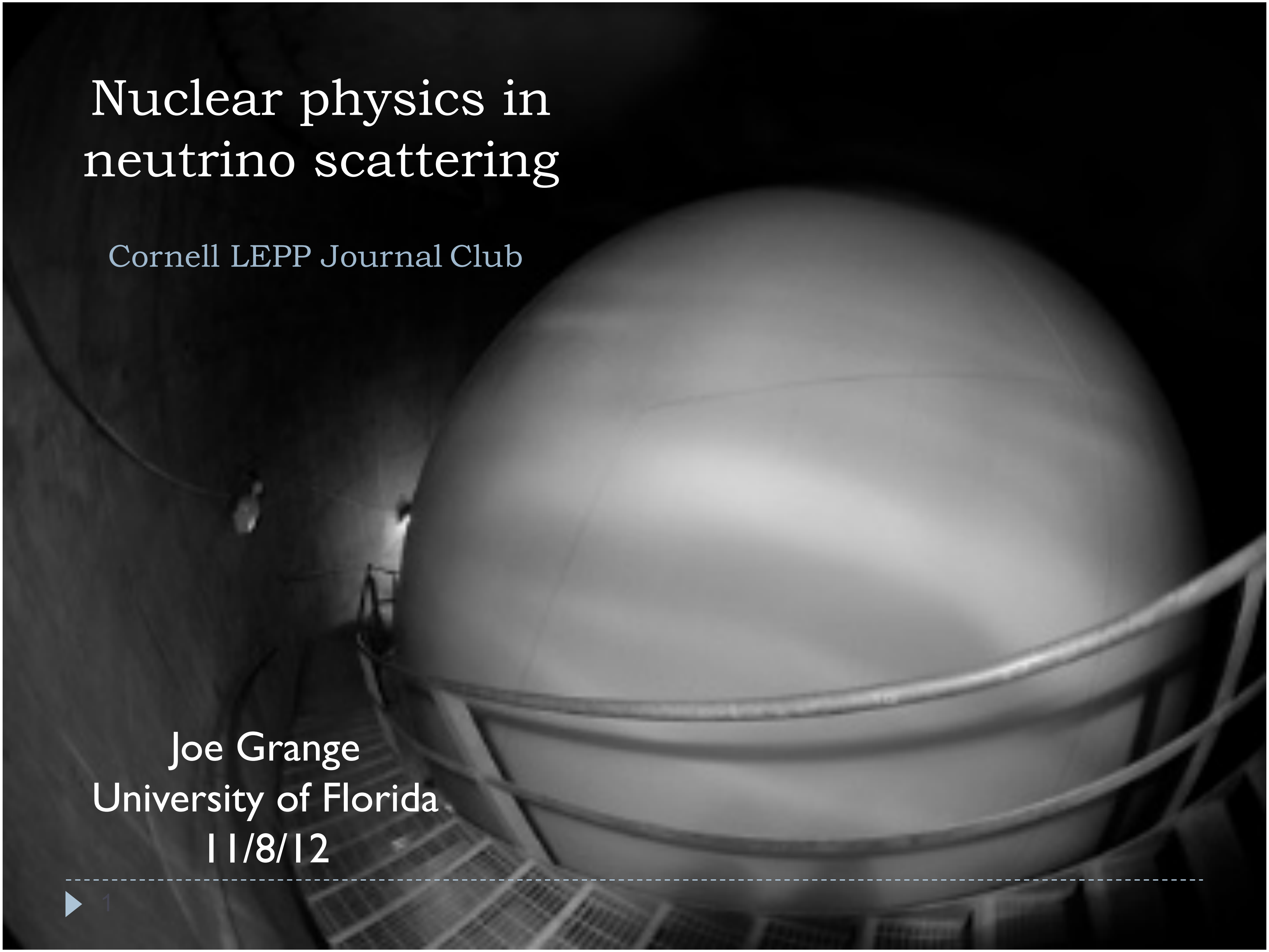
Nuclear physics in neutrino scattering

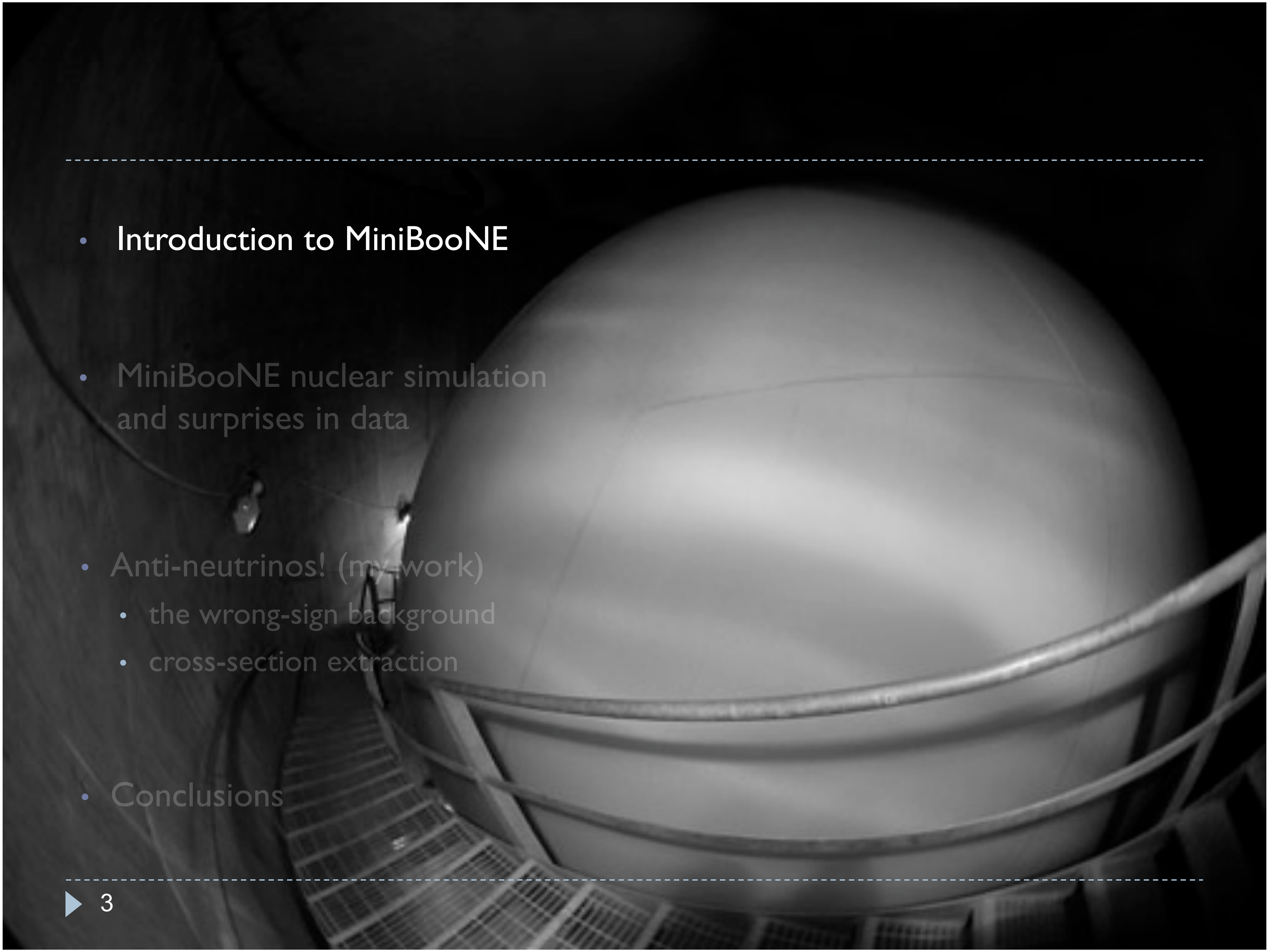
Cornell LEPP Journal Club



Joe Grange
University of Florida
11/8/12

Outline

- Introduction to MiniBooNE
- MiniBooNE nuclear simulation and surprises in data
- Anti-neutrinos! (my work)
  - the wrong-sign background
  - cross-section extraction
- Conclusions



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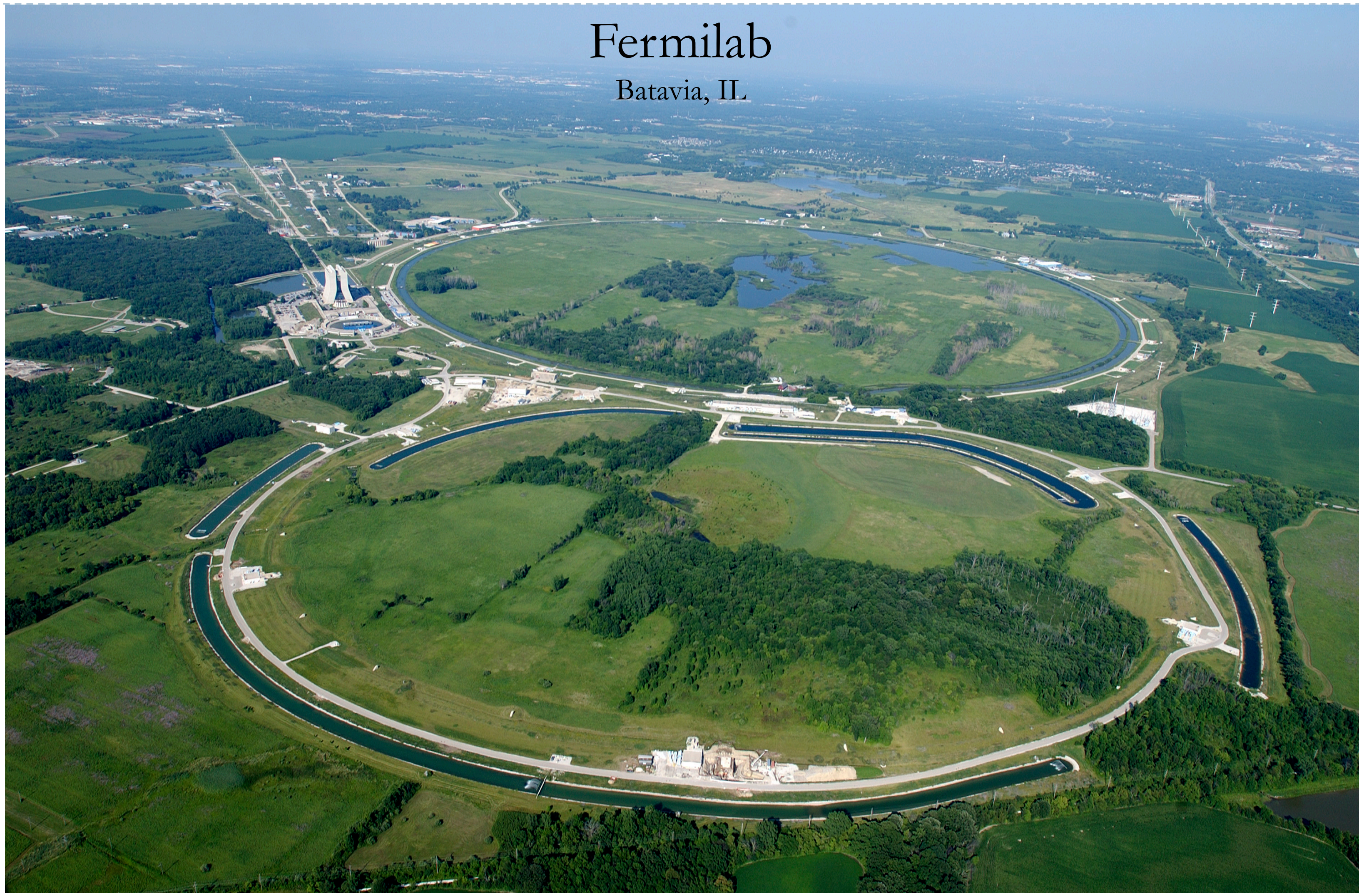
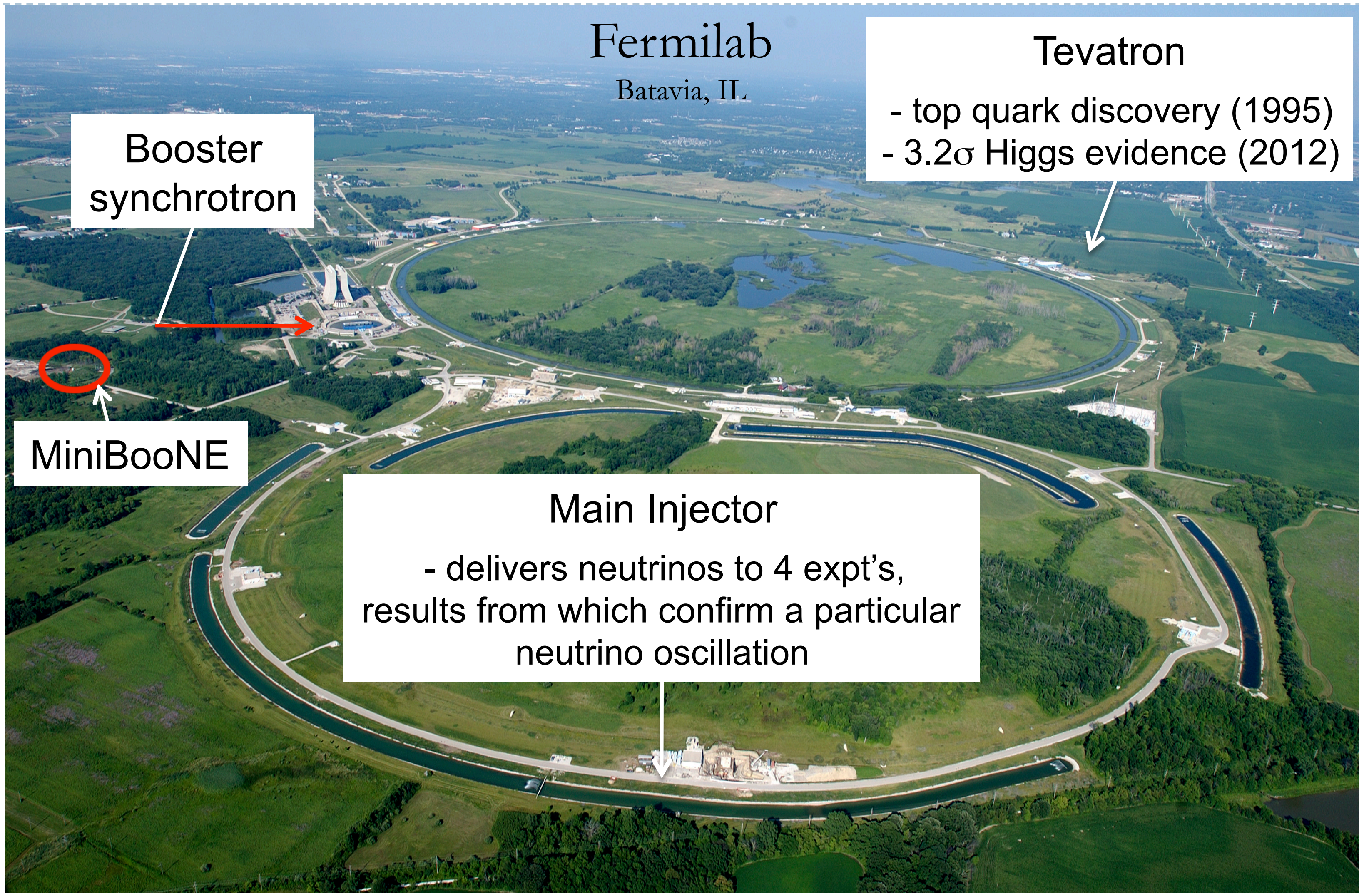
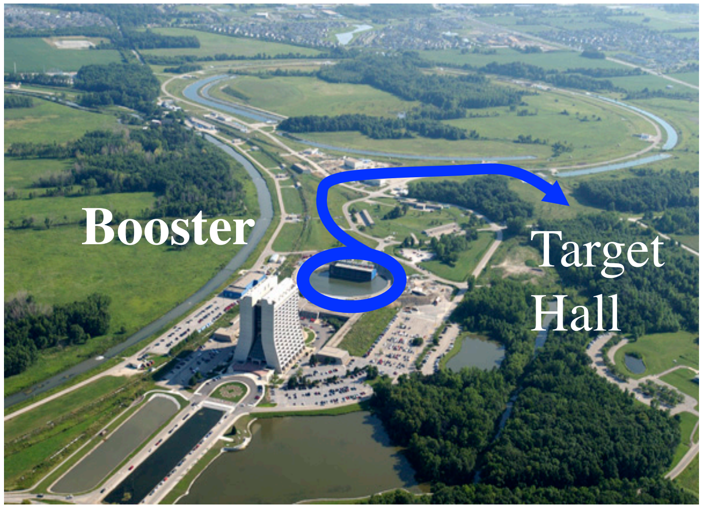
MiniBooNE
Mini Booster Neutrino Experiment



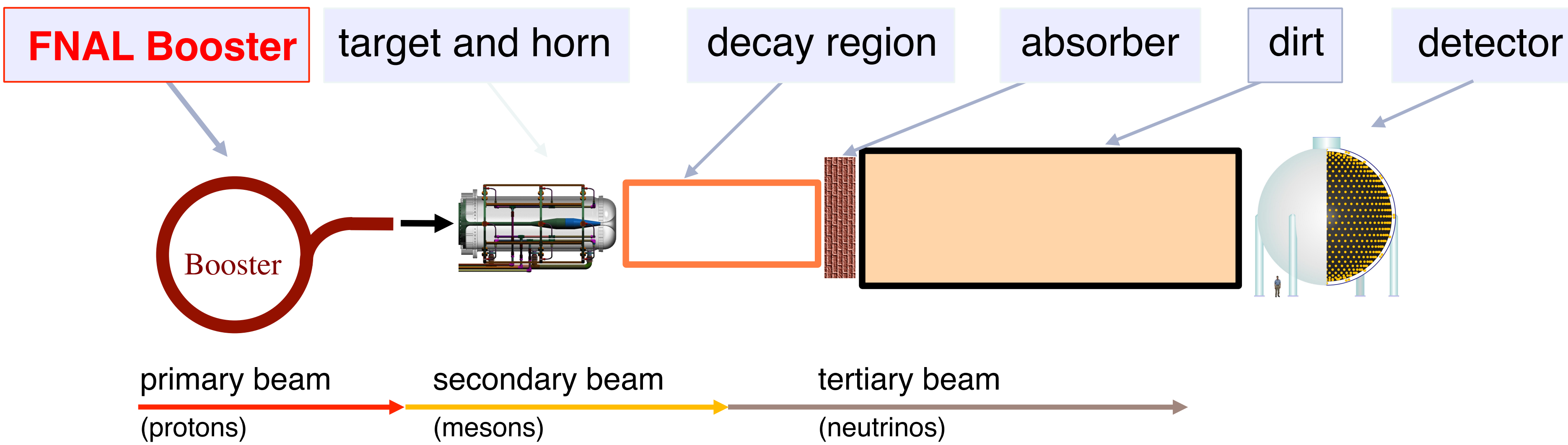
MiniBooNE
Mini Booster Neutrino Experiment



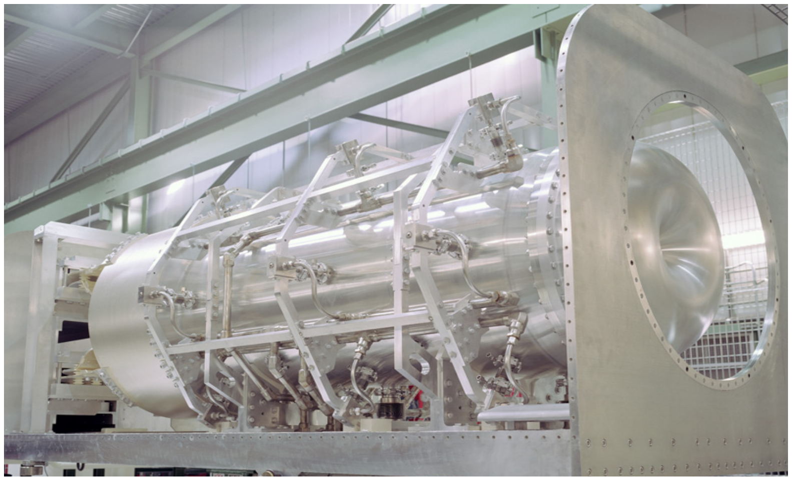
Booster Neutrino Beam



8.9 GeV/c momentum protons extracted from Booster, slammed into a nuclear target, creating particle spray



Booster Neutrino Beam

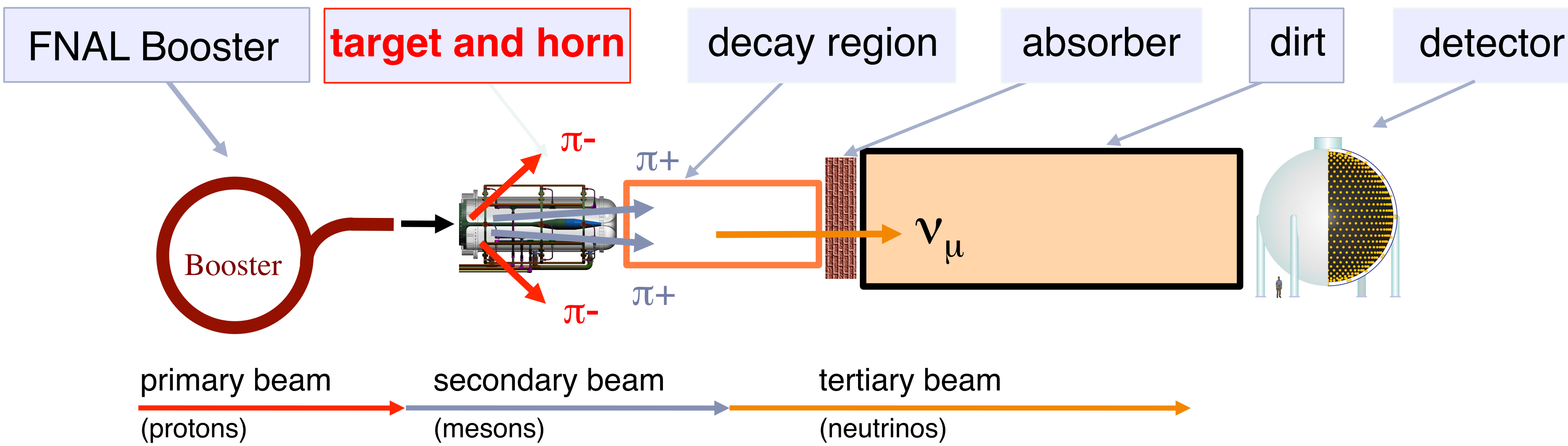


Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons

$$\pi^+ \rightarrow \mu^+ \; \nu_\mu$$

$$\pi^- \rightarrow \mu^- \; \bar{\nu}_\mu$$

("neutrino" vs "anti-neutrino" mode, more later!)

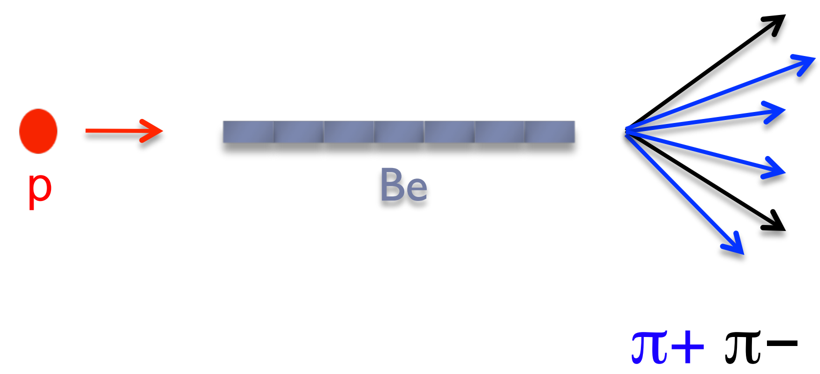


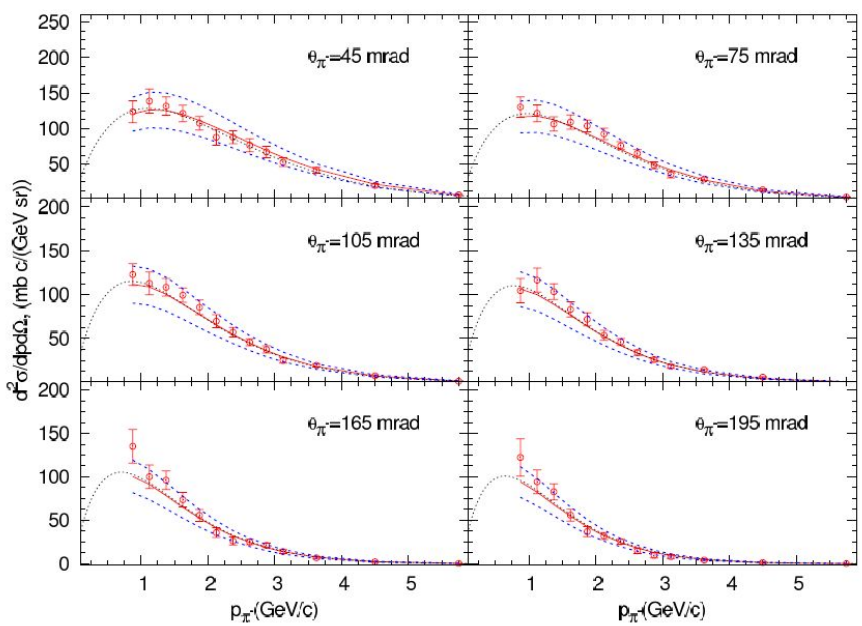
Neutrino Flux

- With external measurements of

$$\frac{d^2\sigma}{dp_\pi d\theta_\pi}(p + \mathrm{Be} \rightarrow \pi^\pm + X)$$

can predict ν, anti-ν flux at detector



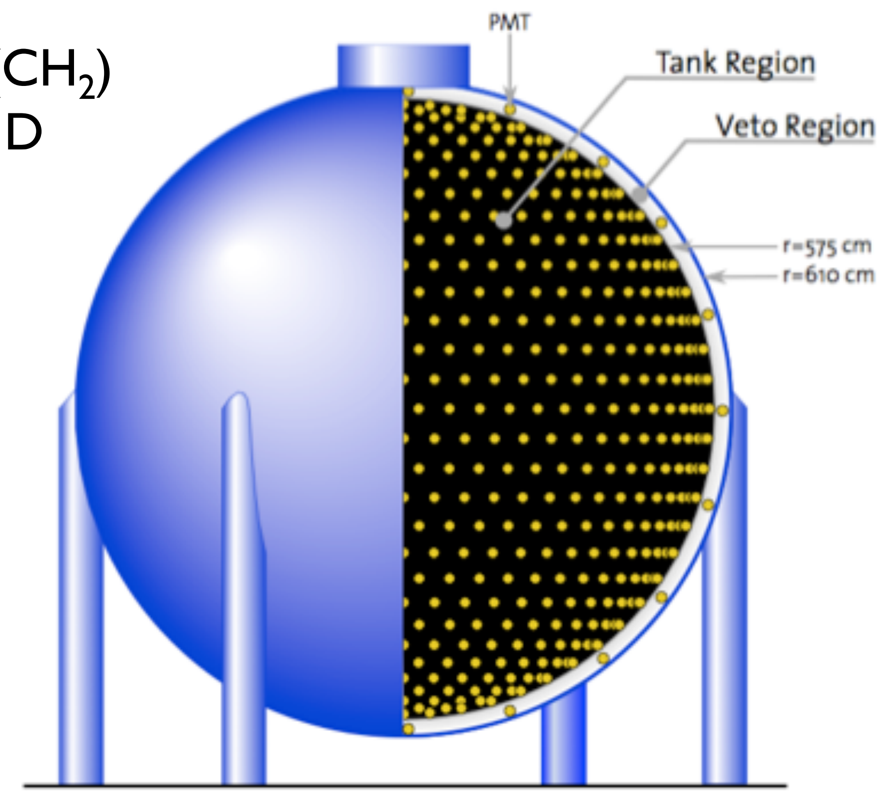


- Dedicated π production data taken by HARP experiment (CERN)
- Spline fit to these data bring ν flux uncertainty to ~9% level
  - (only valid for ν-parent π's constrained by these data - important later!)

