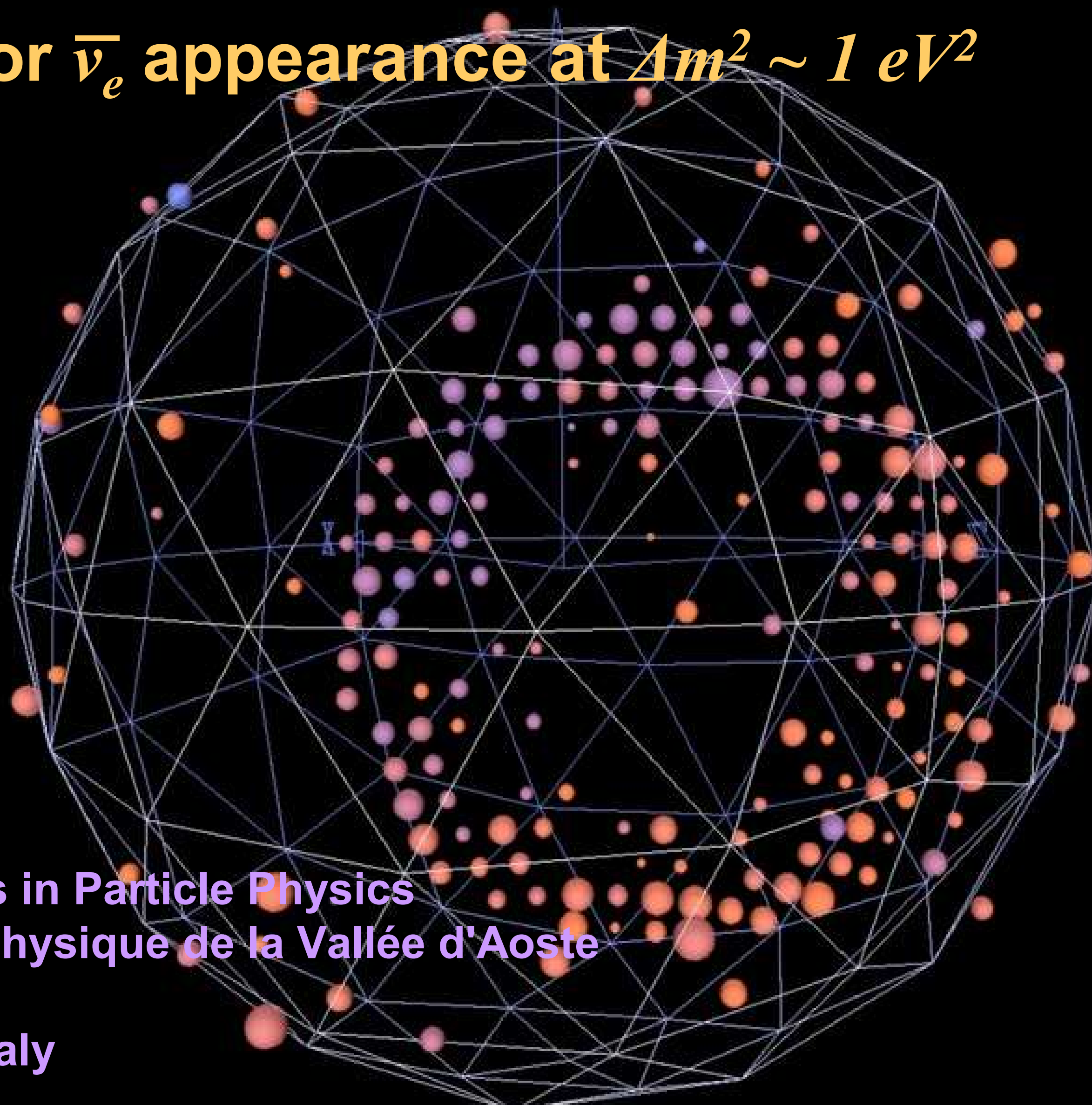
New Results from MiniBooNE:

A search for $\bar{\nu}_e$ appearance at $\Delta m^2 \sim 1\ eV^2$



Georgia Karagiorgi, MIT
Results and Perspectives in Particle Physics
Les 23rd Rencontres de Physique de la Vallée d'Aoste

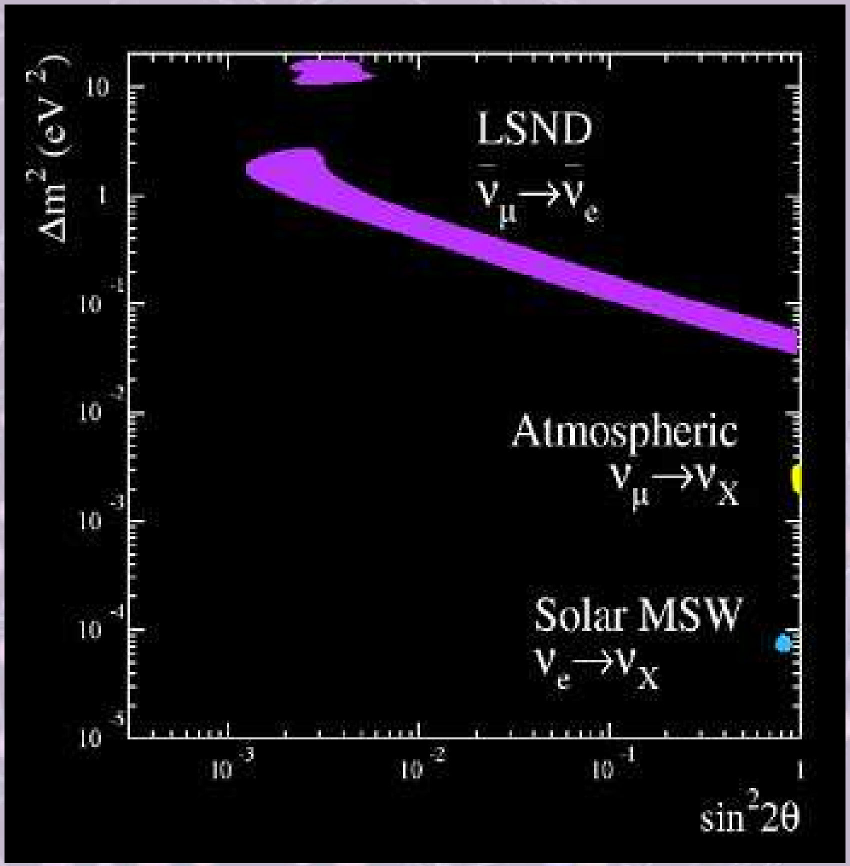
LaThuile, Aosta Valley, Italy
March 1-7, 2008

Another Δm^2?

LSND experiment:

- Detected anti-ν_e from stopped pion source: $\pi^+ \rightarrow \mu^+ \rightarrow \overline{\nu_\mu}$
  observed excess:
  $87.9 \pm 22.4 \pm 6.0$ anti-ν_e events (3.8σ)

  [arXiv:hep-ex/0104049]



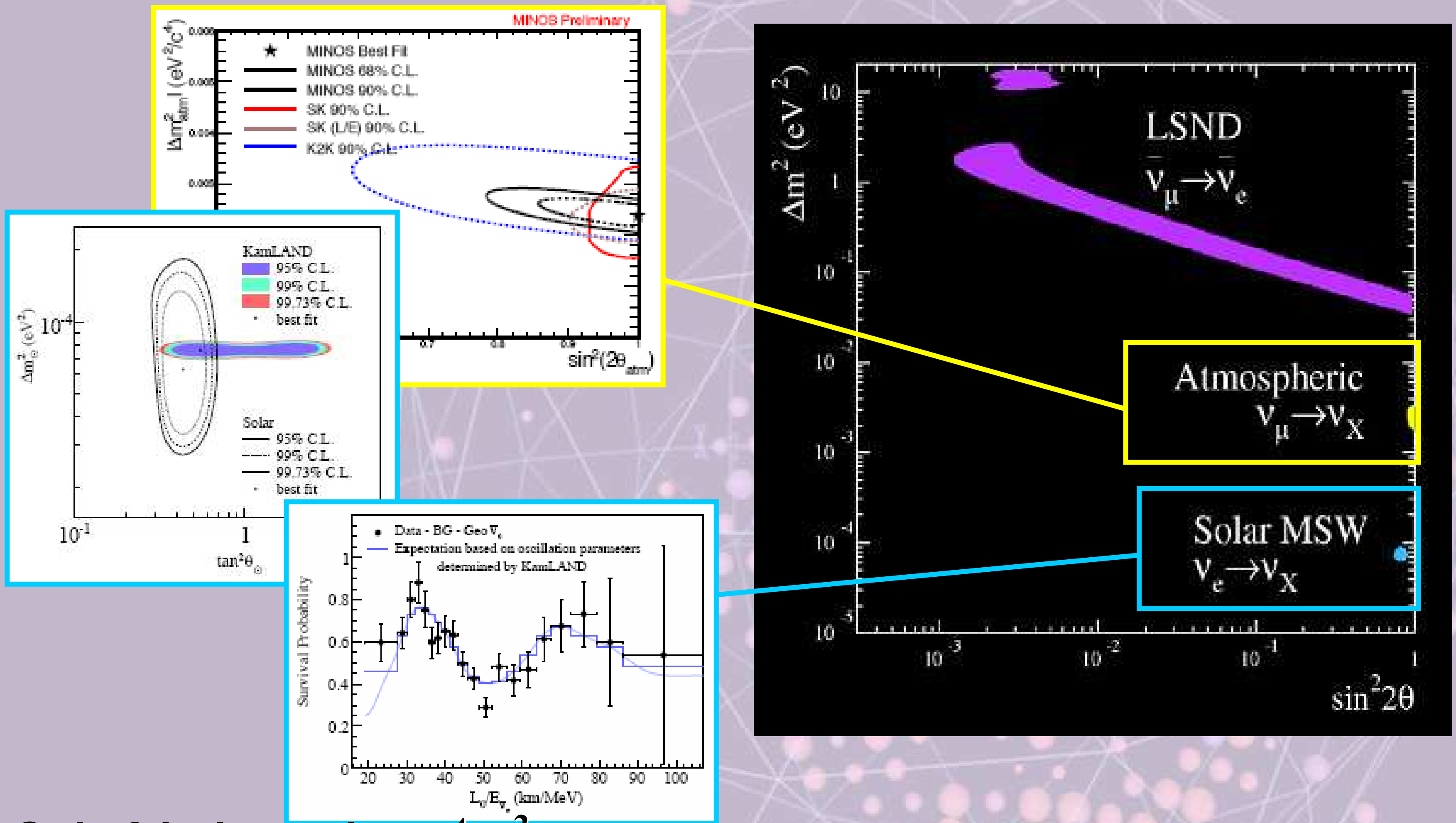
Possible interpretation:

2-neutrino mixing with:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\,\sin^2\left(\frac{1.27\,L\,\Delta m^2}{E}\right) = 0.245 \pm 0.067 \pm 0.045\ \%$$

Best fit: $\sin^2(2\theta) = 0.003$, $\Delta m^2 = 1.2\ eV^2$

Why not?

