Appearance Results from MiniBooNE

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WIN'11 – Cape Town, South Africa

Outline of this talk:

1993 -1998 – The LSND excess signal:
Evidence for high-Δm^2 oscillations

1998 – The MiniBooNE experiment

2001 -2008 – MiniBooNE neutrino mode oscillation results:
LSND signature refuted

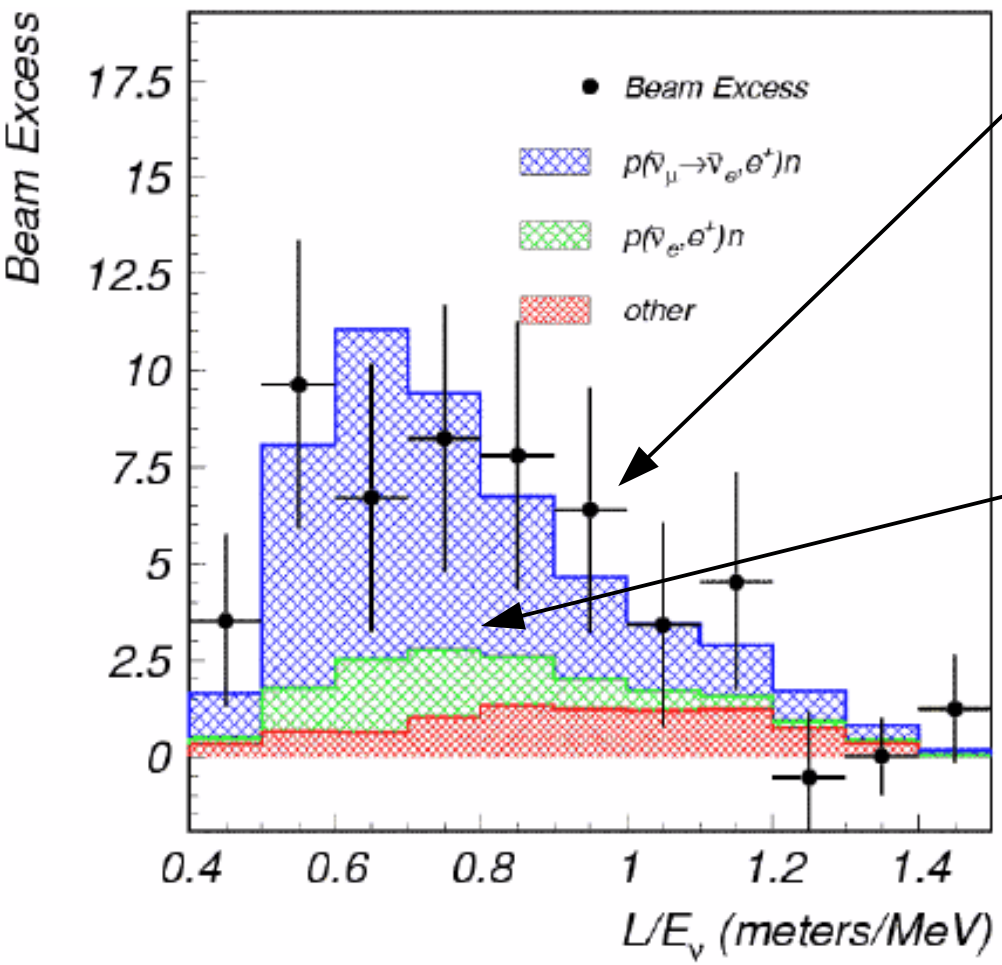
2006 -2010 – MiniBooNE antineutrino mode oscillation results:
LSND signature confirmed ?

2010 – Light sterile neutrino oscillations: Where we stand today

2012 -... – Future searches: MiniBooNE, MicroBooNE

Why is the LSND signal anomalous?

1998: Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos



Observed $\bar{\nu}_e$ data in a $\bar{\nu}_\mu$ beam:

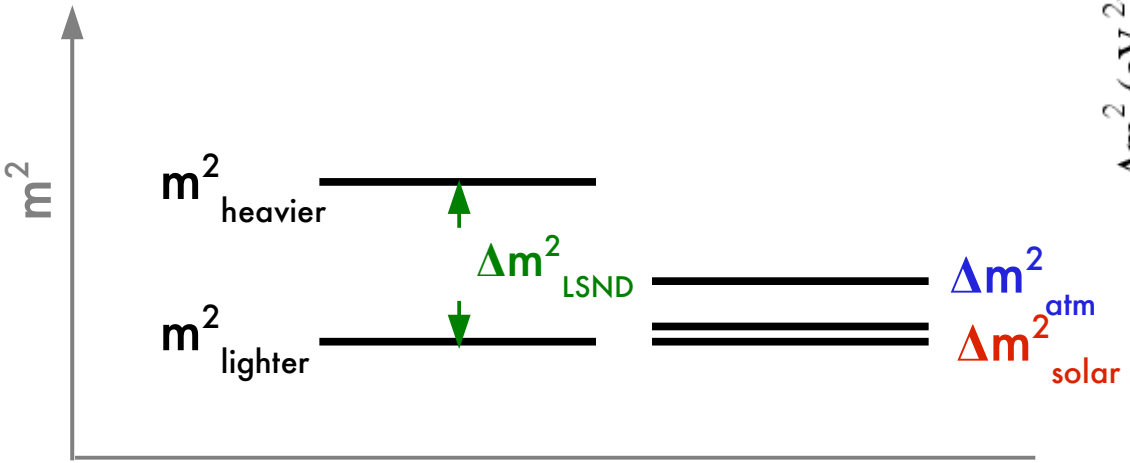
In excess of background prediction (3.8σ significance)

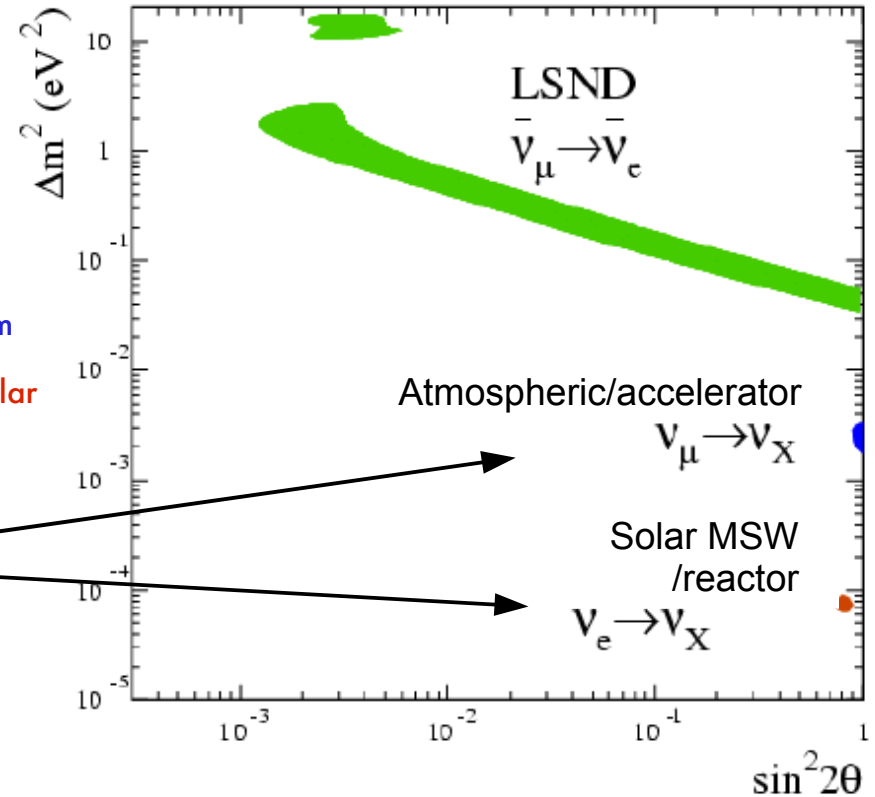
Could be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with osc. probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$
$$= 0.26\%$$

Why is the LSND signal anomalous?

(Simplest) oscillation interpretation implies:





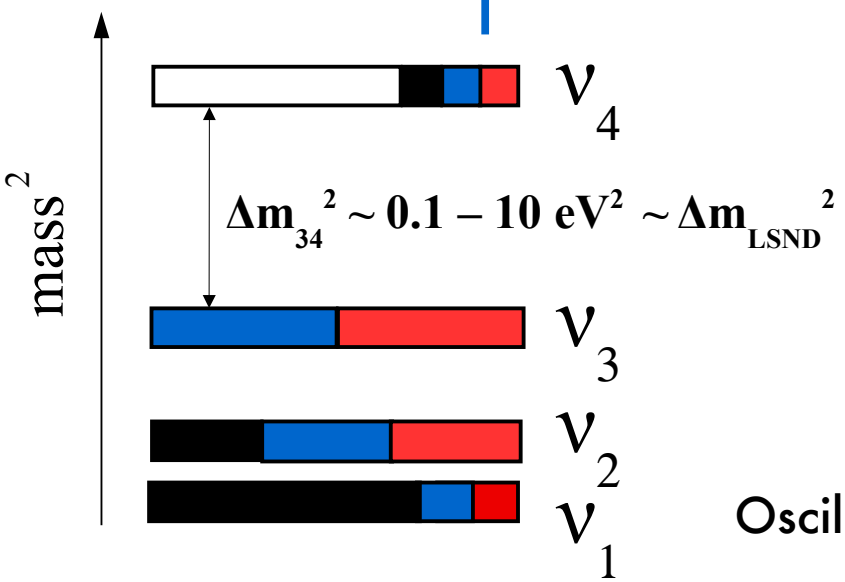
In conflict with well-understood, three-neutrino mixing model in the Standard Model (defined by only two independent oscillation signatures)

Needs further confirmation ! → Motivation for MiniBooNE

A neutrino oscillation picture accommodating LSND

(Simplest) oscillation interpretation requires New Physics:

3 active neutrinos + 1 sterile neutrino: "(3+1)"



very small flavor content consistent with small mixing amplitude and oscillation probability

large mass splitting accommodated by LSND's short baseline

Oscillation probability in this model, approximated as **two-neutrino oscillation***:

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27\ \Delta m^2_{41}\ L/E)$$

$$\text{or, } P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27 \Delta m^2\ L/E)$$

*same for ν and $\bar{\nu}$

MiniBooNE was designed to test this picture

(Simplest) oscillation interpretation requires New Physics:

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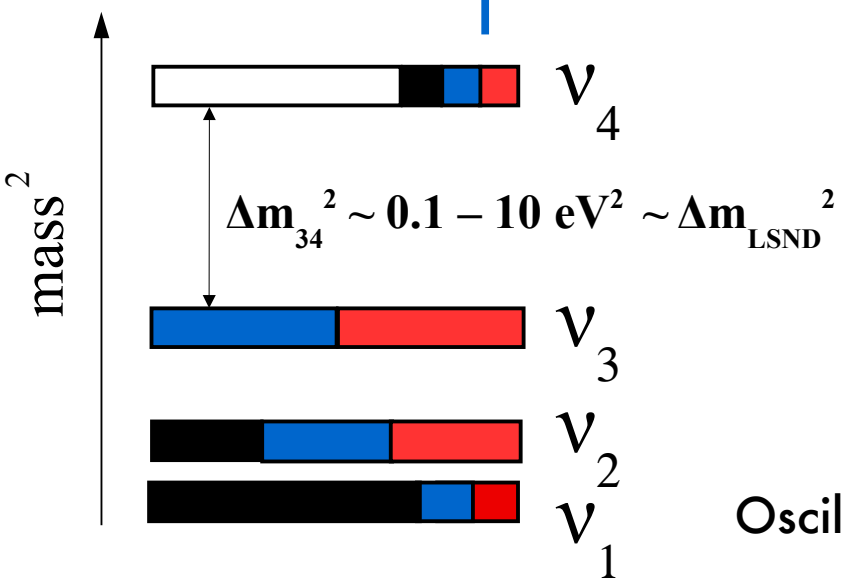

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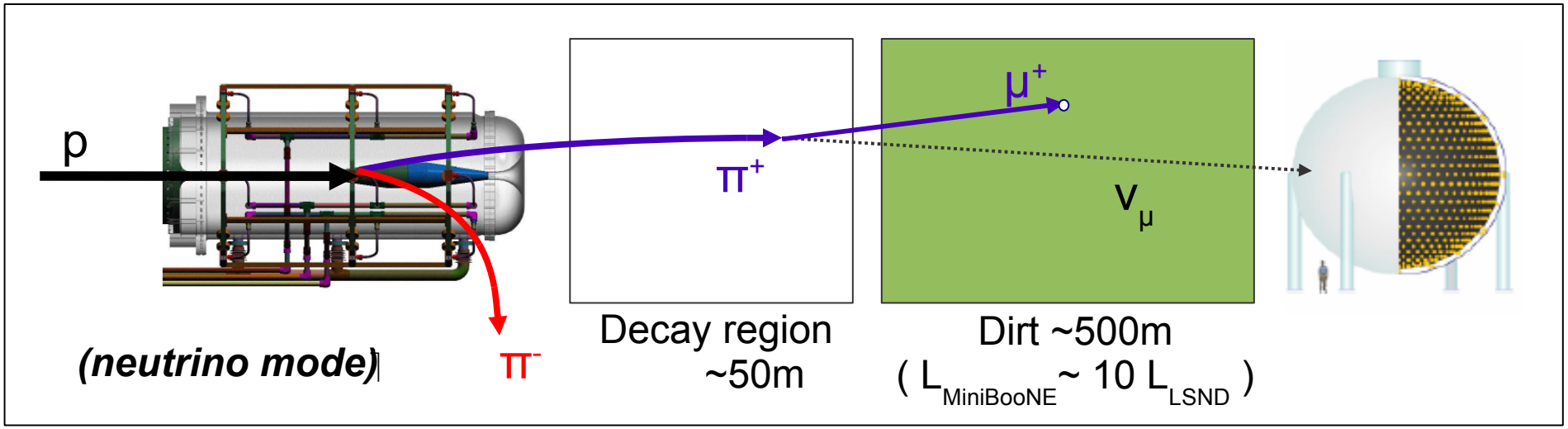
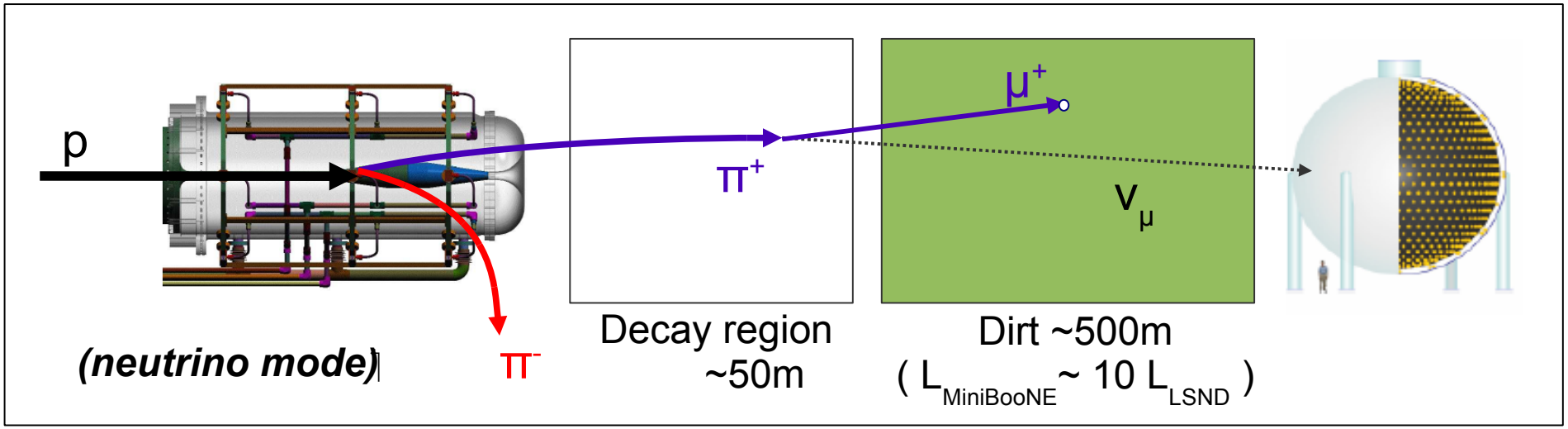
MiniBooNE [Mini Booster Neutrino Experiment @ FNAL]



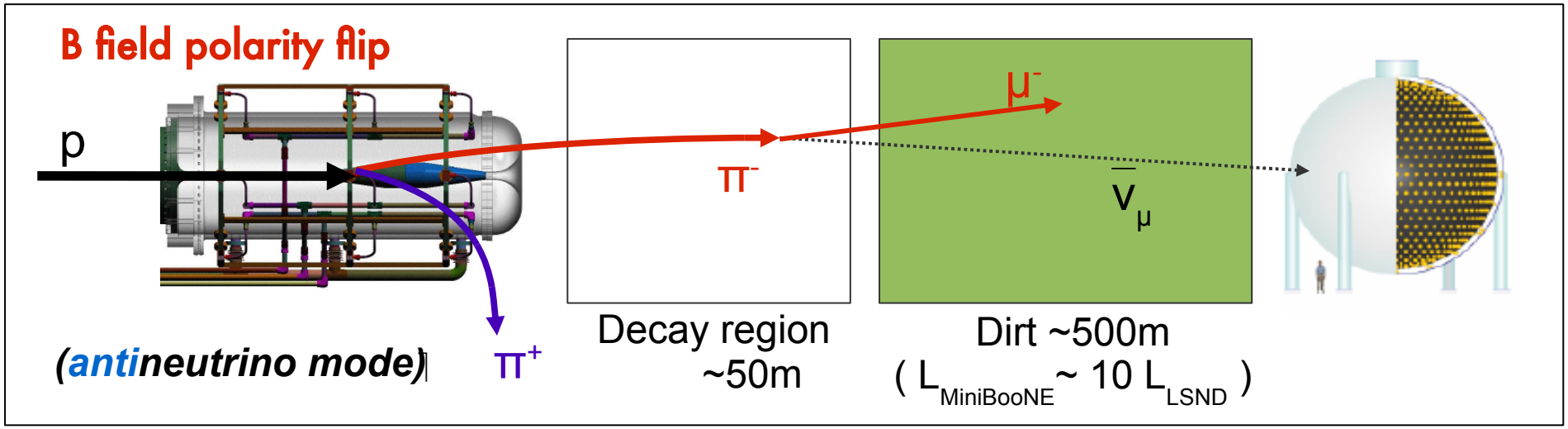
Makes a primarily ν_μ beam (neutrino running mode)

