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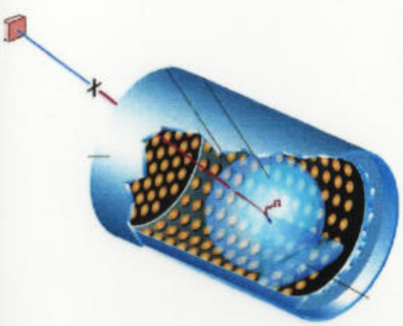
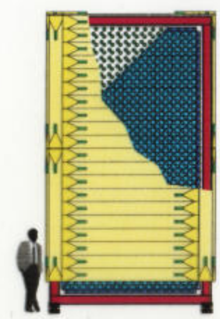
Neutrino 2002 Munich

Final Neutrino Oscillation Results from

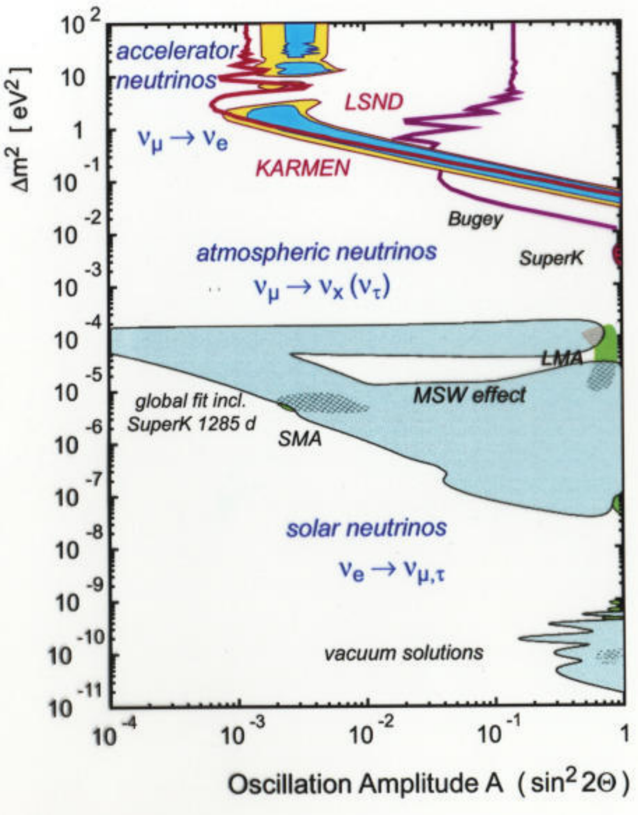


LSND and KARMEN



- I Introduction : SBL accelerator experiments at beam stops
- II LSND : global analysis $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ and $\nu_\mu \rightarrow \nu_e$
- III KARMEN2 : final oscillation results 1997-2001
- IV Common Likelihood Analysis KARMEN2-LSND
- V Conclusion

Status of neutrino oscillations



Implications of a verification of LSND

3 independent Δm^2 scales : sterile neutrino ν_s

2+2

m_4, m_3: $\Delta m^2_{atm.}$ = (1 - 8) x 10^{-3} eV^2

Δm^2_{LSND} = 0.3 ... 2 eV^2

m_2, m_1: $\Delta m^2_{sol.}$ = ~10^{-5} eV^2 MSW

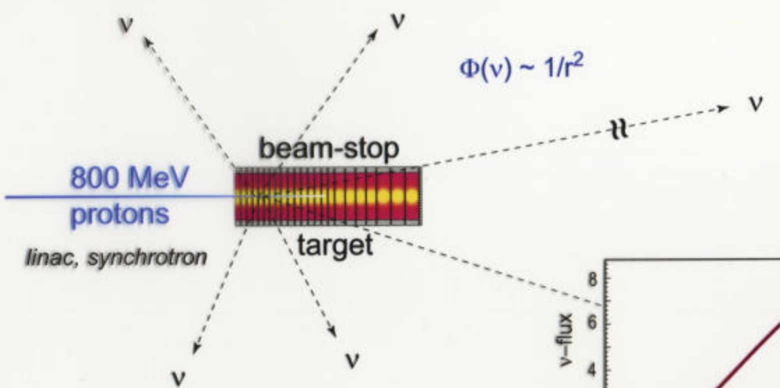
cosmology: neutrino hot dark matter

Σm_ν up to few-eV range (1 m_ν > 0.4 eV)

Ω_ν up to ~ 0.1 νHDM and LSS

astrophysics: r-process nucleosynthesis and oscillations of SN-ν

$\bar{\nu}_\mu$ - $\bar{\nu}_e$ Oscillation Searches at Beam Stop Sources



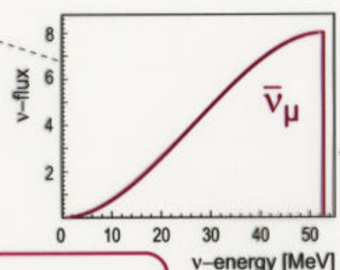
short baseline geometry

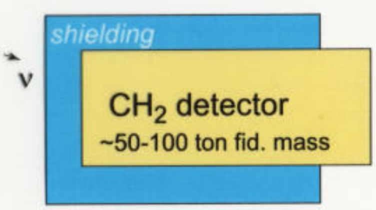
$\langle L_\nu \rangle$ = 15-30 m from target

$\langle E_\nu \rangle$ = 35 MeV

$\langle L_\nu / E_\nu \rangle \sim$ 1 m / MeV

Δm^2 scale ~ 1 eV^2





~10^{30} free protons

decay at rest (DAR)

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

analytical ν-spectra 0-53 MeV

$$\bar{\nu}_\mu \xrightarrow[\text{oscillation}]{\text{flavour}} \bar{\nu}_e + p \to e^+ + n$$

inverse ß-decay off free protons: delayed coincidence signature

π^- and μ^- captured by nuclei

→ small intrinsic $\bar{\nu}_e$ contamination (few x 10^{-4})

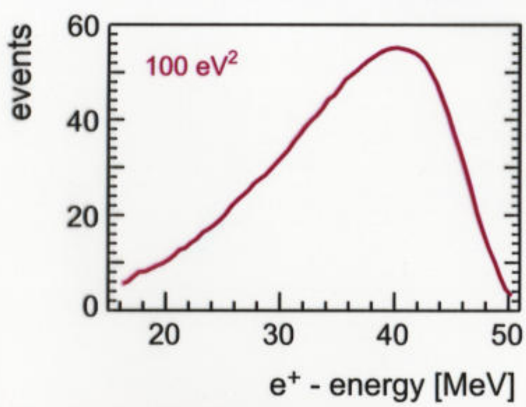
$\bar{\nu}_e$ - *Appearance Searches*

Oscillation Signal

$\bar{\nu}_e + p \rightarrow n + e^+$

Q = -1.8 MeV

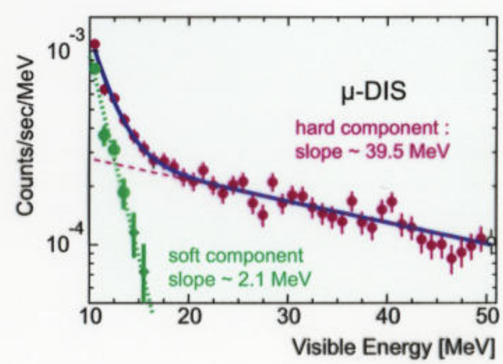
therm. & capt. → $p(n,\gamma)$ 2.2 MeV, $Gd(n,\gamma)$ 7.8 MeV



clear signature (del. coincidence)
point-like ν-target: excl. L/E resolution
s ~10^{-41}cm^2: expect small signal (<100evts)
extr. small contamination, small ν-bg

CR Background Source

μ-induced deep inelastic scattering
in Fe-shielding of experiment
HE- neutrons : recoil proton & n-capture γ

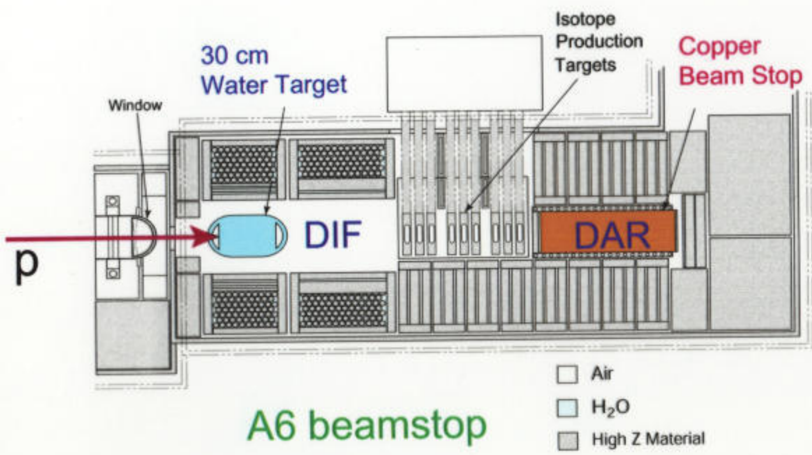


LSND:	KARMEN2:
PID for e^+ and proton	active veto of μ-DIS duty cycle

LAMPF Neutrino Source

1 mA proton beam @ 800 MeV

100 Hz / 600 μs pulses (6% d.c.)



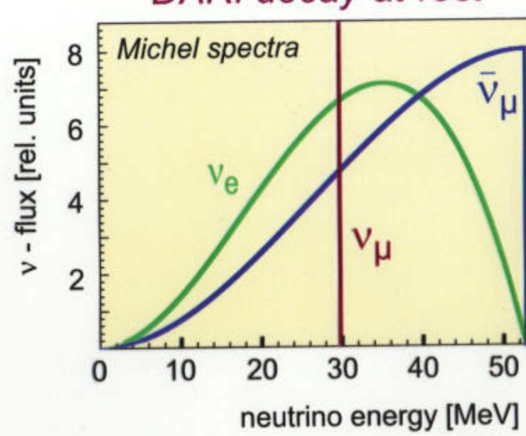
DIF

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

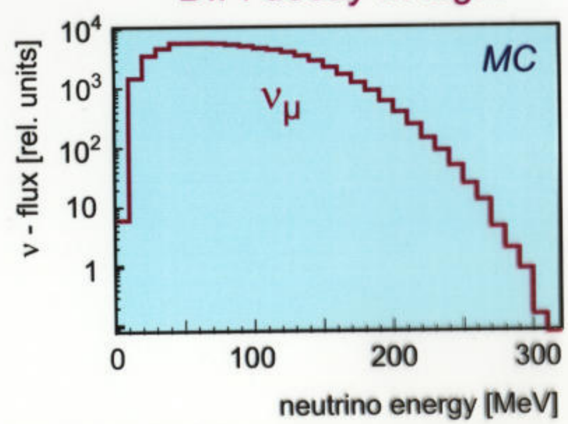
DAR

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

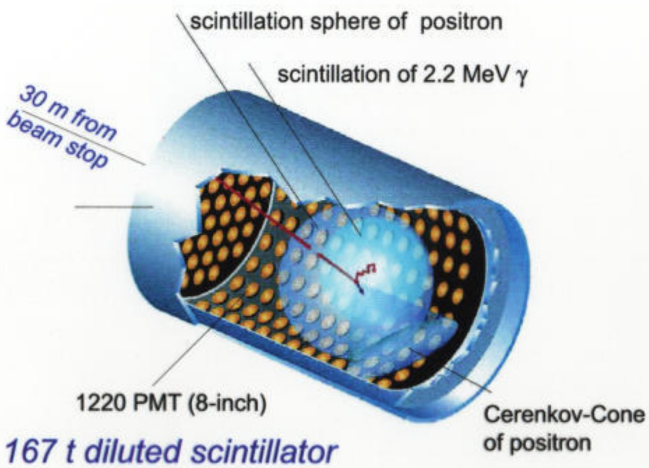
DAR: decay-at-rest



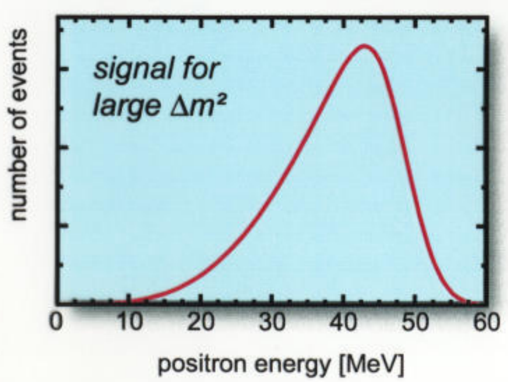
DIF: decay-in-flight



LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance search



167 t diluted scintillator



$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow \; \tau = 186\ \mu s$$
$$p(n,\gamma)d \quad (2.2\ \text{MeV})$$

e^+ identification:

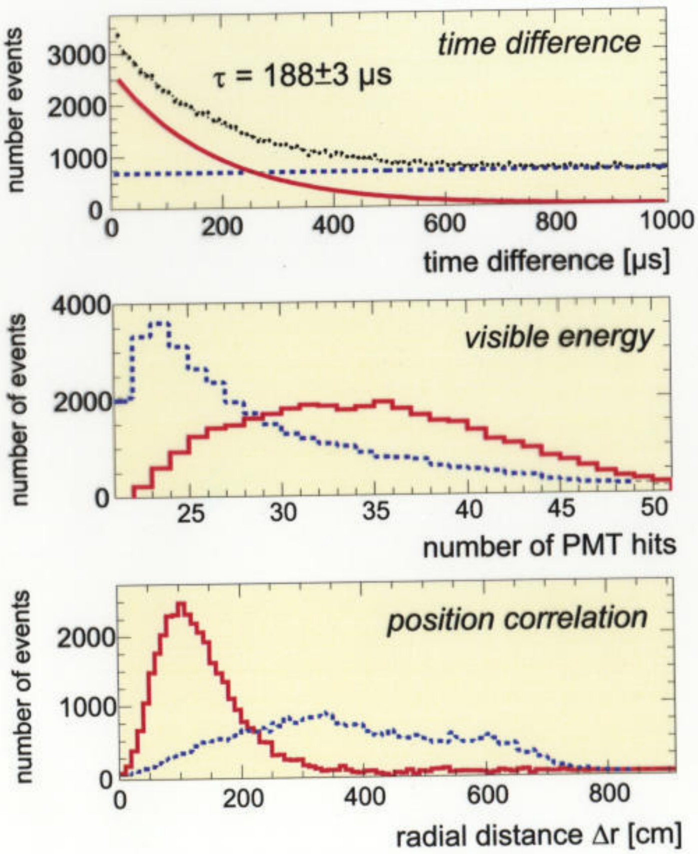
a) check veto activity
discriminate cosmic rays
b) PID: relativistic particle (Cerenk.+scint.)
discriminate neutrons, muons
c) positron energy 20(36)-60 MeV
discriminate ν-nucleus interactions

γ identification:

a) low detector threshold 1 ms after e^+
b) R-parameter distribution
Likelihood Ratio correlated/uncorrelated
use : energy / time / position correl.
discriminate accidentals

LSND : correlated and uncorrelated gammas

n - detection via $p(n,\gamma)d$ with $E_\gamma = 2.2$ MeV



cosmic ray neutron sample:
correlated / *accidentials*

Likelihood function

$L = P(\Delta t) \times P(\#PMT) \times P(\Delta r)$

Likelihood Ratio

R = L(*correlated*) / L(*accidential*)

high R : *correlated*

low R : *accidential*

LSND 1993-98 data - final results

positrons in 20-200 MeV range followed by low-energy (n,γ) candidates

χ^2 fit to R_γ - distribution yields :

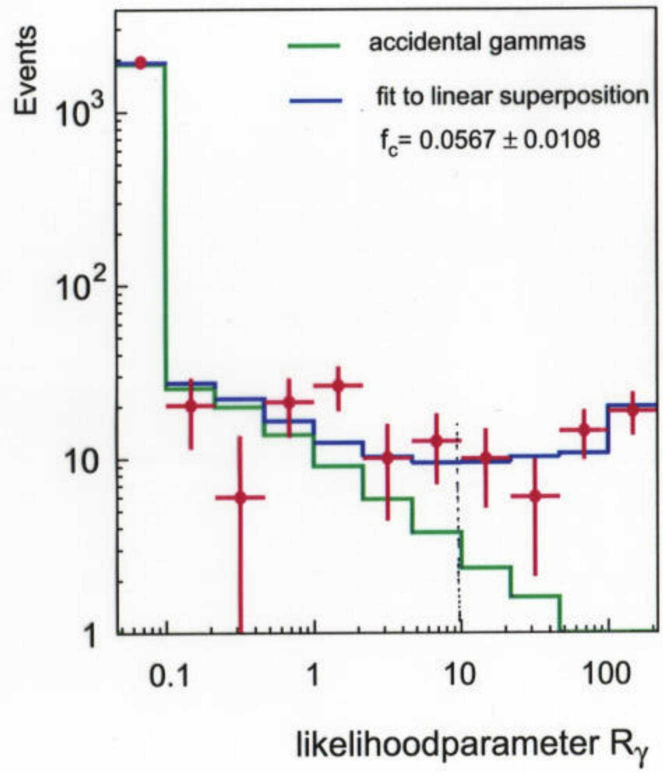
beam on-off excess : 117.9 ± 22.4 evts
DAR ν-background : 19.5 ± 3.9 evts
DIF ν-background : 10.5 ± 4.6 evts

beam excess events $87.9 \pm 22.4 \pm 6.0$
stat. syst.

Oscillation Probability P:

P = (0.264 ± 0.067 ± 0.045) %
stat. syst.

P = $(0.31 \pm 0.12 \pm 0.05)$ % (1993-95 data)



Oscillation Candidates: 'gold plated' sample $R_\gamma > 10$

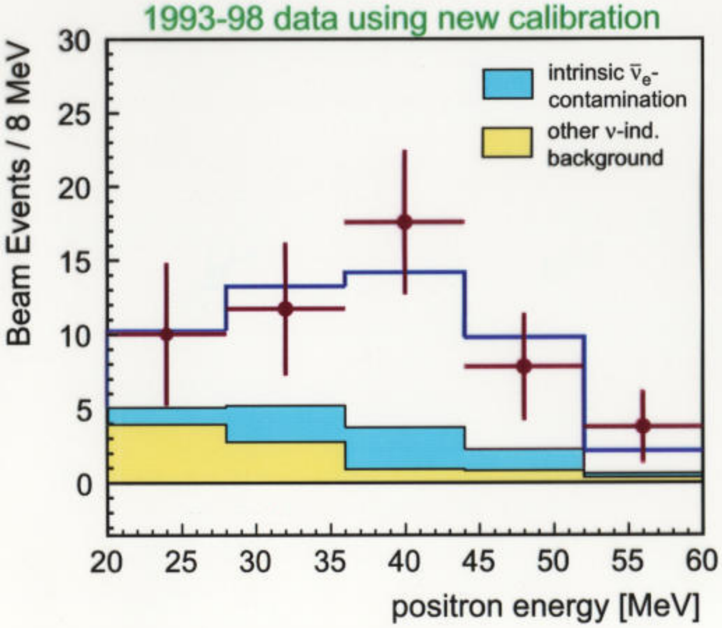
strongly correlated (n,γ) sequence
suppresses background signals

(49.1 ± 9.4) (beam on-beam off) excess

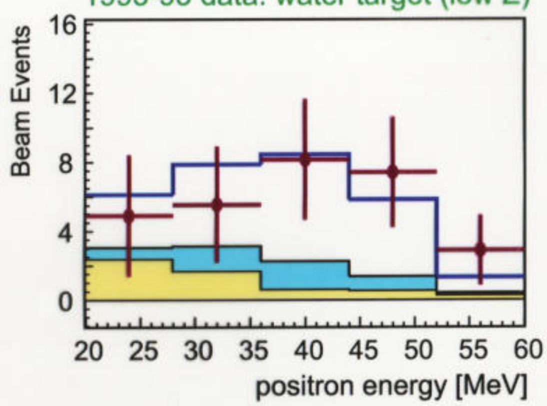
(16.9 ± 2.3) neutrino induced background

(32.2 ± 9.4) event excess (attr. to oscillations)

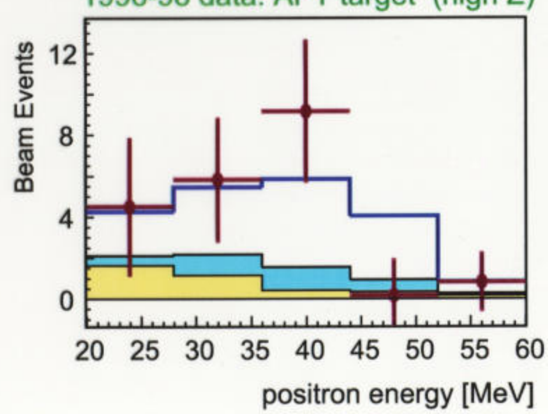
1993-98 data using new calibration



1993-95 data: water target (low Z)



1996-98 data: APT target (high Z)



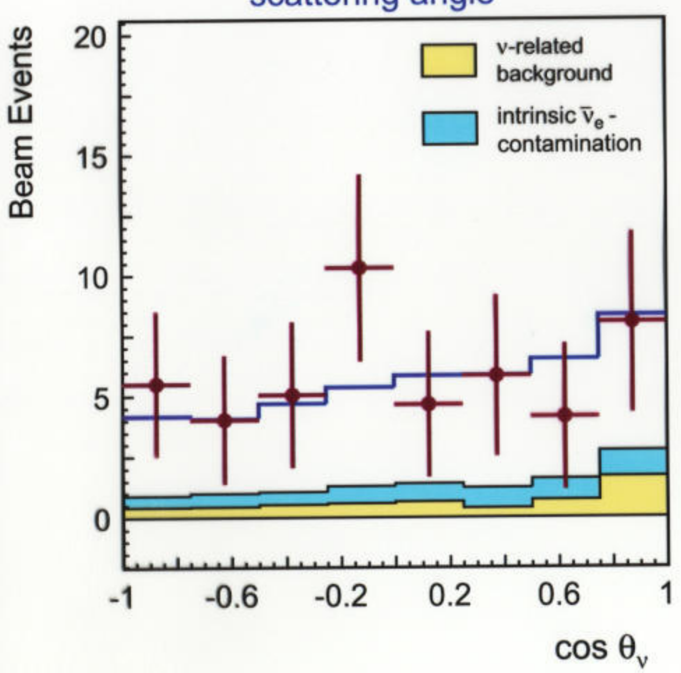
Oscillation Candidates: clean sample $R_\gamma > 10$

further parameters : e^+ scattering angle & L_ν / E_ν distribution

$R_\gamma > 10$, E (e^+) = 36-60 MeV

$\langle \cos\theta_\nu \rangle = 0.04 \pm 0.12$ (expect : 0.12)

