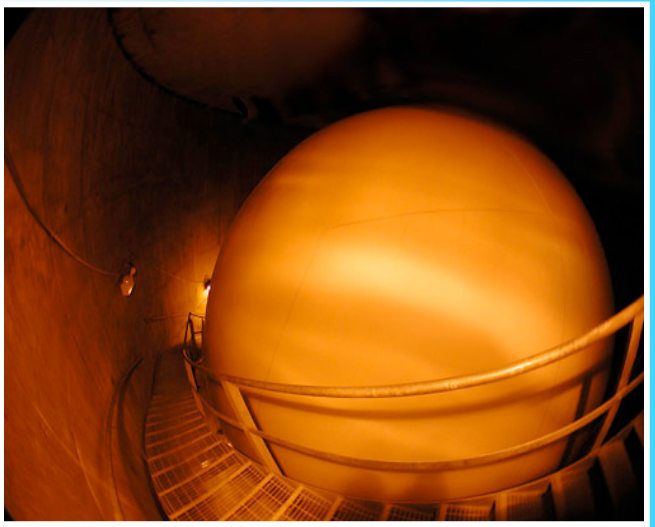
Recent ν Scattering Results from MiniBooNE

Sam Zeller
LANL

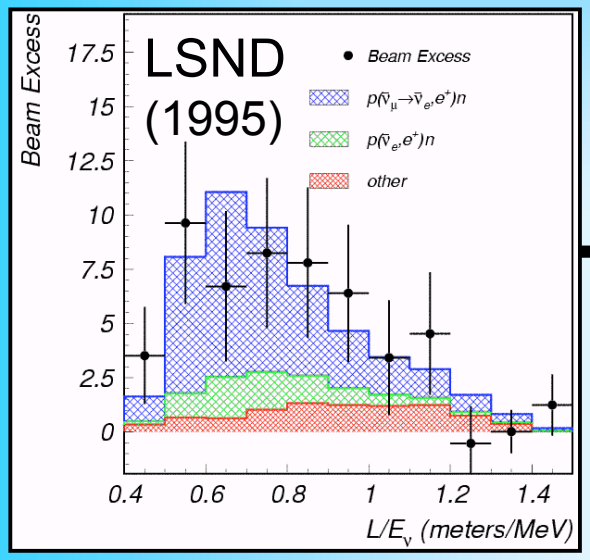
BNL seminar

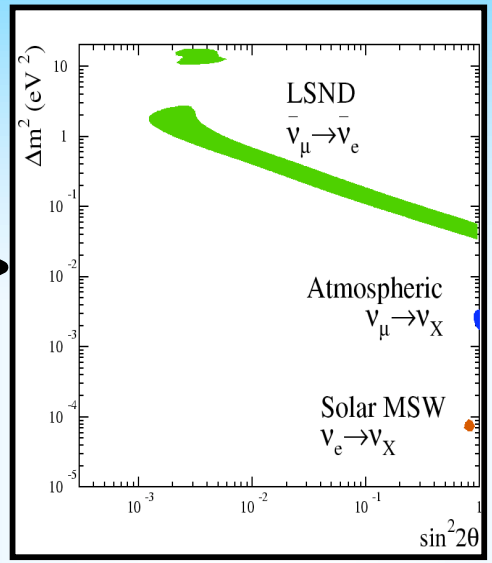
June 18, 2009



- hope to show you a different side to the MiniBooNE experiment

Most Familiar with ν Oscillations at MiniBooNE





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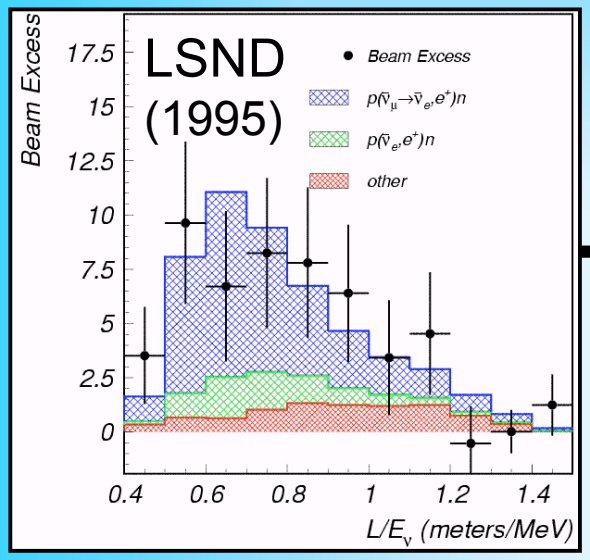

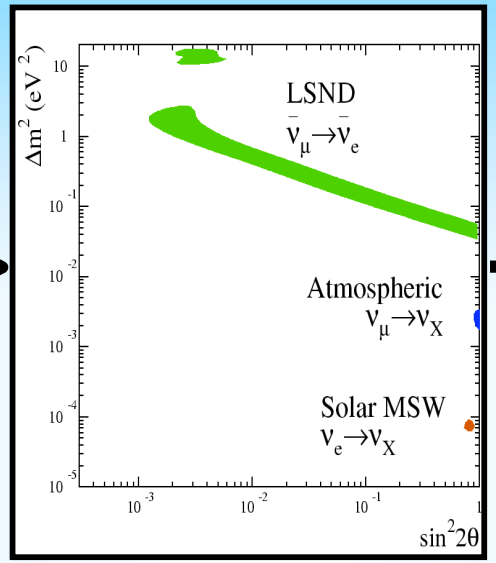

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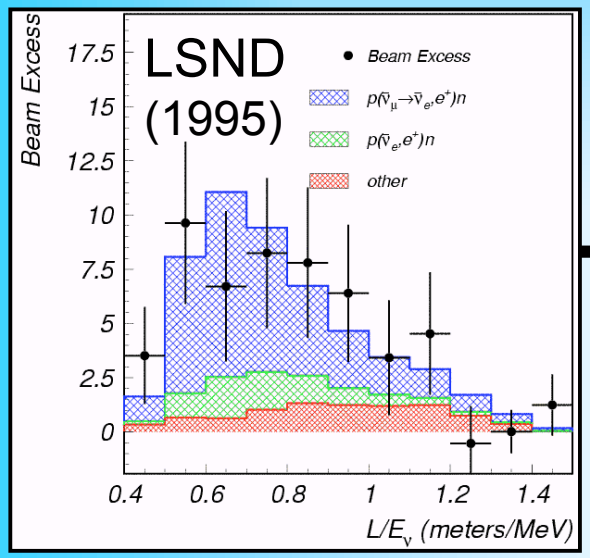

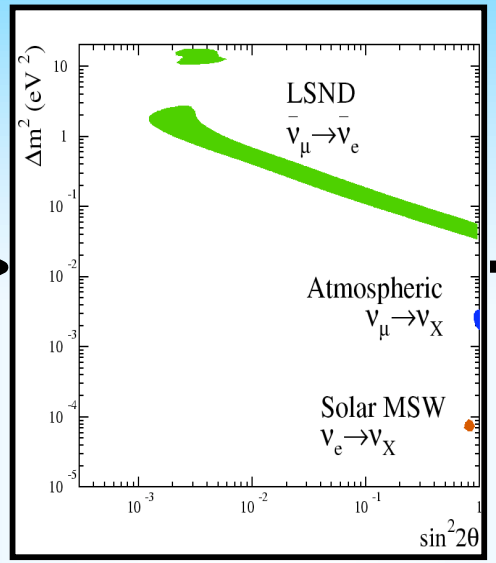

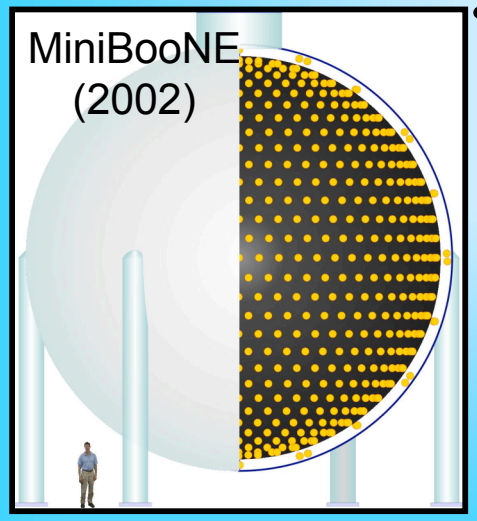

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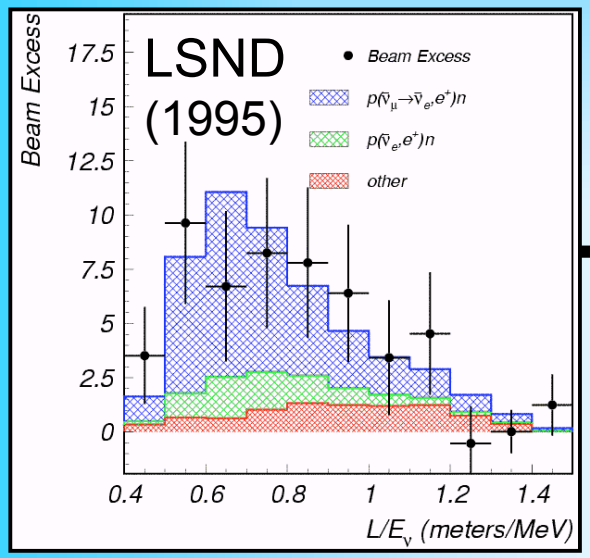

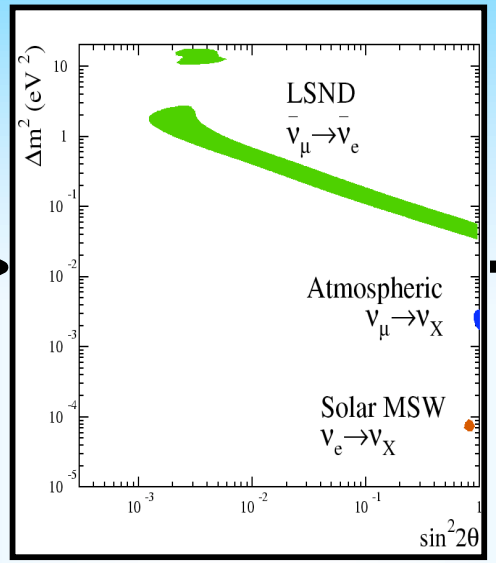

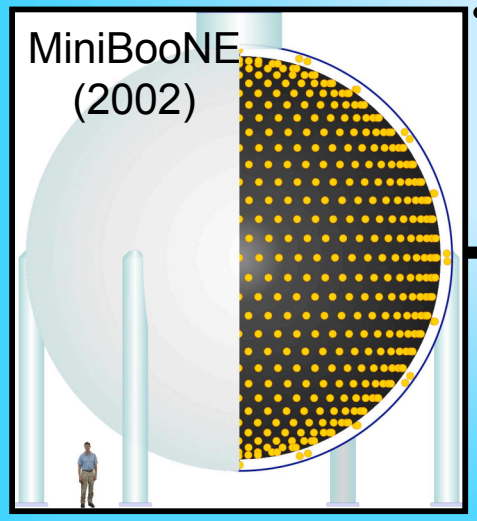

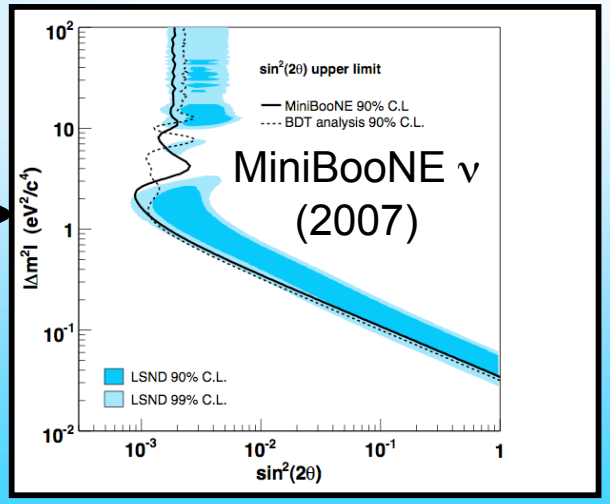

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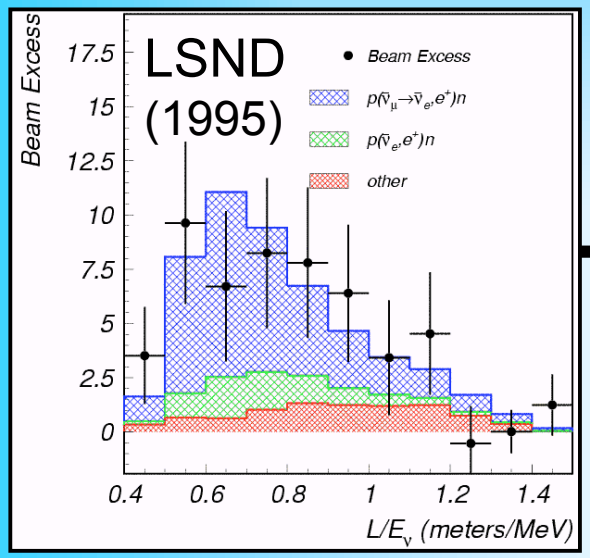

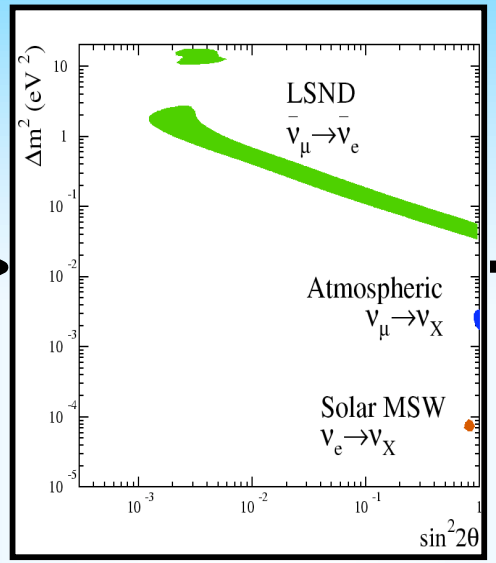

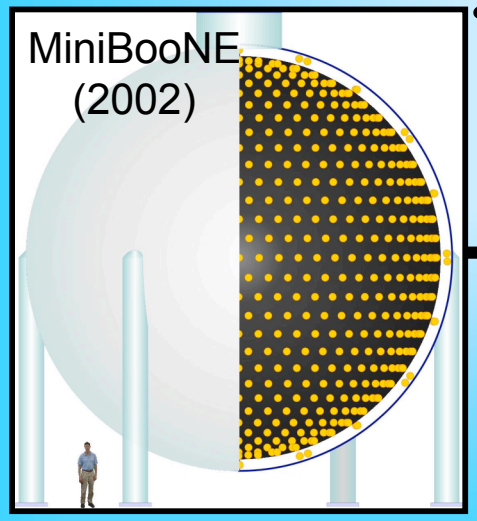

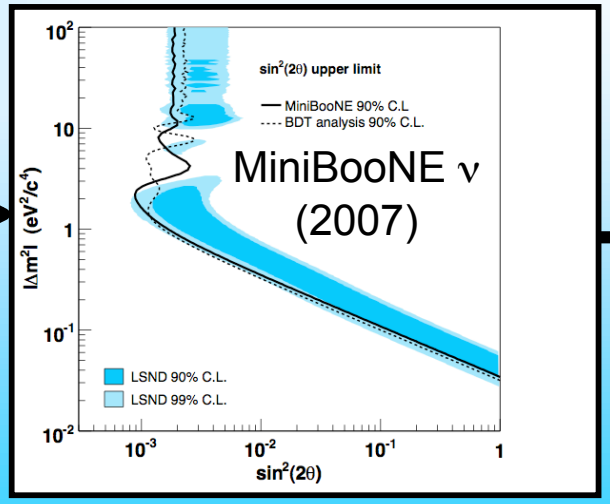

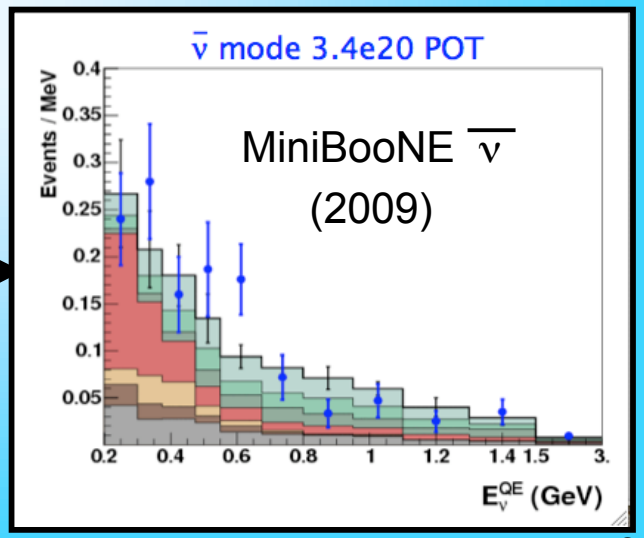

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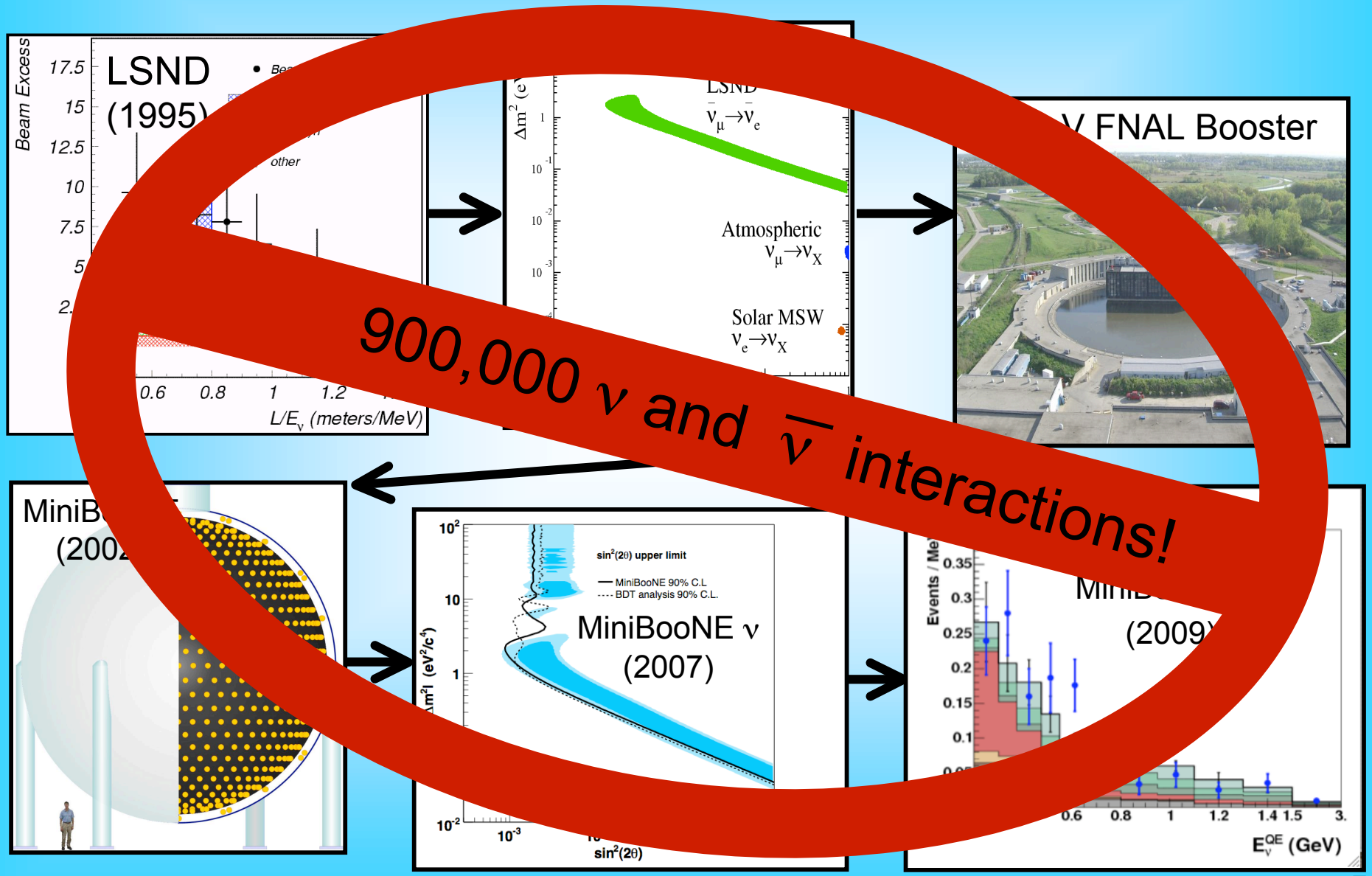


900,000 ν and $\bar{\nu}$ interactions!

Outline

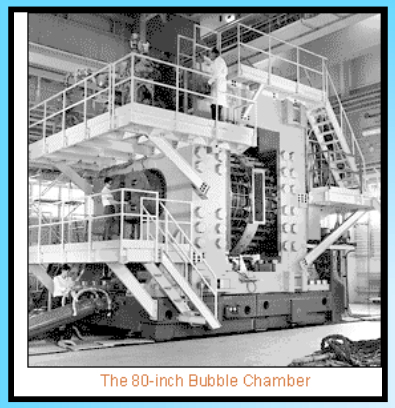
- heard a talk on recent **MiniBooNE ν oscillation results**
  (Chris Polly, BNL seminar, January 2009)

- this talk: **MiniBooNE ν scattering program**

  - ν cross section results have recently released
  - in fact, all were made public <u>last month</u> at NuInt09
  - "hot off the press"

- will point out their utility for ν oscillation experiments

- first, a little history on how we got here …


The 80-inch Bubble Chamber

bubble chambers

(ANL, BNL, CERN, FNAL, Serpukhov)

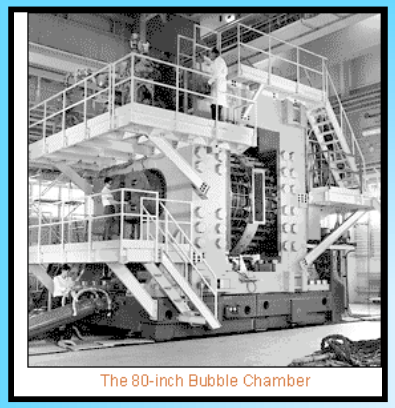
- 1st ν cross section measurements
- typically low E_ν

1970

1980

1990

2000



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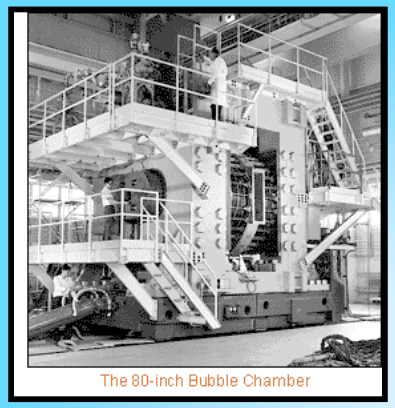
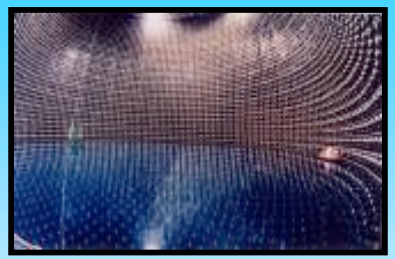
counter experiments

(CDHS, CHARM II, CCFR, NuTeV, NOMAD)

- move to higher E_ν, higher statistics
- DIS cross section, structure functions





neutrino oscillations!

- ν oscillation parameters
- back to low E_ν
- high intensity ν beams

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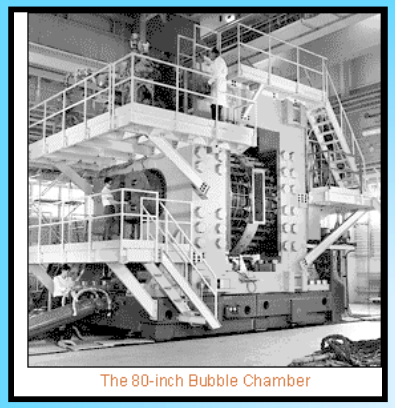

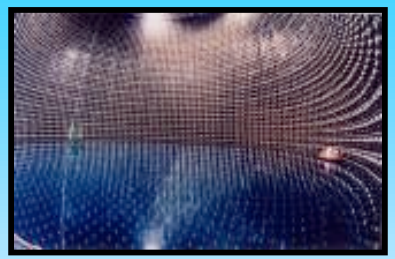

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precision measurements, θ_{13}, mass hierarchy, CP, ...

