Low Energy ν Cross Sections

Sam Zeller
LANL

Neutrino 08
May 28, 2008

- review of experimental programs at K2K, MiniBooNE, SciBooNE, and MINERνA

Neutrino Cross Sections

- over the past ~5 years, renewed interest in low energy ν cross sections for two reasons:

- advent of new high intensity ν sources has brought with it a host of new ν cross section measurement opportunities

  - taking a giant leap forward (both in terms of precision & sample sizes)
  - new data revealing some rather intriguing results!

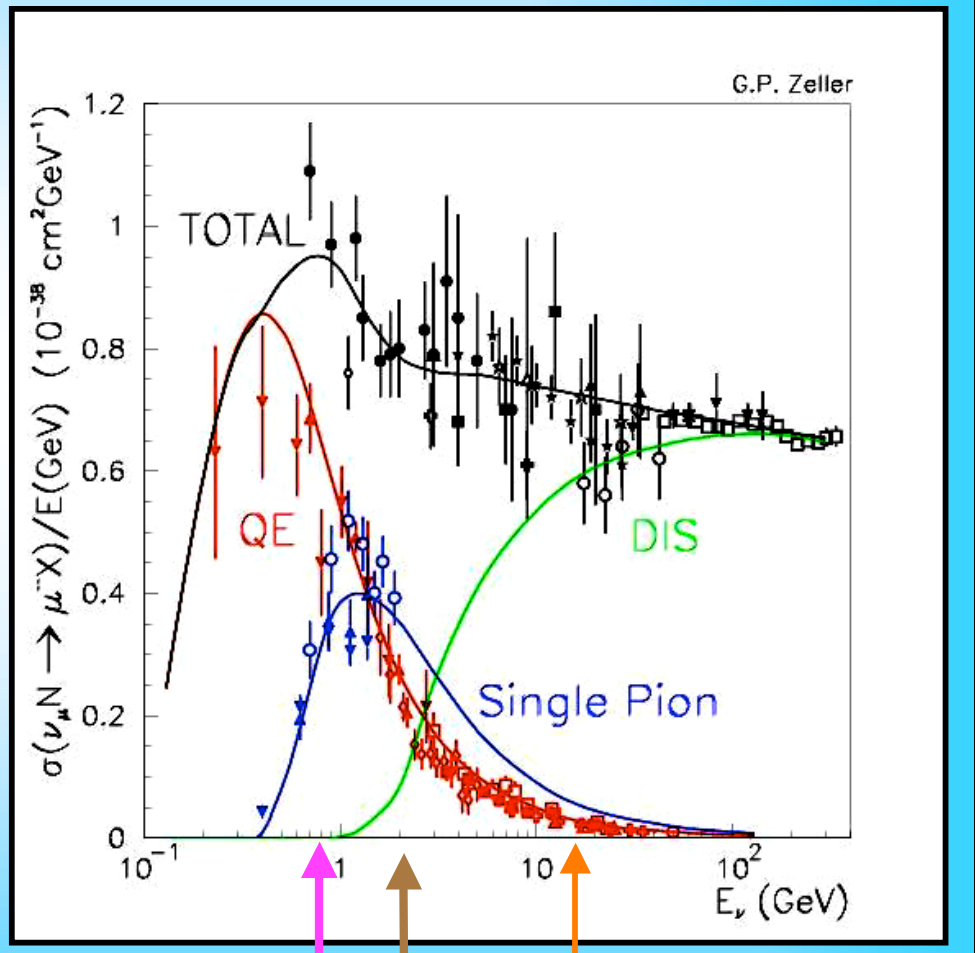
- growing realization that this is a very important ingredient to describe what seeing in ν oscillation experiments

$$N_\nu(E) \sim \varepsilon \times \Phi_\nu(E) \times \sigma_\nu(E)$$

(M. Sorel's talk you just heard) (this talk)

"Low Energy" ν Cross Sections

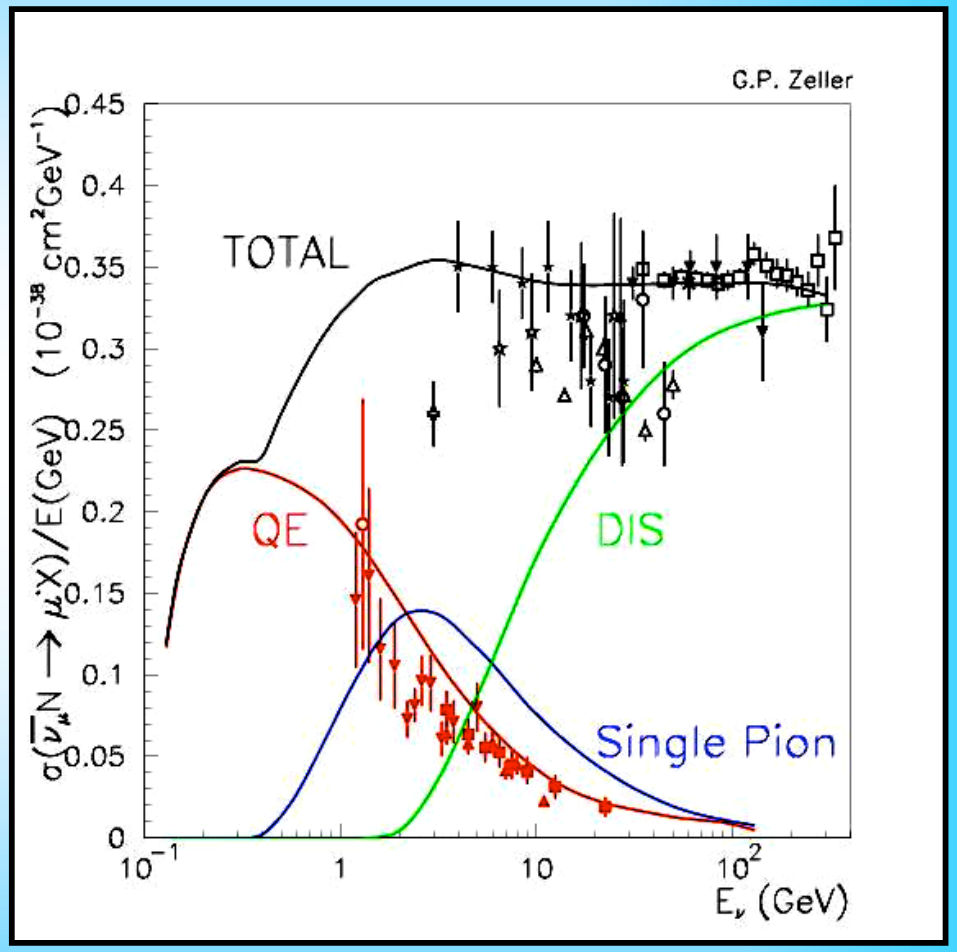
- atmospheric & accelerator-based exps (100's MeV to few-GeV)
- dominant interactions are
  QE & single pion production
  (signal) (background)
- measurements in 70s-80s
  - mostly bubble chambers
  - largely H_2, D_2
- never looked back until now
- really need improved σ_ν
  at low E especially on nuclear targets!



Antineutrino Cross Sections

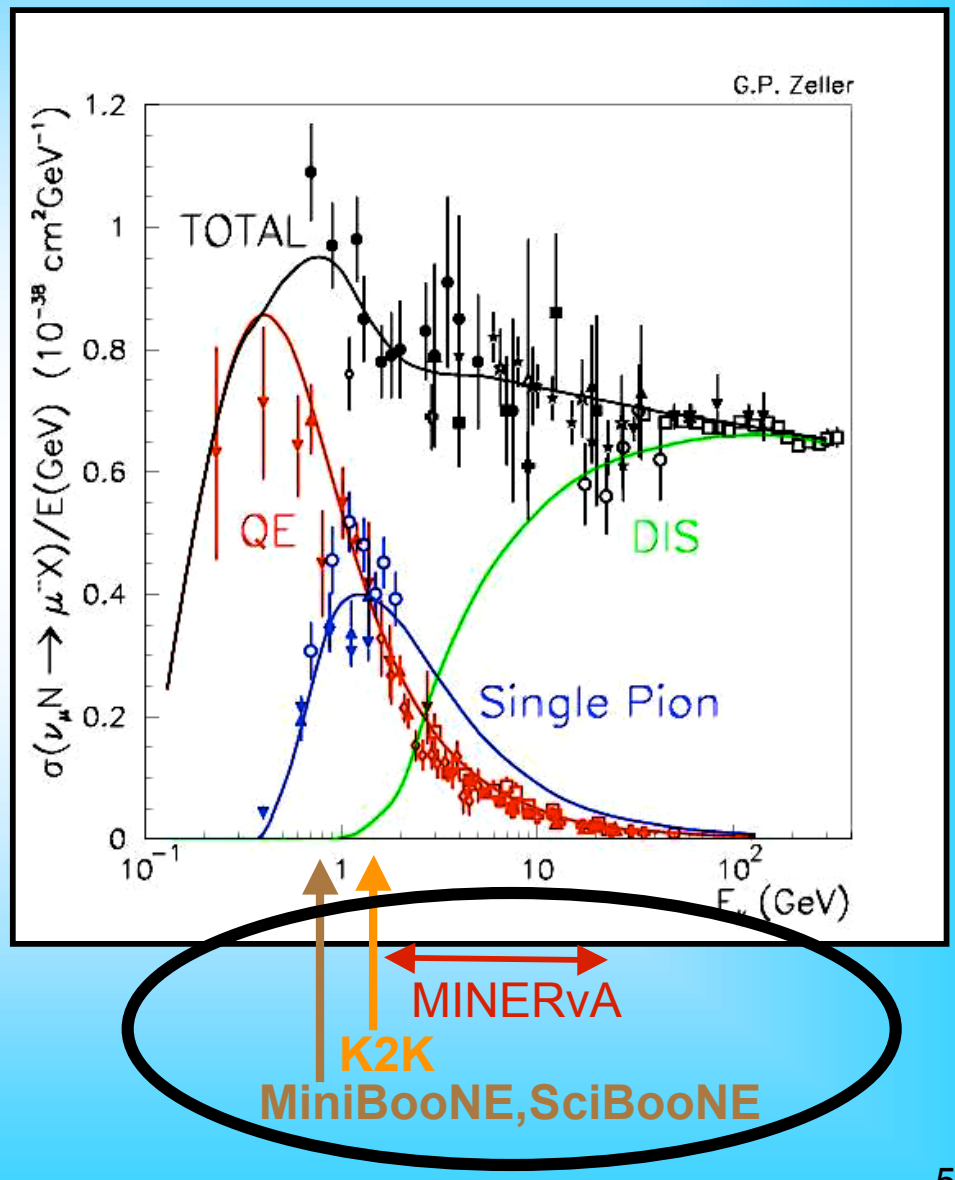
- will measure $\not{CP}$ by comparing ν vs. $\overline{\nu}$ oscillation probabilities

- would prefer not to rely on extrapolation of predictions where no existing data



- so need to repeat this program for antineutrinos as well

Good News …


G.P. Zeller
TOTAL
QE
DIS
Single Pion
$\sigma(\nu_\mu N \rightarrow \mu^- X)/E(GeV)$ $(10^{-38}\ cm^2 GeV^{-1})$
E_ν (GeV)
MINERvA
K2K
MiniBooNE,SciBooNE

New σ_ν Measurements

new ν data is (& will be) coming in from a variety of sources …

results right now

- **present**:
  - K2K (1999 - 2004)
  - MiniBooNE (2002 - present)
  - SciBooNE (2007 - present)

coming soon !

