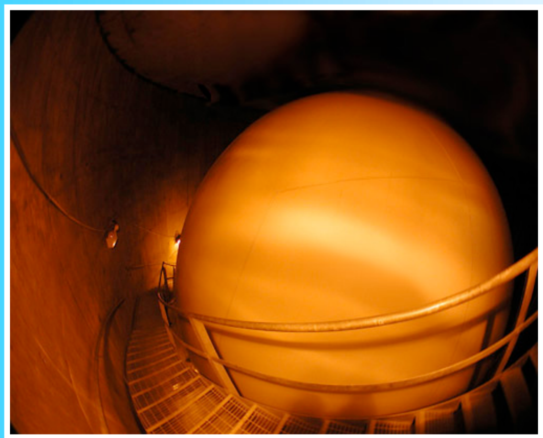
Neutrino Cross Sections at MiniBooNE



Sam Zeller
LANL

Elba X Workshop
June 26, 2008

- show you a slightly different side to MiniBooNE
- program for measuring low energy ν interactions on nuclei

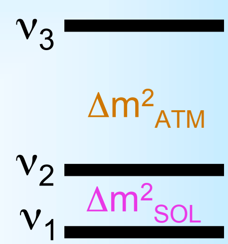
Outline

- motivation for improved ν cross section measurements
  - interesting in themselves
  - also a critical ingredient for ν oscillation exps (main customer)
- measuring ν interactions at MiniBooNE
  - several new MiniBooNE results
    - while providing some historical context
    - also, 1st look at new antineutrino data
  - new ν data quite interesting … revealing some surprises !

Neutrino Roadmap

- one of the most exciting developments: ν's oscillate!
- some big questions that we will be actively trying to answer …

  - what are the masses of neutrinos?
  - what is the mass hierarchy?



  - what is the exact pattern of mixing between neutrinos?
    - precise values of ν osc pars: Δm^2_{23}, θ_{23}, $\theta_{13} \neq 0$?
  - is CP violated in the ν sector? (do ν's behave differently than $\bar{\nu}$'s?)

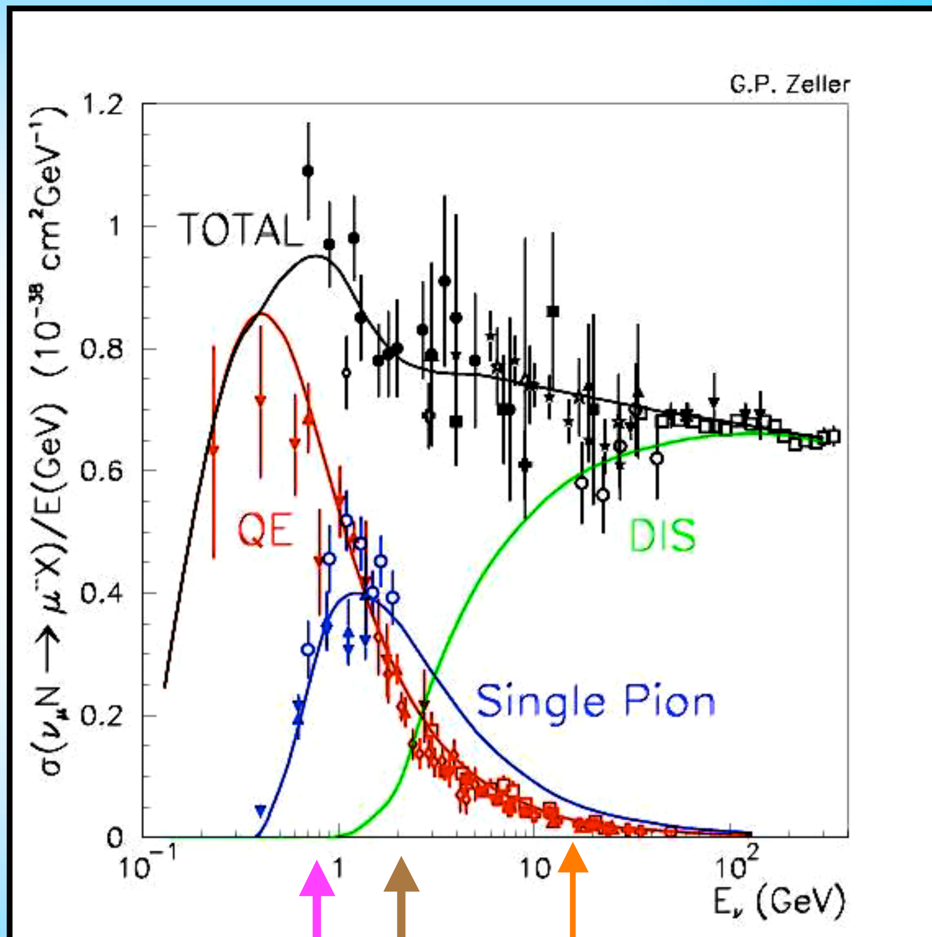
… this is what people are excited about!

- to complete this program, need to understand how ν's interact w/ matter more precisely than have had to know in past

“Low Energy” ν Cross Sections

(100’s MeV to 10’s GeV)

- dominant interactions are QE & single pion production
- measurements in 70s-80s
  - not as precise as we’d like
  - mostly H_2, D_2
- never looked back until now
- really need improved σ_ν at <u>low E on nuclear targets</u>!

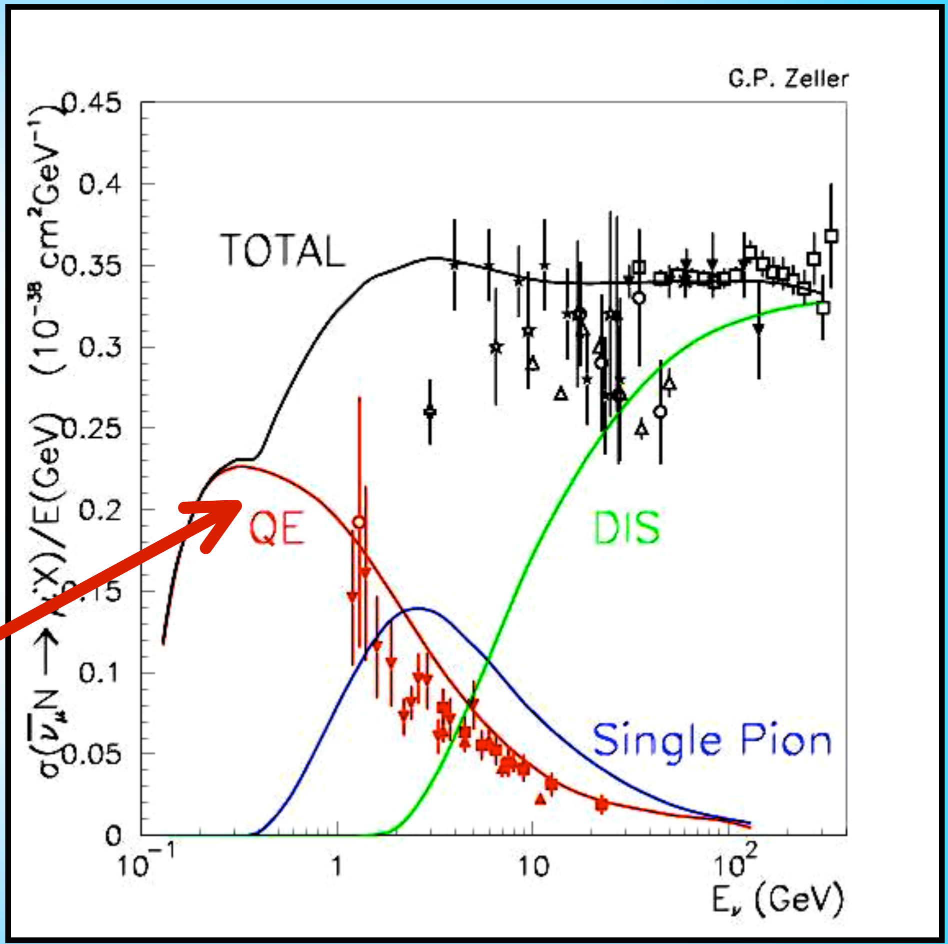


we’ll talk about which σ’s matter & why

Antineutrino Cross Sections

- even fewer existing $\bar{\nu}$ measurements

- for future ~~CP~~ searches (one of the items on our list), prefer not to rely on extrap of predictions where no data



will show some 1^{st} $\bar{\nu}$ data in this region in this talk!

need updated $\bar{\nu}$ measurements as well!

Low Energy ν Interaction Physics

- compared to electron scattering sector, we are behind in terms of measuring & modeling ν interactions in this E regime
  - decades old exp'l data
  - QE scattering (Llewellyn-Smith, 1972)
  - Fermi gas model (Smith-Moniz, 1972)
  - single π production (Rein-Sehgal, 1981)
- have been left in a "time warp"

we're just getting back into this game

- **good news:** this is changing!
  - there has been >50 papers featuring new theoretical calculations on ν scattering in the past year alone!
  - coupled with brand new exp'l measurements!

New ν Data

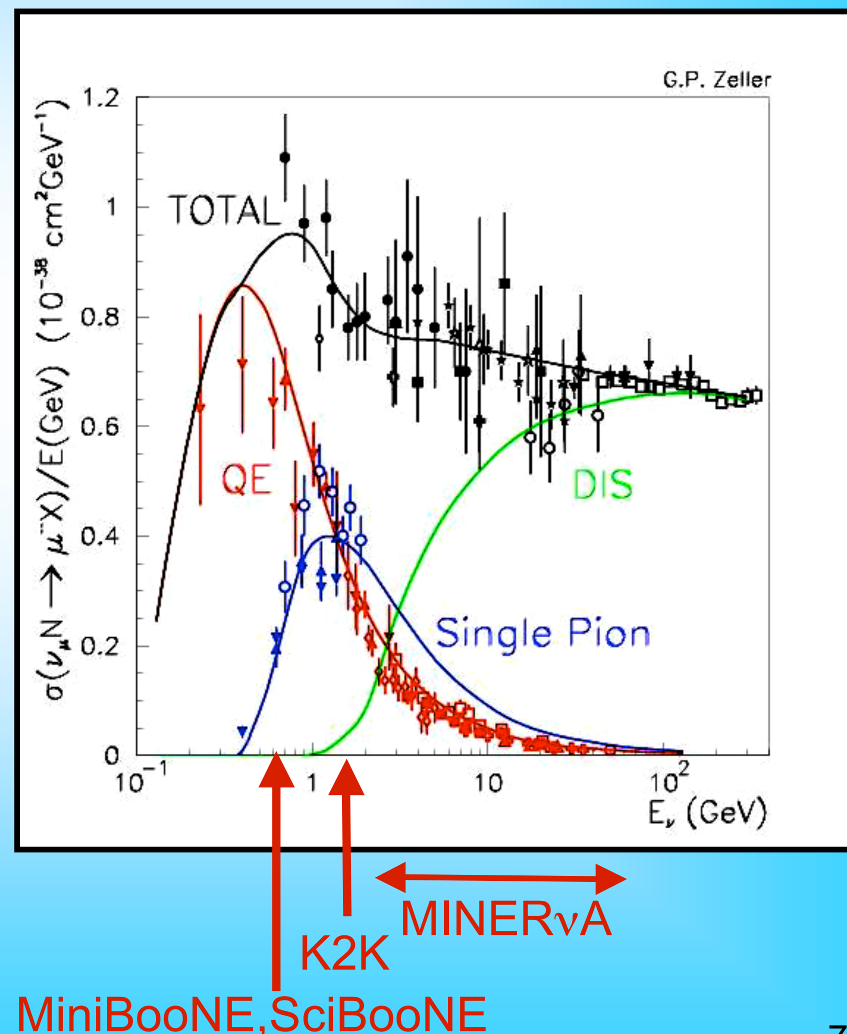
- new ν data is (& will be) coming in from a variety of sources …

results right now

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

coming very soon !

- **being built now:**
  - MINERνA (2009)



- together, all 4 will probe energy range we care the most about
- & building on heritage of past exps

New ν Data

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

results right now

• **present:**

- K2K (1999 - 2004) (Sakuda)
- MiniBooNE (2002 - present)
- SciBooNE (2007 - present) (Wascko)

my talk will focus on new MiniBooNE σ_ν results

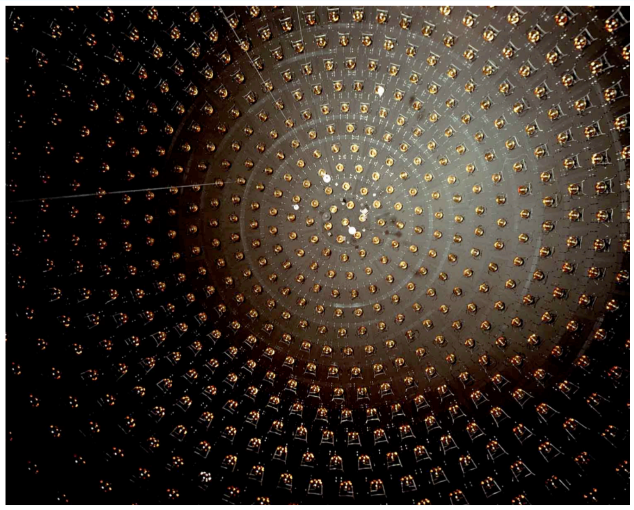
coming very soon !

