F. Boehm
Neutrino Telescopes
Venice, February 1999

UPDATE ON REACTOR NEUTRINOS

Neutrino Oscillations

$\sim \sin^2 (1.27\ \Delta m^2\ L/E_\nu)$ (eV^2, m, MeV)

sensitivity to small Δm^2 → Atmospheric ν

CHOOZ

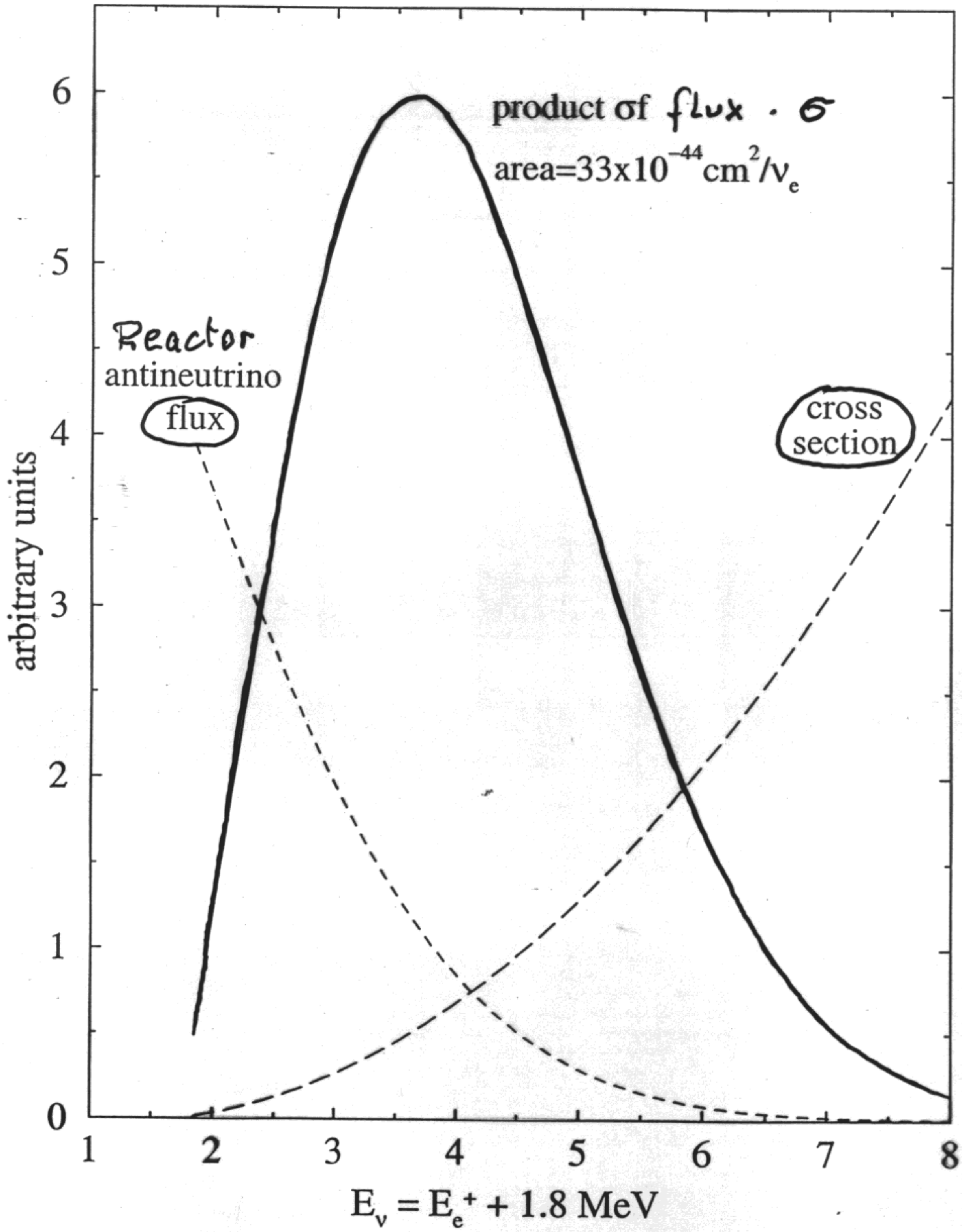
PALO VERDE

KAMLAND → Suzuki's Talk

Neutrino Magnetic Moment

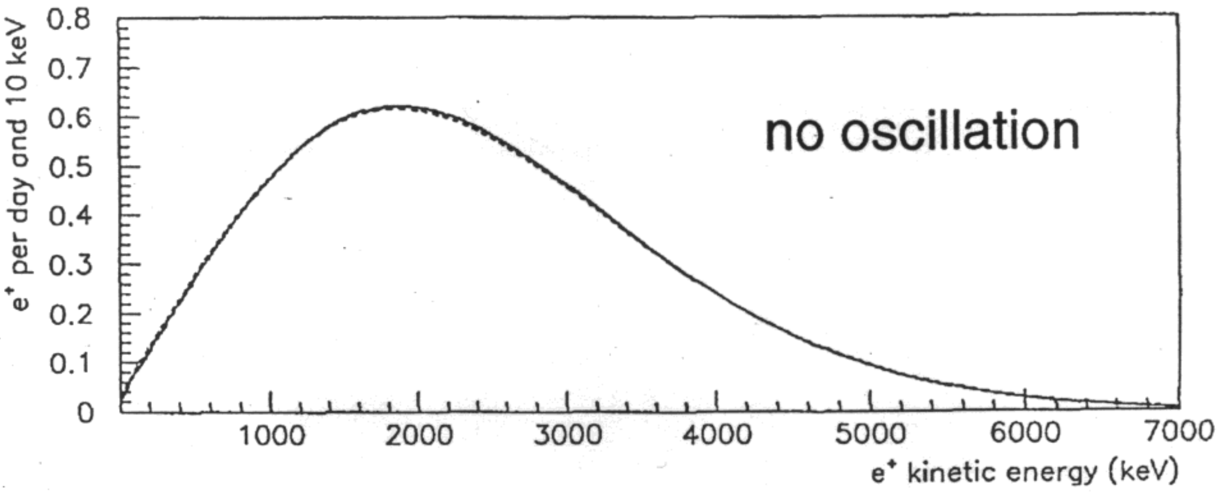
$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$

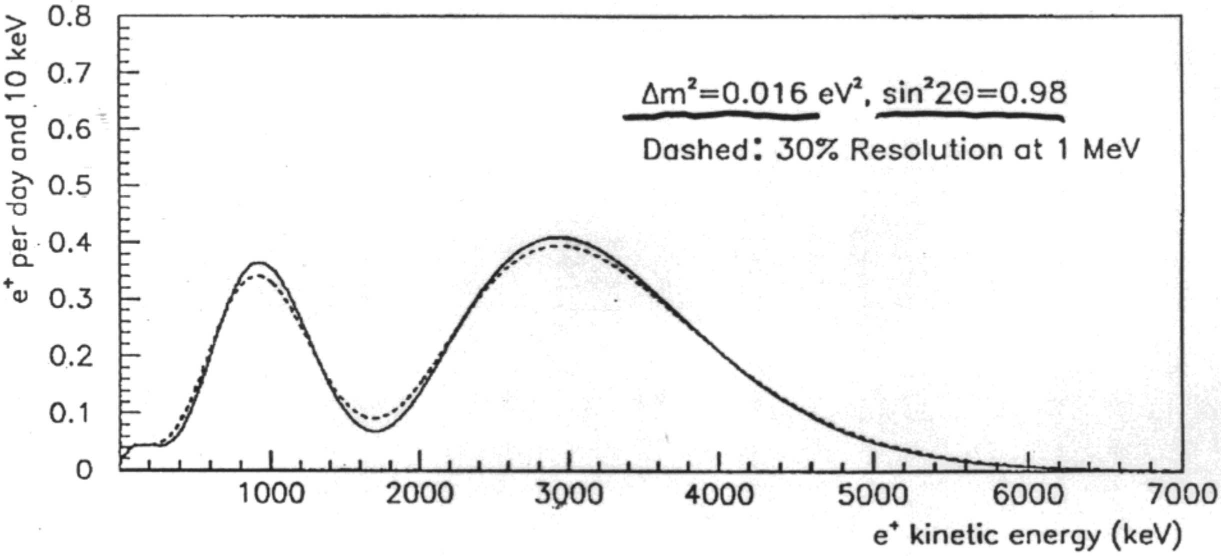
large effects at small recoil (< 0.5MeV)

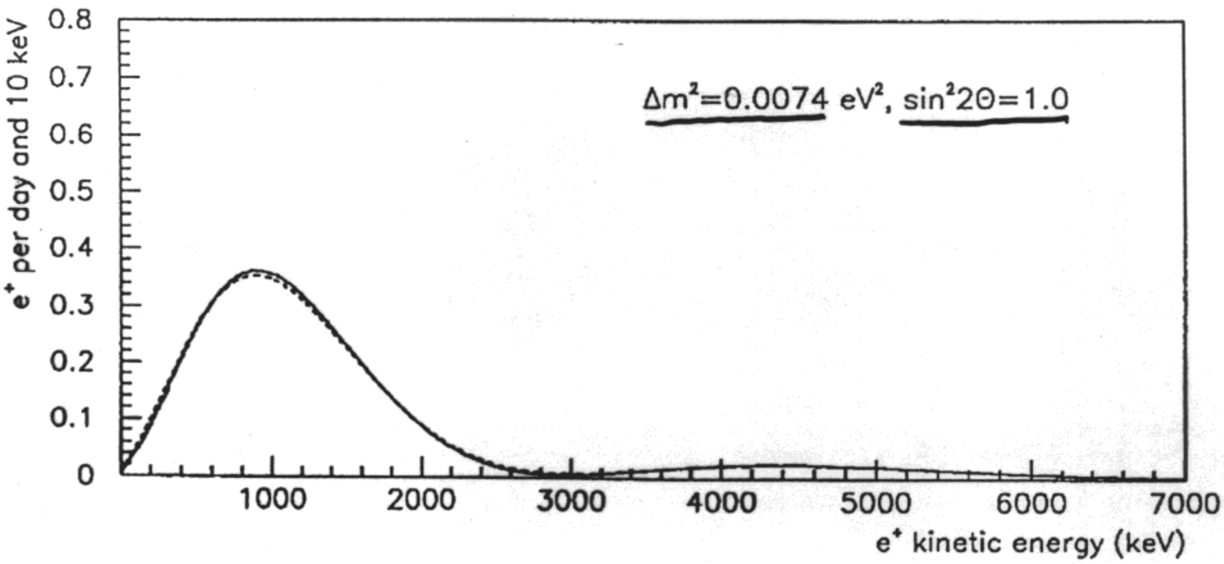


product of flux · σ
area=33x10^-44 cm^2/ν_e
Reactor
antineutrino
flux
cross
section
arbitrary units
0
1
2
3
4
5
6
1
2
3
4
5
6
7
8
E_ν = E_e+ + 1.8 MeV

Expected Positron Spectrum







THE CHOOZ AND PALO VERDE EXPERIMENTS

$\nu_e p \rightarrow e^+ n$

— correlated signature

↓ Gd capt gammas ($\lesssim$ 8 MeV)

Short capt time ($\sim 25\,\mu s$)

0.1% Gd in Mineral Oil based Scintillator

Long Baseline (ca 1km) $\rightarrow$ **$\Delta m^2 \sim 10^{-3} eV^2$**

5 events/ton day

Background Rejection, Shielding

Reactor-on/Reactor-off Runs

Angular Correlation $\nu_e - n$ *(Palo Verde)*

CHOOZ	PALO VERDE
8.5 GW_{th}	11 GW_{th}
300 mwe	25 mwe
0.4 μ/m^2s	22 μ/m^2s
Homogeneous	Segmented
5 t	12 t
Low Cosmic Ray	Active Rejection
1115m, 998 m	890m, 750m
25 events/d	21 events/d
Total 1320 events	Total 237 events (1998)

PALO VERDE NEUTRINO-OSCILLATION EXPERIMENT

PaloVerde Collaboration

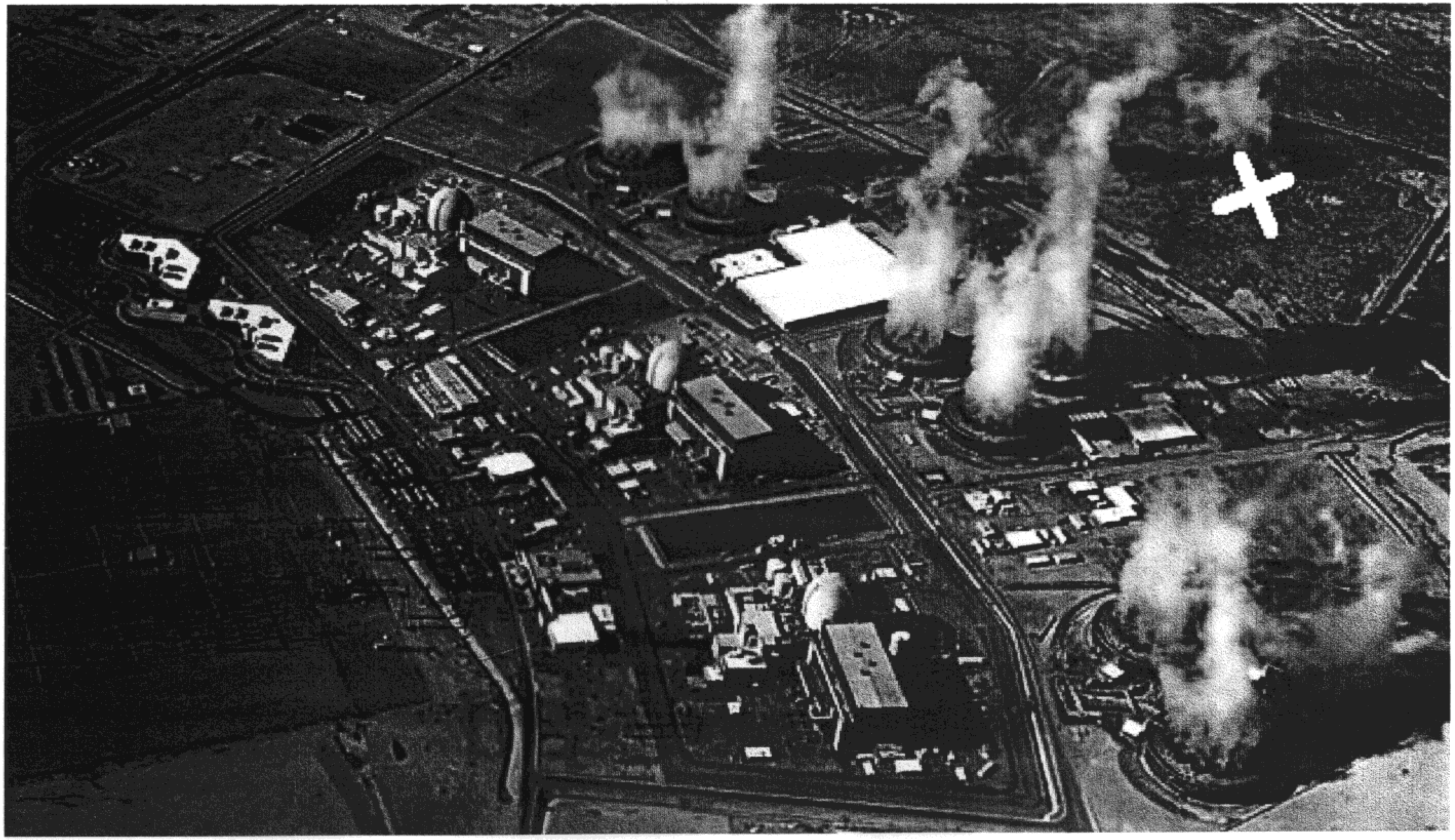
Norman Bridge Laboratory, California Institute of Technology, Pasadena CA 91125
F. Boehm, B. Cook, J. Hanson, H. Henrikson, K. B. Lee, D. Michael, V.M. Novikov, A. Piepke and P. Vogel

