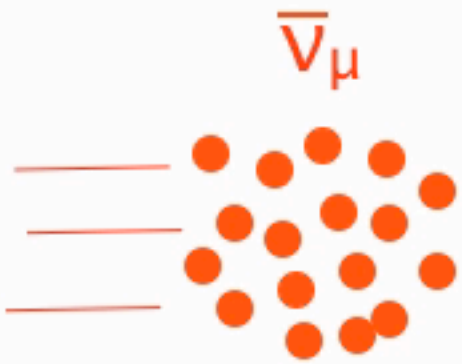
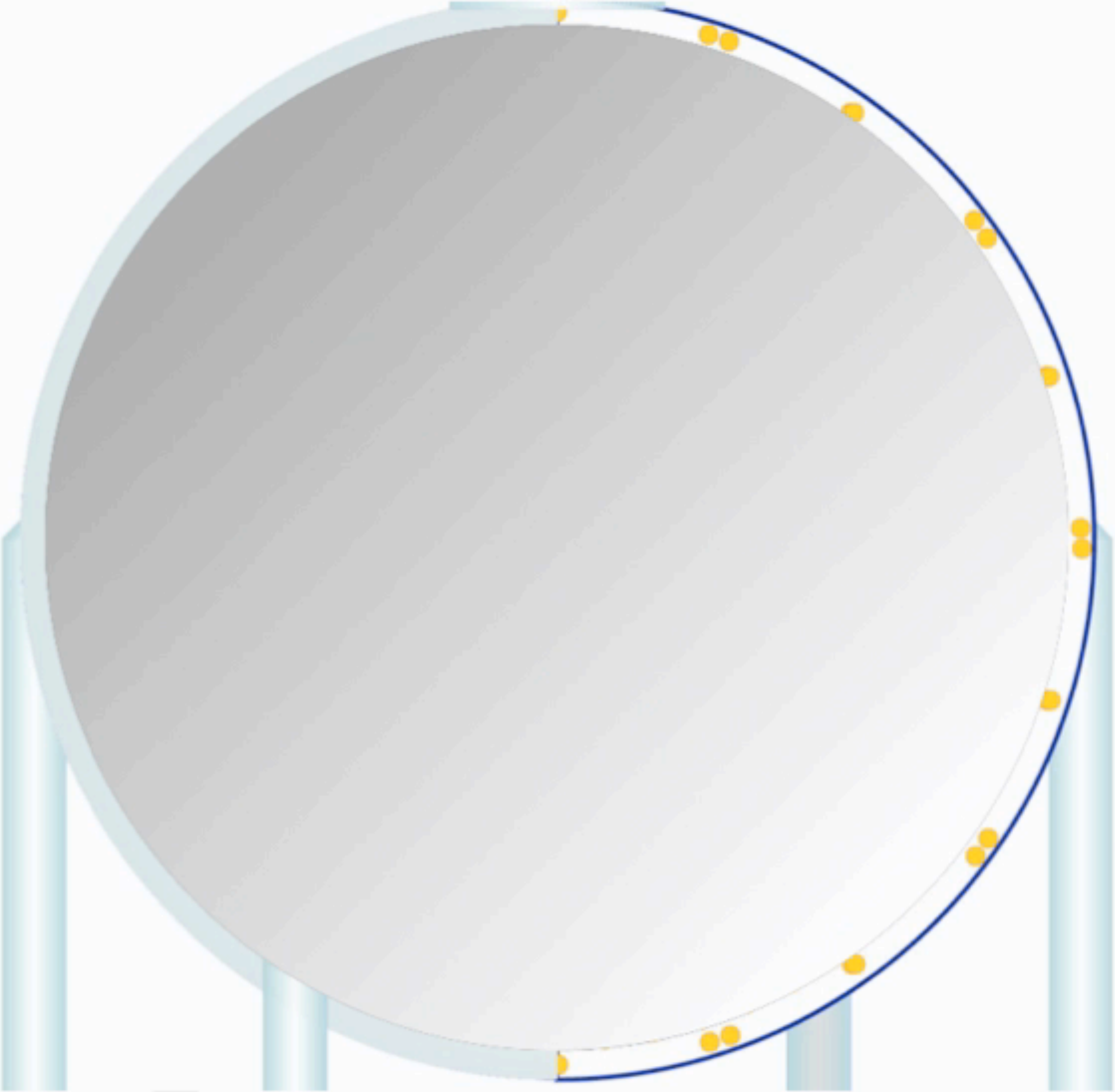
New Anti-Neutrino Cross Sections from MiniBooNE





Joe Grange
University of Florida
Joint Experimental-Theoretical Seminar
11/30/12

Outline

1. Introduction

ν cross sections in a single-detector oscillation exp't

recent σ interest from MiniBooNE neutrino-mode data

2. Anti-neutrino analyses

ν_μ background (wrong signs)

$\bar{\nu}_\mu$ CCQE σ (new!)

$\bar{\nu}_\mu$ NCE σ (new!)

3. Outlook and summary

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3. Outlook and summary

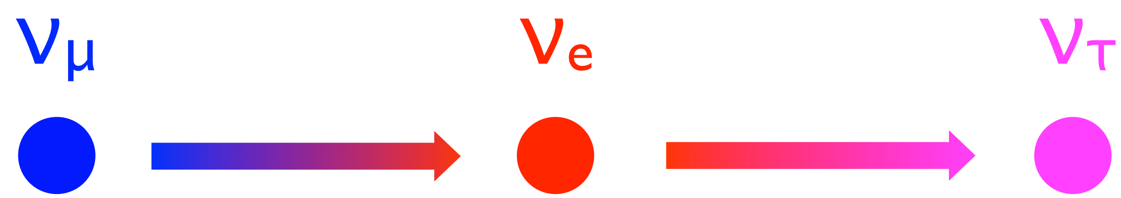
- Primary physics goal: neutrino oscillations, designed to test an anomalous signal in data from LSND

- Along the way our secondary physics goals of ν cross sections have become increasingly interesting

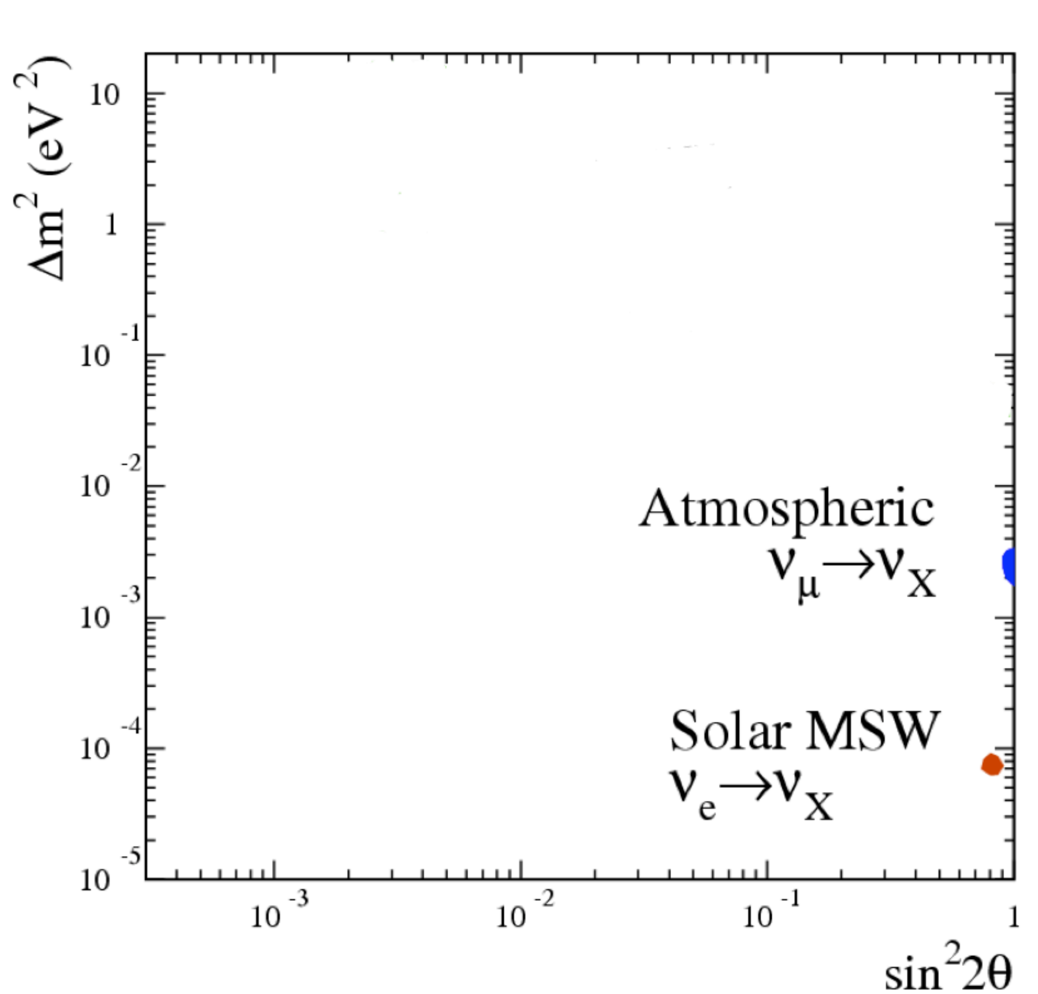
- Successful 10-year run, HUGE data set in both neutrino and anti-neutrino running (thanks AD!)

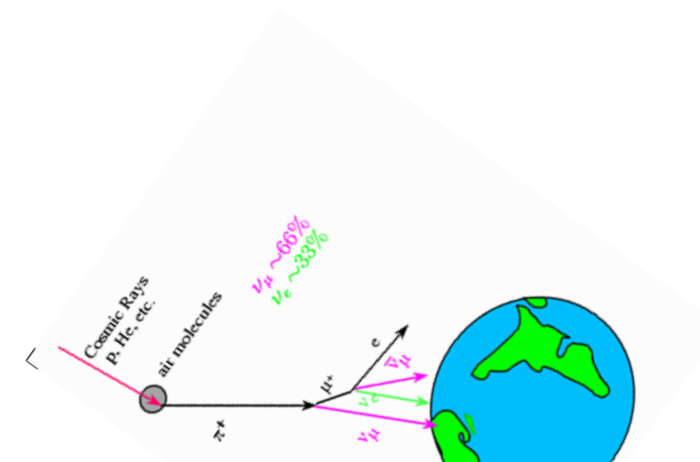
MiniBooNE crosses the finish line

- One of the few concrete results not predicted by the Standard Model: ν's oscillate!

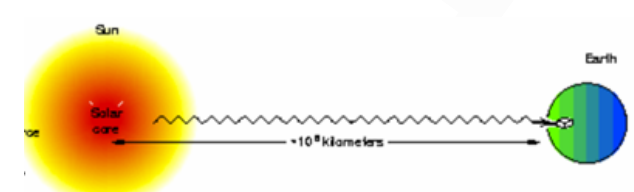


- In just the last 14 years, two independent mass splittings and three mixing angles have been confirmed
  - observations of both artificial and natural ν sources





Confirmation with Super-K, K2K and MINOS data



Confirmation with SNO, Kamland data

Why do we care?

- Two-neutrino approximation for ν_β to appear from a source of ν_α:

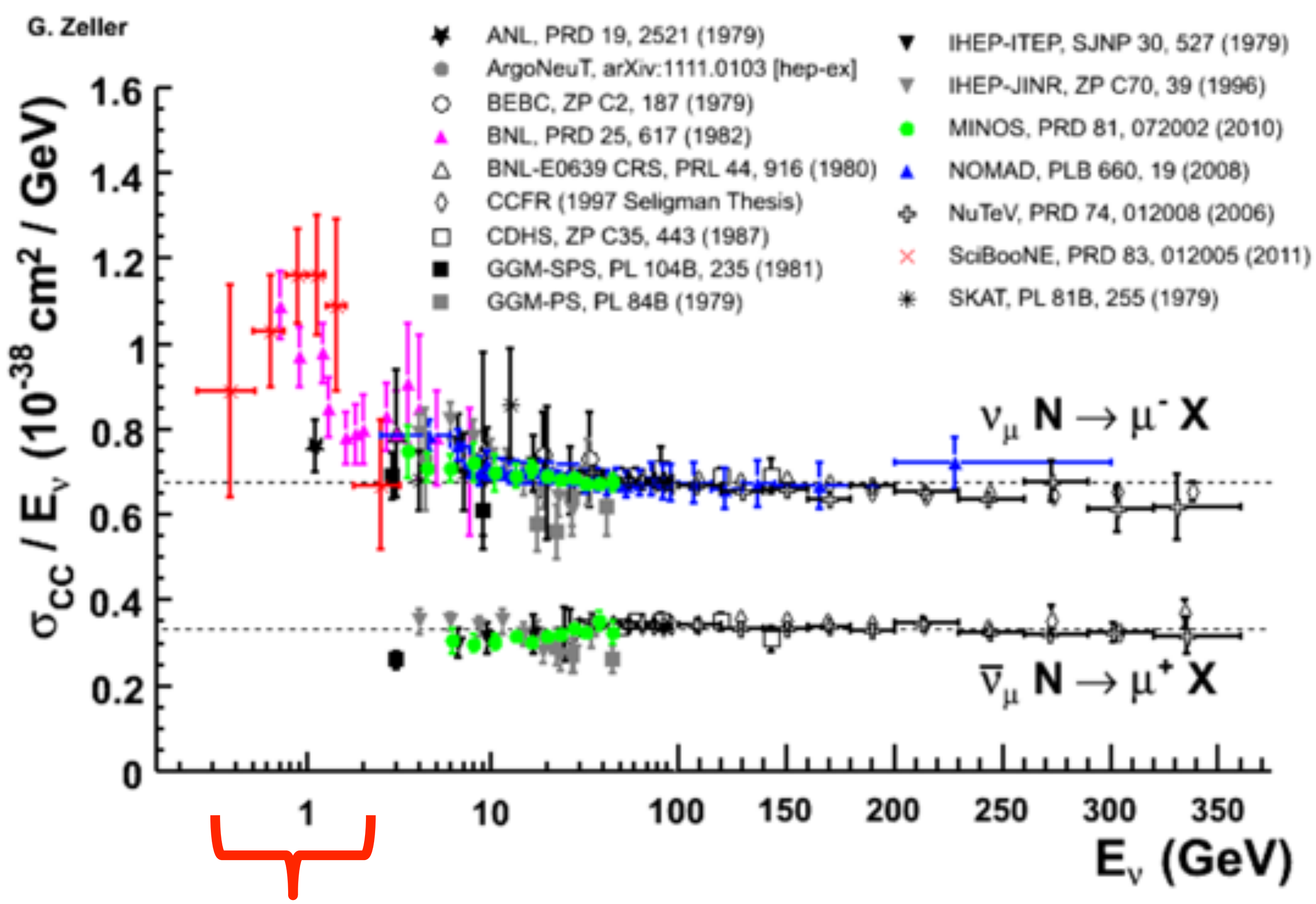
$$P(\underset{\alpha \neq \beta}{\nu_\alpha \rightarrow \nu_\beta}) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- (Of course) ν oscillations observed with analysis of ν interactions. To understand the rate (~θ) and the energy dependence (~Δm^2) of oscillations, must decouple their signature from ν flux and cross-section effects (typically each are also energy dependent!)

- If ν source is artificial, spectrum usually constrained by using two-detector setup, one close to the source to constrain the nominal rate as $f(E_\nu)$, one placed at a distance affording sensitivity to the (Δm^2,θ) of interest

Single-detector expt's

- If second detector not available, can still make appearance (ν_e) measurements based on constraints from control sample (ν_μ)
  - MiniBooNE analysis strategy, also currently the favored LBNE phase 1 config.
- Single-detector expt's naturally more sensitive to ν cross sections. MiniBooNE observes ν_μ beam of ~GeV. Modern CC inclusive cross section knowledge:

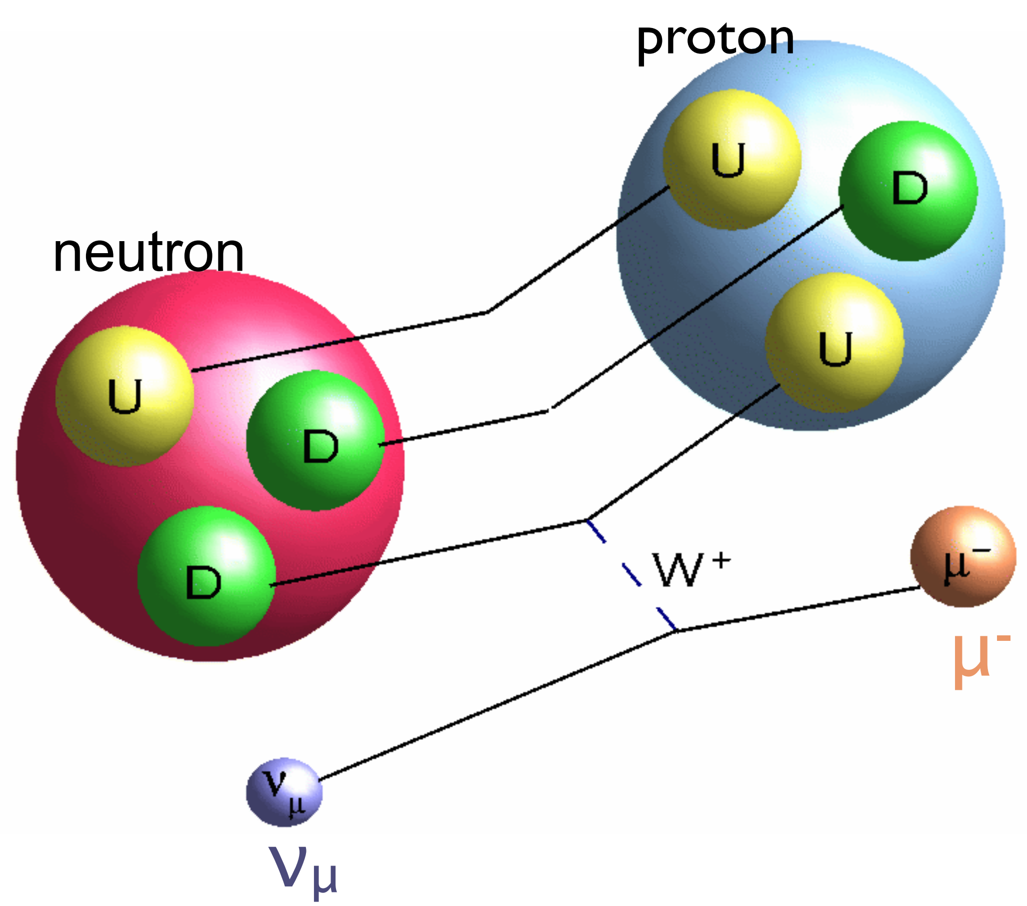


- Sparse and uncertain measurements!
  - Particularly for $\bar{\nu}$'s - first $\langle E_{\bar{\nu}} \rangle < 1$ GeV charged current σ today!

MiniBooNE range

CCQE - the golden channel

- Due to simple multiplicity and ability to reconstruct ν energy based solely on lepton kinematics, charged current quasi-elastic interactions are the preferred channel for osc. measurements



MiniBooNE only reconstructs outgoing μ

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

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

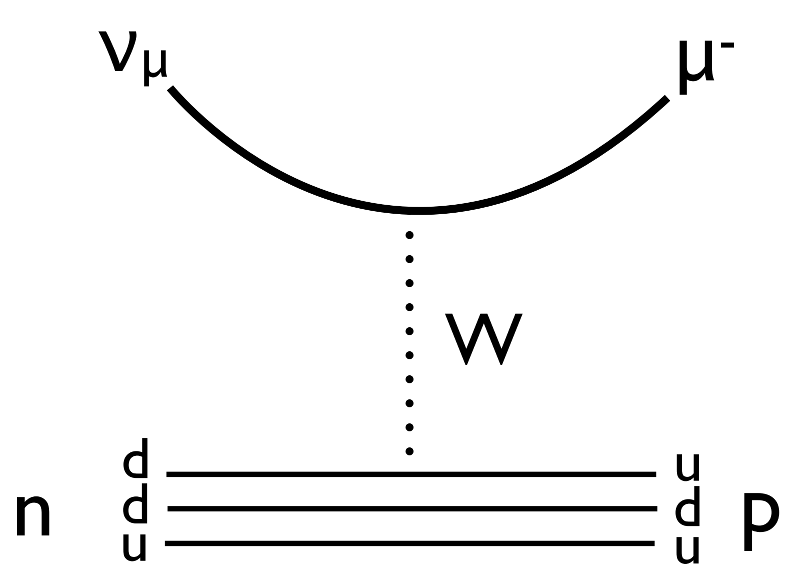
- E_ν recovery assumes interaction with at-rest, independently acting nucleons, regardless of nuclear material

CCQE Expectations

- Expectation starts with calculation for free nucleons: Phys. Rep. 3, 261 (1972)

$$\frac{d\sigma}{dQ^2}\begin{pmatrix} \nu_l + n \to l^- + p \\ \bar{\nu}_l + p \to l^+ + n \end{pmatrix} = \frac{M^2 {G_F}^2 cos^2\theta_c}{8\pi {E_\nu}^2}\left\{A(Q^2) \pm B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right\}$$

- Using CVC, vector and tensor form factors measured in (e,e') data



- Axial form factor F_A typically assumed to have dipole form

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

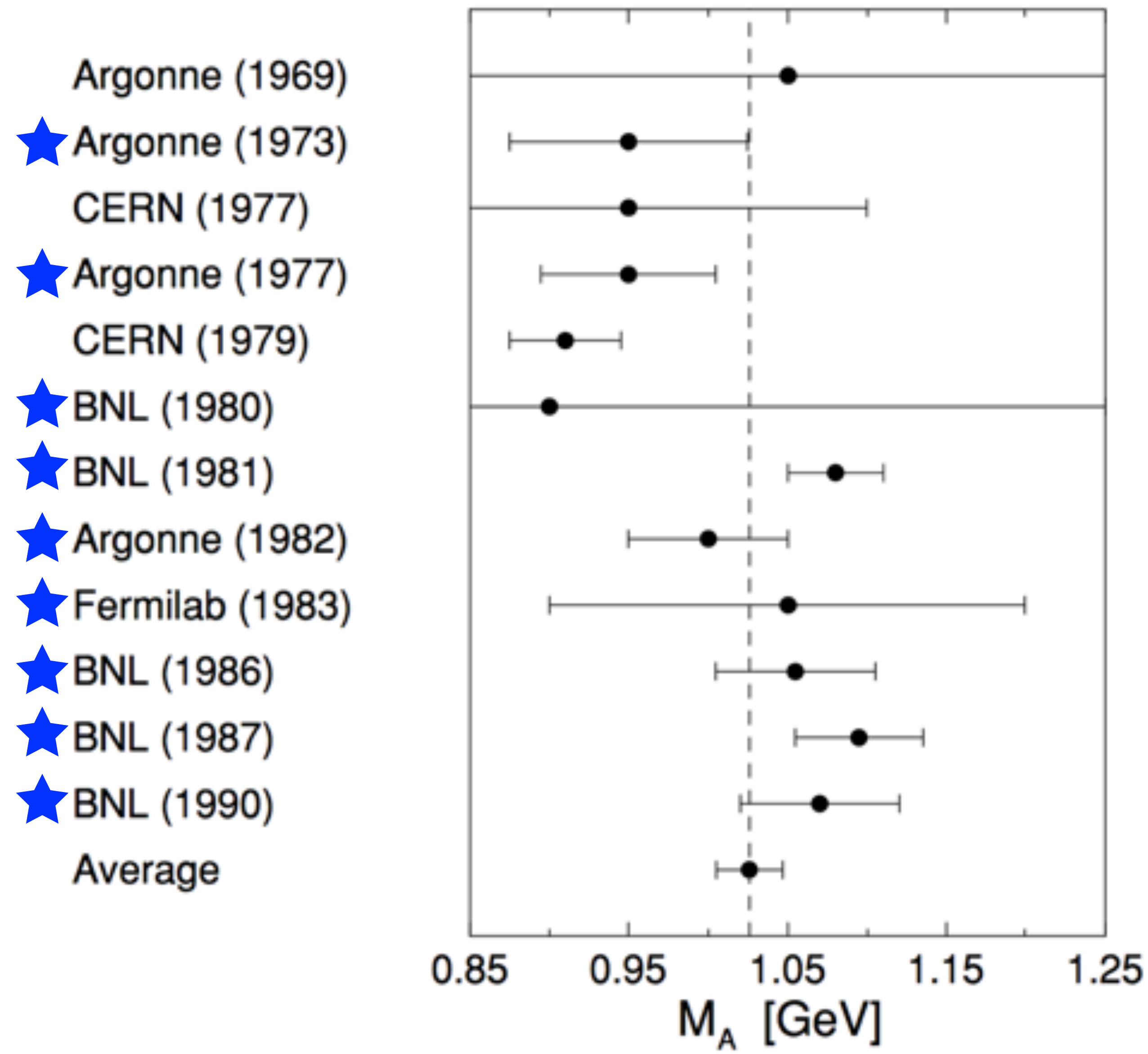
- g_A measured from β decay, that leaves axial mass M_A to be determined

M_A Measurements

- M_A measured for decades in ν scattering on mostly Z = 1 targets with a variety of techniques
  - both total cross section and shape of Q^2 strongly influenced by M_A

★ H or ^2H

- Global average to these data find M_A = 1.03 ± 0.02 GeV
  - fit driven by light-target expt's
- With discovery of ν oscillations (1998), suddenly require nuclear targets to get higher rates needed to nail osc. physics



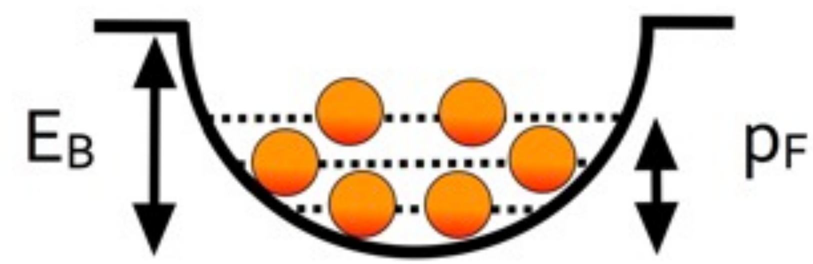
Bernard et al 2002 J. Phys. G: Nucl. Part. Phys. 28 R1

Put it in a nucleus - ^{12}C

- MiniBooNE (and everyone else) uses the Relativistic Fermi Gas model (RFG)

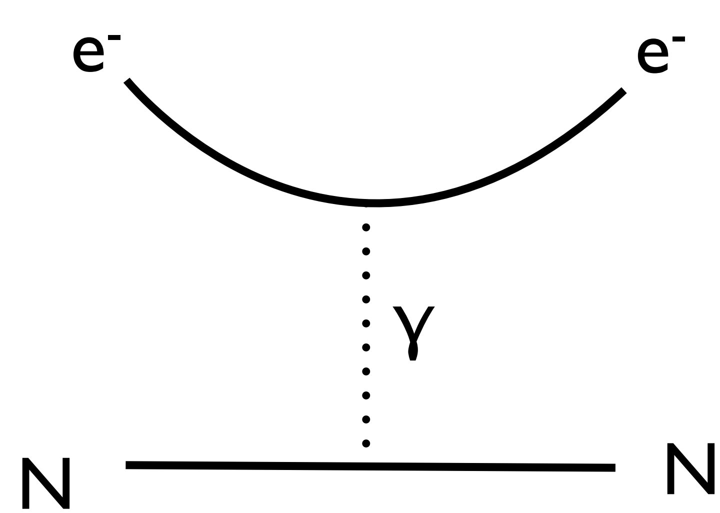
  Nucl. Phys. B43, 605 (1972)

  - Models nucleons as independent, quasi-free particles bound by a binding energy E_B
  - All outgoing nucleons subject to Pauli blocking. Enforced by a global Fermi momentum p_F



G. Perdue

- Electron scattering data on ^{12}C informs both E_B, p_F



That's it!

- RFG combines bare nucleon physics with a potential energy well and Pauli blocking.
  - treats all spectator nucleons as entirely passive - nature may be much more interesting!

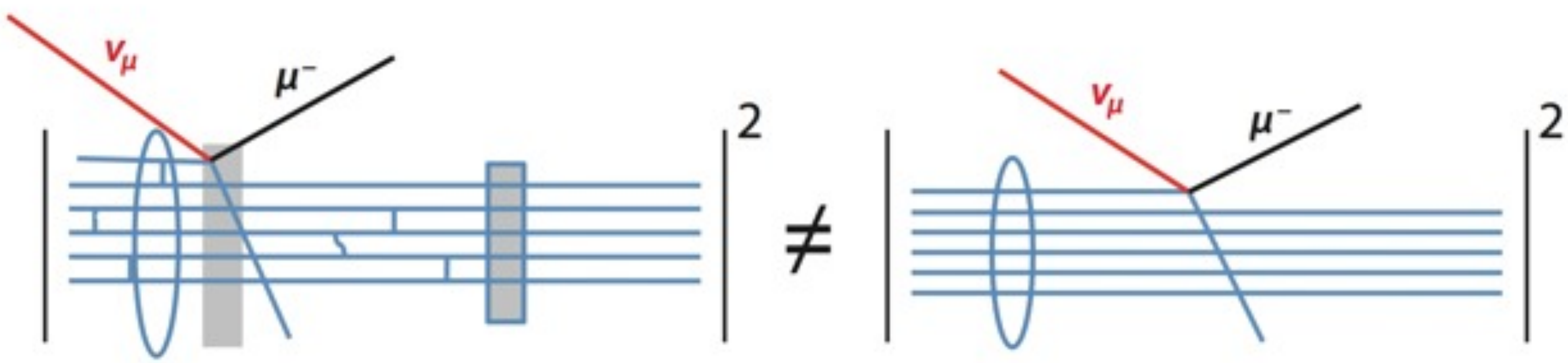


Fig. from Ann. Rev. Nucl. Part. Sci. 2011. 61:355–78

- We've seen evidence in recent years that this model is incomplete for GeV ν scattering in a nuclear environment

Early days of MiniBooNE

- Subsequent to understanding detector response and verifying reconstruction algorithms on variety of calibration data, we found surprises in this ν_μ CCQE channel (recall understanding this interaction is crucial for the ν_e appearance analysis)

1. Once a flux prediction obtained from dedicated hadroproduction data (more later), a 30% excess found relative to RFG

2. Disagreement in μ kinematics

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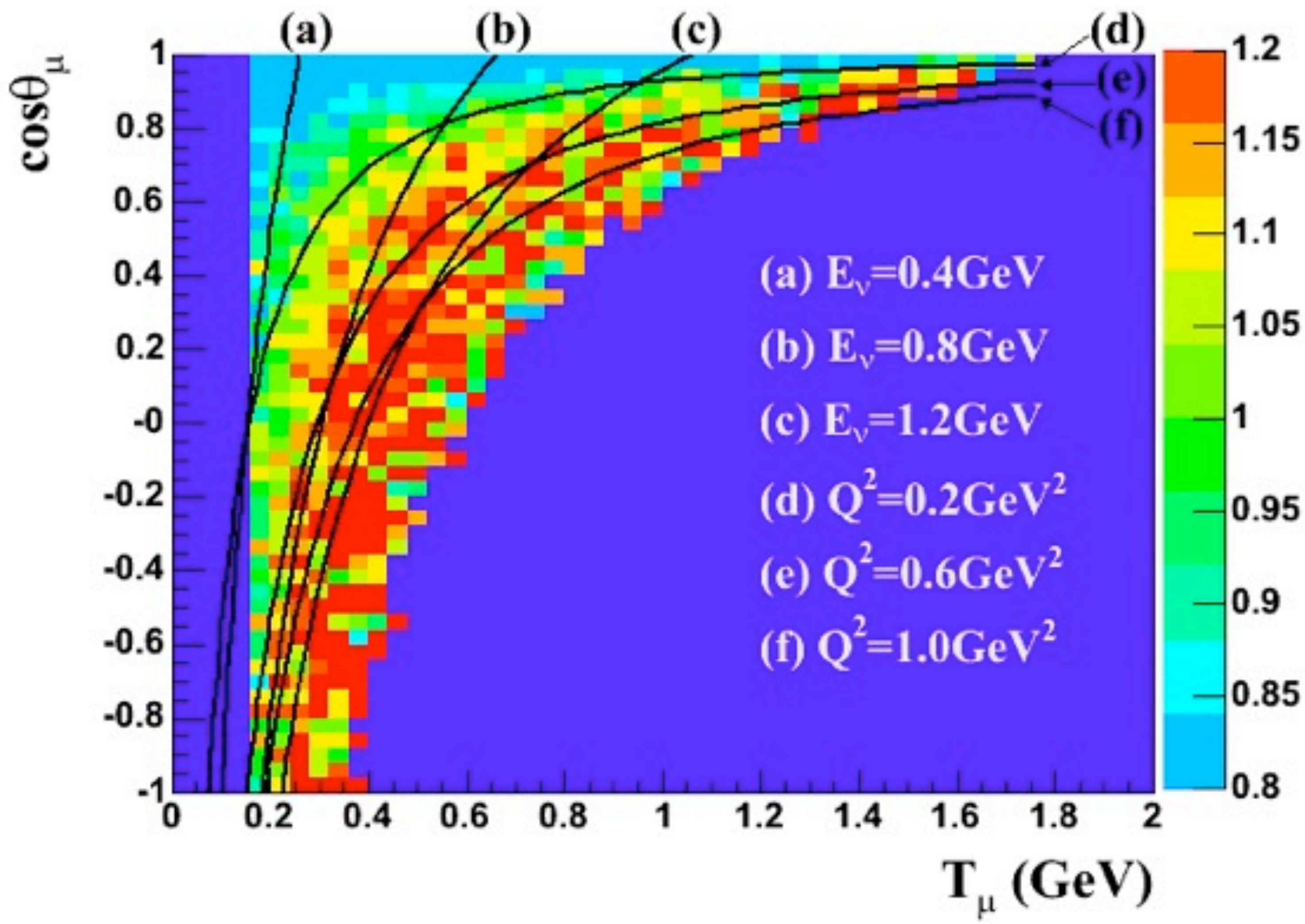
2. Disagreement in μ kinematics

Implies cross section is the likely culprit

μ kinematics

- With more than 10x statistics of previous CCQE measurements *combined,* MiniBooNE can look at kinematics with unprecedented precision

data/RFG



(broadly)

✳ $\Phi(E_\nu)$

✳ $\sigma(Q^2)$

- Lines of kinematic discrepancy follow lines of Q^2, not E_ν

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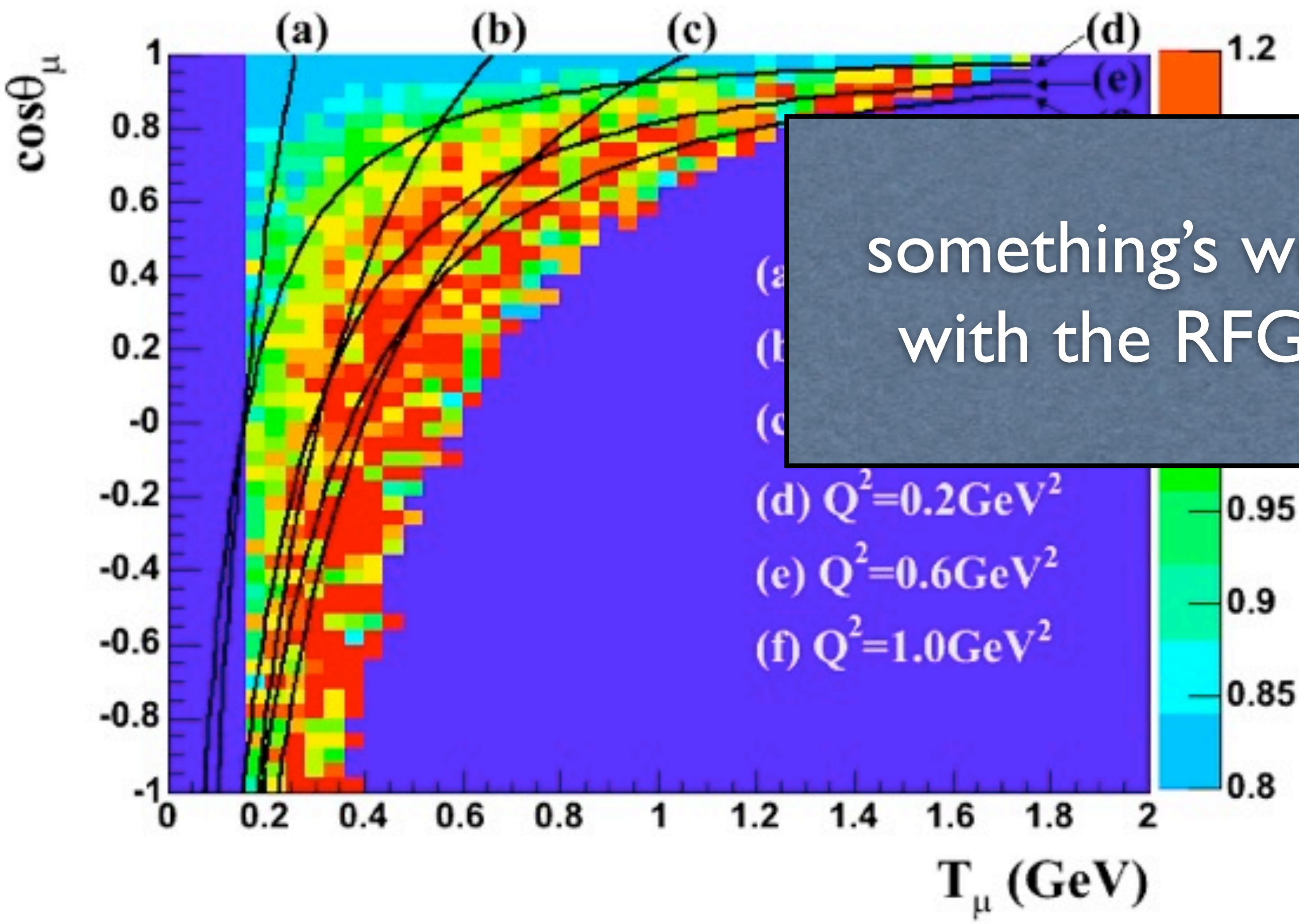


something's wrong with the RFG σ!