• **being built now:**

- MINERνA (2009)

with all 3 talks will get good sense of where we stand now

MiniBooNE Experiment

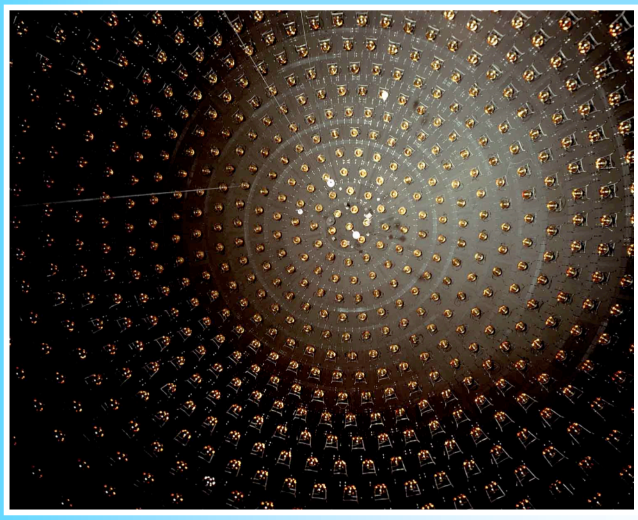


- **Čerenkov detector**
  - lined with 1520 phototubes
  - 800 tons mineral oil (CH_2)

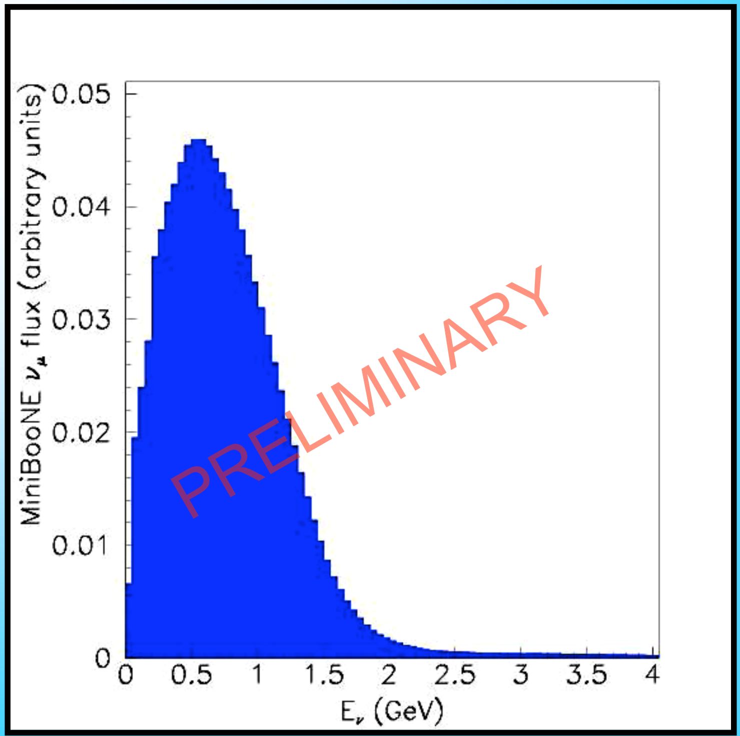
- **~700,000 contained ν events**
- **~70,000 contained $\bar{\nu}$ events**

(record size samples at these energies)

MiniBooNE Experiment



- FNAL Booster ν beamline
  - $<E_\nu>$ ~ 700 MeV
  - well-suited for σ_ν
- new 74 page flux paper
  (arXiv:0806.1449)



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- **~700,000 contained ν events**
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(record size samples at these energies)

Low Energy ν Interactions

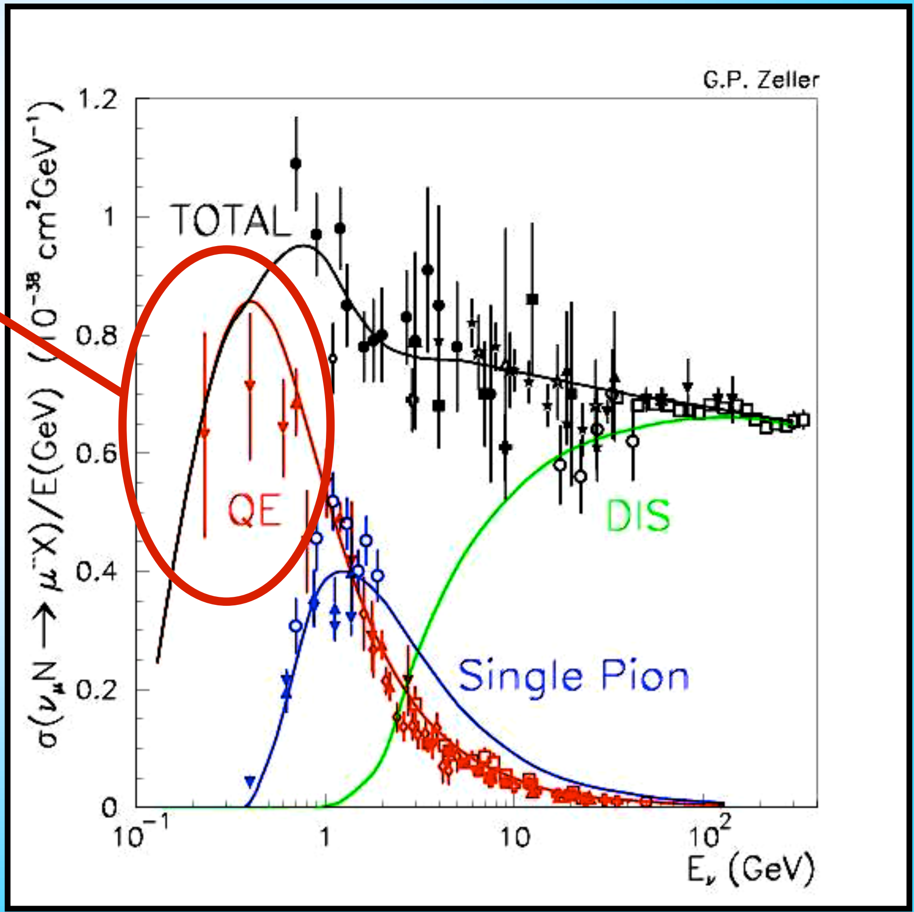
• starting with the first interaction on our list …

(1) quasi-elastic (QE)

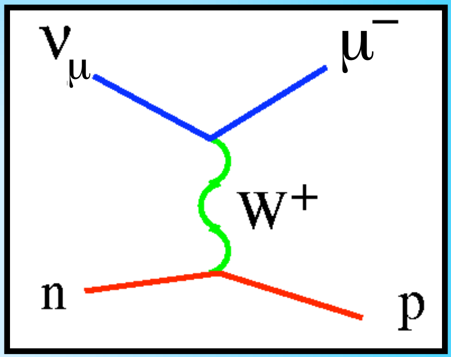
- dominates E_ν < 1 GeV
- 48% of MB events are QE

(2) NC $1\pi^0$ production

(3) CC 1π production



Quasi-Elastic (QE) Scattering



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

Why important?

- **important for ν oscillation experiments**
  - CC so can tag flavor of incoming ν
  - simple 2-body interaction means can reconstruct E_ν
  - dominant interaction at ~1 GeV means high statistics

- <u>examples:</u>

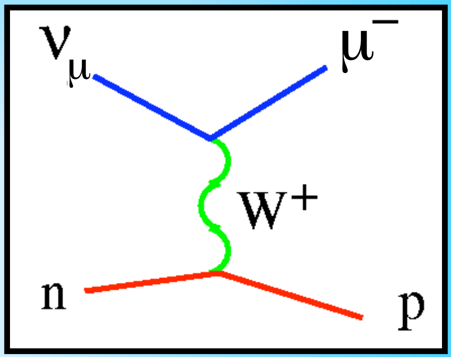
  $\nu_\mu \rightarrow \nu_e$ (ν_e appearance)

  $\nu_\mu \rightarrow \nu_X$ (ν_μ disappearance)

signal sample for ν oscillation experiments (in both cases)

Quasi-Elastic (QE) Scattering

Why important?



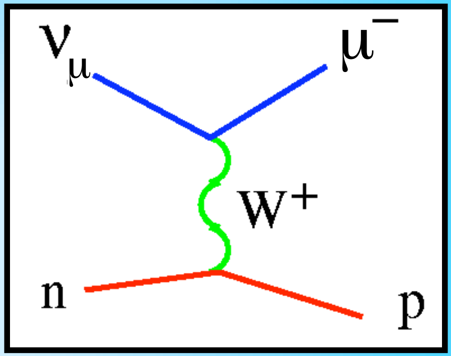
$\nu_\mu\, n \rightarrow \mu^-\, p$

- **interesting on its own**

  - valuable probe of structure of nucleon
  - extract information on axial form factor of the nucleon (in a way that is complimentary to electron scattering based measurements)

Quasi-Elastic (QE) Scattering

Why important?



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

- **where are we now?**

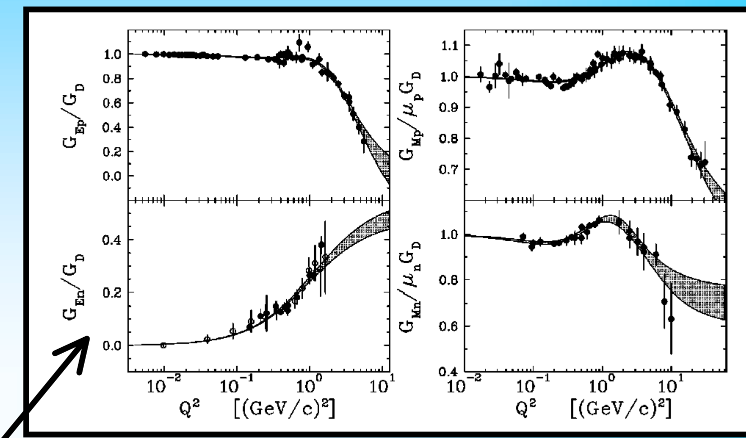
  - order of magnitude larger ν_μ QE samples now available
  - starting to study nuclear effects (something that has not been studied before in any detail)
  - making new determinations of axial FF of the nucleon (for the 1st time in >10 years!)

Starting Point

- ν experiments all assume the same basic underlying ν QE model

  - **nuclear model**
    - relativistic Fermi Gas model (S-M)

  - **nucleon form factors**
    - vector FF well known from e^- scattering
    - axial FF not as well known (g_A=1.267 from β decay)



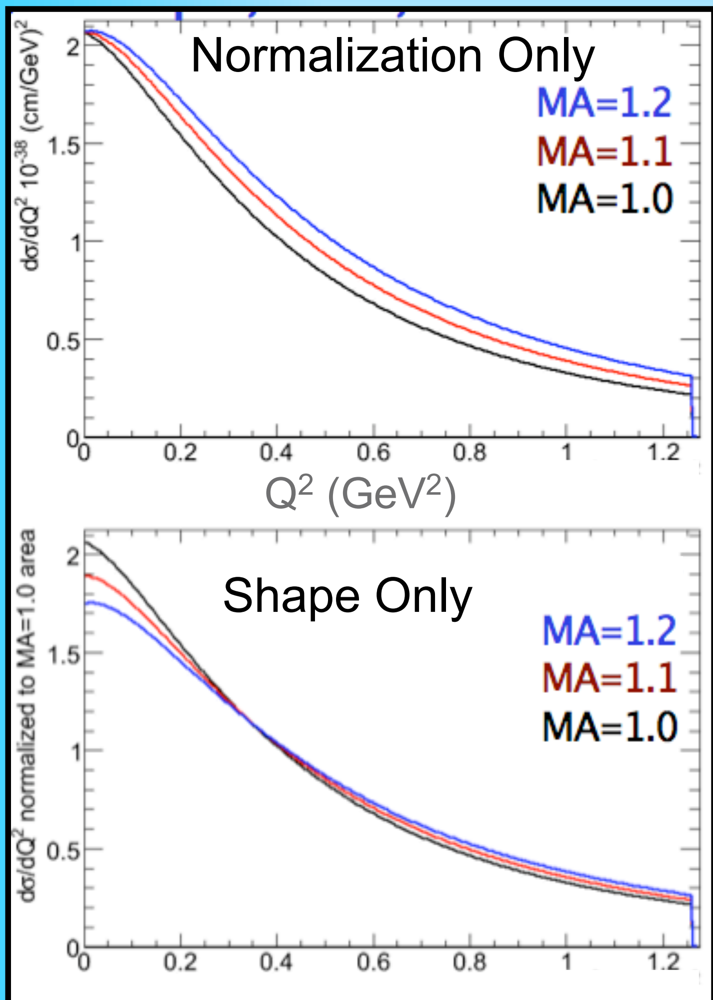
J.J. Kelly, PRC**70**, 068202 (2004)

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

form factor usually parametrized by dipole form

fcn of single parameter "**axial mass**"
determined experimentally - ν scattering: $\mathbf{M_A = 1.03}$ **GeV**
- also, π electroproduction, QE e^- scattering

How Do You Measure M_A with ν's?