HARP collaboration,
Eur. Phys. J. C52 29 (2007)

MiniBooNE Detector

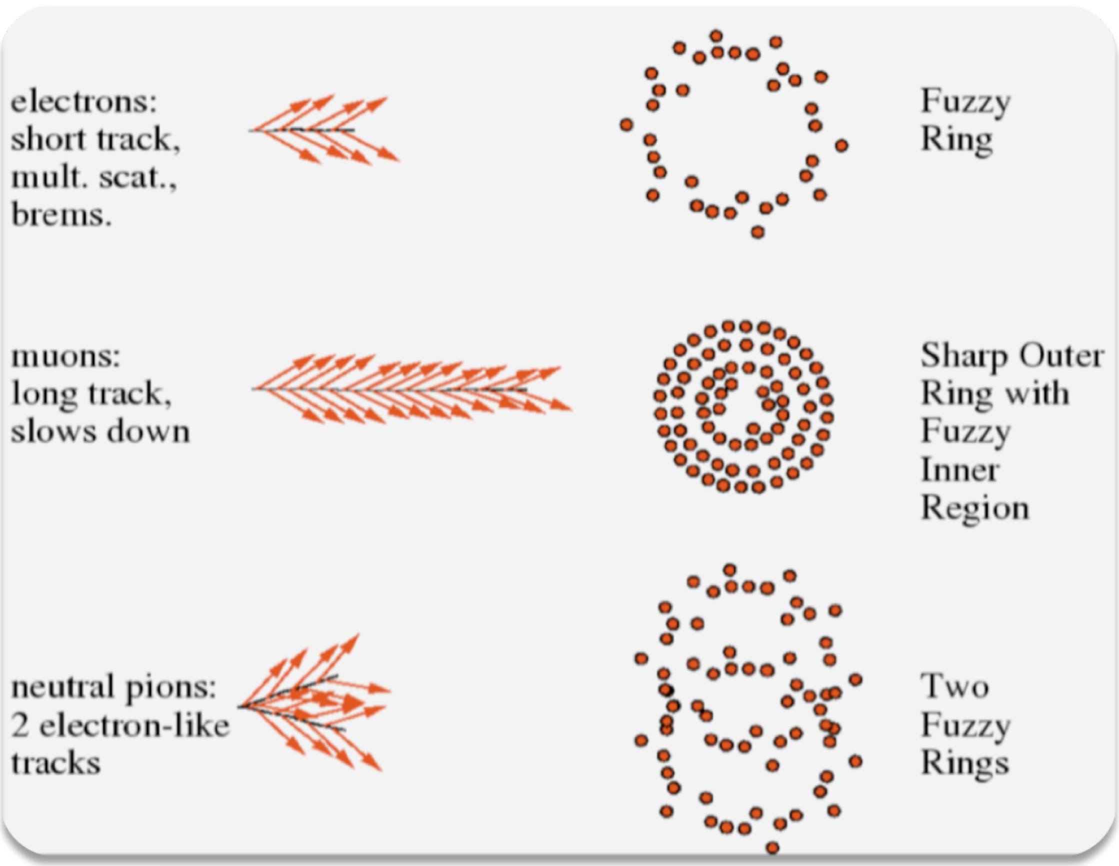
- 6.1m radius sphere houses 800 tons of pure mineral oil
- Oil serves as both the nuclear target (CH_2) and medium for particle tracking and ID
- 1520 photomultiplier tubes (PMTs) uniformly dispersed in 2 tank regions:
  - 1280 inner signal
  - 280 outer veto

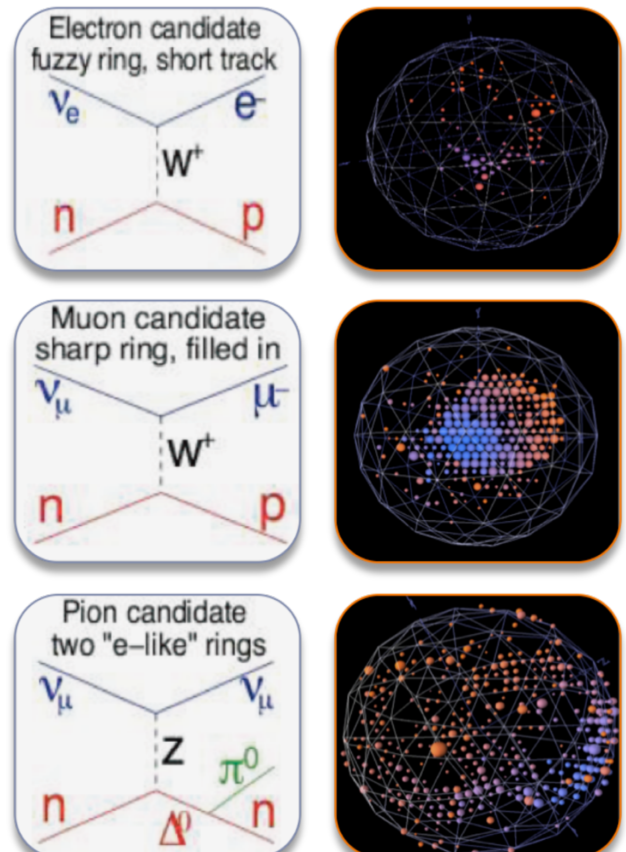


Nucl. Instr. Meth. A599, 28 (2009)

Particle ID

- PID and event reconstruction obtained primarily through topology and timing of PMT activity





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Nuclear Simulation

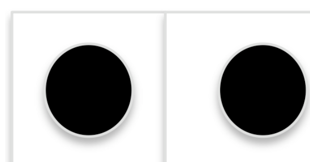
- MiniBooNE uses the Relativistic Fermi Gas model (RFG) Nucl. Phys. B43, 605 (1972)
  - Models nucleons as independent, quasi-free particles bound by a constant E_B
  - All struck (outgoing) nucleons subject to Pauli blocking. This is enforced by a global Fermi momentum k_F

That's it!

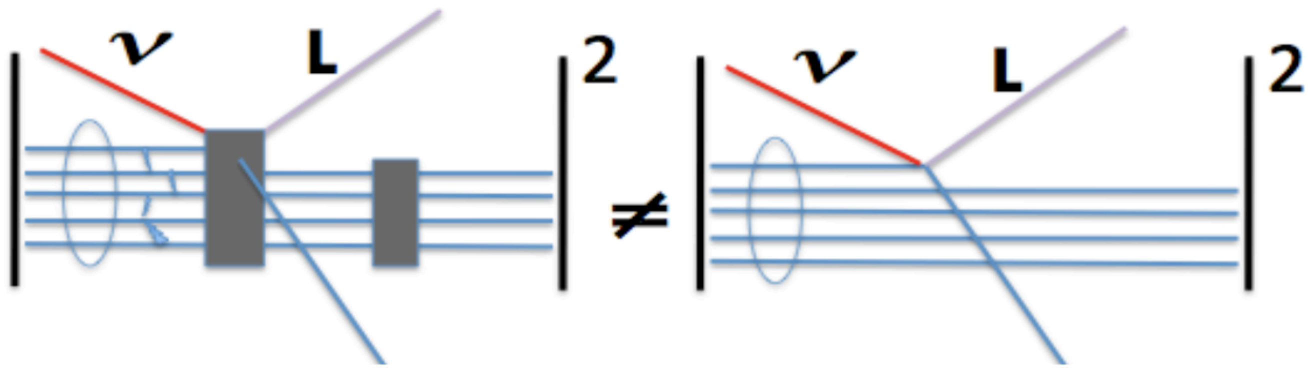
- Specifying E_B, k_F fully describes the RFG model - it combines bare nucleon physics with a potential energy well and Pauli blocking.
- A quick calculation:
  - Nuclear density approximately constant: $R = r_0 A^{1/3}$
  - The mean separation distance between nucleons is

$$\left(\frac{V}{A}\right)^{1/3} = \left(\frac{4\pi(1.2\,fm)^3}{3}\right)^{1/3} = 1.93\,fm$$

  - The nucleon diameter is 1.25 *fm*.
  - Naïve to assume nucleon independence



Another way of saying

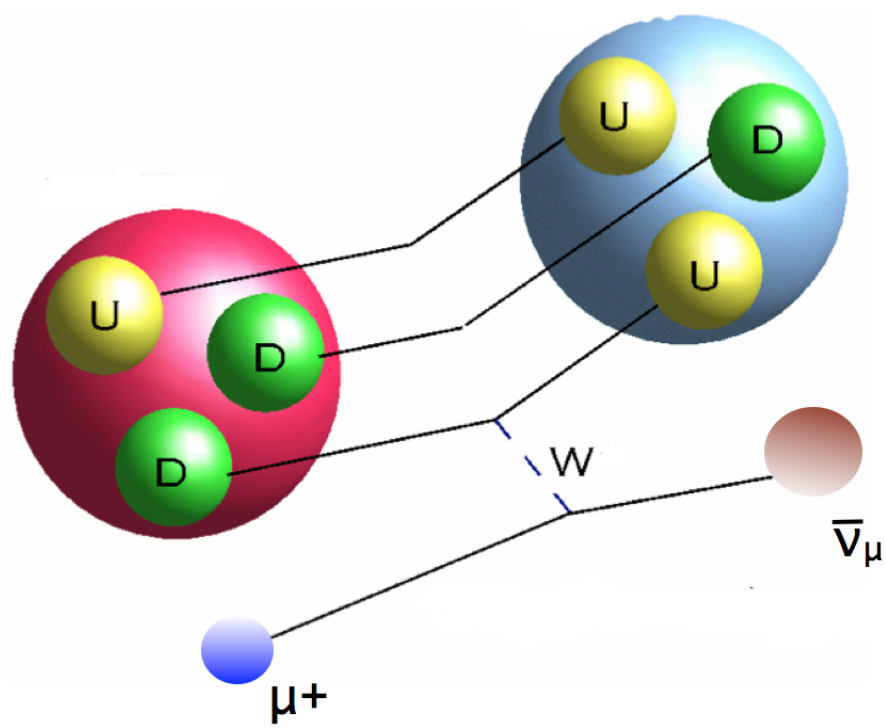


- The nucleus very likely has a rich structure the RFG falls short of approximating well

- We've seen evidence of this in MiniBooNE data

The "golden channel"

- Many experiments use the interaction ν_μ + N -> μ + N' (Charged-current Quasi-Elastic, or CCQE) to study neutrino oscillations due to it's simple multiplicity



The "golden channel"

- Many experiments use the interaction ν_μ + N -> μ + N' (Charged-current Quasi-Elastic, or CCQE) to study neutrino oscillations due to it's simple multiplicity
- Crucial for osc. expt's: can reconstruct initial neutrino energy and momentum transfer based solely on observing the outgoing lepton (dominantly μ in MiniBooNE):

$$E_\nu^{QE} = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

- History of ν physics inextricably tied to this interaction

The "golden channel"

- Bare-nucleon CCQE cross section:

  Nucl. Phys. B43, 605 (1972)

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \,|V_{ud}|^2}{8\pi E_\nu^2}\left[A\left(Q^2\right) \pm B\left(Q^2\right) \times \left(\frac{s-u}{M^2}\right) + C\left(Q^2\right) \times \left(\frac{s-u}{M^2}\right)^2\right]$$

- A, B, C functions of vector and axial form factors
- Using conserved vector current we use form factors extracted from electron scattering for the vector contribution
- In this model, this leaves neutrino experiments one and only one parameter to measure, the axial mass M_A

The “golden channel”

- Bare-nucleon CCQE cross section:

  Nucl. Phys. B43, 605 (1972)

$$\frac{d\sigma}{dQ^2} = \frac{M}{\ldots}$$

$$\ldots \times \left(\frac{s-u}{M^2}\right)^2 \Bigg]$$

for a much more complete theoretical description, see G. Paz, “Charge Radius of the Proton”, 9/14 LEPP Journal Club

- A, B, C functi

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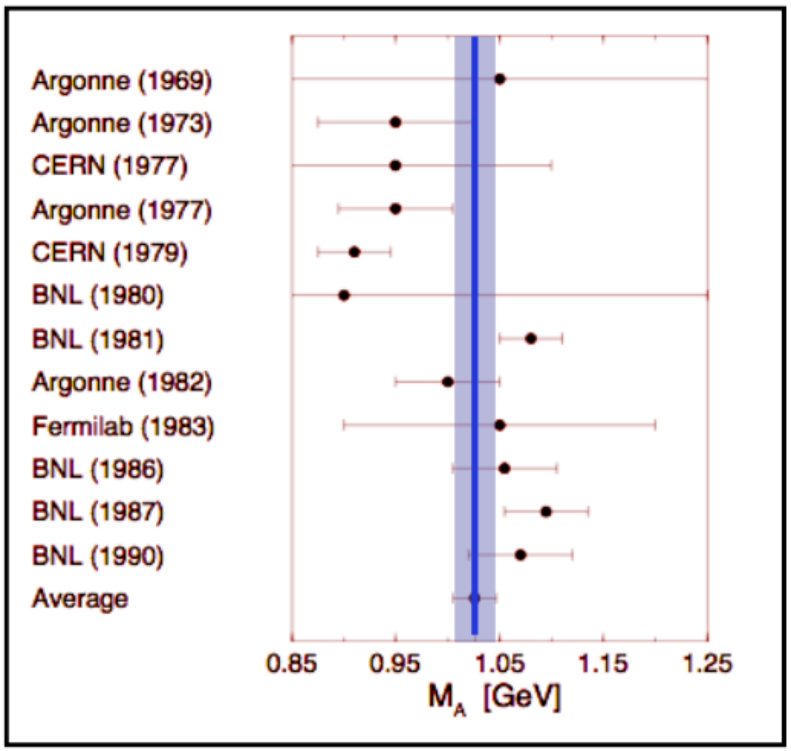
The "golden channel"

- Many neutrino experiments measured M_A by shooting high energy neutrino beams typically at bubble chamber detectors housing mostly **light nuclear targets**



- Measurements converged around M_A = 1.0 GeV

world average, these data:
$M_A = 1.02 \pm 0.01$ GeV

J. Phys.: Conf. Ser. **110** 082004 (2008)

Early Days of MiniBooNE

- Subsequent to understanding detector response and verifying event reconstruction algorithms on calibration data, MiniBooNE found surprises in this CCQE golden channel

  1. Around 30% discrepancy between predicted (RFG), measured event rate
  2. Muon scattering angle shape wrong

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Implies cross section is the likely culprit

In principle, this could be due to either flux or cross section mismodeling (remember ν flux is constrained to ~9% error)

Early Days of MiniBooNE

- Subsequent to understanding d… …rifying event reconstruction algo… MiniBooNE found su…

  1. Around … …red event ra…

The interaction cross section is wrong!!

…the …culprit

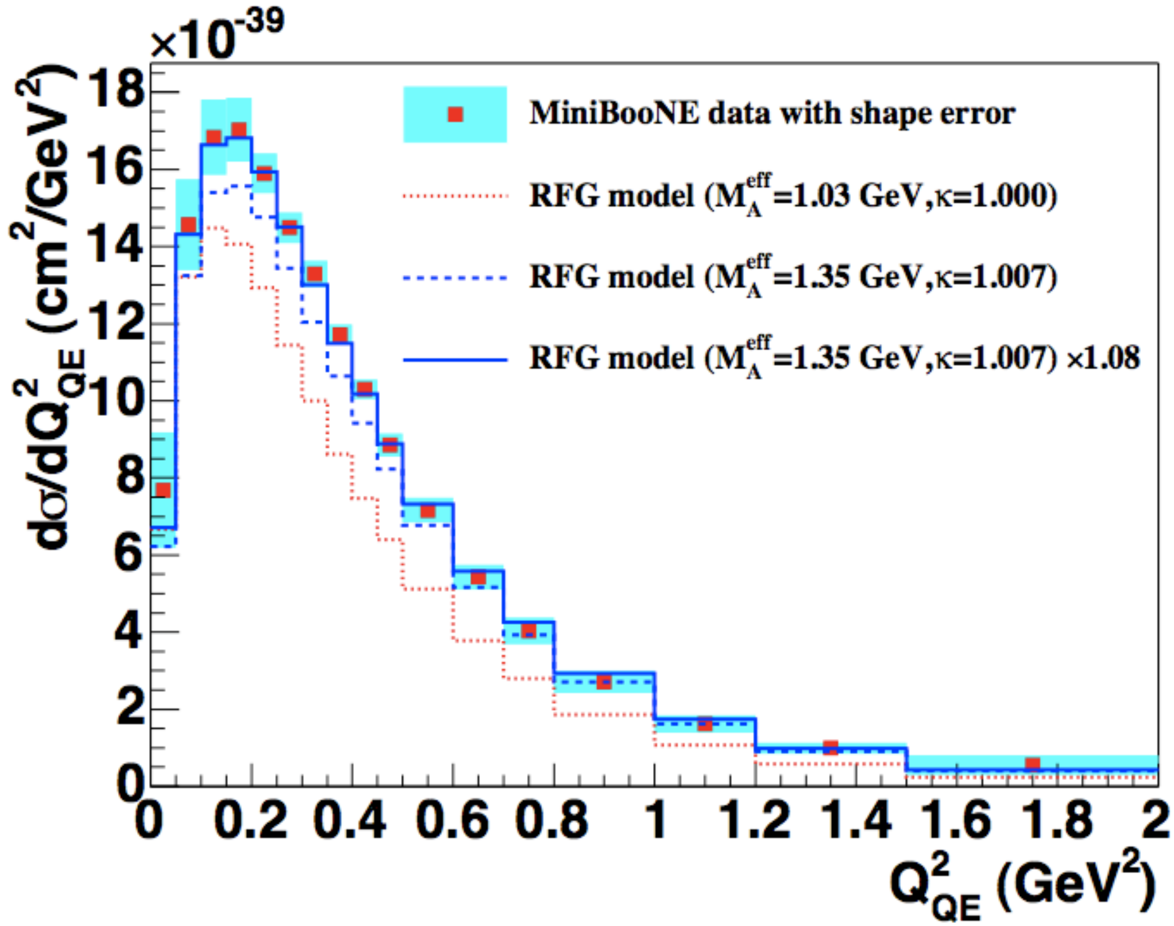
In principle, this could be due to either flux or cross section mismodeling (remember ν flux is constrained to ~9% error)

Finding a "solution" within the RFG

Using the RFG nuclear model, tuning the axial mass M_A to a surprisingly high value describes data!

$M_A = 1.35 \pm 0.17$ GeV

previous exp'ts: $M_A \sim 1$ GeV, few-percent error



Finding a “solution” within the RFG

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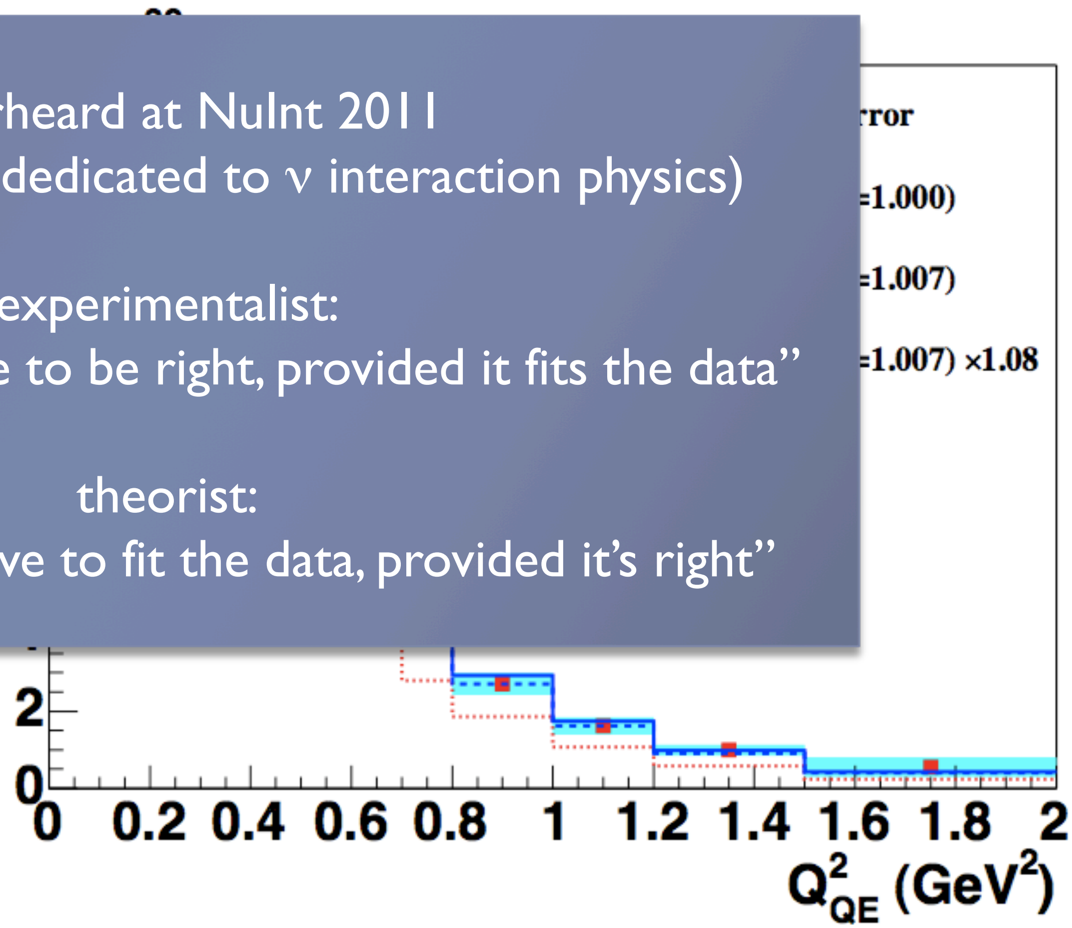
M_A = 1.

previous e
few-percent error

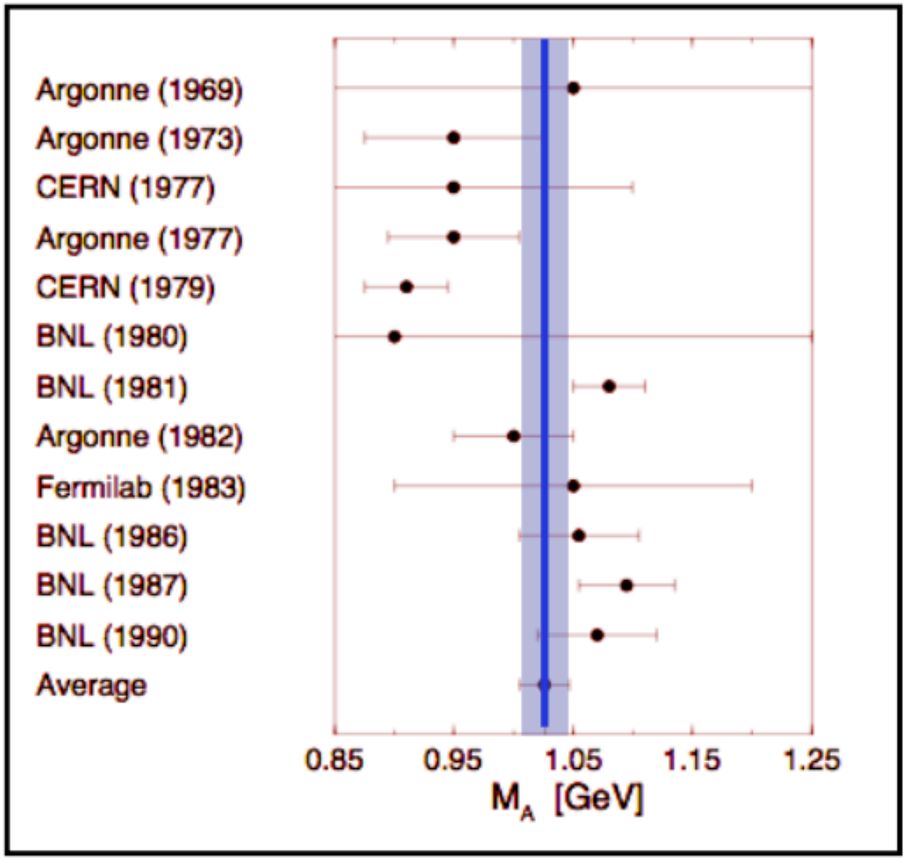
Overheard at NuInt 2011
(conference series dedicated to ν interaction physics)

experimentalist:
“a model doesn’t have to be right, provided it fits the data”

theorist:
“a model doesn’t have to fit the data, provided it’s right”