(broadly)

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

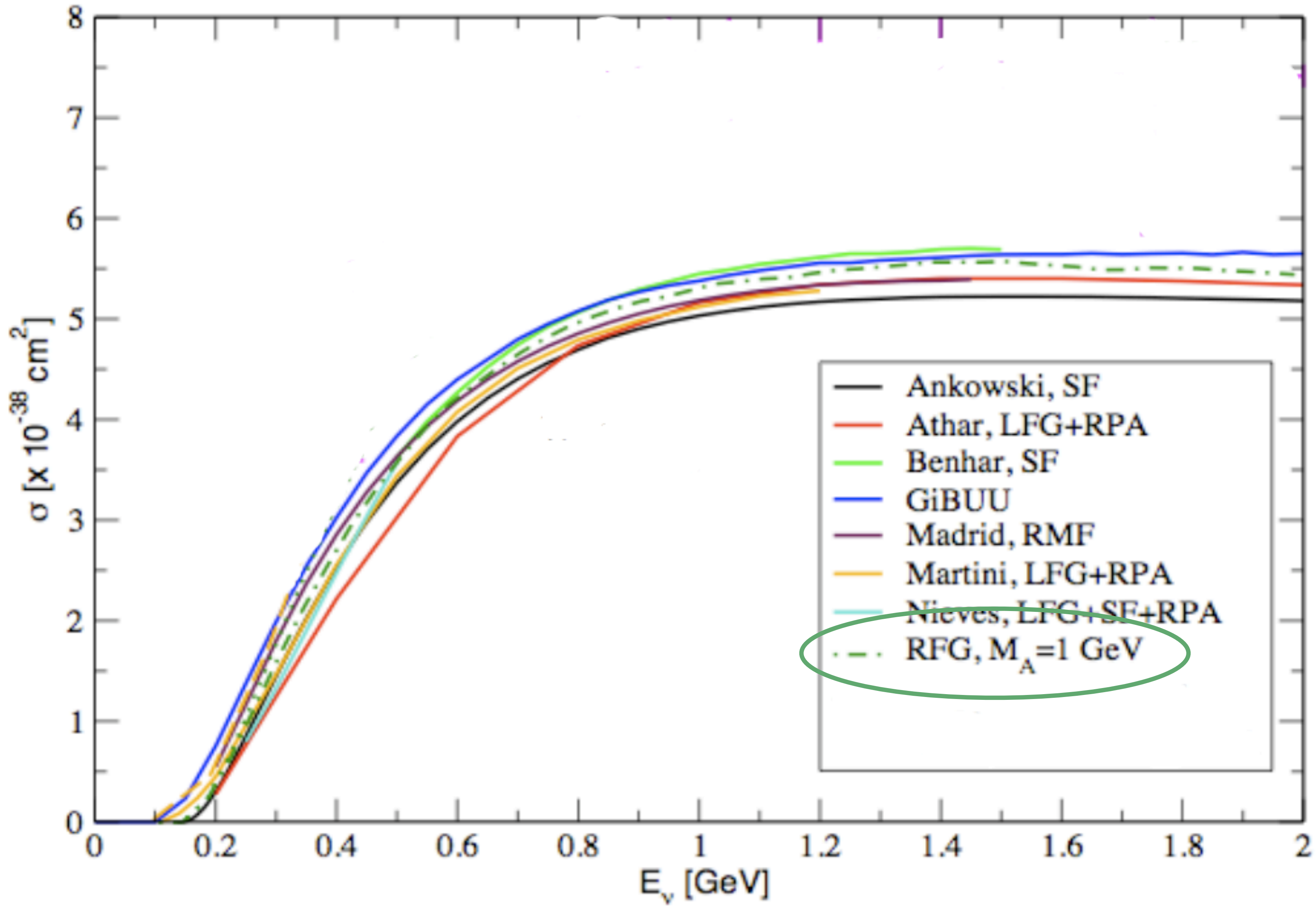
- Lines of kinematic discrepancy follow lines of Q^2, not E_ν

Looking for alternatives

- With the admission the RFG may be insufficient, we look to more modern calculations

- Find general theory consensus that RFG with $M_A \sim 1$ GeV is about right
  - at least for the total σ

- In fact, most modern models predict nuclear effects *suppress* the σ, not enhance it!

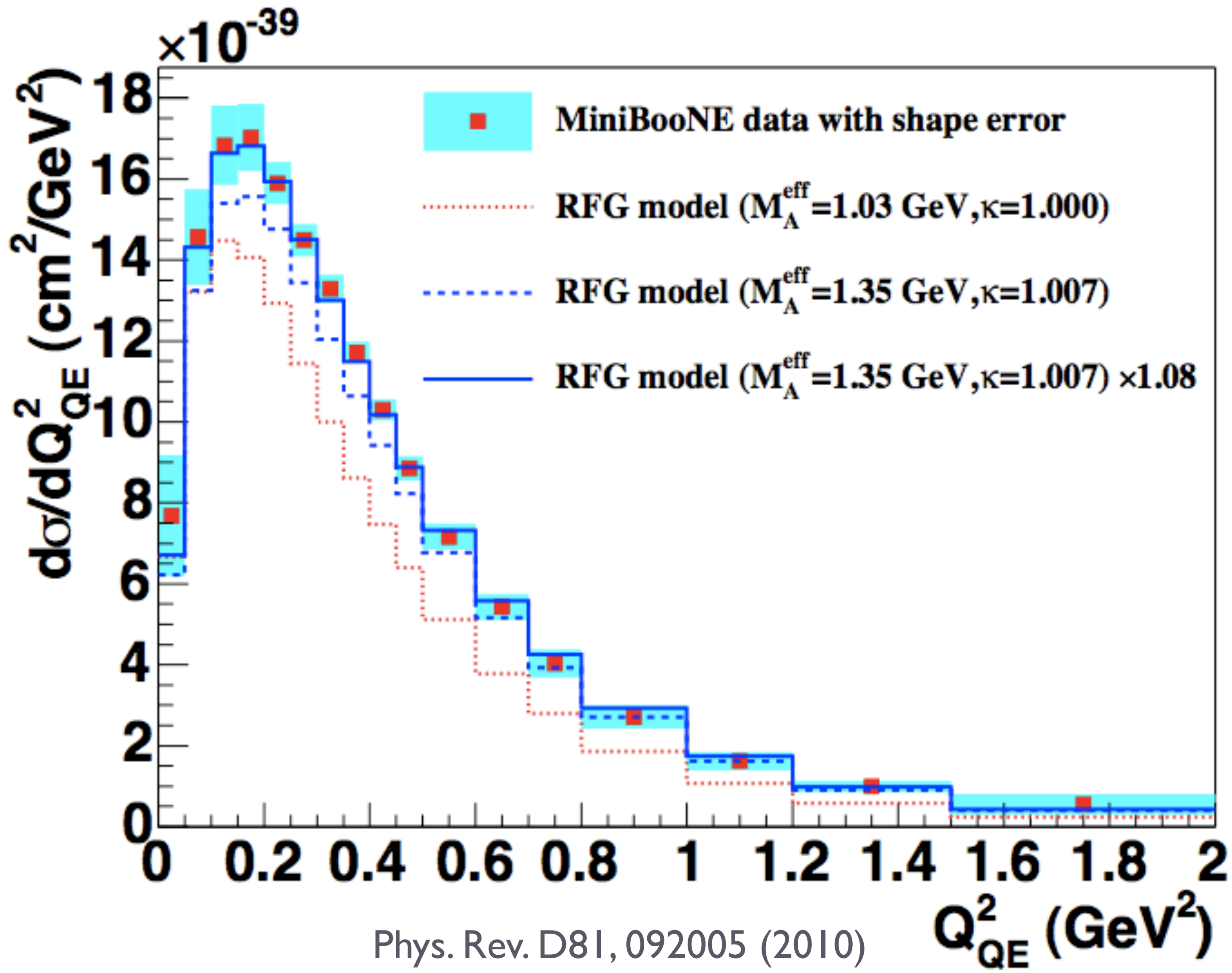


Finding a "solution" within the RFG

- Need to reproduce observed ν_μ CCQE in simulation to obtain a reliable ν_e CCQE prediction

➡ Tuned M_A and an empirical Pauli blocking scale κ

M_A = 1.35 ± 0.17 GeV



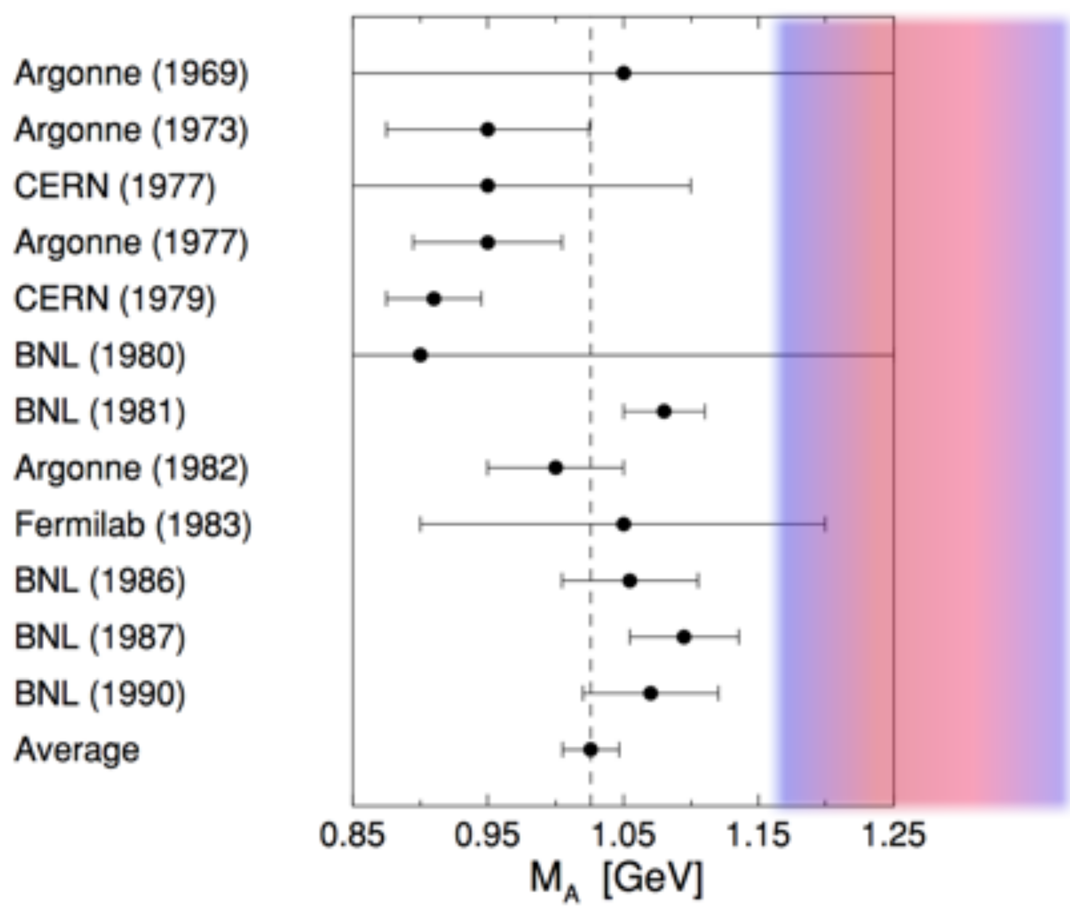
Phys. Rev. D81, 092005 (2010)

This simultaneously fixed the muon kinematics problem *and* provided agreement with measured event rates

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

Axial Mass Tension

- M_A ~ 1.3 GeV clearly disagrees with previous data, but MiniBooNE not alone in finding this tension



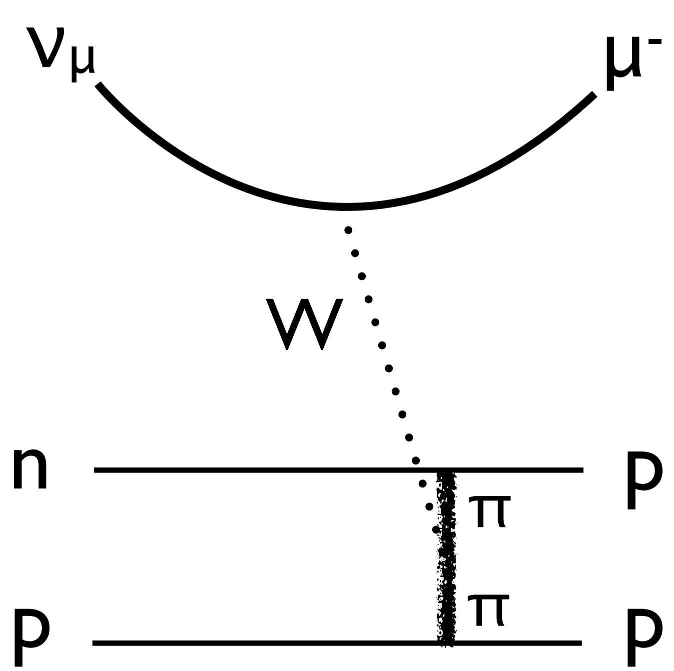
Experiment	Target	Cut in Q^2 [GeV^2]	$M_A[GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut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

Maybe the physics model is wrong?

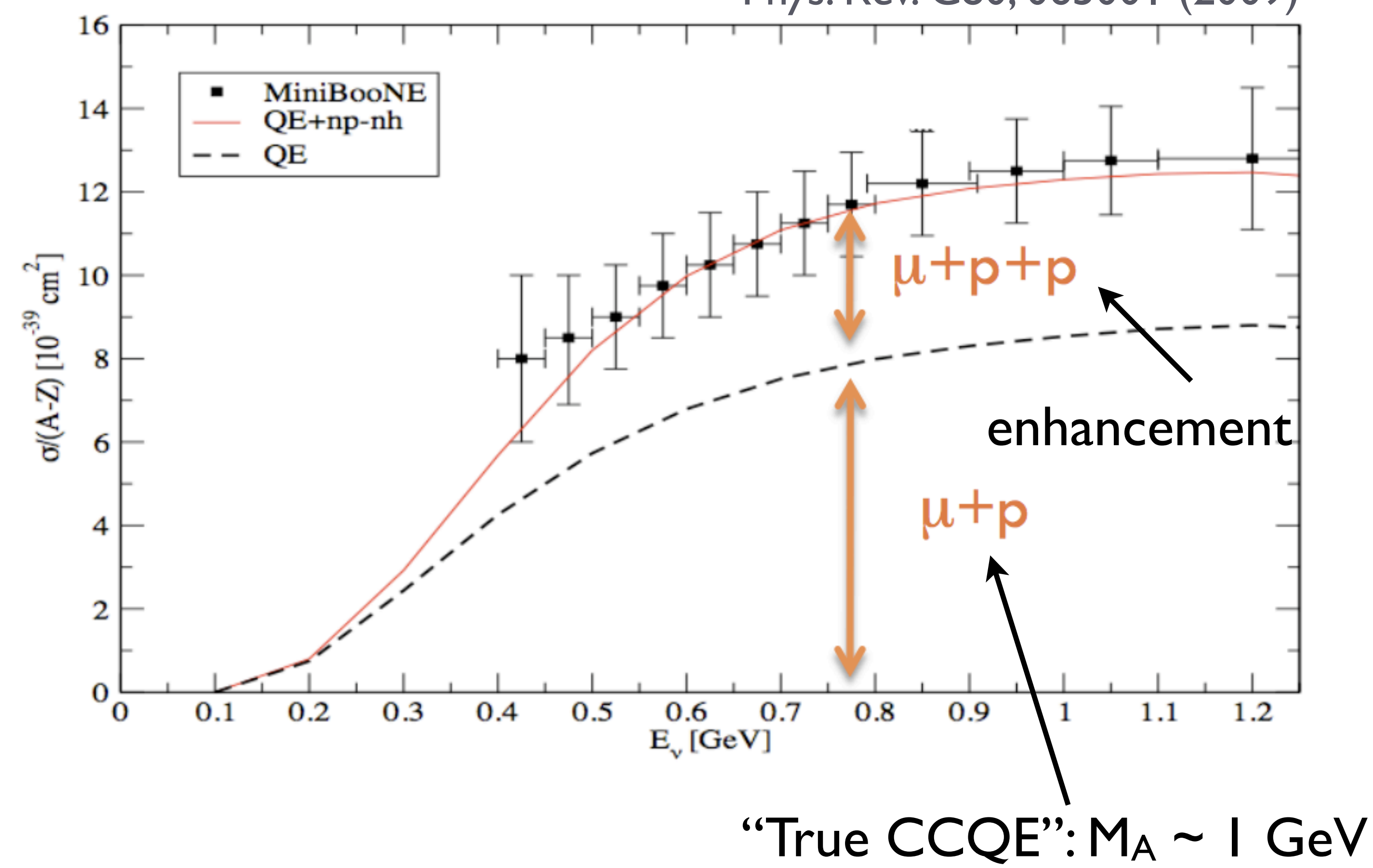
- Published double-differential $\sigma(T_\mu, \theta_\mu)$, asked theorists for help

New interaction?

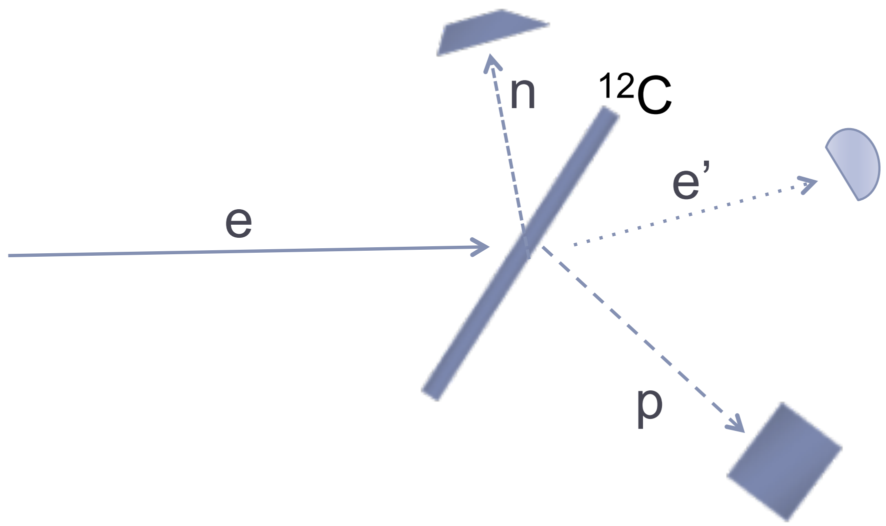
- 2009, first group to propose unification of apparently discrepant data sets Martini *et al.*
- Nuclear correlation effects in ^{12}C result in a large enhancement
  $(\nu_\mu + [n+p] \rightarrow \mu^- + p + p)$
  not present in light target experiments and indistinguishable from "true CCQE" in MiniBooNE
  - no selection on outgoing nucleons

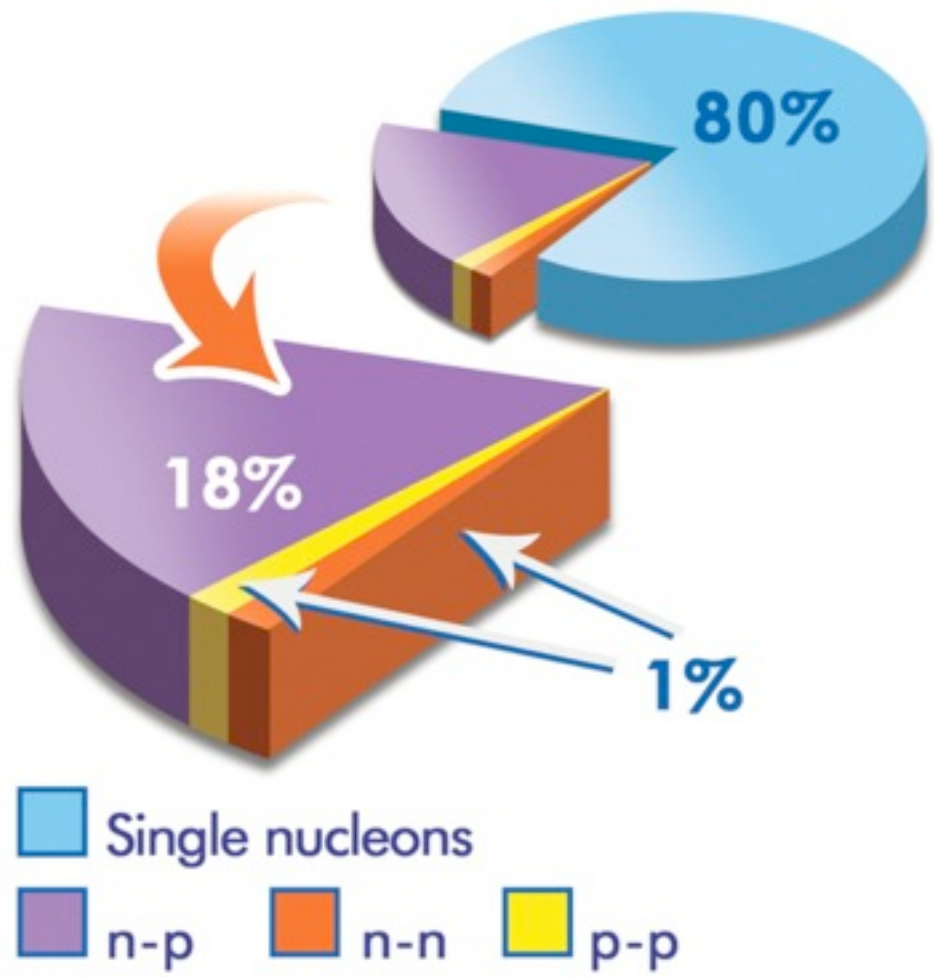


Phys. Rev. C80, 065001 (2009)



- JLAB observed analogous process in electron scattering data





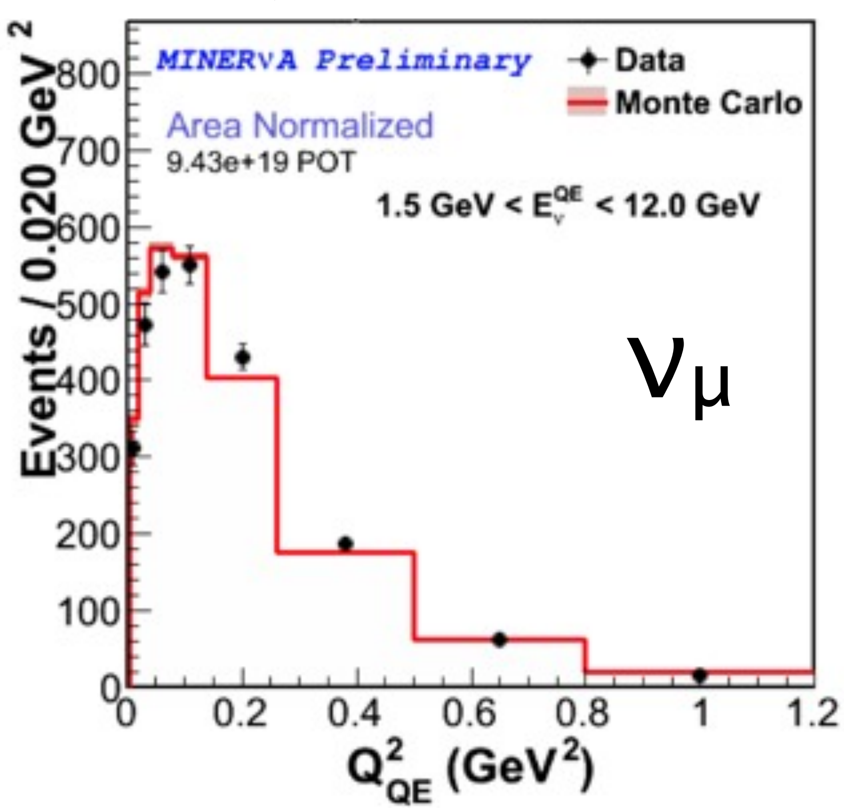
Science 320, 1476 (2008)

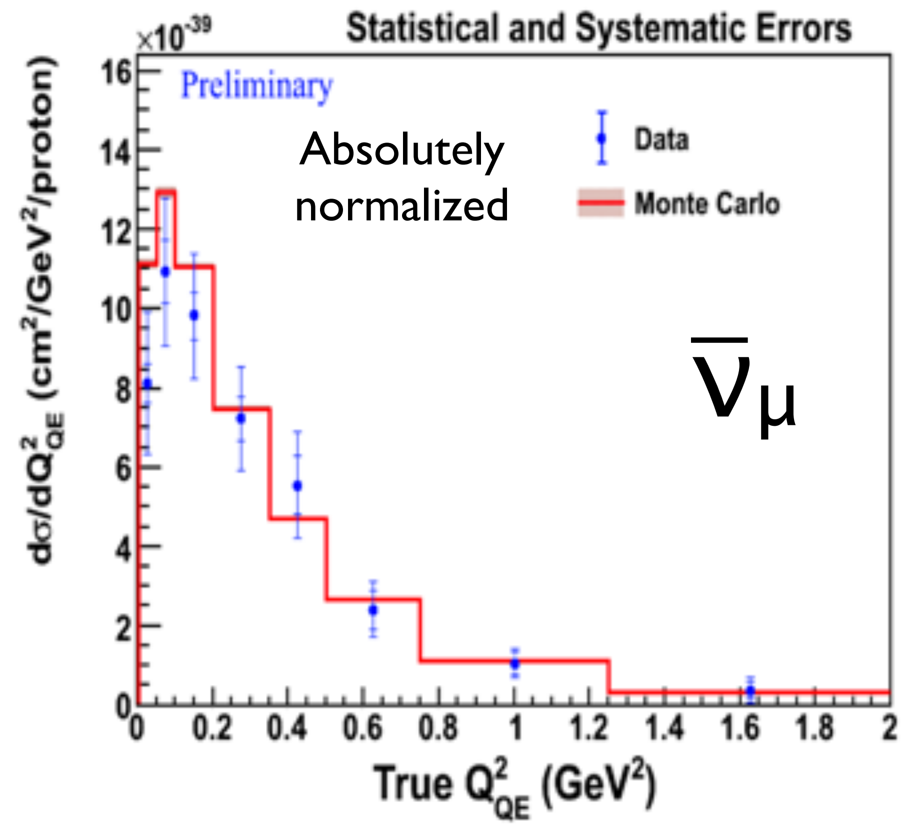
- Nothing like this included in RFG!
- Something like this *should* be in ν scattering as well
  - *at least* in the vector piece
- Some attempts to describe connection to ν scattering. Axial enhancement?

- No hint of this process in recent ^{12}C experiment NOMAD: measured $M_A \sim 1$ GeV with ~ 5% error for both ν_μ and $\bar{\nu}_\mu$

- Similar for recent MINERνA data: prelim. analyses for ν_μ, $\bar{\nu}_\mu$ events suggest $M_A \sim 1$ GeV is sufficient

L. Fields, NuInt2012

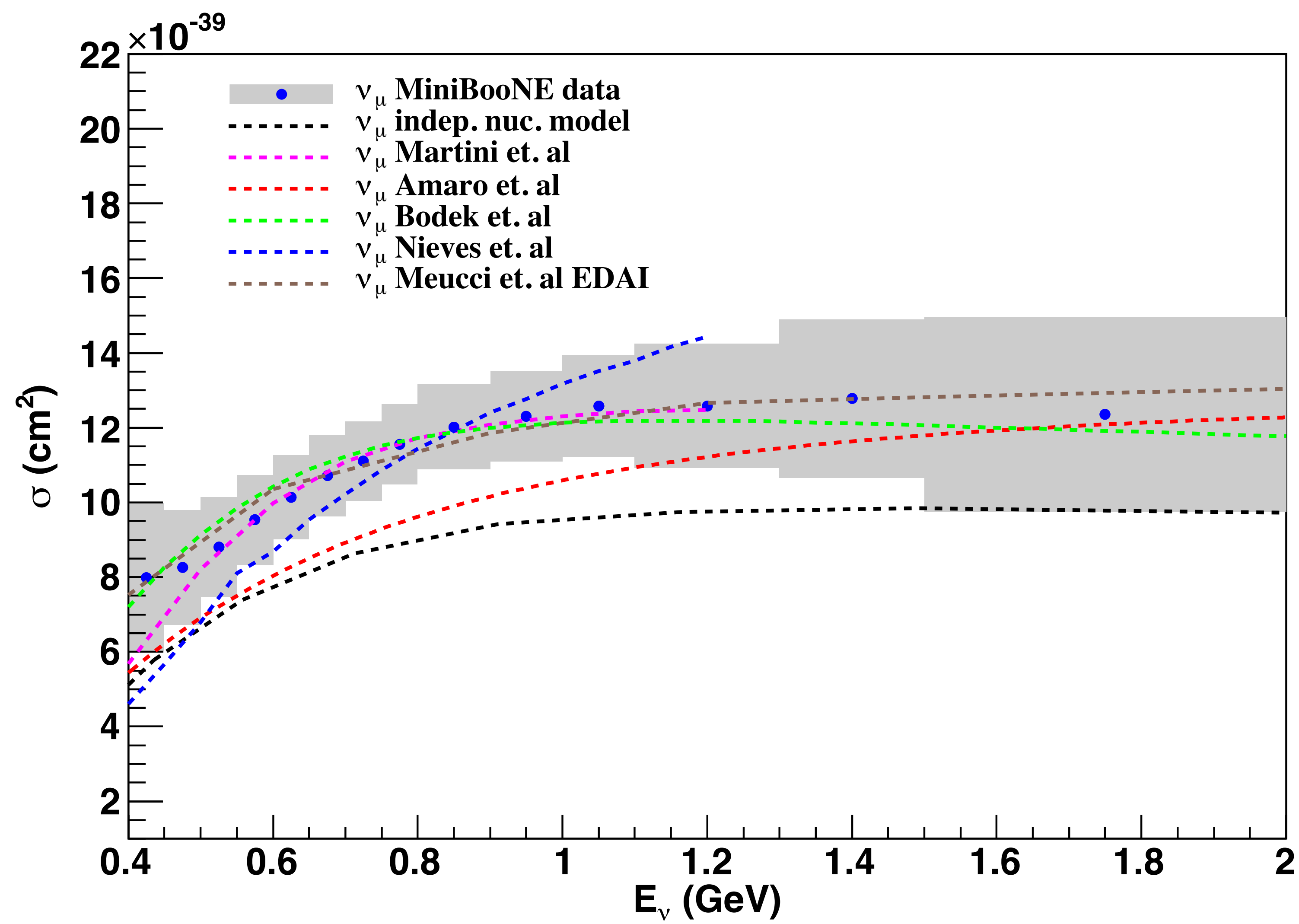




- Trouble in comparing results: different energy ranges, different detector technologies, selection criteria, etc.
  - have seen only a few calculations for correlated scattering > 2 GeV

- 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 available with anti-neutrinos
  - probes a different mix of axial, vector σ pieces. How might this new process contribute to anti-neutrino CCQE in MiniBooNE?



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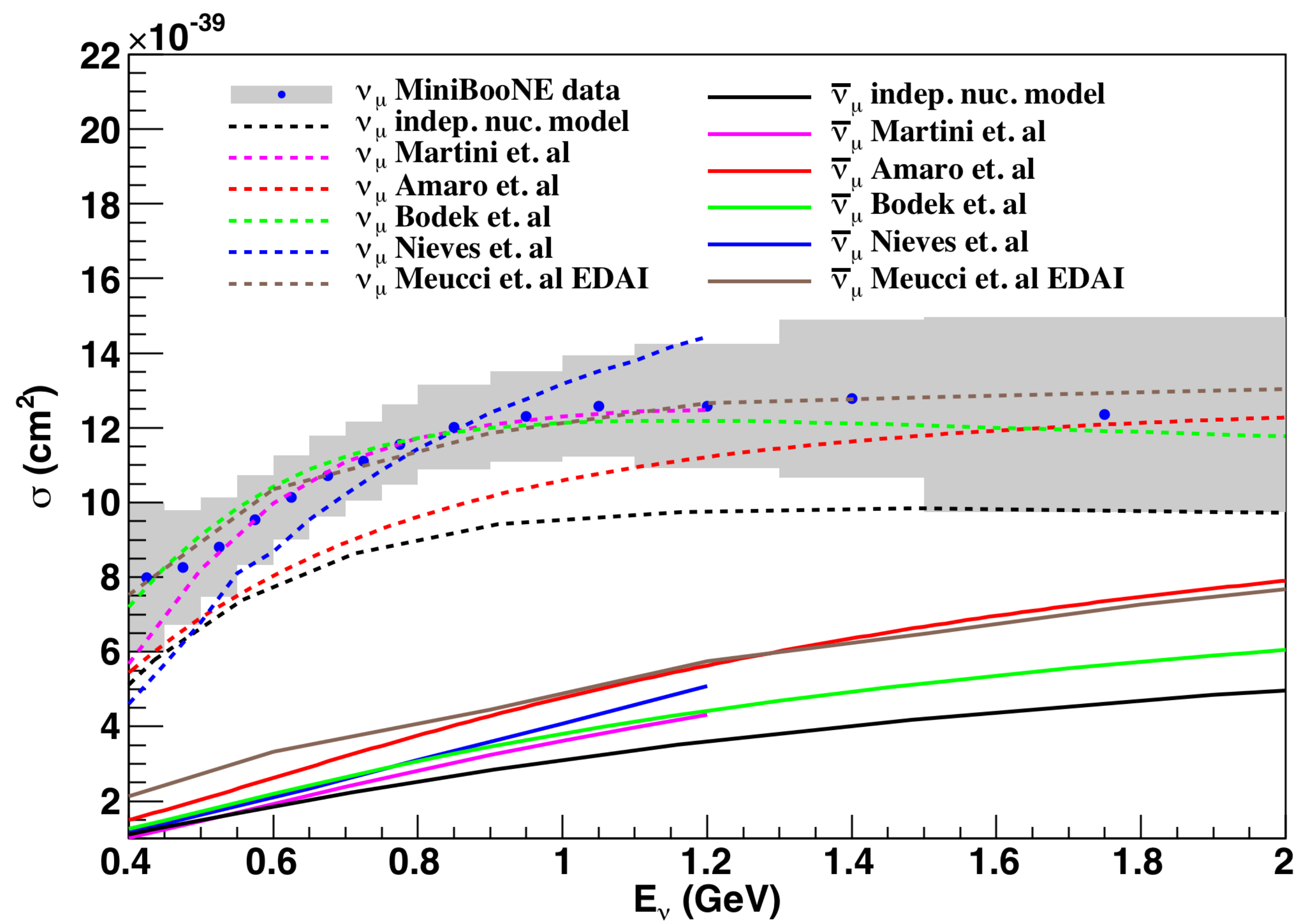
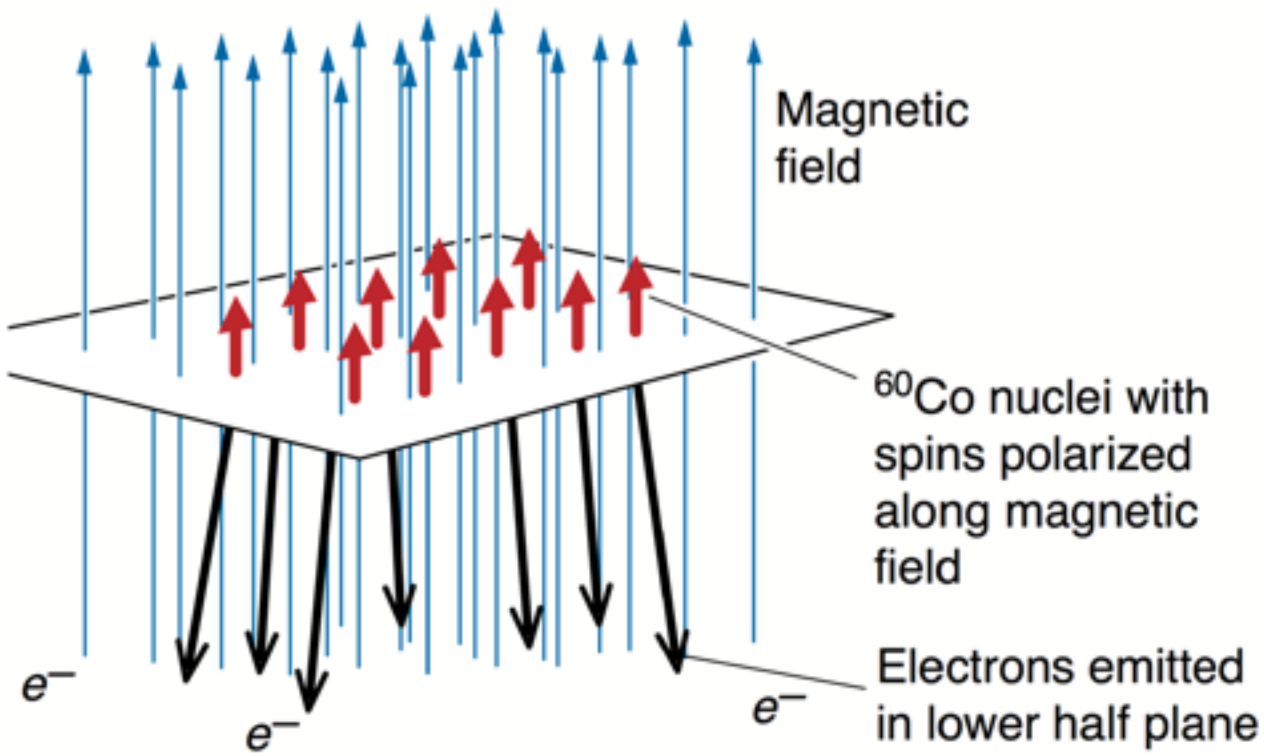
  - $\bar{\nu}_\mu$ predictions differ by as much as factor of two!



- Parity violation in weak interaction discovered same year as the ν
  - ➡ immediately implied reduction of ν cross sections by factor 2

Fig. from *Celebrating the Neutrino,* LANL



Phys. Rev. 105, 1413 (1957)

No left-handed $\bar{\nu}$'s!