(R. Gran NuInt07)

M_A has two effects on QE predictions:

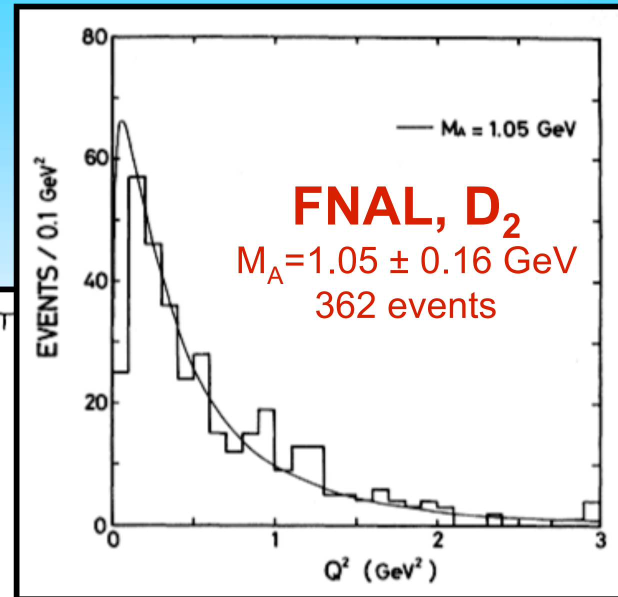
(1) **changes normalization**
(↑ M_A, ↑ σ)

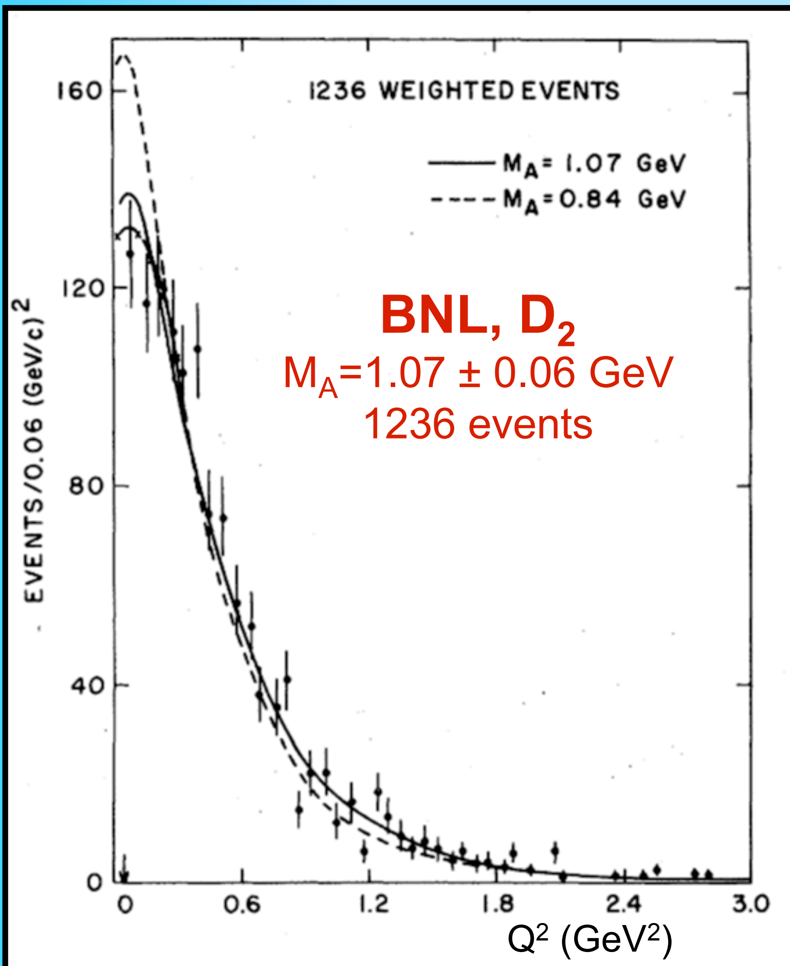
(2) **changes Q^2 dependence**
(↑ M_A, → harder Q^2)

typically ν experiments measure M_A using 2nd method
(many past ν experiments did both)
and fit $Q^2 > Q^2_{min}$

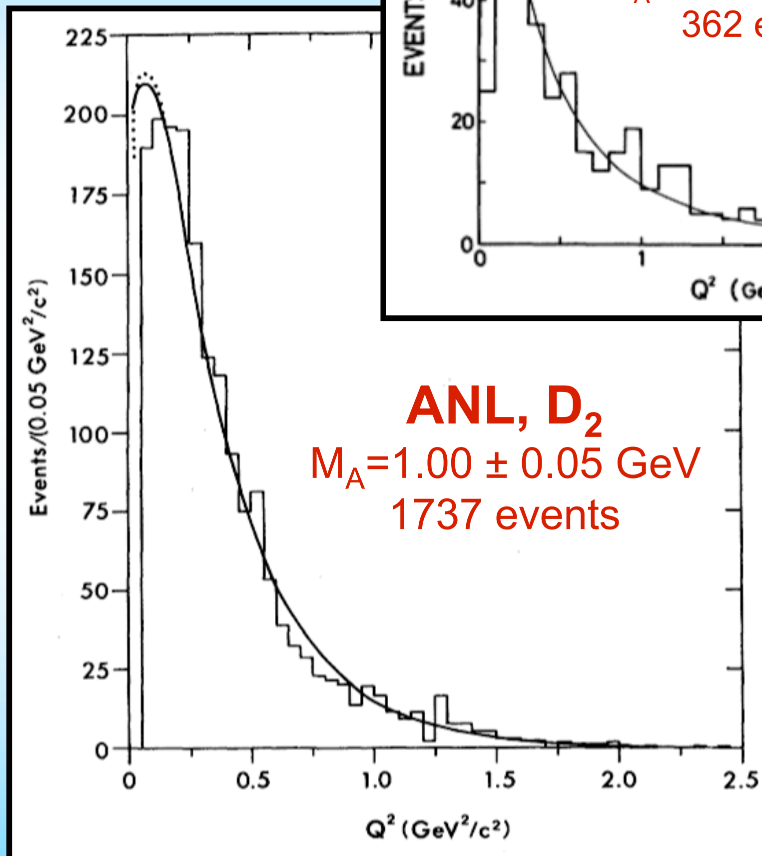
Some Examples

Kitagaki, PRD **28**, 436 (1983)





Baker, PRD **23**, 2499 (1981)

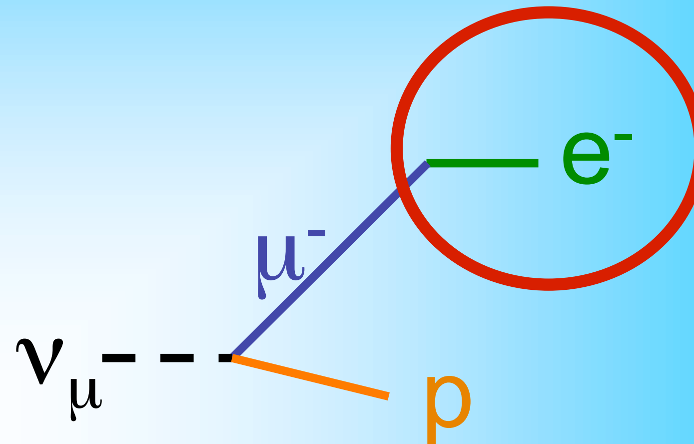


Miller, PRD **26**, 537 (1982)

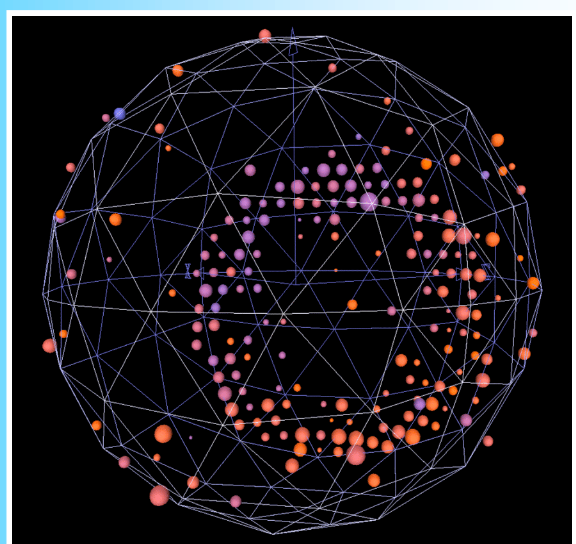
a lot of interest and attempts to re-measure M_A recently

MiniBooNE ν_μ QE Selection

- events tagged by $\mu^- \rightarrow e^-$ decay,
  (not by reconstructing outgoing proton)



- selection is simple and unique
  (helps reduce model dependence)



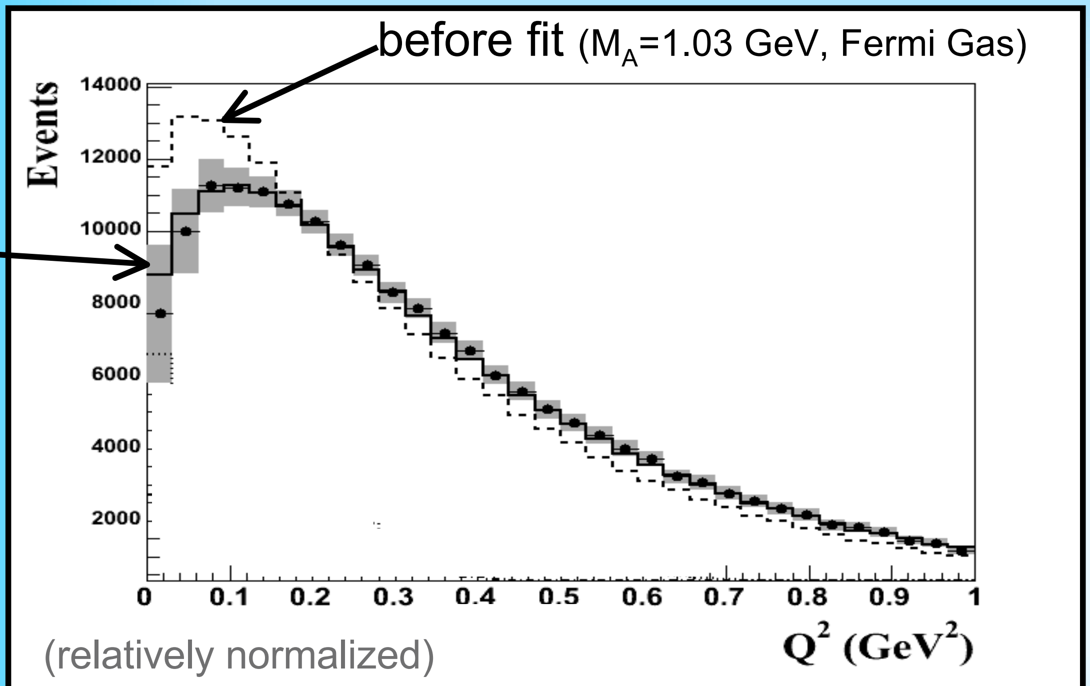
(μ candidate in MB detector)

- and successful …
  - 74% pure ν_μ QE
  - 35% efficiency

- 193,709 ν_μ QE events passing selection cuts

- measure T_μ, $\theta_\mu \Rightarrow E_\nu$, Q^2

MiniBooNE QE Results



(T. Katori)

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

Phys. Rev. Lett. **100**, 032301 (2008)

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

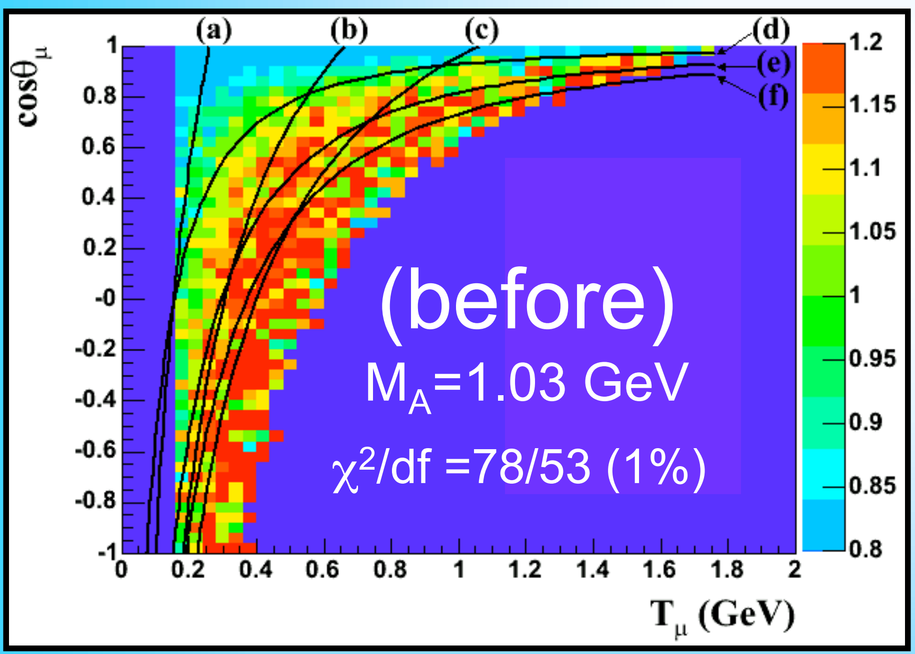
! - M_A = 1.23 ± 0.20 GeV → fixes high Q^2

