MiniBooNE at First Physics

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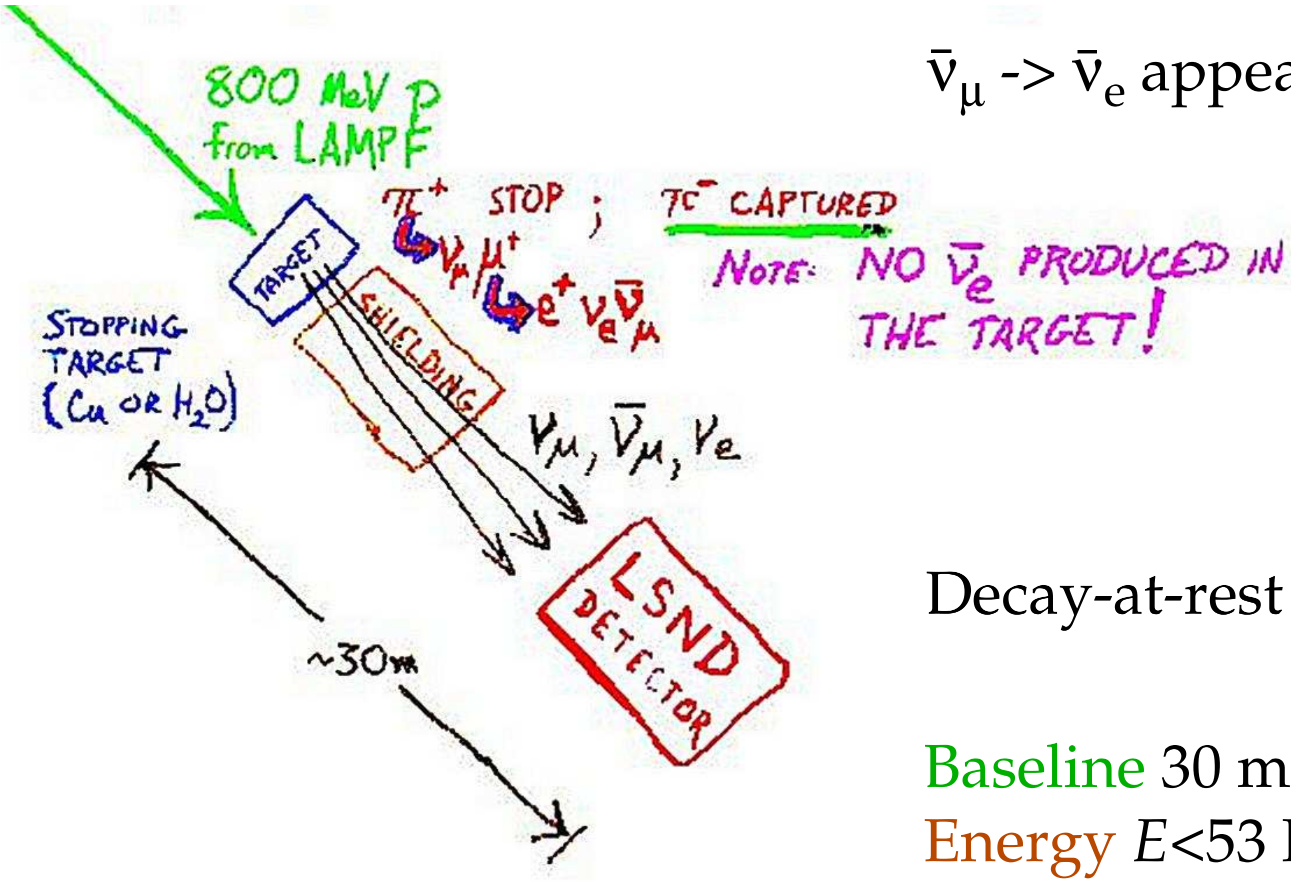
MiniBooNE at First Physics

- Physics motivation: LSND
- MiniBooNE overview
  - Beam
  - Detector
  - Reconstruction and particle ID
- First physics results
- Status and near future

LSND decay-at-rest neutrino source



$\bar{\nu}_\mu$ -> $\bar{\nu}_e$ appearance search

Decay-at-rest E_ν<53 MeV

Baseline 30 meters

Energy E<53 MeV

L/E ~ 1-1.5 km/GeV

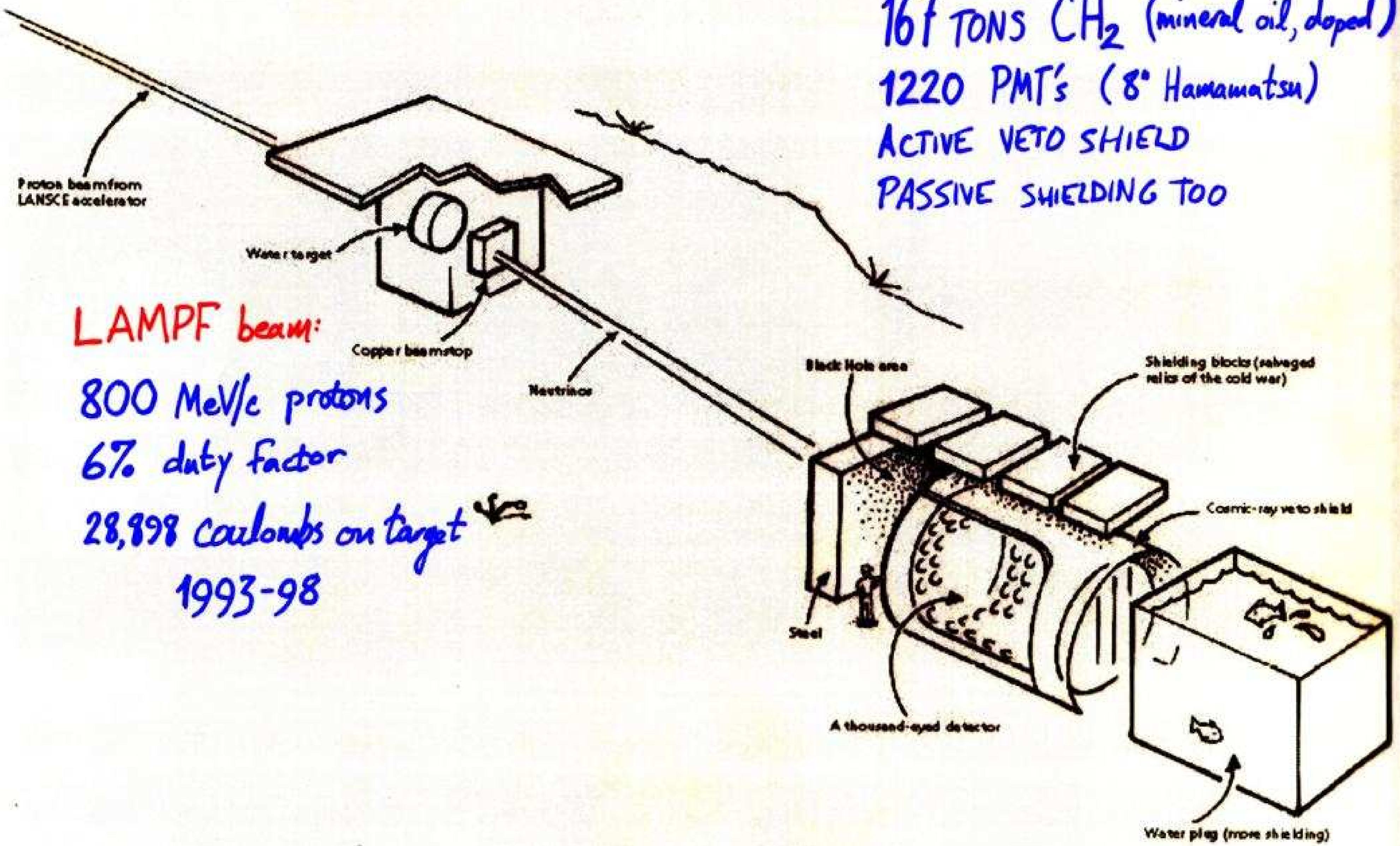
LSND DETECTOR:

167 TONS CH_2 (mineral oil, doped)

1220 PMT's (8" Hamamatsu)

ACTIVE VETO SHIELD

PASSIVE SHIELDING TOO



LAMPF beam:

800 MeV/c protons

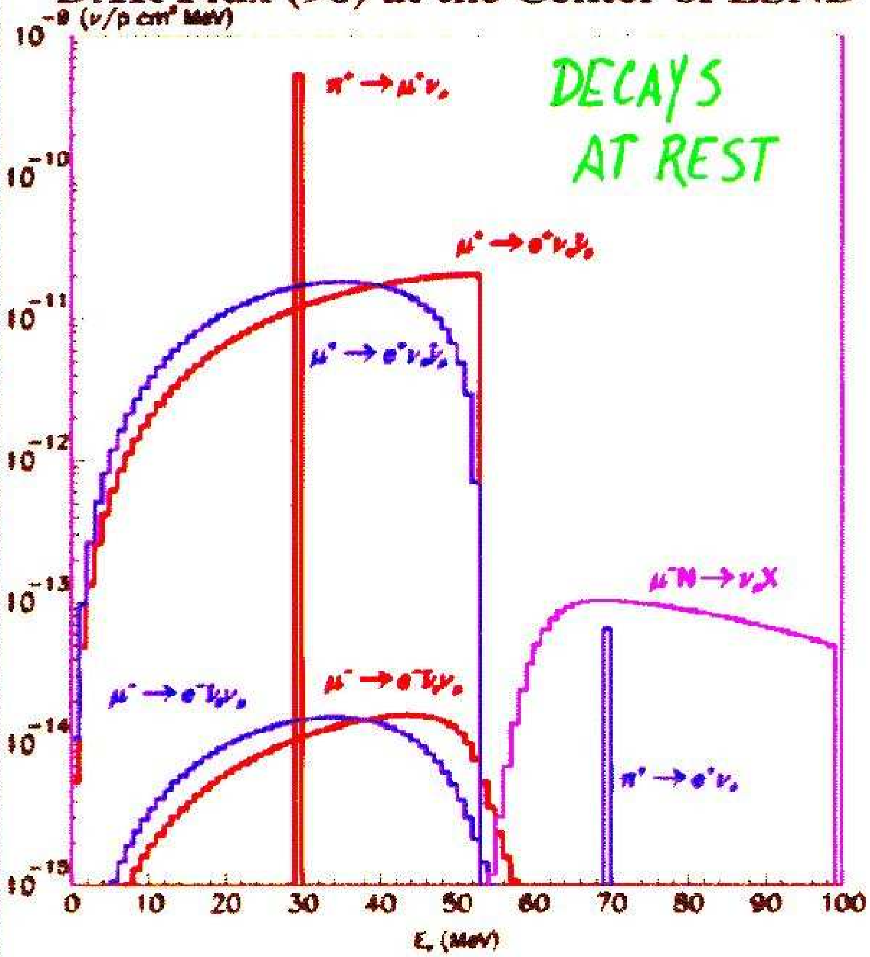
6% duty factor

28,898 coulombs on target

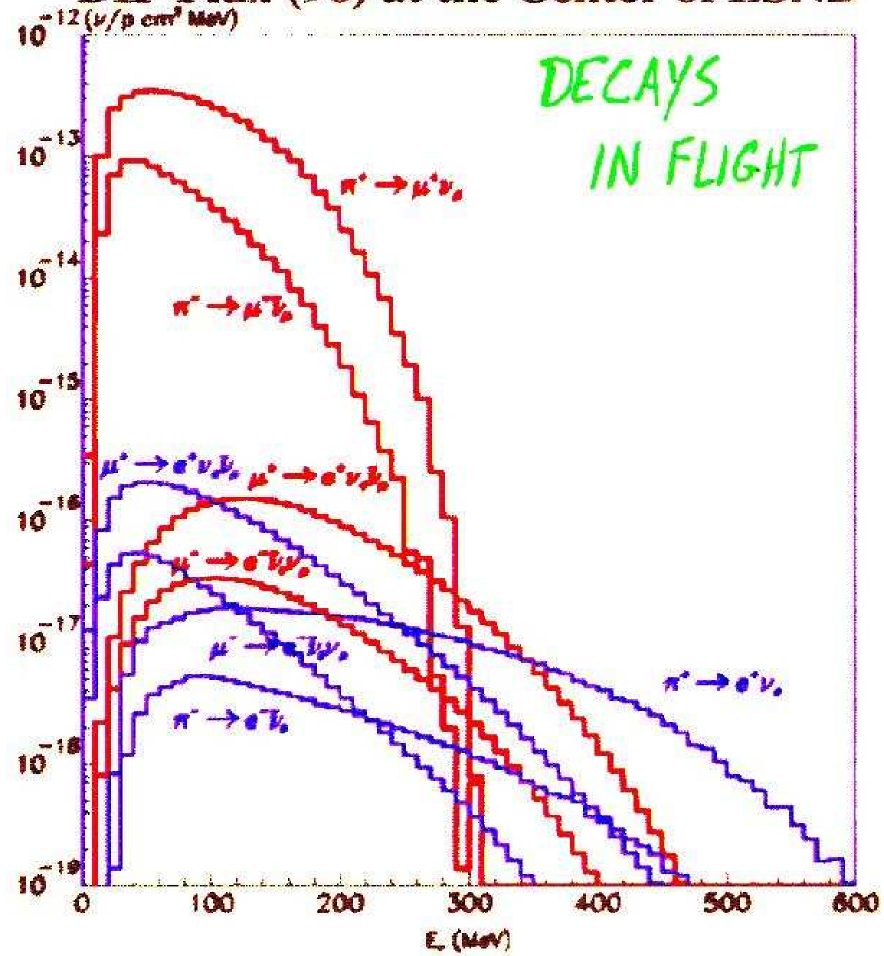
1993-98

Neutrino Fluxes

DAR Flux (96) at the Center of LSND

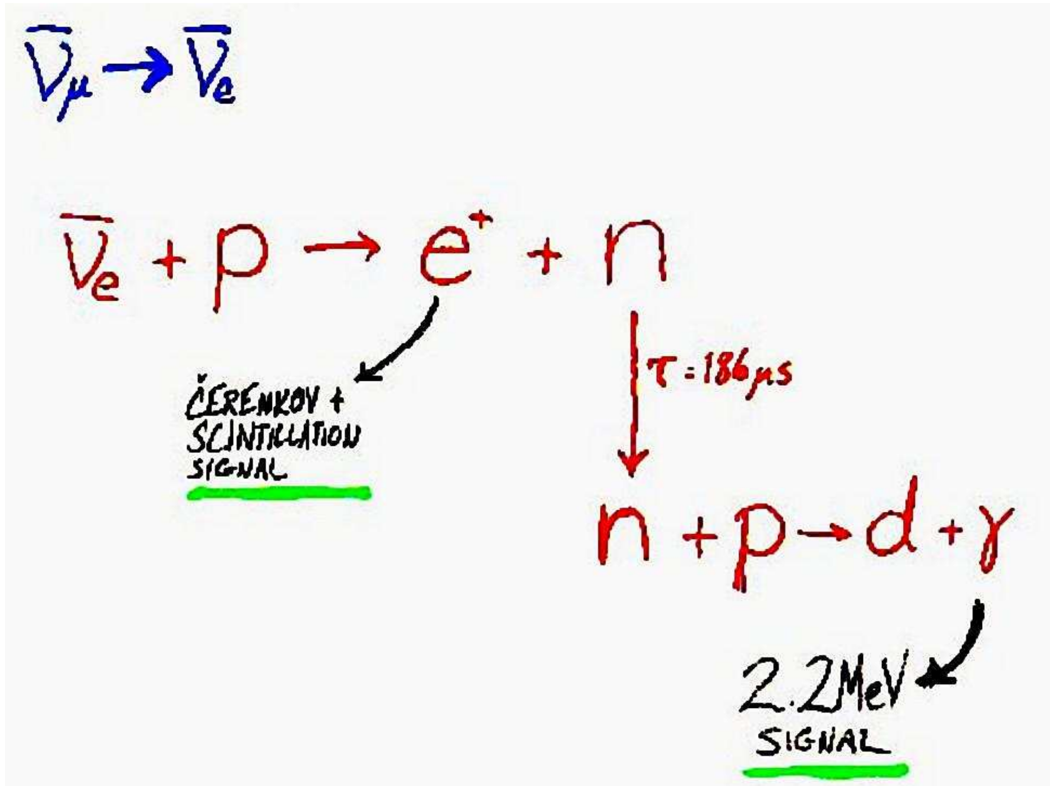


DIF Flux (96) at the Center of LSND



LSND oscillation signature

From μ^+ decay at rest:



Reconstruct e^+ and γ with appropriate delayed coincidence

Event selection criteria at LSND

TARGETED BACKGROUND	CUTS
NON-ELECTRON	PARTICLE ID USING ČERENKOV CONE SHAPE AND TIMING DISTRIBUTION
COSMIC RAY MUON	VETO SHIELD
COSMIC RAY NEUTRON	ONLY ONE γ RECONSTRUCTS
POSITRON FROM μ DECAY	NO MUON-LIKE ACTIVITY IN 15 μs BEFORE EVENT
ACCIDENTAL γ COINCIDENCE	CUT ON LIKELIHOOD RATIO R (INCORPORATES SPATIAL, TEMPORAL PROXIMITY)
REMAINING BEAM-UNRELATED BACKGROUNDS	MEASURE USING BEAM-OFF DATA (94% OF LIVE TIME) AND SUBTRACT.