(light and active)

- Resolution to this puzzle not likely to be as important, but will be crucial for current and next-generation oscillation experiments searching for CP violation

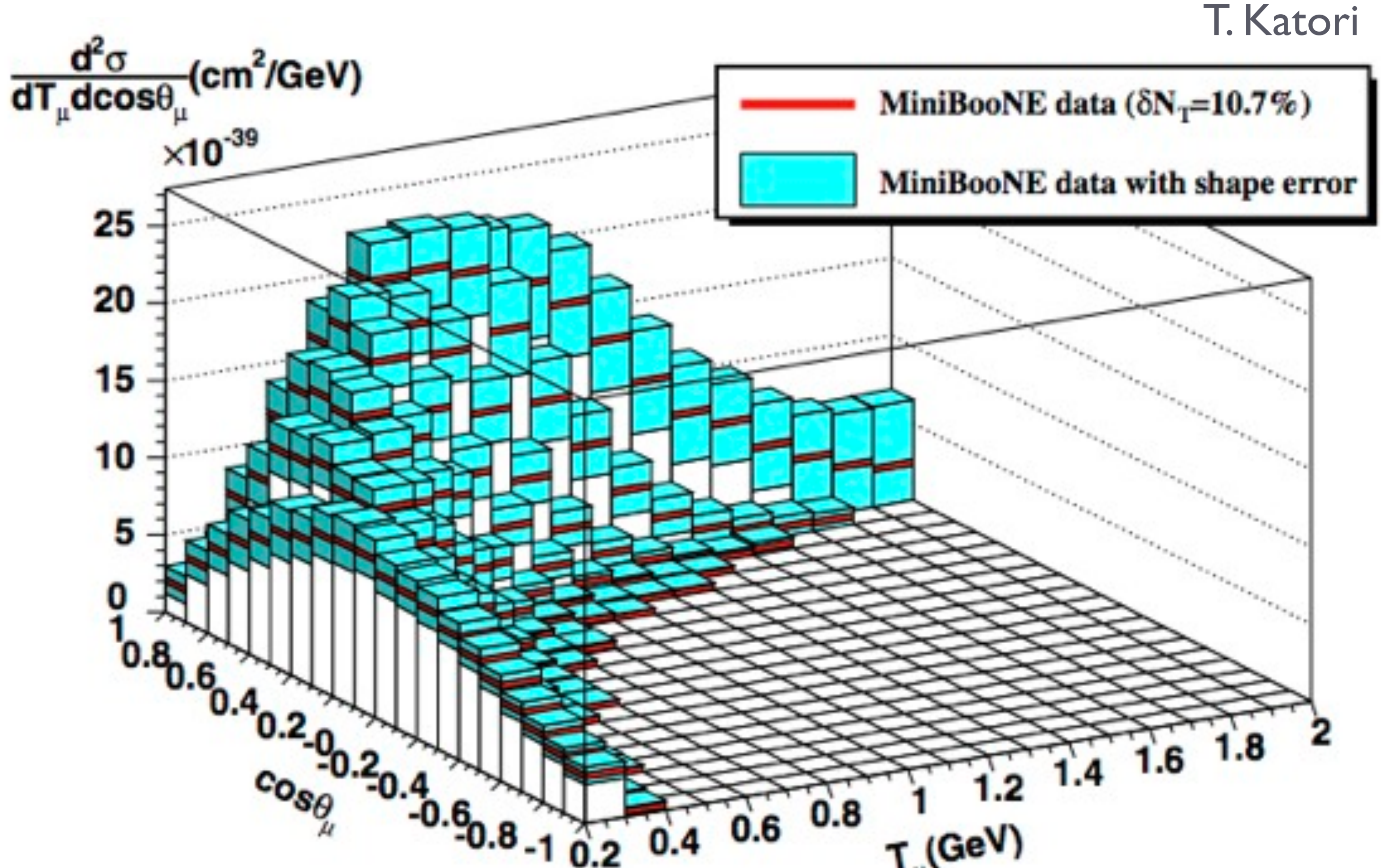
Primary CCQE result: $\sigma(T_\mu,\theta_\mu)$

- Total cross section $\sigma(E_\nu)$ extraction biased by interaction assumptions: only valid for interaction with at-rest, independently interacting nucleons
  - the very question we must address!

- Much better idea: report *what we measure*, double-differential $\sigma(T_\mu,\theta_\mu)$
  - also fully exploits MiniBooNE's unprecedented statistics

- Various levels of agreement with multi-nucleon predictions with double-differential σ

T. Katori



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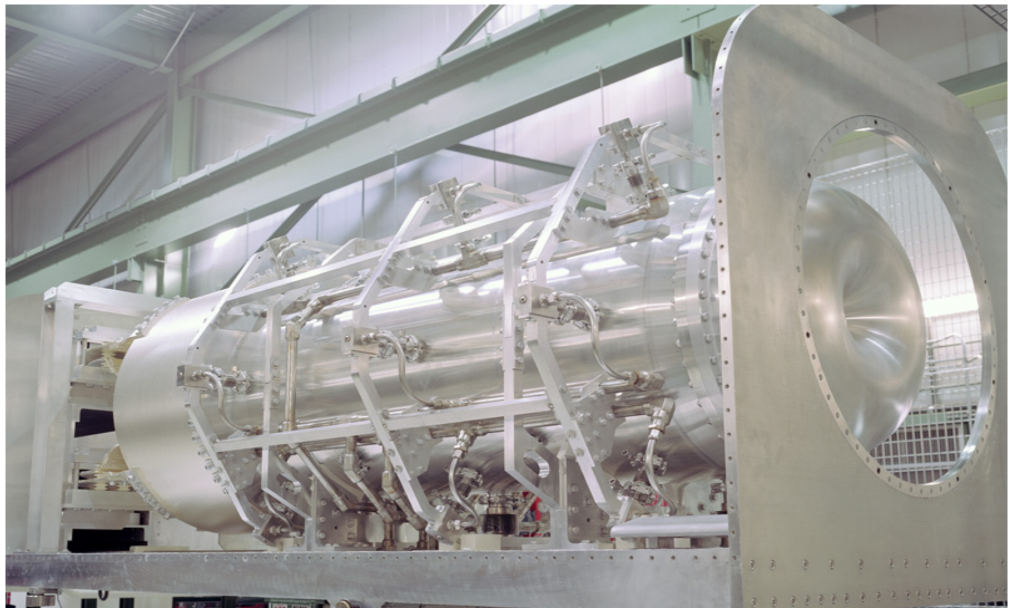
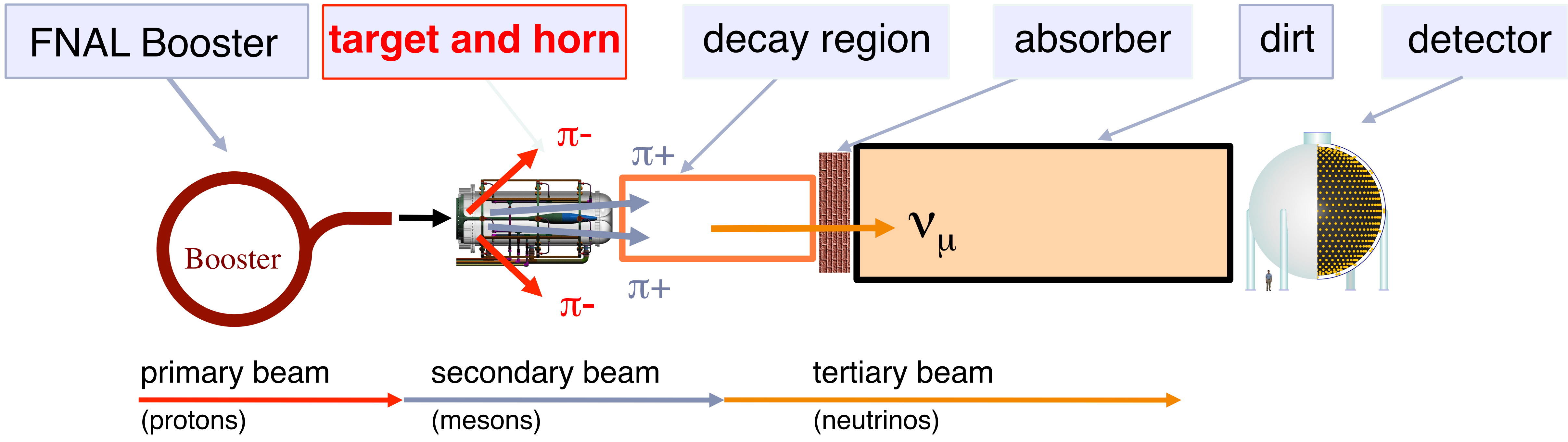
Booster neutrino beam

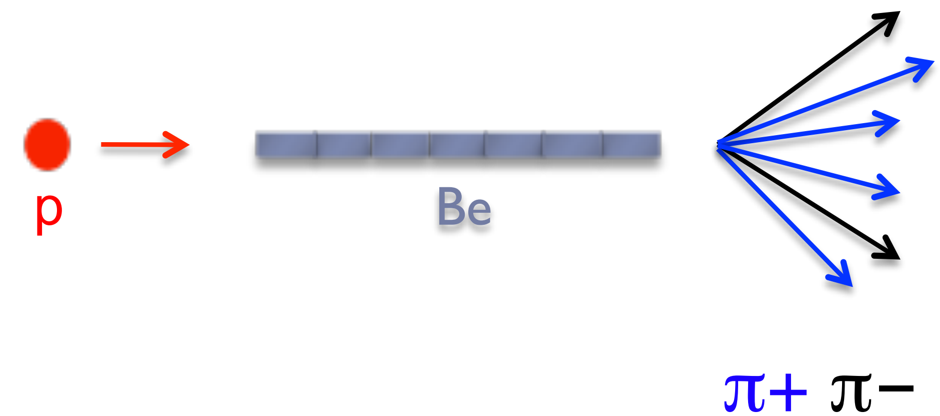


Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons

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



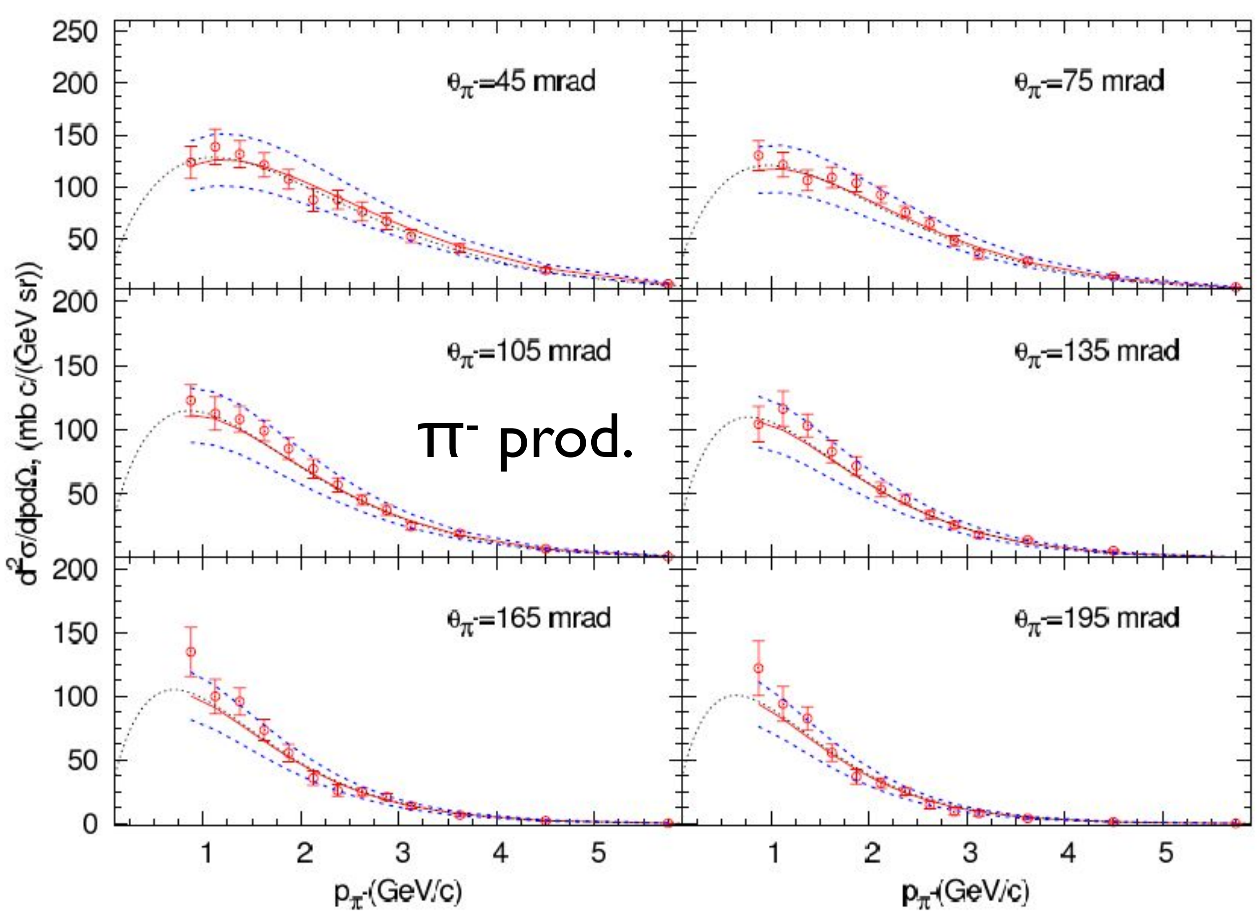
Neutrino flux



- With measurements of

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

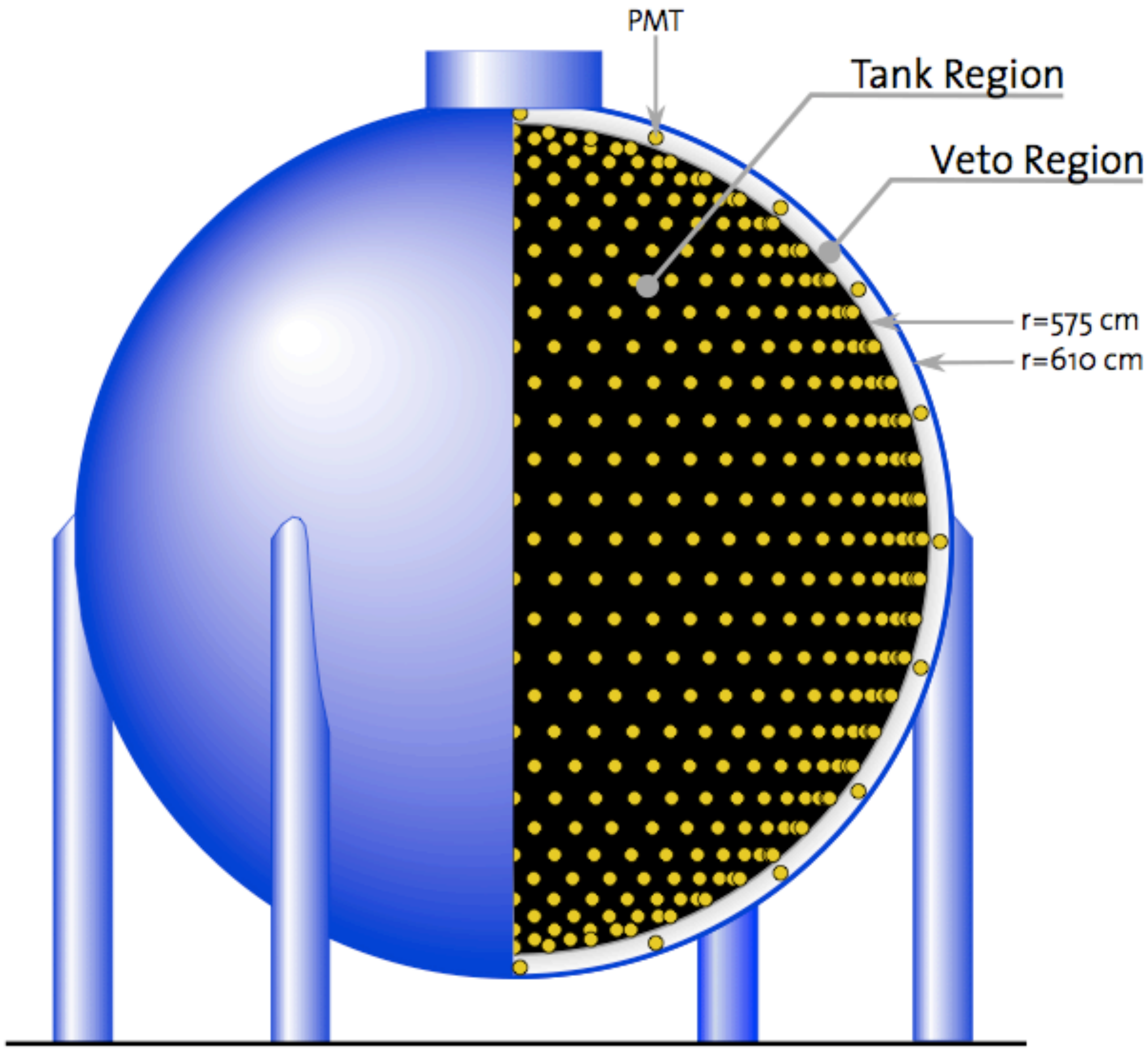
can predict ν, anti-ν flux at detector



- Dedicated π production data taken by HARP experiment (CERN)
  - "thin target" results used (5% λ), thick target data also taken and actively being analyzed
- Spline fit to these data (along with beamline geometry simulation) brings ν flux uncertainty to ~9%
  - only valid for ν parent π's constrained by these data - important later!
- Absolute Φ knowledge nearly model independent

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

Detector

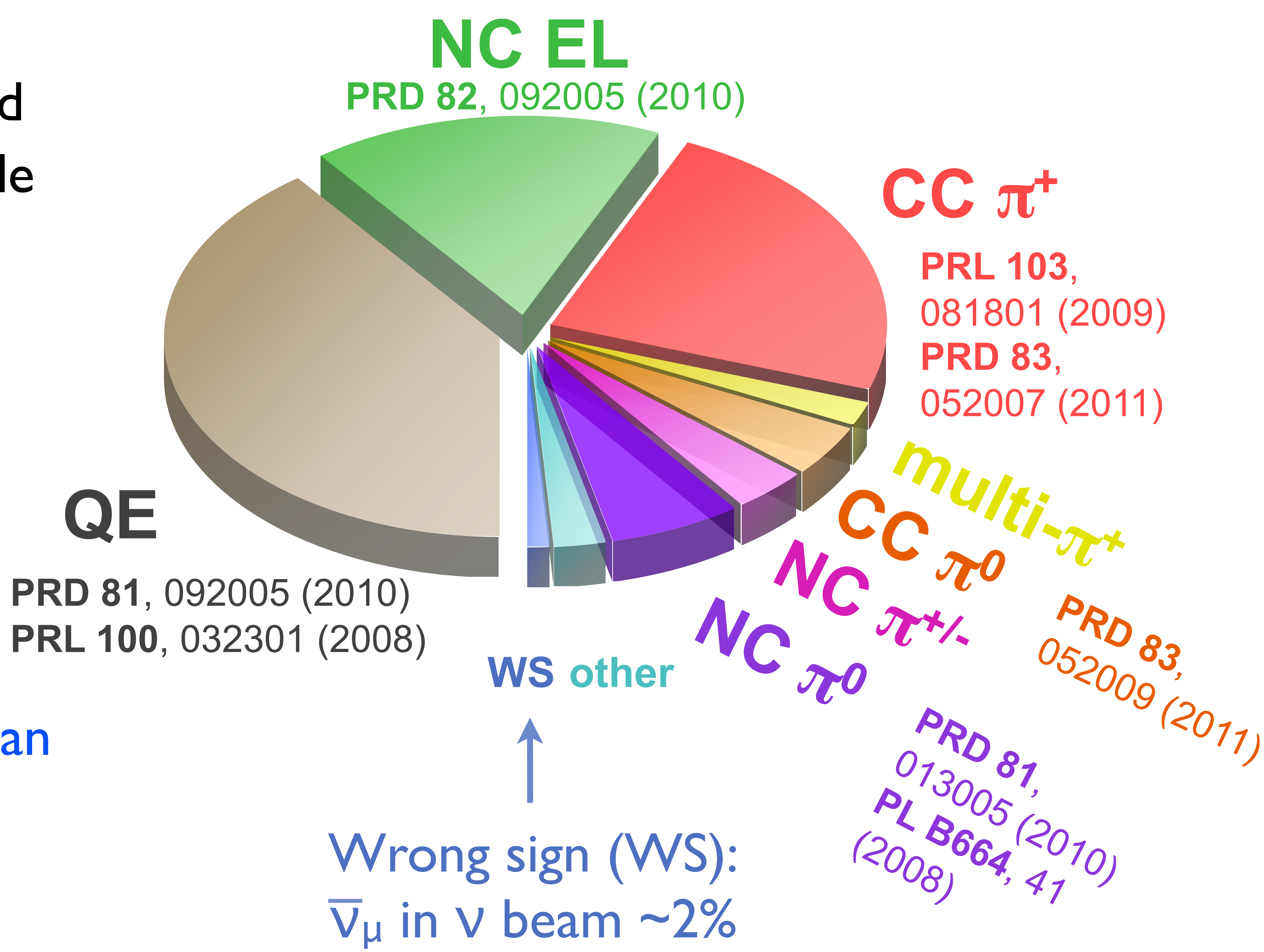


Nucl. Instr. Meth. A599, 28 (2009)

- 6.1m radius sphere houses 800 tons of pure mineral oil
- Primarily a Cherenkov detector, best at reconstructing leptons
- However we've shown late light can be used to reconstruct protons well (neutral current elastic measurement)

ν-mode rate

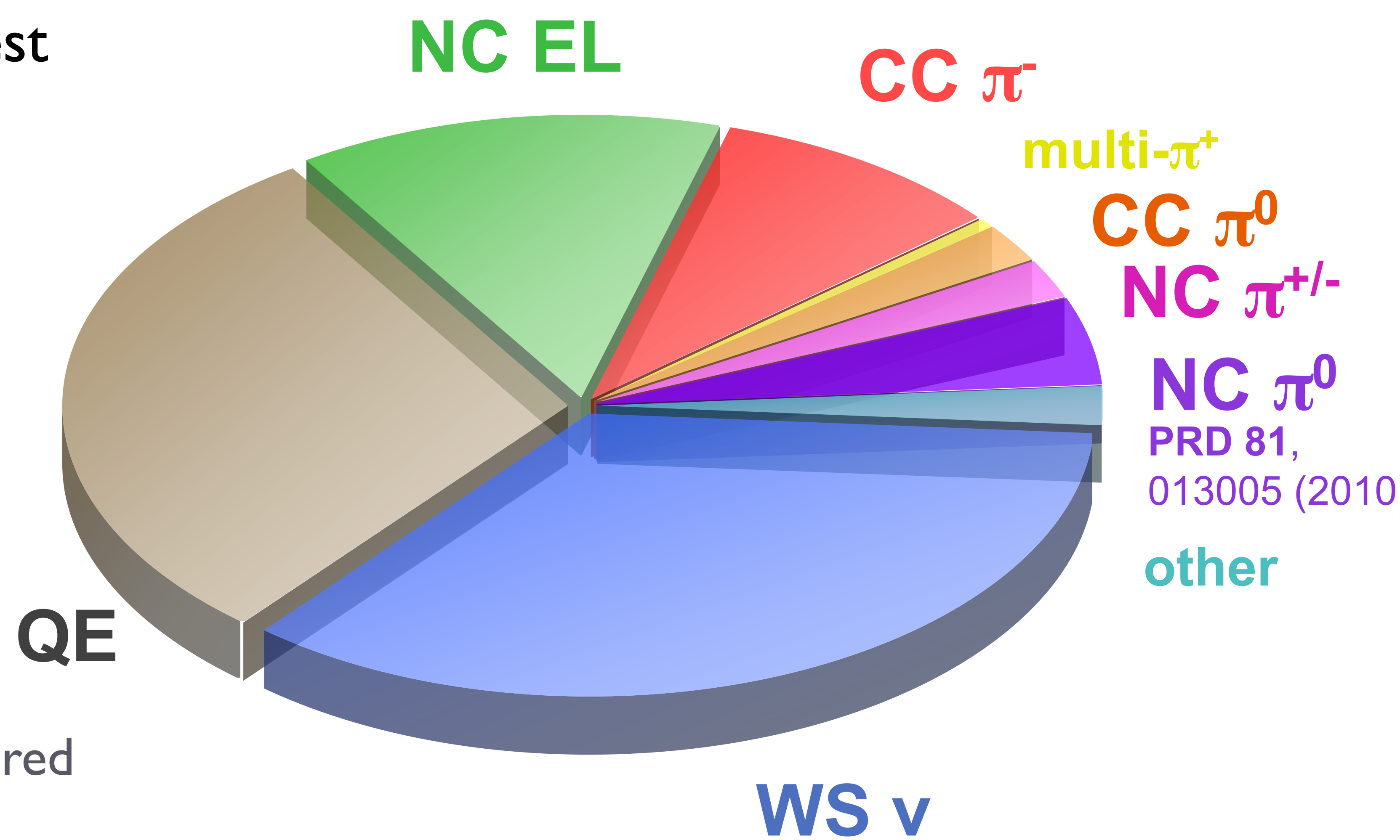
- MiniBooNE has published ~90% of the total ν-mode rate



- Lots of interest: more than 500 citations from these papers in < 4 yrs!

$\bar{\nu}$-mode rate

- Before able to make precision $\bar{\nu}_\mu$ σ's, must deal with largest background: wrong-sign ν_μ



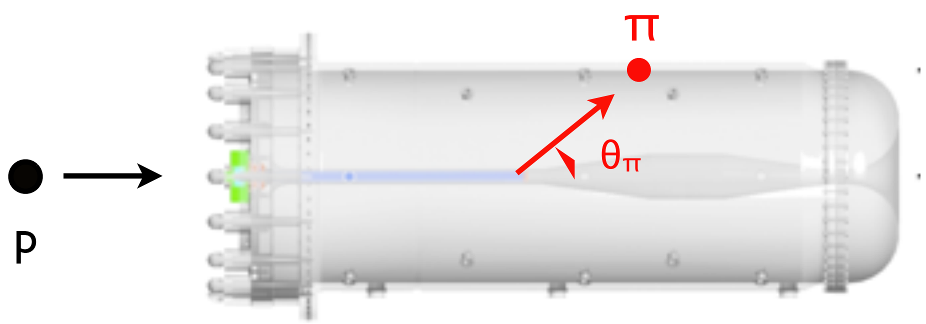
PRD 84, 072005 (2011)

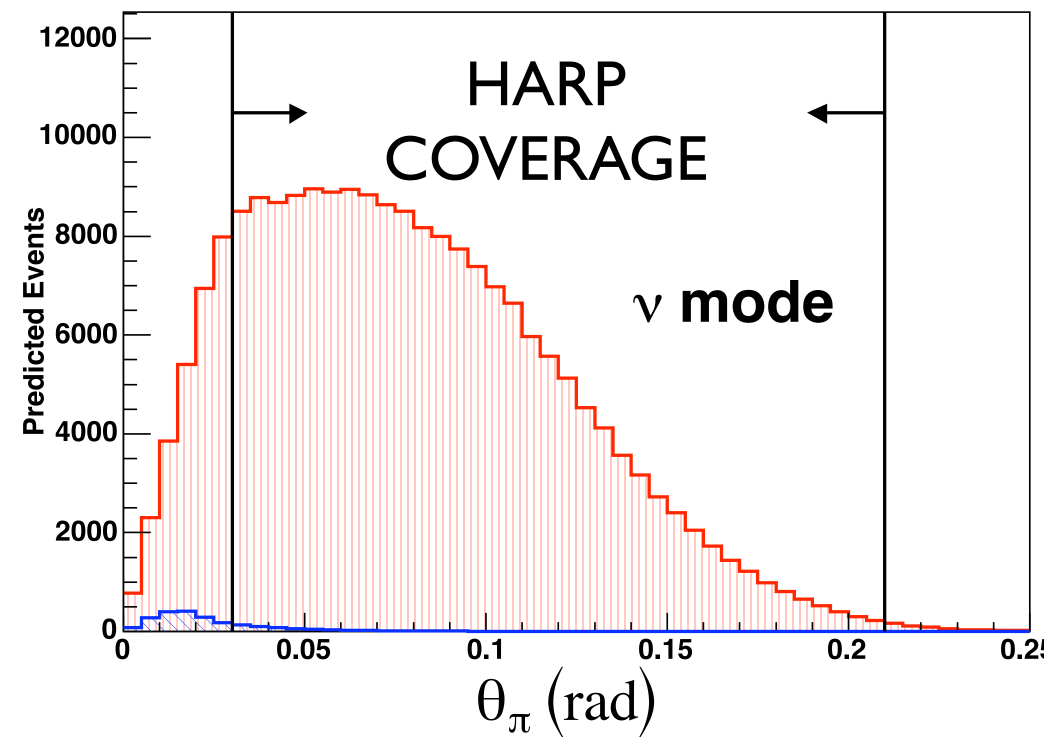
Wrong sign:
ν_μ in $\bar{\nu}$ beam ~40%!

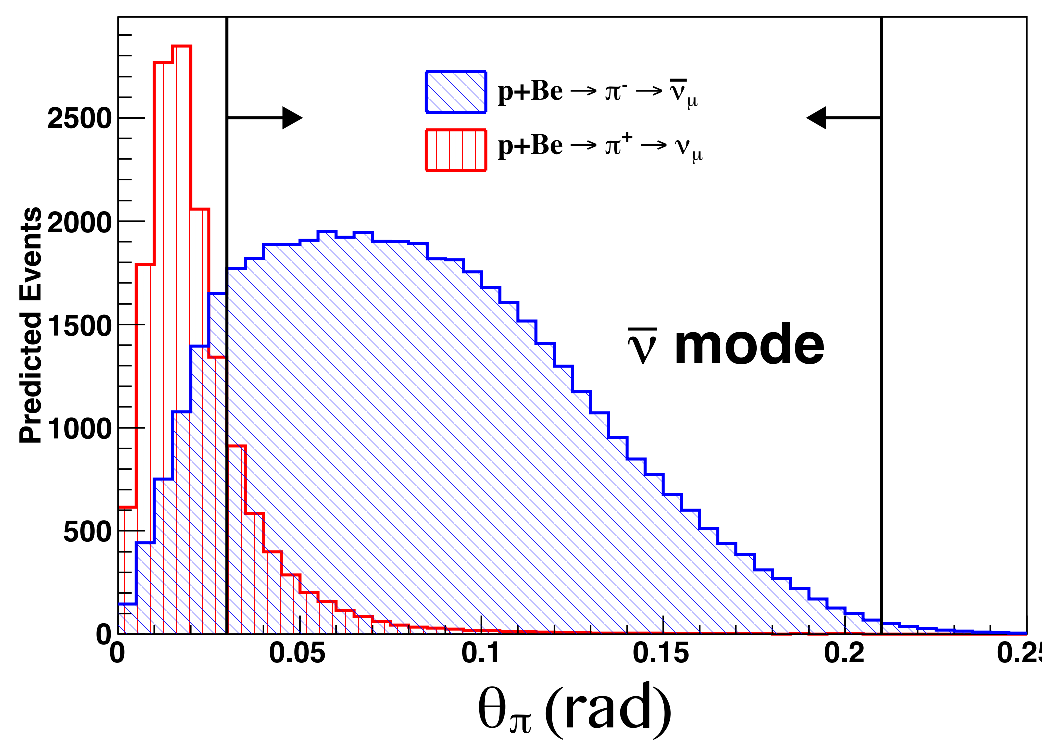
- Unprecedented $\bar{\nu}$ statistics
  - 1.0 x 10^{21} POT in an unexplored energy region

Wrong-sign background

- Even worse: ν_μ parent π^+ production in $\bar{\nu}$ mode (“wrong signs”) mostly not constrained by HARP measurements
  - overall rate highly uncertain!







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  - need to check flux spectrum!

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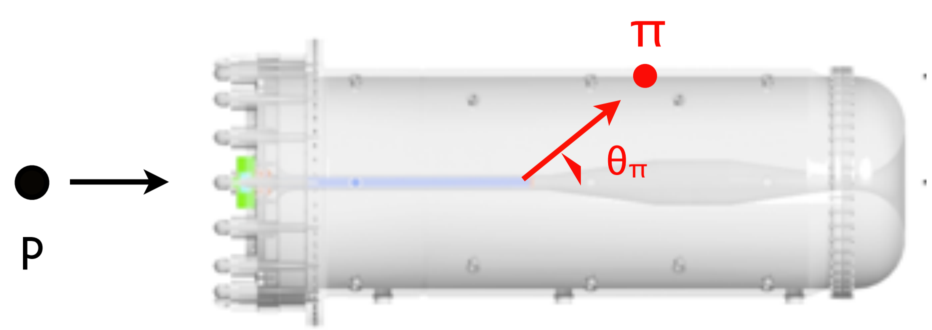
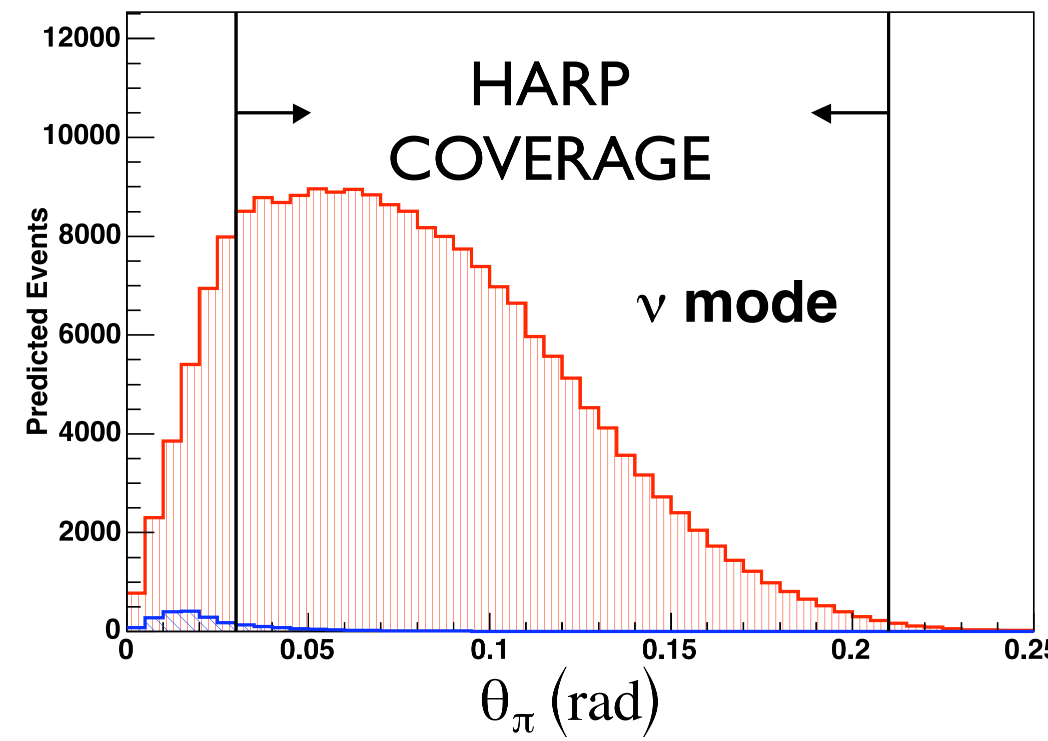
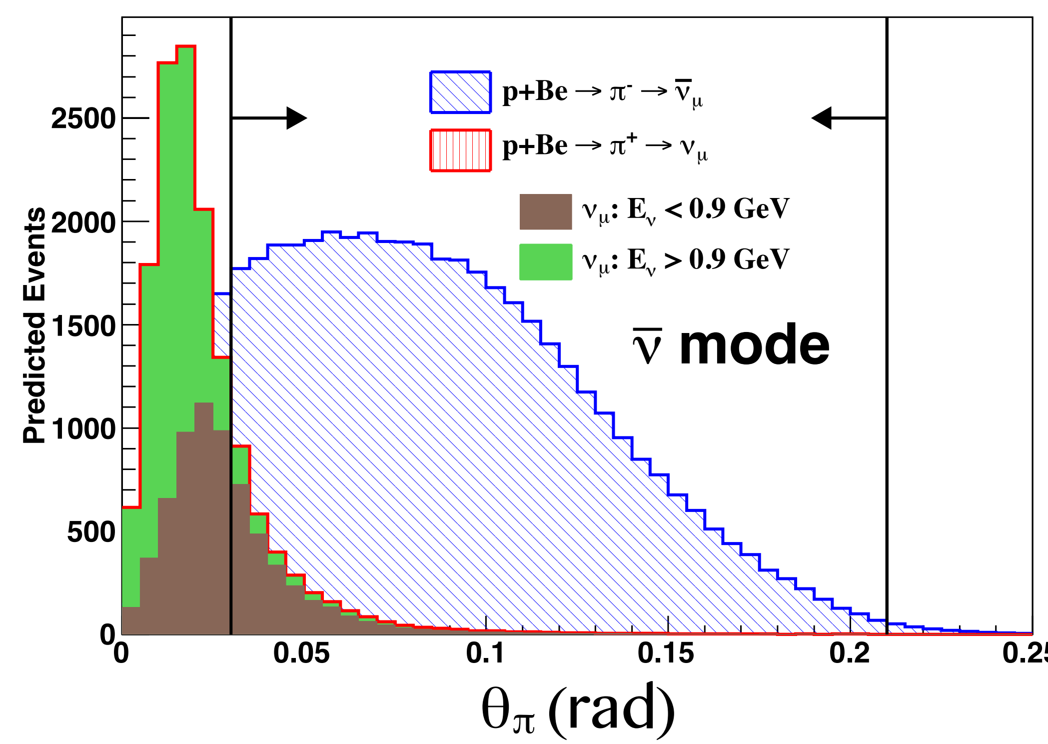


- Moreover, accepted π angle a mild function of energy
  - need to check flux spectrum!





Wrong-sign measurements

- Other detectors employ magnetic field to separate CC ν_μ / $\bar{\nu}_\mu$
  - MiniBooNE unmagnetized, must use statistical techniques

- Never been done before, had to get creative! General strategy:
  1. exploit asymmetries between ν_μ, anti-ν_μ interactions in the detector
  2. apply measured σ's from neutrino-mode data (CCQE, CCπ^+)

$$\frac{\mathrm{Rate}^{\mathrm{data}}}{\mathrm{Rate}^{\mathrm{sim}}} = \frac{\Phi^{\mathrm{data}} \times \sigma^{\mathrm{data}}}{\Phi^{\mathrm{sim}} \times \sigma^{\mathrm{data}}} = \frac{\Phi^{\mathrm{data}}}{\Phi^{\mathrm{sim}}}$$

  3. level of data-simulation agreement then reflects accuracy of (highly-uncertain) ν_μ flux prediction

Three ν_μ flux measurements

- Three complementary measurements based on:
  1. ν_μ CCπ^+ sample (exploits π^- nuclear capture)
  2. μ-only and μ+e rates (exploits μ^- nuclear capture)
  3. backward scattering region in CCQE sample (dominated by ν_μ)

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    3. backward scattering region in CCQE sample (dominated by ν_μ)

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

- Could be used in current + future unmagnetized ν detectors
    - future expt's may be too big to be practically magnetized?

