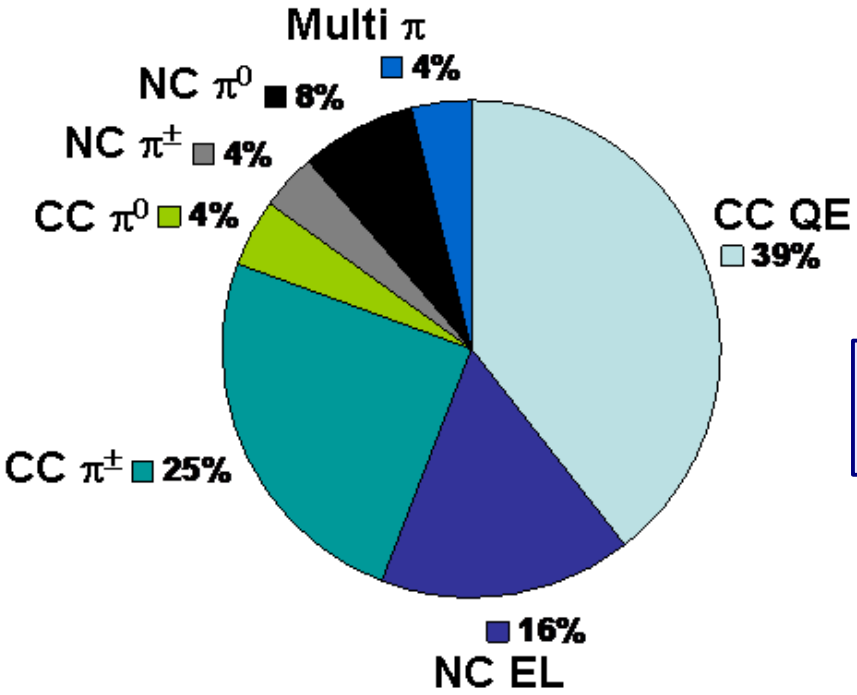
Number of accumulated neutrino interactions: $7.4 \cdot 10^5$

