INTRODUCTION TO THE EXPERIMENTAL TALKS ON QE SCATTERING

Sam Zeller
Fermilab

INT workshop
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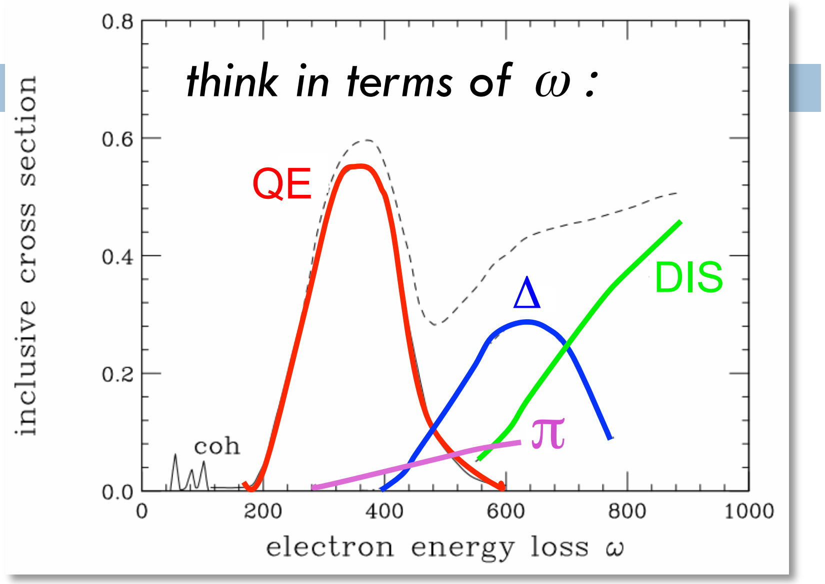
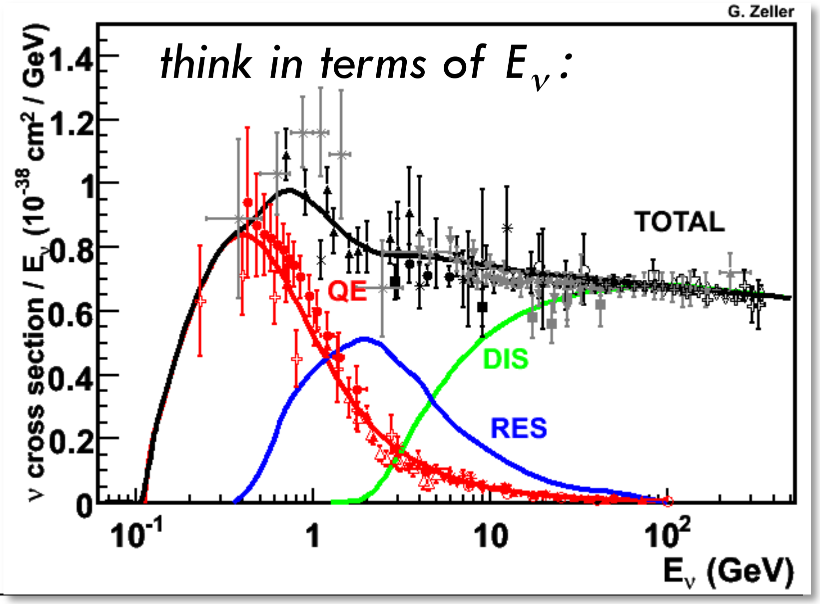
QE Scattering

- **electron scattering:**
  - inclusive (e,e') at low ω or exclusive (e,e'p), (e,e'pp)
  - beam energy is known, monochromatic
  - energy & momentum transferred to the nucleus can be precisely measured



(Benhar, Day, Sick, Rev. Mod. Phys. 80, 189 (2008))

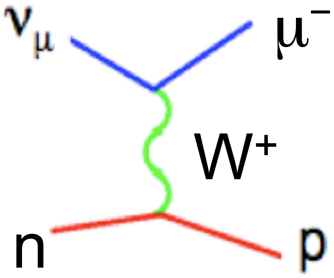
- **neutrino scattering:**
  - ν_μ CC scattering with low ν (or no π's) or ν_μ n → μ^- p, μ^- p p
  - beam energy is <u>not</u> known, <u>not</u> monochromatic (spectrum of E_ν)
  - infer E_ν from $E_{lep}+E_{had}$ or E_{lep},θ_{lep}
  - addition of axial-vector contribution
  - have poorer kinematic specification



Neutrino QE Scattering

Why important?

- **important for ν oscillation experiments**
  - biggest piece of the cross section at energies $E_\nu \lesssim 1$ GeV, so typically gives the largest contribution to signal samples in many osc exps
  - can infer E_ν from the out-going lepton kinematics
  - once thought of as the simplest neutrino process to calculate



(typically thought of as a process with a single knock-out nucleon)

(heavily studied in 1970's and 80's, one of the 1st ν interactions measured)

Neutrino QE Measurements

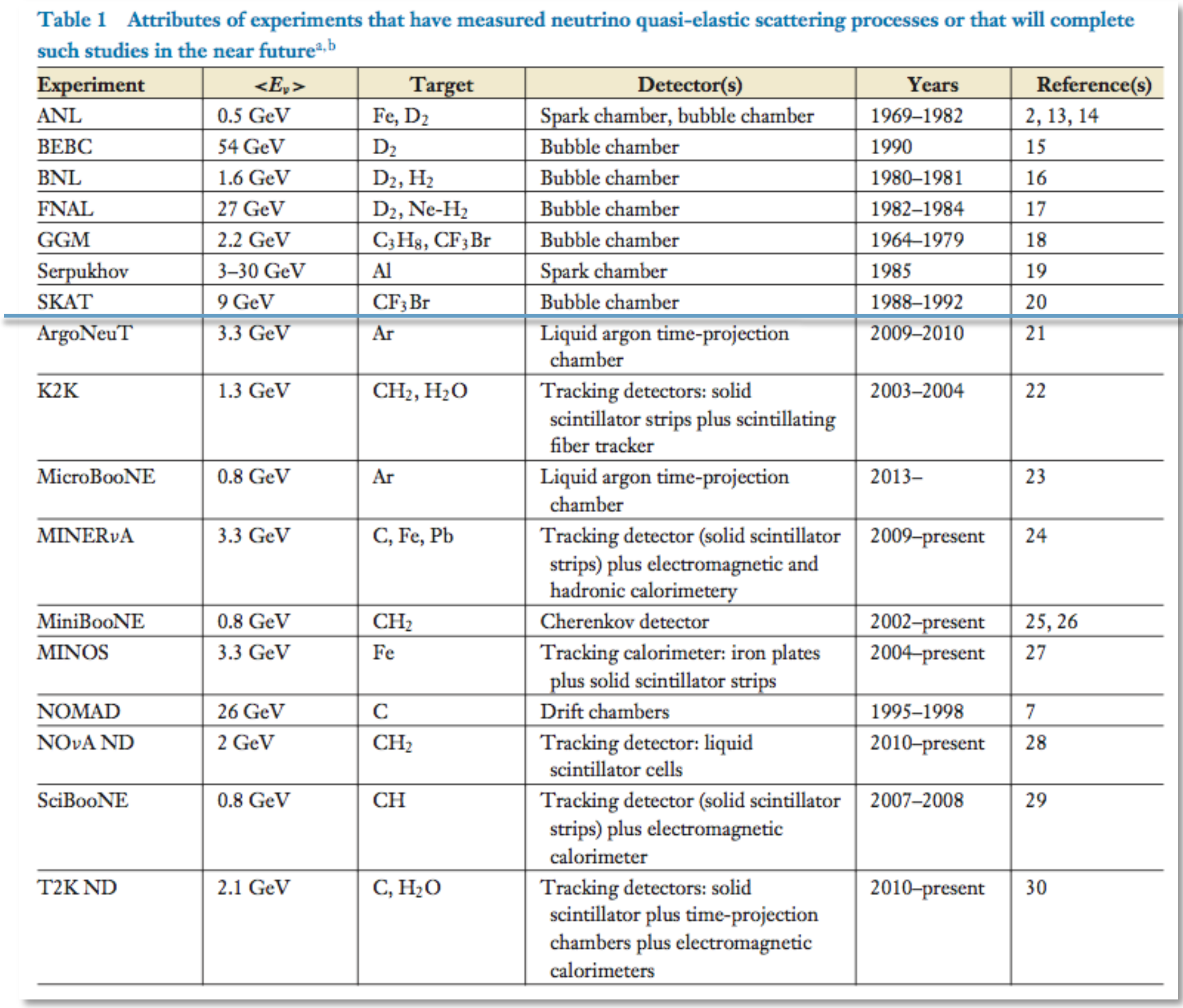


Table 1 Attributes of experiments that have measured neutrino quasi-elastic scattering processes or that will complete such studies in the near future[a,b]