MiniBooNE [Mini Booster Neutrino Experiment @ FNAL]



Makes a primarily ν_μ beam (neutrino running mode)

– or –



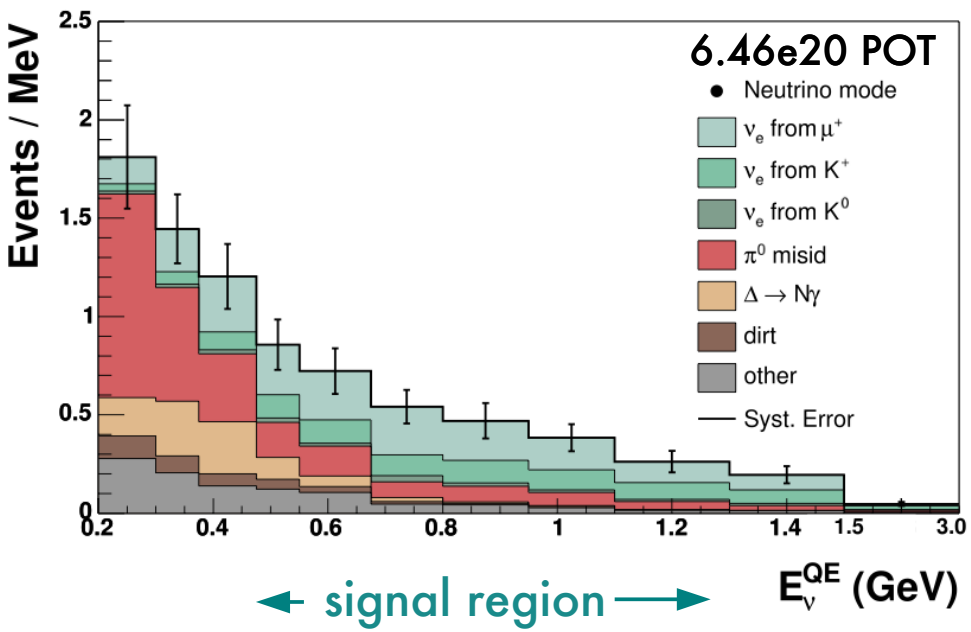
Makes a primarily $\bar{\nu}_\mu$ beam (antineutrino running mode)

MiniBooNE ν_e and $\bar{\nu}_e$ appearance searches

Two separate searches, one in <u>neutrino mode</u>, and one in <u>antineutrino mode</u>:

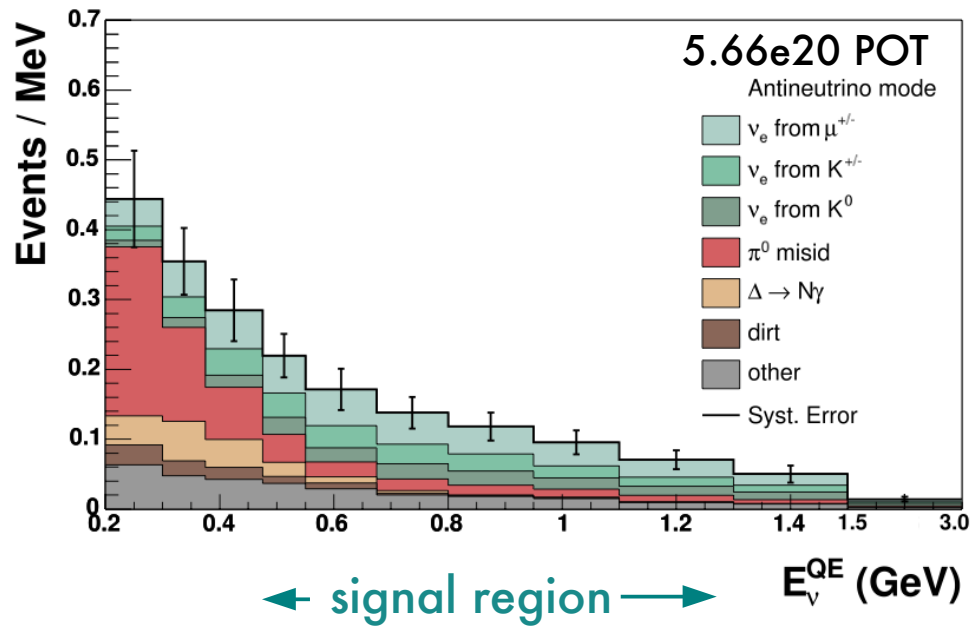
Look for appearance of ν_e or $\bar{\nu}_e$ events above background prediction described by a two-neutrino oscillation probability

MC background ν mode



← signal region →

MC background $\bar{\nu}$ mode



← signal region →

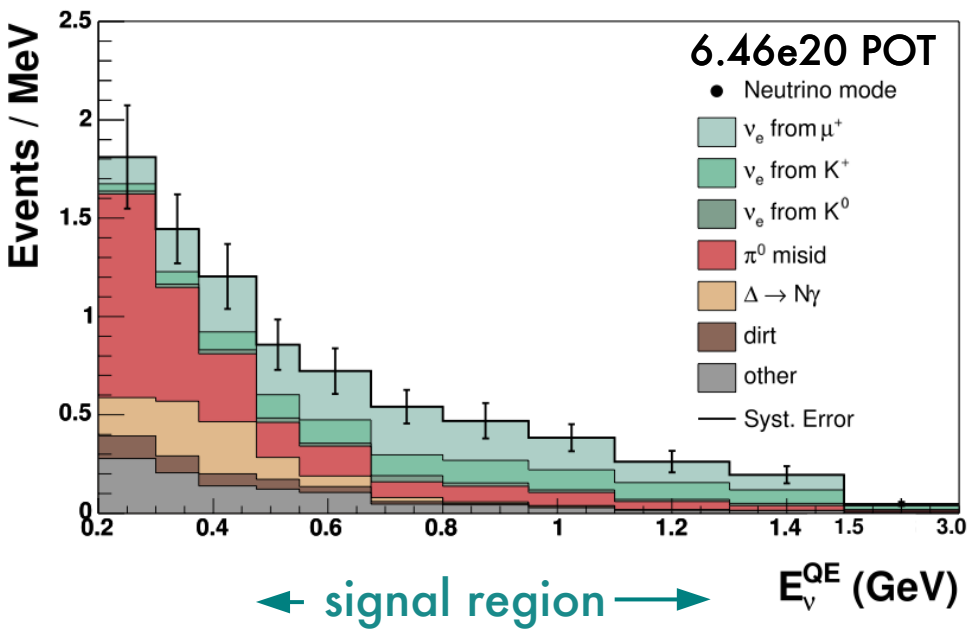
MiniBooNE ν_e and $\bar{\nu}_e$ appearance searches

Two separate searches, one in <u>neutrino mode</u>, and one in <u>antineutrino mode</u>:

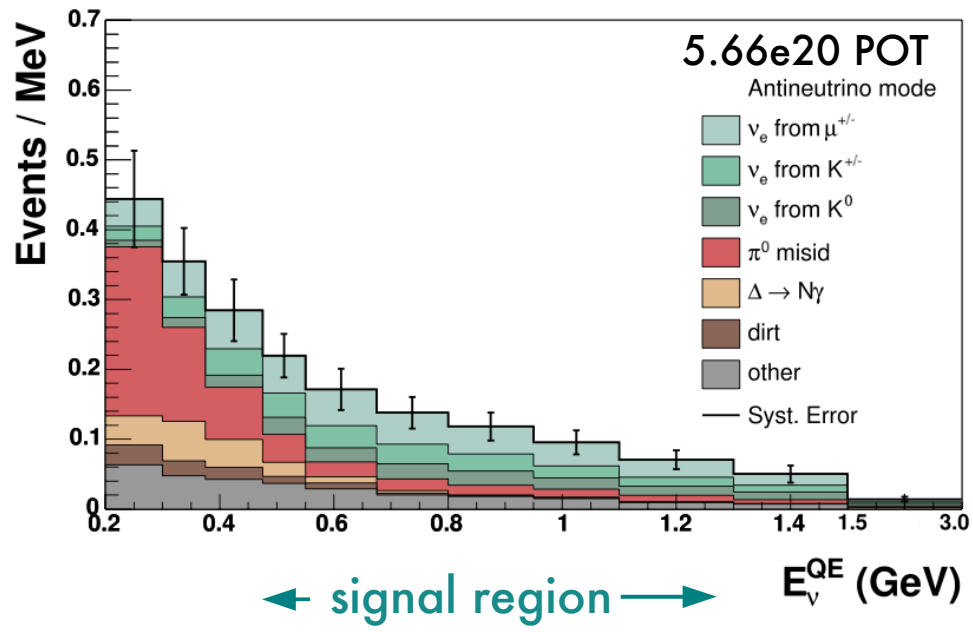
High statistics, powerful test of LSND's simplest interpretation

Lower statistics (less powerful), but a direct test of LSND excess

MC background ν mode



MC background $\bar{\nu}$ mode



MiniBooNE appearance search recipe

Oscillation probability drives MiniBooNE's design parameters:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\Delta m^2 L[m]/E_\nu[MeV]) = 0.26\%$$

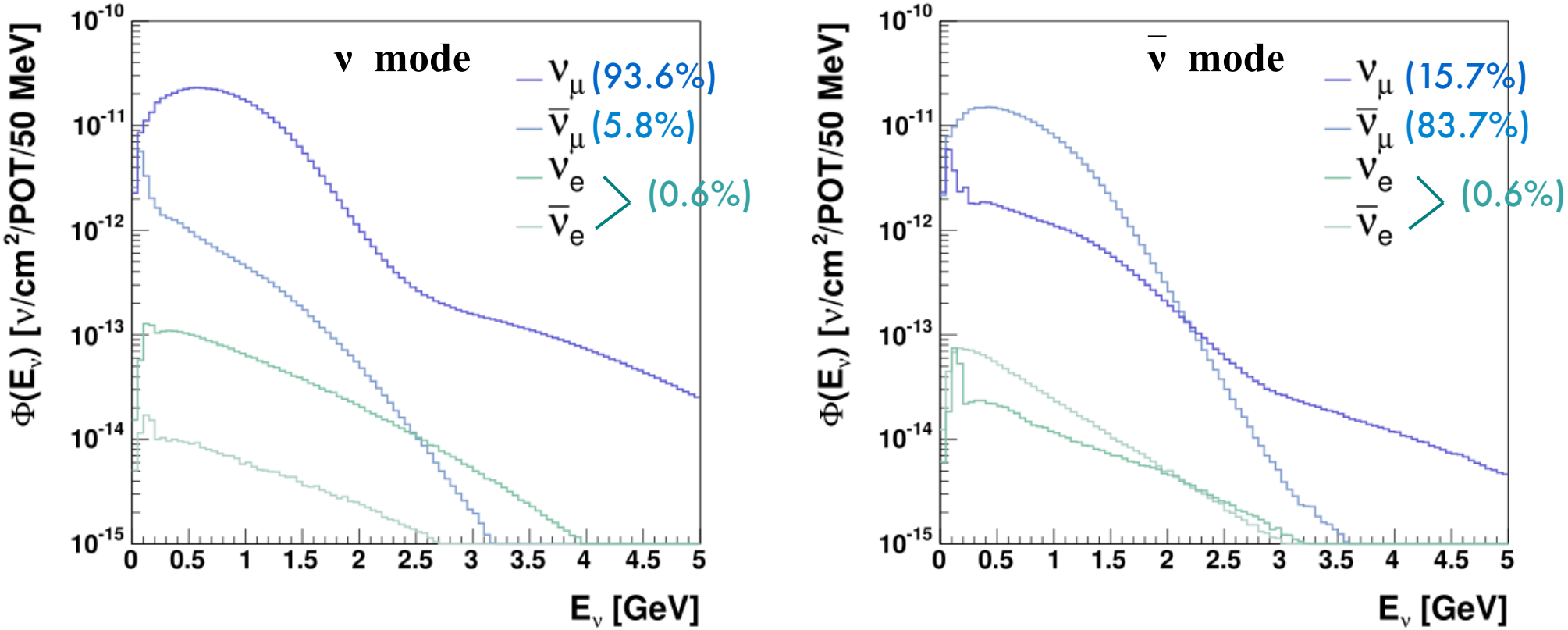
One needs:

- ☐ same L/E as LSND
- ☐ high-intensity (anti-)ν_μ beam with low intrinsic (anti-)ν_e contamination
- ☐ high efficiency in differentiating (anti-)ν_e from (anti-)ν_μ events in the detector

MiniBooNE appearance search recipe

- ☑ same L/E as LSND
- ☑ high-intensity ν_μ beam with low intrinsic ν_e contamination

MiniBooNE flux predictions: *Phys. Rev. D79, 072002 (2009)*



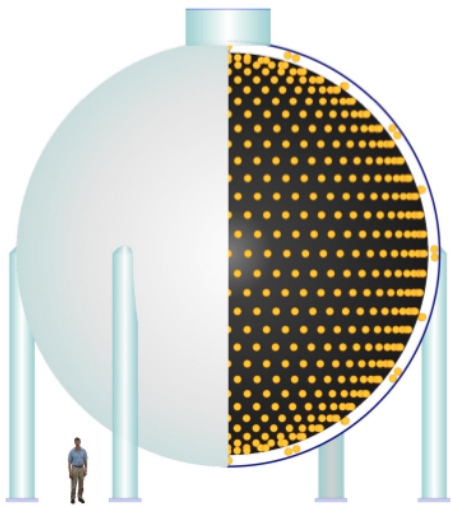
<1% ν_e flux contamination in either running mode!

MiniBooNE appearance search recipe

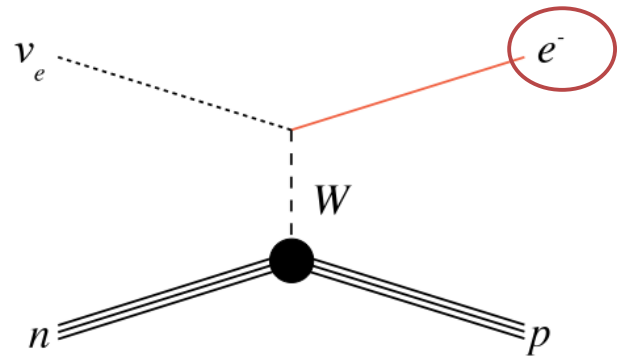
☑ high efficiency in differentiating ν_e from ν_μ events in the detector

Events in the MiniBooNE detector:

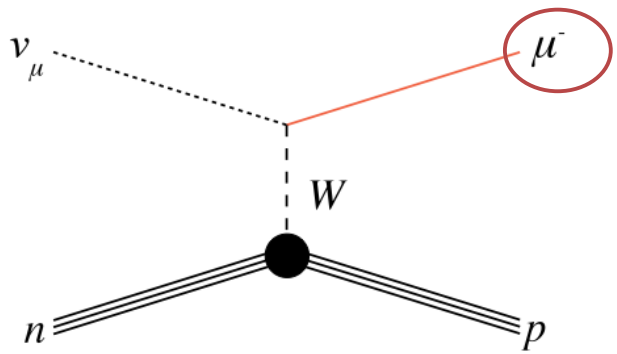
Dominant neutrino cross section: Charged Current Quasi-Elastic (CCQE) on $C_N H_{2N}$

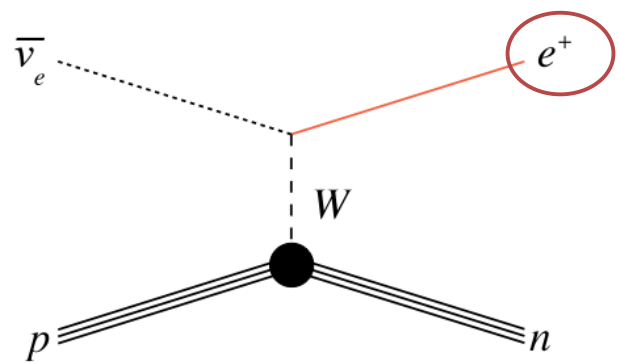


450 ton fid. volume CH_2 Cherenkov detector, lined with 1280 PMT's (10% photocathode) & optically isolated veto (240 PMT's)

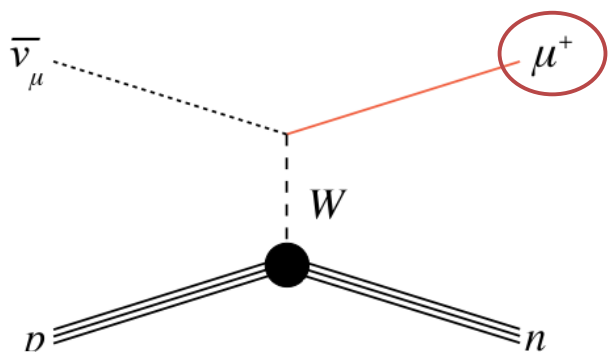


(C nucleus)





(C or H nucleus)



signal: e

dominant beam component: μ

MiniBooNE appearance search recipe

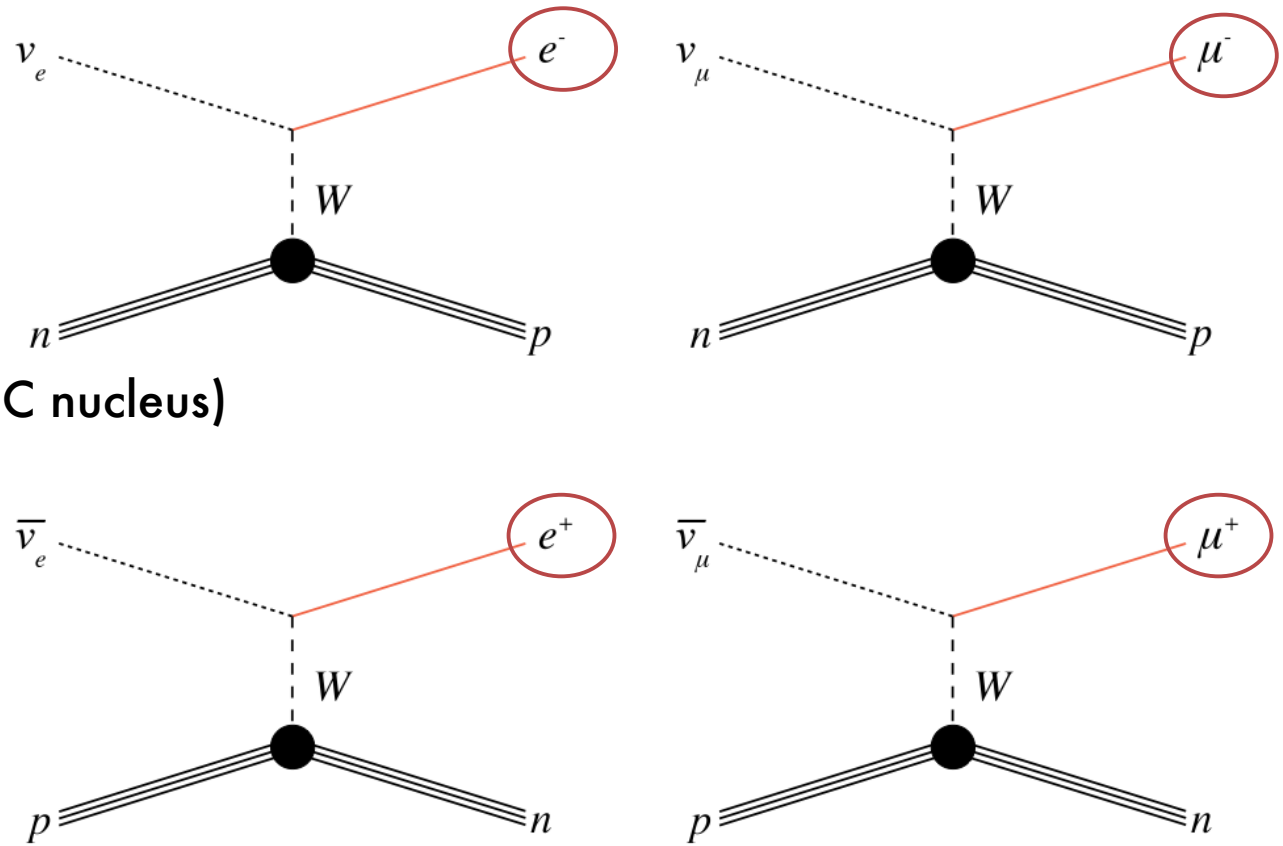
☑ high efficiency in differentiating ν_e from ν_μ events in the detector

Events in the MiniBooNE detector:

Dominant neutrino cross section: Charged Current Quasi-Elastic (CCQE) on $C_N H_{2N}$

Neutrino flavor is determined by the flavor of the outgoing lepton...

neutrino kinematics also determined by the kinematics of the outgoing lepton.