$CC\pi^+$ sample

- From lepton and charge conservation, single-π production (mostly via Δ resonance) results in π^+ for ν_μ, π^- for $\bar{\nu}_\mu$

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

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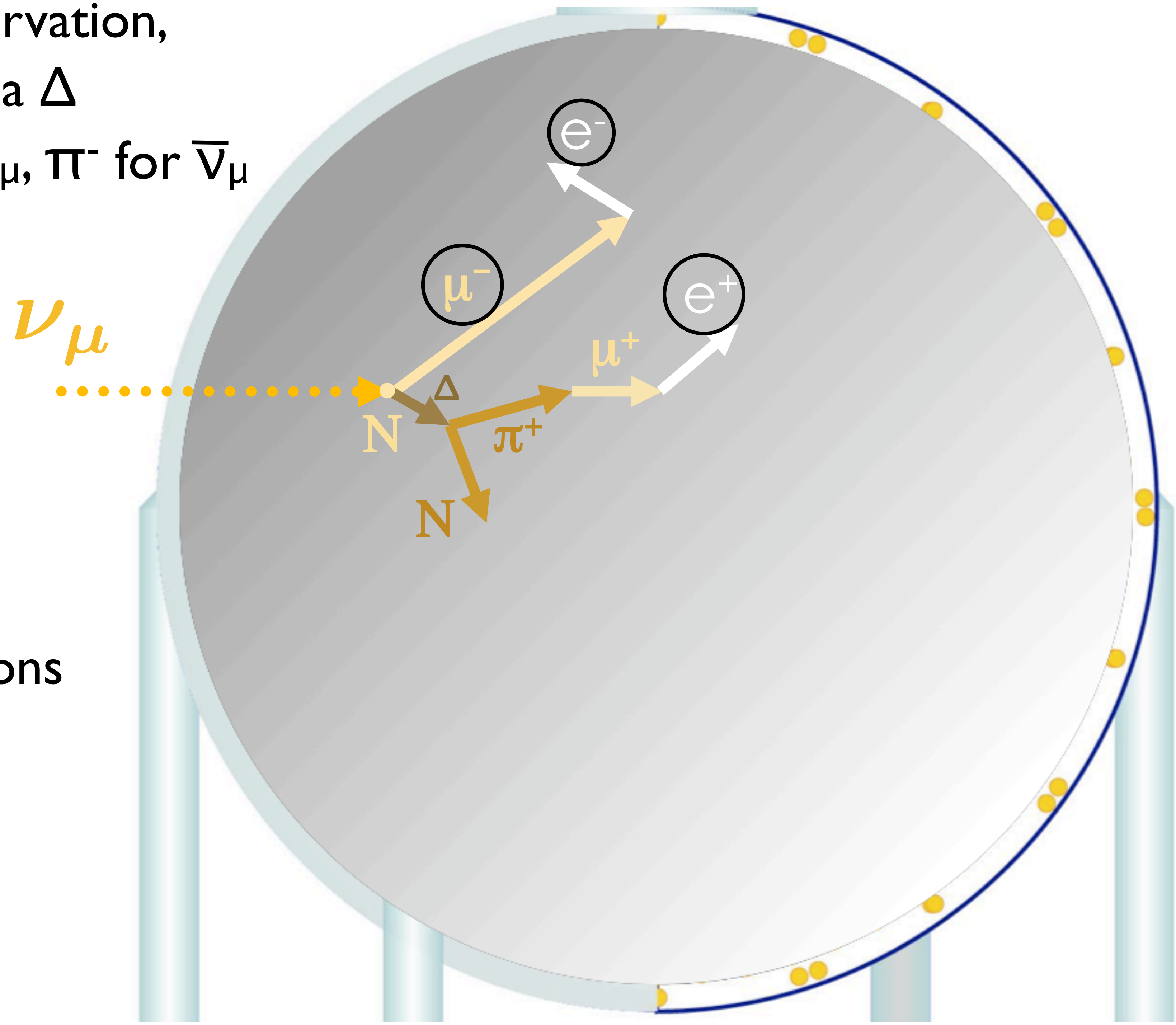


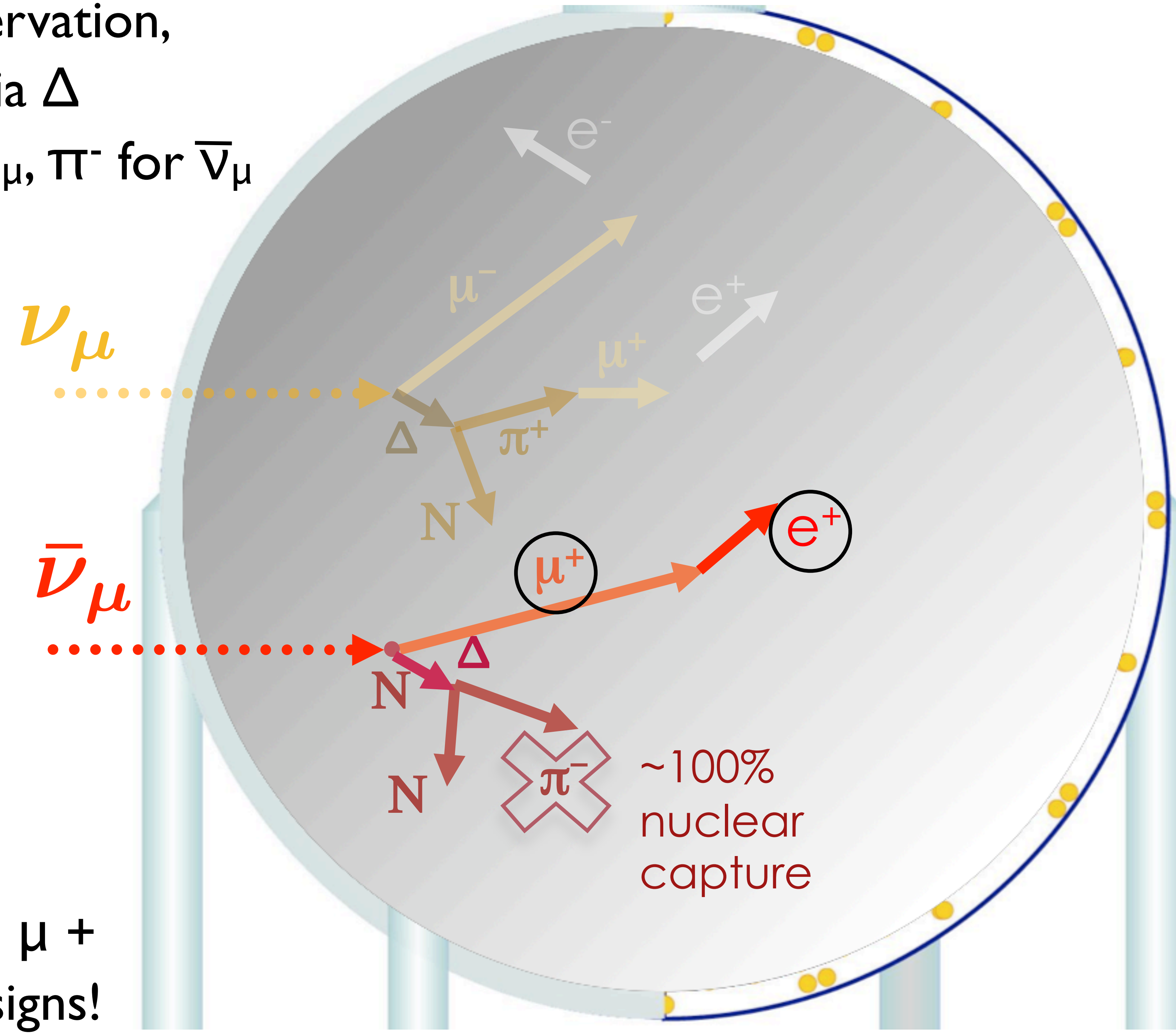
- ν_μ process leads to three leptons above Cherenkov threshold
  1. primary μ
  2. decay positron
  3. decay electron

CCπ⁺ sample

- From lepton and charge conservation, single-π production (mostly via Δ resonance) results in π^+ for ν_μ, π^- for $\bar{\nu}_\mu$

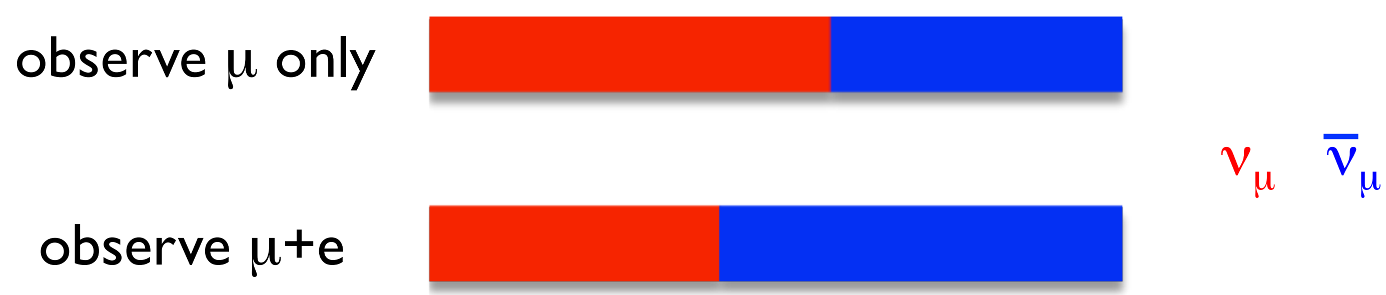
$$\nu_\mu N \rightarrow \mu^- \pi^+ N$$
$$\bar{\nu}_\mu N \rightarrow \mu^+ \pi^- N$$

- Due to π^- nuclear capture (~100%), $\bar{\nu}_\mu$ single π process only has two
  1. primary μ
  2. decay positron
- Can do simple rate analysis on μ + 2e sample to measure wrong signs!



μ^- capture measurement

- Due to μ- nuclear capture (~8% in carbon) ν_μ CC events less likely to produce decay electrons compared to $\bar{\nu}_\mu$
- Sample composition:



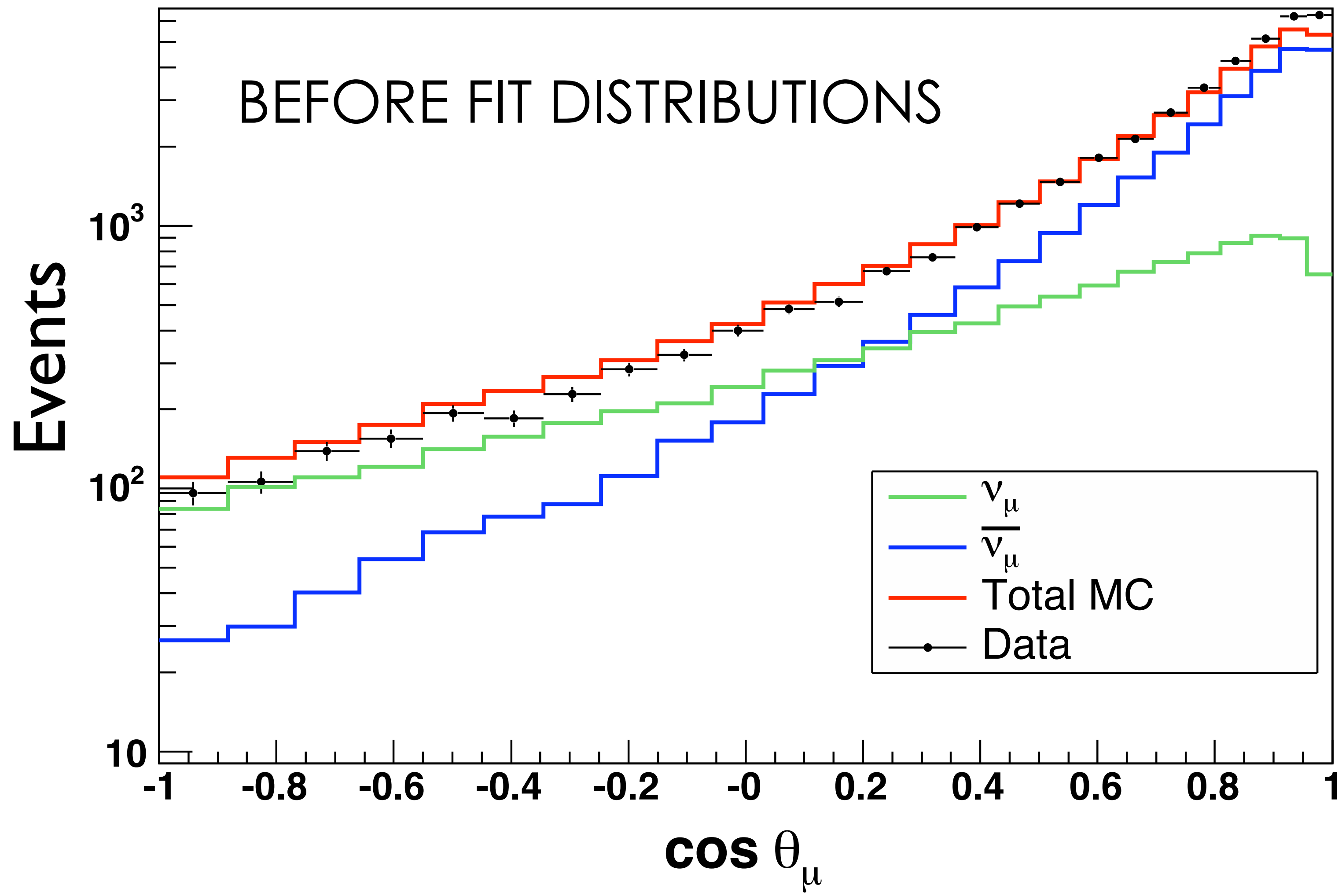
- Scale the two contributions to match data simultaneously in both samples
  - (two eqns, two unknowns)

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

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

CCQE angular fits

- Due to axial-vector interference term in CCQE σ, $\bar{\nu}_\mu$ events expected to be much more forward-going compared to ν_μ
  - perform simple fit to data in reconstructed energy bins

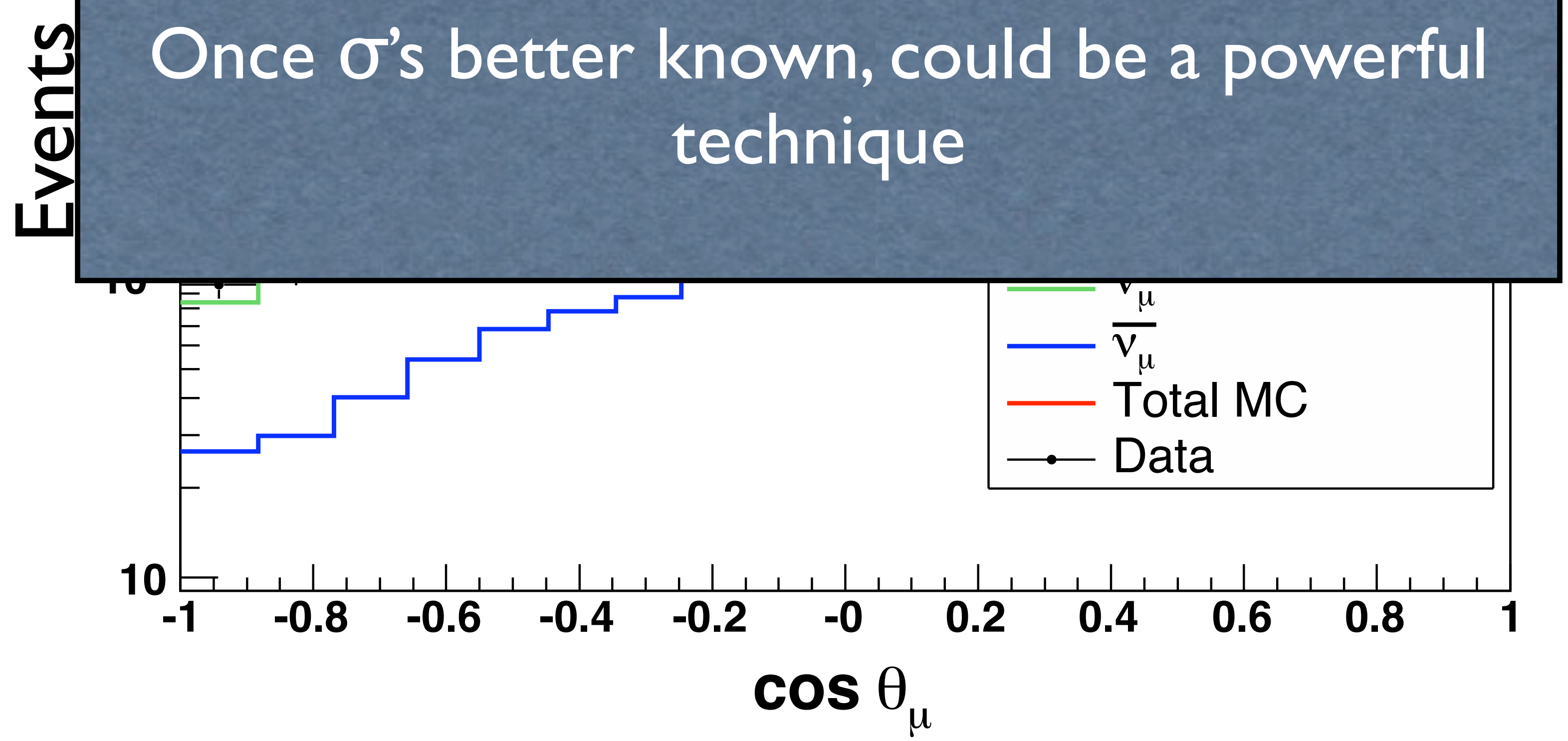


CCQE angular fits

- Due to axial-vector interference term in CCQE σ, $\bar{\nu}_\mu$ events expected to be much more forward-going compared to ν_μ
  - perform simple fit to data in reconstructed energy bins

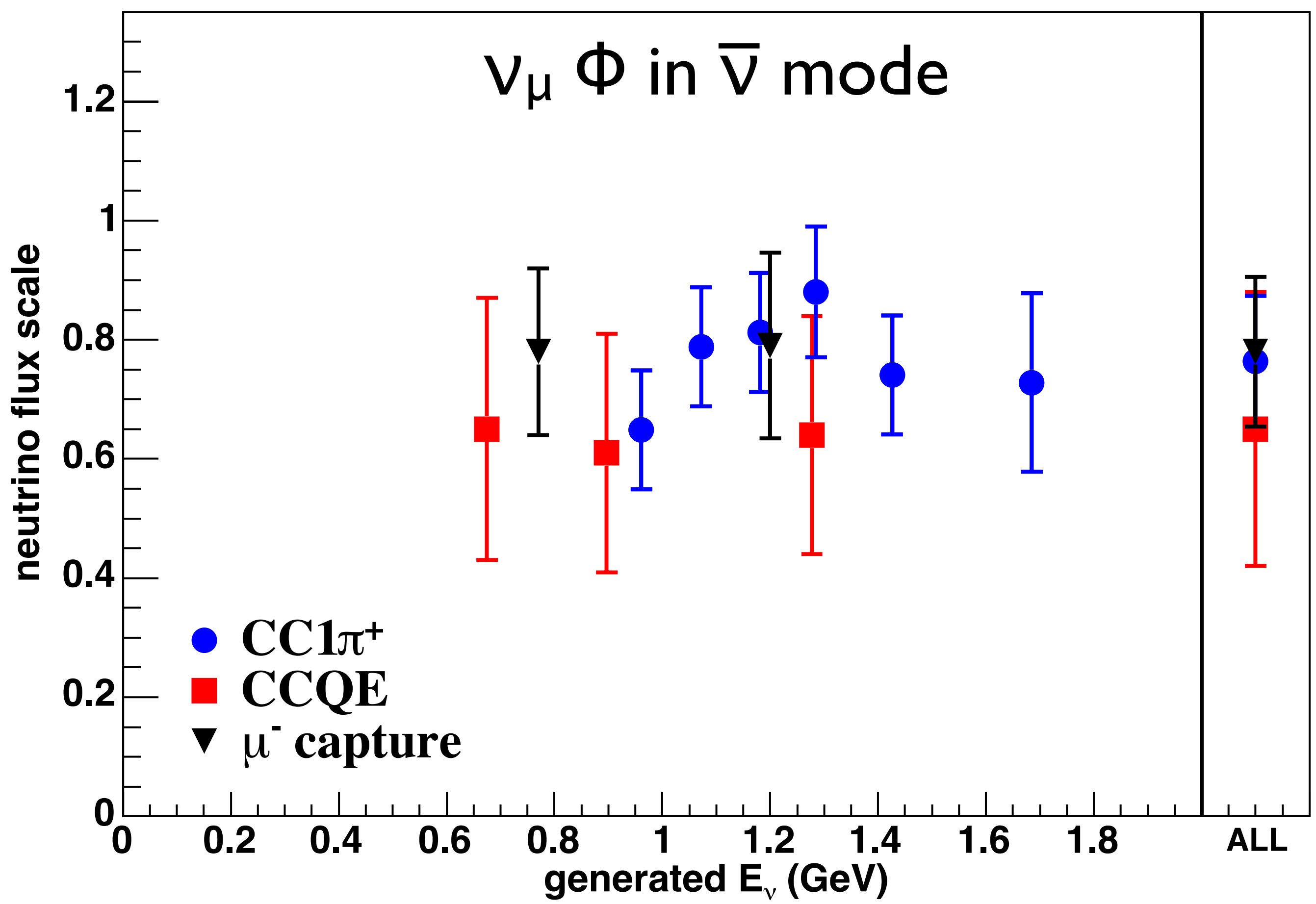
Results dependent on $\bar{\nu}_\mu$ σ!
Results NOT USED to extract cross sections

Once σ's better known, could be a powerful technique



Wrong-sign flux results

- Results binned in energy as finely as allowed by statistics
  - nominal prediction ~20% high in normalization, simulated spectrum appears adequate



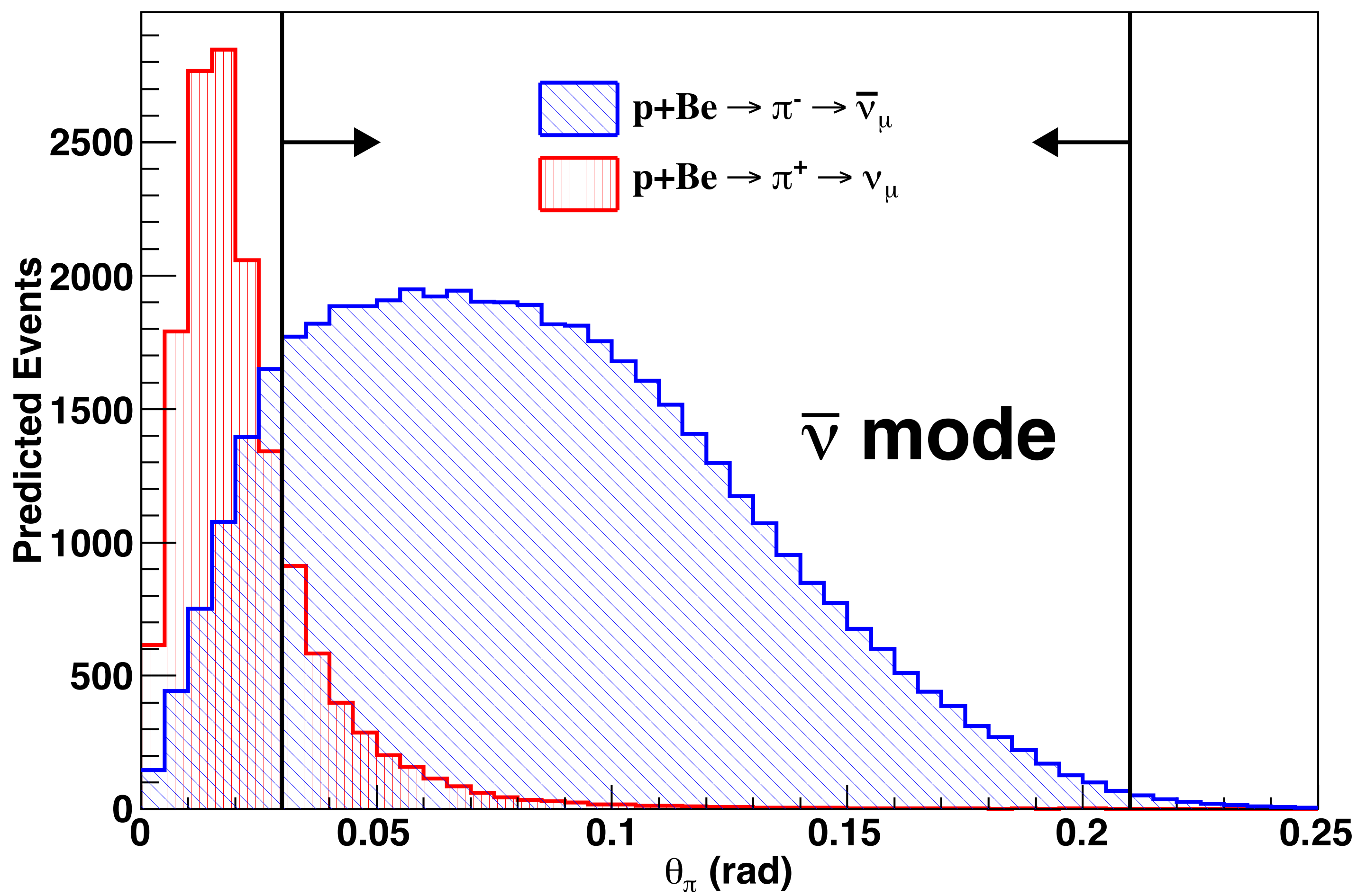
Wrong-sign Φ extrapolated from hadroproduction data! ~20% discrepancy with prediction not surprising

- Predicted ν_μ flux in $\bar{\nu}$ mode constrained by < 15%. Not bad with no magnetic field!

Last word on $\bar{\nu}$-mode flux

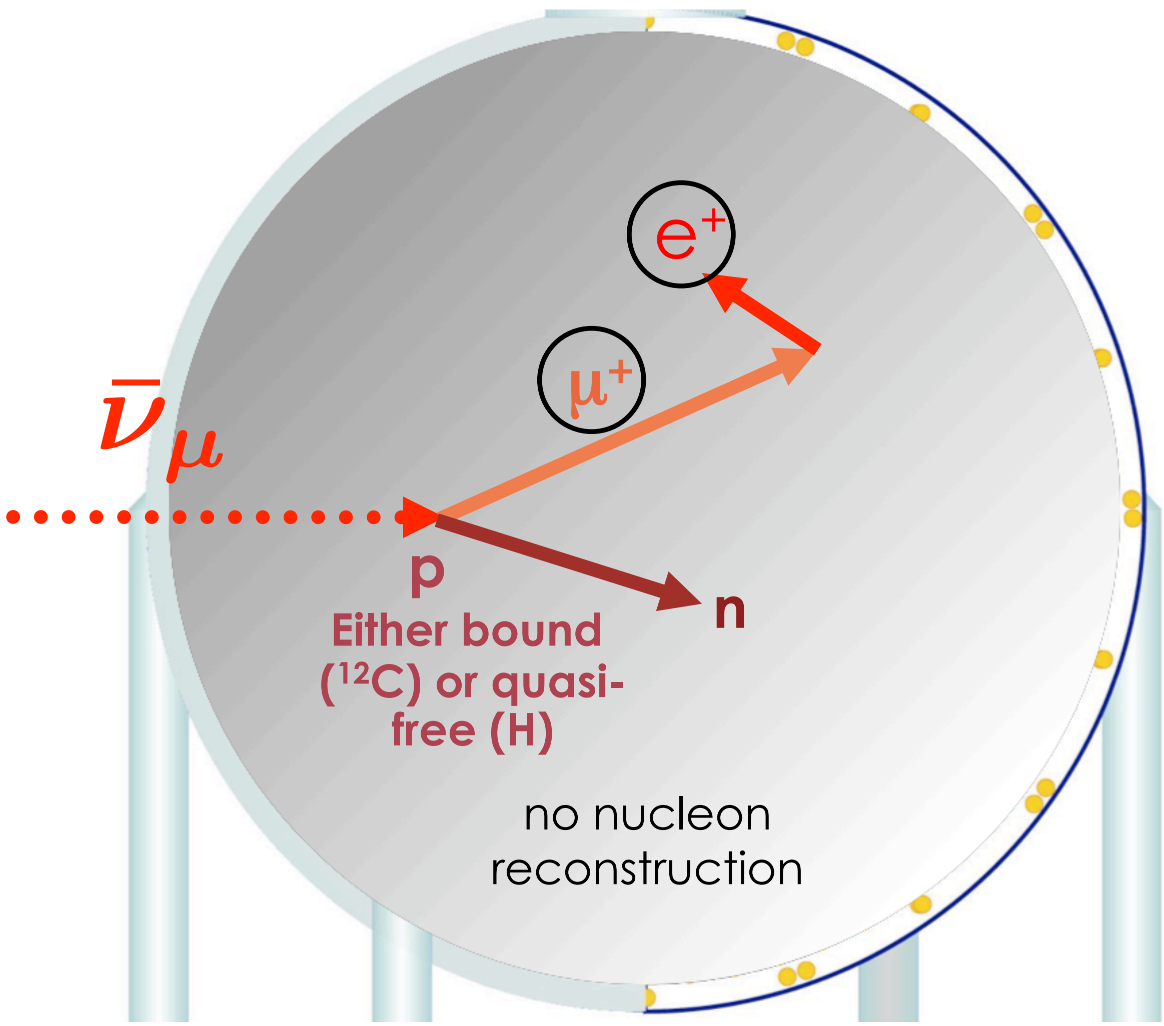
- Wrong signs constrained to a sub-dominant uncertainty in all $\bar{\nu}$ mode analyses
- Let's move to $\bar{\nu}$ events, where we *can* exploit HARP data

(arrows indicate HARP coverage)

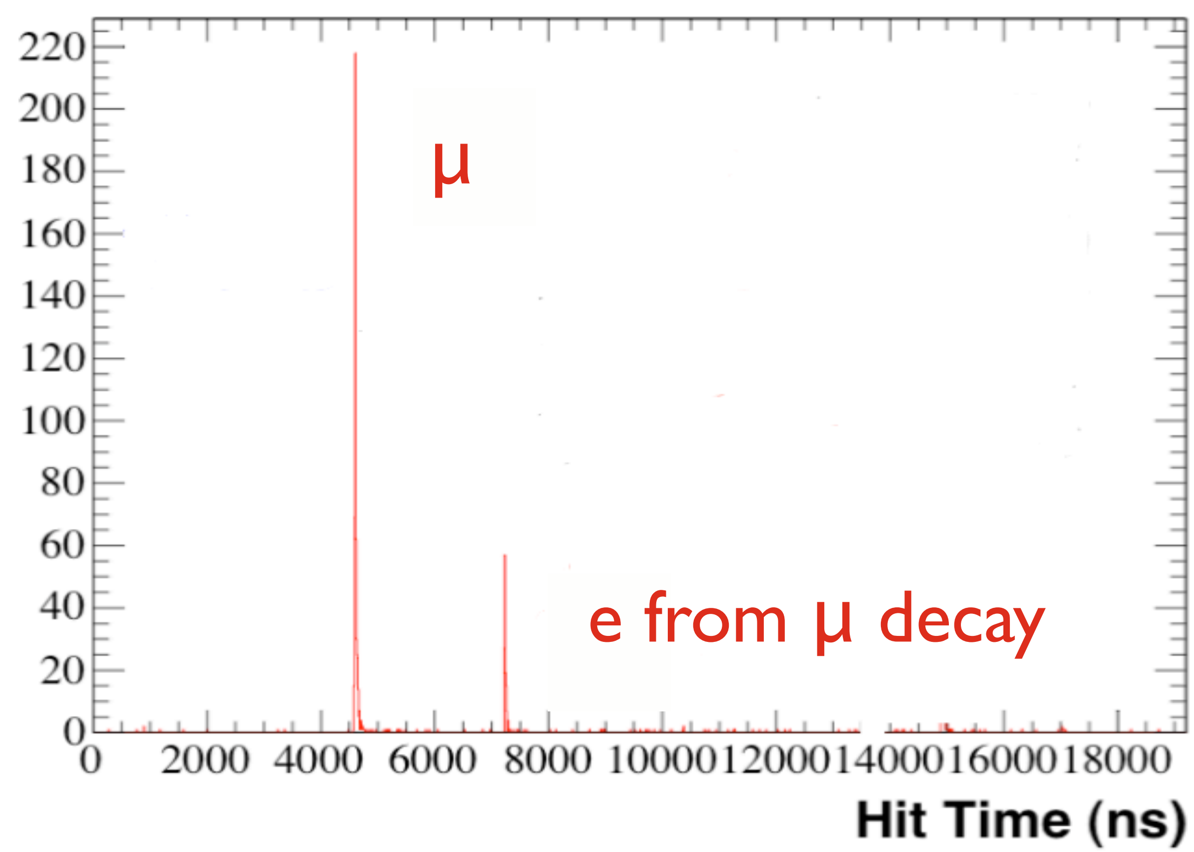


"right sign" $\bar{\nu}_\mu$ flux well-predicted by HARP data

- $\bar{\nu}_\mu$ CCQE only involves protons: MiniBooNE medium CH_2, so sample is mix of bound and free scattering
  - unlike ν_μ analysis: all n targets housed in ^{12}C

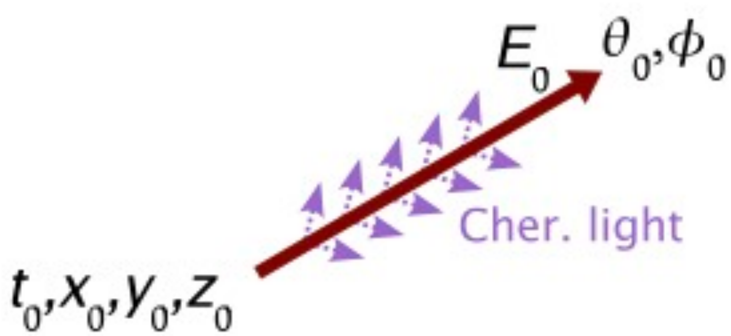


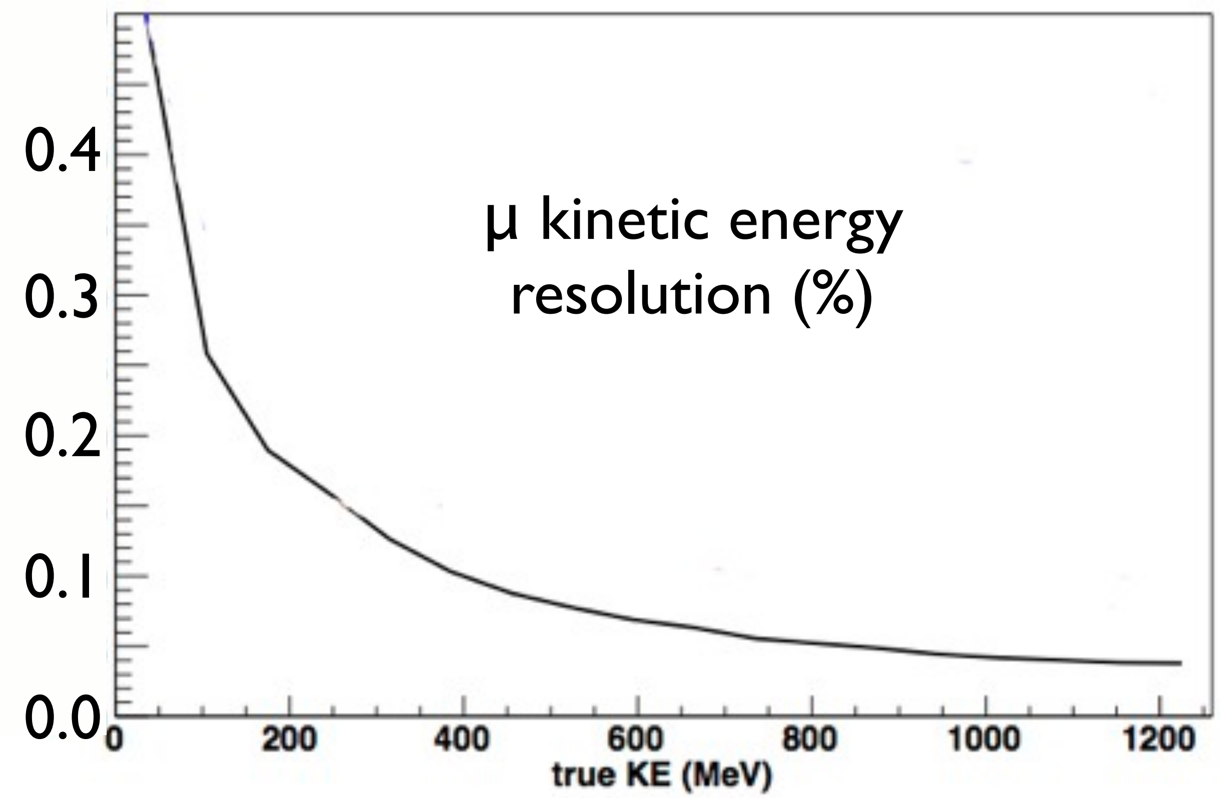
typical event - two "subevents"



$\bar{\nu}_\mu$ CCQE reconstruction

- μ kinematics identified by fitting PMT hit topology and timing





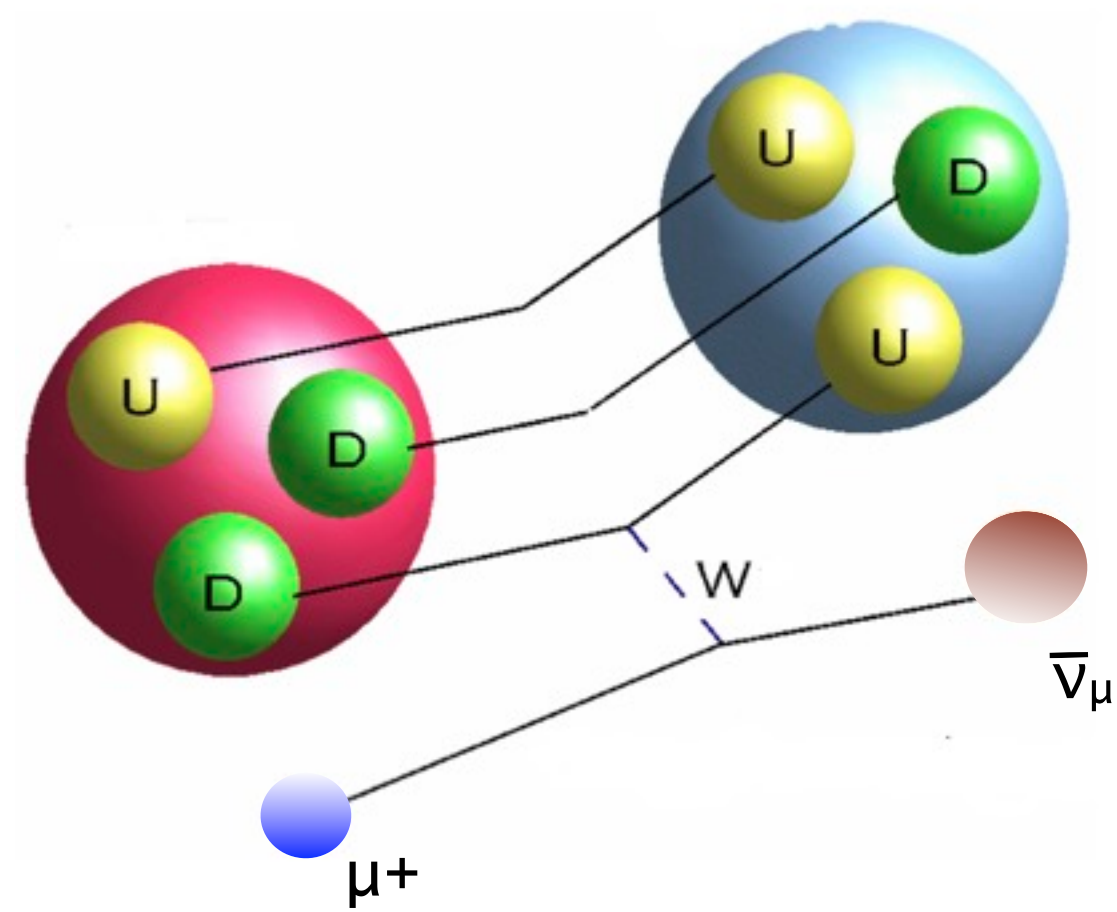
Nucl. Instrum. Meth. A608, 206 (2009)

- μ's leave distinctive Cherenkov ring, reconstruction performs well

- This motivates exploitation of our large statistics to map the σ as a function of μ kinematics

$\bar{\nu}_\mu$ CCQE selection

1. Two subevents
   - consistent with prompt μ + decay e
2. In time with ν beam
3. T_μ > 200 MeV
   - removes beam-unrelated e's
4. 2nd subevent vertex consistent prompt particle
   - based on observed μ kinematics
5. μ/e separation PID
   - single-pion bkgs look more e-like
6. 5m fiducial volume
7. Low veto activity
   - containment + nothing coming in



Identical selection to ν_μ CCQE analysis:
single μ, 0 π, any # nucleons

$\bar{\nu}_\mu$ sample composition

- 70k events: 60% $\bar{\nu}_\mu$ CCQE purity
  - largest $\bar{\nu}_\mu$ CCQE sample ever recorded!
- 30% efficiency
- Largest background: ν_μ CCQE
  - measured!