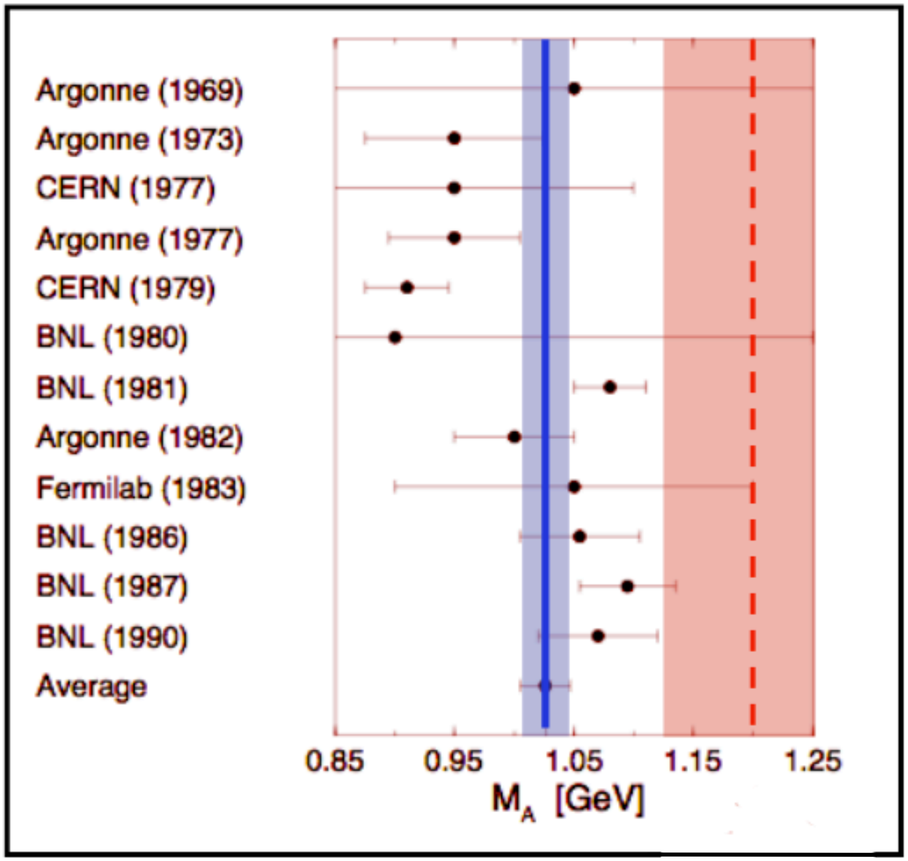
M_A tension



- $M_A = 1.35 \pm 0.17$ GeV clearly disagrees with the measurements from light target data
- However…

M_A tension

arxiv: 1007.2195



Experiment	Target	Cut in Q^2 [GeV^2]	M_A[GeV]
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

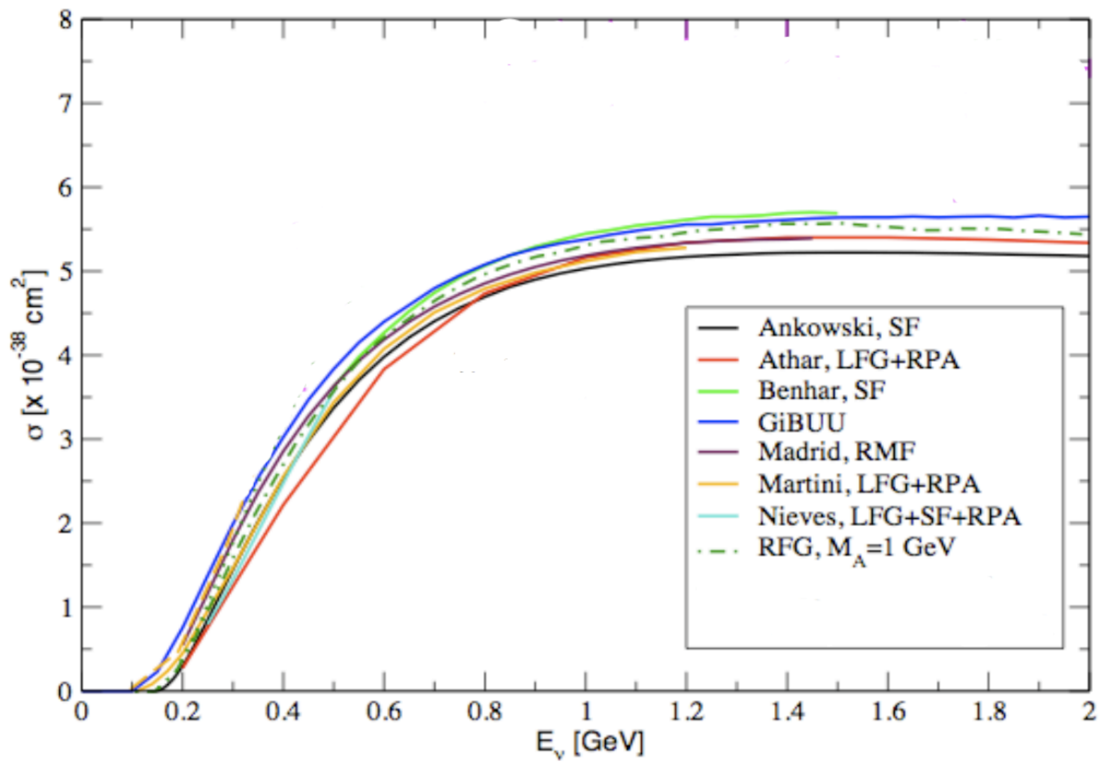
TABLE I. Recent M_A measurements

- More recent measurements have also observed higher values of M_A
- These measurements mostly from fitting Q^2 shapes
- M_A is important for overall normalization as well

Looking for alternatives

- With the admission the RFG is inadequate, we look to more modern models…

- Find general theory consensus that the absolute interaction cross section with the RFG and M_A = 1 GeV is about right



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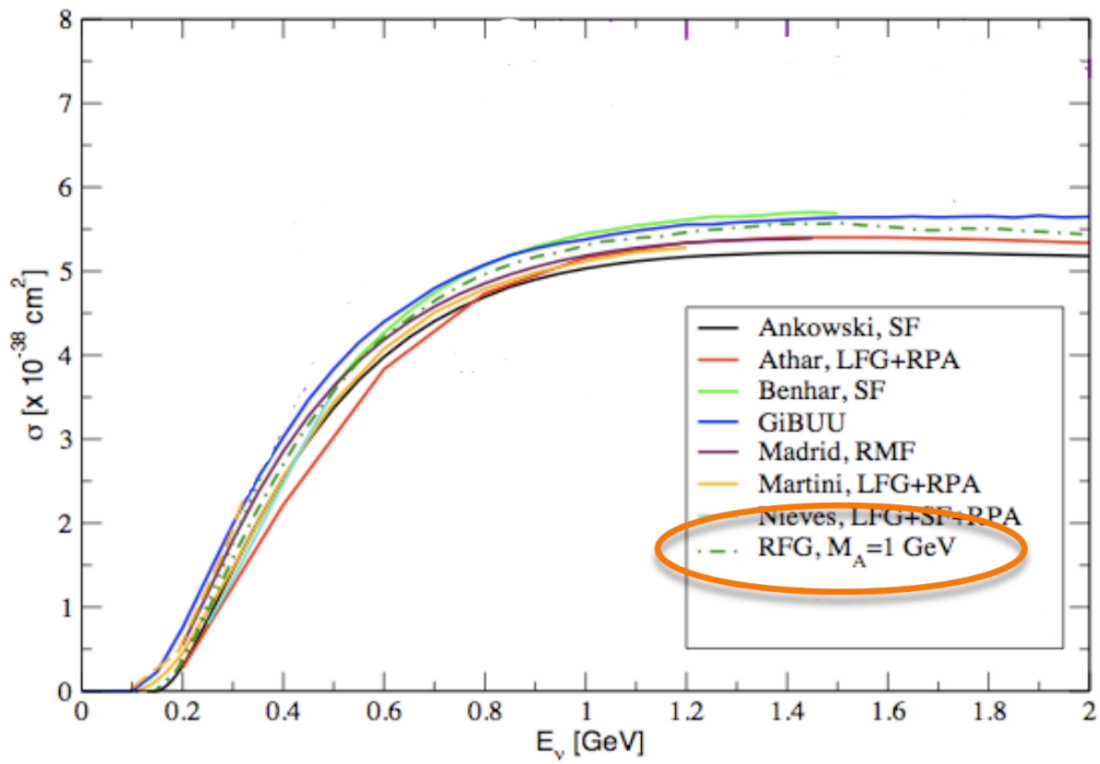
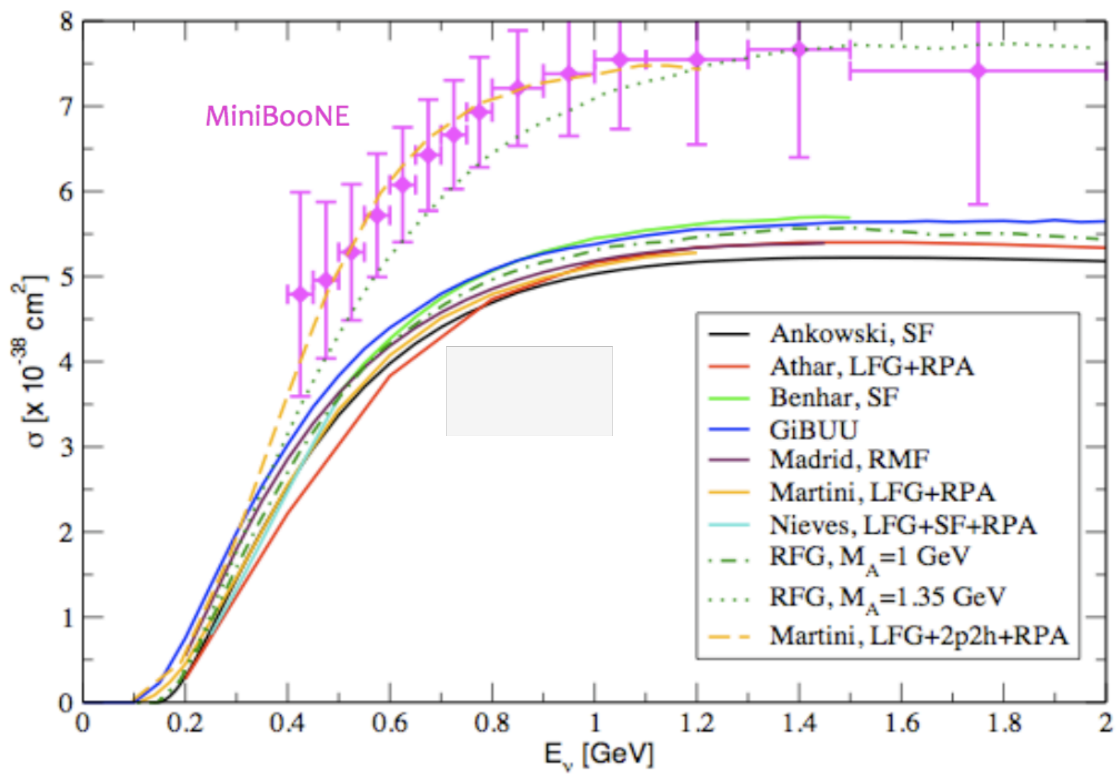


Total MiniBooNE cross section

- MiniBooNE CCQE cross section ~40% higher than most modern models (!)
- The first model to predict the observed excess includes a sizeable contribution from an unexpected source…



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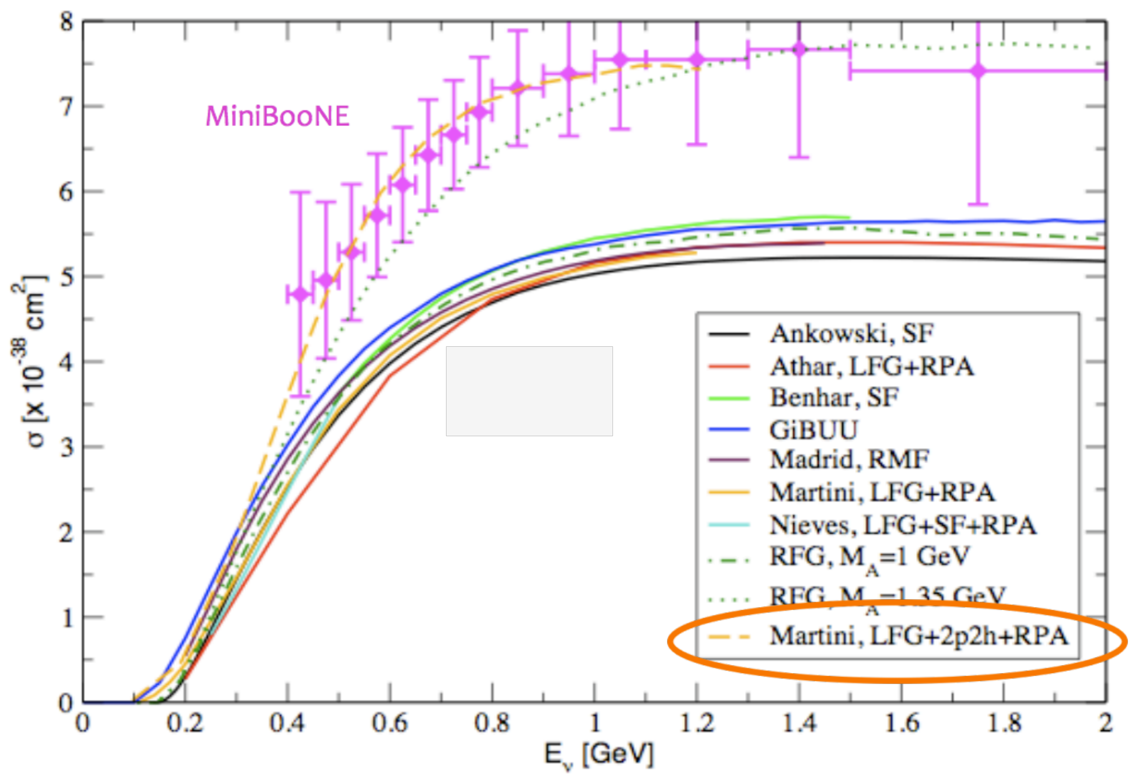
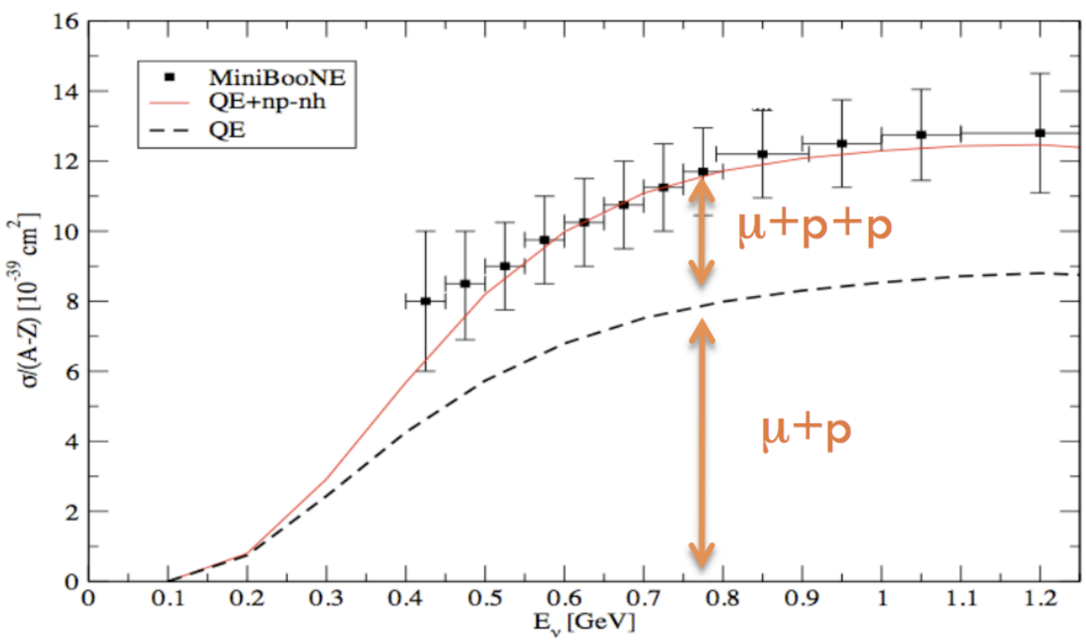


New interaction?

- Possible M_A reconciliation: nuclear correlation effects in ^{12}C result in an "extra" (ν_μ + [n+p] -> μ^- + p + p) part of the CCQE cross section not present in light target experiments and indistinguishable from "true CCQE" (ν_μ + n -> μ^- + p) in MiniBooNE

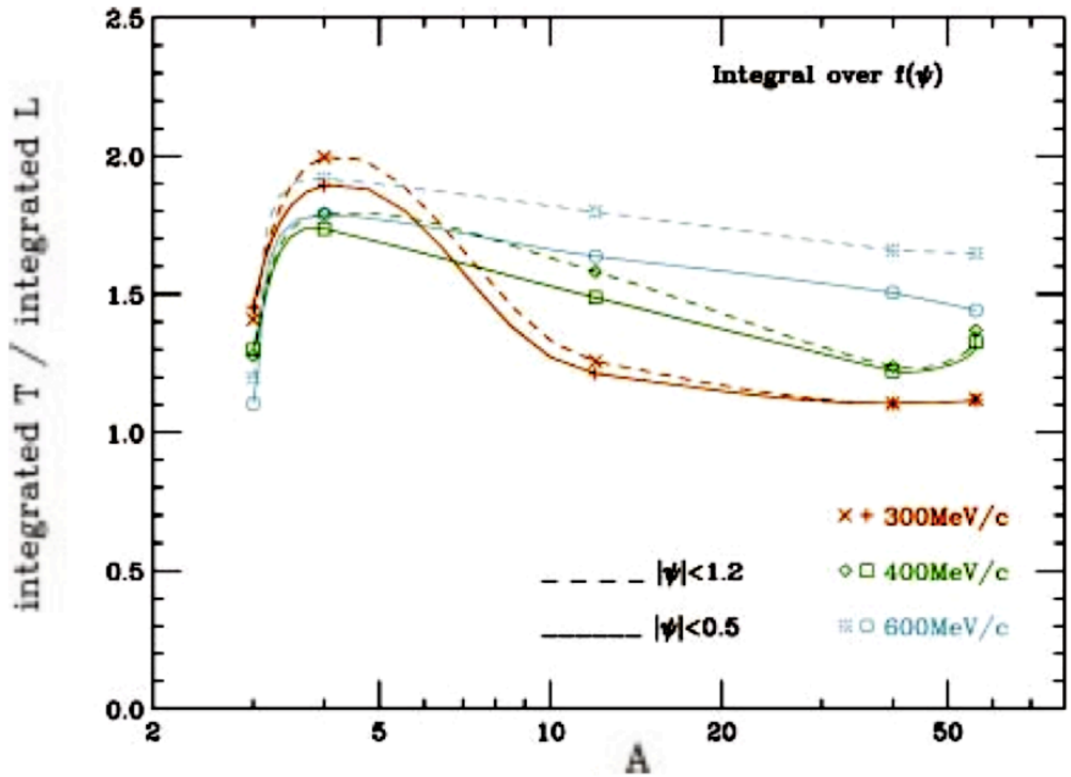
- MiniBooNE "blind" to outgoing nucleons



PRC 80, 065001 (2009)

Support in electron scattering data

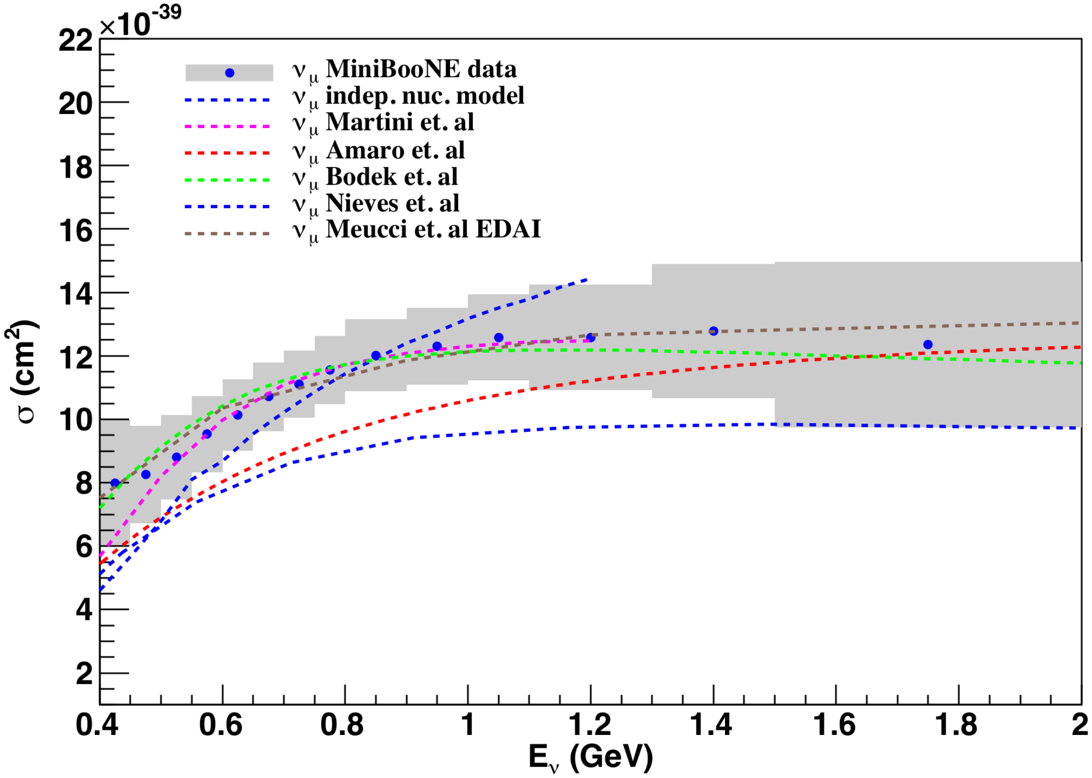
- Transverse current significantly greater than longitudinal in (e,e') data
- In RFG, $f_L = f_T$ (!!)
- Something like this *should* be in ν scattering as well
  - *at least* in the vector part of the cross section



- No rigorous connection between ν and (e,e') cross section yet
  - Axial enhancement?

Since then…

- Confirmation from independent groups that *something like* the multi-nucleon mechanism can account for observed enhancement
  - variety of different approaches represented here: parametrizations, extrapolations, and *ab initio* calculations
- Strong test of the underlying physics can be obtained with anti-neutrinos
  - Probe a different mix of axial, vector σ pieces. How might this new process contribute to anti-neutrinos?



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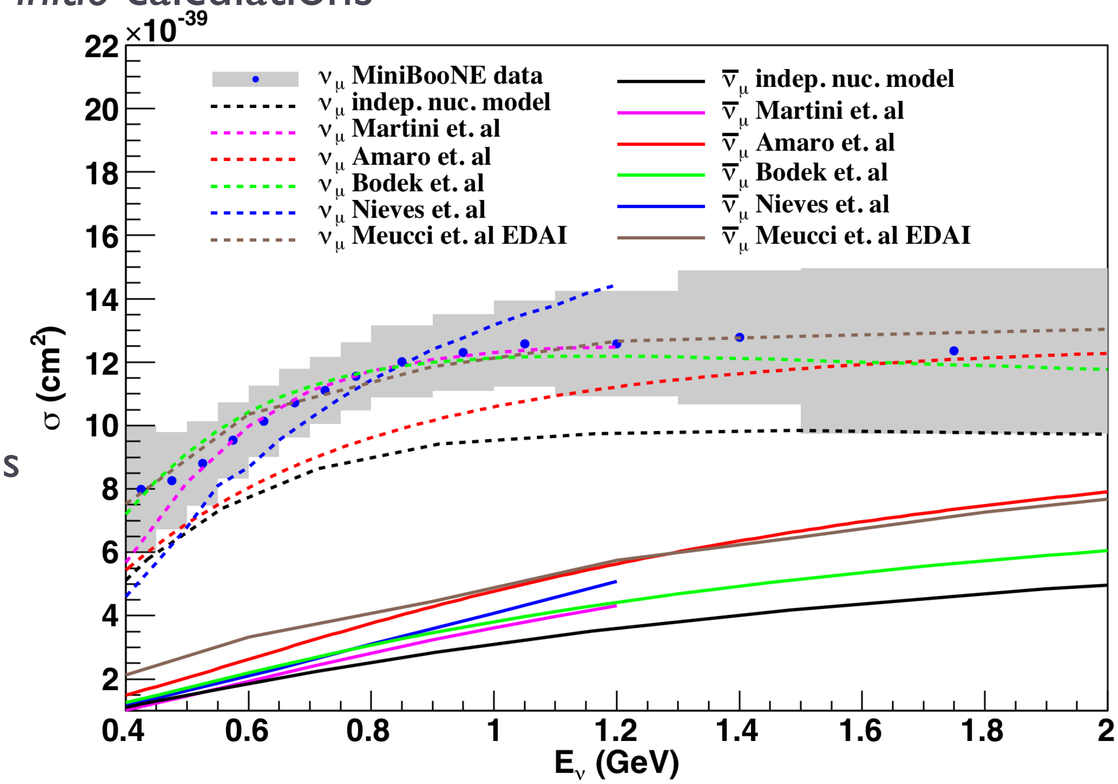
  - Predictions range by factor of 2!