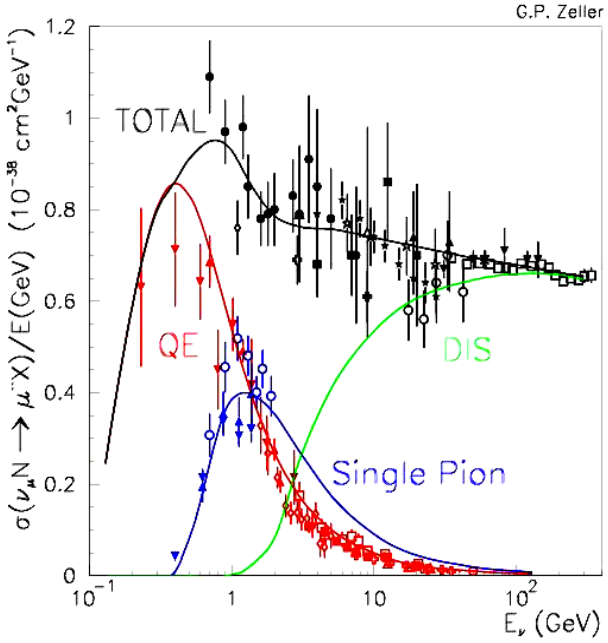
Neutrino Interactions at MiniBooNE

- Several interaction channels contribute in ~1 GeV neutrino energy regime

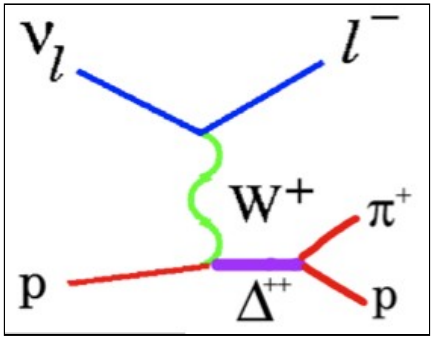
Neutral current π^0 production



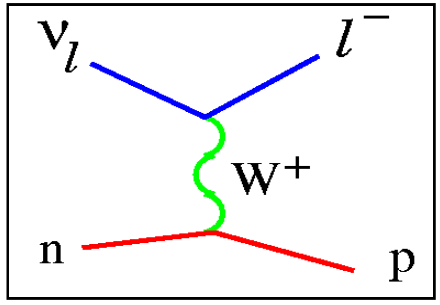




Charged current π^+ production



Charged current quasi-elastic scattering

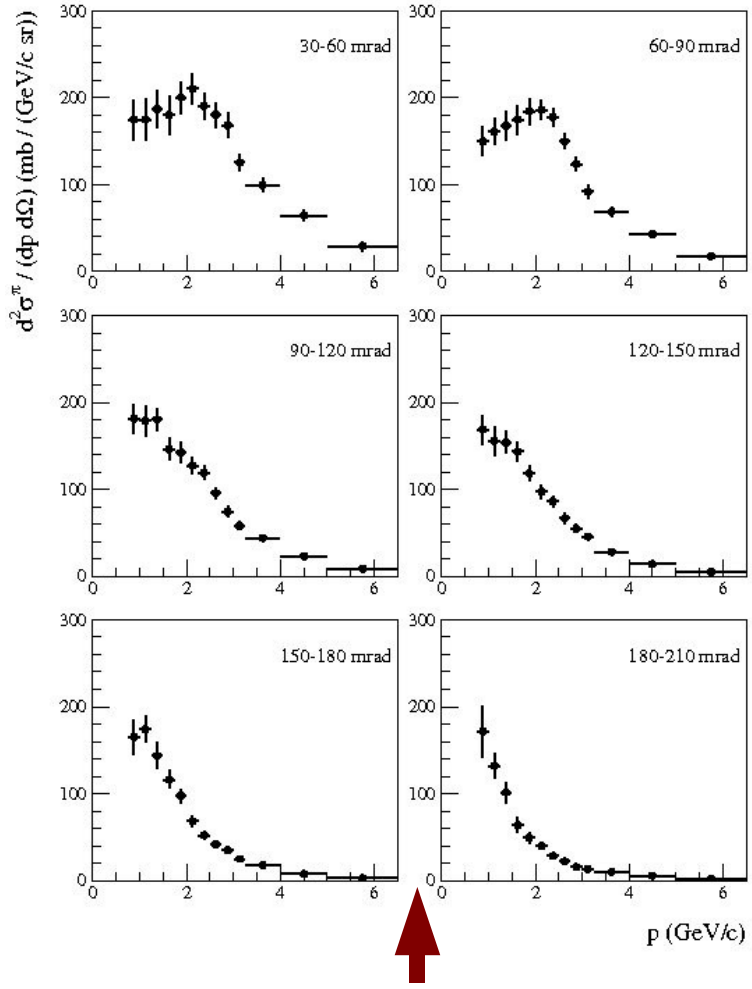


Modeling Neutrino Fluxes

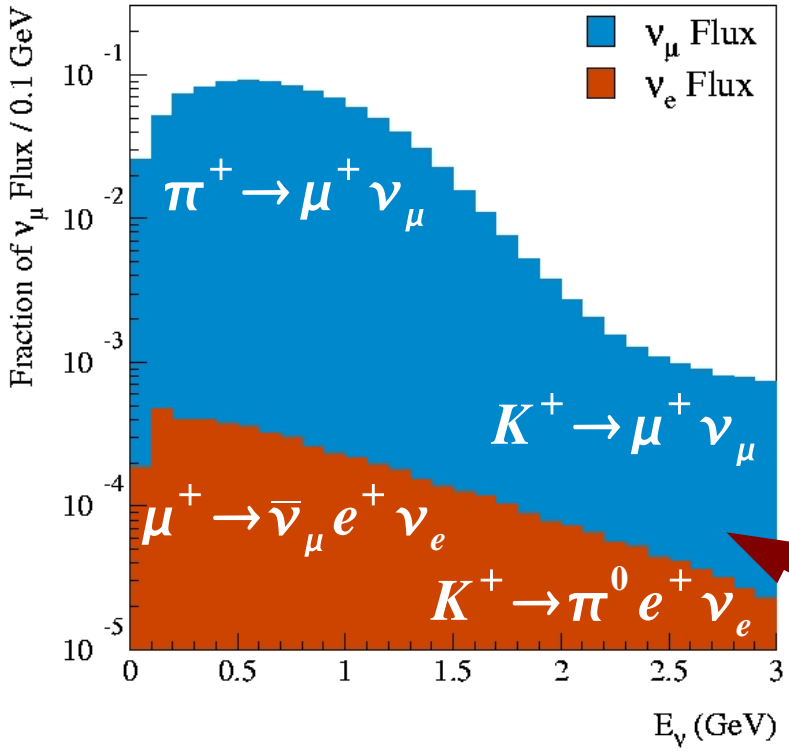
GEANT4 beamline description, simulating:

- Primary protons, geometry, materials and horn field
- Interactions, focusing, meson and muon decays

- Pion/kaon production data on beryllium is the most important external physics input to the simulation
-> parametrized according to relevant hadron production data sets



HARP data on:
p(8.9 GeV/c) + Be $\rightarrow \pi^+$ + X
(hep-ex/0702024)



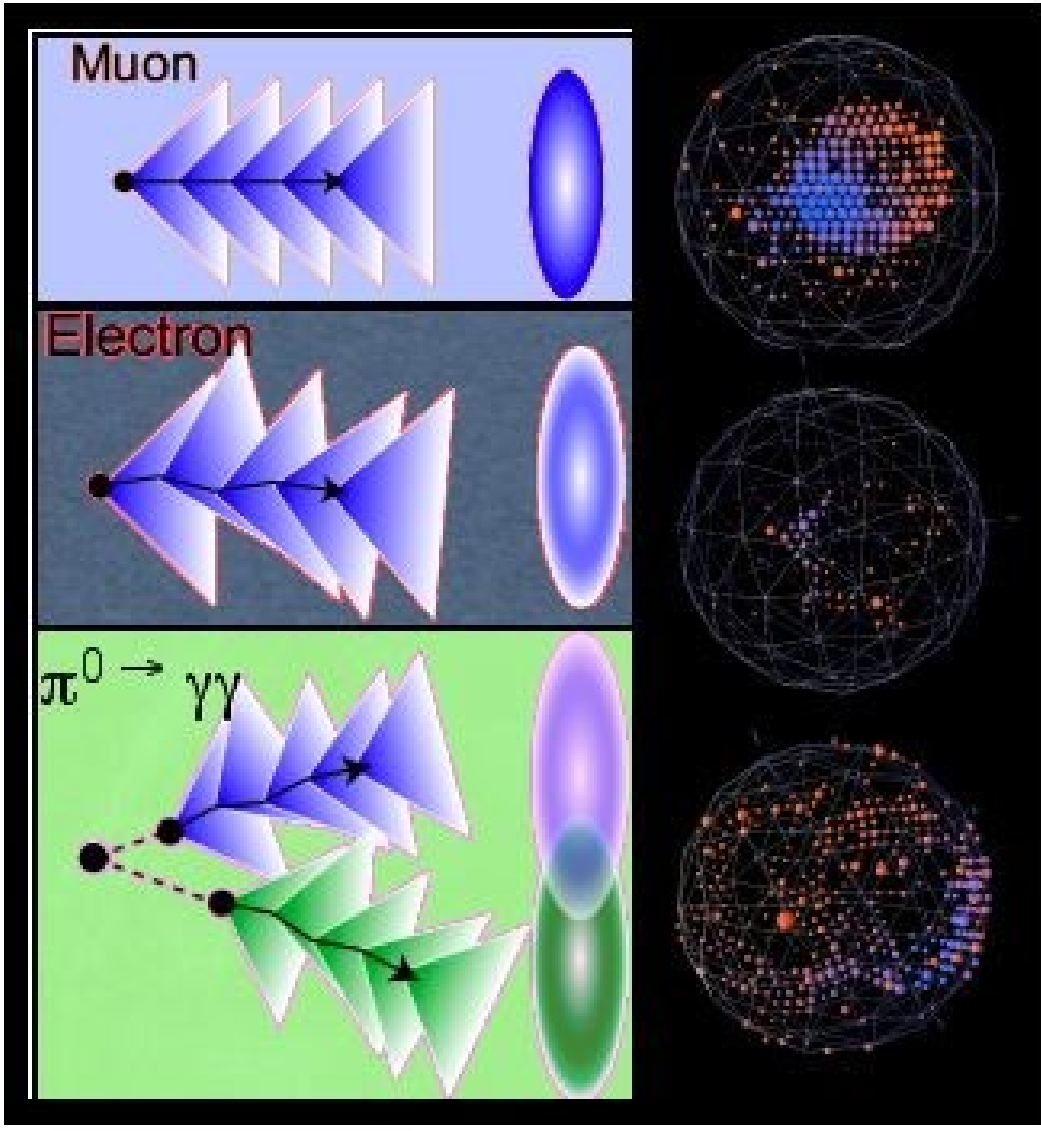
ν_μ and ν_e flux predictions. $\nu_e/\nu_\mu \sim 0.5\,\%$