- **near future**:
  - MINERνA (2009)

together, a rather powerful ensemble of experiments (as you'll see)

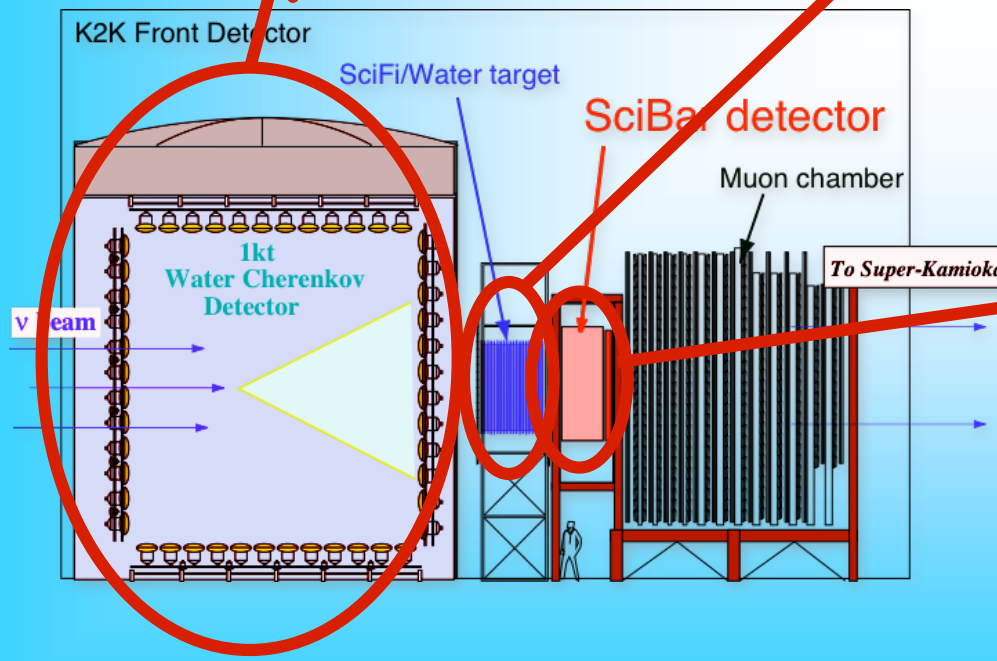
- field of low energy ν cross section physics extremely active

(>50 theory papers in past year, talk will concentrate on new exp'l results in past year)

K2K Experiment

… each detector responsible for at least one important publication in K2K …

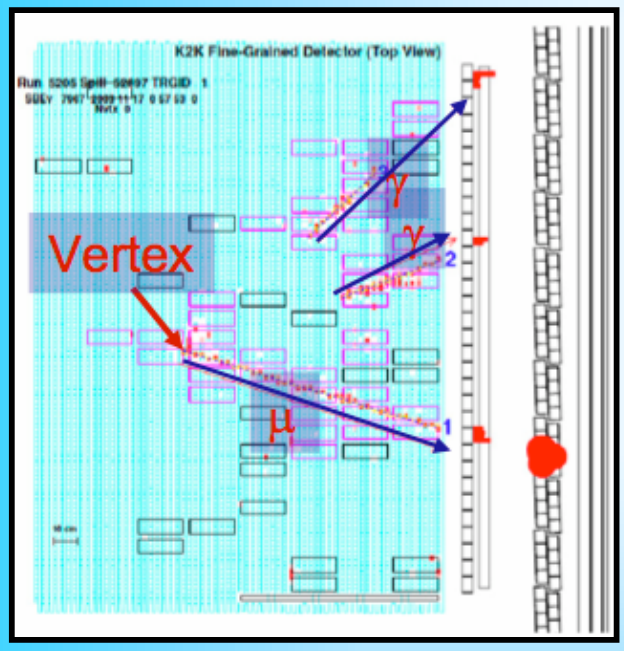
- 1kton water Cerenkov detector
  (1/50th scale miniature replica of Super-K)
- 1st meas of NC π^0 prod in H_2O
  - PLB **619**, 255 (2005) -



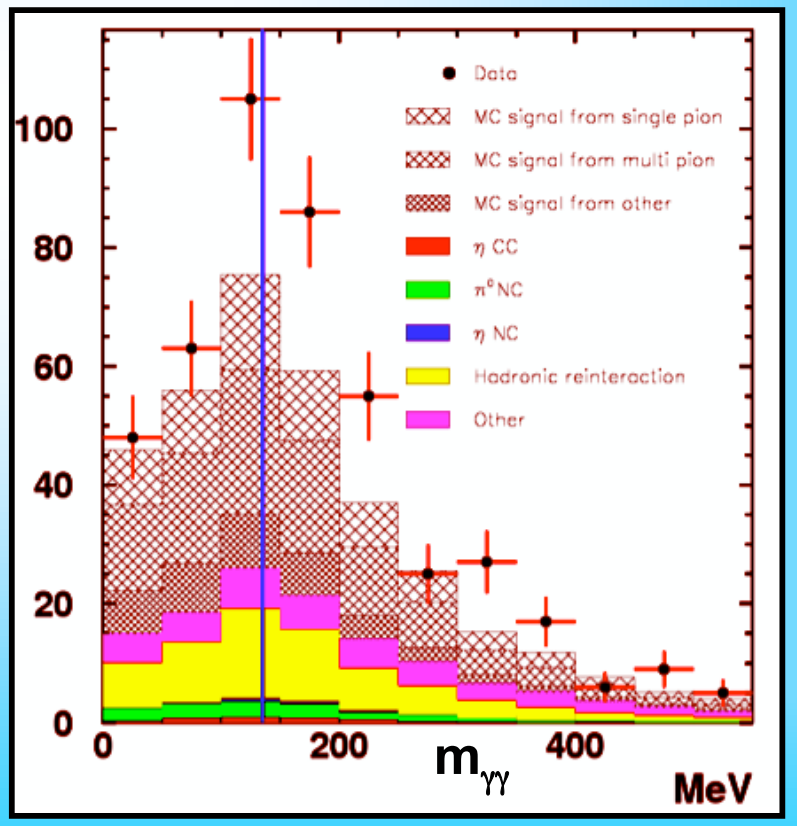
- scintillating fiber tracker
  SciFi (H_2O target)
- 1st meas of M_A^{QE} in H_2O
  - PRD **74**, 052002 (2006) -
- fully-active scintillator strip
  SciBar (C_8H_8 target)
- 1st search for CC coherent π^+ production at low energy
  - PRL **95**, 252301 (2005) -
- became part of SciBooNE!

New K2K Result: CC π^0

- new measurement of CC π^0 events from K2K SciBar (^{12}C)
- 1st time have revisited this reaction channel in ~20 years



$\nu_\mu N \rightarrow \mu^- N' \pi^0 X$



(C. Mariani)

- 479 CC π^0 events
- 59% purity, 8% ε

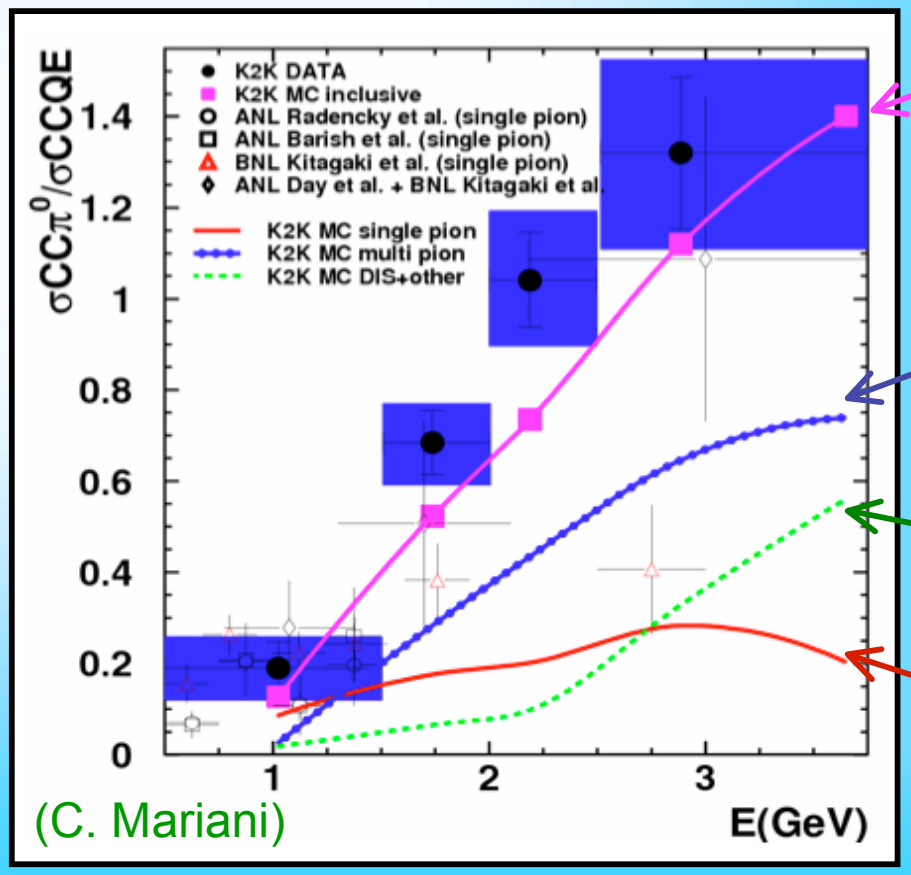
New K2K Result: CC π^0

- inclusive CC π^0/QE cross section ratio (paper in preparation)

$$\sigma_{CC\,\pi^0}/\sigma_{QE} = 0.306 \pm 0.023(\text{stat}) \,{}^{+\,0.023}_{-\,0.021}(\text{syst})$$

(10% measurement)

- rare glimpse at multi-π prod
  (not well-measured σ historically)
- ~40% higher than MC prediction
- already telling us something about the inadequacies of our multi-π predictions
  (larger effect for higher E exps)

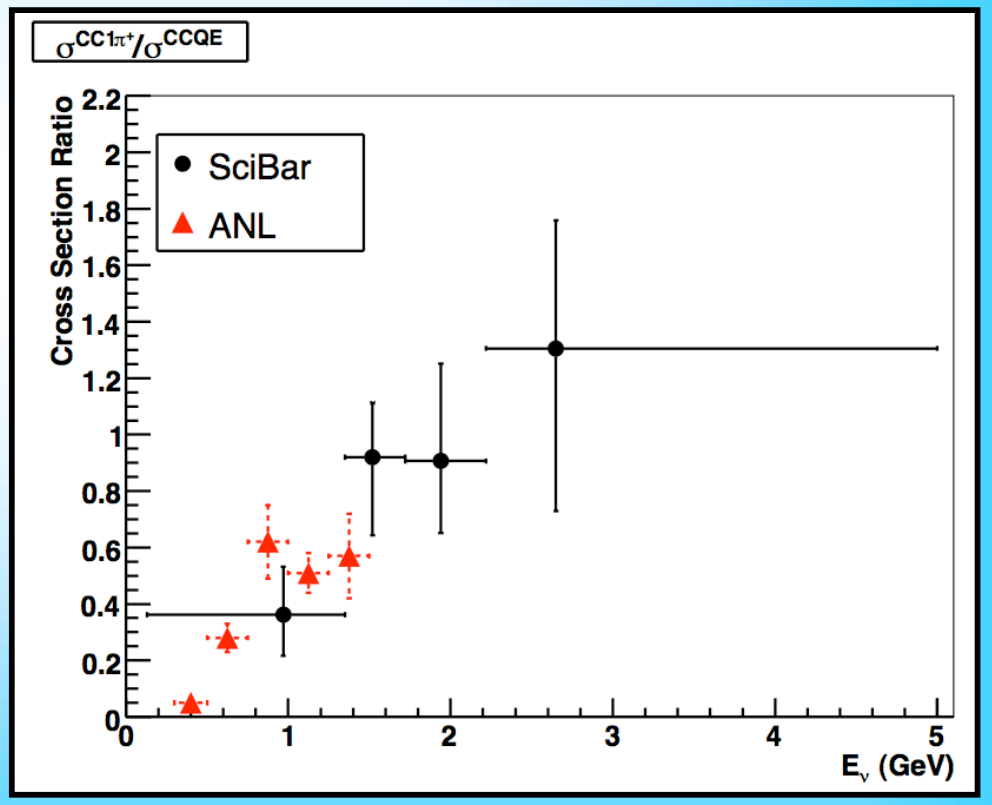


New K2K Result: CC π^+

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

(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



(important for future ν_μ disappearance exps that we start filling in this region! goal = 5% for T2K)