Stanford University, Stanford, CA 94305
G. Gratta, L. Miller, D. Tracy and F. -Y. Wang

University of Alabama, Tuscaloosa AL 35487
J. Busenitz, J. Kornis, A. Vital and J. Wolf

Arizona State University
D. Lawrence and B. Ritchie

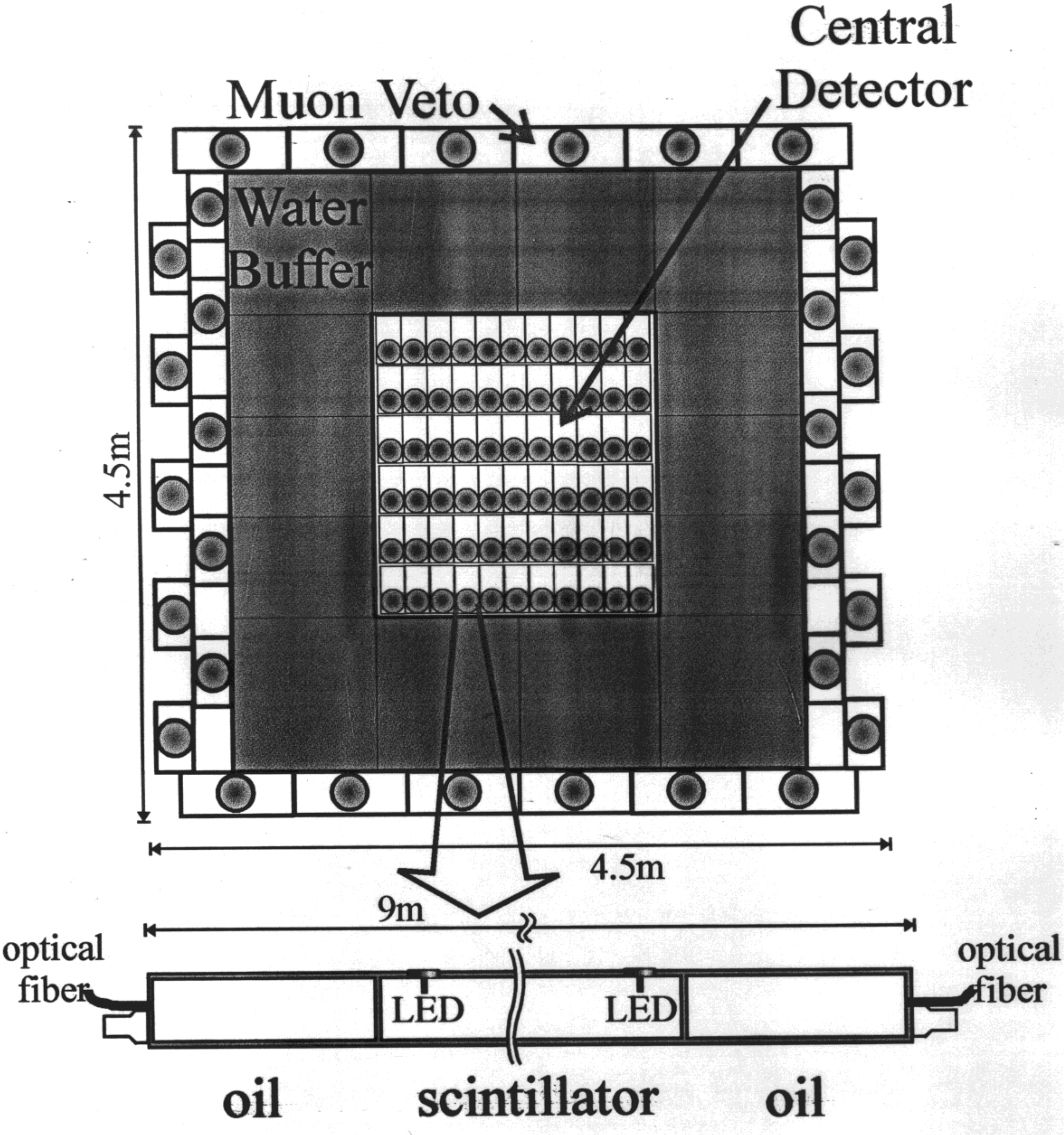
Palo Verde Nuclear Generating Station



Palo Verde Neutrino Detector

- 12 t of liquid scintillator (BC521)
  - 36% pseudocumene
  - 60% mineraloil
  - 4% alcohol
  - 0.1% gadolinium
  - eff. attenuation length ~ 10 m
- segmented: 66 individual cells
  - 25 cm × 13 cm × 7.4 m + 2 × 0.8 m oil buffer
  - removable
  - one EMI 5" PMT at each end
  - both anode and dynode signals read out (1-1000 PE)
  - a blue LED 90 cm from each PMT
  - optical fiber at each end
  - 18 teflon tubes between cells to insert radioact. sources
- passive water buffer, 1m thick
  - shield against external radioactivity and
  - muon induced neutrons
  - 105 t of water
- Veto detector
  - 32 Macro tanks (12 m) for sides, top and bottom
  - removable endcap veto at each end
  - 50 t of liquid scintillator

Palo Verde Neutrino Detector

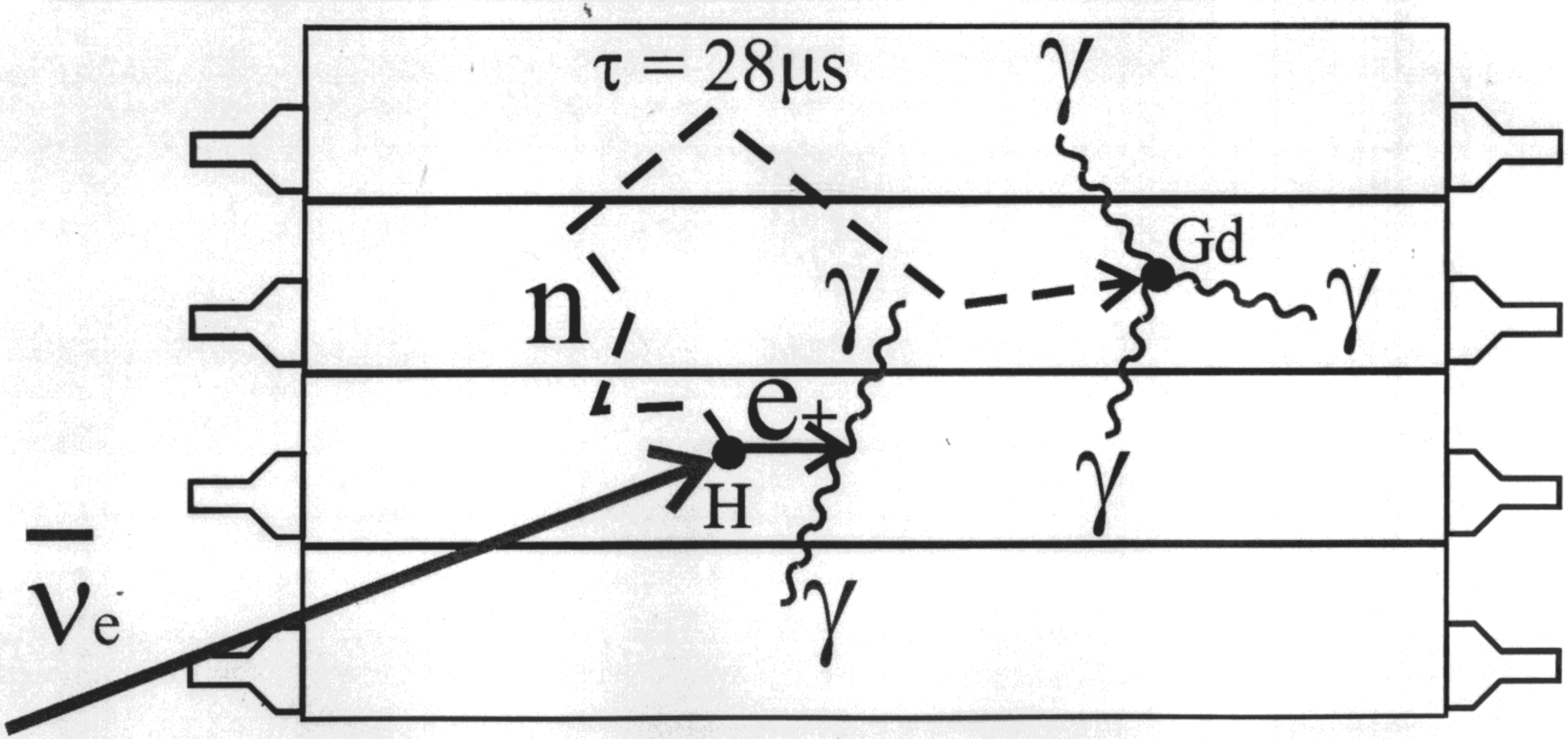


Neutrino Signature

$$\bar{\nu}_e + p \rightarrow n + e_+ \rightarrow 2\,\gamma$$

$$\downarrow \tau = 28\ \mu s$$

$$n + Gd \rightarrow Gd + \gamma\ (\Sigma 8 MeV)$$



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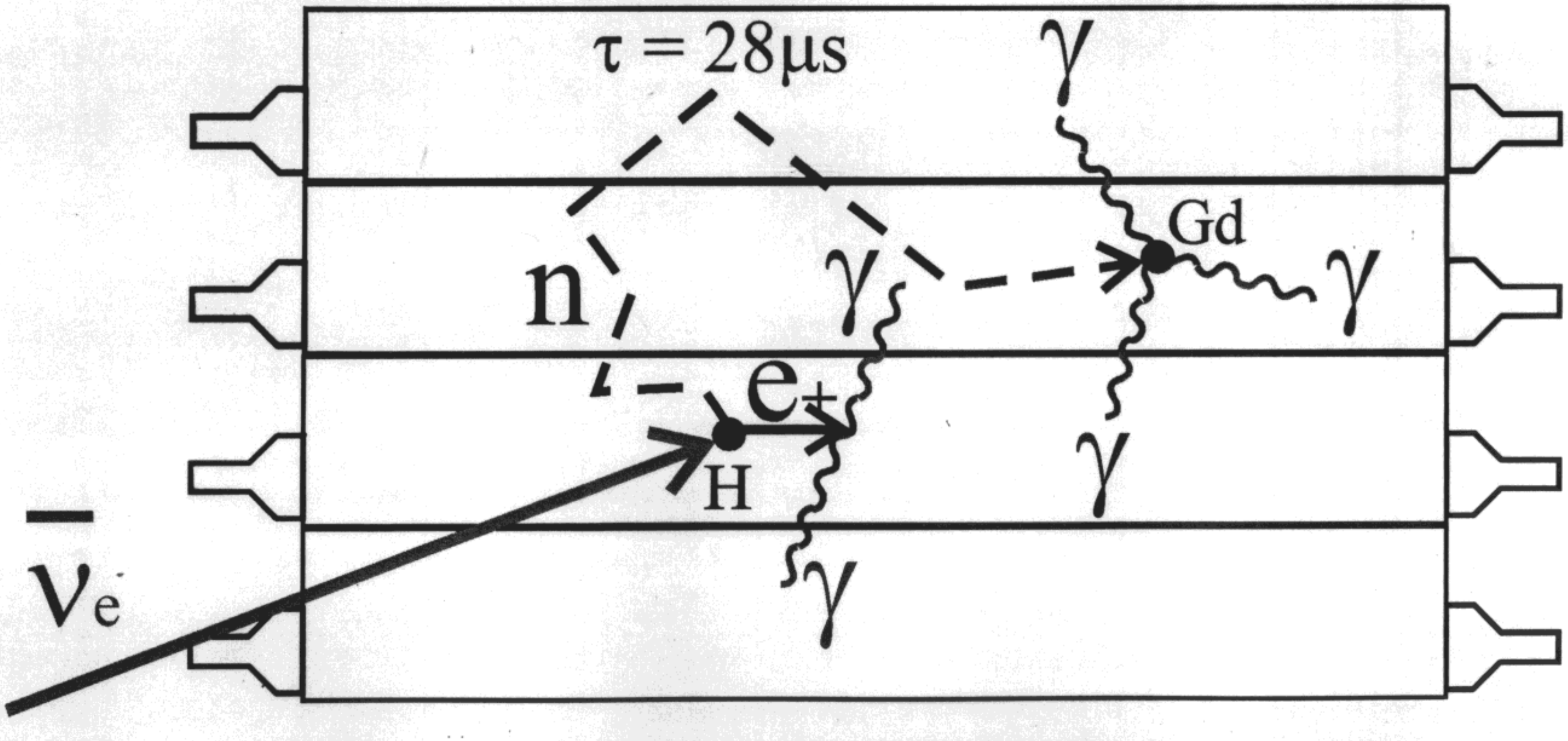
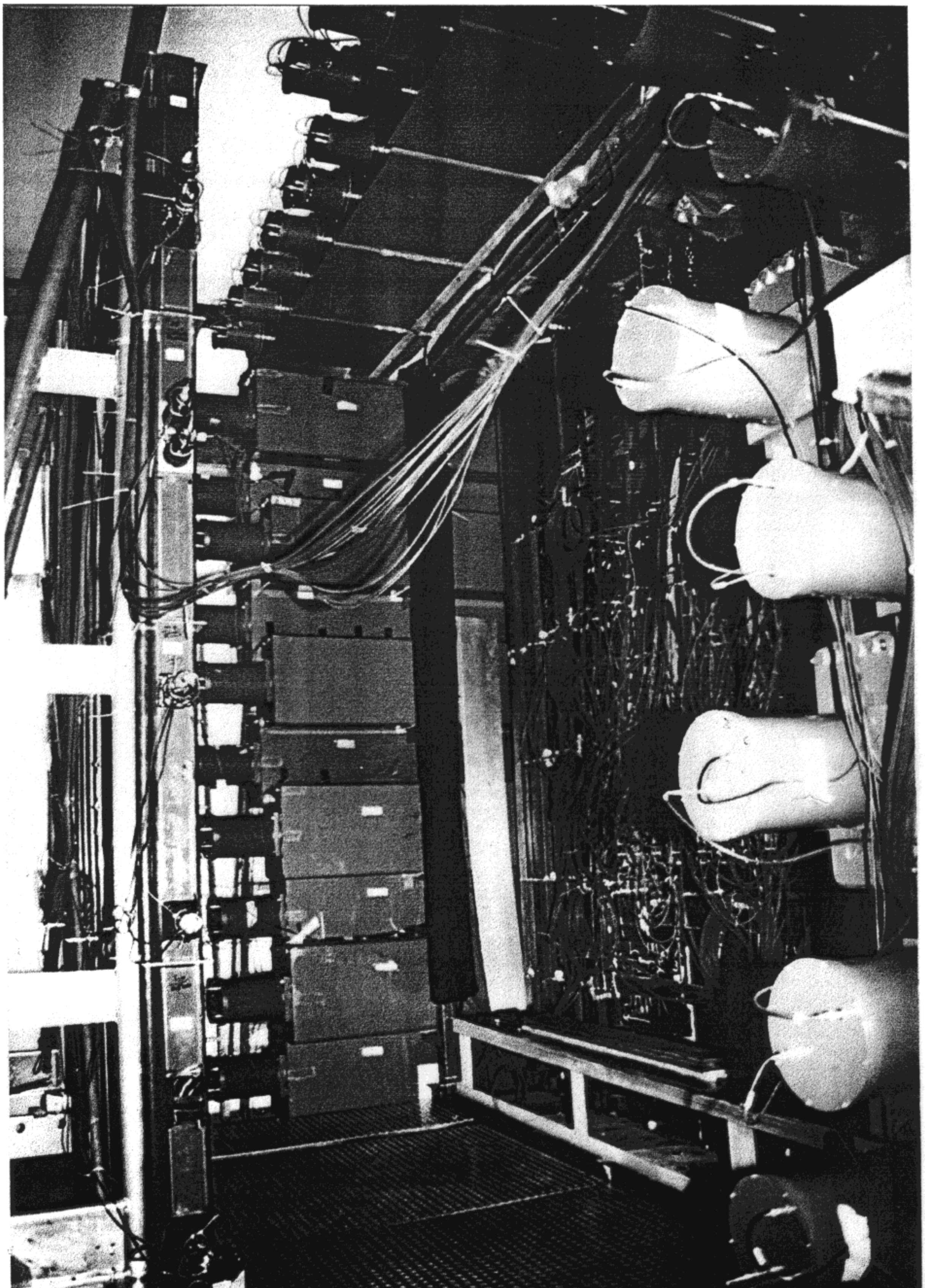