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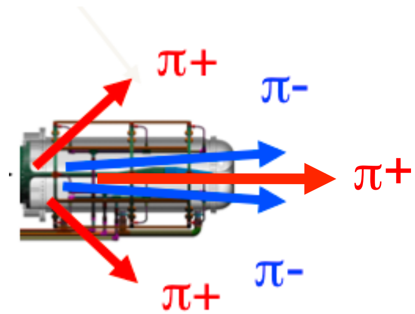
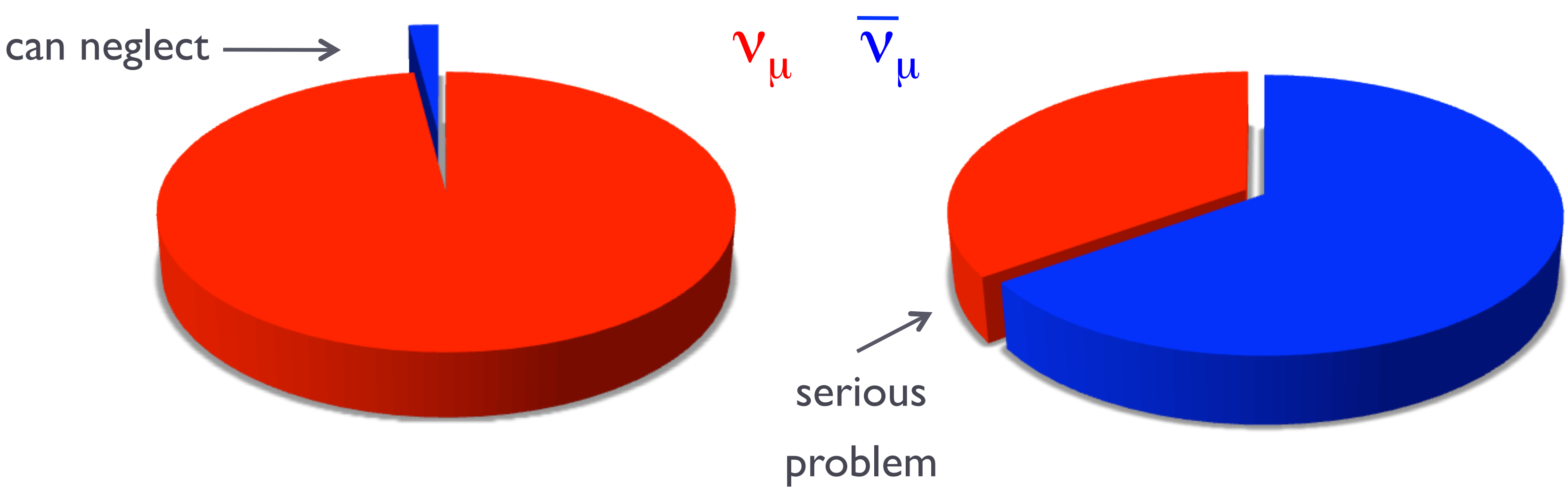
Before we get to σ's: messy backgrounds

- Running mode defined by polarity of focusing horn
  - neutrinos a much larger problem for anti-neutrino running ("wrong-signs") than *vice versa*



"neutrino mode"

"anti-neutrino mode"

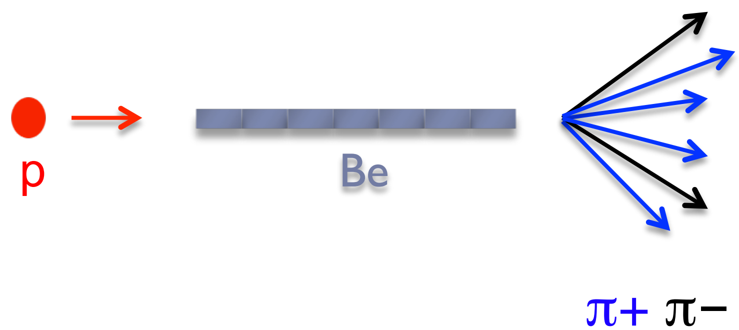


Why so different?

- Both flux and cross-section effects conspire to suppress anti-neutrino interactions and amplify neutrinos

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2) \times \left(\frac{s-u}{M^2}\right) + C(Q^2) \times \left(\frac{s-u}{M^2}\right)^2\right]$$

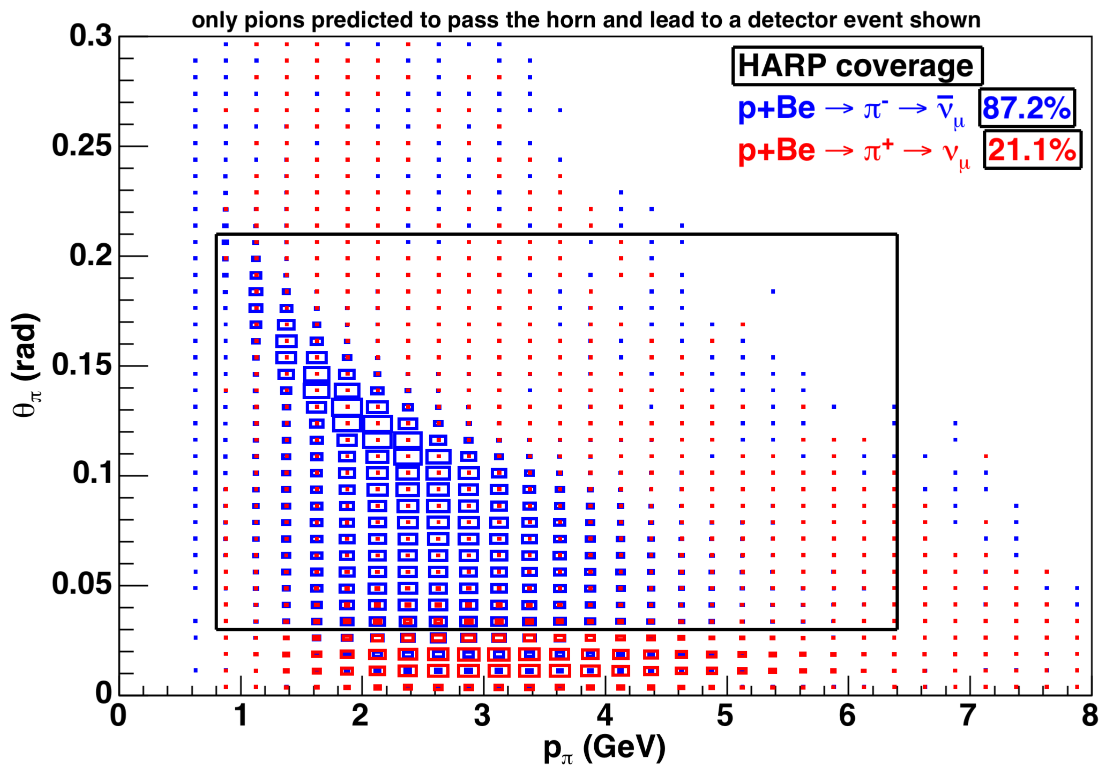
Cross section: at MiniBooNE energy (~1 GeV), ν's around 3x as likely to scatter as anti-ν's



Flux: positively-charged initial state naturally produces more ν parents (π+) than anti-ν parents (π-)

Even worse

- MiniBooNE not magnetized (other expt's separate ν species based on outgoing lepton charge)
- HARP π-production measurements do not help here
- ν's form a large and uncertain background to the anti-ν mode analyses: demands dedicated studies to assure anti-ν cross sections and oscillation results not biased



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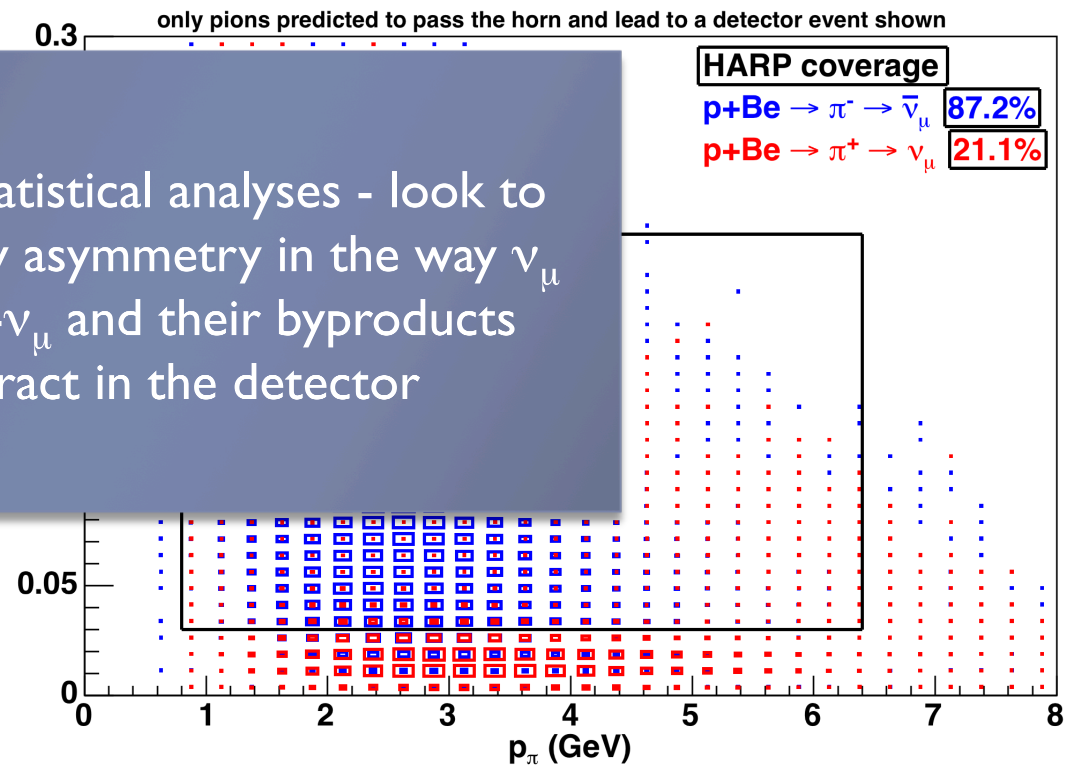
turn to statistical analyses - look to exploit any asymmetry in the way ν_μ and anti-ν_μ and their byproducts interact in the detector



Background measurement philosophy

- Consistency
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Wrong-sign measurements

- Three independent and complementary measurements of the ν_μ background:

  1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
  2. Comparing predicted to observed event rates in the $CC\pi^+$ sample
  3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

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First measurement of the ν_μ content of a $\bar{\nu}_\mu$ beam using a non-magnetized detector.
Phys. Rev. D81: 072005 (2011)

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Phys. Rev. D81: 072005 (2011)

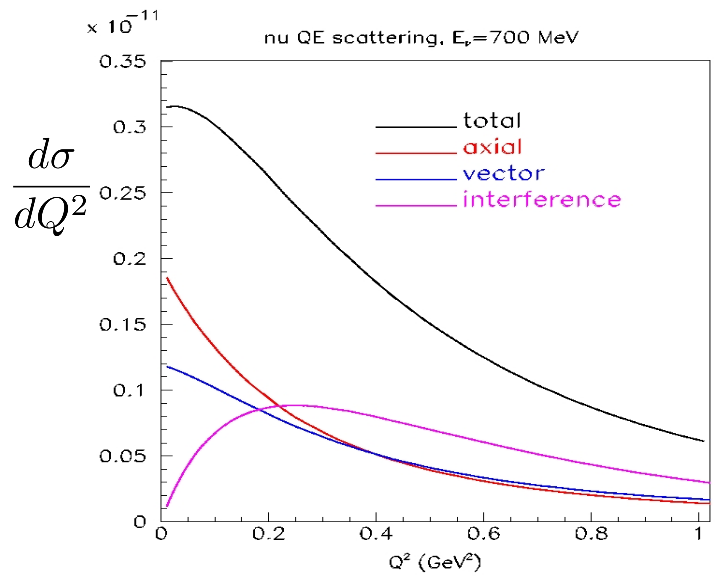
in draft

Fitting the outgoing muon angular distribution

- Interference term in "canonical CCQE" model not only causes rate difference, but large kinematic asymmetry as well

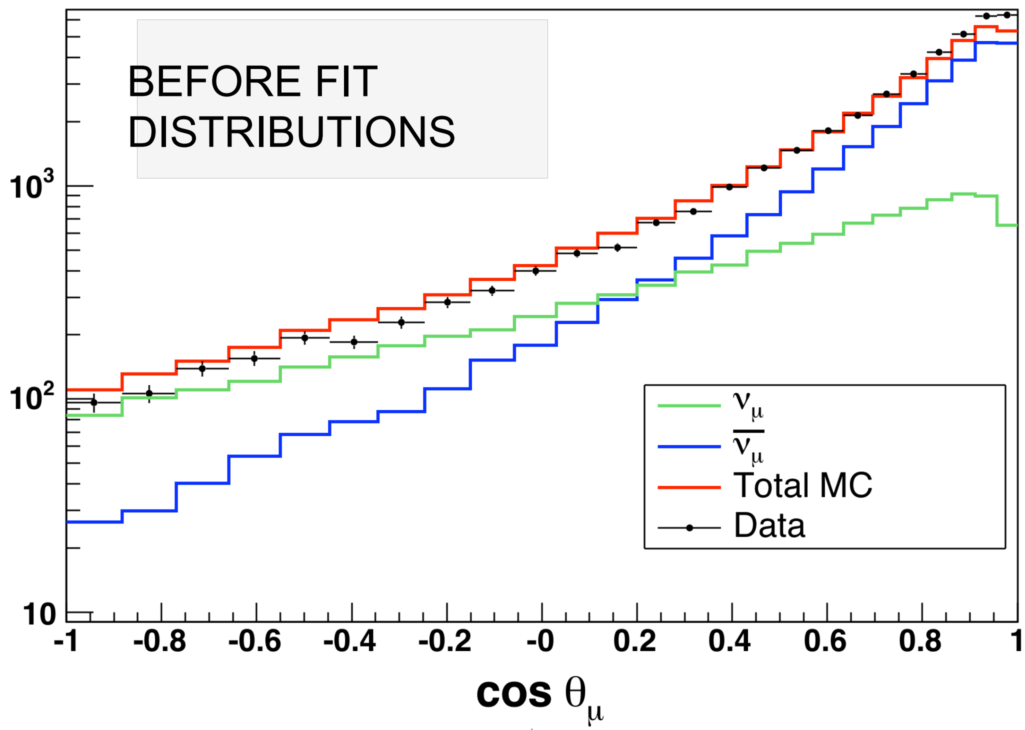
$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \,|V_{ud}|^2}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2)\times\left(\frac{s-u}{M^2}\right) + C(Q^2)\times\left(\frac{s-u}{M^2}\right)^2\right]$$

- The divergence is more pronounced at higher Q^2, which is strongly correlated with backward scattering muons



Fitting the outgoing muon angular distribution

- We form a linear combination of the neutrino and anti-neutrino content to fit the CCQE data:

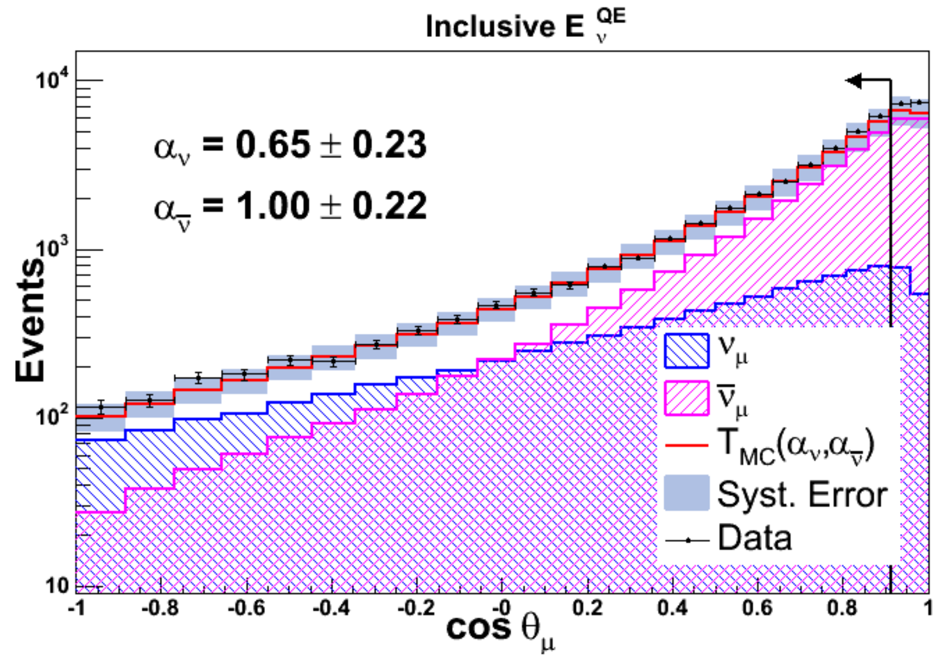


(angle between outgoing μ and incoming ν beam)

Fitting the outgoing muon angular distribution

- Results indicate the ν_μ flux is over-predicted by ~30%

- Consistency checks:
  1. Fit to data in exclusive energy regions
  2. Fit Θ_μ instead of cos Θ_μ
  3. Linear fit to data is analytic - can numerically check results
  4. Check fits as a function of run # (systematic shift in the detector?)



Fitting the outgoing muon angular distribution

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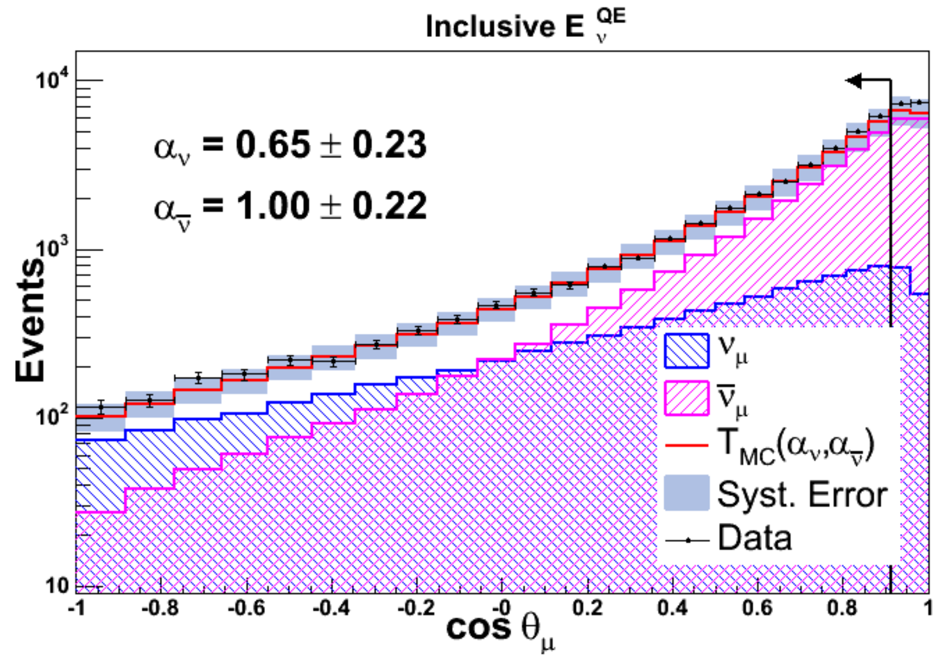


Results all consistent with a uniform reduction of the ν_μ flux compared to the (highly uncertain) prediction

Wrong-sign measurements

- Three independent and complementary measurements of the wrong-sign background:

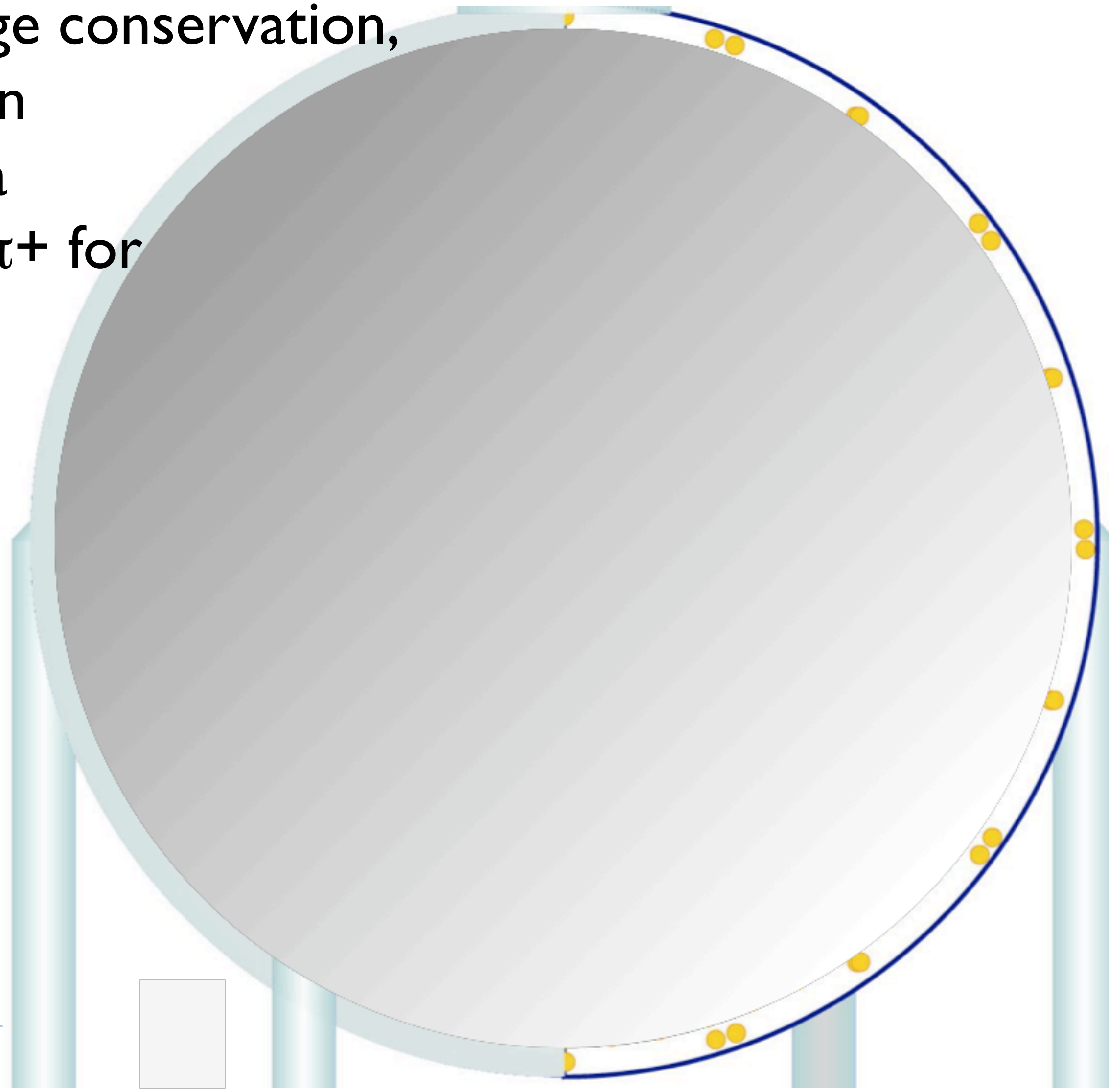
1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
2. Comparing predicted to observed event rates in the $CC\pi^+$ sample
3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

CCπ+ sample formation

- From lepton and charge conservation, the single-π production mechanism (mostly via resonance) results in π+ for ν_μ scattering, π- for anti-ν_μ interactions