Experiment	$<E_\nu>$	Target	Detector(s)	Years	Reference(s)
ANL	0.5 GeV	Fe, D_2	Spark chamber, bubble chamber	1969–1982	2, 13, 14
BEBC	54 GeV	D_2	Bubble chamber	1990	15
BNL	1.6 GeV	D_2, H_2	Bubble chamber	1980–1981	16
FNAL	27 GeV	D_2, Ne-H_2	Bubble chamber	1982–1984	17
GGM	2.2 GeV	C_3H_8, CF_3Br	Bubble chamber	1964–1979	18
Serpukhov	3–30 GeV	Al	Spark chamber	1985	19
SKAT	9 GeV	CF_3Br	Bubble chamber	1988–1992	20
ArgoNeuT	3.3 GeV	Ar	Liquid argon time-projection chamber	2009–2010	21
K2K	1.3 GeV	CH_2, H_2O	Tracking detectors: solid scintillator strips plus scintillating fiber tracker	2003–2004	22
MicroBooNE	0.8 GeV	Ar	Liquid argon time-projection chamber	2013–	23
MINERνA	3.3 GeV	C, Fe, Pb	Tracking detector (solid scintillator strips) plus electromagnetic and hadronic calorimetery	2009–present	24
MiniBooNE	0.8 GeV	CH_2	Cherenkov detector	2002–present	25, 26
MINOS	3.3 GeV	Fe	Tracking calorimeter: iron plates plus solid scintillator strips	2004–present	27
NOMAD	26 GeV	C	Drift chambers	1995–1998	7
NOνA ND	2 GeV	CH_2	Tracking detector: liquid scintillator cells	2010–present	28
SciBooNE	0.8 GeV	CH	Tracking detector (solid scintillator strips) plus electromagnetic calorimeter	2007–2008	29
T2K ND	2.1 GeV	C, H_2O	Tracking detectors: solid scintillator plus time-projection chambers plus electromagnetic calorimeters	2010–present	30

historical measurements

↑

↓

modern measurements

exploring these differences is a main goal of this session

(Gallagher, Garvey, Zeller, Ann. Rev. Nucl. Part. Sci, 61, 355 (2011))

Deuterium

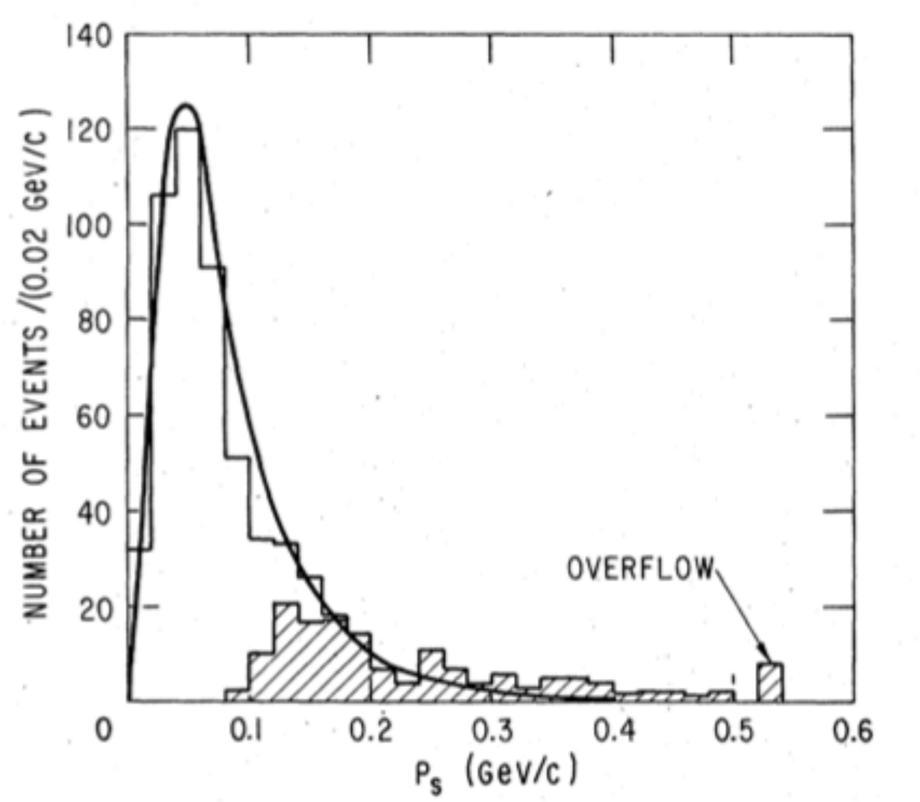


FIG. 19. Spectator momentum distributions for events fitting $\nu d \rightarrow \mu^- p p_s$. The shaded area represents the events with a visible spectator. The curve is the Hulthén wave function normalized to the total number of events.

(ANL, S.J. Barish et al., PRD 16, 3103, 1977)

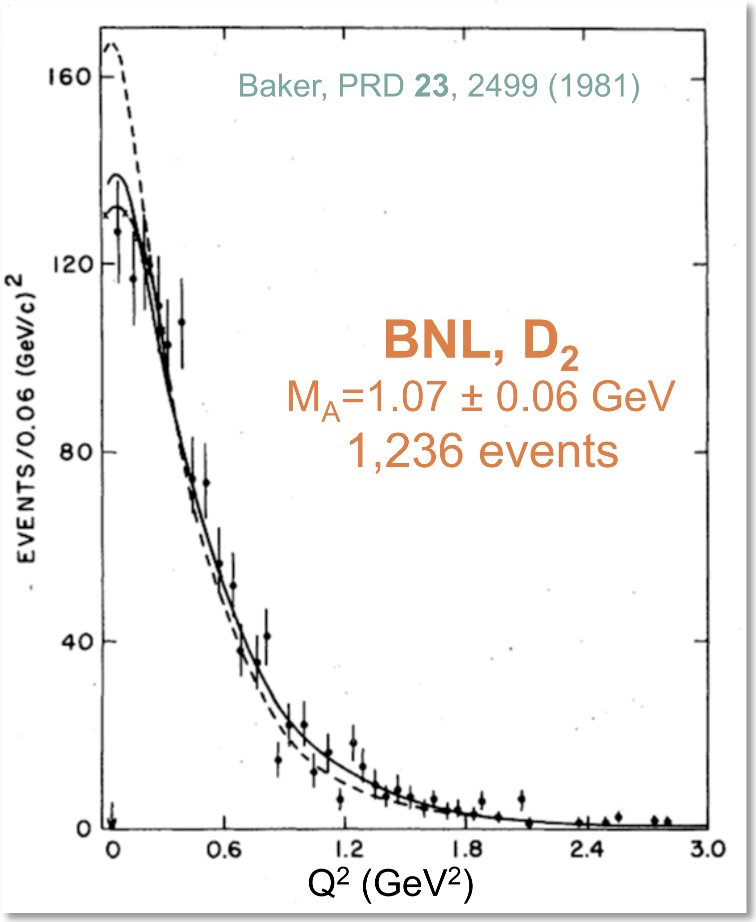
- many of these early neutrino experiments used bubble chambers filled with deuterium as their neutrino target (less influenced by nuclear effects)