QE Scattering

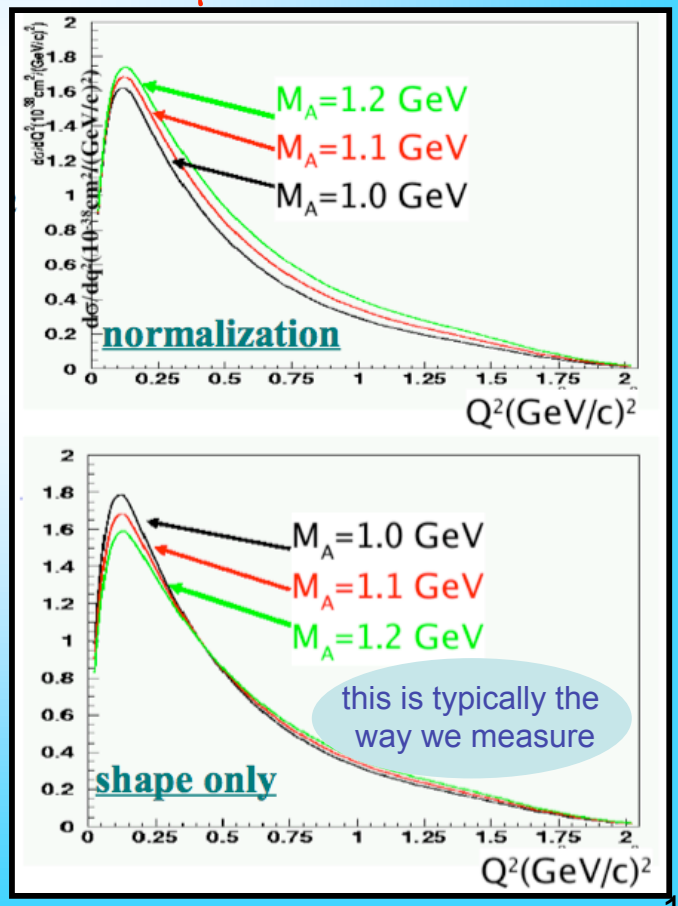
- QE scattering important because is our signal sample
  - **nuclear model**
    - experiments assume Fermi Gas model
  - **nucleon form factors**
    - vector FF well known from e^- scattering
    - axial FF from ν scattering (not as well known)

$$F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A^2)^2}$$

dipole form; fcn of single parameter
"**axial mass**", M_A = 1.03 GeV

- M_A controls normalization & Q^2 shape of QE σ (a lot of interest & attempts to re-measure)

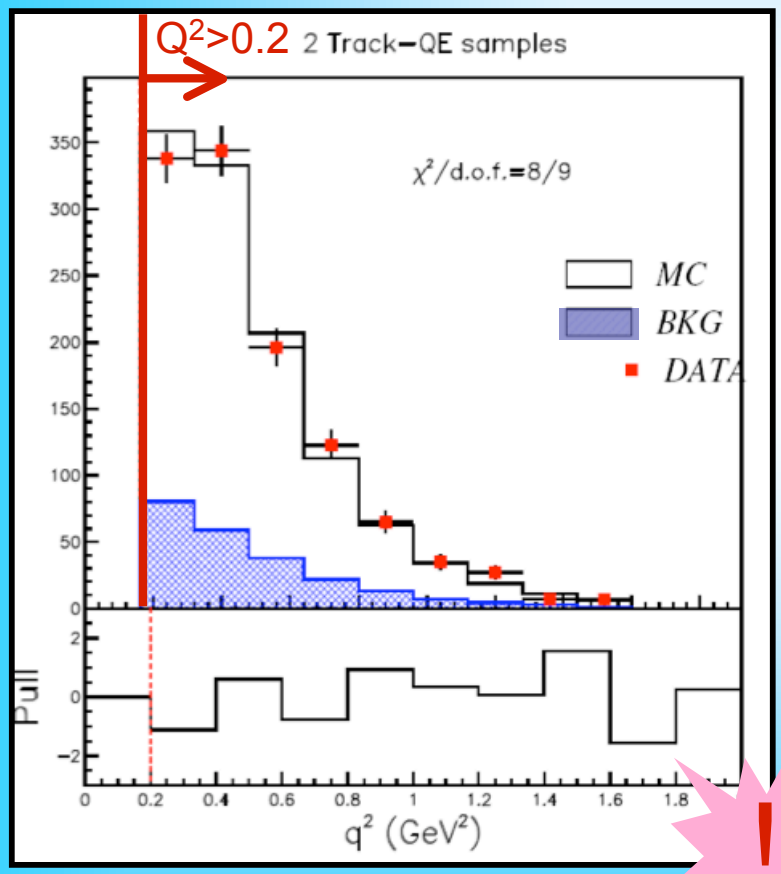
$\nu_\mu\, n \rightarrow \mu^-\, p$



(R. Gran)

New K2K Result: QE

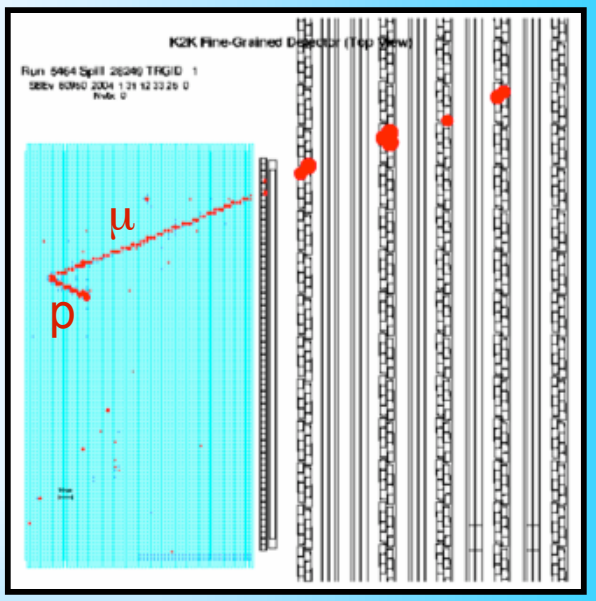
- new measurement of M_A from SciBar (^{12}C) (paper in preparation)



(F. Sanchez)

- $Q^2>0.2$ GeV^2

  (common fit technique to exclude region where nuclear effects are largest)

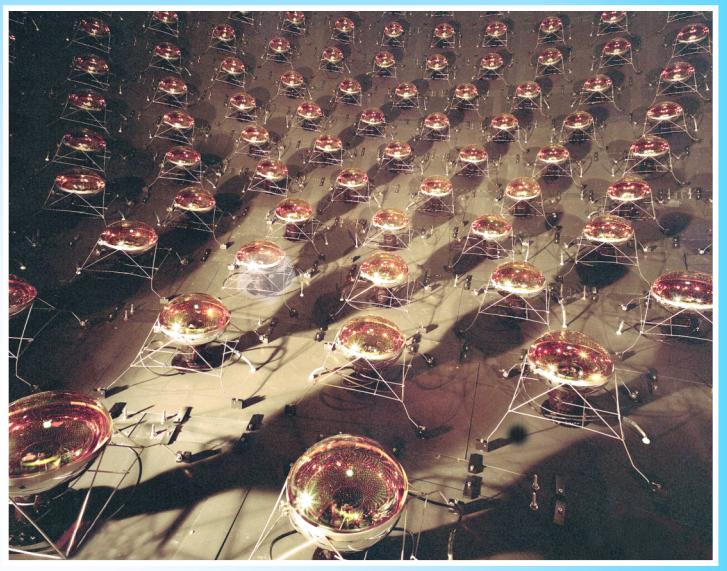


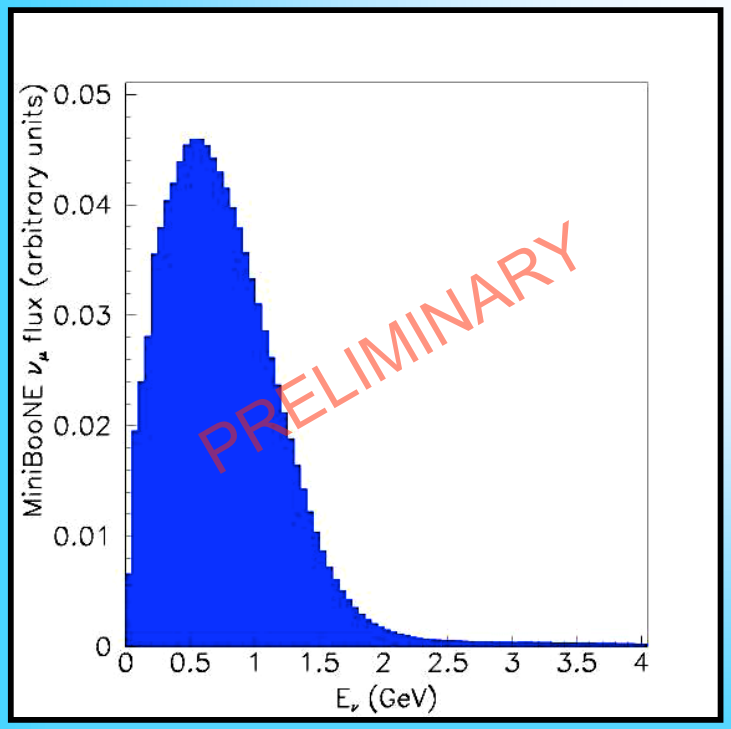
$$M_A = 1.144 \pm 0.077(fit)^{+0.078}_{-0.072}(syst.)$$

(historical M_A=1.03 GeV, will come back to this)

MiniBooNE Experiment

- single detector designed to check LSND
- FNAL BNB, $\langle E_\nu \rangle$ = 0.7 GeV

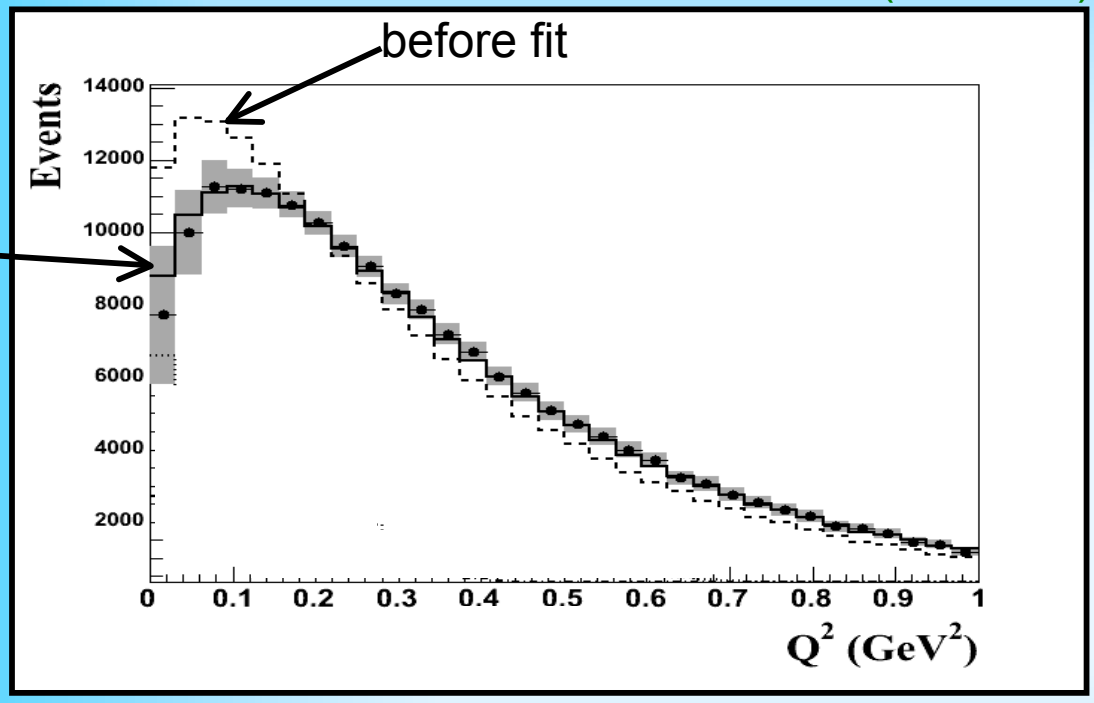


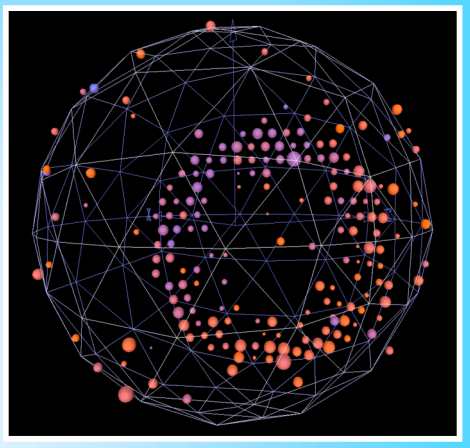


- Cerenkov detector (CH_2)
  - record size event samples in this E range
  - recent addition of new $\overline{\nu}$ data