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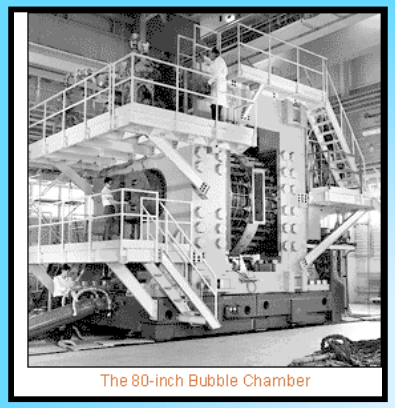

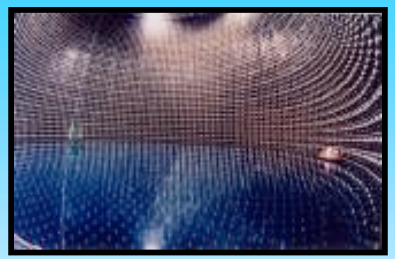

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produced renaissance in low energy ν interaction physics

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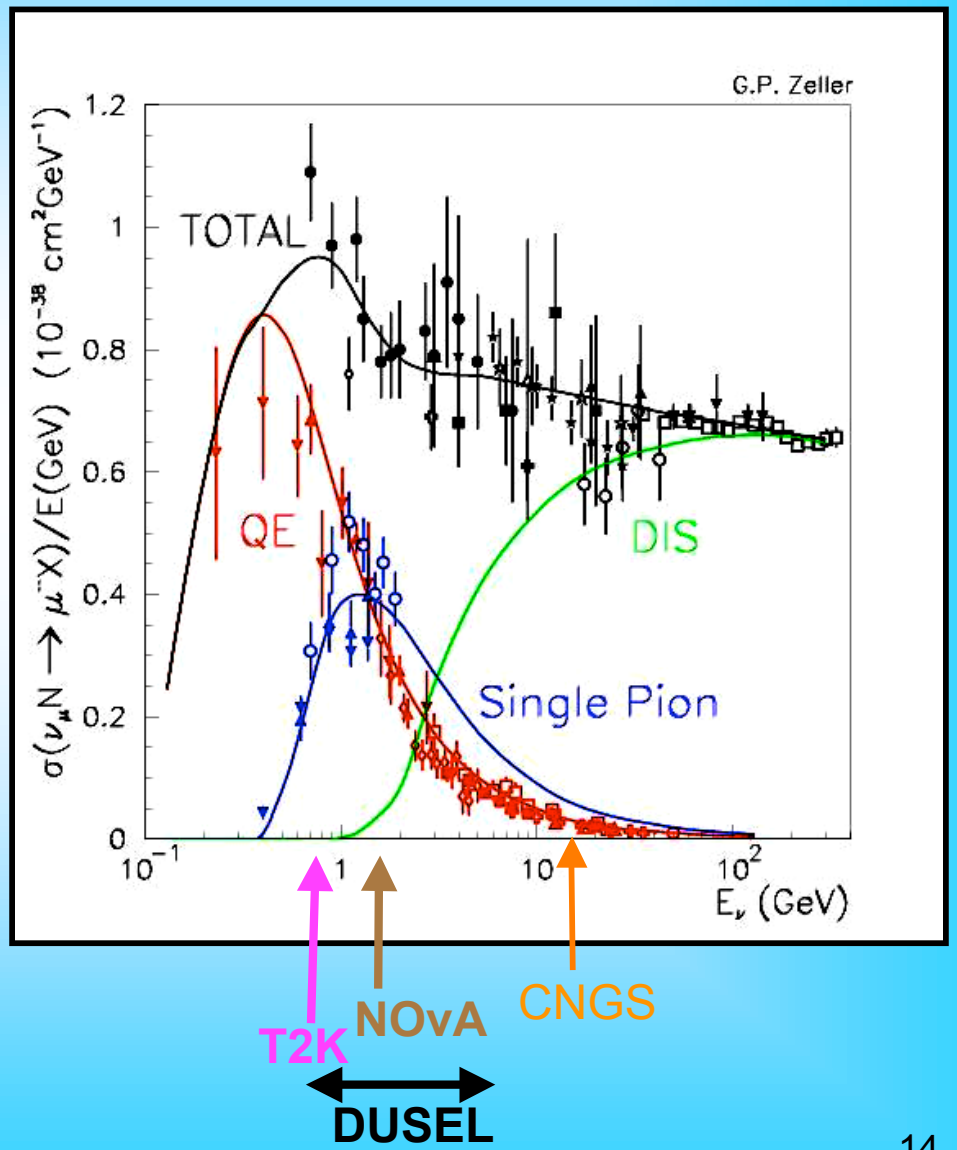
Neutrino Cross Sections

- future accelerator-based ν oscillation experiments will be operating in few-GeV E range

  - all sitting in this murky transition region where multiple processes are contributing



Neutrino Cross Sections

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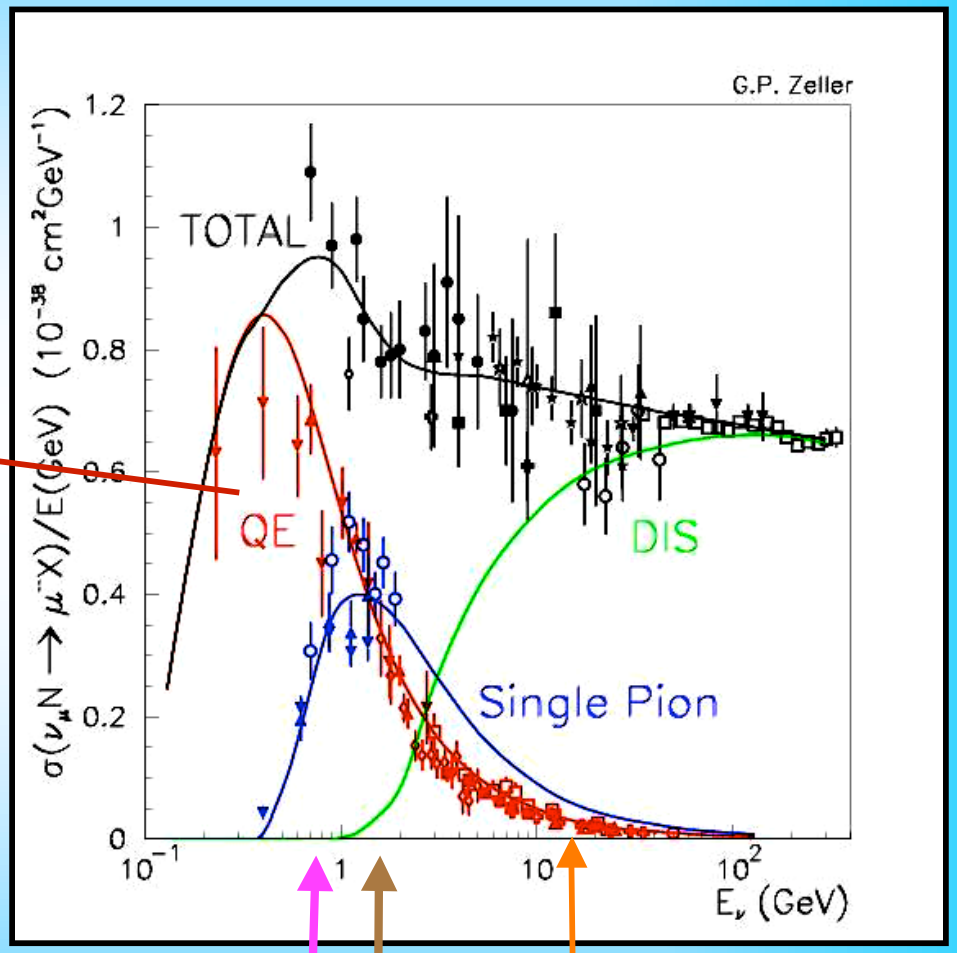
quasi-elastic (QE) signal



T2K NOvA CNGS

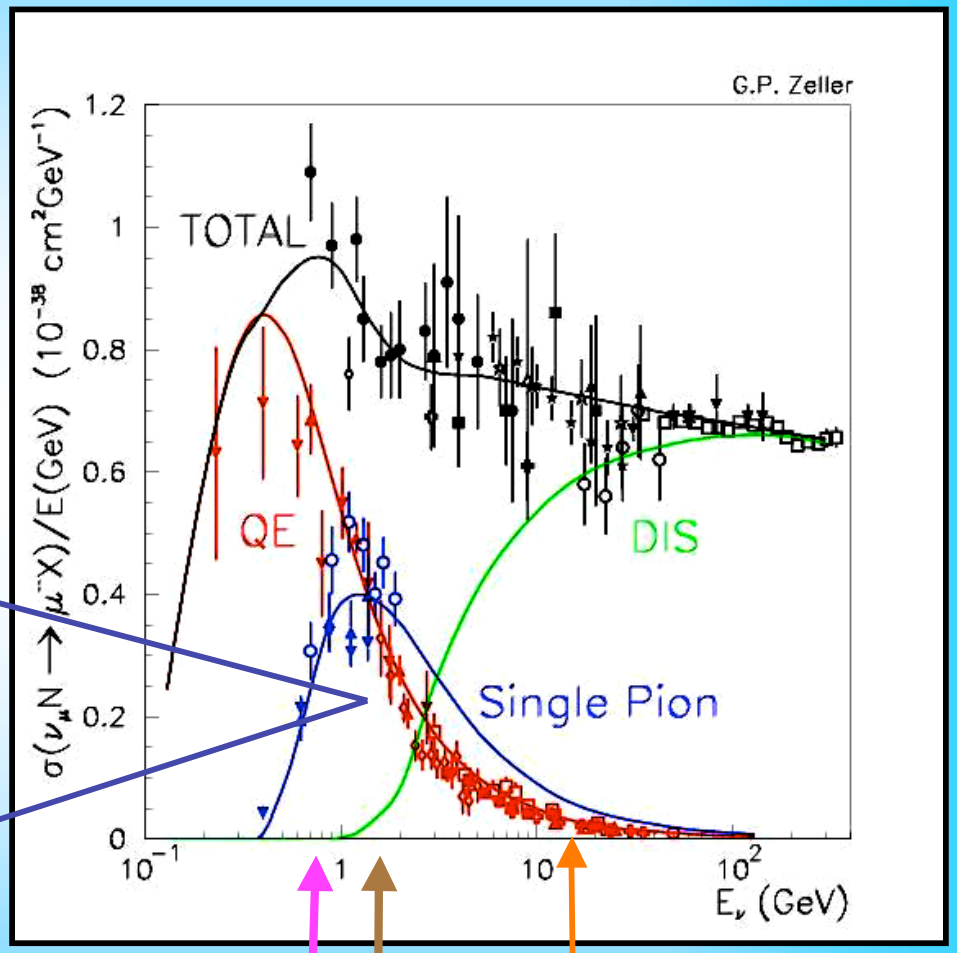
DUSEL

Neutrino Cross Sections

- future accelerator-based ν oscillation experiments will be operating in few-GeV E range

NC π^0
(background to ν_e appearance)

CC π^+
(background to ν_μ disappearance)



T2K NOvA CNGS

DUSEL

Neutrino Cross Sections

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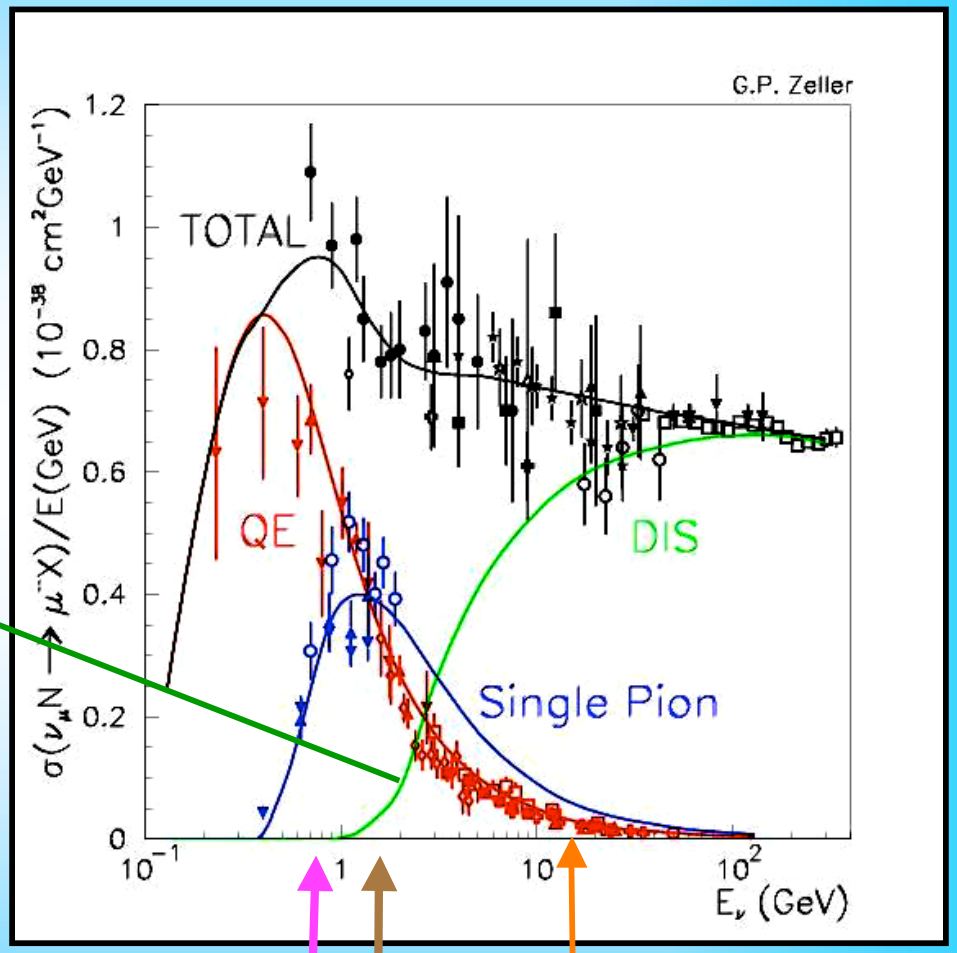
DIS
(need to extrapolate into low energy region)



- need to know each of these processes individually
- each has their own model

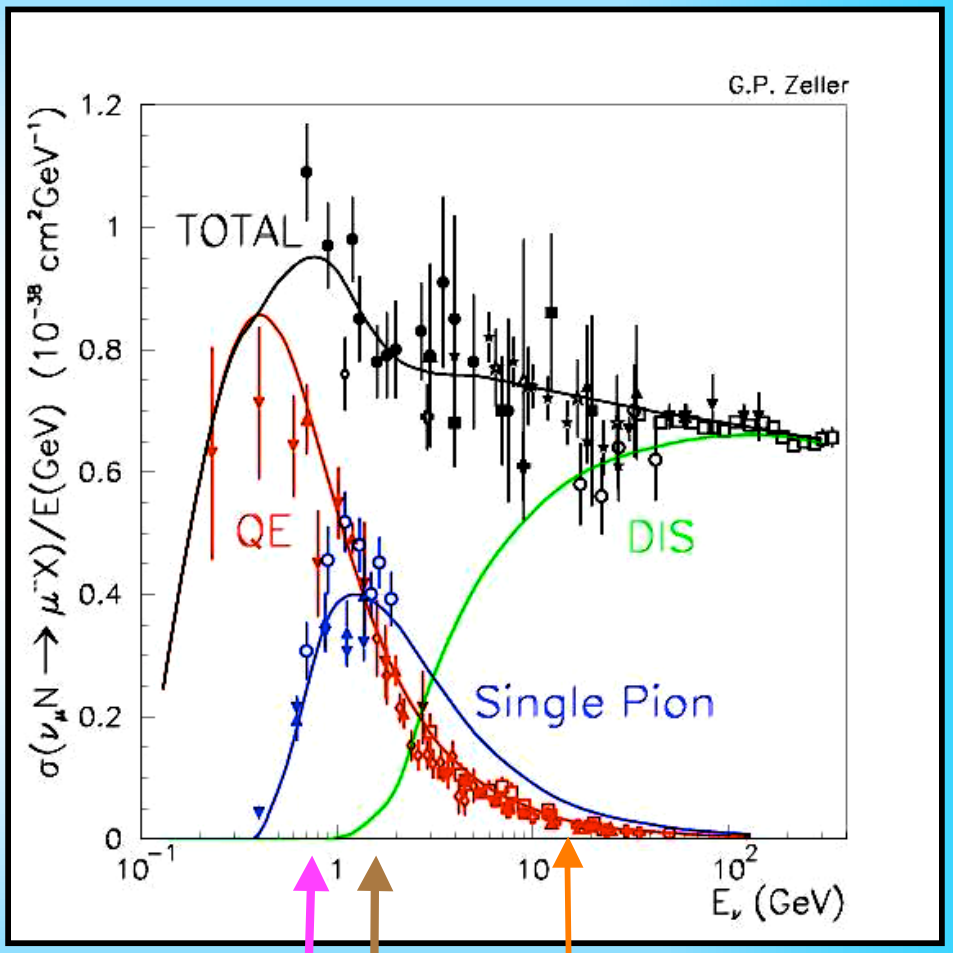
Neutrino Cross Sections

- future accelerator-based ν oscillation experiments will be operating in few-GeV E range

- data are 20-30 years old
  - 100's of events, mostly D_2
  - calcs we use are also old

- situation have been suffering with for past 30+ years

- luckily has been improving



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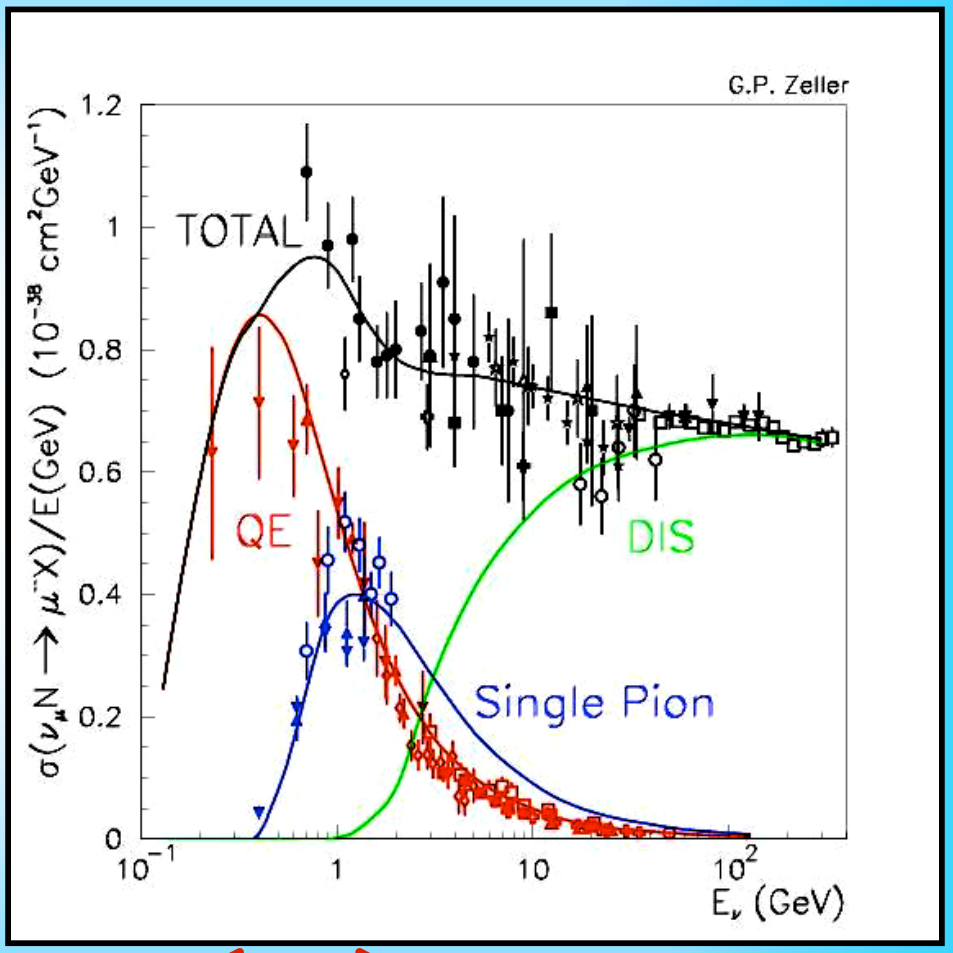


K2K, MiniBooNE, SciBooNE

nuclear targets!

MINOS, MINERνA

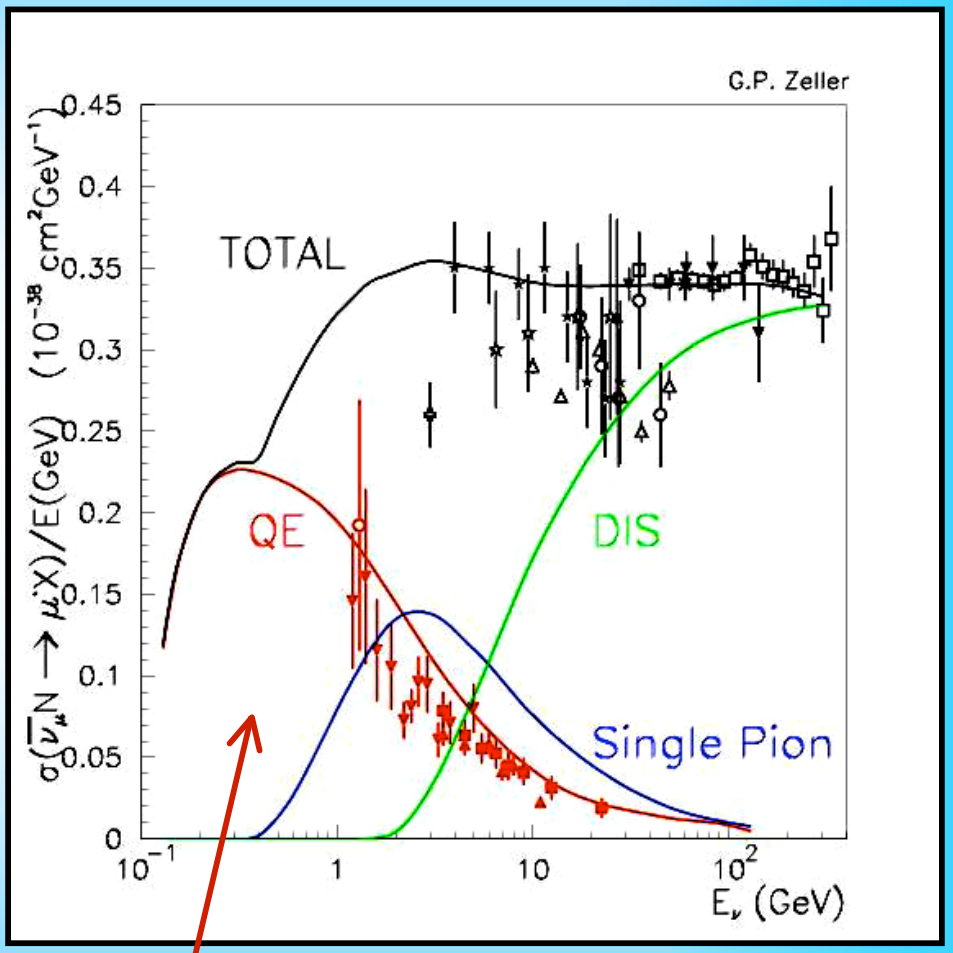
Antineutrino Cross Sections

- situation is even worse for $\bar{\nu}$, data is even more sparse

  - measure $\not{C}\not{P}$ δ by comparing oscillation probabilities of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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

- need to complete program in antineutrinos as well



MiniBooNE has 1st $\bar{\nu}$ data in this sub-1 GeV energy range

ν Scattering at MiniBooNE

- MiniBooNE has recently gotten into this ν scattering business

- primarily driven by our <u>own needs</u>
  (ν_e appearance, ν_μ disappearance in both ν and $\bar{\nu}$)

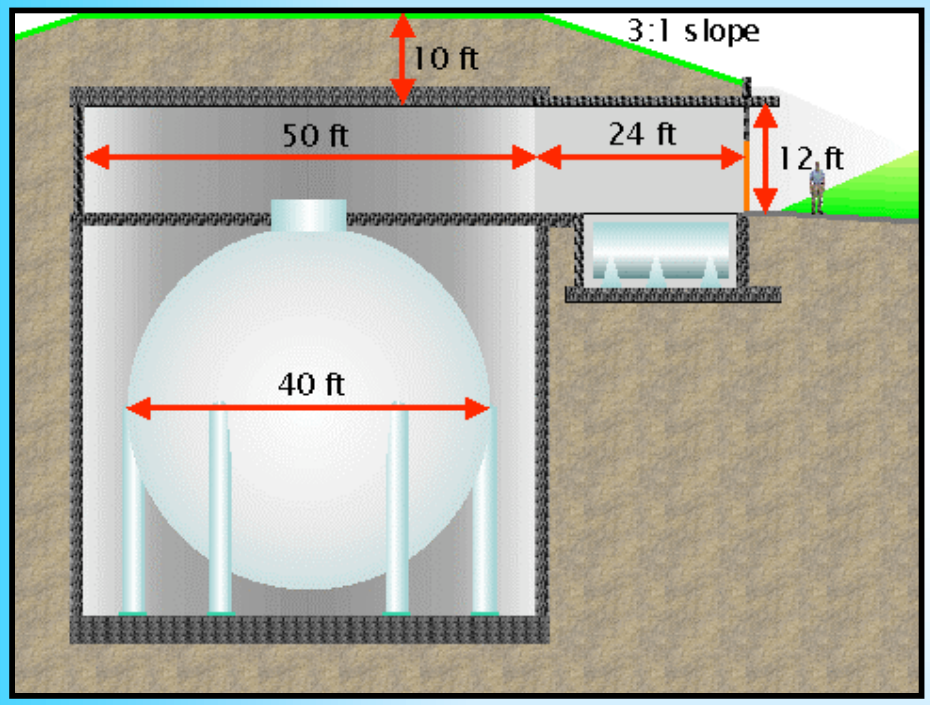
  - QE Aguilar-Arevalo *et al.*, PRL **100**, 032301 (2008) — signal
  - NC π^0 Aguilar-Arevalo *et al.*, PLB **664**, 41 (2008) — background

- have since transitioned to producing more <u>general purpose</u> σ_ν measurements (recognizing value of our high statistics data samples)

  - gap to fill
  - data in new regions
  - some surprises !

NEW!

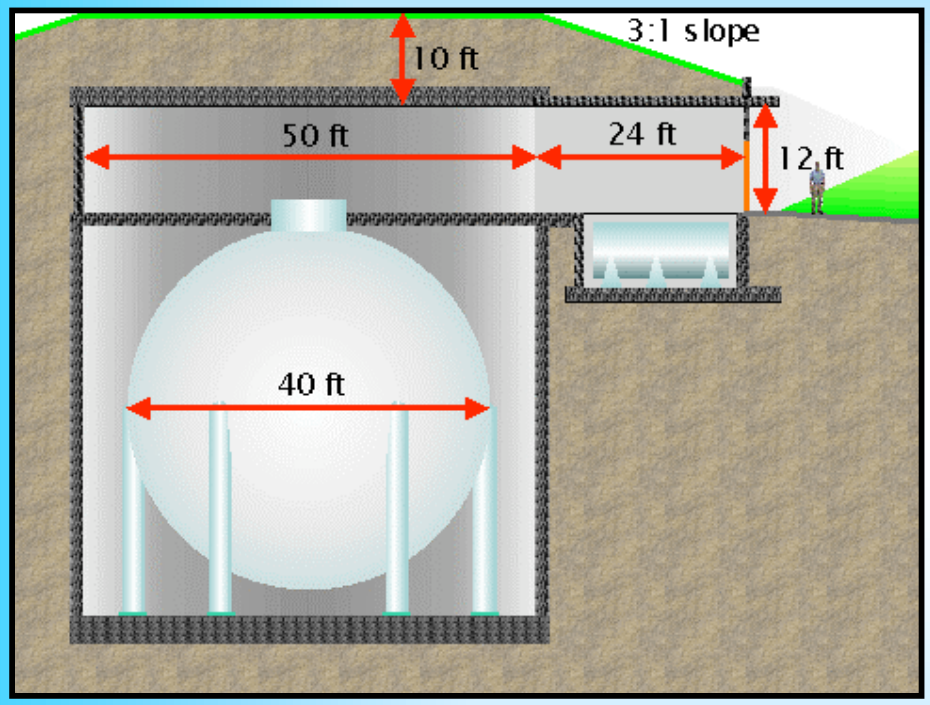
MiniBooNE Detector

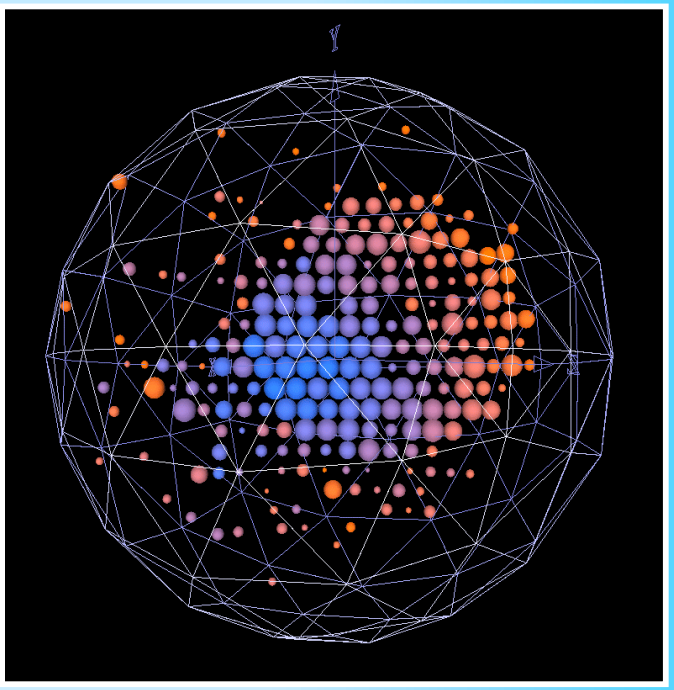


- 800 tons of mineral oil
- ν interactions on CH_2
- Čerenkov detector

Aguilar-Arevalo *et al.*, NIM **A599**, 28 (2009)

MiniBooNE Detector





muon in MiniBooNE

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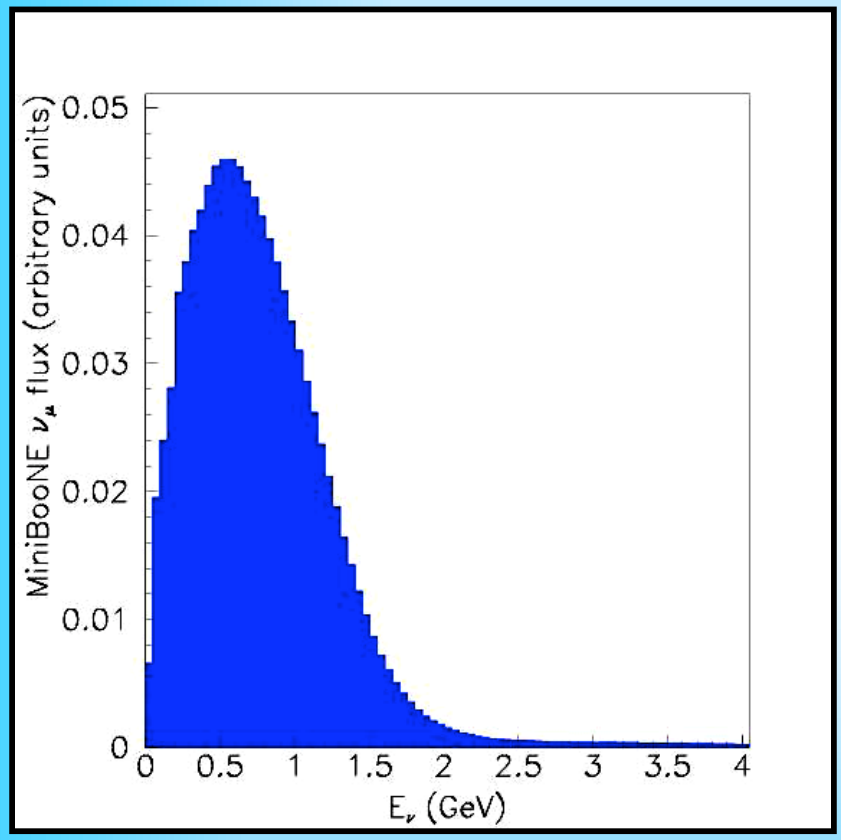
MiniBooNE Flux



predicted ν_μ energy spectrum

- high purity, >99% ν_μ in flavor
- well-suited for low energy ν cross section studies