Endcap Veto-Detector open



May
1998

NEUTRINO SIGNAL

Fast (30 ns) $e^+\gamma\gamma$ Triple Trigger Within a 3 x 5 cell matrix

1st hit >500keV (e^+, near PM)

2nd hit > 30keV (511, near PM)

Note: 30keV in mid cell
corresponds to 1P.E./PM

Followed by

Slow Neutron Signal (200 μ in TDC)

from 8MeV γ Shower in 5 x 7 matrix

CALIBRATIONS

Neutron Efficiency:	Tagged Am-Be	
	^{252}Cf	
Positron Efficiency:	^{22}Na	
	^{76}Ge source in scint. (later)	
Energy Calibration:	^{228}Th	(2.6 MeV γ)
Atten. Length:	^{65}Zn	(1.12 MeV γ)
	^{137}Cs	(0.66 MeV γ)
	^{57}Co	(0.122 MeV γ)
PMT Linearity:	Fiberoptics flasher	

Single Photo-electron Blue LED flasher

ν_e – Interactions in Detector and Efficiency

Calculated Number of ν_e Interactions in Detector (no Oscillations)

from ν_e Flux, σ(E), Number of Protons

3 Reactors (890m,750m, 890m)

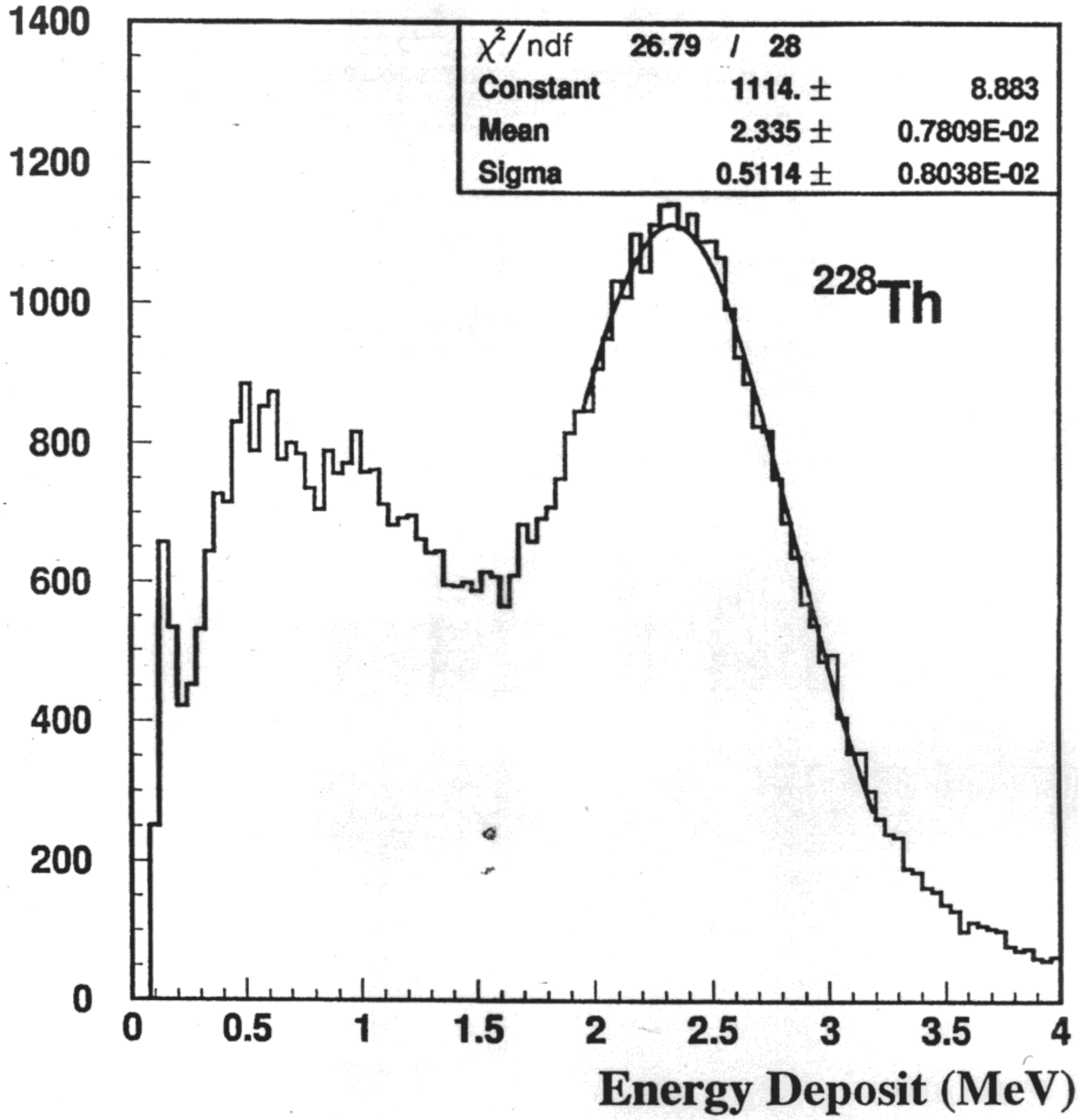
(Depending on Fuel Cycle): 201 ± 3% / d

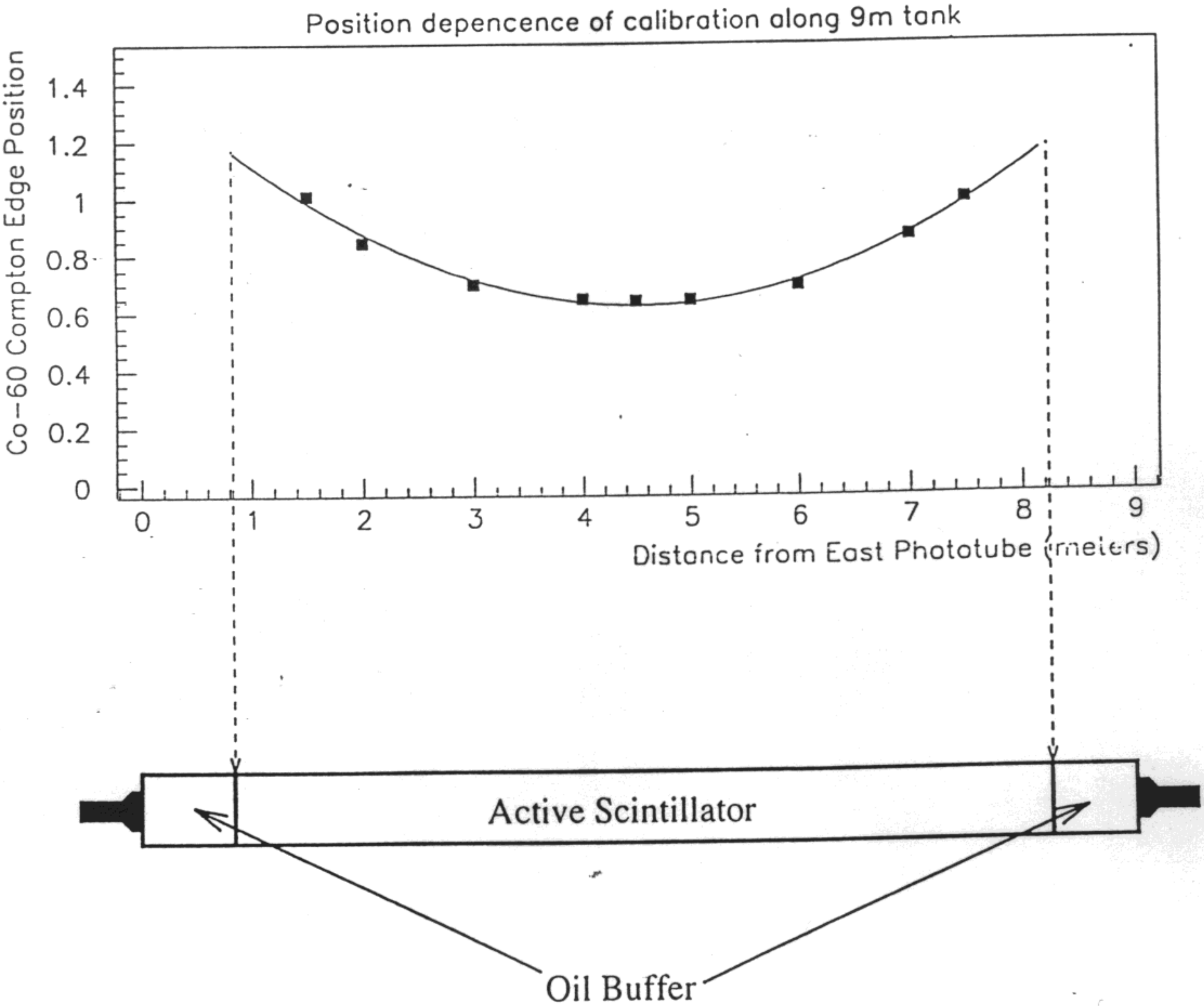
Number of ν_e Interactions from one 890m Reactor 59 ± 2

Averaged (over detector) **Efficiency**	
from MC, ^{22}Na, AmBe (Analysis Cuts)	0.159
DAQ Live	0.82
Veto Live (2kHz)	0.632
Total Efficiency	0.083

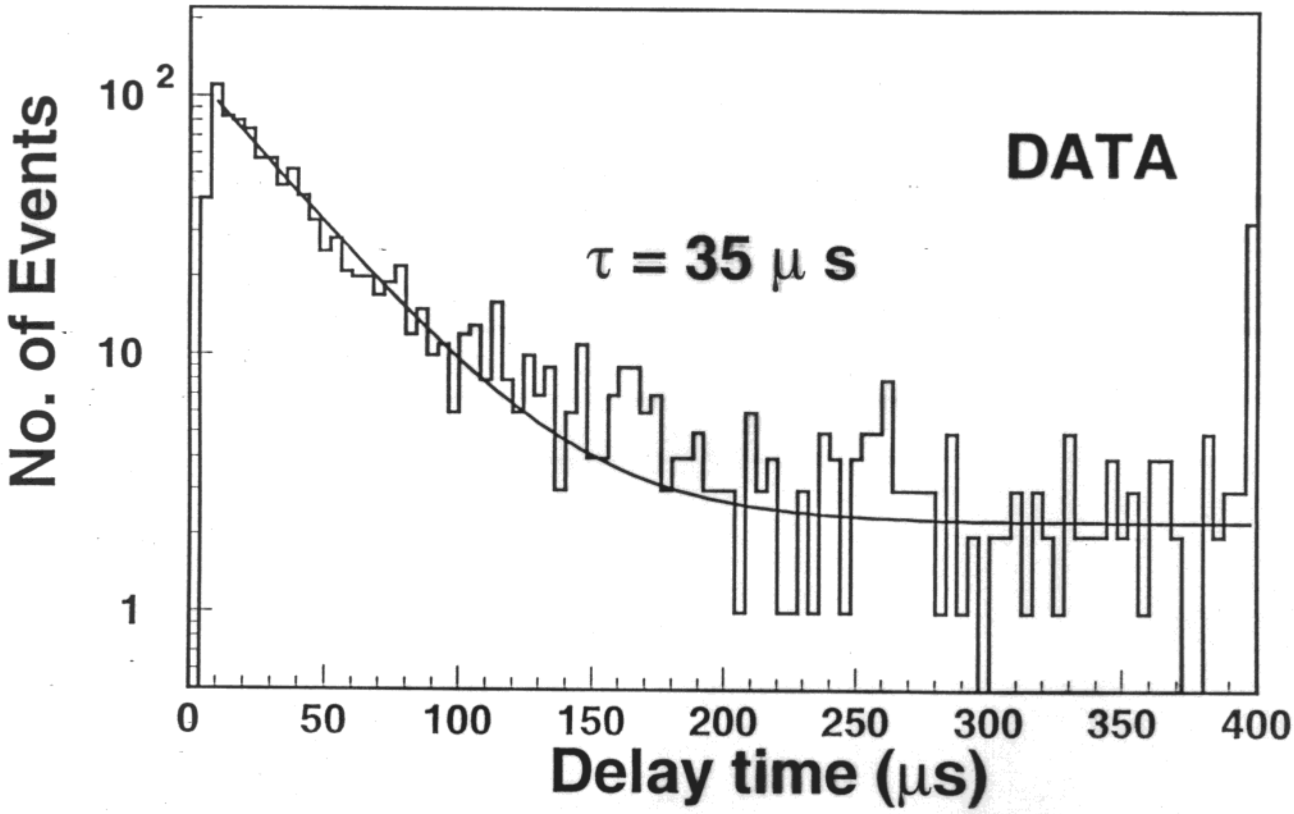
Expected Count Rate	3 Reactors	17/d
	850 m Reactor	5 / d

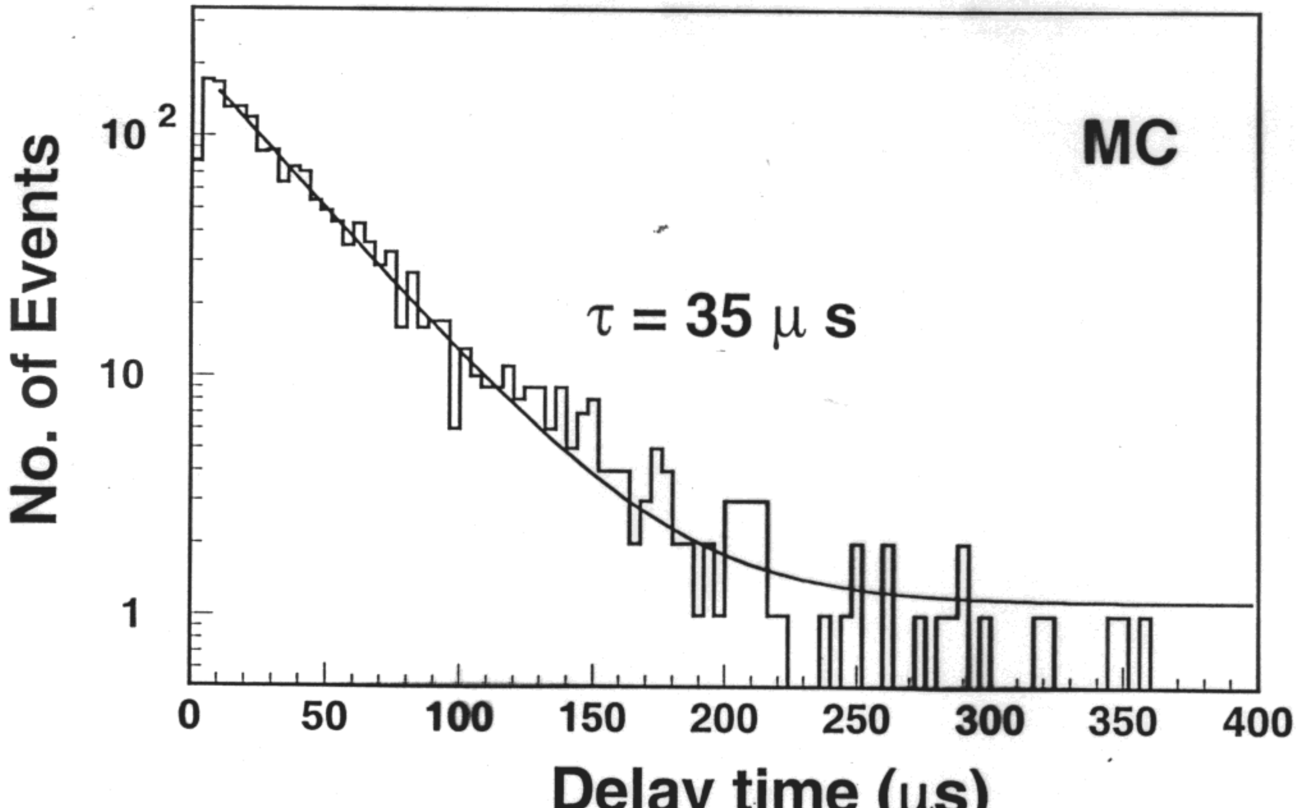
γ-Energy of ^{228}Th source (<2.6MeV)