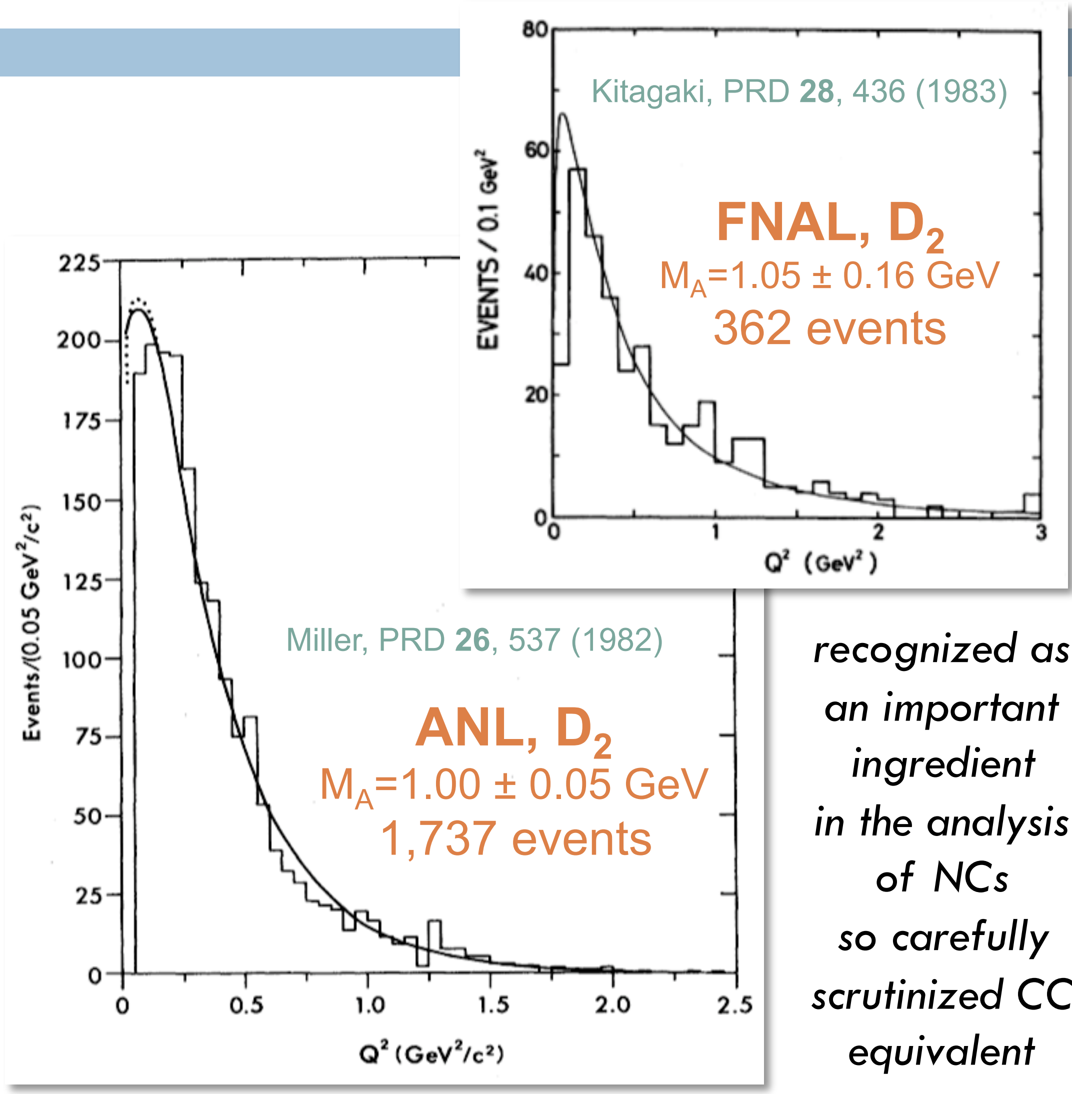
- advantage is that can observe:

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

- <u>advantages</u>:
  - event selection is more robust
  - 97-99% QE purities

Historical Data





recognized as an important ingredient in the analysis of NCs so carefully scrutinized CC equivalent

- primary aim of these exps was to measure the free nucleon form factor

ν_μ QE Measurements

(Gallagher, Garvey, Zeller, Ann. Rev. Nucl. Part. Sci, 61, 355 (2011))

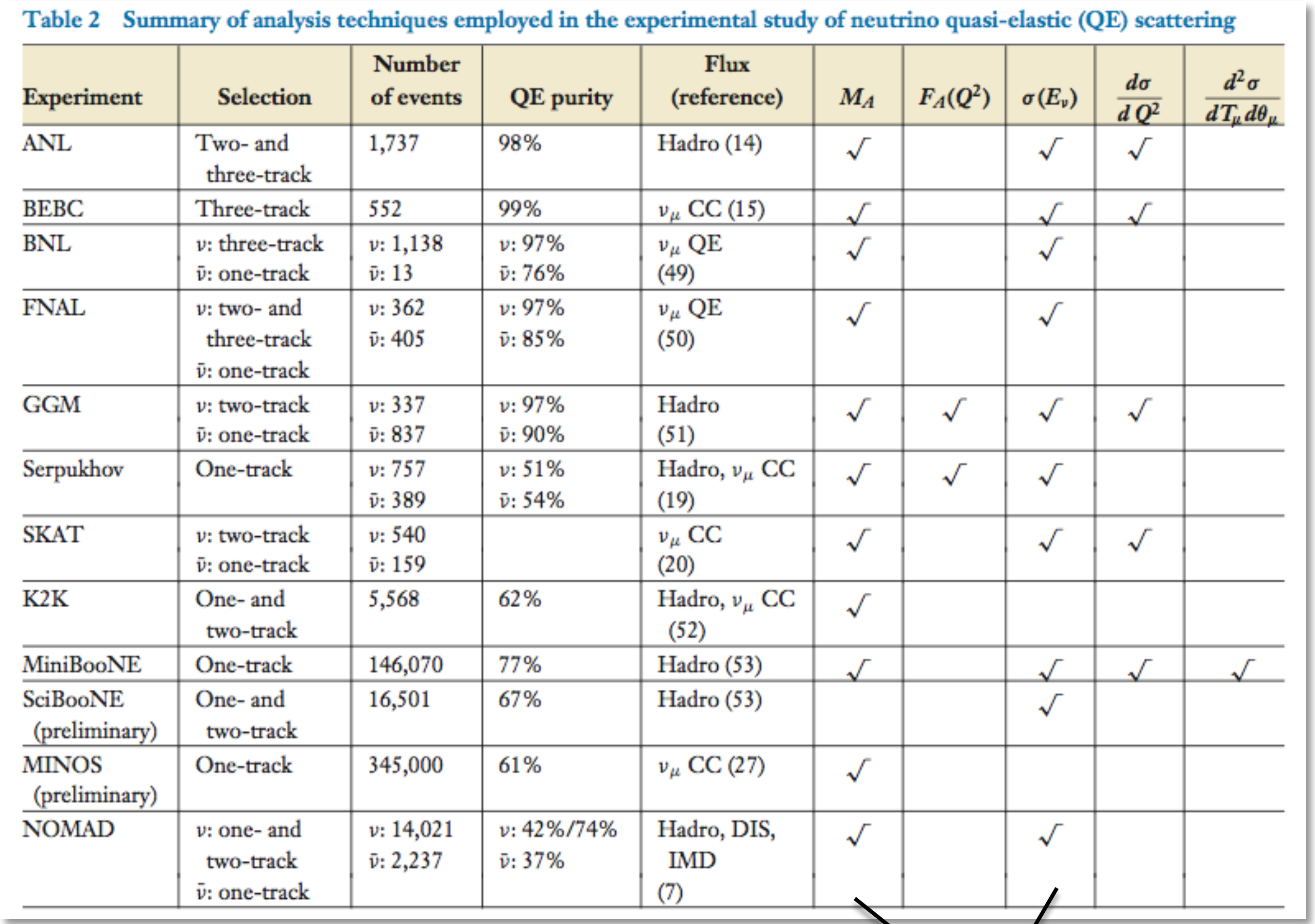


Table 2 Summary of analysis techniques employed in the experimental study of neutrino quasi-elastic (QE) scattering