Particles to Identify in Appearance Search

Muons (background):
- long tracks
- sharp Cherenkov ring
- ~80% with decay electron tag

Electrons (signal and intrinsic background):
- short tracks
- fuzzy Cherenkov ring
- single subevent

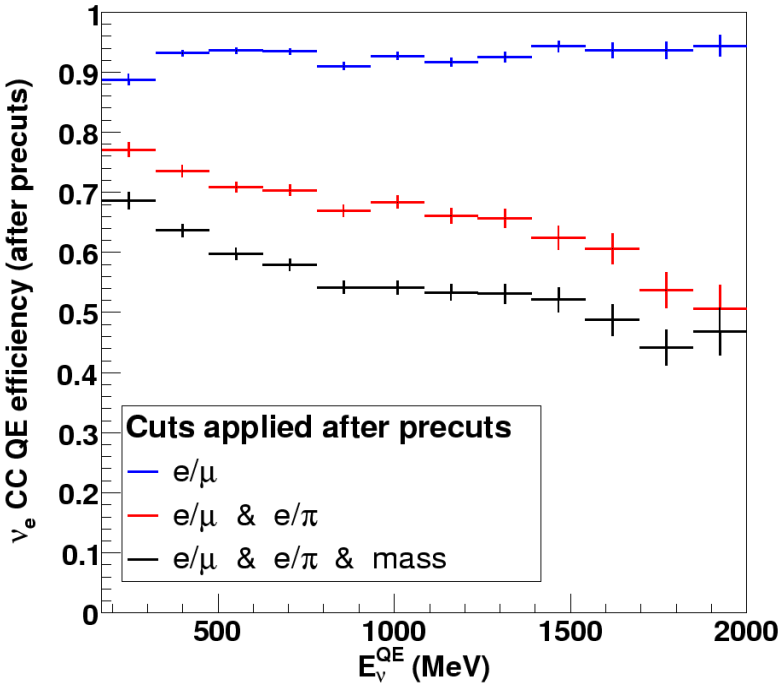
π^0 -> $\gamma\gamma$ decays (background):
- disconnected short tracks
- typically two fuzzy Cherenkov rings
- single subevent

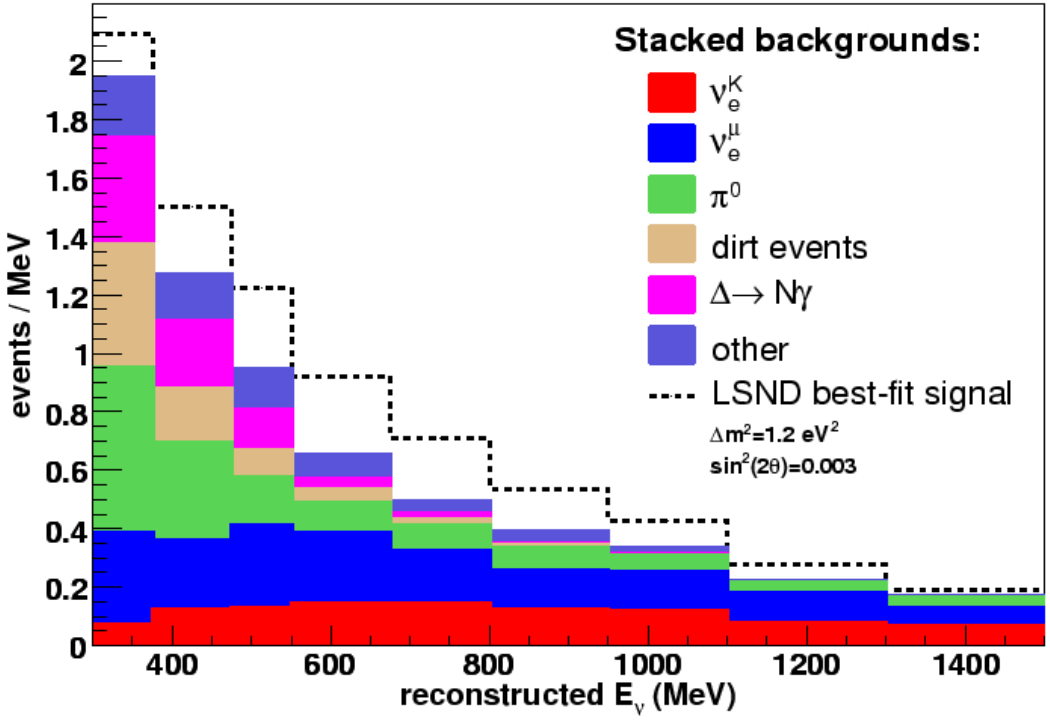


Signal Efficiency and Background Composition

- Signal efficiency:

Single subevent,hit-level,
fiducial volume, energy threshold cuts
+ $\mathrm{Log}(L_e/L_\mu)$
+ $\mathrm{Log}(L_e/L_\pi)$
+ invariant mass cuts





- Background events in signal region can be constrained or checked with other samples:

high energy events
ν_μ CC QE
π^0
high radius events
π^0
ν_μ CC QE
ν_μ CC QE

Electron Neutrino Box Opening Procedure

Step 1: perform fit of E_ν distribution of electron candidate events in the $300 < E_\nu < 3000$ MeV energy range to oscillation hypothesis, where best-fit oscillation signal added to background prediction is unknown. Disclose χ^2 values from data/MC comparisons of several diagnostic variables

Step 2: disclose histograms for data/MC comparisons of same diagnostic variables

Step 3: disclose χ^2 value for E_ν data/MC comparison over oscillation fit range, still retaining blindness to oscillation signal component

Step 4: disclose full information on electron candidate events and oscillation fit results