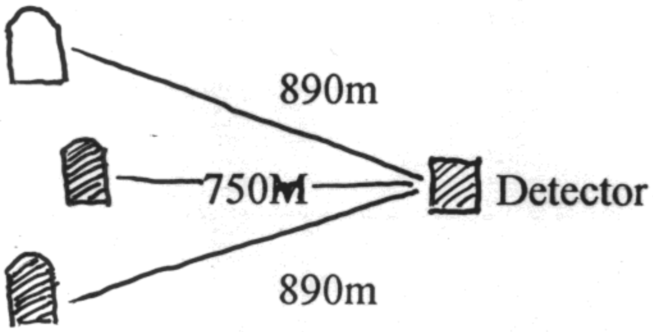


Position depencence of calibration along 9m tank
Co-60 Compton Edge Position
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
7
8
9
Distance from East Phototube (meters)
Active Scintillator
Oil Buffer


DATA
τ = 35 μ s
No. of Events
Delay time (μs)


MC
τ = 35 μ s
No. of Events
Delay time (μs)

Results from 1998 Run



37d at Full Power (Nov-Dec 98) (39.1 ± 1.0 st) / d

33d at "2/3" Power (Oct 98) (32.6 ± 1.0 st) / d

Attribute Signal to one 890m Reactor

→ **(6.4 ± 1.4 (stat)) / d**

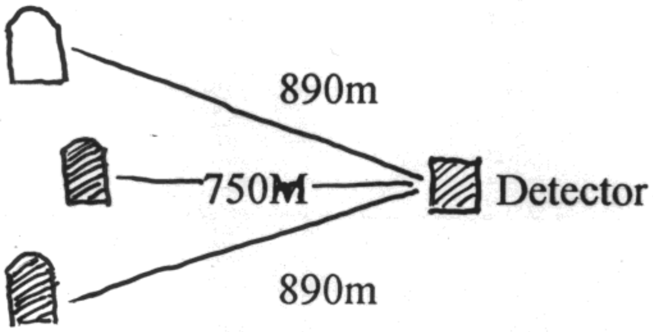
→ $\frac{S}{N} = \frac{21.1}{18.0} = 1.2$

Corrected for Efficiency:

Number of ν Interactions from one 890m Reactor:

→ **77 ± 17 (stat) ± 11 (sys) / d**

Results from 1998 Run



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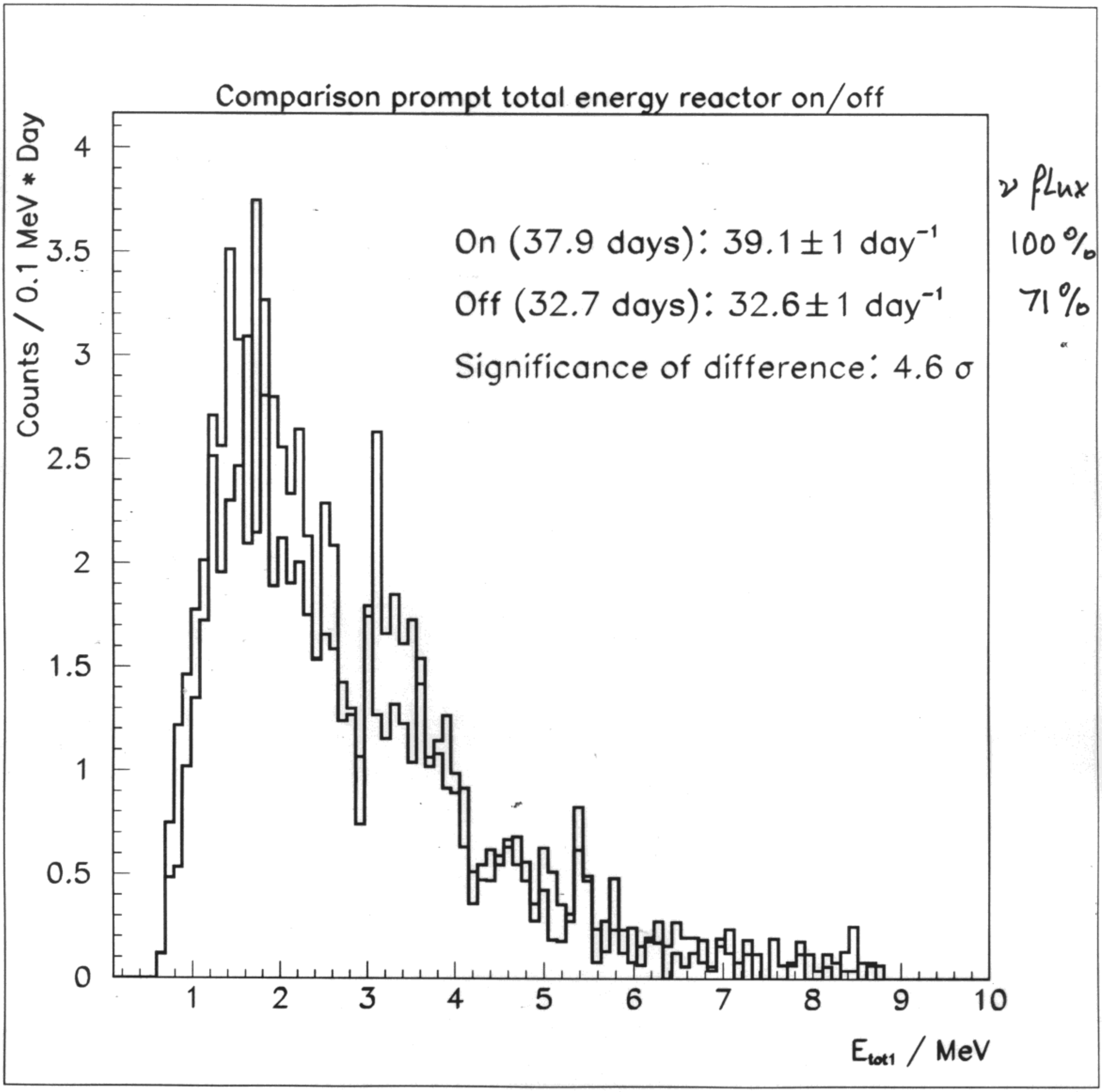
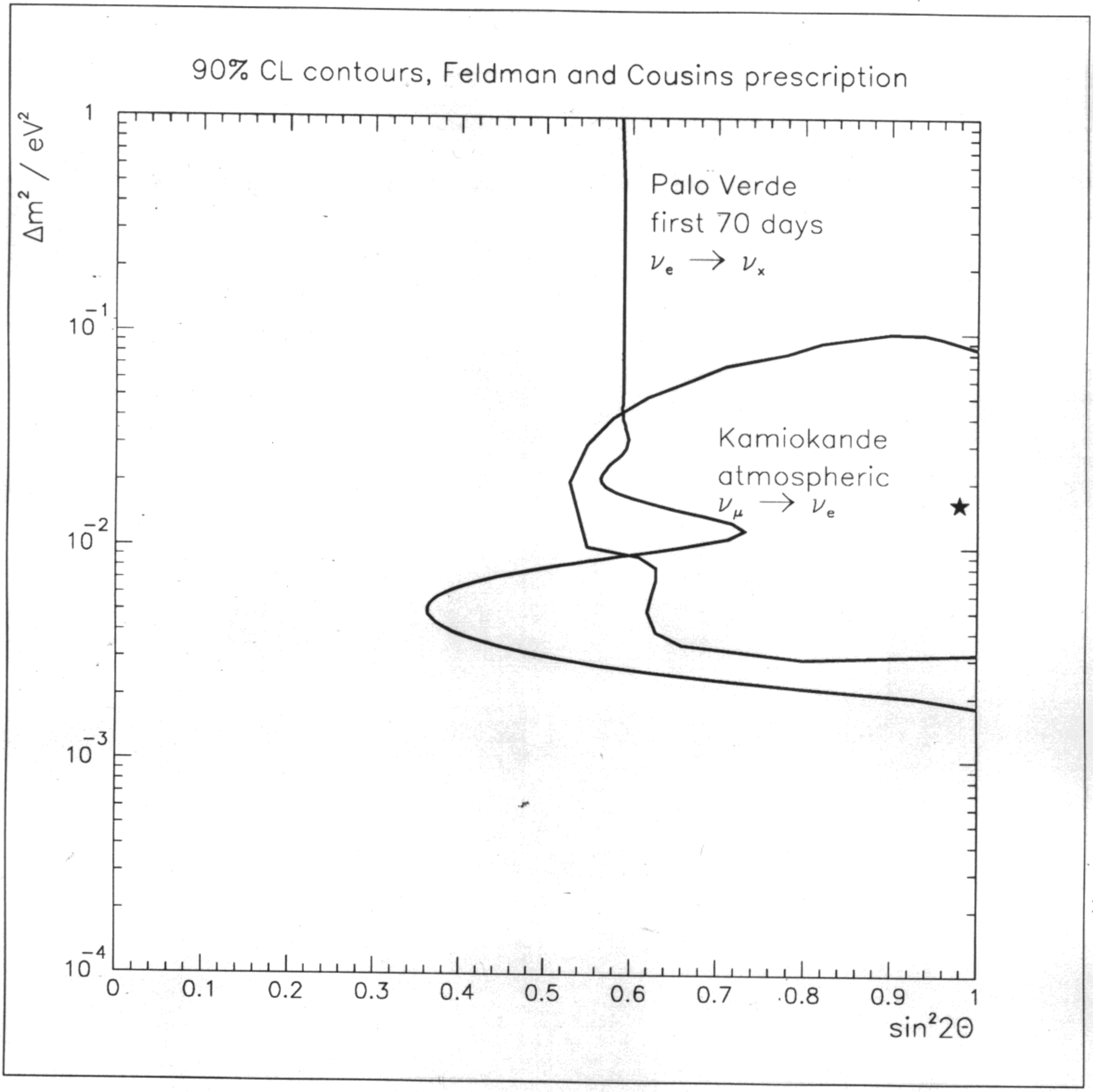
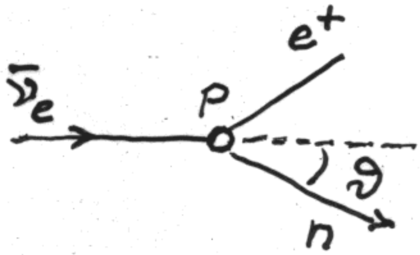

Comparison prompt total energy reactor on/off
On (37.9 days): 39.1±1 day⁻¹
Off (32.7 days): 32.6±1 day⁻¹
Significance of difference: 4.6 σ
ν flux
100%
71%
Counts / 0.1 MeV * Day
E_tot1 / MeV
0
0.5
1
1.5
2
2.5
3
3.5
4
1
2
3
4
5
6
7
8
9
10



90% CL contours, Feldman and Cousins prescription
Δm² / eV²
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
Palo Verde
first 70 days
νe → νx
Kamiokande
atmospheric
νμ → νe
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
sin²2Θ