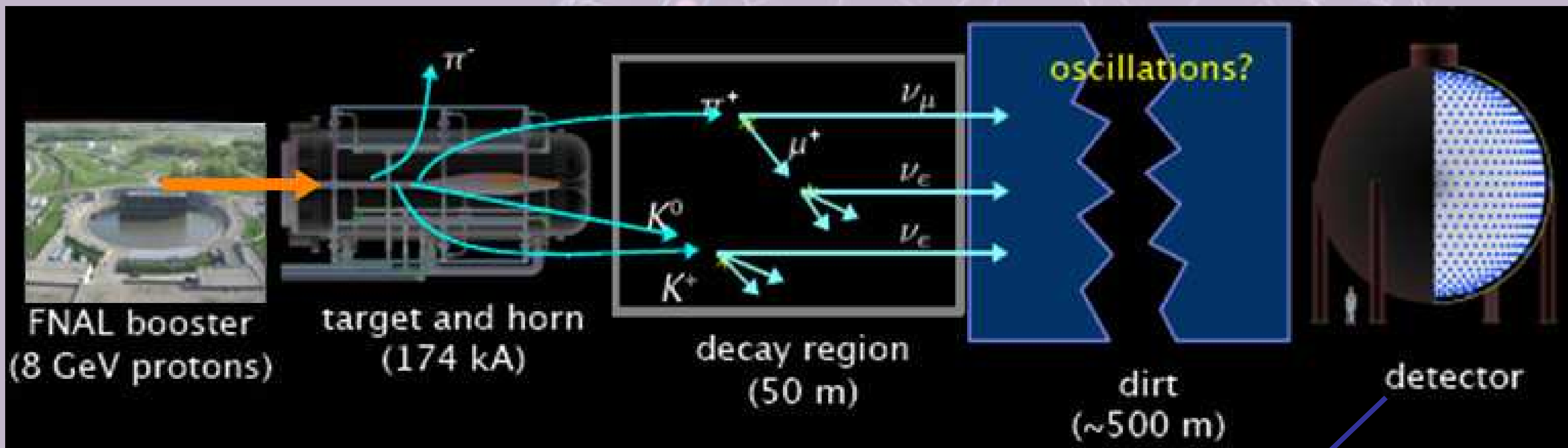


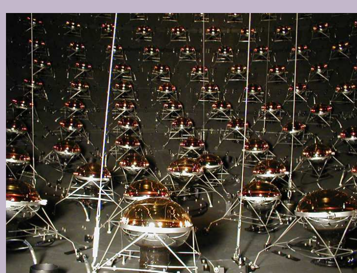
Only 2 independent Δm^2:

3-neutrino mixing scheme established by atmospheric and solar experiments cannot accommodate for the LSND oscillation interpretation

The MiniBooNE Experiment:

Designed to test: $P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\,L\,\Delta m^2}{E}\right) \approx 0.25\ \%$





800 ton mineral oil Cherenkov detector
12 m in diameter (450 ton fiducial volume)
lined with 1280 inner PMT's, and 240 outer veto PMT's

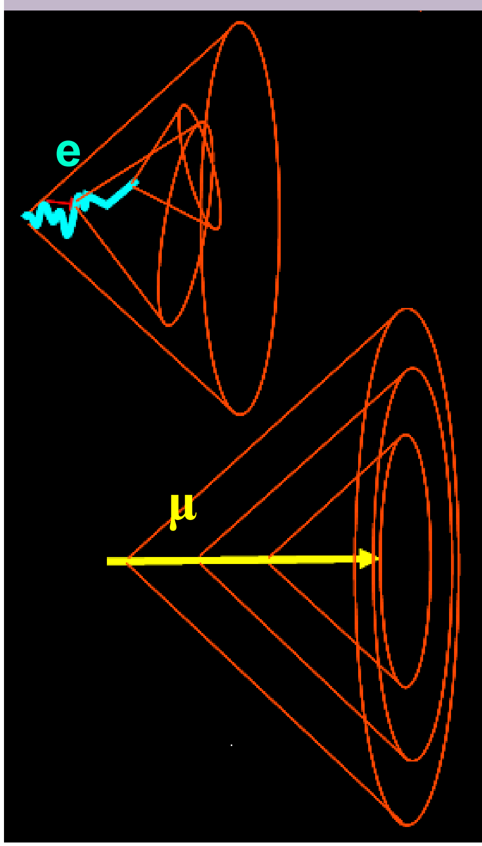
[arXiv: 0806.4201[hep-ex], Nucl. Instr. Meth. A599 (2009) 28-46]

Requirement: Place detector to preserve LSND L/E →
MiniBooNE: 500 m / 800 MeV
LSND: 30 m / 50 MeV
[Different detection method and systematics]

The MiniBooNE Experiment:

Event signatures:

Looking for ν_e signal in ν_μ dominated beam…



Signal

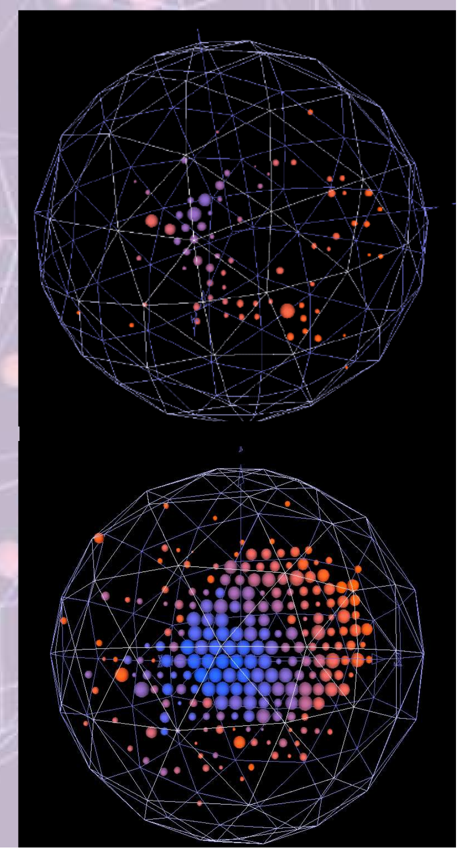
ν_e charged-current quasi-elastic events

$$\nu_e + n \rightarrow e^- + p$$

Dominant type of interaction

ν_μ charged-current quasi-elastic events

$$\nu_\mu + n \rightarrow \mu^- + p$$



The analysis…

A **blind** analysis chain was implemented…

[arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)]
[arXiv:0812.2243 [hep-ex], accepted by Phys. Rev. Lett.]

Track-based analysis (TBA)
*[but also boosted-decision-tree (**BDT**) analysis]*

Beam Flux Prediction →	Cross Section Model →	Optical Model →	Event Reconstruction →	Particle Identification →	Simultaneous Fit to ν_μ and ν_e events
Start with a Geant 4 flux prediction for the ν spectrum from π and K produced at the target	Predict ν interactions using the Nuance event generator	Pass final state particles to Geant 3 to model particle and light propagation in the tank	Use track-based event reconstruction	Use hit topology and timing to identify electron-like or muon-like Cherenkov rings and corresponding charged current neutrino interactions	Fit reconstructed energy spectrum for oscillations

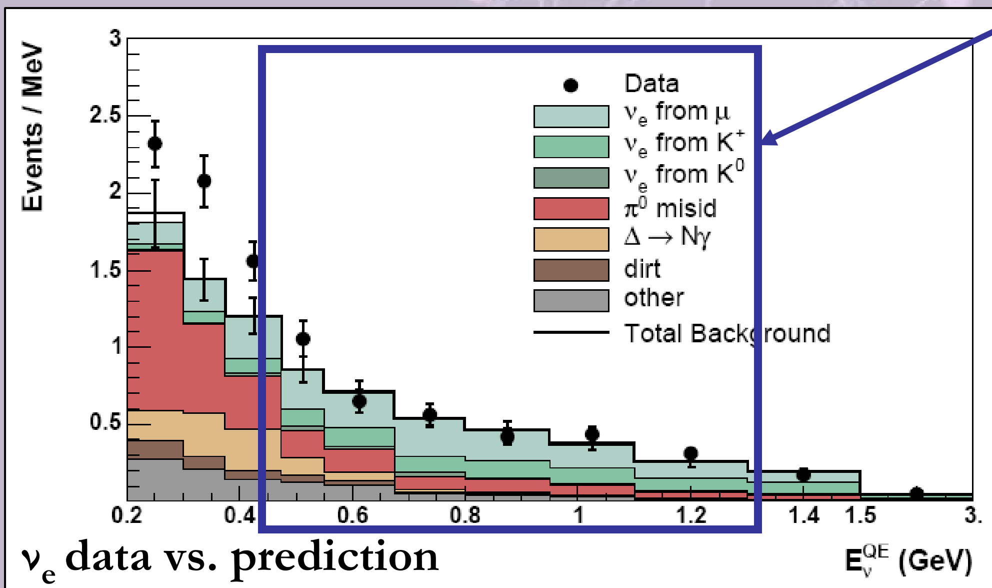
A glimpse of hope…

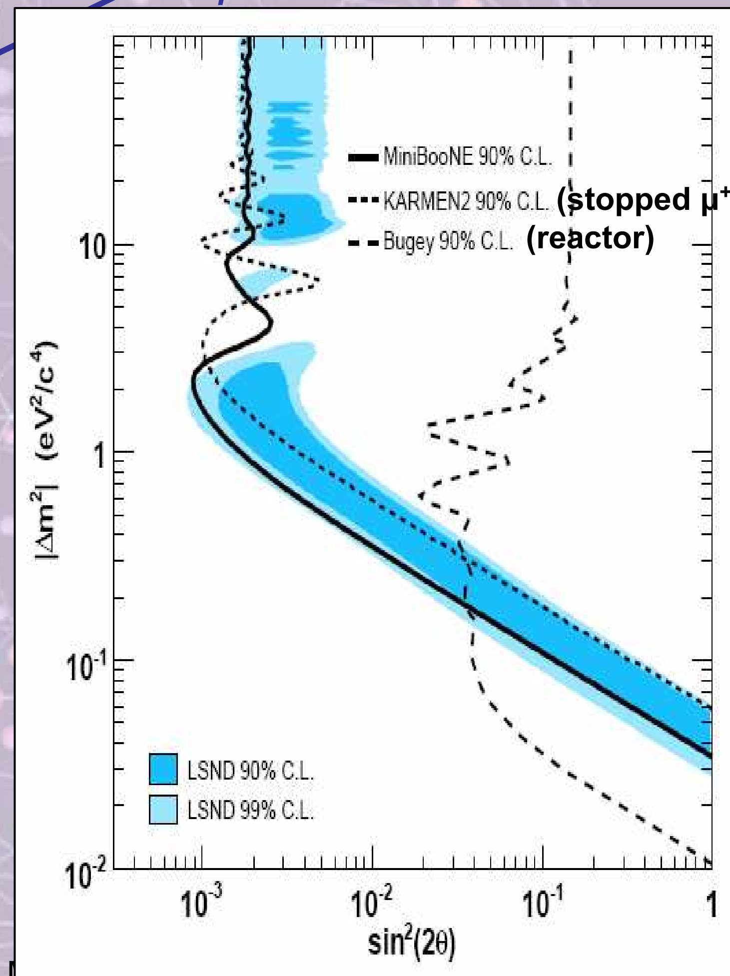
MiniBooNE has searched for $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 \sim 1$ eV^2

[arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)]

Observed no excess consistent with the LSND two-neutrino oscillation…

$\nu_\mu \rightarrow \nu_e$ signal region





…and therefore ruled out LSND $\nu_\mu \rightarrow \nu_e$ oscillation interpretation:

Assumptions:

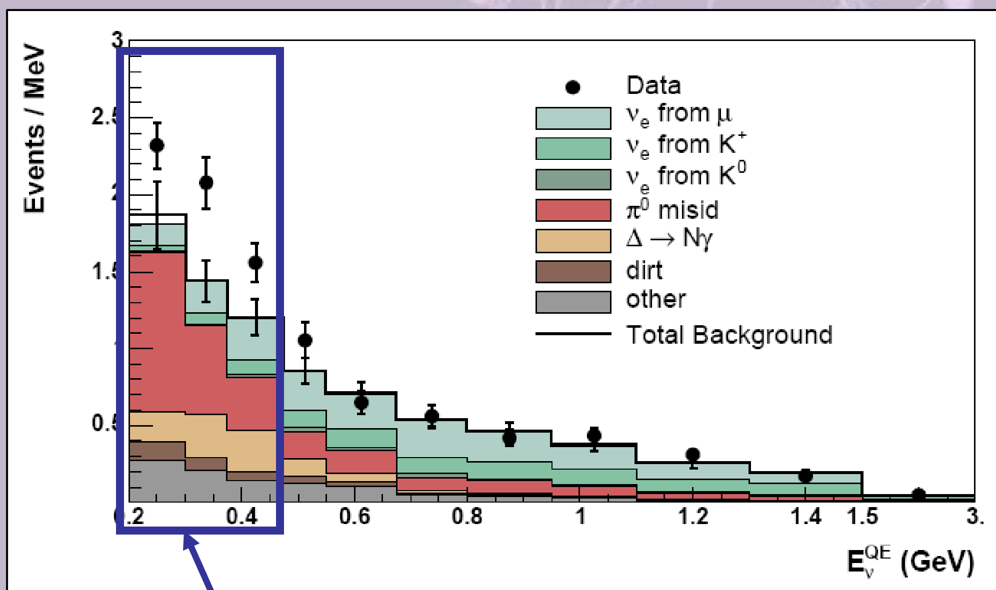
2-ν oscillation, with standard L/E dependence

→ no CP or CPT violation

But another mystery…

But observed **unexpected excess** of events at low energy…

[arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)]
[arXiv:0812.2243 [hep-ex], accepted by Phys. Rev. Lett.]



low energy excess region
128.8 ± 43.4 excess events (3.0σ)

Interpretations include:

- CP violation with 2 sterile ν
  [Maltoni, Schwetz, hep-ph/0705.0107, G.K., *et al*, hep-ph/0609177]
- Extra dimensions
  [Pas, Pakvasa, Weiler, hep-
- New particles
  [Nelson, W ...)]
- CP ...tion
  ...ecky, Tayloe, PRD 74, 105009 (2006)]
- ...teractions
  [Harvey, Hill, Hill, hep-ph/0708.1281]
- VSBL ν_e disappearance
  [Giunti, Laveder, PRD 77, 093002 (2008)]

predictions for MiniBooNE
$\bar{\nu}_\mu \to \bar{\nu}_e$ signal

Addressing the MiniBooNE and LSND anomalies

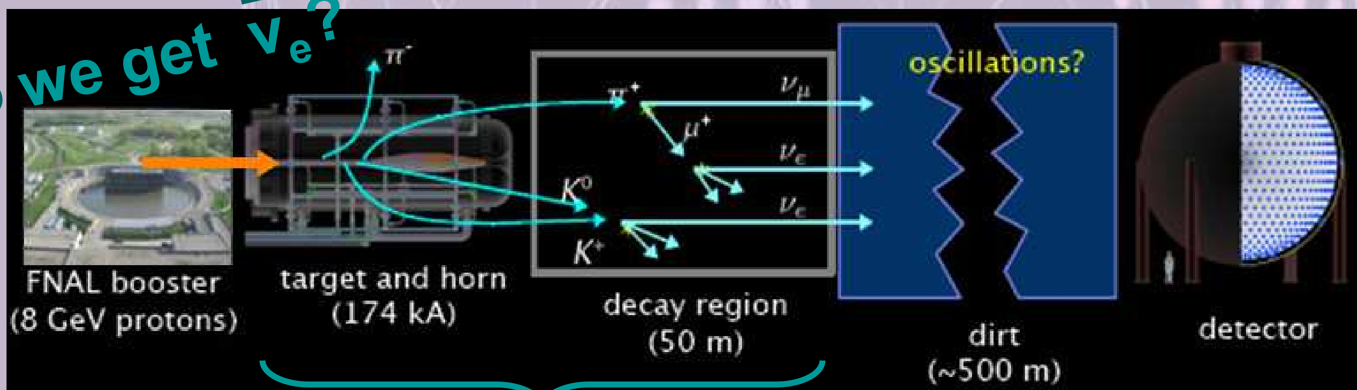
Through antineutrino running @ MiniBooNE: $\bar{\nu}_e$ appearance search

First antineutrino results (this talk), for 3.4e20 protons on target (POT)!

(new results coming soon, for 5.0e20 POT)

First look at antineutrinos

How do we get $\bar{\nu}_e$?



by switching horn polarity, we focus negatively charged mesons, yielding an anti-ν_μ beam

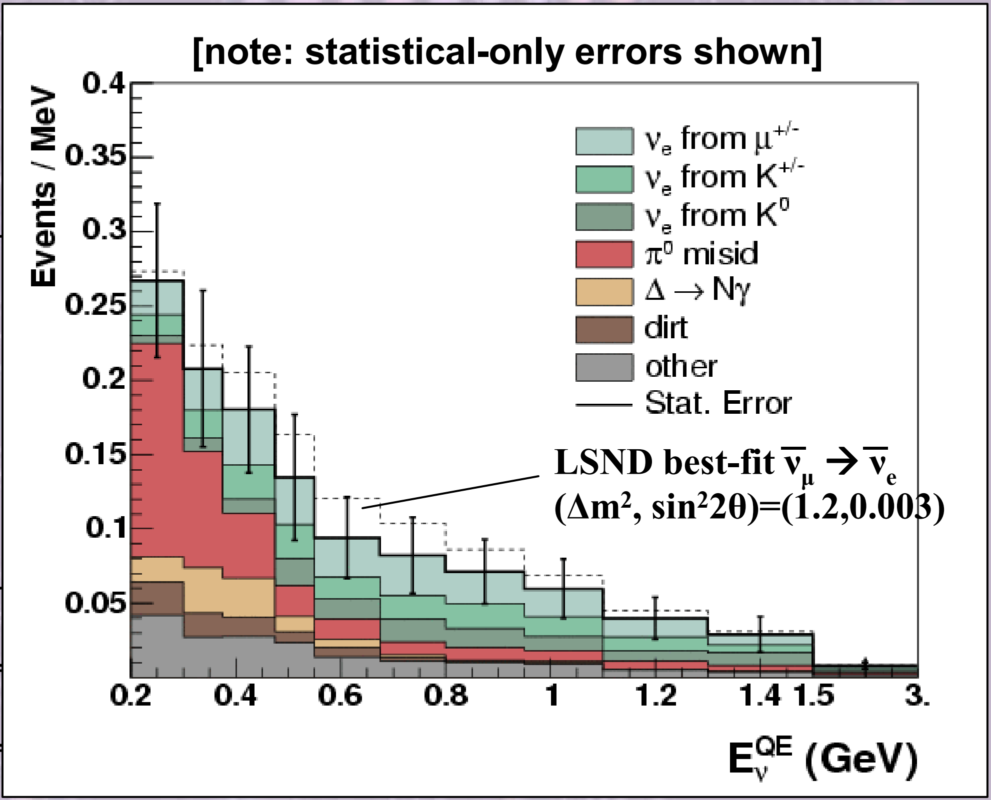
Antineutrino dataset is used to address both **CP/CPT violating $\nu_\mu \rightarrow \nu_e$ oscillations**, and **MiniBooNE low energy excess** interpretations

Looking for $\bar{\nu}_e$ signal…

Background composition for $\bar{\nu}_e$ appearance search (3.4e20 POT):

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.7	43.2
from $\pi^{\pm}/\mu^{\pm}$	8.4	17.1
from $K^{\pm}$, K^0	8.2	24.9
other ν_e	1.1	1.2
mis-id ν_μ	42.5	14.6
CCQE	2.9	1.2
NC π^0	24.6	7.2
Δ radiative	6.6	2.0
Dirt	4.7	1.9
other ν_μ	3.8	2.2
Total bkgd	60.3	57.8
LSND best fit	4.3	12.6

(only anti-ν_μ assumed to oscillate)



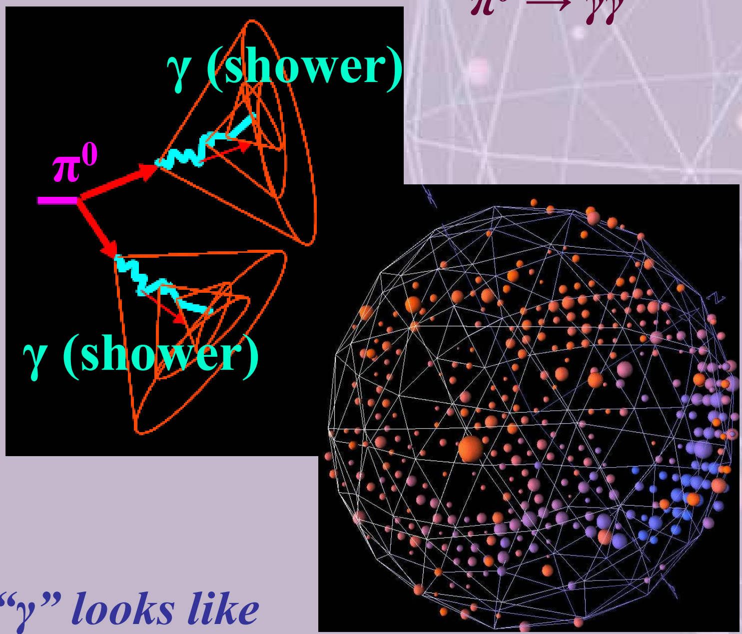
Looking for $\bar{\nu}_e$ signal…

Dominant background (at low energy)