R>10 = "golden mode"

LSND

20 MeV ≤ $E_{visible}$ ≤ 60 MeV data

- From R>10 sample (lowest background):

OBSERVED EVENTS		83
BEAM-UNRELATED BACKGROUND	(-)	33.7
$\bar{\nu}_e$ BACKGROUND (mostly from μ^- in beam dump)	(-)	8.5
$\bar{\nu}_\mu$ BACKGROUND (μ^+ decay in detector)	(-)	3.5
OTHER ν BACKGROUNDS (WITH NO NEUTRON)	(-)	4.6
UNEXPLAINED EXCESS		32.7 ± 9.2

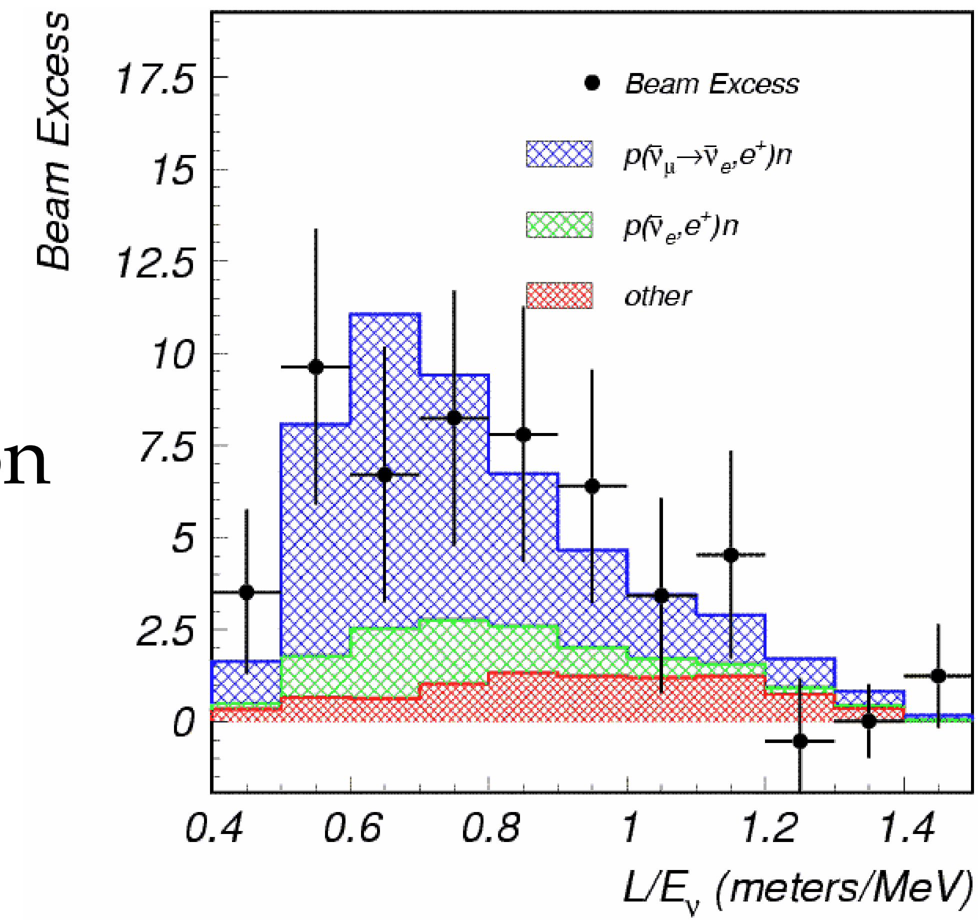
- From fit to R distribution:

OSCILLATION EXCESS	83.5 ± 21.2
$\bar{\nu}_\mu \to \bar{\nu}_e$ OSCILLATION PROBABILITY	$(2.5 \pm 0.6 \pm 0.4) \times 10^{-3}$

LSND

R>10 data

Energy distribution consistent with oscillations



Δm^2 ~ 0.2-10 eV^2

KARMEN2: similar expt in England, no evidence for oscillations.

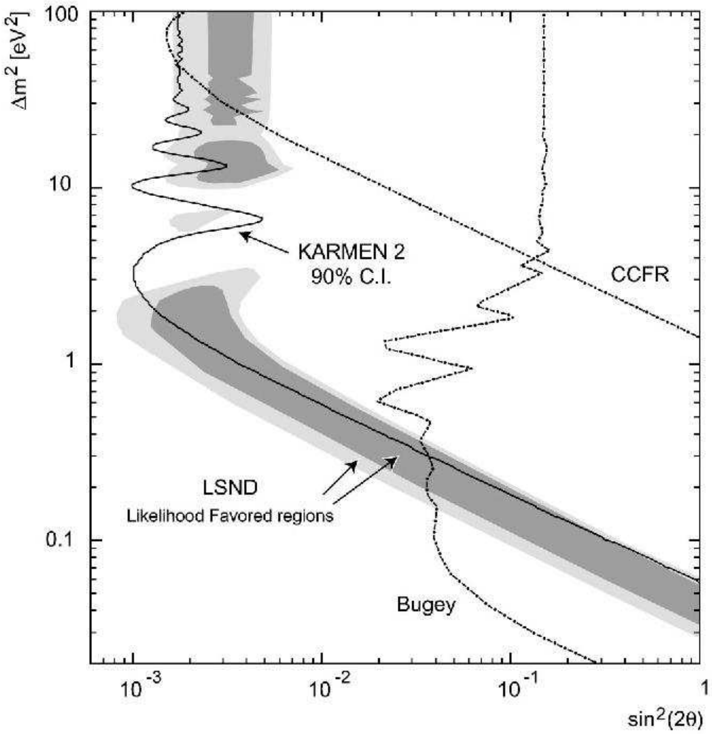


FIG. 14. Comparison of oscillation searches performed by different short baseline experiments.

These examples based on expected additional $\bar{\nu}_e$ events from $\bar{\nu}_\mu \to \bar{\nu}_e$ demonstrate that at smaller values of Δm^2 there is a restricted parameter region statistically compatible with both experimental results. At high Δm^2 values, the LSND solutions are in clear contradiction with the KARMEN upper limit.

VIII. CONCLUSION

Results based on the entire KARMEN2 data set collected from 1997 through 2001 have been presented. The extracted candidate events for $\bar{\nu}_e$ are in excellent agreement with background expectations showing no signal for $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations. A detailed likelihood analysis of the data leads to upper limits on the oscillation parameters $\sin^2(2\Theta)$ and Δm^2 excluding parameter regions not explored analyzed by other experiments.

These limits exclude large regions of the parameter area favored by the LSND experiment. A more quantitative statistical statement on the compatibility between KARMEN and LSND has to be based on a combined statistical analysis of both likelihood functions [65]. Such a detailed joint statistical analysis has been performed [66].

The negative search for $\bar{\nu}_e$ from muon decay at rest presented here sets also stringent limits on other potential processes of $\bar{\nu}_e$ production such as lepton family number violating decays $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ or neutrino oscillations $\nu_e \to \bar{\nu}_e$ which will be discussed in a separate paper. Future experiments such as the MiniBooNE experiment at Fermilab [67] aim at investigating the LSND evidence and the oscillation parameters not yet excluded by the $\bar{\nu}_\mu \to \bar{\nu}_e$ search presented here.

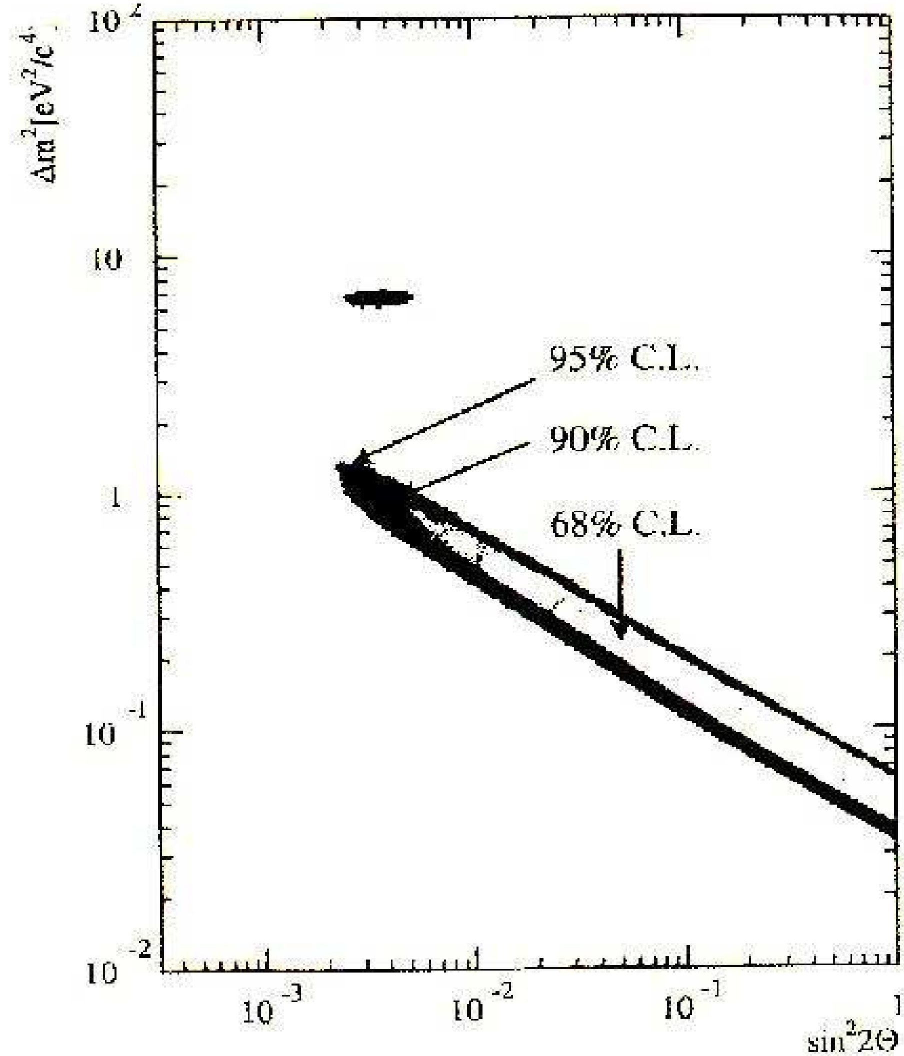
ACKNOWLEDGMENTS

We gratefully acknowledge the financial support from the German Bundesministerium für Bildung und Forschung (BMBF), the Particle Physics and Astronomy Research Council (PPARC), and the Council for the Central Laboratory of the Research Councils (CCLRC). In particular, we thank the Rutherford Appleton Laboratory and the ISIS neutron facility for hospitality and steady support during years of data taking.

Joint KARMEN-LSND analysis:

- No disagreement between experiments

- Narrows allowed parameter range



E. CHURCH et al, hep-ex/0203023

Too many Δm^2's:

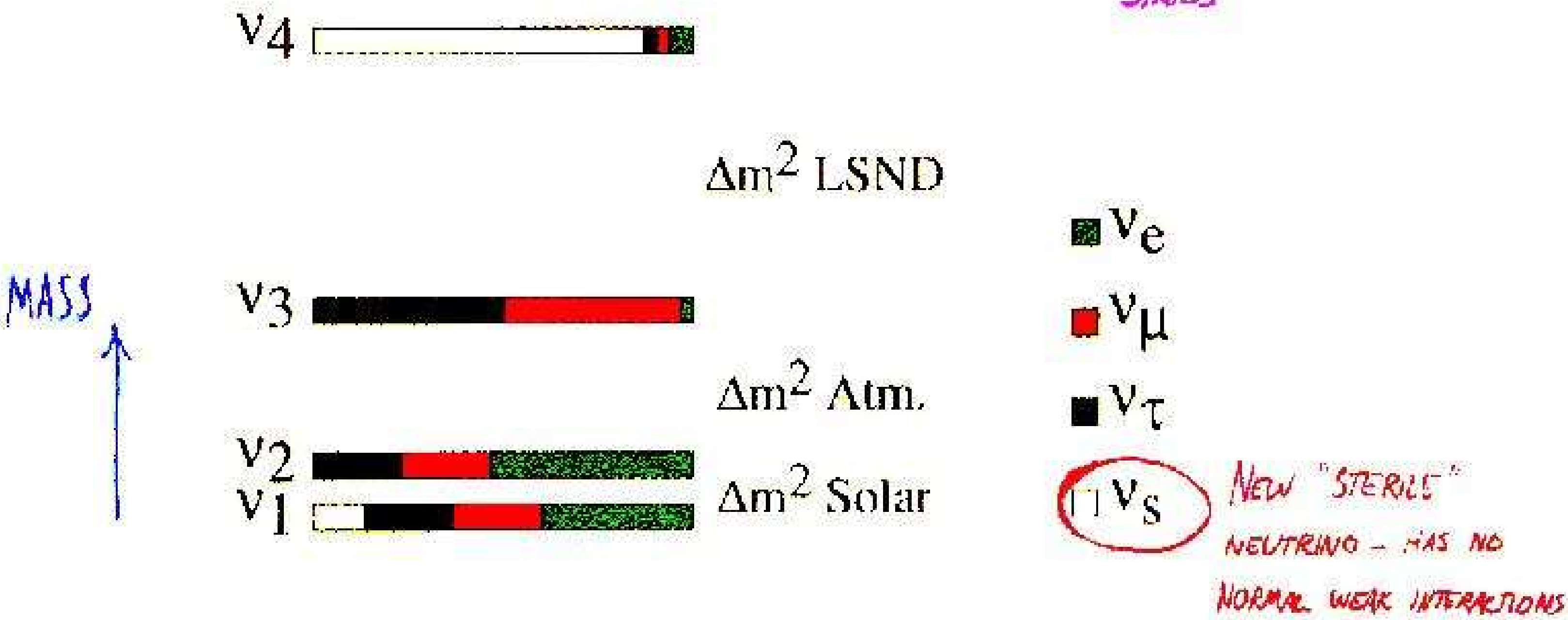
- Only 3 light, weakly interacting neutrinos (LEP,SLD)
- Solar/KAMLAND Δm^2: 7×10^{-5} eV^2 (mostly $\nu_e \to \nu_{\mu,\tau}$)
- Atmospheric Δm^2: 2×10^{-3} eV^2 (mostly $\nu_\mu \to \nu_\tau$)
- LSND Δm^2: 0.2-10 eV^2 (mostly $\nu_\mu \to \nu_e$)
- $\Delta m^2_3 = \Delta m^2_1 + \Delta m^2_2$
- What's going on?
  - One set of experiments is not seeing oscillations
  - The neutrino sector contains nonstandard physics beyond oscillations

New Physics I: Sterile Neutrinos

An Experimentally Allowed Model

- Bimaximal mixing in 3 + 1 models
  - W. Krolikowski HEP-PH/0106350
  - R.N.Mohapatra Phys.Rev. D64 (2001) 091301,

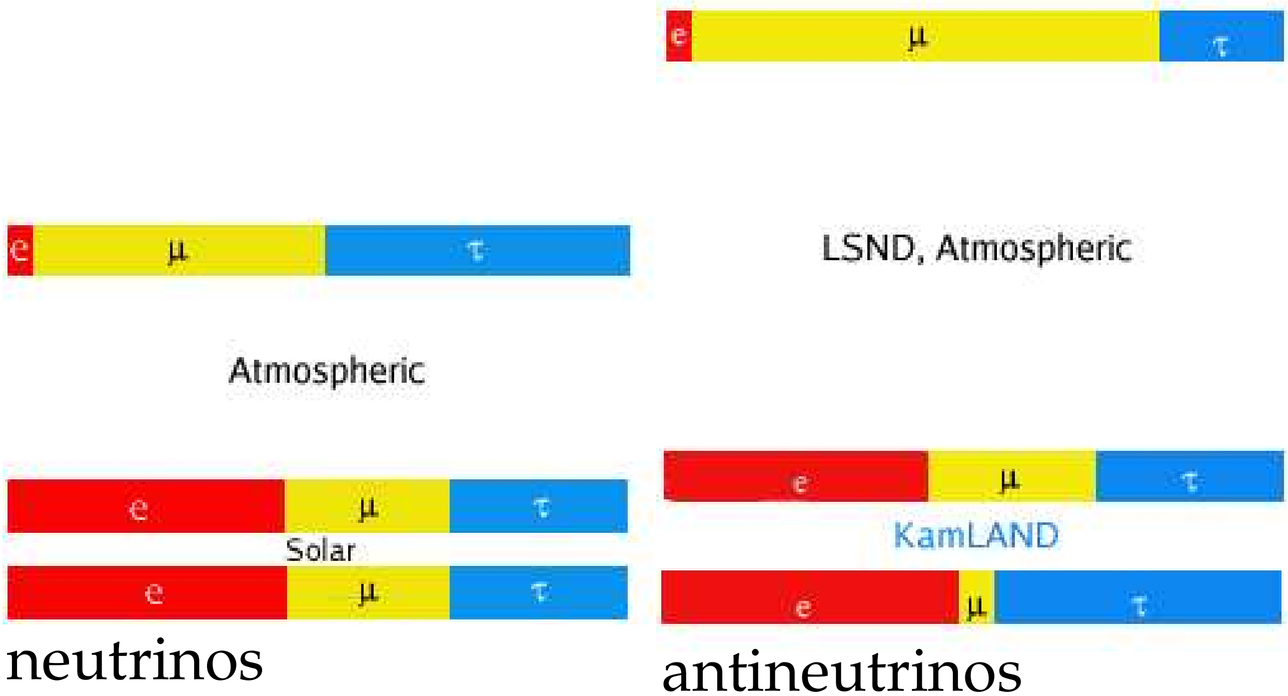
SOLVE "TOO MANY Δm^2" PROBLEM BY ADDING EXTRA NEUTRINO MASS STATES



New Physics II: Maximal CPT violation

(Barenboim, Borissov, and Lykken, hep ph/0212116)

- Independent mass hierarchies for ν and $\bar{\nu}$.

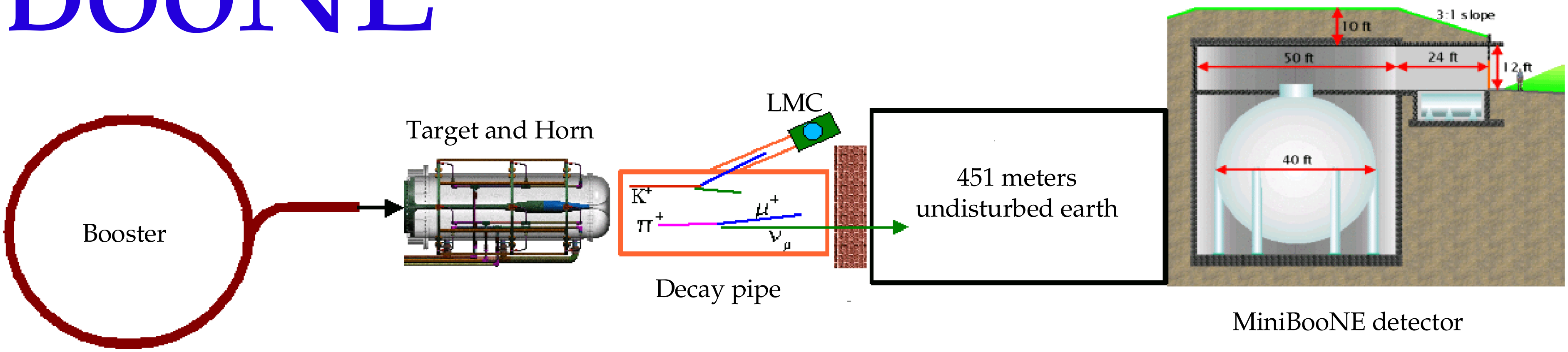


- Proposed in 2001, but accomodates KamLAND

- Side benefit: heavier antineutrinos allow early universe leptogenesis in thermal equilibrium

- Compatibility with SuperK data may be a stretch.