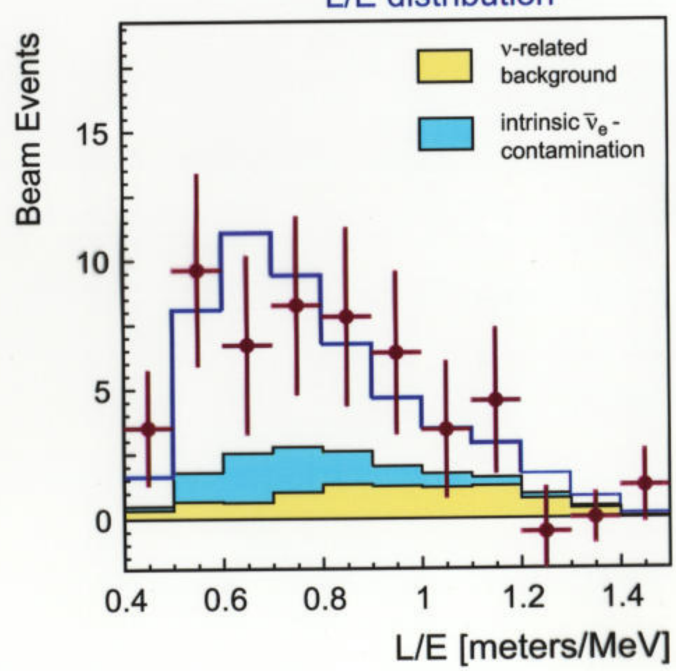
scattering angle



$R_\gamma > 10$, E (e^+) = 20-60 MeV

L/E distribution for low Δm^2

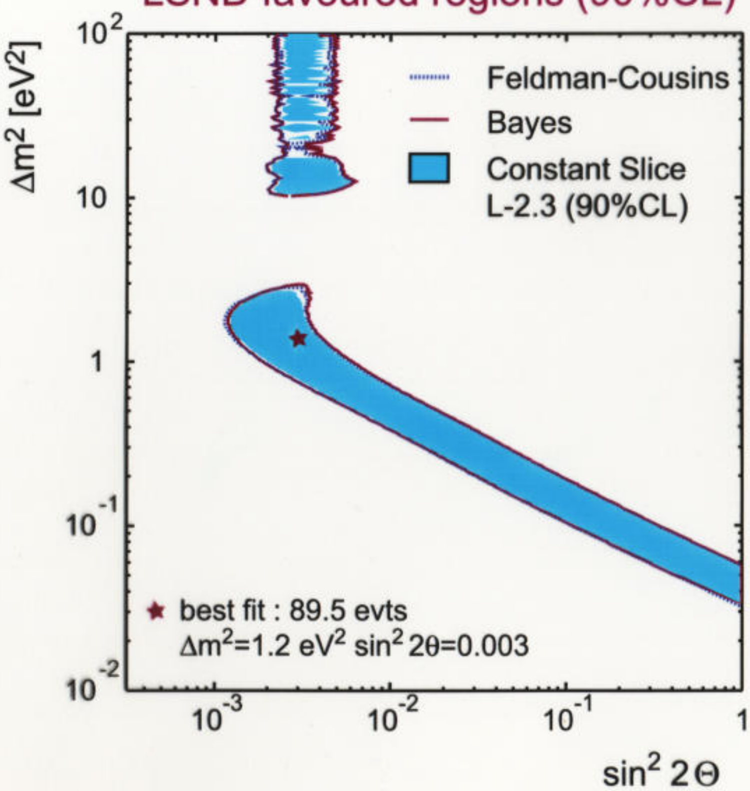
L/E distribution



LSND event based maximum likelihood analysis

A. Aguilar et al. (LSND Collab.), Phys. Rev. **D64** (2001) 112007

LSND favoured regions (90%CL)



5697 candidate events
with 4 fit variables (3600 bins) :

electron energy E_e
scattering angle cos Θ_ν
distance along axis z
likelihood ratio R_γ

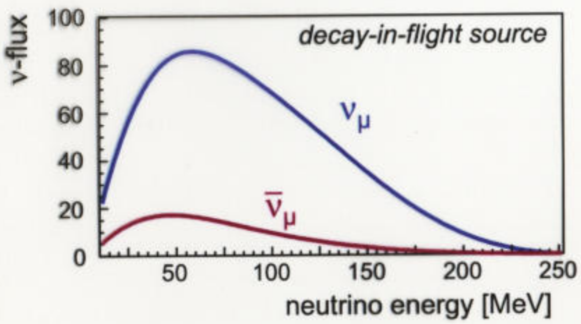
'combined' LSND likelihood
contour for DAR *and* DIF data

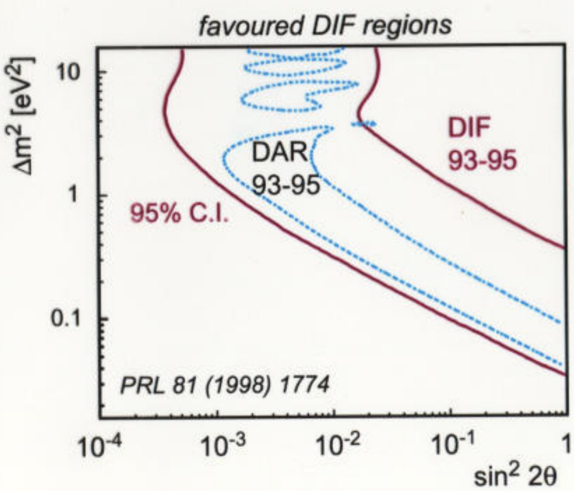
electron energy range : 20-200 MeV

global $\bar{\nu}_\mu$ - $\bar{\nu}_e$ *and* ν_μ - ν_e analysis

Final LSND $\nu_\mu \rightarrow \nu_e$ Oscillation Results

Decay-In-Flight (DIF) Neutrino Analysis





$\nu_\mu \rightarrow \nu_e$ osc. signal range: 60-200 MeV electrons

1993-95 data : maximised acceptance for $\nu_\mu \rightarrow \nu_e$

total osc. excess = (18.1 ± 6.6 ± 4.0) evts

$$P_{osc} = (\,2.6 \pm 1.0 \pm 0.5\,) \times 10^{-3}$$

1993-98 data : optimised acceptance for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

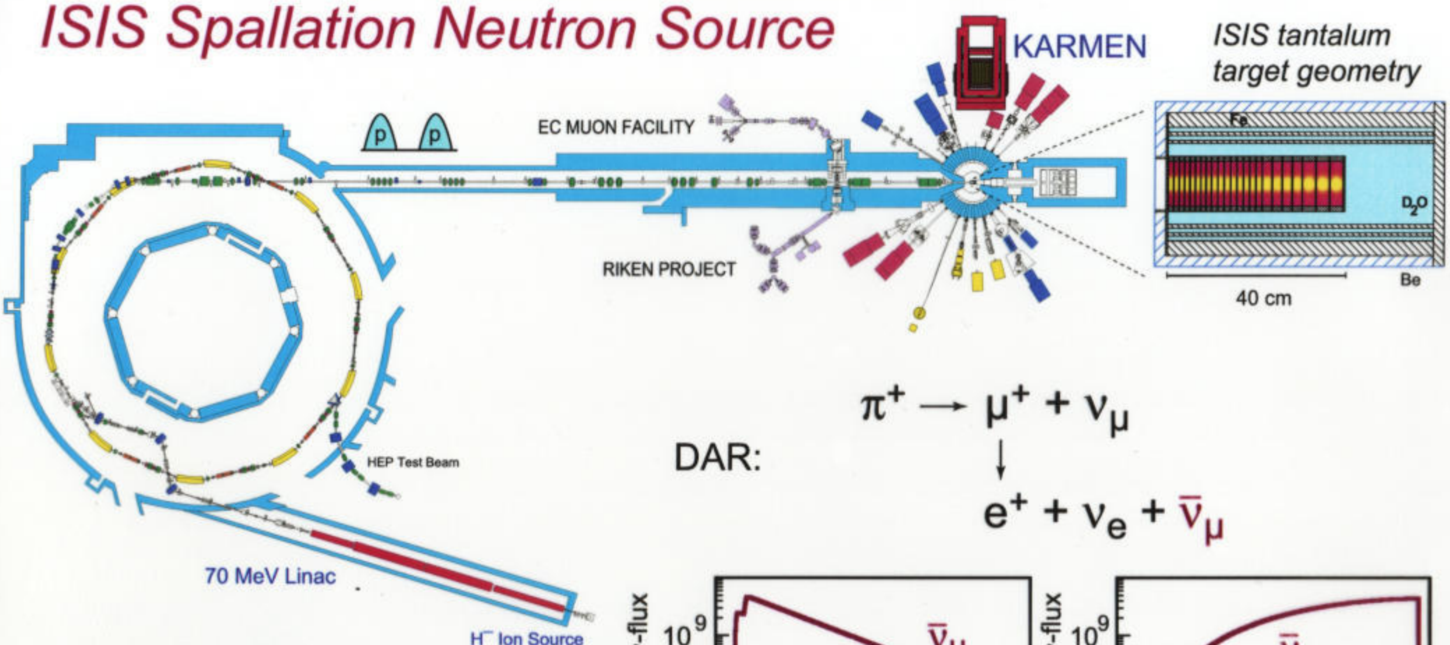
total osc. excess = (8.1 ± 12.2 ± 1.7) evts

$$P_{osc} = (\,1.0 \pm 1.6 \pm 0.4\,) \times 10^{-3}$$

no stat. significant DIF oscillation signal

DAR expectation
- large Δm^2 $P_{osc} = 2.6 \times 10^{-3}$
- small Δm^2 $P_{osc} = 0.5 \times 10^{-3}$

ISIS Spallation Neutron Source



DAR: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\quad\quad\quad\quad\quad\downarrow$