- κ = 1.019 ± 0.011 (Pauli blocking parameter) → fixes low Q^2

MiniBooNE QE Results

- 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:

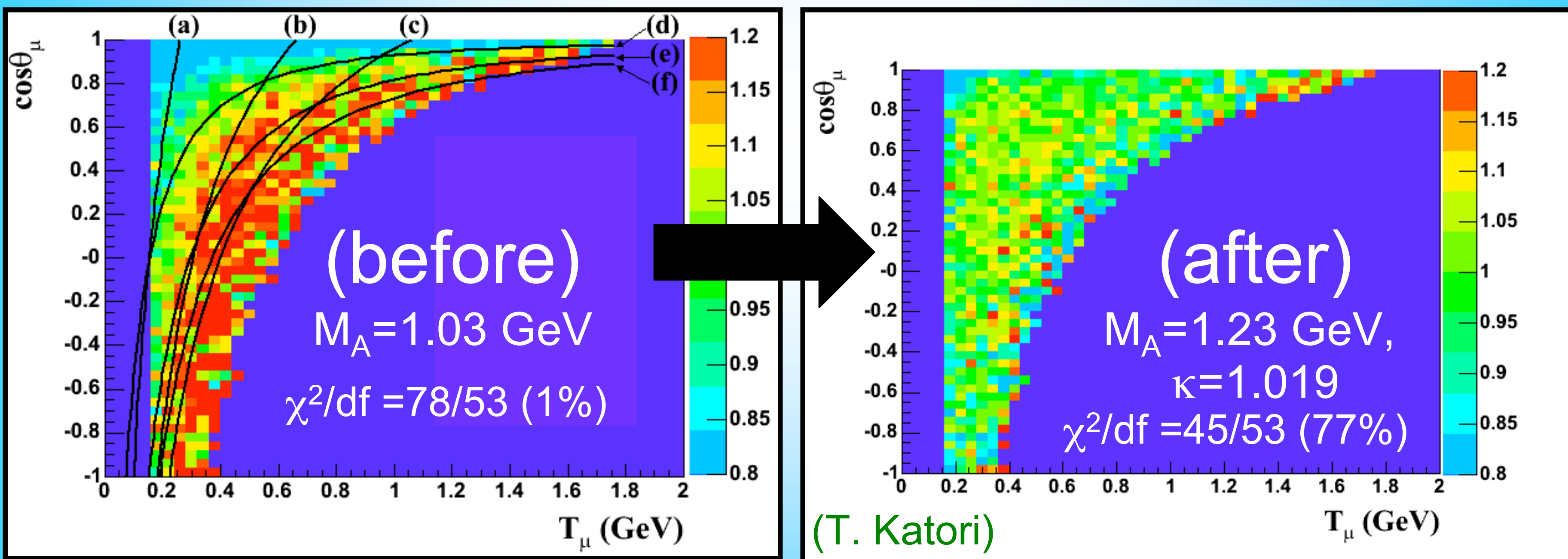


(T. Katori)

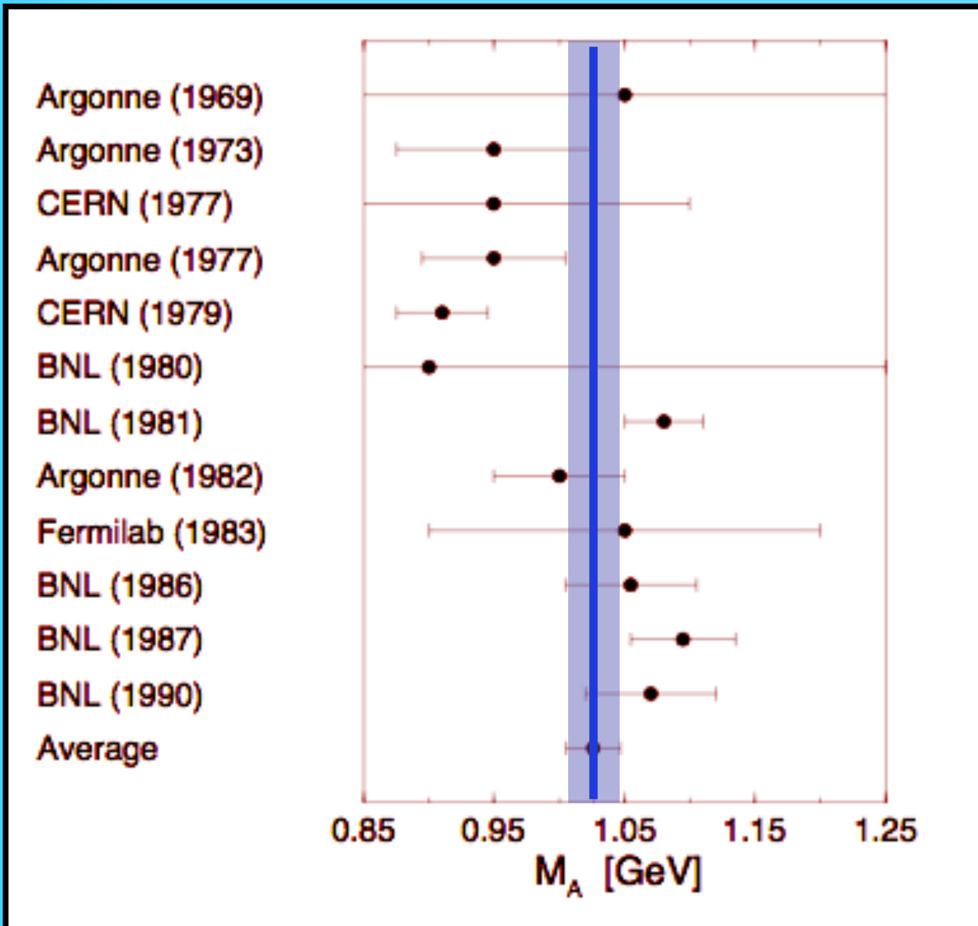
MiniBooNE QE Results

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



- stunning agreement across entire phase space! important for MiniBooNE oscillation analysis
- also of interest is M_A value itself …



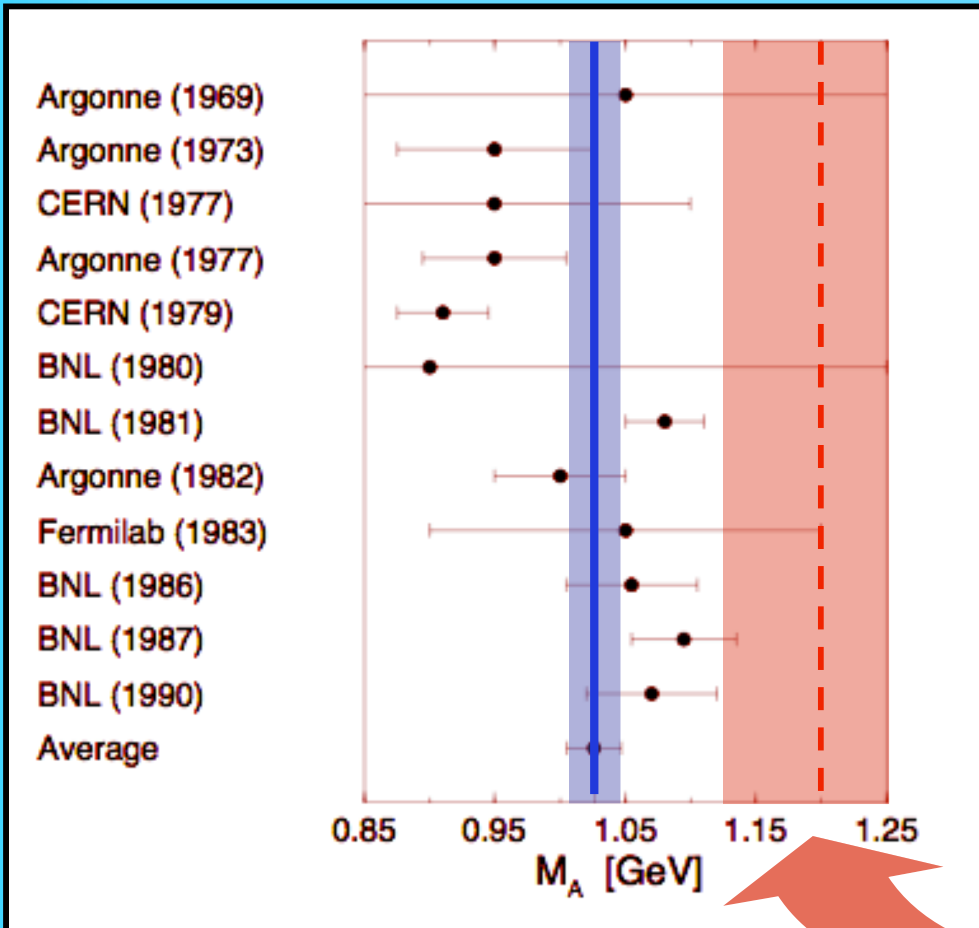
past ν world avg: M_A = 1.026 ± 0.021 GeV (largely set by D_2 measurements)

ν with modern F_v: M_A = 1.014 ± 0.014

π electroproduction: M_A = 1.014 ± 0.016

J. Phys. **G28**, R1 (2002), arXiv:0709.3538

(M_A=1.19 ± 0.07)



- **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

modern ν data measuring a systematically higher M_A **(measuring an "effective M_A"?)**

!

past ν world avg: M_A = 1.026 ± 0.021 GeV

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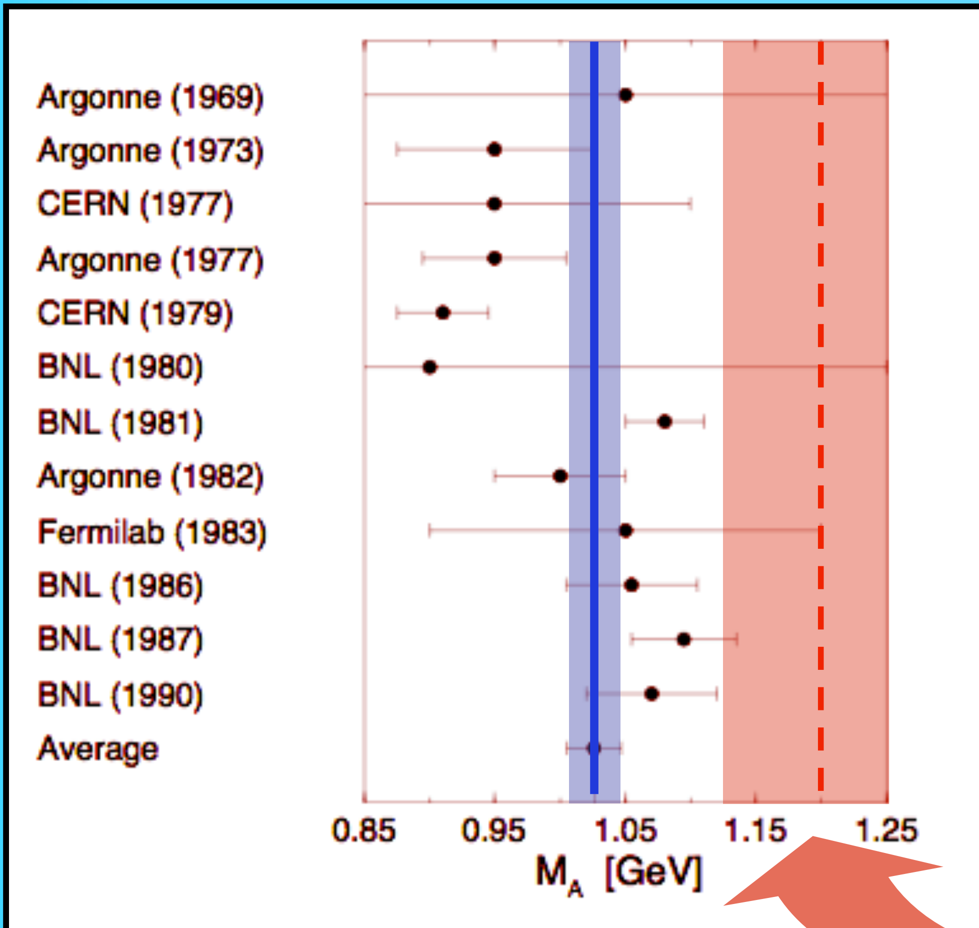

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SciBooNE & MINERνA will have something to say on this too!