(C nucleus)

(C or H nucleus)

signal: e

dominant beam component: μ

MiniBooNE ν_e and $\bar{\nu}_e$ appearance searches

Number of Events = (flux) x (cross-section) x (detector response)

How are event rates constrained for single-detector setup?

Constrained by HARP p-Be pion and other production measurements & ν_μ event rate measured at MiniBooNE directly.

Constrained by external and direct measurements at MiniBooNE (π^0, Δ, dirt, ν_μ).

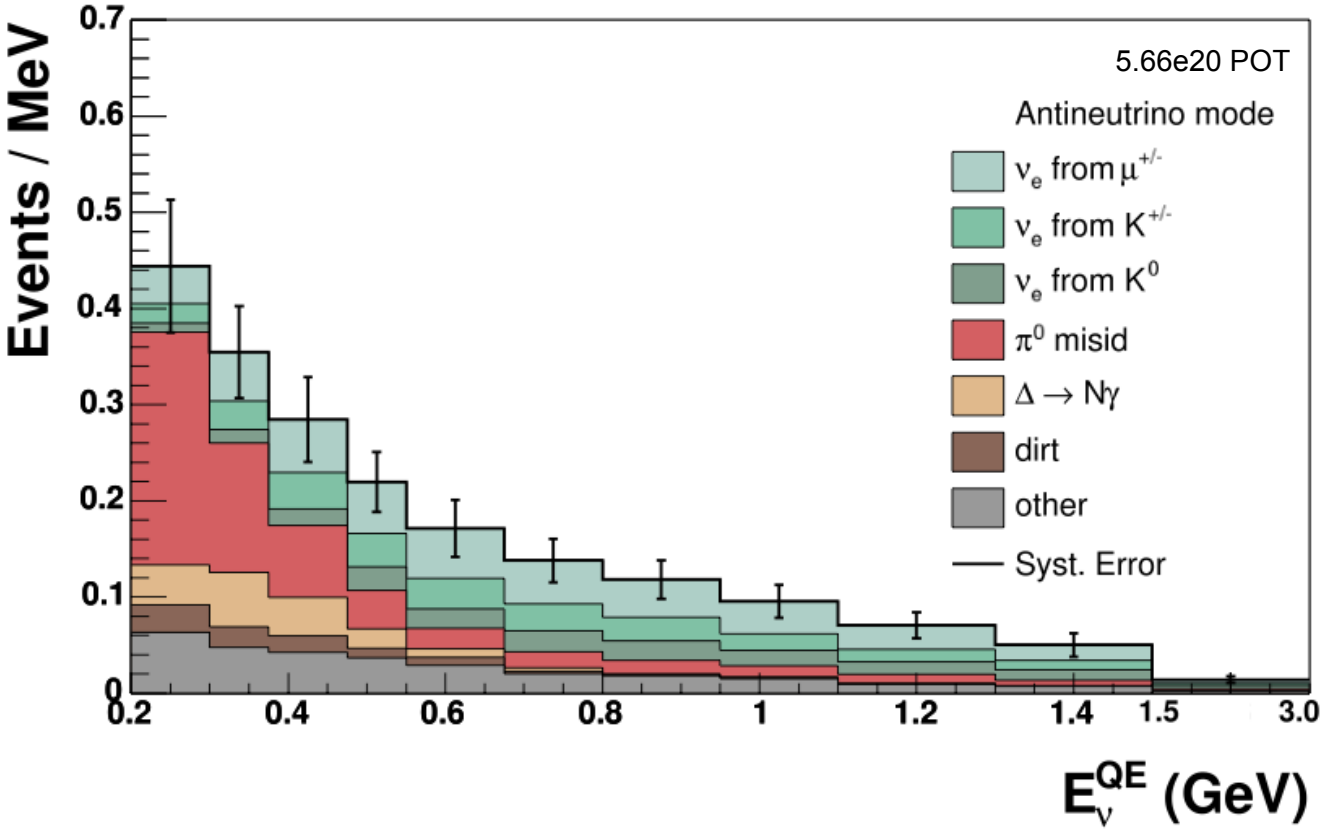
Detailed detector simulations checked by neutrino and calibration data.

MiniBooNE ν_e and $\bar{\nu}_e$ appearance searches

What are the backgrounds?

@ high E: intrinsic ν_e

- **from π, μ**
  - HARP p+Be $\pi^{\pm}$ production data
  - MiniBooNE data
- **from K**
  - Sanford-Wang fits to world K^0/K^+ production data *Phys. Rev. D79, 072002 (2009)*



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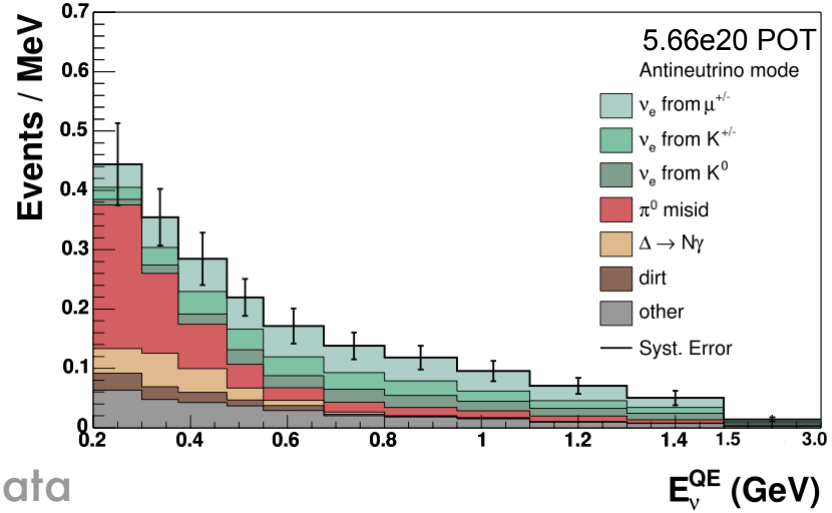

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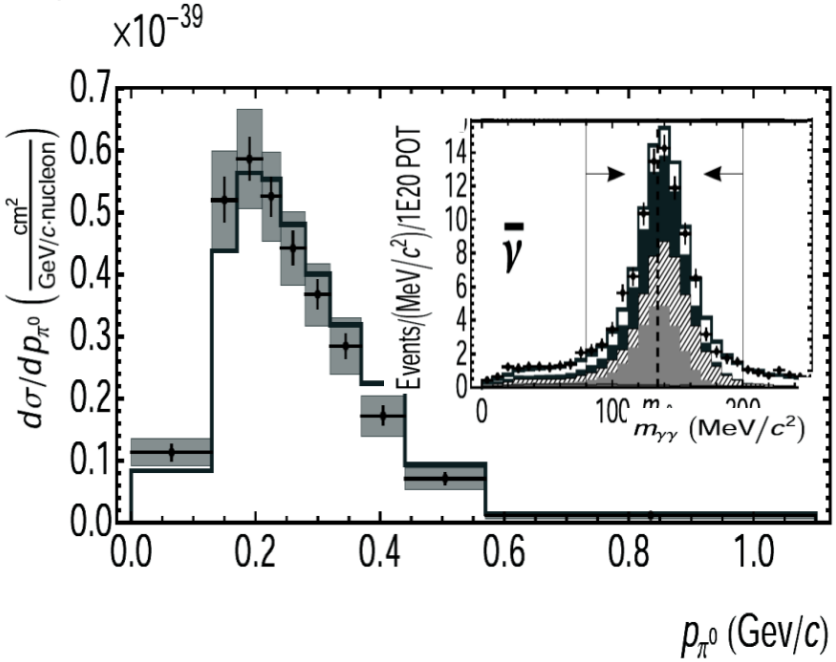
Phys. Rev. D79, 072002 (2009)

@ low E: mis-identified ν_μ

- **through NC π^0**
  - MiniBooNE direct NC π^0 rate measurement

Phys. Rev. D81, 013005 (2010)

- **through NC followed by Δ radiative decay**
  - MiniBooNE NC π^0 measurement times branching fraction



MiniBooNE ν_e and $\bar{\nu}_e$ appearance searches

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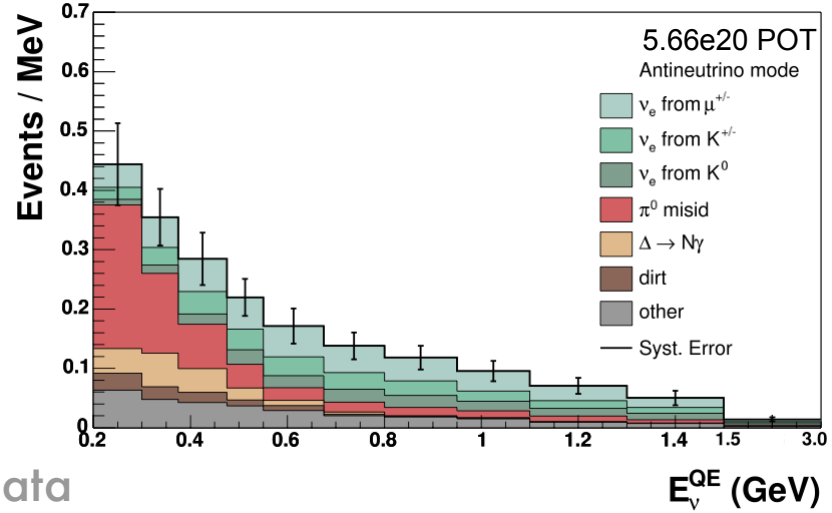

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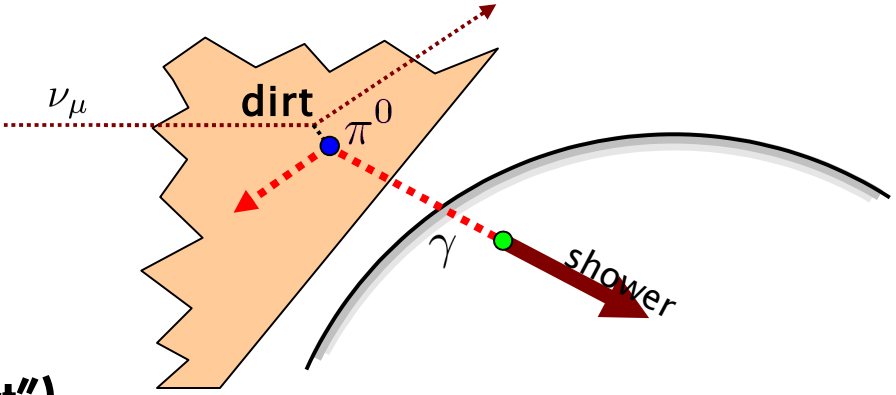

- **through NC followed by Δ radiative decay**
  - MiniBooNE NC π^0 measurement times branching fraction
- **through interactions outside the detector ("dirt")**
  - MiniBooNE direct rate measurement (events at high R headed inwards, low visible E)

MiniBooNE [Mini Booster Neutrino Experiment @ FNAL]

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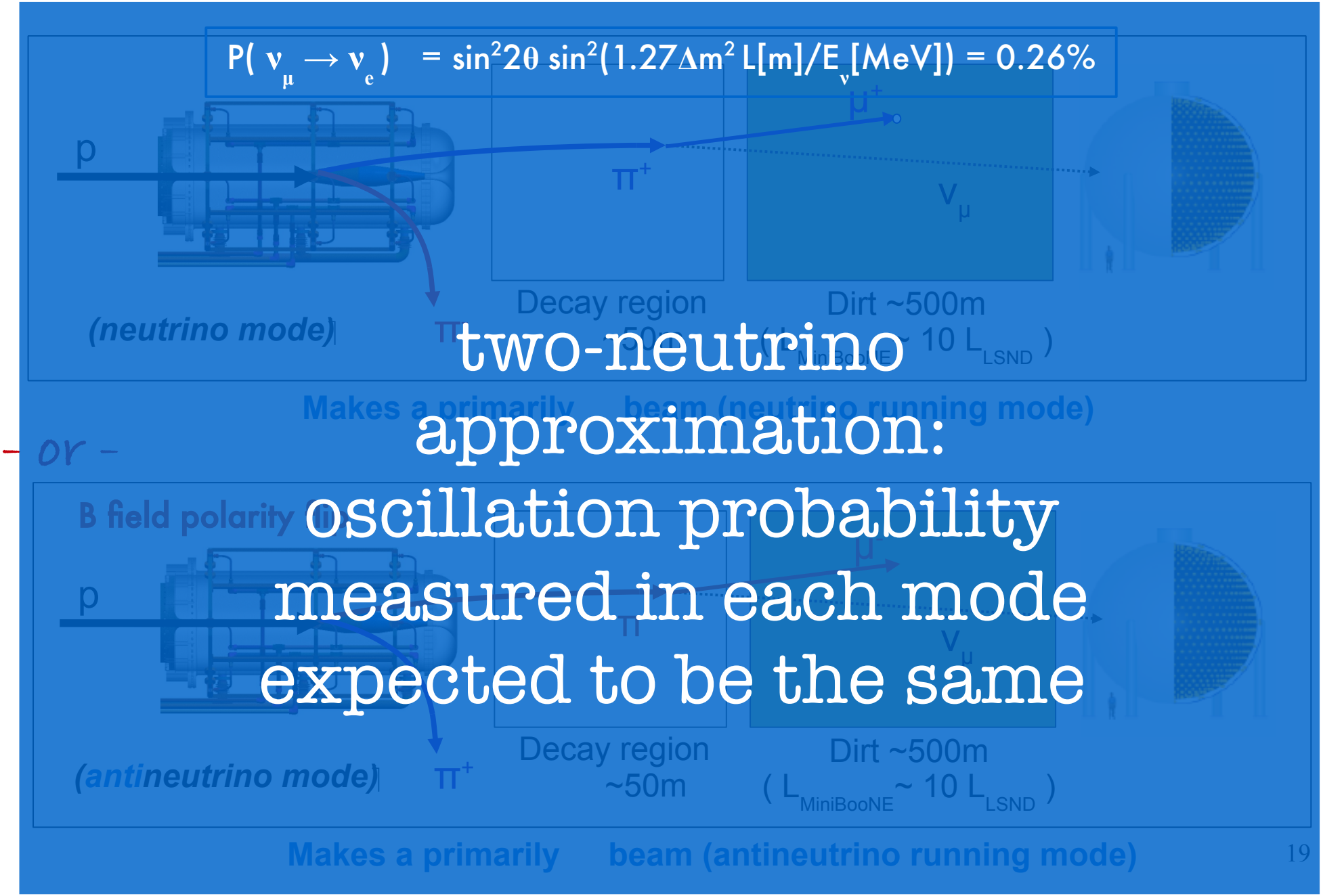

two-neutrino approximation: oscillation probability measured in each mode expected to be the same

Going back to basics:

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\alpha \to \nu_\beta \mid U \to U^*)$$

In the case of two-neutrino approximation, matrix is real:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \Rightarrow P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = P(\nu_\alpha \to \nu_\beta)$$

Q: If $P(\bar{\nu}_\mu \to \bar{\nu}_e) = P(\nu_\mu \to \nu_e)$... then why both neutrino and antineutrino searches?

A: Equality holds to the extend that only two mass/flavor eigenstates participate (most-dominantly) in oscillations.