$\quad\quad\quad\quad\quad e^+ + \nu_e + \bar{\nu}_\mu$

ISIS rapid cycling synchrotron

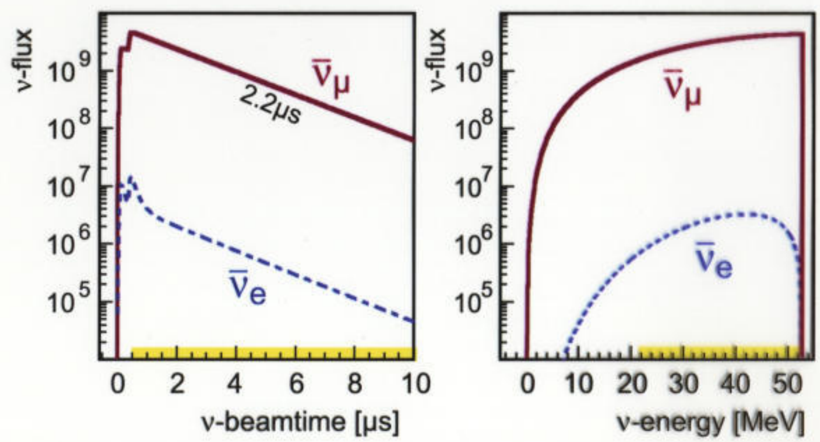
800 MeV protons

200 μA current

50 Hz extraction

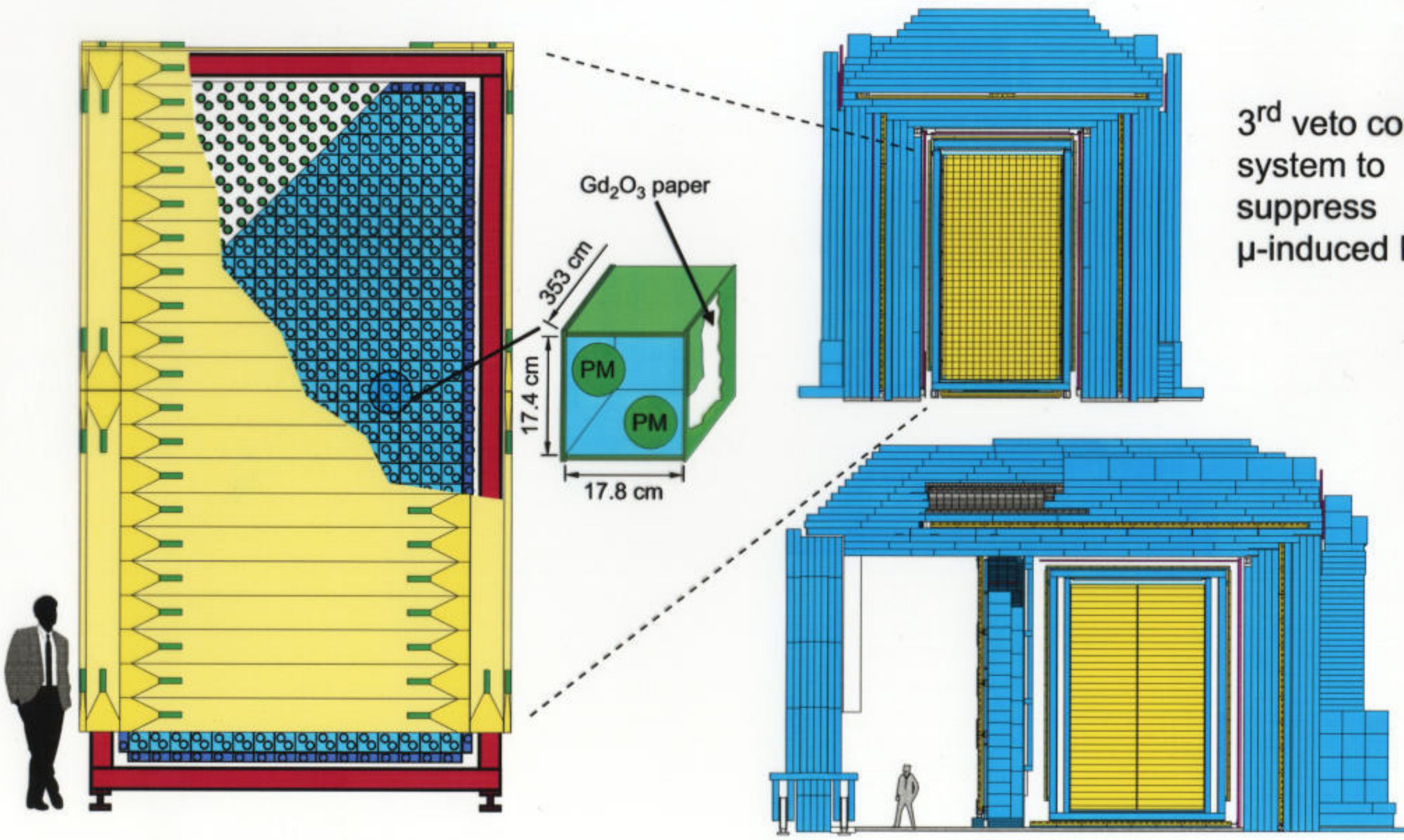
10^{-5} duty cycle

6.4×10^{-4} $\bar{\nu}_e$ contamination

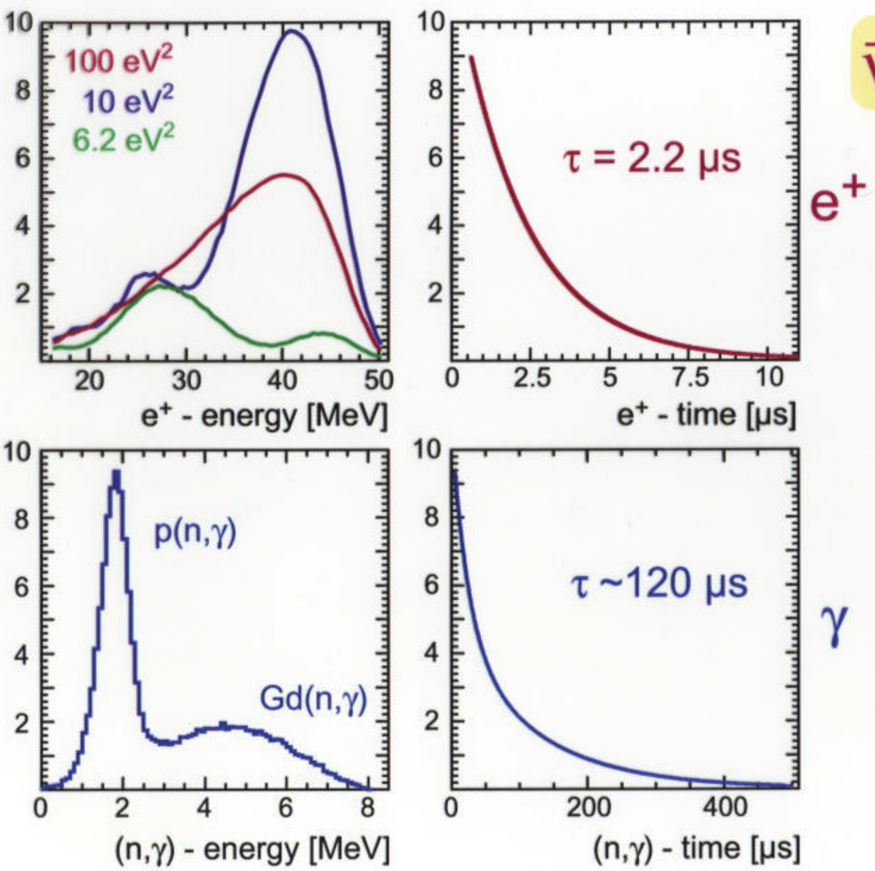


KARMEN liquid scintillation calorimeter

56 to. scintillator $(5.6 \times 3.2 \times 3.5)\,m^3$ $\Delta E/E = 11.5\%\sqrt{E(MeV)}$



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ *oscillation signature*



$\bar{\nu}_e + p \rightarrow n + e^+$

Q = -1.8 MeV

therm. + capt.

→ Gd(n,γ)

$\Sigma E_\gamma = 8$ MeV

→ p(n, γ)

$E_\gamma = 2.2$ MeV

spatially correlated
delayed coincidence

$\langle\sigma\rangle = 0.93 \times 10^{-40}$ cm^2

KARMEN2 Neutrino Oscillation Search

measuring period : 2/97 - 2/02 (9.425 C p.o.t.) ν- flux : 2.71 x 10^{21} $\bar{\nu}_\mu$

main feature:
μ-ind. HE neutrons suppressed by veto, enhanced n-detection efficiency

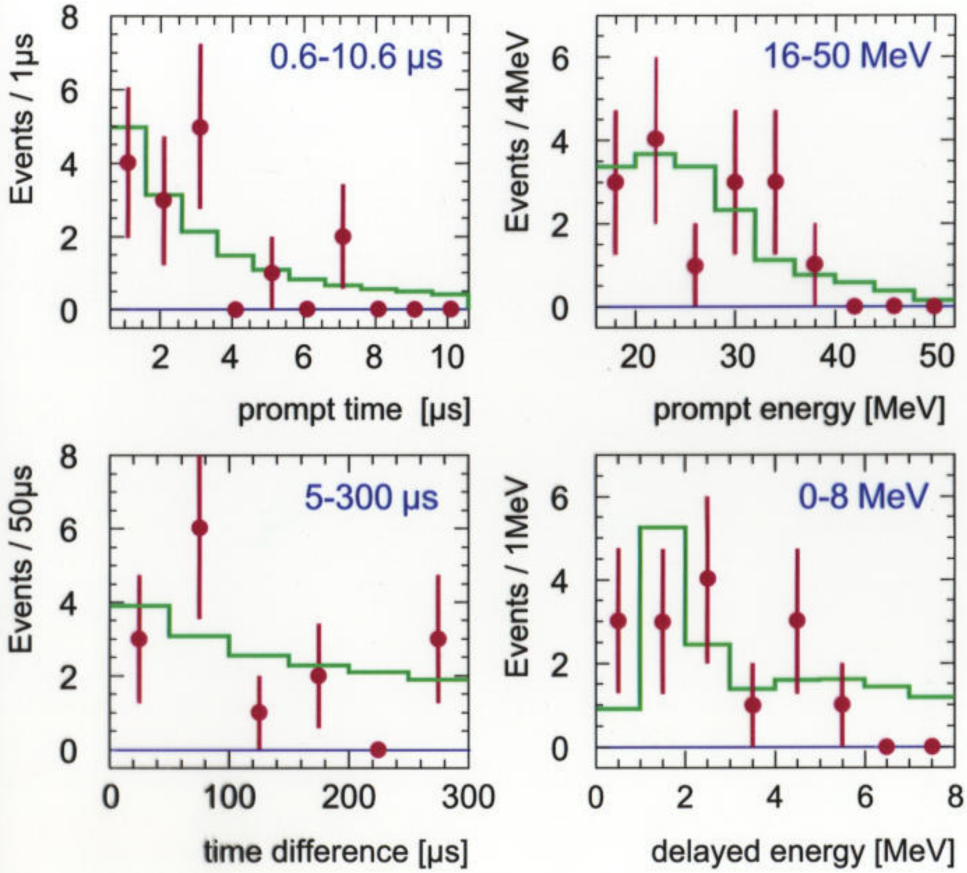
data analysis - I : single events — 3.7 x 10^9 evts

- *no prompt activity in 2 inner vetos*
  skip events with module hit spread > 40 ns
- *no previous activity :*
  up to 24 μs : central detector, 2 inner vetos
  up to 17 μs : new outer veto counter system
- *no prompt activity in outer veto counter*

data analysis - II : coincidences — 3464 evts

- *require spatially correlated (1.5m³) coincidence*
- *MC optimised cuts for prompt and delayed event* → *final event ensemble*

final KARMEN2 candidate event ensemble



15 candidate events

(15.8 ± 0.5) background events are expected

cosmic background : 3.9 ± 0.2 evts

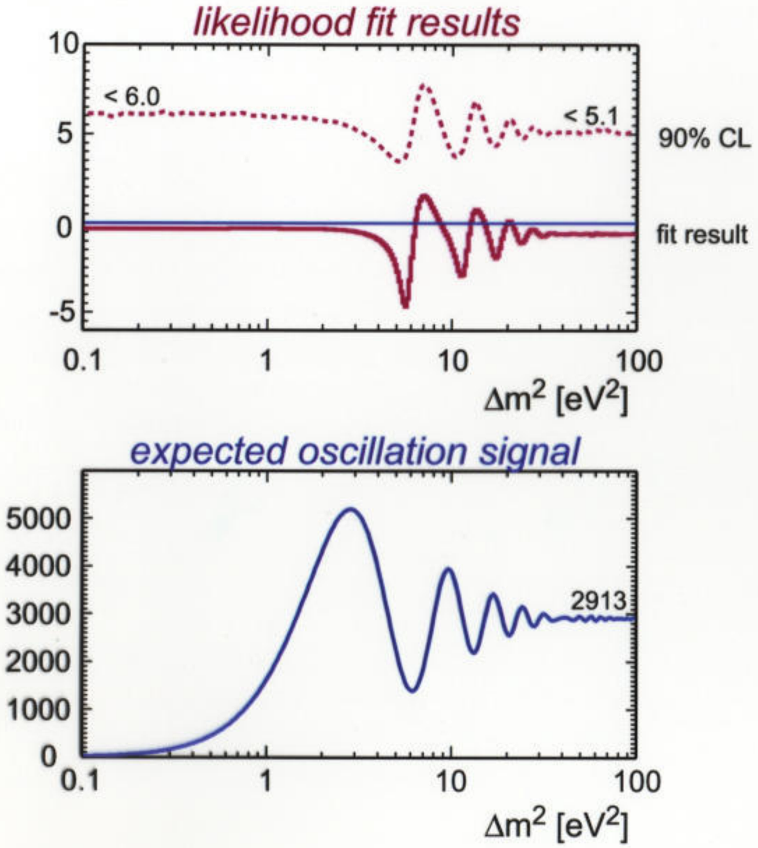
ν_e-induc. excl. CC : 5.1 ± 0.2 evts

ν_e-ind. CC & rand. γ : 4.8 ± 0.3 evts

intrin. contamination : 2.0 ± 0.2 evts

no oscillation excess

KARMEN2 : event based maximum likelihood analysis



5 parameter likelihood fit :

$E(e^+)$ $t(e^+)$ $E(\gamma)$ $\Delta t(\gamma)$ $\Delta x(e^+,\gamma)$

+ poisson distributed background

with expectation (15.8 ± 0.5) evts

fit in excl. agreement with

null hypothesis: no oscillations

LSND expectation :

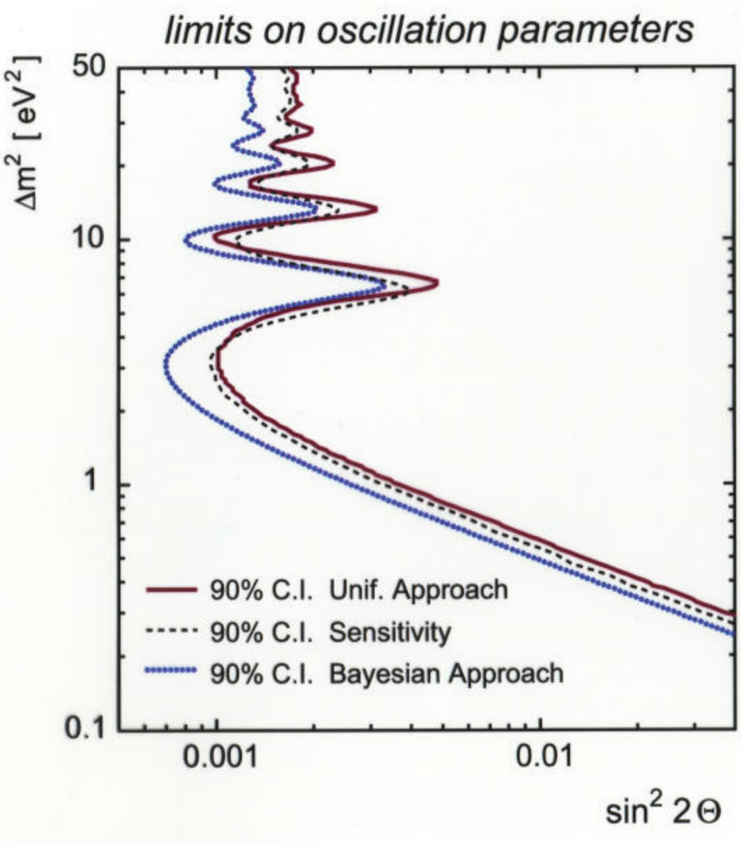
small Δm^2 : 3 - 14 events

large Δm^2 : 7 - 13 events

confidence intervals :

unified (frequentist) approach

KARMEN2: Frequentist Limit and Sensitivity & Bayesian Limit



unified (frequentist) approach :
(Feldman-Cousins)

90% C.I. limits :

$\sin^2 2\theta < 1.7 \times 10^{-3}$ *large Δm^2*

$\Delta m^2 < 0.055$ eV^2 *$\sin^2 2\theta = 1$*

sensitivity :

$\sin^2 2\theta < 1.6 \times 10^{-3}$ *large Δm^2*

limit and sensitivity almost identical !