BooNE



- BooNE will test the LSND result with:
  - x10 statistics
  - Different beam
  - Different energy
  - Different oscillation signature
  - Different systematics
- Primary beam: 8 GeV protons from Fermilab Booster
- Horn-focused secondary π, *K* decay in flight to neutrinos
- 500 meter oscillation baseline
- 800 ton mineral oil/Čerenkov detector

The BooNE Collaboration

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BooNE Collaboration
(with summer students)
Summer 2002

OSCILLATION SIGNATURE AT BOONE:

$\nu_e N \to e^- N'$ quasielastic scattering

NEUTRINO ENERGY 0.5 ~ 1 GeV

NORMALIZE TO $\nu_\mu N \to \mu^- N'$ (several $\times 10^5$ interactions)

PARTICLE ID BY ČERENKOV RING SHAPE.

BACKGROUNDS TO OSCILLATION:

INTRINSIC ν_e IN BEAM:

- FROM $\pi \to \mu \to \nu$ DECAY IN SECONDARY BEAM
- FROM Ke_3 DECAYS ($K^+ \to \pi^0 e^+ \nu_e$, $K^0_L \to \pi^0 e^\pm \overset{(-)}{\nu}_e$)

PARTICLE MIS-ID IN DETECTOR

- μ DECAYS TO e, μ NOT OBSERVED
- μ MIS-ID AS e, DECAY NOT SEEN
- π^0 PRODUCED IN NEUTRAL CURRENTS, MIS-ID AS e

WHAT IS "MINI-BOONE?"

- **FIRST** PHASE OF THE BOONE PROGRAM:
  - A SINGLE NEUTRINO DETECTOR, BASELINE 500 m
  - GOAL IS DEFINITIVE TEST OF LSND SIGNAL
  - SOME SENSITIVITY TO ν_μ DISAPPEARANCE

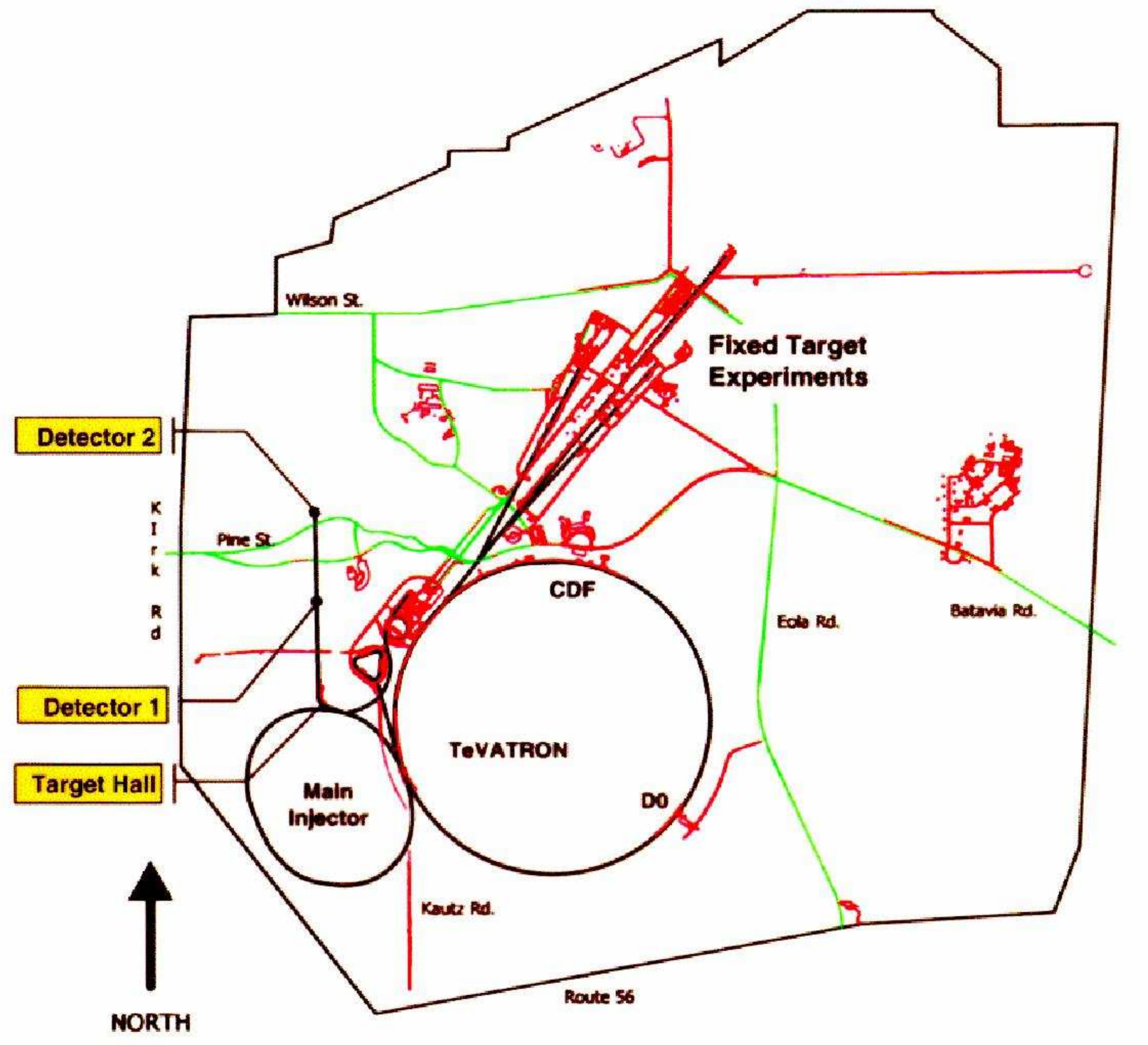
THIS IS EXPERIMENT 898, OR "MINI-BOONE."

IT IS APPROVED, FUNDED, AND RUNNING

- **FUTURE** PHASE OF THE PROGRAM:

  ASSUMING LSND CONFIRMED,
  - BUILD A SECOND DETECTOR OF SIMILAR DESIGN
  - NEW DETECTOR BASELINE OF 1000 m (IF LOW Δm^2)
250 m (IF HIGH Δm^2)
  - PRECISE MEASUREMENT OF OSCILLATION PARAMETERS
  - MUCH BETTER SENSITIVITY TO ν_μ DISAPPEARANCE.

BooNE Location on the Fermilab Site



BooNE's Neutrino Beam

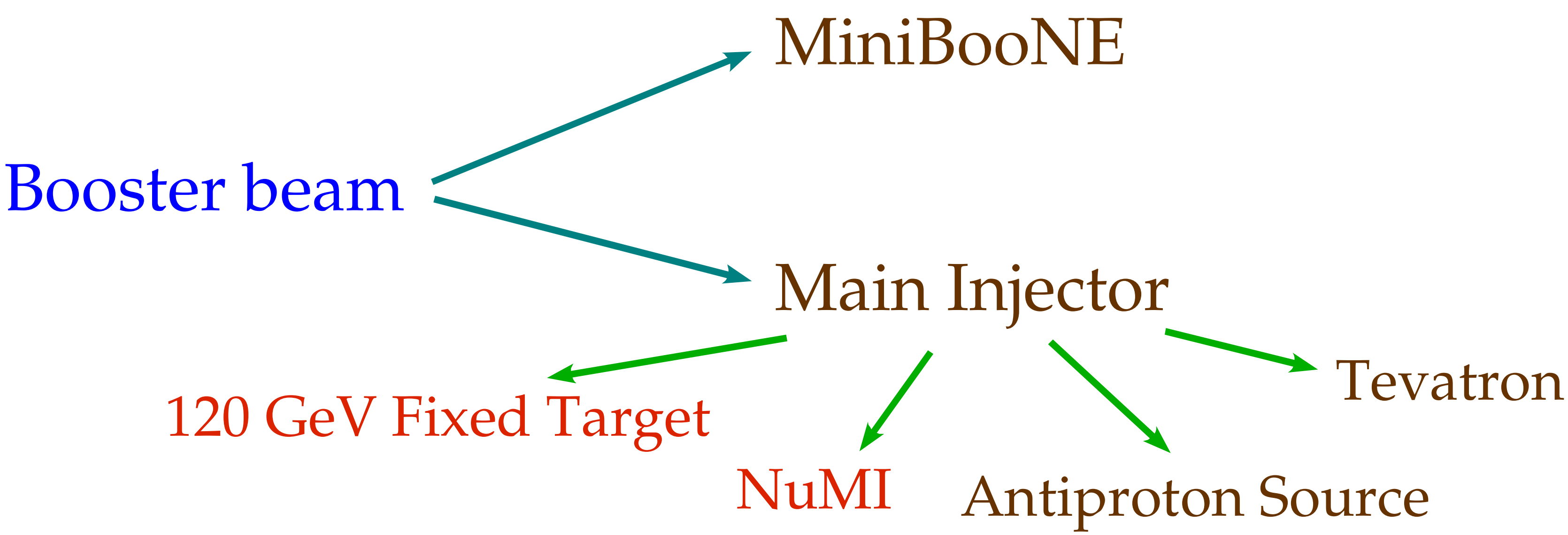
- The Booster
- Horn and Target
- Decay Pipe
- Beam Absorbers
- Kaon Monitoring (LMC)

The Booster

- 8 GeV proton accelerator
  - Built to inject protons into Main Ring
  - Now injects Main Injector
  - Has excess capacity
  - Magnets cycle at 15 Hz

- Extraction
  - All beam extracted in a single turn
  - Pulse is 1.6 μs long; consists of ~82 bunches ("RF buckets") spaced 19 ns apart
  - 10^{-5} duty factor -> eliminates non-beam backgrounds
  - New 8 GeV fixed target facility built for BooNE; can accomodate other users too in future

Demands on the Booster

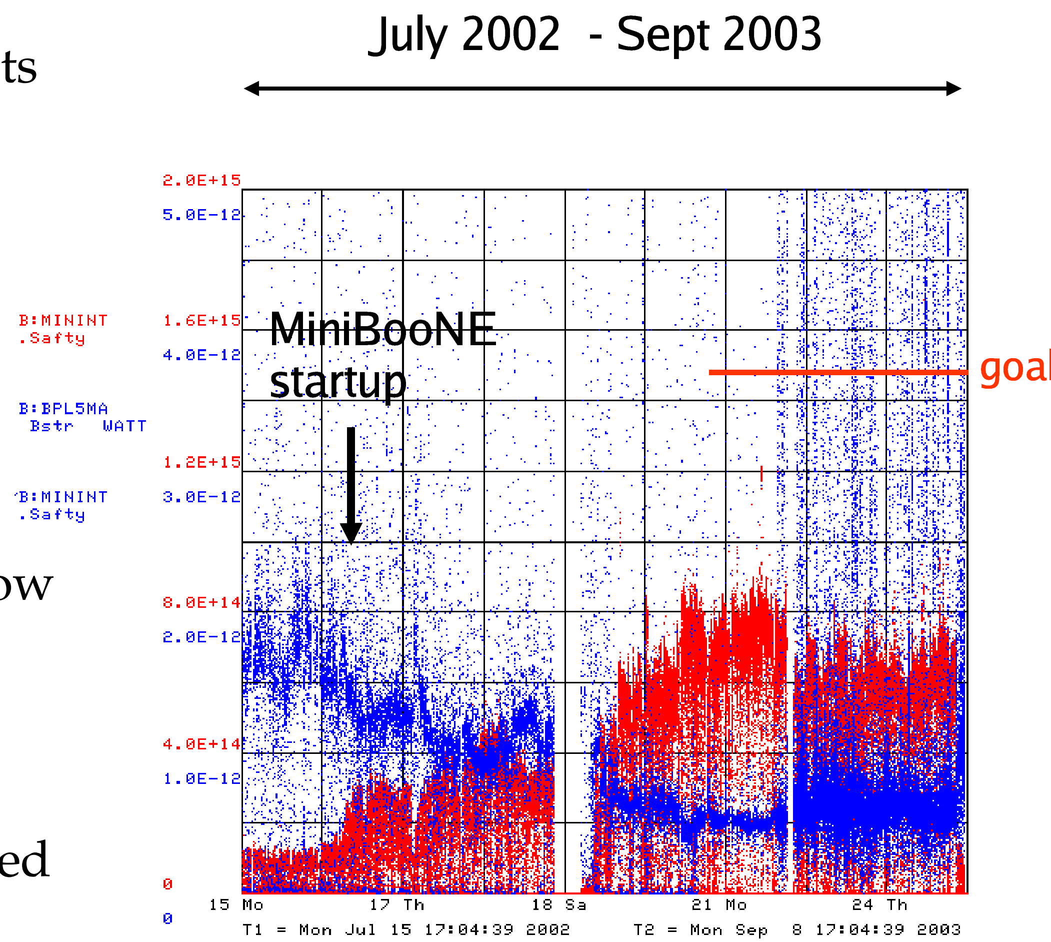


Need record Booster performance for MiniBooNE to operate at satisfactory rate simultaneously with the rest of the FNAL program.

Beam losses are currently limiting the rate.

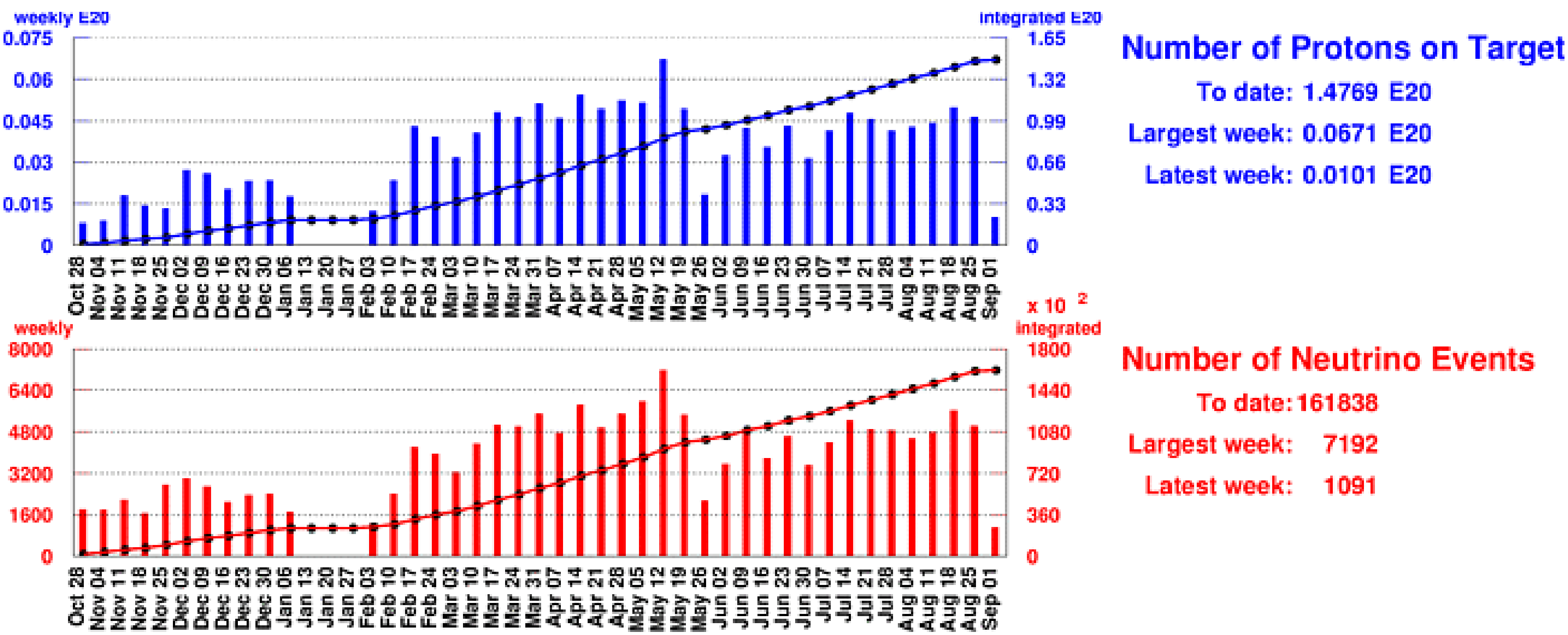
Booster Performance

- Must limit radiation levels and activation of Booster components
  - Increase proton rate
  - Decrease beam loss
- Steady improvements so far through
  - Careful tuning
  - Understanding optics
- Rate about a factor of 2 or 3 below what's needed for us to see 10^{21} p.o.t. before early 2005
- Further improvements:
  - Collimator project (completed in Autumn 2003 shutdown)
  - Lattice improvements
  - (later) larger aperture RF cavities