Process	Contribution
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (p from ^{12}C)	43%
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (p from H_2)	17%
All ν_μ	20%
$CC\pi^-$	14%

Cross-section calculation, uncertainties

- Calculation identical to ν_μ CCQE σ analysis

independent of physics model!

unfolding matrix, reco data, reco bkg

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

bin widths, detection efficiency, int. flux, nucleon targets

Uncertainty summary

- Most uncertainties on parameters, processes that affect the final measurement evaluated through "many universe" MC method:

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

k: parameter/process excursion from "best-guess"

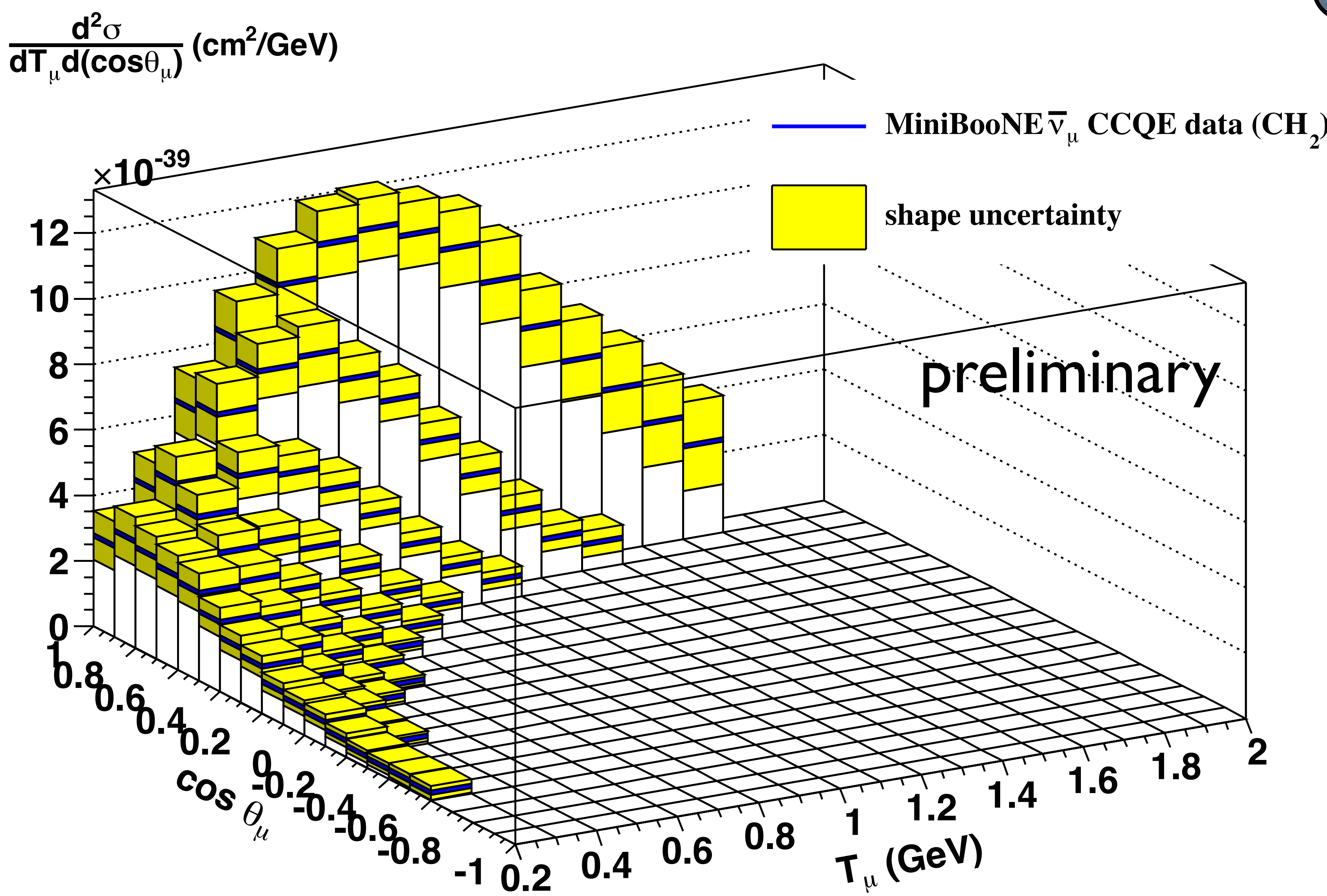
- Difference of these alternate σ's from central-value sets systematic uncertainty

Error source	Normalization uncertainty (%)
$\bar{\nu}$ flux	9
Backgrounds	9
Detector	5
Unfolding	2
Total (includes correlations)	**14**

- Leading uncertainties: split between anti-neutrino flux and backgrounds

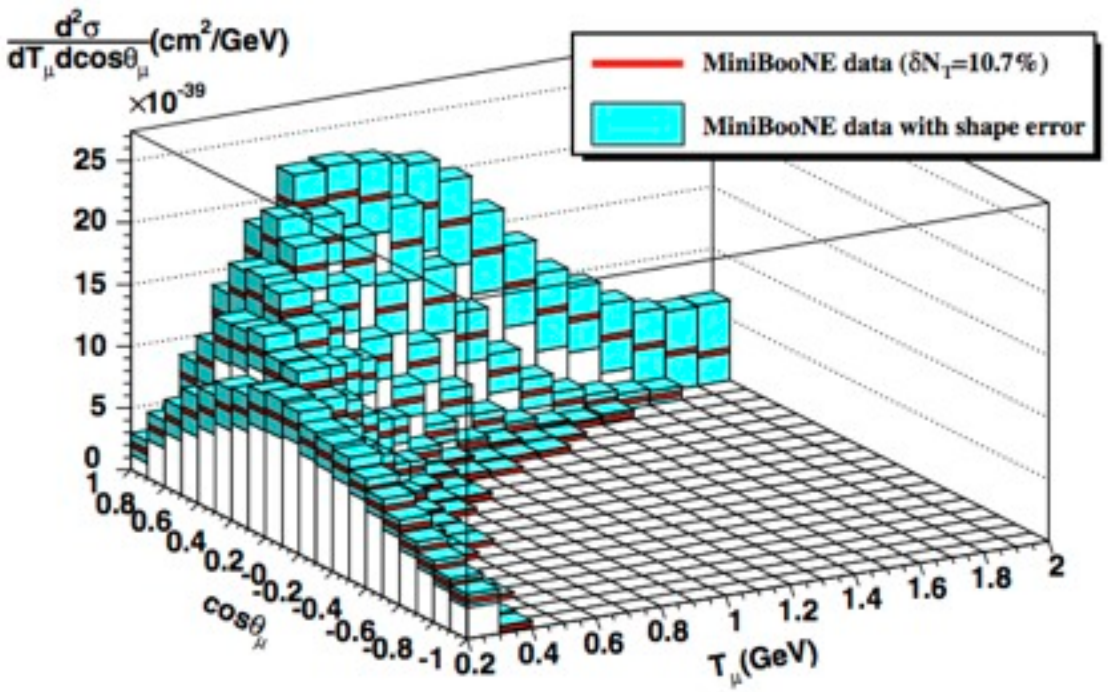
- Least model-dependent measurement possible with MiniBooNE data. Independent of CCQE interaction assumptions

2nd time publicly shown

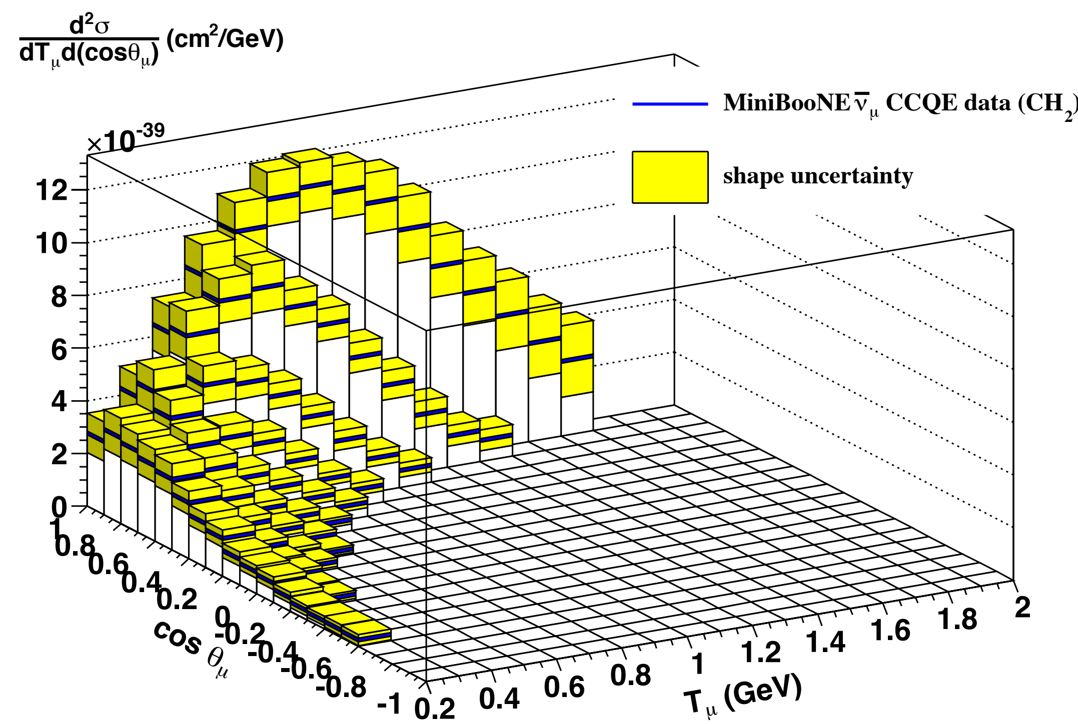


Results: double-differential on CH_2

- First time in ν history we've been able to make this kind of comparison
- $\bar{\nu}_\mu$ CCQE much more forward-going compared to ν_μ



ν_μ CCQE



$\bar{\nu}_\mu$ CCQE

- Consequence of parity violation: (ν - q) vs ($\bar{\nu}$ - q) interactions:

$\vec{p}$ $\vec{s}$

ν q

(in COM frame)

$\bar{\nu}$ q

No net spin

Net spin: forward-going μ preferred

$\bar{\nu}_\mu$ CCQE σ's on ^{12}C only

- To facilitate comparisons with theoretical calculations, CCQE on hydrogen subtracted to form ^{12}C-only σ (using M_A = 1.02 GeV)
  - introduces model dependence, also larger errors due to lower sample purity

$\bar{\nu}_\mu$ CCQE σ's on ^{12}C only

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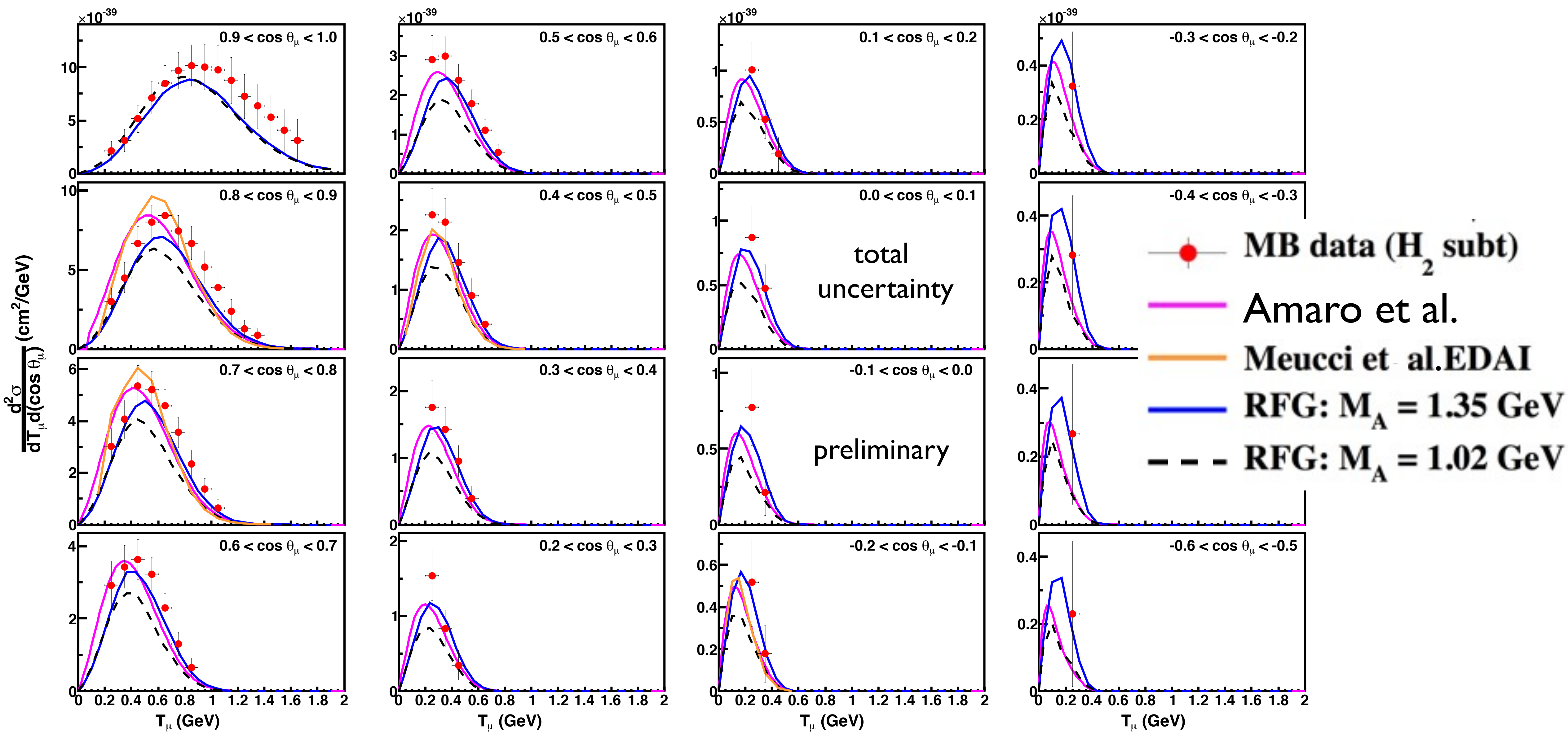
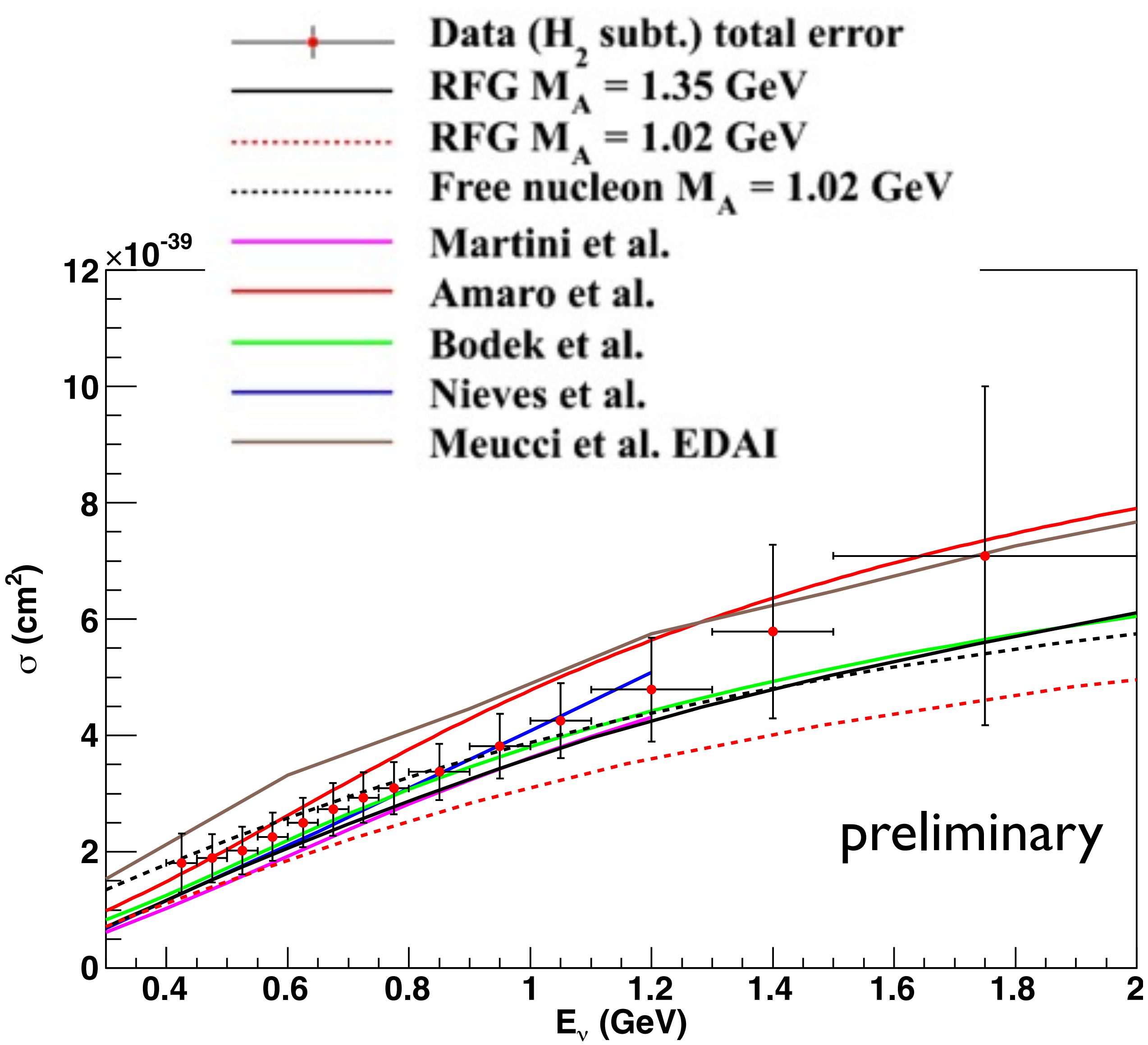
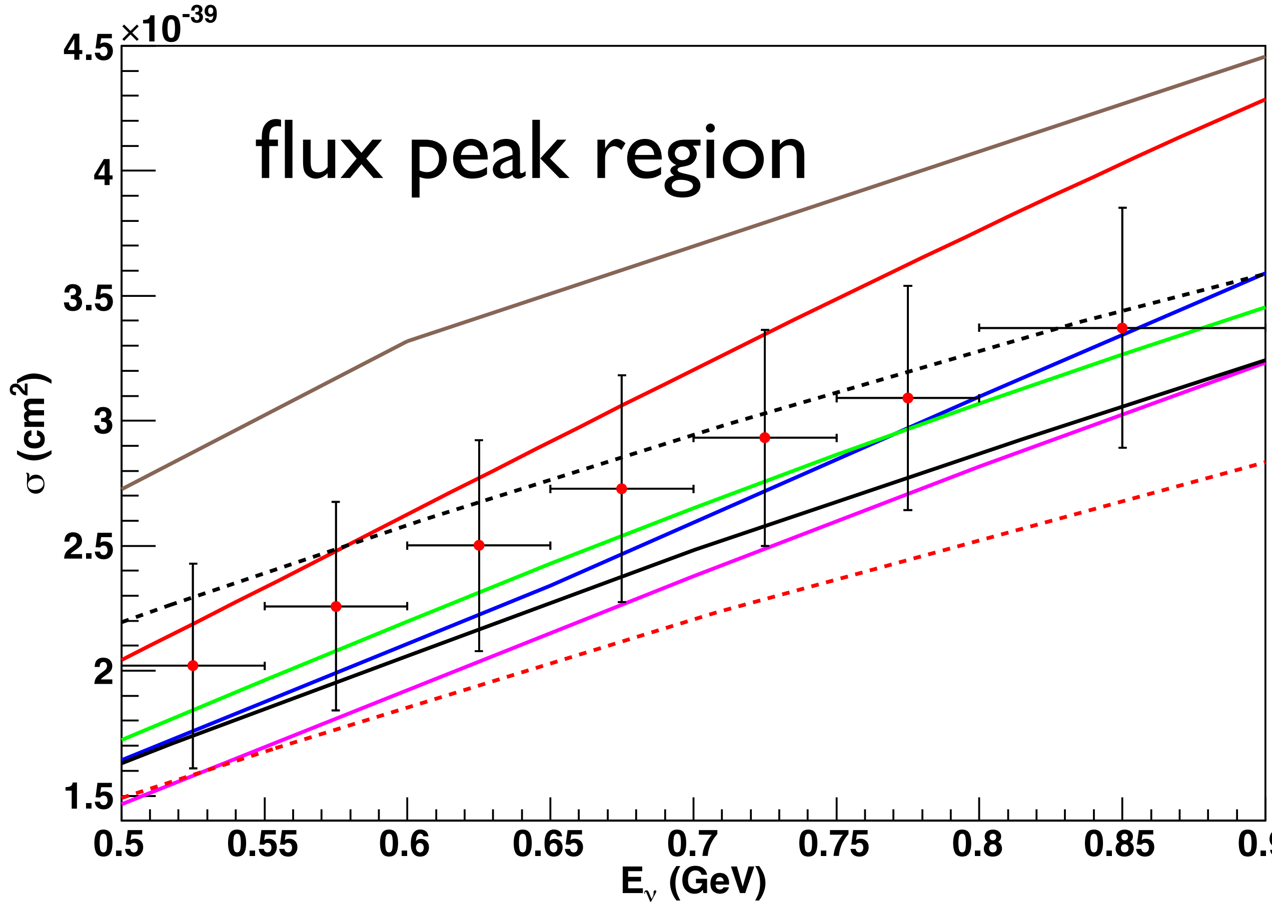


$\bar{\nu}_\mu$ CCQE σ's on ^{12}C only

- Total $\sigma(E_\nu)$ results: WARNING MODEL DEPENDENT
  - assumes independent, at-rest nucleon

Martini *et al.*:	Phys Rev C81, 045502 (2010)
Amaro *et al.*:	arxiv: 1112.2123
Bodek *et al.*:	Eur. Phys. J. C 71 1726 (2011)
Nieves *et al.*:	Phys. Rev. C83 045501 (2011)
Meucci *et al.*:	Phys. Rev. D85, 093002 (2012)





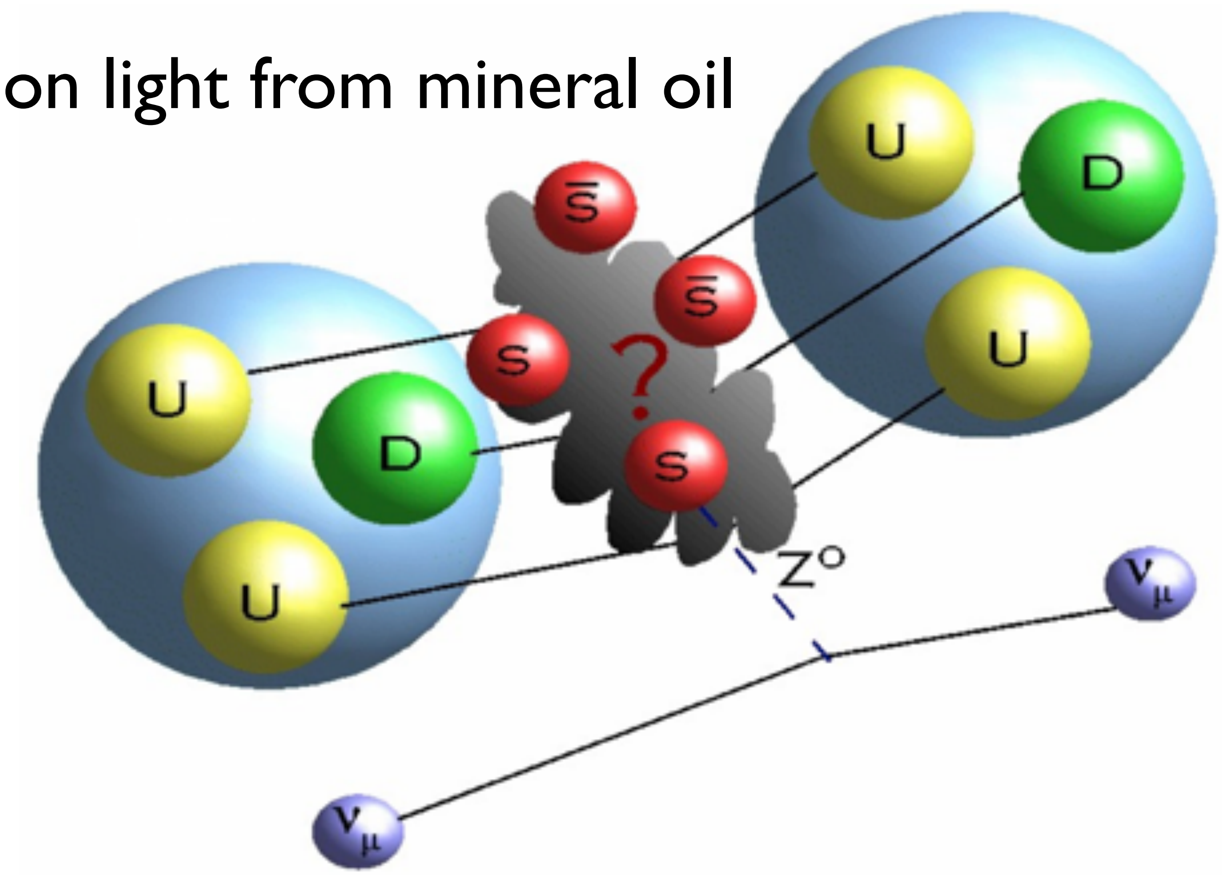
Thursday, February 21, 13

(Anti) neutrino-nucleon neutral current elastic (NCE) scattering

- CCQE reconstruction based only on μ observations, NCE offers access to the hadronic side of the neutral-current version of this process

$$\nu_\mu N \rightarrow \nu_\mu N$$

- Only possible due to scintillation light from mineral oil impurities
  - challenging! first time done in (primarily) Cherenkov detector



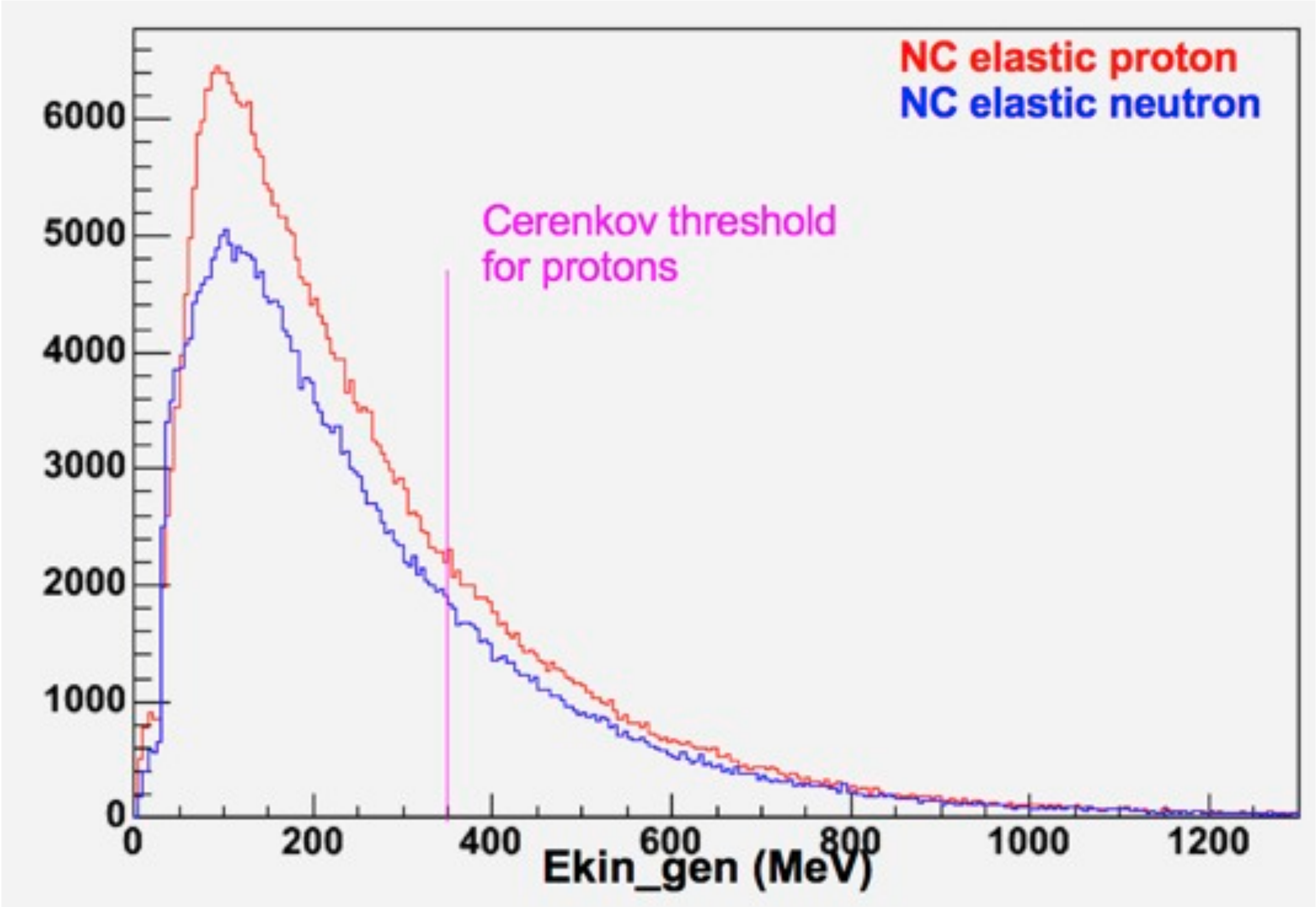
- Represents work of

  R. Dharmapalan

  University of Alabama

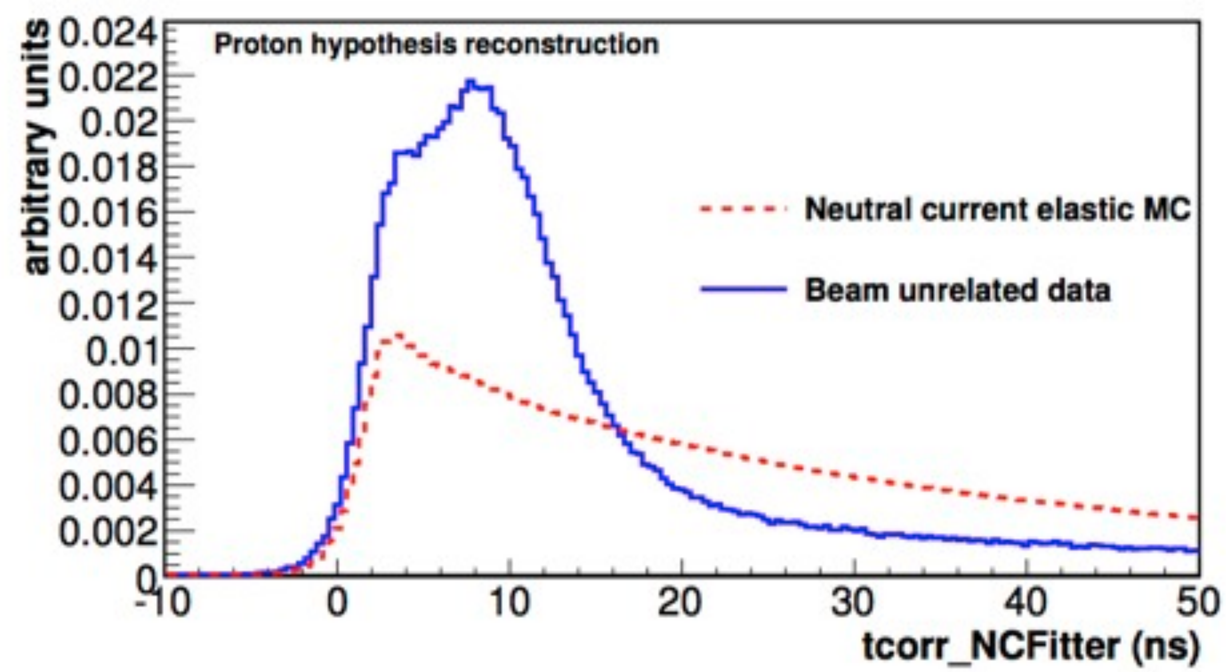
Nucleon reconstruction

- We measure sum of n+p NC interactions: identical isotropic scintillation signature for bulk of spectra
- Some separation above Cherenkov threshold (350 MeV)
- Dedicated fitter identifies kinematics via PMT hit charge and time-likelihood maximization
  - position res. ~0.7 m
  - energy res. ~20%



Event selection

1. One subevent
   - removes decaying particles (μ, π)
2. In time with ν beam
3. Low veto activity
   - ensures containment, rejects incoming
4. Signal PMT hits > 12
   - reconstructible event
5. Cut on time $\ln(L_e/L_p)$
   - rejects beam-unrelated e's
6. Reco. energy < 650 MeV
   - rejects high E backgrounds
7. 5m fiducial volume



Exp't def'n: 0 μ's, 0 FS π's, any # of nucleons

NCE sample

- 61k events pass selection
  - more than an order of magnitude larger than all other published $\bar{\nu}_\mu$ NCE data sets

Process	Contribution
$\bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + N$	48%
All ν_μ	19%
"Dirt"	17%
NC π	14%

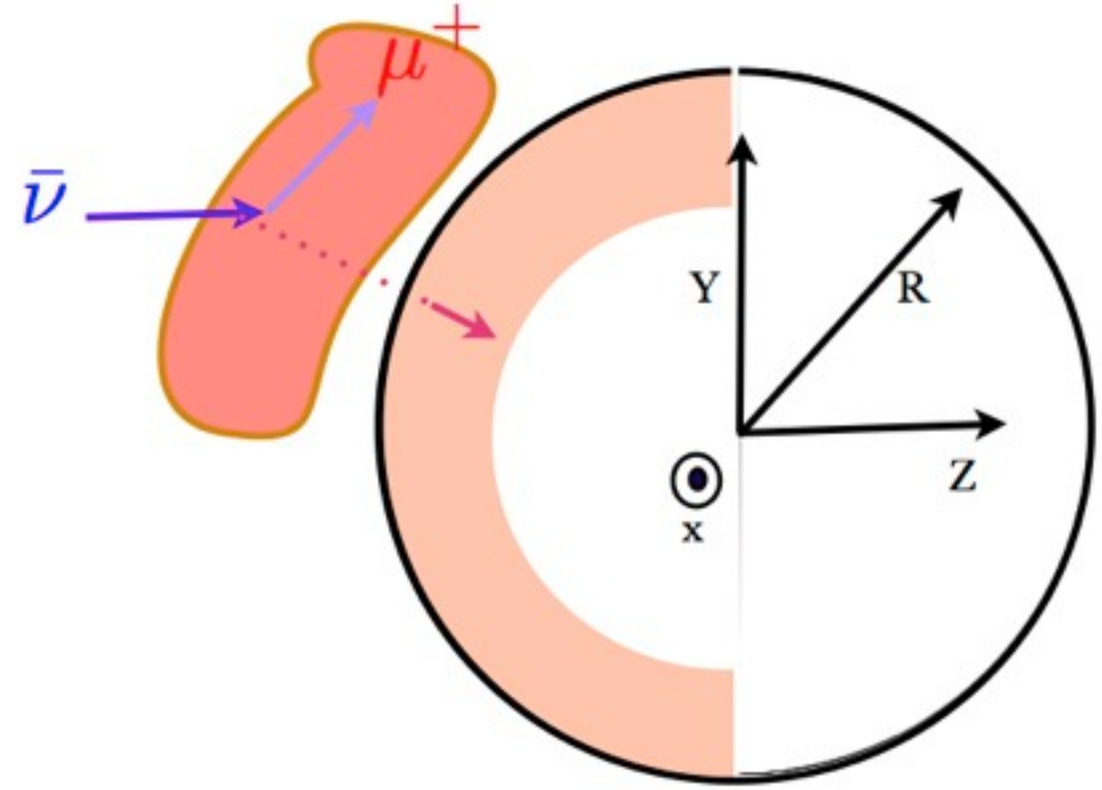
Constrained by wrong-sign measurements (→ All ν_μ)

Dedicated background measurement (→ "Dirt")

Irreducible bkg: NCπ with no final-state π (→ NC π)