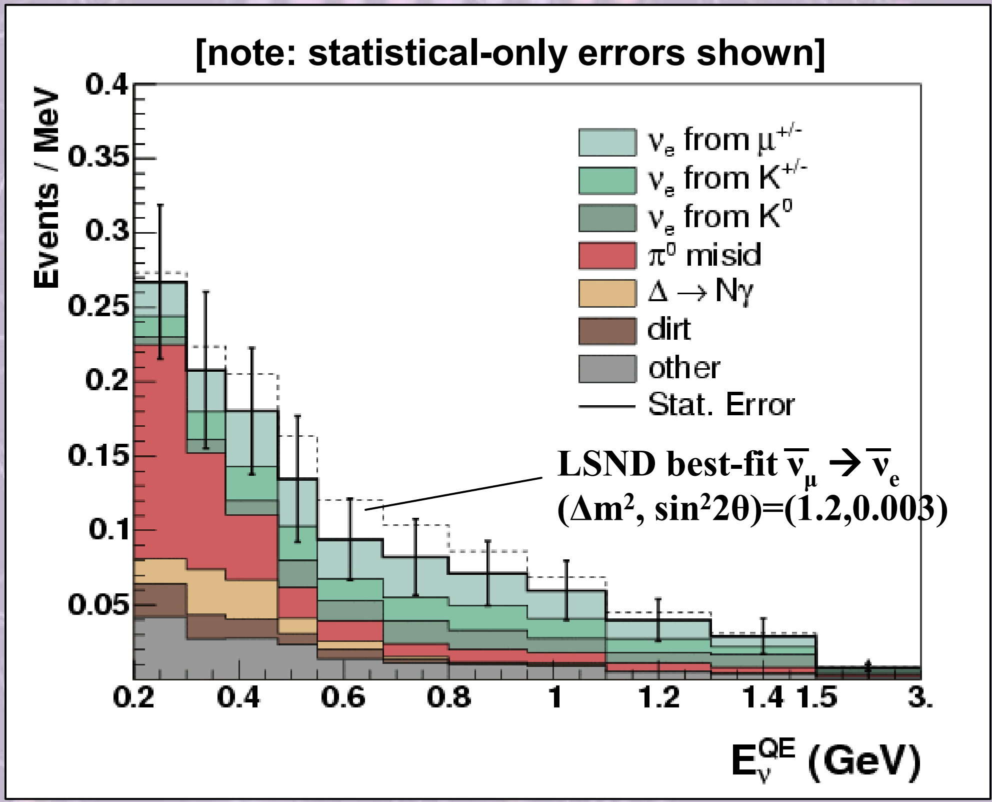
$\bar{\nu}_\mu$ neutral-current interactions with photon(s) in the final state

For example, NC π^0:

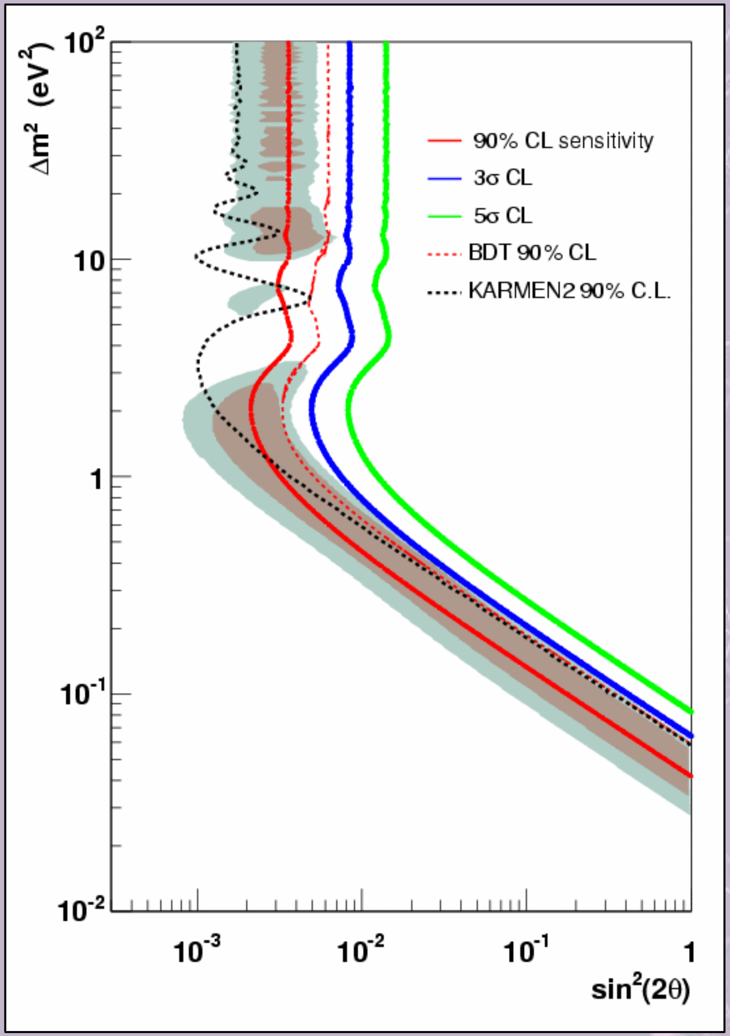
$$\bar{\nu}_\mu + n/p \rightarrow n/p + \pi^0 + \bar{\nu}_\mu$$
$$\pi^0 \rightarrow \gamma\gamma$$

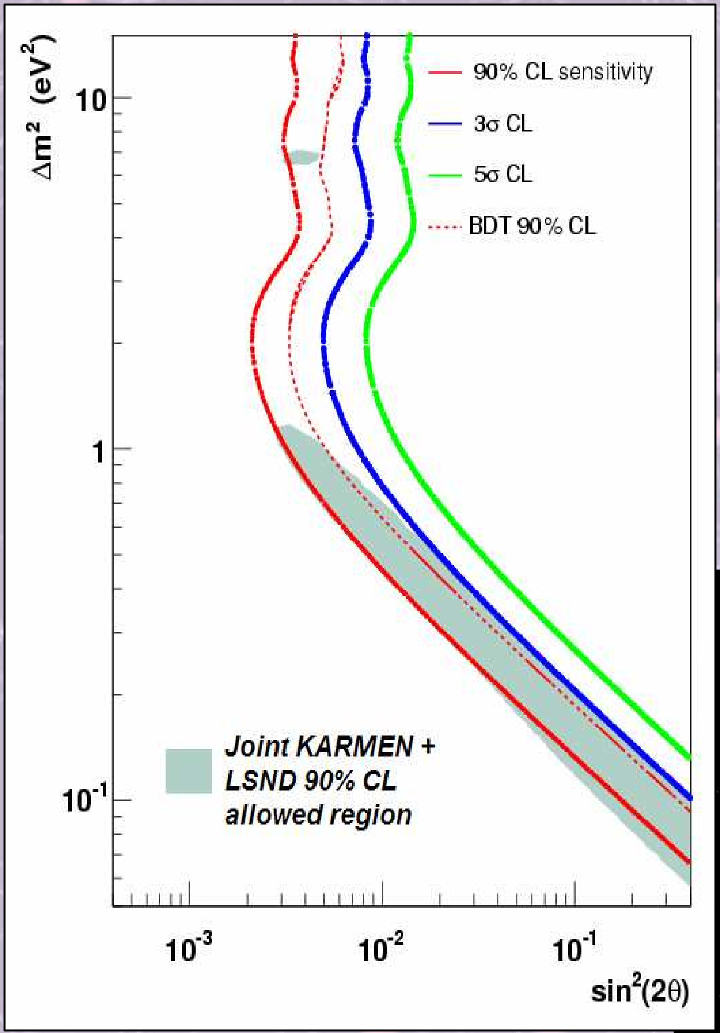


…"γ" looks like "e" in a Cherenkov detector



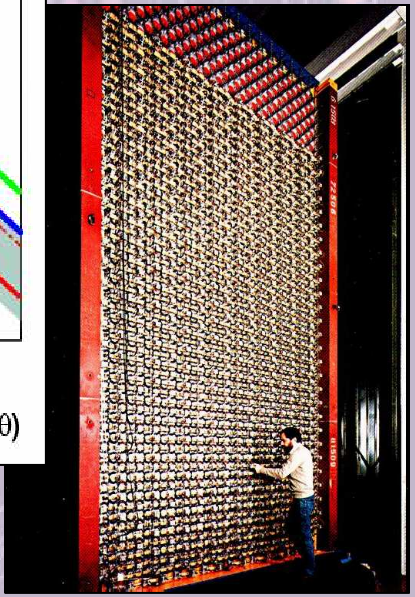
MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ sensitivity (3.4e20 POT)





KARMEN:
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search

Compatibility with LSND at 64% CL



[KARMEN: hep-ex/0203021, Phys. Rev. D 65, 112001 (2002)]
[KARMEN-LSND compatibility: hep-ex/0203023, Phys. Rev. D 66, 013001 (2002)]

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

$\bar{\nu}_e$ data vs. background distribution (3.4e20 POT):

First antineutrino result!

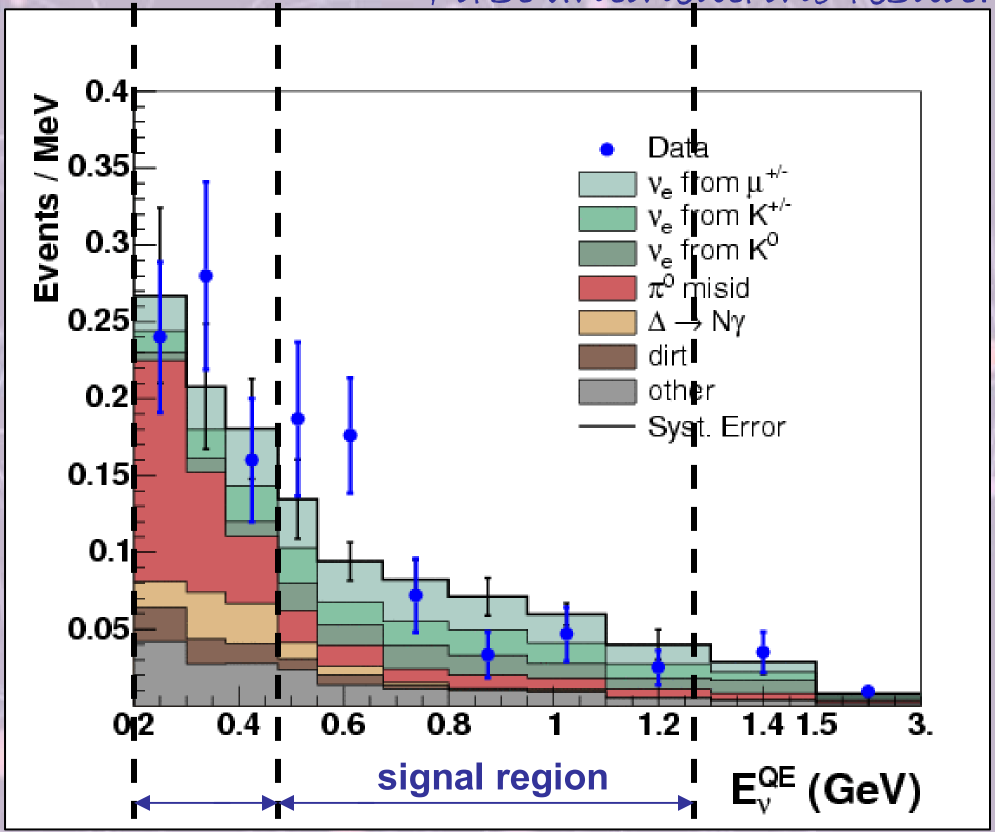
$\chi^2_{null}(dof) = 24.5\ (19)$
$\chi^2\text{-probability} = 17.7\%$