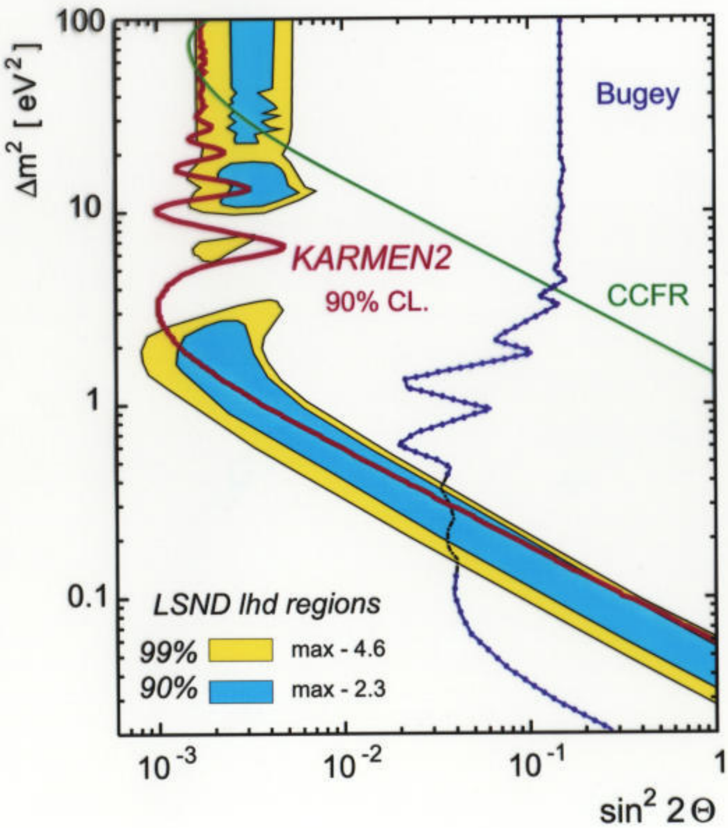
Bayesian approach

90% C.I. limit :

$\sin^2 2\theta < 1.3 \times 10^{-3}$ (90% CL.)

use uniform prior in logarithmic metric of oscillation parameters

Final KARMEN2 limit and final LSND regions



4y KARMEN2 data taking 2/97 - 2/02

unified (frequentist) approach
Feldman-Cousins

oscillation limit :

$\sin^2 2\theta < 1.7 \times 10^{-3}$ (90% CL.)

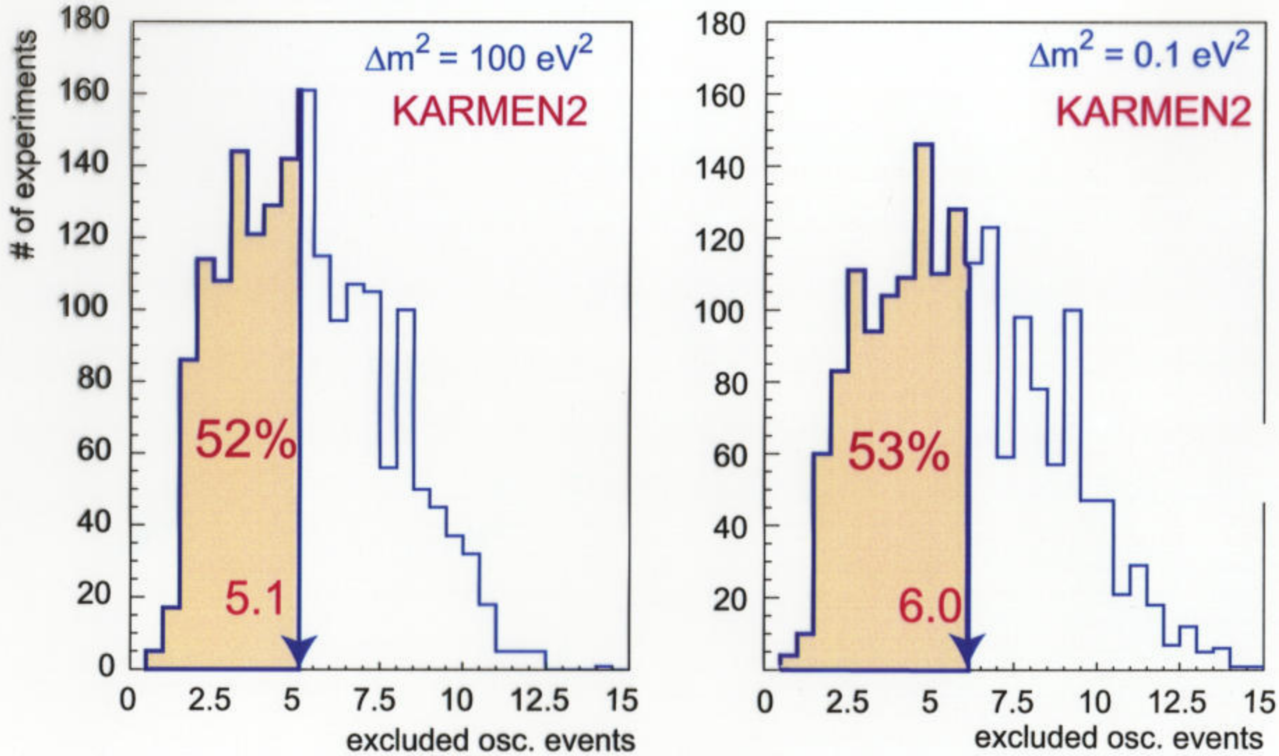
large Δm^2

oscillation sensitivity :

$\sin^2 2\theta < 1.6 \times 10^{-3}$ (90% CL.)

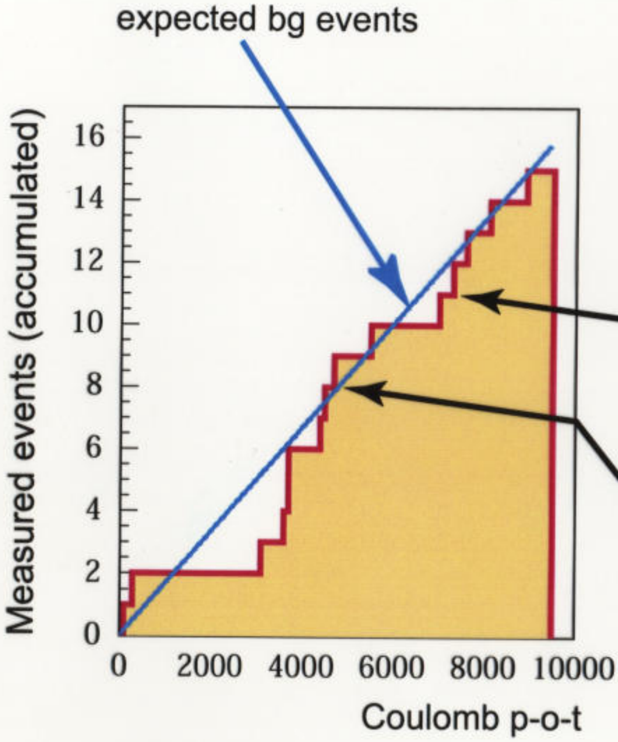
KARMEN2 excludes a significant part of the LSND parameter space

Sensitivity



2000 K2 samples with <15.8> background events, no signal created by MC and analysed with max. lhd. analysis

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



Feb.´97 through March 2001
K2 total: 9425 Coulombs p-o-t
15 events with 15.8 bg expected
$\sin^2 2\Theta < 1.7 \times 10^{-3}$ (large Δm^2)
sensitivity: $\sin^2 2\Theta = 1.6 \times 10^{-3}$ (large Δm^2)

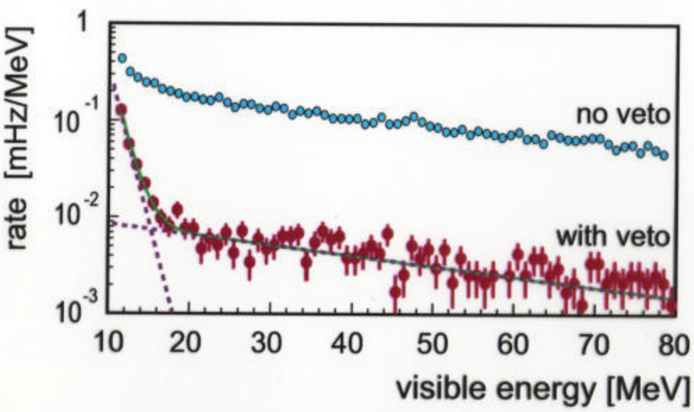
Feb.´97 through March 2000
11 events with 12.3 bg expected
$\sin^2 2\Theta < 1.3 \times 10^{-3}$ (large Δm^2)
sensitivity: $\sin^2 2\Theta = 1.8 \times 10^{-3}$ (large Δm^2)

Feb.´97 through February 1999
8 events with 7.8 bg expected
$\sin^2 2\Theta < 2.1 \times 10^{-3}$ (large Δm^2)
sensitivity: $\sin^2 2\Theta = 2.3 \times 10^{-3}$ (large Δm^2)

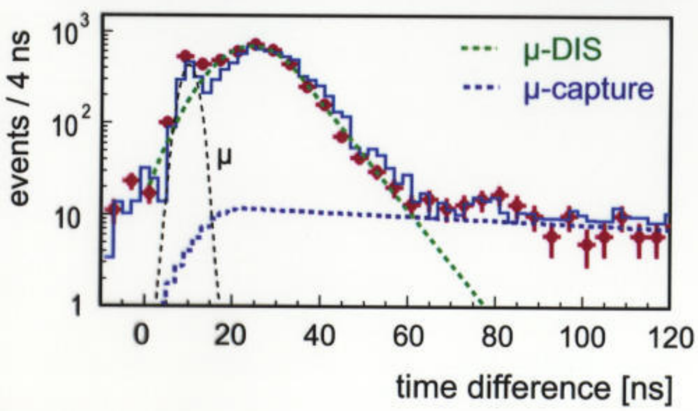
limits from likelihood analysis using spectral event information
sensitivity based on unified frequentist approach

suppression of μ-induced DIS with active veto

bg rate without & with veto-information



Time Of Flight distribution of HE neutrons



$$\mu^{\pm} + {}^{56}\mathrm{Fe} \rightarrow \mu^{\pm} + {}^{56\text{-}x\cdot n}\mathrm{X} + x\cdot n$$