Experiment	Selection	Number of events	QE purity	Flux (reference)	M_A	$F_A(Q^2)$	$\sigma(E_\nu)$	$\frac{d\sigma}{dQ^2}$	$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$
ANL	Two- and three-track	1,737	98%	Hadro (14)	✓		✓	✓	
BEBC	Three-track	552	99%	ν_μ CC (15)	✓		✓	✓	
BNL	ν: three-track $\bar{\nu}$: one-track	ν: 1,138 $\bar{\nu}$: 13	ν: 97% $\bar{\nu}$: 76%	ν_μ QE (49)	✓		✓		
FNAL	ν: two- and three-track $\bar{\nu}$: one-track	ν: 362 $\bar{\nu}$: 405	ν: 97% $\bar{\nu}$: 85%	ν_μ QE (50)	✓		✓		
GGM	ν: two-track $\bar{\nu}$: one-track	ν: 337 $\bar{\nu}$: 837	ν: 97% $\bar{\nu}$: 90%	Hadro (51)	✓	✓	✓	✓	
Serpukhov	One-track	ν: 757 $\bar{\nu}$: 389	ν: 51% $\bar{\nu}$: 54%	Hadro, ν_μ CC (19)	✓	✓	✓		
SKAT	ν: two-track $\bar{\nu}$: one-track	ν: 540 $\bar{\nu}$: 159		ν_μ CC (20)	✓		✓	✓	
K2K	One- and two-track	5,568	62%	Hadro, ν_μ CC (52)	✓				
MiniBooNE	One-track	146,070	77%	Hadro (53)	✓		✓	✓	✓
SciBooNE (preliminary)	One- and two-track	16,501	67%	Hadro (53)			✓		
MINOS (preliminary)	One-track	345,000	61%	ν_μ CC (27)	✓				
NOMAD	ν: one- and two-track $\bar{\nu}$: one-track	ν: 14,021 $\bar{\nu}$: 2,237	ν: 42%/74% $\bar{\nu}$: 37%	Hadro, DIS, IMD (7)	✓		✓		

- trends:

  - QE event selection varies from exp to exp
  - much larger event samples have become available
  - purities are typically lower in modern exps (due to use of heavier nuclear targets)

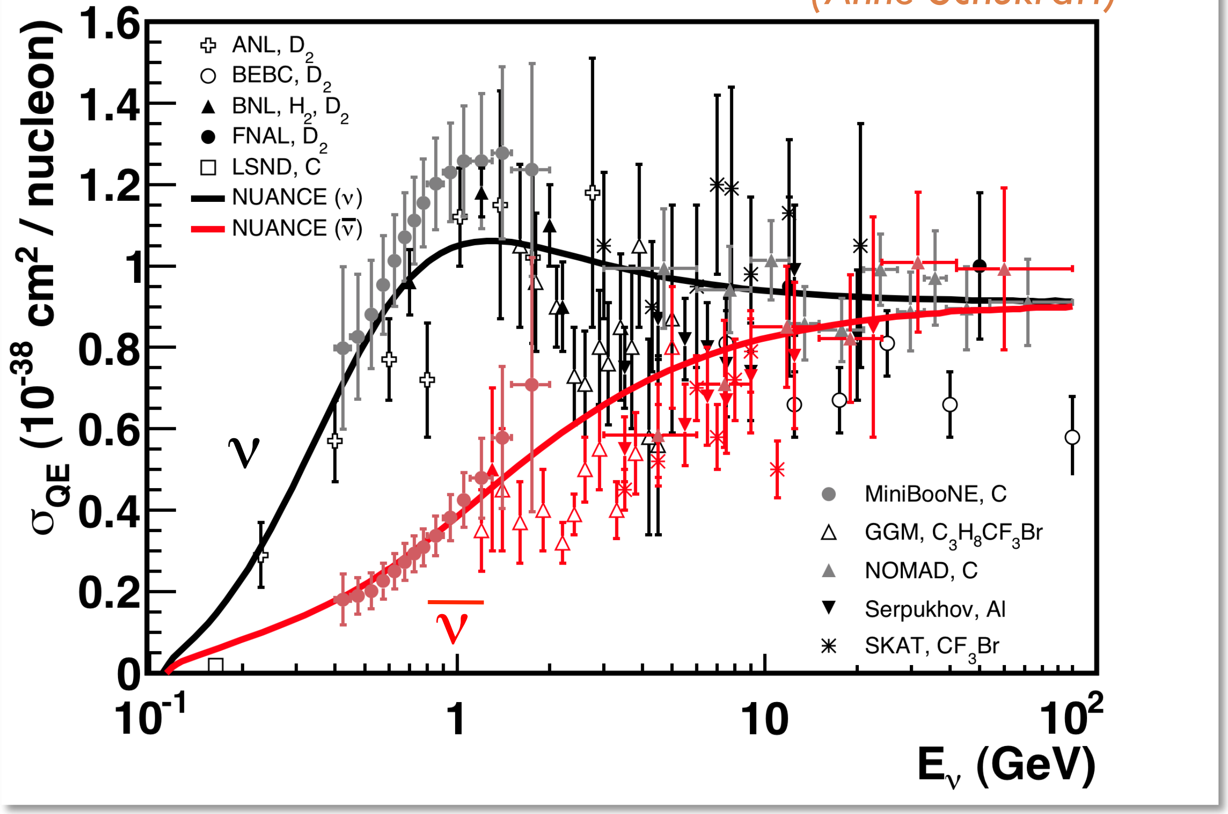
was the main focus

\+ new MINERvA QE results!

ν_μ QE Cross Section as a Function of E_ν

- reporting $\sigma(E_\nu)$ has the advantage that can compare measurements from different experiments

(Anne Schukraft)



(Review of Particle Properties, to appear in 2014 edition)

- but are we all really measuring the same thing? what is it that we're each calling QE?
- also, now recognized that M_A, $\sigma(E_\nu)$ are model-dependent quantities, especially when scattering off nuclear targets; diff'l σ in term s of μ,p preferred

Main Goal

- there are multiple modern experimental measurements of neutrino QE scattering, all use targets heavier than D_2

  - *much higher statistics*
  - *more well-known incoming neutrino flux predictions*
  - *but the use of **nuclear targets** brings additional complications*

- <u>the goal is to leave this first day of the workshop with a crisp understanding of what each experiment measures and defines as QE scattering</u>

what is ν quasi-elastic scattering?

Line-Up of Talks

- (Sam Zeller) **Introduction and MiniBooNE**
- (Roberto Petti) **NOMAD**
- (Kendall Mahn) **SciBooNE and T2K**

coffee break

- (Nate Mayer) **MINOS and NOvA**
- (Ornella Palamara) **ArgoNeuT**
- (Gabe Perdue) **MINERvA**

what have
we measured?

what do we
need to know
moving
forward?

- (Debbie Harris) **Looking Forward to the Future Needs of Oscillation Experiments**

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- *what are the exp'l results telling us?*
- *to what extent are the different exps observing the same or diff interactions?*
- *to what extent are the measurements in tension?*

- (Debbie Harris) **Looking Forward to the Future Needs of Oscillation Experiments**

Four Questions

(1) How do you select QE events?
i.e., how do you define a QE scattering event?

(2) How do you determine your neutrino flux?

(3) What are your primary QE measurements and
what do you find most important about your data?

(4) What additional QE measurements do you have planned
for the future that could shed further light on these issues?

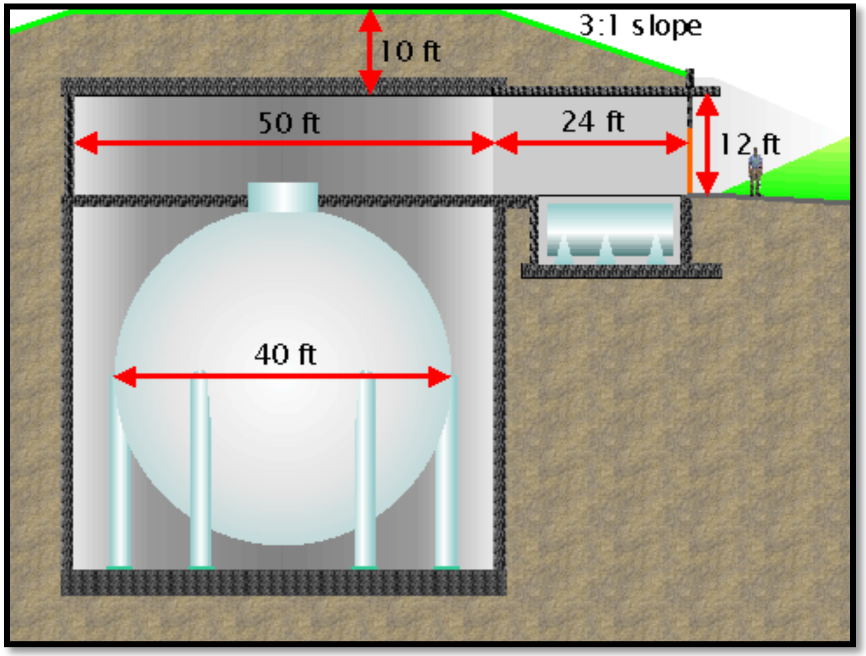
Plus, each experiment will present a summary table so that we have this detailed information at our fingertips for discussion