New MiniBooNE Result: QE

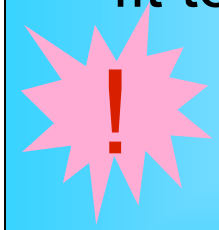
(T. Katori)





- fit to a single sample
- 193,709 ν_μ QE events
- 74% purity, 35% ε

- fit to Q^2 distribution, $Q^2>0$, carbon



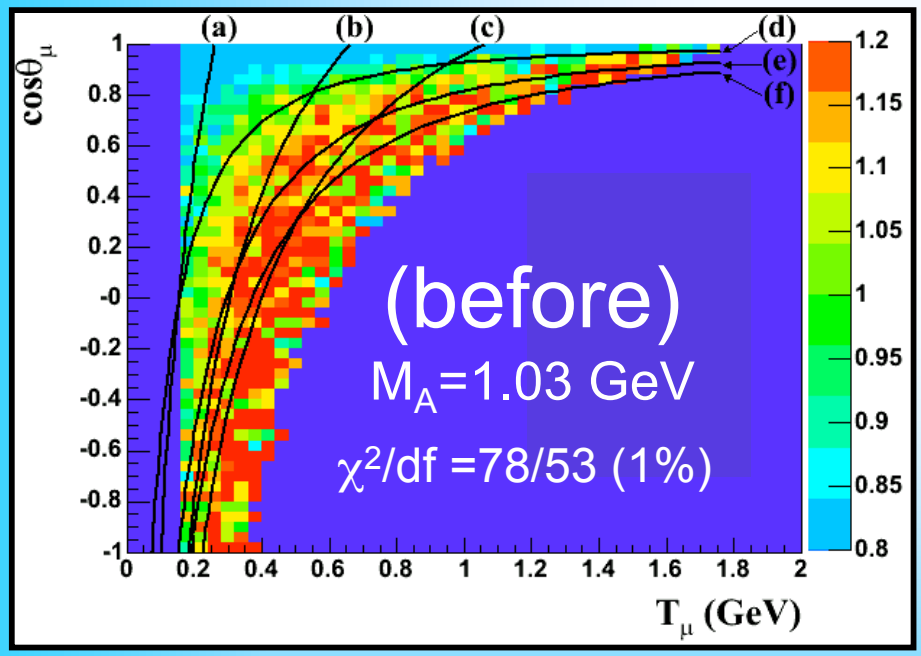
- M_A = 1.23 ± 0.20 GeV → fixes high Q^2
- κ = 1.019 ± 0.011 (Pauli blocking par) → fixes low Q^2

(PRL **100**, 032301 (2008))

New MiniBooNE Results: QE

- one of the advantages of having high stats (193k) is can check in 2D (1st time in history have looked at 2D distributions!)

past world-avg M_A & Fermi Gas model:



(T. Katori)

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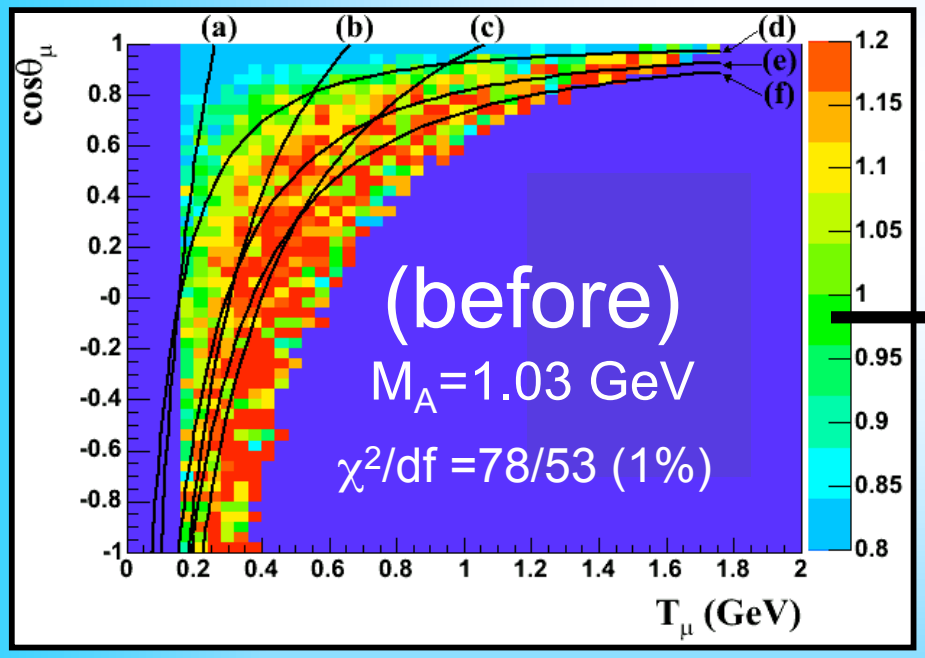
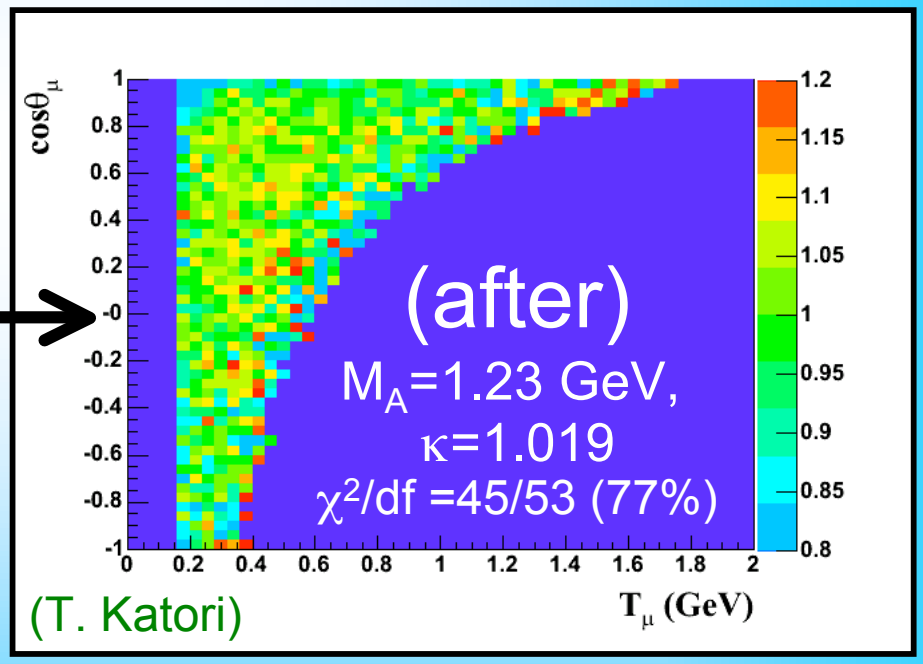
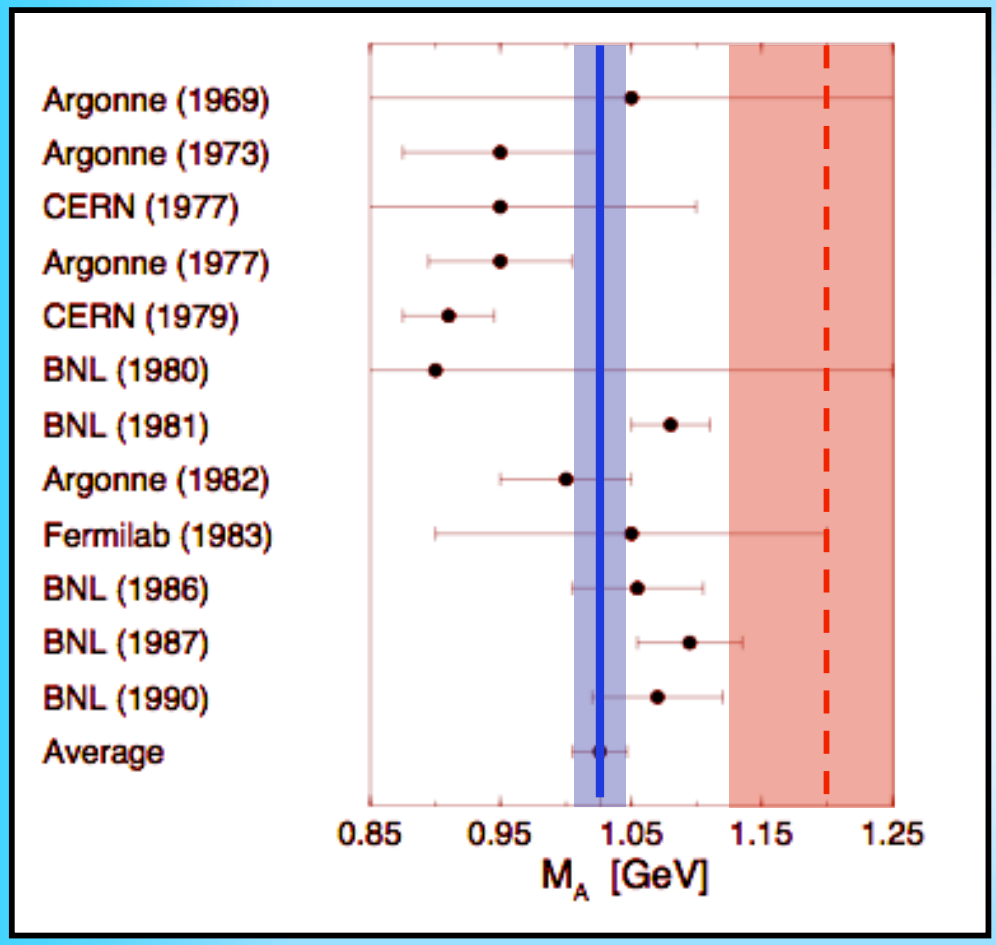


after MiniBooNE fit in Q^2 (2 pars):



- stunning agreement across entire phase space! important for MiniBooNE oscillation analysis
- since Fermi Gas model - is of broader utility … also of interest is M_A value itself …

Modern Determinations of M_A



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

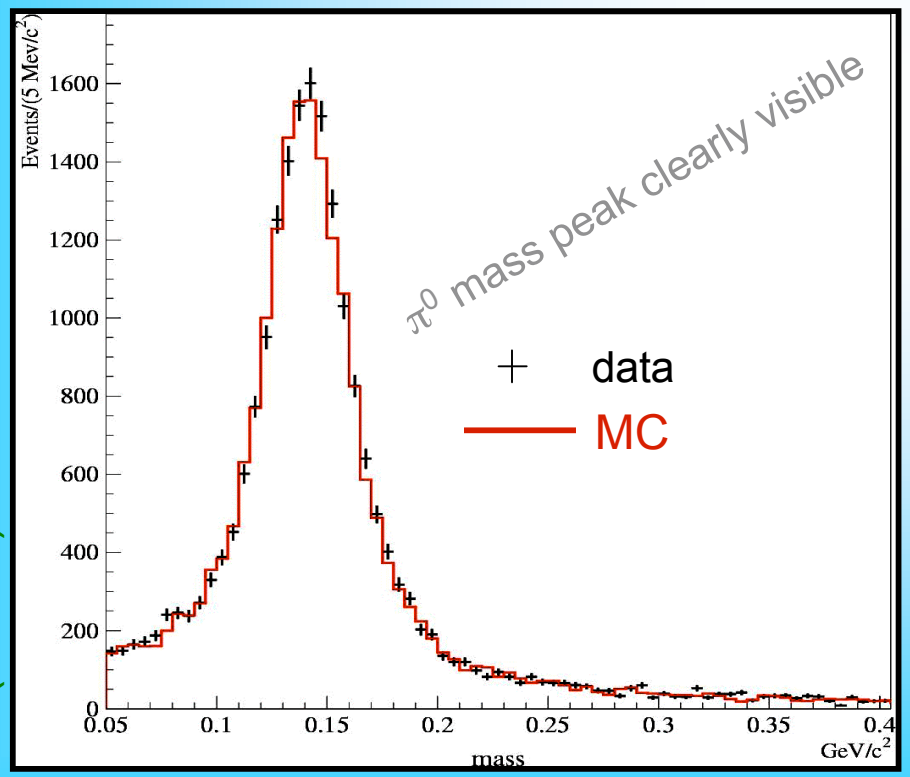
- **K2K SciFi** (^{16}O, Q^2>0.2)
  Phys. Rev. **D74**, 052002 (2006)
  M_A=1.20 ± 0.12 GeV
- **K2K SciBar** (^{12}C, Q^2>0.2)
  M_A=1.14 ± 0.11 GeV
- **MiniBooNE** (^{12}C, Q^2>0.25)
  Phys. Rev. Lett. **100**, 032301 (2008)
  M_A=1.25 ± 0.12 GeV

- new results consistent
- modern data measuring systematically higher M_A

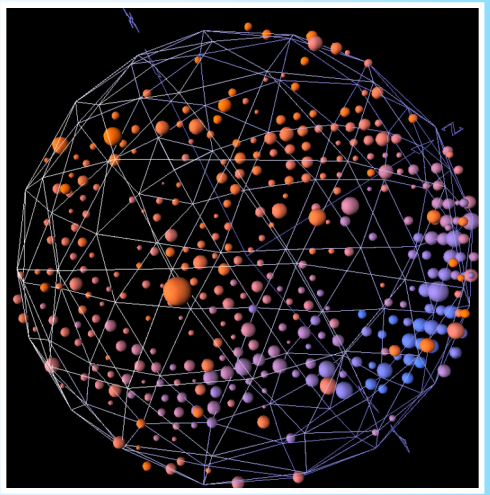
(measuring an "effective M_A"?)