$\chi^2_{best\text{-}fit}(dof) = 18.2\ (17)$
$\chi^2\text{-probability} = 37.8\%$

MiniBooNE best-fit:

(Δm^2, $\sin^2 2\theta$) = (4.4 eV^2, 0.004)

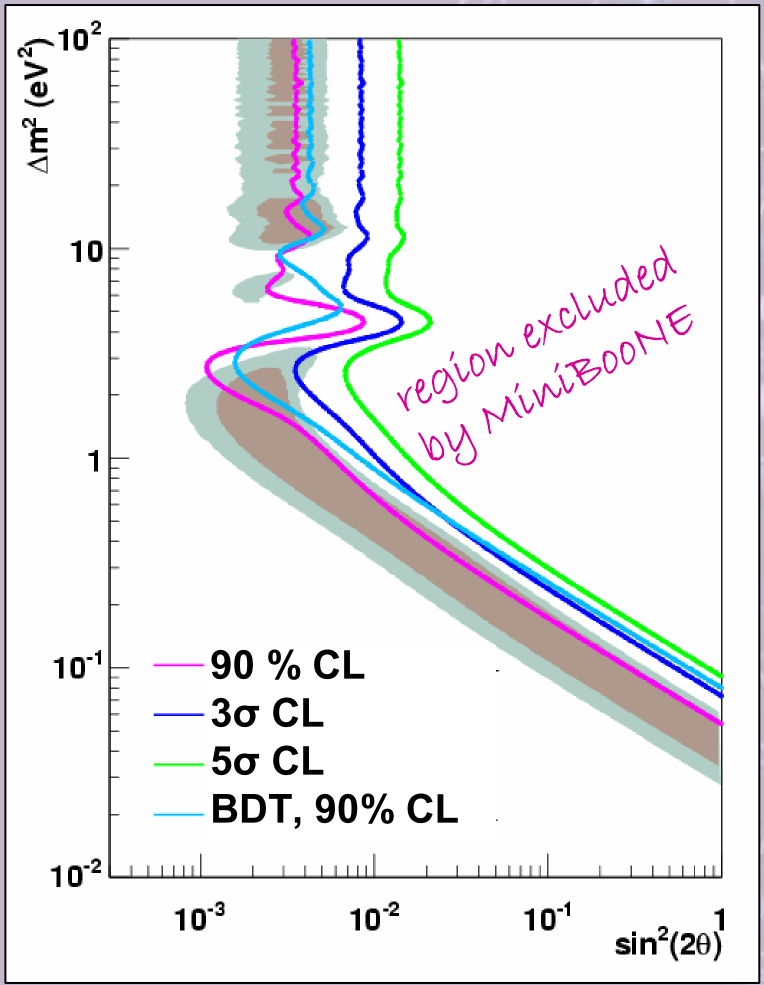
No significant excess observed at both low and high energy!

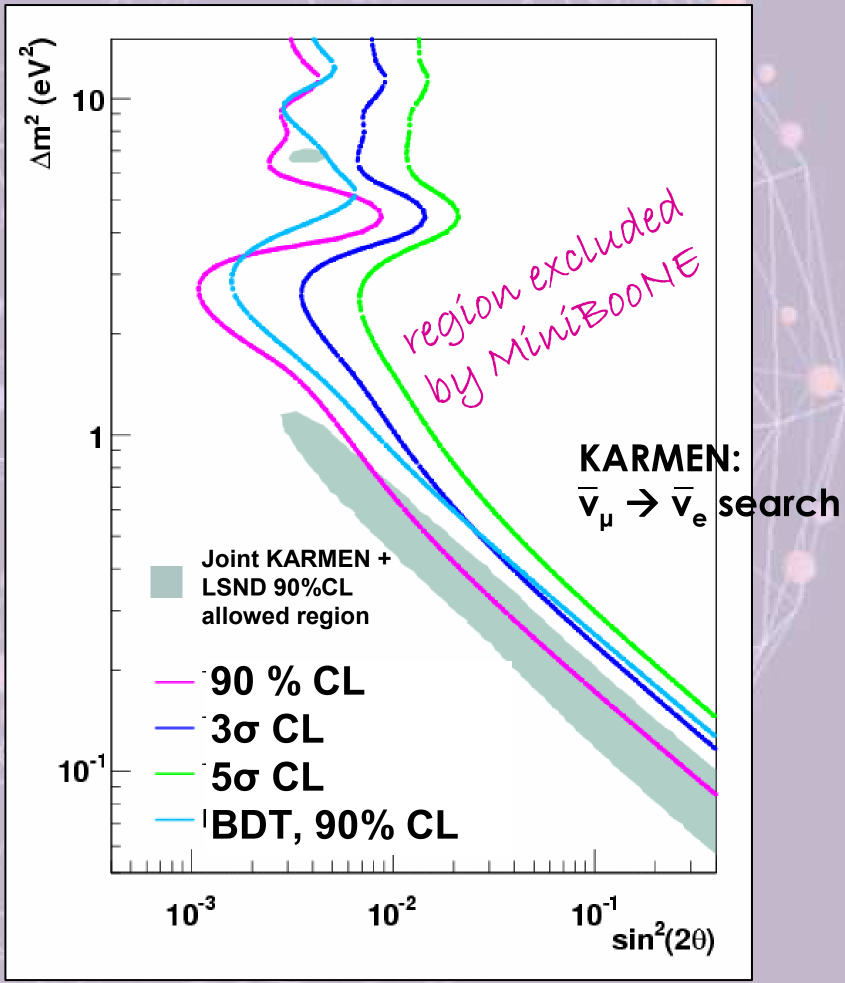


low energy region

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

With 3.4e20 POT, MiniBooNE places a limit to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:





What about the low energy excess?

E_ν^{QE} *range (MeV)* (same binning as in neutrino mode)		$\bar{\nu}$ *mode (3.4e20 POT)*	ν *mode (6.5e20 POT)* [hep-ex/0812.2243]
200-475	*Data*	*61*	*544*
	MC ± sys+stat (constr.)	*61.5 ± 11.7*	*415.2 ± 43.4*
	Excess (σ)	*-0.5 ± 11.7 (-0.04)*	*128.8 ± 43.4 (3.0)*
475-1250	*Data*	*61*	*408*
	MC ± sys+stat (constr.)	*57.8 ± 10.0*	*385.9 ± 35.7*
	Excess (σ)	*3.2 ± 10.0 (0.3)*	*22.1 ± 35.7 (0.6)*

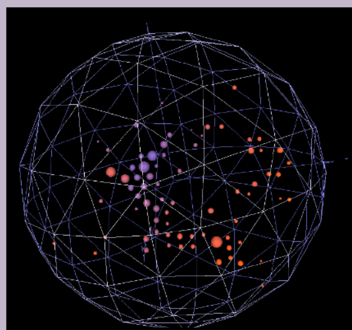
How consistent are excesses in neutrino and antineutrino mode under different underlying hypotheses as the source of the low energy excess in neutrino mode?

Possibilities:

Background & New Physics

What about the low energy excess?

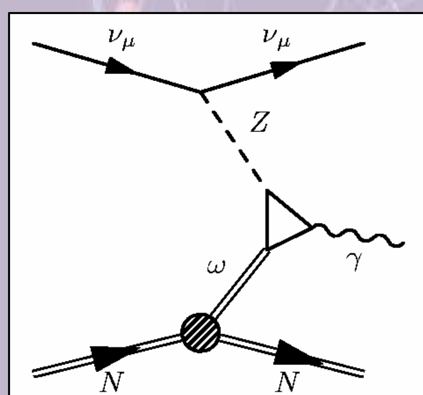
Suggested hypotheses:



Include processes contributing either a single-electron or a single-gamma

"New" physics? E.g.

Anomaly-mediated photon production?



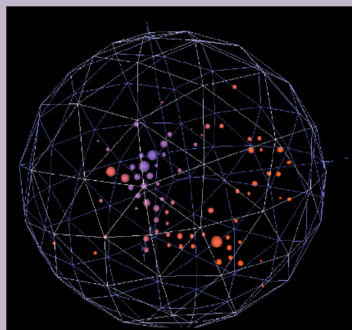
[Harvey, Hill, and Hill, hep-ph0708.1281]

Standard Model, but odd…

Assumed to contribute equally for neutrinos and antineutrinos

What about the low energy excess?

Suggested hypotheses:



Include processes contributing either a single-electron or a single-gamma

Or background? E.g.

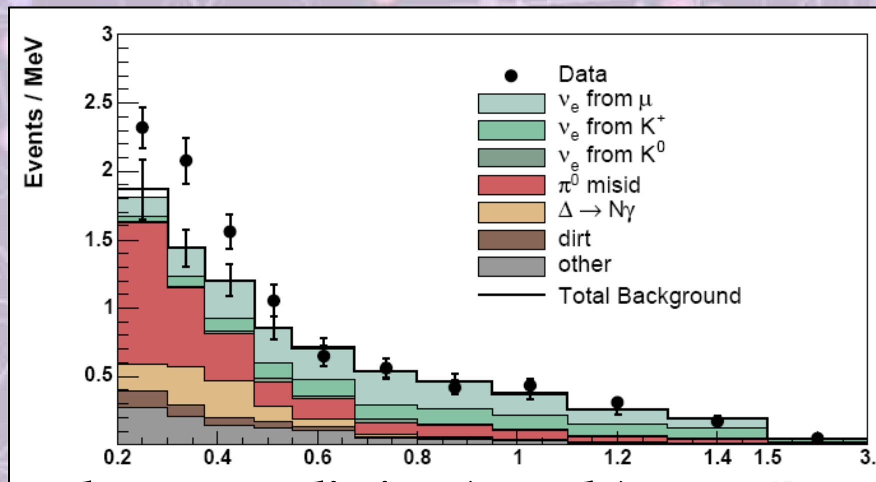
- **Misestimated π^0?**

To account for ν mode excess, π^0 background would have to be misestimated by a factor of 2...

Unlikely, since the π^0 rate is measured to 5%.

[Phys. Lett. B664, 41 (2008)]

π^0: most dominant background at low energy



ν_e data vs. prediction (ν mode)

What about the low energy excess?

In testing these hypotheses, the excess is assumed to scale from neutrinos to antineutrinos as follows:

- **The same $\nu,\bar{\nu}$ NC cross section** (e.g. HHH axial anomaly [hep-ph/0708.1281])
- **The same cross section ratio as NC π^0 background** (cross section is different for ν, $\bar{\nu}$)
- **With POT** (e.g. K0L-induced events)
- **With Background**
- **CC cross section ratio**
- **Low-E Kaons**
- **Neutrinos only (no antineutrinos)** (neutrino induced interaction)

Flux and protons on target (POT) in neutrino and antineutrino mode were taken into account in the scaling.