To Help Kick Things Off

- let’s consider MiniBooNE as a case example …

(1) MiniBooNE QE Selection

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



- ν interactions on CH_2
- Čerenkov detector

  ring imaging for event reconstruction & PID

- **spherically symmetric detector**

  - *lower beam energy +4π coverage leads to full μ angular coverage*

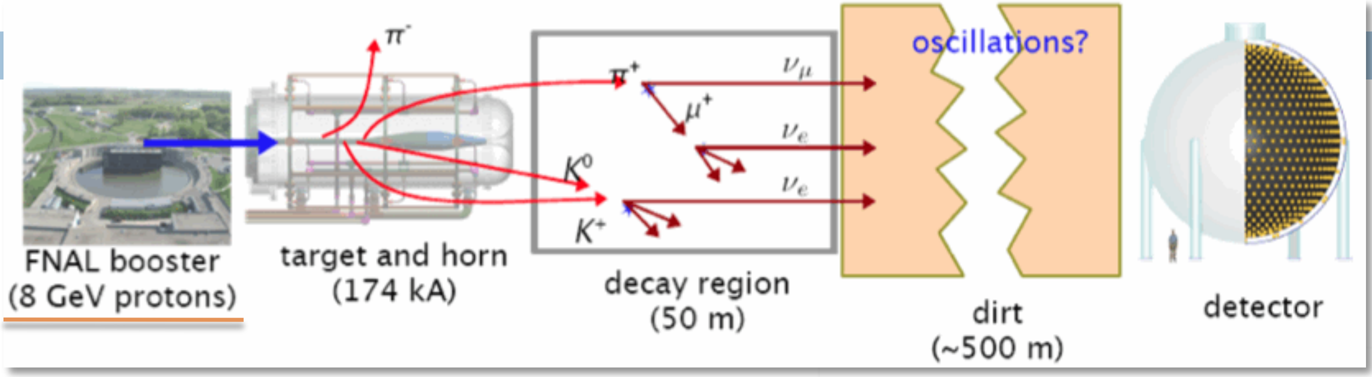
- use **particle decays** for event ID (QE requirement = μ + 1 Michel e^-)

  - no p or π detection thresholds, just require particles to decay → this lessens some of the model-dependence

- with this, QEs in MB are defined as **ν_μ CC with no π's, any # nucleons**

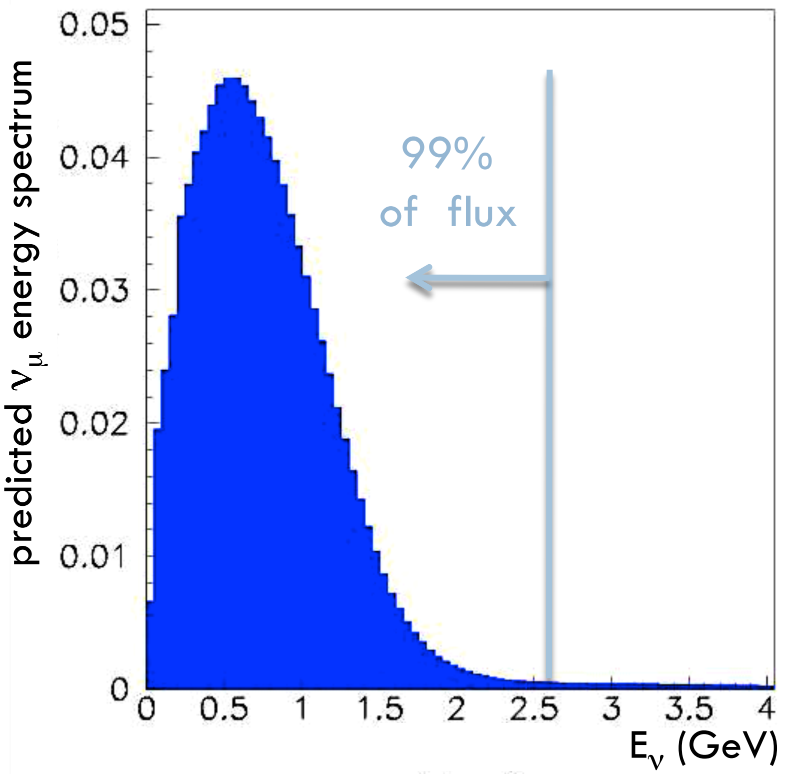
- dominant background from CC π^+ events with π^+ absorbed: constrain with data & subtract-off but report

(2) MiniBooNE Flux



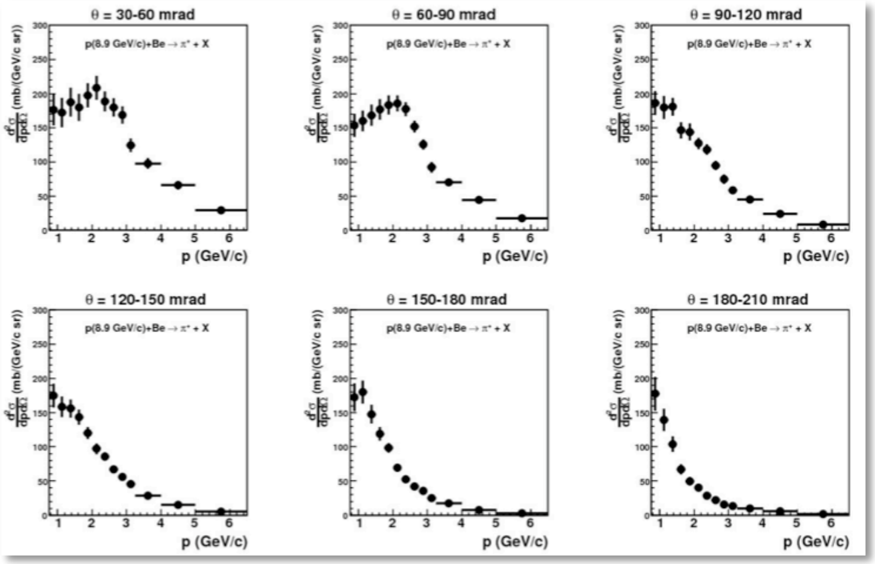
flux of neutrinos seen by the detector:

- both ν and $\overline{\nu}$ modes
- $<E_\nu>$ ~ 0.8 GeV
- 99% of the flux is below 2.5 GeV, excellent for studying QE events
- 98% of ν events in QE analysis come from π decays in the beam (90% from primary interactions in beam)



(2) MiniBooNE Flux, cont'd

- need to know your ν flux to make ν cross section measurements
  (we spent>5+ years on this on MiniBooNE)



(HARP data, D. Schmitz, Columbia, Ph.D. thesis)

- made dedicated hadro-production meas at CERN specifically for MB
  M. Catanesi *et al.*, Eur. Phys. J. C52, 29 (2007)
  - same beam energy
  - exact replica target
- plus, data from BNL E910
- comprehensive MB ν flux paper
  Aguilar-Arevalo *et al.*, PRD 79, 072002 (2009)

- there was no tuning of the ν flux based on MiniBooNE ν data
- flux known to ~11% at the peak (larger errors at lower and higher E_ν)

