Neutrino Experiments:
Not just for oscillations any more!

Janet Conrad,
Columbia University
JLAB Users Meeting, 2008

What we have learned in the last decade:
Oscillation Experiments

What we are learning right now:
Cross Section Experiments

And the Future!
Because there is more to neutrinos….
A Tevatron-based Program

Part I

What we have learned in the last decade:
Oscillation Experiments

We have a fully self-consistent model
for how neutrinos behave:

They interact via only the weak interaction.
They have mass
They mix
… and therefore they oscillate

It has long been known that neutrinos can, in principle, oscillate…

If we postulate:

- Neutrinos have (different) masses
- The Weak Eigenstate is a mixture of Mass Eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

But to do so would require a violation of the Standard Model

Then a pure ν_μ beam at $t = 0$,
may evolve a ν_e component with time!

The Probability for Oscillations…

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

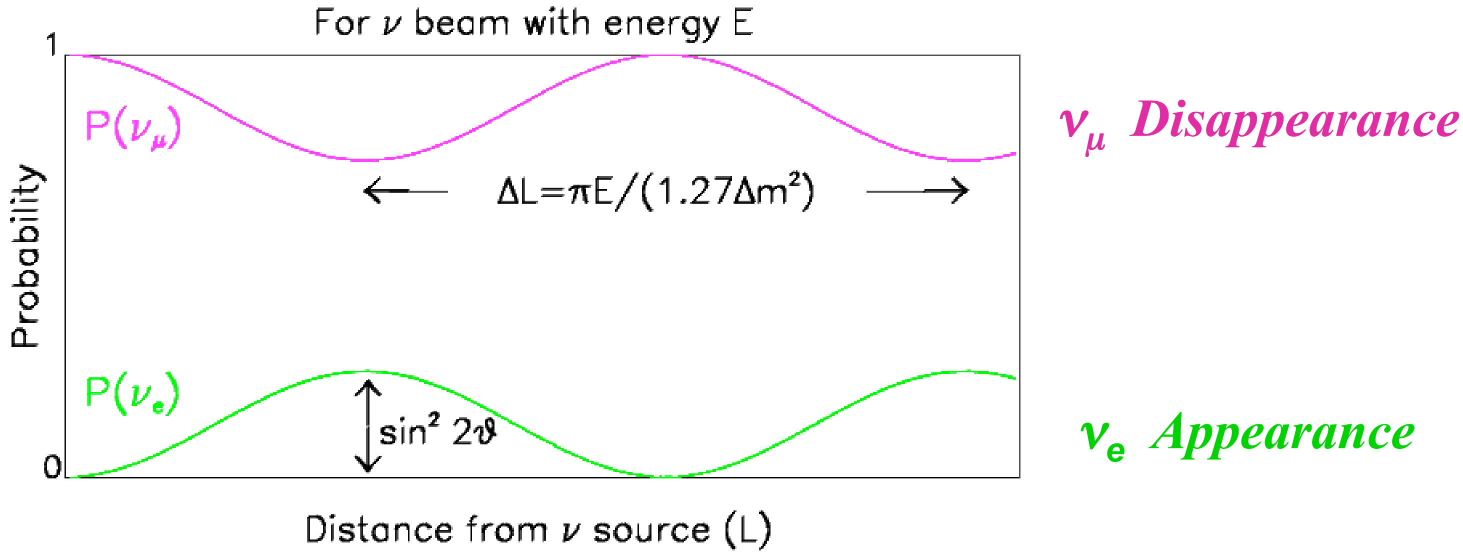
$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$



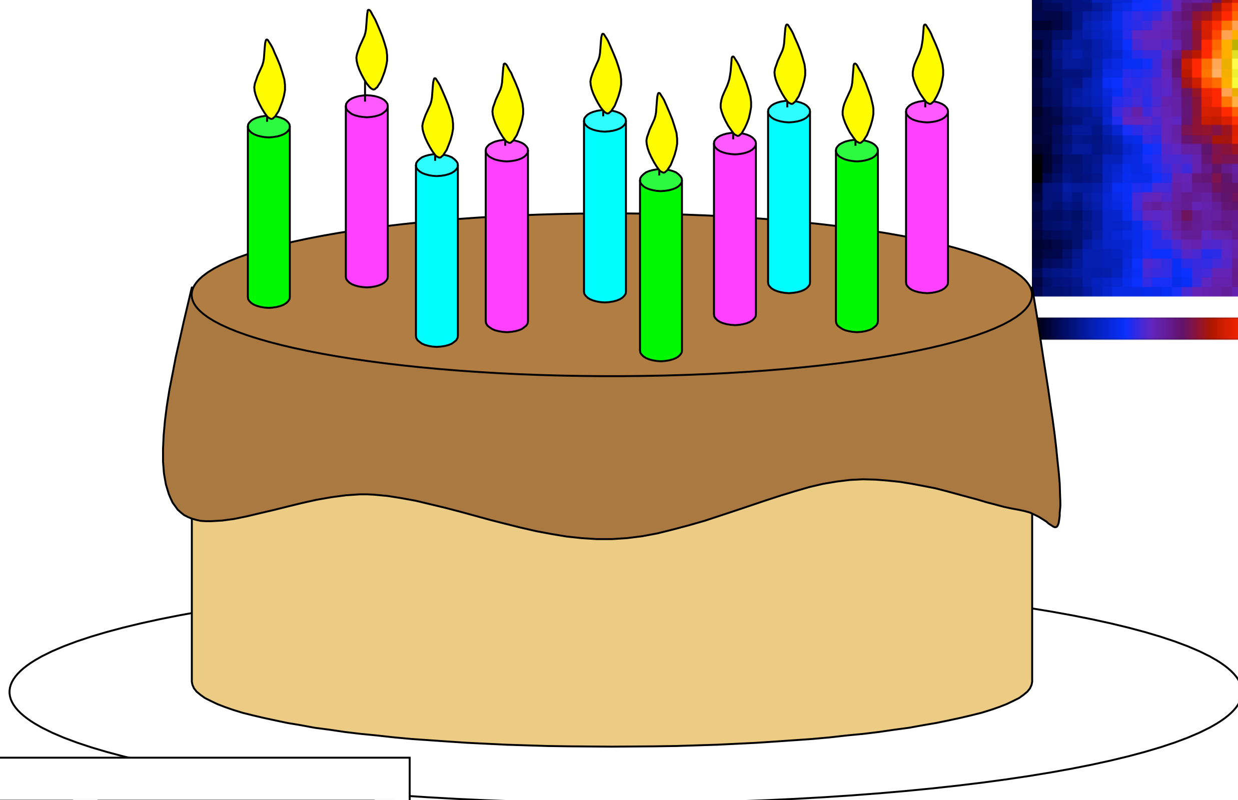
What people told me 10 years ago:

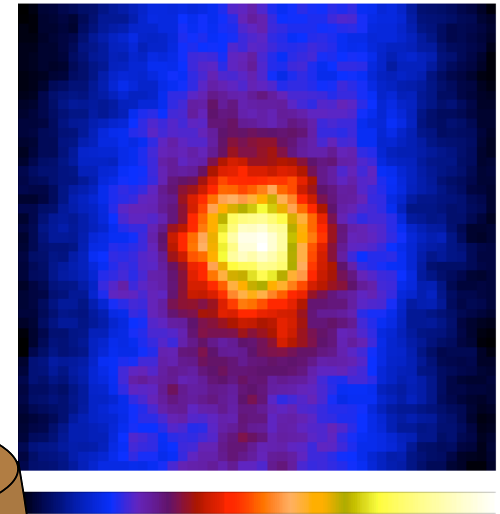
"neutrinos don't have mass, the SM says so!"

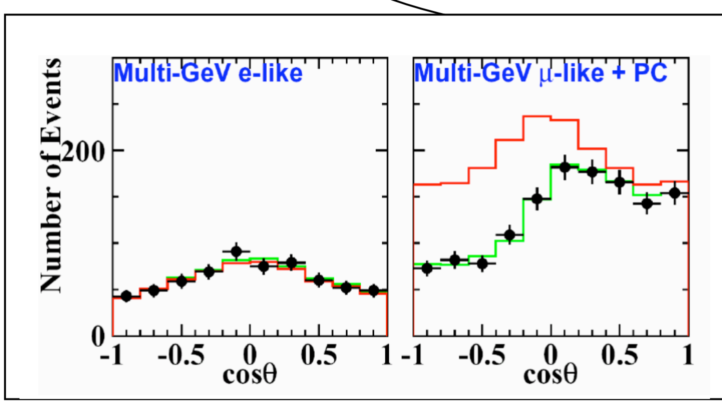
"But if they did have mass, then the natural scale is $\Delta m^2 \sim 10 - 100$ eV^2 In order to explain dark matter"

"And the oscillation mixing angles must be small because it must be like the quark mixing angles"

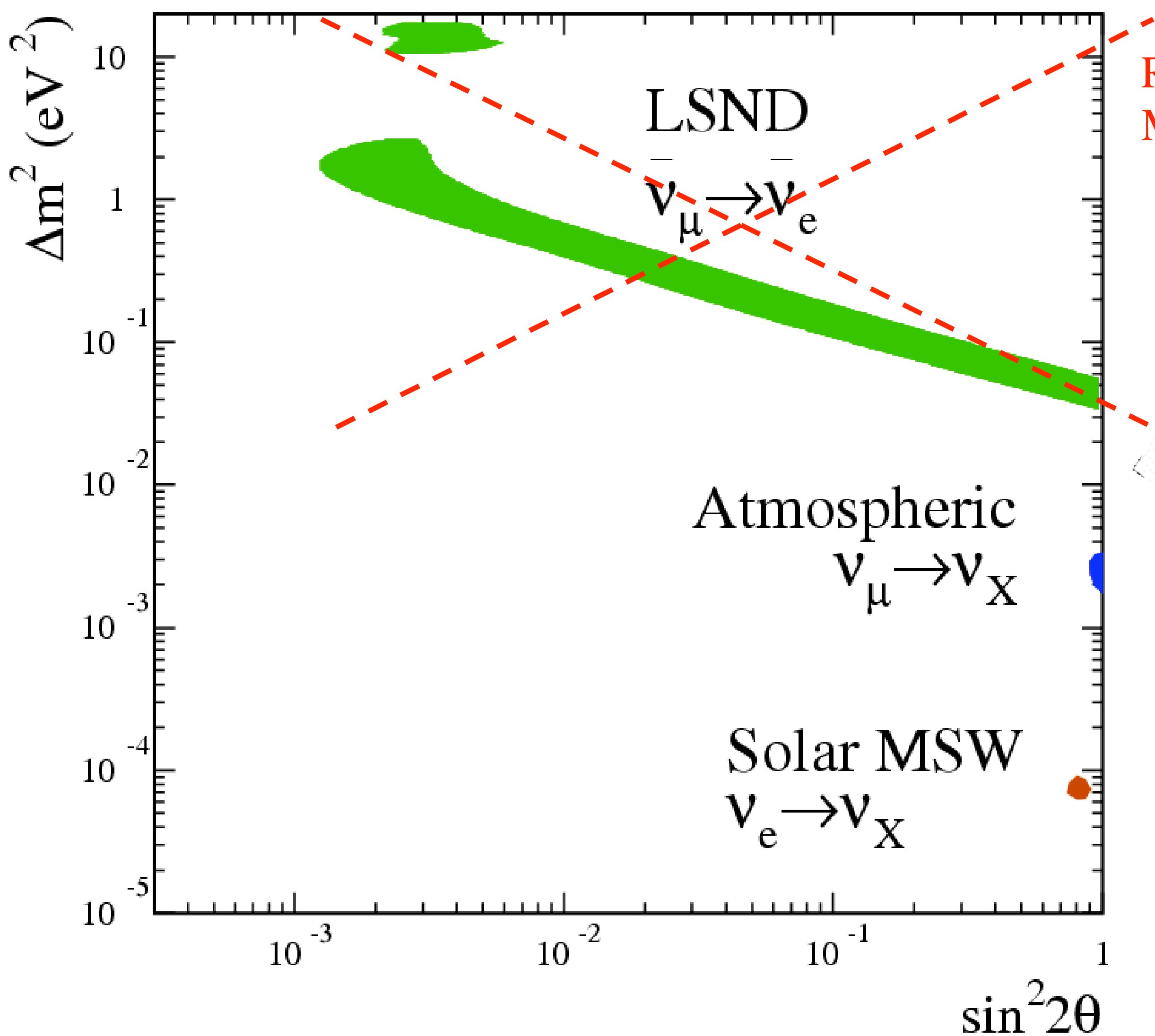
Happy 10th Anniversary
Super-K!



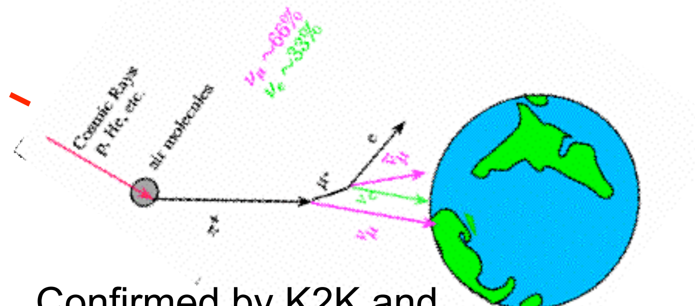




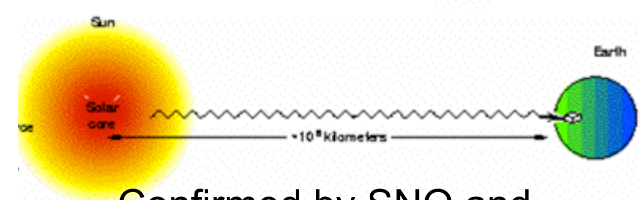
What we have learned since about oscillations...