Dirt background

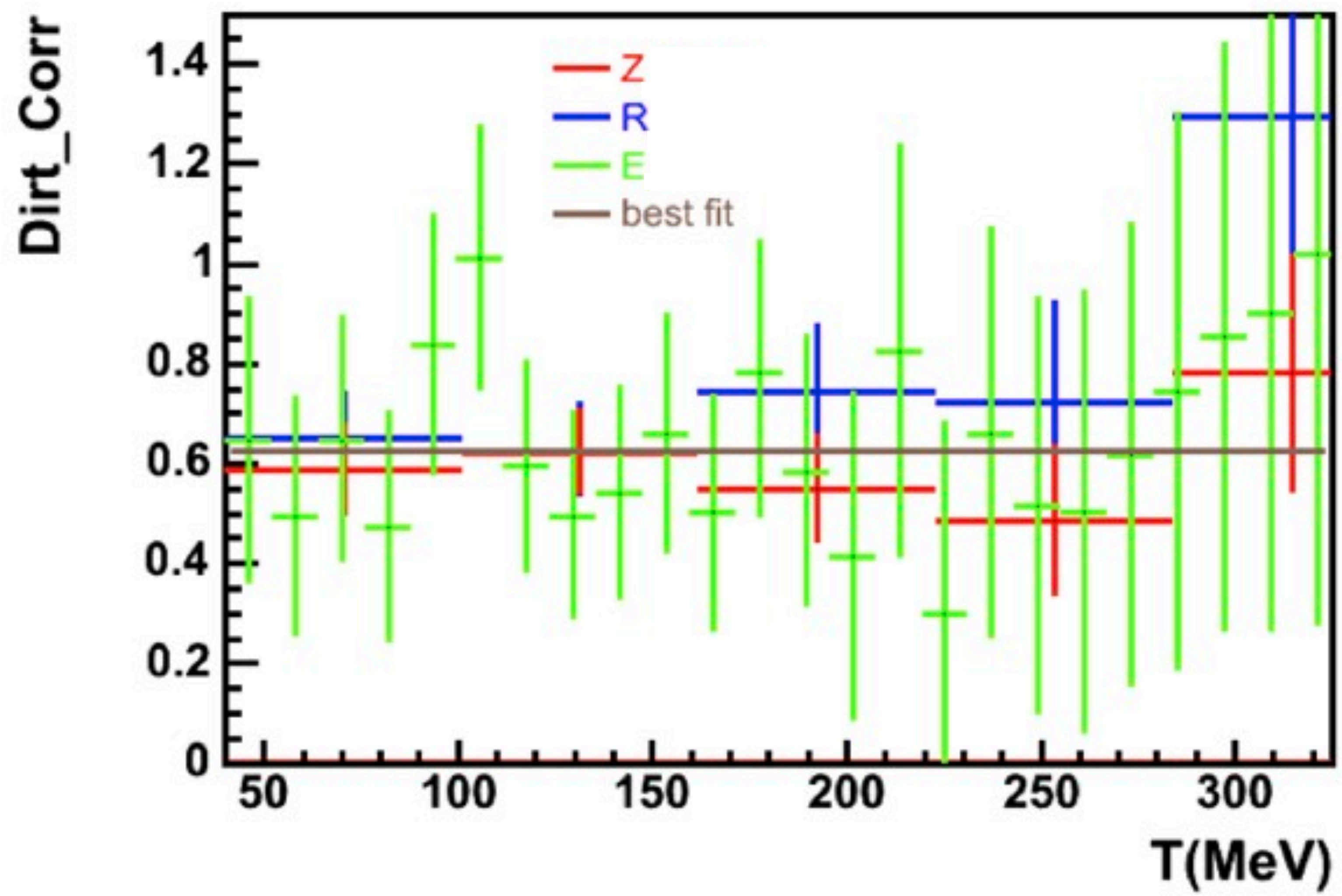
- "Dirt": events produced external to the detector, do not deposit energy in veto, lead to PMT activity
- Tend to pile up at:
  - high radius
  - upstream half of detector
  - low energy



- Form dirt-enriched samples based on these correlations

Dirt background

- Many, many measurements:
  - 10 energy bins in the beam direction (Z) and radius (R)
  - fit the energy spectrum directly (E)
  - Results consistent with ν mode NCE dirt fits
  - final uncertainty on dirt events less than 10%



Cross-section calculation

- Main result is dσ/dQ^2. Can calculate Q^2 based on nucleon energy assuming interaction with an independent, at-rest target

$$Q^2 = 2m_N \sum T_N$$

- Simple σ calculation:

$$\frac{d\sigma}{dQ^2} = \frac{\sum_j U_{ij}(d_j \times \frac{s_j}{s_j+b_j})}{\Delta Q^2 \epsilon_i \Phi T}$$

unfolding matrix (U_{ij}), reco data (d_j), MC signal, bkg (s_j, b_j), bin width (ΔQ^2), detection efficiency (ϵ_i), int. flux (Φ), nucleon targets (T)

Systematic uncertainties

$$\frac{d\sigma}{dQ^2}^k = \frac{\sum_j U^k_{ij}(d_j \times \frac{s^k_j}{s^k_j + b^k_j})}{\Delta Q^2 \epsilon^k_i \Phi^k T}$$

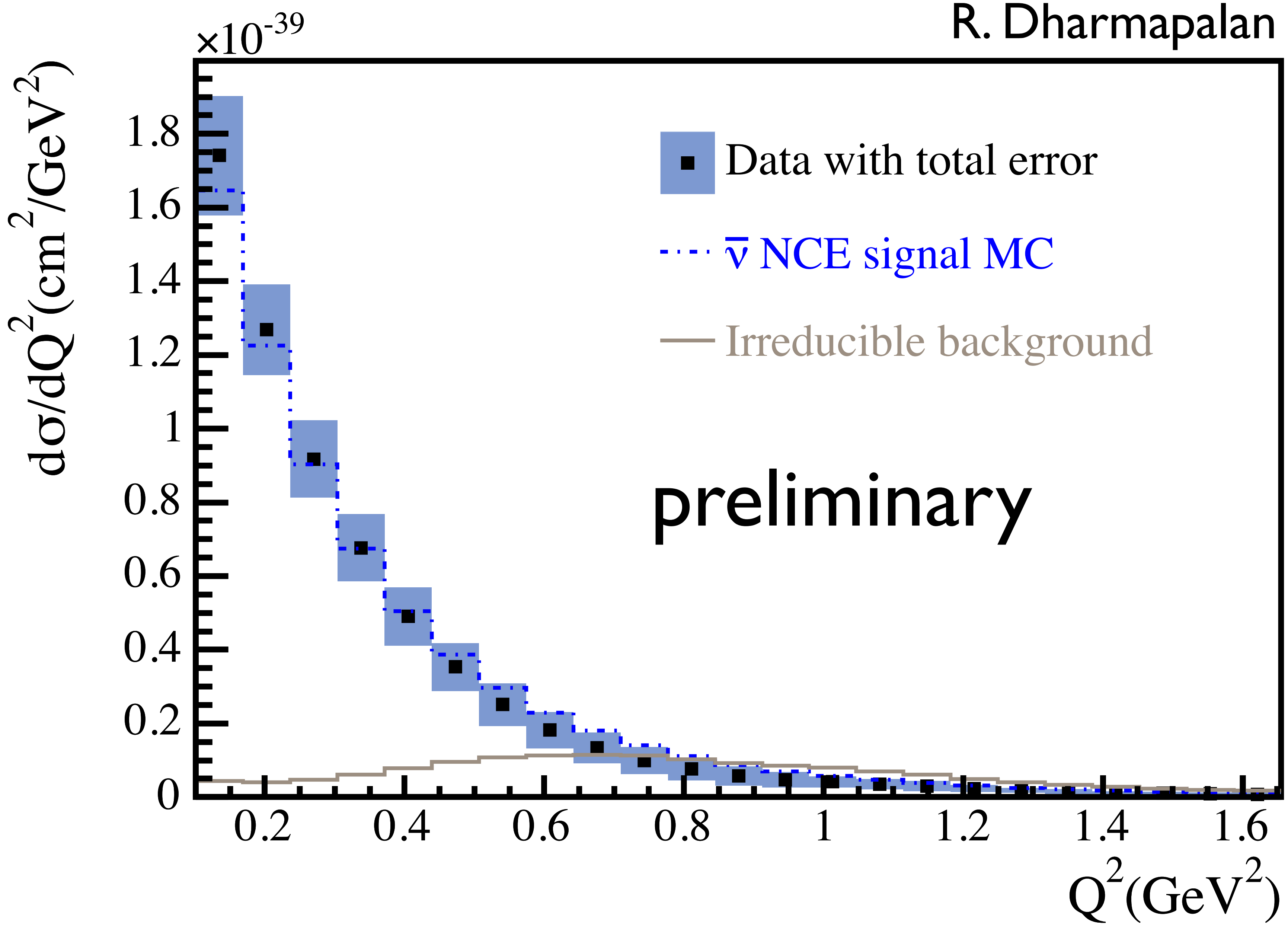
Error source	Normalization uncertainty (%)
anti-ν flux	6
Backgrounds	6
Detector	15
Unfolding	7
Total (includes correlations)	**21**

Uncertainty dominated by light propagation model

Results

R. Dharmapalan

2nd time publicly shown



- Adequate normalization agreement with MC prediction (tuned to ν_μ CCQE data!)
- Some shape disagreement at mid-high Q^2

1. Introduction

ν cross sections in a single-detector oscillation exp't

recent σ interest from MiniBooNE neutrino-mode data

2. Anti-neutrino analyses

ν_μ background (wrong signs)

$\bar{\nu}_\mu$ NCE σ (new!)

$\bar{\nu}_\mu$ CCQE σ (new!)

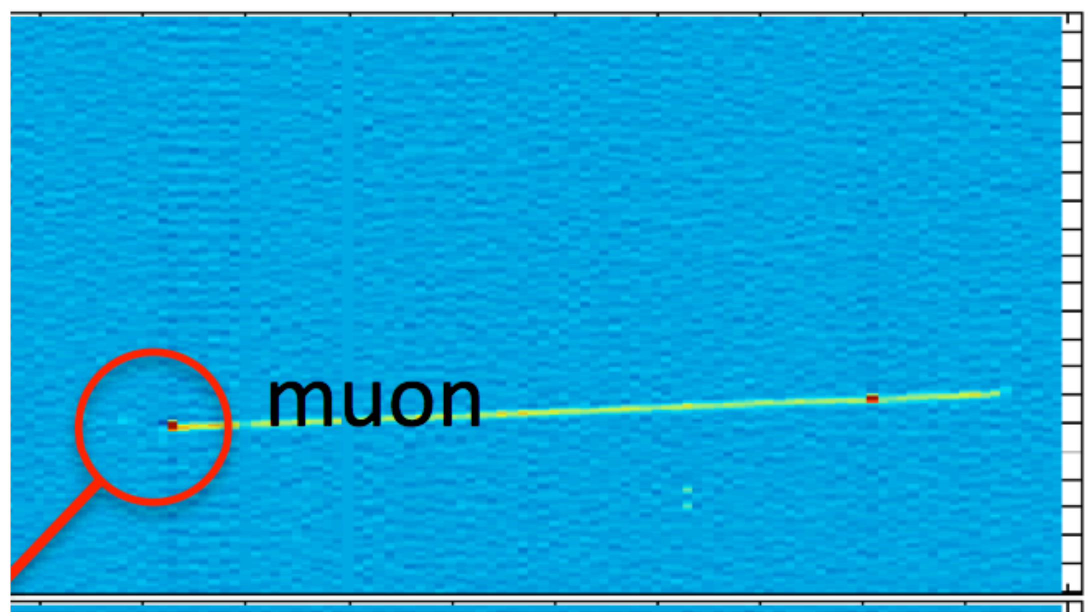
4. Outlook and summary

Future experimental tests

- These new anti-neutrino data beginning to tightly constrain models for proposed multi-nucleon mechanism, lots more work to be ready to meet next-generation oscillation experiment needs
  - experimentally and theoretically!
- Detailed experimental info already here and more coming from variety of detector technologies observing wide range of E_ν (exactly what we need!)

★ - MINERνA (A-dependence!)
★ - ArgoNeuT
★ - NOνA
- T2K
★ - MINOS
- ICARUS
★ - MicroBooNE
★ - SciBooNE

★ FNAL!



K. Partyka for ArgoNeuT, NuInt12

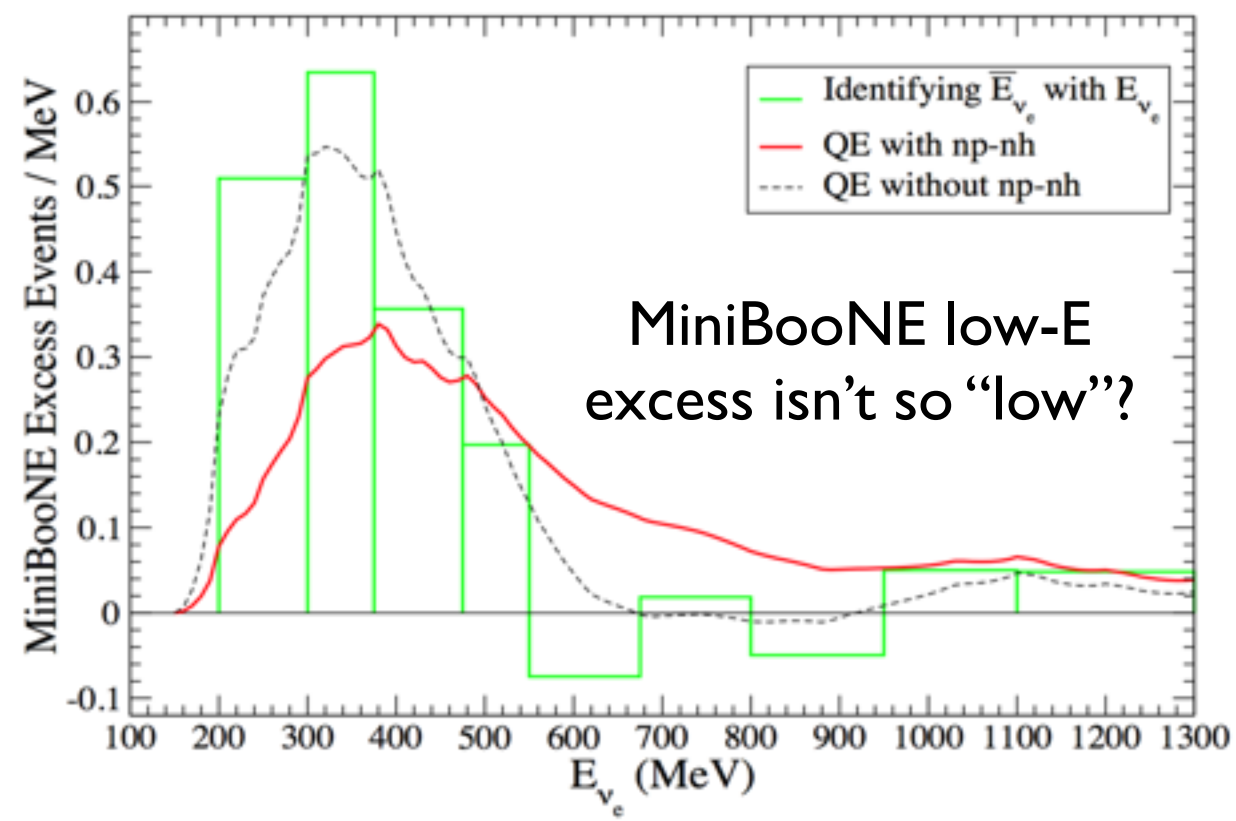
Summary

- Experimental puzzle whose resolution may involve an unexpected interaction type may shed light on intranuclear dynamics
- New anti-neutrino NCE and CCQE σ results constrain many predictions for such a mechanism
- Resolution crucial to understand for future oscillation experiments
- MiniBooNE has published > 90% of neutrino mode data, and today's analyses bring the total in anti-neutrino mode to > 80%
- Papers from both analyses soon!

Backup

Impact on oscillation physics?

Martini *et al.* arXiv:1202.4745

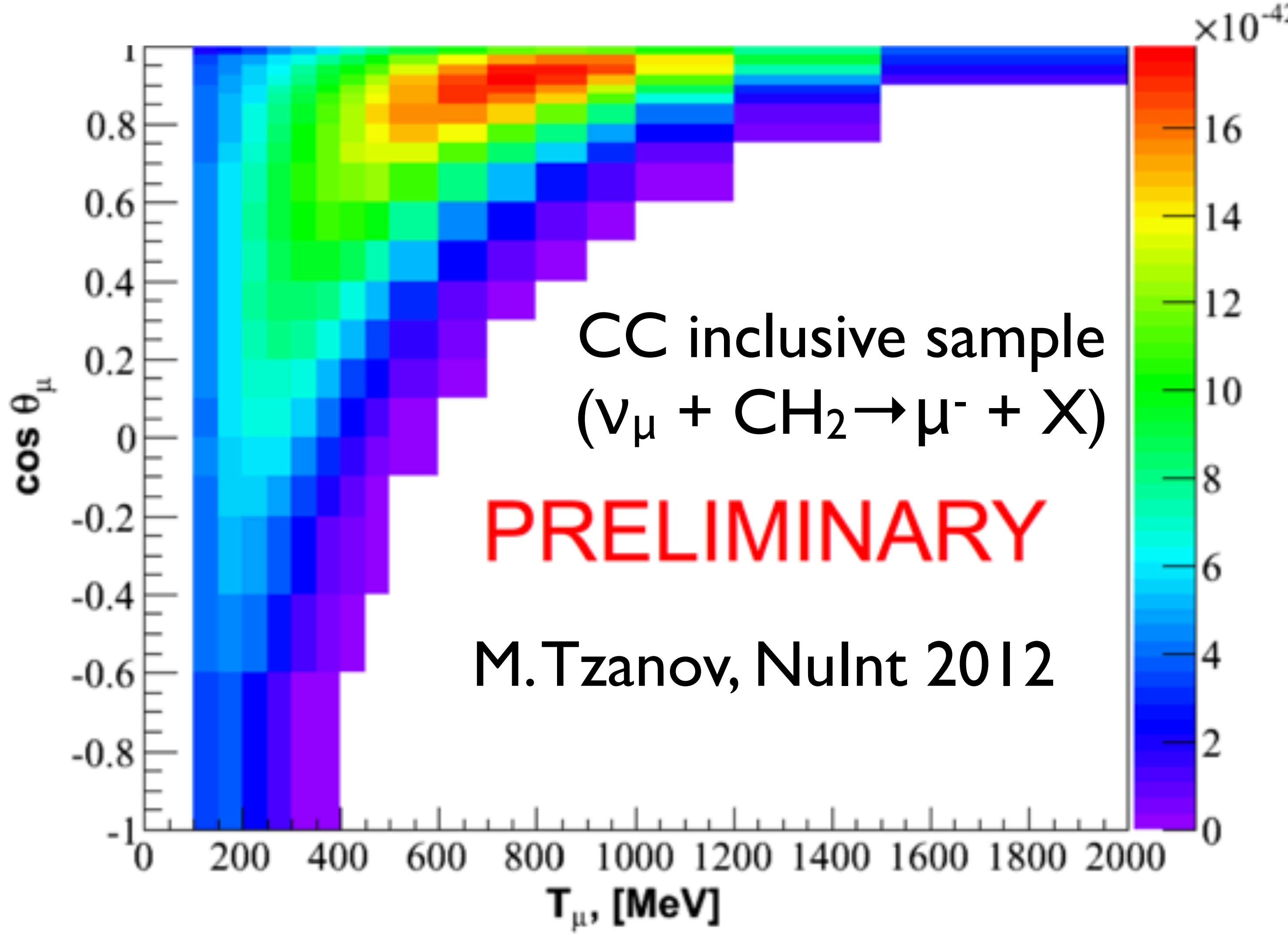


- Multiple theory groups claim the absence of multi-nucleon events in MiniBooNE MC significantly biases the ν_e oscillation results
  - proposed effect: current reconstruction biases events towards lower energy
    - ➡ would effect Δm^2 extraction, change compatibility of data with osc. hypothesis
- Have done some preliminary analyses in MiniBooNE to estimate this effect
  - results suggest much smaller effect than indicated above
  - uncertain if these np-nh events are truly present or not, no proper model exists to rigorously evaluate their effect
- Rigorous test: ν_e σ measurements with νSTORM

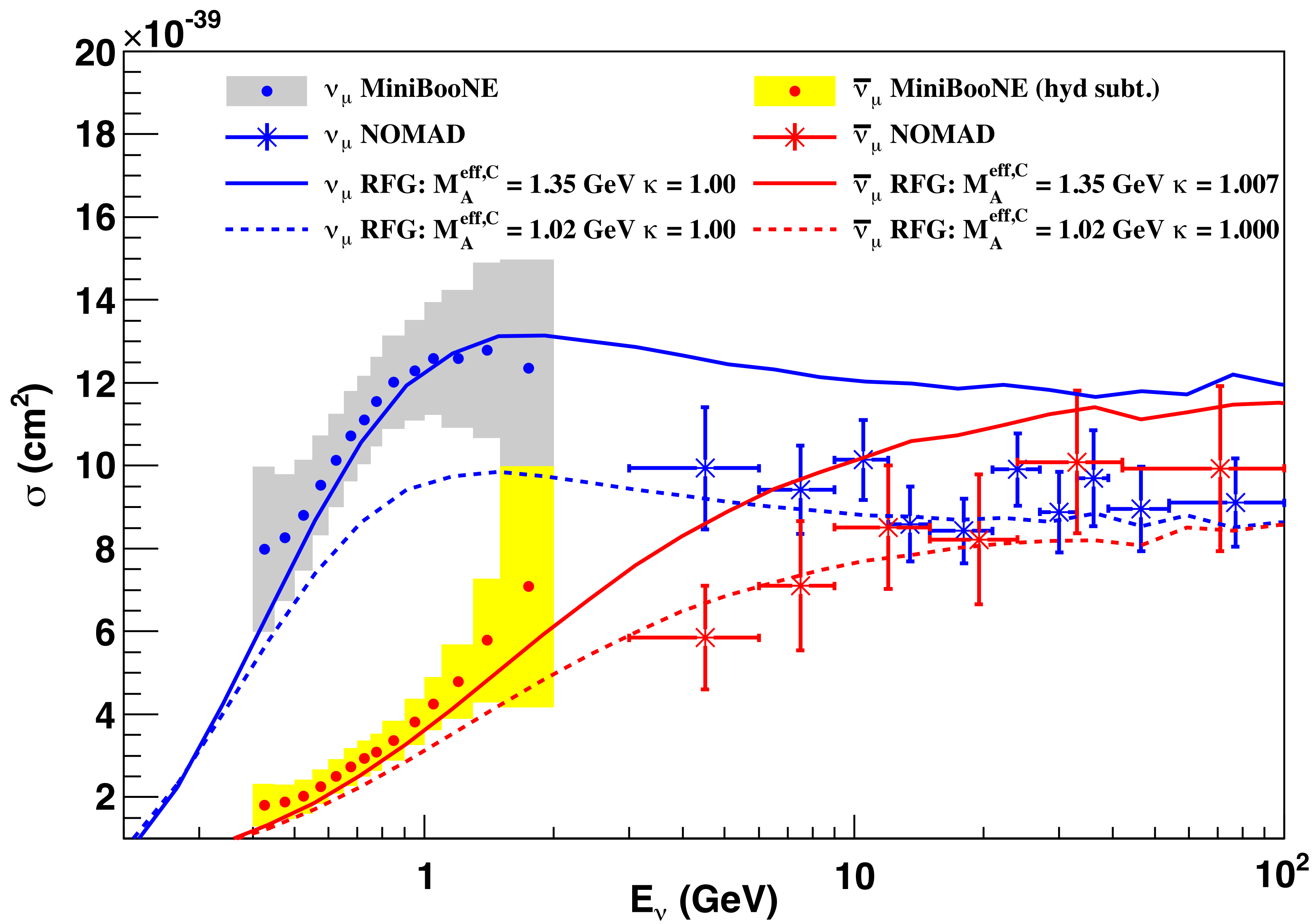
Future experimental tests: MiniBooNE!

- New hadronic late light fitter gives model-independent measurement of E_ν in CC inclusive measurement
  - Does reco. E_ν from hadronic light give larger values compared to that from lepton observations? Might expect so if multinucleon events were 40% of CC rate.

- Merging of μ and proton fitter.
  - if MiniBooNE uses "tracking style selection" (1μ + 1p), does the ν_μ CCQE "excess" go away?

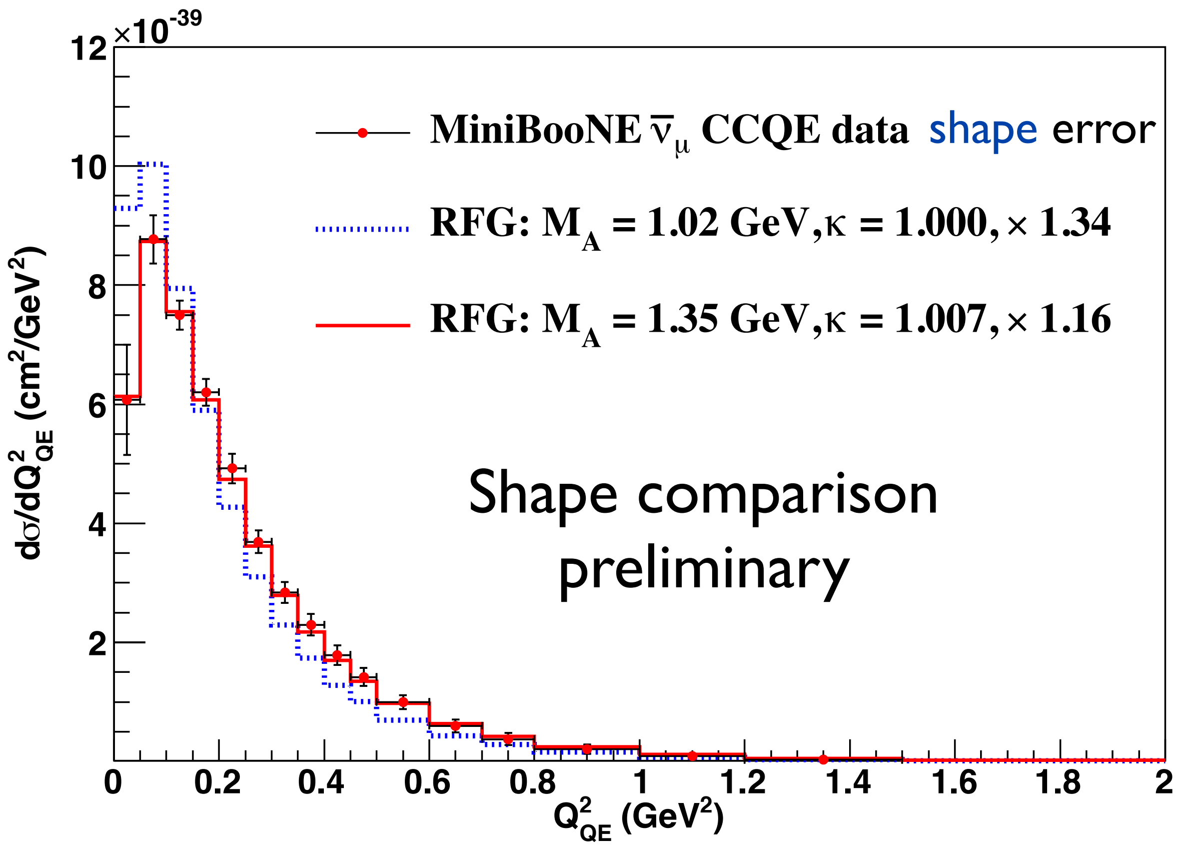


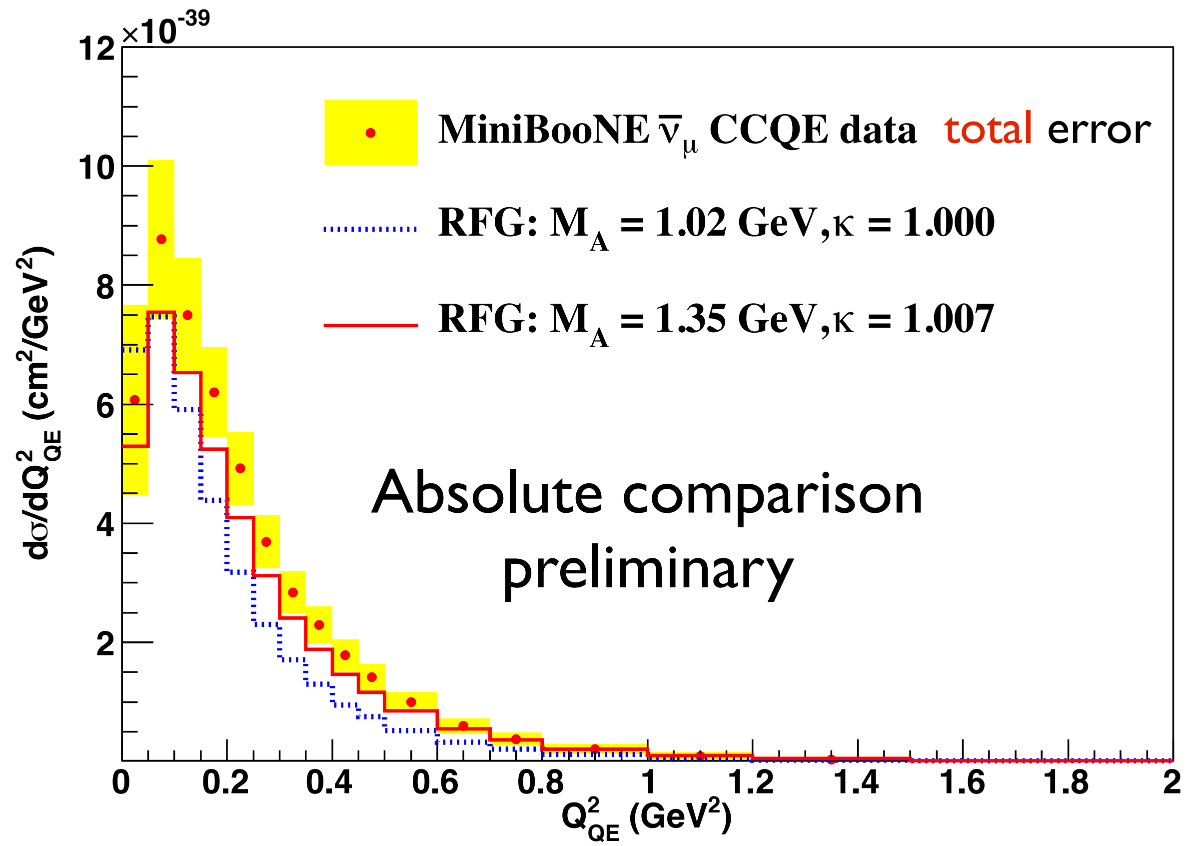
Comparison to NOMAD data



$\bar{\nu}_\mu$ CCQE σ's on ^{12}C only

- Under same assumptions on underlying interaction, can calculate "Q^2_{QE}"

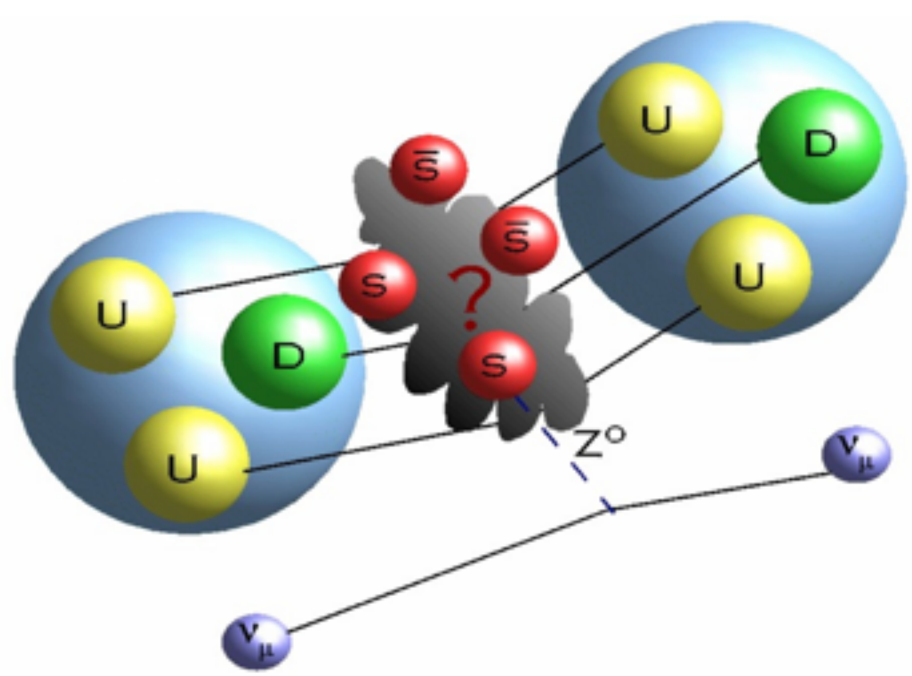


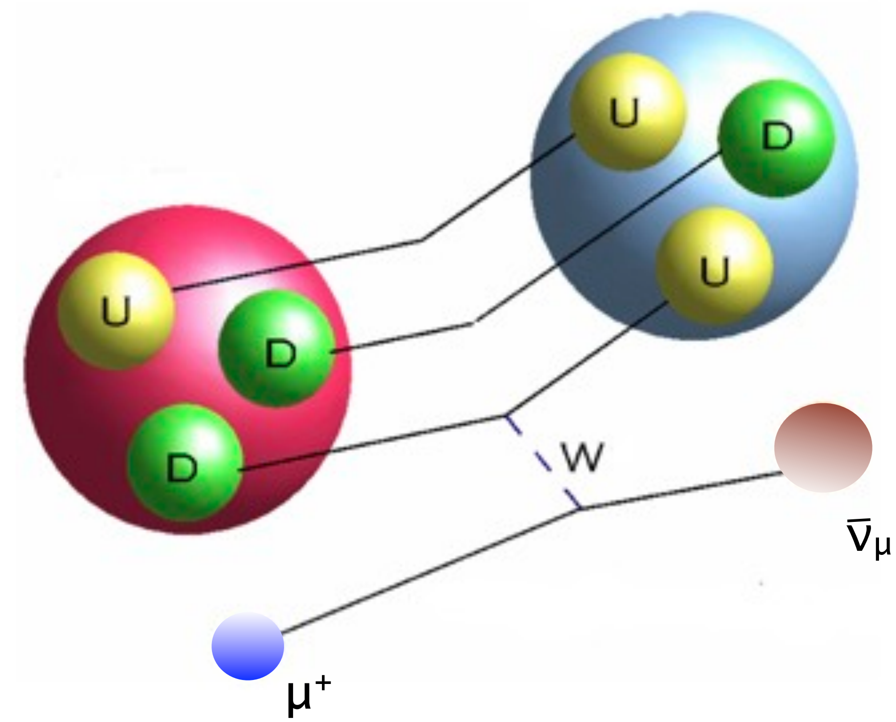


- Again, data prefers higher normalization, harder spectrum compared to expectations with M_A = 1.0 GeV

- Robust MiniBooNE measurements:

ν_μ NCE	$\bar{\nu}_\mu$ NCE	ν_μ CCQE	$\bar{\nu}_\mu$ CCQE
PRD 82, 092005 (2010)	This work	PRD 81, 092005 (2010)	This work



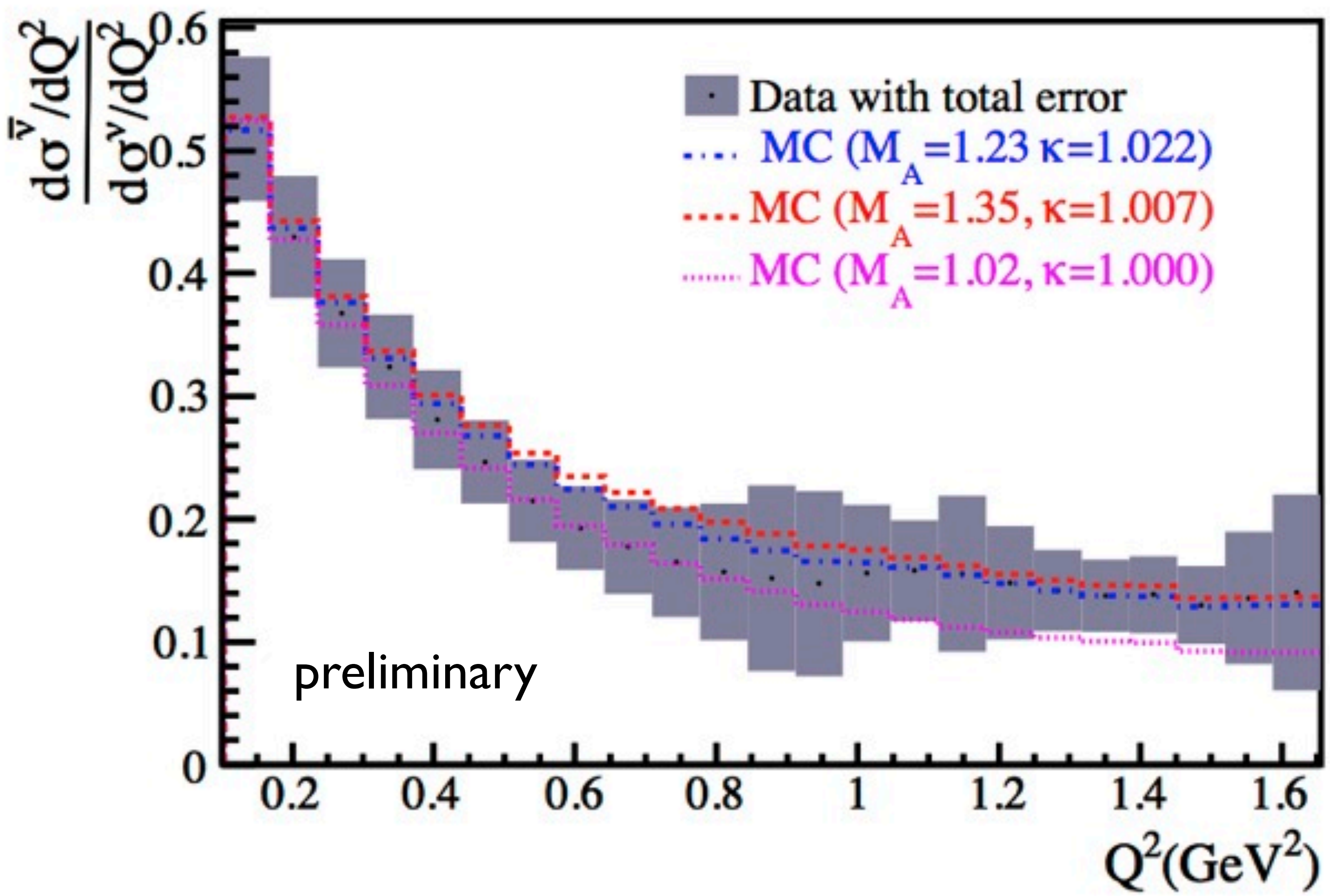


- Can exploit correlated systematics:
  - detector errors: anti-ν_μ / ν_μ, same channel
  - flux errors: NCE/CCQE in same beam