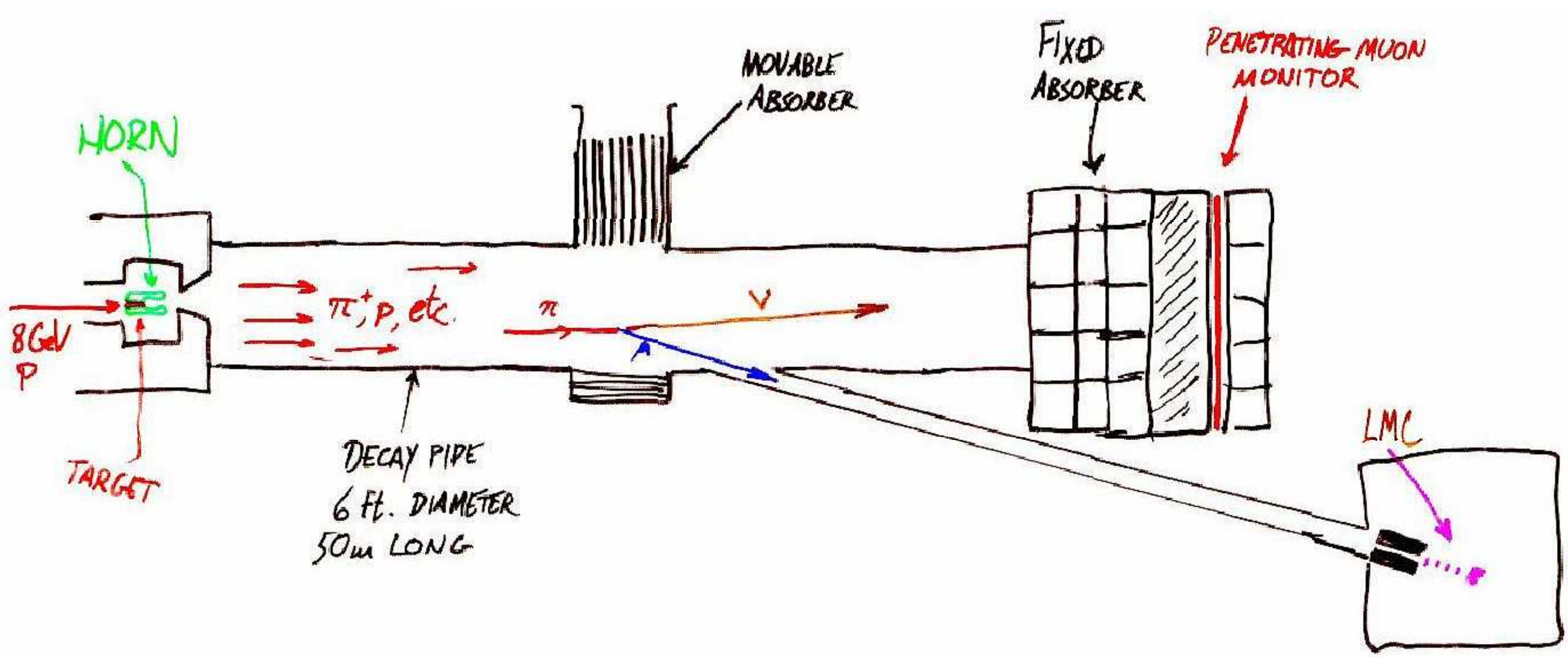


red: Booster output (protons/minute)
blue: energy loss per proton
(W-min/proton)

- Achieved 1.5×10^{20} protons on target before shutdown began September 2.
- Only 15% of goal. We are eagerly awaiting accelerator improvements!



Secondary beam overview

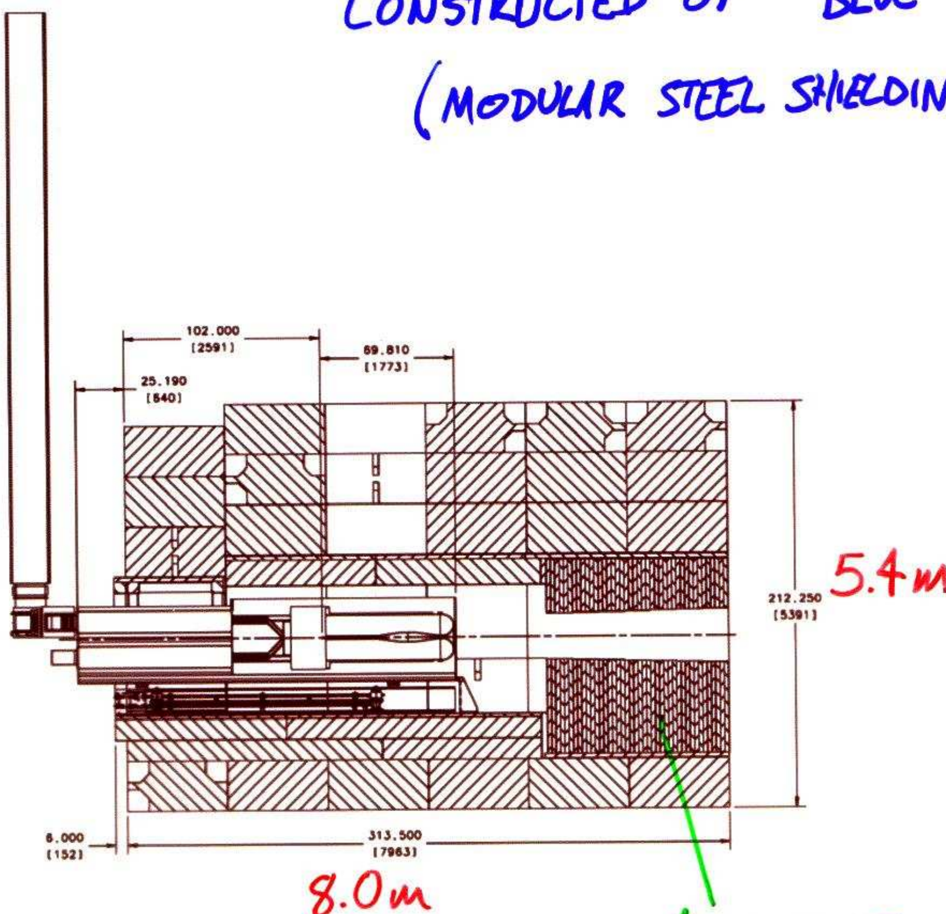


We considered “borrowing” a second horn from BNL to increase our flux, but...

...its condition was somewhat imperfect.

Target Pile

CONSTRUCTED OF "BLUE BLOCKS"
(MODULAR STEEL SHIELDING BLOCKS)



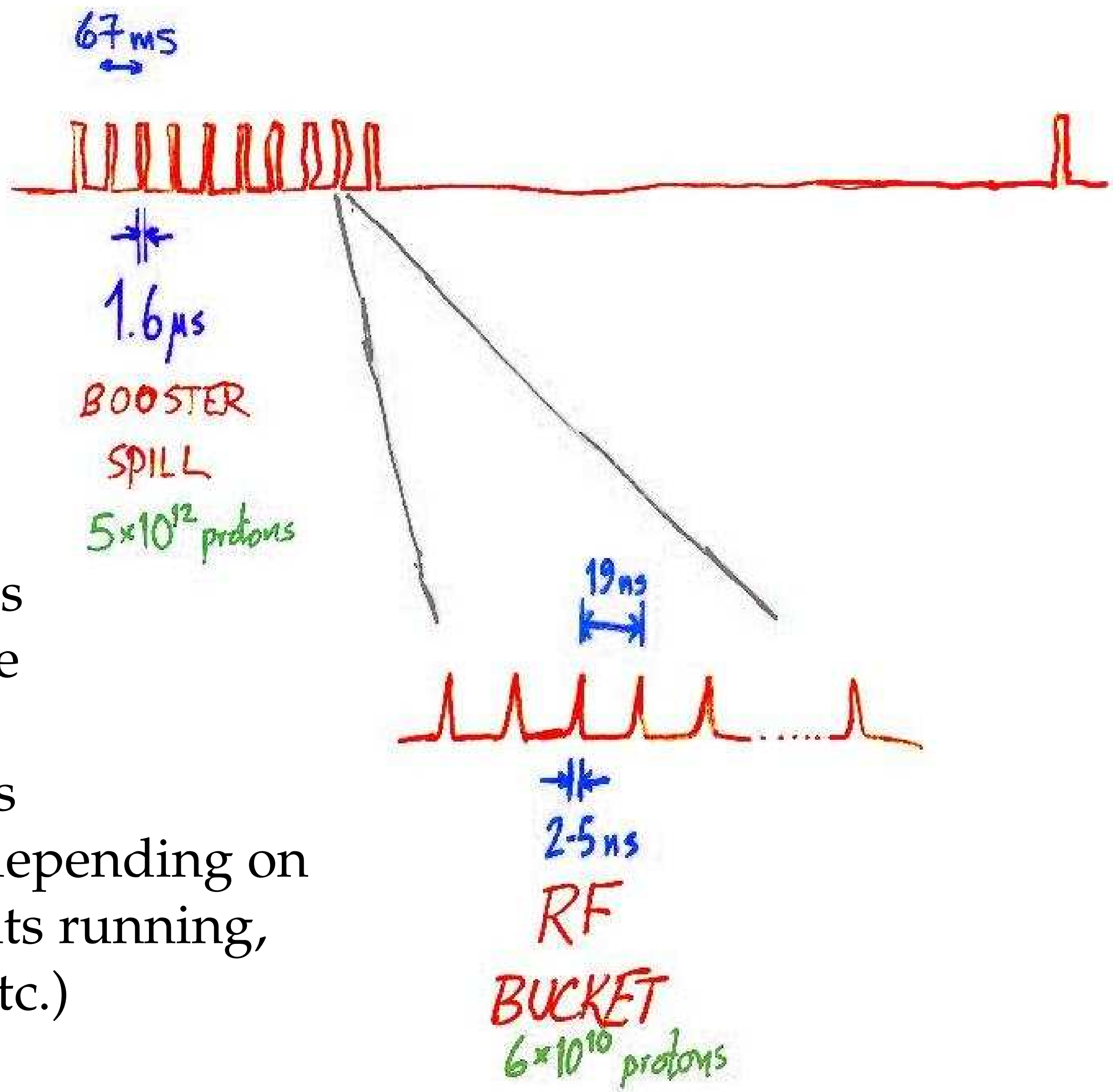
COLLIMATOR
(EXIT 35 in. dia., 5m from target)
CONSTRUCTED OF LAB E STEEL PLATES

Time structure of the beam

Each 2-second cycle:

10 Booster pulses at 15 Hz rep. rate

(many variations on this pattern depending on other experiments running, Booster losses, etc.)



Horn and Target Region

- Primary beam position monitor: air multiwire
- Target: 71 cm beryllium metal (1.7 λ_0), resides inside horn
- Horn:
  - Inner conductor thickness: 3 mm
  - Outer conductor thickness: 25 mm
  - Peak current: 170 kA
  - Pulse width: 140 μs
  - Voltage: ~4 kV

Beryllium Target Assembly

End View

Side View

Horn welding and assembly

THE DECAY PIPE

- 6′ DIA. CORRUGATED METAL PIPE, AIR-FILLED
- SURROUNDED BY GRAVEL SHIELDING
- 50 m LONG, FIXED DUMP AT END
- INTERRUPTED AT 25 m FOR MOVABLE BEAM DUMP

WHY A MOVABLE DUMP? CROSS-CHECK ON BACKGROUNDS:

INTRINSIC ν_e COMES PRIMARILY FROM:

MUONS: $\pi^+ \to \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ → DOUBLE DECAY $\propto \sim L^2$: MOSTLY DOWNSTREAM

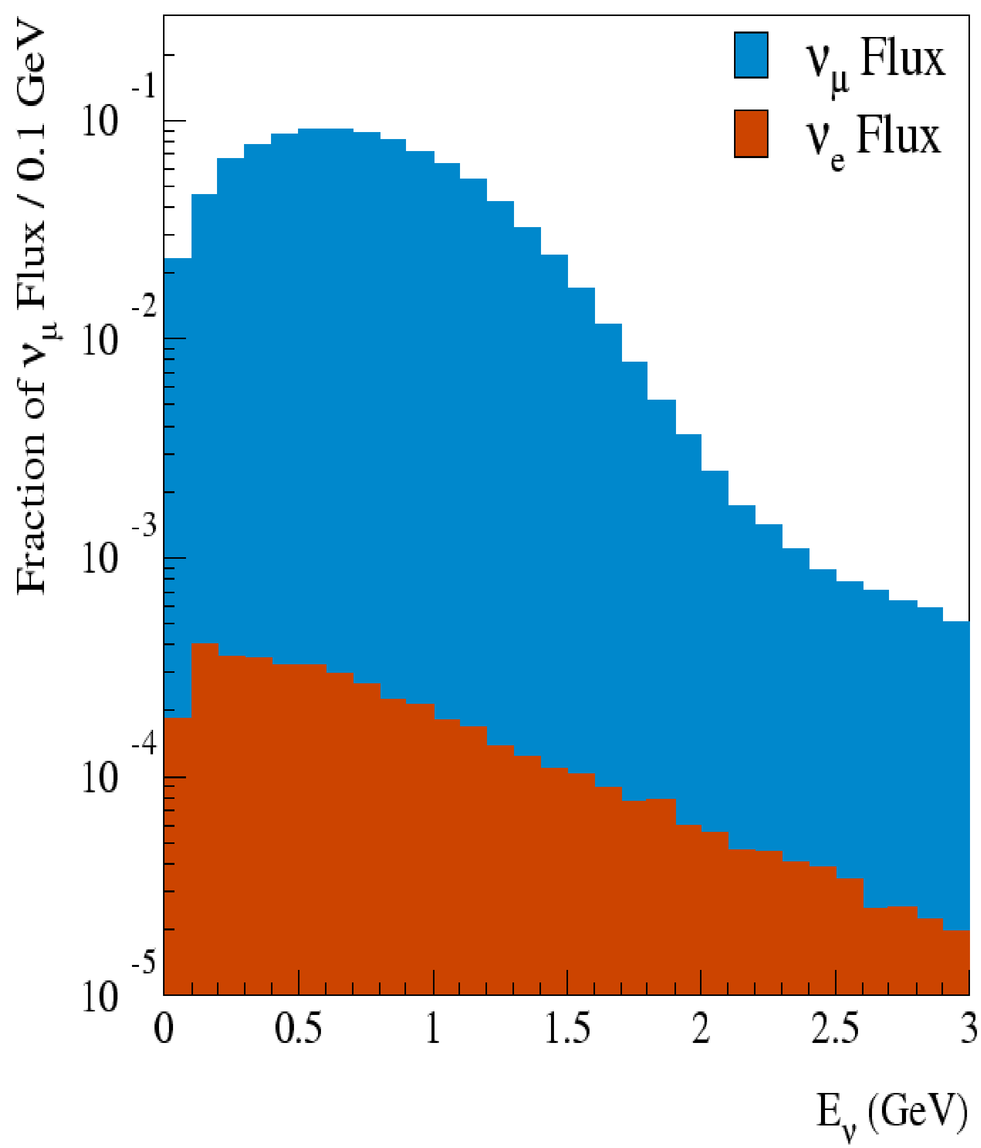
KAONS: $K^+ \to \pi^0 e^+ \nu_e$ → SHORT LIFETIME: MOSTLY UPSTREAM

SAY WE HAVE A 300 EVENT ν_e EXCESS: CHANGE DECAY LENGTH TO 25 m:

DECAY LENGTH	ν_μ EVENTS	ν_e EXCESS: IF $\nu_\mu \to \nu_e$ OSCILLATIONS	ν_e EXCESS: IF ν_e BACKGROUND MISESTIMATE
50 m	≈400000	300	300
25 m	≈220000	165	~250 (if K mis-estimate), ~80 (if μ)

Expected flux at MiniBooNE detector from GEANT4 Monte Carlo

- π^+ production: "JAM" fit to external data using Sanford-Wang parametrization.
- π^- production: Sanford-Wang parameters from Cho et al., PRD 4, 1967 (1971).
- K^+/K^- production: cross-section table derived from MARS production model
- K^0 production: MARS K^+ cross-section weighted by K^0/K^+ ratio from GFLUKA

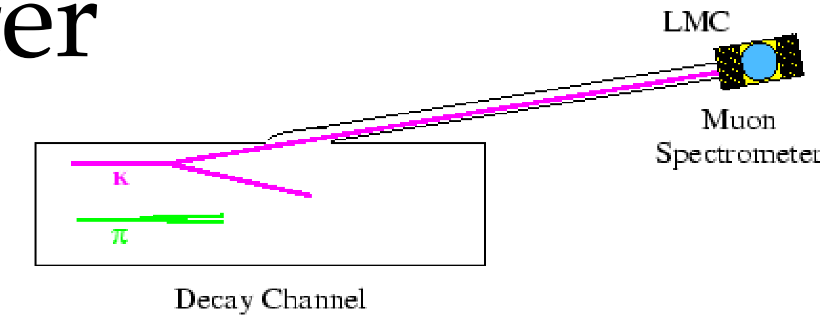


K-decay ν_e background

- MiniBooNE will see ~200-400 ν_e from K^+ and K^0_L decays each year -- comparable to the yield from oscillation physics if LSND is correct.
- Goal is a systematic error of <10% on K-decay ν_e.
- Information on these decays will come from:
  - Monte Carlo (GEANT4, MARS, GFLUKA) ← 50% disagreements!
  - Production measurements (BNL E910, HARP, plus other, older data)
  - In-situ measurement: LMC