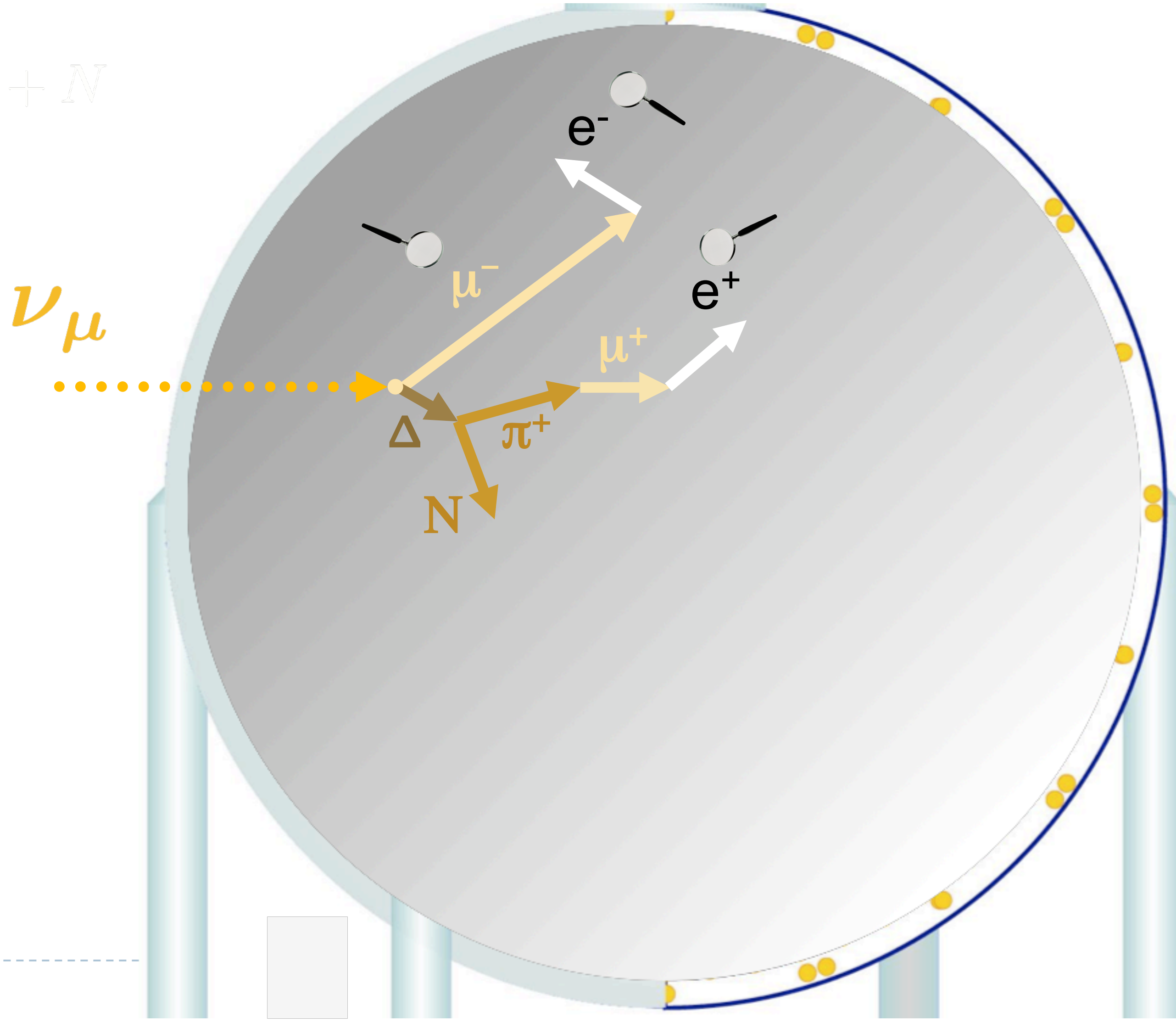
$$\nu_\mu N \rightarrow \mu^- \pi^+ N$$

$$\bar{\nu}_\mu N \rightarrow \mu^+ \pi^- N$$



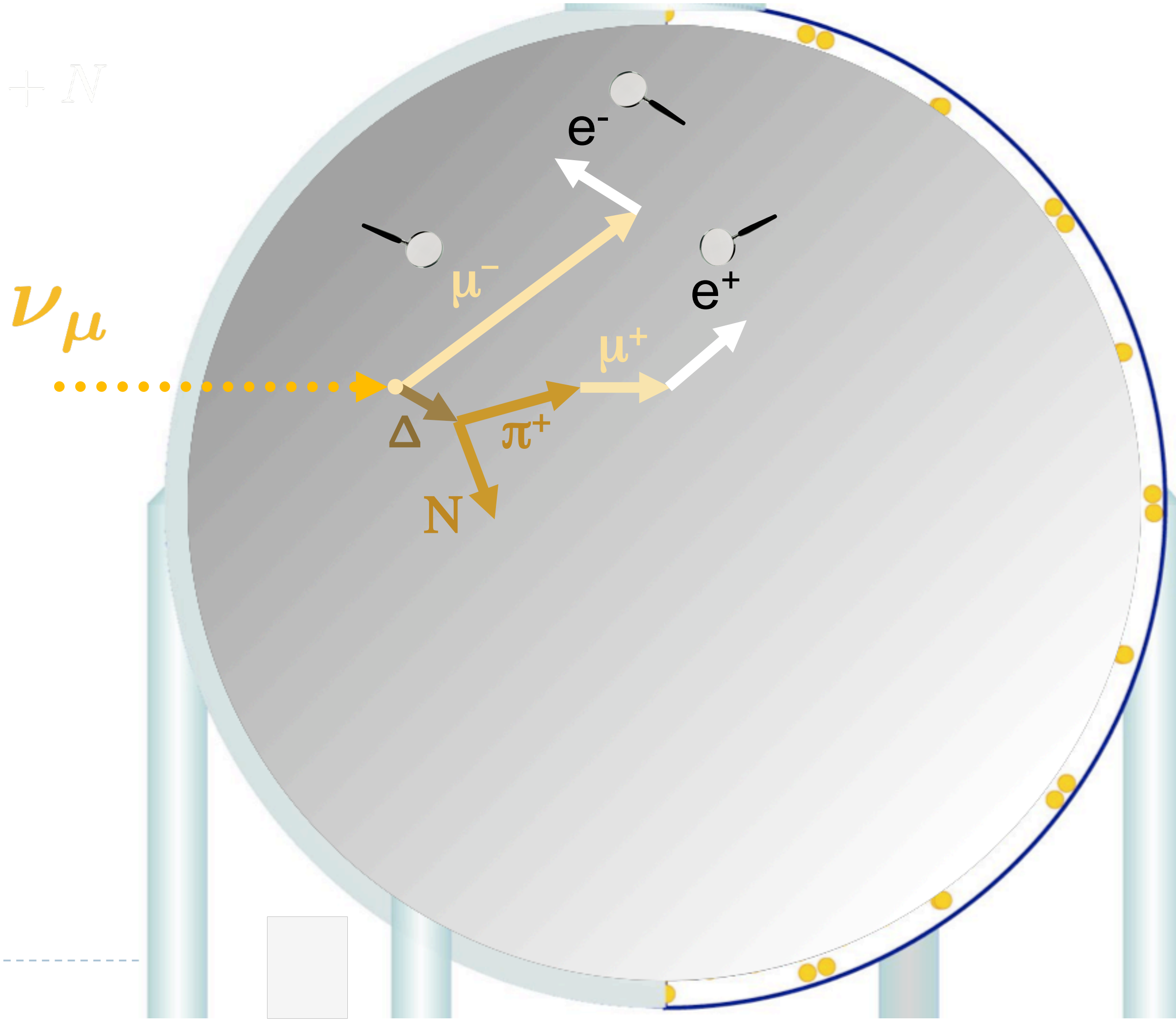
CCπ⁺ sample formation

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



CCπ⁺ sample formation

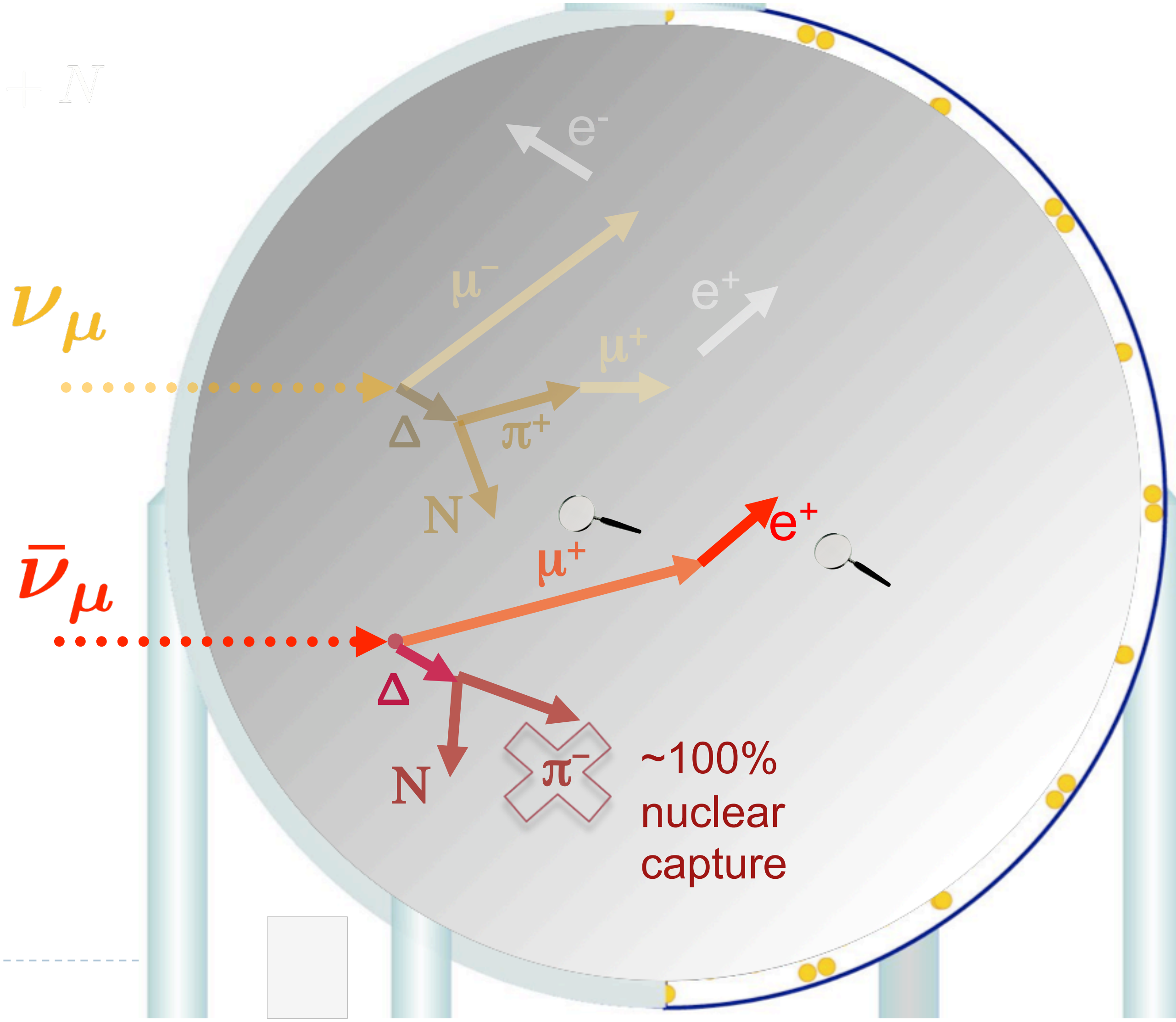
$\nu_\mu + N \rightarrow \mu^- + \pi^+ + N$



- Three observable leptons
  1. Primary muon
  2. Decay electron
  3. Decay positron

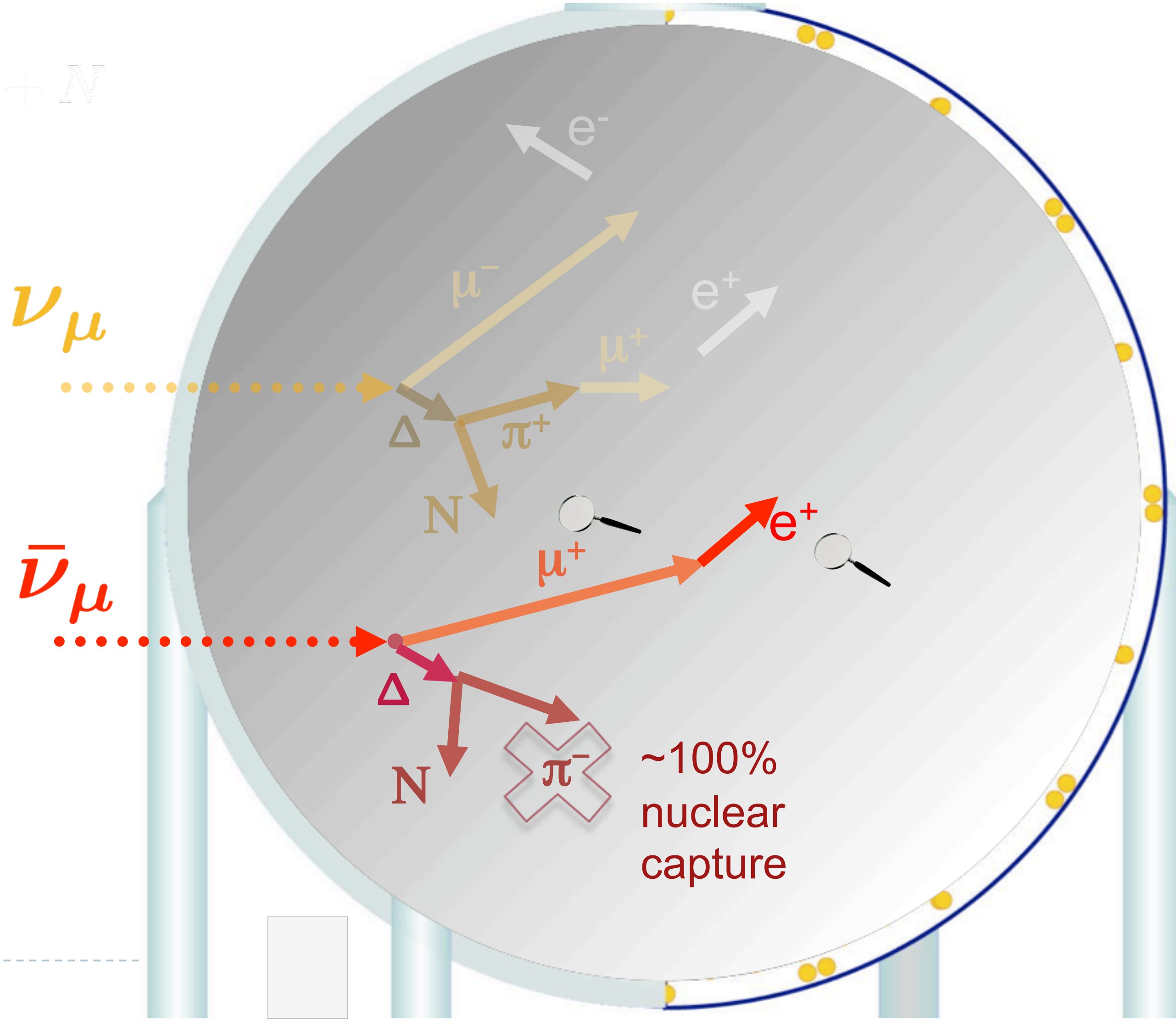
CCπ+ sample formation

$\bar{\nu}_\mu + N \rightarrow \mu^+ + \pi^- + N$



CCπ⁺ sample formation

$\bar{\nu}_\mu + N \rightarrow \mu^+ + \pi^- + N$



* Due to nuclear π⁻ capture, the corresponding anti-neutrino interaction has only two:
  1. Primary muon
  2. Decay positron

$CC\pi^+$ sample formation

- Require two decay electrons after the primary muon, get a sample that is ~80% pure ν_μ.

* Data/simulation ratios in bins of reconstructed energy indicate the neutrino flux is over-predicted in normalization, while the simulated spectrum looks fine

E_ν^Δ (MeV)	ν_μ Φ scale
600 - 700	0.65 ± 0.10
700 - 800	0.79 ± 0.10
800 - 900	0.81 ± 0.10
900 - 1000	0.88 ± 0.11
1000 - 1200	0.74 ± 0.10
1200 - 2400	0.73 ± 0.15
Inclusive	0.76 ± 0.11

$CC\pi$+ σ measurement:
Phys. Rev. D83, 052007 (2011)

Wrong-sign measurements

- Three independent and complementary measurements of the wrong-sign background:

1. Fitting the angular distribution of the CCQE sample for the neutrino and anti-neutrino content
2. Comparing predicted to observed event rates in the $CC\pi^+$ sample
3. Measuring how often muon decay electrons are produced (exploits μ^- nuclear capture)

μ^- capture measurement

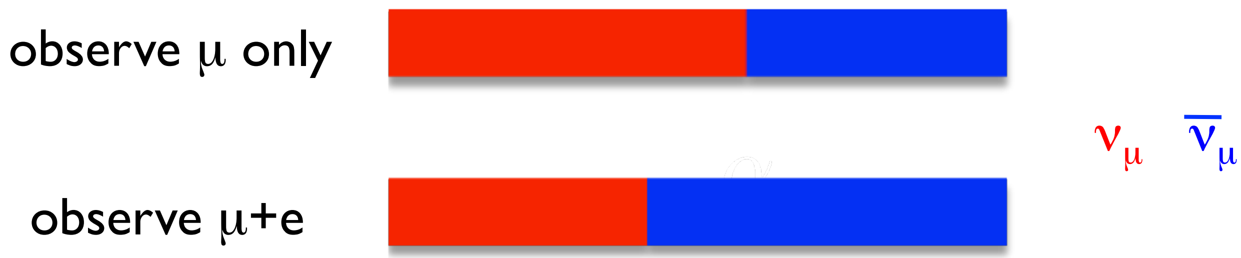
- Charged-current events typically observe both the prompt μ and its decay electron - two reasons why we may not see the electron:

  1. electron detection efficiency
  2. μ^- nuclear capture (ν_μ events only)

* We isolate μ-only and μ+e samples

μ^- capture measurement

- Predicted sample composition:



- Scale the two contributions to match data simultaneously in both samples (two eqns, two unknowns)

$$\mu\,\text{only}^{\text{data}} = \left(\alpha_\nu\,\nu^{\mu\,\text{only}} + \alpha_{\bar{\nu}}\,\bar{\nu}^{\mu\,\text{only}}\right)^{\text{sim.}}$$

$$\mu + e^{\text{data}} = \left(\alpha_\nu\,\nu^{\mu+e} + \alpha_{\bar{\nu}}\,\bar{\nu}^{\mu+e}\right)^{\text{sim.}}$$

μ^- capture measurement

- Predicted sample composition:

observe μ only

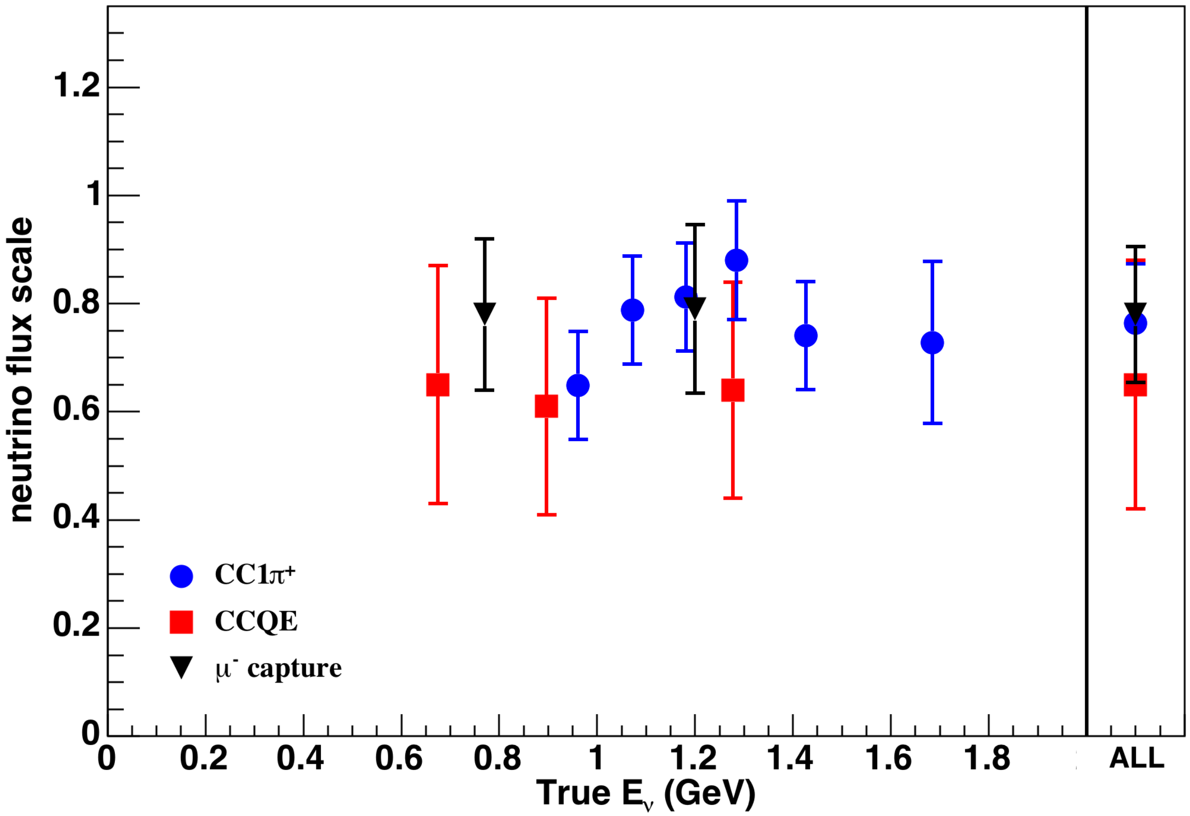
observe μ+e

- Scale the two contributions to match data simultaneously in both samples (two eqns, two unknowns)

Results:

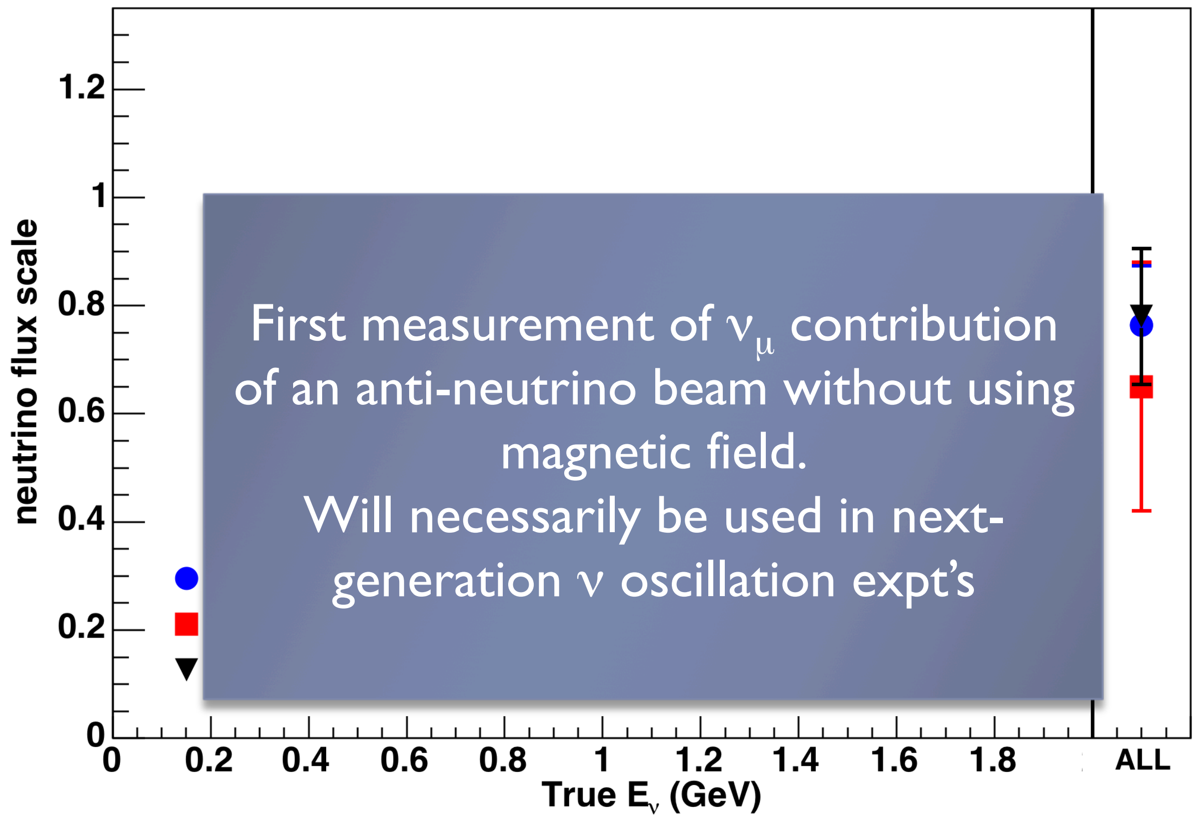
Parameter	E_ν^{QE} (GeV)		
	< 0.9	> 0.9	All
α_ν	0.79 ± 0.14	0.81 ± 0.16	0.80 ± 0.13
$\alpha_{\bar{\nu}}$	1.14 ± 0.22	1.14 ± 0.22	1.14 ± 0.22

ν_μ measurement summary



Discrepancy with prediction appears to be in normalization only - simulated ν_μ shape in energy seems fine.

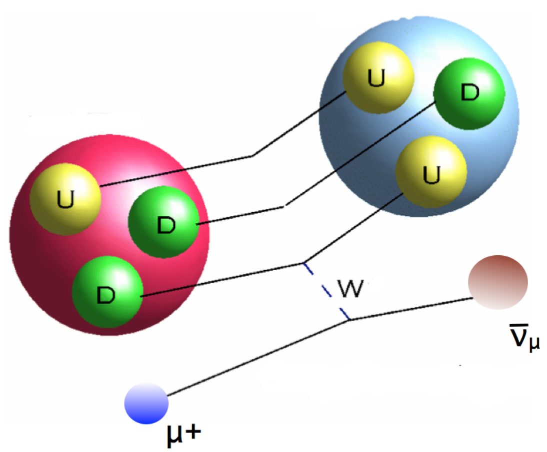
ν_μ measurement summary

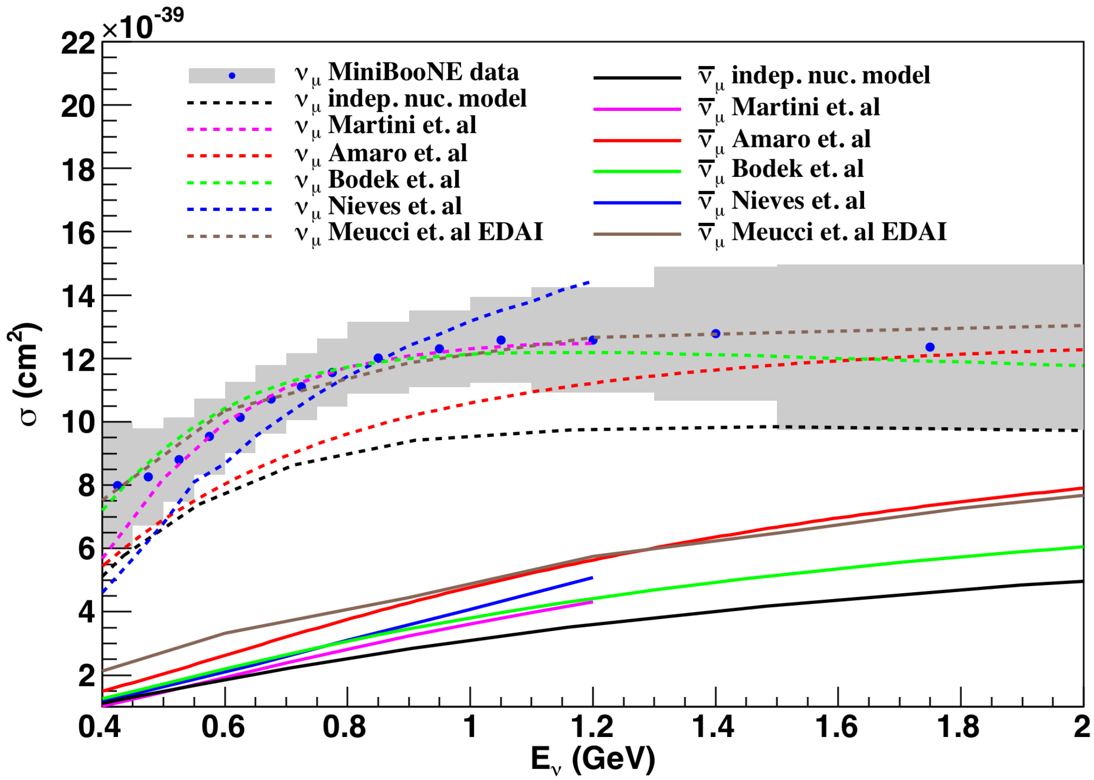


Discrepancy with prediction appears to be in normalization only - simulated ν_μ shape in energy seems fine.