} will show combined measurements of both types

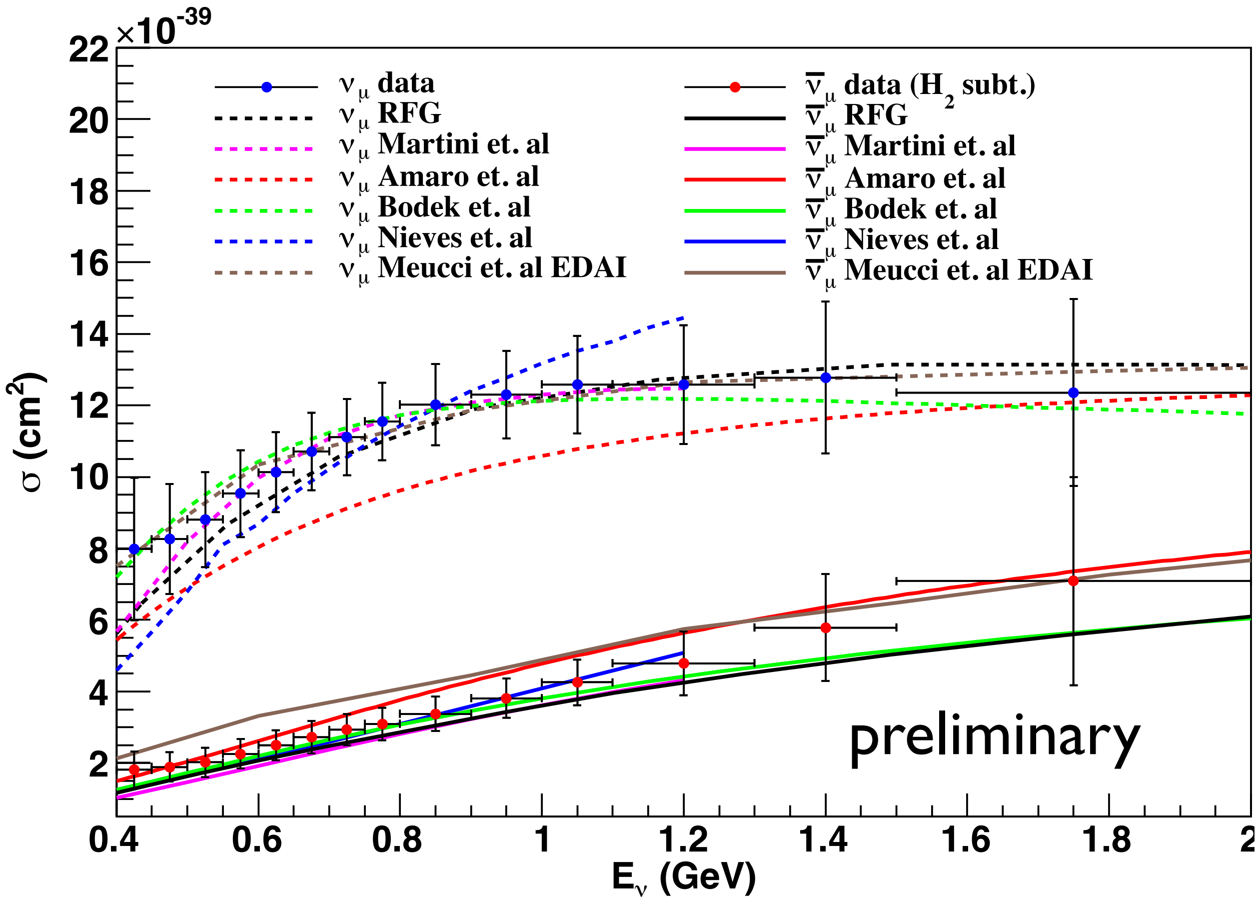
NCE ratio: $\bar{\nu}_\mu$ / ν_μ

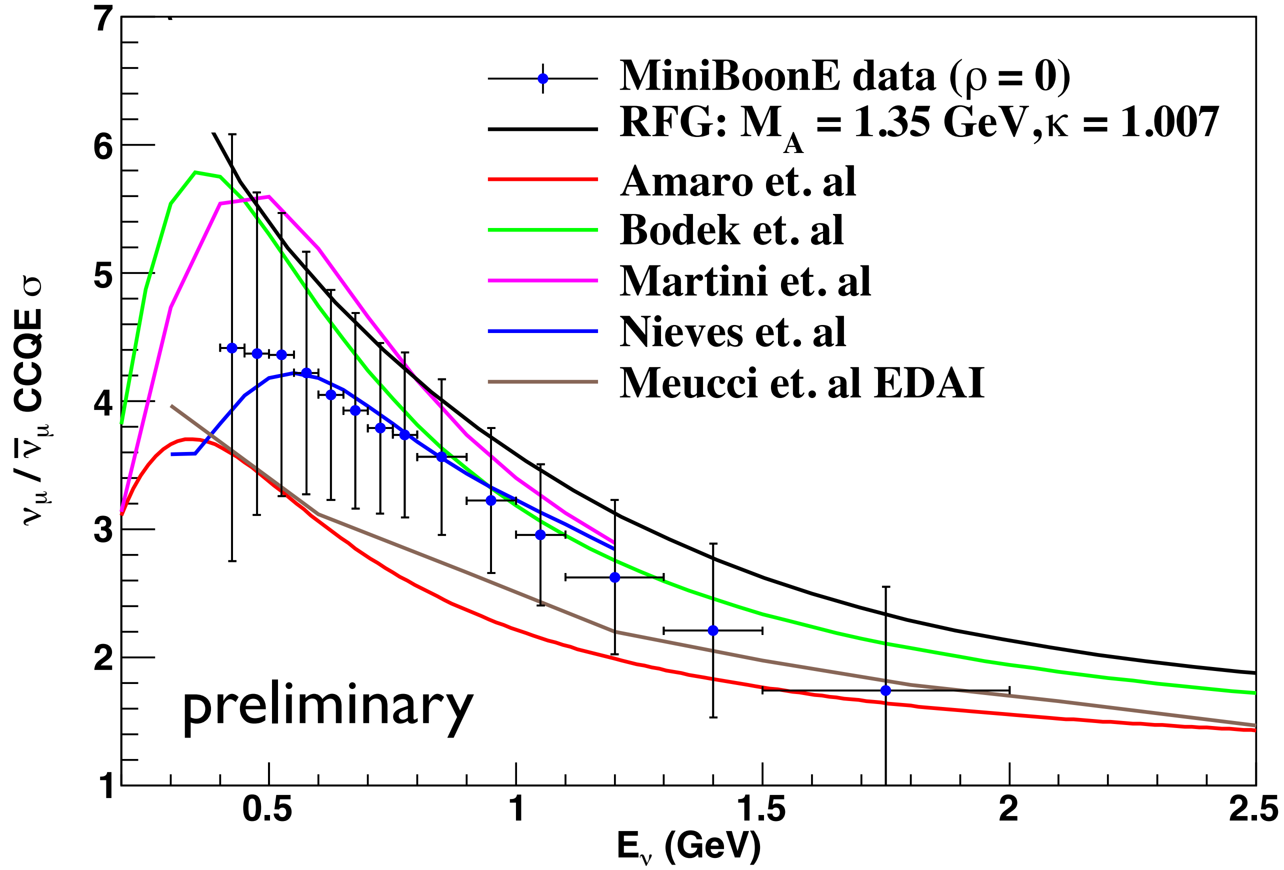
- Carefully evaluated correlated uncertainties implemented
  - biggest gain in light propagation model



CCQE: ν_μ / $\bar{\nu}_\mu$

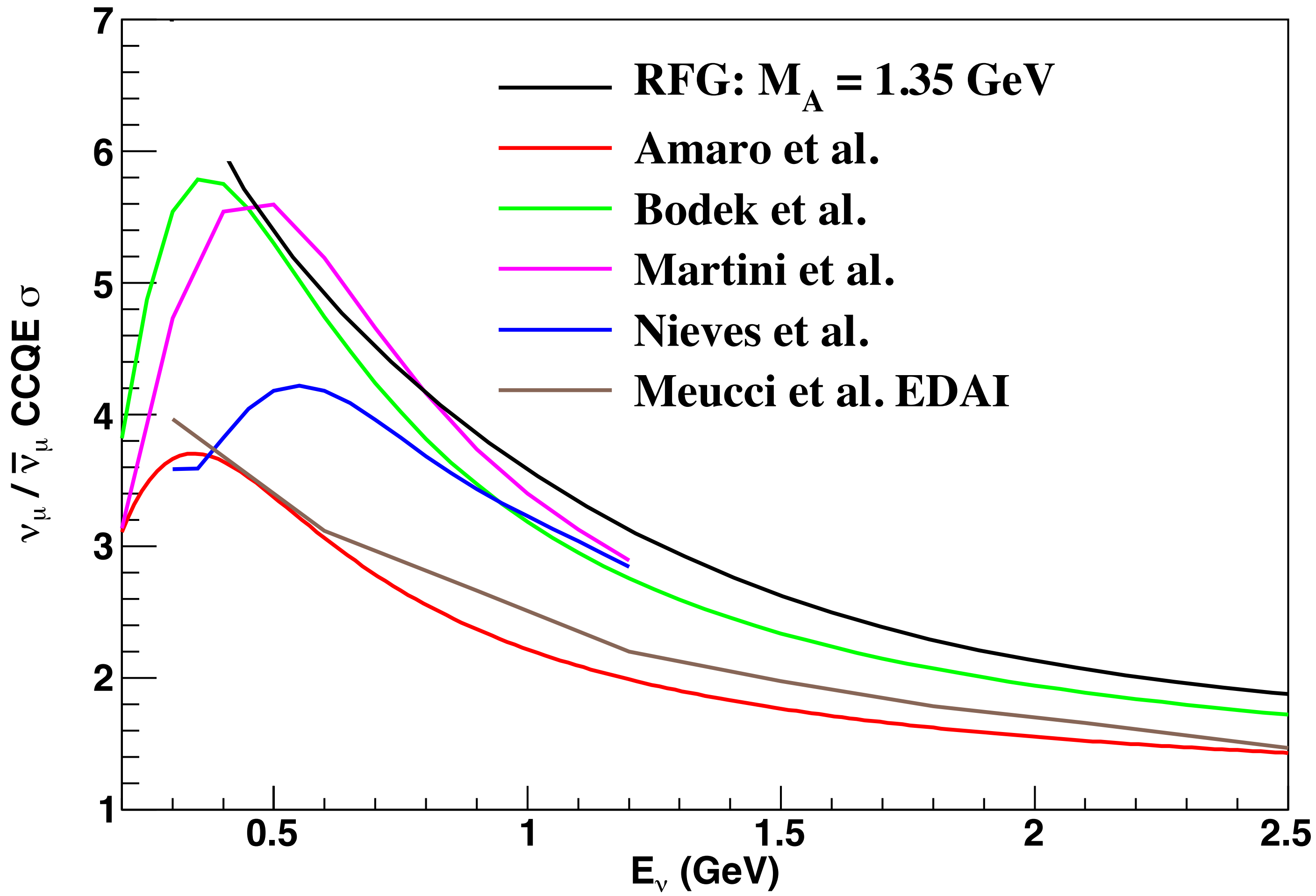
- Correlations not yet evaluated
  - ratio measurement will only get better





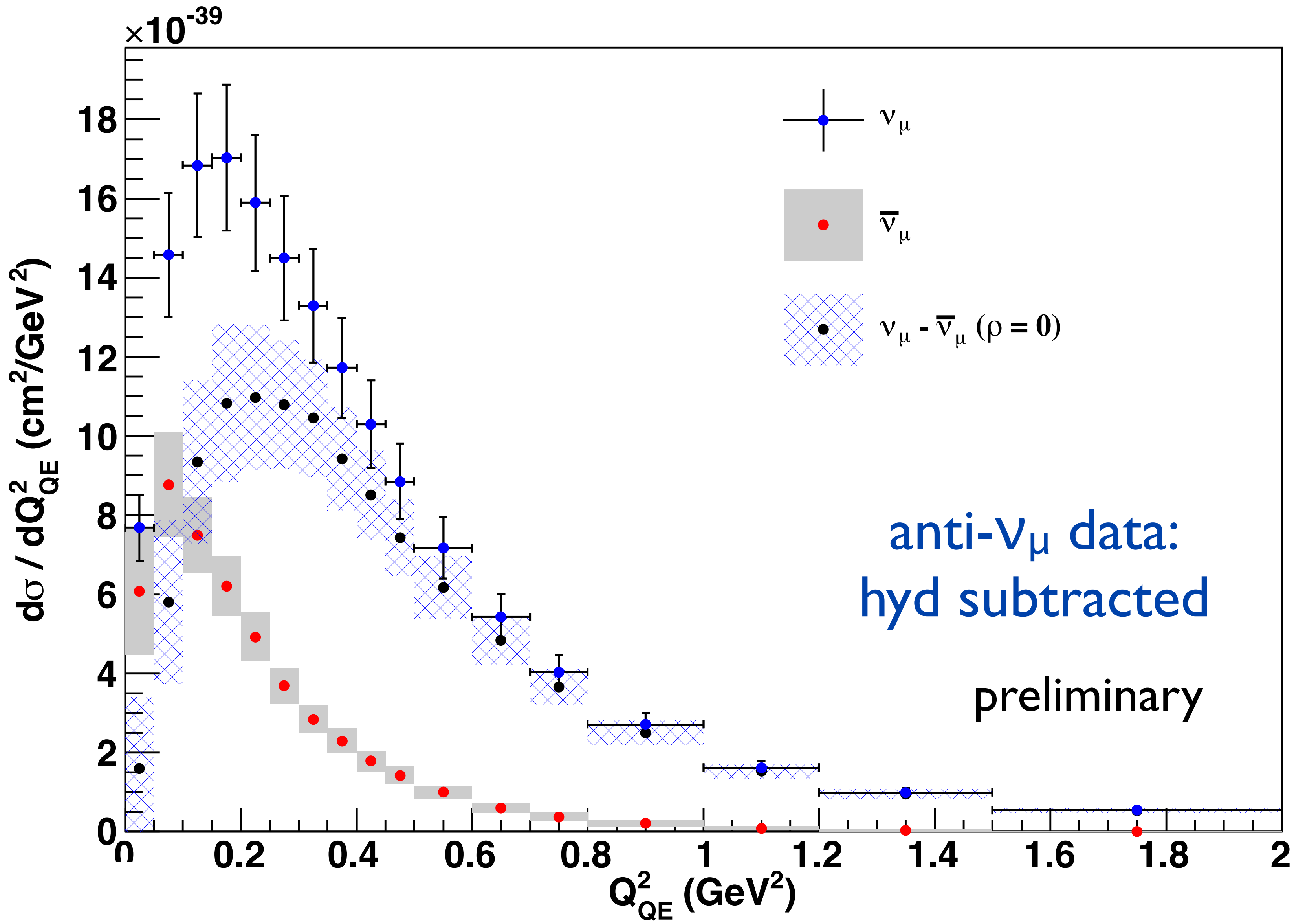
ν_μ / $\bar{\nu}_\mu$ σ predictions

- Next round of osc. experiments will need robust knowledge of both ν and $\bar{\nu}$ cross sections - current level of expectations for both:



- Worst-case scenario, could imagine lack of ν vs. $\bar{\nu}$ cross section knowledge show up as spurious $\not{C}\not{P}$ signal

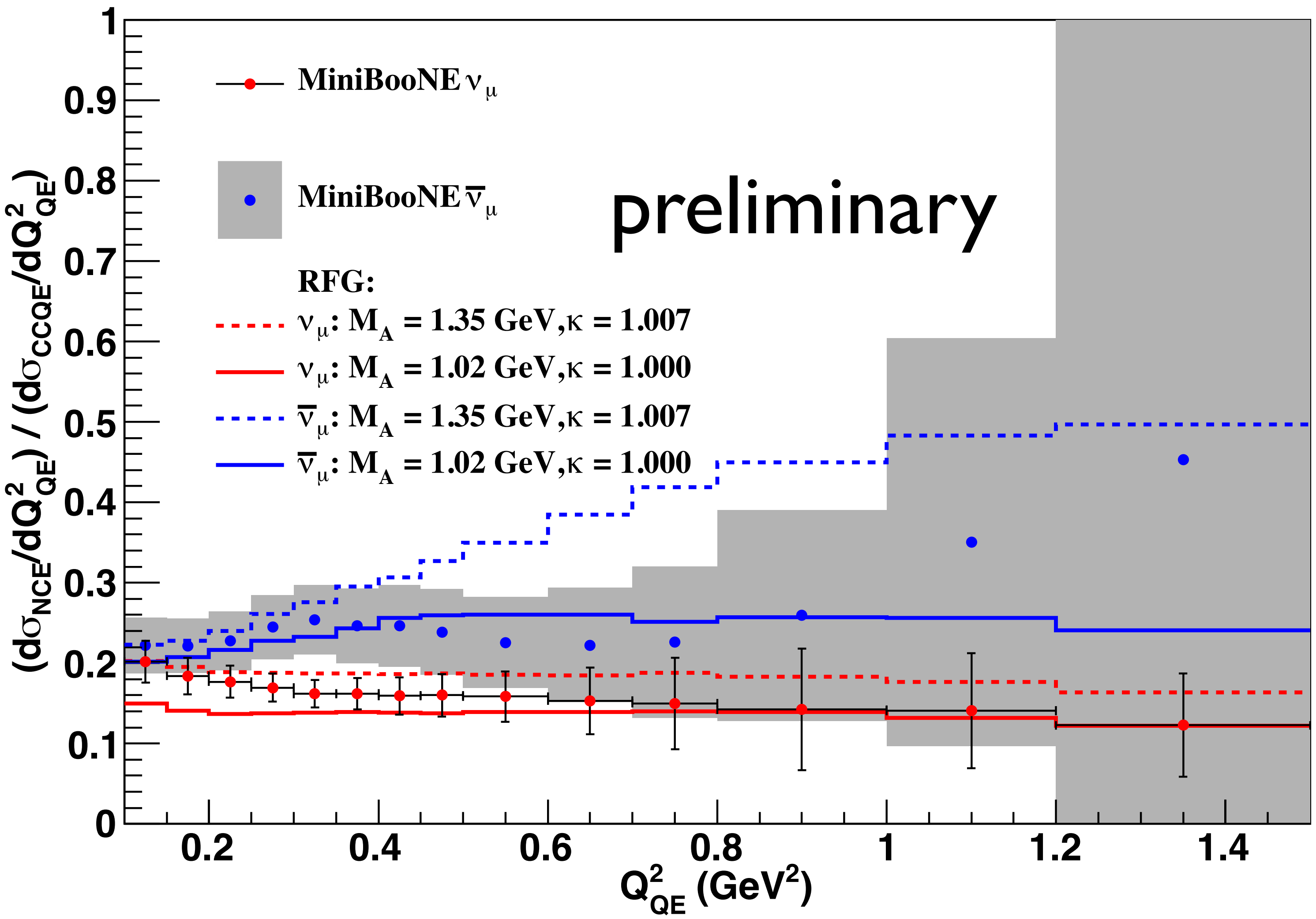
- Difference as a function of Q_2^{QE}
  - again, correlations not yet taken into account



NCE/CCQE ratio for $\nu_\mu, \bar{\nu}_\mu$

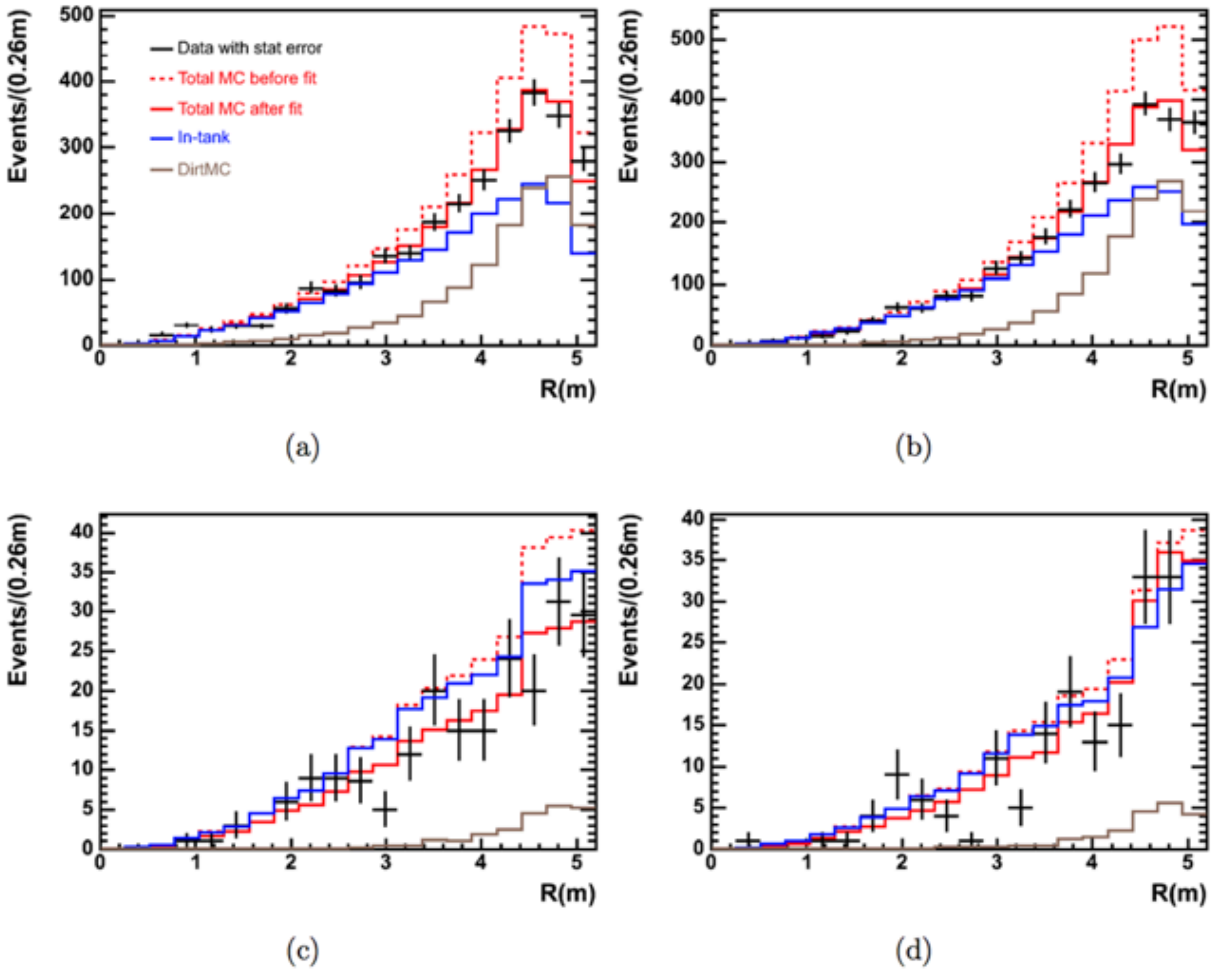
- Recall exp't definitions of Q^2_{QE} very different here: hadronic vs. leptonic observations

$$Q^2_{QE,\mathrm{NCE}} = 2m_N \sum T_N \qquad Q^2_{QE,\mathrm{CCQE}} = 2E_\nu^{QE}(p_\mu \cos\theta_\mu - m_\mu) + m_\mu^2$$



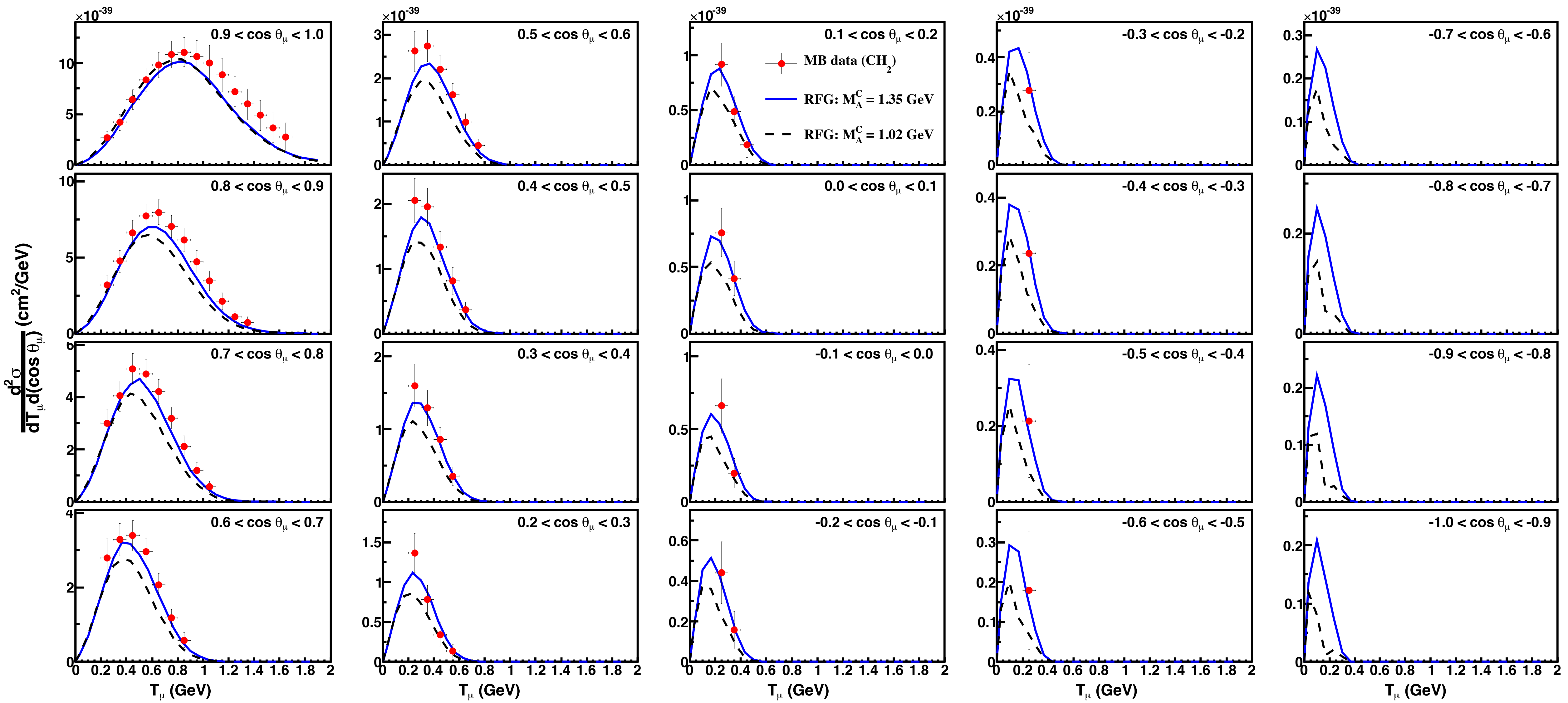
ν_μ ratio:
PRD 82, 092005 (2010)

Example of radius fits in E bins



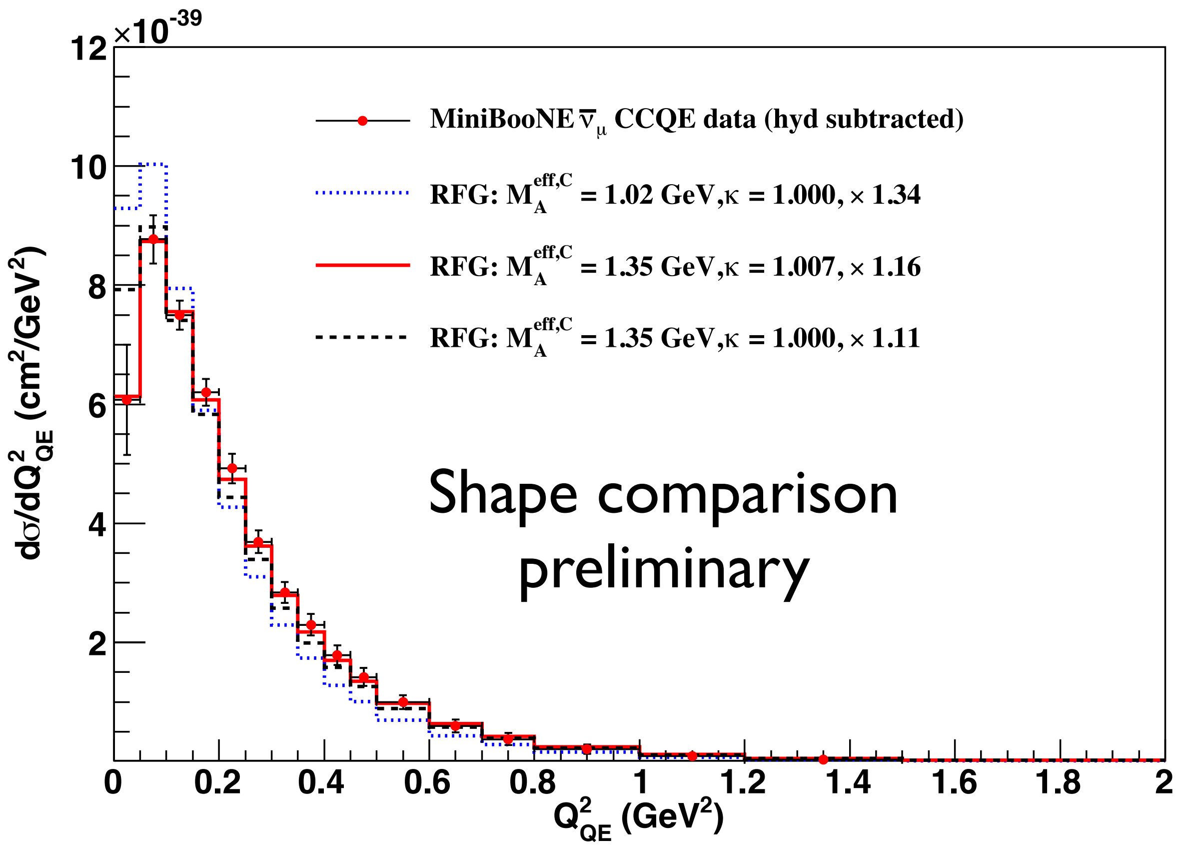
CH_2 comparison to RFG

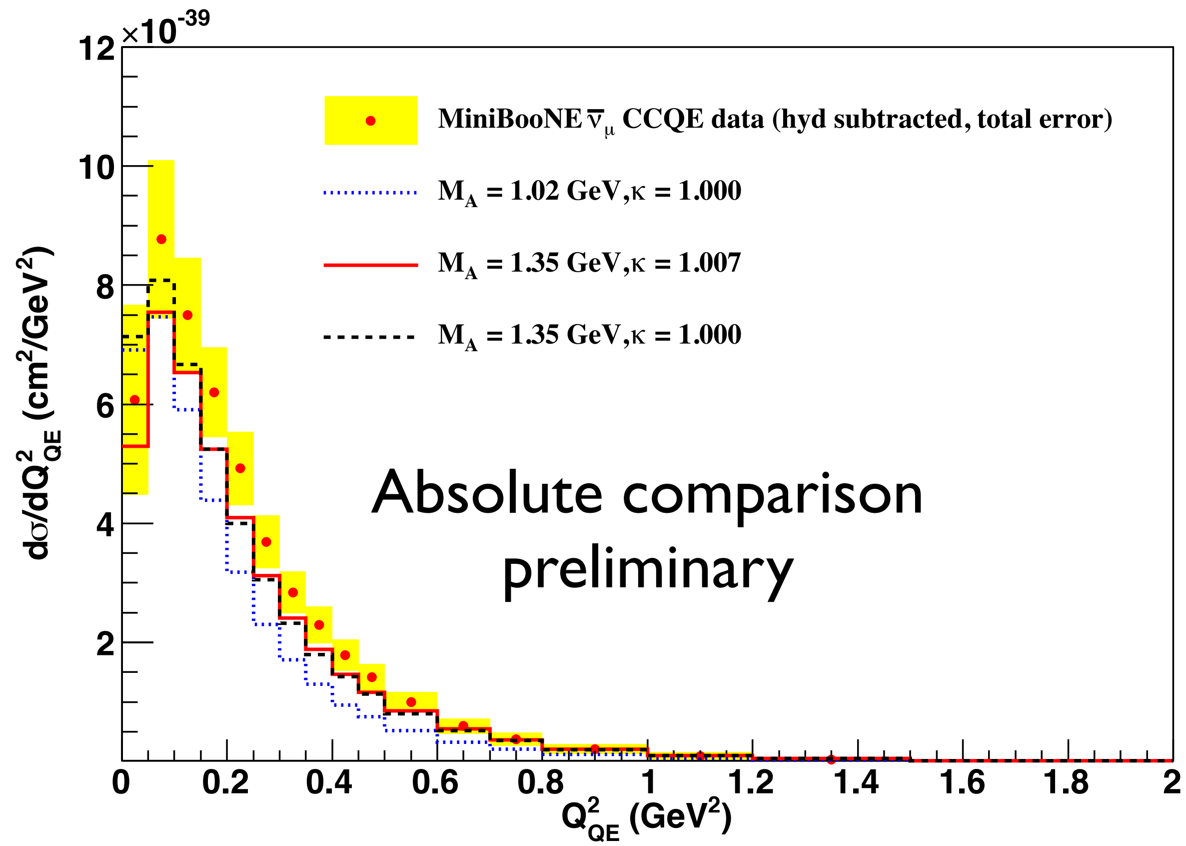
- Data shape favors high effective axial mass
  - data ~10% high of M_A = 1.35 GeV
- Total uncertainty shown here



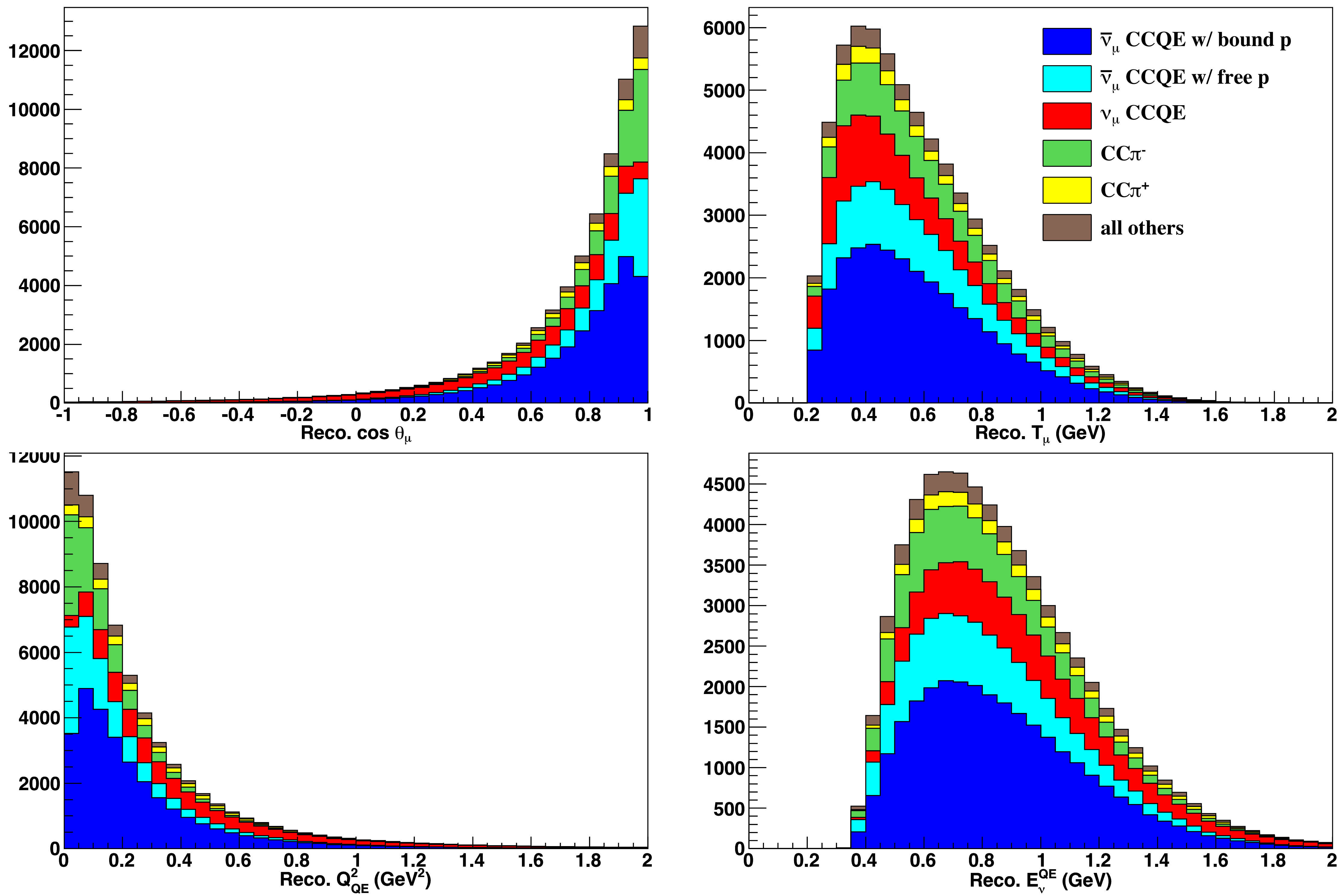
What does κ do?