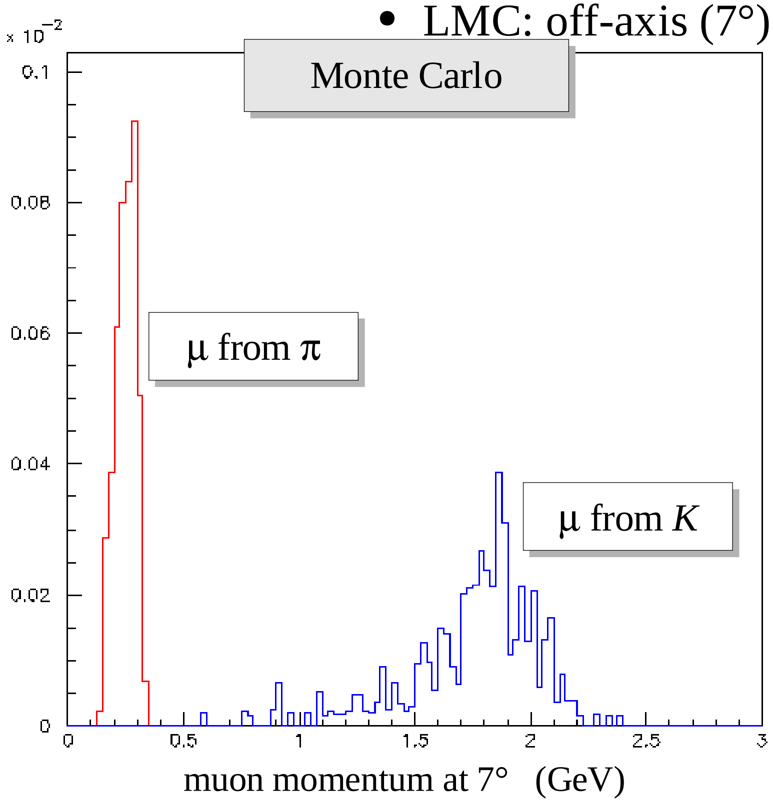
Little Muon Counter

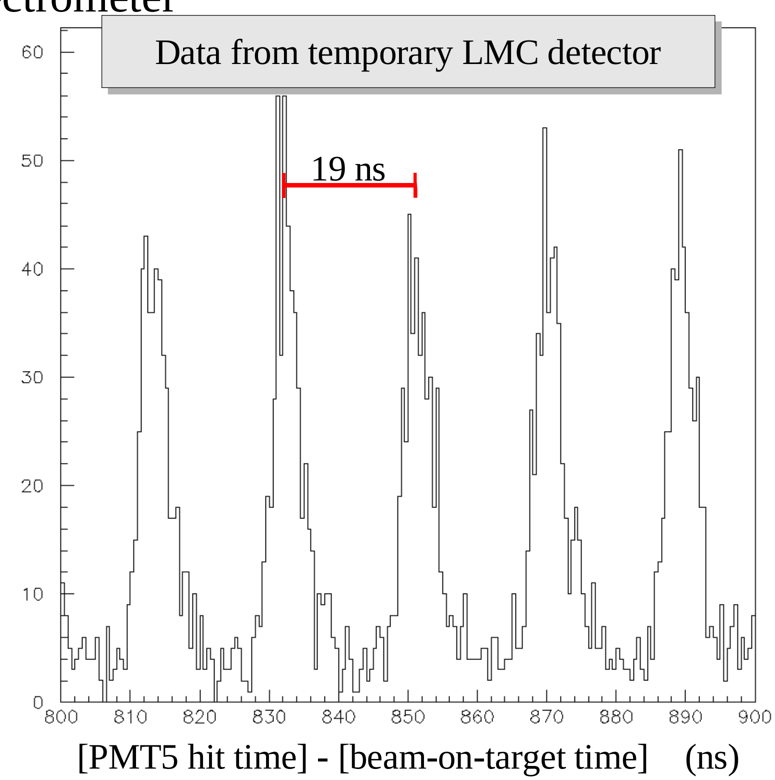
- *K* decays produce higher transverse-momentum muons than π decays
- LMC: off-axis (7°) muon spectrometer
- scintillating fiber tracker
- clean separation of muon parentage



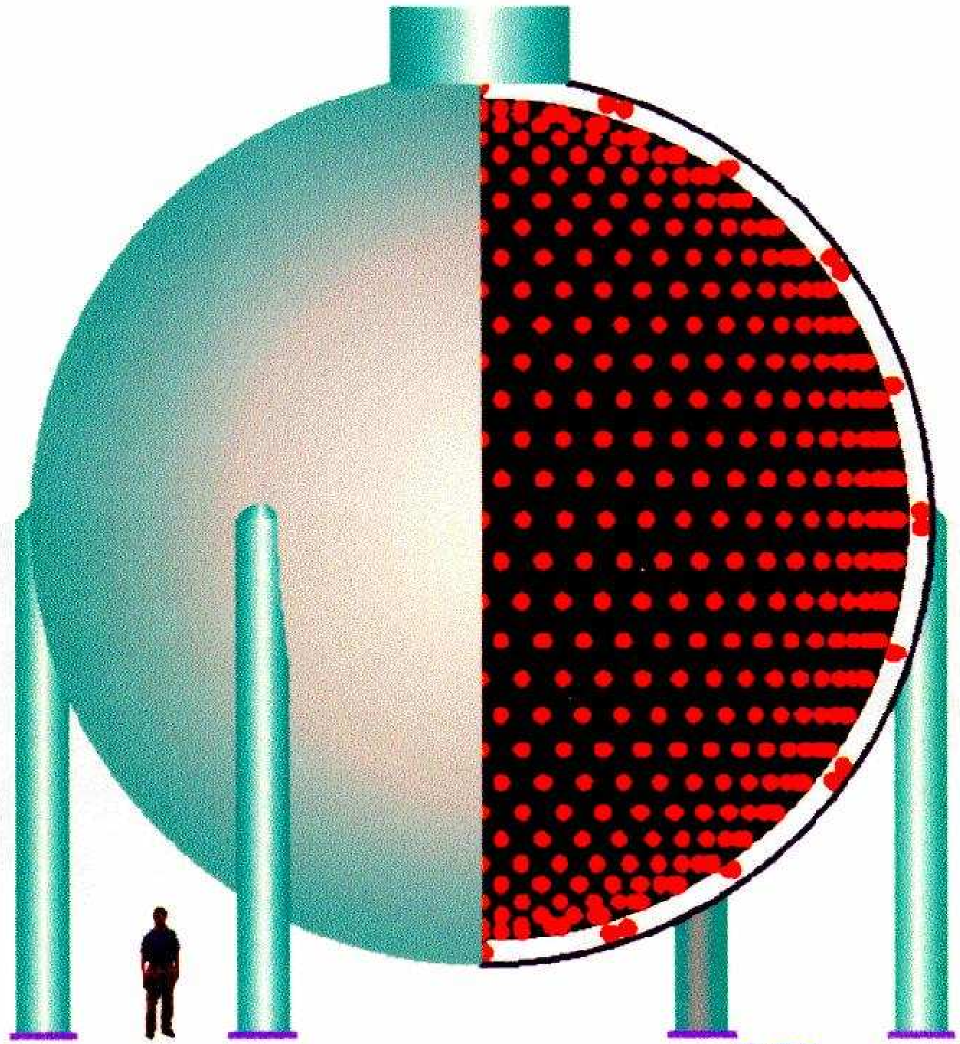
- temporary LMC detector (scintillator paddles):
  - shows that data acquisition is working
  - 53 MHz beam RF structure seen

- LMC: off-axis (7°) muon spectrometer





MINI - BooNE NEUTRINO DETECTOR



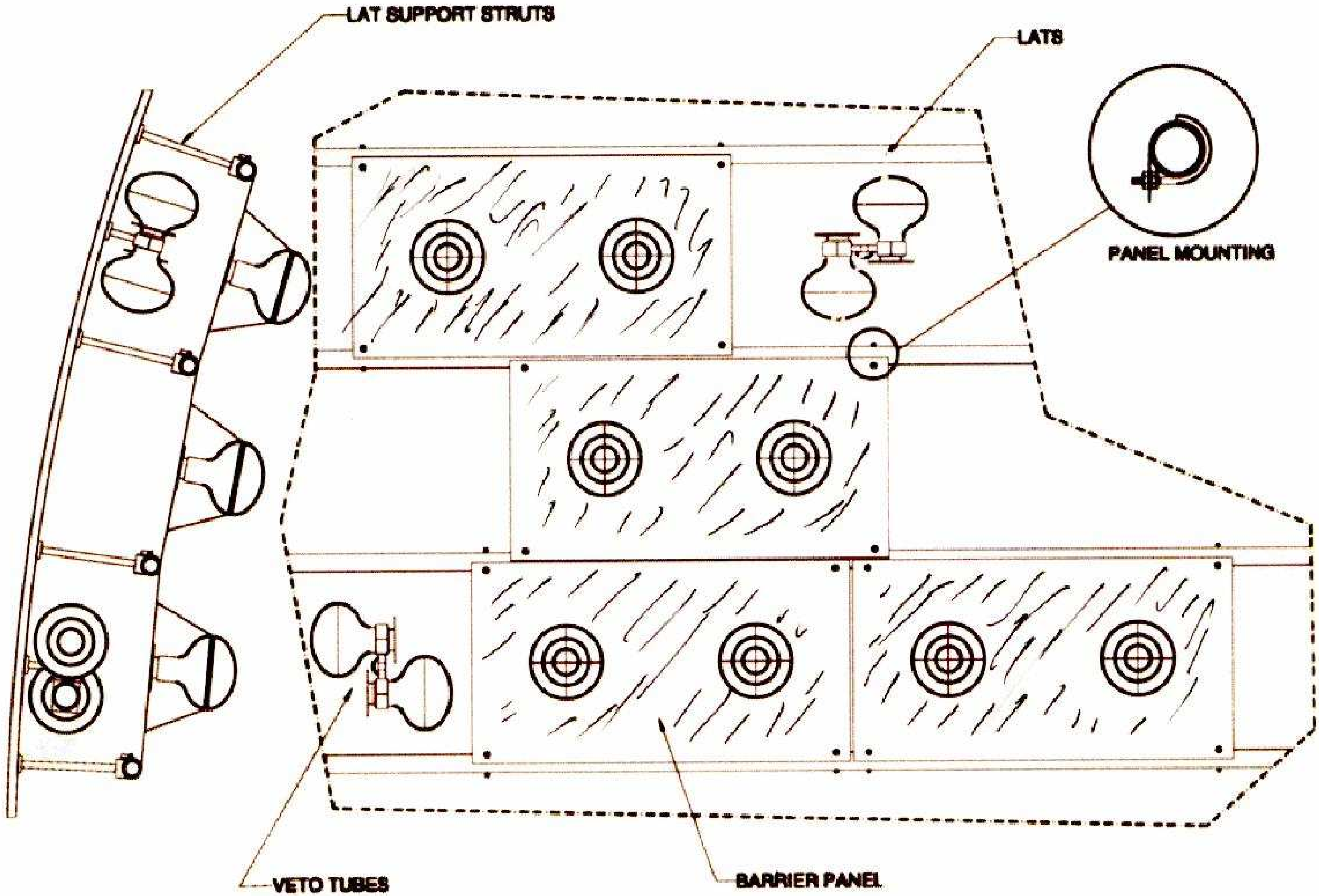
- PURE MINERAL OIL - TOTAL MASS 800 TONS (20' RADIUS)
- FIDUCIAL MASS 445 TONS (5m RADIUS)
- INNER VOLUME HAS 1280 8" PMTS (MOSTLY FROM LSND)
- OUTER (VETO) VOLUME HAS 240 PMTs

Detector site, August 10, 1999

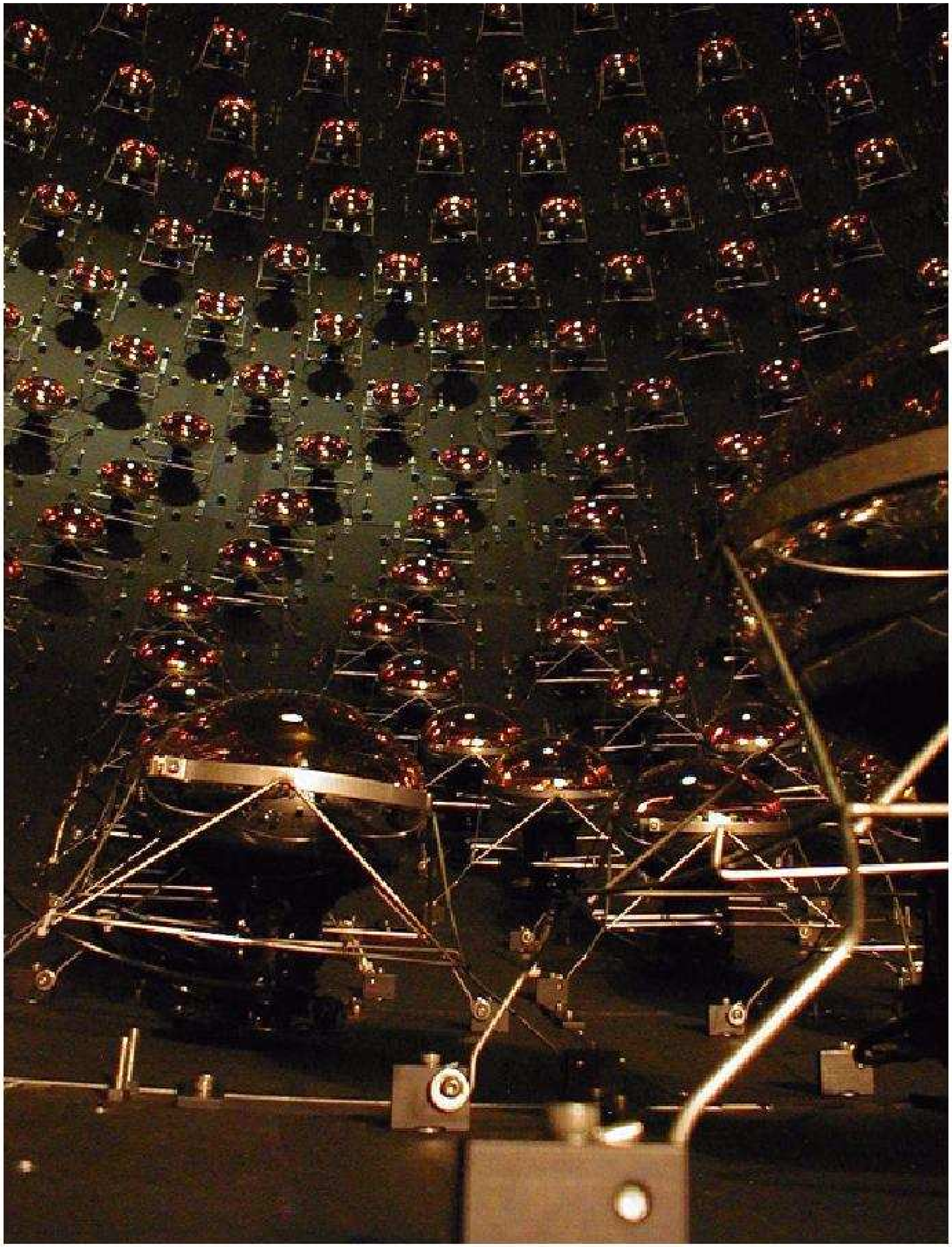
Tank assembly in place, May 4, 2000

Cables/Inner Structure Installation, February 2001

PHOTOTUBE SUPPORT STRUCTURE (PARTIALLY ASSEMBLED VIEW)



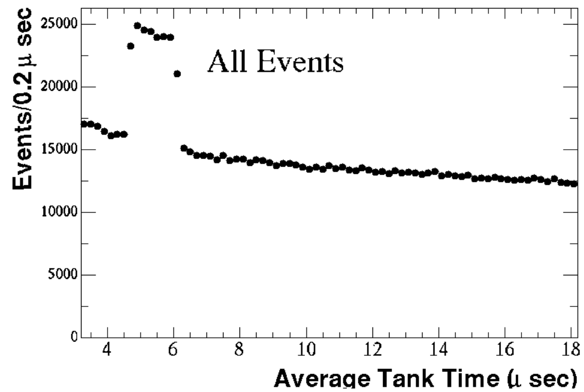
SUPPORT STRUCTURE PANELS FORM OPAQUE BARRIER BETWEEN MAIN VOLUME (BLACK) AND VETO VOLUME (WHITE)



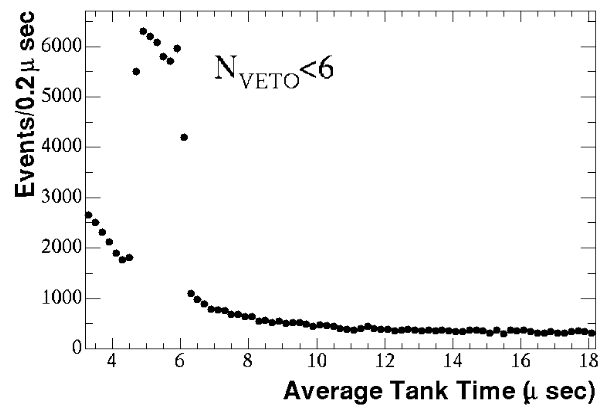
TRIGGER AND READOUT

- ELECTRONICS REUSED FROM LSND
- RECORDS TIME OF FIRST HIT PER TUBE AND CHARGE INTEGRAL OVER 100 ns.
- FULLY PIPELINED READOUT
- TRIGGER:
  - RECORD 20 μs ABOUT EVERY BEAM PULSE
  - TRIGGER ON CERTAIN PATTERNS OF DETECTOR ACTIVITY OFF-SPILL TO CALIBRATE WITH COSMIC RAYS AND GRAB EXTRA PHYSICS (MAY BE ABLE TO SEE NEUTRINOS FROM A GALACTIC SUPERNOVA!)
  - ALSO TRIGGER ON CALIBRATION LASER PULSES

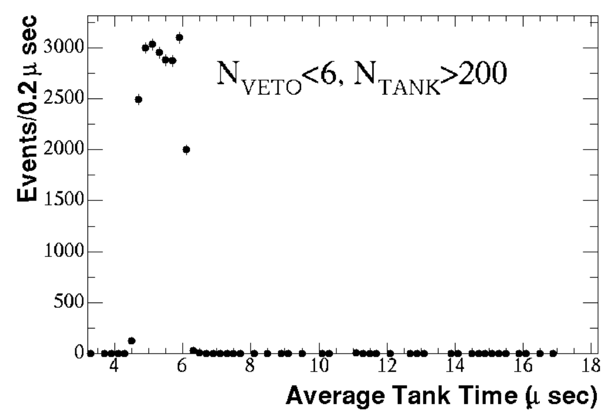
Selecting Neutrino Events



Beam window 1.6 μs

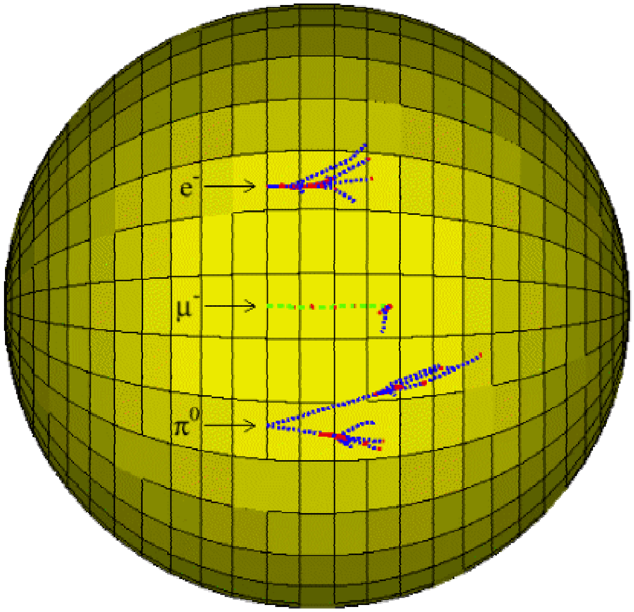


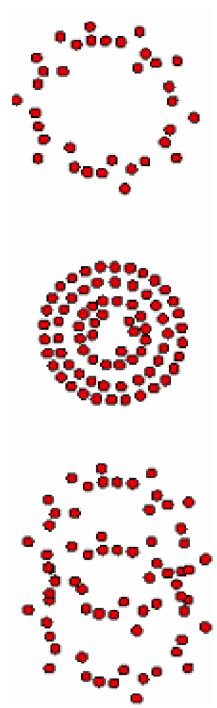
3 simple cuts give great rejection of non-ν events