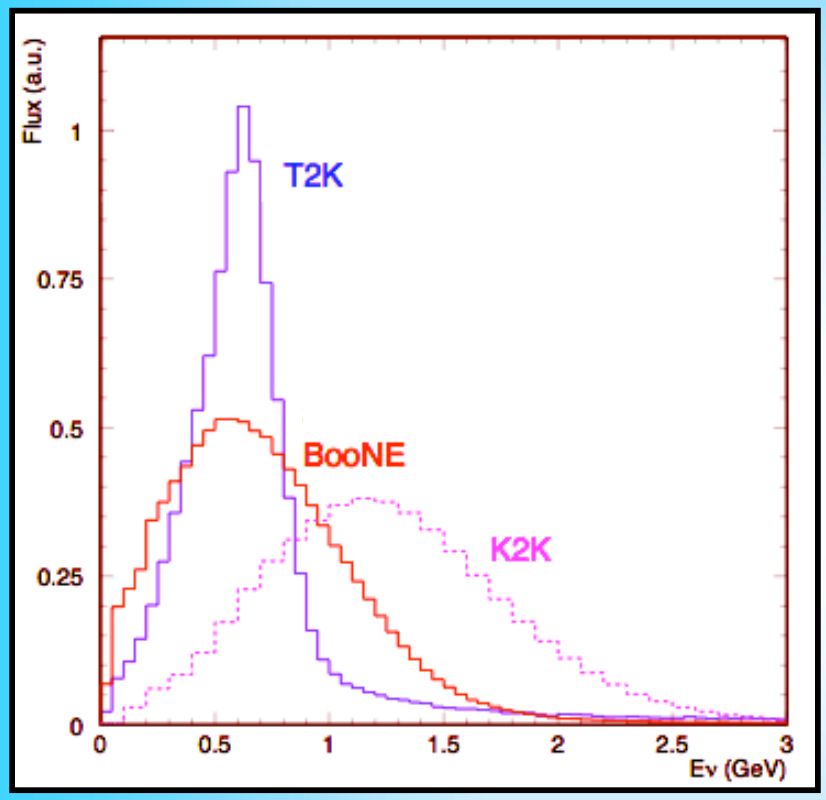
  $\langle E_\nu \rangle \sim 0.8$ GeV

  (similar to BNL WB ν beam)

  enjoy small backgrounds from higher multiplicity ν interactions

  (perfect for QE + 1π!)
- relevant to future experiments

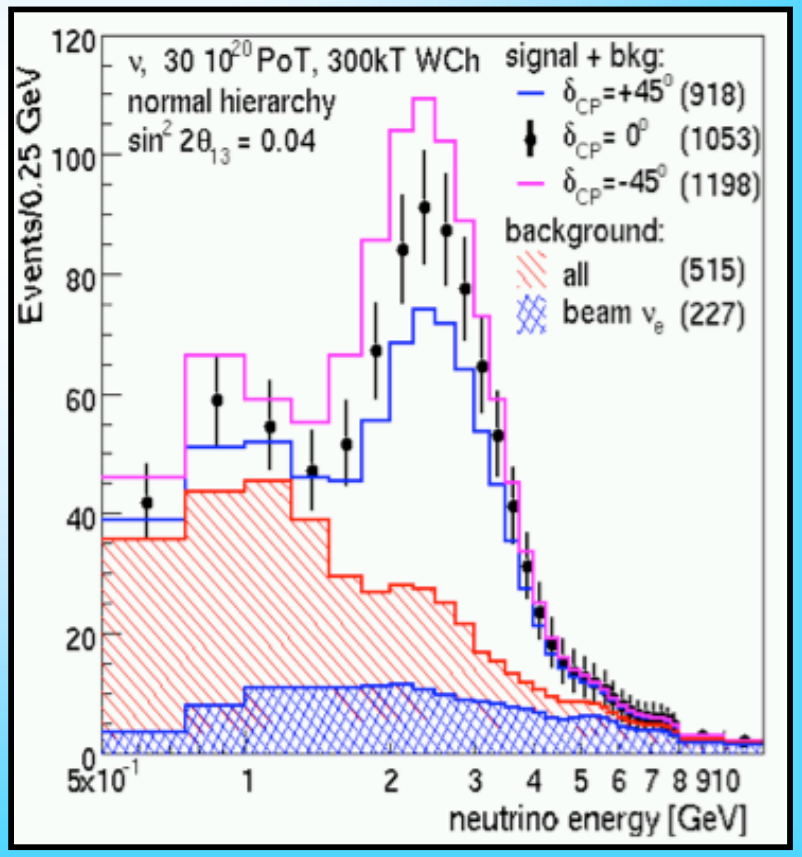
Relevance for Future Experiments



T2K

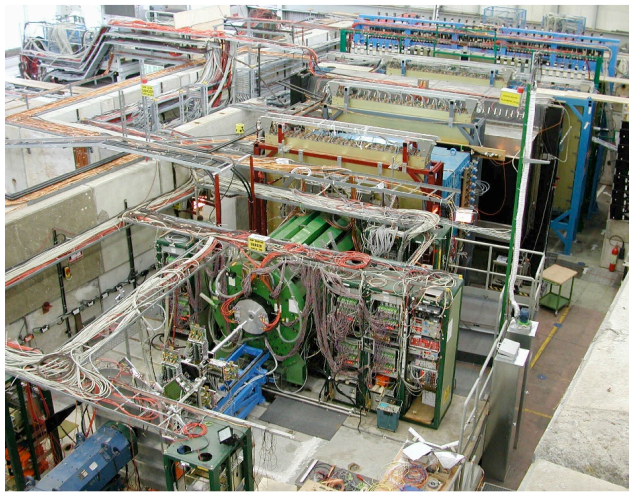
LBNE to DUSEL

($\nu_\mu \rightarrow \nu_e$ at far detector)



(M. Bishai, DUSEL UC Davis collab mtg)

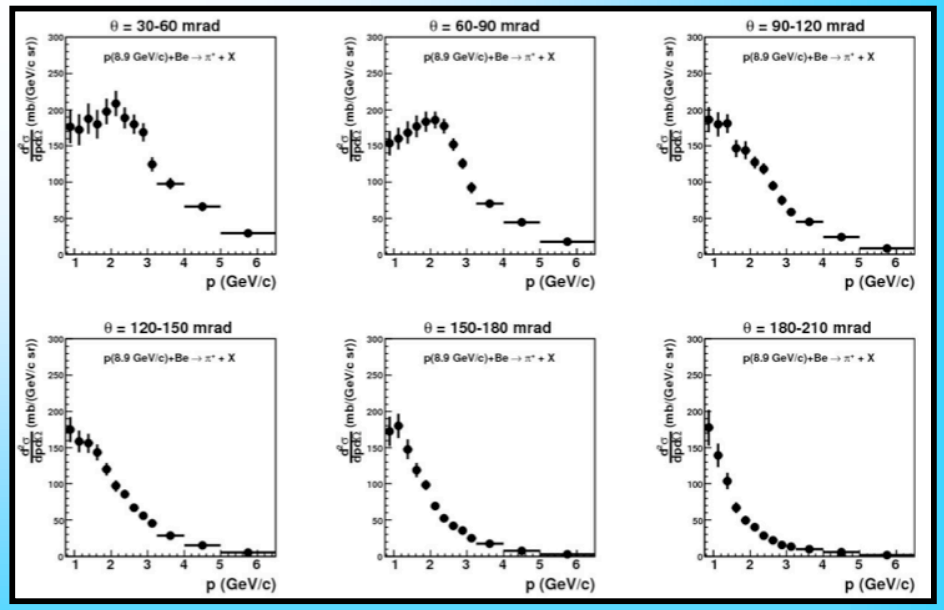
Flux Predictions



- make heavy use of pBe → $\pi^{+/-}$ data from **HARP** experiment

  Catanesi *et al.*, Eur. Phys. J. C52, 29 (2007)

  - 8.9 GeV/c protons
  - exact replica target (5% λ)

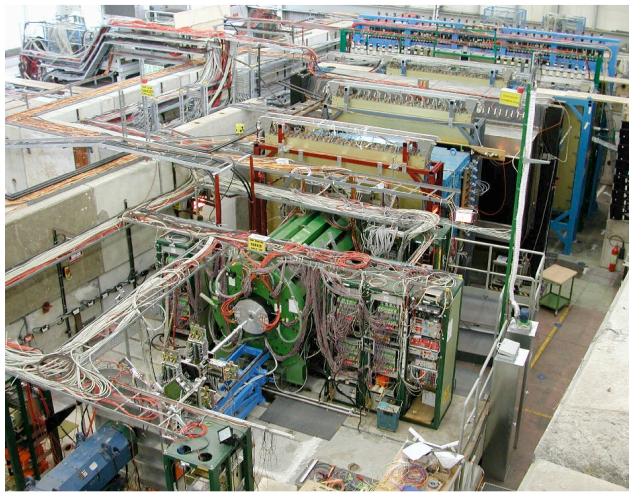


(D. Schmitz)

- caliber of data helped greatly reduce ν flux uncertainties
- comprehensive ν flux paper

  Aguilar-Arevalo *et al.*,
  Phys. Rev. **D79**, 072002 (2009)

Flux Predictions



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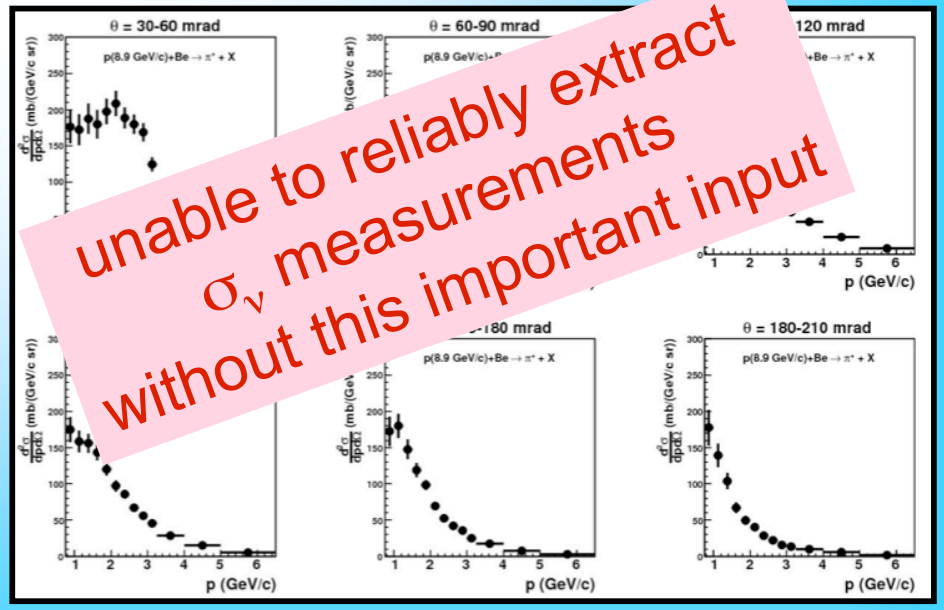

unable to reliably extract σ_ν measurements without this important input

(D. Schmitz)

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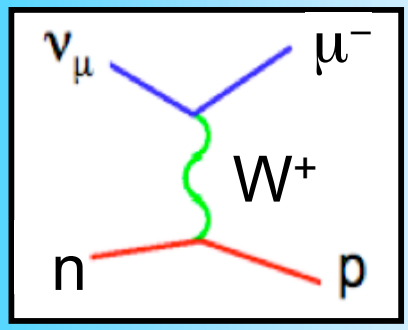
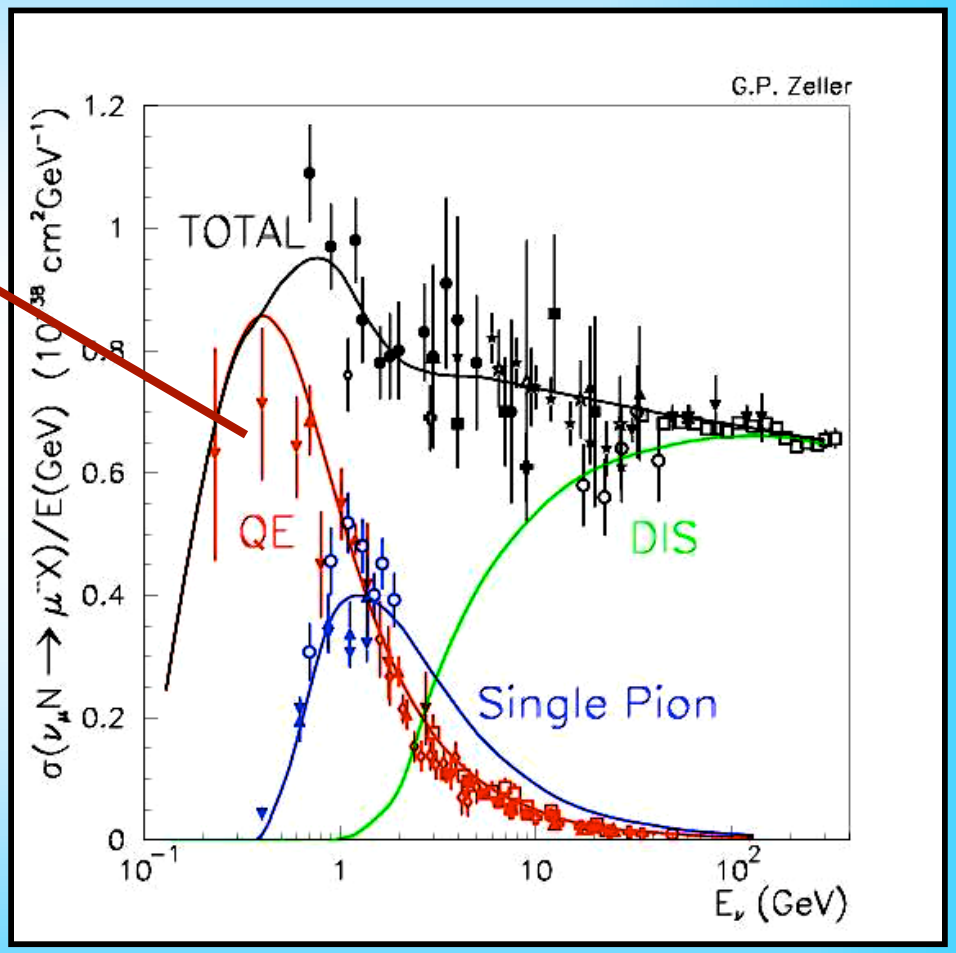
Elastic Scattering Processes

let's talk about measuring some of these exclusive processes …

- CC QE scattering

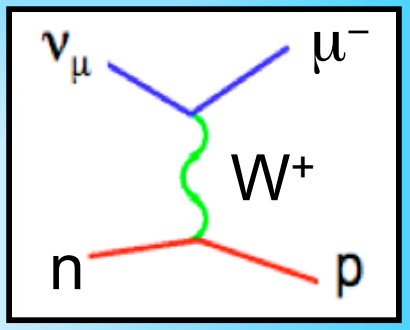


- most abundant sample in MB



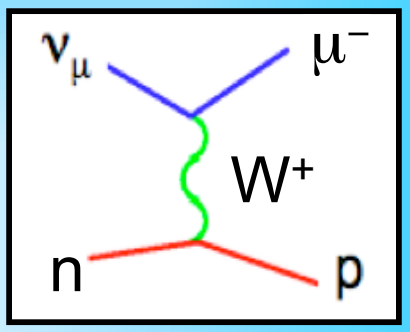
- let's start on the left and work our way up in energy …

Quasi-Elastic Scattering



Quasi-Elastic Scattering

Why important?



- **important for ν oscillation experiments**
  - golden channel
  - CC so can tag flavor of incoming ν
  - even if only the μ is visible, can reconstruct E_ν
  - dominant σ below ~1 GeV

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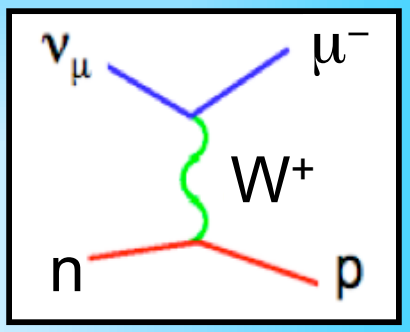

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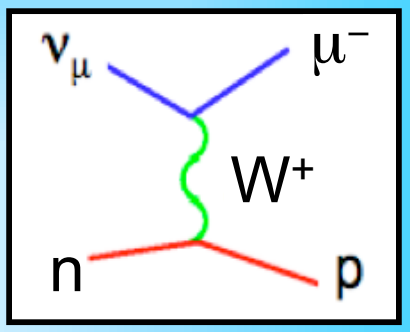

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- examples:

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

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

signal sample for ν oscillation experiments (or portion of signal) in both cases

Quasi-Elastic Scattering

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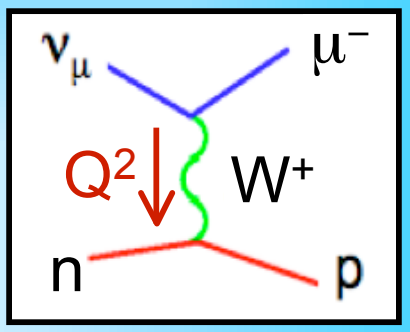

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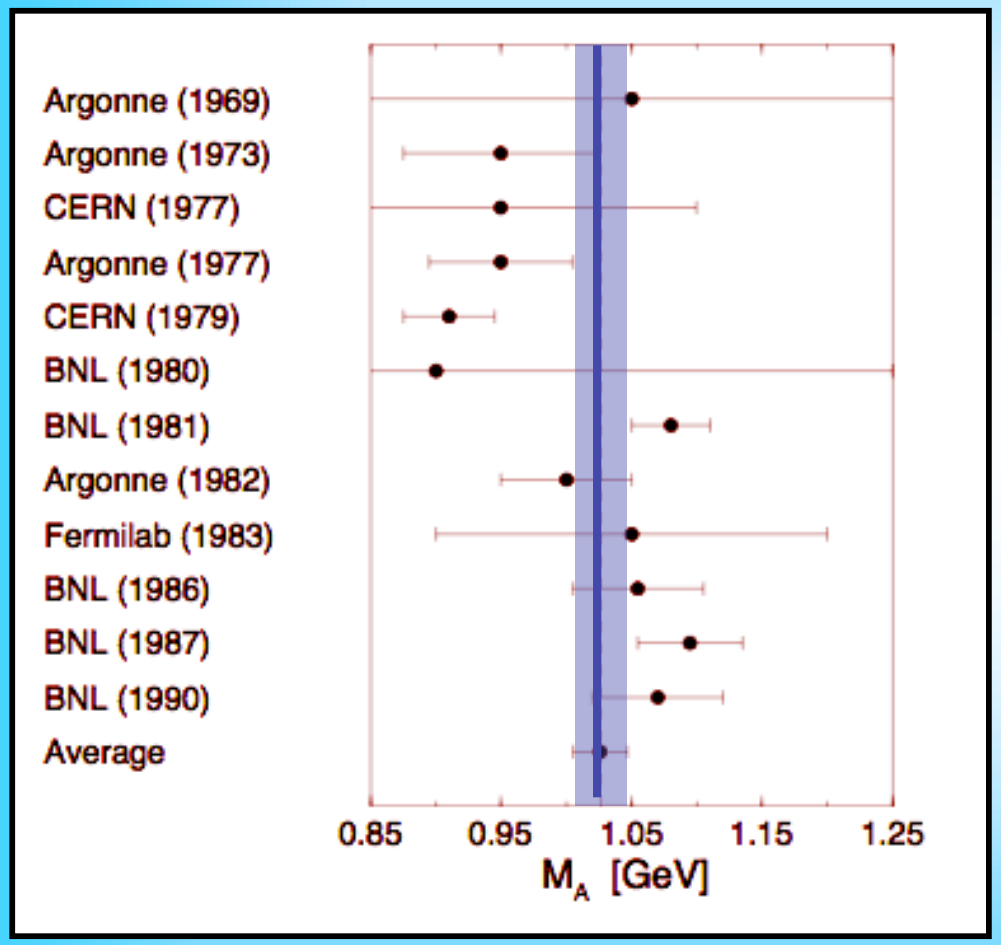
- **interesting on its own**
  - probe nuclear structure (ala electrons, photons)
  - measure axial form factor of the nucleon … $F_A(Q^2) = \dfrac{g_A}{(1 + Q^2/\mathbf{M_A}^2)^2}$
    (for the 1st time in >10 years!)

Value of M_A

- M_A is a parameter that must be determined experimentally



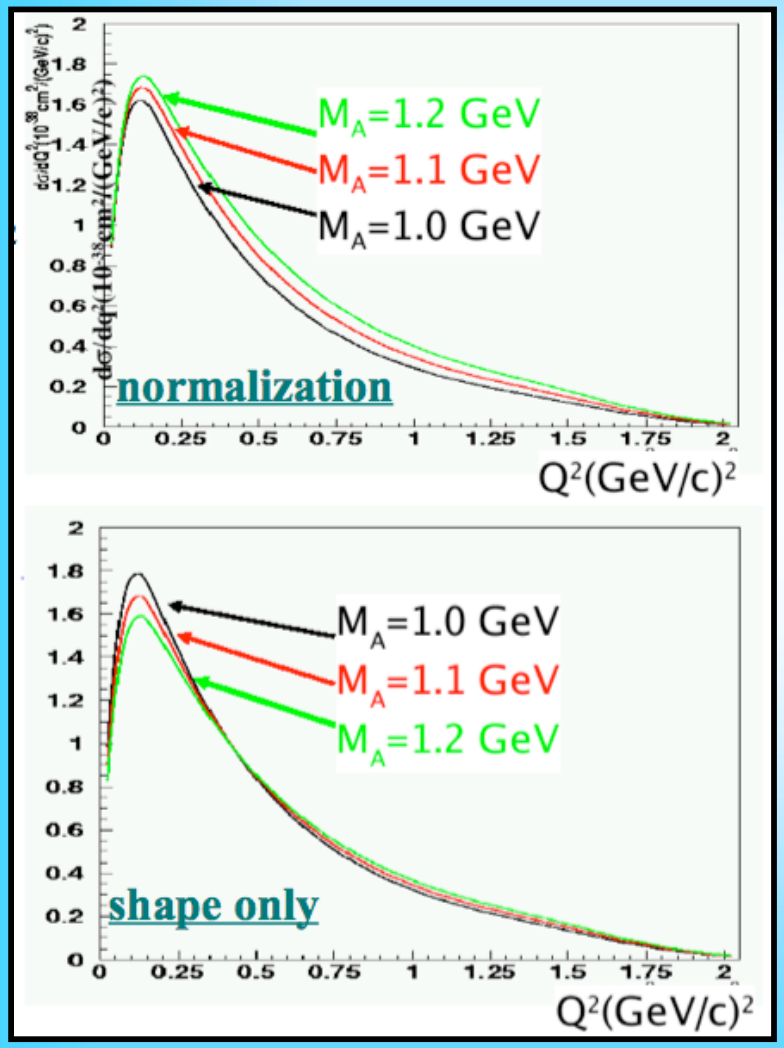
- M_A determined from global fits to historical ν data (1969-1990)

- because plays such a crucial role, a lot of interest in this & attempts to re-measure

world average: $M_A = 1.03 \pm 0.02$ GeV

Bernard *et al.*, J. Phys. **G28**, R1 (2002)

How Do You Measure M_A?