Observing otherwise could suggest:

→ CP violation ($U \neq U^*$) / (3+1) no longer a valid approximation
→ CPT violation or other exotic physics

+ indirect information on other physics scenarios

→ motivation for antineutrino running

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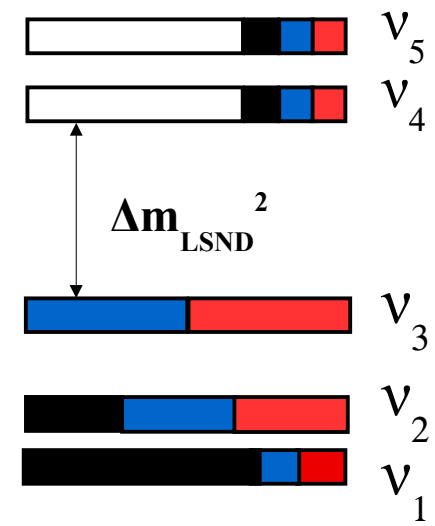
1) CP violating sterile neutrino oscillations

In a <u>three-neutrino oscillation approximation</u>, interference term gives sensitivity to CP violation

$$P(\nu_\mu \rightarrow \nu_e) = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2 \sin^2(1.27\,\Delta m^2_{41} L/E) + 4\,|U_{e5}|^2\,|U_{\mu 5}|^2 \sin^2(1.27\,\Delta m^2_{51} L/E) + 4\,|U_{e4}|\,|U_{\mu 4}|\,|U_{e5}|\,|U_{\mu 5}| \sin(1.27\,\Delta m^2_{41} L/E) \sin(1.27\,\Delta m^2_{51} L/E) \cos(1.27\,\Delta m^2_{54} L/E - \varphi_{45})$$

→ differences in ν vs. $\bar{\nu}$ appearance probabilities, unlike in a two-neutrino oscillation approximation



3 active neutrinos + 2 sterile neutrinos: "(3+2)"

+ indirect information on other physics scenarios

→ motivation for antineutrino running

1) CP violating sterile neutrino oscillations

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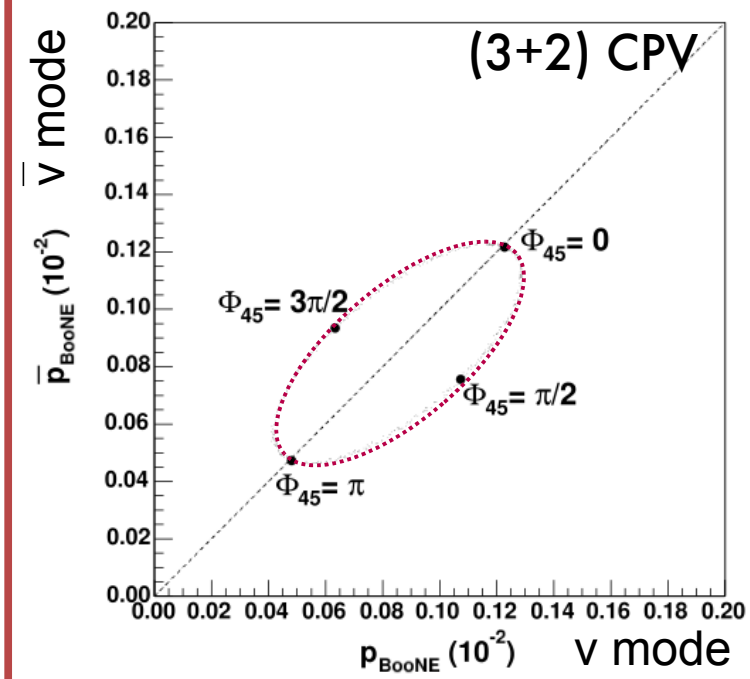
→ differences in ν vs. $\bar{\nu}$ appearance probabilities, unlike in a two-neutrino oscillation approximation

Possible differences in MiniBooNE observable oscillation probabilities:



GK et al., Phys. Rev. D 75, 013011 (2007)

MiniBooNE appearance results

Neutrino mode: *Phys.Rev.Lett.102:101802,2009* 6.46E20 POT

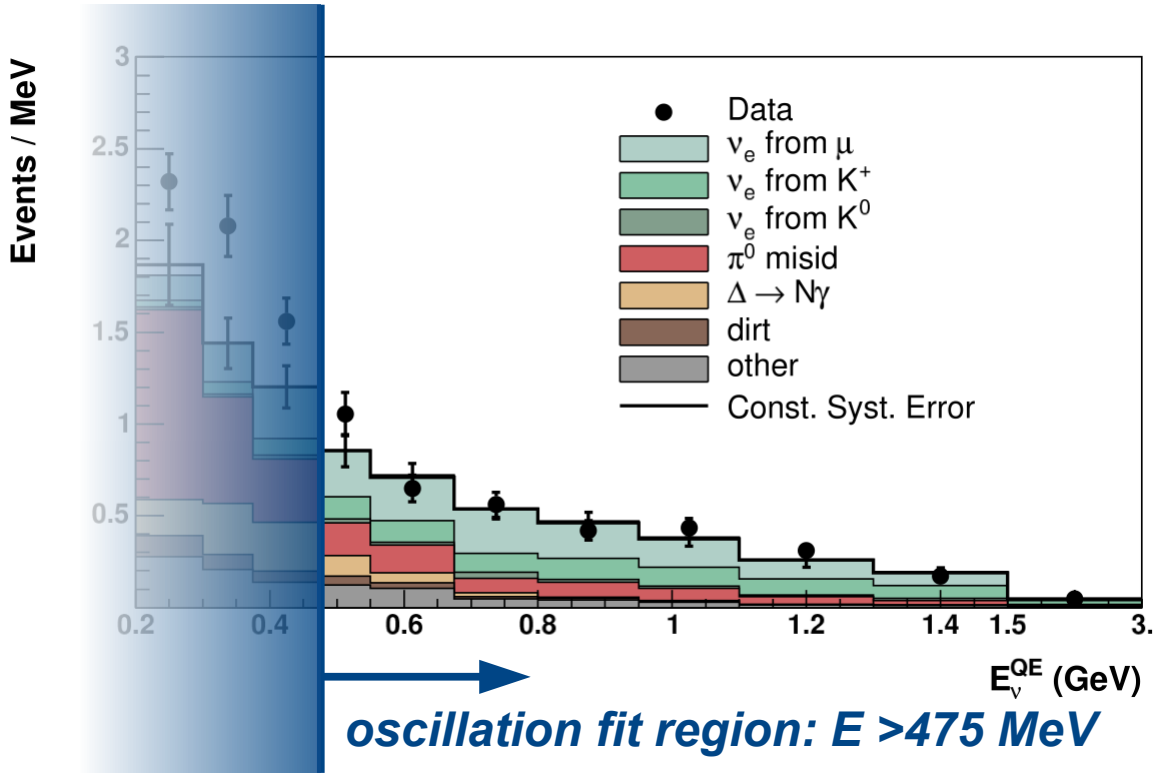
Antineutrino mode: *Phys.Rev.Lett.105:181801,2010* 5.66E20 POT

NEUTRINO2010

MiniBooNE appearance results: neutrino running

A high statistics, powerful test of LSND's simplest interpretation

Phys.Rev.Lett.102:101802,2009



E > 475 MeV:

null: χ^2/dof = 9.1/15 (87%)

bf: χ^2/dof = 7.2/13 (89%)

E > 200 MeV:

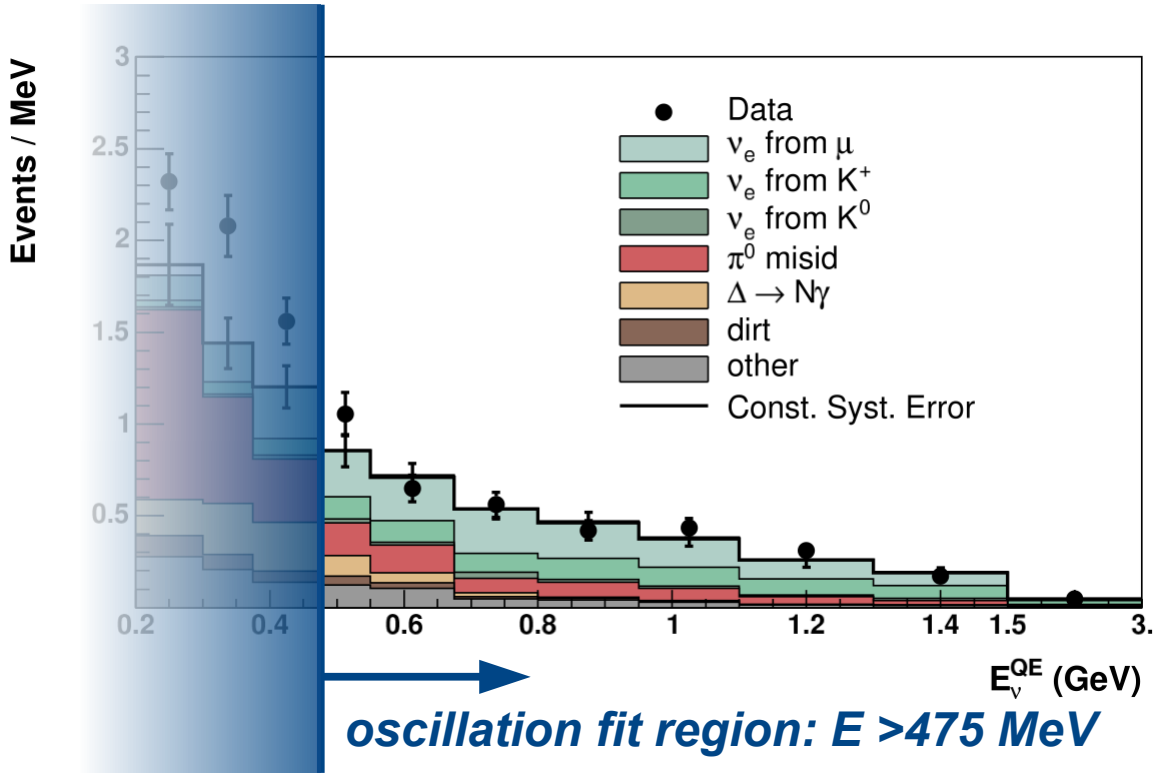
null: χ^2/dof = 22.2/18 (22%)

bf: χ^2/dof = 18.2/16 (31%)

475-1250 MeV, full frequentist approach:
prob = 40%

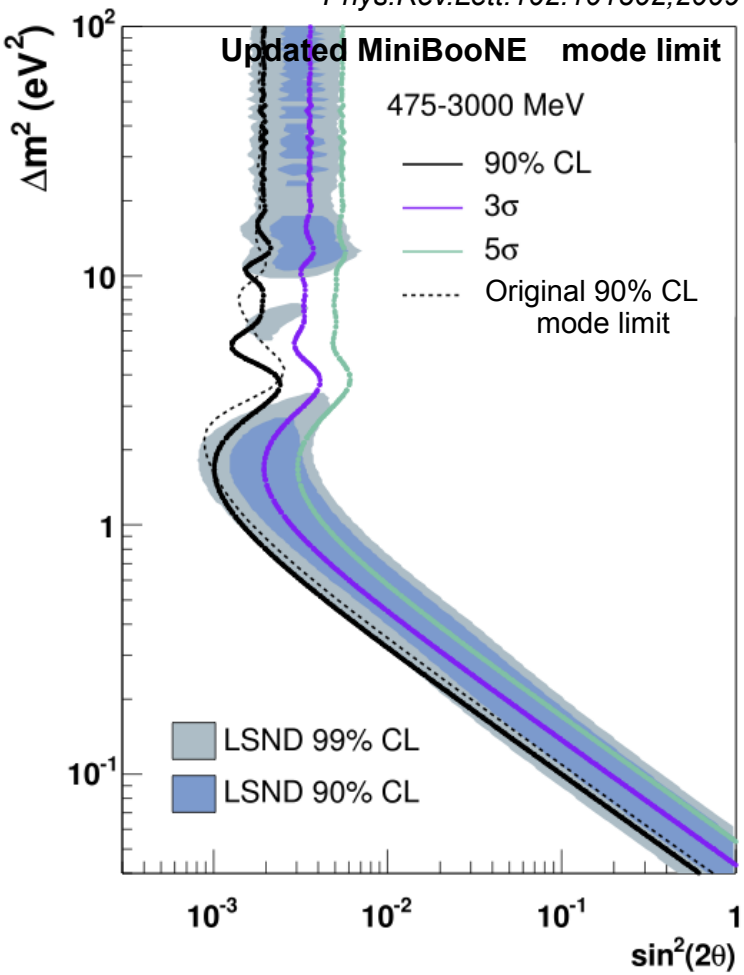
MiniBooNE appearance results: neutrino running

A high statistics, powerful test of LSND's simplest interpretation



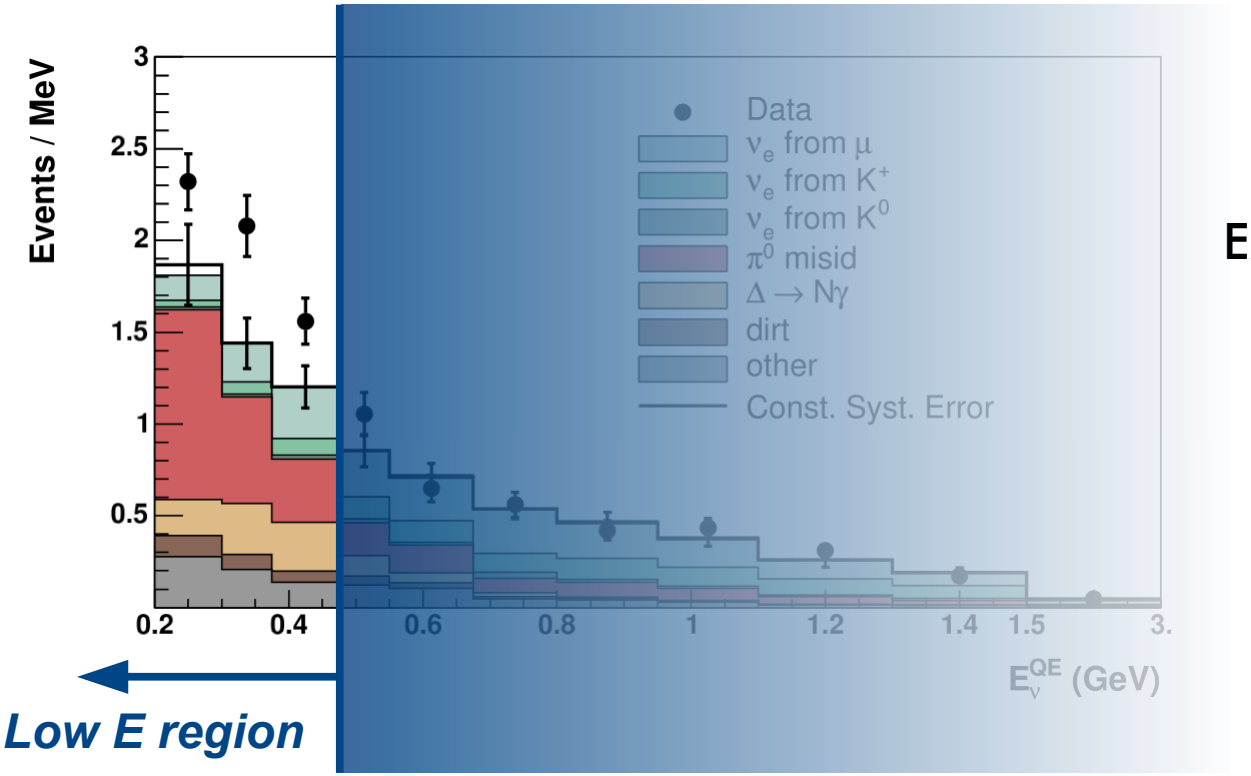
oscillation fit region: E >475 MeV

Phys.Rev.Lett.102:101802,2009



MiniBooNE rules out the LSND two-neutrino oscillation interpretation (assuming no CP or CPT violation)

MiniBooNE appearance results: neutrino running

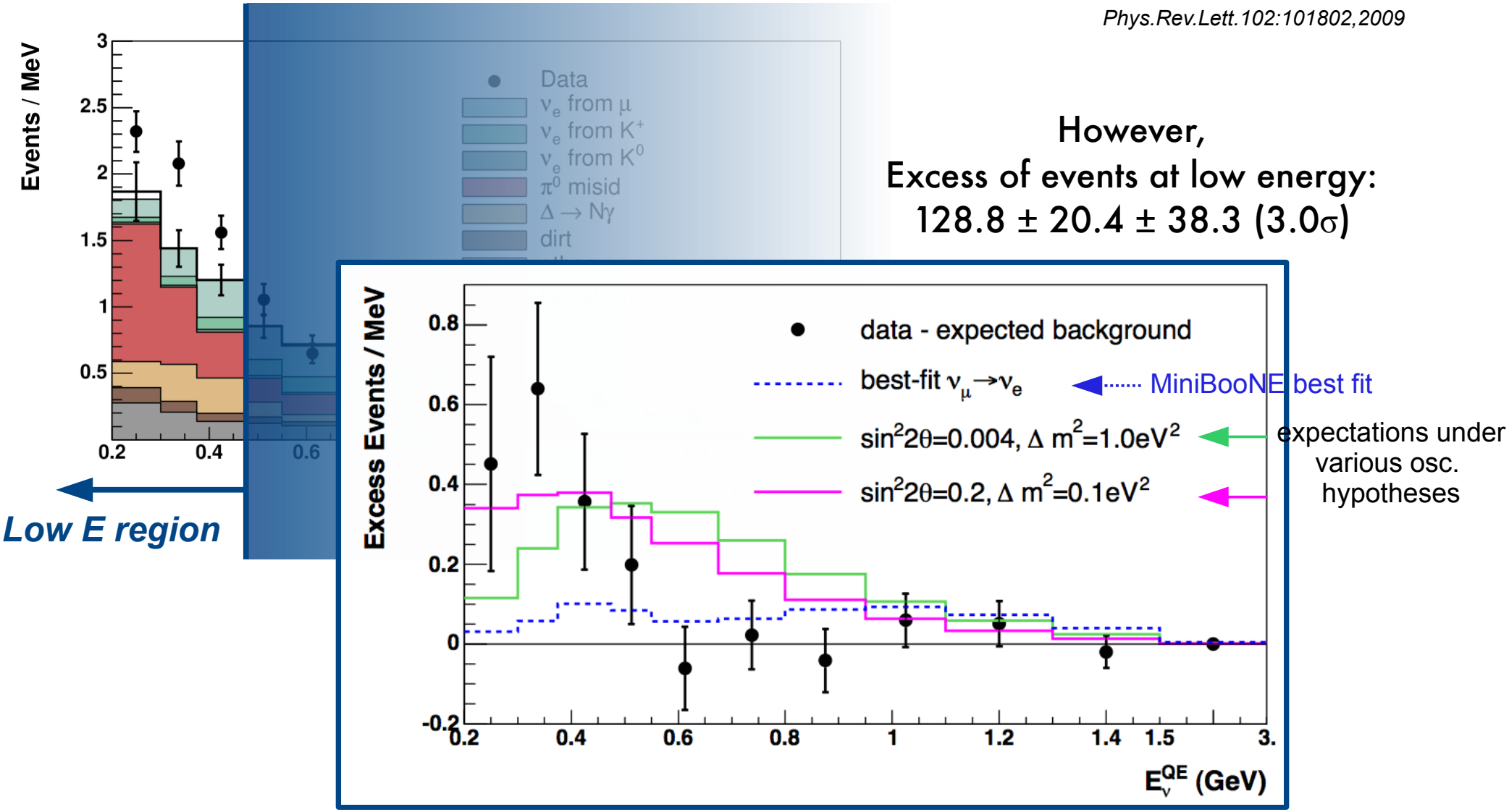


Phys.Rev.Lett.102:101802,2009

However,
Excess of events at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)
(6.3σ stat.)