Open Questions

- is higher M_A due to nuclear effects or inherent axial form factor?
  (important to resolve! T. Laird, Princeton)

  - M_A not only impacts predicted kinematics of QE events, but also their overall rate

    ! (1) if **axial form factor**, then 20% higher M_A can mean 20% more events (E-dep)

    (2) if **nuclear effects**, then this is not the case

but some of new exps also seem to be seeing more QE events than predict?!

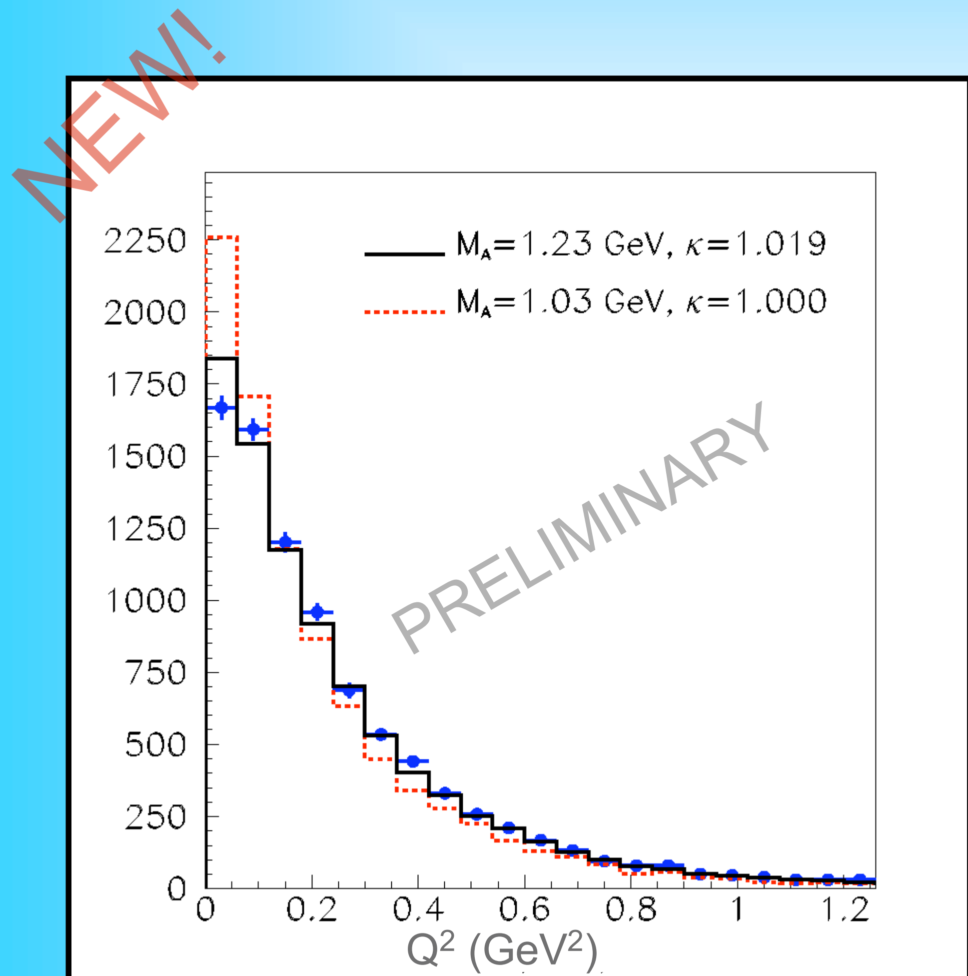
seems more likely

- implications of M_A interpretation on comparisons to e^- & past ν?

- do we see same increased Pauli blocking in e^- scattering?
  (A. Butkevich, Phys. Rev. **C72**, 025501 (2005); recently R. Tayloe & J. Ullman at IU)

- do we see similar effects in $\bar{\nu}$ QE scattering?

1^{st} Look at Antineutrino QE Data



$\bar{\nu}_\mu\, p \rightarrow \mu^+\, n$

- MiniBooNE switched to $\bar{\nu}$ running in 2006

  (along with SciBooNE, only exps with a dedicated $\bar{\nu}$ beam)

- 8,772 $\bar{\nu}_\mu$ QE events

- **preliminary**: parameters also seem to successfully describe MiniBooNE $\bar{\nu}_\mu$

  (nice verification of ν mode results)

- plus will also have $\bar{\nu}$ QE results from SciBooNE!

Low Energy ν Interactions

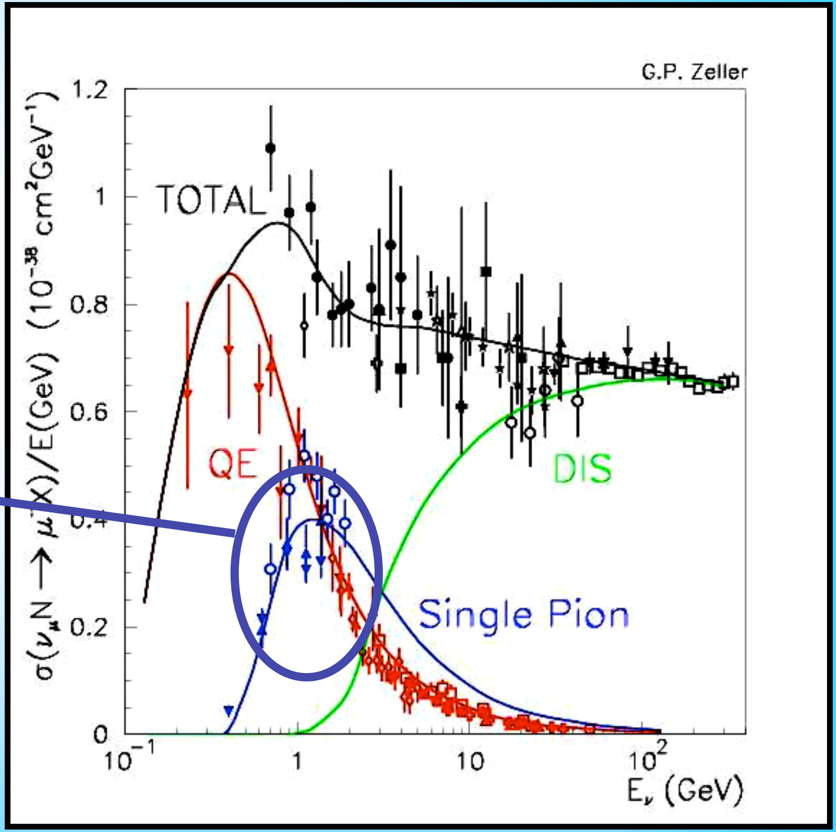
• let's leave the QE's and move up in energy …

(1) quasi-elastic (QE)

(2) NC $1\pi^0$ production

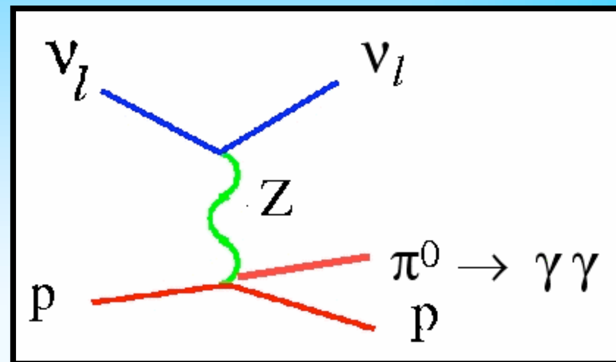
- 8% of MB events

(3) CC 1π production



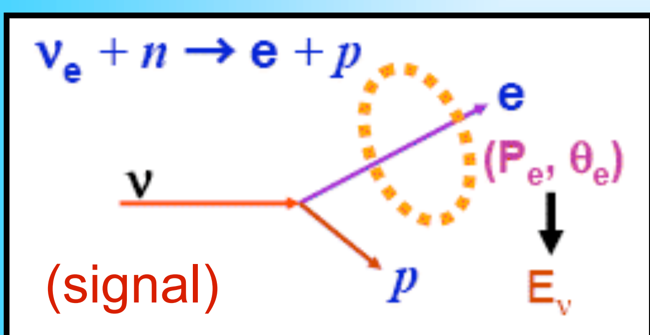
NC π^0 Production

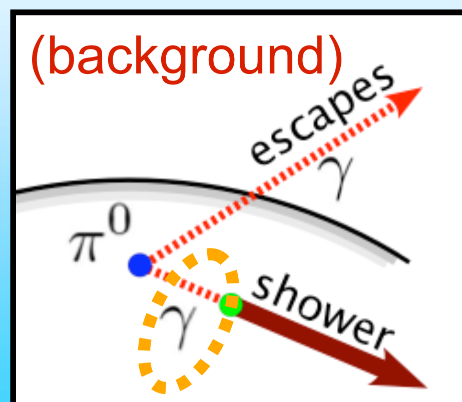
Why important?



ν_μ N $\to$ ν_μ N π^0

- **important for neutrino oscillation experiments**
  - poses a serious background to $\nu_\mu \to \nu_e$ appearance searches
    (can look electron-like; in past, primary method for estimating = MC)



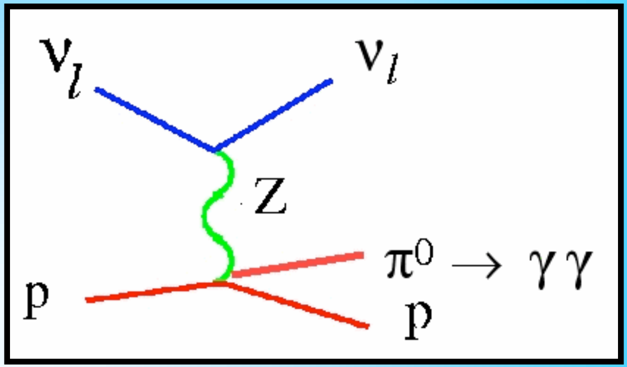


important **background**
for ν osc exps

because $\nu_\mu \to \nu_e$ is so low,
bkgs can have a major impact!

NC π^0 Production

Why important?

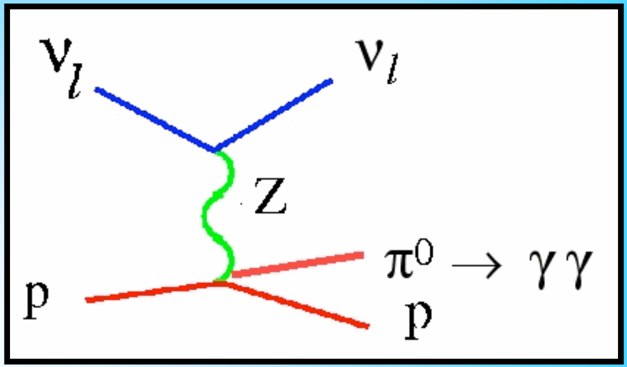


ν_μ N $\rightarrow$ ν_μ N π^0

- **interesting on their own**
  - unfortunately, process has not been well constrained in the past
  - interested in determining mode of production (resonant or coherent)

NC π^0 Production

Why important?