background reduction factor for energy range 20-60 MeV

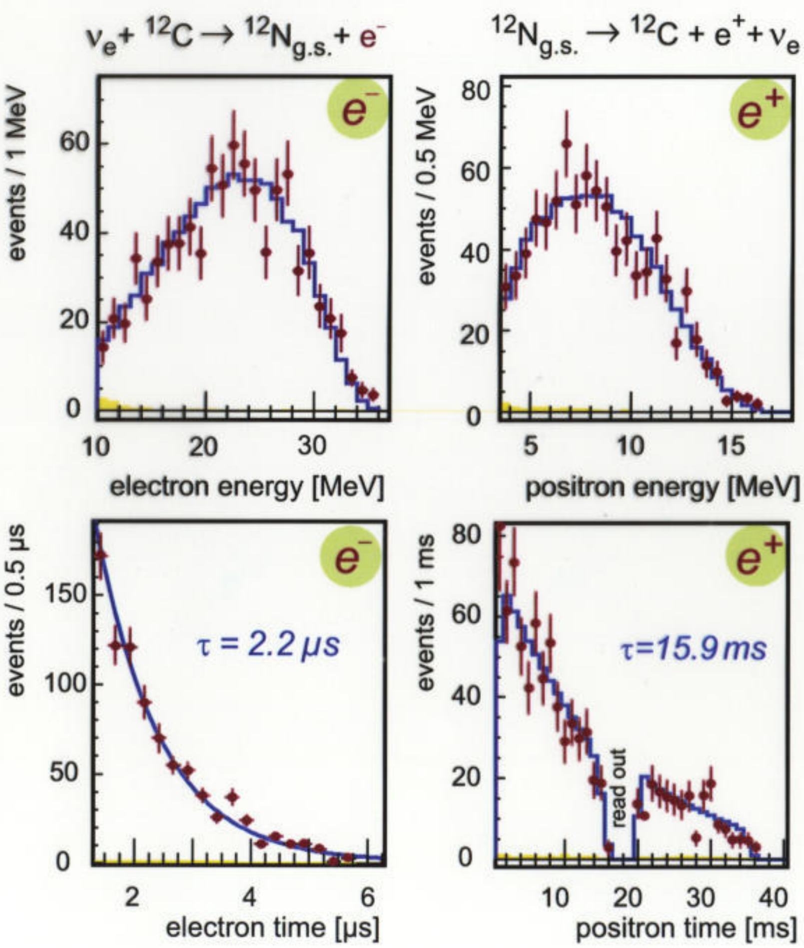
R = 35.3

final cosmic ray bg rate

R = (0.20 ± 0.20) mHz

cosmic ray induced bg smaller than ν-ind. bg

Exclusive Charged Current $^{12}C(\nu_e,e^-)^{12}N_{g.s.}$



global data set KARMEN1&2
June 1990 - Febr. 2001

18.547 C protons-on-target

870 exclusive CC events

17.5 ± 1.4 cosmic bg

S/B = 50 : 1

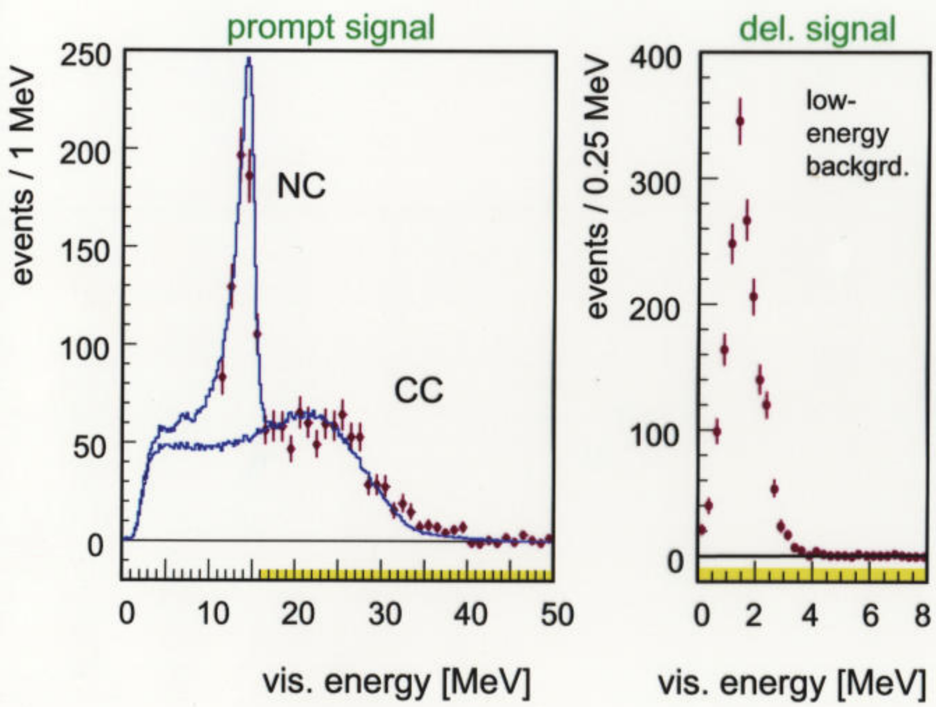
$\langle\sigma\rangle = (9.5 \pm 0.3_{stat.} \pm 0.8_{syst.}) \times 10^{-42}\ cm^2$

LSND: $\langle\sigma\rangle = (8.9 \pm 0.3 \pm 0.9) \times 10^{-42}\ cm^2$

theory: $(8.9 - 9.4) \times 10^{-42}\ cm^2$

KARMEN2: Oscillation Backgrounds

CC/NC neutrino reactions with random coincidence

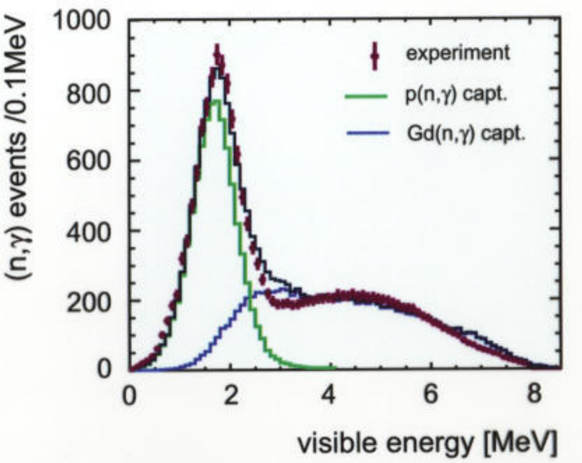


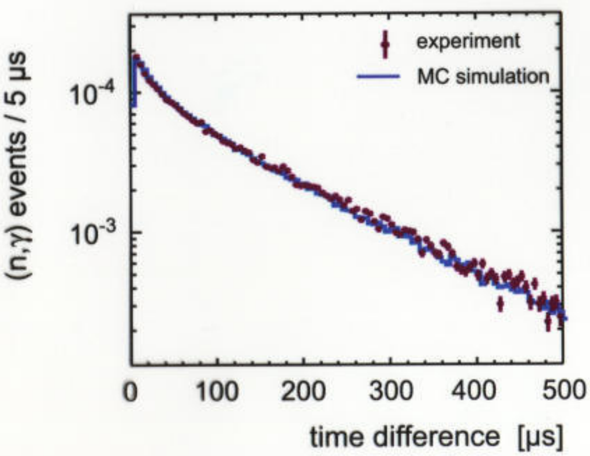
11-50 MeV energy interval :
1567 ν-ind. interactions

Probabilty P
for random coincidence
in 5-300 μs and V=1.3 m^3

$P = (5.5 \pm 0.4) \times 10^{-3}$

KARMEN2 : neutron detection

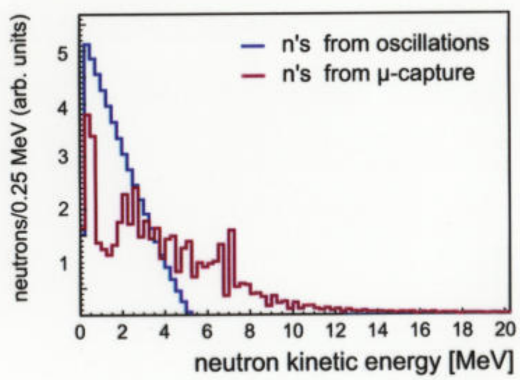




neutron detection efficiency $\varepsilon(n)$

use nuclear capture of stopped cosmic μ^-

$$\mu^- + {}^{12}C \rightarrow {}^{11}B + n + \nu_\mu$$



$$\varepsilon(n) = 0.42 \pm 0.05$$

Compatibility Analysis LSND - KARMEN2

- Q: level of statistical compatibility, if both results are correct
- frequently used A: region of statistical compatibility is
  LSND region left of 90%CL. KARMEN2 exclusion

  straightforward, but misleading!
- can do much better :
  use full experimental information (likelihood function)
- need full access to primary experimental data (open resources)
- LSND-KARMEN2 analysis showcase for other areas
  such as $0\nu\beta\beta$, dark matter, Higgs searches, ...

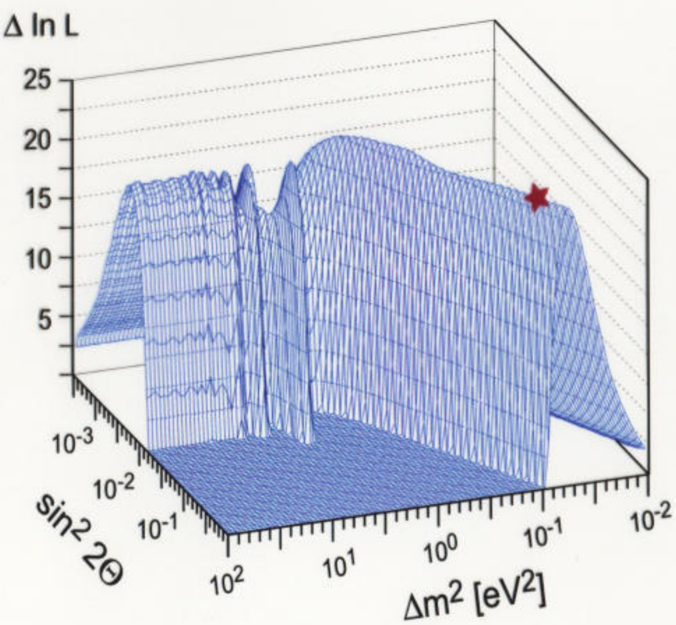
for details see :

E.D. Church, K. Eitel, G.B. Mills, M. Steidl, hep-ex/0203023, acc. for publ. in PRD
K. Eitel, New Jour. Phys. 2 (2000) 1.1
Poster by K. Eitel and M. Steidl on tuesday

Comparison of Likelihood Contours

LSND evidence

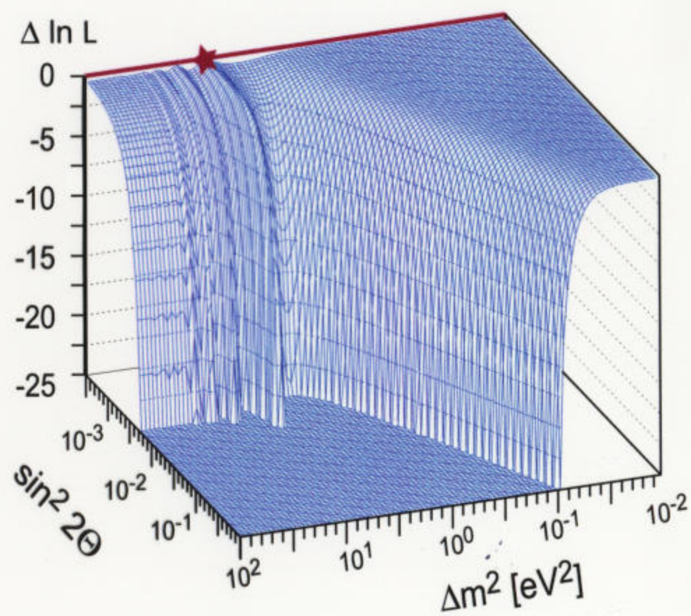
$\Delta \ln L_{max} = 23.5$ (66.7 events)