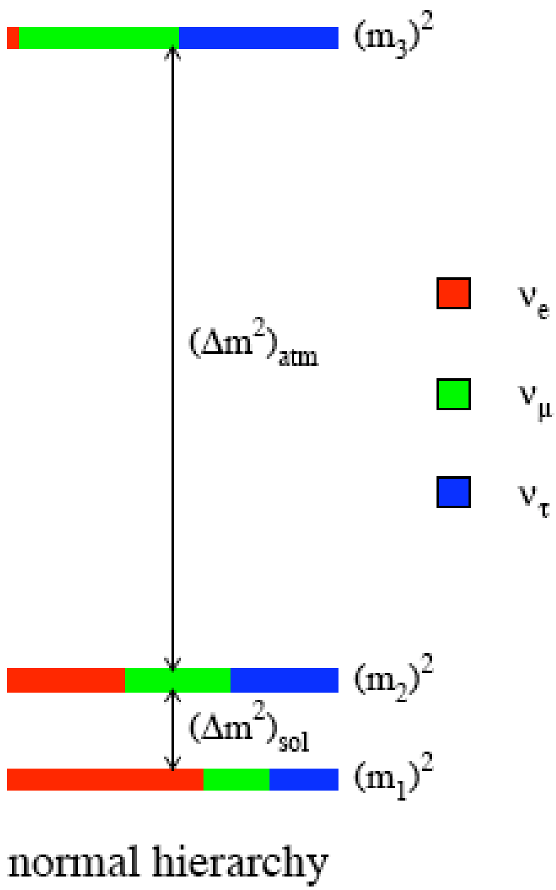
Ruled out by MiniBooNE in ν-mode



Confirmed by K2K and Minos accelerator neutrino exps



Confirmed by SNO and by Kamland reactor neutrino exp



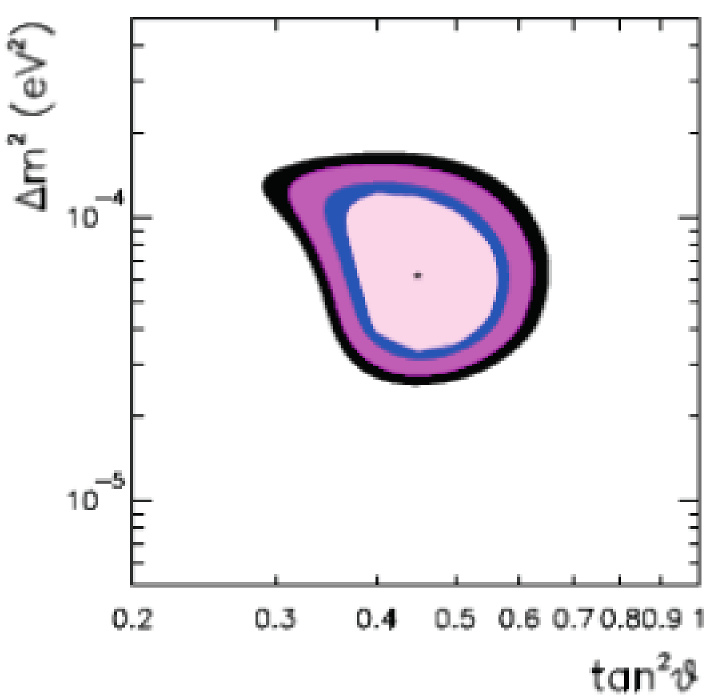
Our Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"mixing" between neutrinos
is parameterized by
three "mixing angles"
$\theta_{12}, \theta_{13}, \theta_{23}$

Our model is predictive!

Allowed region for
solar neutrino oscillation
measurements,



fit by Gonzalez-Garcia

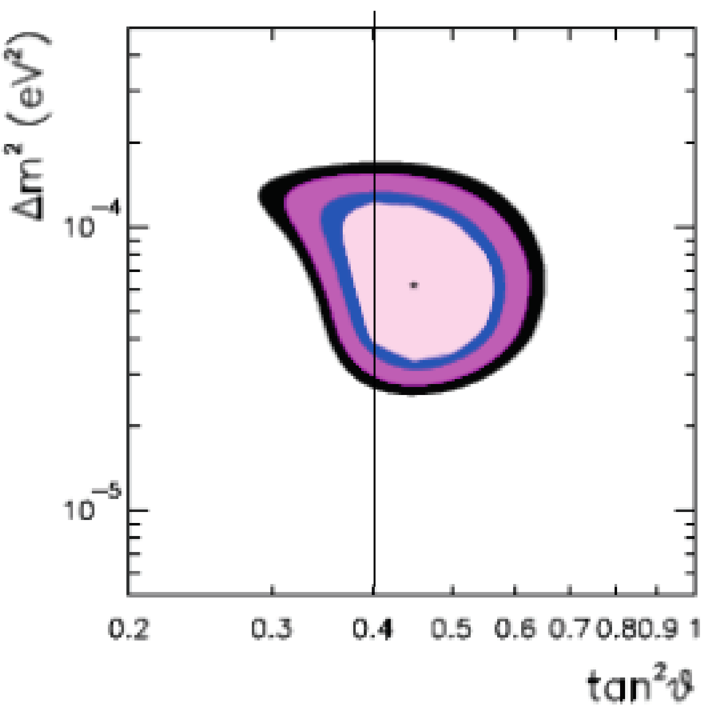
if this is due to $\nu_e \rightarrow \nu_{other}$

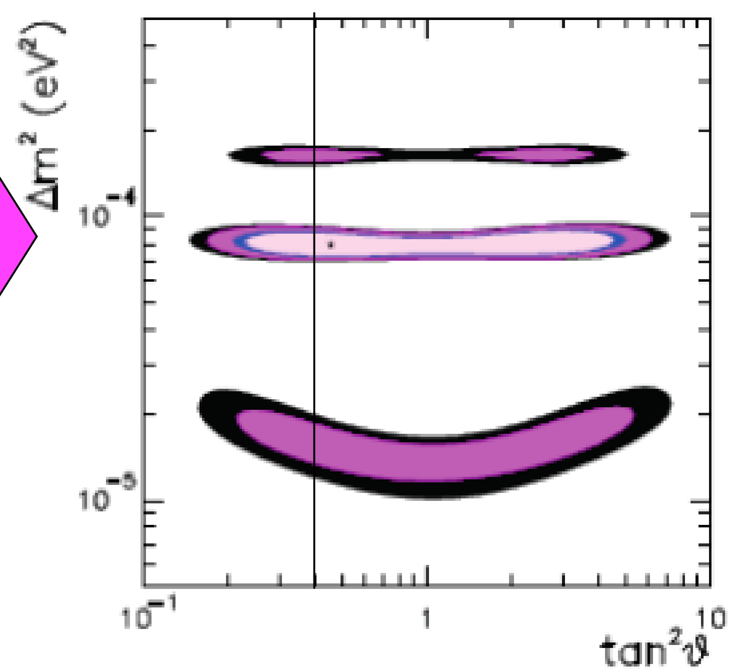
then $\bar{\nu}_e \rightarrow \bar{\nu}_{other}$
should be observable
with the same wavelength

This model is predictive!

Allowed region for solar neutrino oscillation measurements,

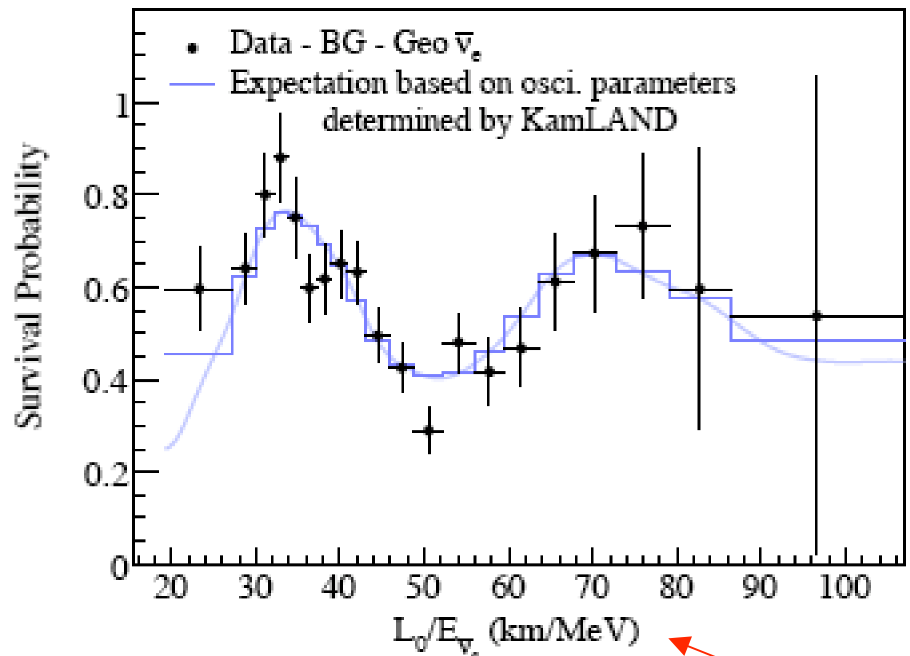
Allowed region for the Kamland reactor $\bar{\nu}_e \rightarrow \bar{\nu}_{other}$ Experiment!





fits by Gonzalez-Garcia

The result from the Kamland reactor experiment also shows the L/E “wavelike” dependence one expects from oscillations!

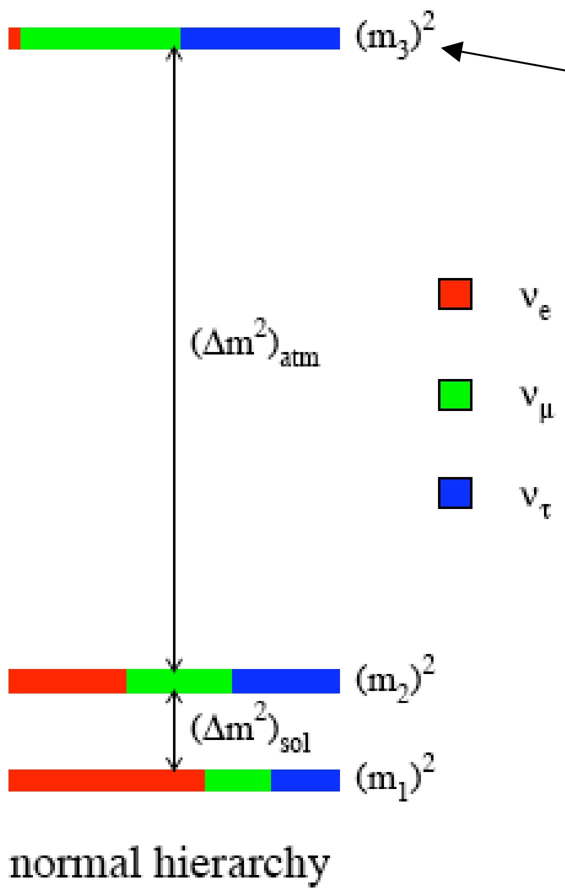


$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L/E\right)$$

arXiv:0801.4589

Our Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



BUT *mysteries* remain….
These mostly center on ν_3

Is there any ν_e content?
i.e. what's the value of θ_{13}?

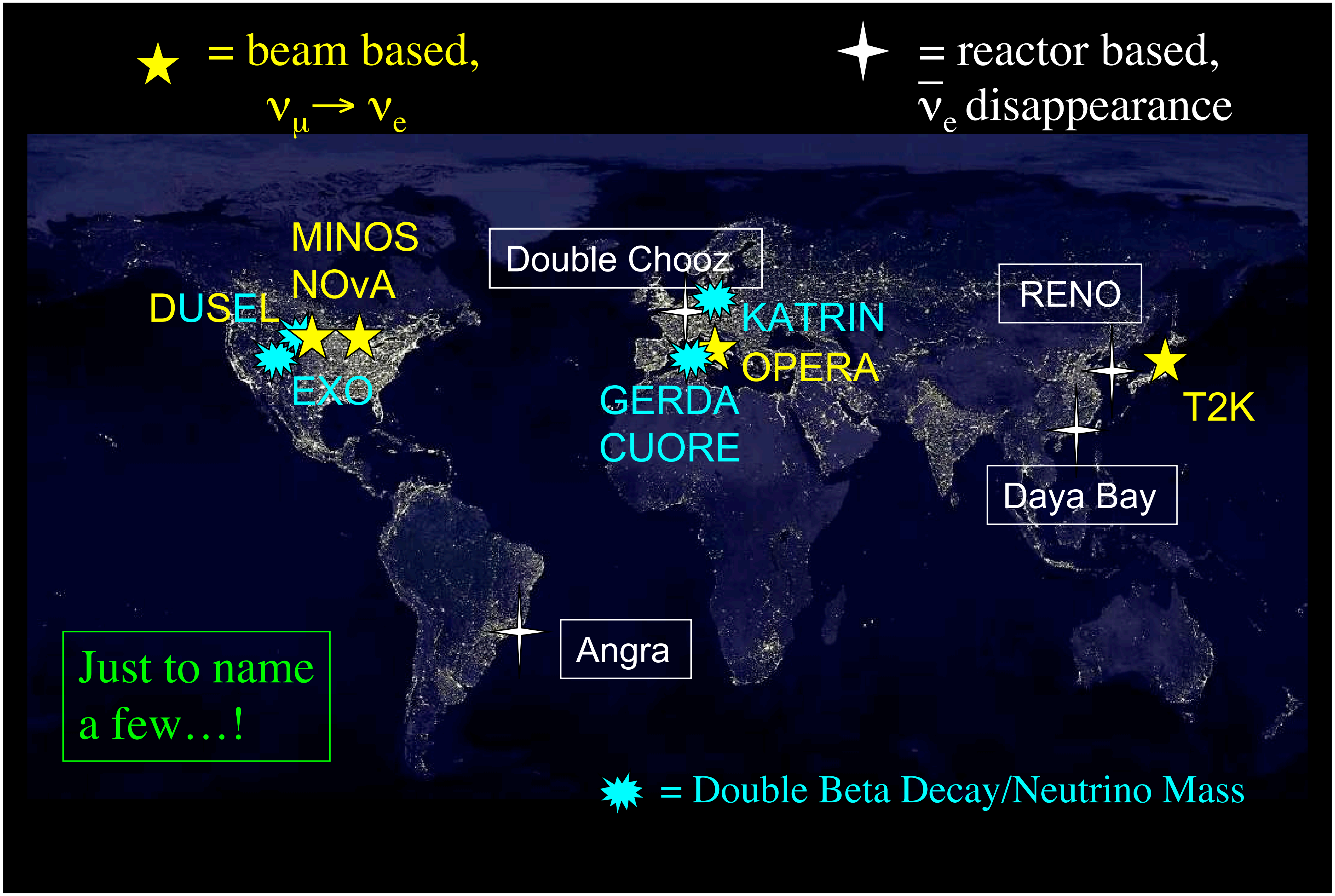
Are we seeing maximal mixing between ν_μ and ν_τ in ν_3?

Is this the mass hierarchy, or is ν_3 on the bottom?