On to the fun stuff

- ν_μ background now constrained to sub-dominant uncertainty, can now turn to finding the anti-ν_μ CCQE cross section





σ calculation

- Relatively straightforward:

"unfolding matrix": corrects for reconstruction bias

data

background

$$\frac{d^2\sigma}{d\mathrm{T}_\mu \, d(\cos\theta_\mu)} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Delta T_\mu \Delta(\cos\theta_\mu)\epsilon_i \Phi T}$$

int. targets

σ in terms of μ kinematics:
least model-dependent measurement possible
with MiniBooNE

flux

detection efficiency

bin widths

σ calculation

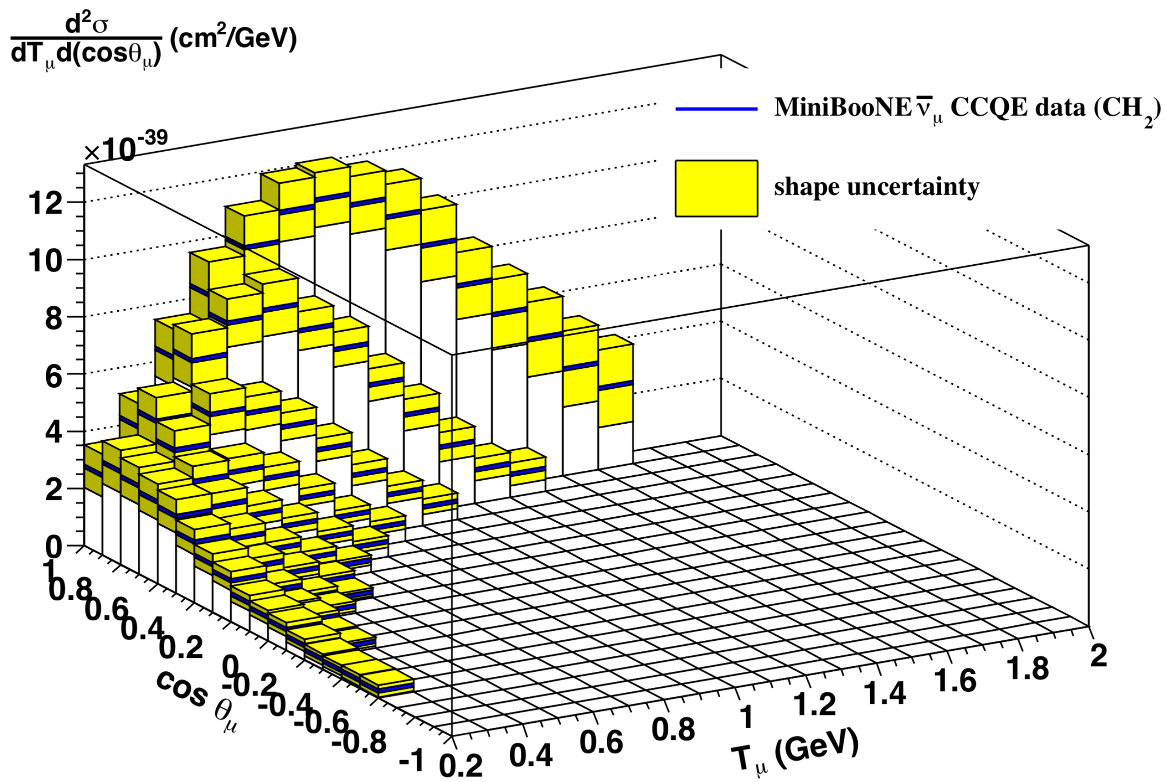
- Systematic uncertainties evaluated by "many universe method": σ recalculated many times varying the underlying processes and parameters affecting the measurement according to the level of their accuracy
  - e.g. flux, bkg knowledge etc. Correlations included.

$$\frac{d^2\sigma}{d\mathrm{T}_\mu\, d(\cos\theta_\mu)} = \frac{\sum_j U_{ij}^k (d_j - b_j^k)}{\Delta T_\mu \Delta(\cos\theta_\mu)\epsilon_i^k \Phi^k T^k}$$

- Difference between these alternate calculations and the "best guess" σ sets the systematic uncertainty

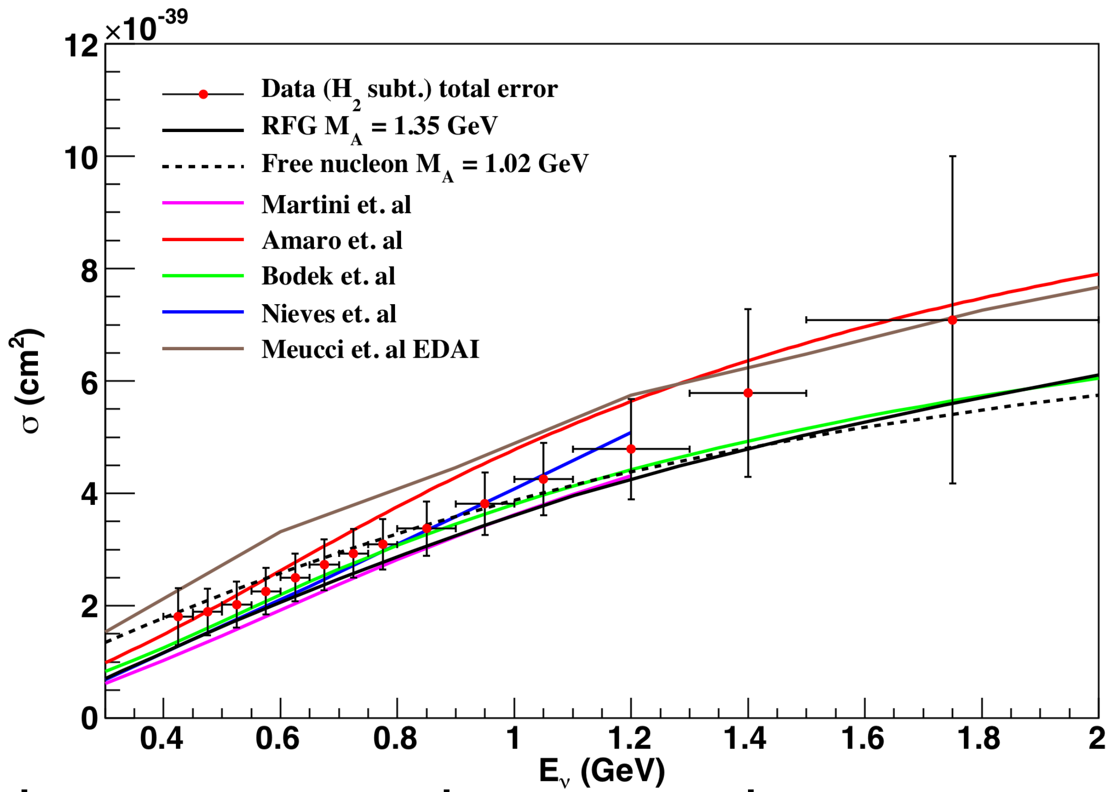
Primary anti-neutrino CCQE result

- Fully exploits MiniBooNE's unprecedented statistics
  - more than 10x all previously published anti-ν_μ CCQE measurements combined!



$\sigma(E_\nu)$

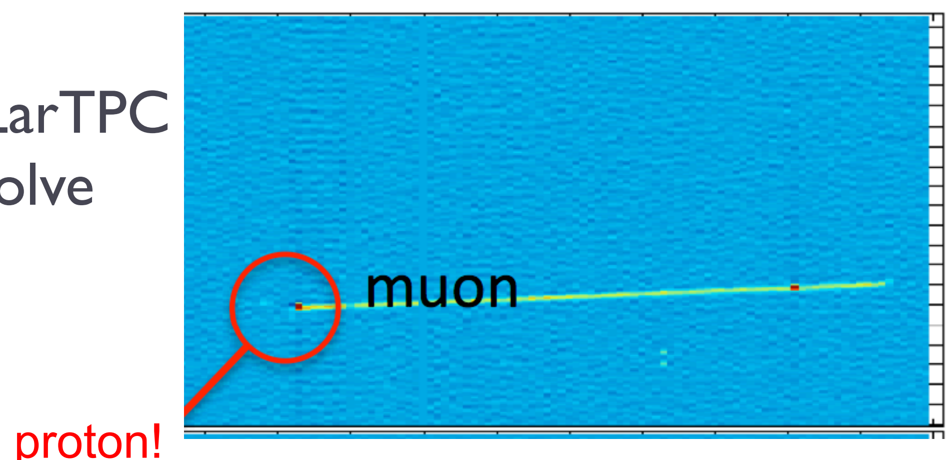
- More model-dependent (neutrino energy *inferred*, not *observed*), but can at least test the normalization of the various predictions



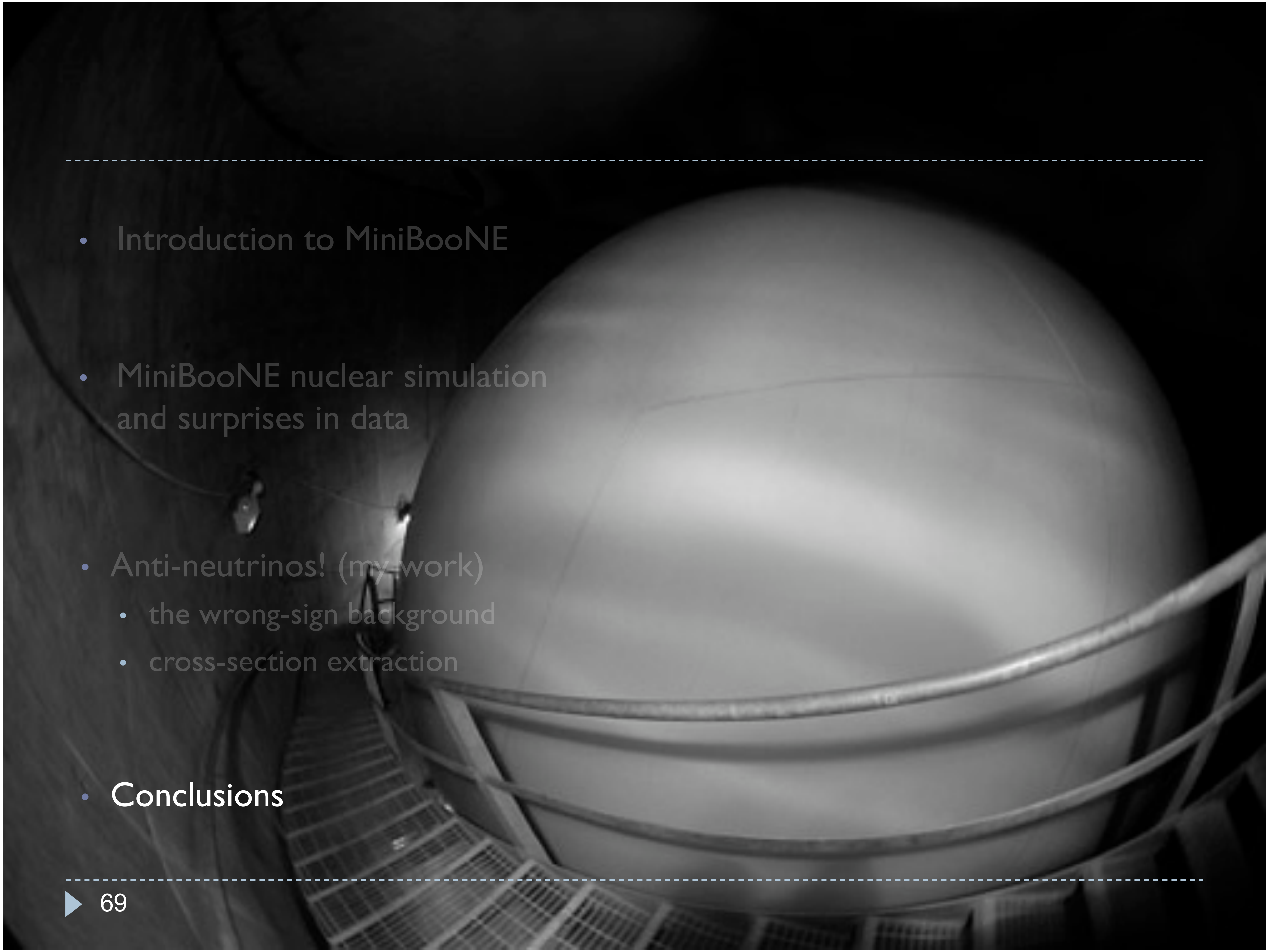
- Data in rough agreement with most predictions
  - most rigorous comparisons will be to μ-kinematic σ's (to come)

Future tests of new mechanism

- If multi-nucleon correlations are responsible, must confirm this with direct experimental evidence
  - theory community seems to agree this is the source, but?
- Will rely heavily on tracking detectors to test hadronic side
  - MiniBooNE and other Cherenkov detectors mostly blind to hadrons
  - Very recently: "Argoneut" LarTPC detector showed it can resolve 21 MeV protons!



K. Partyka, NuInt12



- Introduction to MiniBooNE
- MiniBooNE nuclear simulation and surprises in data
- Anti-neutrinos! (my work)
  - the wrong-sign background
  - cross-section extraction
- **Conclusions**

Conclusions

- MiniBooNE has measured a surprisingly high CCQE cross section for both neutrinos and anti-neutrinos relative to previous expectations
  - Other expt's have observed similar enhancements
- The anti-neutrino analysis required a rigorous and novel series of ν_μ background measurements. First measurements without a magnetic field!
- "New" nuclear physics may account for the σ discrepancy, but time will tell
  - Previously overlooked support for this process in electron scattering data for decades
- It's an exciting time for ν interaction physics!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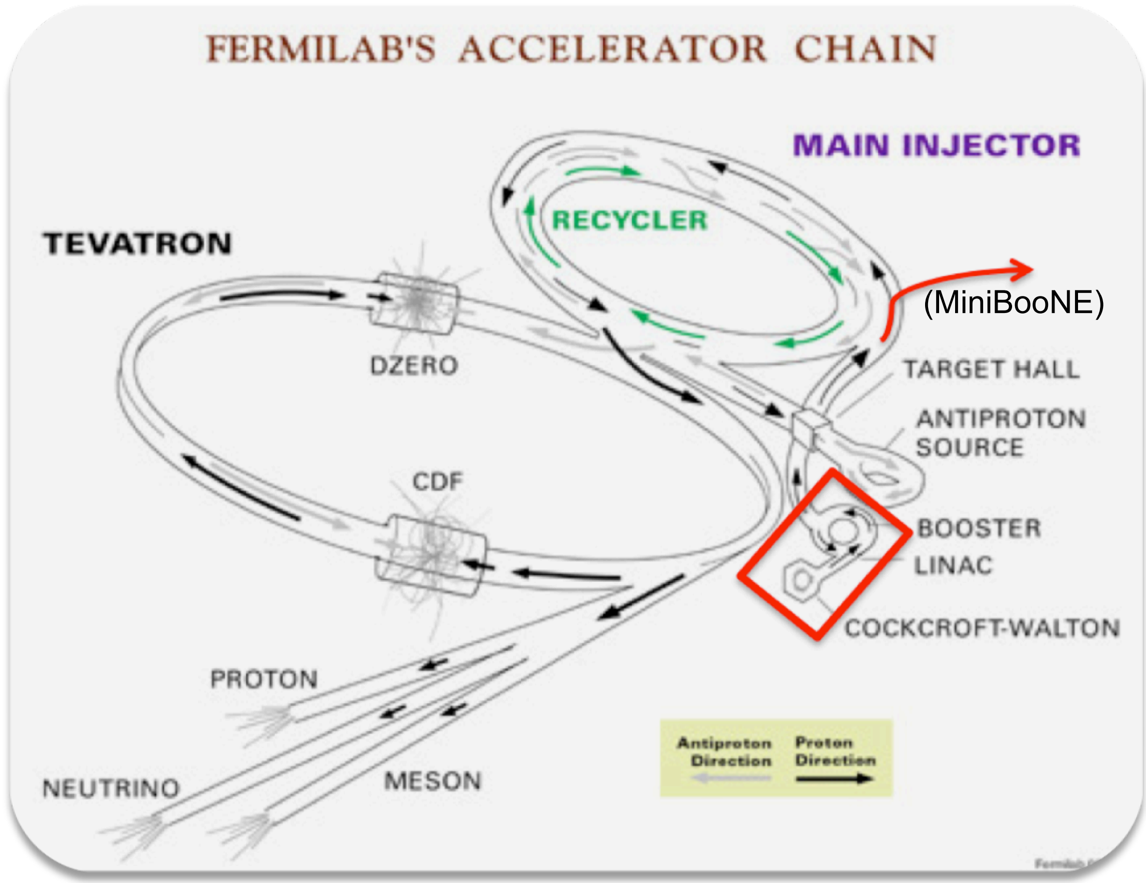
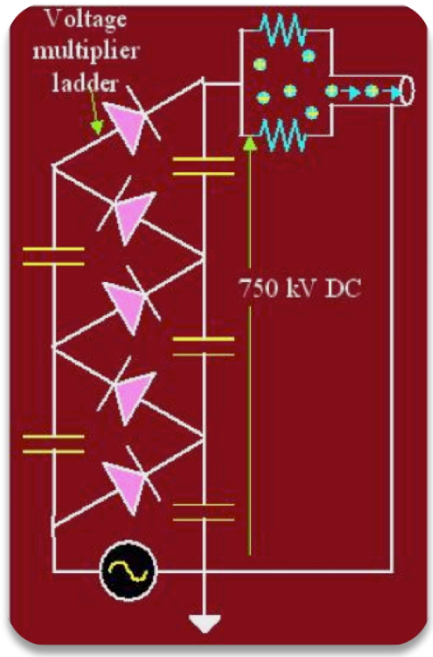
Booster Neutrino Beamline

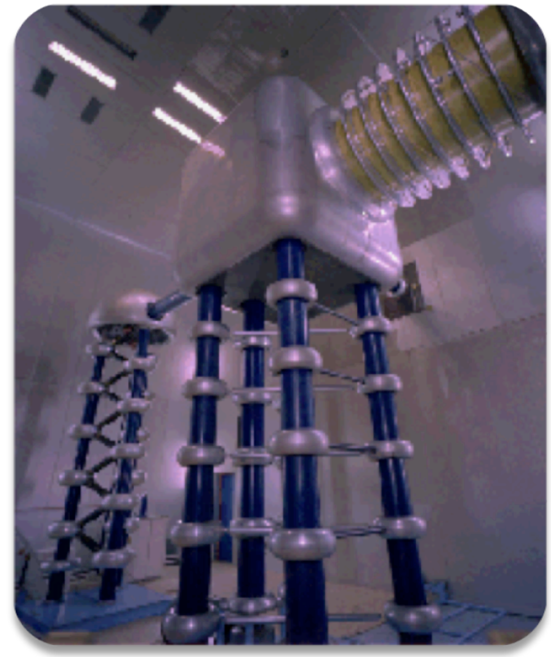
- Three stages:
  1. Cockroft-Walton
  2. Linac
  3. Booster Ring



Booster Neutrino Beamline

- Pulsed DC signal switches polarity in tune with diodes coming on/off. This allows voltage doubling at each successive stage.



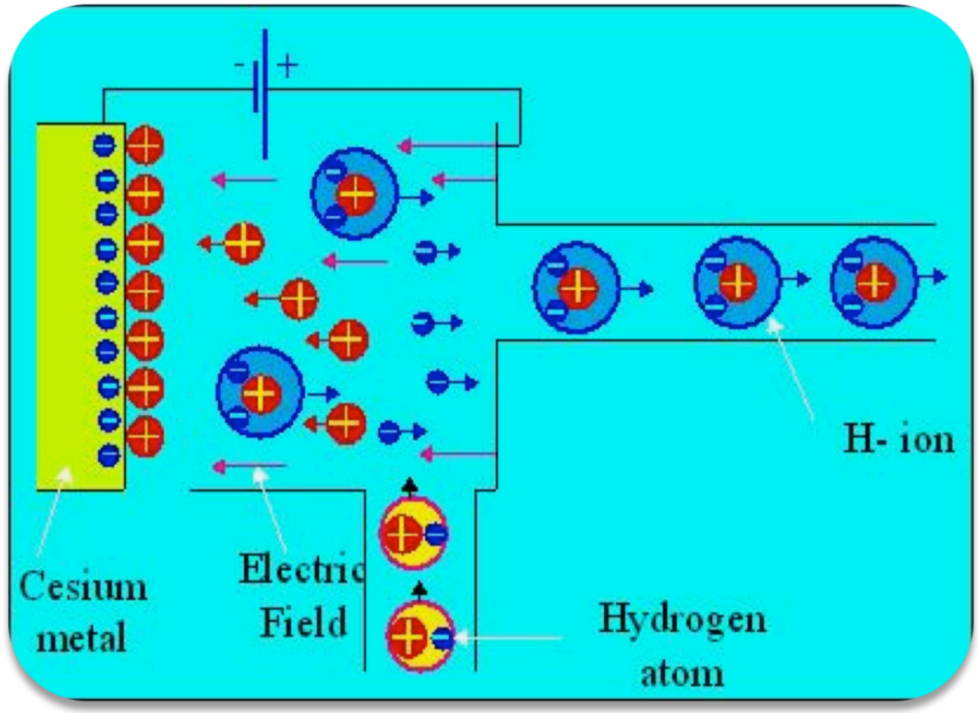


- Details:
  Initially DC signal negative, allows charge from ground to pile on first capacitor. When DC current switches, 1st diode switches off, 2nd diode switches on and the 2nd capacitor receives charge from both first DC signal *and* 1st capacitor. When DC signal switches again, 2nd capacitor has twice the charge the 1st capacitor did.

- Assuming perfect capacitors,
  Charge on *n*th capacitor = 2 × *n* × (input voltage)

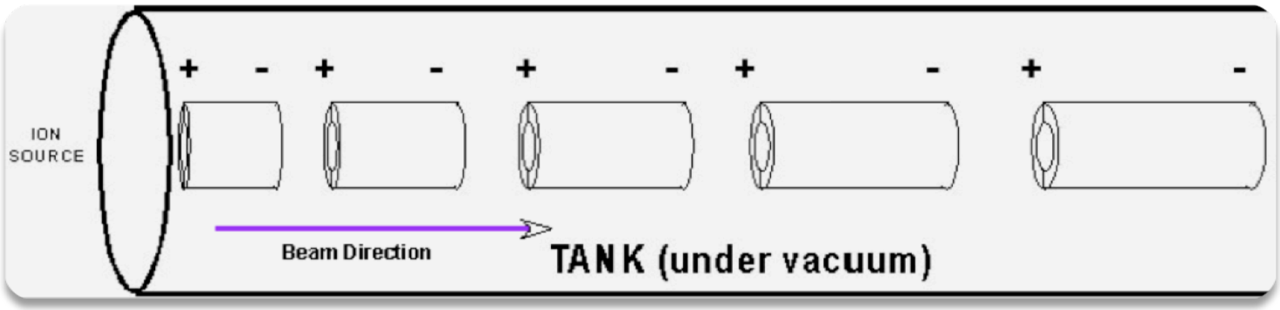
Booster Neutrino Beamline

- Hydrogen atoms injected into ionization care of strong E field created by CW ladder.
- Electron stipped off hydrogen, bare proton drifts to Cesium edge of chamber.



- Electrons easily ripped off Cesium (low work function), occasionally an incoming proton knocks off resting proton with two electrons (H^-), because negatively charged, H^- drifts away from wall, on to the linear accelerator.