New MiniBooNE Result: NC π^0

- important background for ν_e appearance searches (S. Brice's talk)
- one of benefits of large open volume (4π) Čerenkov detector is excellent π^0 containment



(J. Link)



$\pi^0 \rightarrow \gamma\gamma$

world's largest NC π^0 sample

- 28,600 ν_μ NC π^0 events
- 97% purity, 40% ε

NC π^0 Production

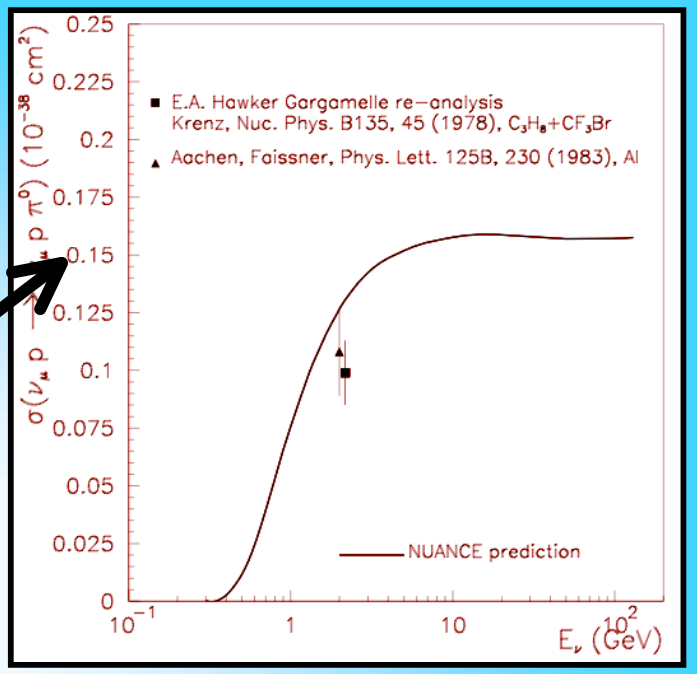
two modes of production
(both are backgrounds to ν_e appearance)

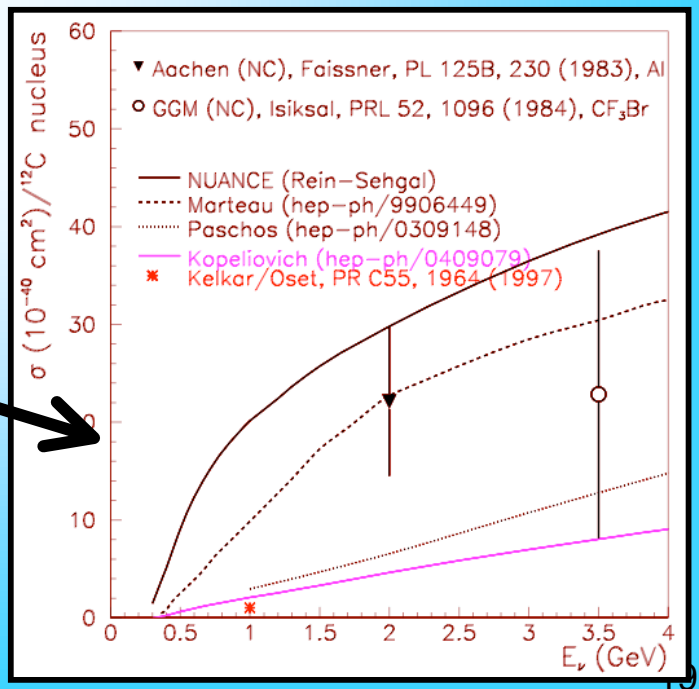
(1) **resonant π^0 production**
(ν_μ N → ν_μ Δ; Δ → N π^0)

- dominates
- 25-40% σ uncertainties

(2) **coherent π^0 production**
(ν_μ A → ν_μ A π^0)

- 100% σ uncertainty
- no existing data < 2 GeV
- very different π^0 kinematics



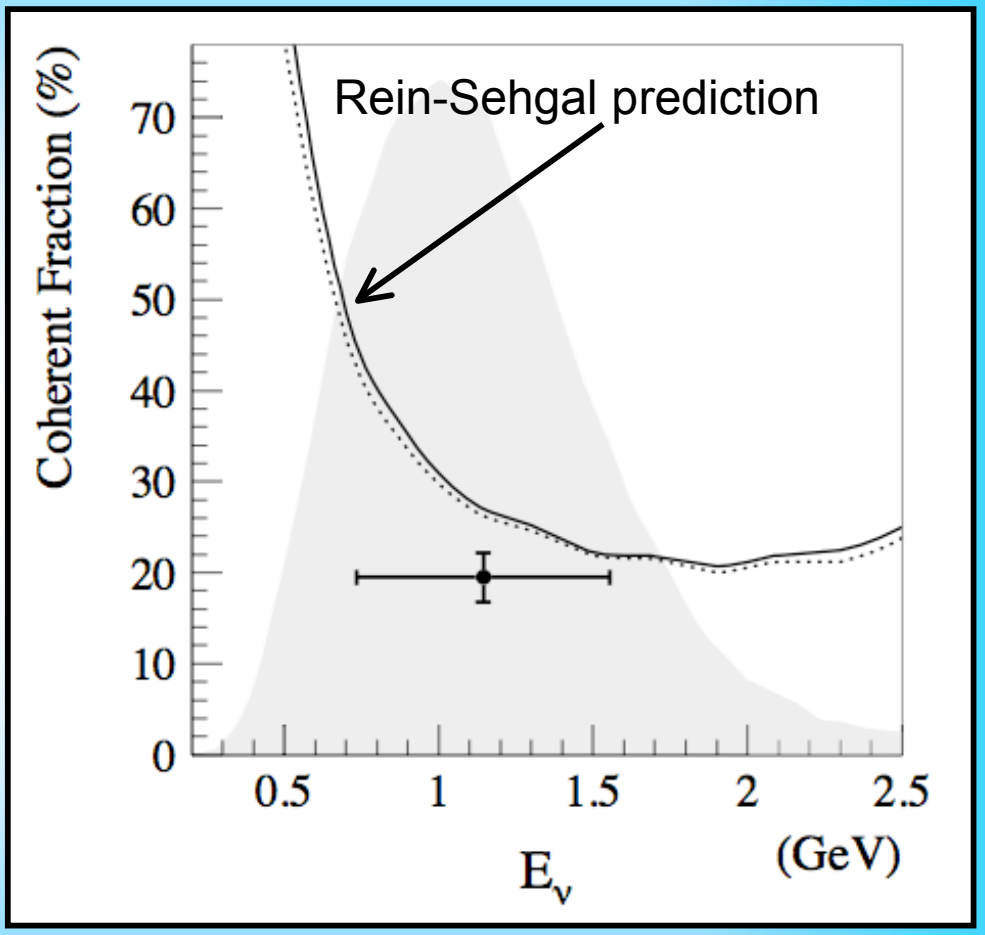


New MiniBooNE Result: NC π^0

- 1st measurement of NC coherent π^0 production at low energy ($E_\nu < 2$ GeV)

- 14% measurement
  (helped reduce uncertainties in MiniBooNE's ν_e search)

- 35% lower than most widely used model prediction
  (forced a change in bkg predictions)

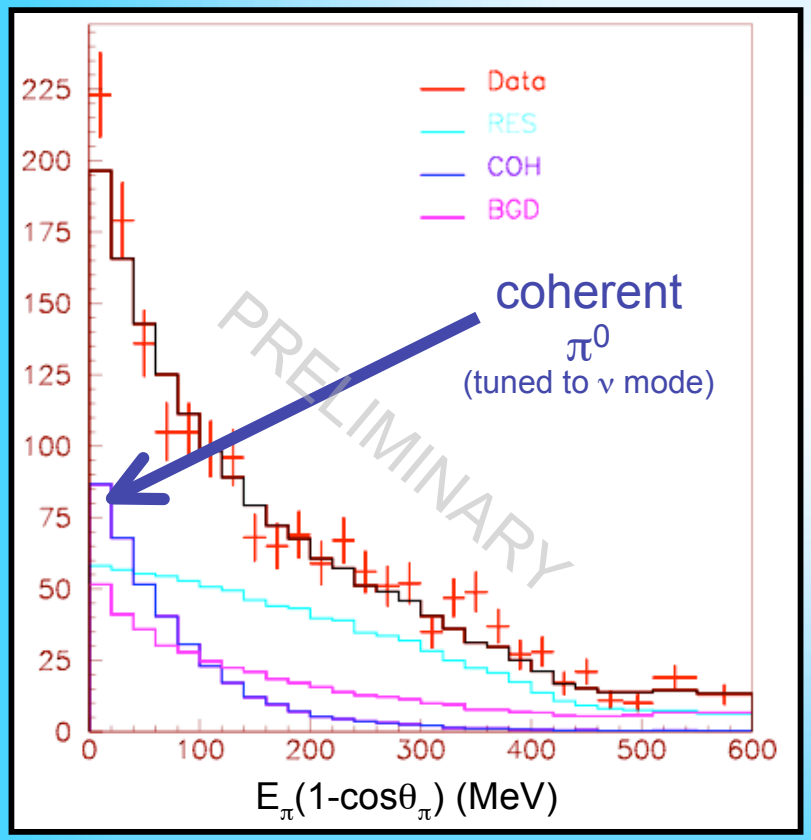


- coherent π^0 fraction = (19.5 ± 2.7)%; MC prediction = 30%

(arXiv: 0803.3423, accepted by Phy. Lett. B earlier this month)

1st Look at MiniBooNE $\overline{\nu}$ Data

- just like in ν case, there are no existing measurements of $\overline{\nu}$ NC coherent π^0 below 2 GeV