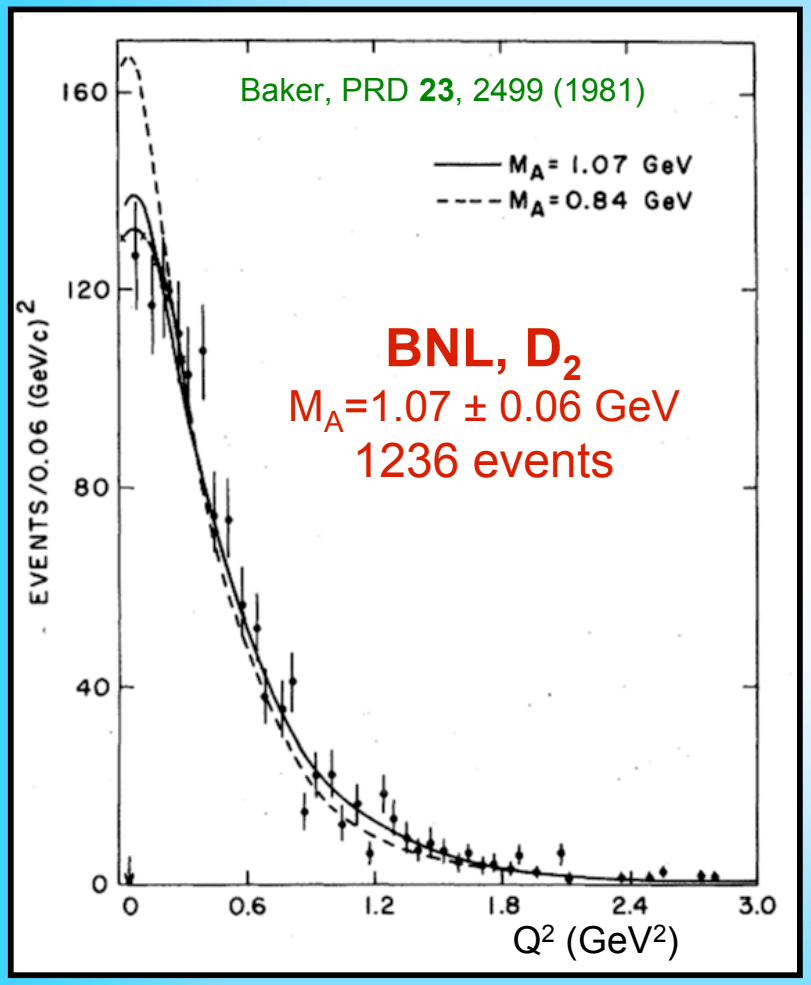
- varying M_A has two effects:

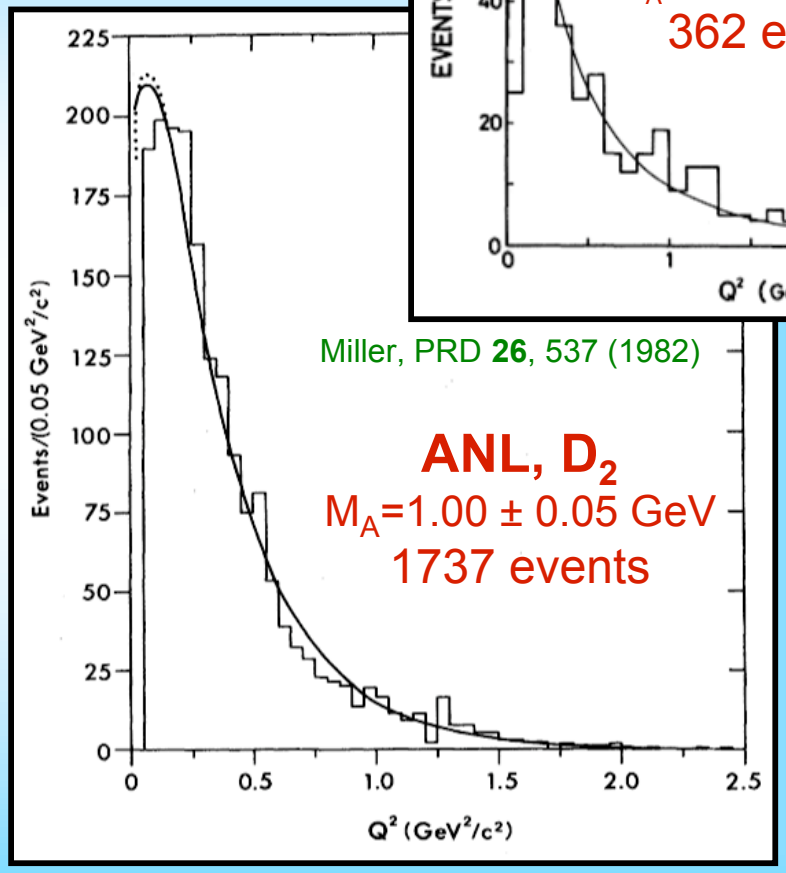
(1) **changes normalization**
($\uparrow M_A$ means $\uparrow \sigma$)

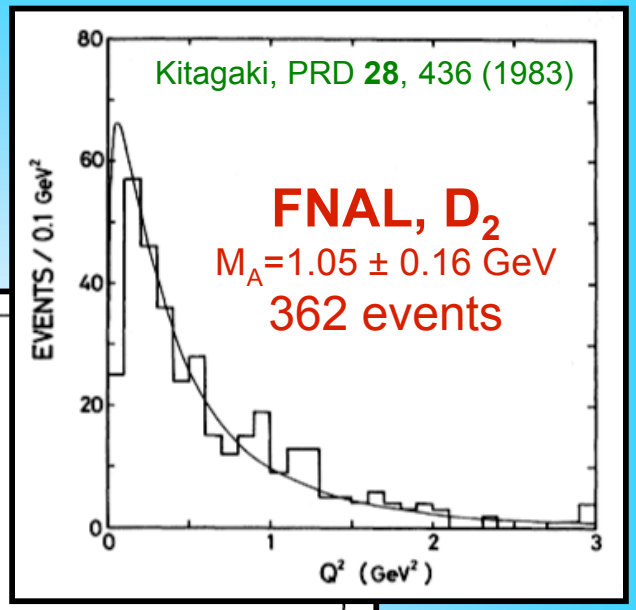
(2) **changes Q^2 dependence**
($\uparrow M_A$ means harder Q^2)

typically ν experiments measure M_A using method (2)
(some experiments did both)

Past Examples

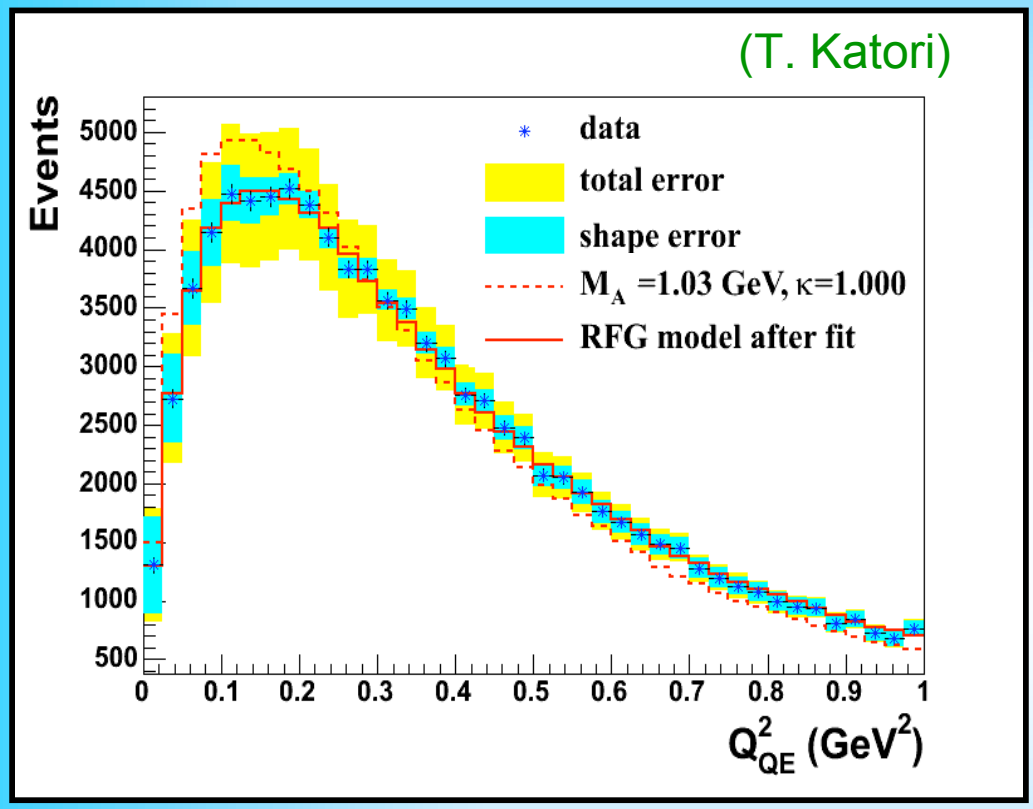




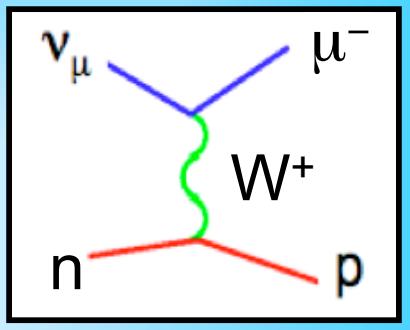


- a lot of time spent on this in early 1980's, D_2
- extract M_A by fitting Q^2 distributions for QE events

QE Scattering at MiniBooNE



NEW!



- 146,070 ν_μ QE events
  (76% purity, 27% ε)
- <u>shape fit</u> to the data

- update of our prior results after improved background estimates
  Aguilar-Arevalo *et al.*, PRL **100**, 032301 (2008)

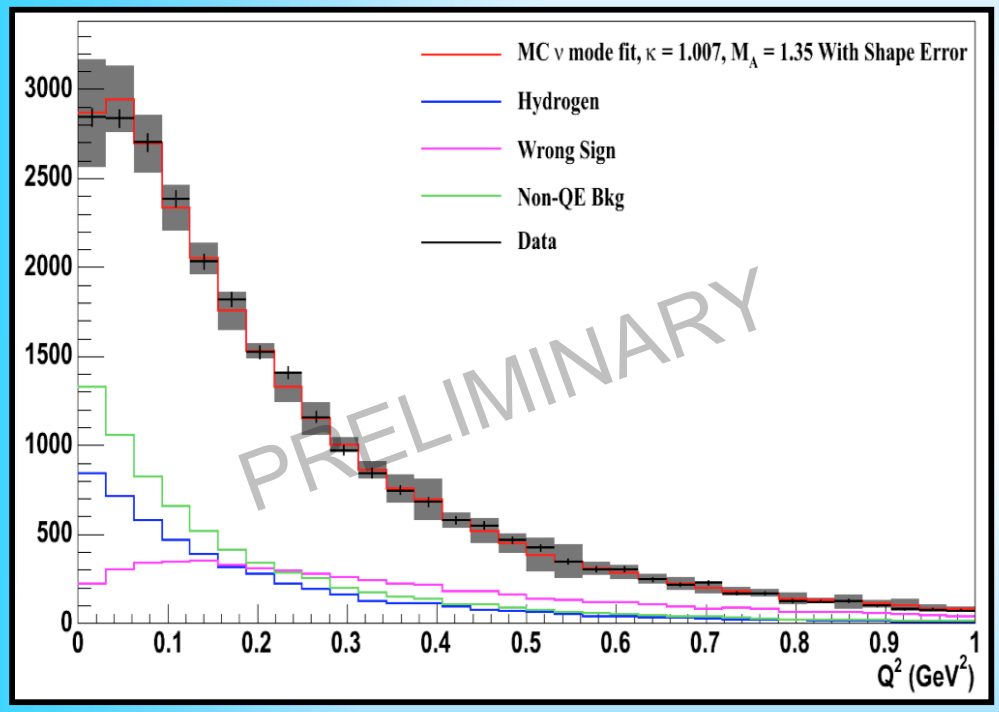
M_A^{eff} = 1.35 ± 0.17 GeV (^{12}C, Fermi Gas model)
κ = 1.007 ± 0.012

!

Antineutrino QE

- first time in history are measuring $\bar{\nu}$ QE events at 1 GeV

(J. Grange)



(data, MC shape comparison)

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

- MiniBooNE switched to $\bar{\nu}$ running in 2006
- 27,000 events (more coming)
- parameters from ν_μ fit also seem to successfully describe MiniBooNE $\bar{\nu}_\mu$

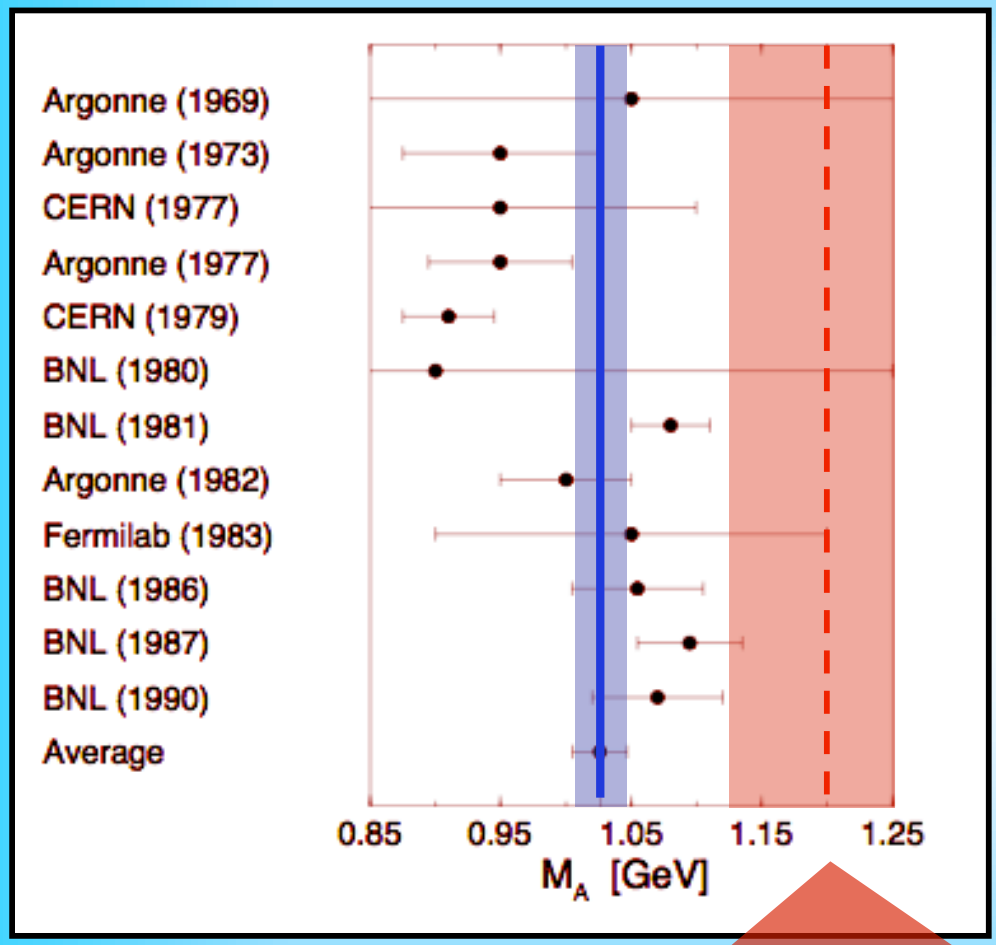
(nice initial verification of ν mode results)

QE Shape Fits

- current situation with modern QE measurements
- consistently measuring a higher M_A from shape fits

- **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, $Q^2>0.2$)
  AIP Conf. Proc. **967**, 117 (2007)
  $M_A=1.14 \pm 0.11$ GeV
- **MiniBooNE** (^{12}C, $Q^2>0$)
  paper in preparation
  $M_A=1.35 \pm 0.17$ GeV
- **MINOS** (Fe, $Q^2>0.3$)
  NuInt09, preliminary
  $M_A=1.26 \pm 0.17$ GeV

QE Shape Fits



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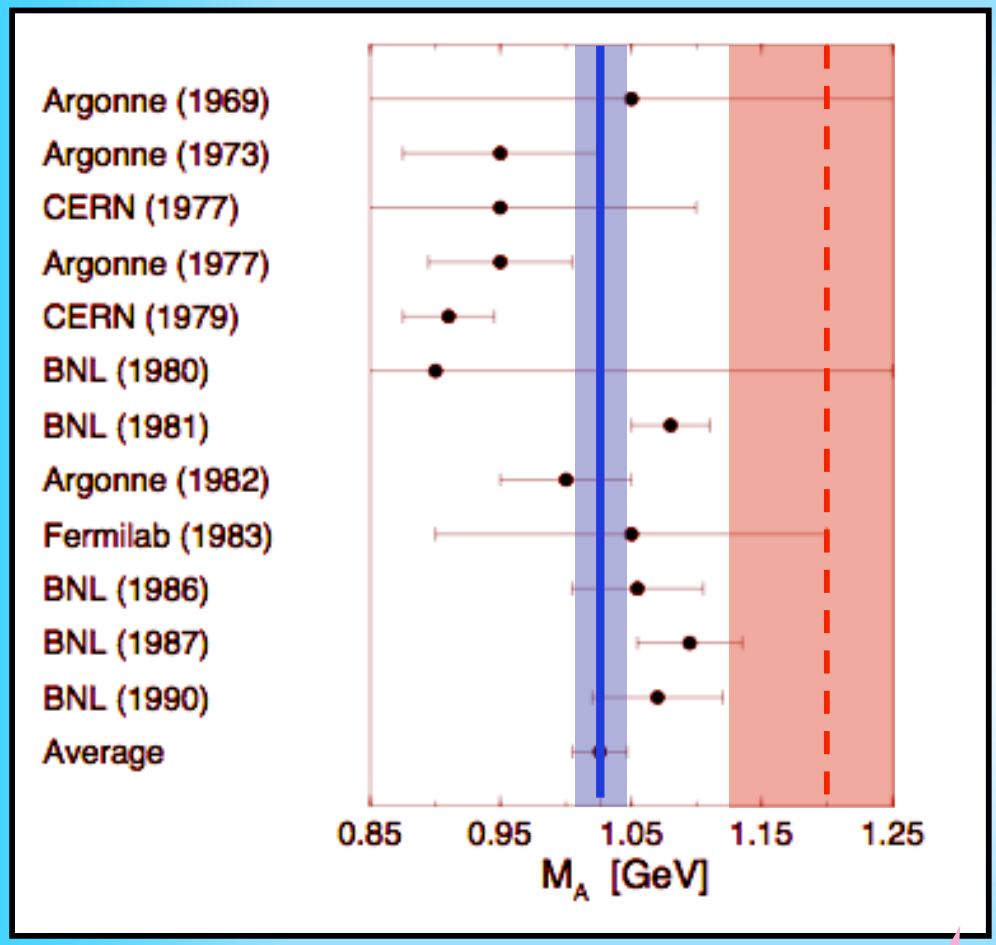

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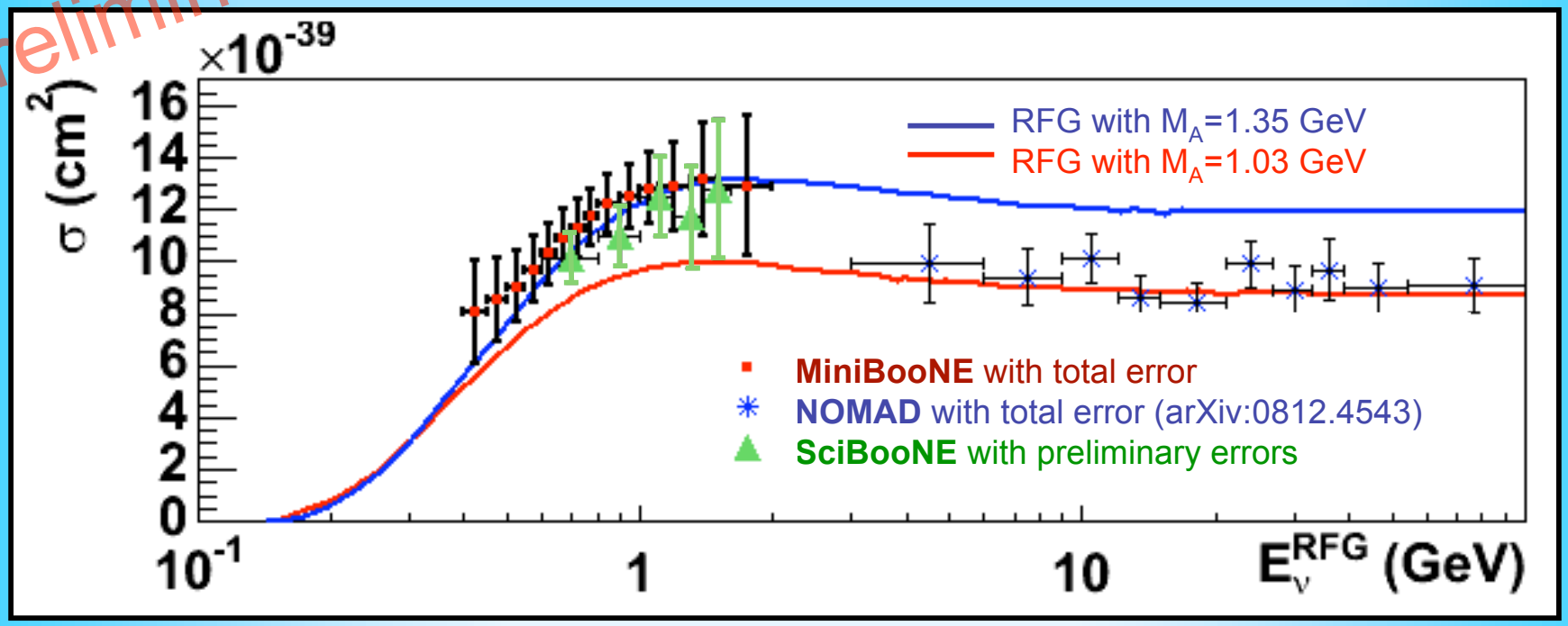
  NuInt09, preliminary
  M_A=1.26 ± 0.17 GeV
- **NOMAD** (^{12}C, Q^2>0)
  arXiv:0812.4543 [hep-ex]
  M_A=1.07 ± 0.07 GeV

QE σ Normalization

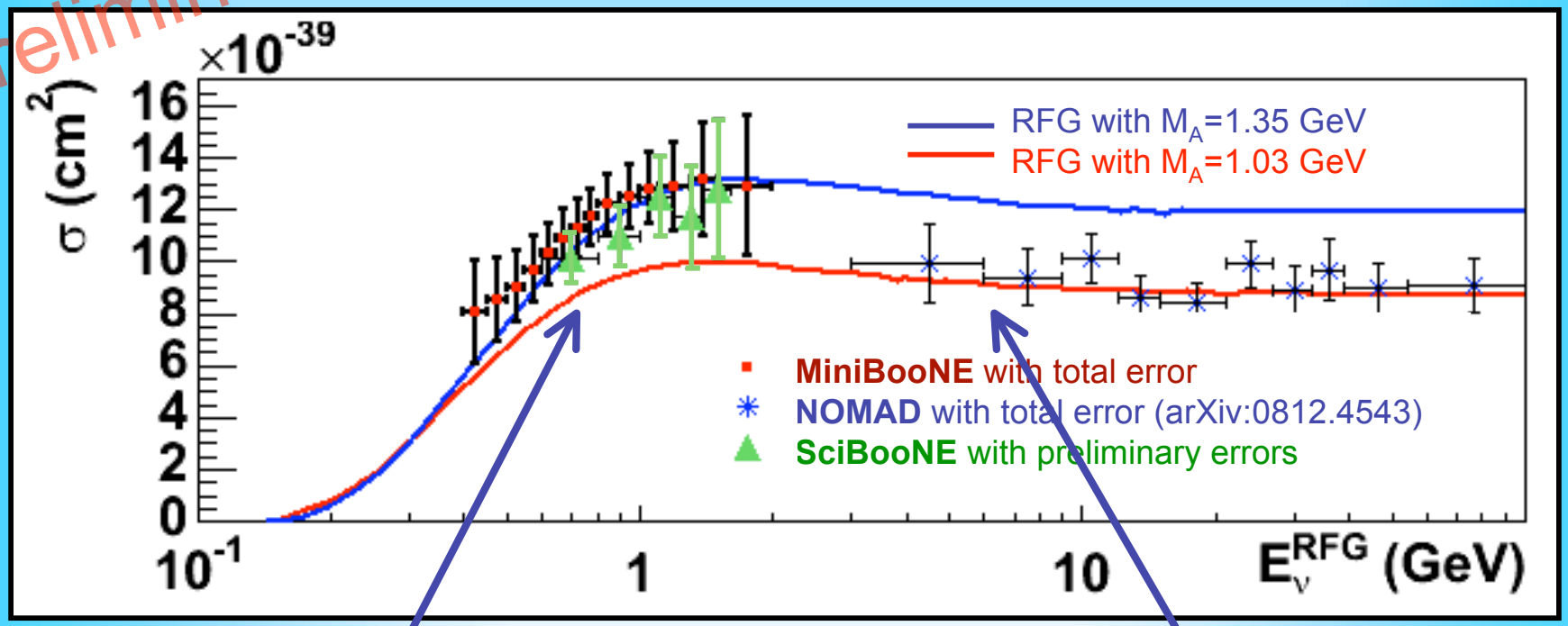
(T. Katori)



- **MiniBooNE** 1st meas on nuclear target at low energy (E_ν < 2 GeV) in agreement with preliminary **SciBooNE** measurement (NuInt09)
- ~30% higher than **NOMAD**?! all three on ^{12}C !

QE σ Normalization

(T. Katori)



consistent story
QE shape + normalization
M_A^{MB} = 1.35 GeV

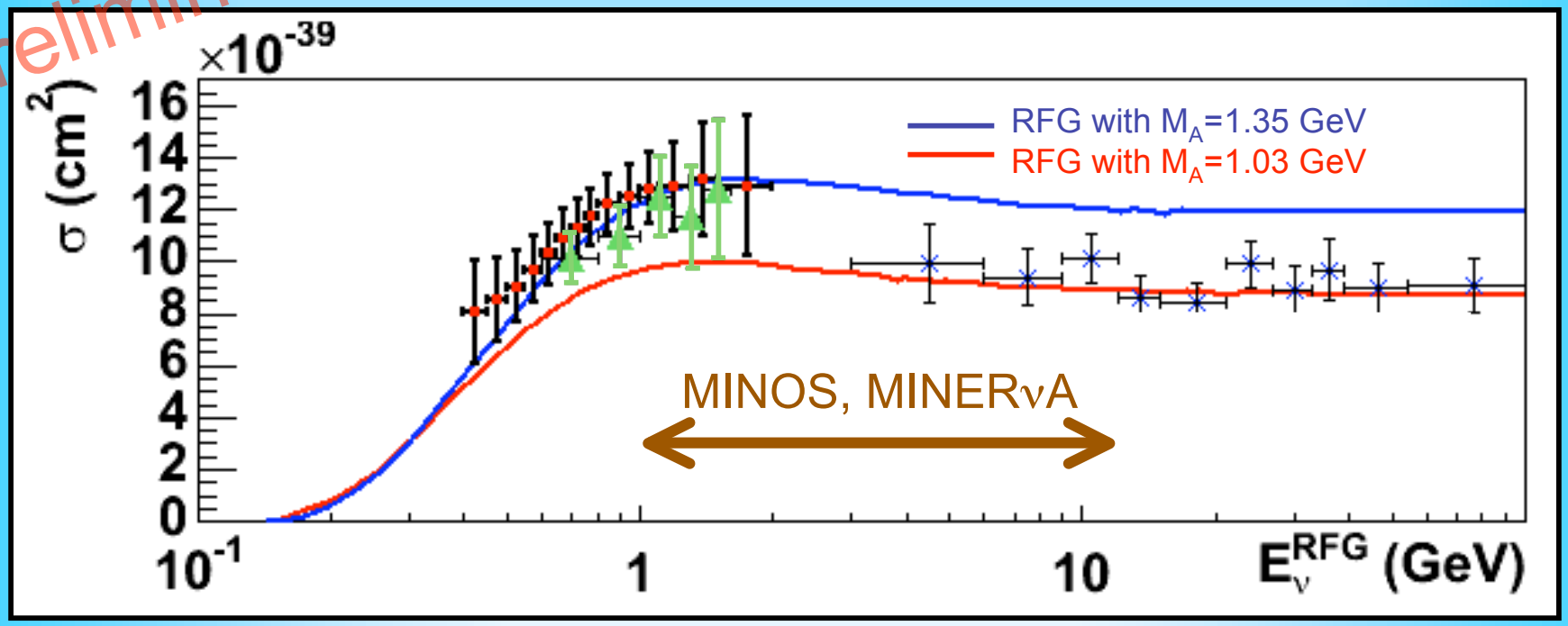
!

consistent story
QE shape + normalization
M_A^{NOMAD} = 1.07 GeV

- leaves one in a dilemma if want to predict how many QE events you expect

QE σ Normalization

(T. Katori)



- luckily, there is more to come on this!