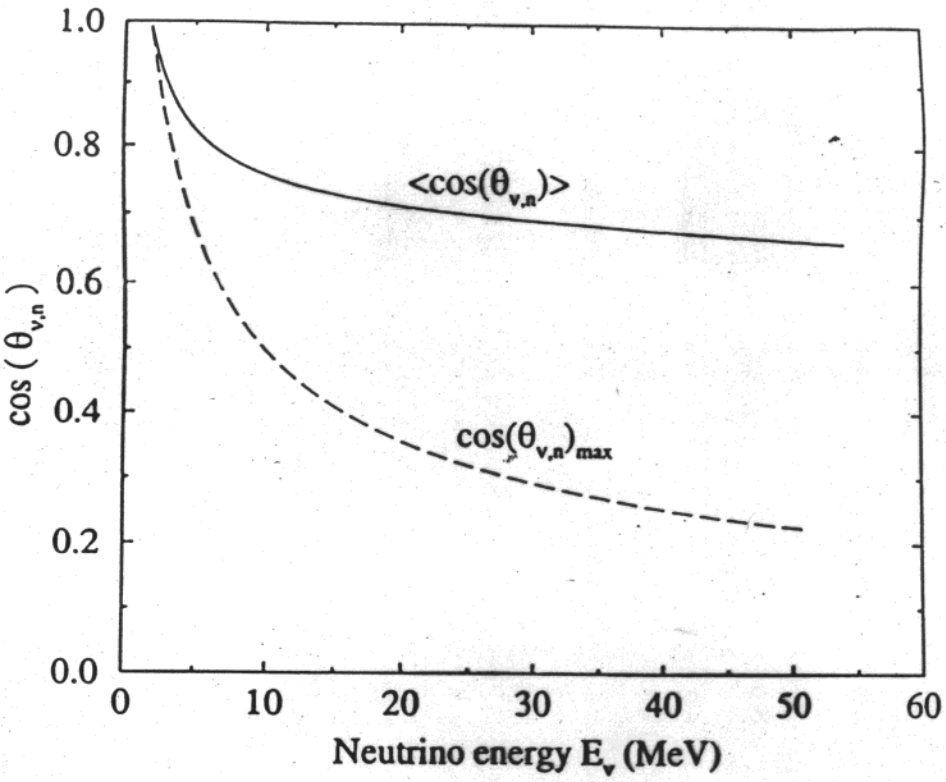
SEGMENTATION PROVIDES INDEPENDENT BACKGROUNDS

$\bar{\nu}_e - n$ Angular Distribution



From Kinematics, n moves along $\bar{\nu}_e$

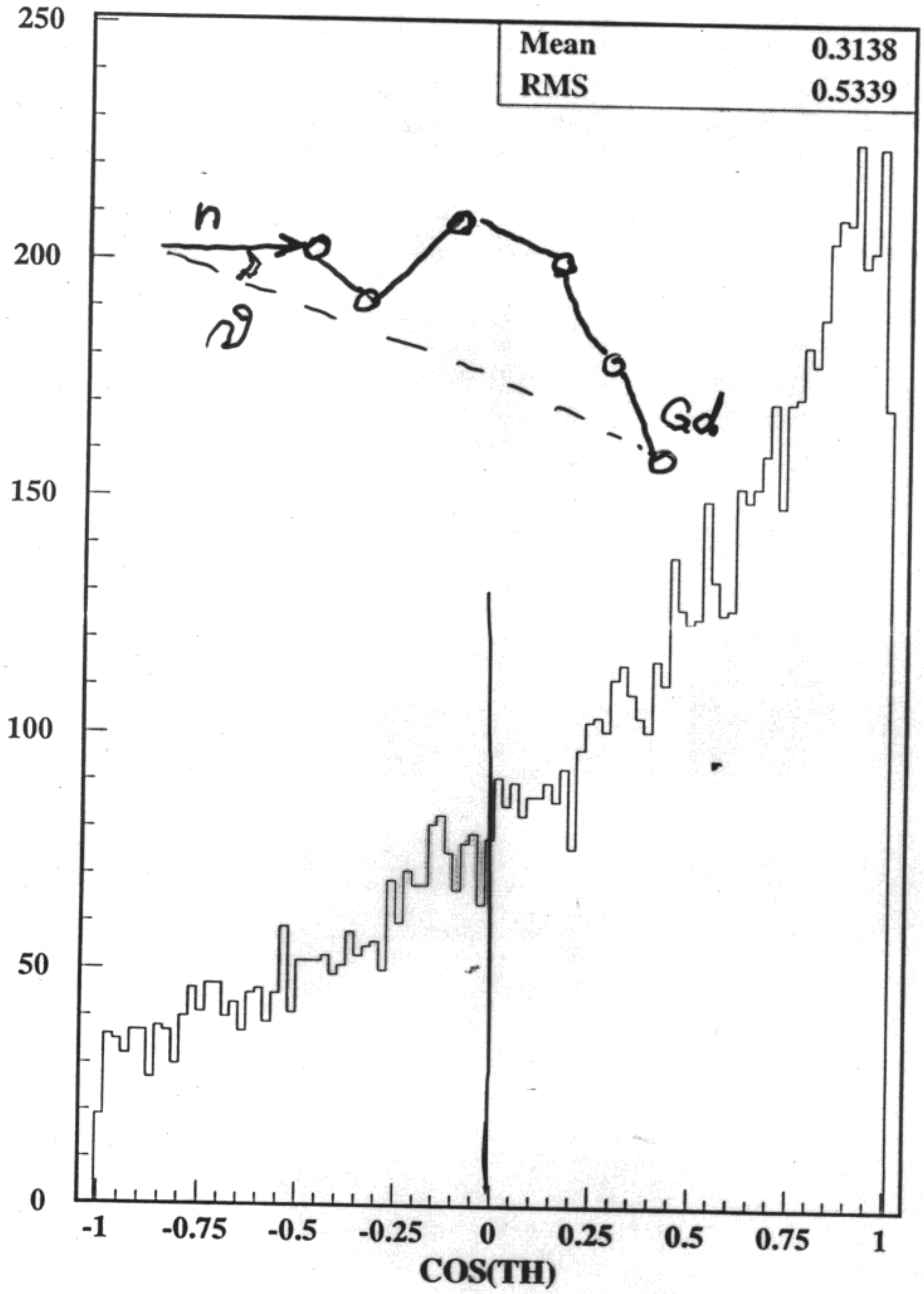
$$\cos(\vartheta_{\nu,n})_{max} \simeq \sqrt{\frac{2\Delta}{E_\nu} - \frac{\Delta^2 - m_e^2}{E_\nu^2}} \qquad (\Delta = M_n - M_p)$$



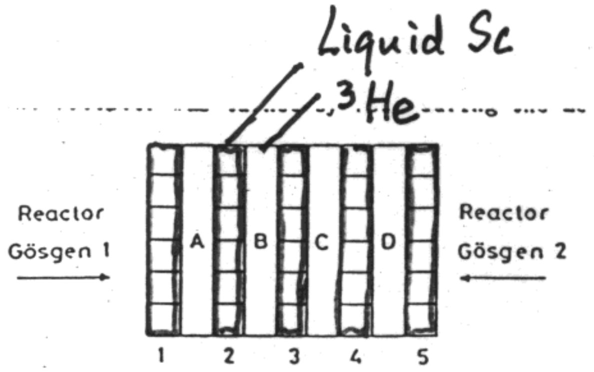
n Scattering (Moderation) preserves Distribution

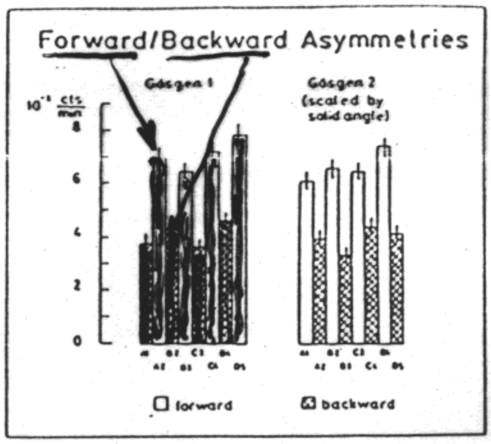
Shift of Capture Center $< x > = 1.7$cm

Spread Angle



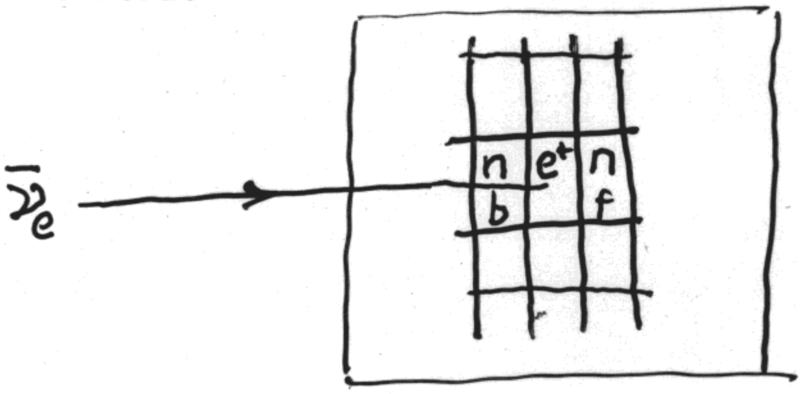
GOESGEN EXPERIMENT (G. Zacek, thesis 1984)

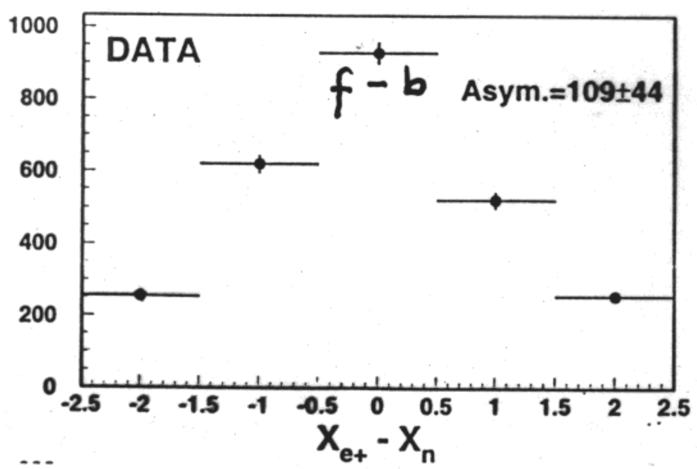


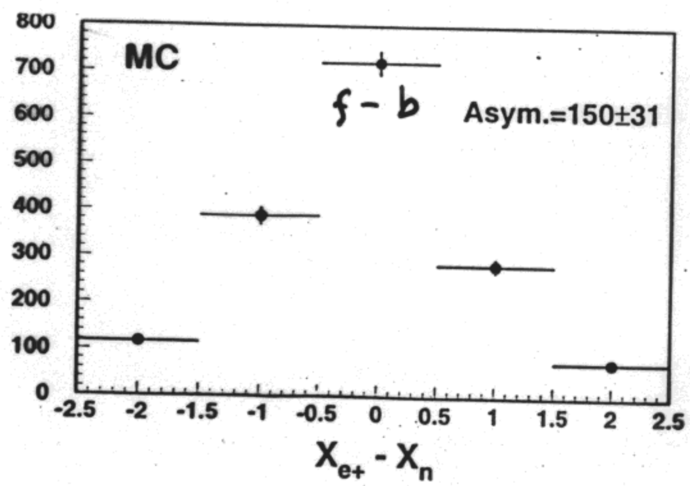


Forward/Backward ~ 2.0

Palo Verde





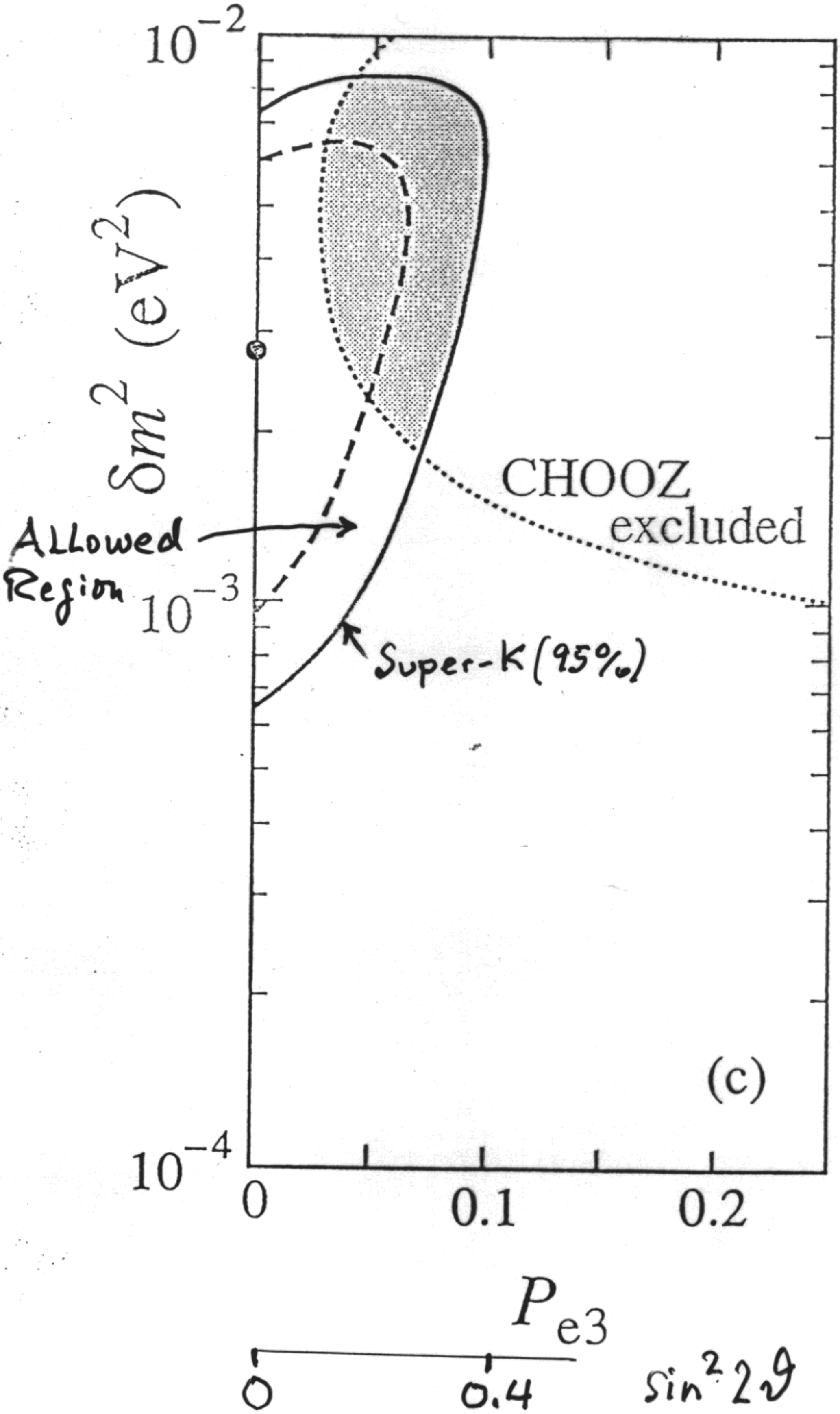


→ S/N ~ 1.2

PALO VERDE - FUTURE

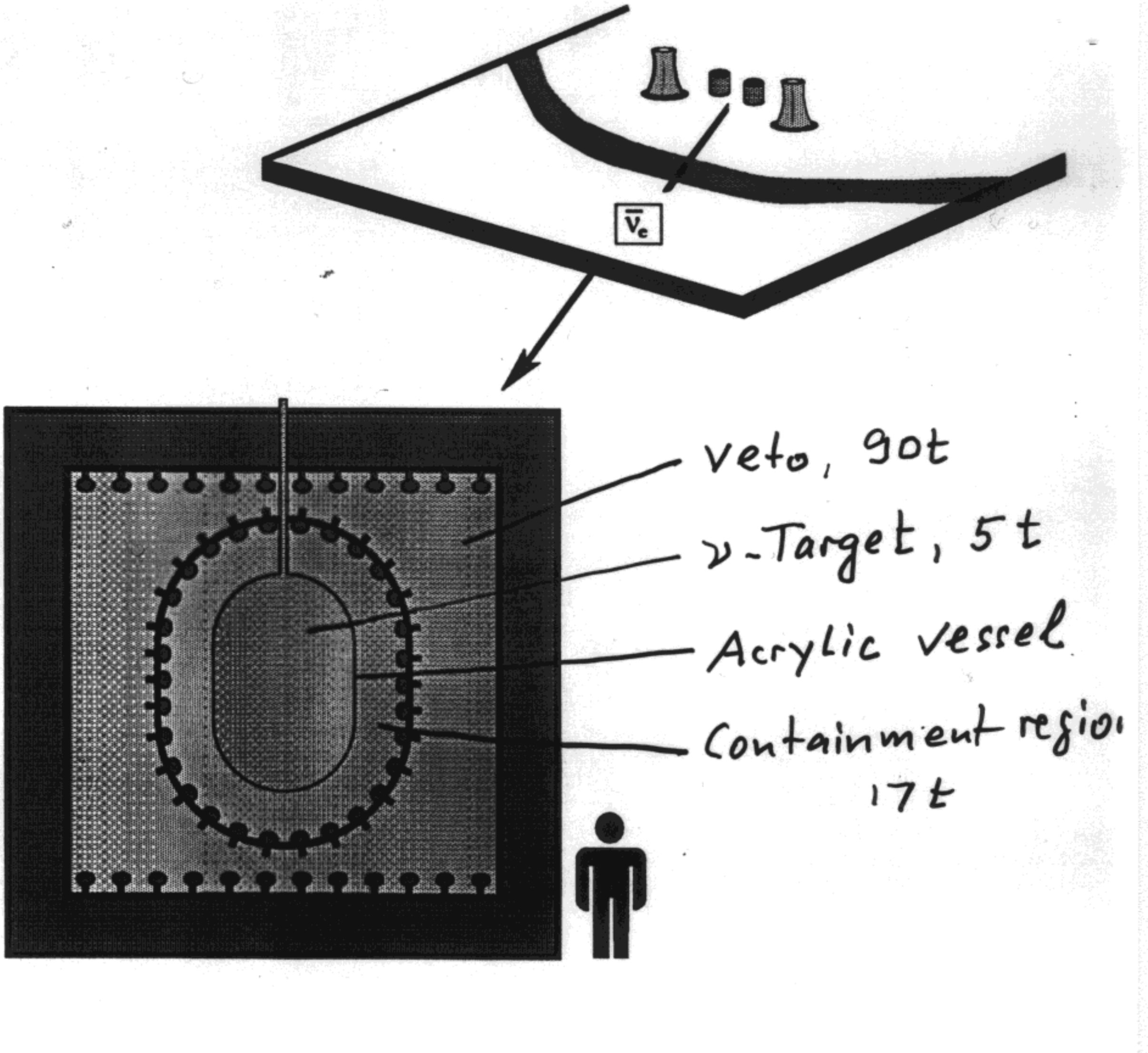
Through 99	Data Runs
	2 Refueling Periods
	10-fold Statistics
	Substantial higher Sensitivity $\sin^2 2\vartheta$
	Foreward - Backward Asym.
	Better e^+ Calibration (^{76}Ge)
Other Issues	
	Tracking - physics of n spallation
	from Cosmic Ray μ