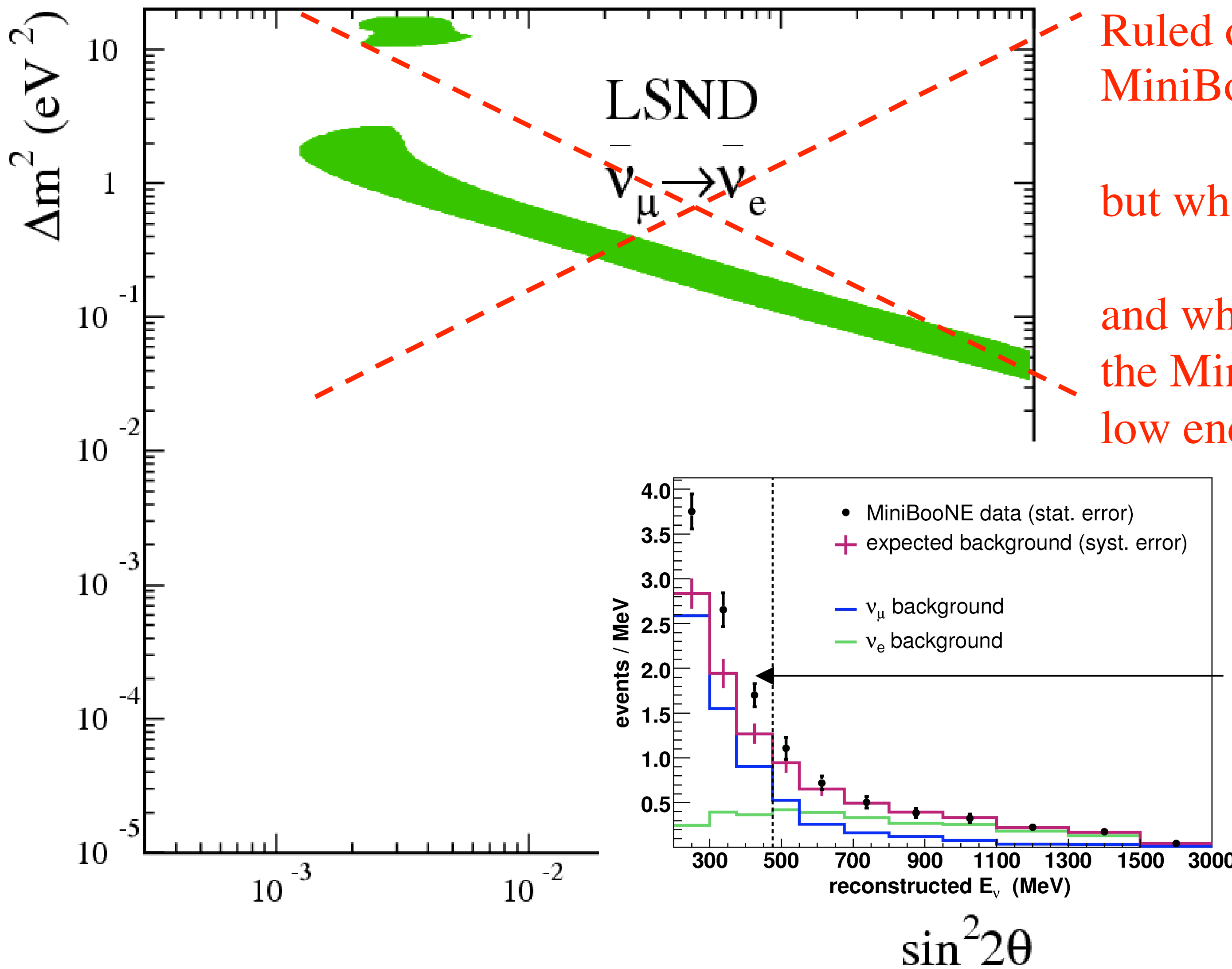
What is the absolute mass of ν_3?
(and ν_1 and ν_2 too!)

Are ν_1, ν_2 ,and ν_3 due to Majorana mass terms?

The Frenzy is ON to find the answers!!!!



There are also continued studies of the LSND high Δm^2 oscillation signal



Ruled out by MiniBooNE in ν-mode,

but what about antineutrinos?

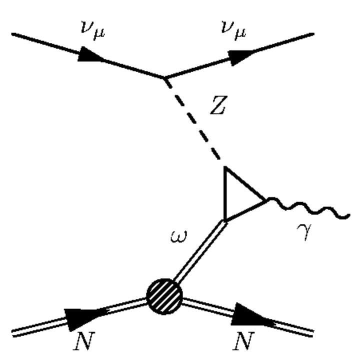
and what is the source of the MiniBooNE low energy excess?

3σ, but not consistent with oscillations…

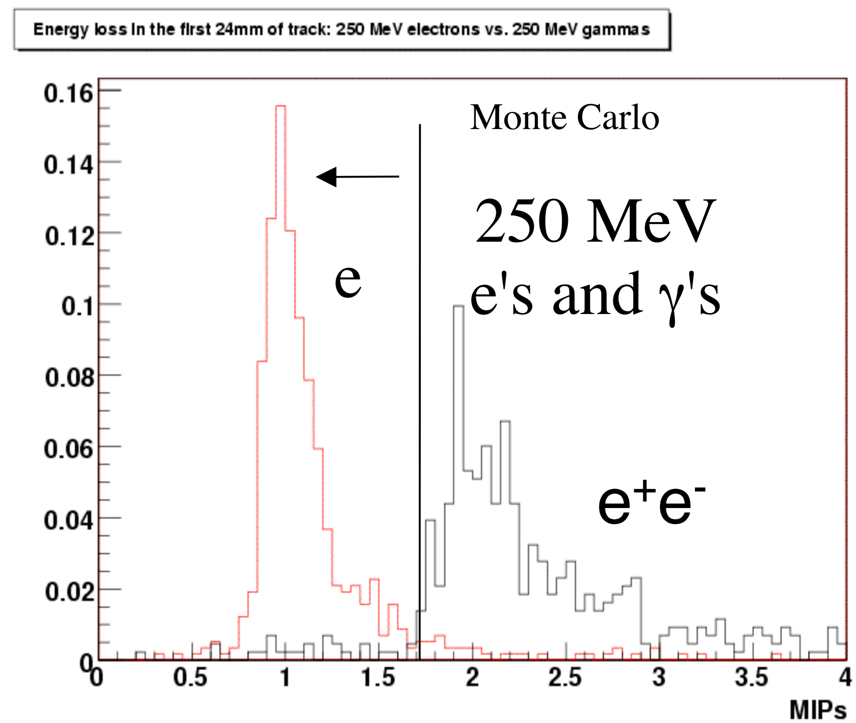
Phys.Rev.Lett.98:231801,2007.arXiv:0704.1500 [hep-ex]

This is the motivation for a new experiment at Fermilab: MicroBooNE, a 70 t fiducial volume LAr TPC

LAr has the capability to differentiate between single photon sources



Phys.Rev.Lett.99:261601,2007.
arXiv:0708.1281 [hep-ph]



And electron-like ($\nu_\mu \rightarrow \nu_e$) sources

- 3+2 with CP Violation
- a new interaction with B-L coupling
- etc.

Briefly,

This is the status of the “Neutrino Oscillation Industry”

A lot of beautiful work has been done!

But you can also ask…

What else is ν?

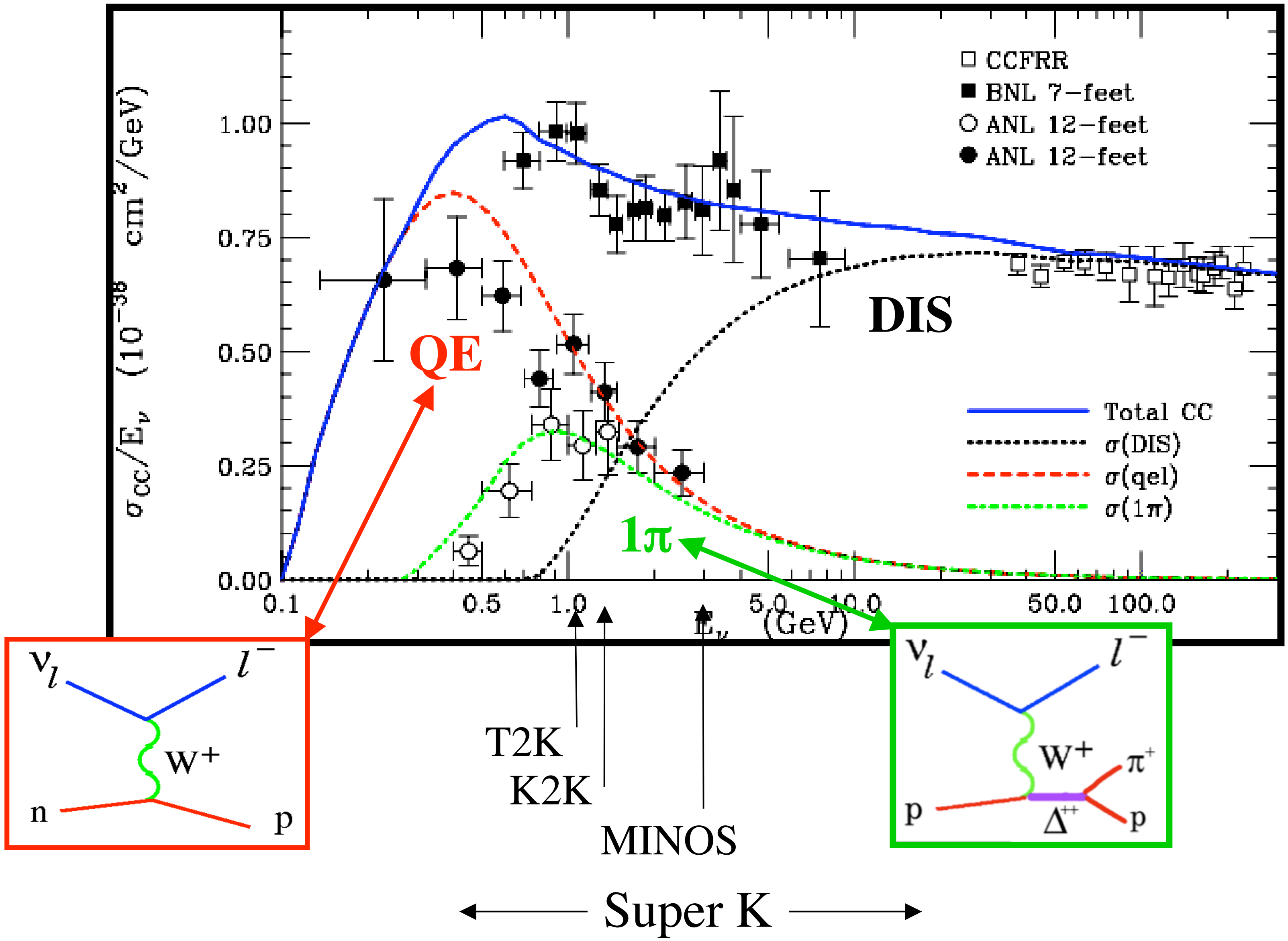
Part II

What we are learning right now:
Cross Section Experiments

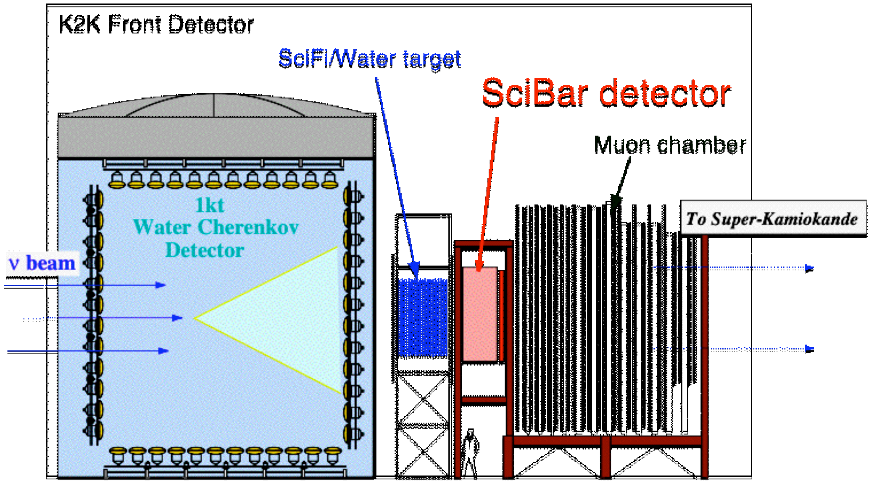
For Oscillations and More!

! = New in the last 3 months!

E_ν is typically ~ 1 to 10 GeV for
"atmospheric" Δm^2 oscillation experiments,



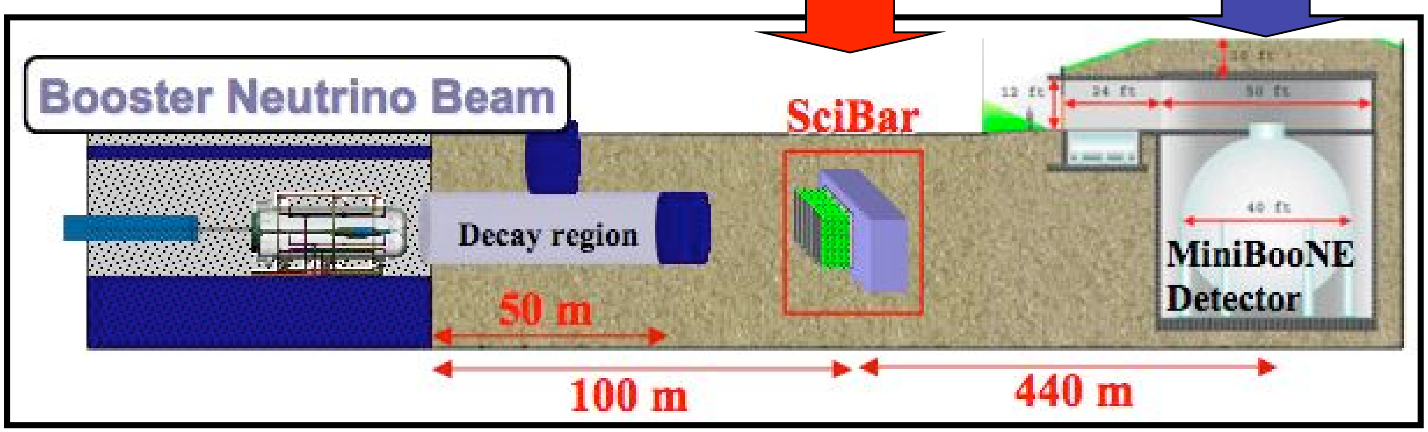
This interest motivated measurements from a series of recent/present experiments:



K2K near detector

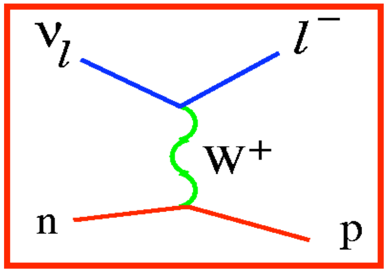
SciBooNE

MiniBooNE



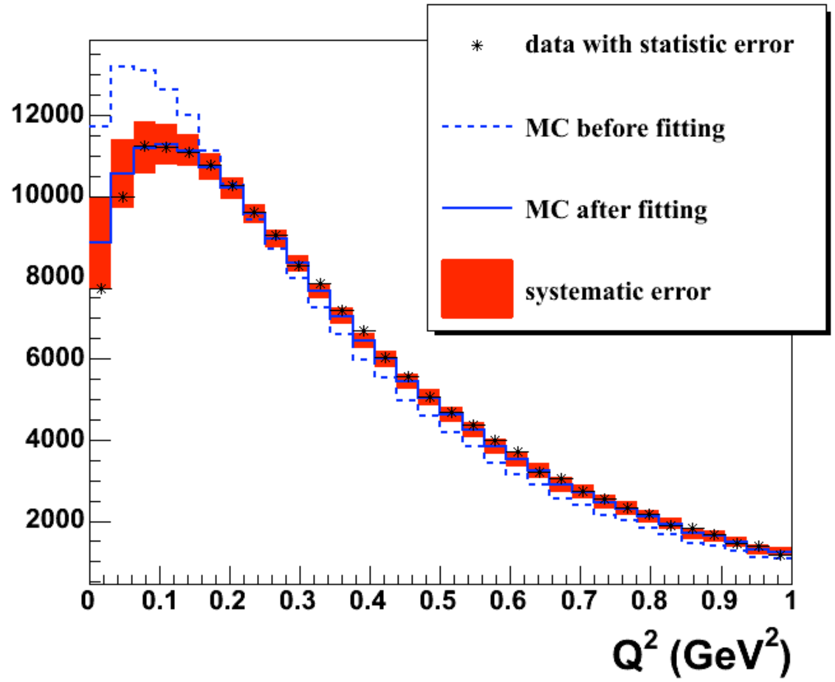
Special interest in CCQE

Low multiplicity ⇒ clean osc. signature



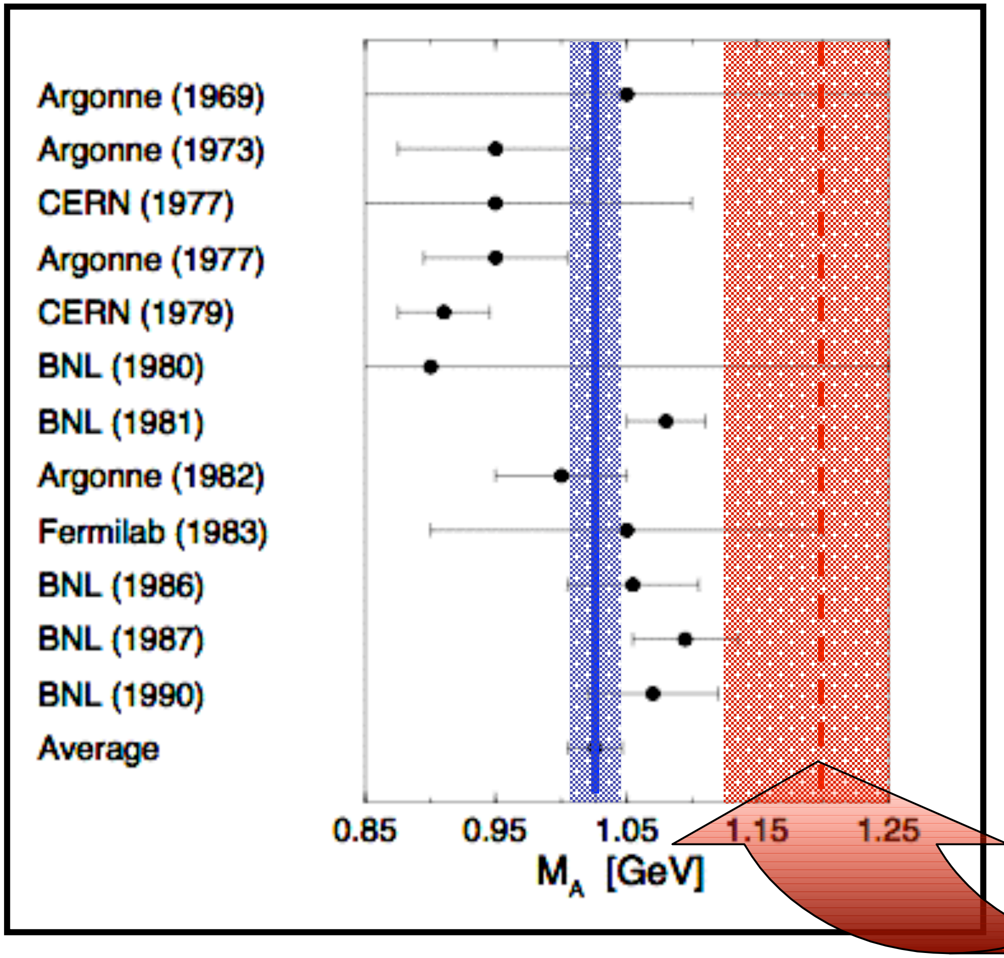
There has been a long-standing problem with modeling the Q^2 dependence (uses a dipole form factor)

hep-ex/0706.0926, *PRL* 100, 032301 (2008)



MiniBooNE:
Tuning M_A and Pauli Blocking parameters gives good fit.

Modern Determinations of M_A



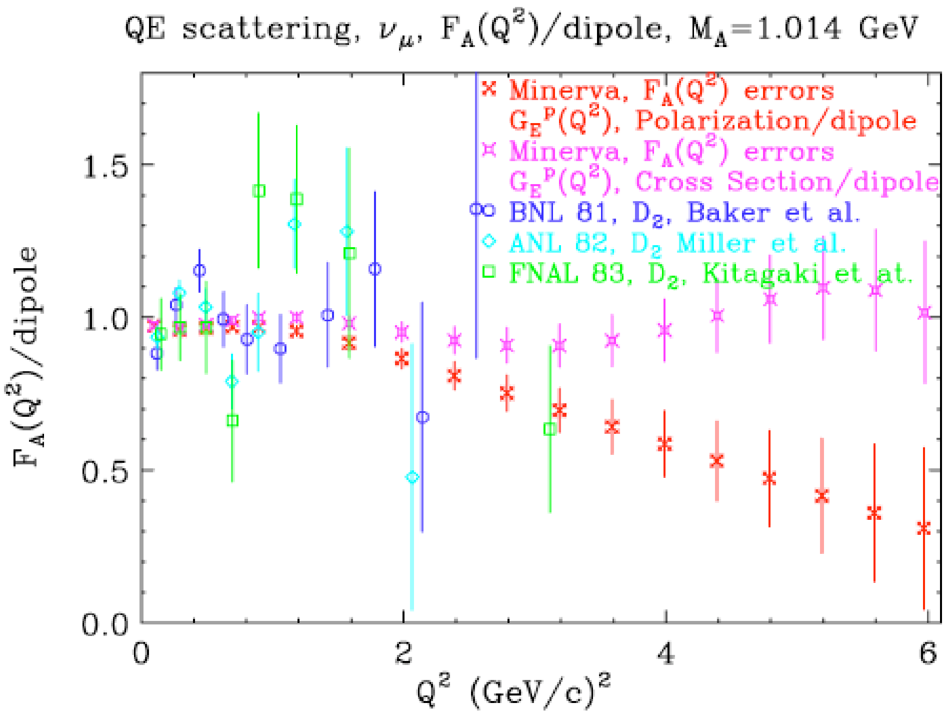
- **K2K SciFi** (^{16}O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  $M_A = 1.20 \pm 0.12$ GeV
- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  $M_A = 1.14 \pm 0.11$ GeV
- **MiniBooNE** (^{12}C, $Q^2>0.25$)
  Phys. Rev. Lett. **100**, 032301 (2008)
  $M_A = 1.25 \pm 0.12$ GeV

past world avg: $M_A = 1.026 \pm 0.021$ GeV
J. Phys. **G28**, R1 (2002)

(from G. Zeller talk on Neutrino Cross Sections, Neutrino 2008)

Testing if the CCQE form factor has a dipole form…!

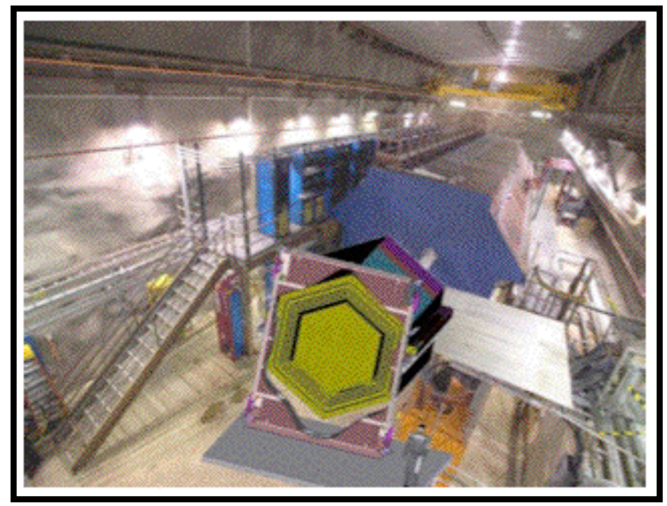
blue, cyan, green -- measurements to date.
red, magneta -- two models as examples of measurement by…

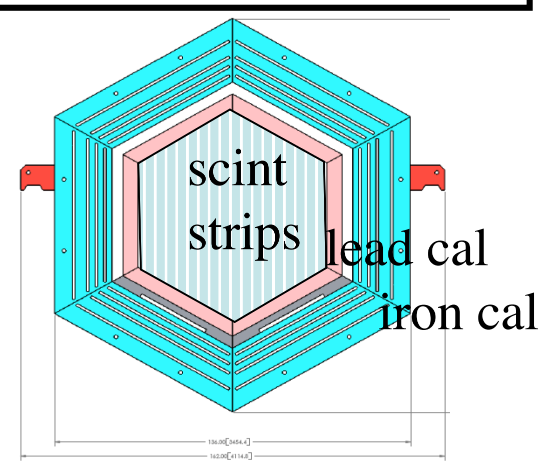


Errors comparable to vector form factor measurements from JLab … finally!

The Minerva Experiment

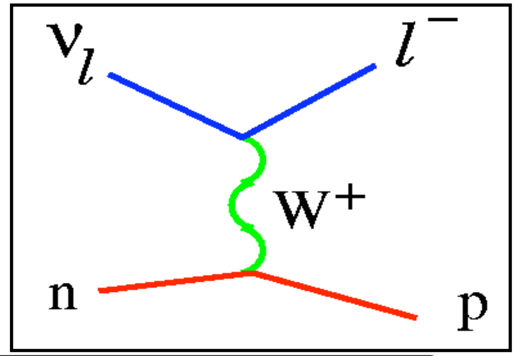
Test run 2008,
First data run 2009!



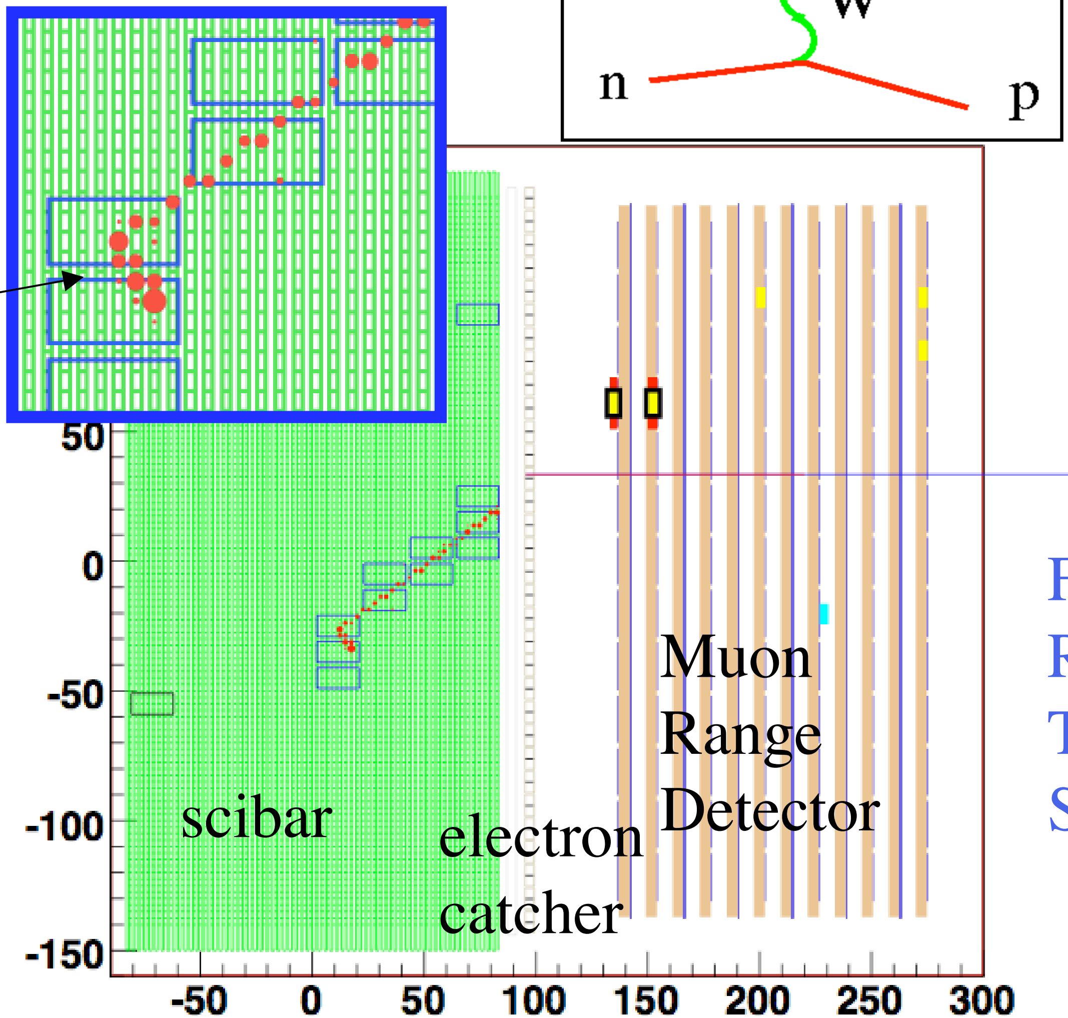


Coming soon to a conference near you!

CCQE from SciBooNE:



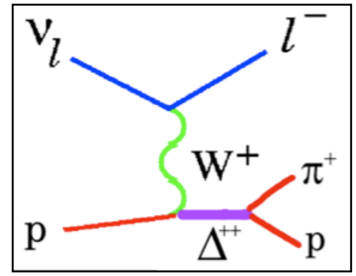
Proton ID via dE/dx



First Results This Summer!