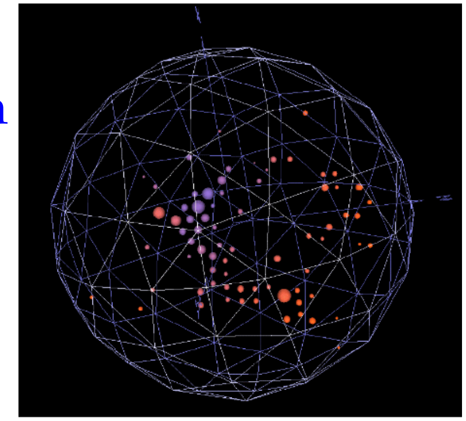
No non-beam backgrounds unlike LSND

Particle ID

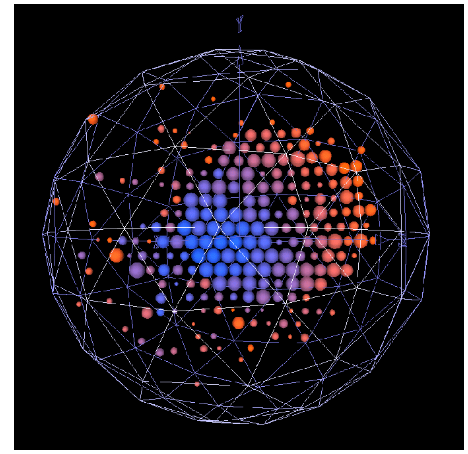




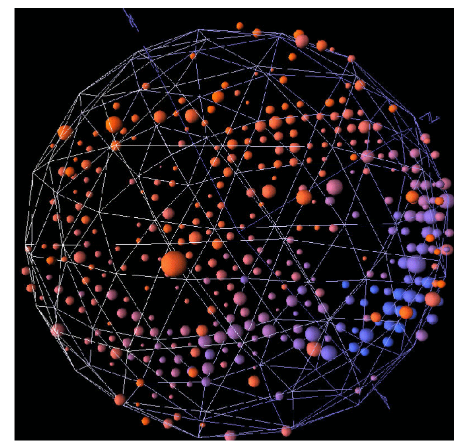
Michel e candidate (e from μ decay)



Beam μ candidate



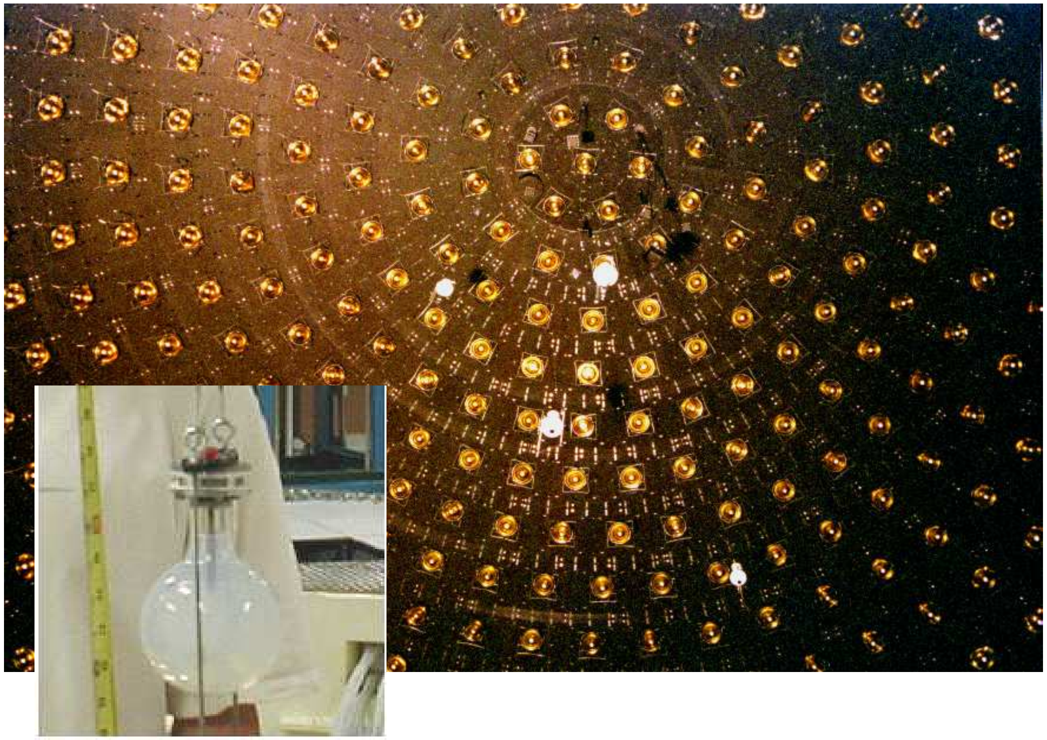
Beam π^0 candidate



Event display key:

- Size: PMT charge
- Color: hit time (Red is early, Blue is late.)

Understanding the Detector

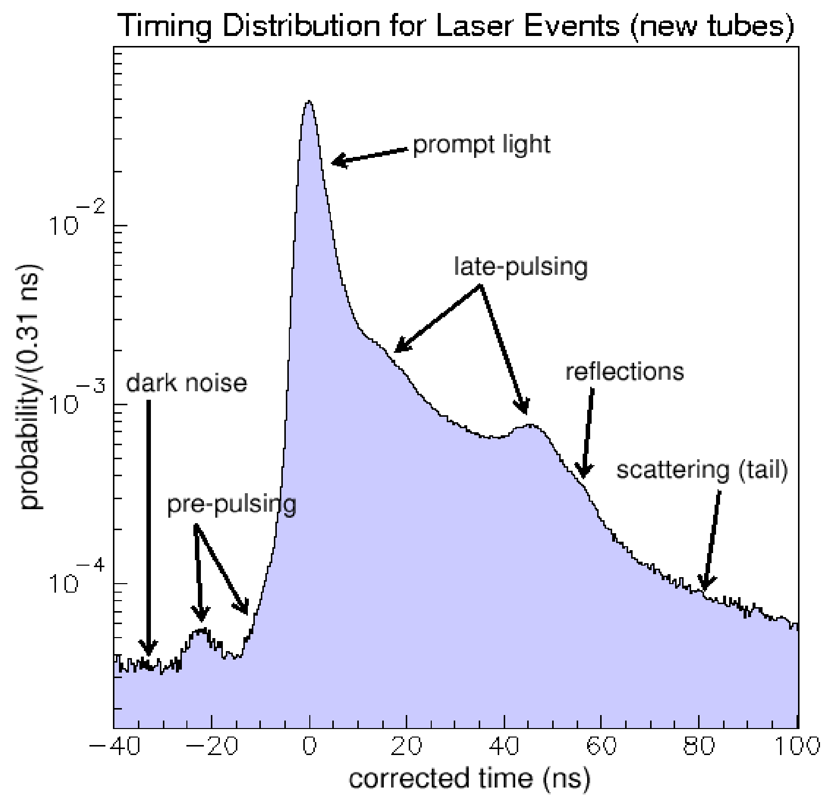


To calibrate PMT's, we measure

- PMT charge
- Timing response
- Oil attenuation length

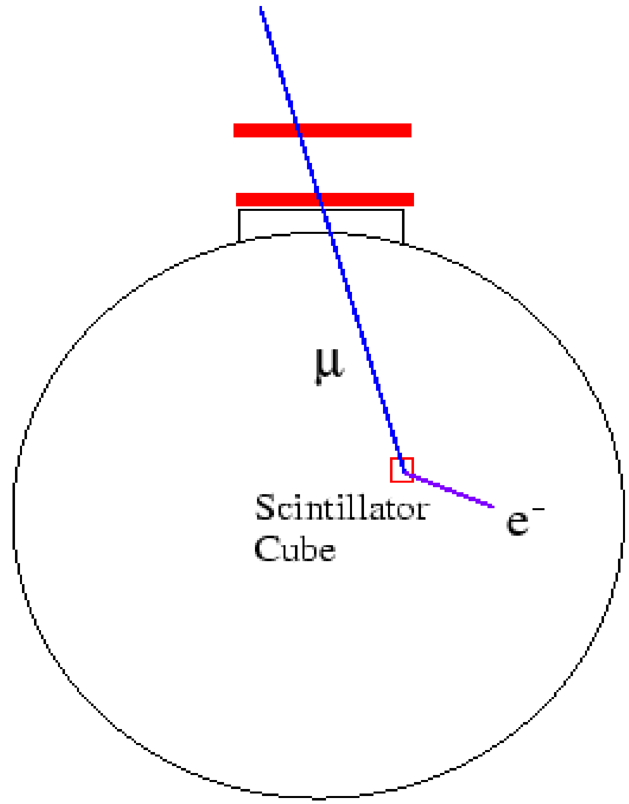
Laser Flasks

- 397 nm laser light
- Four Ludox-filled flasks fed by optical fiber from laser



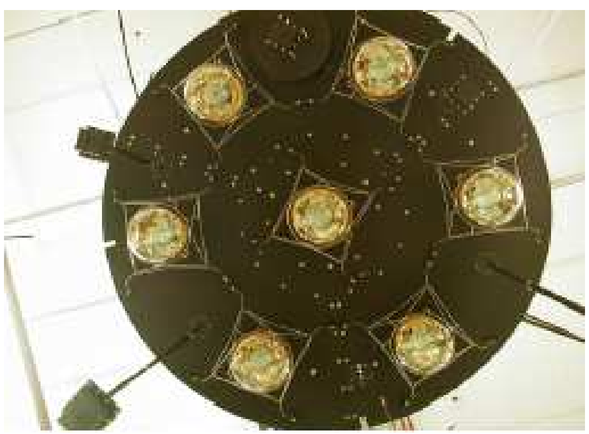
Stopping Muon Calibration System

Cosmic ray hodoscopes above the tank



Optically isolated scintillator cubes in tank:

- six 2-inch (5 cm) cubes
- one 3-inch cube



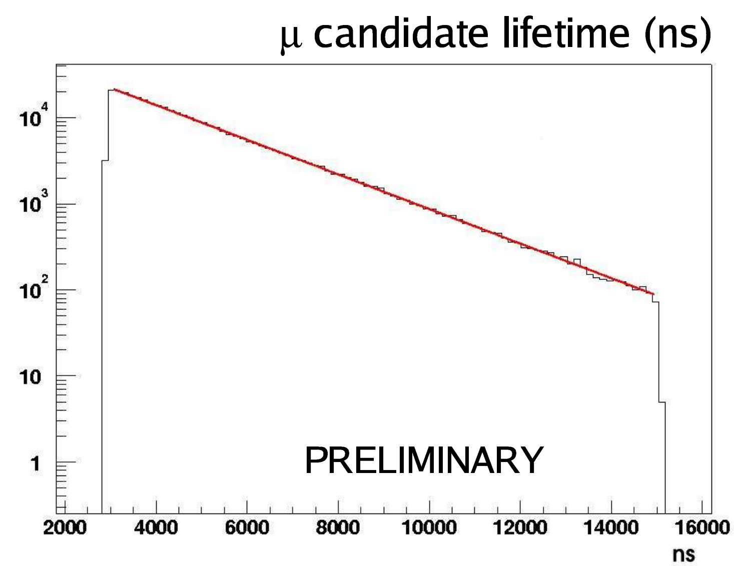
Calibration sample consists of muons up to 700 MeV

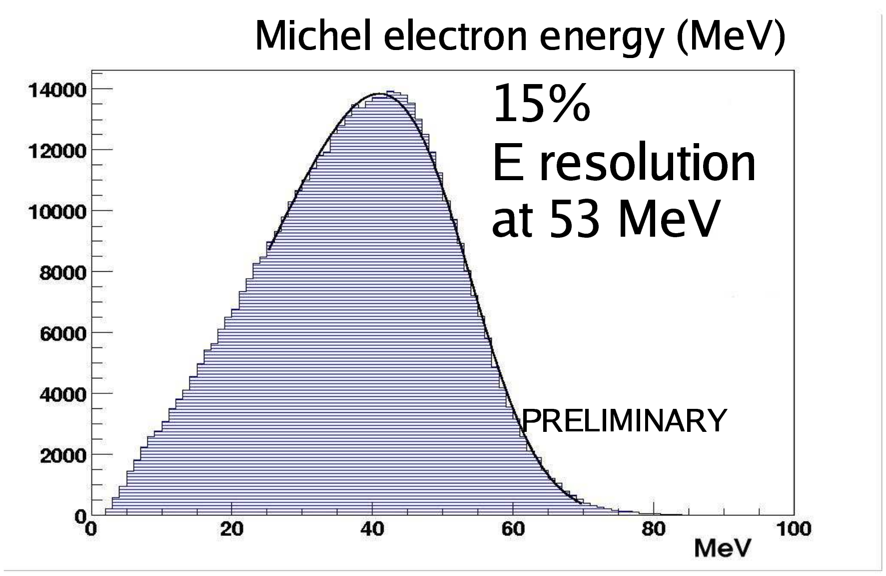
Michel Electron Measurements

- Michel electrons (from decays of stopped cosmic ray muons)
- Muon lifetime in oil:
  - measured: $\tau = 2.15 \pm 0.02\ \mu s$
  - expected: $\tau = 2.13\ \mu s$

(8% of μ^- capture)

- Energy scale and resolution at Michel endpoint (53 MeV)

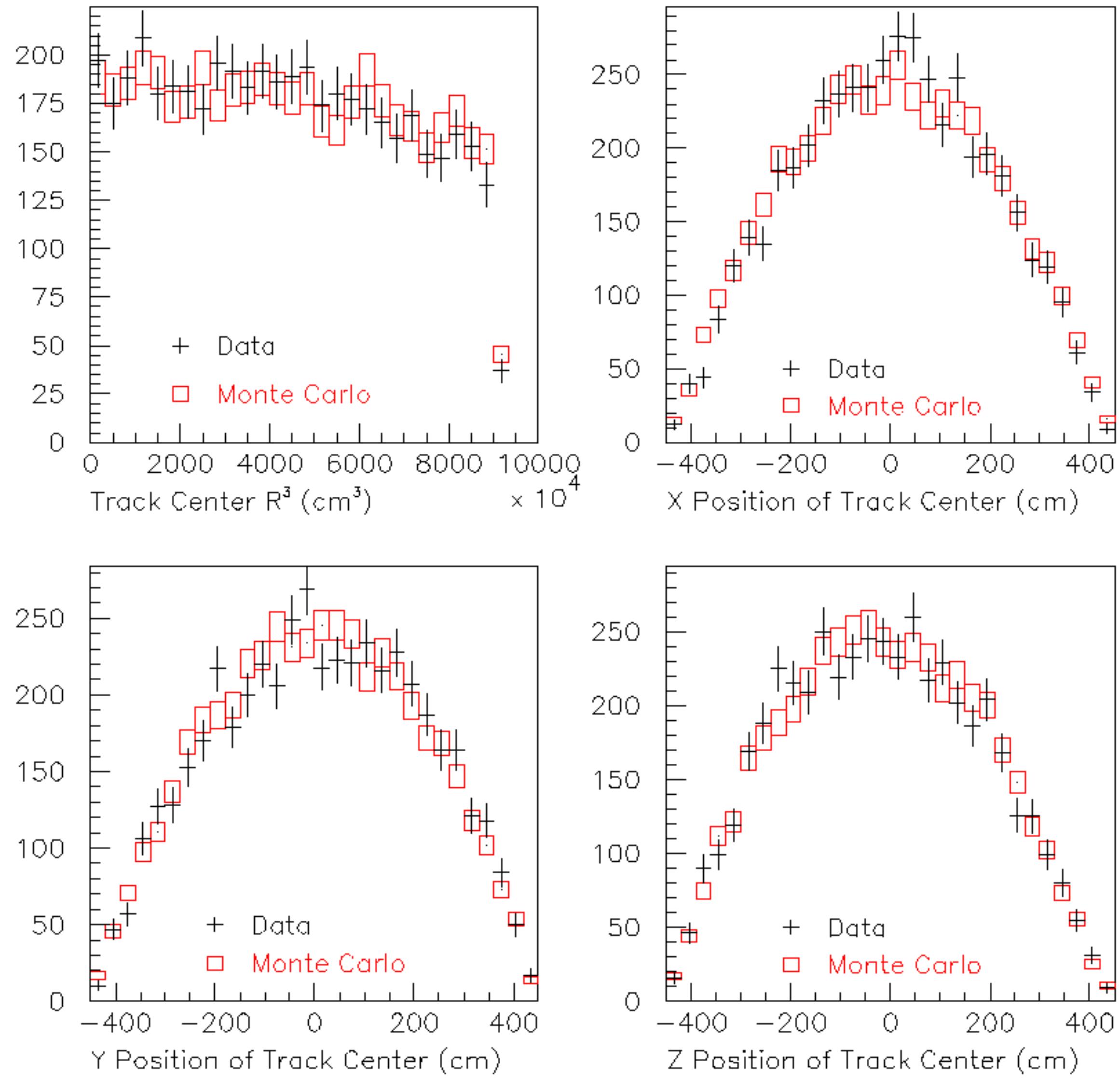




Data/MC Agreement in Vertex Reconstruction

Neutrino events:

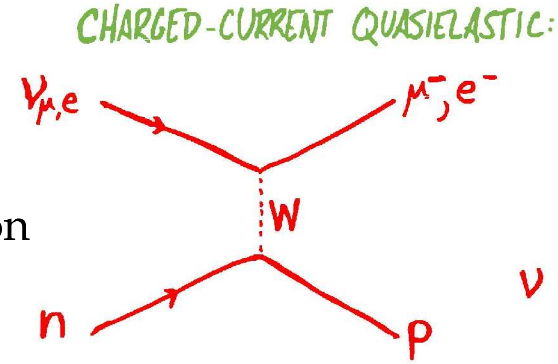
- NHIT > 200
- NVETO < 6
- r < 450cm
- Timing



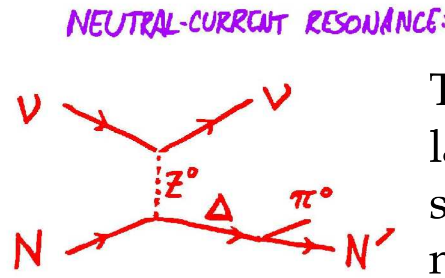
Initial Physics Measurements

- ν_μ Quasielastic Scattering
- Neutral Current π^0 Production
- Neutral Current Elastic Scattering

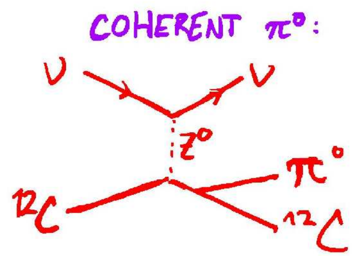
Signatures of neutrino interactions in BooNE



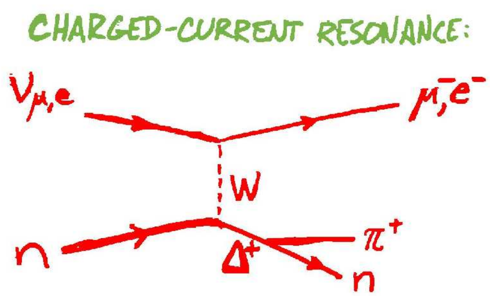
Čerenkov ring
(μ-like or *e*-like)
plus small scintillation
signal



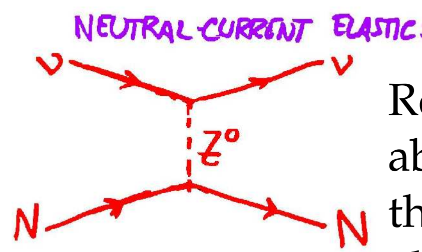
Two *e*-like rings plus
larger scintillation
signal from recoil
nucleon



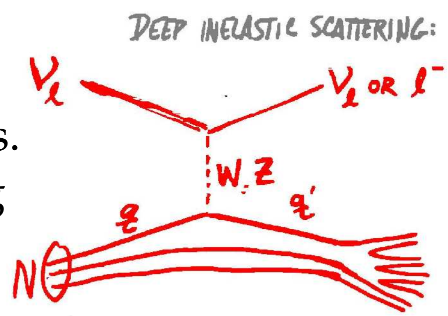
Same as above, but
more forward-peaked



1 or 2 Čerenkov rings
plus larger scintillation
signal



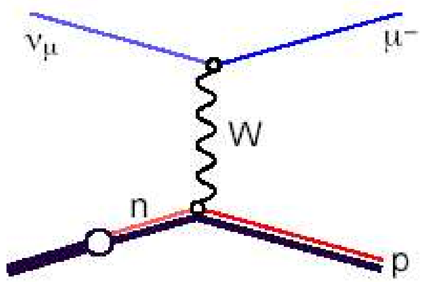
Recoil nucleon rarely
above Čerenkov
threshold; signal is
almost entirely from
scintillation. Very few
PMT hits and low total
charge.

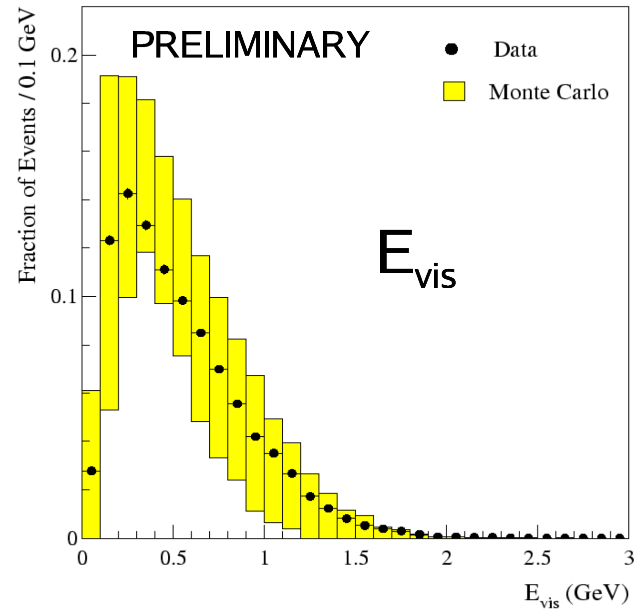


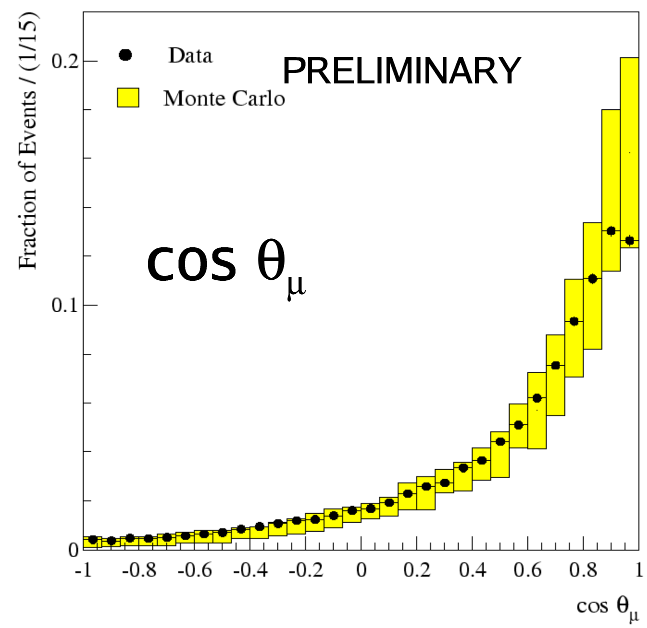
Mostly higher energies.
A very ugly multi-ring
event!

CC ν_μ Quasielastic Events

- Event selection
  - Topology
    - Ring sharpness
    - on- vs. off-ring hits
  - Timing
    - Single μ-like ring
    - Prompt vs. late light
- Variables combined in a Fisher discriminant
- Data and MC normalized to unit area
- Yellow Band: MC with current uncertainties from
  - Flux predicton
  - σ_{CCQE}
  - Optical properties



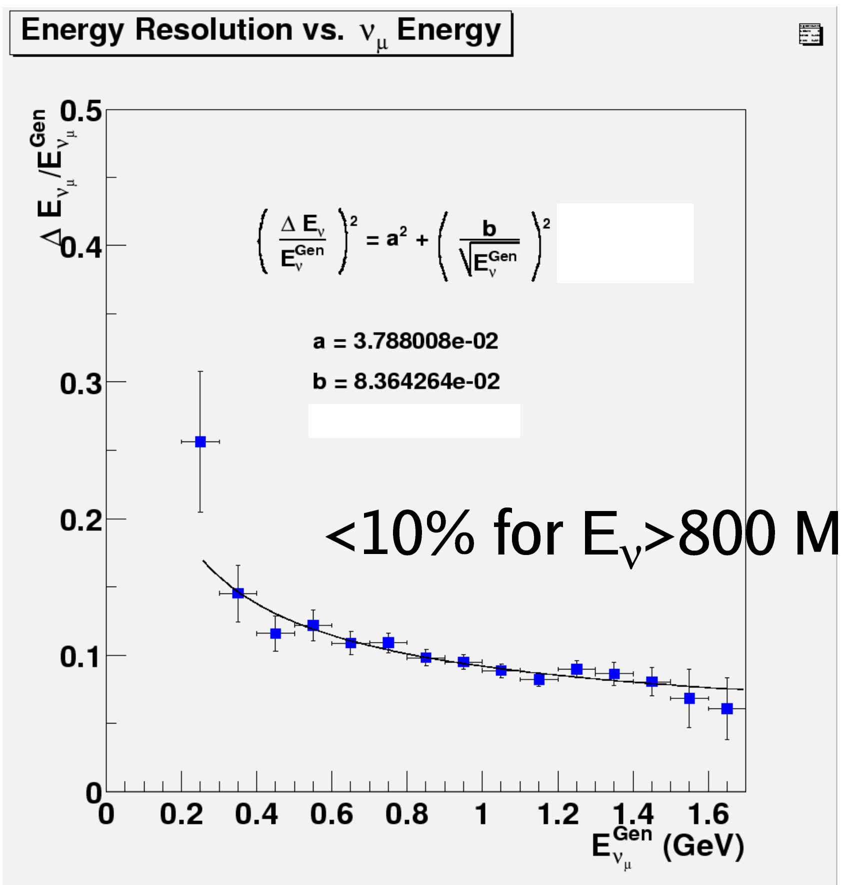




CC ν_μ Quasielastic Events

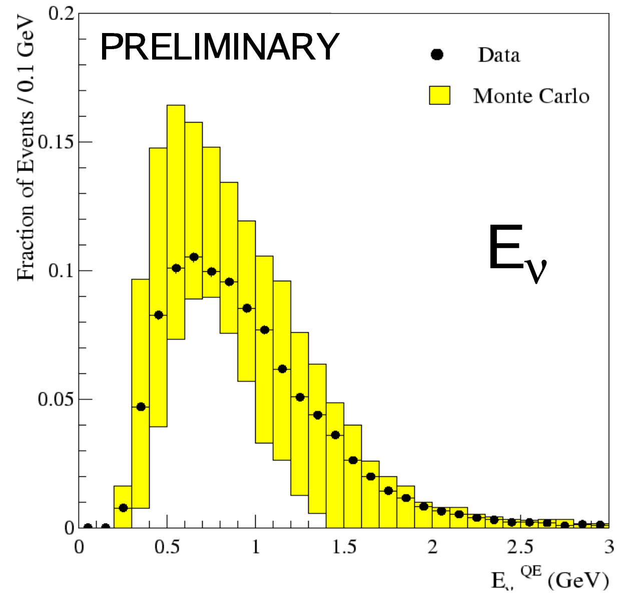
E_μ reconstruction:

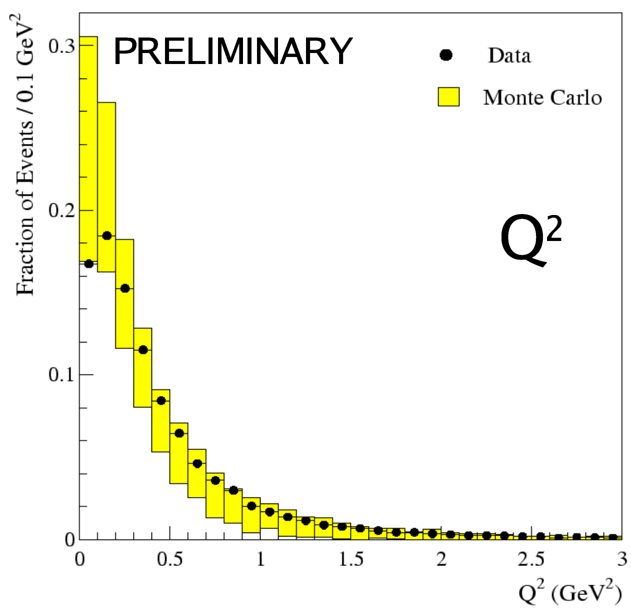
- Assume $\nu_\mu n \rightarrow \mu^- p$.
- Use E_μ, θ_μ, to get E_ν.



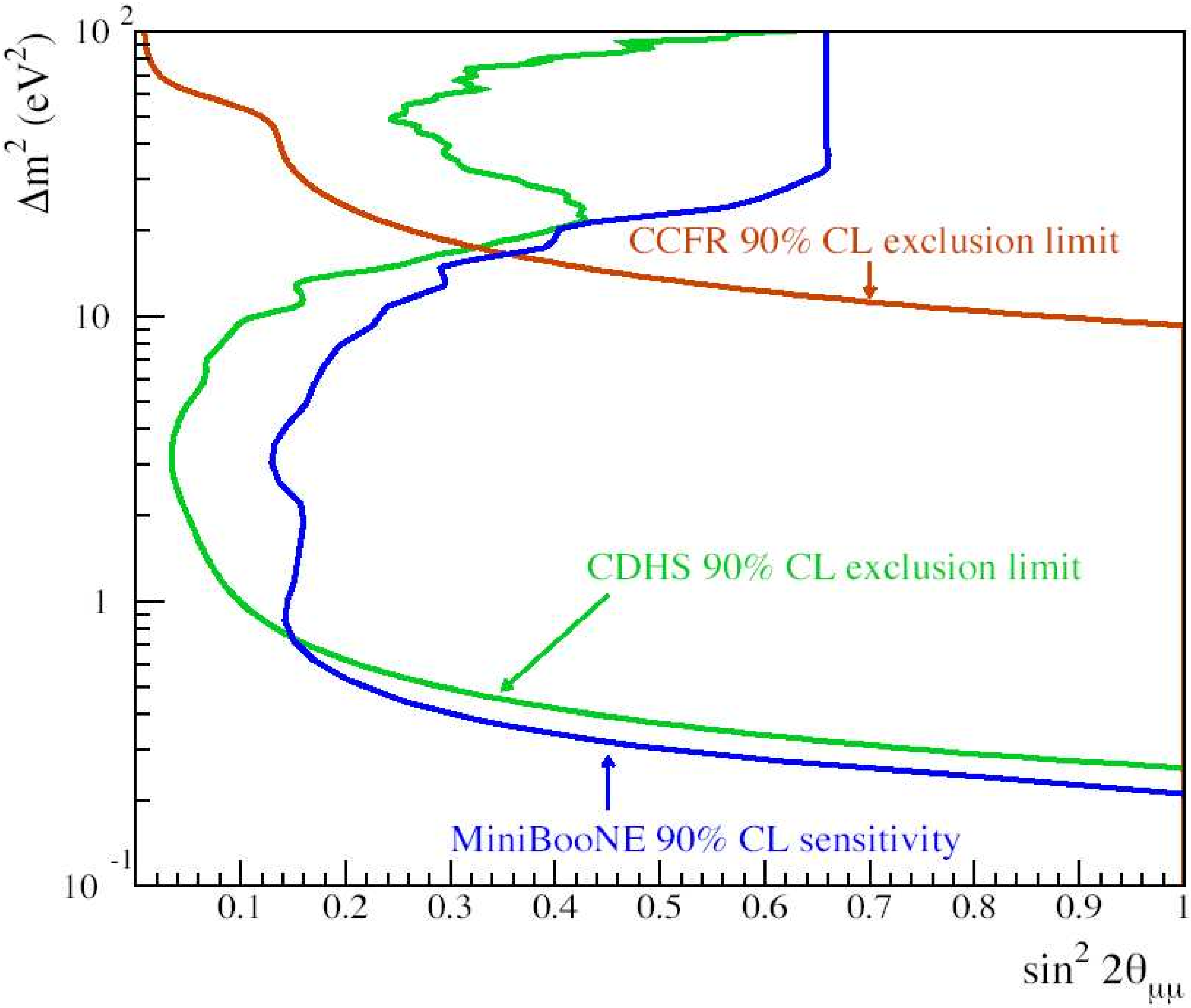
<10% for E_ν>800 MeV

First look at neutrino flux:





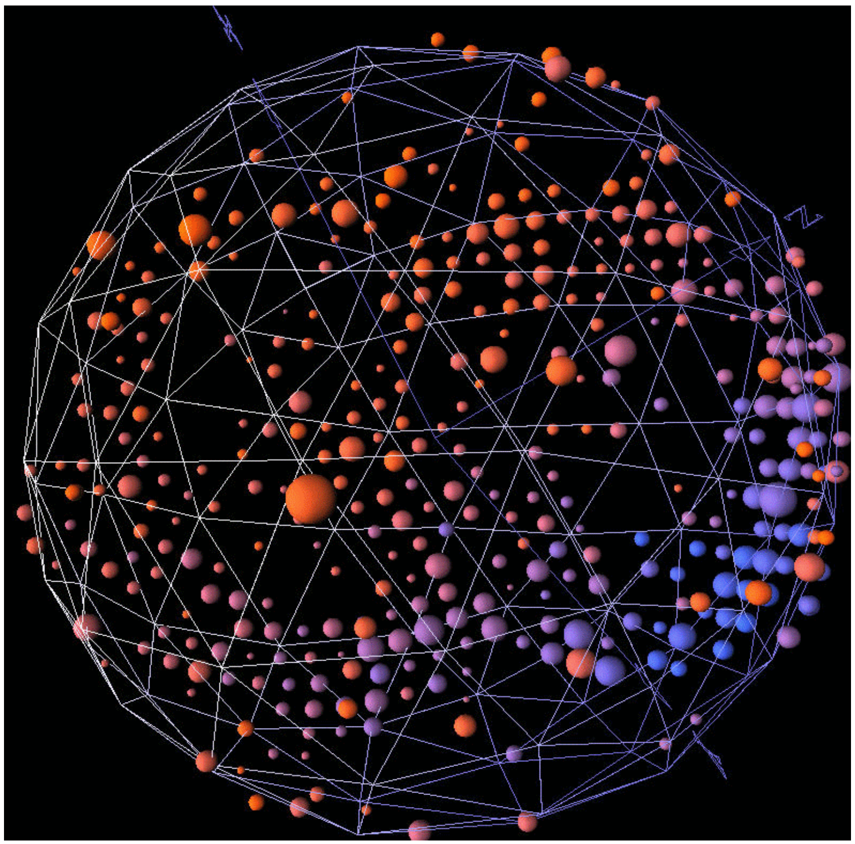
Preliminary ν_μ Disappearance Sensitivity

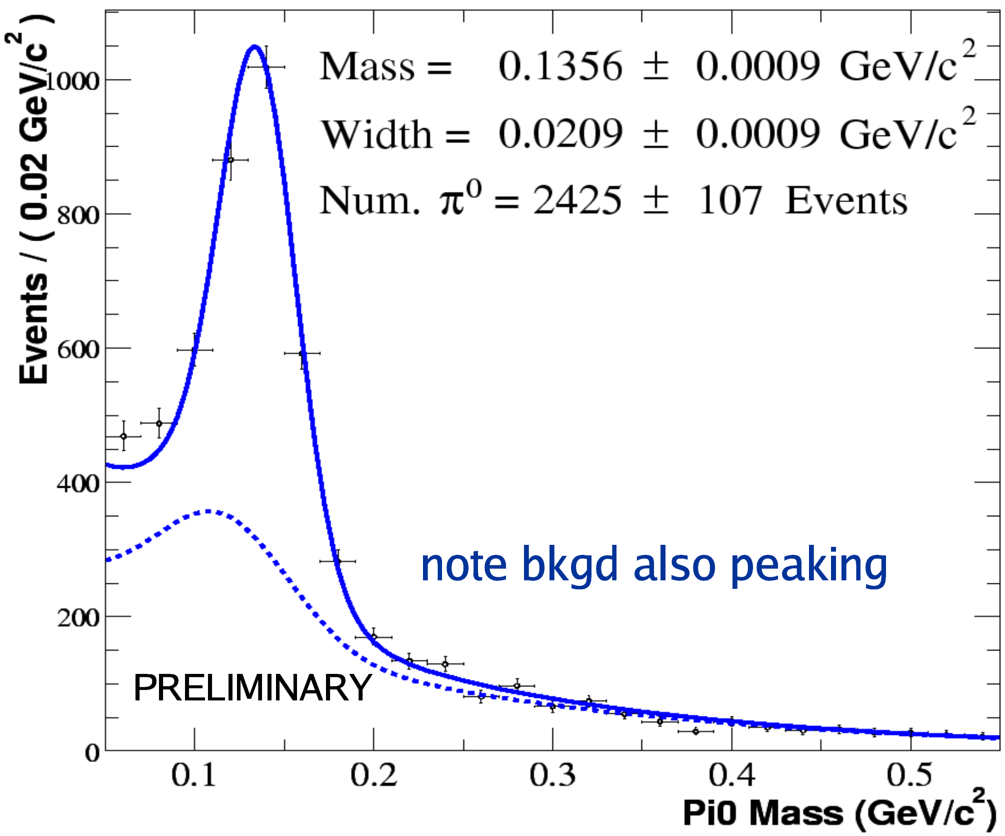


Systematics dominated due to uncertainty in flux prediction.