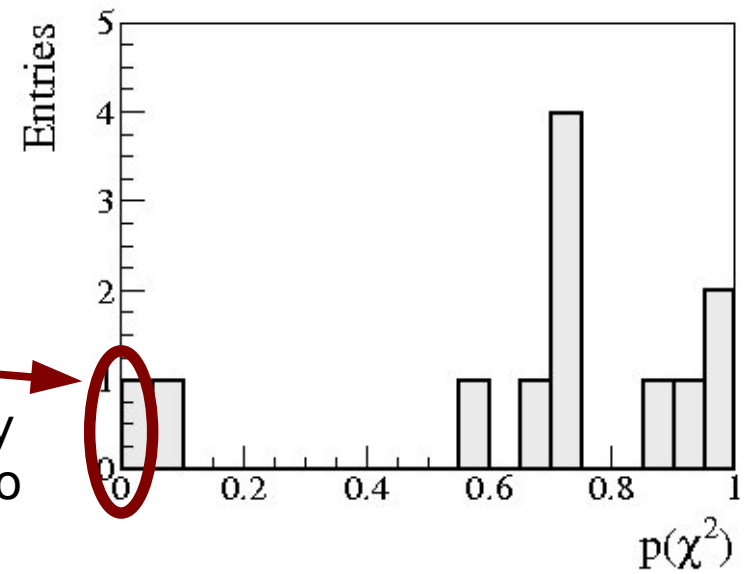
- Progress in a step-wise fashion, with ability to iterate if necessary
- All event selection and oscillation fit procedures were determined before full information on electron candidate events and oscillation fit results was disclosed

Box Opening Step 1: First Try

- X^2 probability for data/MC comparisons on 12 diagnostic variables:

event/track position, direction, visible energy, and PID quantities

- Comparisons looked good except event visible energy: p($X^2 > X^2$(obs)) = 1%



- Indicates poor data/MC agreement beyond ability of 2-neutrino, appearance-only oscillation model to handle

- Triggered further investigations of background estimates and associated uncertainties, using "sideband" samples
-> we found no evidence of a problem

- However, knowing that:

- backgrounds predicted to rise at low energy
- studies focused suspicions in low-energy region
- choice has negligible impact on oscillation sensitivity

-> we decided to look for oscillations (and diagnostic X^2) in the reduced ($475 < E_\nu < 3000$ MeV) range, and report events over full ($300 < E_\nu < 3000$ MeV) one

Oscillation Search Results

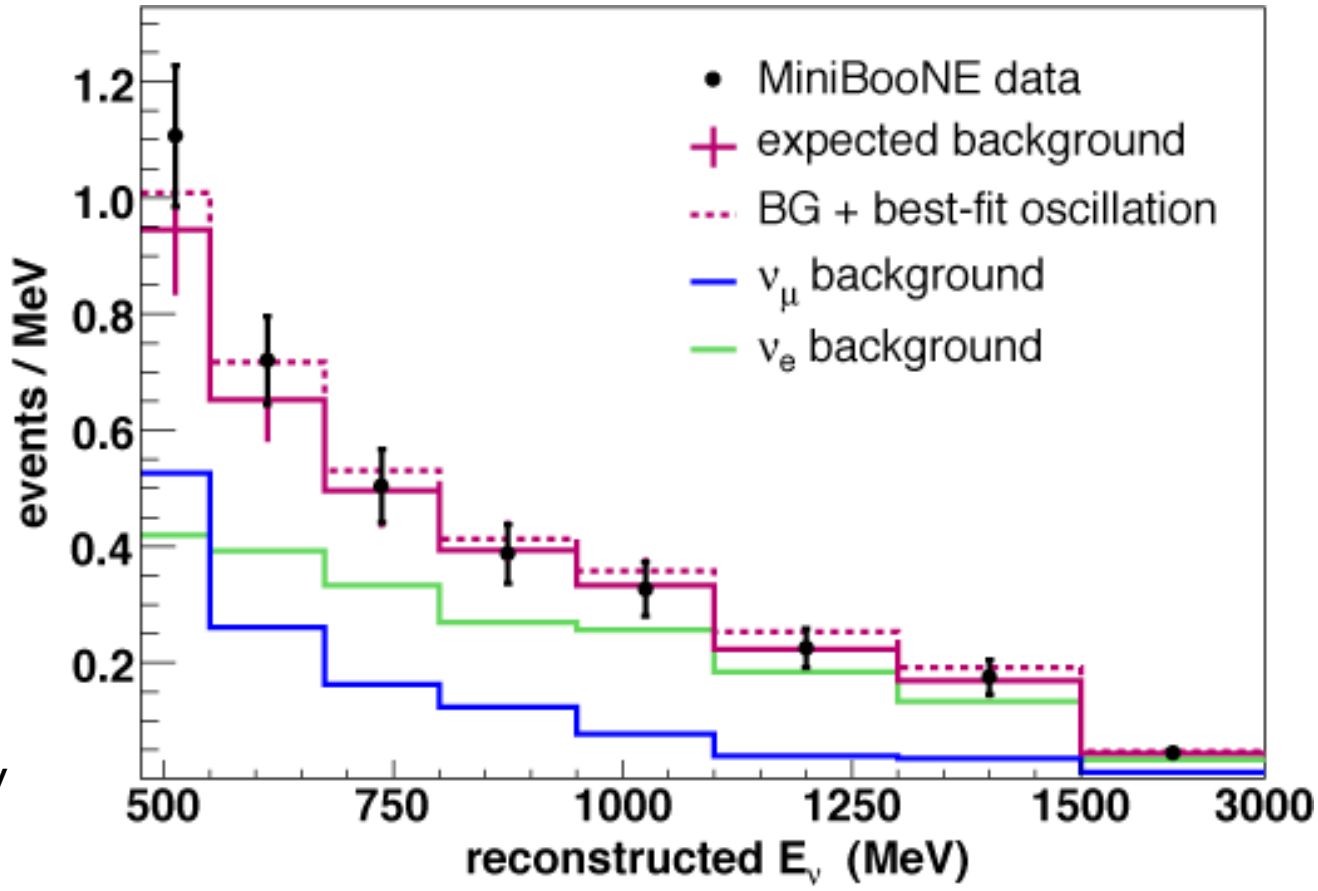
Counting experiment (475-1250 MeV):

- Observe **380 events,** predict **358±19±35 events**
- **0.55 σ** excess over no-oscillations background

No evidence for oscillations

Energy-dependent Oscillation Best-Fit (475-3000 MeV):

- $\sin^2 2\theta = 1.1\times10^{-3}$
- $\Delta m^2 = 4.1\ eV^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.94$