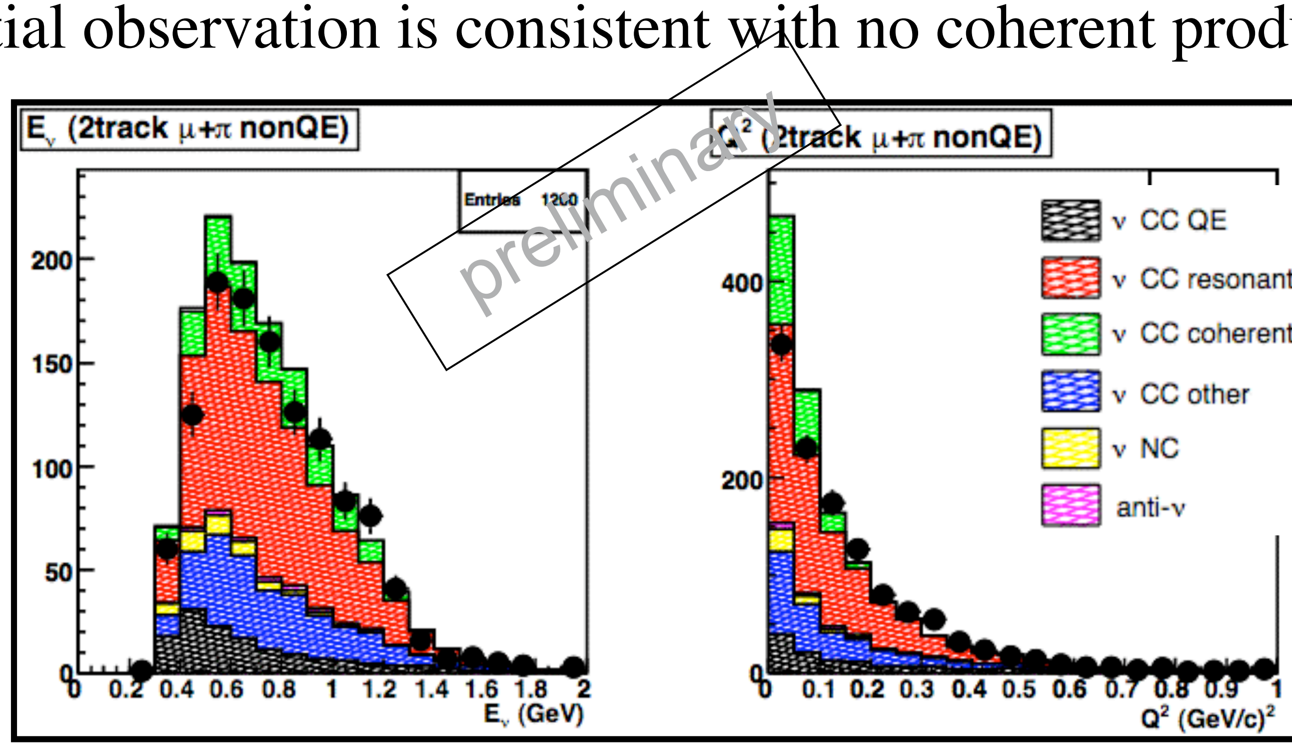
An interesting Preliminary result from SciBooNE

CCπ+ production



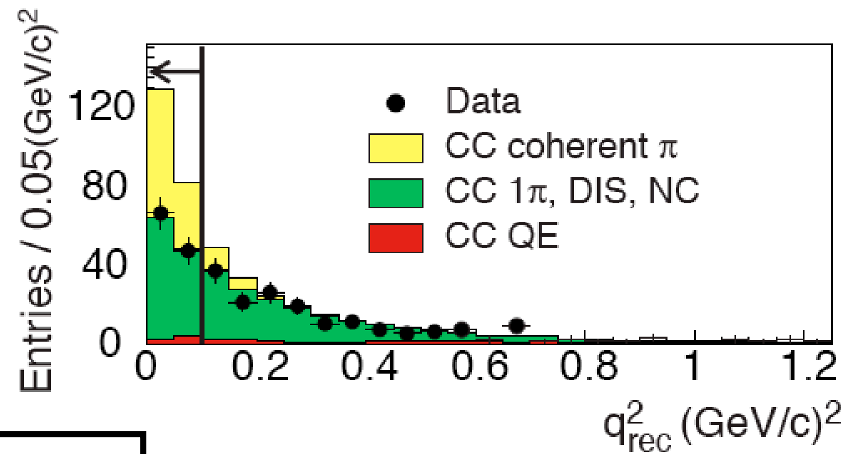
Expect: Resonant and coherent contributions!

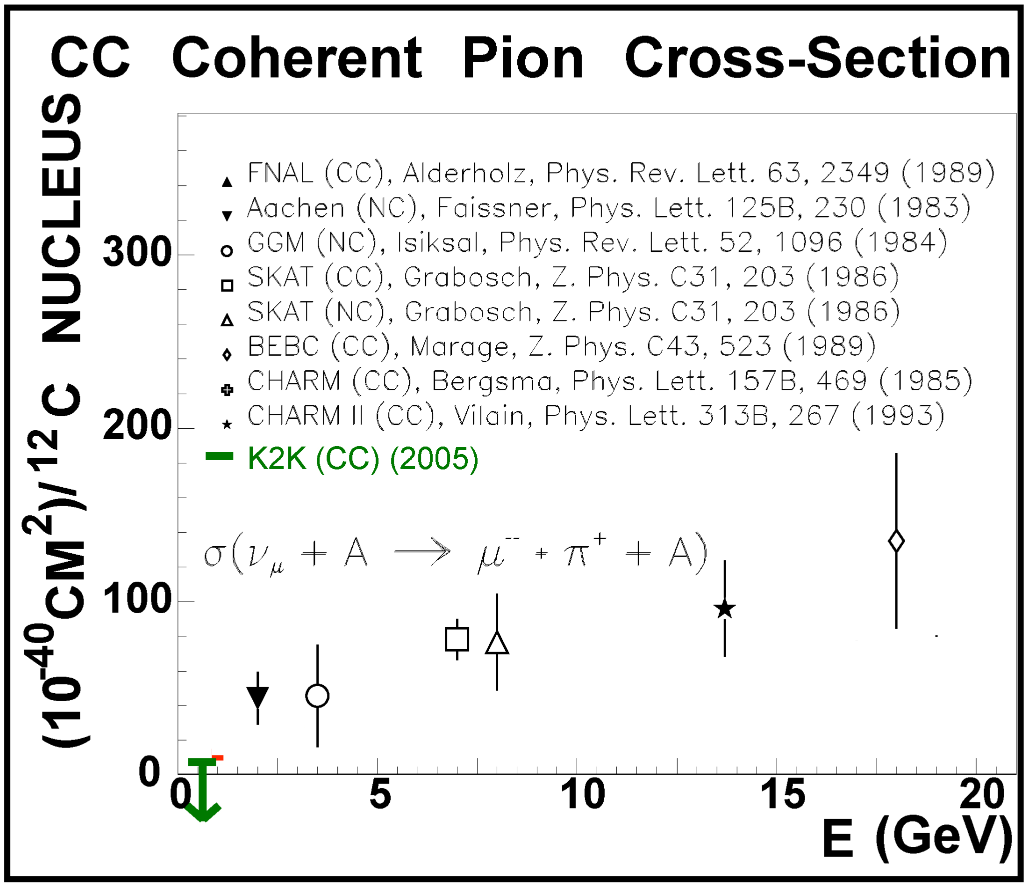
But initial observation is consistent with no coherent production



Under study!

K2K observed the same thing!
….No evidence
for coherent production





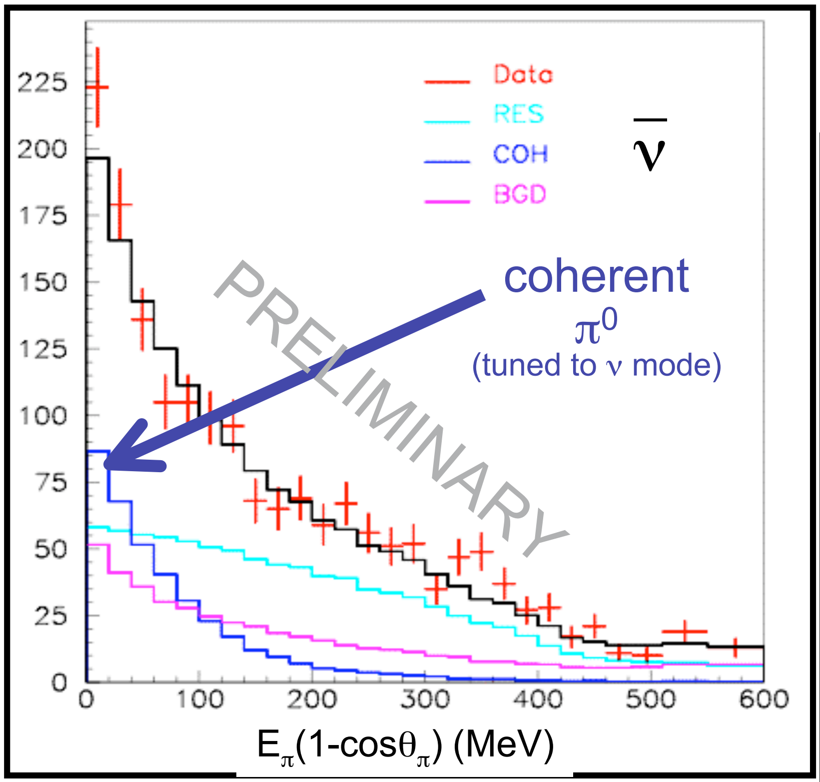
A big surprise because
high energy (>2 GeV)
experiments have
seen clear evidence!

This low energy cut-off
is challenge to the theory!

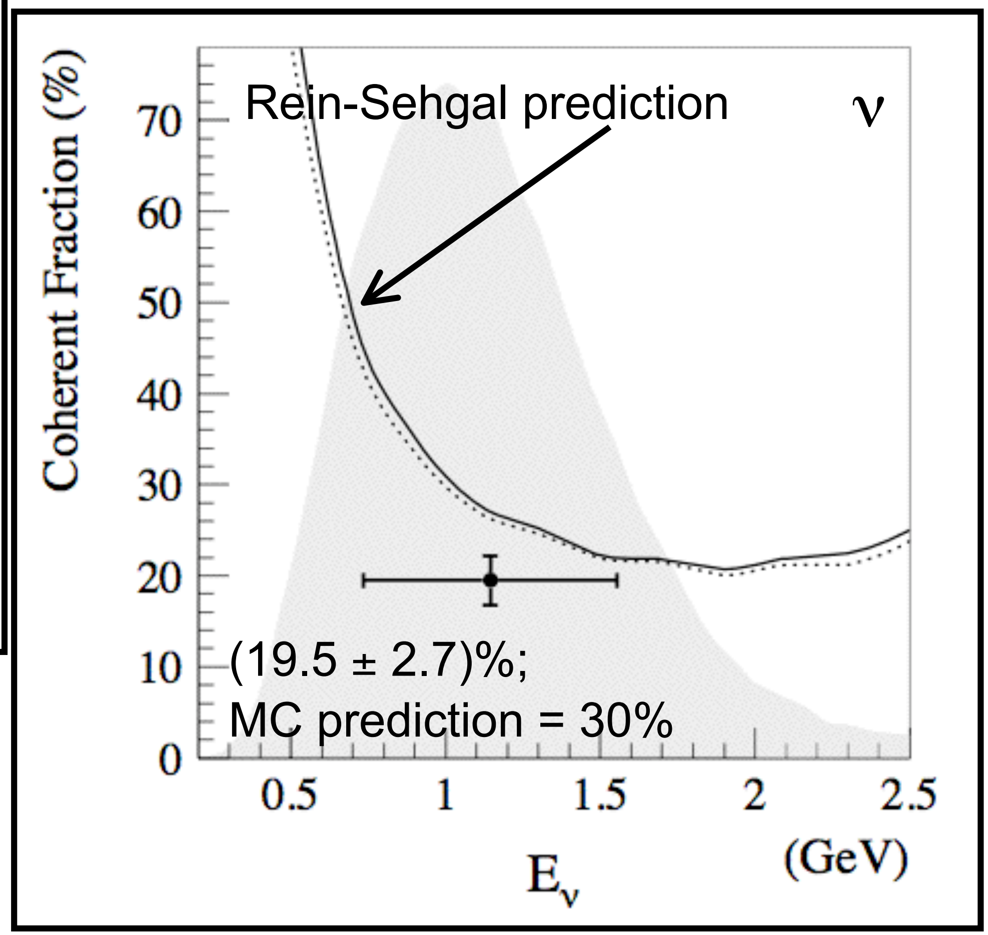
A second challenge to the theory….

At low energies (<2 GeV) there is clear evidence for NCπ0 coherent production from MiniBooNE

!

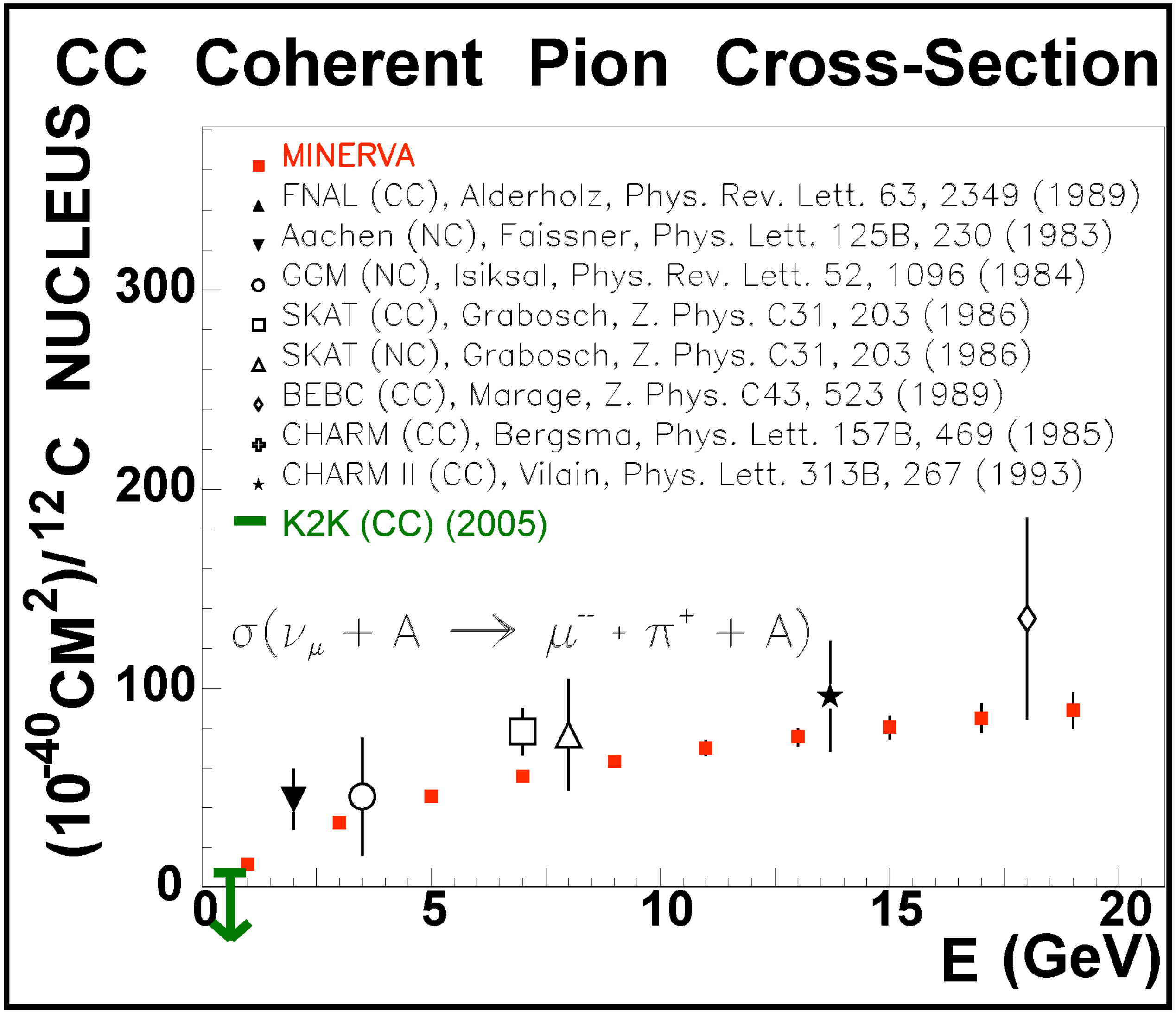


arXiv: 0803.3423, accepted by Phy. Lett. B



One would naively expect a connection between coherent CCπ+ and NCπ0 !