(3) MiniBooNE's Main QE Measurement

- because of high statistics

  (MB QE sample is 146k ν events, 71k $\bar{\nu}$ events)

  can measure double diff'l σ's for the first time (like E_e, θ_e)

$$d^2\sigma/dT_\mu d\theta_\mu$$

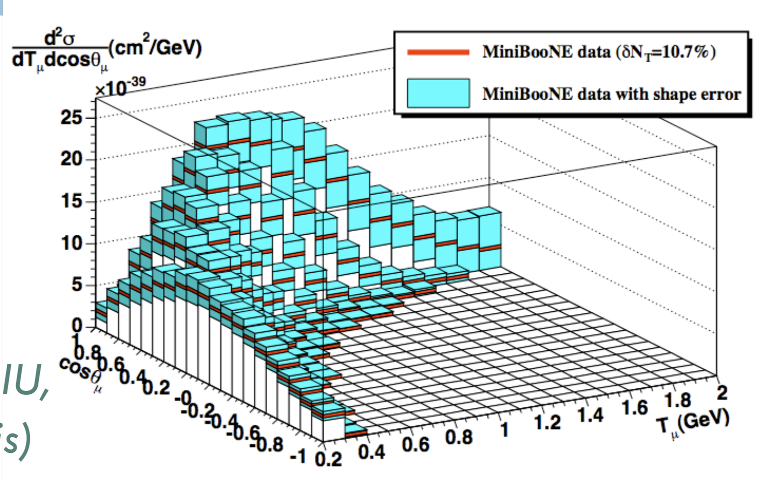
- historically, never had enough statistics to do this

- provides a more rigorous point of comparison than $\sigma(E_\nu)$ or M_A and less model-dependent

  (T_μ, θ_μ directly measured quantities)

ν

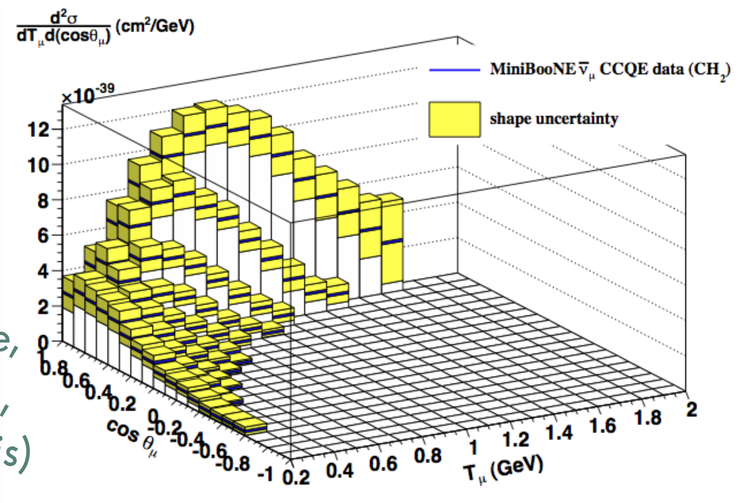
(T. Katori, IU, Ph.D. thesis)



Aguilar-Arevalo et al., PRD 81, 092005 (2010)

$\bar{\nu}$

(J. Grange, U Florida, Ph.D. thesis)



Aguilar-Arevalo et al., PRD 88, 032001 (2013)

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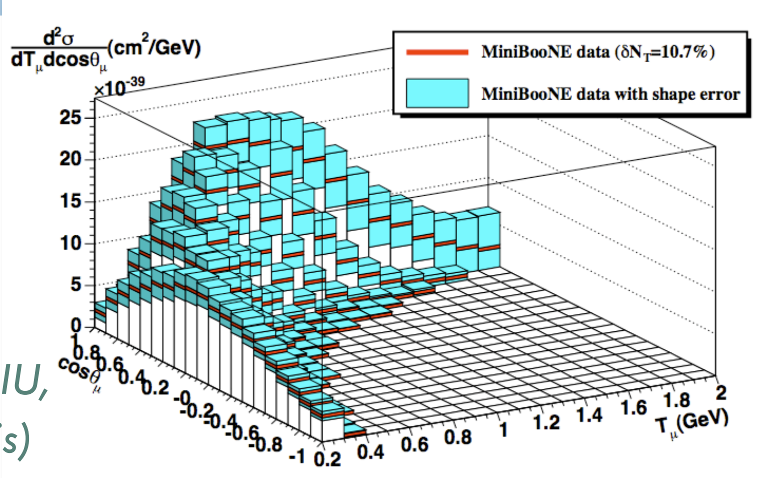

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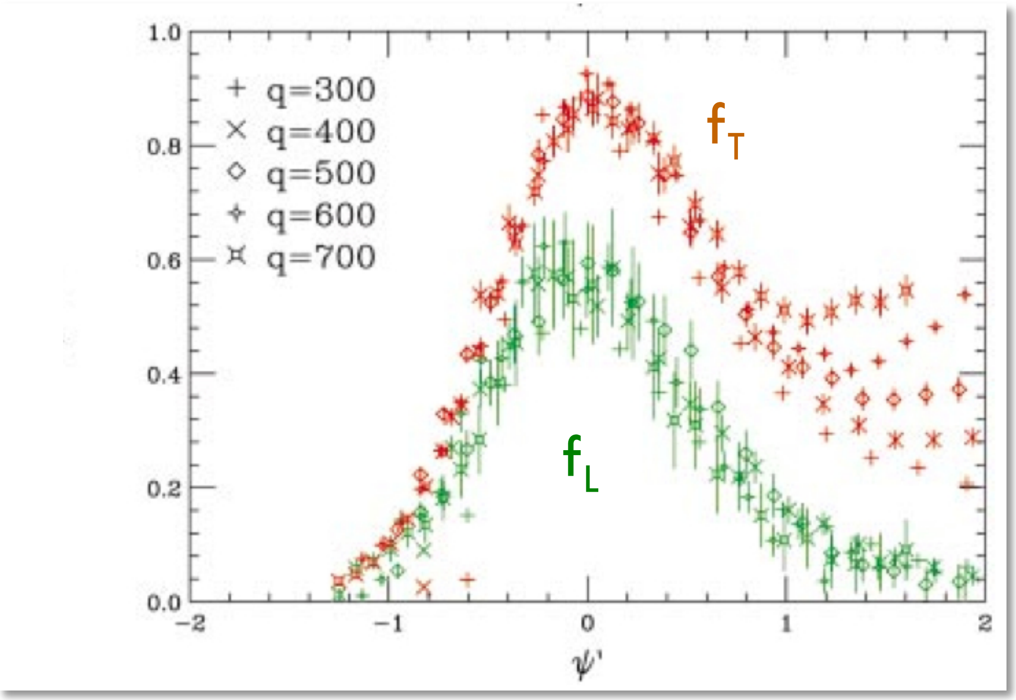
Aguilar-Arevalo et al., PRD 81, 092005 (2010)

with this broader defn of QE, observe a substantially larger cross section than IA-based predictions (effect is larger for larger μ scattering angles)

- an effect 1st seen by K2K, NuInt01

(4) What's Most Interesting?

- there may be important connections to electron scattering (G. Garvey)
- while this physics is new to ν scattering, have known for over 2 decades from e-A scattering that more complicated processes can take place



Carlson et al., PRC **65**, 024002 (2002)

- **longitudinal** part of σ_{QE} can be described in terms of scattering off independent nucleons

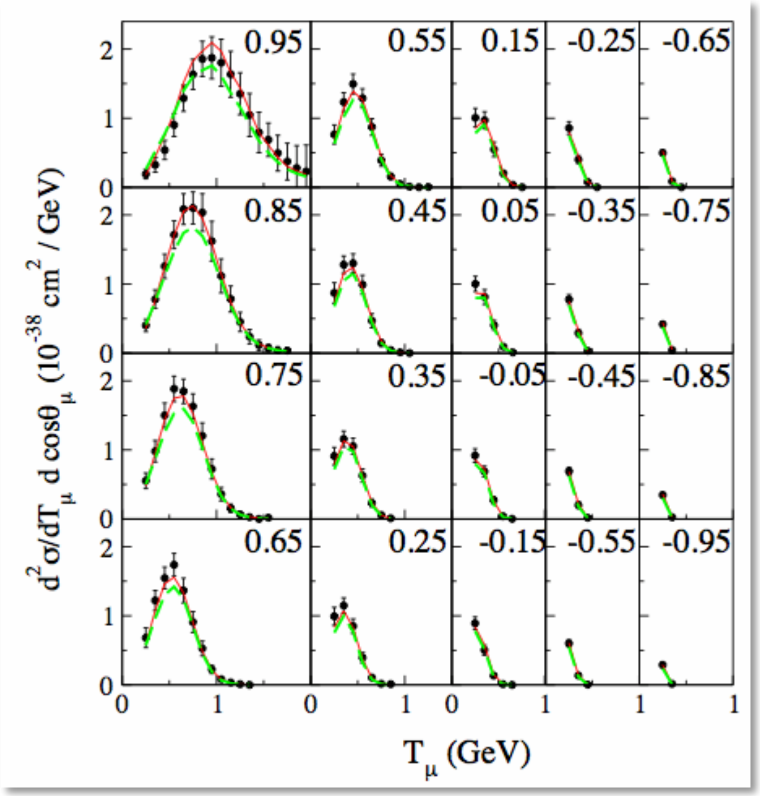
easier to interpret

- in contrast, there is a large enhancement in **transverse** part in both QE peak and dip region ***(due to nucleon pair correlations, MEC)***
  - MB results suggest that these effects may also play a role in ν-nucleus scattering