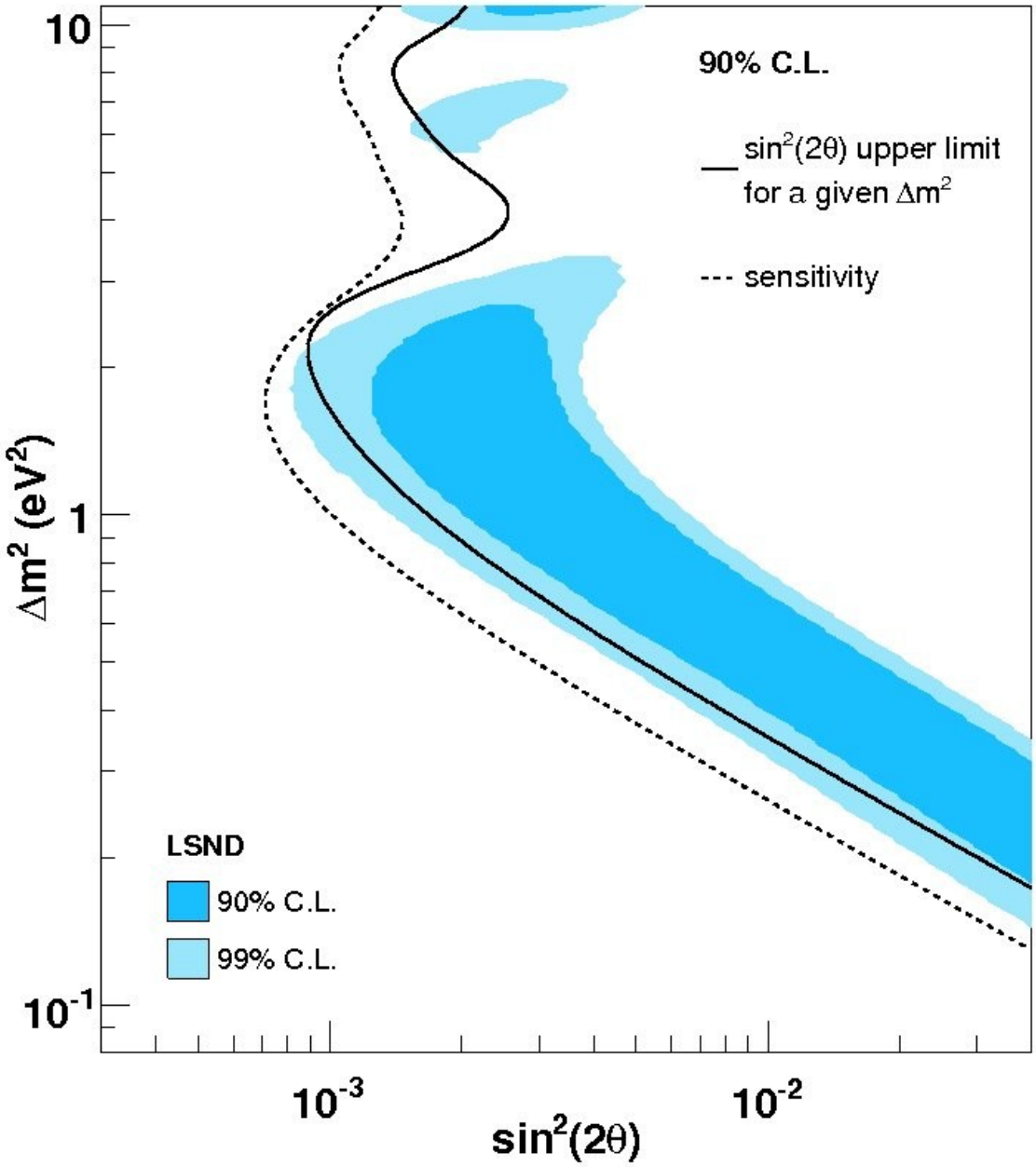
- Data error bars are statistical
- Predictions error bars from diagonal elements of syst.-only covariance matrix

Oscillation Parameters Exclusion

- No overlap in 90% CL allowed LSND and MiniBooNE regions

- MiniBooNE **excludes** two neutrino appearance-only oscillations as the explanation of the LSND anomaly at **~98% CL**

- Any interpetation of the LSND anomaly that would produce a significant excess for E_ν>475 MeV at MiniBooNE is also ruled out