MiniBooNE appearance results: neutrino running

Phys.Rev.Lett.102:101802,2009



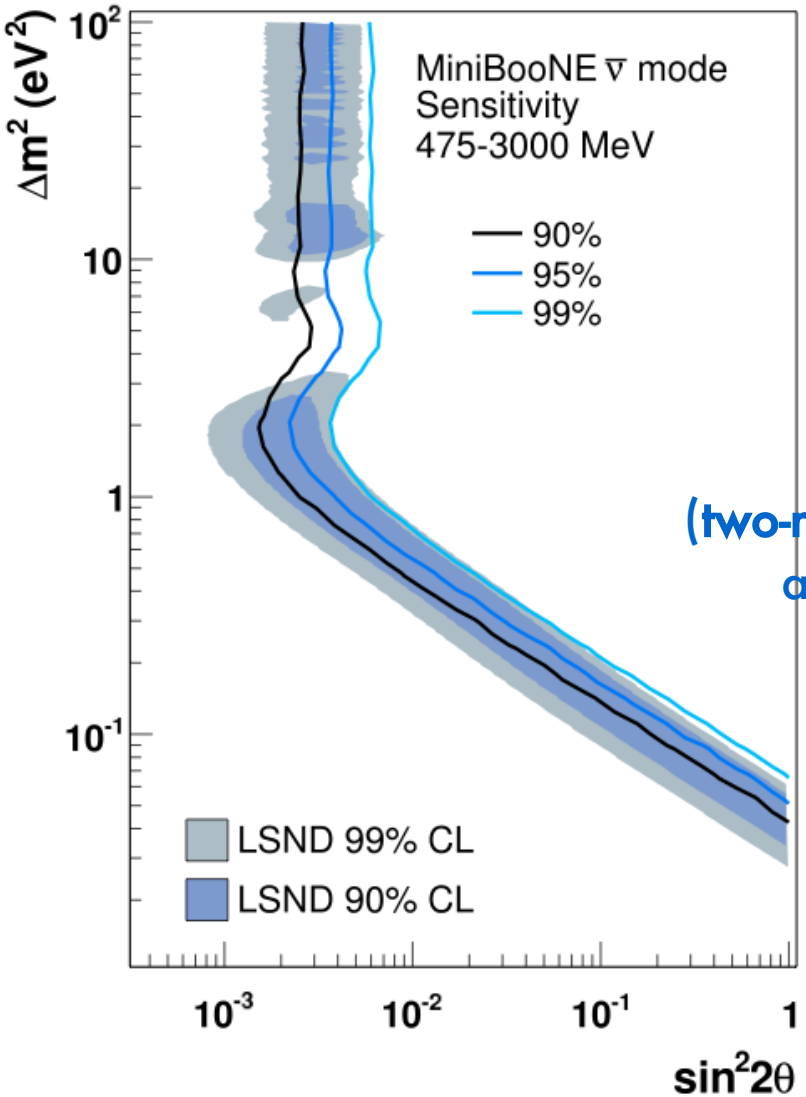
However,
Excess of events at low energy:
128.8 ± 20.4 ± 38.3 (3.0σ)

Low E excess shape is inconsistent with two-neutrino oscillations.
Excess remains unexplained.

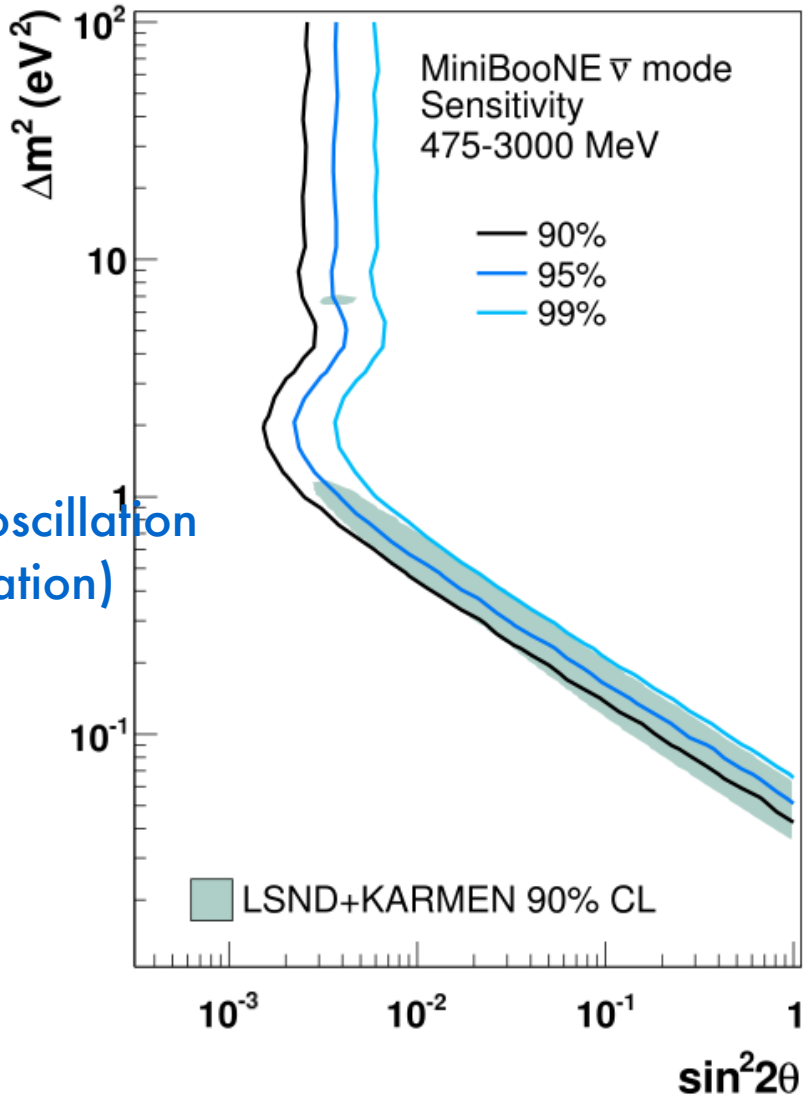
Switching to antineutrinos

MiniBooNE sensitivity to antineutrino appearance (5.66e20 POT):

A direct test of LSND, independent of CP (or CPT) assumptions



(two-neutrino oscillation approximation)



Only antineutrinos (right-sign beam component) are assumed to oscillate!

+ indirect information on other physics scenarios

→ motivation for antineutrino running

1) CP violating sterile neutrino oscillations

2) MiniBooNE low energy excess seen in neutrino mode

Could (3+2) + CPV explain the MiniBooNE neutrino low energy excess, or is the excess due to some other effect ?

+ indirect information on other physics scenarios

→ motivation for antineutrino running

1) CP violating sterile neutrino oscillations

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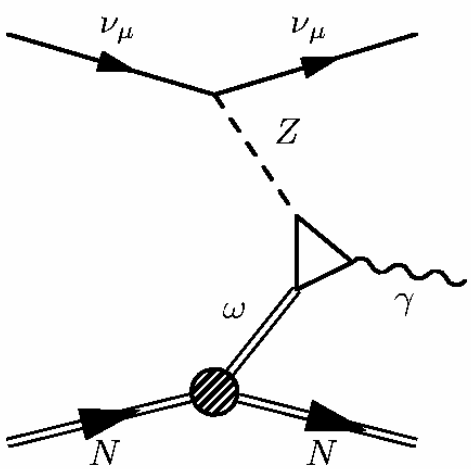
Could (3+2) + CPV explain the MiniBooNE neutrino low energy excess, or is the excess due to some other effect ?

e.g., anomaly-mediated photon production:

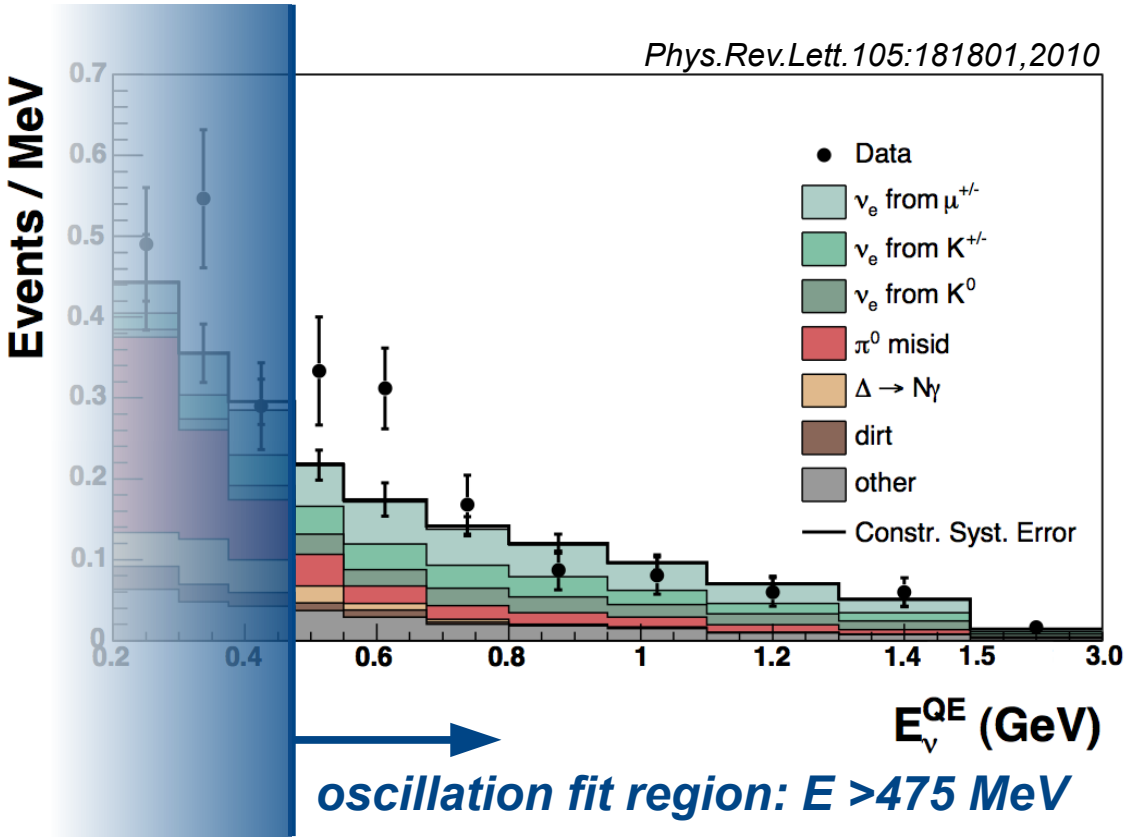


in MiniBooNE, photon shower is indistinguishable from that of an electron

- SM-predicted background
- Same NC cross section for neutrinos and antineutrinos

Jeffrey A. Harvey, Christopher T. Hill & Richard J. Hill, Phys.Rev.Lett.99:261601,2007

MiniBooNE appearance results: antineutrino running



475 < E < 1250 MeV:

χ^2 probability for model-independent, background-only hypothesis: 0.5%

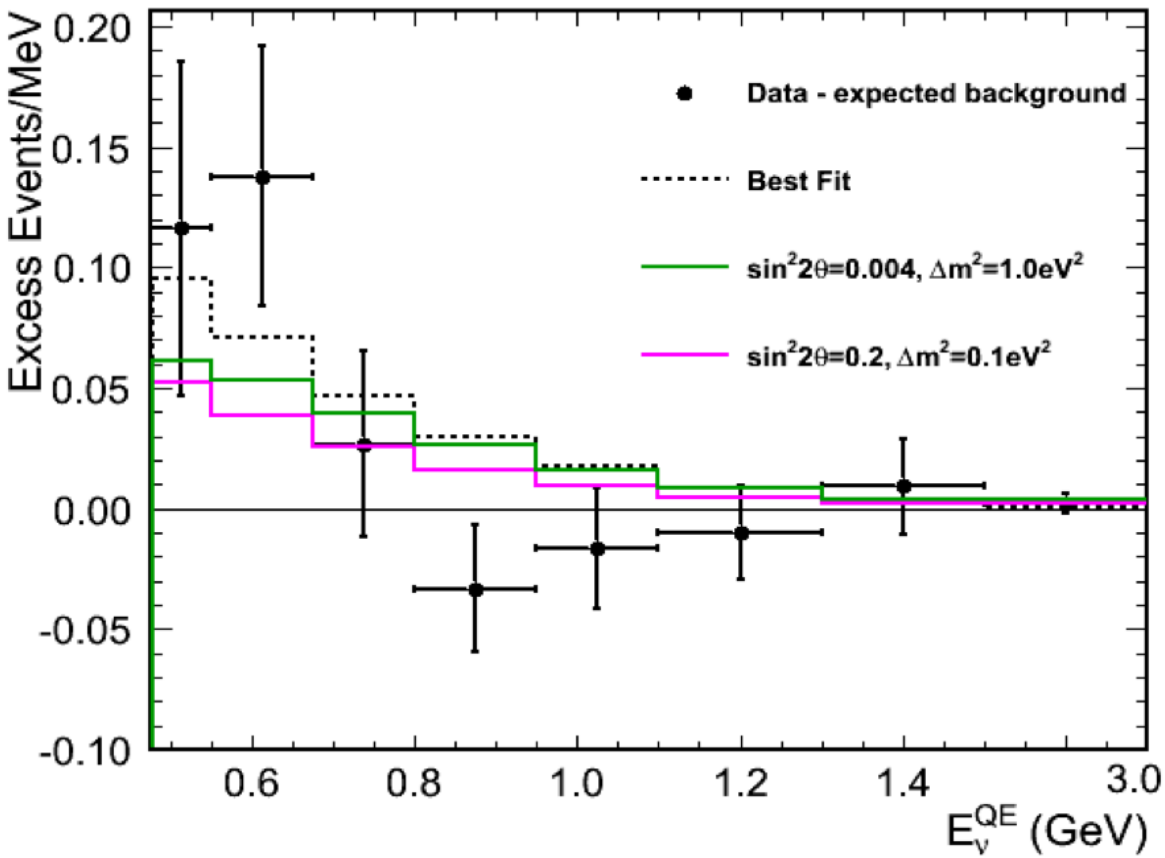
Data:	120
MC:	99.1±14.0
Excess:	20.9±14.0
LSND best-fit expectation:	22

(1.5σ, counting exp.)

MiniBooNE observes an excess of events at high energy consistent in size with that of LSND-like oscillations...

MiniBooNE appearance results: antineutrino running

Phys.Rev.Lett.105:181801,2010



E-dependent fit to oscillations, and frequentist treatment of $\Delta\chi^2$ for two-neutrino oscillations:

Oscillations favored over background hypothesis at 99.4% CL.