More information on the CCπ+ coherent mystery will come from the Minerva experiment

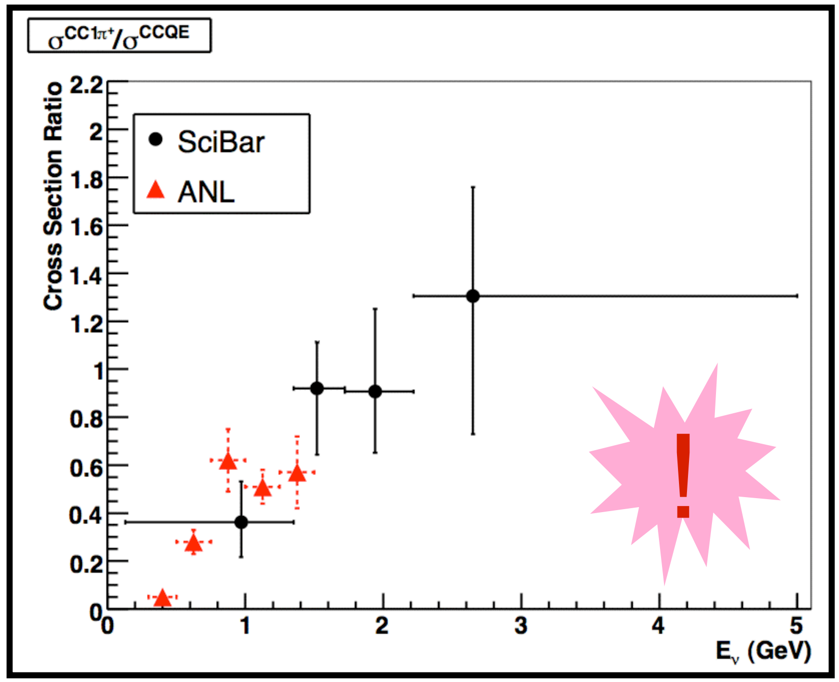


In the meantime:
A new measurement of total CCπ+ production from K2K

$$\sigma_{CC\ \pi+}/\sigma_{QE} = 0.734 \pm 0.086\,(\text{fit})\ {}^{+\,0.076}_{-\,0.103}(\text{nucl})\ {}^{+\,0.079}_{-\,0.073}(\text{syst})$$

(submitted to archive this month!
arXiv:0805.0186)

- consistent with ANL (1982, D_2)
- 20% measurement of σ ratio
- 1st published measurement of such a ratio on carbon target

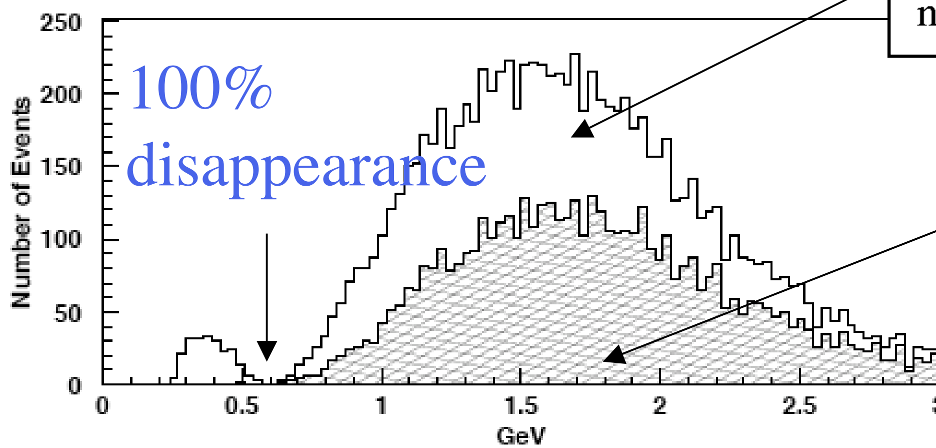


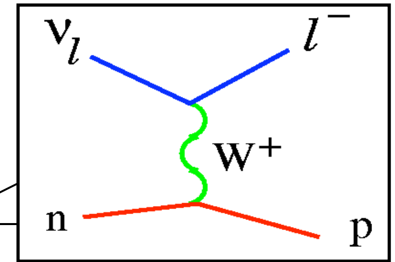
Watch for new results
on this ratio from MiniBooNE
at ICHEP 2008 (July)

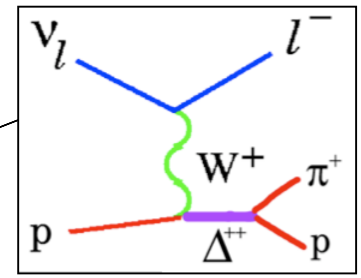
This matters a lot to upcoming oscillation experiments like T2K!

Here are MC events generated with the K2K flux.
with an an atmospheric osc signal

True events

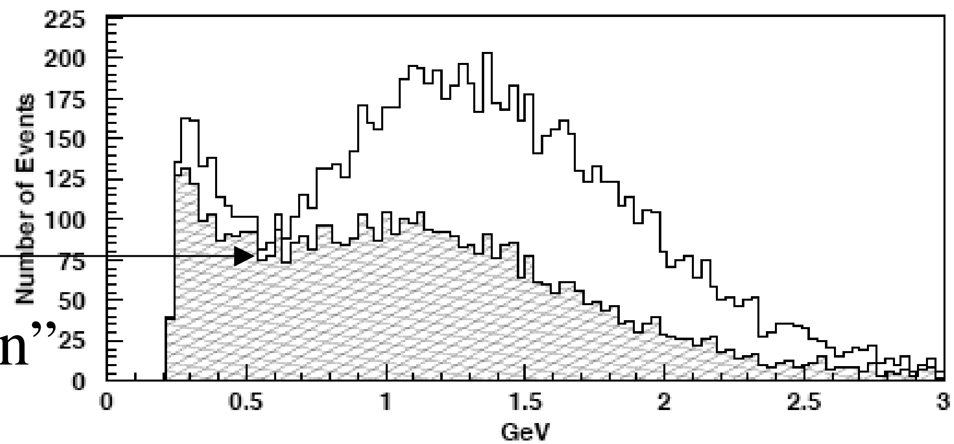






(and multi-pi)

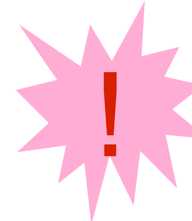
Reconstructed events

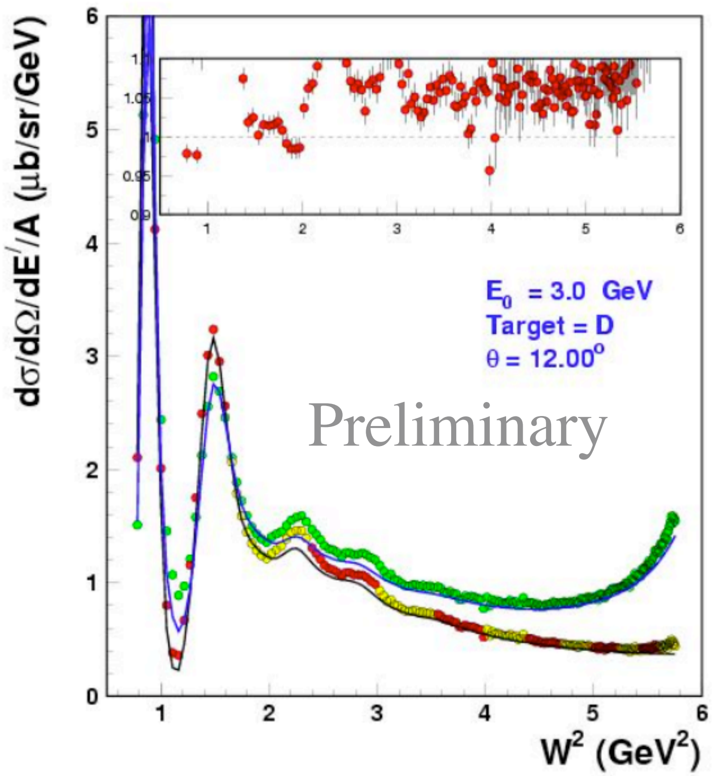


single and multi-pi "fills in" the gap!

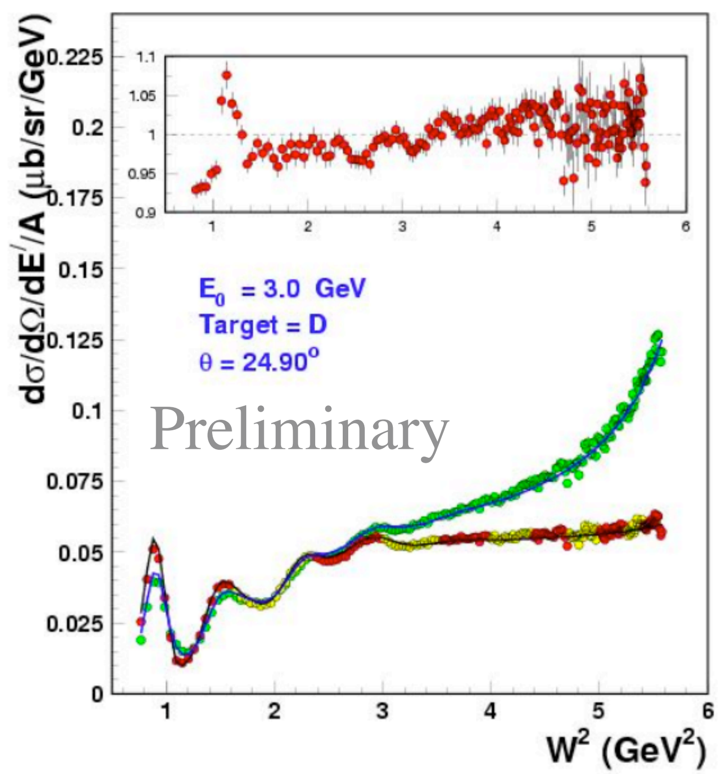
From Walters, hep-ex/0709.3616

Plays well with JLab!



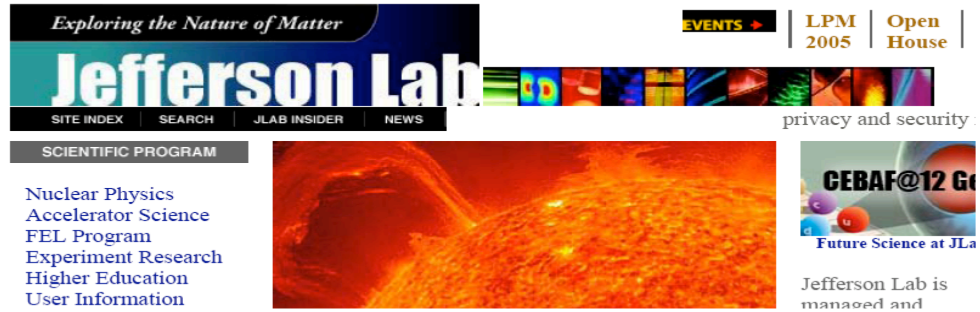


Mapping the resonance region in eD scattering from the Jupiter Expt!



And many other complementary measurements!

ν ♥ e



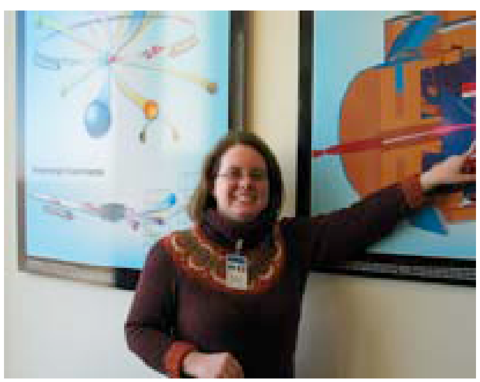
Neutrino Physics Comes to JLab

The inner workings of the sun, the mysteries of dark matter and dark energy and the structure of the early universe all may be unlocked by one cosmic key: neutrinos. Now, new research carried out in Jefferson ...erimental Hall C may help provide insight ...inos, the force that governs their behavior ...isingly, the structure of the nucleus of the atom.

Fermilab Today

Nuclear Option: MINERvA Attracts Nuclear Physicists

This is the fourth article in a series on the MINERvA neutrino experiment.



"MINERvA offers us the possibility of making a bridge in our understanding between the longer distance-scale properties of the nuclear force--responsible for the properties of nuclei--and the very short-distance scales explored in particle physics," says Ransome. "And this intermediate distance scale is of great interest to both communities."

A really great partnership that we hope will continue!

Part III

And the Future!

Because there is more to neutrinos….

A Tevatron-based Program

A Brief History…

The idea has been around for some time,

The call from the Steering Committee for "near term experiments that can be supported by an evolution of the Fermilab accelerator complex" caused the idea to gel.

The concept was endorsed by the Steering Committee:

[An] experiment with an 800 GeV proton beam would impose approximately a five percent tax on NuMI for both Project X and SNuMI. Proton-source upgrades, particularly Project X, make possible a stronger neutrino-science program.

FNAL Steering Group seeks input from HEP community

Director Pier Oddone has charged Deputy Director Young-Kee Kim to lead a Steering Group to develop a strategic roadmap for the accelerator-based HEP physics program at Fermilab (see Director's Corner, Fermilab Today, April 17, 2007). The roadmap will outline discovery opportunities during the period before ILC construction can begin, while supporting the international R&D and engineering design for as early a start of the ILC as possible. The Steering Group, consisting of members of the US HEP community and Laboratory staff, will report to Director Oddone by August 1.

The Steering Group would like to solicit input from the HEP community as widely as possible. As part of this effort, Kim has been meeting with collaborations of experiments at Fermilab, will give a report on the Steering group's work at the Fermilab and SLAC Users Meetings on June 6 and June 7, respectively, and will conduct Town Hall meetings on the same days. To provide input, please email Kim a note or a letter with your thoughts.

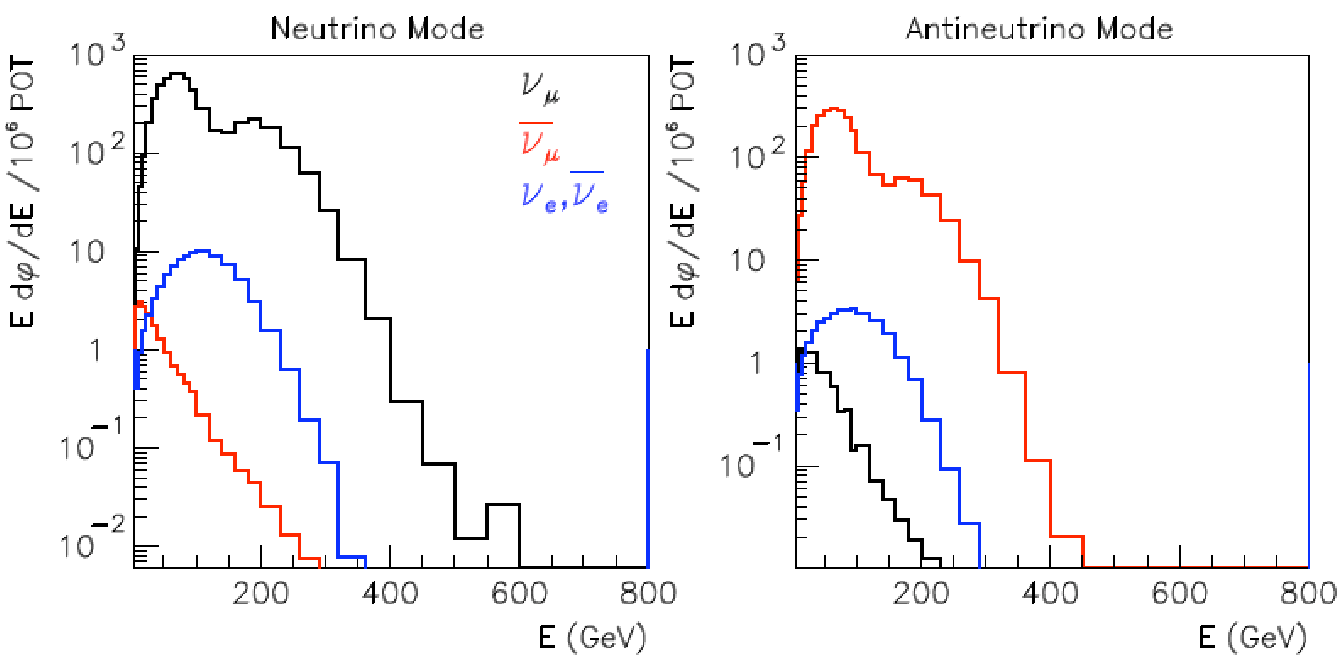
The Steering Group would also like to hear ideas from the community on near-term experiments that can be supported by an evolution of the Fermilab accelerator complex. If you have suggestions, please write up a single-page sketch consisting of the physics case, back-of-envelope discussion of accelerator requirements, and a brief detector description. Please send your input by Monday, June 11.