NC π^0 Production

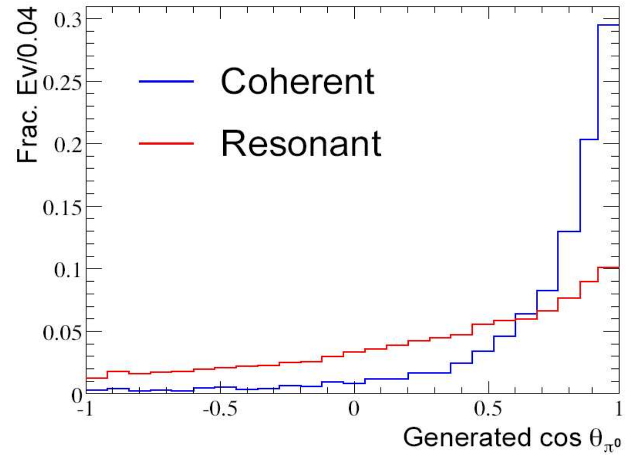
- $N_{TANK} > 200$, $N_{VETO} < 6$, no decay electron
- Perform two-ring fit on ALL events.
- Ring energies > 40 MeV
- Fit mass peak to extract signal yield including background shape from MC.



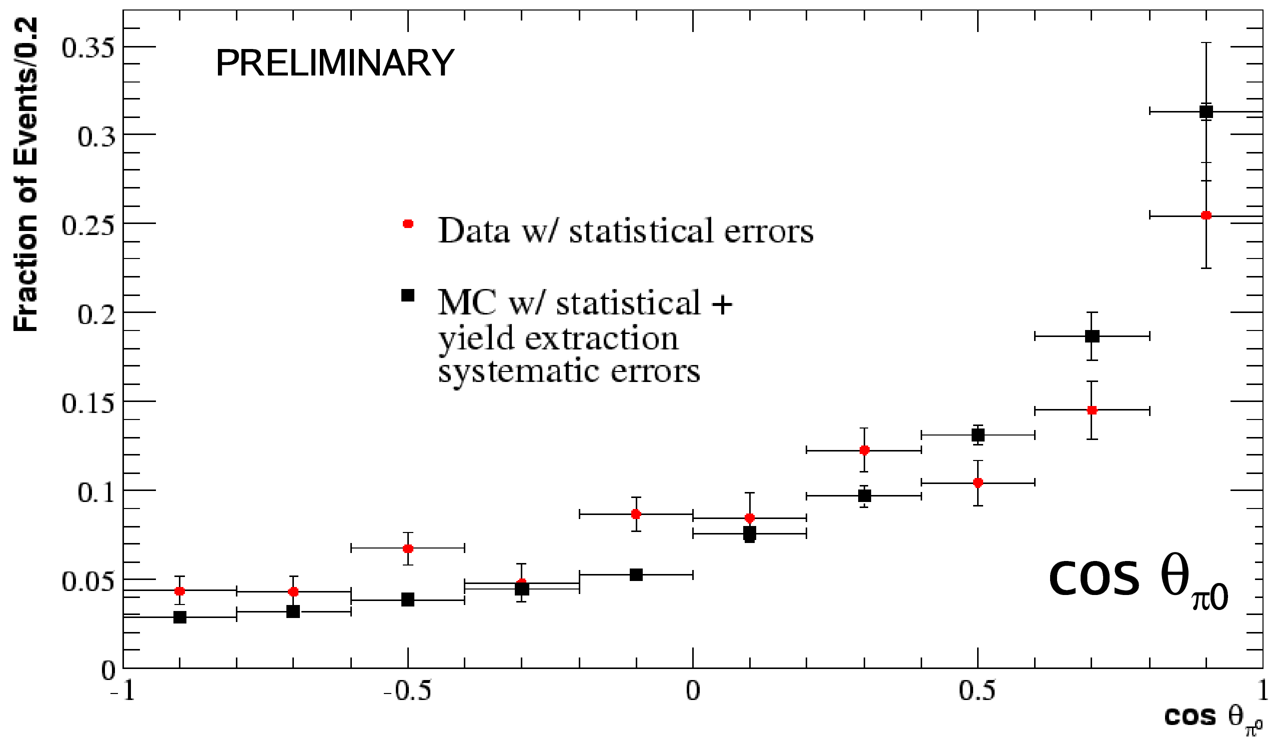


NC π^0 Production Angle

- Production angle is sensitive to production mechanism: coherent is highly forward-peaked.

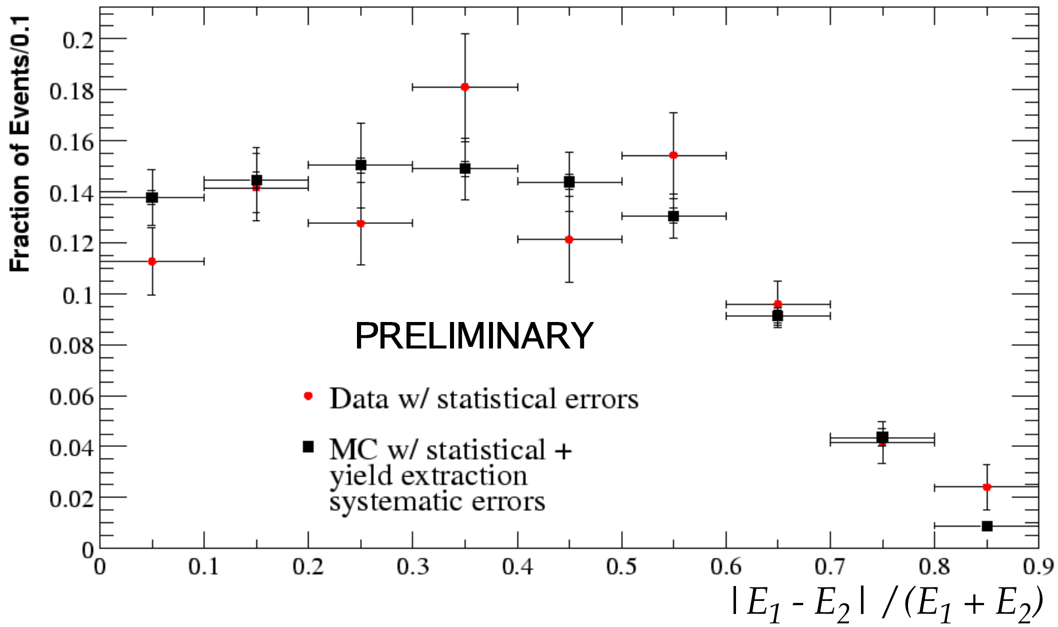


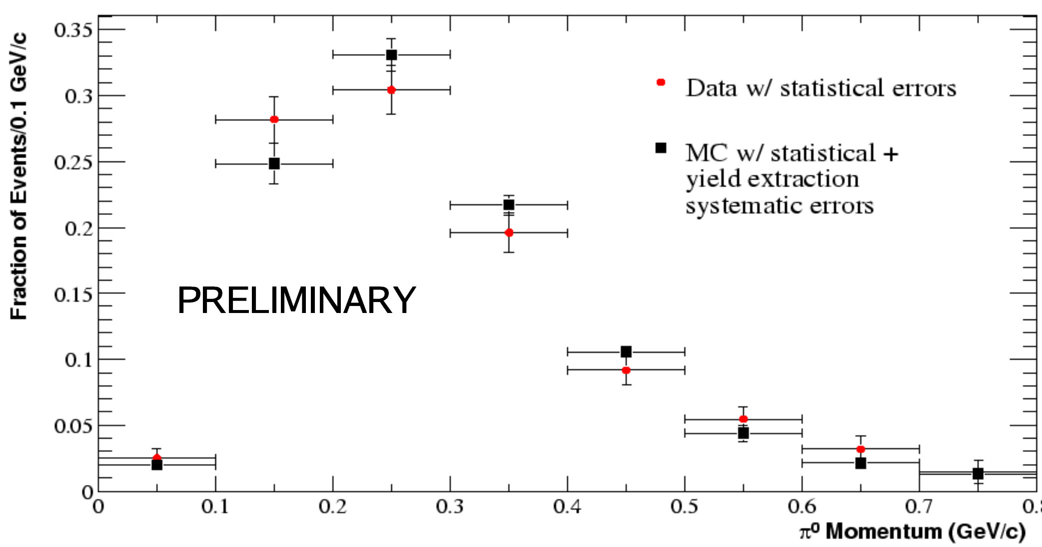
- Data and MC are normalized to unit area.



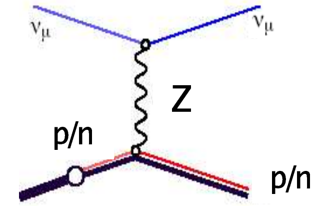
MC uses Rein-Sehgal cross-sections.

NC π^0 momentum and E_γ asymmetry

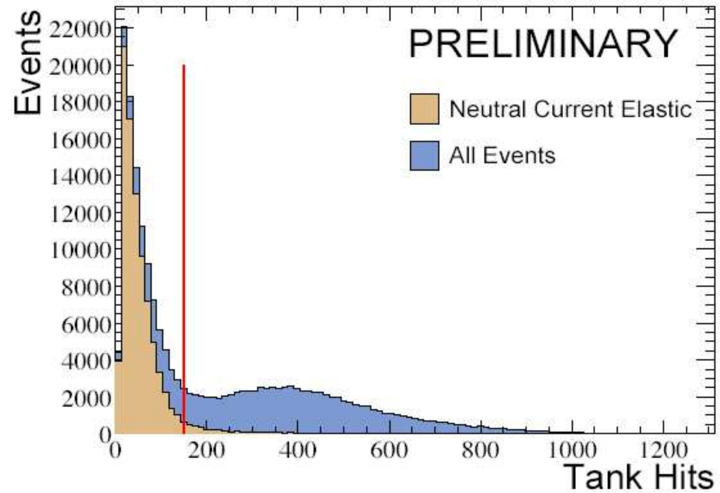




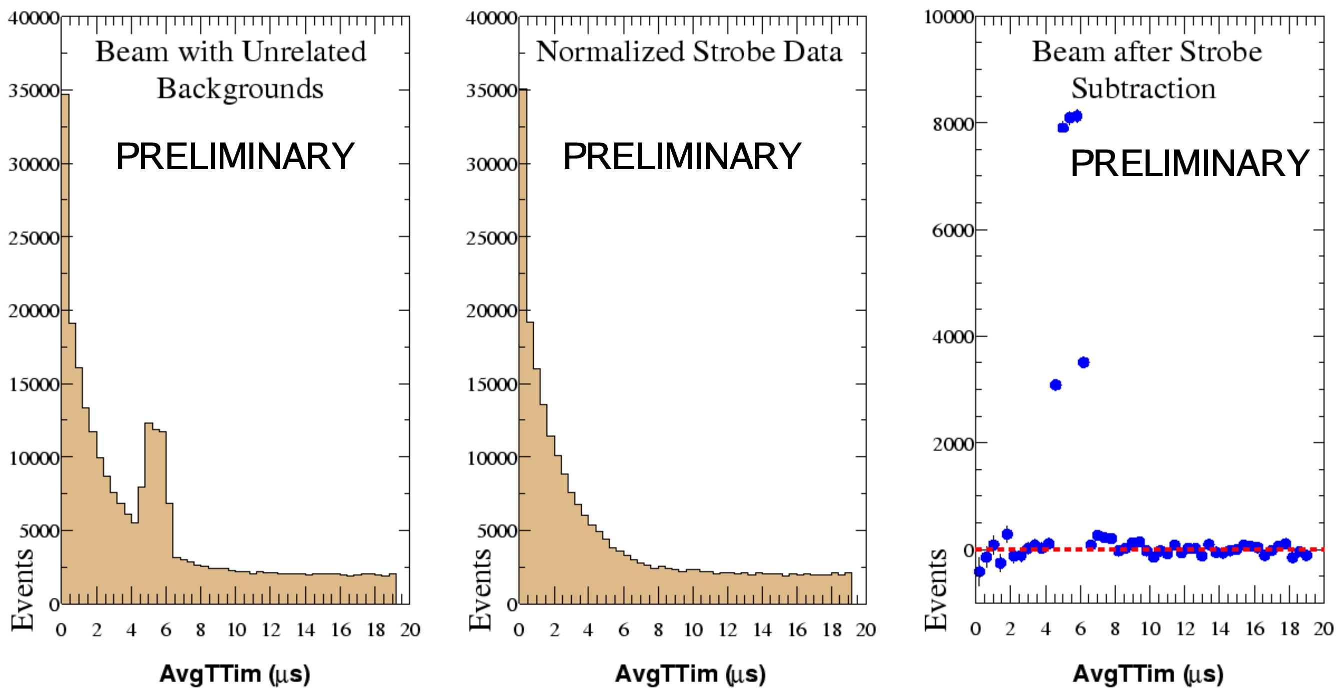
NC Elastic Scattering



- Select $N_{TANK} < 150$, $N_{VETO} < 6$
- Use random triggers
  (Normalized Strobe Data)
  to subtract non-beam background.



- A cut on the fraction of late light in these events may help select NC elastic events.

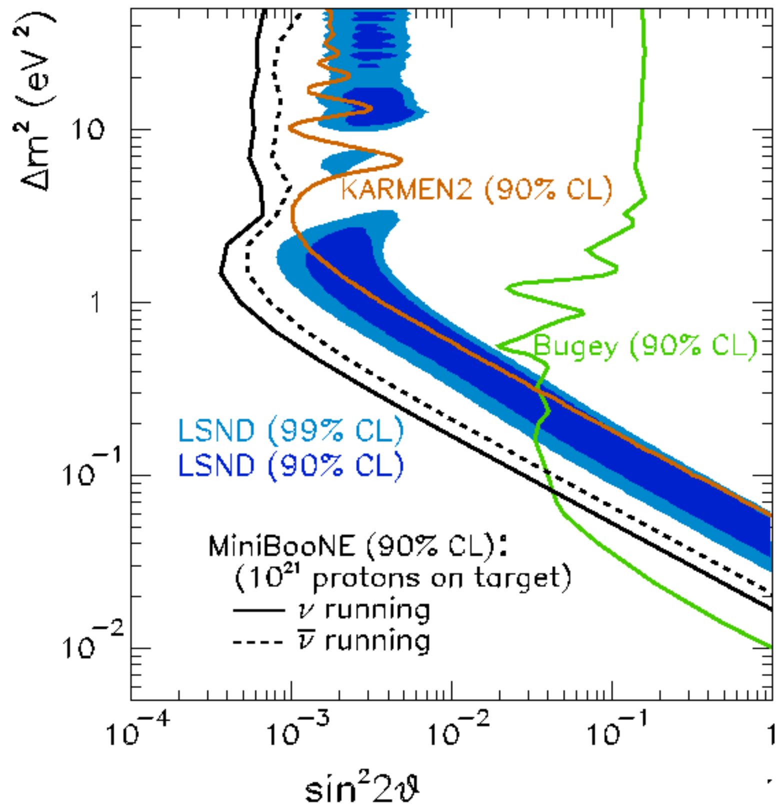


ν_e Appearance Status

- Blind analysis underway.

- Potential ν_e candidates are not available for full analysis (particle ID, etc).

- All events are available for analyses which do not involve particle ID, for detector checks and Monte Carlo development



- Sensitive to LSND region at 5 σ.
- Updated estimates coming.
- Currently expect results in 2005

Conclusions

- Beam and detector running well
- Still need more beam rate
- First physics plots are here

- ≤2 years to ν_e oscillation results:

Either we'll see oscillations and life will be very interesting, or we won't -- and phenomenology gets a lot easier.