QE σ Normalization

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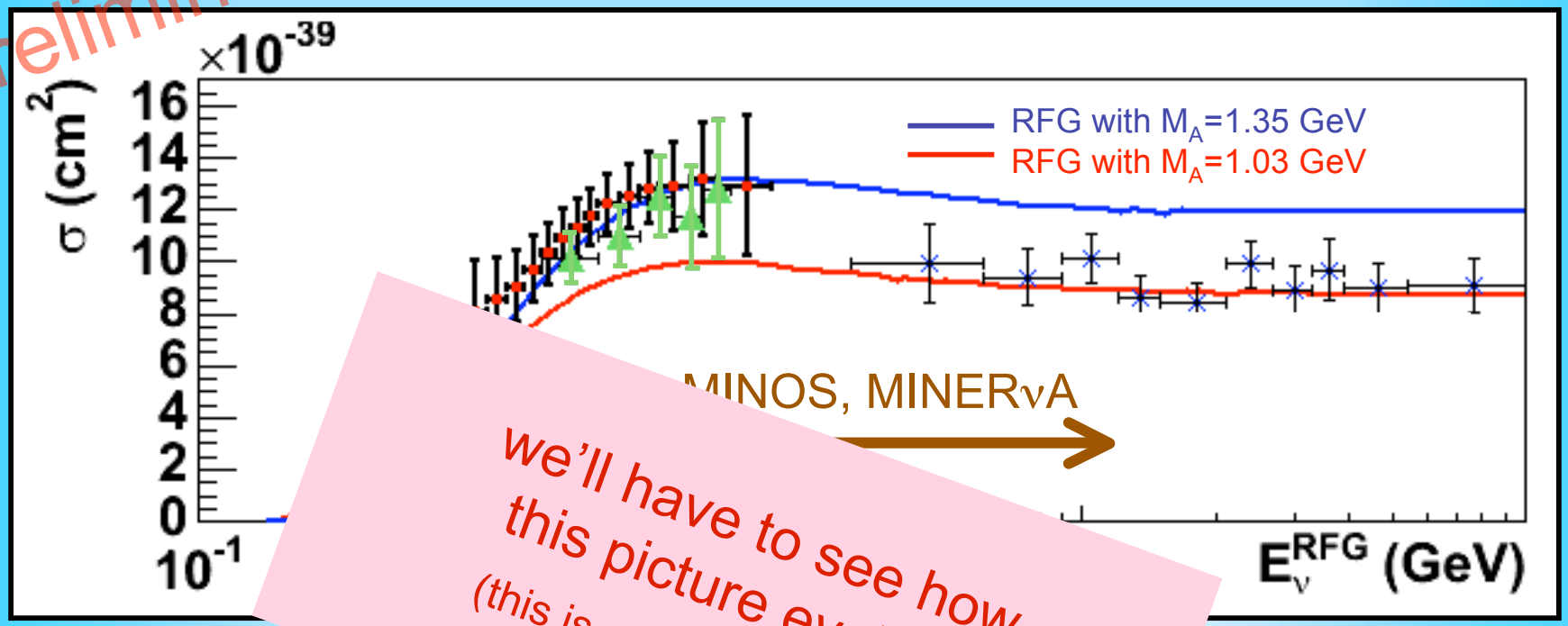
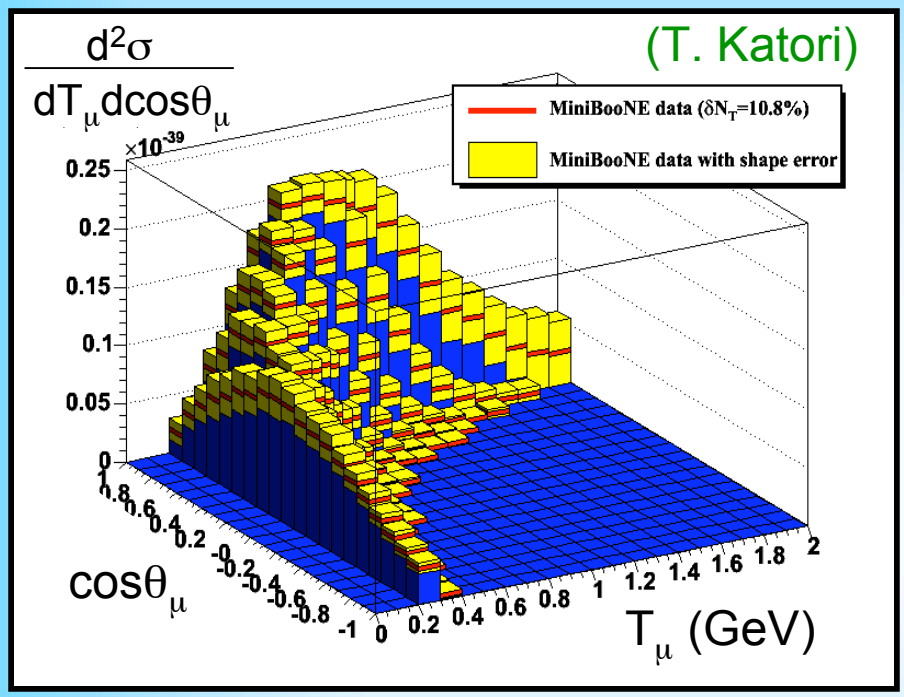


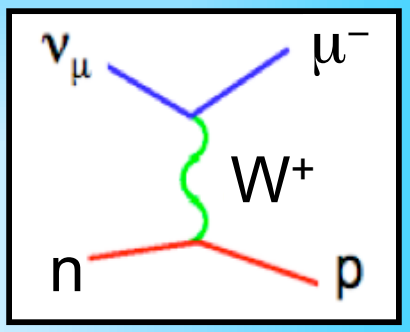
we'll have to see how this picture evolves
(this is a puzzle right now)

- luckily, there is more to c

to add to this picture …

QE Scattering at MiniBooNE

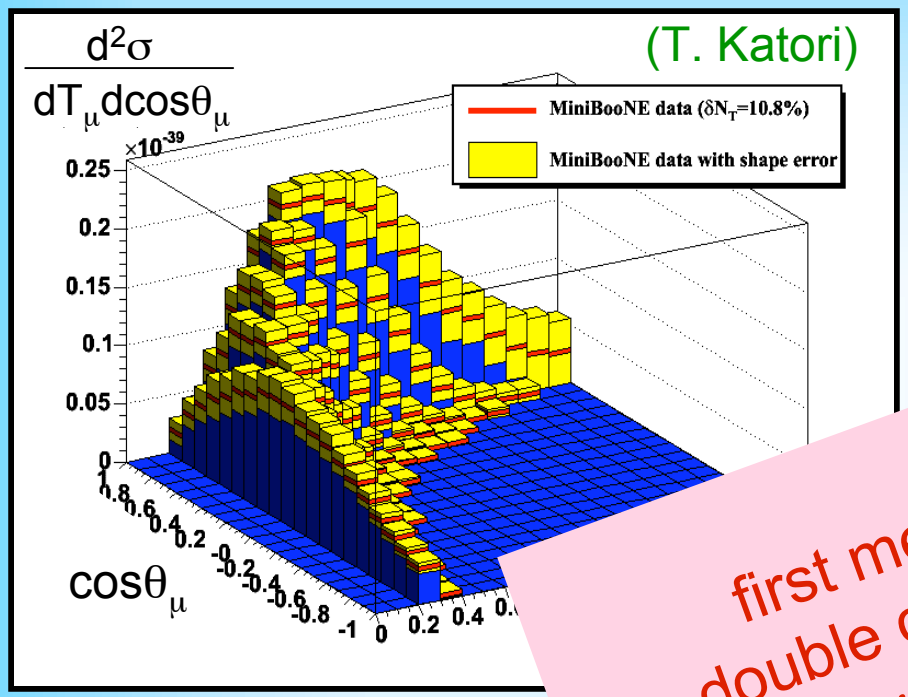


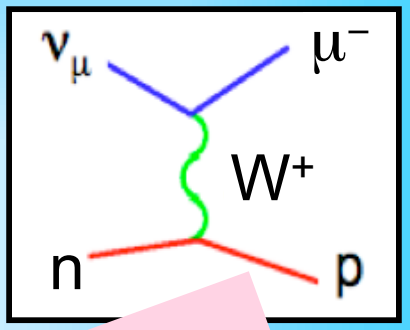


NEW!

- to make this data useful to people outside MiniBooNE …
- measured double differential σ from this data
- provided most complete information on ν QE scattering to date

QE Scattering at MiniBooNE





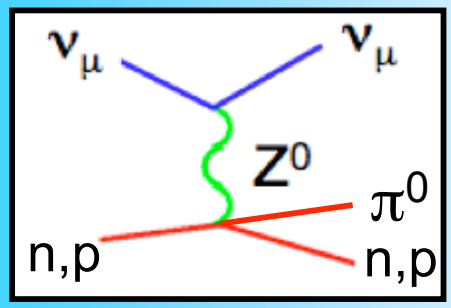
first measurement of double diff'l cross section in ν QE scattering!
(paper will be out soon)

- to make this data useful to … iniBooNE …
- measured double differentia … this data
- provided most complete information on ν QE scattering to date

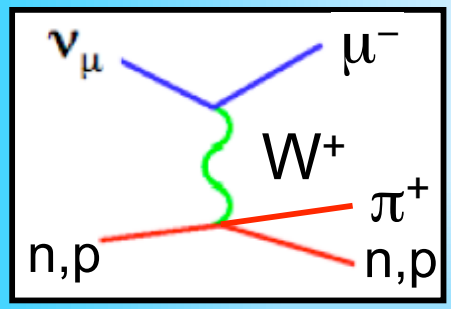
Single π Production

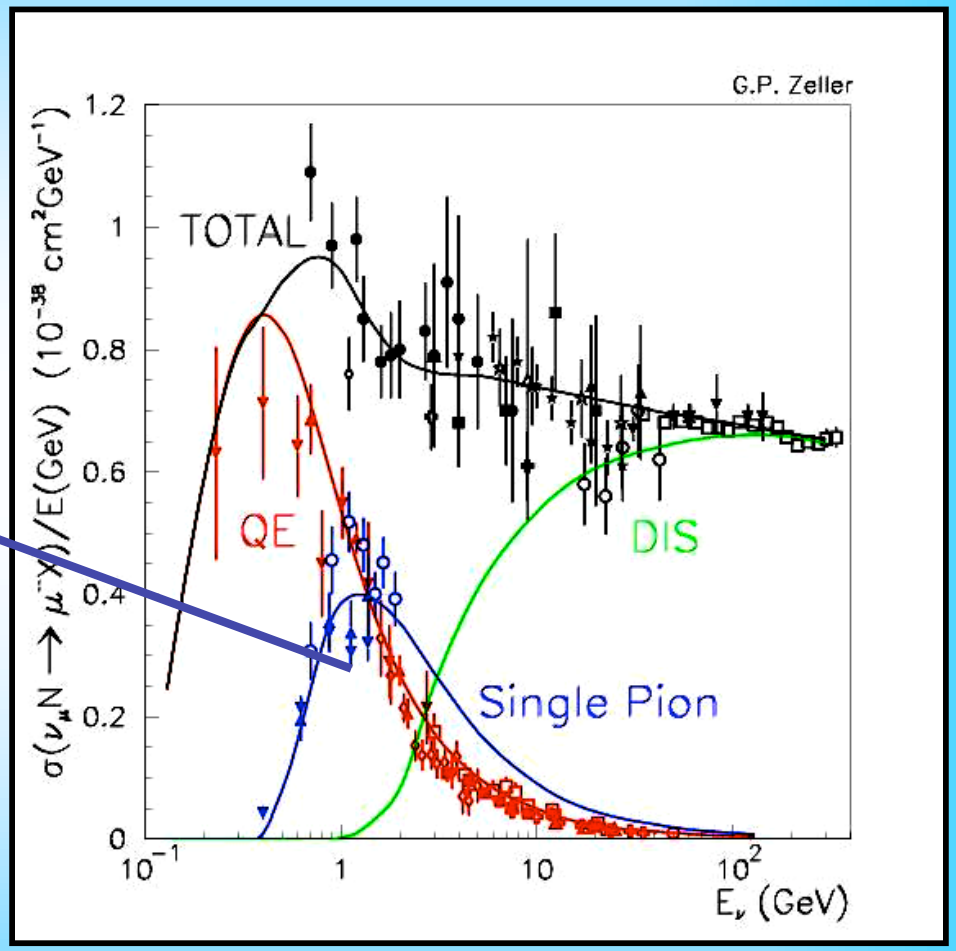
now let's move up in energy and survey the situation there …

- NC π^0 production



- CC π^+ production





- have both NC and CC counterpart
- each important for different reasons

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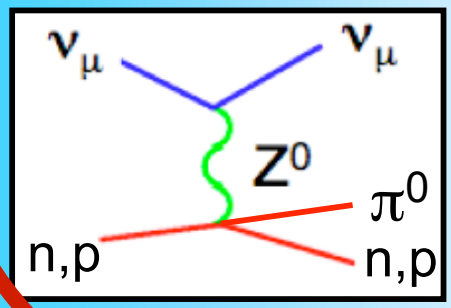

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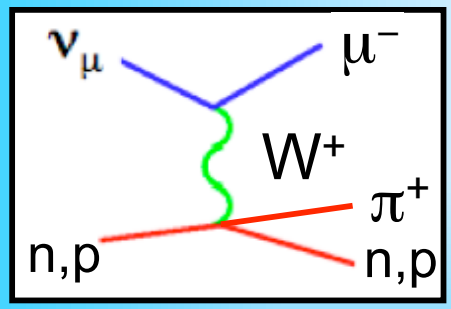

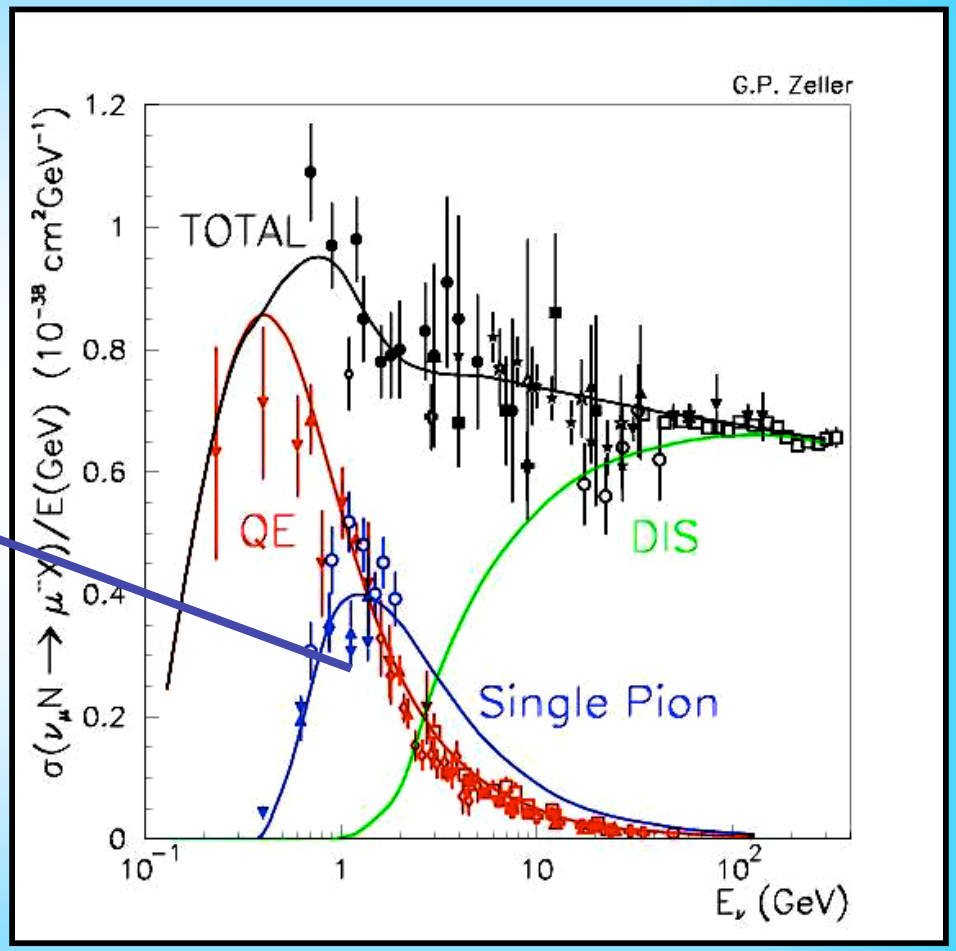

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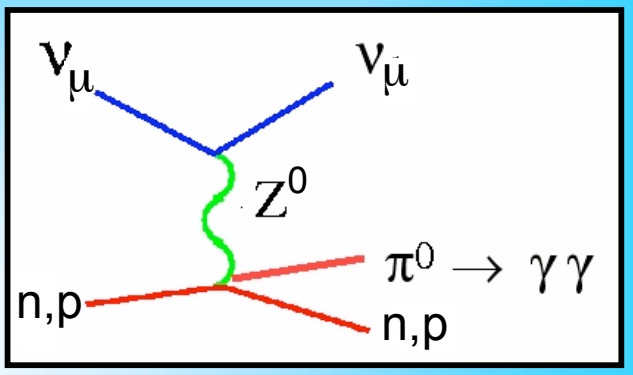
NC π^0 Production



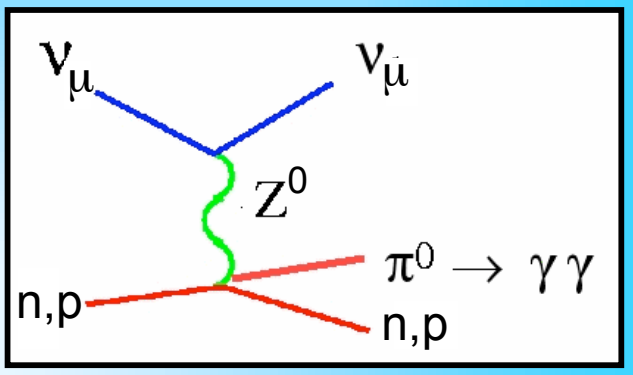
Why important?

- **important for neutrino oscillation experiments**
  - important background for experiments looking for $\nu_\mu \rightarrow \nu_e$, θ_{13} (final state can mimic a ν_e interaction, $\pi^0 \rightarrow \gamma\, \cancel{\gamma}$)

background for
ν oscillation experiments

π^0 can look
like a single e^-

NC π^0 Production



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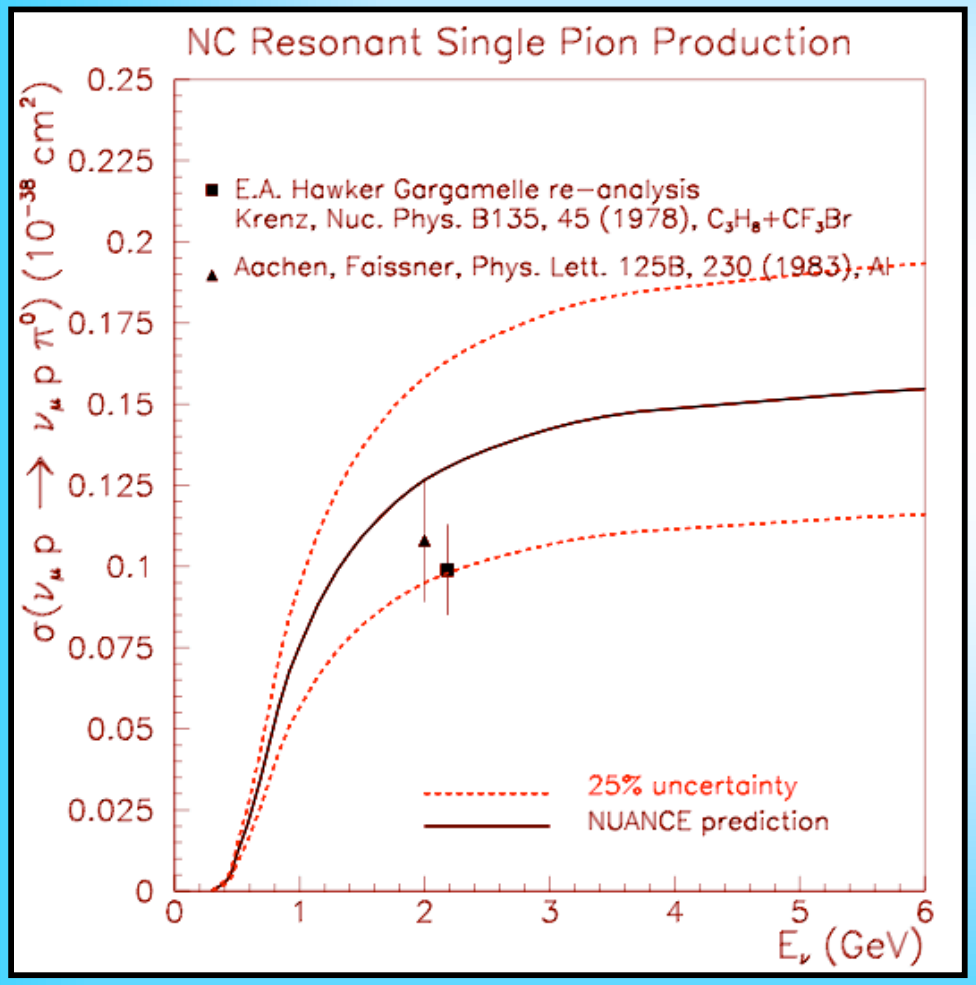
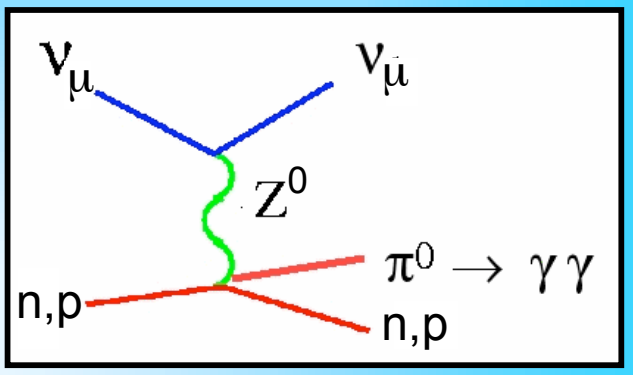
    (final state can mimic a ν_e interaction, $\pi^0 \rightarrow \gamma \cancel{\gamma}$)

- **interesting on their own**
  - very little historical data (100's of events), so not well constrained
  - interest in π^0 prod on nuclei (π^0 can rescatter in nucleus, alters kinematics)

Existing Measurements



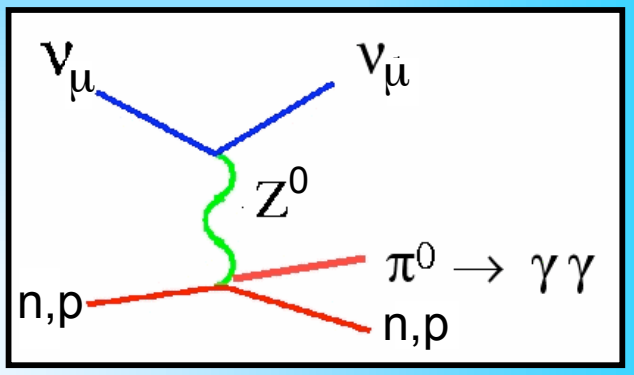


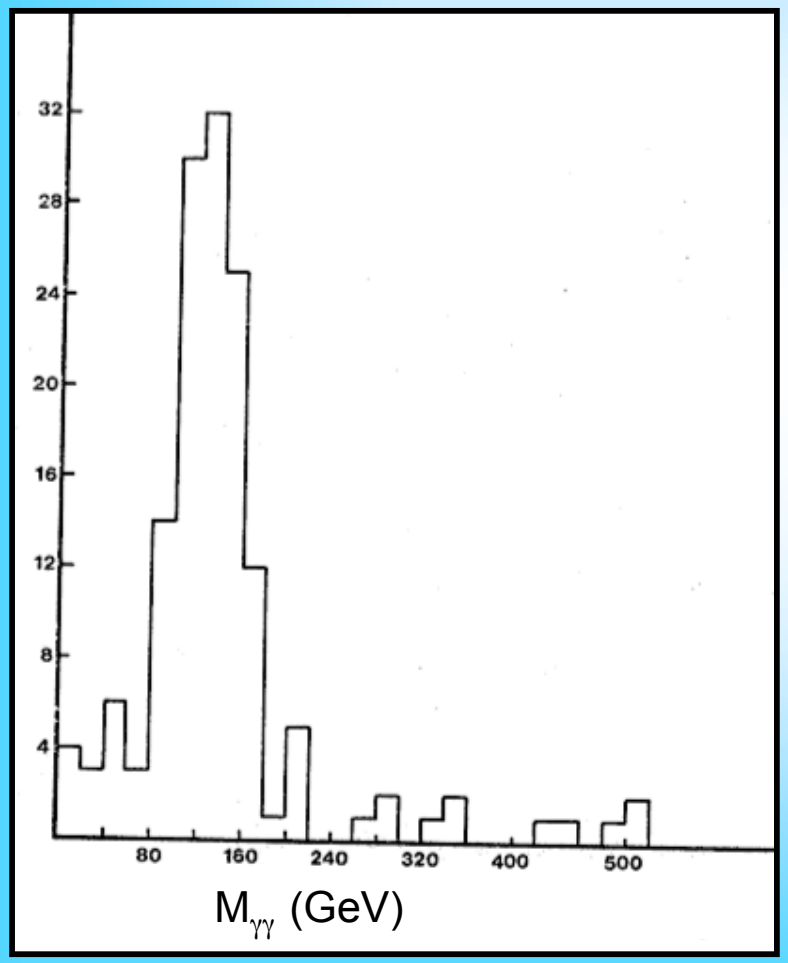
- historically, only two existing measurements of ν_μ NC π^0 production
- together < 500 events

(this σ tells you how many π^0 background events should expect to have; ν osc exps typically assign large uncertainties)

Existing Measurements

- this is the data that defines that σ





- 240 events
- GGM, propane-freon

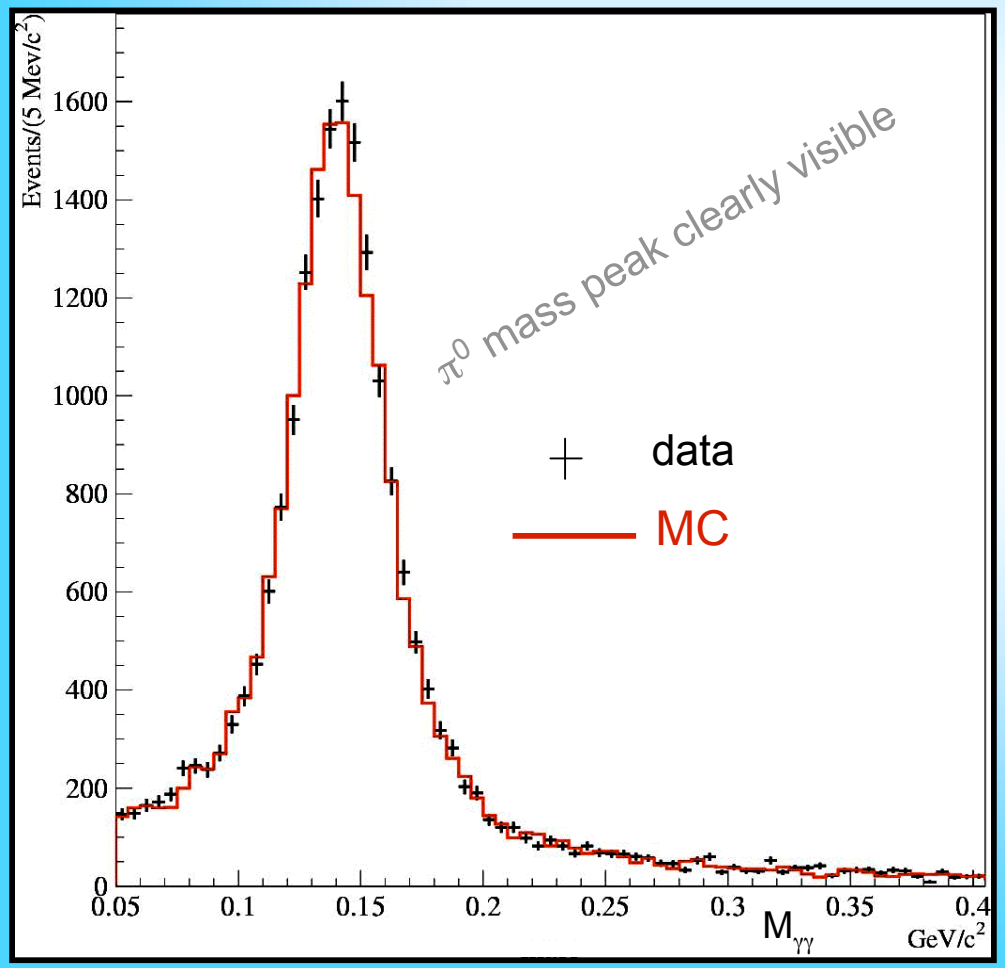
  Krenz *et al*., Nucl. Phys. **B135**, 45 (1978)

- this is what oscillation exps initially knew about their NC π^0 backgrounds going in

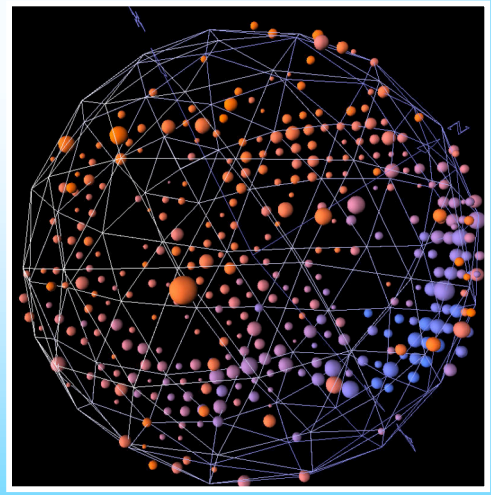
  (including MiniBooNE)