$\nu_\mu N \to \nu_\mu N \pi^0$

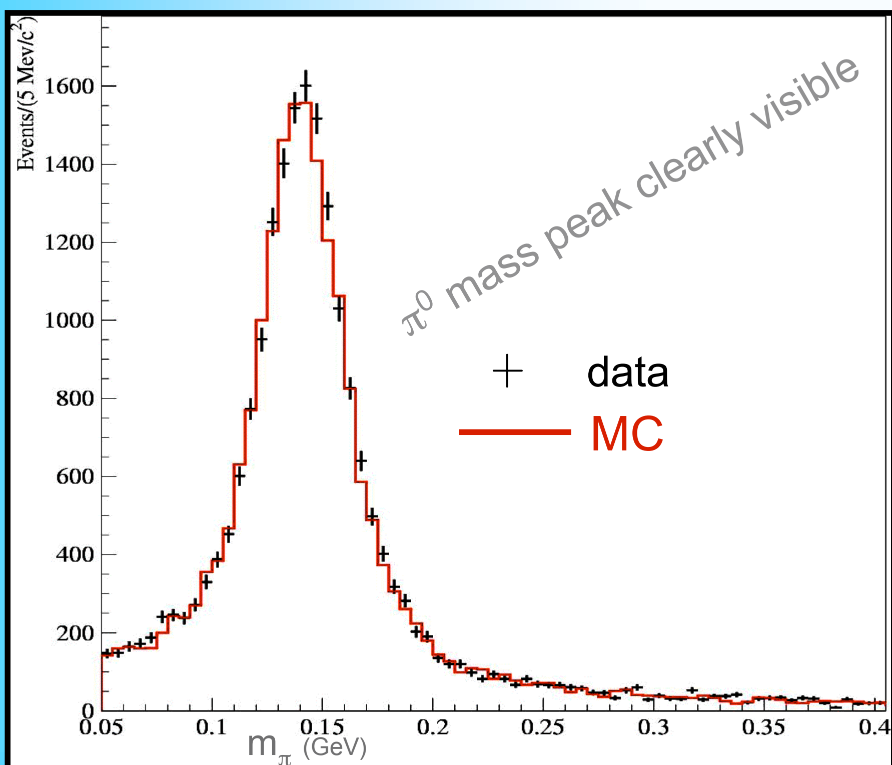
- **where are we now?**

 - now have 2 orders mag larger event samples available (300 → 30,000 events)
 - helping drive ~20-40% uncertainties down to ~5-10% level

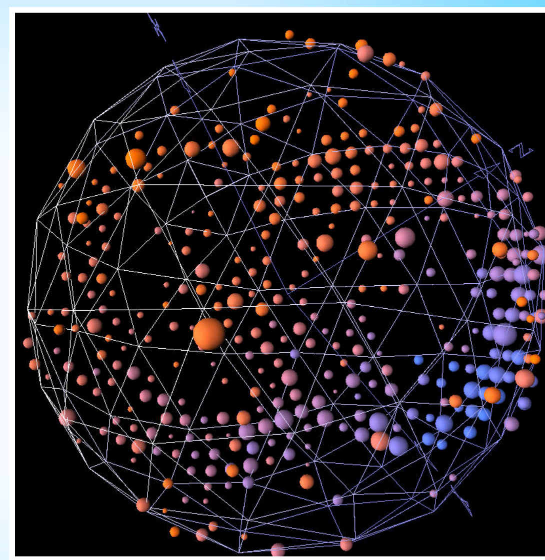
MiniBooNE NC π^0 Sample

• one of benefits of large open volume Cerenkov detector (4π) is excellent π^0 containment; world's largest ν NC π^0 sample

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



(J. Link)



(π^0 candidate in MB detector)

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

$$m_\pi^2 = 2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{12})$$

NC π^0 Production Modes

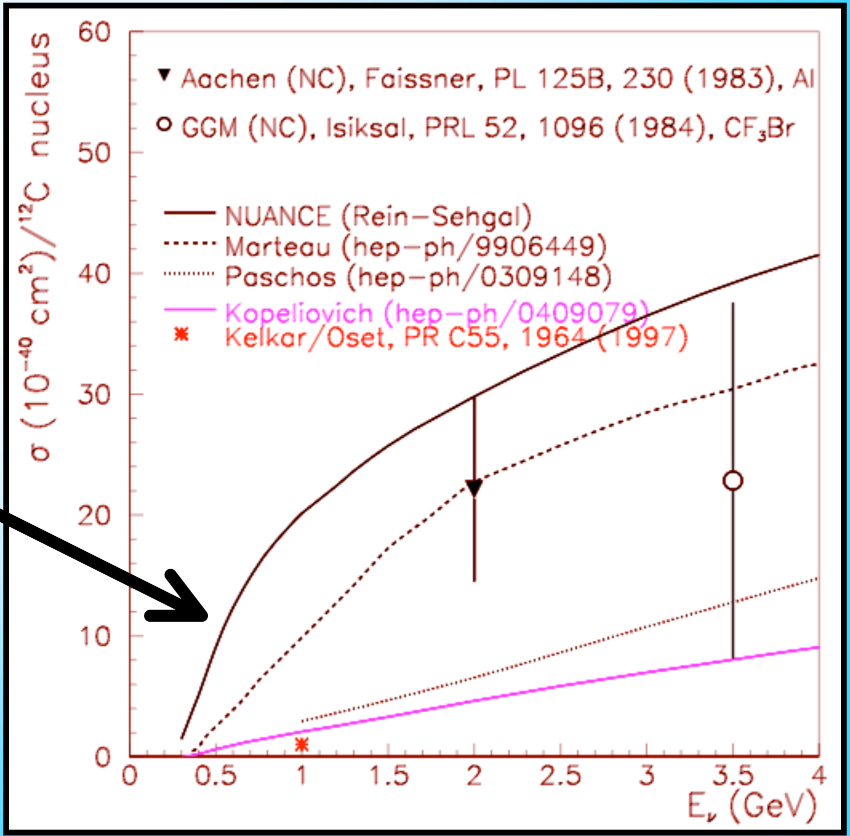
two modes of production (both are backgrounds to ν_e appearance searches)

(1) **resonant π^0 production**
$(\nu_\mu N \rightarrow \nu_\mu \Delta; \Delta \rightarrow N \pi^0)$

- dominant process
- no pre-existing meas of this σ at low energy

(2) **coherent π^0 production**
$(\nu_\mu A \rightarrow \nu_\mu A \pi^0)$

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

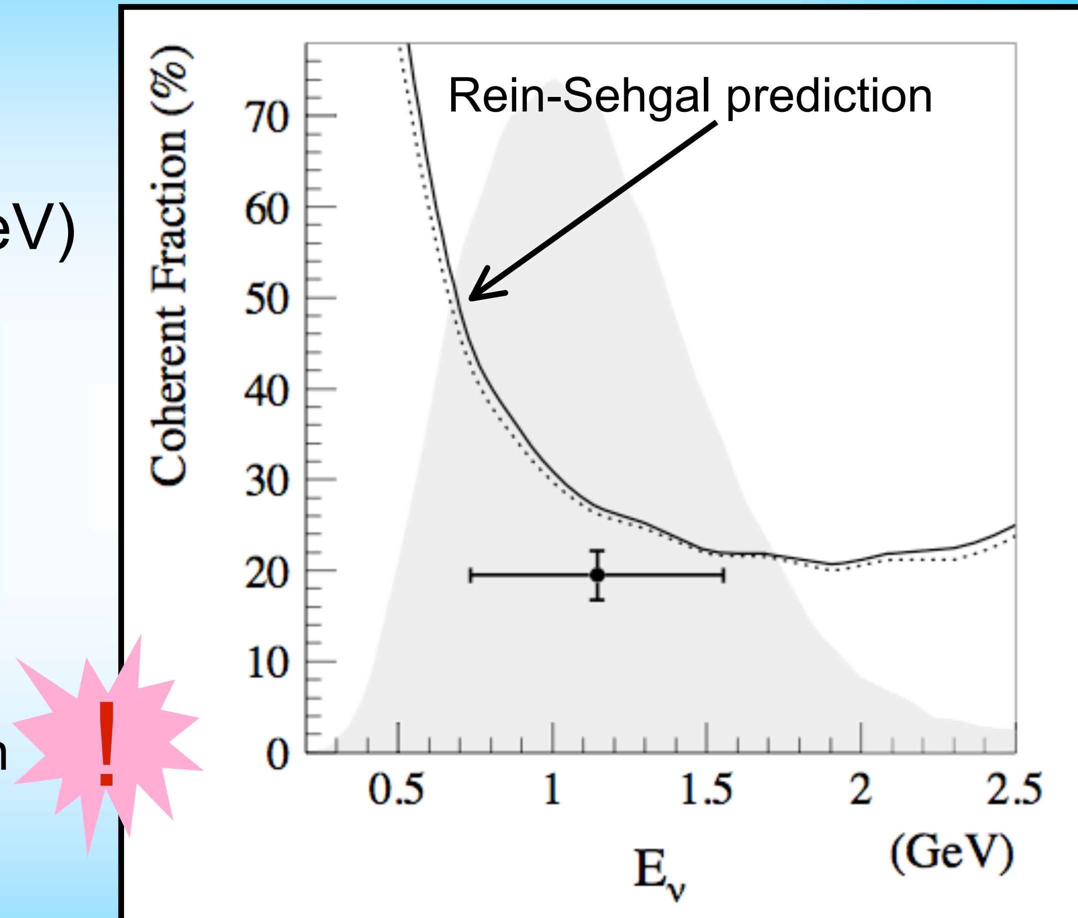


MiniBooNE Coherent NC π^0

- 1^{st} observation of NC coherent π^0 production at low energy (E_ν< 2 GeV)

- 14% measurement
  (helped reduce uncertainties in MiniBooNE's $\nu_\mu \rightarrow \nu_e$ search)

- 35% lower than most widely used model prediction
  (forced an immediate change in our π^0 background predictions)

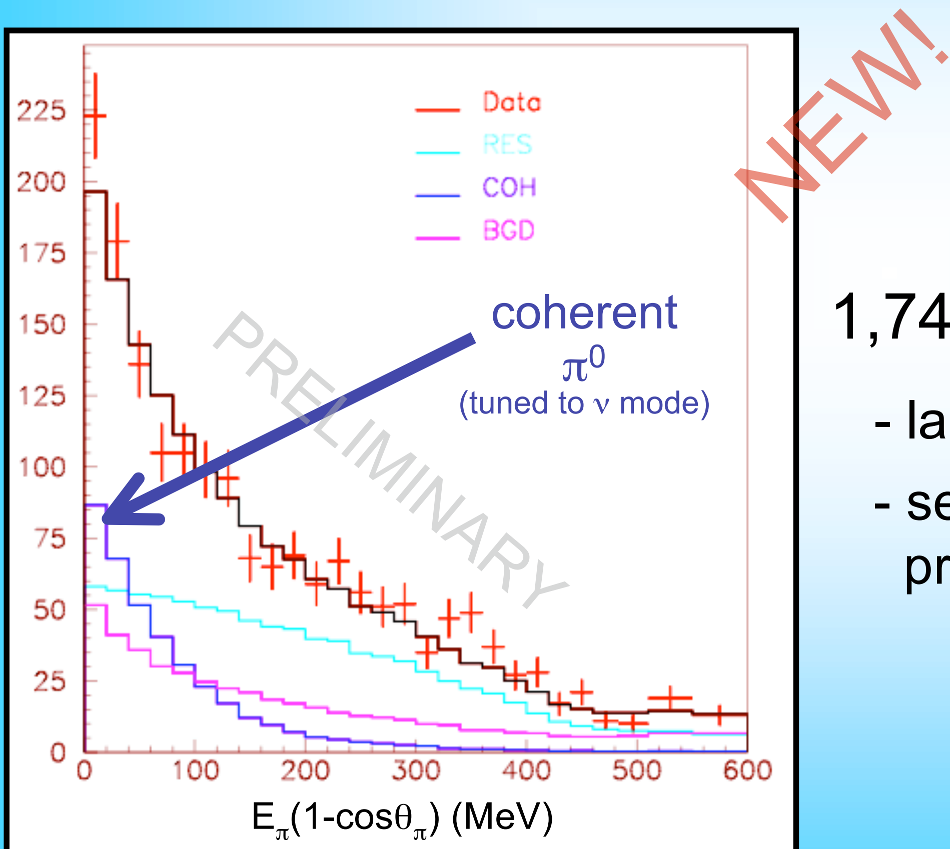


- coherent π^0 fraction = (19.5 ± 2.7)%; MC prediction = 30%

published this month in Phys. Lett. **B664**, 41 (2008)

1^{st} Look at MiniBooNE $\bar{\nu}$ NC π^0

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



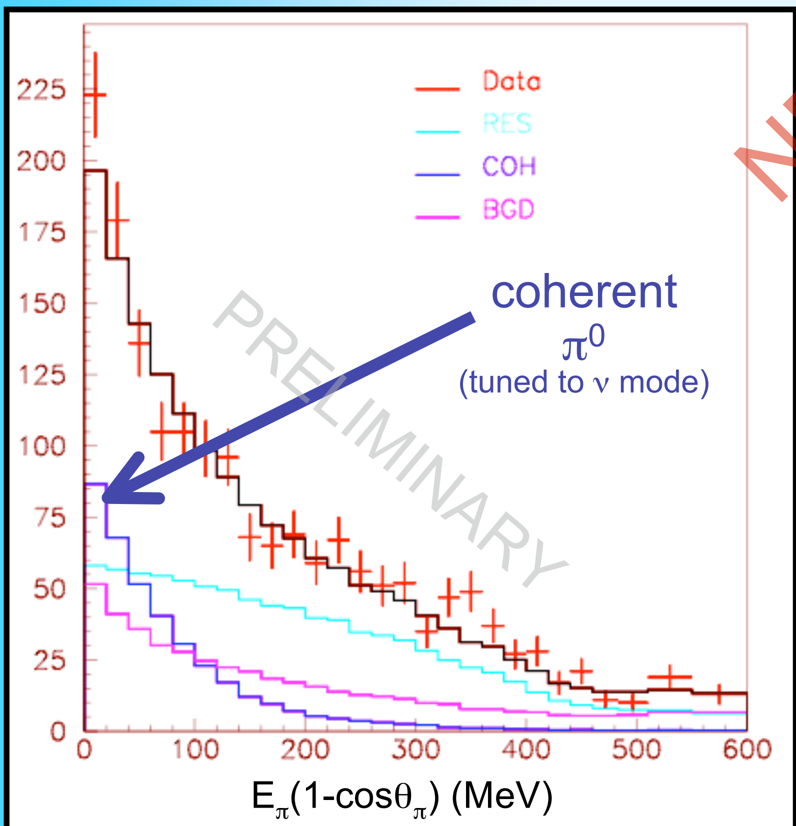
(V. Nguyen)