contains more info

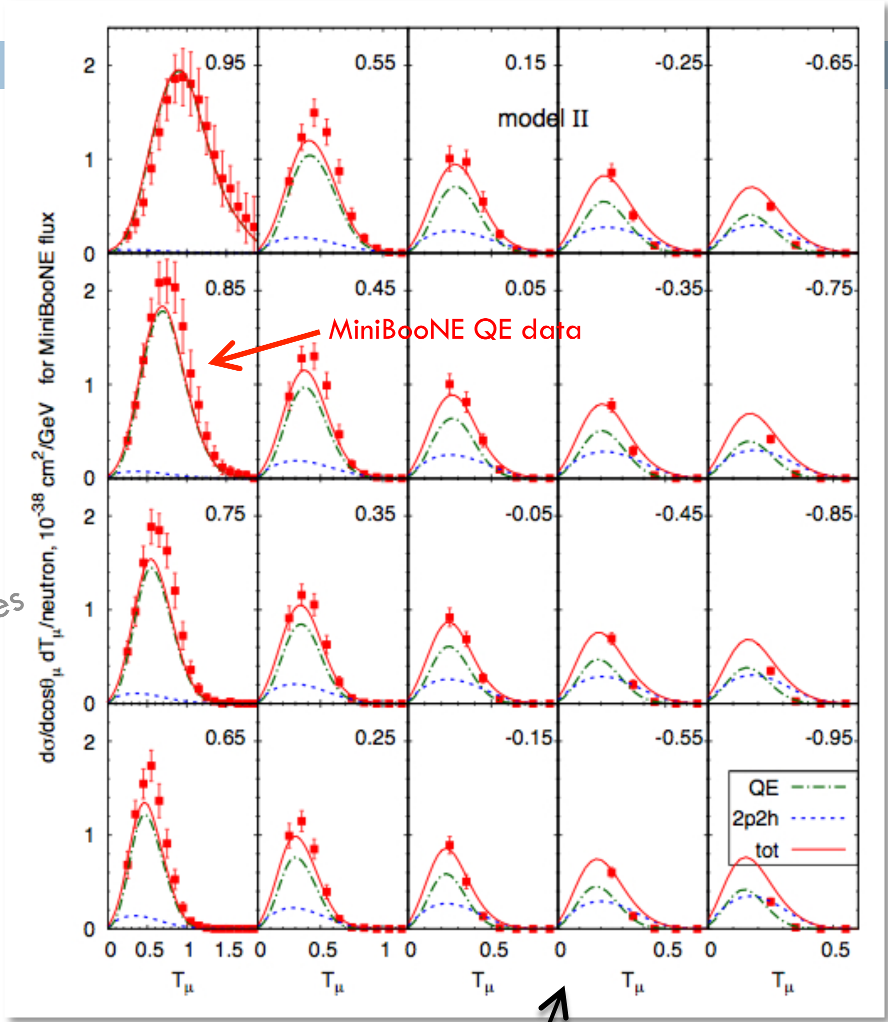
Some Examples

- this is the 1st time we've had this sort of information available; providing the rigorous model tests



Nieves, Simo, Vacas, PL **B707**, 72 (2012)

a couple of examples



MiniBooNE QE data

Lalakulich, Gallmeister, Mosel arXiv:1203.2935

- fractional contrib from nucleon pair correlations is largest at large θ_μ

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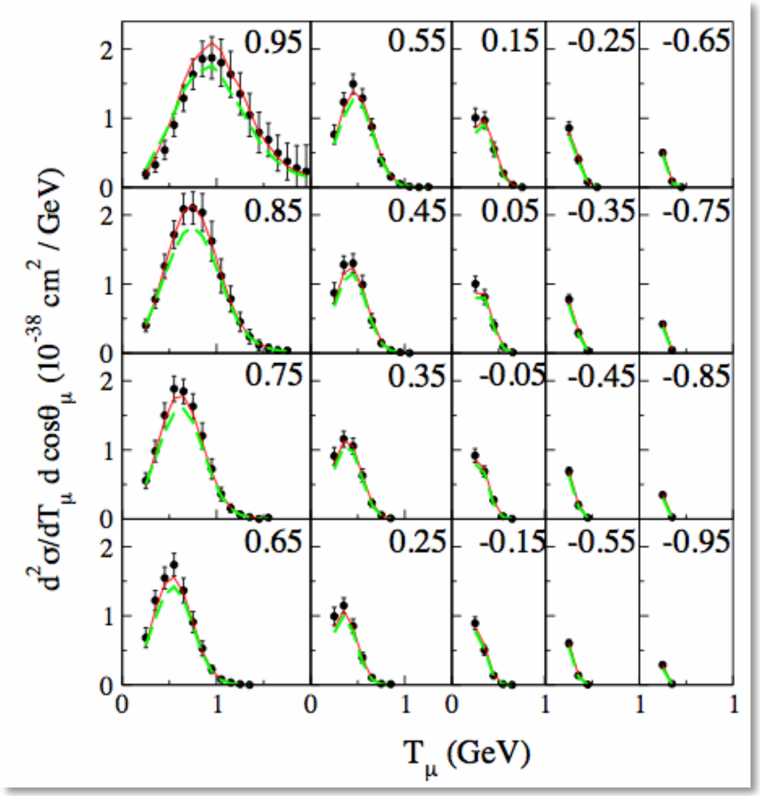