NC π^0 at MiniBooNE

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



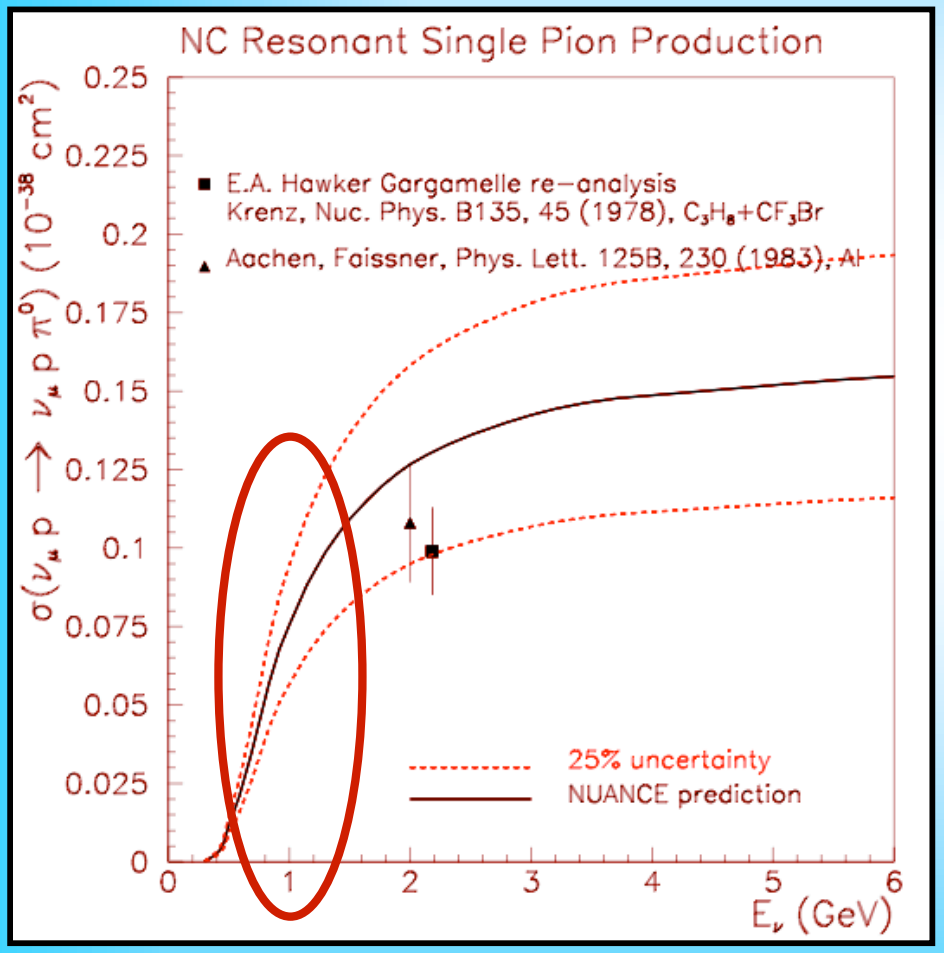
- **21,542 ν_μ NC π^0 events** (73% purity, 36% ε)
- **2,305 $\overline{\nu}_\mu$ NC π^0 events** (58% purity, 36% ε)



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

- this data crucial for our ν_e appearance search

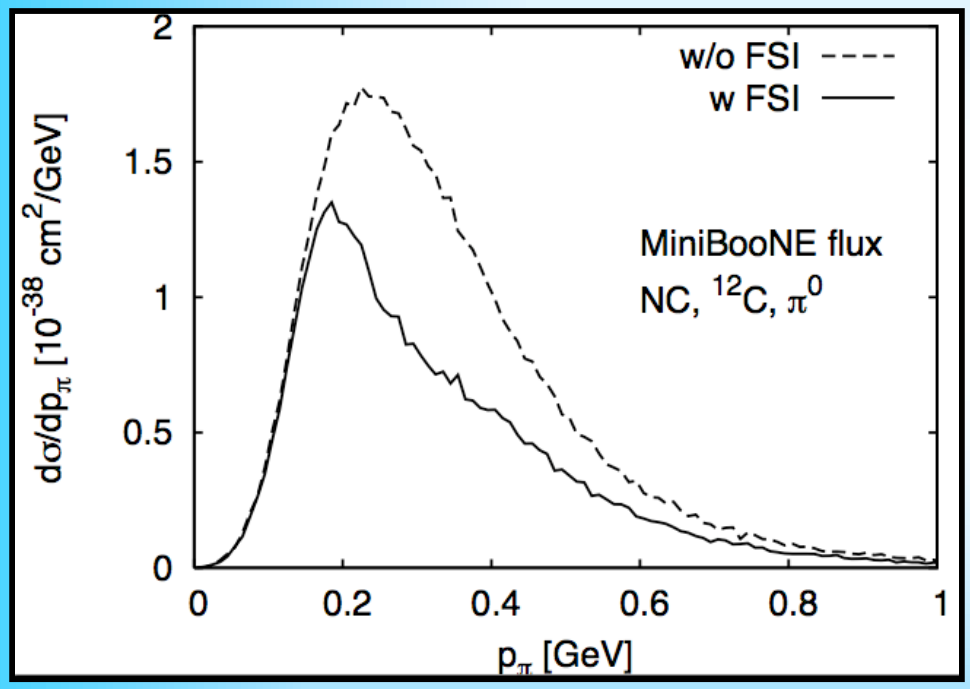
NC π^0 at MiniBooNE



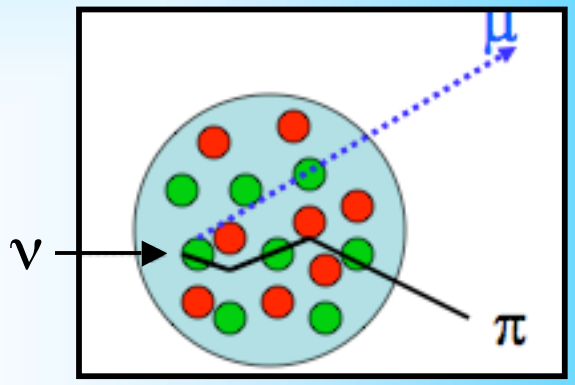
- however, not just an issue of adding another data point to this plot
- from MB experience, this was not good enough …
- don't want to have to trust your MC to get the rest right

NC π^0 at MiniBooNE

- example of why one needs to precisely measure NC π^0 production kinematics … non-trivial nuclear effects



(T. Leitner, integrated over MiniBooNE flux)



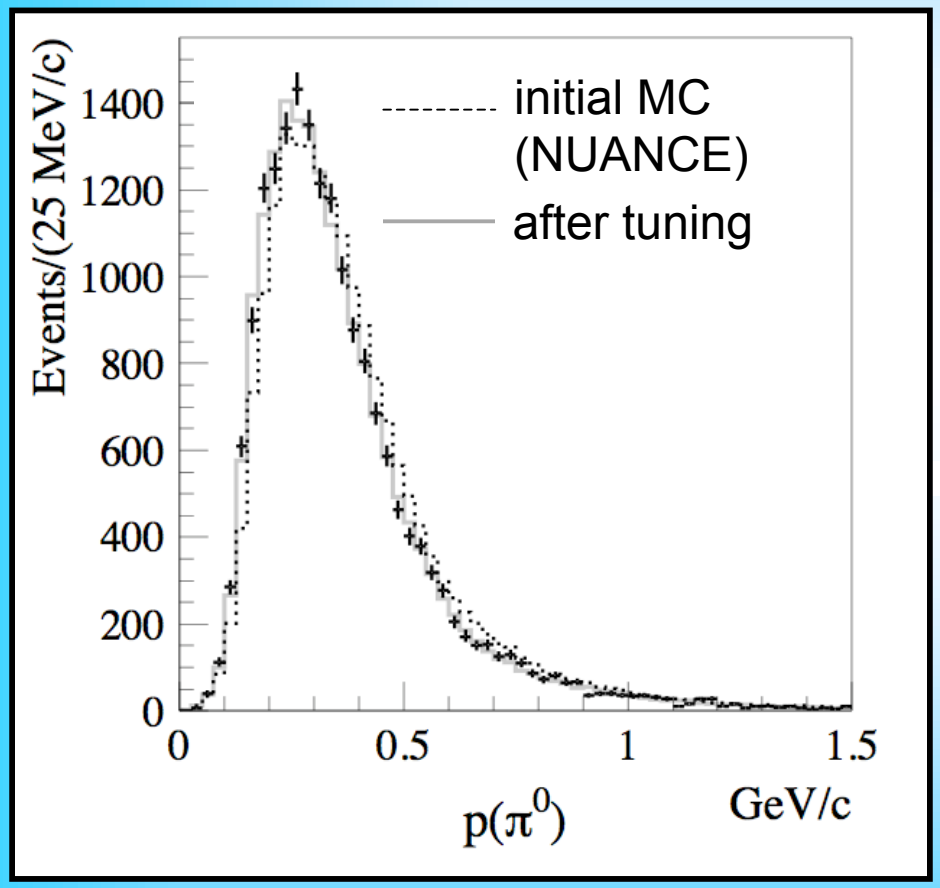
- intra-nuclear rescattering effects (FSI) are strong function of π momentum

- plus want to be able to constrain π^0 bkgs in E_ν

NC π^0 at MiniBooNE

- example of one of our data-based constraints on π^0 production

Aguilar-Arevalo *et al.*, PLB **664**, 41 (2008)



(shape comparison)

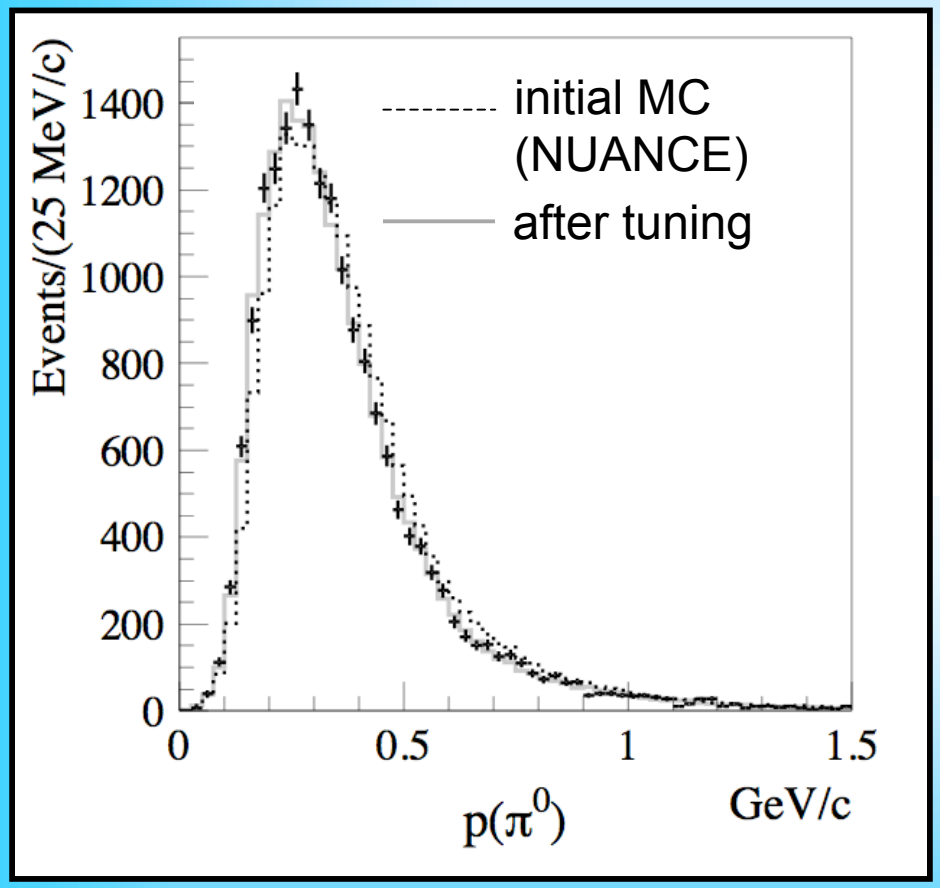
- observed π^0 momentum spectrum softer than the prediction (similar effect seen in K2K)

- intra-nuclear rescattering can give effects like this
  - model isn't perfect
  - probably underestimating these rescattering effects

NC π^0 at MiniBooNE

- example of one of our data-based constraints on π^0 production

Aguilar-Arevalo [illegible] (2008)



(shape comparison)

critical for MiniBooNE ν_e appearance analysis

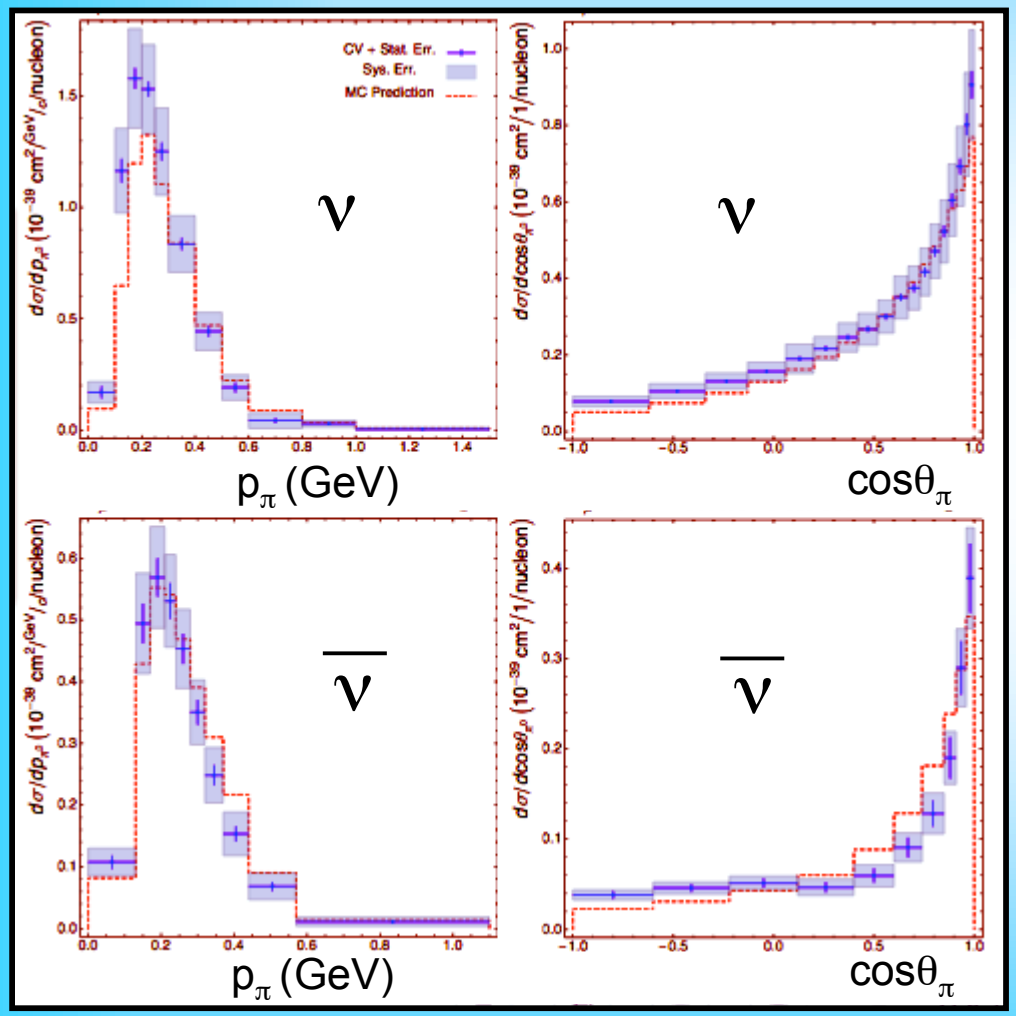
uncertainty in NC π^0 backgrounds reduced by a factor of 5!

(full kinematic constraint)

- have recently gone a step beyond this …

NC π^0 at MiniBooNE

(C. Anderson)

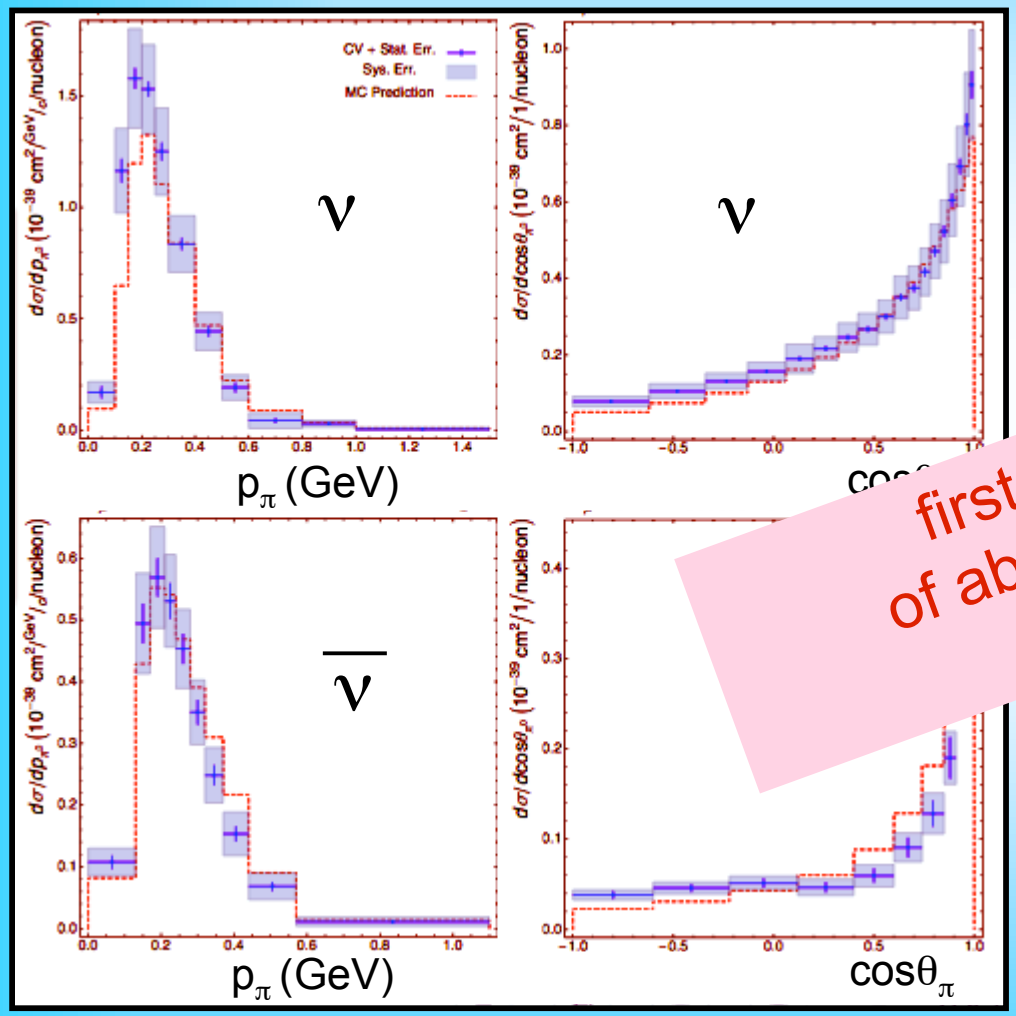


NEW!

- differential cross sections in both π^0 mom and angle
- first data in this energy range for both ν and $\bar{\nu}$
  - on carbon
- hopefully useful to others wanting to check their background estimates

NC π^0 at MiniBooNE

(C. Anderson)



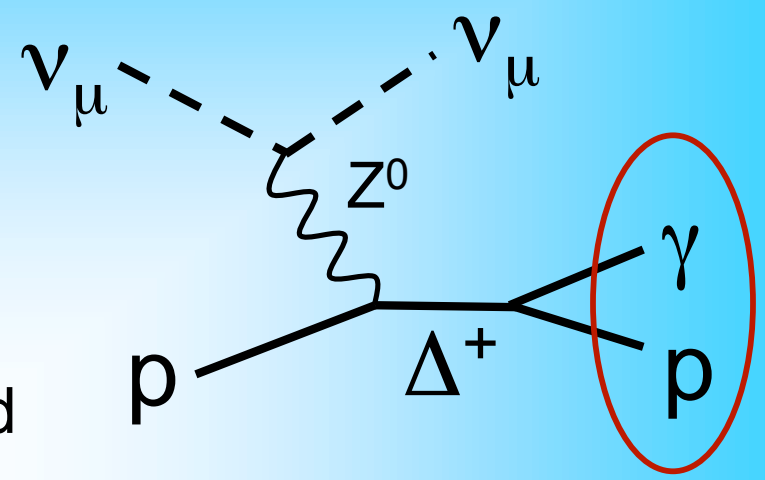
NEW!

first measurement of absolute NC π^0 diff'l cross section

- differential cr ections in both angle
- energy
  - both ν and $\bar{\nu}$
  - on carbon
- hopefully useful to others wanting to check their background estimates

NC γ Production

- not only have $\Delta^{+,0} \rightarrow N\pi^0$ but also $\Delta^{+,0} \rightarrow N\gamma$
- small branching fraction (0.56%)
- but particularly ominous background (looks like ν_e QE, $\nu_e n \rightarrow e^- p$)



- process was completely absent in MC generators
- MiniBooNE: firm prediction for $\Delta \rightarrow N\gamma$ based on $\Delta \rightarrow N\pi^0$

NC γ Production

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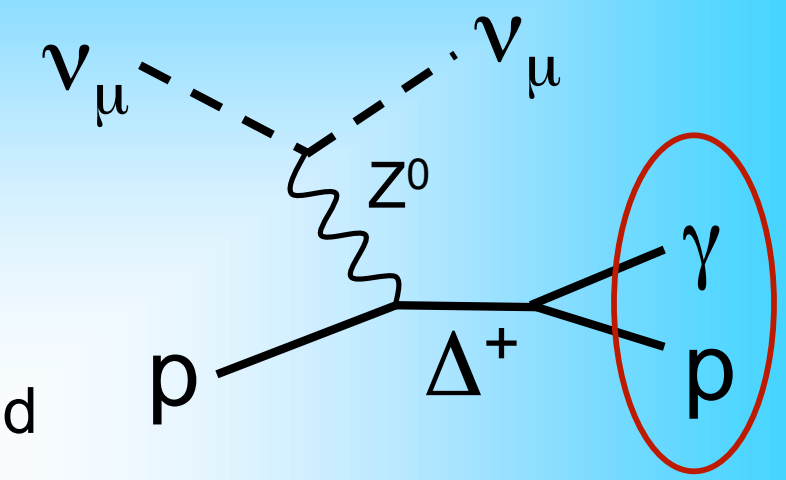
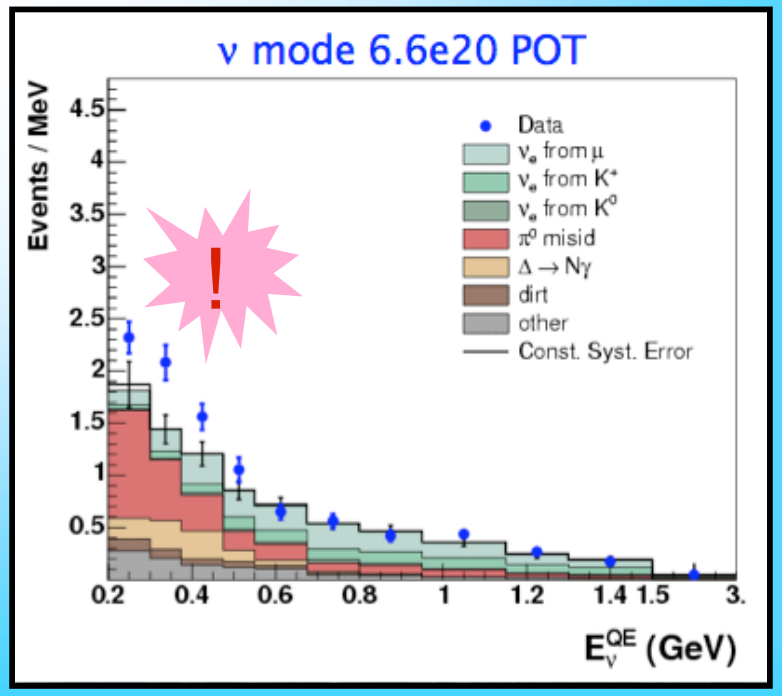


- may be **other** sources of single γ production in ν interactions?

  Hill, arXiv:0905.0291

  Jenkins & Goldman, arXiv:0906.0984

- need to be aware of this as a potential bkg to ν_e searches (guidance from T2K, MiniBooNE $\bar{\nu}$)



PRL 102, 101802 (2009)

NC γ Production

- not only have $\Delta^{+,0} \rightarrow N\pi^0$ but also $\Delta^{+,0} \rightarrow N\gamma$
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- but particularly ominous bac
  (looks like ν_e QE, ν_en
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  γ production in ν interact
  Hill, arXiv:0905.0291
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- need to be aware of this as a potential bkg to ν_e searches
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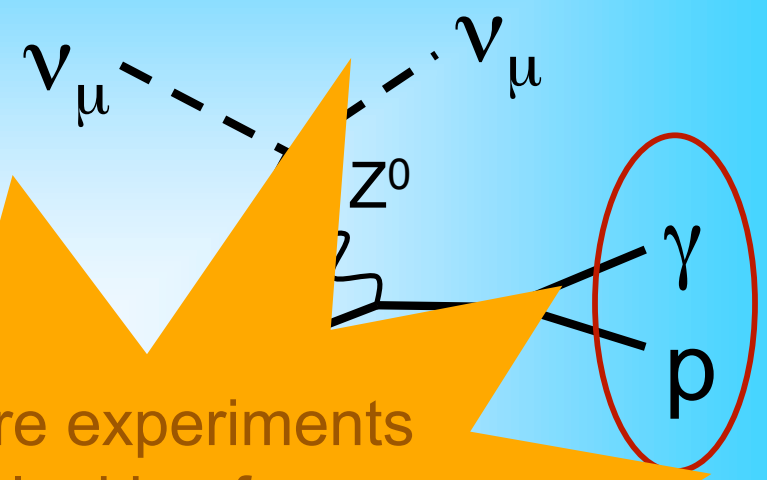
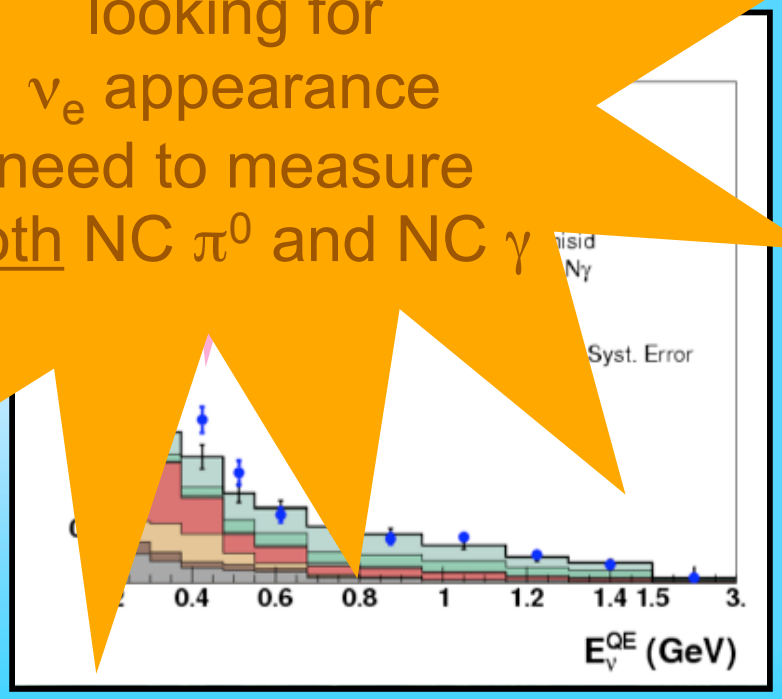


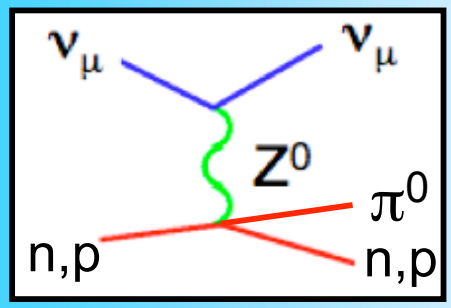
future experiments looking for ν_e appearance need to measure both NC π^0 and NC γ



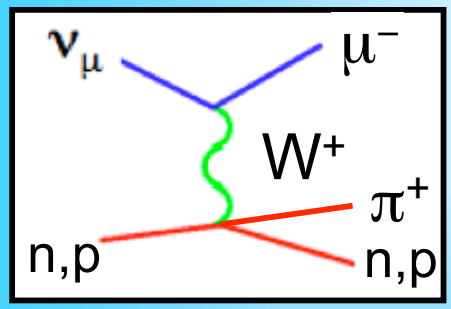
PRL 102, 101802 (2009)