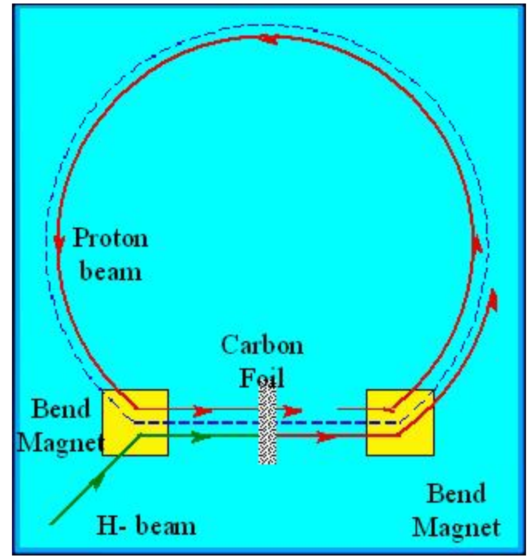
Booster Neutrino Beamline



- Alternately polarized electric field accelerates H^- ions in between gaps of Faraday cage drift tubes
- 130 m long
- Typical pulse length 20 ms
- Beam bunches spaced 5 ns apart
- H^- ions accelerated to 400 MeV KE

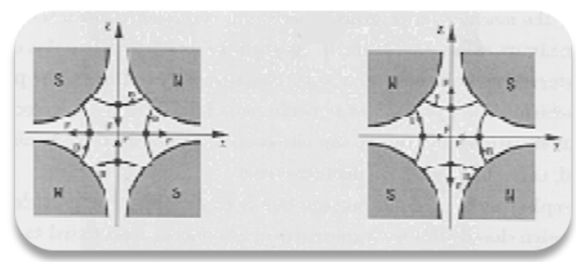
Booster Neutrino Beamline

- H^- ion beam bent to accelerate along with proton beam in ring (beams converge in this region instead of diverge - sole reason for starting with H^- instead of p)



- Both beams incident in thin carbon foil - this strips electrons while not slowing down protons.

- Booster turns protons using alternating focusing - defocusing quadrupole magnets

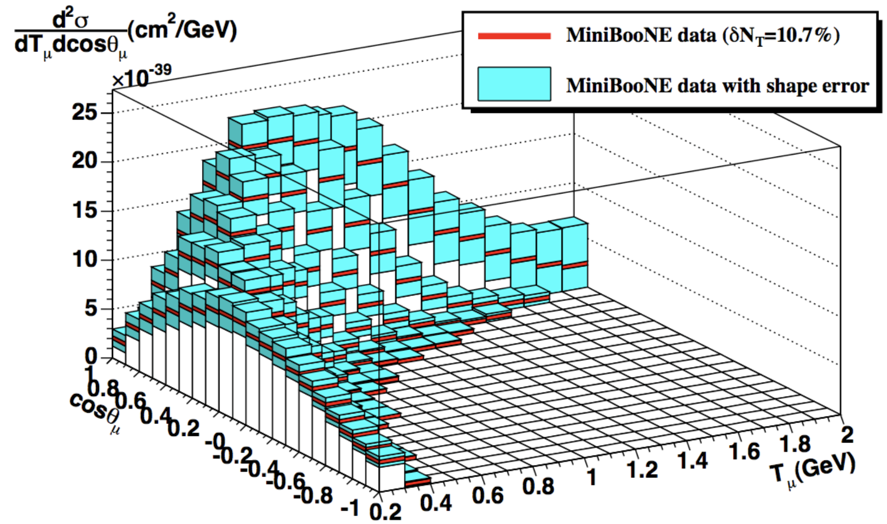


- Booster cirumference: 475 m (~3/40 circ. of Tevatron)

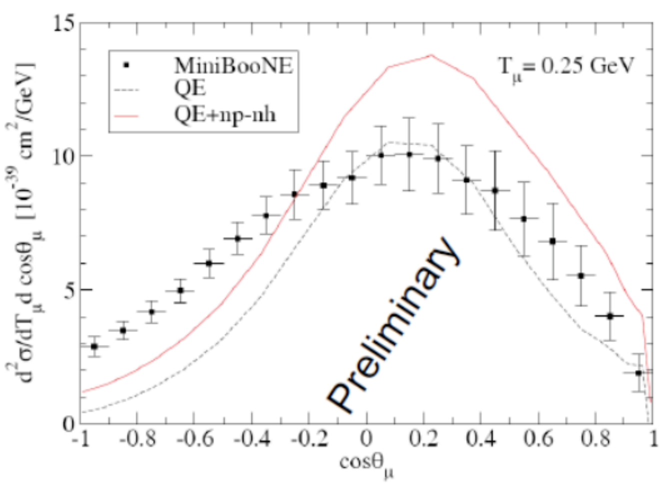
- Proton KE: 400 MeV -> 8 GeV in 33 ms, 16,000 turns

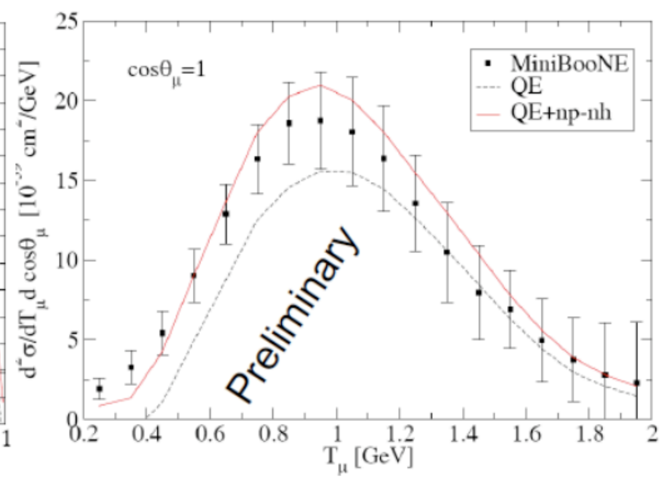
However, comparing to $\sigma(E_\nu)$ not sufficient - kinematics very important

- Main result from MiniBooNE CCQE analysis is the model-independent double-differential cross section as a function of outgoing muon energy, angle



- So far, varying degrees of compatibility with dbl-nucleon knockout model

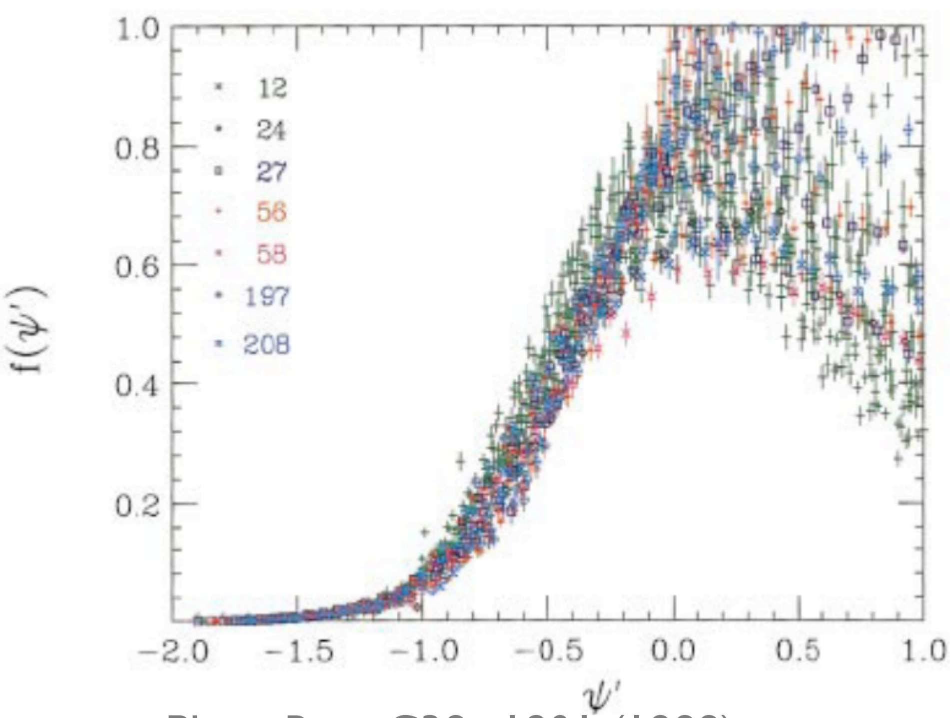




Martini, Elba X

Enhancement in electron scattering data

- "Super Scaling": For A ≥ 12, nuclear density approximately constant - does a simple scaling describe results from one nucleus to another?



Phys. Rev. C38, 1801 (1988),
Phys. Rev. C60, 065502 (1999)

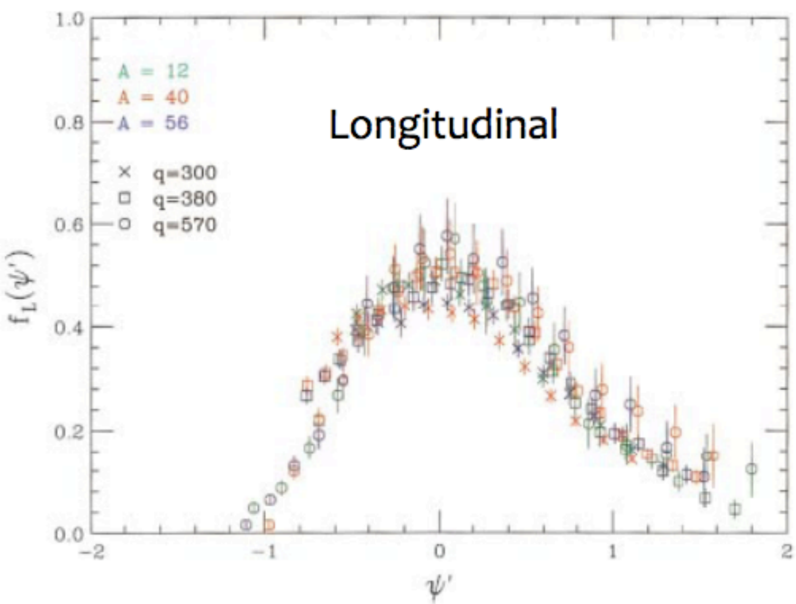
$$\psi = \frac{m_N}{k_F}\left(\lambda\sqrt{1+\tau^{-1}} - \kappa\right)$$

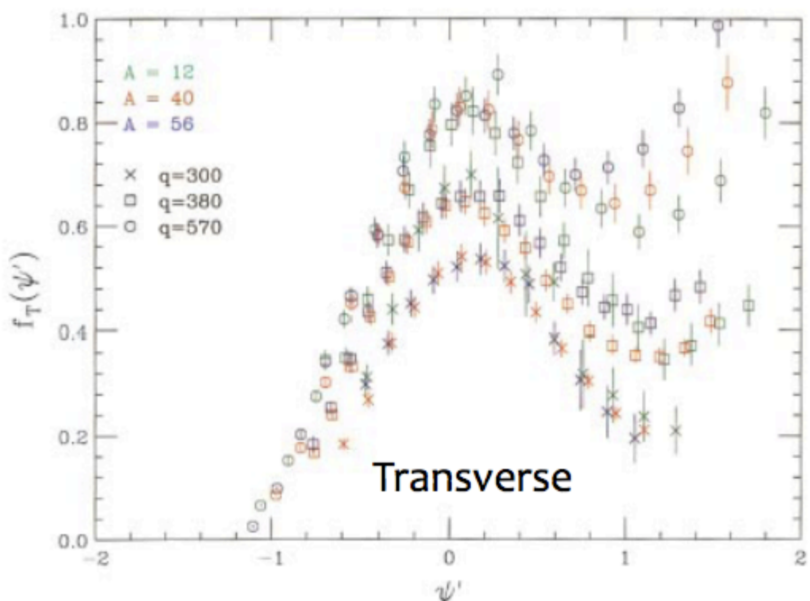
$$\lambda = \frac{\omega}{2m_N};\quad \tau = \frac{Q^2}{4m_N^2};\quad \kappa = \frac{q}{2m}$$

- Scales approximately linearly for different nuclear targets, momentum transfer and $\psi < 0$
- Divergent for $\psi > 0$

Enhancement in electron scattering data

- (e,e') scattering data decades old shows the transverse part of the (e,e') cross section scales with momentum transfer
  - CCQE cross section enhancement due to increasing M_A also grows with momentum transfer

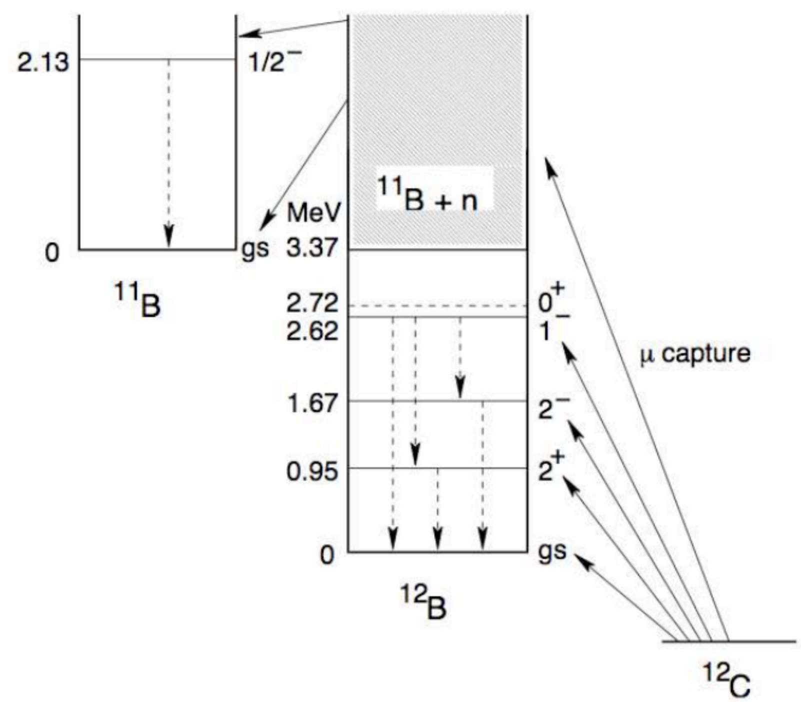




Phys. Rev. C60, 065502 (1999)

μ^- capture measurement

- ~8% of stopped μ^- captures on ^{12}C, but some nuclear de-excitation products (γ's,n's) can "fake" electron
  - "regain" Michel-like event following ~6% of μ^- captures
- ν-mode data has very little wrong-sign contribution, so we use the observed μ+e to μ-only migration rate to calibrate nuclear de-excitation and Michel detection models

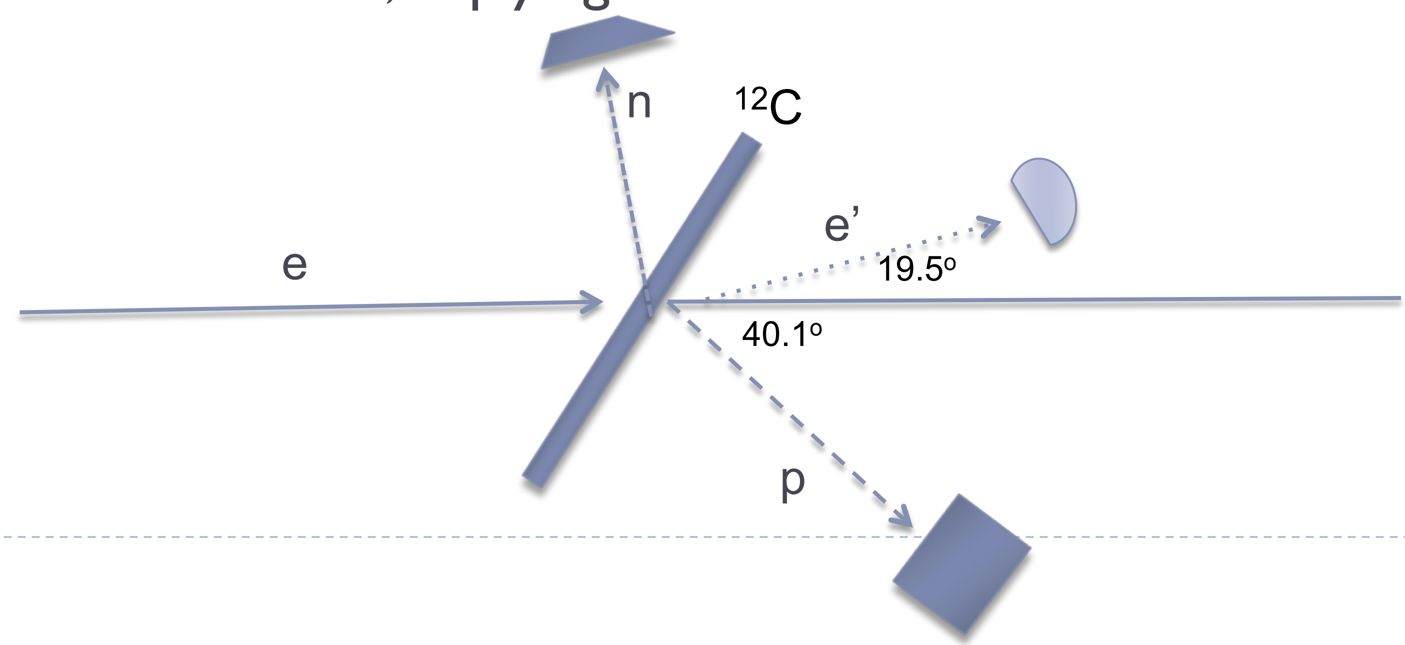


Enhancement in electron scattering data

- Some quotes from T.W. Donnelly, I. Sick, Phys. Rev. C60, 065502 (1999):
  - *"If the reaction mechanism in the quasielastic region is strictly (quasifree) knockout of protons and neutons, then one has $F_L(\psi) = F_T(\psi) = F(\psi)$…"*
  - *"The presence of large excess transverse strength* below *the π threshold means that some other mechanism must be identified as its source"*

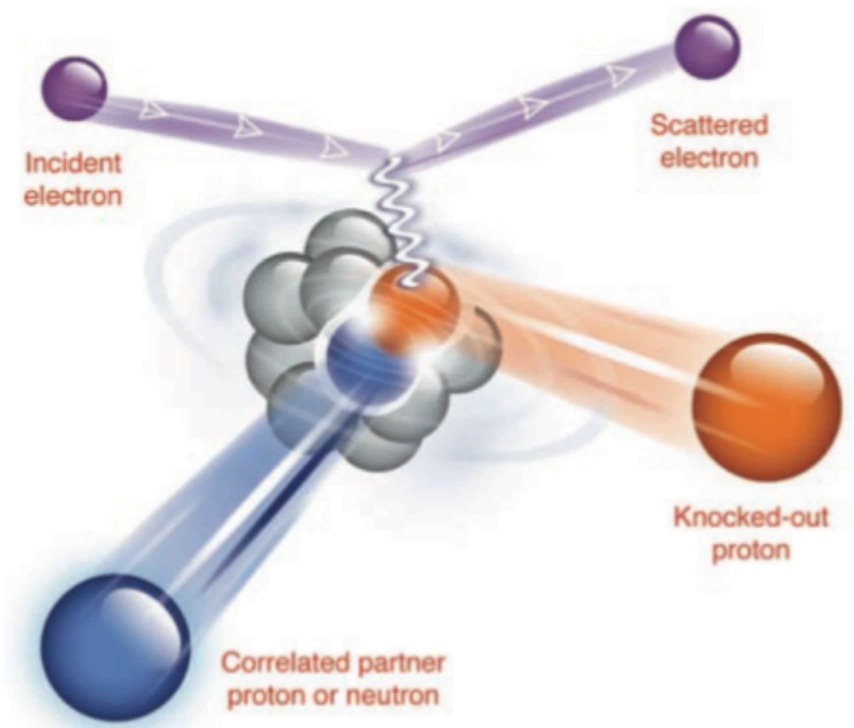
More electron scattering support for NN correlations

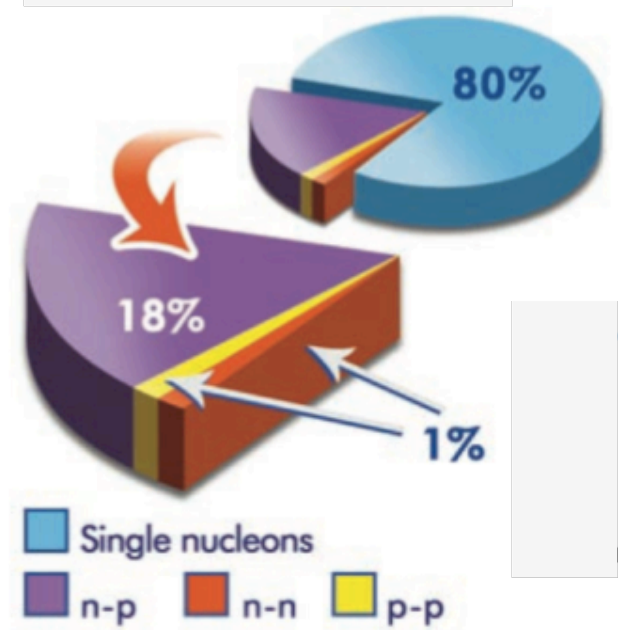
- Recent Jefferson Lab (USA) experiment:
  - scatter electron beam on ^{12}C foil, observe final state electron only in a special kinematic region: $x_B = Q^2/2m\omega = 1.2$; x_B is Bjorken scaling variable, "the fraction of nucleon momentum carried by struck quark".
  - $x_B > 1$ means struck quark carries more momentum than the entire nucleon, implying NN correlation



More electron scattering support for NN correlations

- Results: ~20% of nucleons in correlated states, mostly n-p pairs, which for ν_μ CCQE interactions lead to p-p in final state

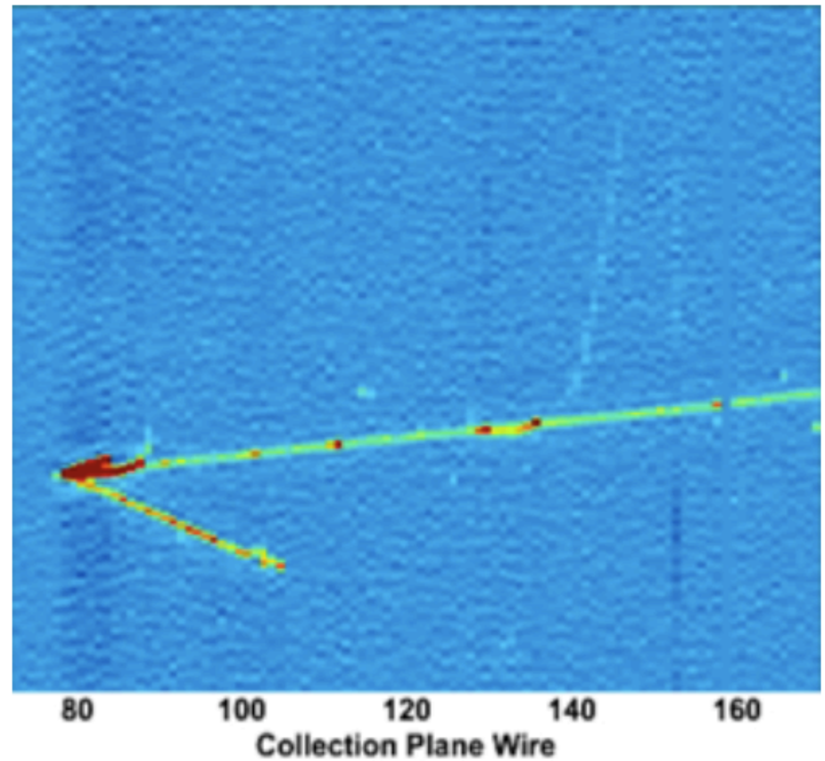




Science 320, 1476 (2008)

Future experimental tests

- Smaller enhancement predicted for anti-neutrinos
  - MiniBooNE
- Tracking detectors sensitive to multi-proton final states
  - ArgoNeut, MINERνA, NOMAD, T2K ND
- Should strive for model-independent measurements

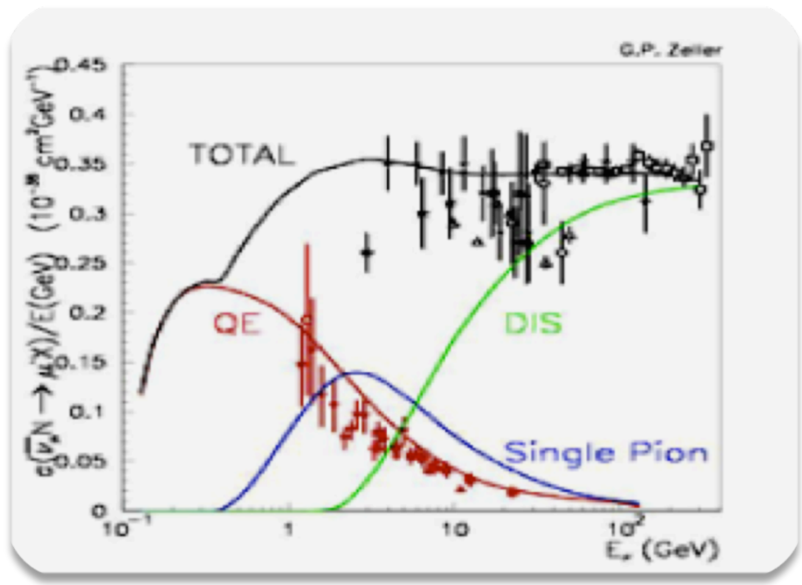


ArgoNeut, arxiv: 1009.2515

Model dependence?

- The μ+e sample is ~60% anti-ν_μ, how much model dependence enters from anti-ν_μ σ's?