What about the low energy excess?

Maximum χ^2 probability from fits to ν and $\bar{\nu}$ excesses in 200-475 MeV range

	Stat Only	**Correlated Syst**	Uncorrelated Syst
Same ν,$\bar{\nu}$ NC	0.1%	**0.1%**	6.7%
NC π^0 scaled	3.6%	**6.4%**	21.5%
POT scaled	0.0%	**0.0%**	1.8%
Bkgd scaled	2.7%	**4.7%**	19.2%
CC scaled	2.9%	**5.2%**	19.9%
Low-E Kaons	0.1%	**0.1%**	5.9%
ν scaled	38.4%	**51.4%**	58.0%
		("lower limit")	("upper limit")

Preliminary

Same ν and $\bar{\nu}$ NC cross-section (HHH axial anomaly), POT scaled, Low-E Kaon scaled: disfavored as an explanation of the MiniBooNE low energy excess!

The most preferred model is that where the low-energy excess comes from neutrinos in the beam (no contribution from anti-neutrinos).

Current status & prospects:

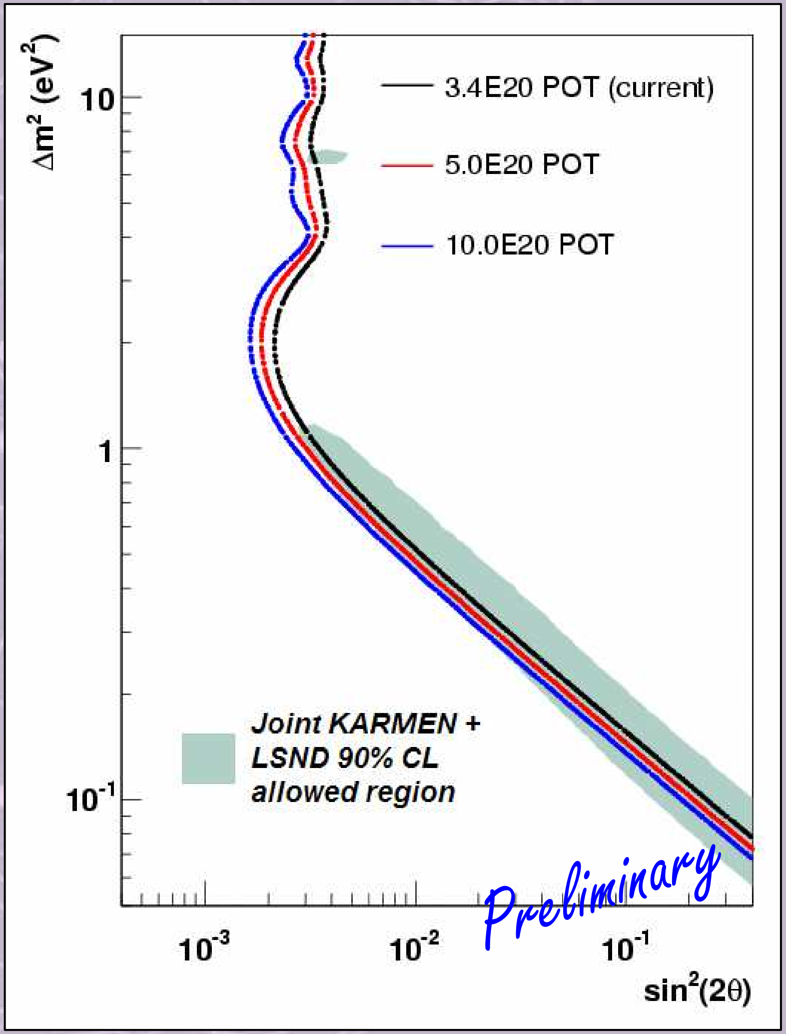
We have performed a blind analysis to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations: $\bar{\nu}_e$ data in agreement with MonteCarlo background prediction as a function of E_ν^{QE}.

So far, no strong evidence for oscillations in antineutrino mode (although currently limited by statistics).

Interestingly, no evidence of significant excess at low energy in antineutrino mode. This has already placed constraints to various suggested low energy excess interpretations.

In process of collecting more data for a total of 5.0e20 POT. This will improve sensitivity to oscillations, and allow further investigation of the ν low energy excess. Have submitted a request for 10.0e20 POT.

Projected MiniBooNE 90% CL $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ sensitivity for extra POT

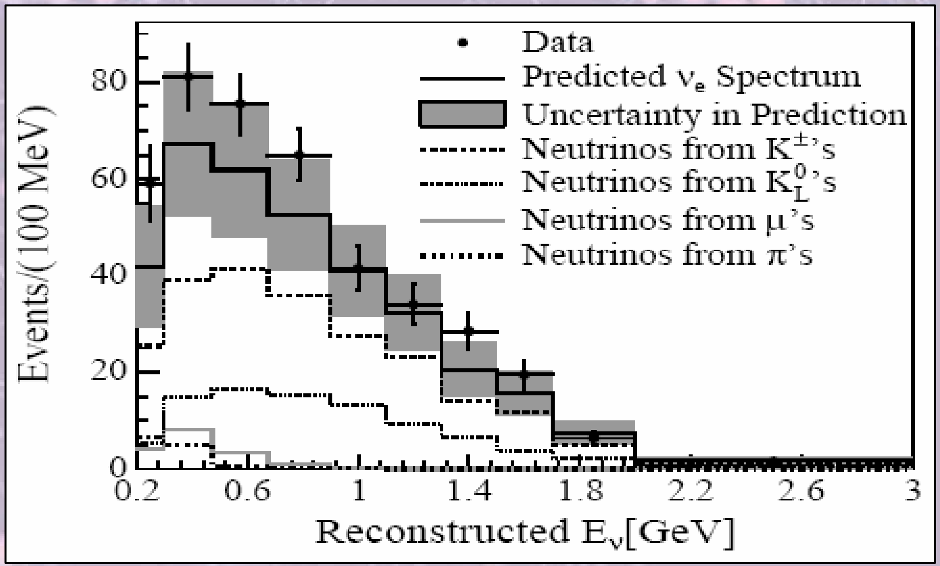


Coming soon…

Combined ν_e and $\bar{\nu}_e$ analysis for low energy events with systematic correlations properly included, for testing various low energy excess interpretations

Combined ν_e and $\bar{\nu}_e$ appearance analysis (with CP violation) for stronger constraints on oscillations

Combined MiniBooNE-NuMI ν_e appearance analysis



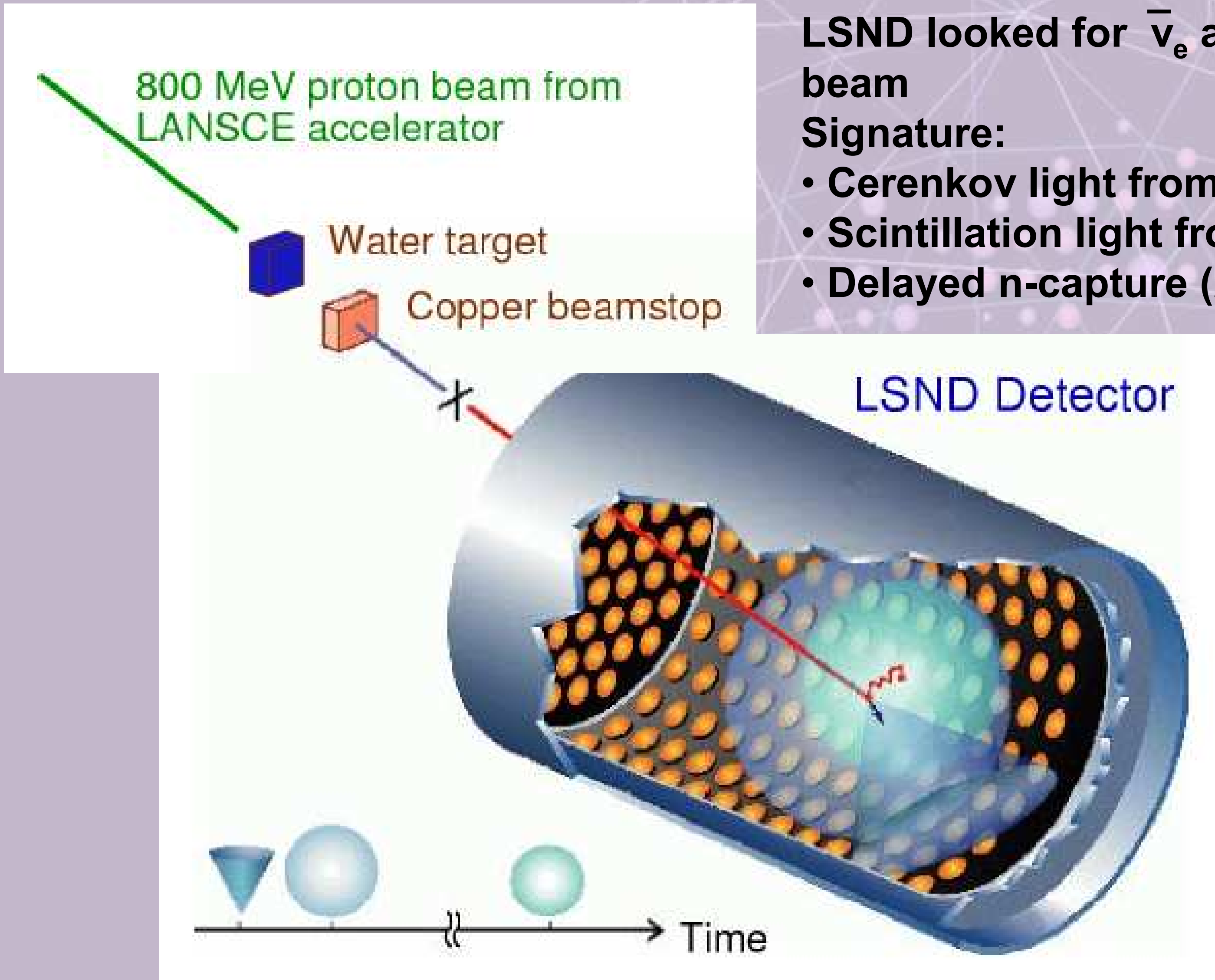
NuMI ν_e distribution
[uses different beam]

[arXiv:0809.2446 [hep-ex], submitted to Phys. Rev. Lett.]

Thank you!