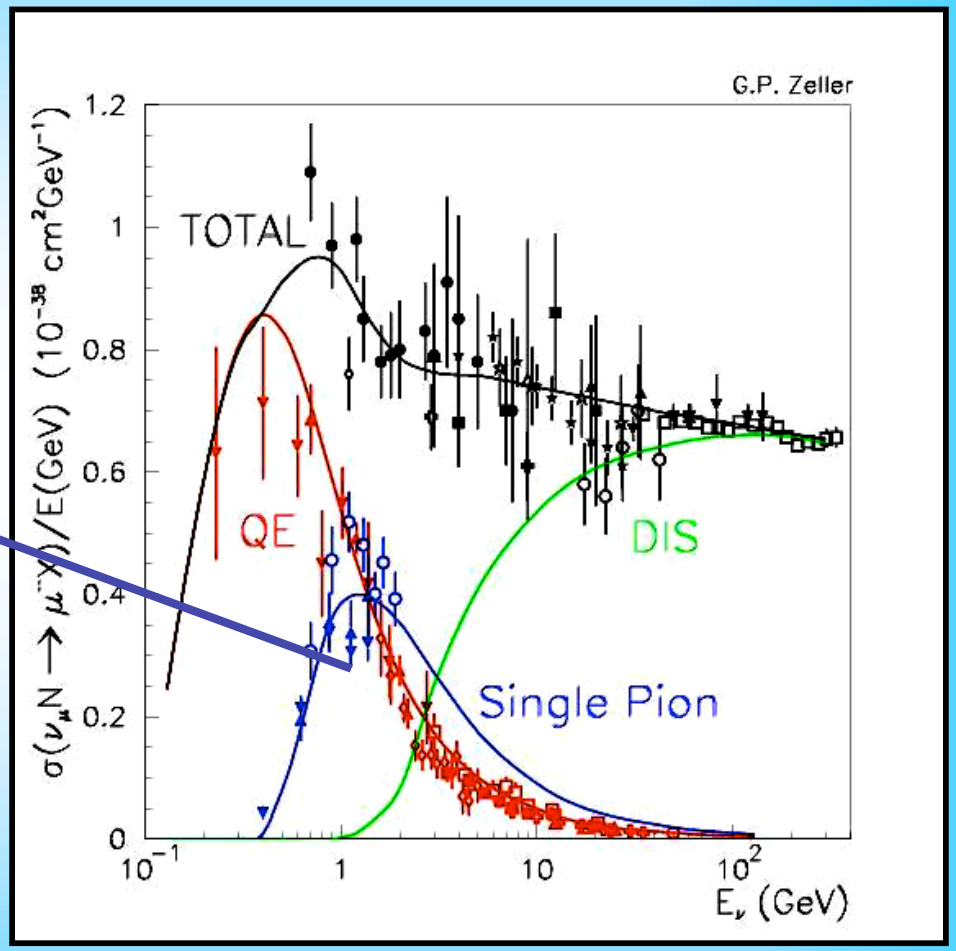
Single π Production

- NC π^0 production



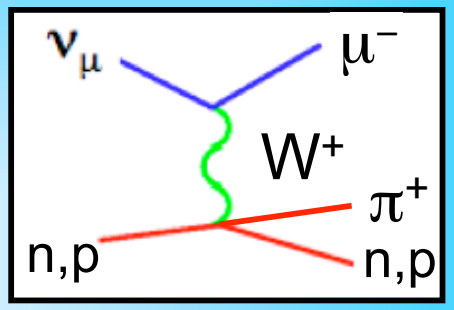
- CC π^+ production





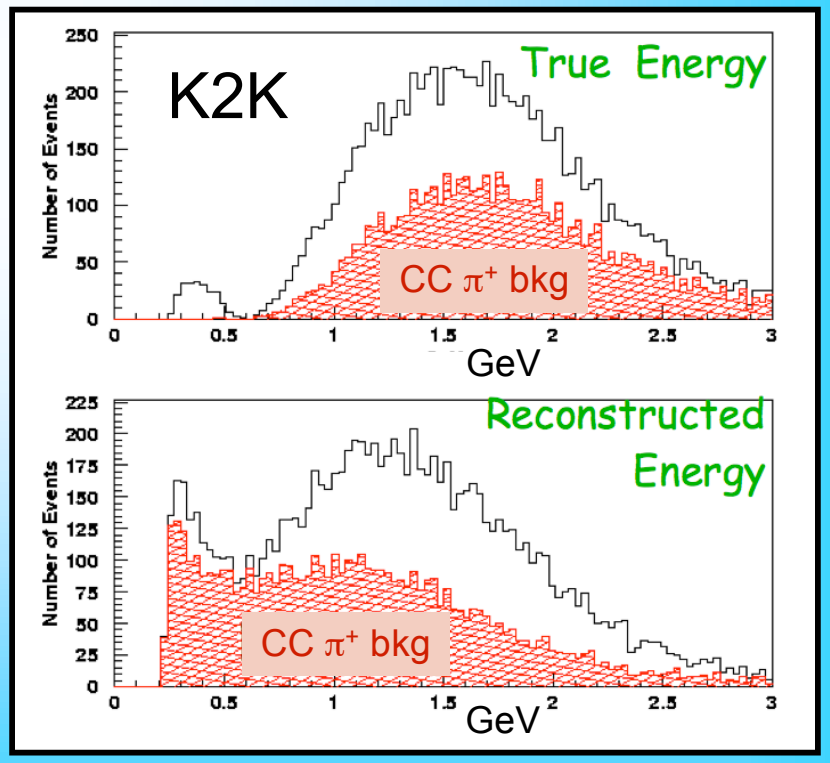
CC π^+ Production

background for
ν oscillation experiments



Why important?

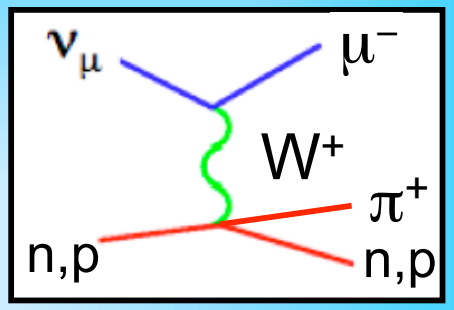
- **important for ν_μ disappearance**
  - at these energies, π re-interaction σ is large (30-40% of π's absorbed)
  - these events mis-reconstruct at low E in the oscillation dip!



(C. Walter, NuInt07)

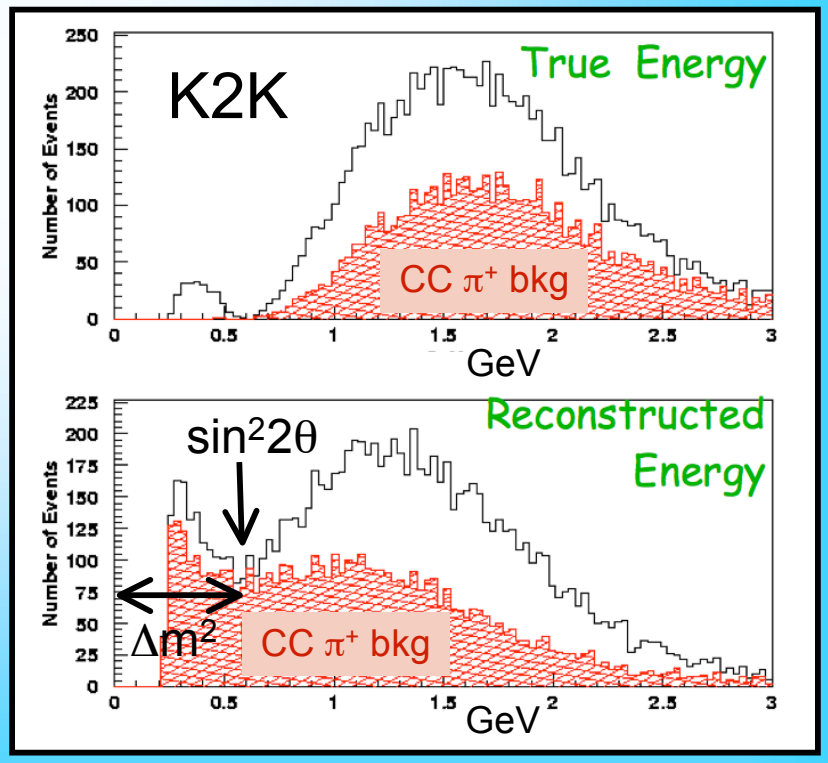
CC π^+ Production

background for
ν oscillation experiments



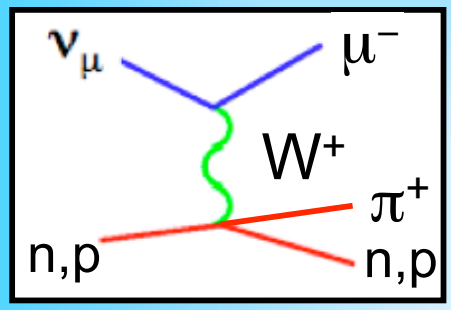
Why important?

- **important for ν_μ disappearance**
  - at these energies, π re-interaction σ is large (30-40% of π's absorbed)
  - these events mis-reconstruct at low E in the oscillation dip!
  - future osc exps must know CC π^+/QE ratio to a few % to measure Δm^2_{23}, θ_{23} (5-10% is quoted goal for T2K)

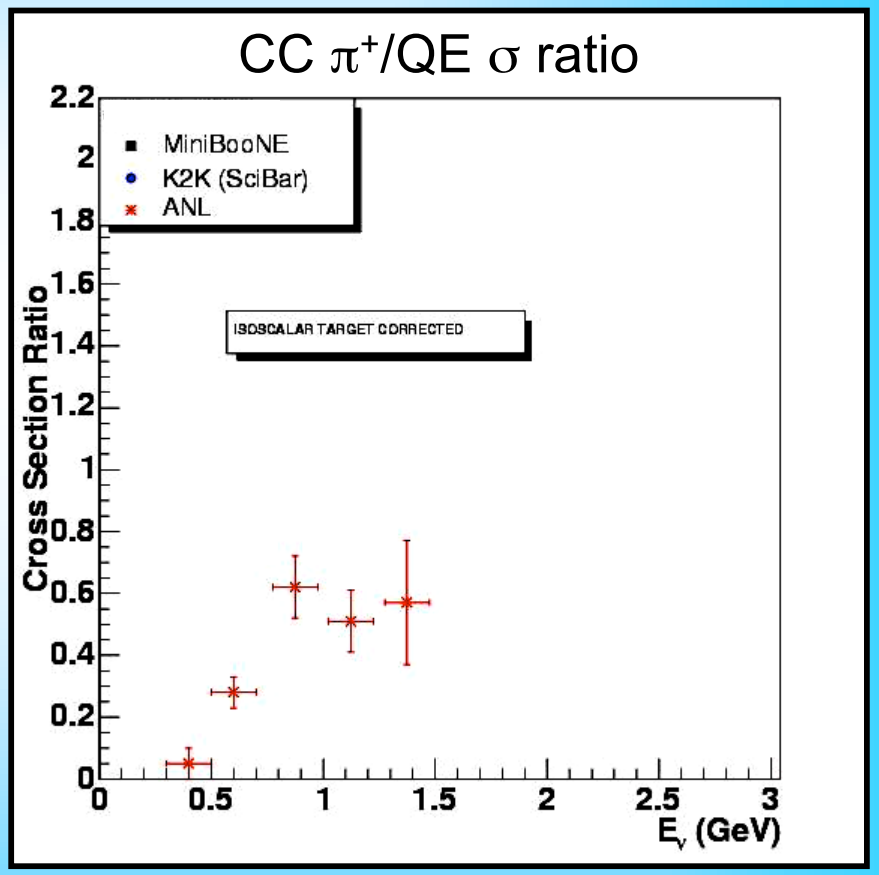


(C. Walter, NuInt07)

CC π^+ at MiniBooNE



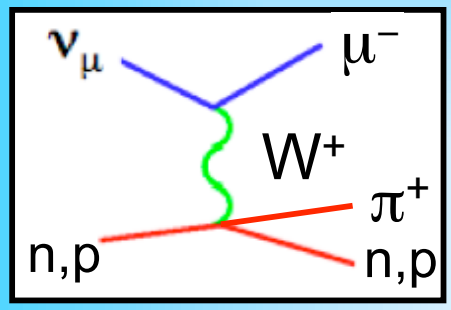
(S. Linden)



- want to know CC π^+/QE ratio in bins of energy
- this has been state of the art

ANL: Phys. Rev. **D25**, 1161 (1982), D_2

CC π^+ at MiniBooNE



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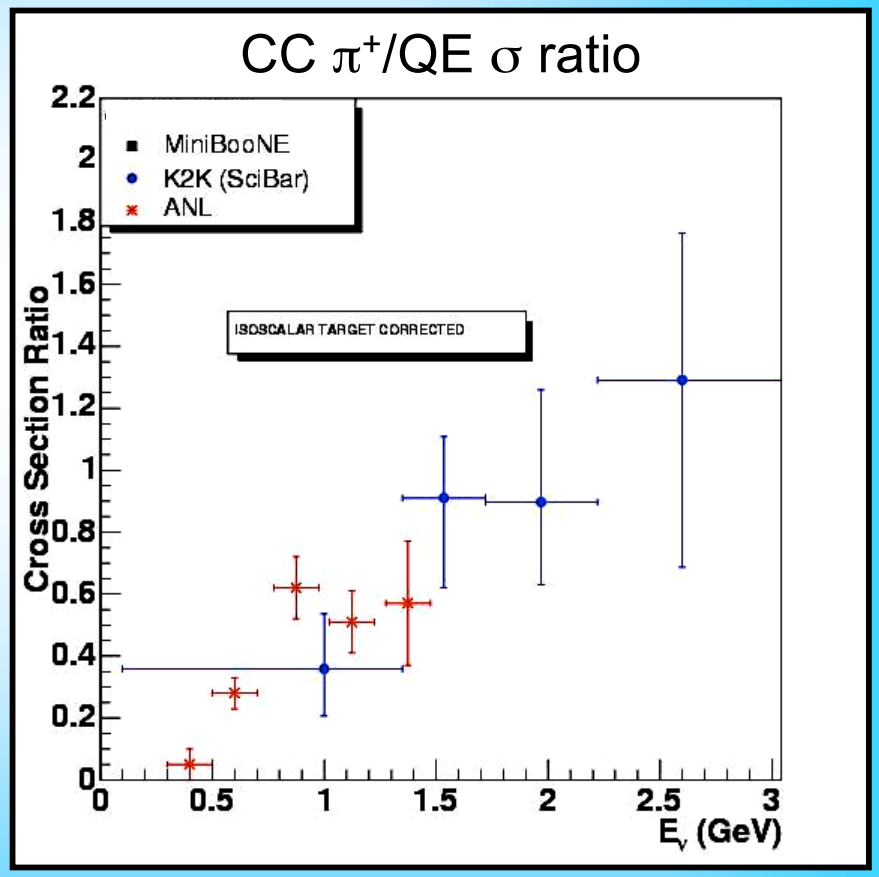
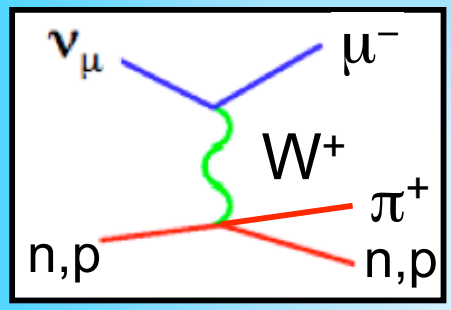


- 26 years later …

K2K: Phys. Rev. **D78**, 032003 (2008), ^{12}C

CC π^+ at MiniBooNE



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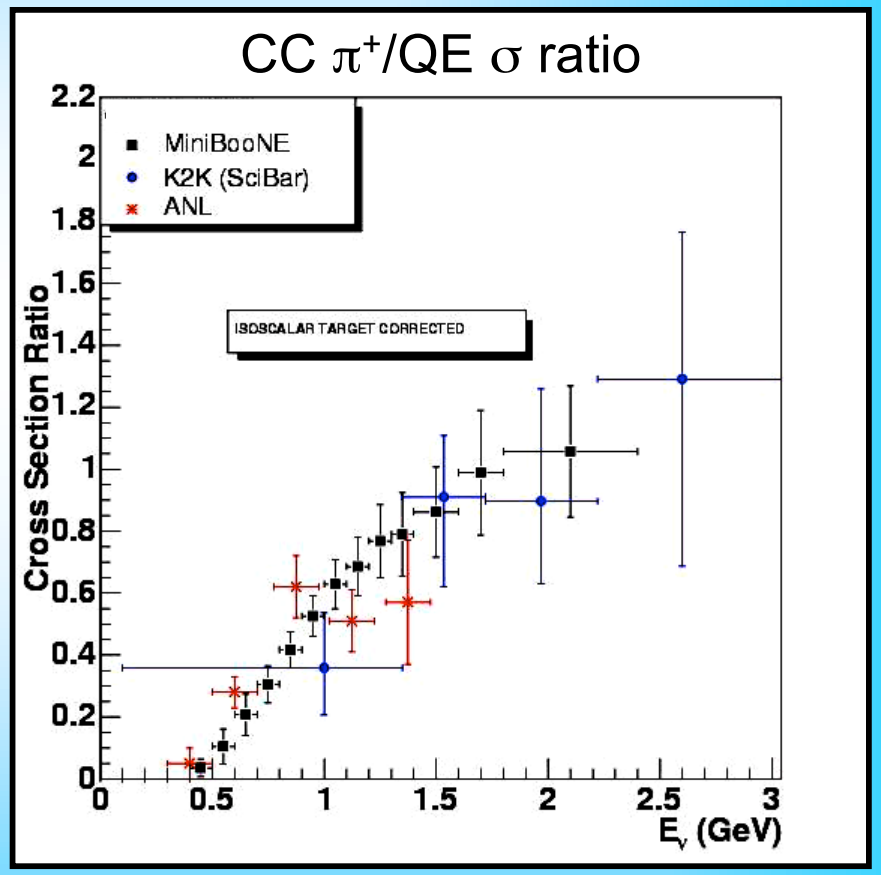
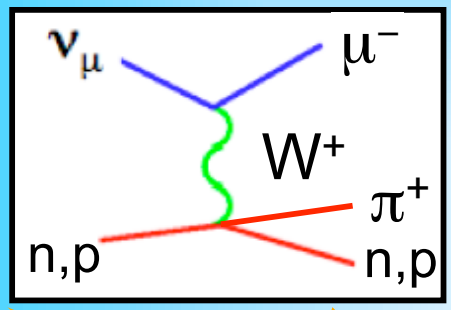


- paper submitted last month
  MiniBooNE: arXiv:0904.3159, ^{12}C

- extended energy reach
- increased precision
  (11% measurement at 800 MeV)

CC π^+ at MiniBooNE



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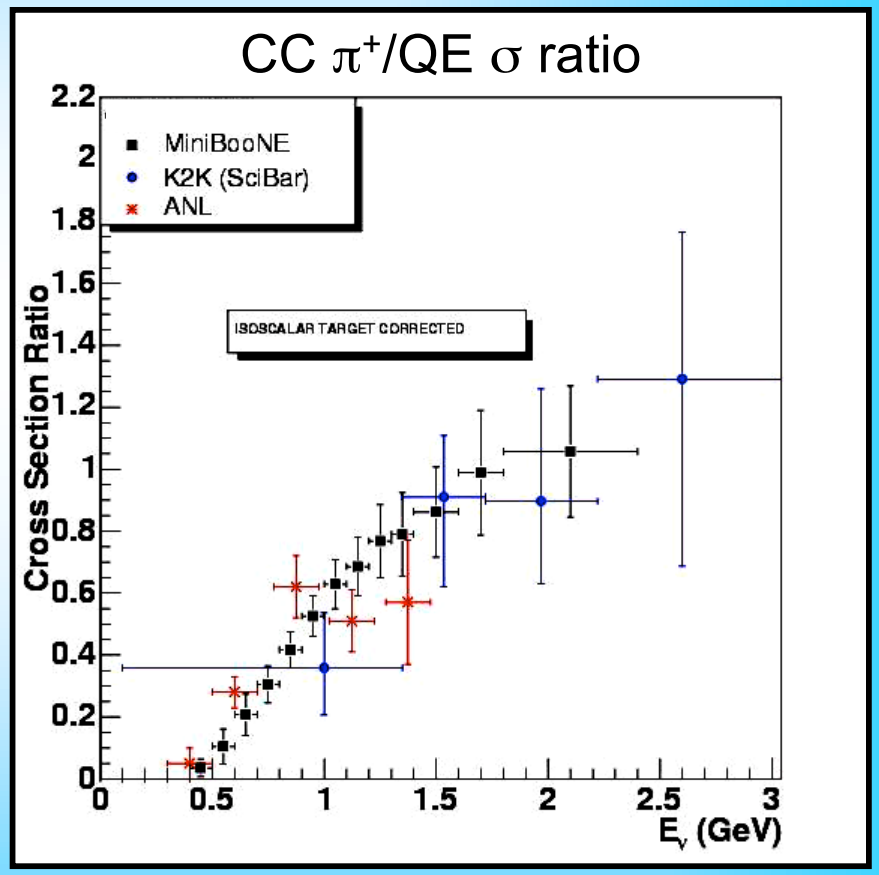
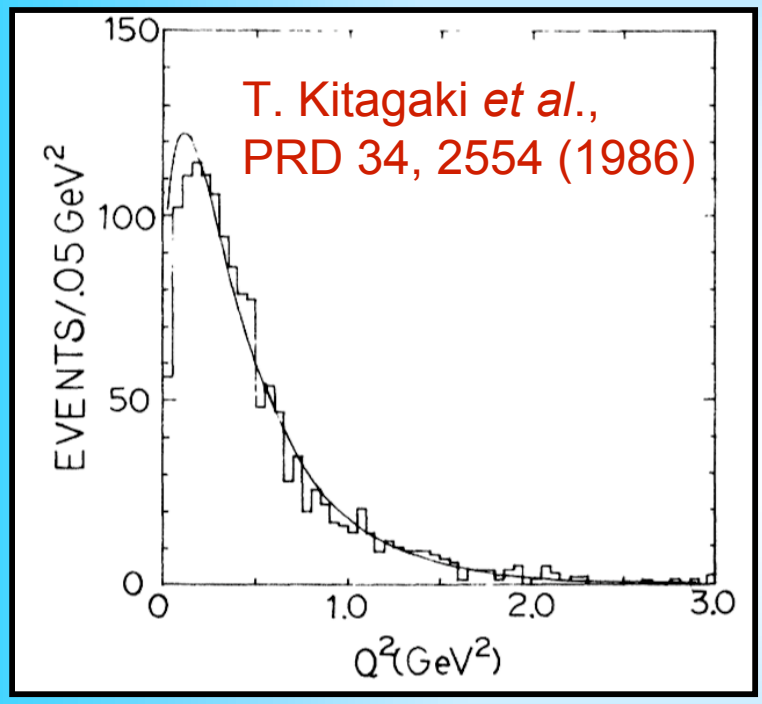


important for MiniBooNE ν_μ disappearance analysis

vetting CC π^+ background predictions & reducing their uncertainty by a factor of 2

CC π^+ Production

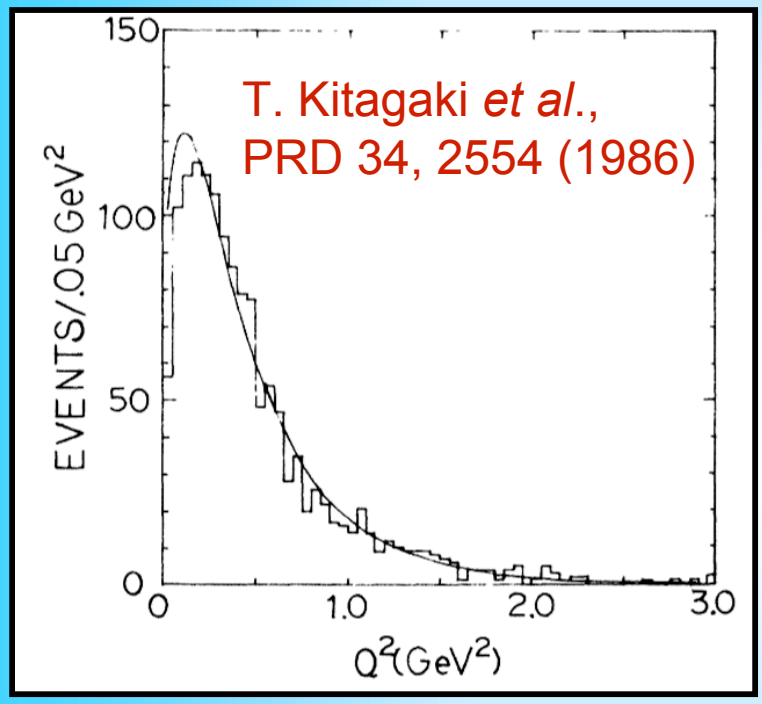
then:



- BNL, 7ft bubble chamber
- 1803 events, D_2
- Adler model with M_A=1.28 GeV

CC π^+ Production

then:



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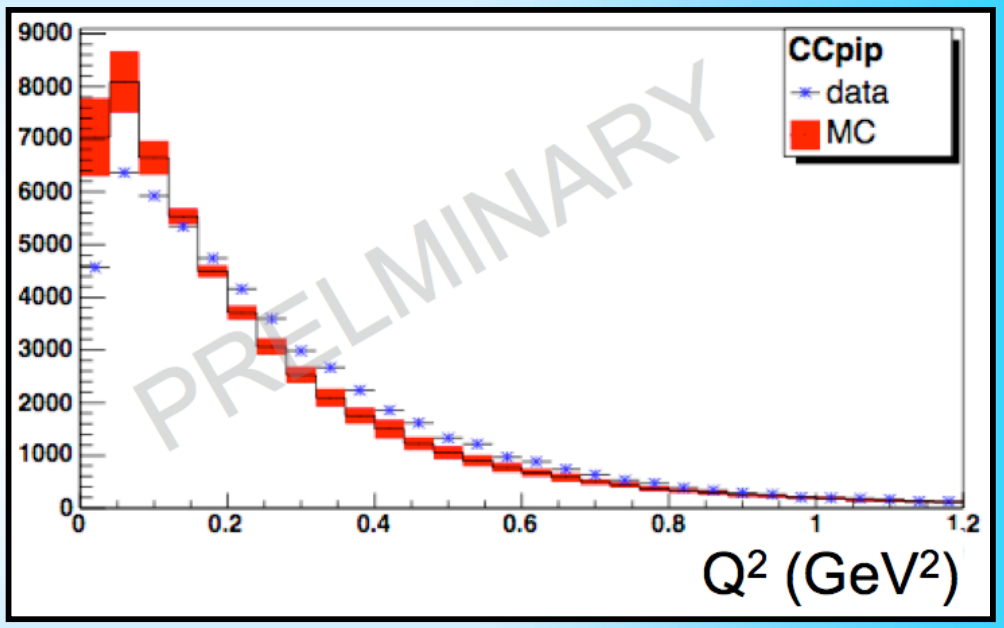
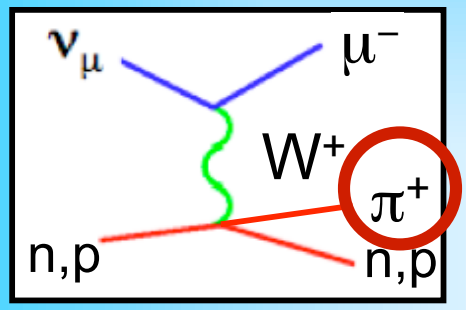
now:



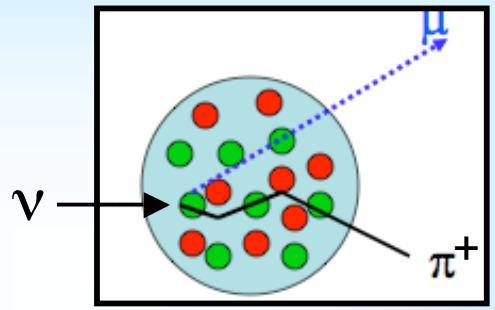
- MiniBooNE
- 48,000 events, CH_2
- Rein-Sehgal model with M_A=1.1 GeV
- revealing form factor deficiencies
  (larger than what see in QE)

CC π^+ at MiniBooNE

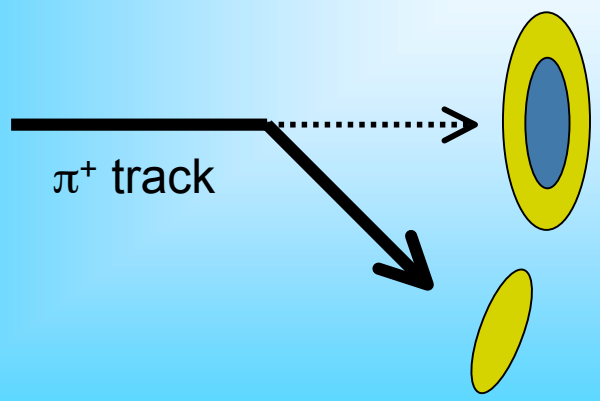


- have gone a step further with this

  (wouldn't it be nice to reconstruct the π^+?)