$\Delta m^2 = 0.055\ eV^2\ \sin^2 2\Theta = 0.85$

KARMEN2 exclusion

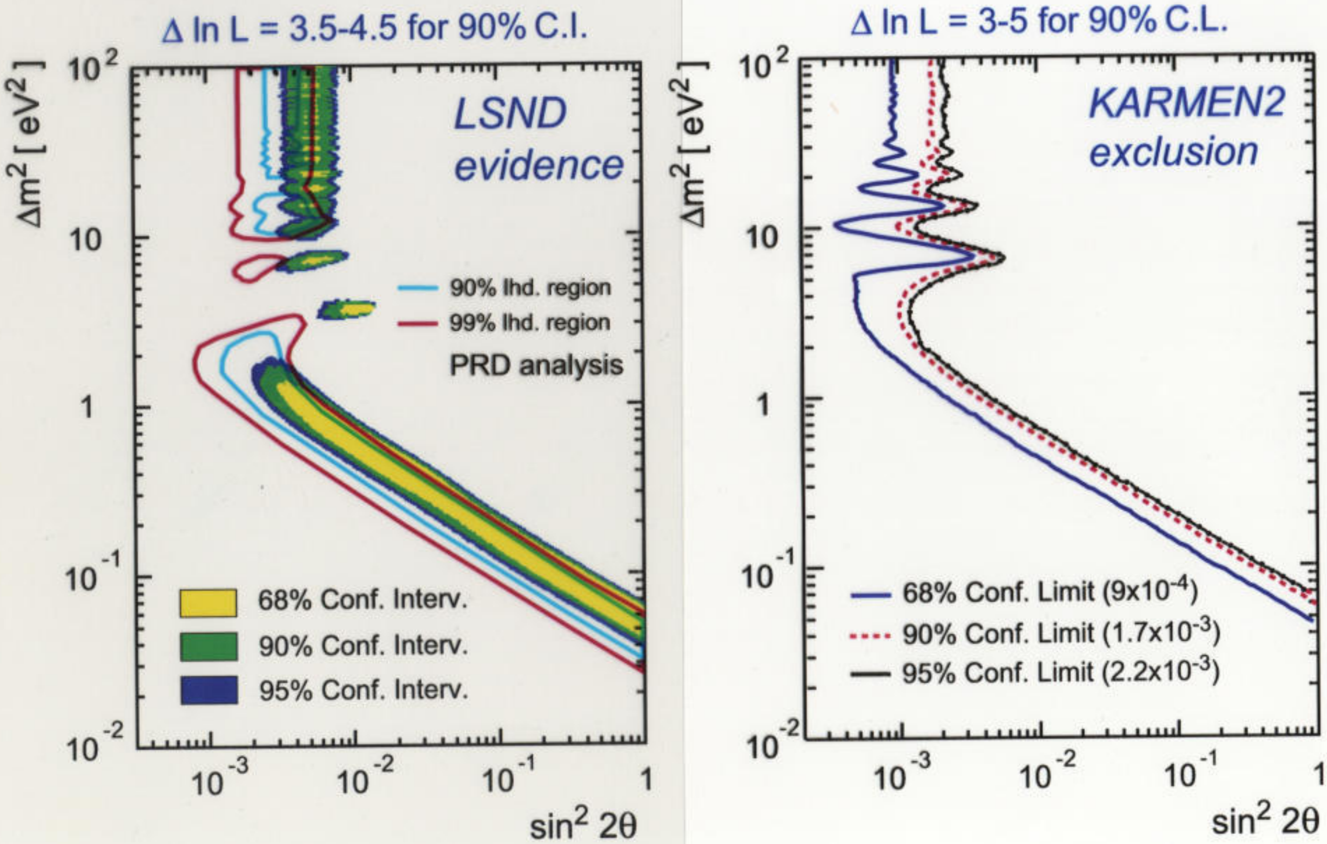
$\Delta \ln L_{max}$ at boundary: no oscil. signal



$\sin^2 2\Theta = 0.0$ (no oscillations)

LSND and KARMEN2 Confidence Intervals/Limits

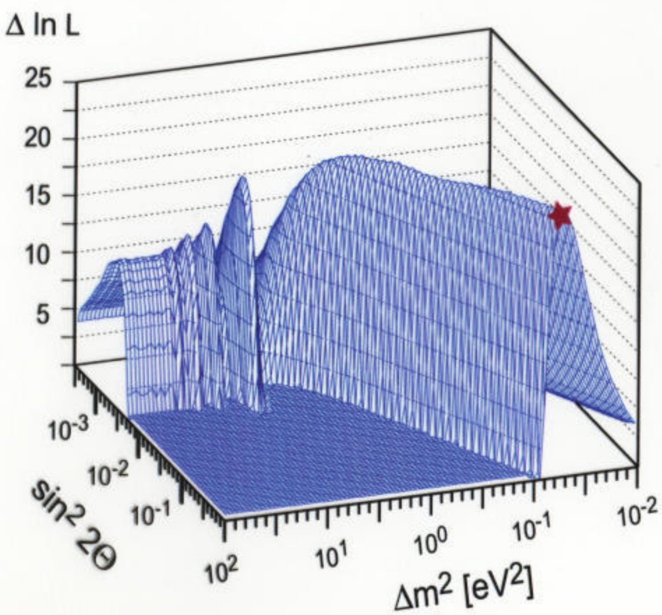
regions based on unified frequentist approach of Feldman/Cousins



Compatibility Analysis of LSND and KARMEN2

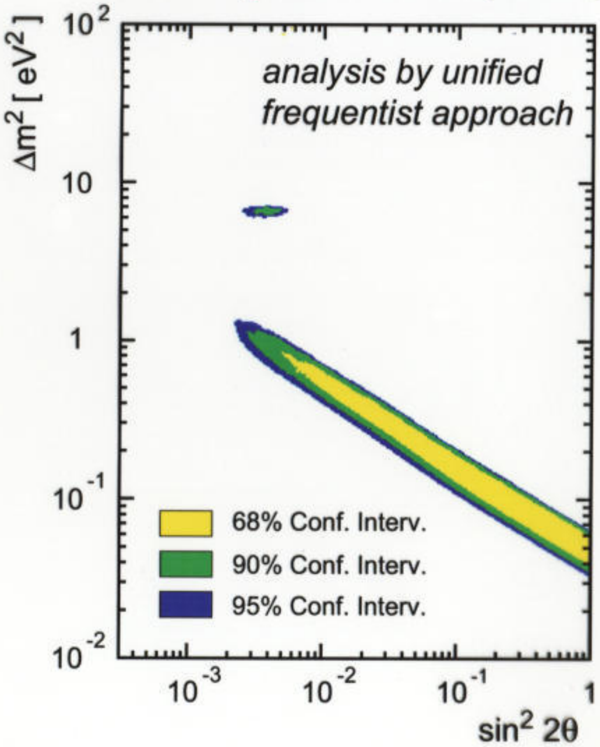
based on full experimental information from likelihood functions

Combined Likelihood Function
LSND-KARMEN2 : add ln L



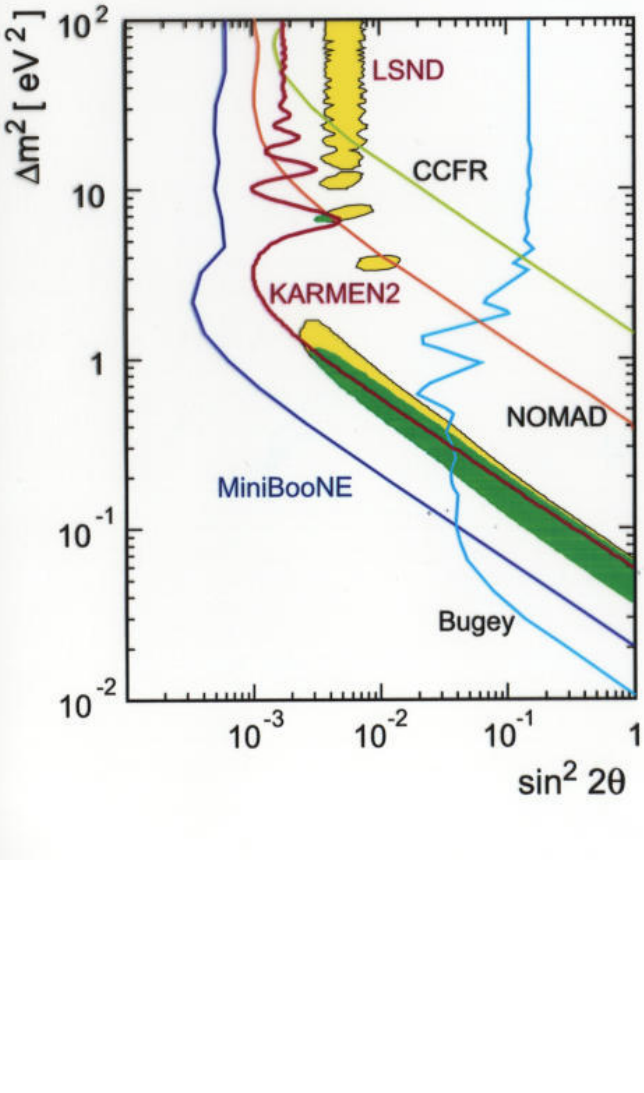
shape for high Δm^2-values significantly modified

combined confidence regions
assuming statistical compatibility



Conclusions

final oscillation results from LSND and KARMEN2 published
and compatibility analysis submitted for publication



LSND (1993-98)

combined DAR & DIF analysis (new reconstr.)
$87.9 \pm 22.4 \pm 6.0$ *beam excess* events
$P = (0.264 \pm 0.067 \pm 0.045)\%$

KARMEN2 (1997-01)

final DAR oscillation analysis 4y of data
15 evts. $\leftrightarrow$ (15.8 ± 0.5) bg expect. *no excess*
$\sin^2 2\theta < 1.7 \times 10^{-3}$, most stringent limit so far

LSND & KARMEN2

detailed statistical analysis using full inform.
incompatibility at individual 60% Confid. Levels
areas of stat. compatibility only at $\Delta m^2 < 1$ eV^2
L-number violating μ-decays excluded

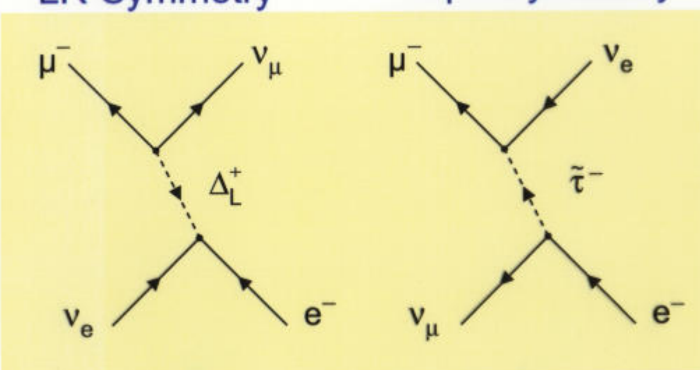
Comparison of LSND and KARMEN2

	LSND (93-98)	*KARMEN2 (97-01)*
proton charge	28.896 C	9.425 C
beam current / pulse	1 mA / 600 μs	200 μA / 0.5 μs
neutrino flux	$1.2 \times 10^{22}\ \bar{\nu}_\mu$	$2.71 \times 10^{21}\ \bar{\nu}_\mu$
intrinsic $\bar{\nu}_e$ contam.	$\sim 8 \times 10^{-4}$	6.4×10^{-4}
detector distance	30 m	17.6 m
fid. detector mass	85 to.	50 to.
bg-suppression	PID (R_γ -likelihood)	duty cycle, veto μ-DIS
osc. detect. efficiency	0.42 ± 0.03	0.192 ± 0.015
max. mixing signal	16.650 evts	2.913 evts
bg-expectation	5.474 evts	15.8 evts
beam-on signal	5.697 evts	15 evts

LSND beam excess and LF-number violation

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

LR-Symmetry SuperSymmetry



LR-symmetric models (P. Herczeg, R. Mohapatra):

LF-violating μ^+ decays: $R \sim 4 \dfrac{|G_+|^2}{|G_F|^2}$ => $|G_+| < 0.014\, G_F$

$M\overline{M}$-conversion: $G_{++} < 0.003\, G_F$ (90% C.L.)

Willmann et al., Phys.Rev.Lett. 82(1999)49

$$R = \frac{\Gamma(\mu^+ \to e^+ \nu_\mu \bar{\nu}_e)}{\Gamma(\mu^+ \to e^+ \bar{\nu}_\mu \nu_e)}$$

preliminary comparison

LSND:

$R = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$

KARMEN2:

$R < 0.85 \times 10^{-3}$ (90% C.L.)