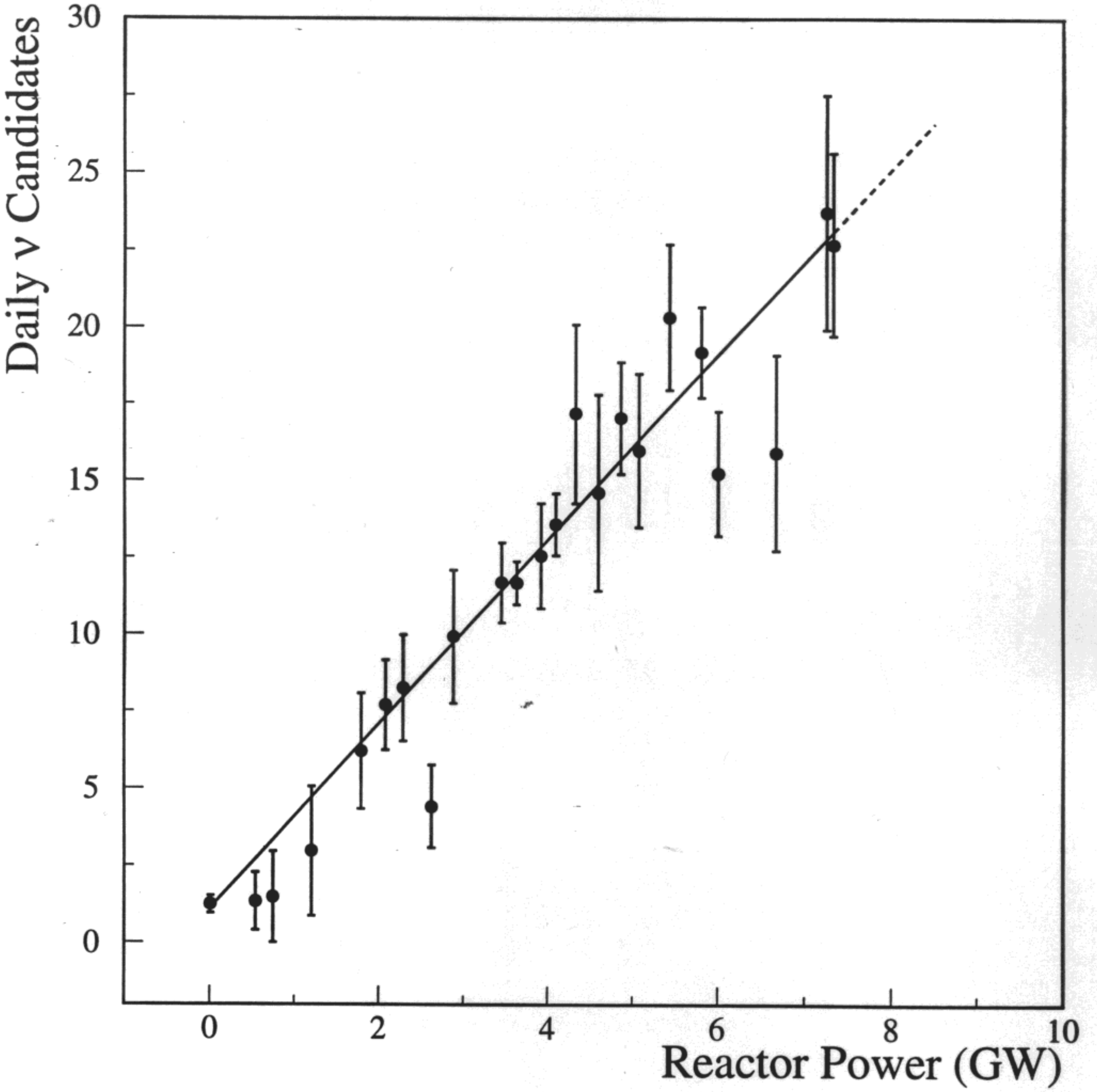
3-Flavor Analysis (Barger et al 7/98)



The Chooz Experiment

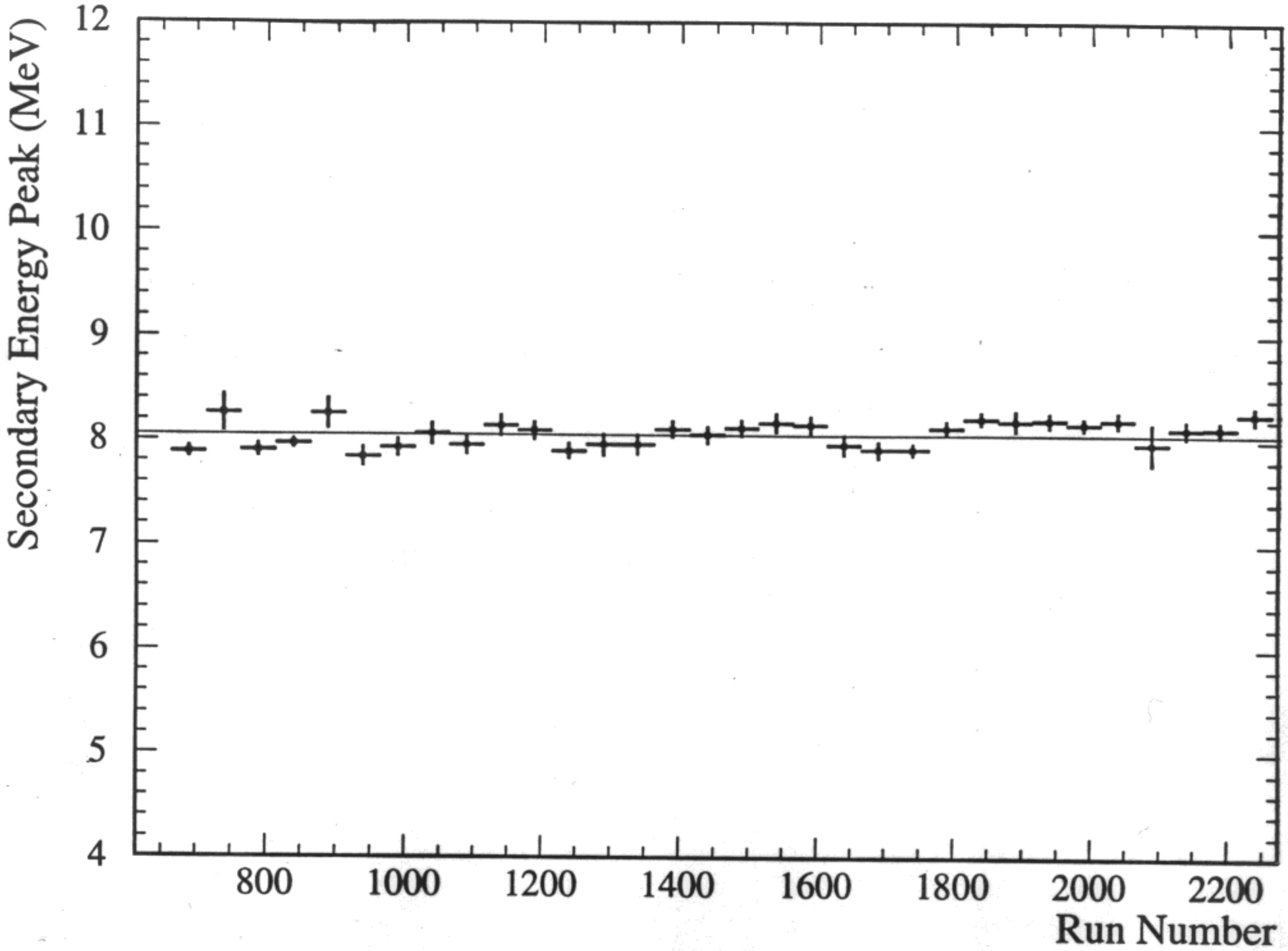
PROPOSAL TO SEARCH FOR NEUTRINO VACUUM OSCILLATIONS TO $\Delta m^2 = 10^{-3}\ eV^2$ USING A 1 KM BASELINE REACTOR NEUTRINO EXPERIMENT