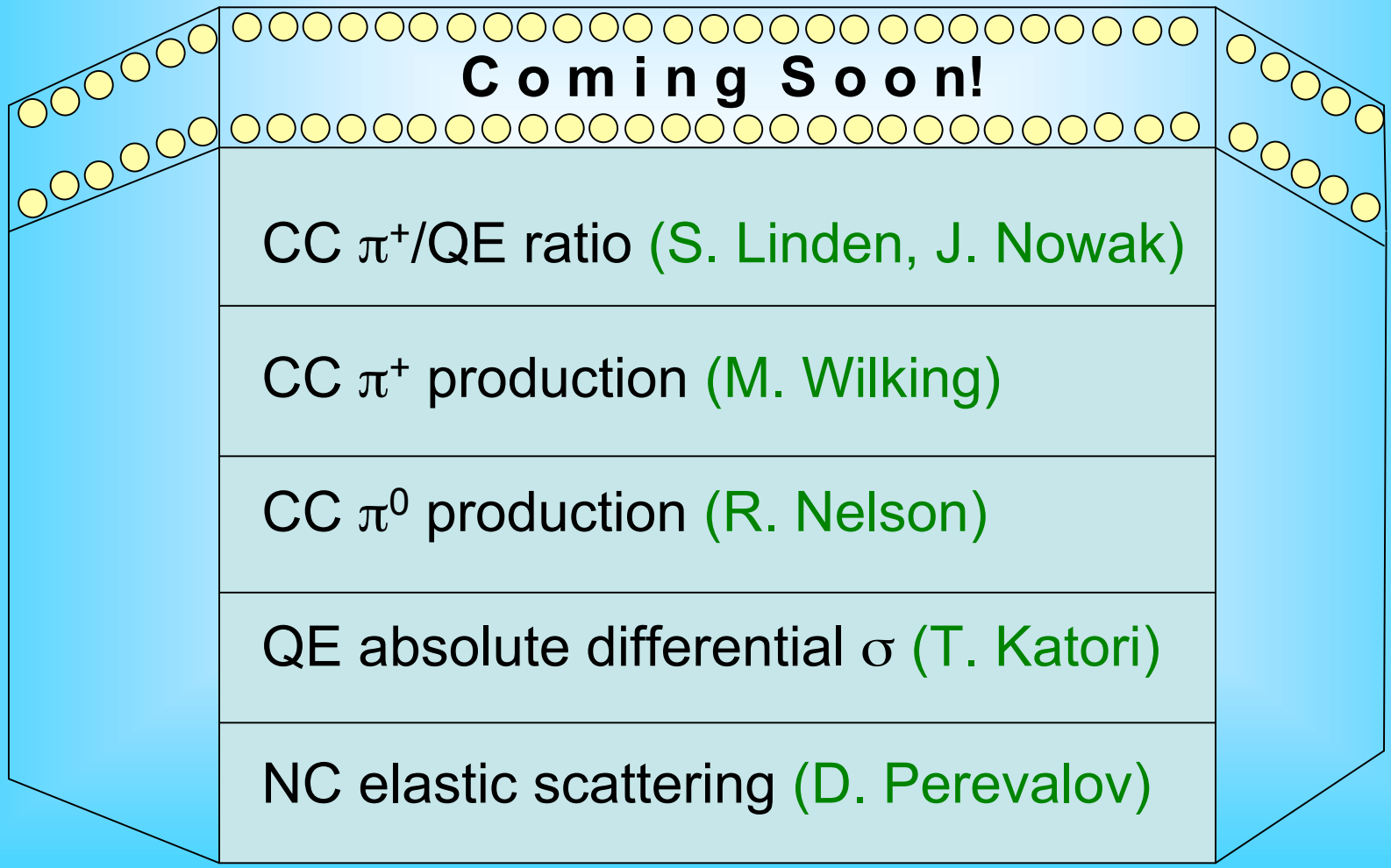
(V. Nguyen)

1,744 $\overline{\nu}_\mu$ NC π^0 events (more soon)

- largest sample of its kind
- see clear evidence for NC coherent π^0 production in both ν and $\overline{\nu}$ data

Also from MiniBooNE

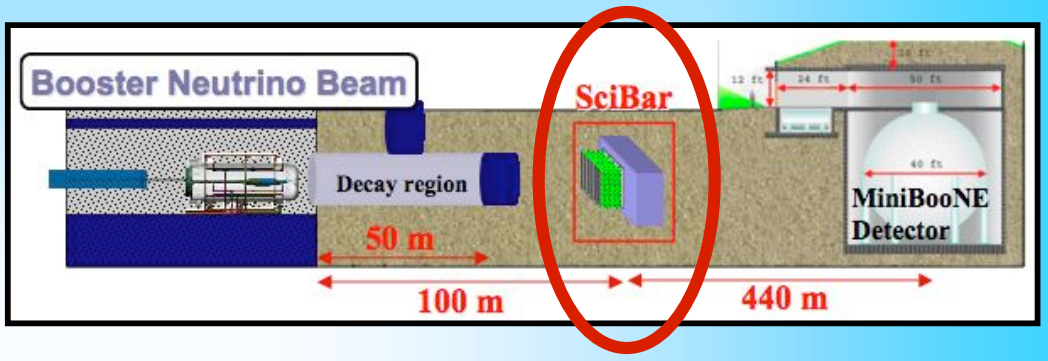
several other cross section measurements in the pipeline …

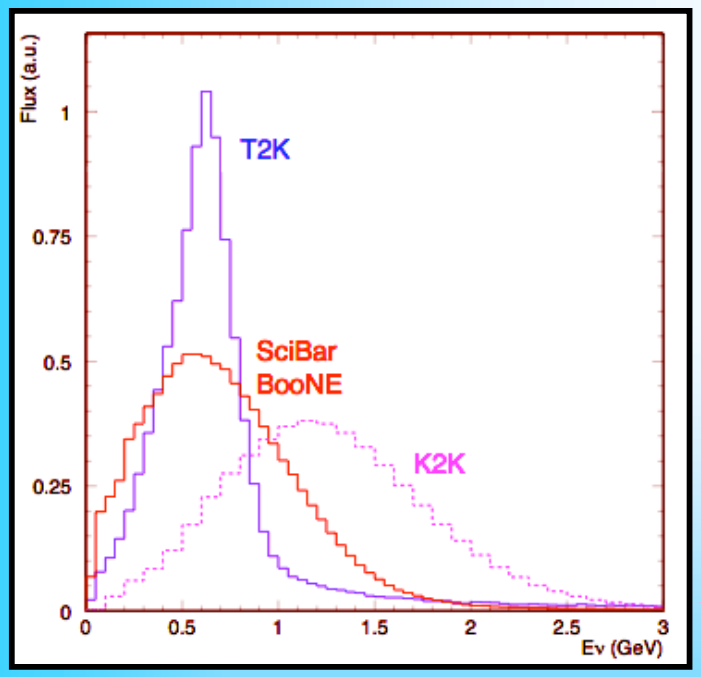


SciBooNE Experiment

carrying on tradition first pioneered with the SciBar detector at K2K …

- dedicated σ_ν experiment
- FNAL BNB,
  $\langle E_\nu \rangle$ = 0.7 GeV

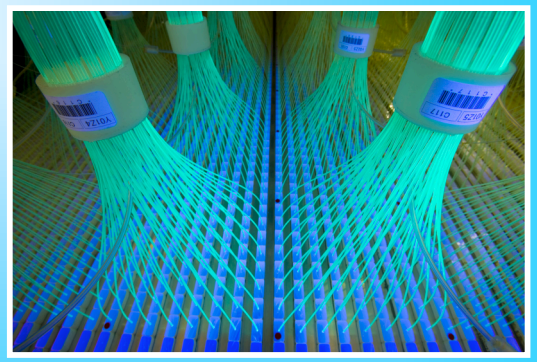




- familiar detector in a familiar beam
- has come a long way in a short time

  (experiment 1st proposed in Nov 2005)
- both ν and $\overline{\nu}$
- just finished ν run

  (0.99x10^{20} POT, full ν run)

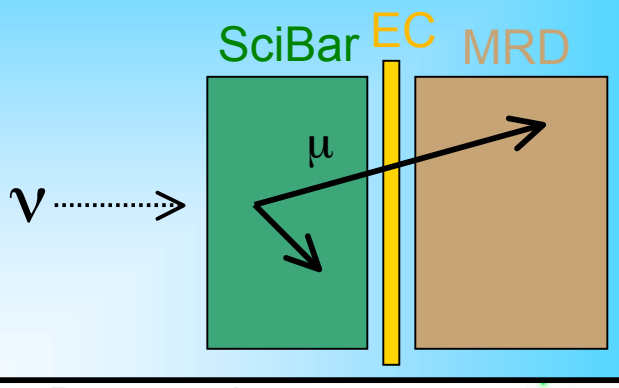


- M. Wascko poster

1st results a
a month later!

SciBooNE: CC Inclusive

- μ's easily identified if penetrate MRD
- 96% pure CC
- 21,431 events

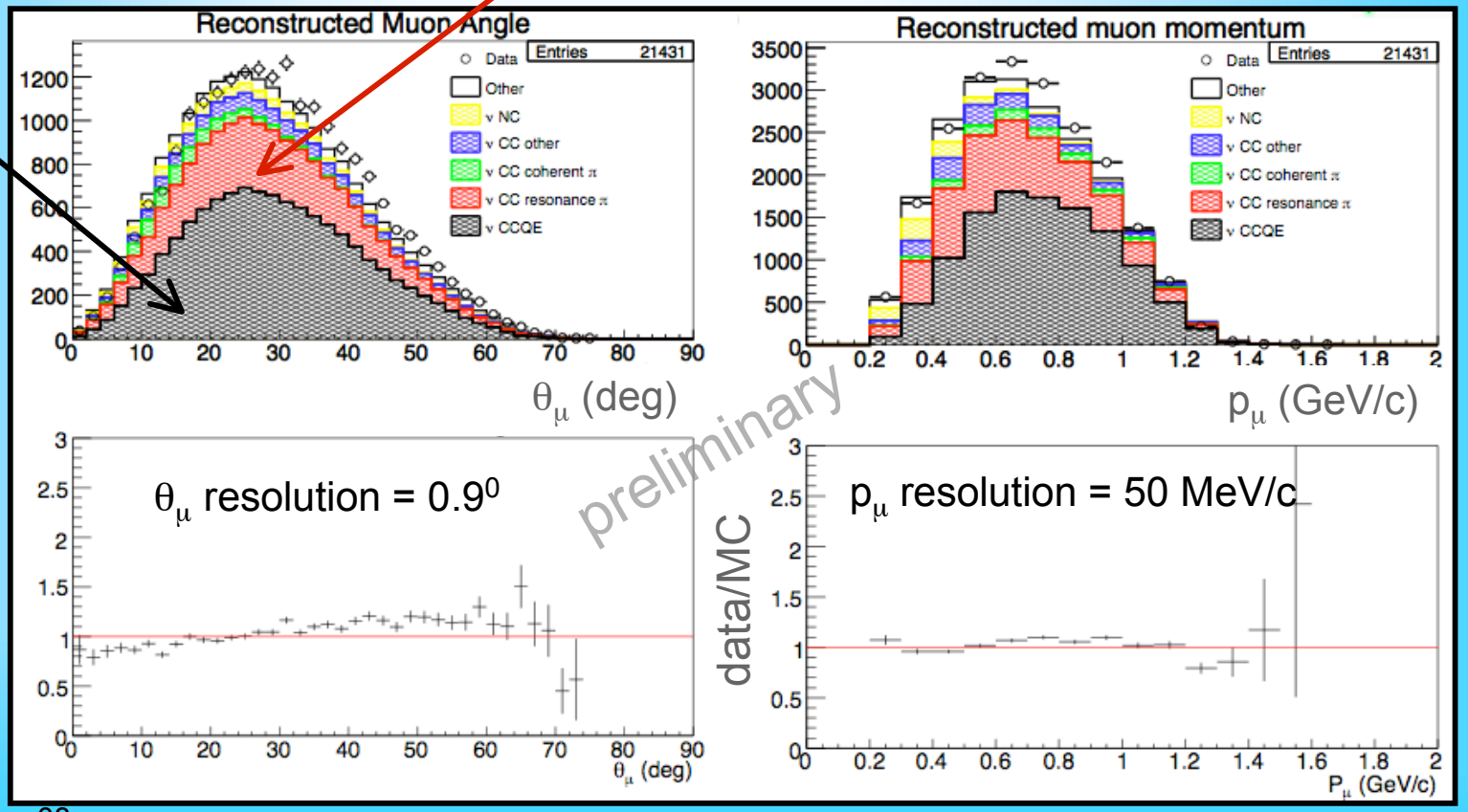


CC π^+

QE

normalized to # MRD-matched events

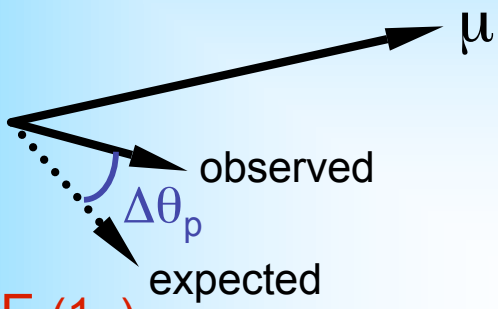
angular disagreement a physics effect?