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

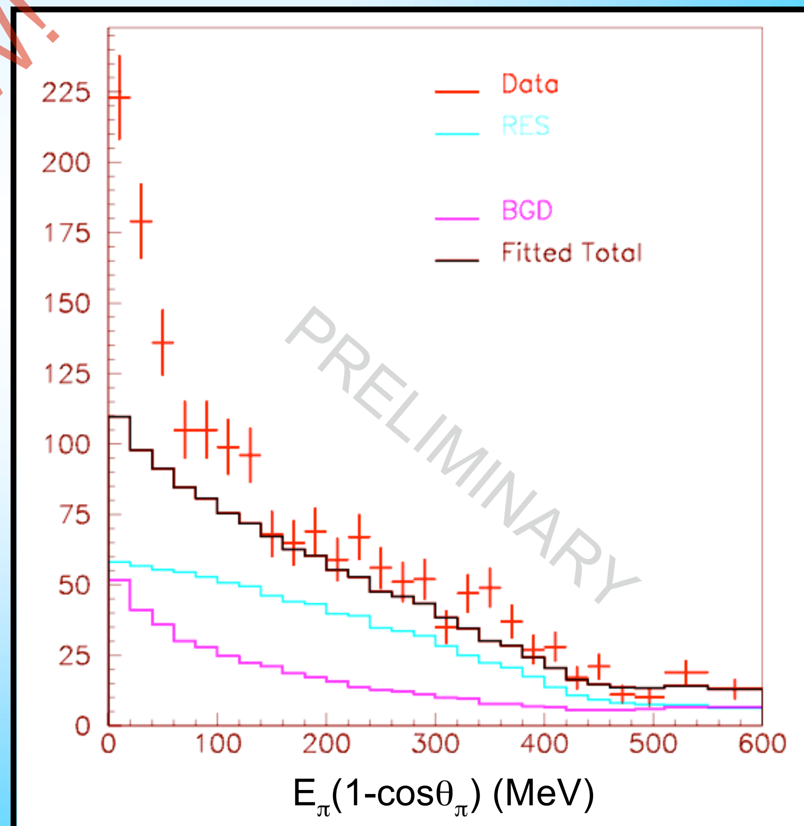
- largest sample of its kind
- see clear evidence for NC coherent π^0 production in both ν and $\bar{\nu}$ data

1^{st} Look at MiniBooNE $\bar{\nu}$ NC π^0

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



NEW!



(V. Nguyen)

(prediction if no coherent π^0 contribution)

1st Look at MiniBooNE $\bar{\nu}$ NC π^0

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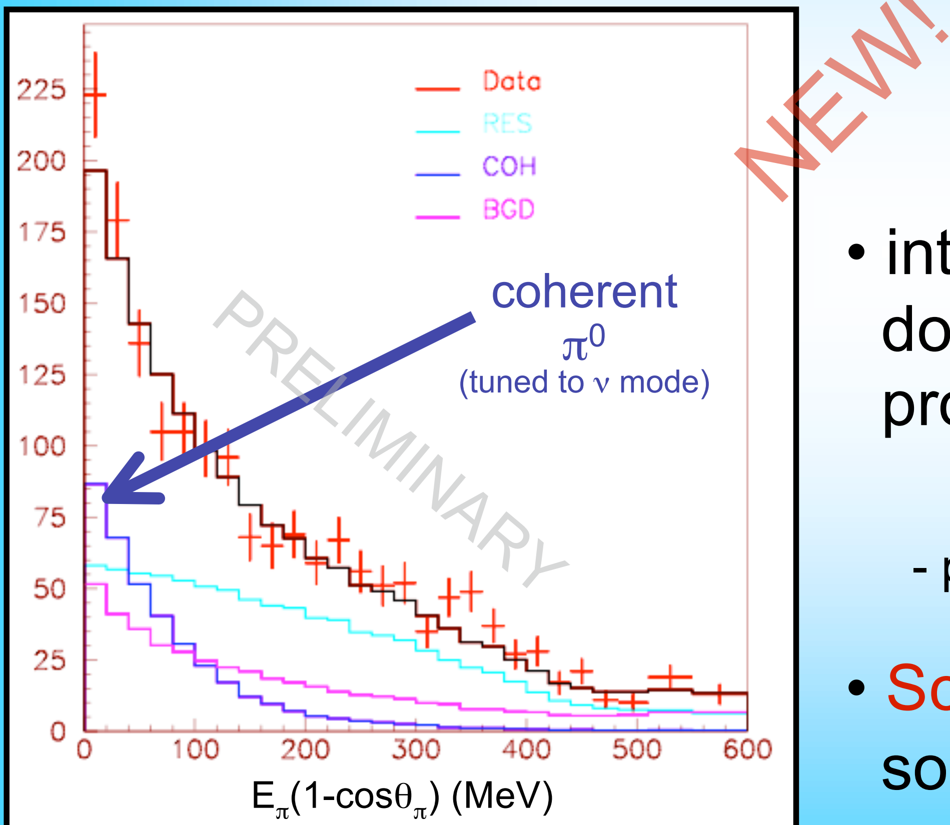


(V. Nguyen)

- interesting because K2K does not see evidence for this process in the CC π^+ channel
  (PRL **95**, 252301 (2005))
  - providing a challenge for theorists !

- SciBooNE & MINERνA will have something to say on this too!

Low Energy ν Interactions

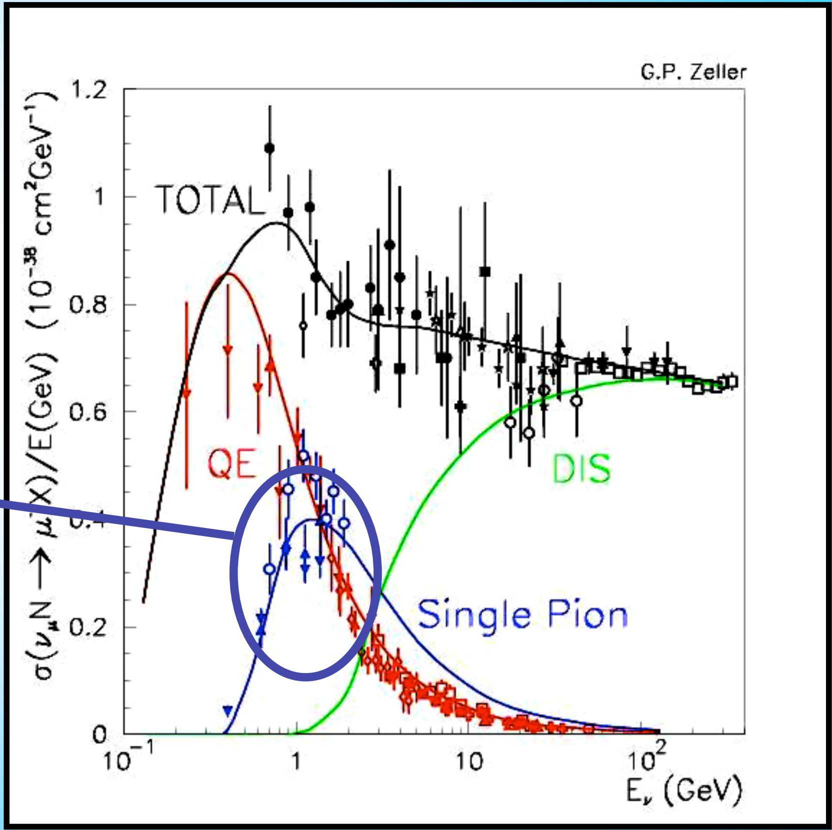
• moving on from NC to CC single pion production …

(1) quasi-elastic (QE)

(2) NC 1π^0 production

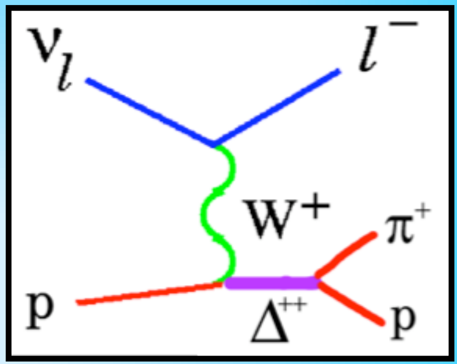
(3) CC 1π production

- 31% of MB events are CC π^+
- 5% of MB events are CC π^0



CC 1π Production

Why important?



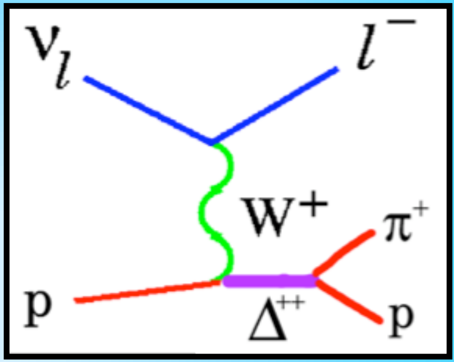
$\nu_\mu N \rightarrow \mu^- N \pi$

- **important for neutrino oscillation analyses**
  - dominant background to QE signal samples
  - at these E's, π re-interaction σ is large (30-40% of π's absorbed in nucleus)

really important **background** for ν oscillation experiments

CC 1π Production

Why important?

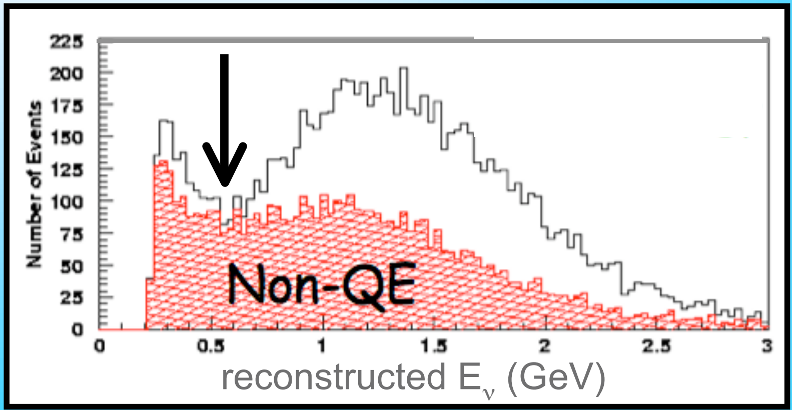


$\nu_\mu N \rightarrow \mu^- N \pi$

- **important for neutrino oscillation analyses**
  - dominant background to QE signal samples
  - at these E's, π re-interaction σ is large (30-40% of π's absorbed in nucleus)

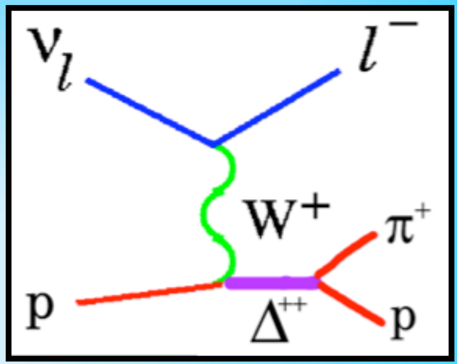
- <u>example:</u>

  $\nu_\mu \rightarrow \nu_X$ (ν_μ disappearance)



(C. Walter, NuInt07)

CC 1π Production

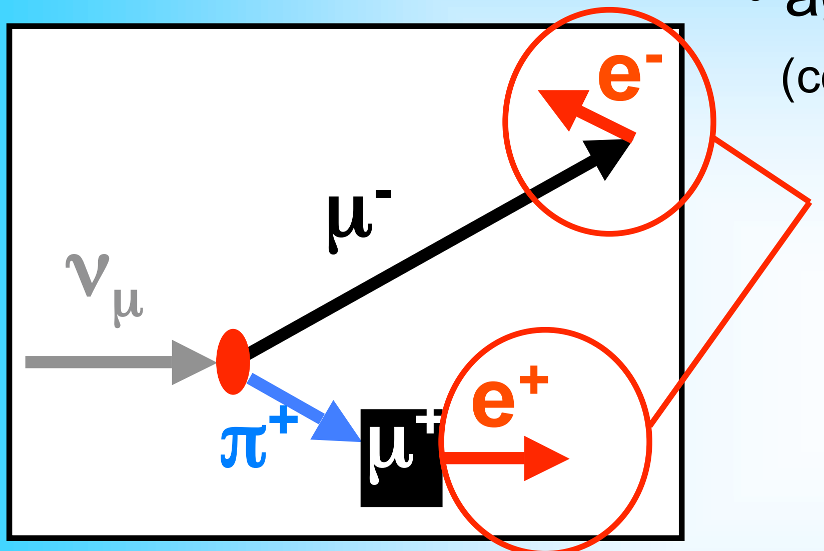


$\nu_\mu N \to \mu^- N \pi$

Why important?