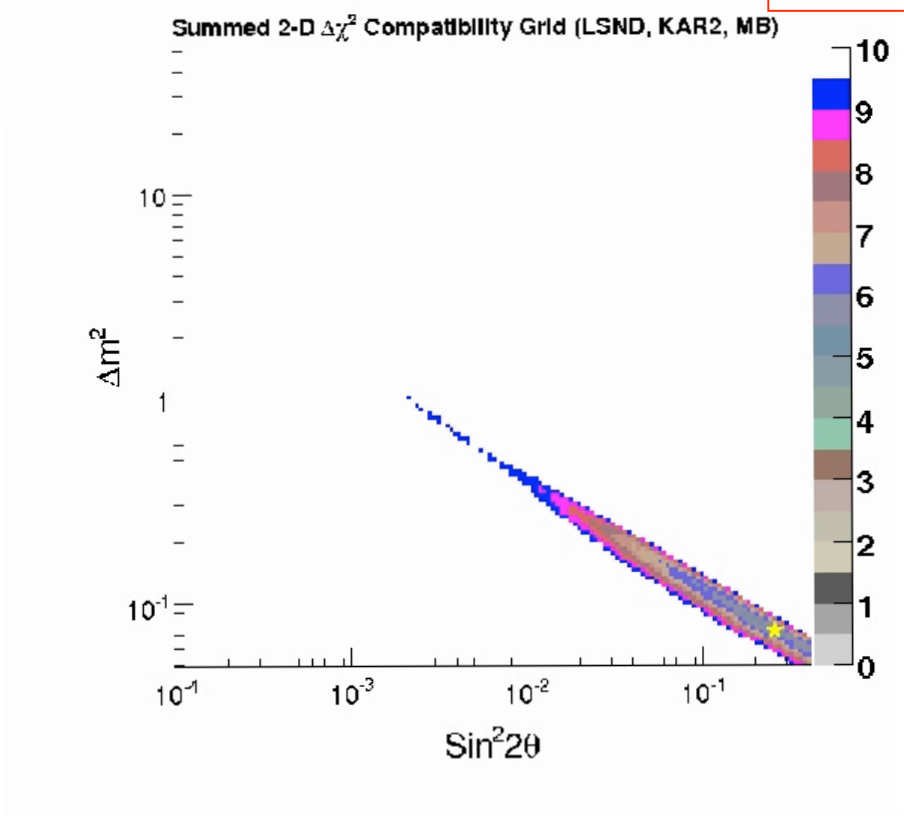


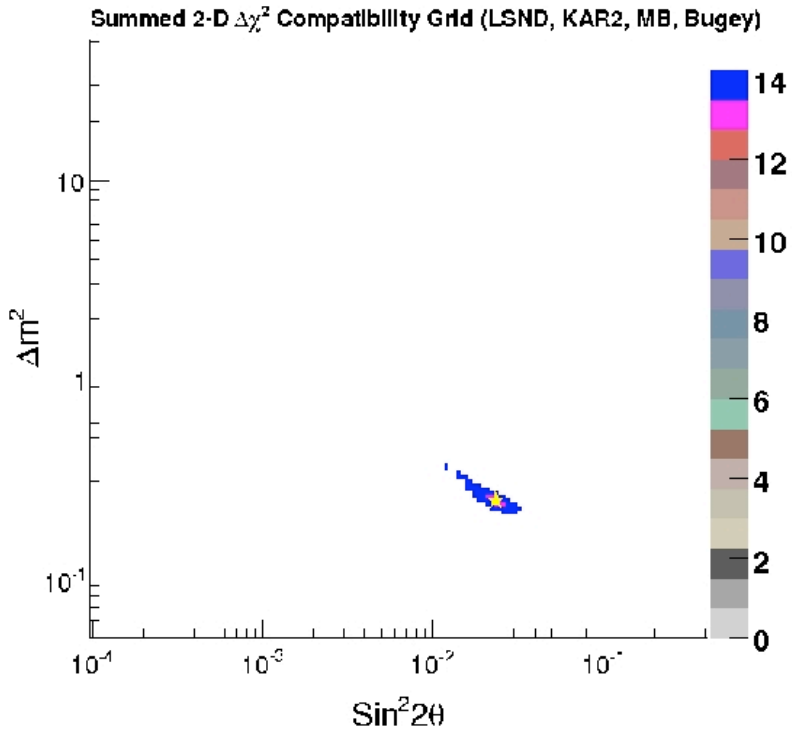
Global Fit Results (H. Ray)

- Combine results from several experiments--LSND, MiniBooNE, Karmen and Bugey
- Convert each to a chisq. However, only Delta chisq is available.
- Do fits with this. Omits effect of goodness-of-fit of individual experiments
- 2-D fits--both oscillation parameters fitted
- 1-D fits-- only sinsq theta fit. For each delta-msq asks: " If this is the true deltamsq, what is the compatibility?"