You can find the charge, membership and activities of the Steering Group here.

The 800 GeV Neutrino Program can provide two beams…

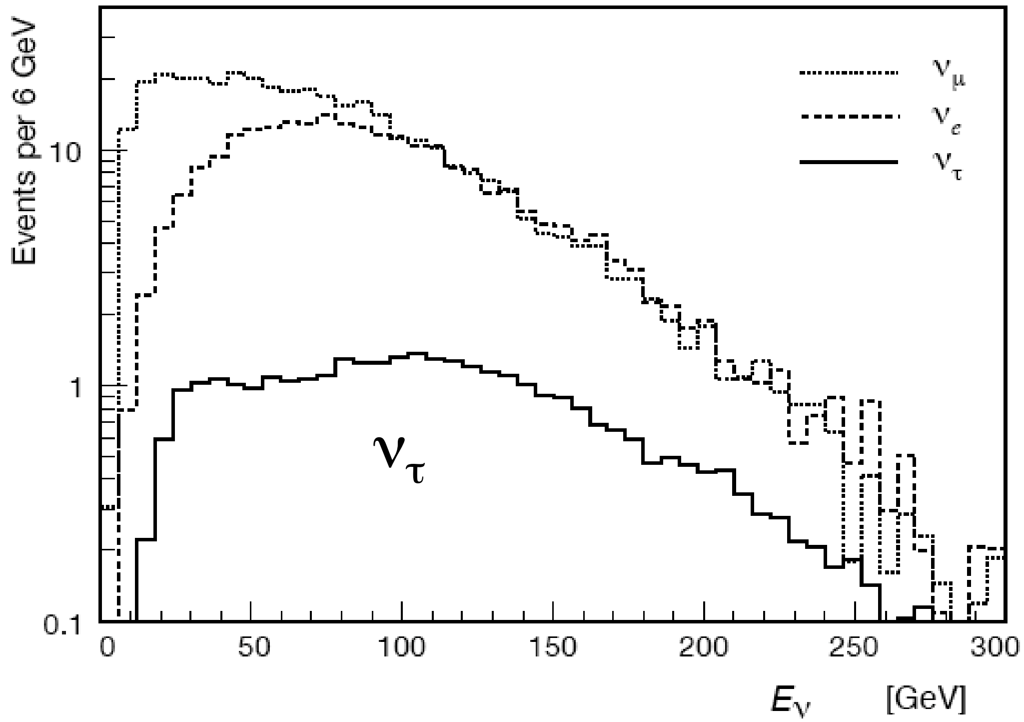
Beam 1:

Uniquely high energy, and low background,
produced using a sign-selected quad-triplet



Beam 2:

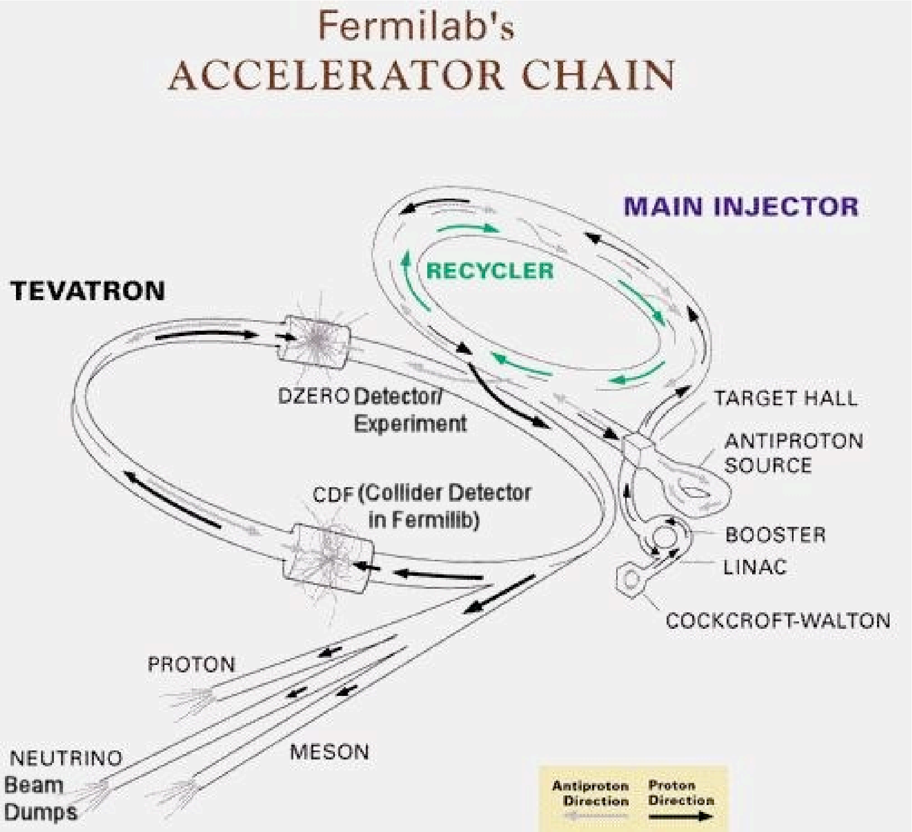
A beam dump flux:



Uniquely enriched in ν_τ's which are above threshold for CCQE

5×10^{19} POT/year

Requires upgrades
to the Tevatron!



$15M/year to run

Two useful publicly-available memos:

http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=2222
http://beamdocs.fnal.gov/AD-public/DocDB/ShowDocument?docid=2849

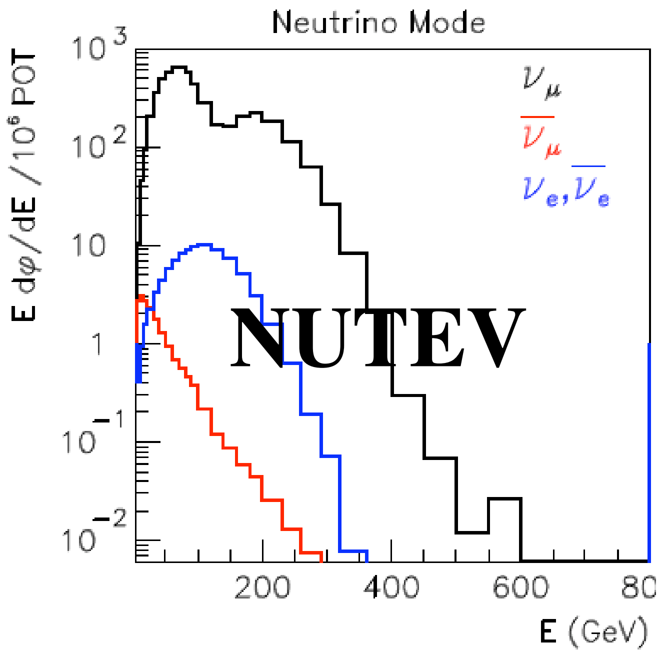
A suite of interesting experiments:

- NuSOnG
- A small ν_τ experiment to obtain ×100 DoNuT statistics
- A large (~5kt) magnetized LAr detector for 1E6 ν_τ events and neutrino factory measurements
- A small dedicated search for neutrissimos (moderately-heavy neutral heavy leptons)
- A high resolution neutrino scattering experiment to study charm and QCD (HiResMuNu)

None of these experiments can be done anywhere else.

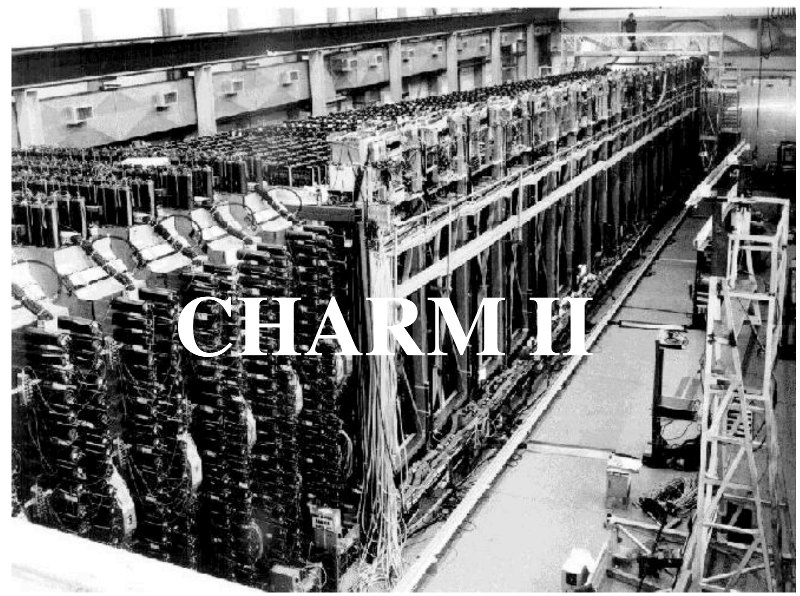
This program is unique to Fermilab.

NuSOnG: Neutrino Scattering On Glass



High energy,
very pure beam
(×20 POT)

+



Fine-grained,
massive detector
(×6 mass)

1.5E20 POT in ν , 0.5E20 POT in $\bar{\nu}$

High Statistics!

Process	Rate	Physics	
$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ **[IMD]** $\bar{\nu}_\mu + e^- \rightarrow \mu^- + \bar{\nu}_e$	**700k** **0**	**normalization, "WSIMD", non-standard interactions**	40x CHARM II
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ **[ES]** $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$	**75k** **7k**	**new "heavy" physics (Z', ν mixing with heavy singlets), new "light" physics, modified couplings, $\sin^2\theta_w$,** ρ, R-parity, extended Higgs	20x CHARM II
$\nu_\mu + q \rightarrow \nu_\mu + X$ **[DIS]** $\bar{\nu}_\mu + q \rightarrow \bar{\nu}_\mu + X$ $\nu_\mu + q \rightarrow \mu^- + X$ $\bar{\nu}_\mu + q \rightarrow \mu^+ + X$	**190M** **12M** **600M** **33M**	ν-q non-standard interactions, **$\sin^2\theta_w$,** ΔxF_3, F_2, isospin violation, hevy quarks, nuclear effects	100x NuTeV
decays in low density decay regions	***60??***	**new long-lived heavy neutral particles**	30x NuTeV

As many thesis topics as I can type in 5 minutes…

Electroweak!

1. **The weak mixing angle meas[illegible] from neutrino-electron scattering**
2. **The weak mixing angle m[illegible] from neutrino-quark scattering**
3. **New physics limits pro[illegible]ough coupling to the Z**
4. **New physics limits f[illegible] inverse muon decay cross section**
5. **Cross section mea[illegible]ent of neutrino and antineutrino electron scattering**
6. **A search for N→ [illegible] decay in the 5 GeV mass range**
7. **Searches for light mass neutrissimos**
8. **ν_μ disappearance at very high Δm^2**

Searches!

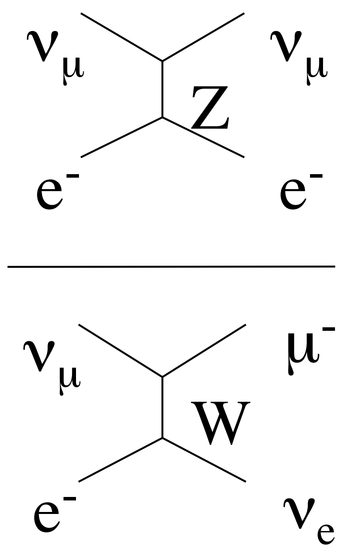
9. **A search for evidence of nonu[illegible]rity of the 3 neutrino matrix**
10. **A search for neutral heavy [illegible] in the 5 GeV mass range**
11. **Constraints on muonic p[illegible]**
12. **Measurement of the C[illegible]ross section at high energy**
13. **Measurement of the [illegible] cross section at high energy**
14. **A study of the transition from single pion to DIS production at high energy**
15. **Measurement of F_2 and xF_3 at very high statistics**
16. **Comparisons of F_2 on nuclear targets from low to high x**
17. **High precision measurement of R from neutrino scattering**

QCD!

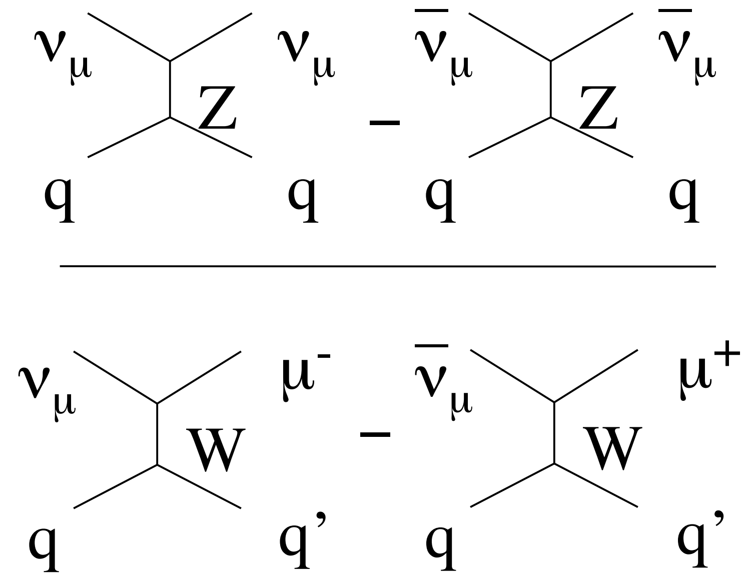
18. **Constraint on isospin violation [illegible]m ΔxF_3**
19. **Charm production in the e[illegible]arget and a measure of B_c**
20. **Measurement of the stra[illegible]and Δs from dimuon production**
21. **Measurement of the charm [illegible]a from wrong-sign single muon production in DIS**
22. **Neutrino vs antineutrino nuclear effects**

Electroweak Measurements:

New!