Excess is consistent with two-neutrino oscillations due to (best-fit): $(\sin^2 2\theta, \Delta m^2) = (0.96, 0.064\ \text{eV}^2)$

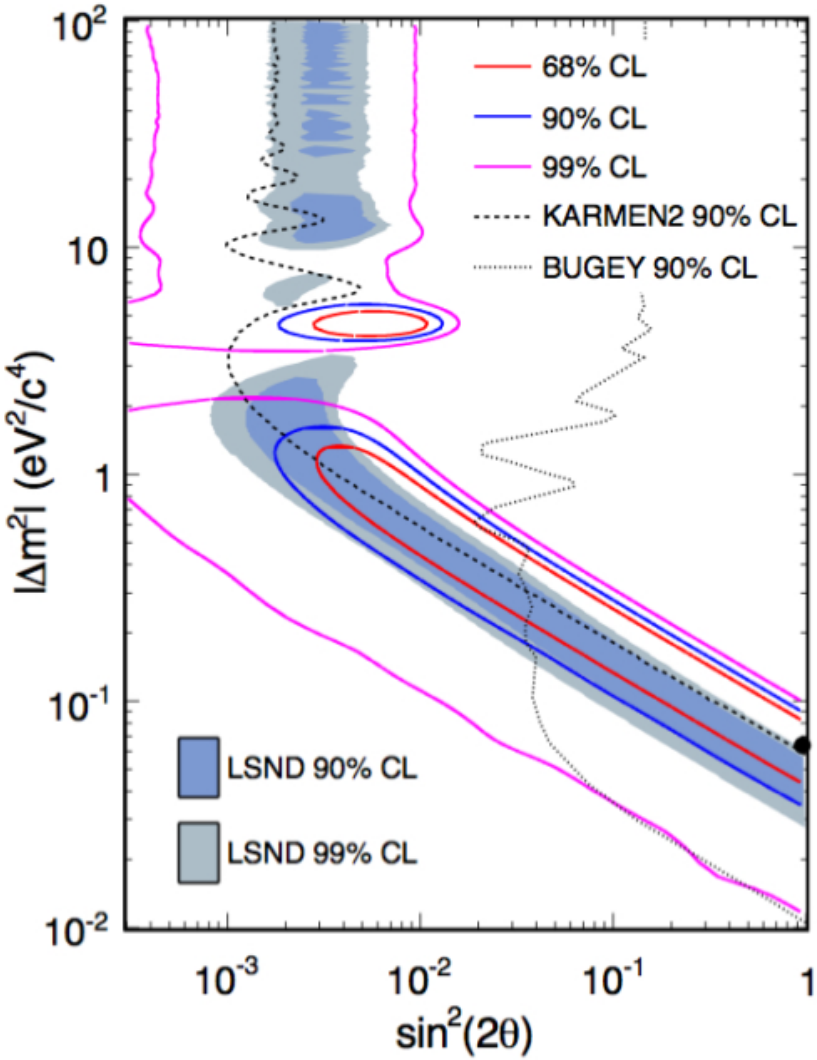
$\chi^2/\text{dof} = 8.0/4$ (475-1250 MeV)

χ^2-prob = 8.7%

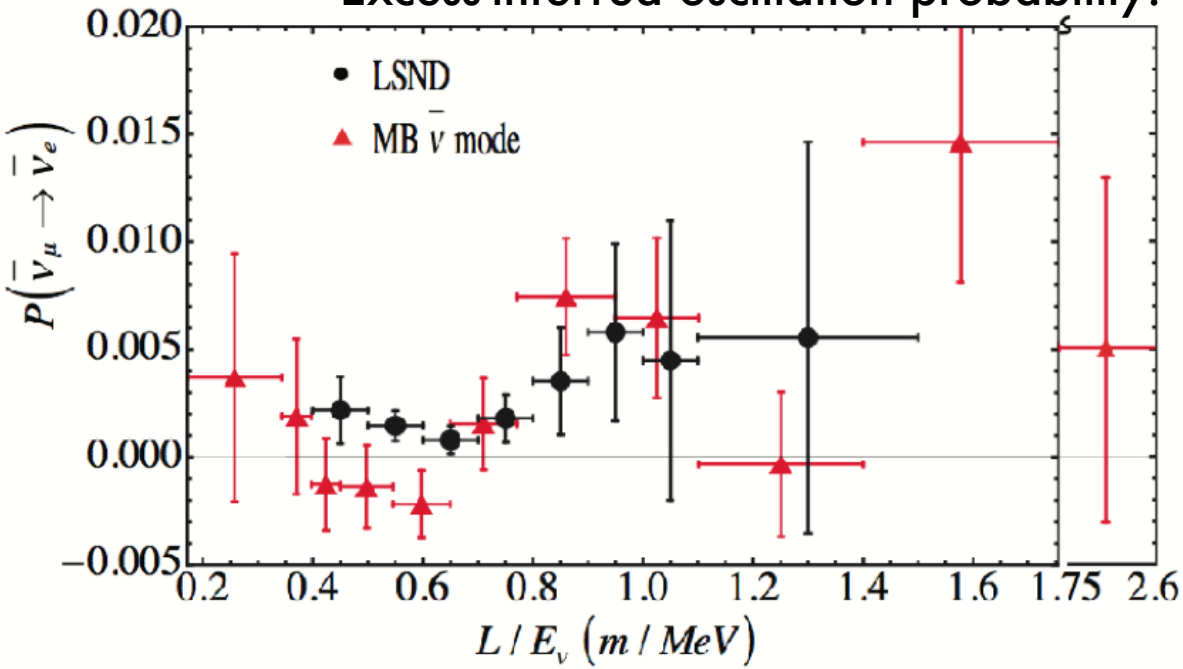
MiniBooNE appearance results: antineutrino running

MiniBooNE antineutrino mode appearance search (5.66e20 POT):

A direct test of LSND, independent of CP or CPT assumptions

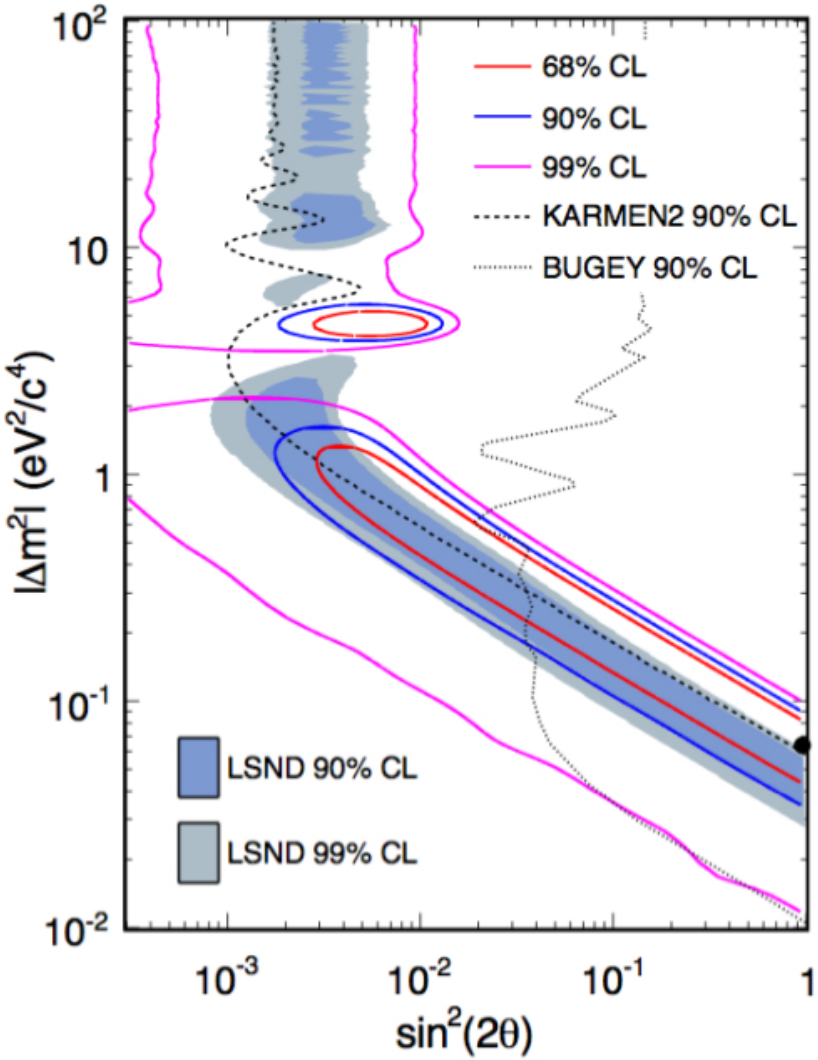


Excess-inferred oscillation probability:

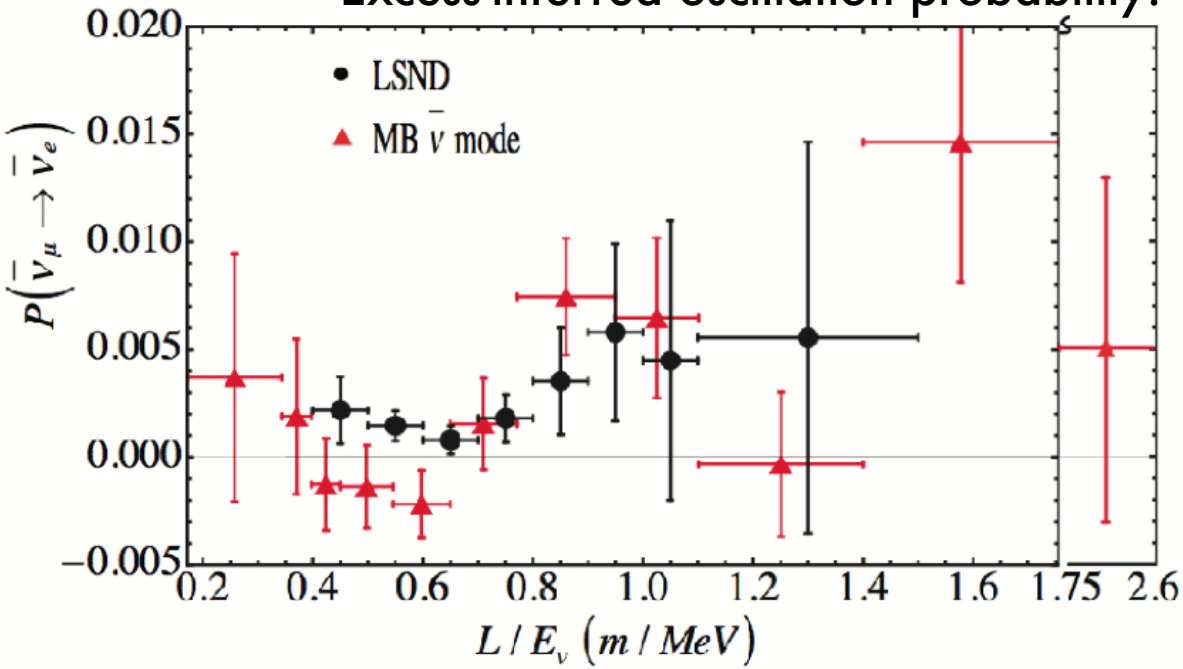


MiniBooNE appearance results: antineutrino running

MiniBooNE antineutrino mode appearance search (5.66e20 POT):
A direct test of LSND, independent of CP or CPT assumptions



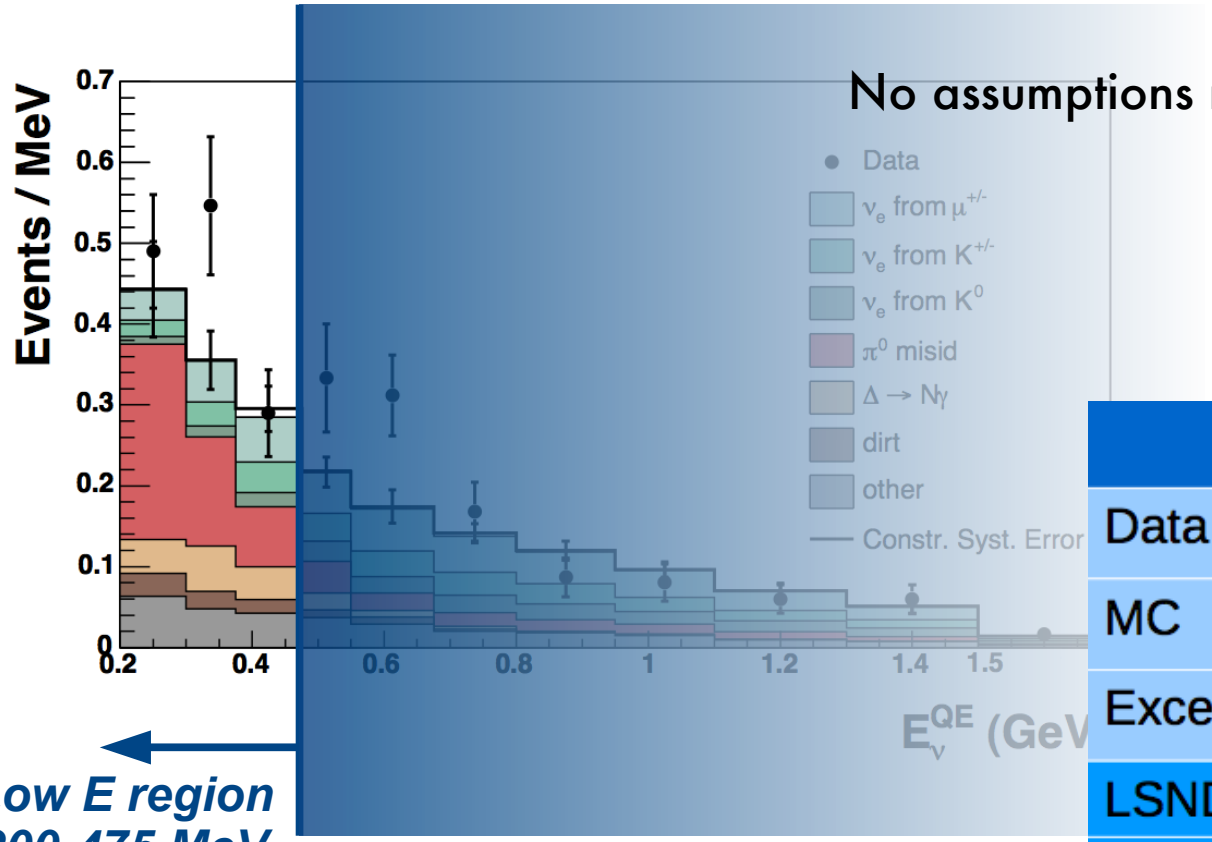
Excess-inferred oscillation probability:



MiniBooNE is consistent with two-neutrino $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at the LSND level, at 99.4% CL

MiniBooNE appearance results: antineutrino running

What about the low energy region?



No assumptions made about low energy in MC.

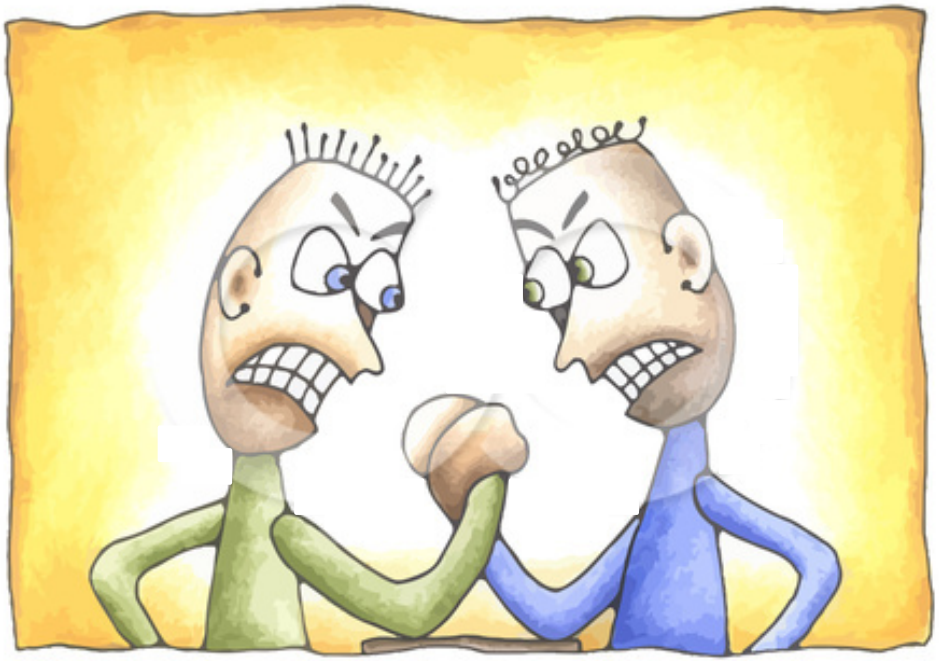
Low E region 200-475 MeV

	200-475MeV
Data	119
MC	100.5±14.3
Excess	18.5±14.3
LSND Best Fit	7.6
Expectation from ν low E excess	11.6
LSND+Low E	19.2

Assuming **only neutrinos** in the beam contribute to the excess, and scaling from neutrino mode observed excess.

Summary of MiniBooNE results

ν

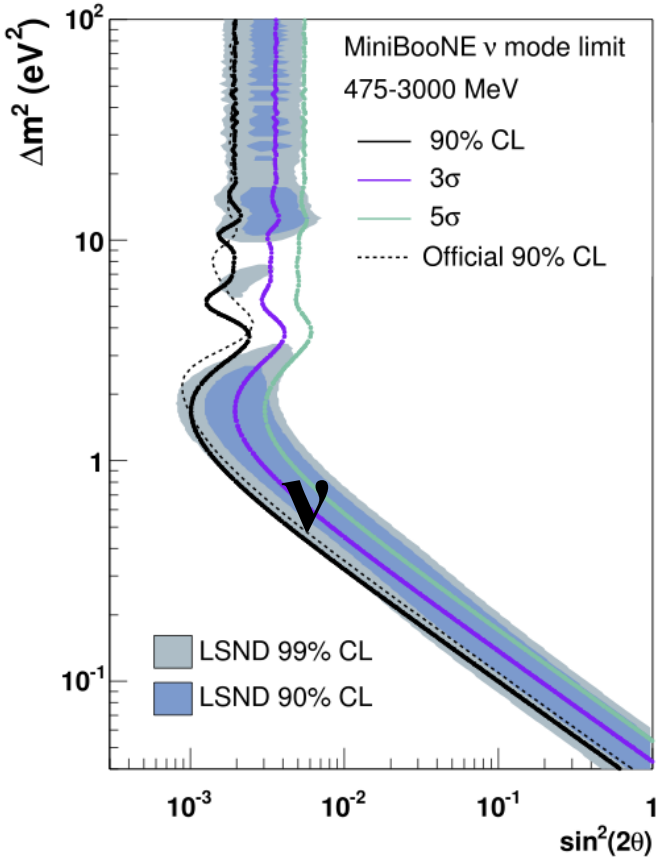


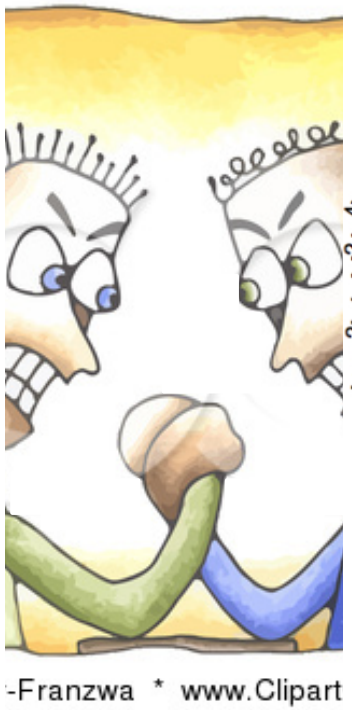
© C Charley-Franzwa * www.ClipartOf.com/50195