Global Fit Results-2D Fits

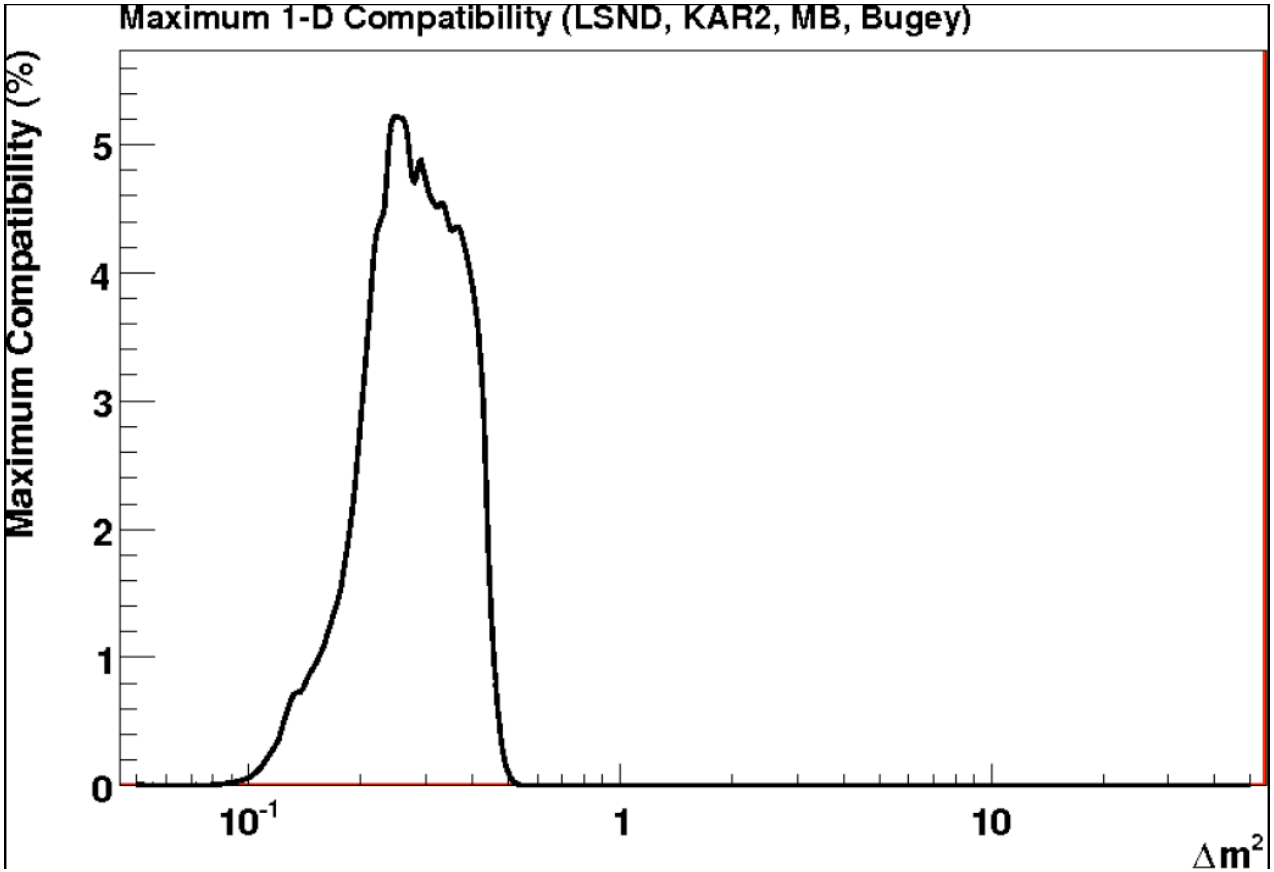
Colors represent $\Delta\chi^2$





- The star is the point of maximum compatibility
- LSND, KARMEN2, MB + BUGEY

Global Fits Results--1D



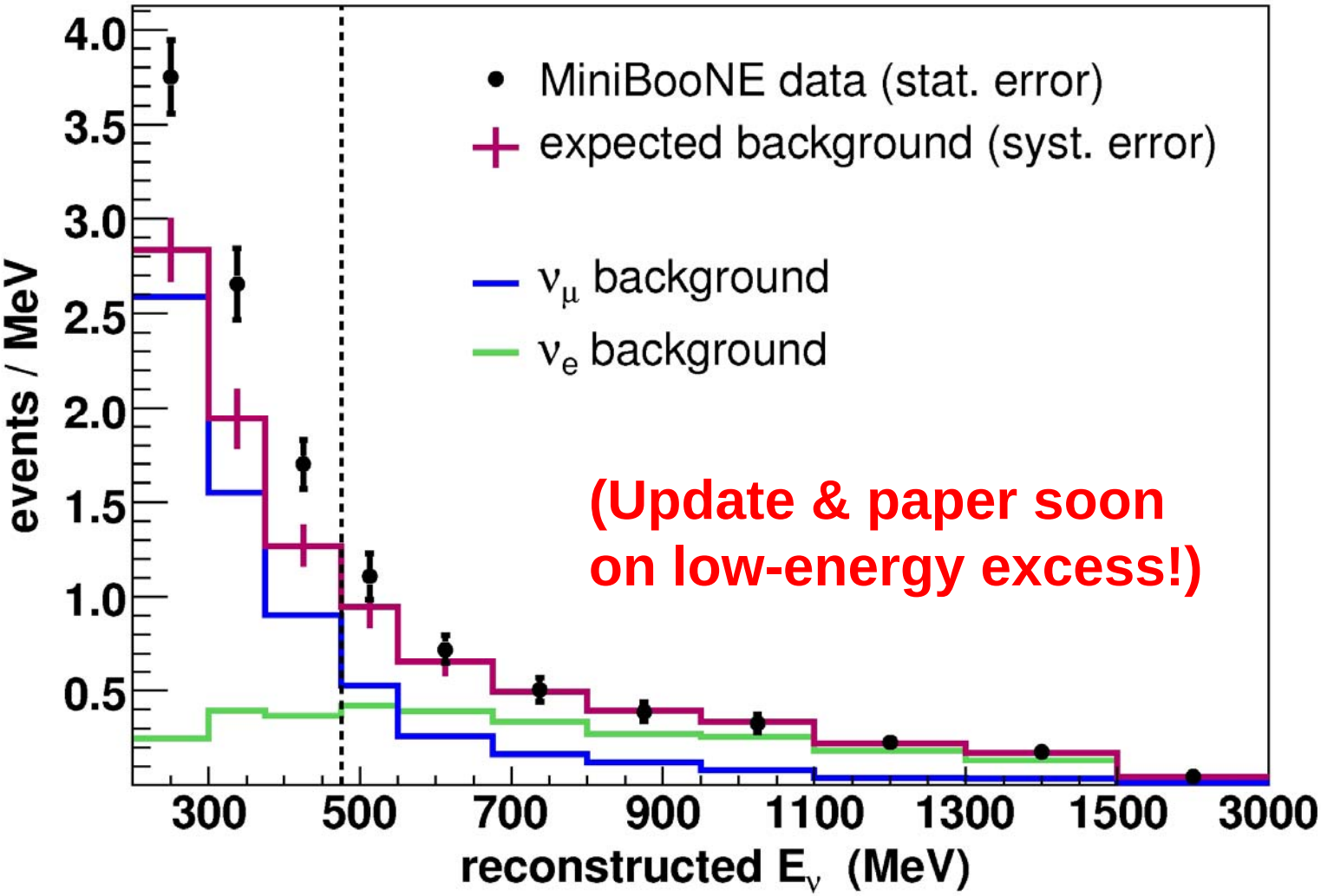
Maximum compatibility as a function of Δm^2 for the 1-D LSND, KARMEN2, MB, BUGEY analysis.

Global Fits to Experiments

LSND	KARMEN2	MB	Bugey	Max Compat (%)	Δm^2	$\sin^2 2\theta$
X	X	X		25.36	0.072	0.256
X	X	X	X	3.94	0.242	0.023
	X	X		73.44	0.052	0.147
	X	X	X	27.37	0.221	0.012
X		X		16.00	0.072	0.256
X		X	X	2.14	0.253	0.023
X	X			32.21	0.066	0.4