Purely leptonic

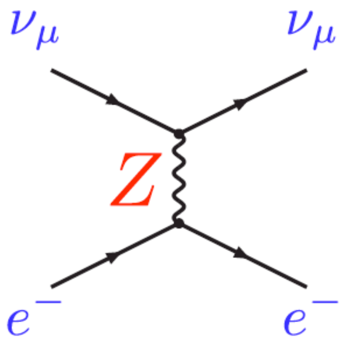


NuTeV-style
"Paschos-Wolfenstein"

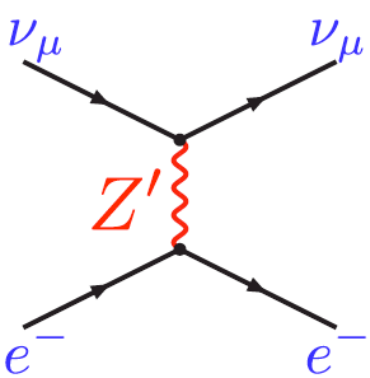
Expected errors
0.7% conservative,
0.4% best case

0.4% conservative
0.2% best case

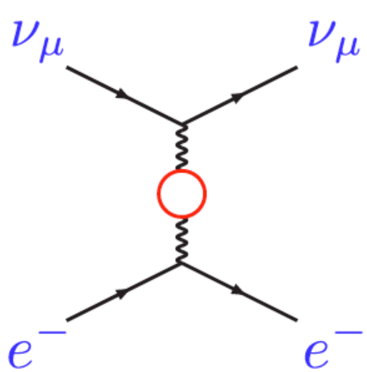
Our quoted physics case is based on the conservative estimates



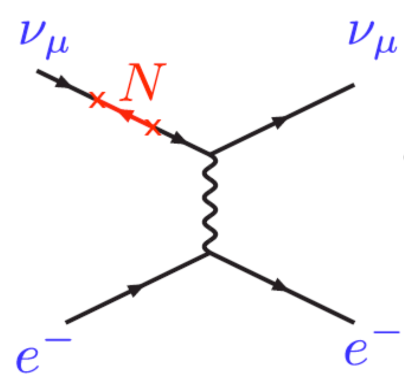
- A fantastic probe of TeV-scale (BSM) Physics!



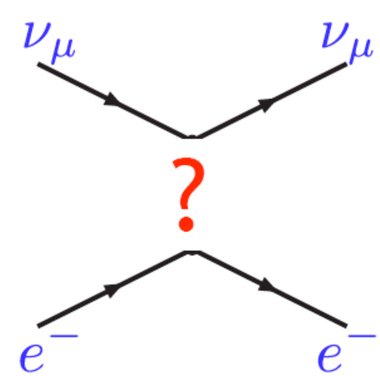
Heavy Z'



Oblique Corrections



Sterile Mixing



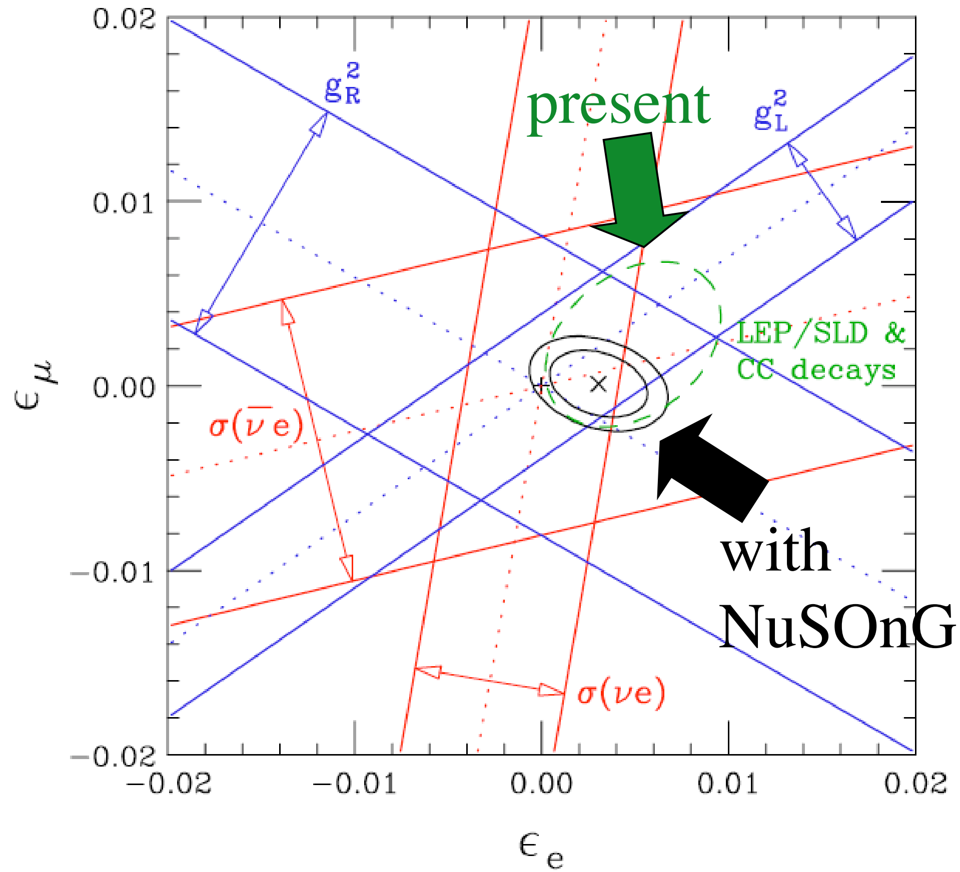
NuTeV Anomaly?

Terascale Physics Opportunities at a High Statistics, High Energy Neutrino Scattering Experiment: NuSOnG

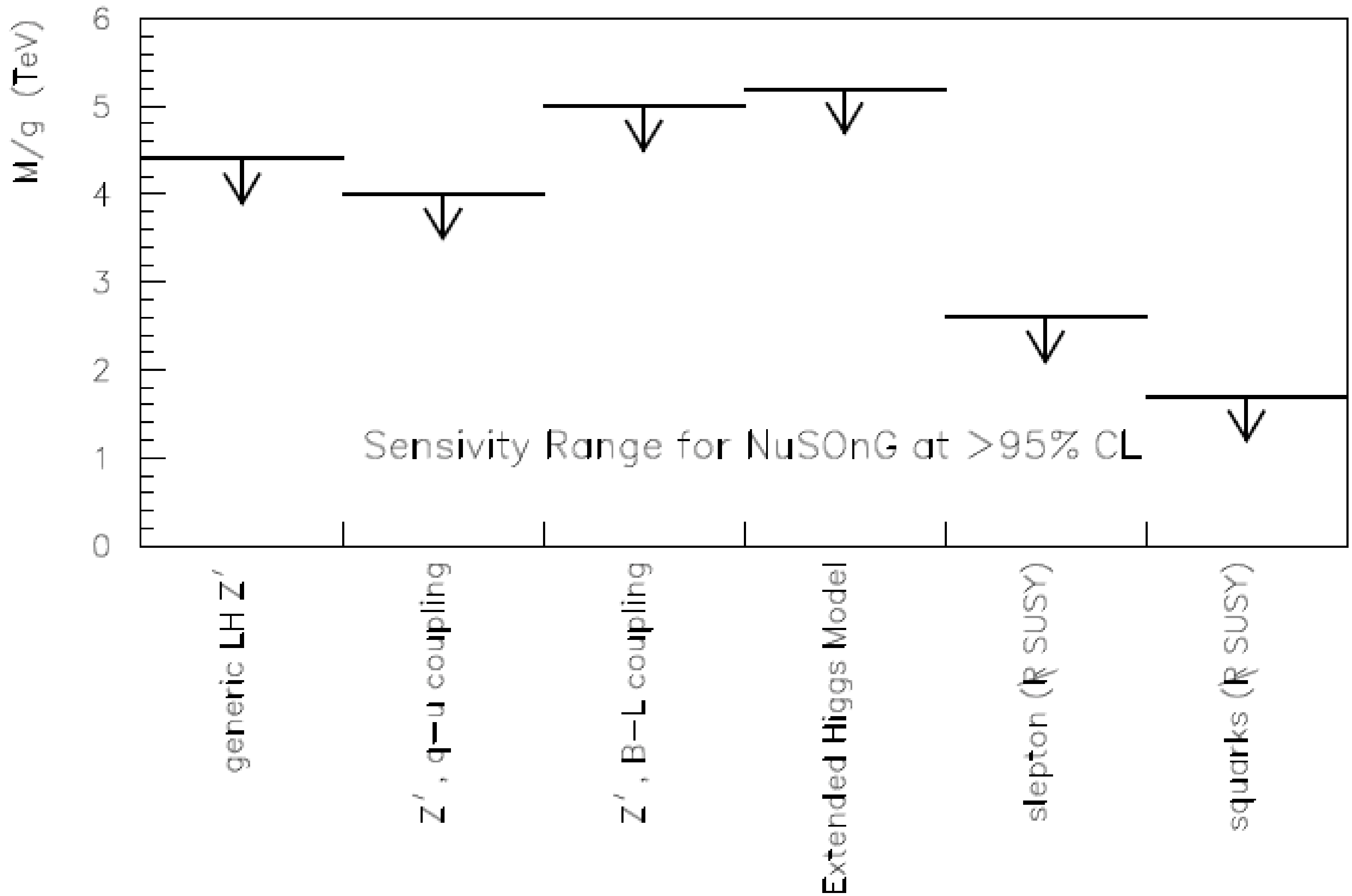
! http://arxiv.org/abs/0803.0354

Unique access to
certain new physics,
e.g. non-universal couplings

Complementary info
to LHC can help
identify new physics

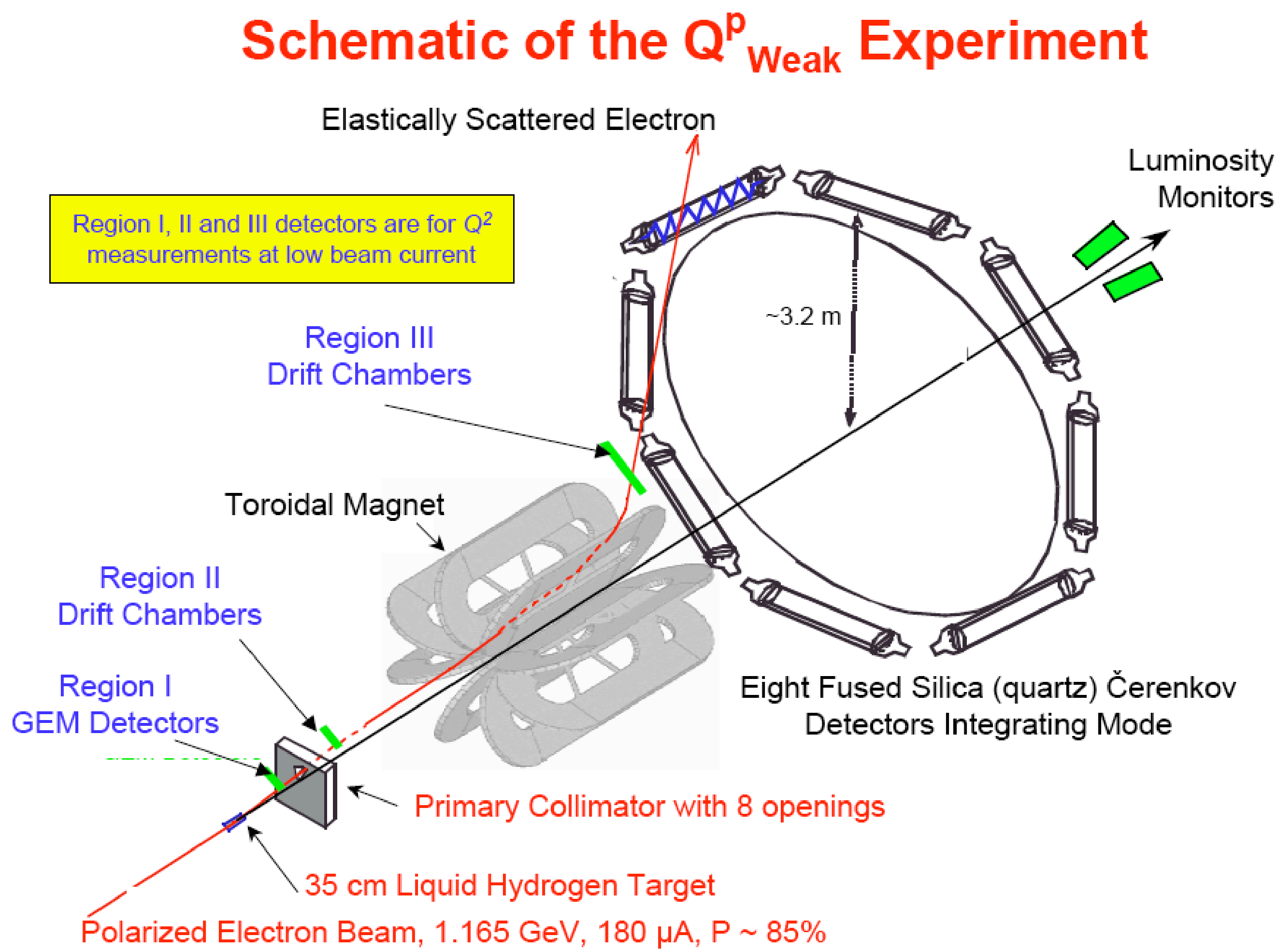


NuSOnG in the Context of Specific “Typical” Models



Z-prime Extended Higgs SUSY

Again…Plays well with JLab!

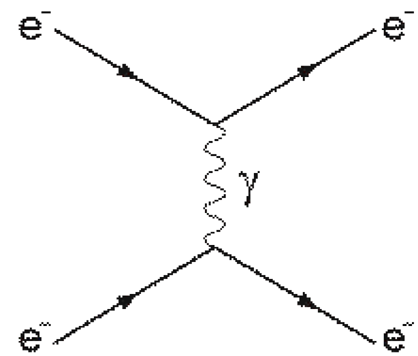


Reach of M/g ~ 2-5 TeV for parity-violating new physics,
Complements NuSOnG's search!

And then… the next generation!

ν ♥ e

"Moller Scattering"



In the 12 GeV upgrade of JLAB.
Again: this explores Parity Violating BSM physics,
with "oblique correction" (loop) sensitivity different from NuSOnG.

This is timely physics,
complementary to NuSOnG & LHC!

Fermilab is supporting a Tev-based program
beyond Neutrino Physics!

FutureTev!

Workshop at Fermilab on Sept 4-5 -- **Please Come!**

Working Wiki -- **Please Explore!**
http://www.nevis.columbia.edu/twiki/bin/view/FutureTev/WebHome

Listserv --- **Please Sign up!**
Send an e-mail message to listserv@fnal.gov
Leave the subject line blank

Type "SUBSCRIBE FUTURE_TEV_AT_FERMILAB FIRSTNAME LASTNAME"
(without the quotation marks) in the body of your message.

Conclusions


ν ♥ e
I think this is just the beginning
of a beautiful friendship.