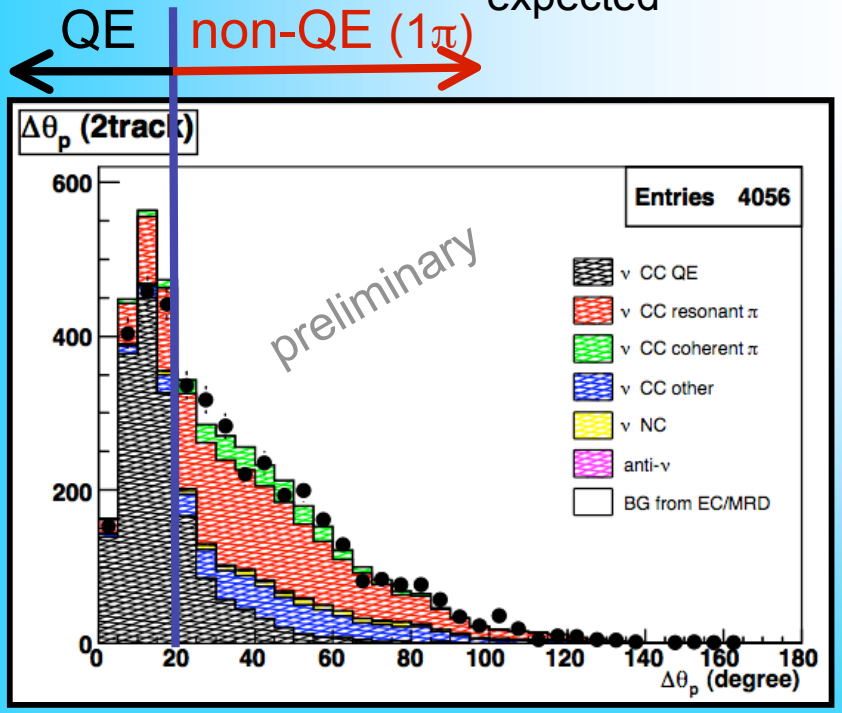


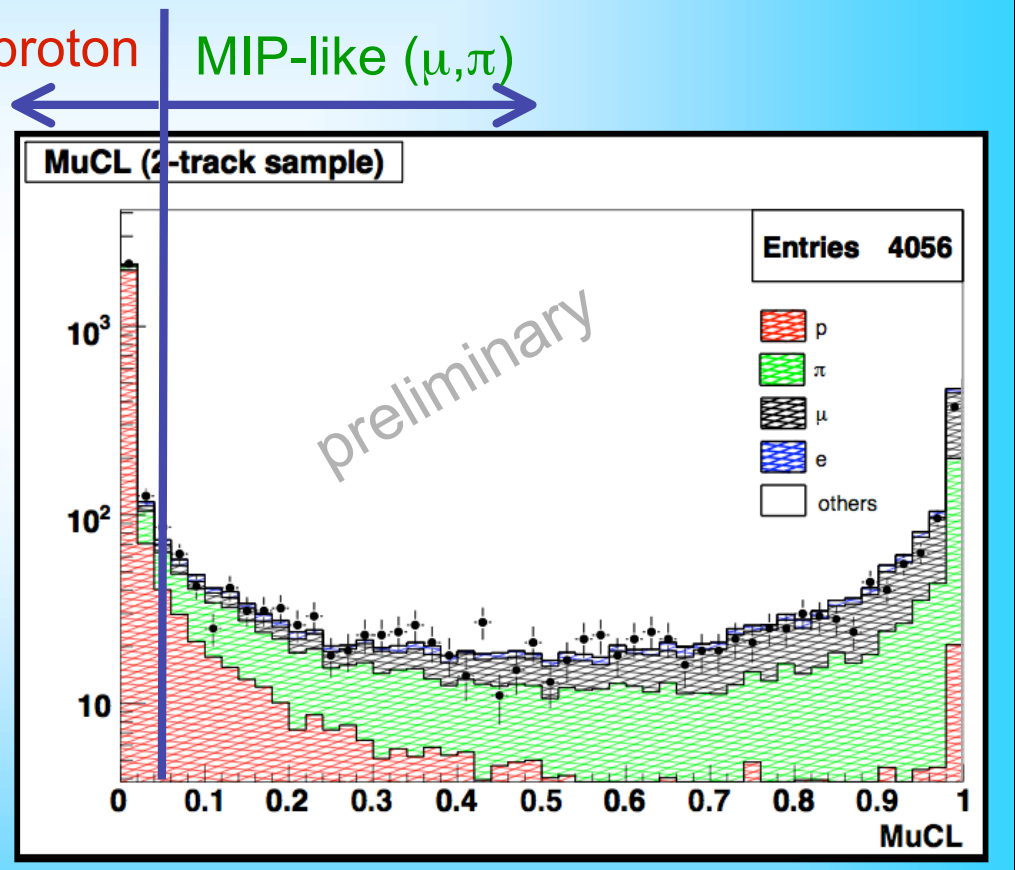
(Y. Nakajima)

QE and CC 1π Separation

- sample can be further sub-divided to gain information on "signal" & "background" samples to our ν oscillation searches







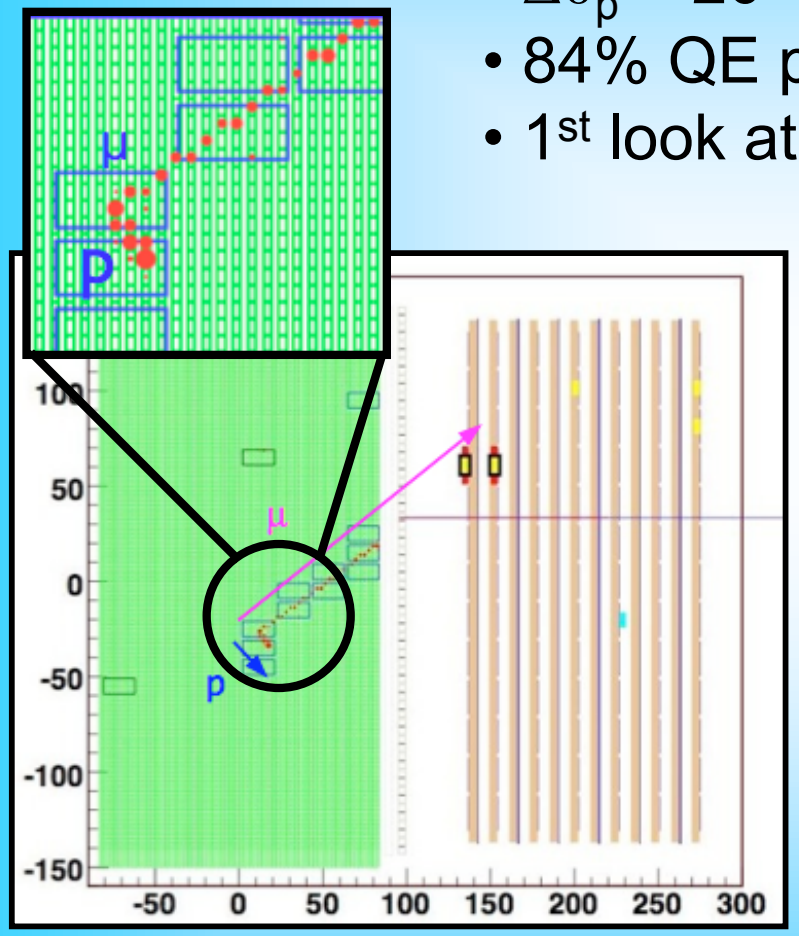
(K. Hiraide)

for CC π^+: 84% π efficiency
90% p rejection

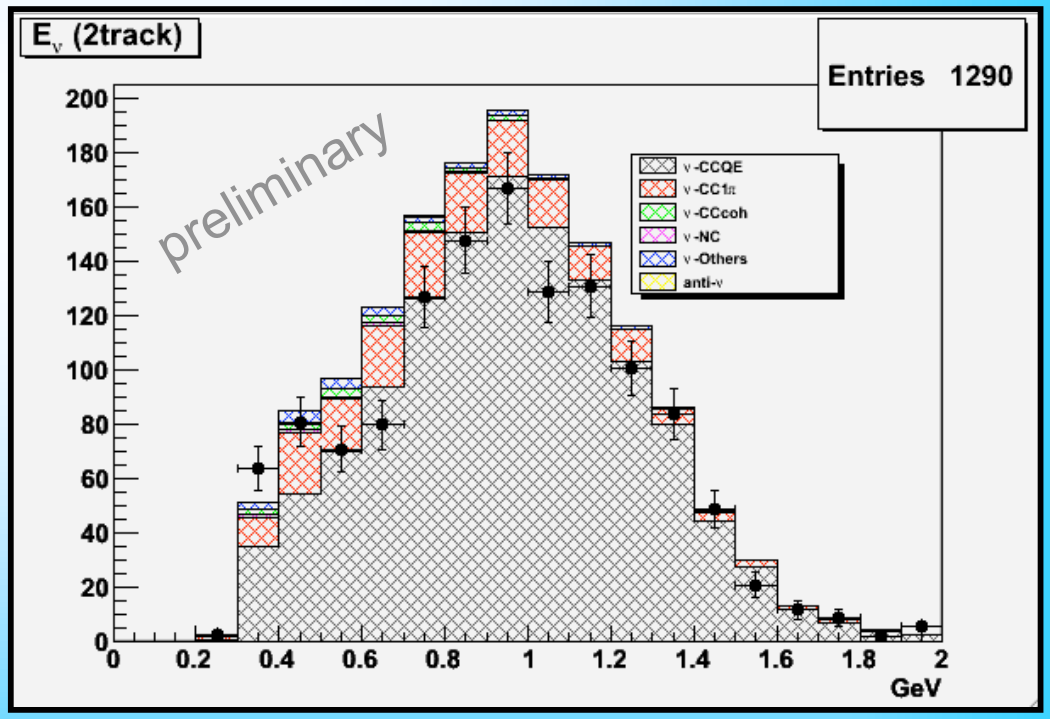
SciBooNE: QE

- $\Delta\theta_p$ < 20° (QE) + 2 track
- 84% QE purity, ~1300 events
- 1st look at this data!

(J. Alcaraz)



(SciBooNE QE event candidate)

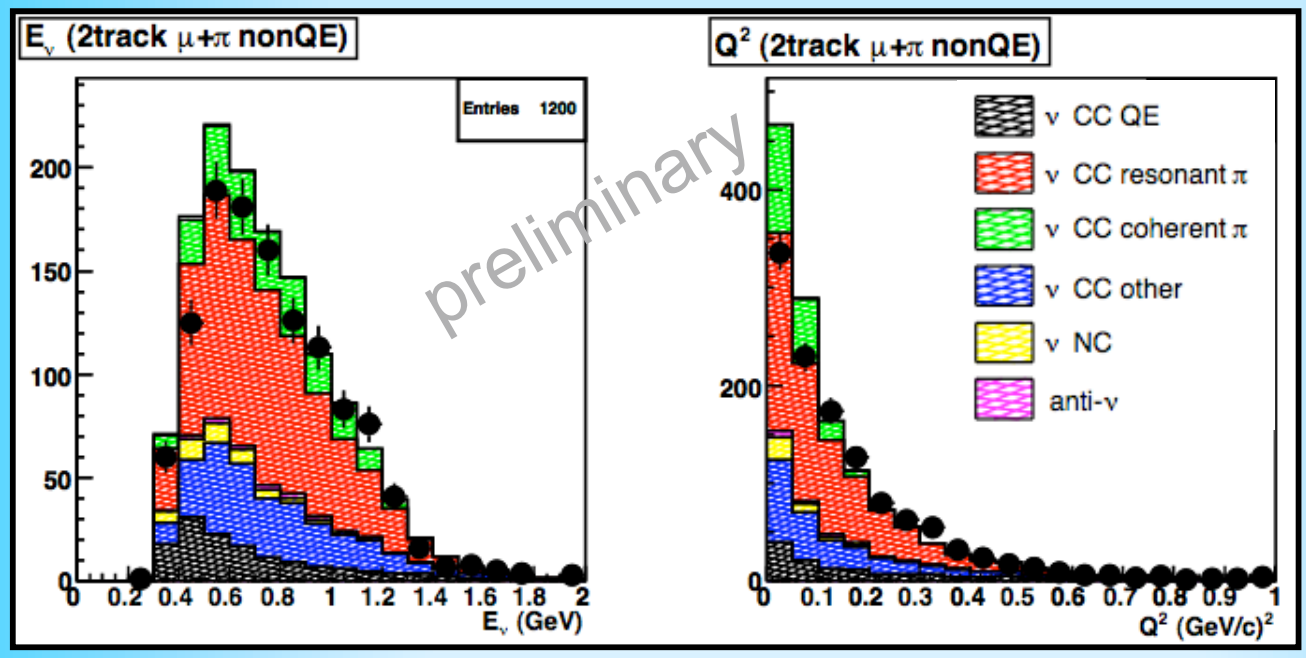


normalized to # MRD-matched events

SciBooNE: CC π^+

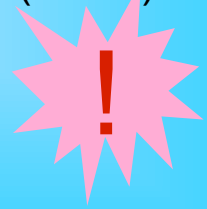
- $\Delta\theta_p$>20^o + 2nd track PID (μ + π), 67% CC π^+,~1200 events

(K. Hiraide)



see familiar disagreement at low Q^2

- new data consistent with no CC coherent π^+ production?
  (further analysis underway; this is similar to what was seen at K2K, PRL **95**, 252301 (2005))
- interesting that we see this process at high energy and in NC at low E, but not here! (challenge for theorists?!)