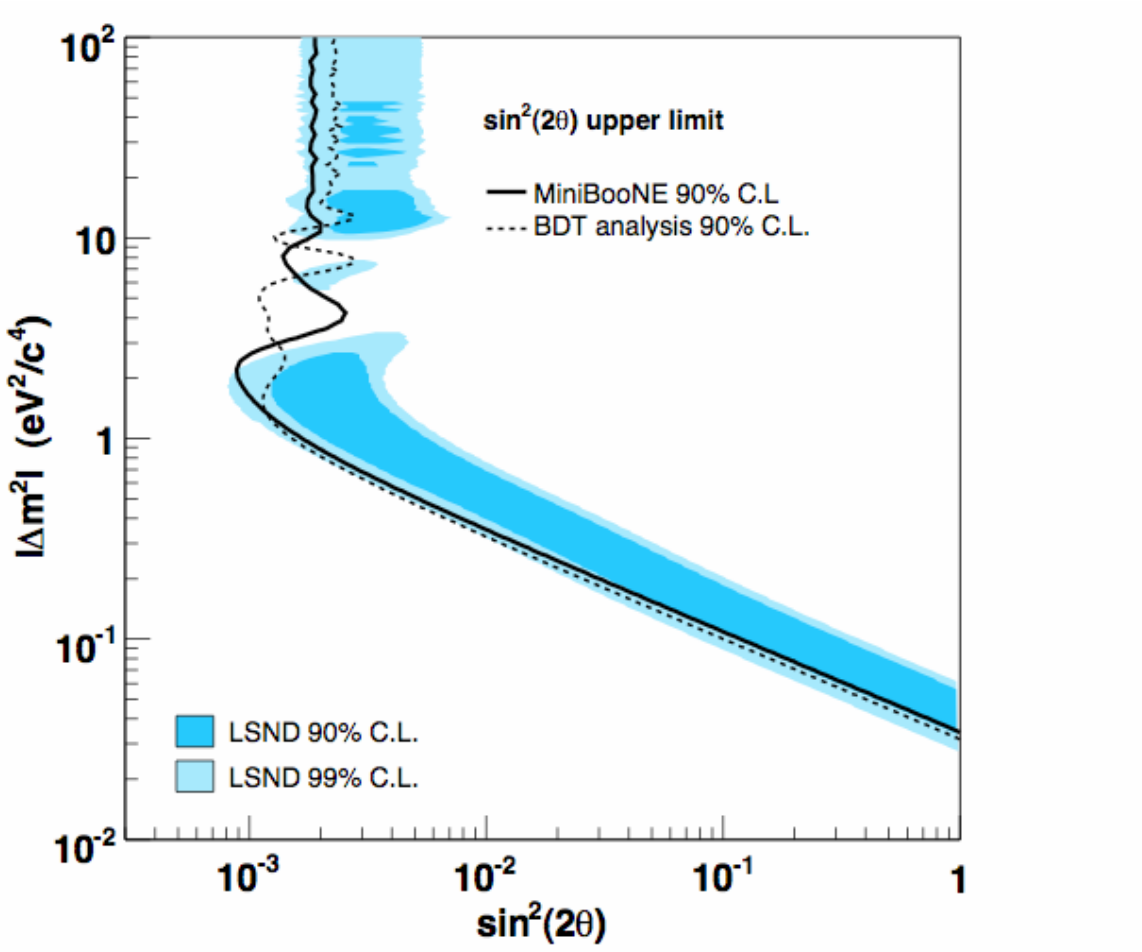
MiniBooNE observes a low-energy excess!

A. A. Aguilar-Arevalo et al., PRL98, 231801 (2007);



Oscillation Limit

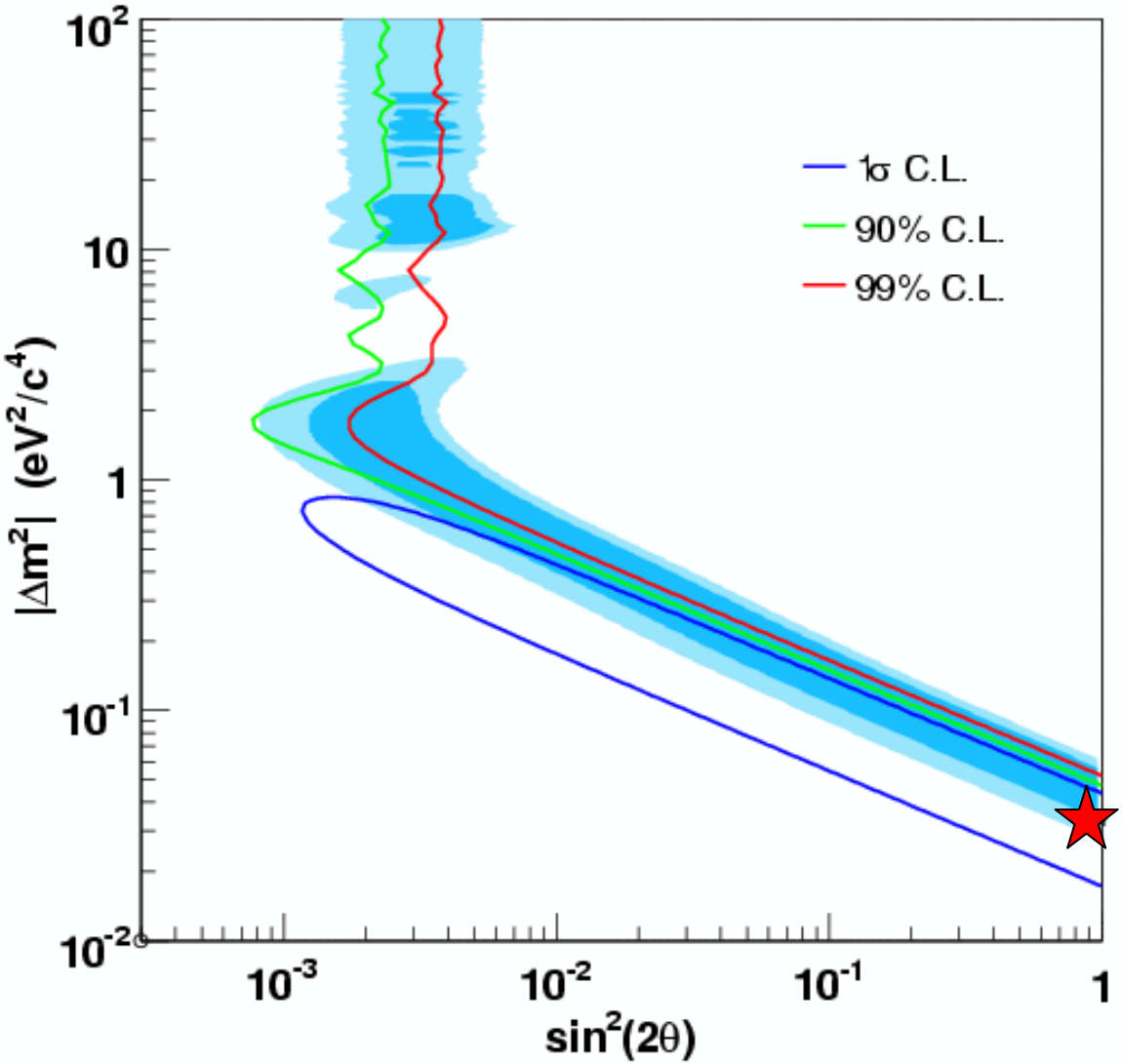
Energy fit: $475 < E_\nu^{QE} < 3000$ MeV



Simple 2-neutrino oscillations excluded at 98% C.L.

Allowed Region

Energy Fit : $300 < E_{\nu}^{QE} < 3000$ MeV



Possible Explanations for the Low-Energy Excess

- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281
- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107
- Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017
- Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009
- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303
- New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

Other data sets (NuMI, <u>antineutrino</u>, SciBooNE) may provide an explanation!