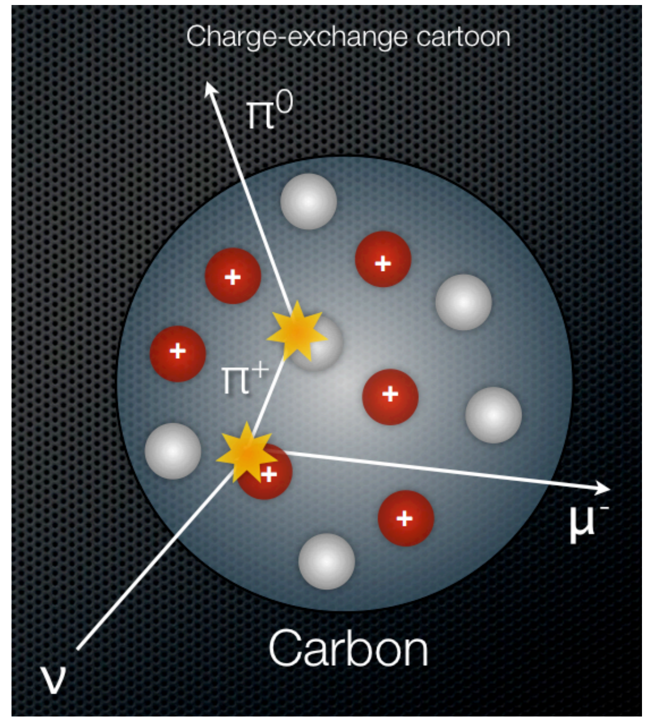
* Flux measurement negligibly sensitive to anti-ν_μ σ: model would have to be wrong by > 50% to see an impact on extracted ν_μ Φ (it's not)



Using your own σ measurements

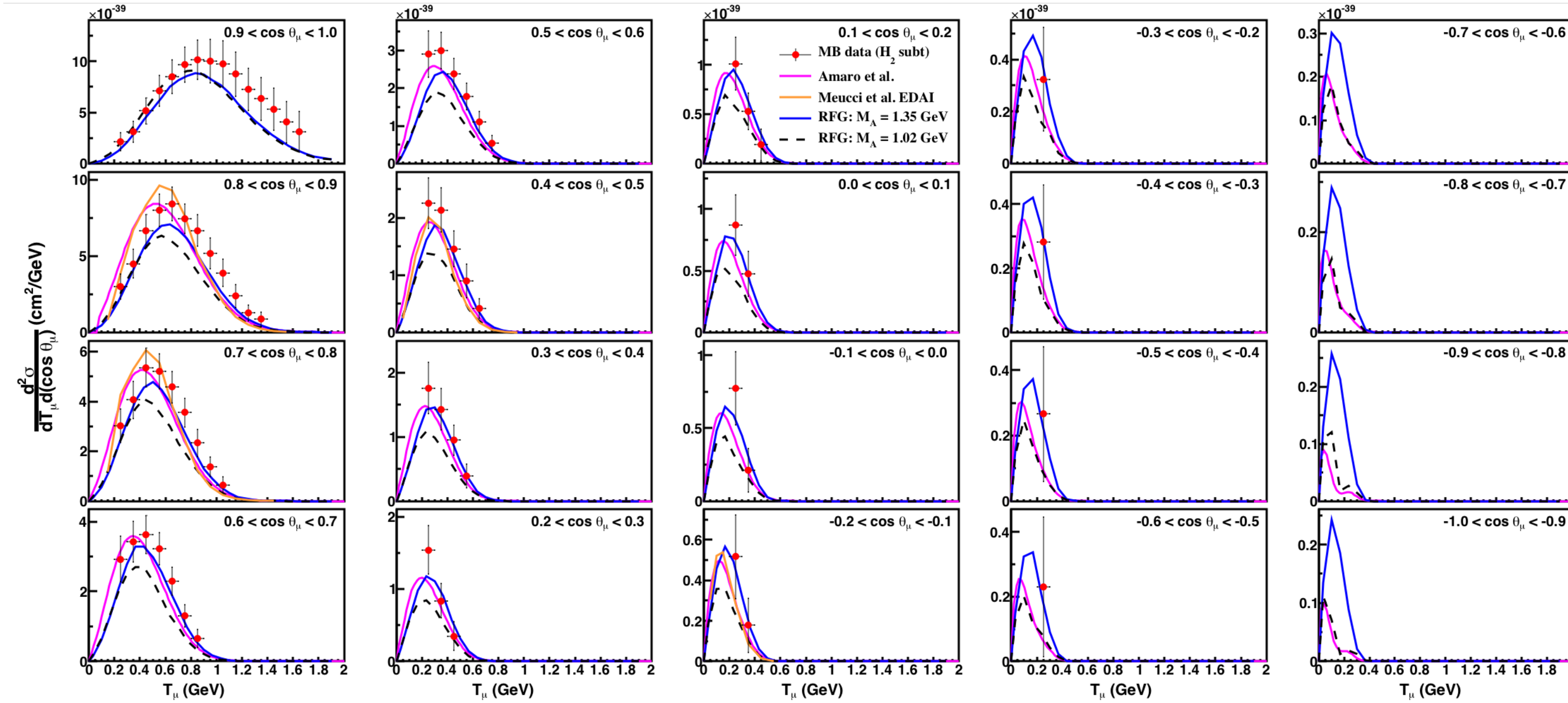
- Most detector errors cancel by correcting anti-ν mode MC for σ's observed in the ν exposure
- Similar to two-detector osc experiments, but instead of 1 beam + 2 detectors, we use 2 beams + 1 detector
- Φ uncertainty dominated by ν-mode Φ knowledge and stats

R. Nelson



Φ measurement insensitive to FSI!

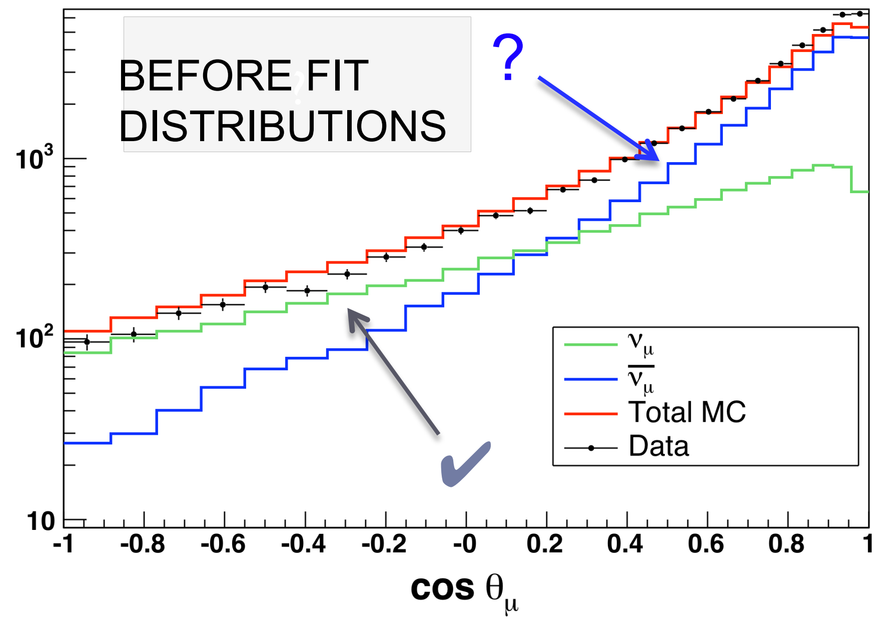
Some double-differential comparisons



Model dependence

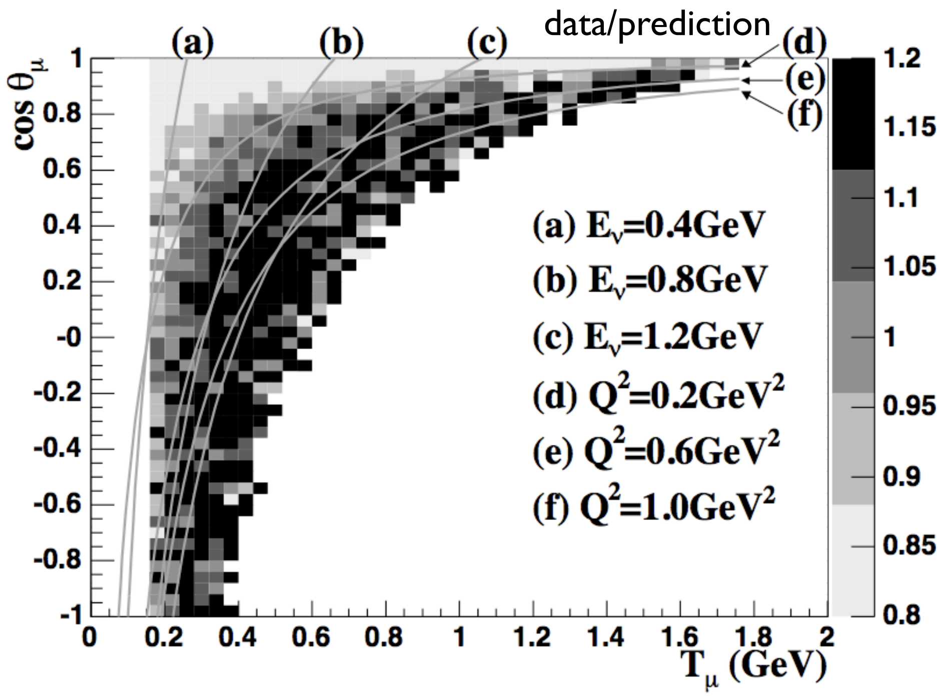
- Though the ν_μ CCQE cross section is known (from our measurement), the result is correlated to the (*a priori* unknown) anti-ν_μ distribution and therefore biased

* Many exp't and theory improvements recently, σ knowledge will improve and this technique could be very powerful in the future



Outgoing μ kinematics

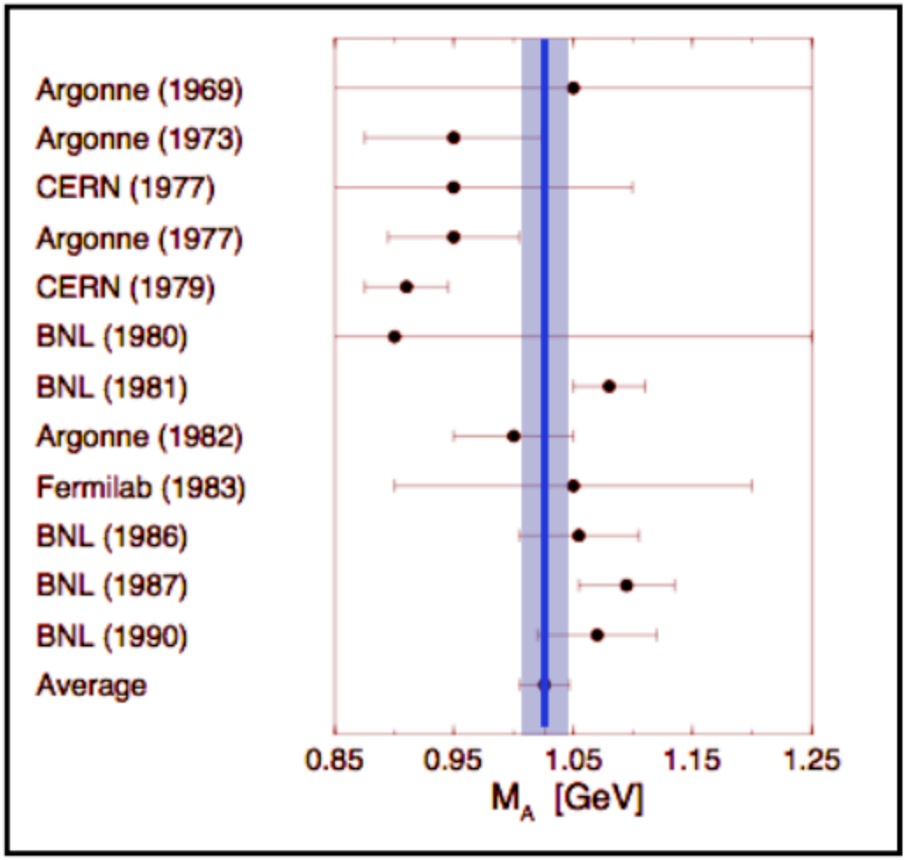
- With plenty of statistics taken (more than all events from all previous CCQE scattering experiments *combined!*), able to strongly comment on the muon scattering shape problem



- $\sigma(Q^2)$
- $\Phi(E_\nu)$

- Lines of data/prediction discrepancy generally follow lines of constant Q^2, not E_ν

M_A tension



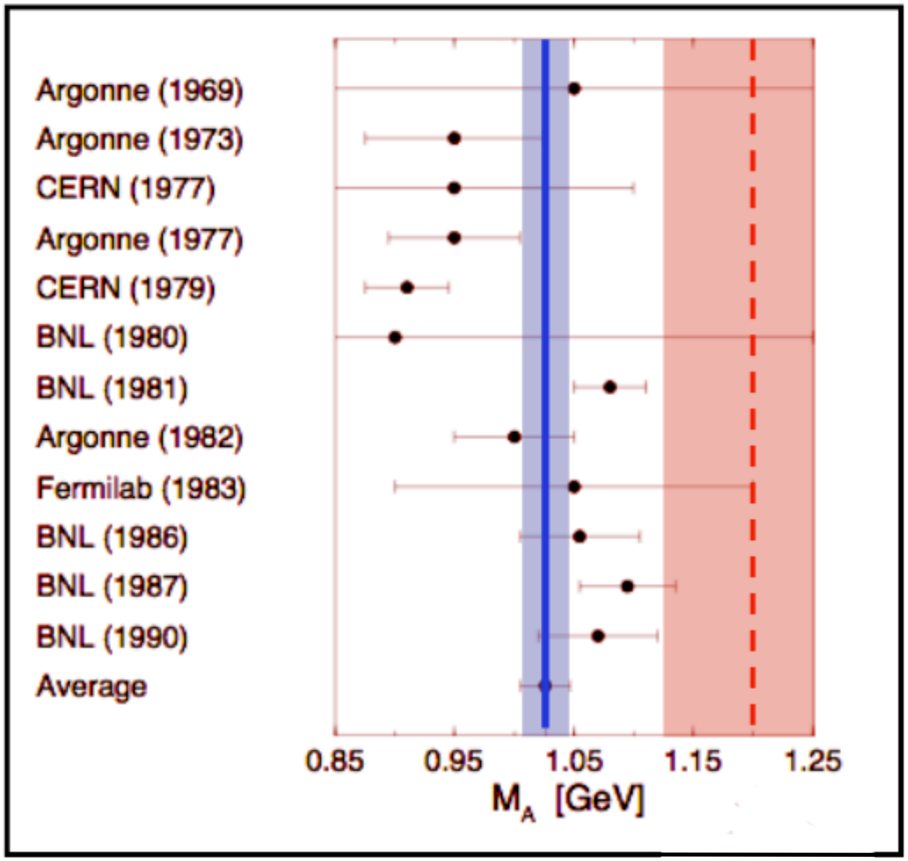
- M_A = 1.35 ± 0.17 GeV clearly disagrees with the measurements from light target data
- However…

M_A tension

arxiv: 1007.2195

Experiment	Target	Cut in Q^2 [GeV^2]	M_A[GeV]
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

TABLE I. Recent M_A measurements



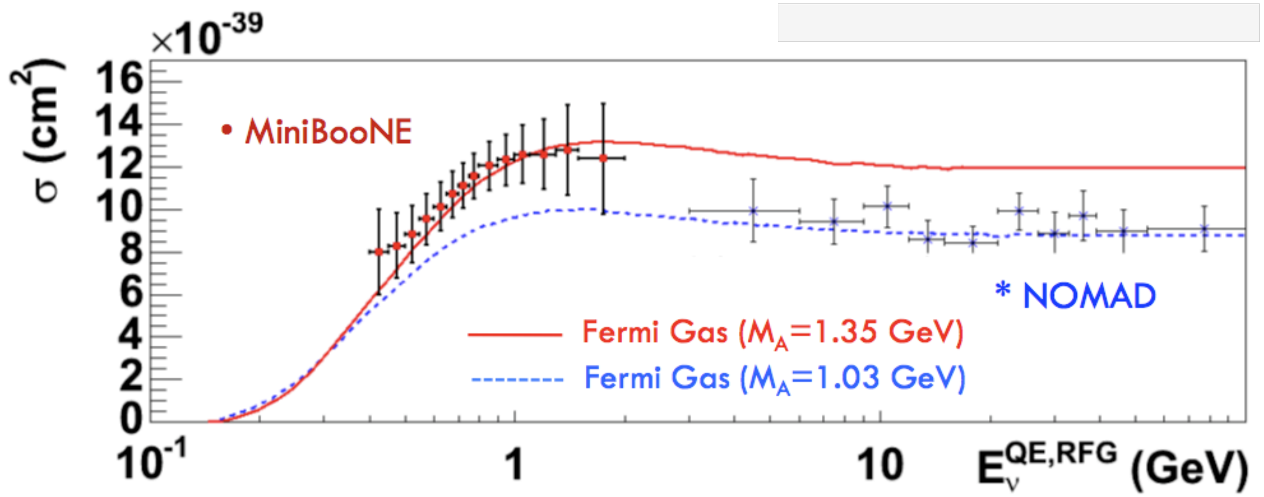
- More recent measurements have also observed higher values of M_A
- These measurements mostly from fitting Q^2 shapes
- M_A is important for overall normalization as well

Comparison to NOMAD

- NOMAD one of the few other neutrino σ measurements with absolute flux knowledge
  - Normalized from deep inelastic scattering (ν_μ + ^{12}C -> μ^- + X) and inverse muon decay (ν_μ + e^- -> μ^- + ν_e) events
- Same nuclear target as MiniBooNE (^{12}C), much higher energy, and absolute cross section measurement consistent with expectations!
- Detector technology + double-nucleon knockout mechanism may explain the discrepancy

NOMAD: μ + p

MiniBooNE: μ + no π's + any # p's

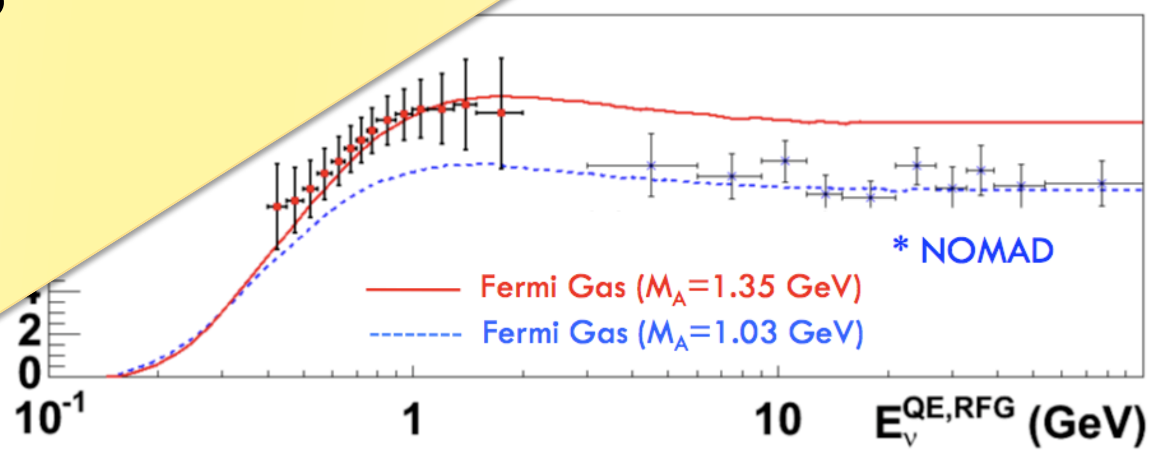


Comparison to NOMAD

- NOMAD one of the few other neutrino σ … bsolute flux knowledge
  - Normalized from deep inelastic s… rse muon decay (ν_μ + e^- -> μ^- + …
- Same nuclear targe… bsolute cross section …
- Dete… t…

  …
  m…
  exp…
  discre…

Beware experimental signal definitions!

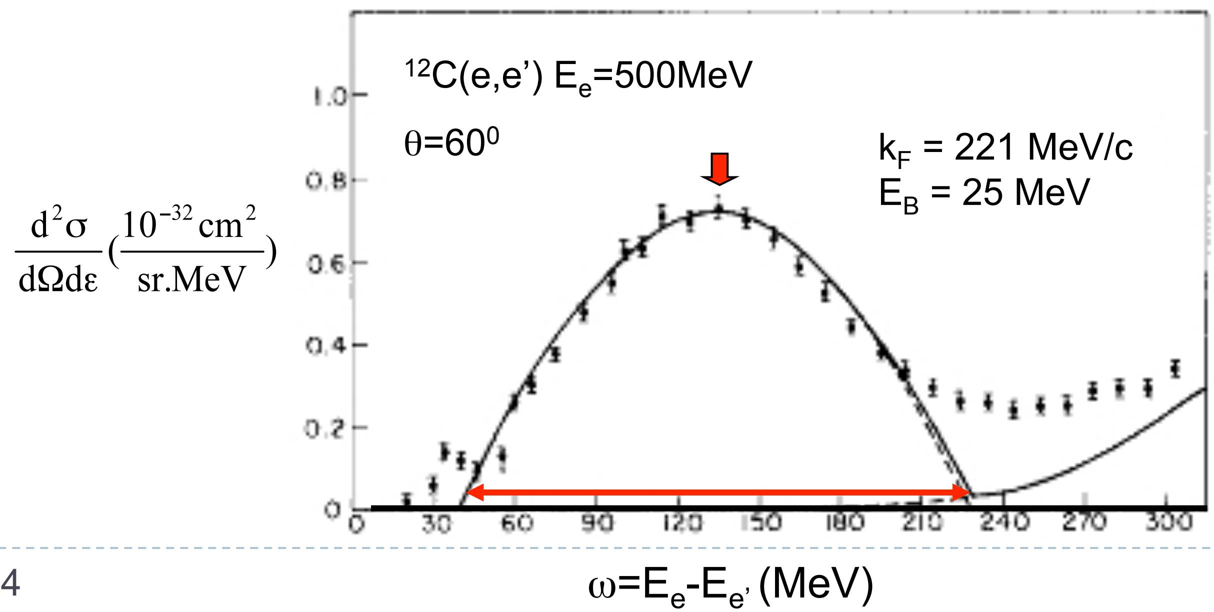


NOMAD: …

MiniBooNE: … no π's + any # p's

Determining E_B, k_F

- Electron scattering data on ^{12}C as a function of energy transfer informs both parameters:
  1. Peak of energy transfer distribution represents scattering off nucleons at rest. This position is shifted from the same position in free nucleon by the binding energy appropriate to (e,e') neutral current scattering
  2. Fermi momentum k_F set by the width of the distribution



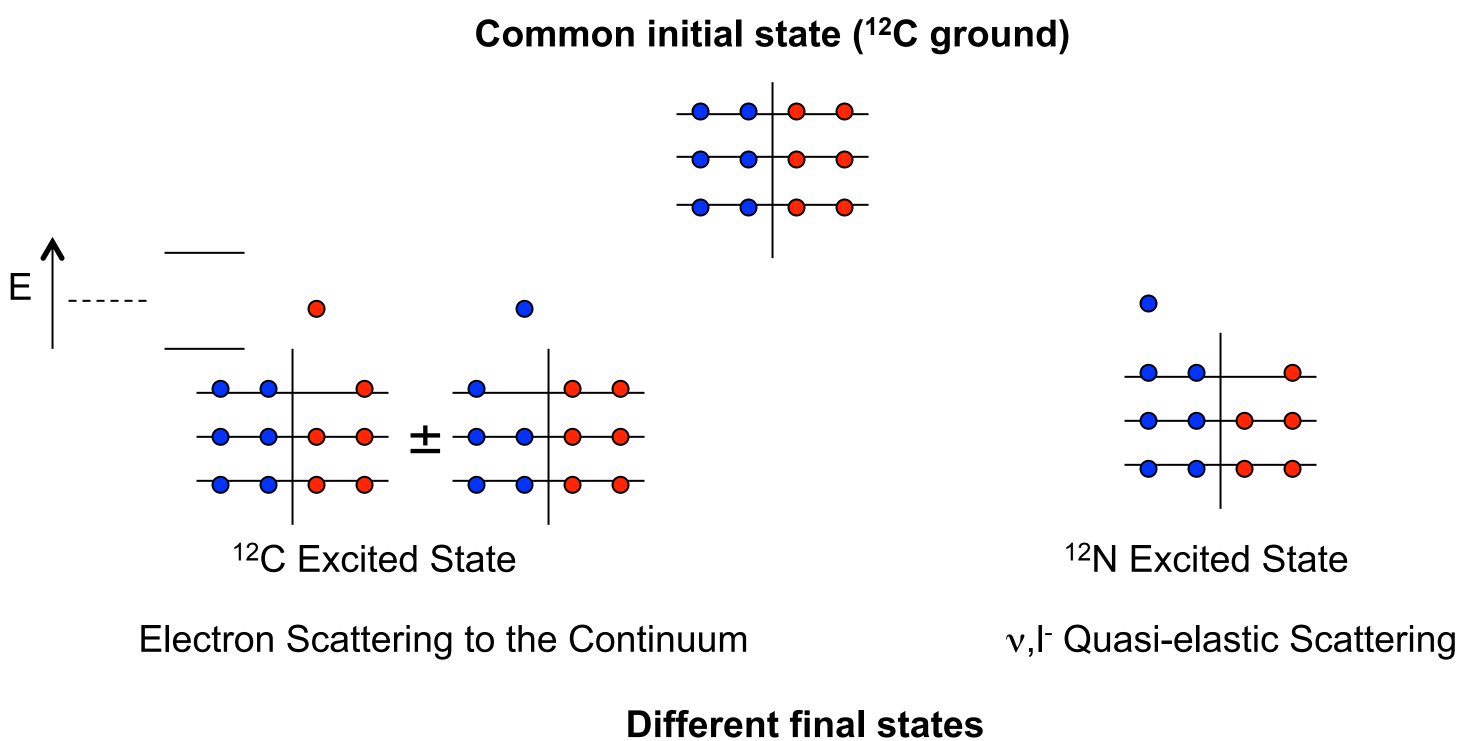
$\omega = \omega_{FN} - \varepsilon_b$

ie. $\mathbf{k}\cdot\mathbf{q} = 0$

Nucl. Phys. A402, 515 (1983)

Determining E_B, k_F

- E_B for neutrino charged-current (ν + N -> $l^{\pm}$ + X) interactions distinct from neutral-current (e + N -> e + N) E_B, as separation energy between final, initial states are different



Determining E_B, k_F

- How much different? The splitting can be estimated by the symmetry term in the semi-empirical mass formula:

$$E_s = 28(A-2Z)^2/A \ \ MeV$$

- E_S = 9 MeV for A = 12, Z = 7
  (for CC interactions with n -> p)

- E_B = 25 + 9 MeV = 34 MeV

(e,e') data — symmetry splitting