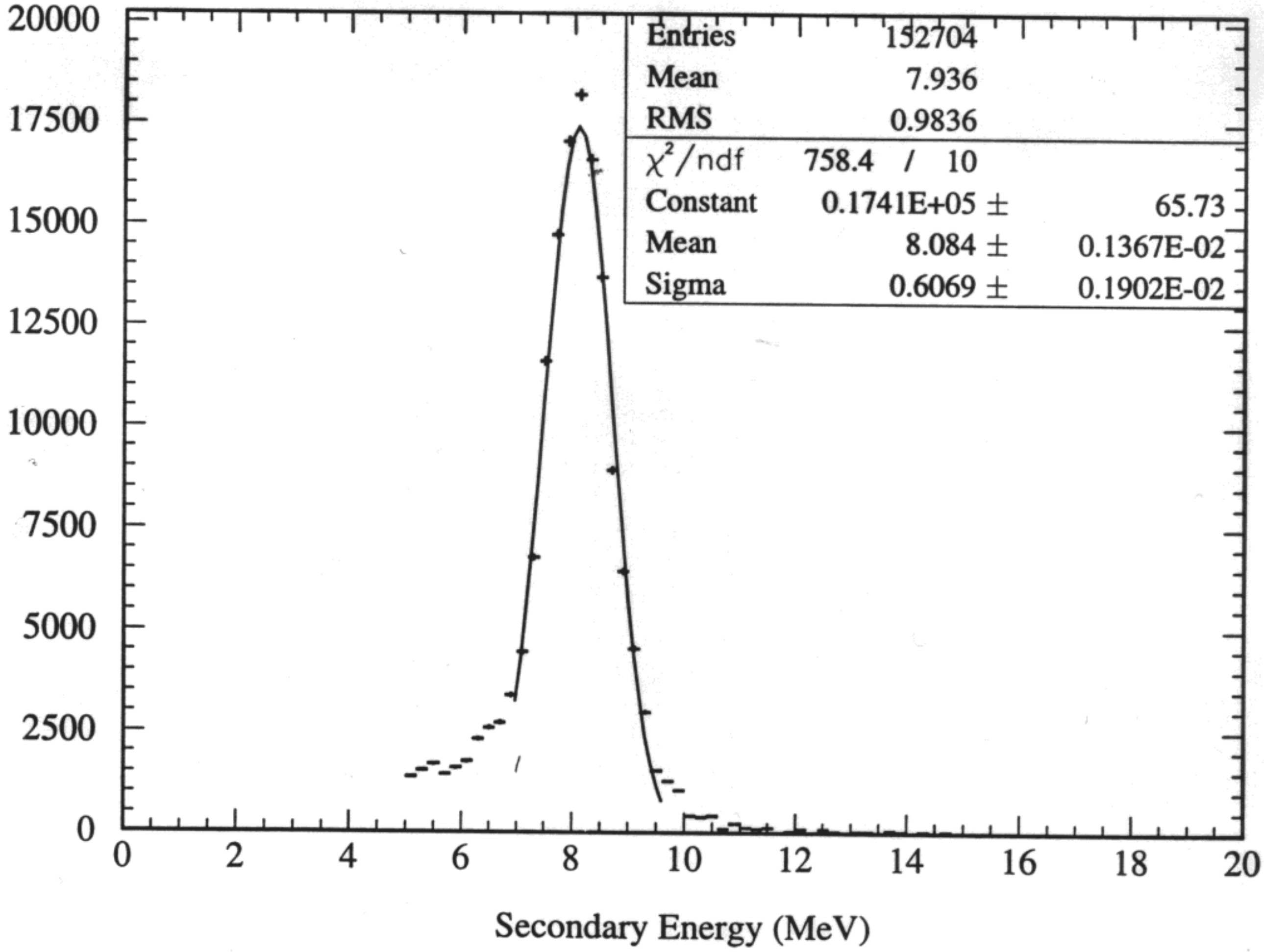


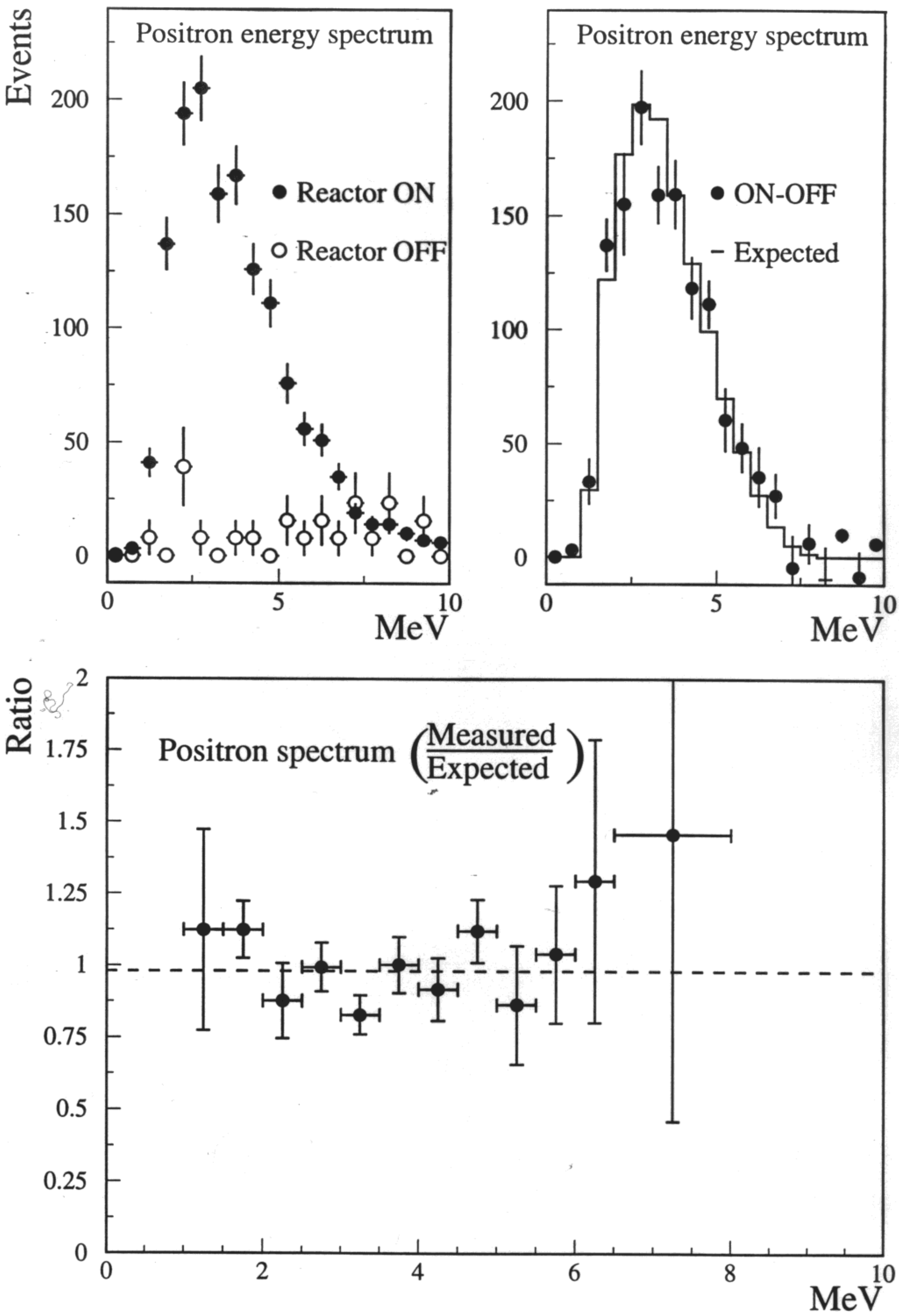


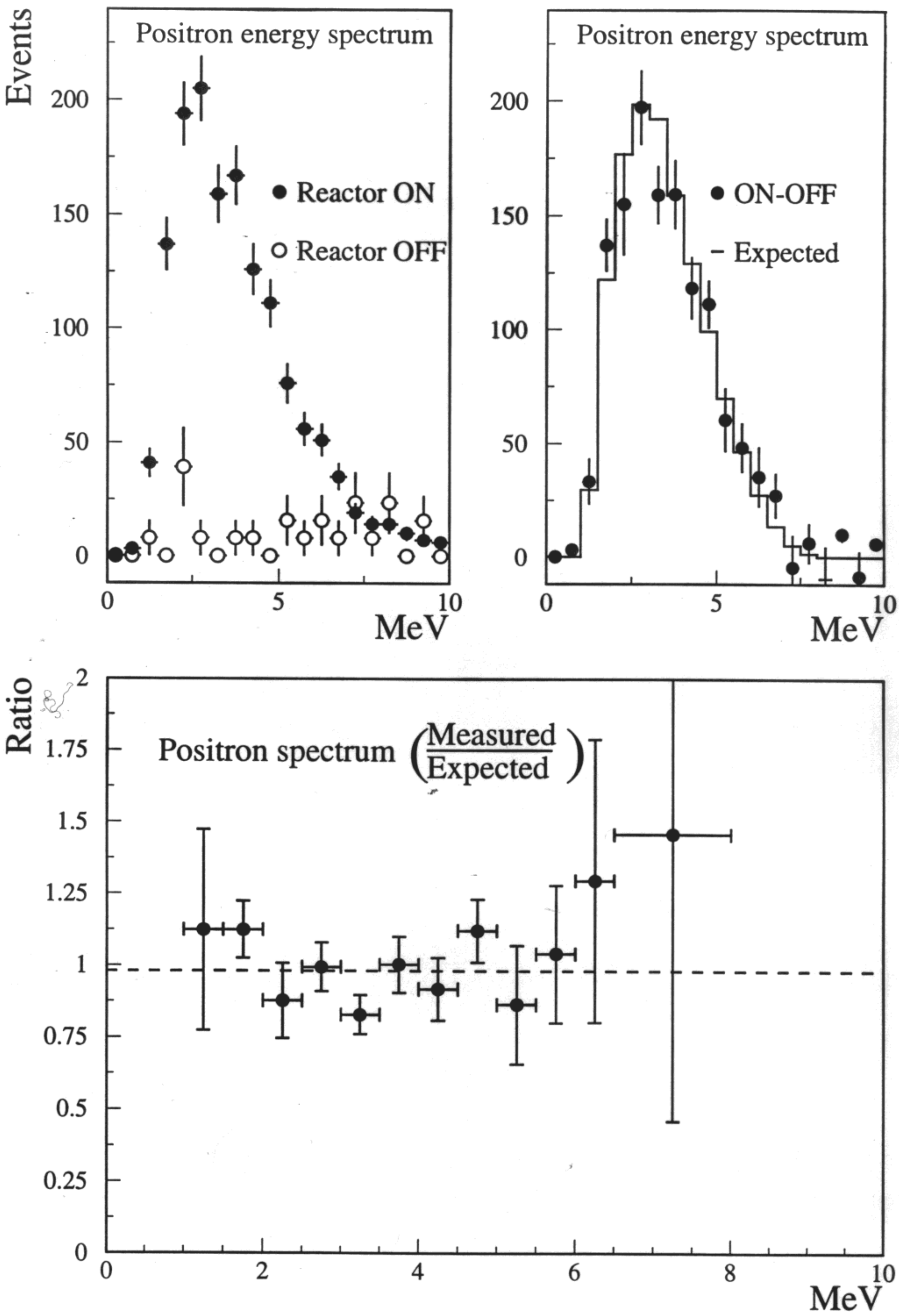
Daily ν Candidates
30
25
20
15
10
5
0
0
2
4
6
8
10
Reactor Power (GW)

Data from Run 664 to Run 2250






Positron energy spectrum
Events
Reactor ON
Reactor OFF
MeV
Positron energy spectrum
ON-OFF
Expected
MeV
Ratio
Positron spectrum (Measured / Expected)
MeV



Events
Positron energy spectrum
Reactor ON
Reactor OFF
MeV
Positron energy spectrum
ON-OFF
Expected
MeV
Ratio
Positron spectrum (Measured / Expected)
MeV

Predicted # of events

- $\frac{\sigma}{\text{fission}} \times \frac{\text{fissions}}{\text{GW}} \times P \times \Omega \times T \times \frac{\rho \cdot V \cdot \%H}{m_p} \times \text{spill} - \text{in/out}$

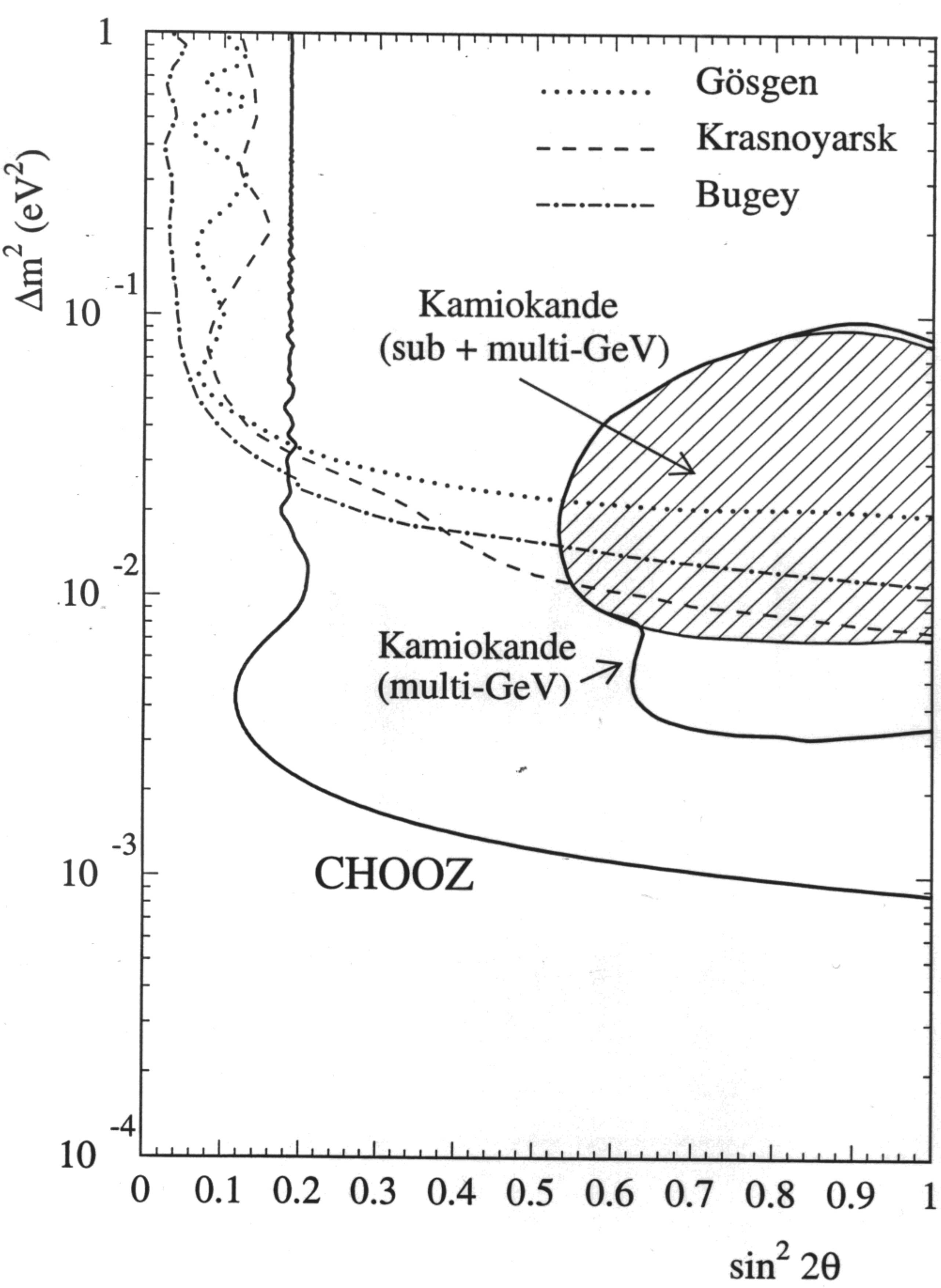
Quantity	Error	
σ/fission	2.7%	••
# fissions/GW	0.5%	
ρ	0.1%	
V	0.3%	
P	1.5%	•
sp.in/out (factor = 1.01)	0.1%	
$\%H$	1.2%	•
	3.4%	

- Efficiences

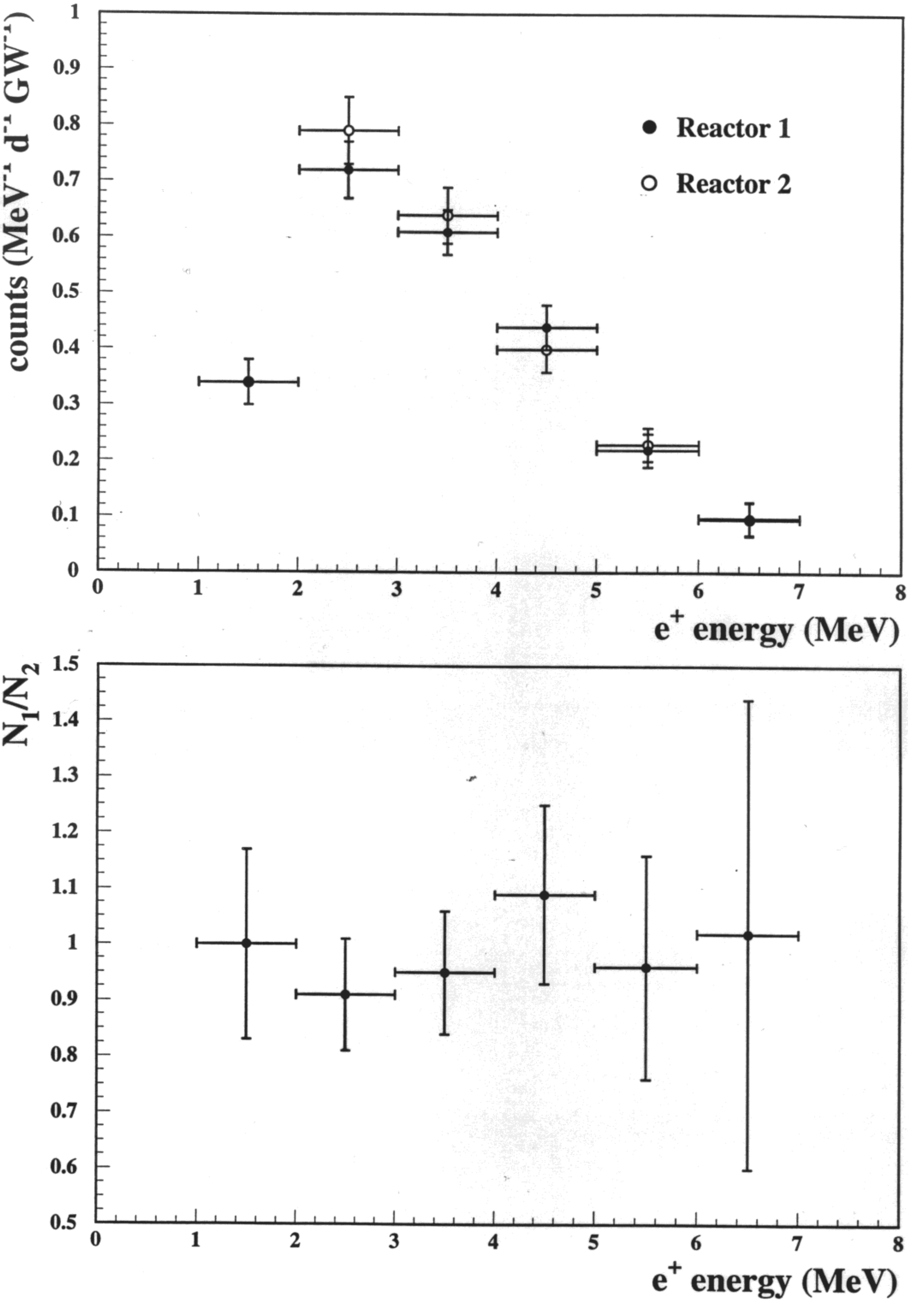
Cf+ MC	0.84	ε_{ncapt}	1%	
QVT + MC	0.97	ε_{e^+} (thr-8 MeV, d > 30 cm)	0.7%	
Cf+ MC	0.95	ε_n (6-12 MeV, d > 30 cm)	1%	
Cf+ MC	0.97	ε_{drel}($\leq$ 100 cm)	1.5%	•
Cf	0.94	$\varepsilon_{\Delta t}$ (2-100 μs)	0.5%	
Bkg. rate	0.99	ε_{1n}		
			2.2%	

$$\varepsilon_{tot} = 0.71 \pm 0.02$$

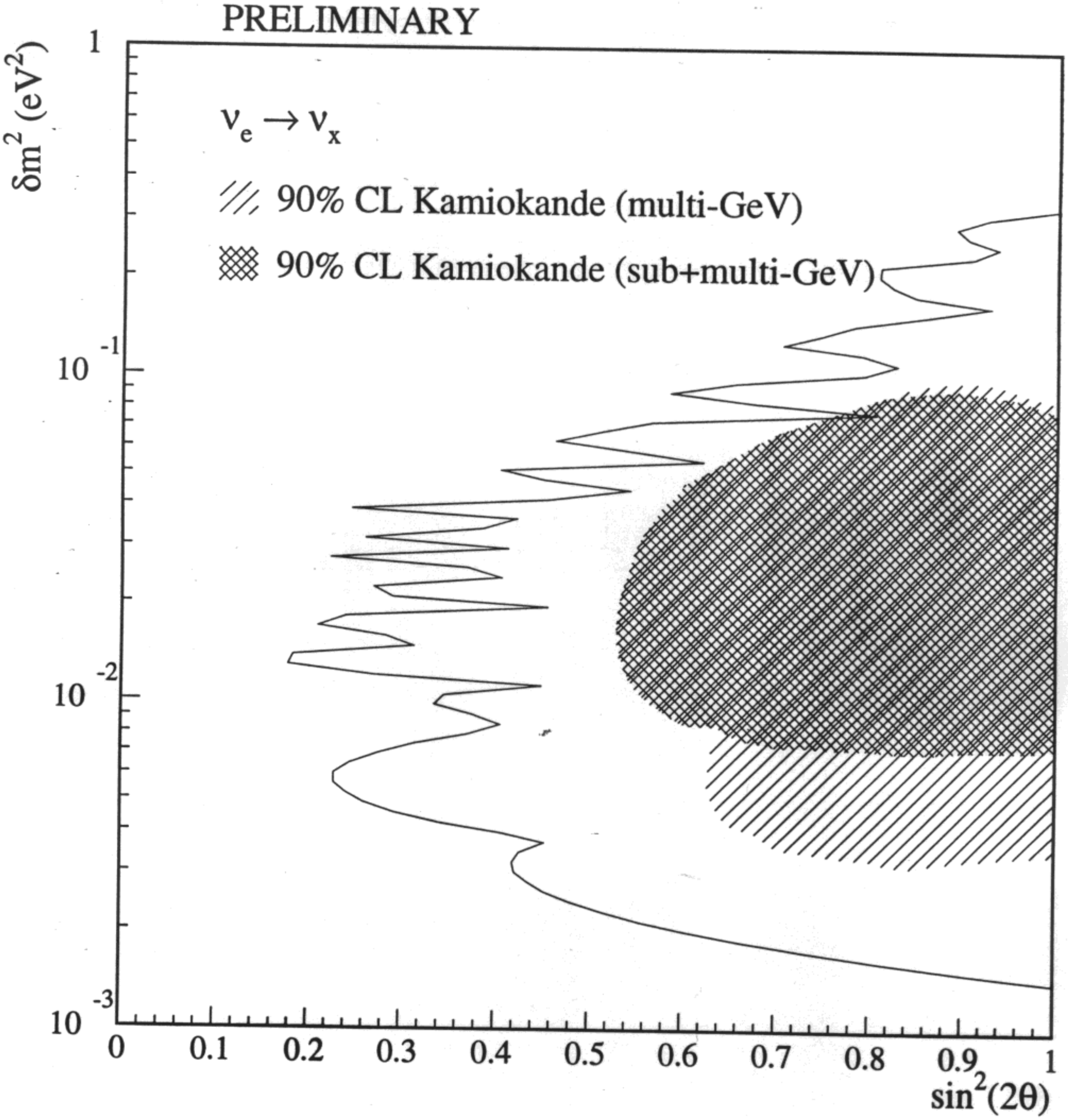
$$\#\ \text{expected at full power} = 26.1 \pm 1.1$$