Y.Liu, D.Perevalov, I.Stancu
University of Alabama
S.Koutsoliotas
Bucknell University
E.Hawker, R.A.Johnson, J.L.Raaf
University of Cincinnati
T. L. Hart, R.H.Nelson, M.Tzanov, M.Wilking, E.D.Zimmerman
University of Colorado
A.A.Aguilar-Arevalo, L.Bugel, L.Coney, Z. Djurcic, K.B.M.Mahn, J.Monroe, D.Schmitz M.H.Shaevitz, M.Sorel
Columbia University
D.Smith ***Embry Riddle Aeronautical University***
L.Bartoszek, C.Bhat, S.J.Brice B.C.Brown, D. A. Finley, R.Ford, F.G.Garcia, C. Green, P.Kasper, T.Kobilarciik, I.Kourbanis, A.Malensek, W.Marsh, P.Martin, F.Mills, C.D.Moore, E.Prebys, A.D.Russell , P.Spentzouris, R.J.Stefanski, T. Williams
Fermi National Accelerator Laboratory
D.C.Cox, T.Katori, H.Meyer, C.C.Polly, R.Tayloe
Indiana University
H.Ray, B. Osmanov, J. Grange, J. Mousseau
University of Florida
G.T.Garvey, A.Green, C.Green, W.C.Louis, G.McGregor, G.B.Mills, V.Sandberg, R.Schirato, Z. Pavlovic R.Van de Water , D.H.White, G.P.Zeller
Los Alamos National Laboratory
R.Imlay, J.A. Nowak, W.Metcalf, S.Ouedraogo, M. Sung, M.O.Wascko
Louisiana State University
J.M.Conrad, G. Karagiorgi, V. Nguyen
Massachusetts Institute of Technology
J.Cao, Y.Liu, B.P.Roe, H.J.Yang
University of Michigan
A.O.Bazarko, E. M. Laird, P.D.Meyers, R.B.Patterson, F.C.Shoemaker, H.A.Tanaka
Princeton University
P.Nienaber ***Saint Mary's University of Minnesota***
J. M. Link ***Virginia Polytechnic Institute***
C.E Anderson, A.Curioni, B.T.Fleming,S.K. Linden, M. Soderberg
Yale University

The LSND experiment



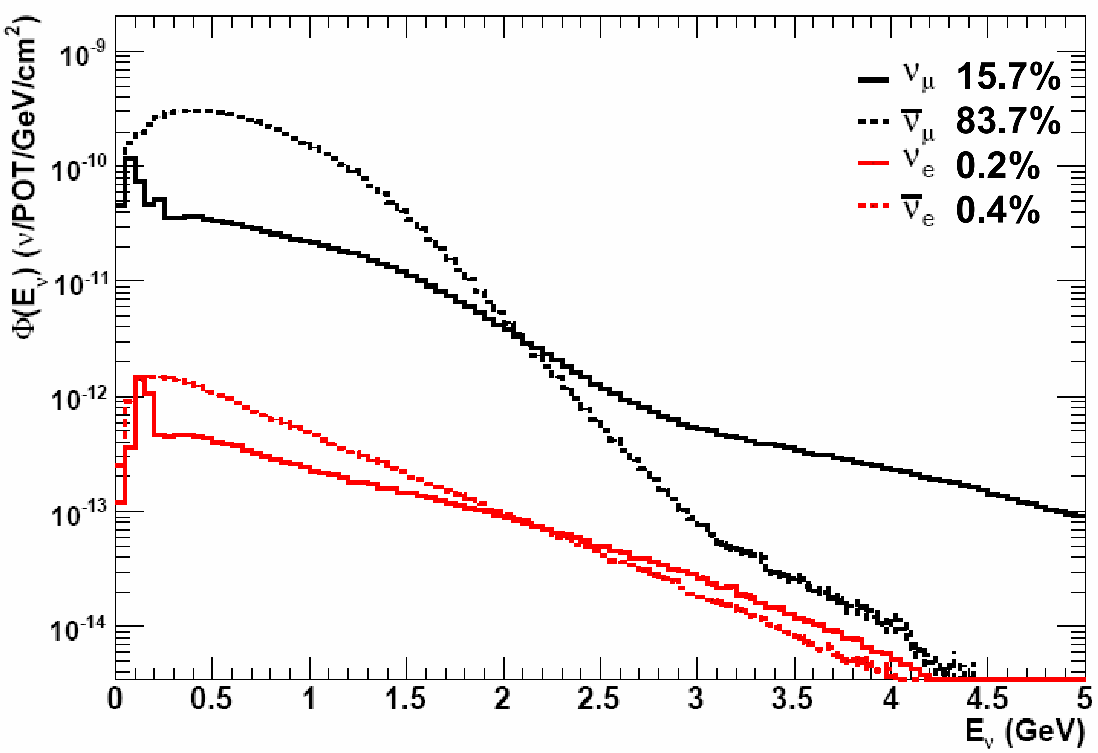
LSND looked for $\bar{\nu}_e$ appearing in a $\bar{\nu}_\mu$ beam

Signature:

- **Cerenkov light from e+ (CC)**
- **Scintillation light from nuclear recoil**
- **Delayed n-capture (2.2 MeV)**

MiniBooNE antineutrino running

MiniBooNE antineutrino flux prediction:



[arXiv:0806.1449 [hep-ex], accepted by Phys. Rev. D]

Event rates:

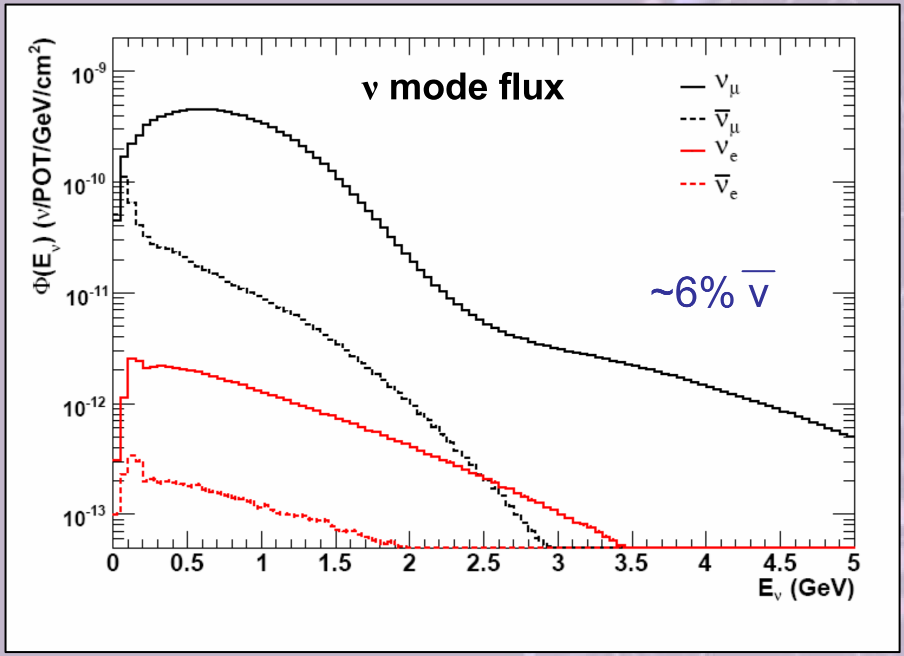
(xsec-weighted, after selection cuts)

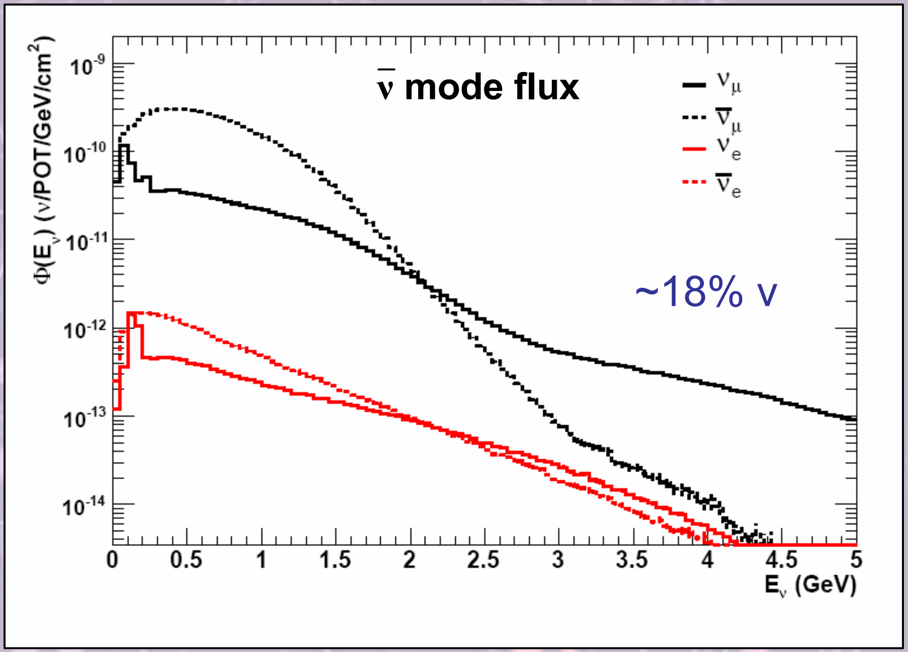
~14,000 $\bar{\nu}_\mu$ CCQE events (~70% pure)

~ 140 $\bar{\nu}_e$ CCQE events (~40% pure)

First antineutrino results correspond to dataset collected for 3.4e20 POT

MiniBooNE flux prediction





WS further amplified to ~30% in $\bar{\nu}$ mode due to cross-section

neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search [Phys. Rev. Lett. 98, 231801 (2007)]

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

MiniBooNE event rate prediction

ν channel	events
all channels	895k
CC quasielastic	375k
NC elastic	165k
CC π^+	200k
CC π^0	33k
NC π^0	53k
NC $\pi^{+/-}$	30k
CC/NC DIS, multi-π	39k