LF-violating μ-decay unlikely source of LSND beam excess

see also hep-ph/0204236
K. Babu & S. Pakvasa

Comparison of LSND and KARMEN2

	LSND (93-98)	*KARMEN2 (97-01)*
proton charge	28.896 C	9.425 C
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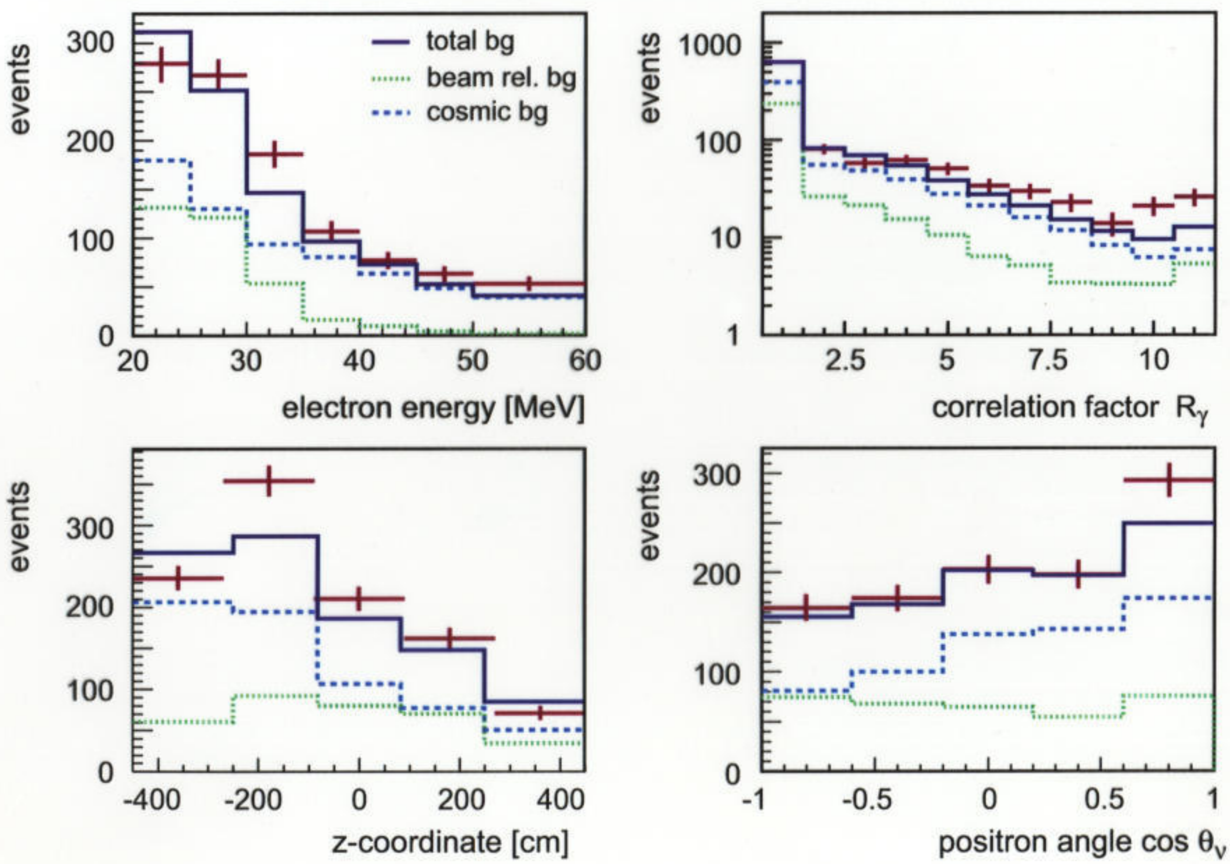
intrinsic $\bar{\nu}_e$ contam.	$\sim 8 \times 10^{-4}$	6.4×10^{-4}
detector distance	30 m	17.6 m
fid. detector mass	85 to.	50 to.
bg-suppression	PID & $R\gamma > 10$	duty cycle, veto μ-DIS
osc. detect. efficiency	0.164 ± 0.02	0.192 ± 0.015
max. mixing signal	6.494 evts	2.913 evts
bg-expectation	53.8 evts	15.8 evts
beam-on signal	86 evts	15 evts

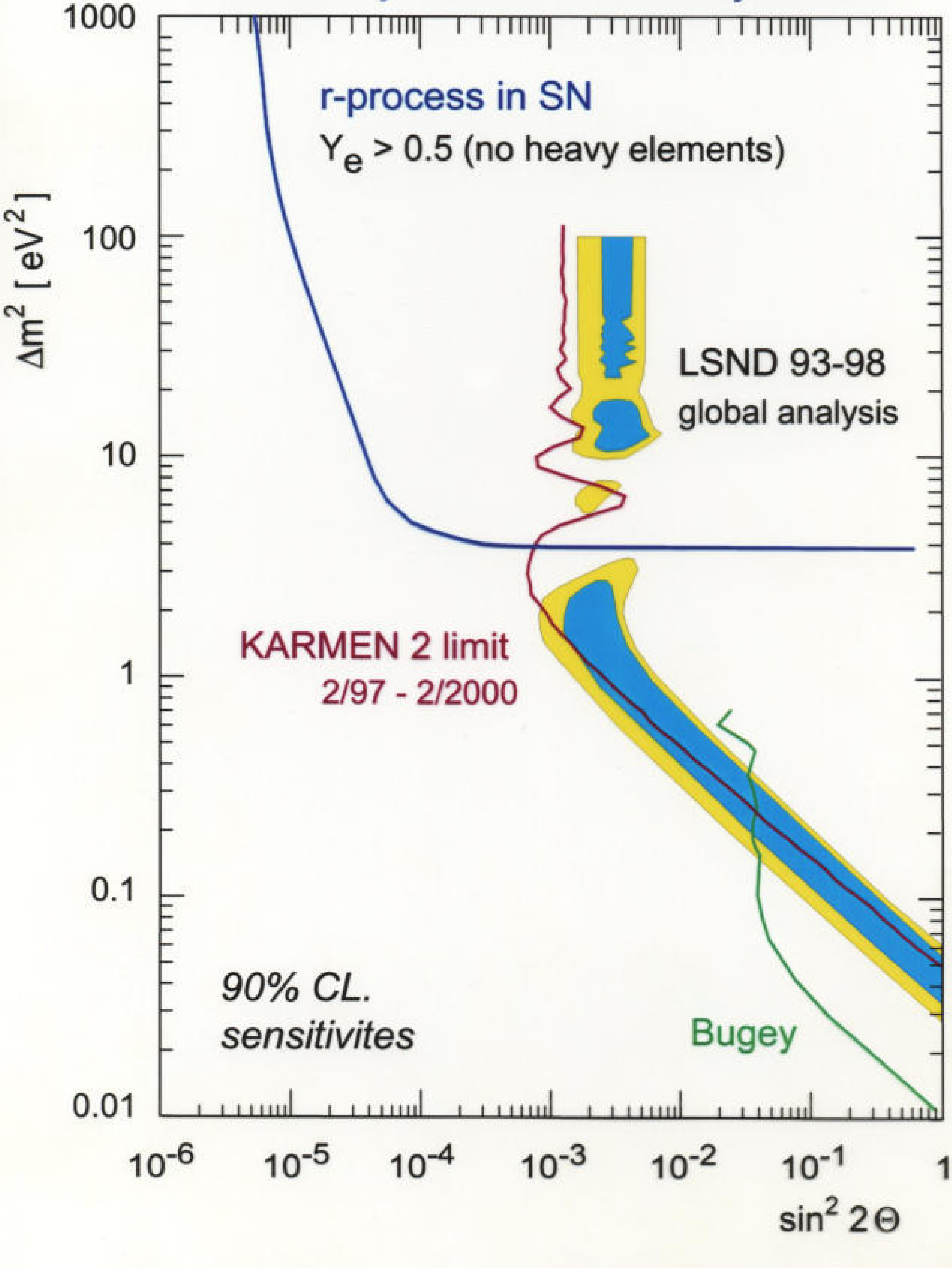
LSND event ensemble for likelihood analysis

1032 beam-on events with $R_\gamma > 10^{-5}$ and positron energy 20-60 MeV



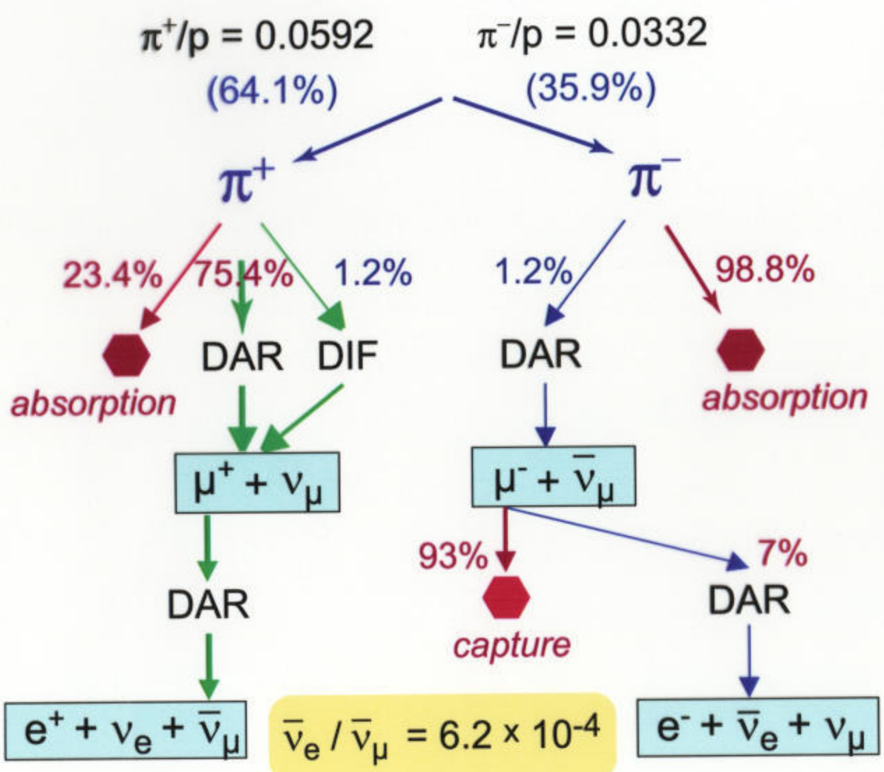
limits from r-process and KARMEN2 - LSND

MSW - transitions in Supernovae and heavy element nucleosynthesis

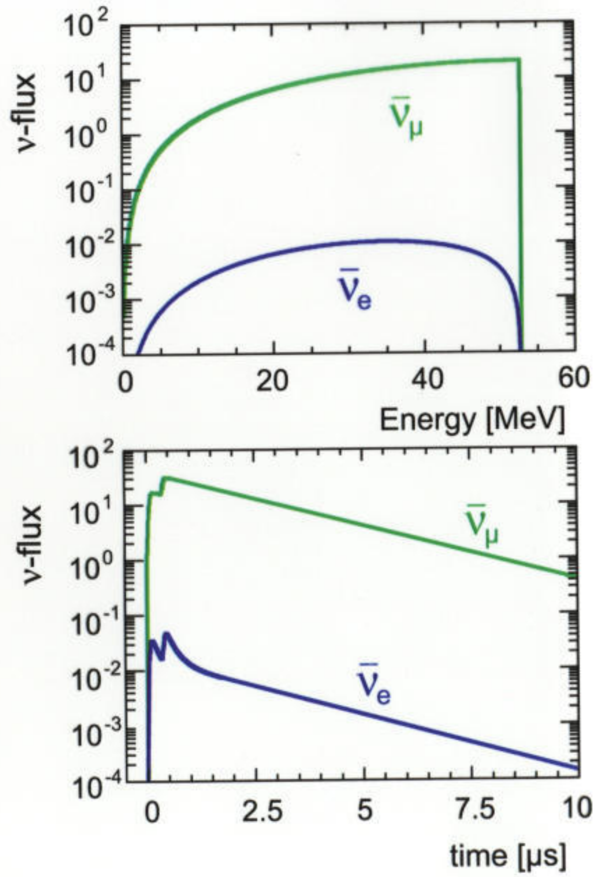


Neutrino Production at ISIS

pion and muon decay and capture modes



energy and time spectra



$^{12}C(\bar{\nu}_e, e^+ n)^{11}B$

Kolbe et al. 1998

$Q = 13.4$ MeV

$\sigma = 8.5 \times 10^{-42}\ cm^2$

$E > 20$ MeV: $\varepsilon = 57$ %