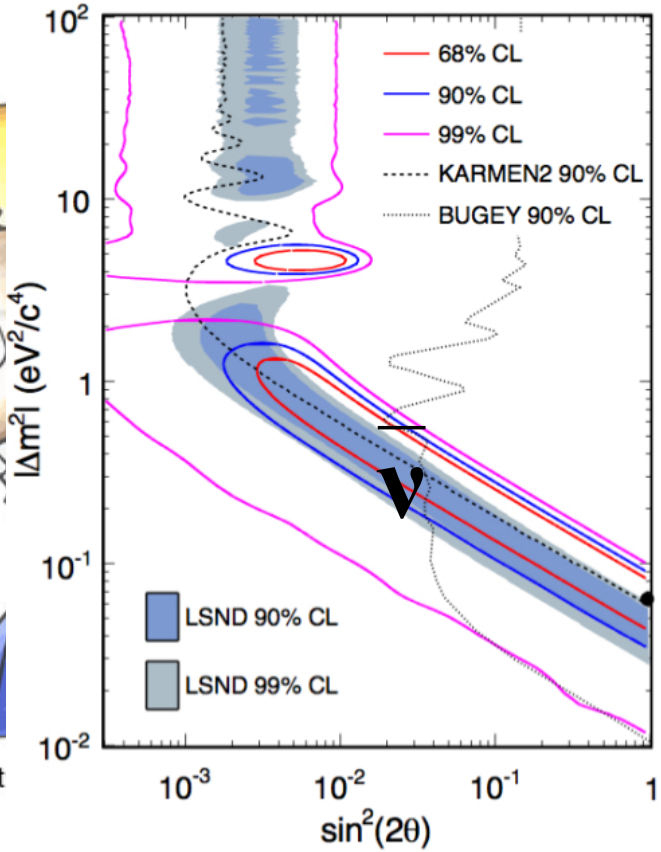
$\bar{\nu}$

Summary of MiniBooNE results

@ High E:

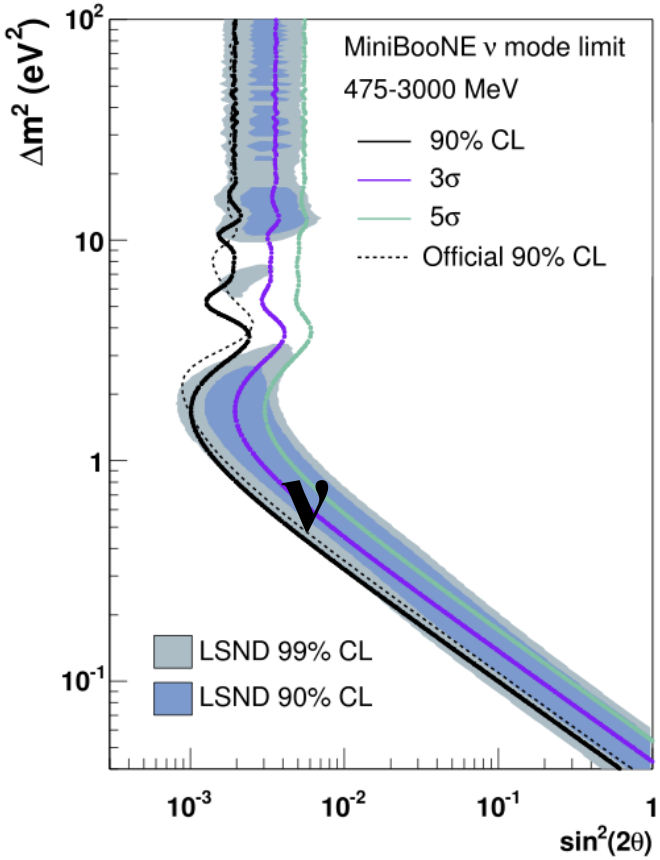


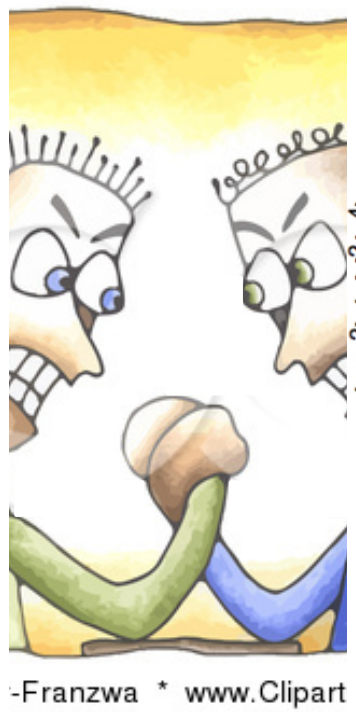


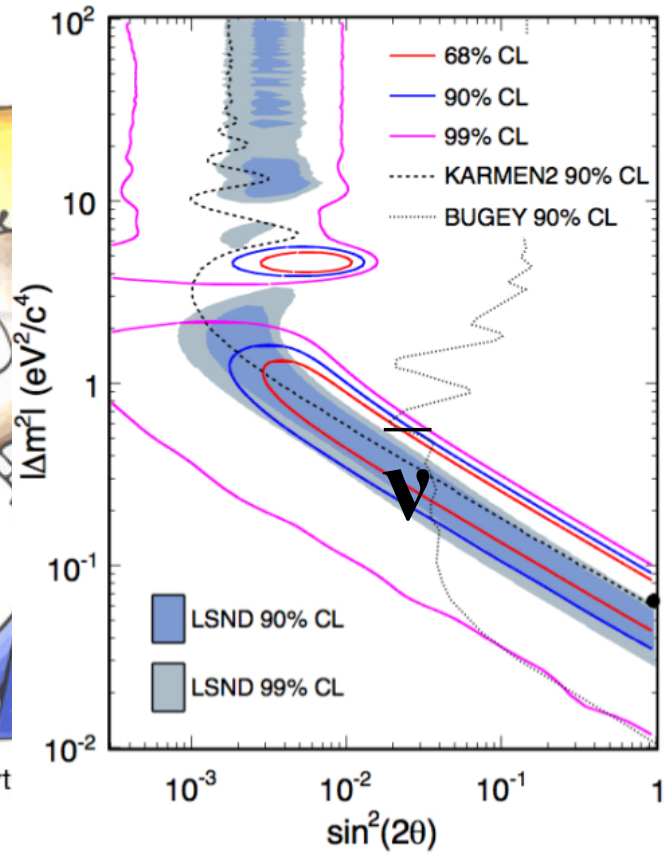


Summary of MiniBooNE results

@ High E:







@ Low E:

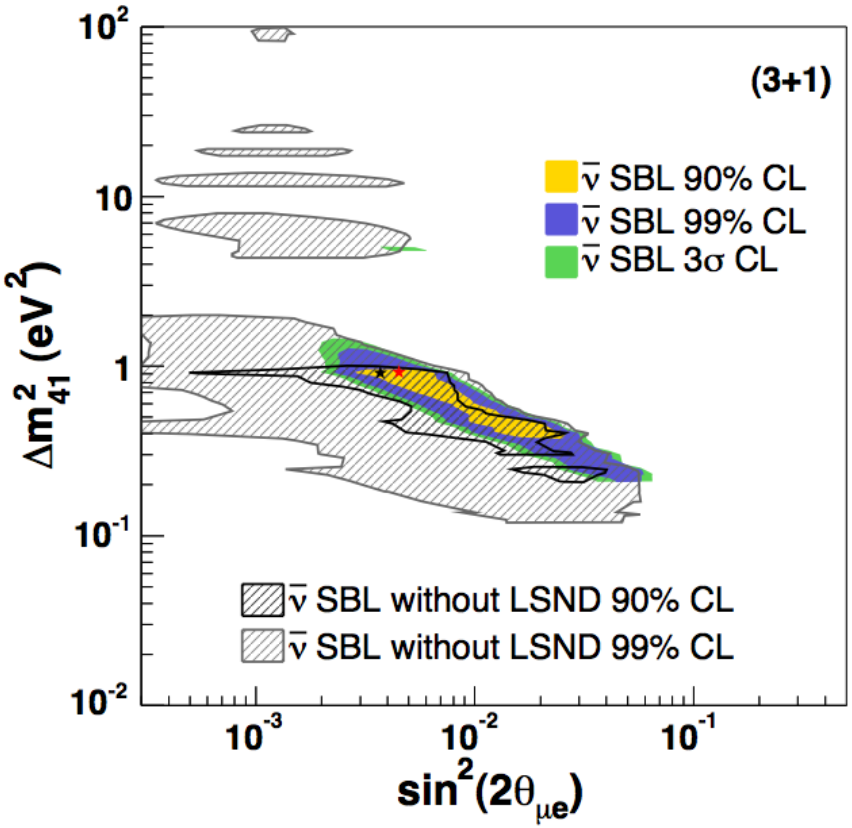
	ν_e Analysis (6.46e20 POT)	$\bar{\nu}_e$ Analysis (5.66e20 POT)
Data:	544	119
Background:	415.2 ± 43.4	100.5 ± 14.3
Excess:	128.8 ± 43.4 **(3.0σ)**	18.5 ± 14.3 **(1.3σ)**

Light sterile neutrino oscillations: Where we stand today

The big picture

Under (3+1) sterile neutrino oscillation hypothesis:

All antineutrino experimental results, including appearance and disappearance constraints, are compatible at 20%.



GK et al., Phys. Rev. D80, 073001 (2009), updated to accommodate recent MiniBooNE antineutrino results.

A fit to all antineutrino short-baseline data excludes no oscillations at >3σ, and at >99% CL when LSND is not included in the fit.

Best-fit:	χ^2/dof	Δm^2	$\sin^2 2\theta_{\mu e}$	$\sin^2 2\theta_{ee}$	$\sin^2 2\theta_{\mu\mu}$
$\bar{\nu}$	85.0/103	0.92	0.0045	0.043	0.37
$\bar{\nu}$ w/o LSND	80.3/98	0.91	0.0037	0.046	0.30

Predicts large $\bar{\nu}_\mu$ disappearance!

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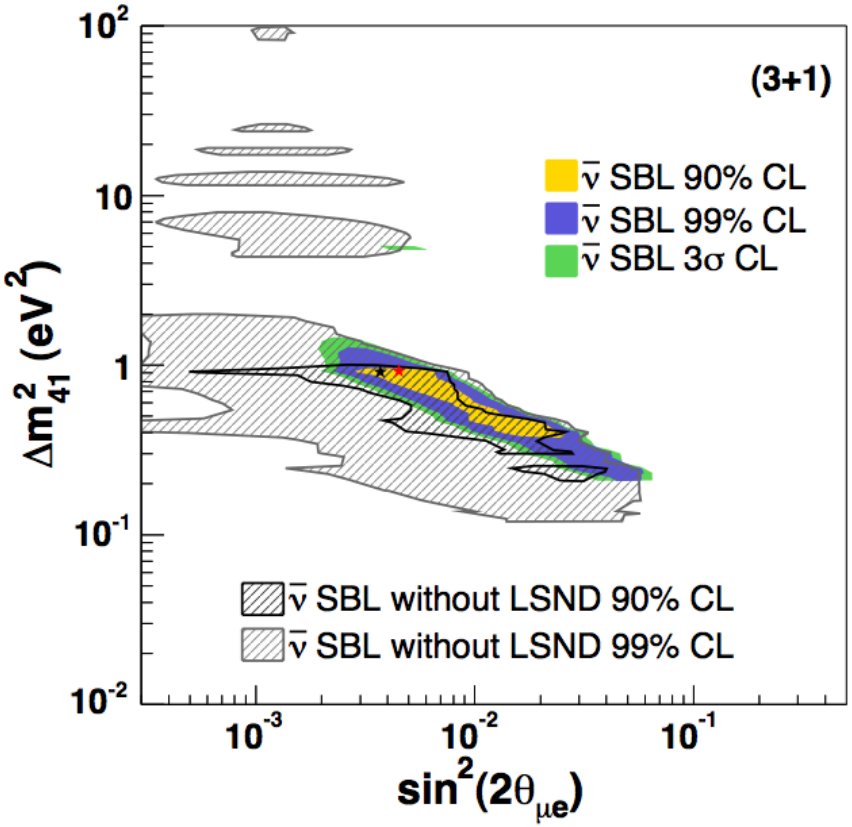

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A fit to all antineutrino short-baseline data excludes no oscillations at >3σ, and at >99% CL when LSND is not included in the fit.

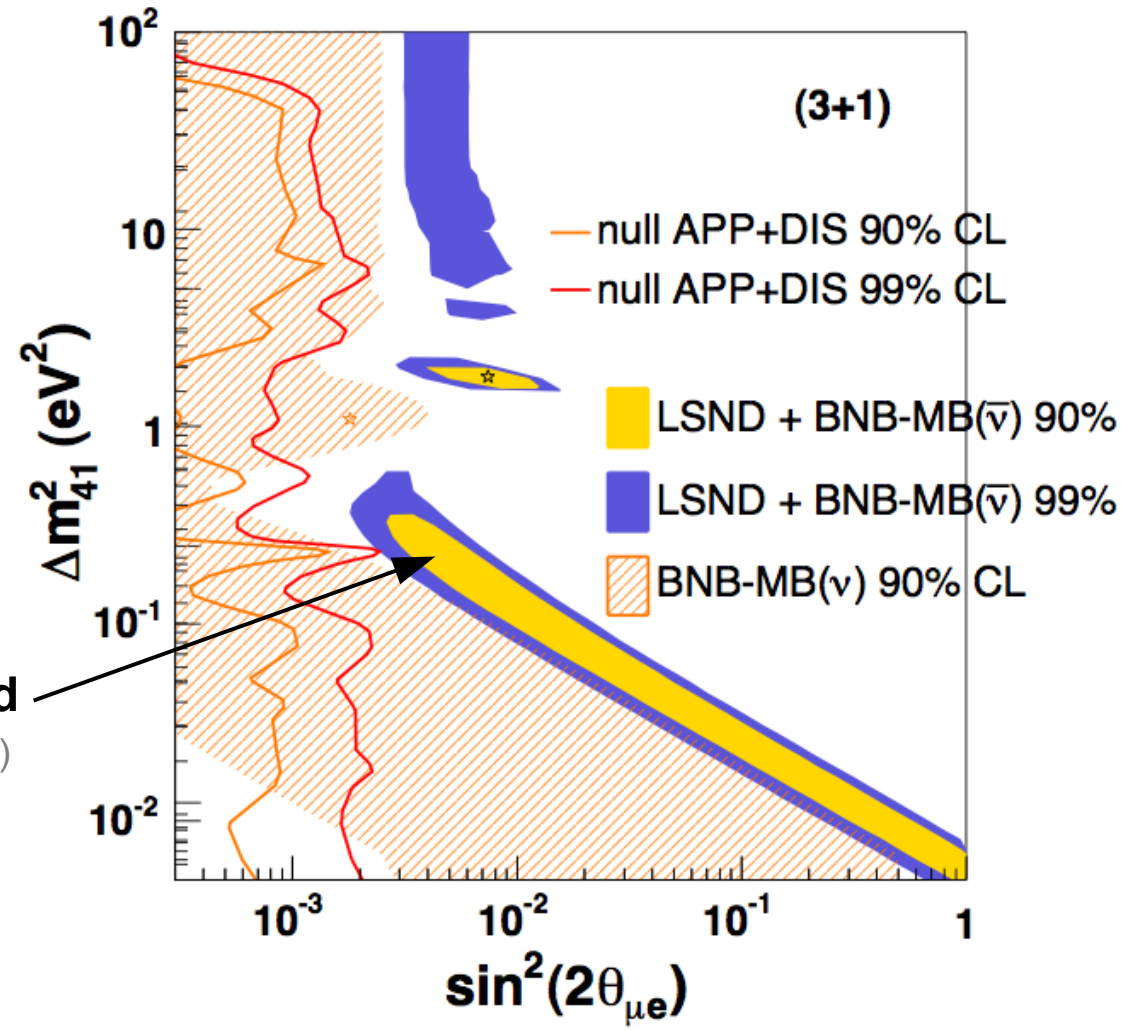
Similarly, neutrino short-baseline and atmospheric data are compatible with each other at 6.5% (MiniBooNE low energy excess driven).

The big picture

Under (3+1) sterile neutrino oscillation hypothesis:

Combining all neutrino and antineutrino short-baseline and atmospheric results →

compatibility = 0.04%



Joint **LSND+MiniBooNE($\bar{\nu}$)* allowed**

(compatible at 49%)

**corresponds to old (3.39e20 POT) MiniBooNE antineutrino results*

GK et al., Phys. Rev. D80, 073001 (2009)

The big picture

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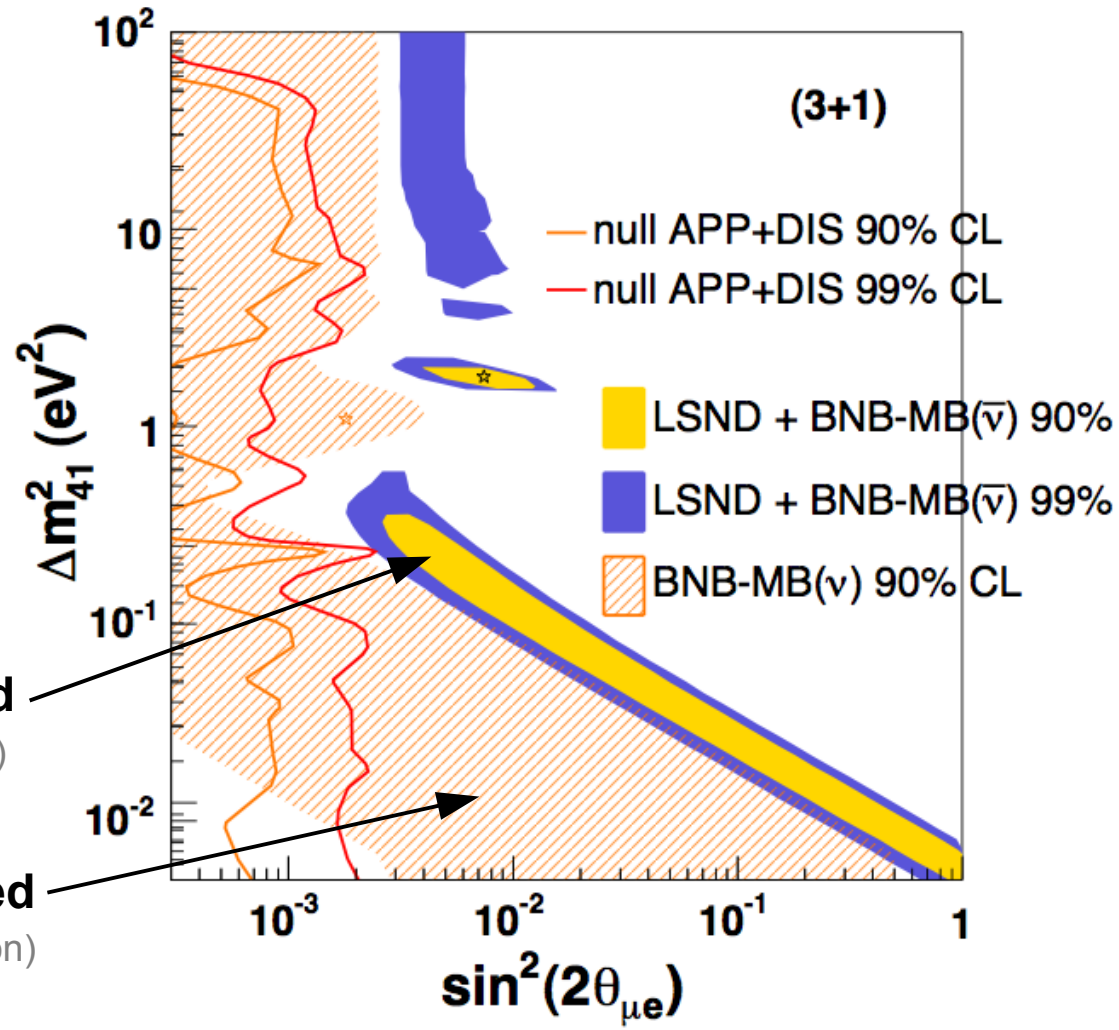