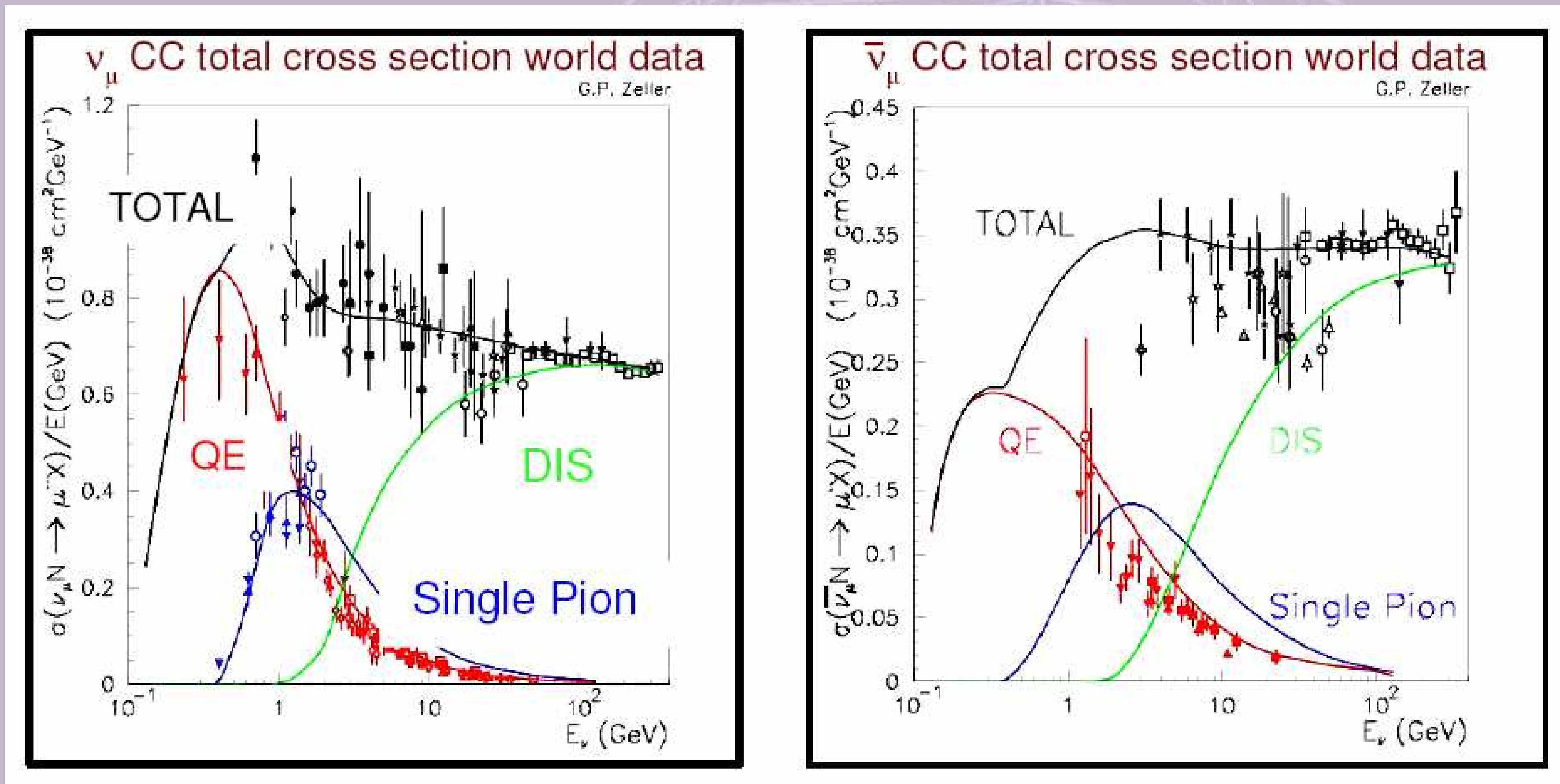
6.6×10^{20} POT
ν mode

$\bar{\nu}$ channel	events
all channels	83k
CC quasielastic	37k
NC elastic	16k
CC π^-	14k
CC π^0	2.6k
NC π^0	7.6k
NC $\pi^{+/-}$	2.8k
CC/NC DIS, multi-π	2.9k

3.4×10^{20} POT
$\bar{\nu}$ mode

Although delivered POT only reduced by a factor of ~2, overall rate down by almost an order of magnitude!

Neutrino cross sections



Channel of interest at MiniBooNE: CCQE

MiniBooNE systematics:

Background systematic uncertainties

Source E_ν^{QE} *range (MeV)*	uncertainty (%) *200-475*	*475-1100*
Flux from π^+/μ^+ decay	0.4	0.7
Flux from π^-/μ^- decay	3.3	2.2
Flux from K^+ decay	2.3	4.9
Flux from K^- decay	0.5	1.1
Flux from K^0 decay	1.5	5.7
Target and beam models	1.9	3.0
ν cross section	6.4	12.9
NC π^0 yield	1.7	1.6
Hadronic interactions	0.5	0.6
External interactions (dirt)	2.4	1.2
Optical model	9.8	2.8
Electronics & DAQ model	9.7	3.0
Total (unconstrained)	*16.3*	*16.2*

ANTINEUTRINO APPEARANCE SEARCH IS STATISTICS LIMITED

Antineutrino results

Background systematic uncertainties

E_ν^{QE} fit	χ^2_{null}(dof) χ^2-prob	χ^2_{null}(dof)* χ^2-prob	$\chi^2_{best\text{-}fit}$(dof)* χ^2-prob	$\chi^2_{LSND\ best\text{-}fit}$(dof) χ^2-prob
> 200 MeV	24.51(19) 17.7%	20.18(17) 26.5%	18.18(17) 37.8%	20.14(19) 38.6%
> 475 MeV	22.19(16) 13.7%	17.88(14) 21.2%	15.91(14) 31.9%	17.63(16) 34.6%

(*Covariance matrix approximated to be the same everywhere by its value at best fit point)

Antineutrino results

[hep-ex/0812.2243]

E_ν^{QE} range (MeV) (same binning as in neutrino mode)		$\bar{\nu}$ mode (3.4e20 POT)	ν mode (6.5e20 POT)
200-475	Data	61	544
	MC ± sys+stat (constr.)	61.5 ± 11.7	415.2 ± 43.4
	Excess (σ)	-0.5 ± 11.7 (-0.04)	128.8 ± 43.4 (3.0)

- Performed 2-bin χ^2 test for each assumption
- Calculated χ^2 probability assuming 1 dof

$$\chi^2 = \sum_{i,j} \left(D_i - (B_i + S_i)\right) M_{ij}^{-1} \left(D_j - (B_j + S_j)\right)$$

$i, j = \nu, \bar{\nu}$ 200-475MeV bin

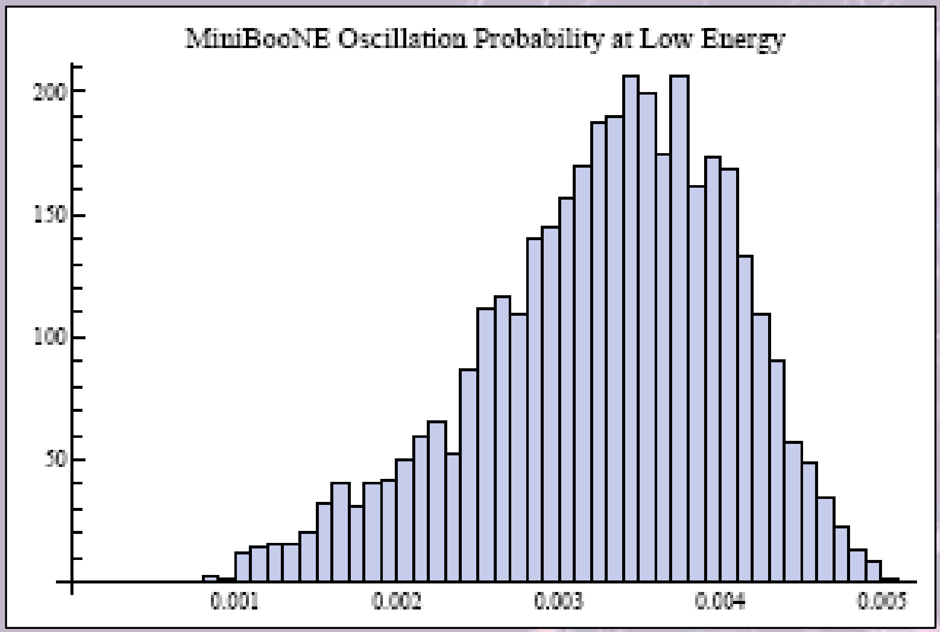
The underlying signal for each hypothesis, S, was allowed to vary (thus accounting for the possibility that the observed signal in neutrino mode was a fluctuation up, and the observed signal in antineutrino mode was a fluctuation down), and an absolute χ^2 minimum was found.

- Three extreme fit scenarios were considered:
  - Statistical-only uncertainties
  - Statistical + fully-correlated systematics
  - Statistical + fully-uncorrelated systematics

Low E interpretations

New light gauge boson

[Nelson and Walsh, Phys. Rev. D 77, 033001 (2008)]



- **3 sterile neutrinos + gauged B-L interaction**
- **gives rise to MSW-type potential → strong energy dependence in SBL, small mixing oscillations**

Predicts higher anti-ν than ν oscillation probability

Low E interpretations

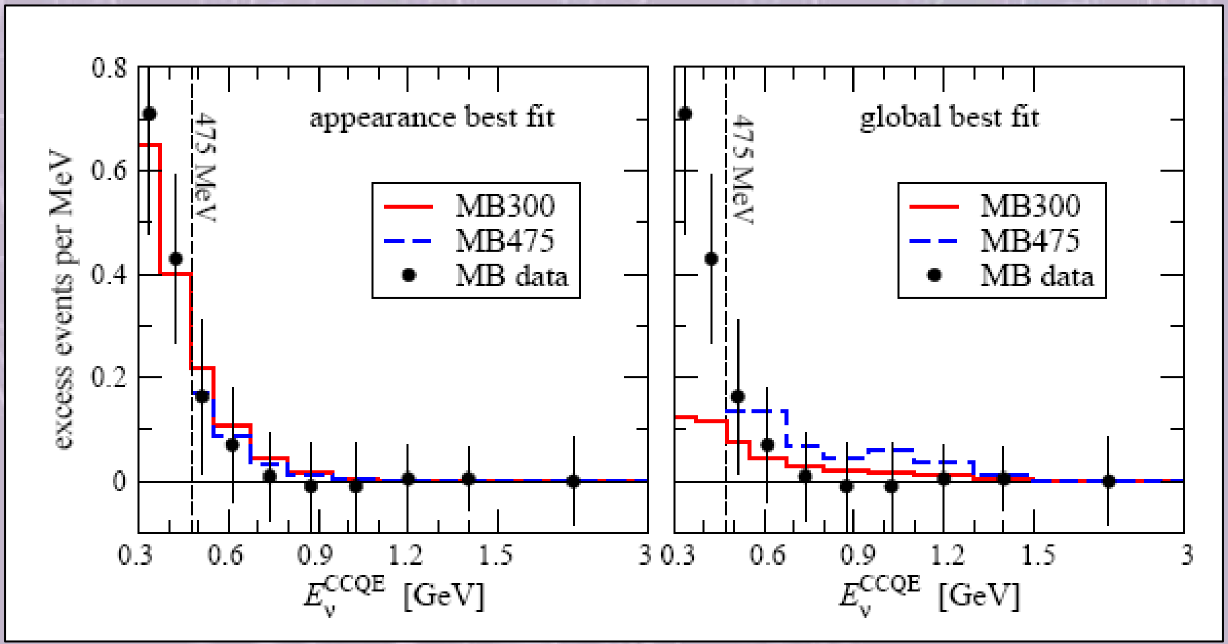
CP violation

[Maltoni, Schwetz, hep-ph/0705.0107; G.K., *et al*, hep-ph/0609177; G.K., AIP Conf.Proc.981:210-212,2008]

3+2 sterile neutrino model oscillation probability:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = 4|U_{\mu4}|^2|U_{e4}|^2 \sin^2 x_{41} + 4|U_{\mu5}|^2|U_{e5}|^2 \sin^2 x_{51} + 8\,|U_{\mu5}||U_{e5}||U_{\mu4}||U_{e4}|\,\sin x_{41} \sin x_{51} \cos(x_{54} \pm \varphi_{45})$$

Dirac CPV phase



Maltoni, Schwetz, hep-ph/0705.0107