Gösgen
Krasnoyarsk
Bugey
Kamiokande
(sub + multi-GeV)
Kamiokande
(multi-GeV)
CHOOZ
Δm^2 (eV^2)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\theta$



counts (MeV⁻¹ d⁻¹ GW⁻¹)
Reactor 1
Reactor 2
e⁺ energy (MeV)
N1/N2
e⁺ energy (MeV)



PRELIMINARY
δm^2 (eV^2)
1
10^{-1}
10^{-2}
10^{-3}
$\nu_e \rightarrow \nu_x$
90% CL Kamiokande (multi-GeV)
90% CL Kamiokande (sub+multi-GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2(2\theta)$

KamLAND

The Ultimate Reactor (and Solar) ν Experiment

Definite Exploration of large Mixing Solar MSW Solution
(from Reactor $\bar{\nu}_e$ Disappearance)

Shed Light on small Mixing Solar MSW at Low E_ν
(from Solar Be ν_e)

Shed Light on "Just So" Solution
(from Seasonal Variations)

$\bar{\nu}_e$ from 16 Power Reactors at 100-300km

1 kt Liquid Scintillator at Kamiokande

Rate: 1075/y

$\Delta m^2 > 4 \times 10^{-6}\ eV^2$

Begin > 2001

NEUTRINO MAGNETIC MOMENT

AT A REACTOR

Impetus:
- Time-dependent solar ν in ^{37}Cl detector suggests $\mu_\nu \sim 10^{-11} - 10^{-10}$ μ_B
  Resonant Spin Flavor Precession RSFP
- ν – Interaction in Supernovae, etc.
- Basic ν – Mass

$\nu_e e^- \rightarrow \nu_e e^-$ scattering has μ_ν dependent part at low recoil energy

Previous Results at Reactors

Reines (1976), 16kg Plastic Sc, $\mu_\nu = 2\text{-}4 \; 10^{-10}$ μ_B

Gurevitch (1991), 103kg $C_6 F_6$, $\mu_\nu < 2.4 \; 10^{-10}$

Derbin (1994), 75kg Si, $\mu_\nu < 1.8 \; 10^{-10}$

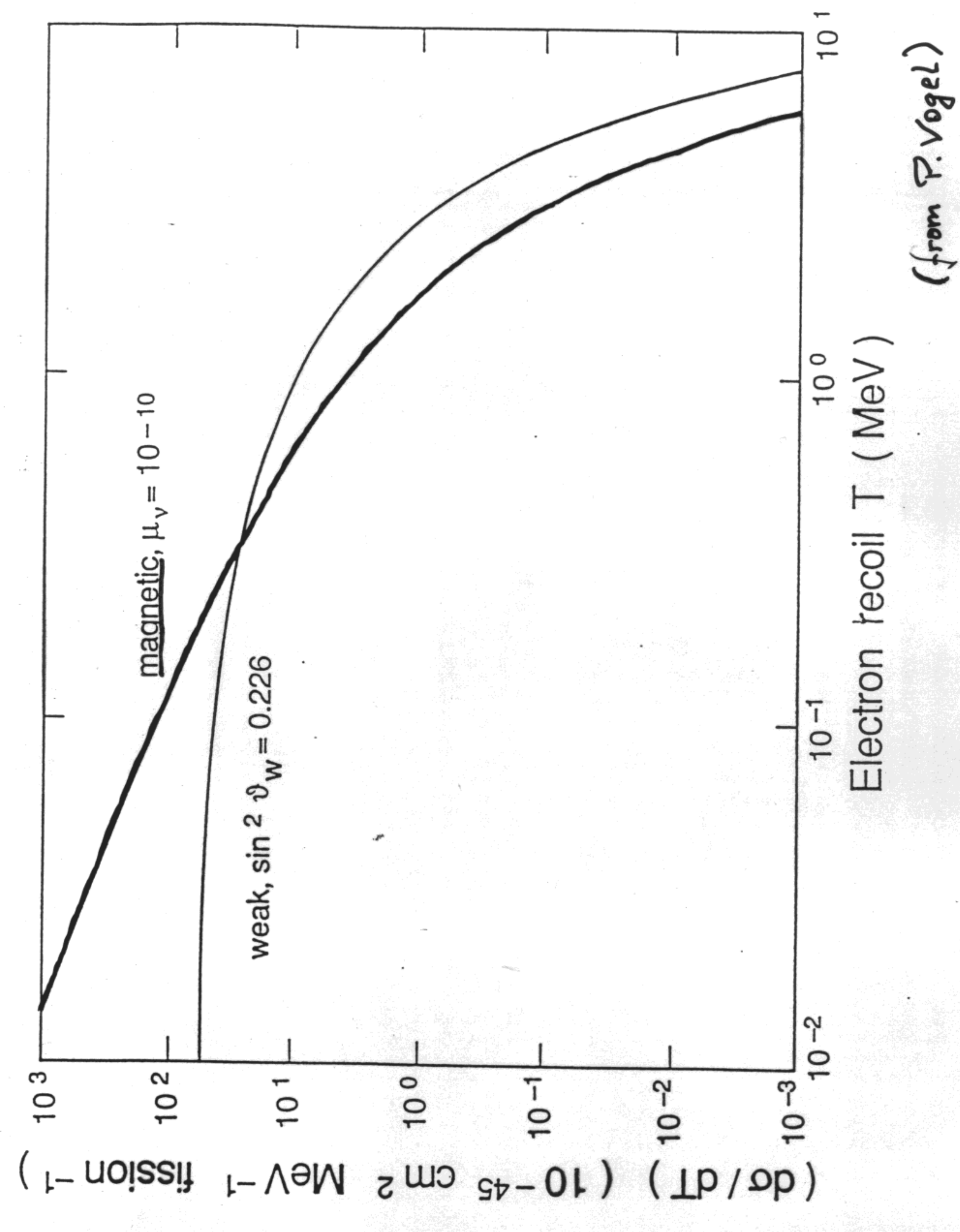


Figure 1: Contributions to the expected cross-section for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ scattering averaged over the reactor $\bar{\nu}_e$ spectrum. The contribution from weak interaction alone (first line of eq. 3) and from a magnetic moment $\mu_\nu = 10^{-10}$ alone (second line) are shown separately [9].

THE MUNU EXPERIMENT

(Grenoble, Münster, Neuchâtel, Padova, Zürich)

Target: CF_4, 1000L at 5 bars (18.5kg)

works as TPC

Anti-Compton Shield

Reactor Flux (BUGEY) : $10^{13}\ \bar{\nu}/cm^2\ s$

Expected Events

0.5 - 1 MeV	5.1 /d
> 1 MeV	4.6 /d

Expected Background 4.5 /d

Use Angular Correlation $\bar{\nu}_e$, e−

Expected sensitivity $\mu_\nu \sim 3 \times 10^{-11}$

Status: TPC installed + operating

No Data yet

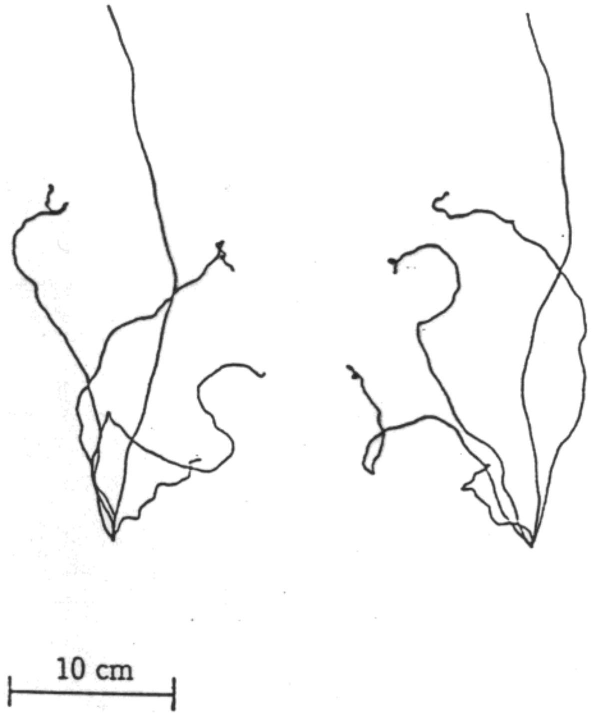


Figure 3: Simulated electron tracks (T > 0.5 MeV) in CF_4 at 5 $bars$ from $\overline{\nu}_e e^-$ at a reactor. The neutrinos come along the z axis, the $x - z$ and $y - z$ projections are shown.

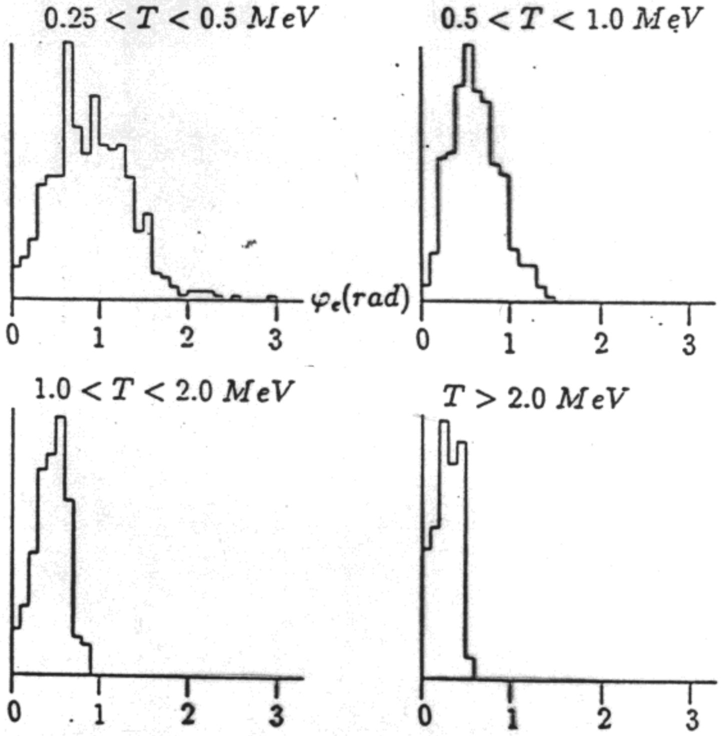


Figure 4: Simulated angular distribution of the recoil electron determined from the first 2 cm of track in CF_4 at 5 bar.

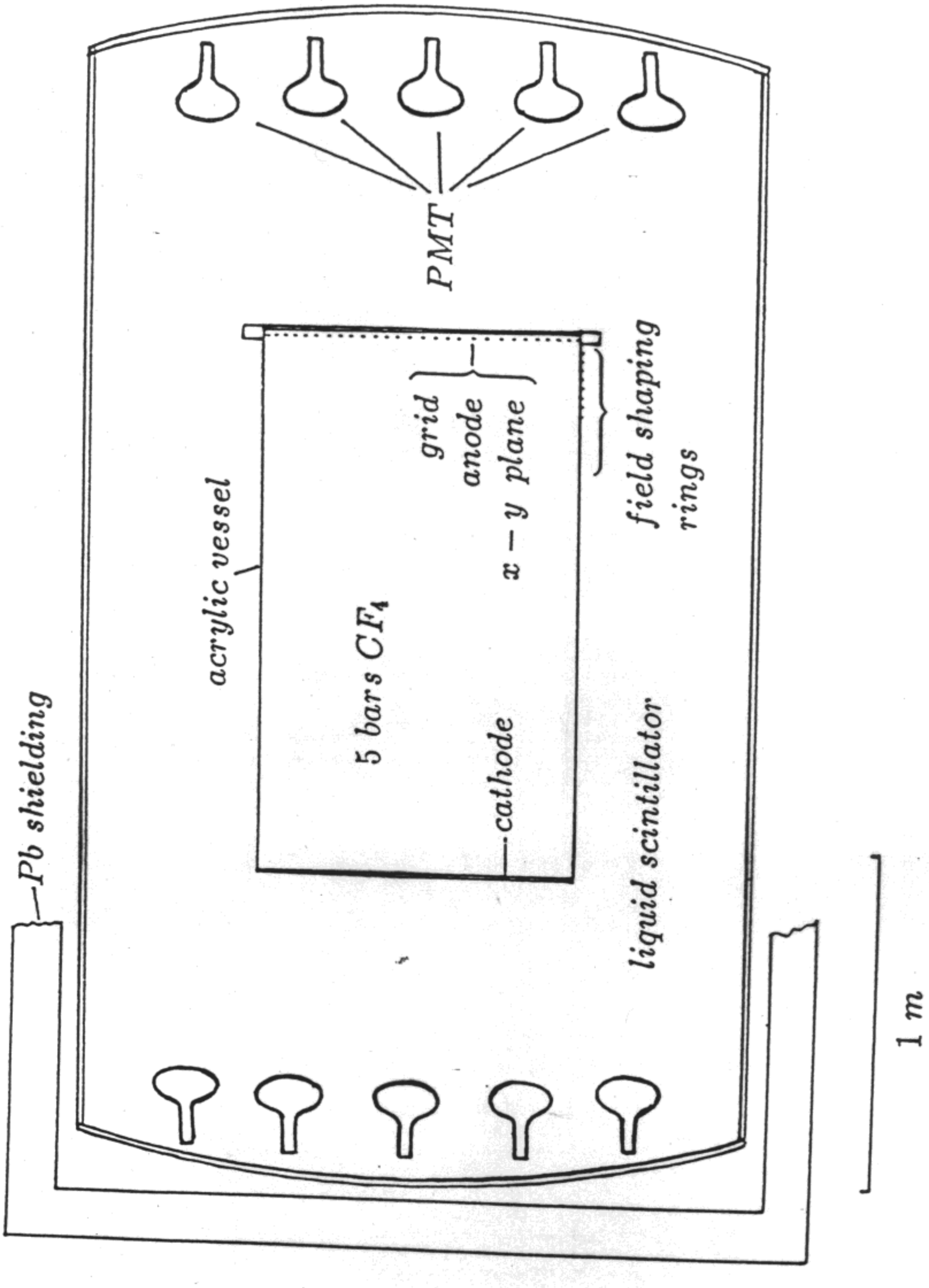


Figure 2: General layout of the detector.

CONCLUSION

Kamiokande ν_μ deficiency
ruled out as $\nu_\mu \to \nu_e$

Chooz : with very large CL

Paloverde (early): with 90% CL

Remains study of small $\sin^2 2\vartheta$
(3-flavor solution)

Kamland → Suzuki

Munu progress but no data