Joint **LSND+MiniBooNE($\bar{\nu}$)* allowed**

(compatible at 49%)

MiniBooNE(ν) allowed

(including low E region)

**corresponds to old (3.39e20 POT) MiniBooNE antineutrino results*

GK et al., Phys. Rev. D80, 073001 (2009)

The big picture

Under (3+1) sterile neutrino oscillation hypothesis:

Combining all neutrino and antineutrino short-baseline and atmospheric results →

compatibility = 0.04%

Combined **exclusion limits from null** atmospheric ν_μ disappearance and null experiments:

Bugey and Chooz: $\bar{\nu}_e$ disappearance

CCFR, CDHS: ν_μ disappearance

NOMAD, NuMI-MiniBooNE $\nu_\mu \rightarrow \nu_e$ appearance

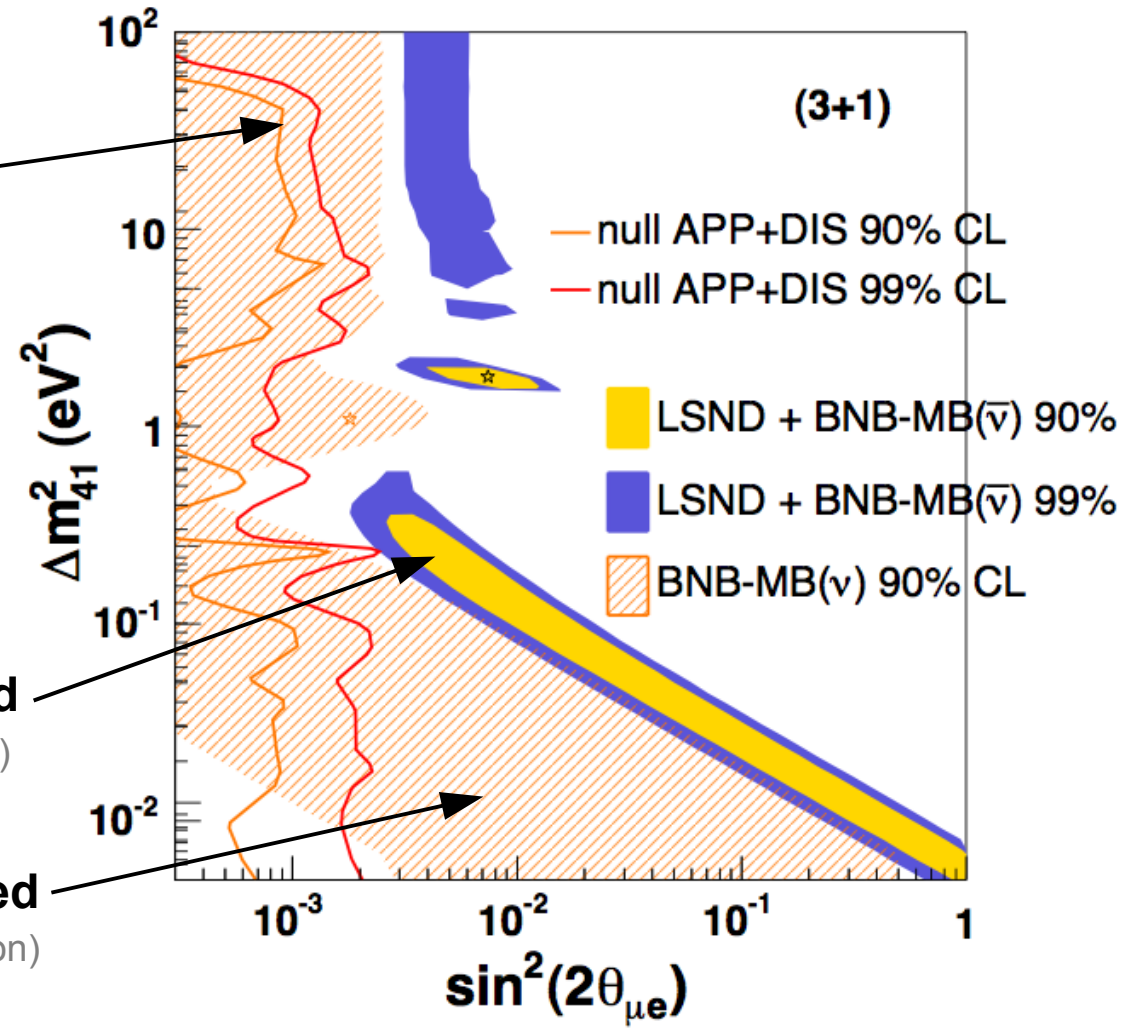
KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

Joint **LSND+MiniBooNE($\bar{\nu}$)* allowed**

(compatible at 49%)

MiniBooNE(ν) allowed

(including low E region)



**corresponds to old (3.39e20 POT) MiniBooNE antineutrino results*

GK et al., Phys. Rev. D80, 073001 (2009)

Where we stand today

Is this CP violation? Not so clear...

(3+2) CP-violating fits to all data sets also yield low compatibility: 3%.
(tension due to strict disappearance constraints)

Still, there is clear compatibility among all **antineutrino** datasets
as well as compatibility among all **neutrino** datasets,
even in the simplest, (3+1), model.

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Still, there is clear compatibility among all **antineutrino** datasets
as well as compatibility among all **neutrino** datasets,
even in the simplest, (3+1), model.

Some misunderstood systematic effect? Or hints of new physics?

MORE EXOTIC POSSIBILITIES:

Extra Dimensions 3+1 Model: Pas, Pakvasa & Weiler, Phys. Rev. D72 (2005) 095017
CPT violation 3+1 Model: Barger, Marfatia & Whisnant, Phys. Lett. B576 (2003) 303
Lorentz violation: Katori, Kostelecky & Tayloe, Phys. Rev. D74 (2006) 105009
Light-gauge boson (sterile neutrinos not fully sterile): Ann E. Nelson & Jonathan Walsh, Phys. Rev. D77 (2008) 033001
Heavy sterile neutrino decay: Gninenko, Phys. Rev. D83 (2011) 015015

Near future:

What can we learn?

Lots of signals. Which do we go after?

LSND($\bar{\nu}$)	**3.8σ**
MiniBooNE(ν)	**3.0σ**
MiniBooNE($\bar{\nu}$)	**2.7σ**

2010-2012

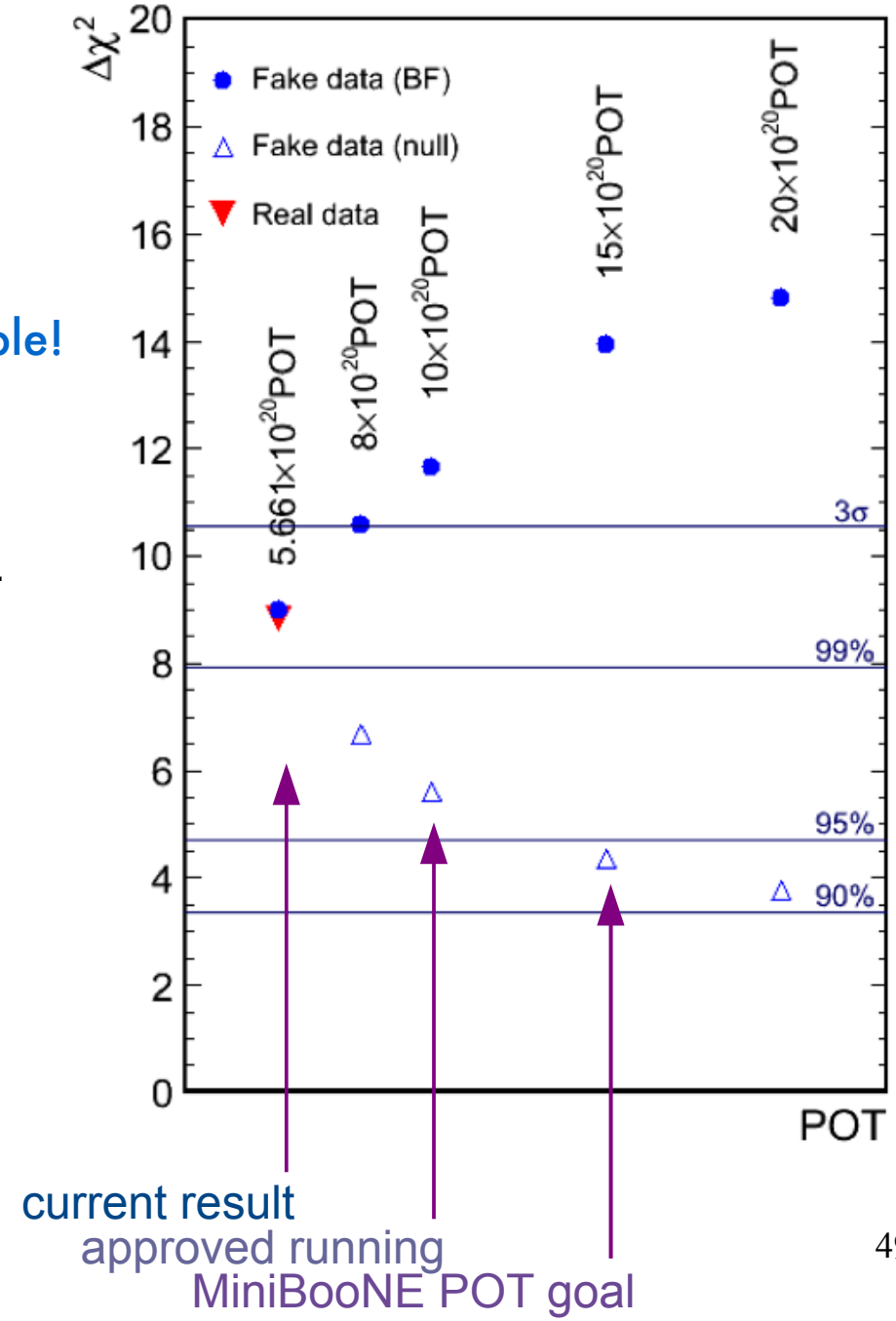
1) Antineutrinos:
Make as much use of MiniBooNE as possible!

Current results is still statistics-limited. MiniBooNE antineutrino running approved to 1e21 POT (~doubles current statistics)

Collaboration submitted a proposal for 1.5e21 POT by March 2012 shut-down. Positively received.

2012-...

2) Neutrinos:
MicroBooNE experiment!



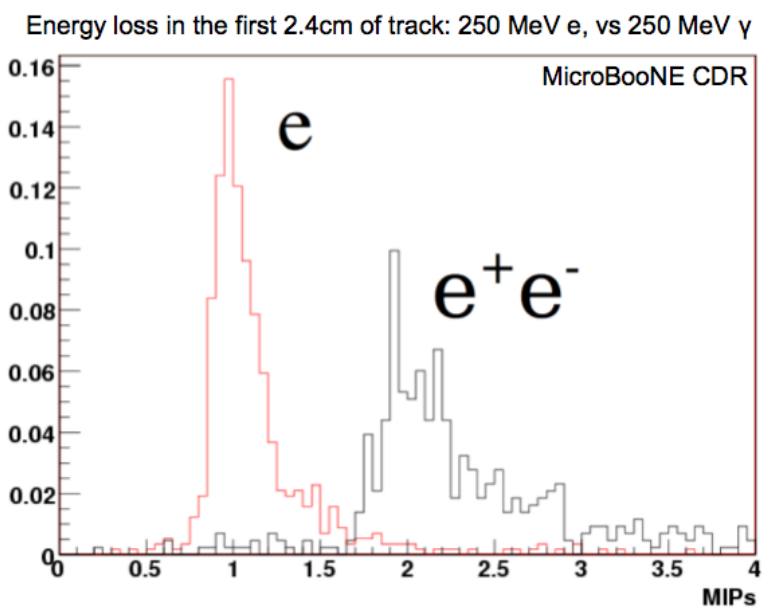
Lots of signals. Which do we go after?

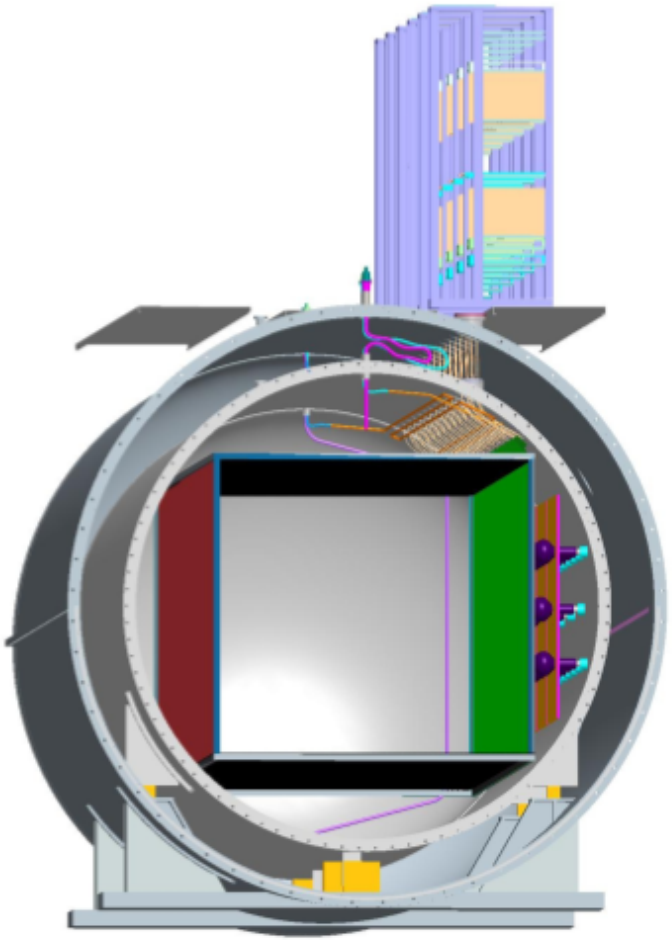
The MicroBooNE experiment

70 ton fiducial volume LArTPC detector in the MiniBooNE beamline

Will run in neutrino mode (6.0e20 POT)

Can determine the source of the excess as either ν_e CCQE, or mis-identified single photon



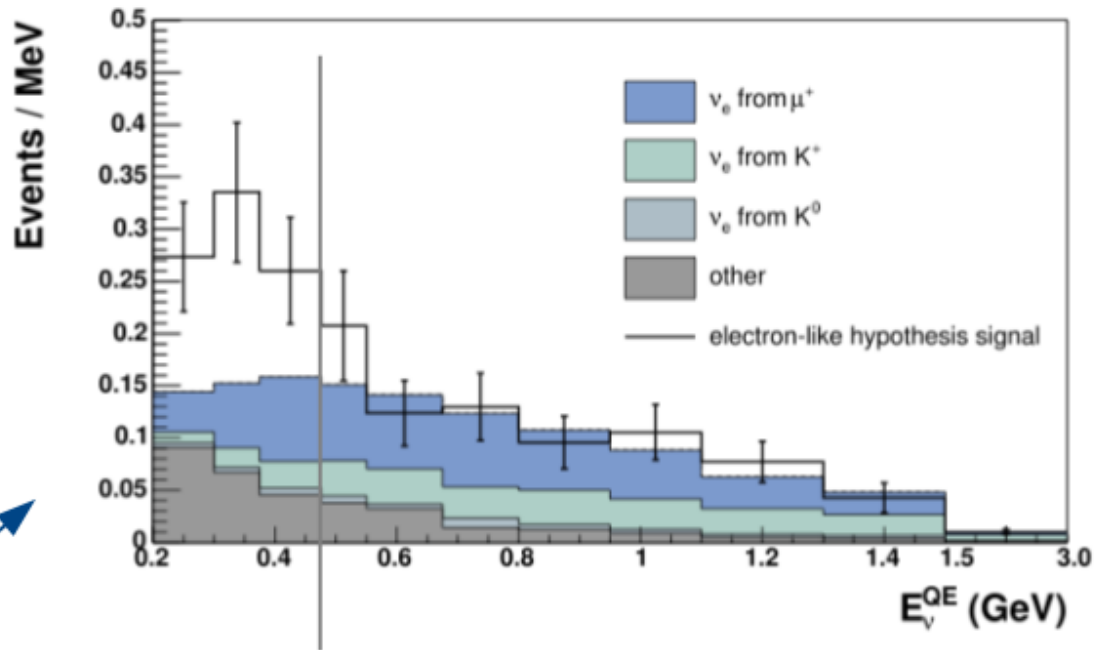


Lots of signals. Which do we go after?

The MicroBooNE experiment

MicroBooNE sensitivity to low energy excess:

(neutrino running,
70 ton fiducial volume,
x2 higher PID efficiency than MiniBooNE,
3% mis-ID,
6.0e20 POT)



Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7σ stat. significance

Conclusions

Evidence of an excess at low energy in neutrino mode
currently unexplained

ν

Hints of an excess at both low and high energy in antineutrino mode
Excess at high energy consistent with LSND two-neutrino oscillation
interpretation at 99.4% CL

$\bar{\nu}$

(3+1): all antineutrino data compatible
all neutrino data compatible
(3+2) CPV: appearance experiments compatible
but in conflict with disappearance constraints

BIG PIC

Future tests include MiniBooNE additional antineutrino running for increased
sensitivity, and MicroBooNE low energy excess search in a LArTPC
Others (not mentioned): MINOS, IceCube, LArTPC at CERN-PS, BooNE,...

!