- **where are we now?**
  - no measurements of this important background process on nuclear targets at low energy until now!
  - future ν oscillation exps would like to know this cross section to ~5%

MiniBooNE CC π^+ Selection

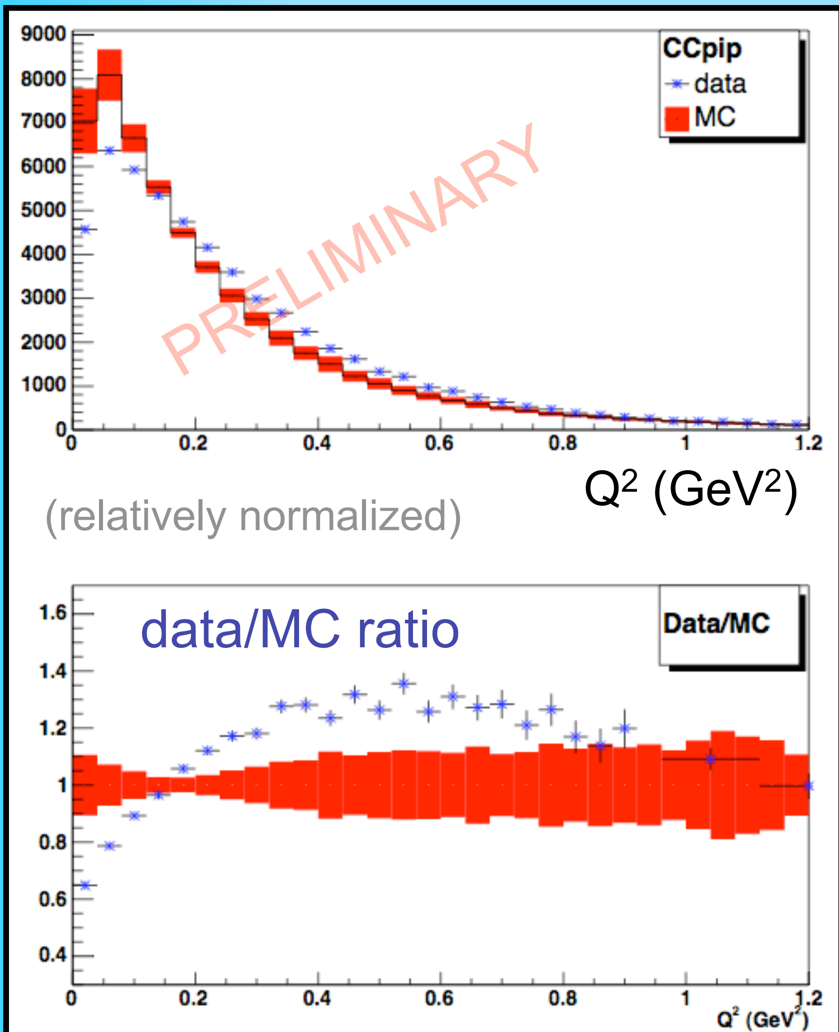


- again, very simple selection (count decay electrons):
  - select events with 2 decay electrons (1 each from μ & π^+ decay chain)
  - selection unique to MiniBooNE

- 87% pure CC π^+, 12% efficiency
- 46,649 ν_μ CC π^+ events (order of magnitude > than all past exps combined)
- reconstruct T_μ, θ_μ from outgoing μ $\Rightarrow Q^2$

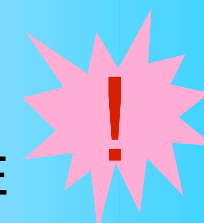
MiniBooNE CC π^+

(J. Nowak, S. Linden)



- previously reported a CC π^+/QE cross section ratio measurement (hep-ex/0602050; in process of updating)

- large inconsistency seen in Q^2 dependence these events
  - Rein-Sehgal (1981)
  - also seen in other exps
  - larger than what see in QE



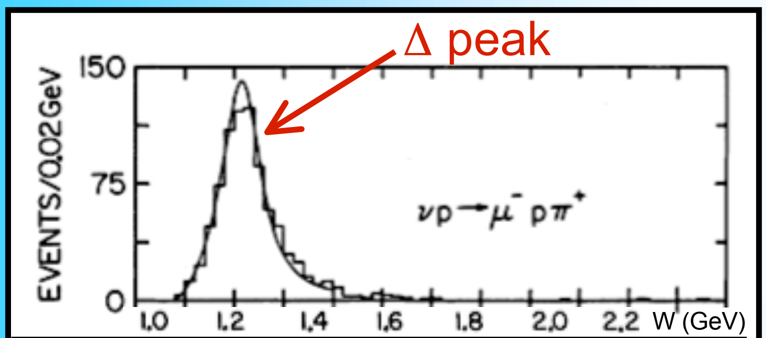
- outdated form factors? M_A?
- missing nuclear effects?
- additional muon mass effects?
- CC coherent π^+ absent?

add'l info right now from K2K & SciBooNE, plus will have from MINERνA!

New CC π^+ Fitter

- have made significant improvements to CC π^+ reconstruction in particular, can now identify and reconstruct outgoing π^+

(M. Wilking)



ANL, Phys. Rev. **D25**, 1161 (1982)

- last time looked at invariant mass distribution in ν_μ CC π^+
- ANL, 12ft bubble chamber, D_2
- 1,115 events
- one of highest statistics probes of resonance structure with ν's

- have studied resonance structure in detail with e^-'s & γ's, but for ν's this was as good as it got

New CC π^+ Fitter

• have made significant improvements to CC π^+ reconstruction in particular, can now identify and reconstruct outgoing π^+

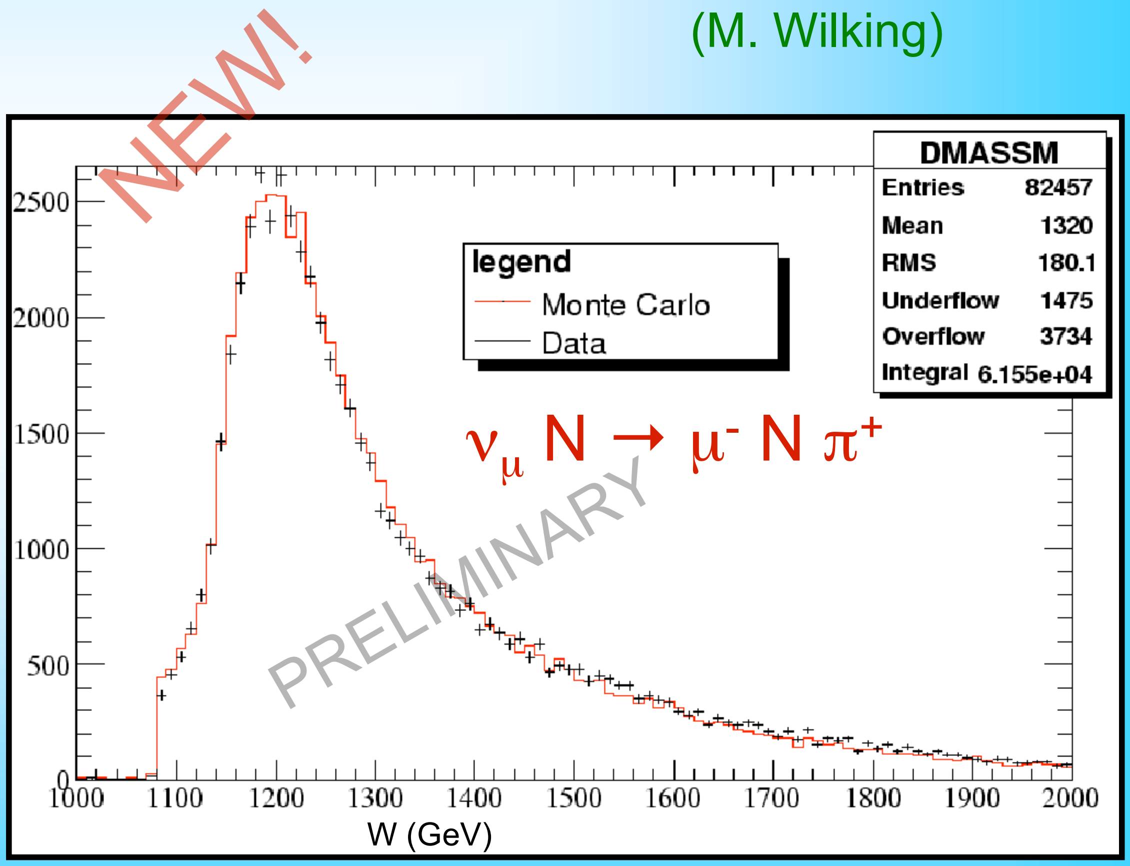
(M. Wilking)

• brand new MiniBooNE results

• ~82,000 events

• 1st time have seen W dist in modern ν data (and on nuclear target)!

• good agreement w/ prediction (Rein-Seghal)

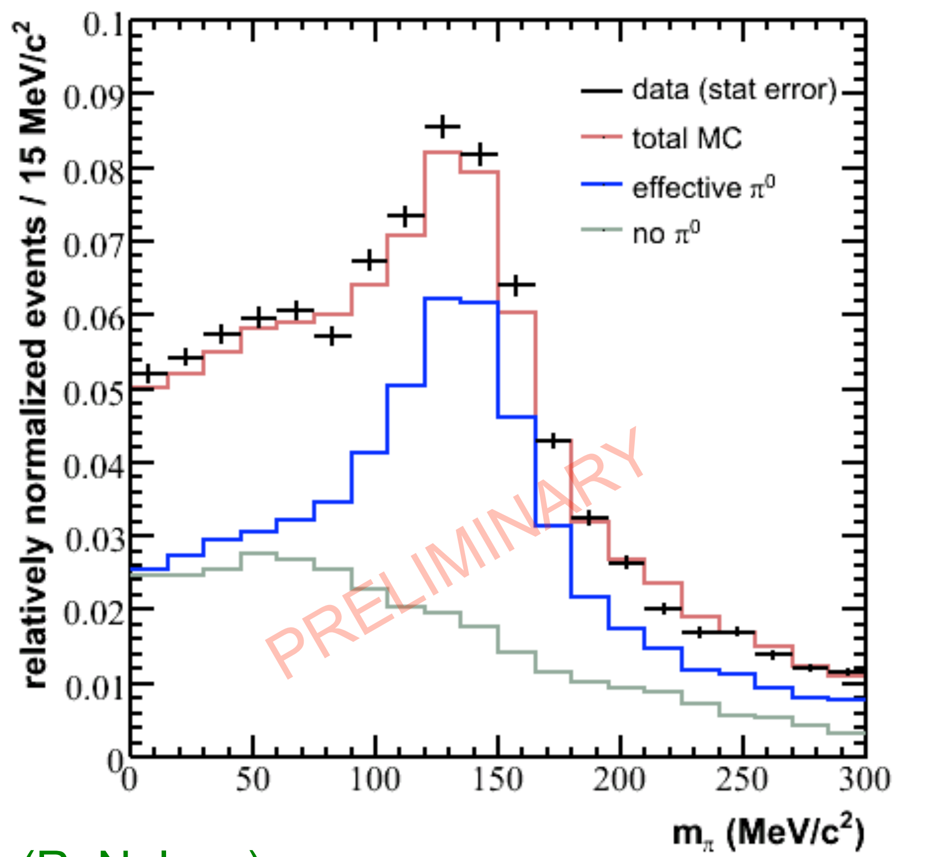


MiniBooNE CC π^0

NEW!

• developed a new 3-ring fitter ($\mu + \gamma\gamma$) for this new σ_ν analysis

(5% of MiniBooNE events)



(R. Nelson)

$\nu_\mu\, n \rightarrow \mu^-\, p\, \pi^0$

• 31,755 events

• provides means to test resonance model alone with ν scattering

(no coherent π prod in this case)

also, new results from K2K now!

(+ soon from SciBooNE & MINERνA)

Coming Soon

- mentioned MiniBooNE QE and NC π^0 papers which came out this year
- several other ν cross section measurements/publications in the pipeline …

Coming Soon!

- QE differential cross section (T. Katori)
- NC elastic cross section (D. Perevalov)
- CC π^+/QE ratio (S. Linden, J. Nowak)
- CC π^+ cross sections (M. Wilking)
- CC π^0 cross sections (R. Nelson)

The "Take Away"

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

- **signal samples = QE**

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

- **backgrounds: NC π^0 = bkg to ν_e appearance**
  CC $\pi^{+,0}$ = bkg to ν_μ disappearance

  - 1^{st} measurement of these σ's on nuclear targets at low E
  - several cases where significantly different than expectation (~30-40%)
  - nagging kinematic Q^2 disagreement in CC π^+ (source?)
  - intriguing difference between NC, CC coherent π prod at low E (tension)

Conclusions

- collection of past low E ν σ meas is quite sparse, especially on nuclear targets
- important that we know these for ν osc experiments, plus interesting on their own!
- active field of investigation at MiniBooNE
  - MiniBooNE has amassed world's largest ν sample @ 1 GeV (~700,000 ν and ~70,000 $\bar{\nu}$ events)
  - results from 3 samples: QE, NC π^0, CC $\pi^{+,0}$
  - including meas in region that haven't been probed before
  - new data uncovering some interesting surprises !
- complimentary to new measurements from K2K, plus look forward to future ν results from SciBooNE & MINERνA!
- finally starting to elevate ν scattering to "e^- scattering caliber"

Thank You!