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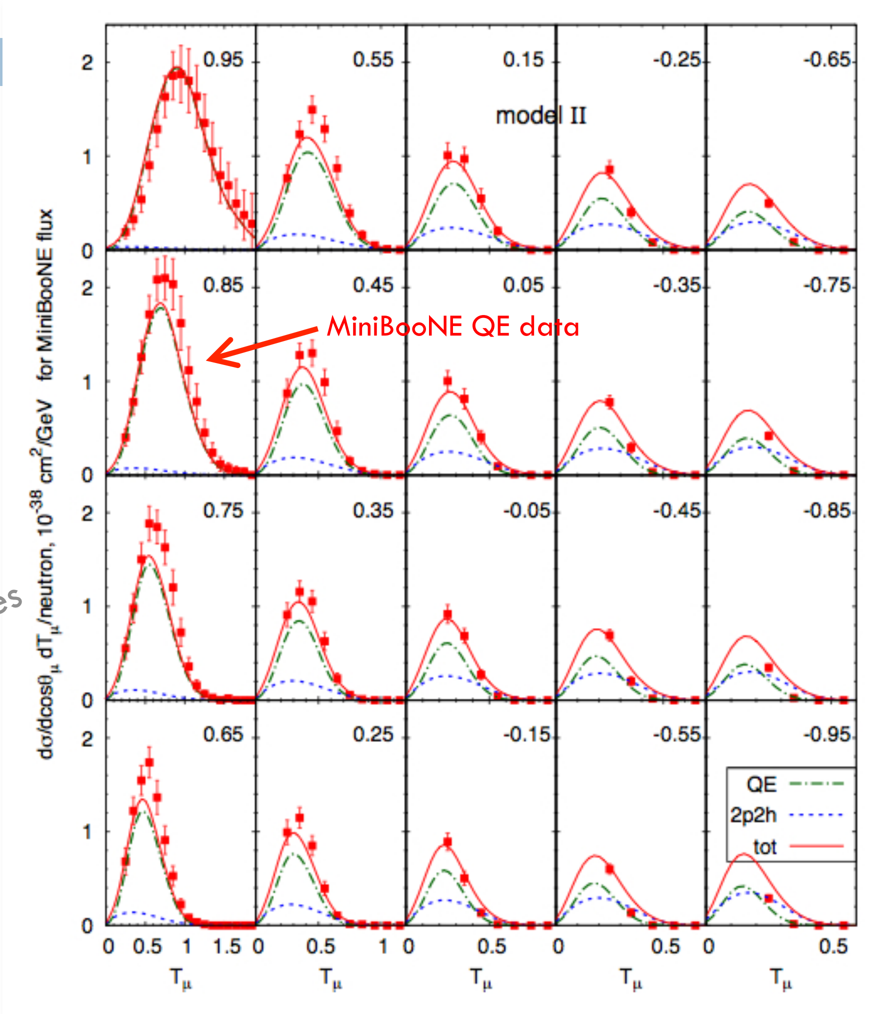
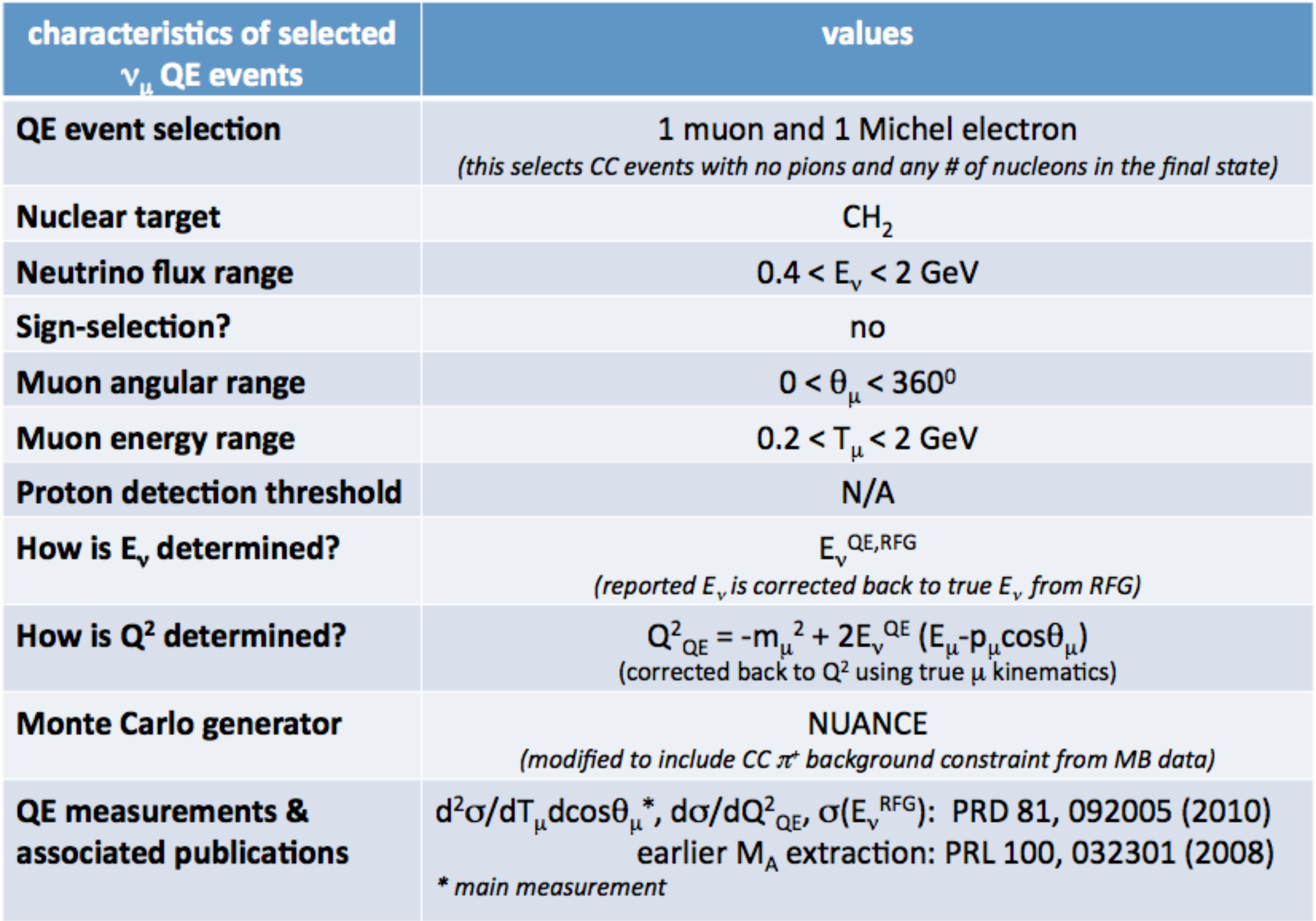


MiniBooNE QE data

Lalakulich, Gallmeister, Mosel arXiv:1203.2935

- needed: diff'l σ measurements like this at other E_ν, A + for outgoing proton(s)

MiniBooNE QE Summary



characteristics of selected ν_μ QE events	values
QE event selection	1 muon and 1 Michel electron *(this selects CC events with no pions and any # of nucleons in the final state)*
Nuclear target	CH_2
Neutrino flux range	$0.4 < E_\nu < 2$ GeV
Sign-selection?	no
Muon angular range	$0 < \theta_\mu < 360^0$
Muon energy range	$0.2 < T_\mu < 2$ GeV
Proton detection threshold	N/A
How is E_ν determined?	$E_\nu^{QE,RFG}$ *(reported E_ν is corrected back to true E_ν from RFG)*
How is Q^2 determined?	$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE} (E_\mu - p_\mu \cos\theta_\mu)$ (corrected back to Q^2 using true μ kinematics)
Monte Carlo generator	NUANCE *(modified to include CC π^+ background constraint from MB data)*
QE measurements & associated publications	$d^2\sigma/dT_\mu d\cos\theta_\mu$*, $d\sigma/dQ^2_{QE}$, $\sigma(E_\nu^{RFG})$: PRD 81, 092005 (2010) earlier M_A extraction: PRL 100, 032301 (2008) ** main measurement*

What Have We Learned?

- implications → something as simple as QE scattering is not so simple
  - nuclear effects can significantly <u>increase</u> the QE cross section

    (this was certainly not part of our thinking prior to the MB measurements)
  - idea that could be missing ~40% of σ at low E_ν in our simulations is a big deal

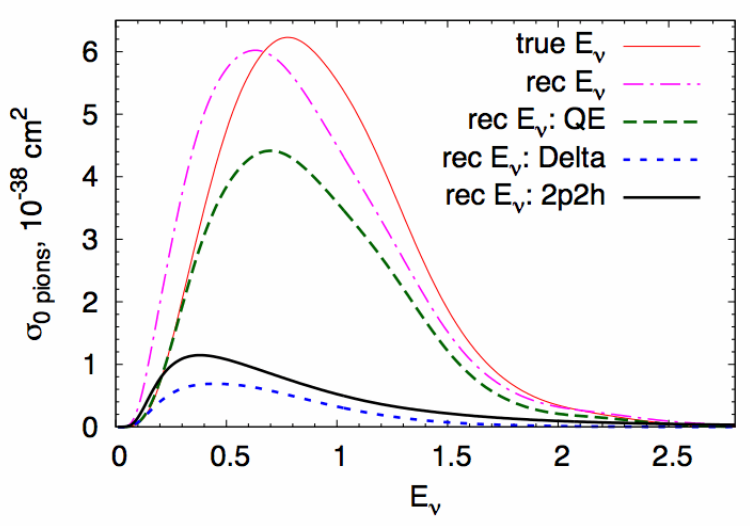
- <u>good news</u>: expect larger event yields

- <u>bad news</u>: need to understand the underlying physics

(1) impacts E_ν determination

(2) effects can be different for ν vs. $\overline{\nu}$

(at worse, could produce a spurious $\cancel{CP}$ effect)



one example: Lalakulich, Gallmeister, Mosel, arXiv: 1203.2935

- caveat: these effects not evident in all experiments (e.g., NOMAD QE)

Rest of the Morning Session …

- the goal is to leave this first day of the workshop with a crisp understanding of what each experiment measures and defines as QE scattering

what are we each really measuring?

what are the results telling us?

hope to better understand some of the differences between QE measurements & approaches

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