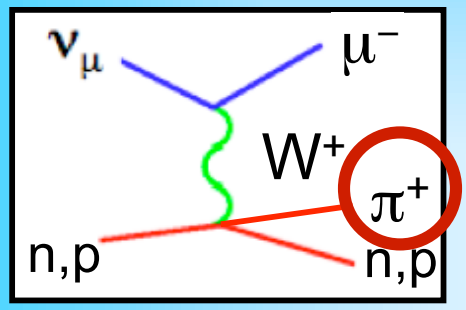
- developed a new μ + π^+ fitter (exploit fact that π's undergo hadronic ints)



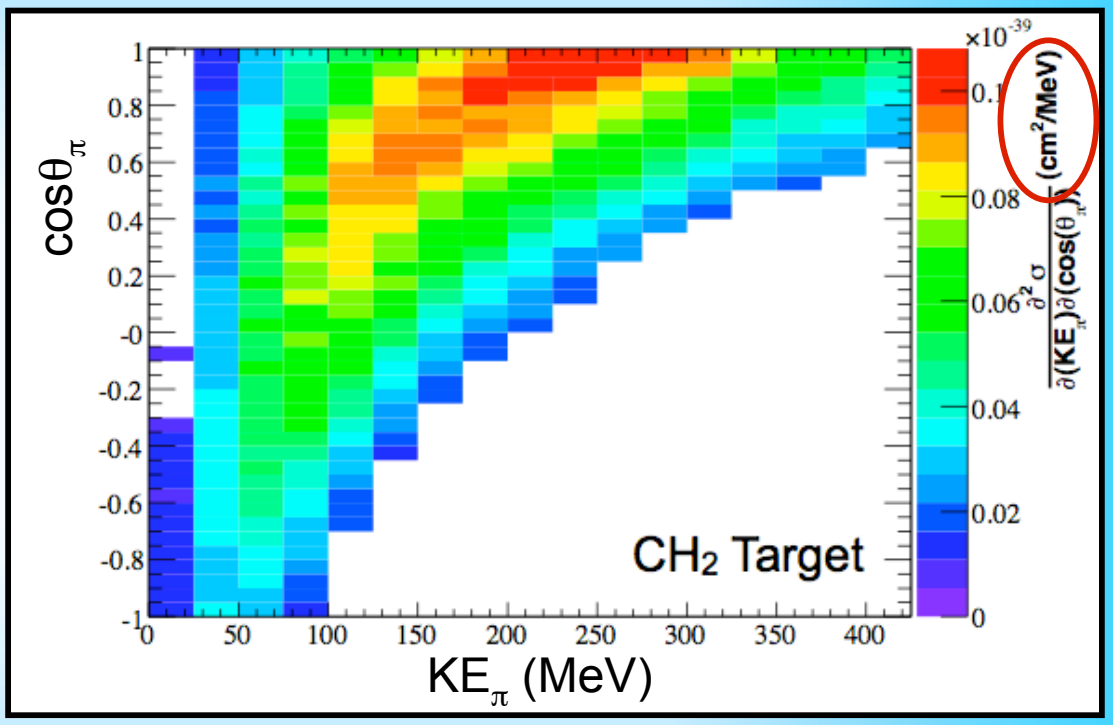
- with kinked track fitter, correctly identify μ, π^+ 88% of the time

- first time has been done in a Č detector

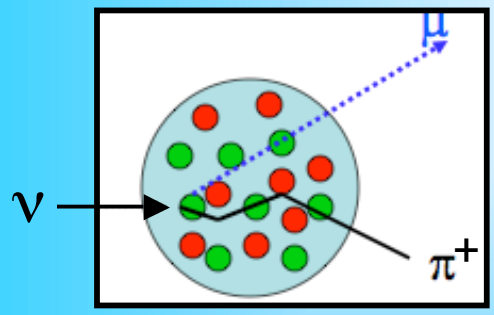
CC π^+ at MiniBooNE



(M. Wilking)



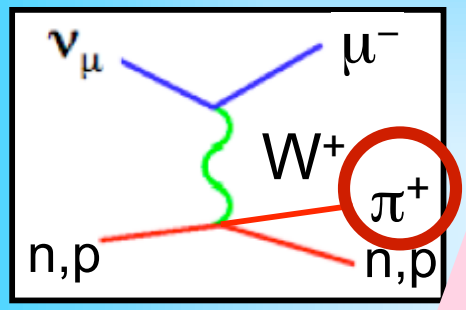
- measuring nuclear effects (not correcting this out)



- **measured 8 different cross sections:**

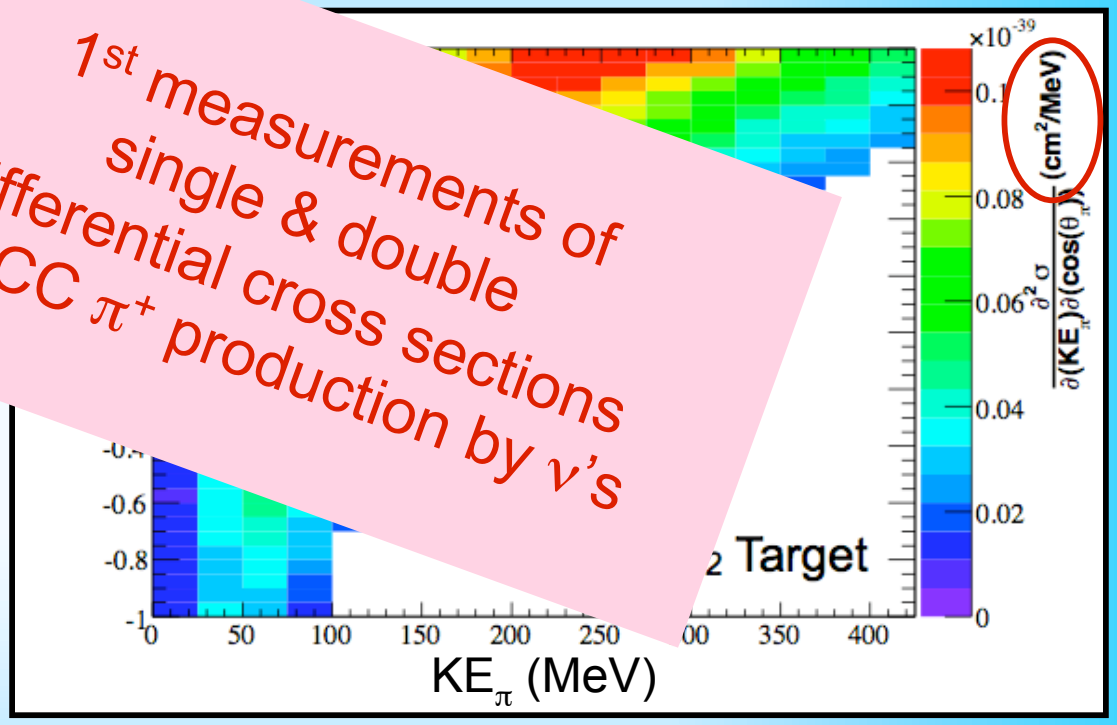
$\sigma(E_\nu)$, $d\sigma/dQ^2$, $d^2\sigma/dT_\mu d\theta_\mu$, $d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$, $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\pi d\theta_\pi$

CC π^+ at MiniBooNE



1st measurements of single & double differential cross sections for CC π^+ production by ν's

(M. Wilking)



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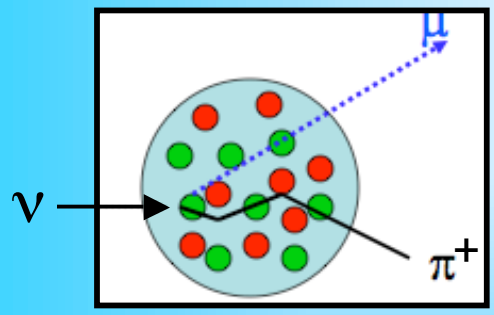

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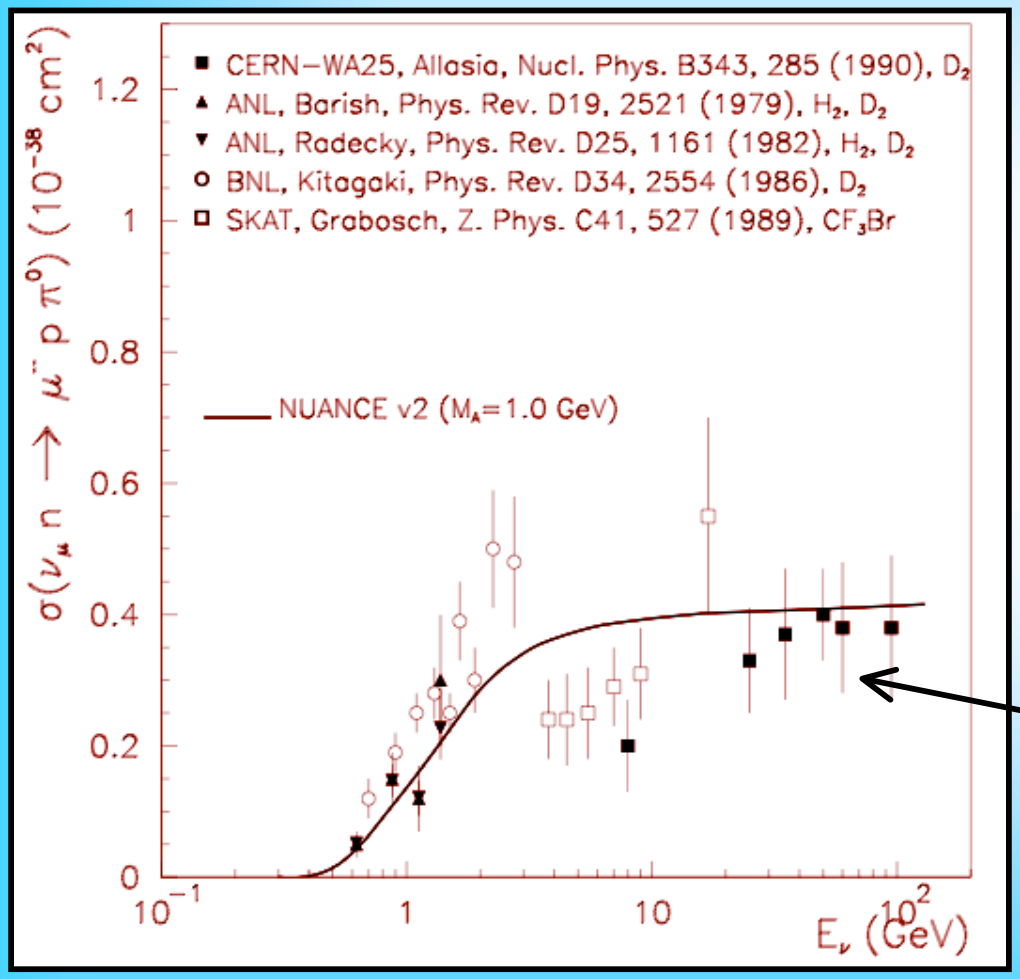
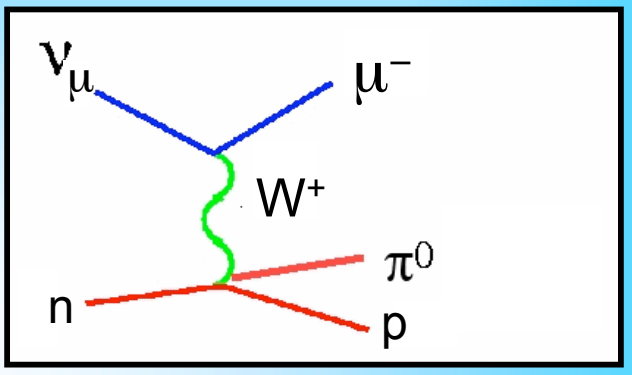
CC π^0 at MiniBooNE



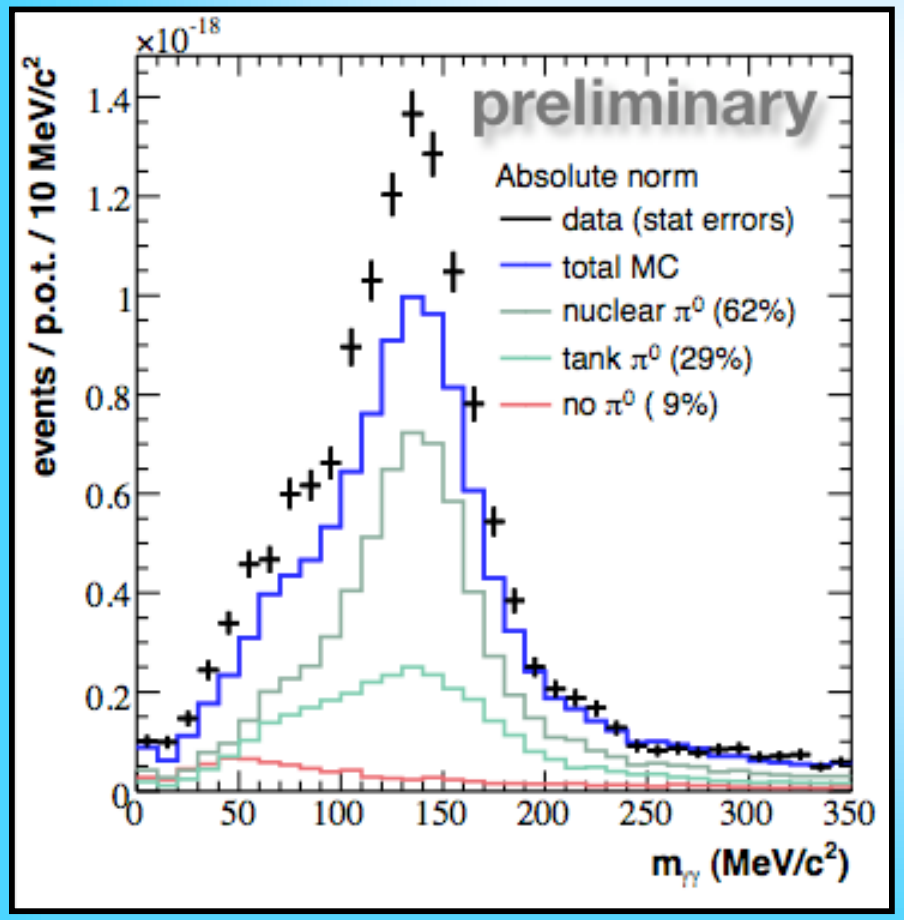


- can also produce π^0's in CC ν interactions
- this is what we've known on this reaction

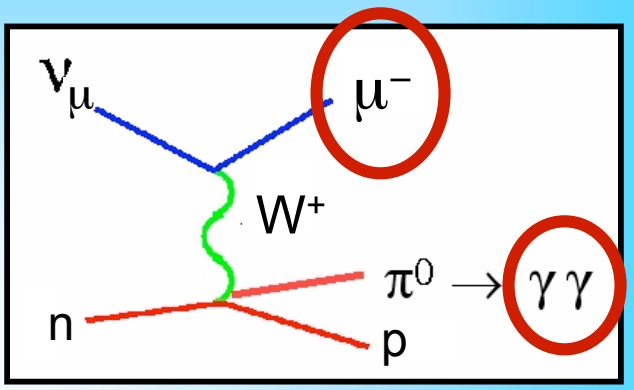
(>2 difference between light & heavy target measurements)

CC π^0 at MiniBooNE

- also working on a 3-ring fitter to reconstruct CC π^0 events



(B. Nelson)



- 9,000 events in MiniBooNE
- 62% purity with basic cuts
- σ measurements in this sample coming soon!
- really trying to get the most out of our data

	# events	purity	MiniBooNE σ results
CC π^+/QE ratio (S. Linden, J. Nowak)	193,000 QE 46,000 CC π^+	83% (72%) 92% (87%)	observed ratio in E_ν (& FSI-corr) Q^2 studies in CC π^+ sample
ν_μ CCQE (T. Katori)	146,000	76%	$d^2\sigma/dT_\mu d\theta_\mu$ $d\sigma/dQ^2$, $\sigma(E_\nu)$
ν_μ NC EL (D. Perevalov)	94,000	65% (80% w/ Irreducibles)	$d\sigma/dQ^2$
ν_μ CC π^+ (M. Wilking)	48,000	90%	$d\sigma/dT_\mu$, $d\sigma/d\theta_\mu$, $d^2\sigma/dT_\mu d\theta_\mu$ $d\sigma/dT_\pi$, $d\sigma/d\theta_\pi$, $d^2\sigma/dT_\pi d\theta_\pi$ $d\sigma/dQ^2$, $\sigma(E_\nu)$
ν_μ NC π^0 $\bar{\nu}_\mu$ NC π^0 (C. Anderson)	21,000 2,000	73% 58% ($\bar{\nu}$-only)	$d\sigma/dp_\pi$ $d\sigma/d\theta_\pi$ total observed NC $1\pi^0$ σ
ν_μ CC π^0 (B. Nelson)	9,000	62%	kinematic comparisons
$\bar{\nu}_\mu$ CCQE (J. Grange)	27,000	54% ($\bar{\nu}$-only)	kinematic comparisons

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ν_μ NC π^0 $\bar{\nu}_\mu$ NC π^0 (C. Anderson)	21,000 2,000	73% 58% ($\bar{\nu}$-only)	$d\sigma/dp_\pi$ $d\sigma/d\theta_\pi$ total observed NC $1\pi^0$ σ
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$\bar{\nu}_\mu$ CCQE (J. Grange)	27,000	54% ($\bar{\nu}$-only)	kinematic comparis

order of magnitude more data (in many cases)

many firsts!

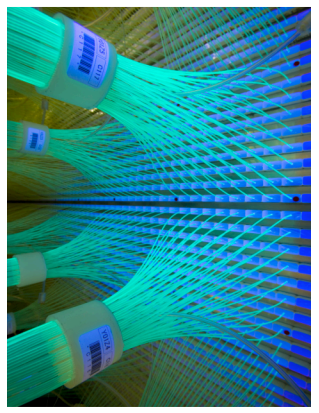
papers coming soon

Outlook

- situation is improving (new data is helping), but there is more to do!
- add'l σ_ν meas from other experiments on the horizon ...

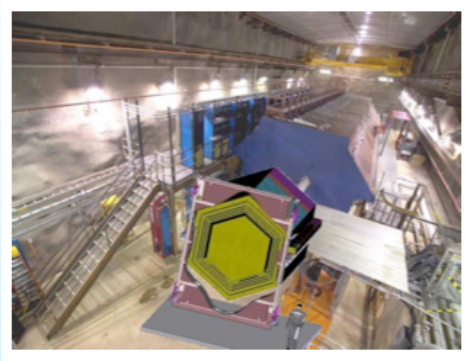
  - **MINERνA** (higher E, coming soon)
  - **SciBooNE** (lower E, data now)

  dedicated σ_ν experiments (fine-grained detectors)



  - **MINOS** (higher E, data now)
  - **T2K ND280** (lower E, coming soon)

  near detectors



- there is certainly more to come on this!

Conclusions

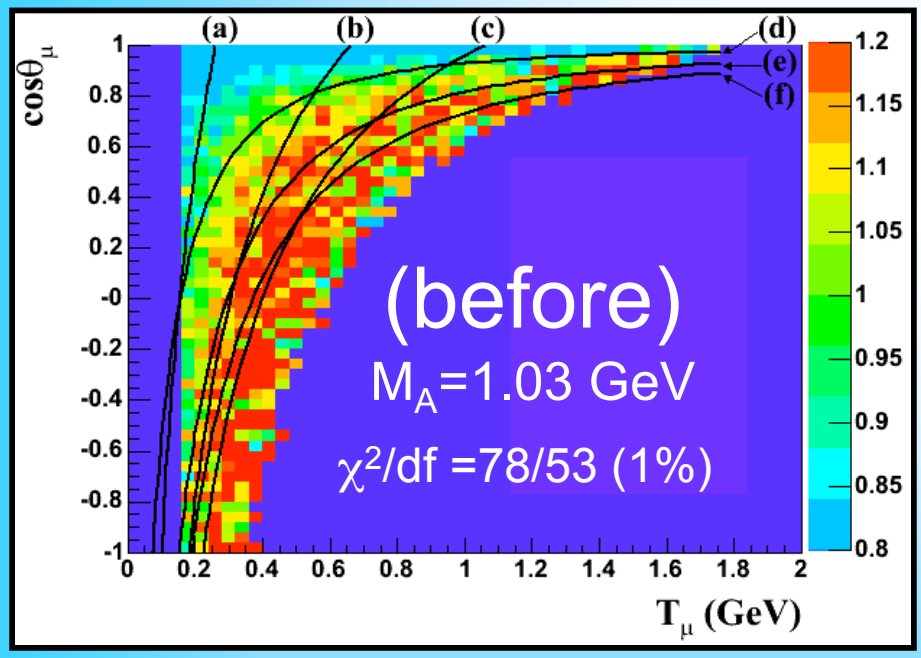
- collection of existing measurements of low energy ν σ's is quite sparse, especially on nuclear targets
  - precise measurements crucial for ν oscillation experiments
- modern experiments have started going back to look at this ν scattering physics decades later
  - there are still things we don't understand !
- very active field of investigation at MiniBooNE (>900,000 events)
  - measurements of use to outside community
  - QE, NC π^0, CC $\pi^{+,0}$
  - hopefully showed you different side to familiar experiment
- look forward to future results (SciBooNE & MINERνA)
- increasingly relevant for future osc exps (T2K, NOνA, DUSEL, …)

Backups

QE Scattering at MiniBooNE

- one of the advantages of having high stats (146k) is can check in 2D (1st time in history have looked at 2D distributions!)

past world-avg M_A & Fermi Gas model:



ratio of data/MC in muon kinematics

(remember T_μ, $\theta_\mu \rightarrow E_\nu$)

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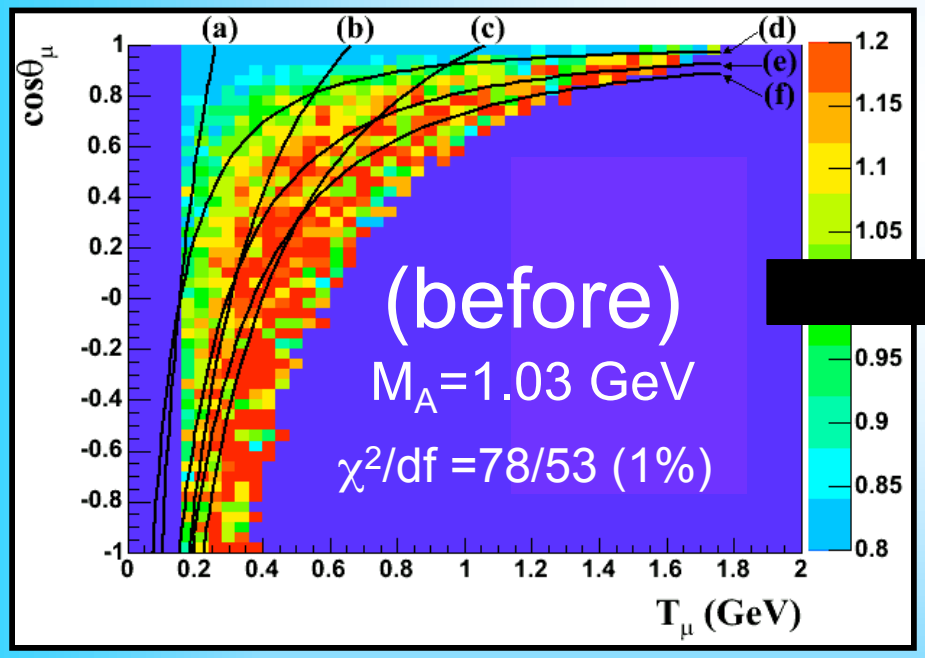
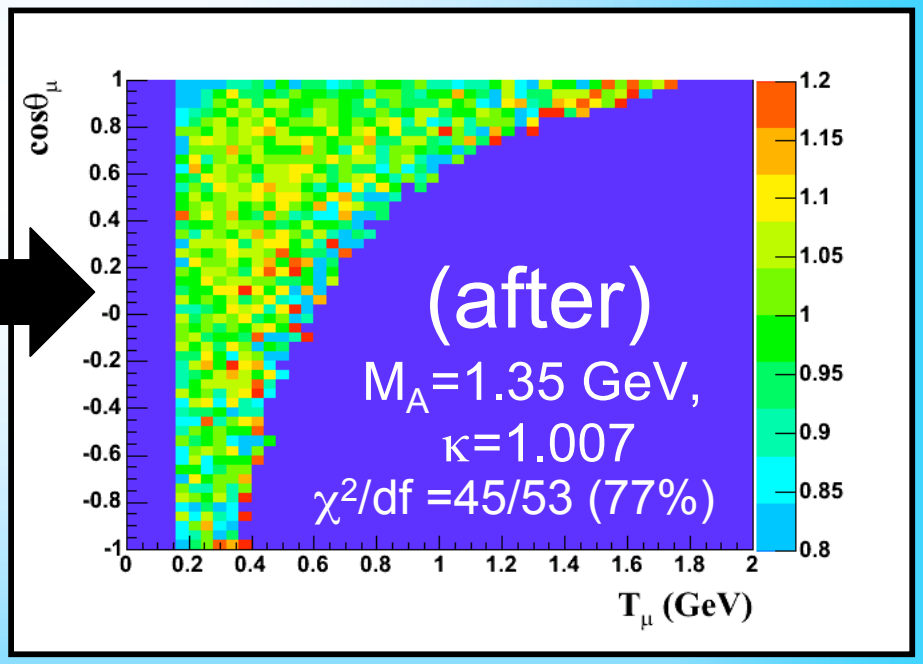


after MiniBooNE fit in Q^2 (2 pars):



- stunning agreement across entire phase space!

QE Scattering at MiniBooNE

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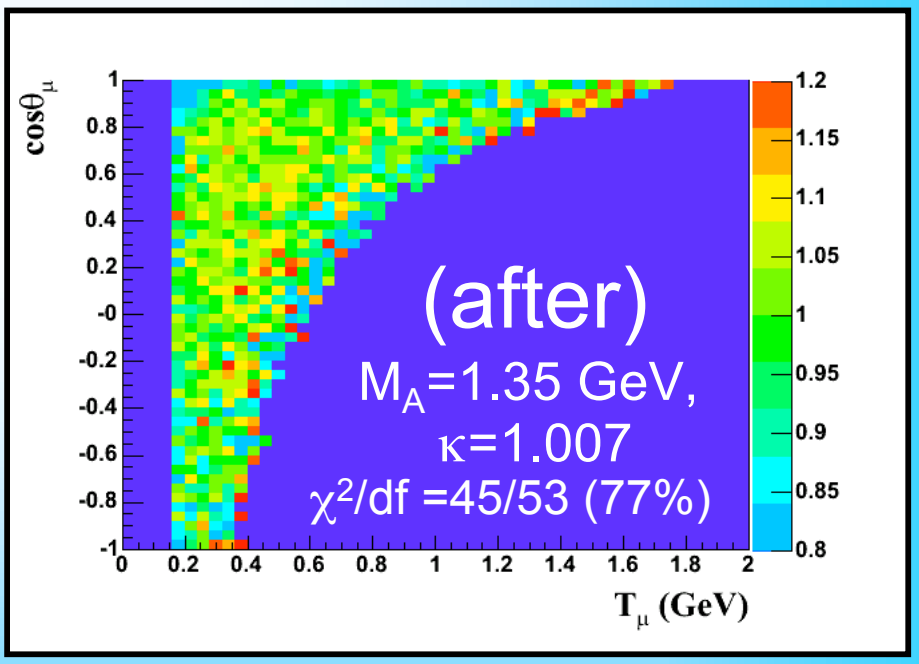
important for MiniBooNE oscillation analyses

QE is signal channel so want to measure as accurately as we can

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



- stunning agreement across entire phase space!