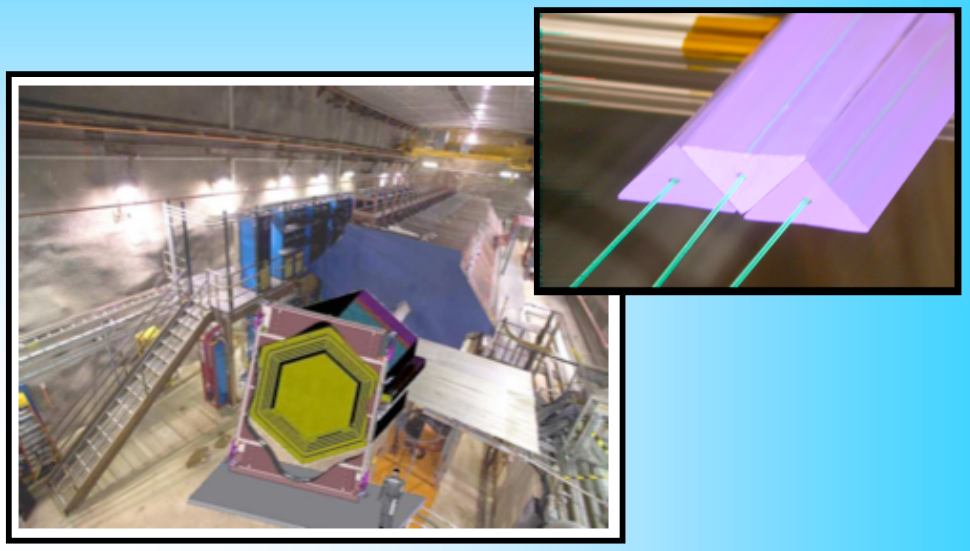
Also from SciBooNE

several other analyses also currently in progress …

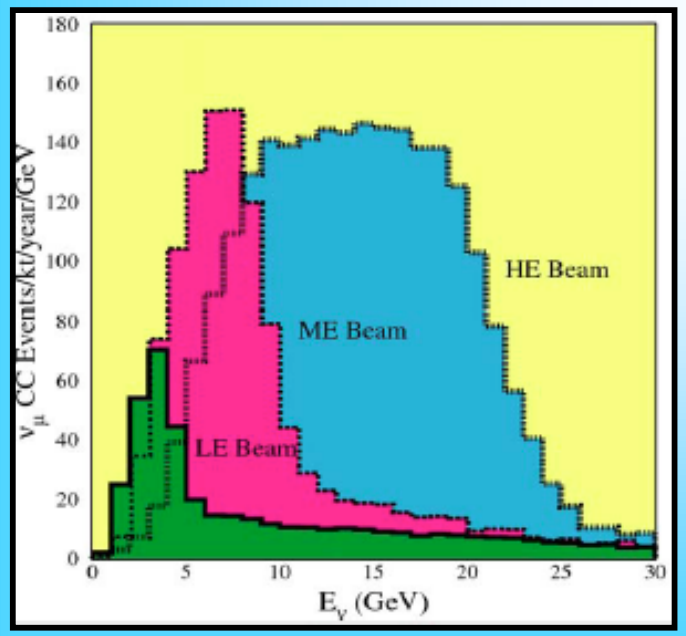
in addition to anticipating upcoming results from SciBooNE, also look forward to …

MINERνA Experiment

- dedicated σ_ν experiment
- FNAL NuMI beam
  - LE: E_ν^{peak} = 3 GeV
  - ME: E_ν^{peak} = 7 GeV
  - HE: E_ν^{peak} = 12 GeV



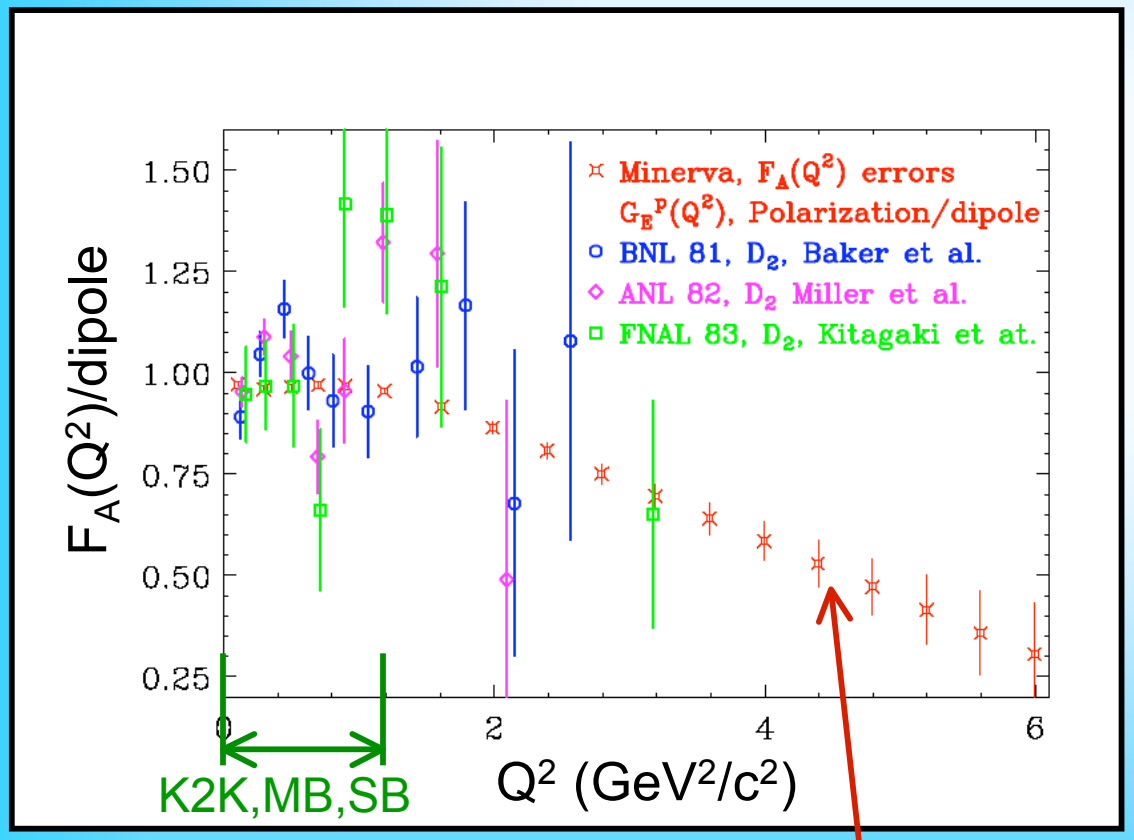
(exploit fact that NuMI beam is tunable)



- observe ν ints over broad E range
- nuclear targets (He, C, Fe, Pb)
  - allow detailed study of nuclear effects in ν's for the first time!
- impressive physics program:
  - channels from QE to DIS, millions of events!
  - just to give you 2 illustrative examples…

MINERνA: QE Scattering

- already seen systematically higher values of M_A from modern ν data; also like to make a precise determination of $F_A(Q^2)$



- is the axial form factor really dipole?
- MINERνA can uniquely access high Q^2 region
  - important to settle this
  - finally elevating ν meas to the level have seen in the e^- sector for years

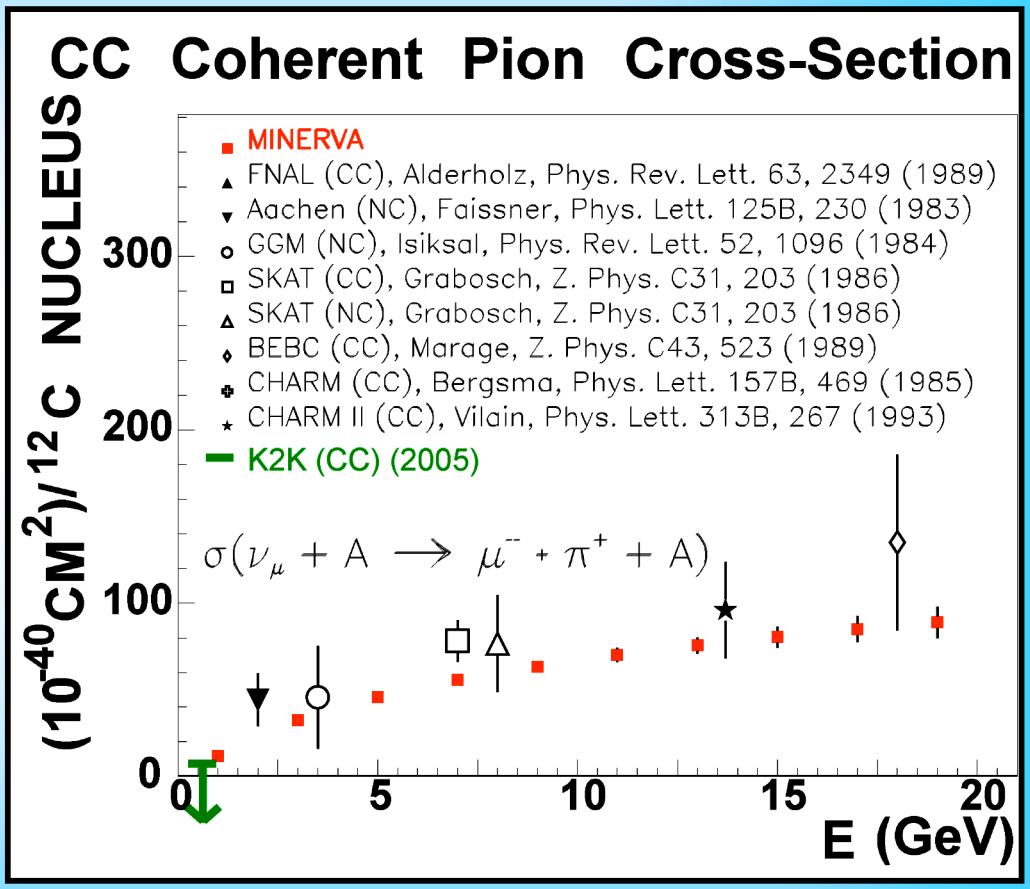
(long overdue!)

MINERνA: Coherent π Production

- MB, K2K have made single flux-integrated meas at low E

- able to precisely meas this σ as fcn of energy
- compare coherent σ on various nuclei (He to Pb)
  - able to carefully measure A dependence of this σ

85k CC coherent π^+
37k NC coherent π^0



- MINERνA on-schedule to start data-taking in 2009!
- also, see poster session … J. Morfin and R. Gran

The "Take Away"

- making large strides in filling the gap in our understanding
- but there are still things we don't understand! some examples:

- **signal samples = QE**
  - order magnitude more data
  - starting to study nuclear effects (has not been studied before in detail)
  - higher M_A (nuclear effects? or axial form factor?)

- **backgrounds: CC $\pi^{+,0}$ = bkg to ν_μ disappearance**
  NC π^0 = bkg to ν_e appearance
  - 1st measurement of these σ's on nuclear targets at low E
  - several significantly different than expectation (~30-40%)
  - nagging kinematic disagreement in CC π^+ (low Q^2)
  - intriguing difference between NC & CC coherent π prod at low E

The "Take Away"

- making large strides in filling th gap in our understanding
- but there are still things we d understand! some examples:

- **sig samples :**
  - orde
  - startin re in detail)

will have to come back to this
in a few years
and see how this turned out!

- **backgro arance**
  g t ppearance
  - 1st measurem t of th 's on nu ar targets at low E
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Conclusions

- compelling evidence of ν oscillations has increased both interest & need for σ_ν meas

- lot of activity over past year!
  - latest results from K2K, MiniBooNE, SciBooNE
  - including some surprises !

- MINOS will also have σ_ν on Fe

- now entering a phase where these input σ's will be even more critical for the success of future ν oscillation experiments
  - MINERνA collecting data soon … taking this to the next level!


Thank You!