- Small value of κ (1.007) does appreciably affect low Q^2_{QE}

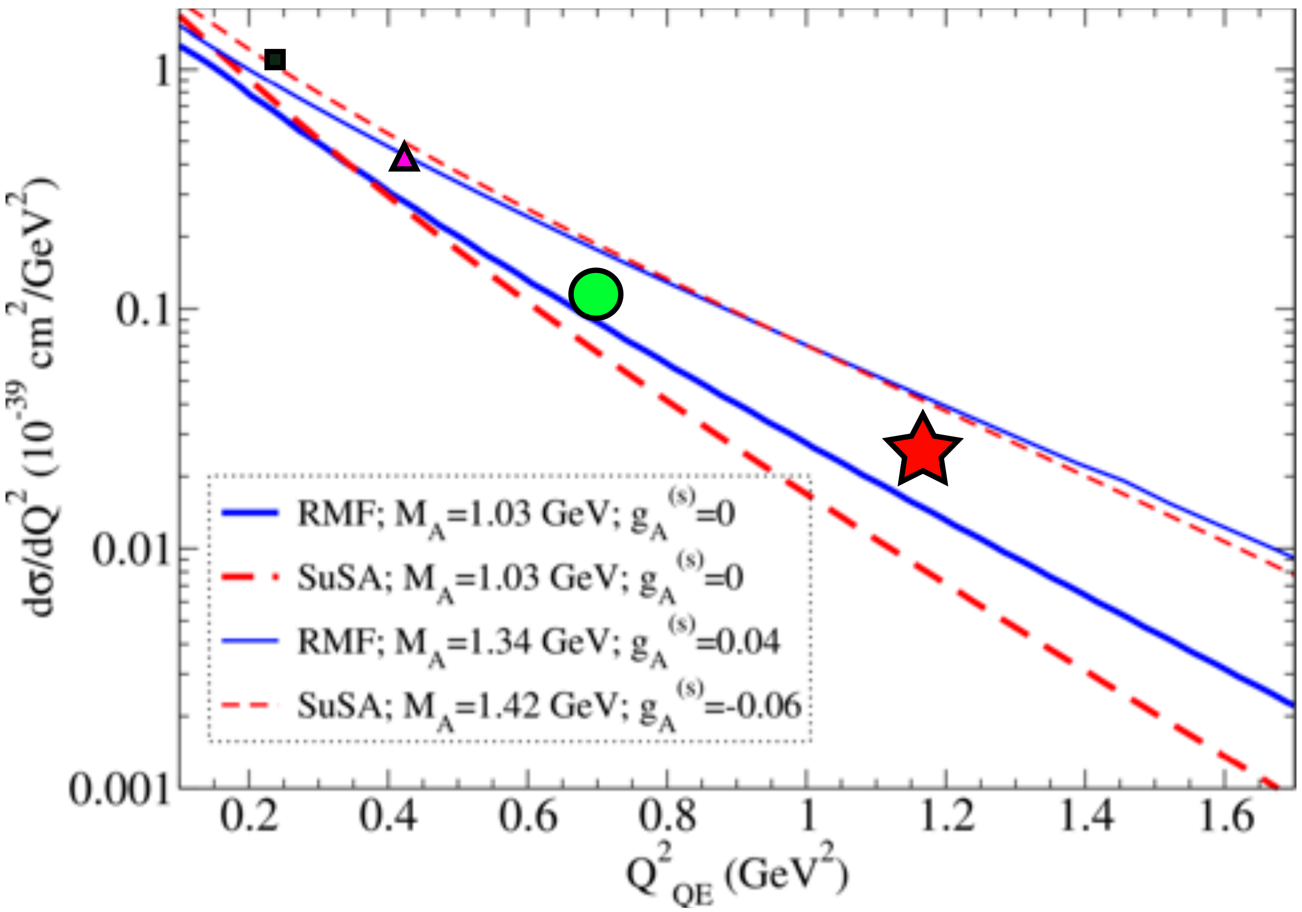


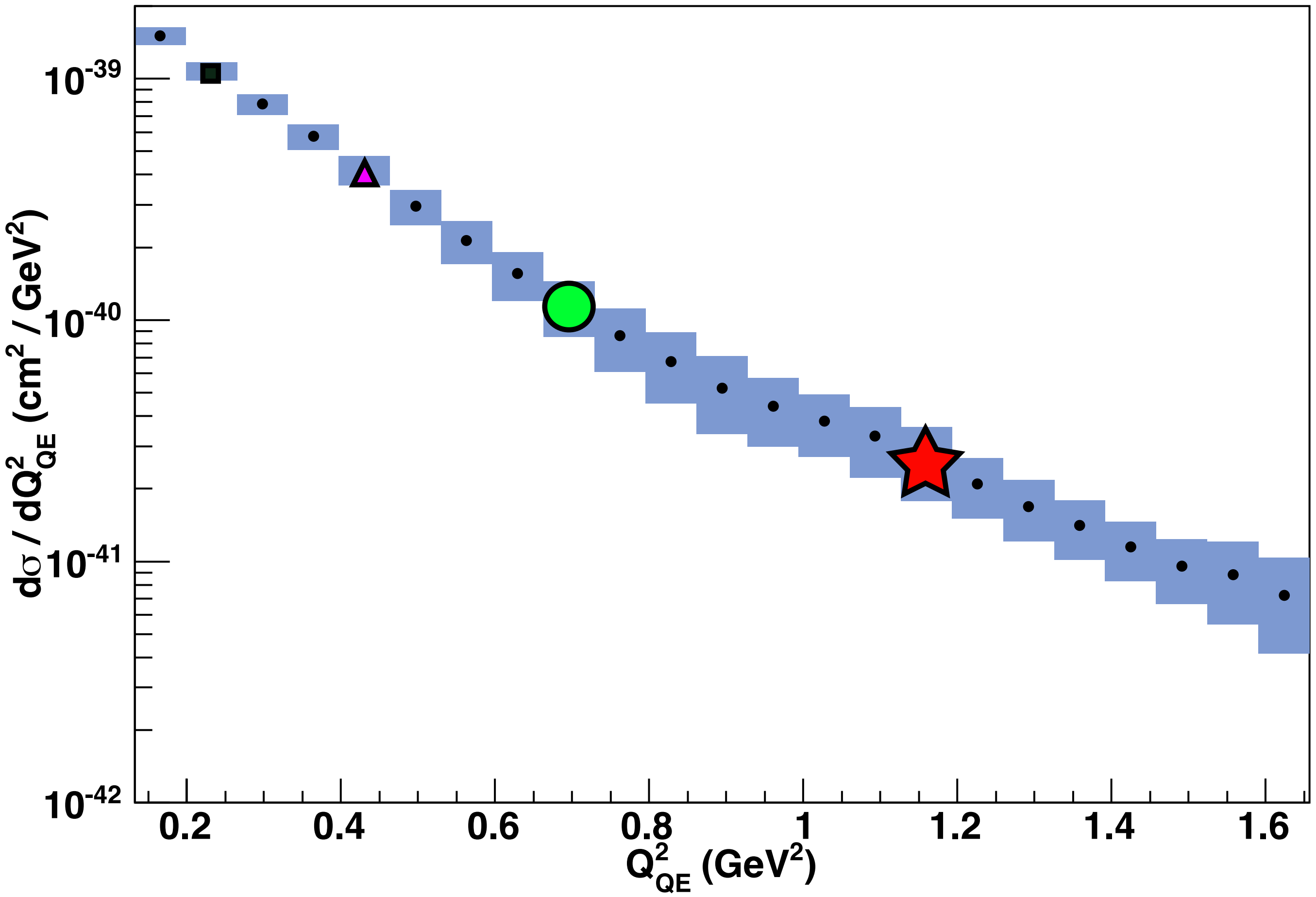


$\bar{\nu}_\mu$ sample composition

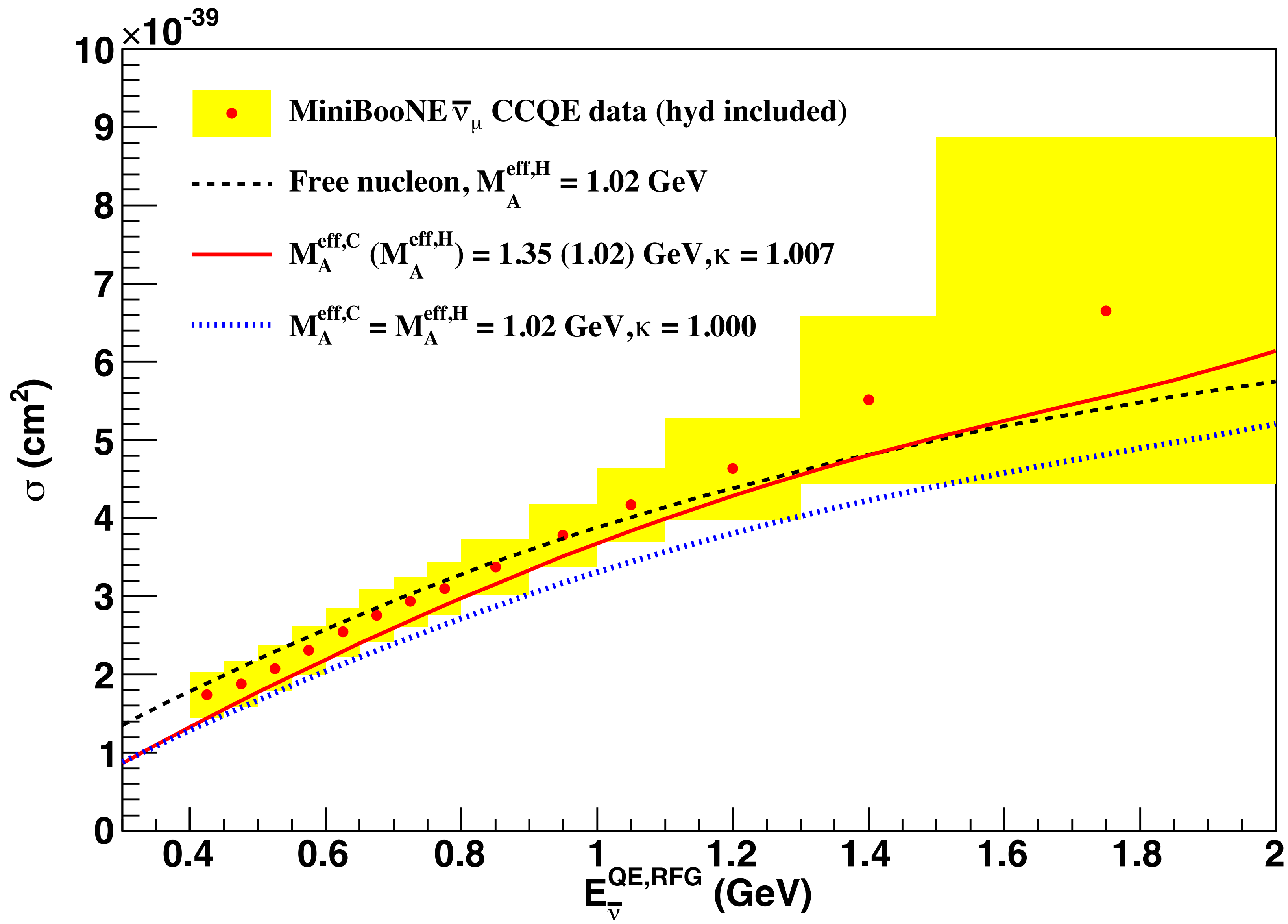


Anti-ν NCE recent calculation

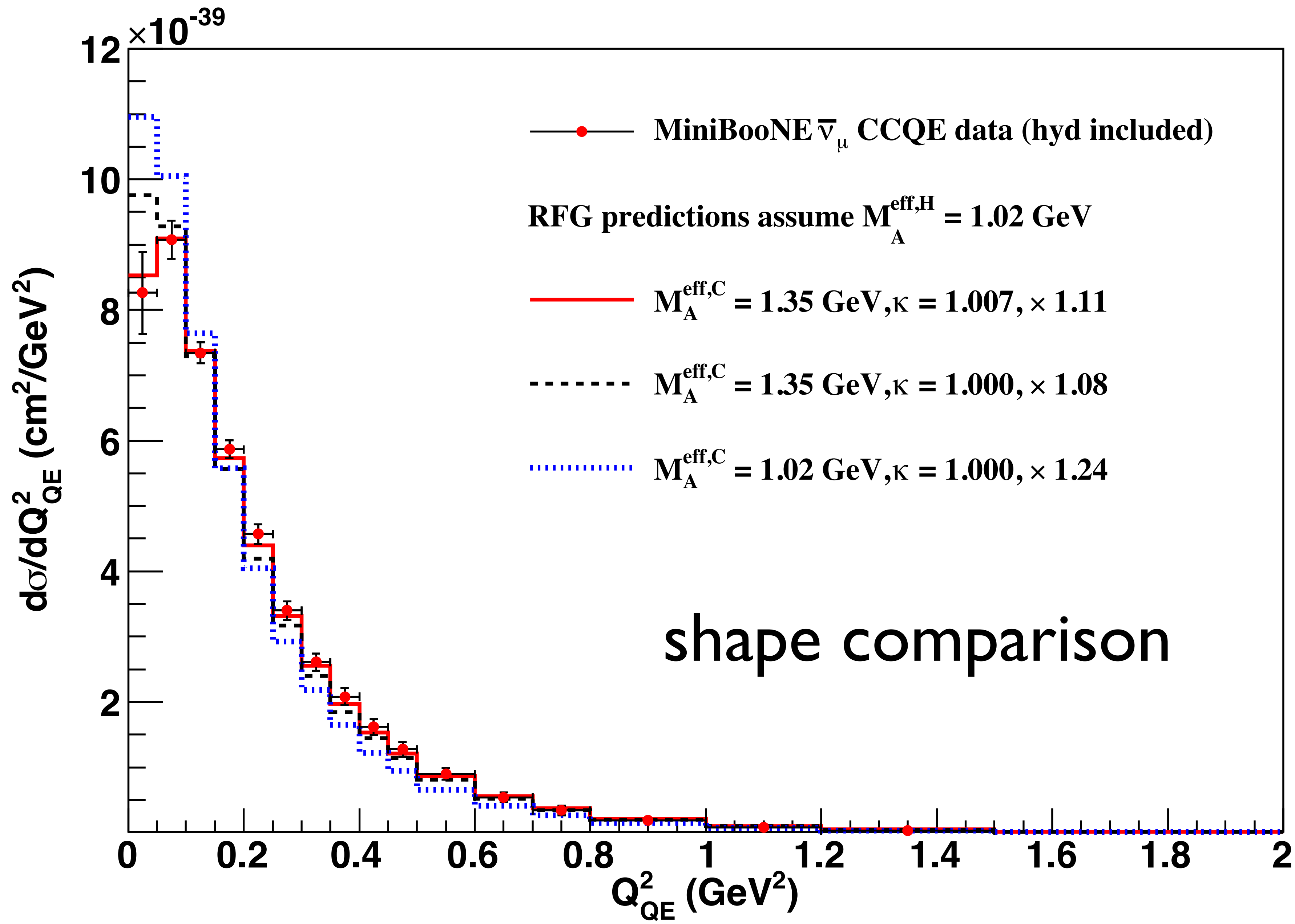




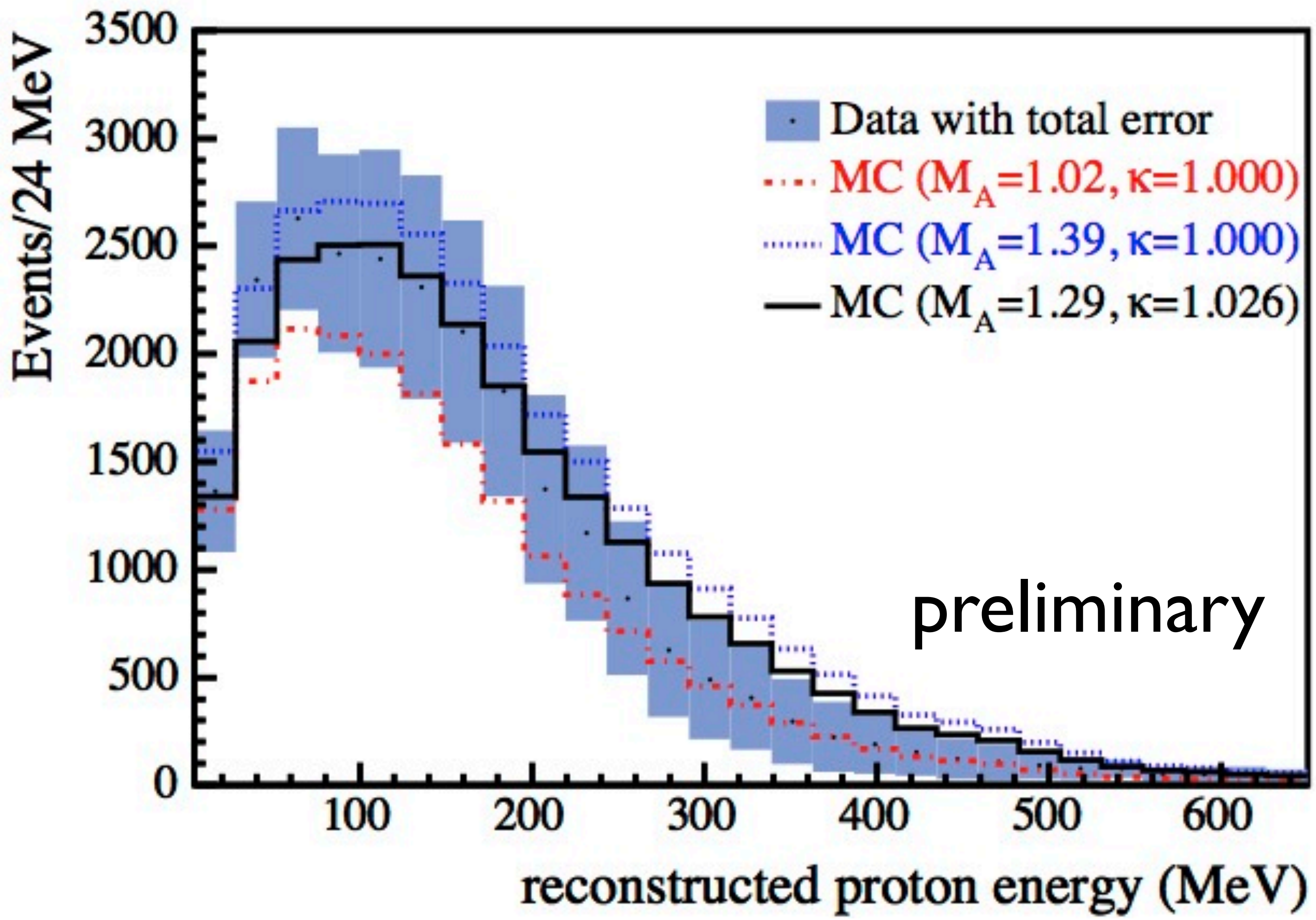
Total σ: CH_2


×10^-39
MiniBooNE $\bar{\nu}_{\mu}$ CCQE data (hyd included)
Free nucleon, $M_A^{eff,H}$ = 1.02 GeV
$M_A^{eff,C}$ ($M_A^{eff,H}$) = 1.35 (1.02) GeV,κ = 1.007
$M_A^{eff,C}$ = $M_A^{eff,H}$ = 1.02 GeV,κ = 1.000
σ (cm²)
$E_{\bar{\nu}}^{QE,RFG}$ (GeV)
0
1
2
3
4
5
6
7
8
9
10
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

Single-differential $d\sigma/dQ^2_{QE}$: CH_2



More model comparisons



- Not much shape sensitivity to model parameters

$CC\pi^+$ measurement

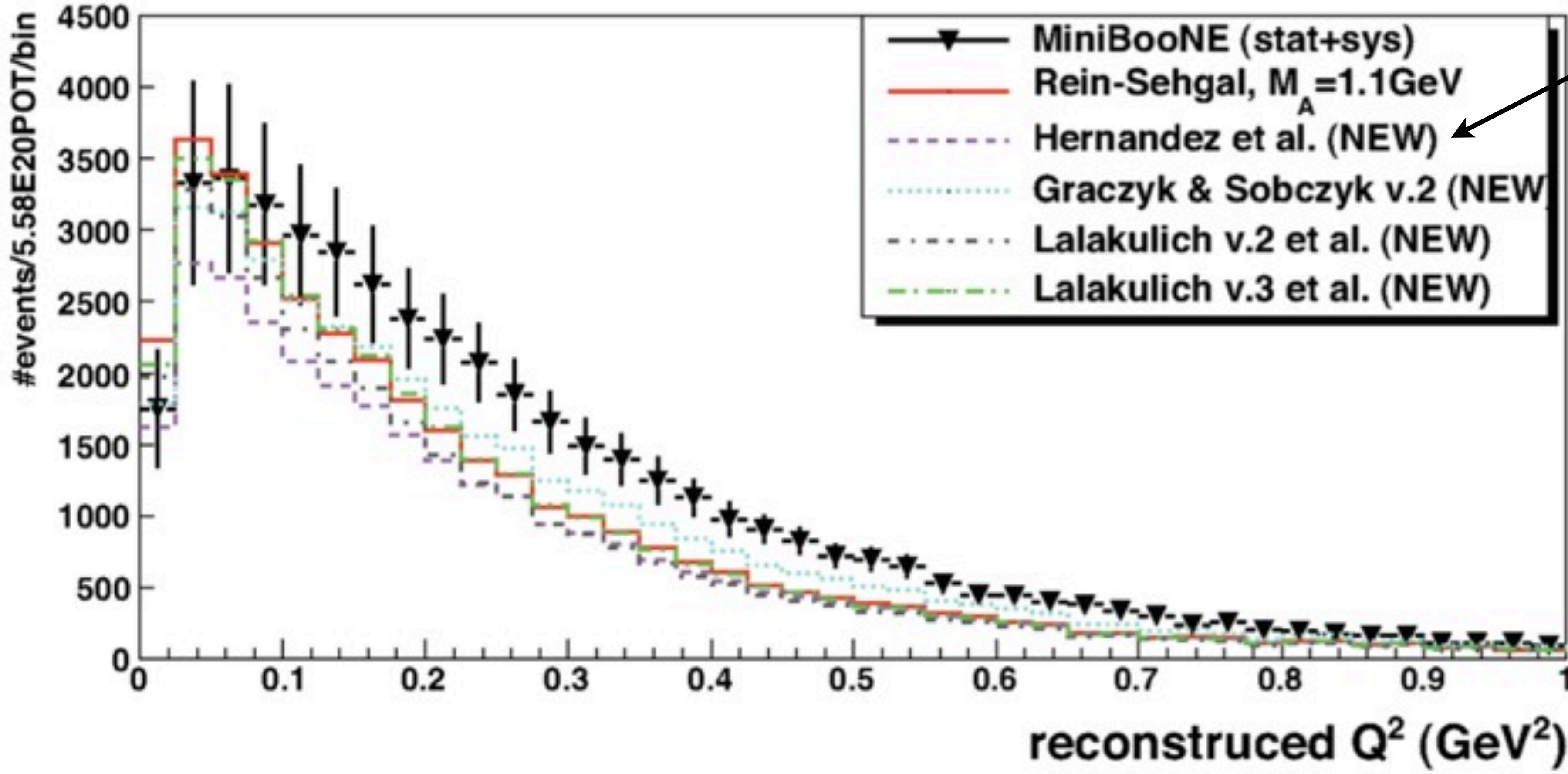
- Simply require two decay electrons after prompt μ, get a sample of ~80% ν_μ (wrong sign) interactions

- 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

More π models

Phys. Rev. D **76,** 033005 (2007).



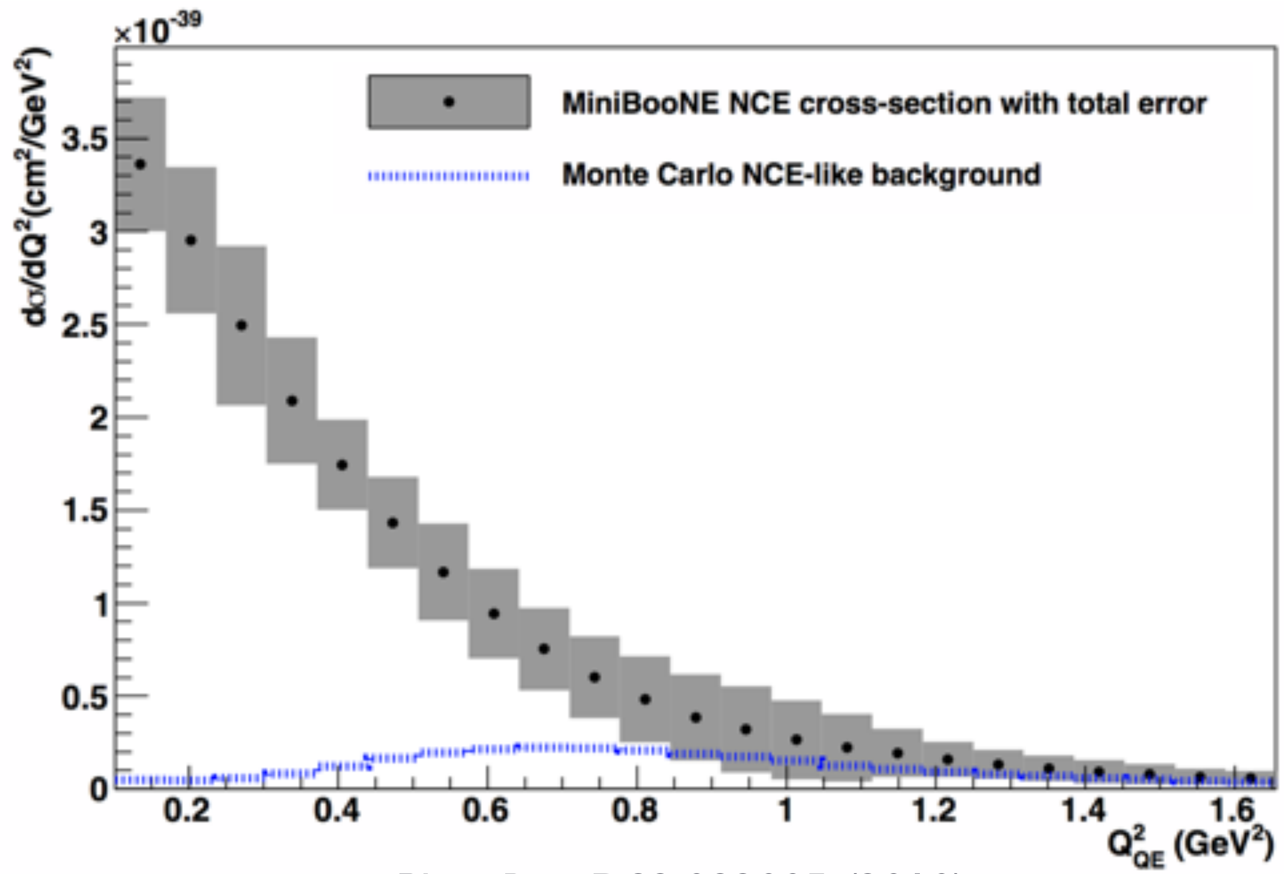
- Neutral current elastic: similar formalism to CCQE,

$$\nu_\mu N \rightarrow \nu_\mu N$$

- Also sensitive to M_A: fit to observations of nuclear recoil energy shape find $M_A = 1.39 \pm 0.11$ GeV

$$Q^2_{QE} = 2m_N \Sigma T_N$$

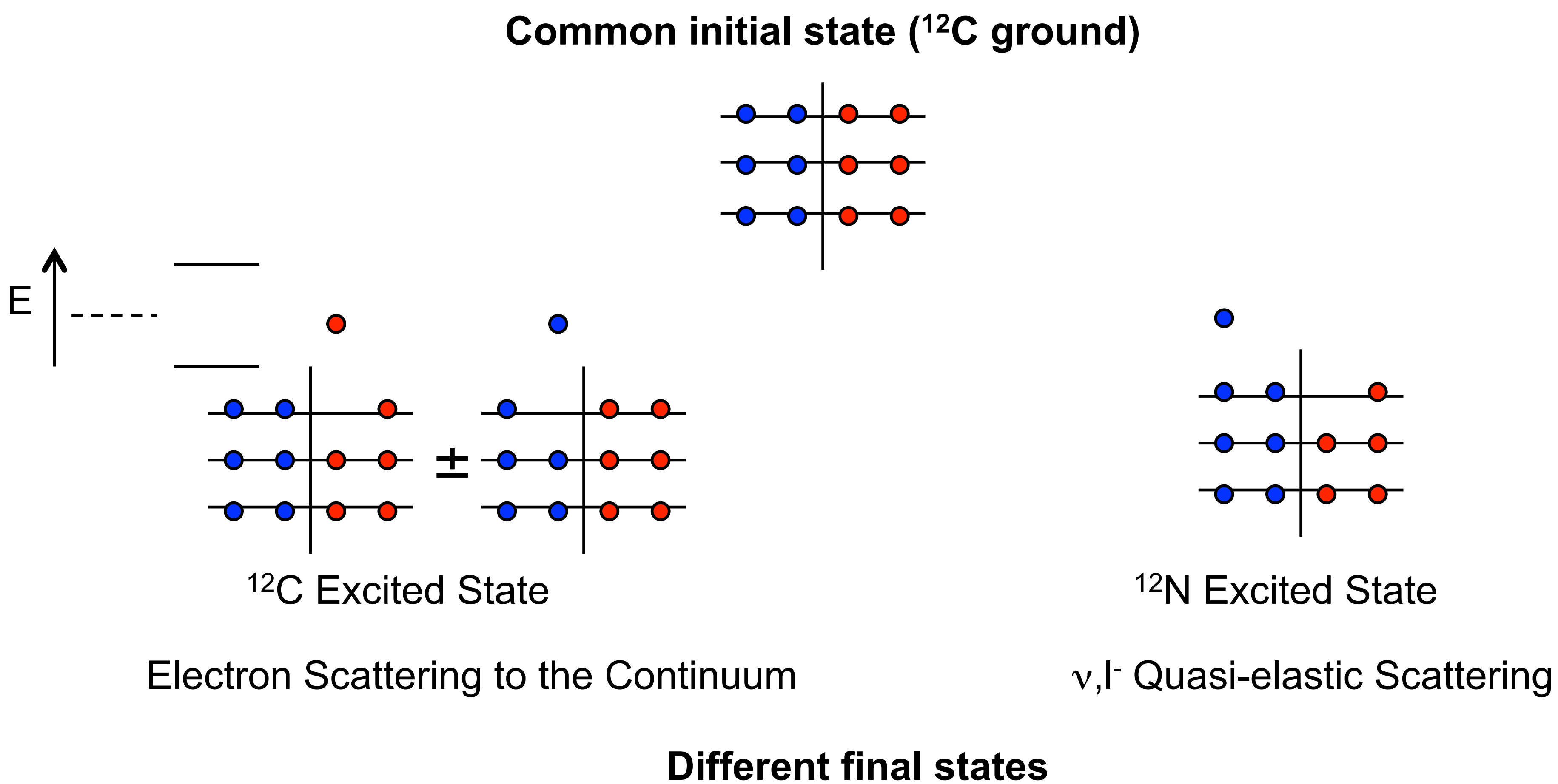
Interesting to note, fits for M_A consistent between CCQE (based only on lepton activity) consistent with NCE (based only on hadronic activity)



Phys. Rev. D82:092005 (2010)

Determining E_B, k_F

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



How much different?

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

$$\mathrm{E_S}(\mathrm{MeV}) = \frac{28(A-2Z)^2}{A}$$

- E_S = 9 MeV for A = 12, Z = 7
  - (CC interactions with n → p, e.g. ν_μ CCQE)

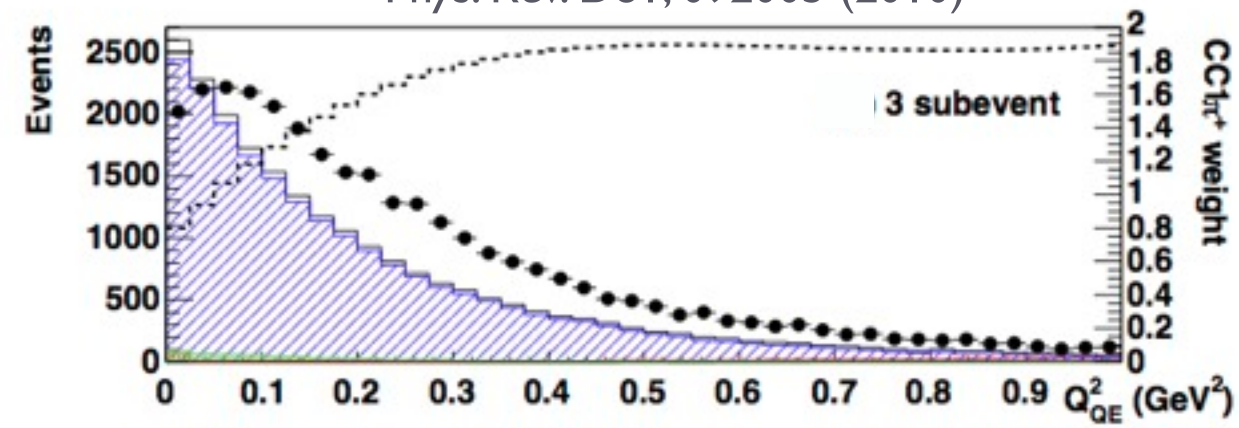
- E_B = 25 + 9 MeV = 34 MeV

(e,e') data ↑ 25 — symmetry splitting ↑ 9

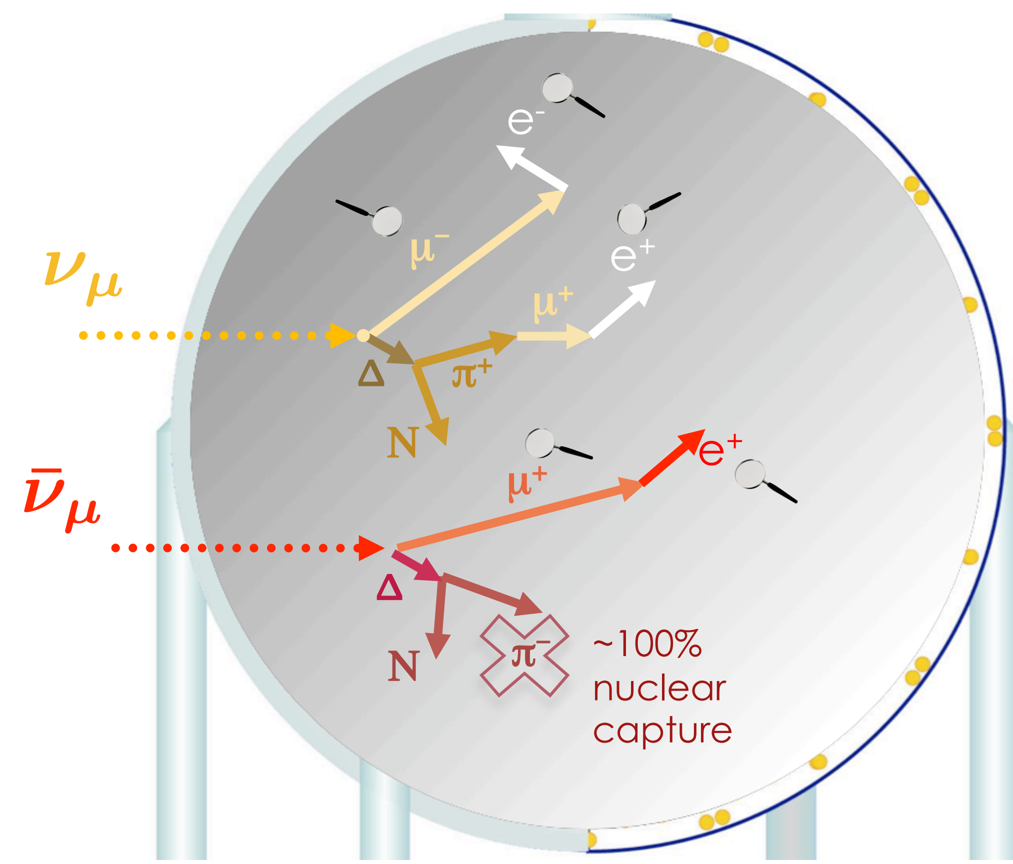
CCπ⁻

- Single-π bkg for ν_μ CCQE analysis: ID'd CCπ⁺ events using 2-Michel tag
  - empirically constrained their rate + shape, apply to bkg prediction

Phys. Rev. D81, 092005 (2010)



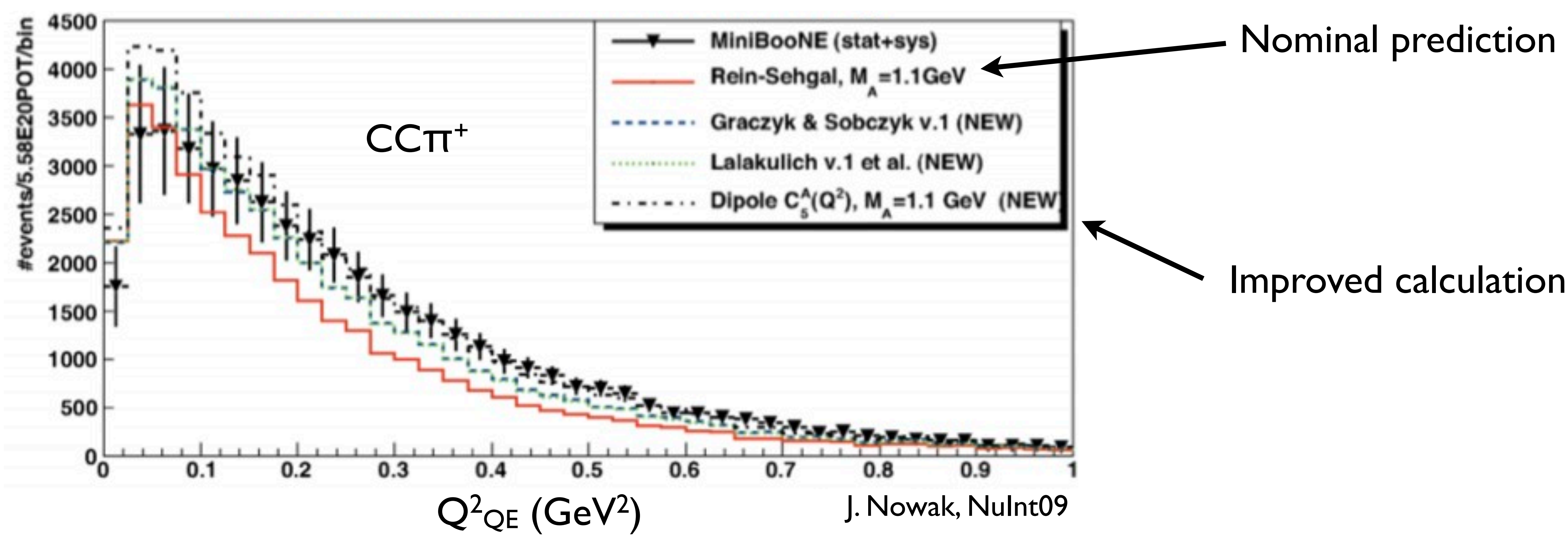
- Not possible in anti-ν mode: single-pion mechanism CC1π⁻, stopped π⁻ absorbed in medium ~100%, 2nd Michel not produced



Thursday, February 21, 13

$CC\pi^-$

- Apply the same constraint measured in $CC\pi^+$ sample to $CC\pi^-$ events
  - uncertain extrapolation!
- Can do better: use improved π-production model that agrees with MB $CC\pi^+$ data as cross-check
  - improvements include muon mass effects (absent in nominal model)



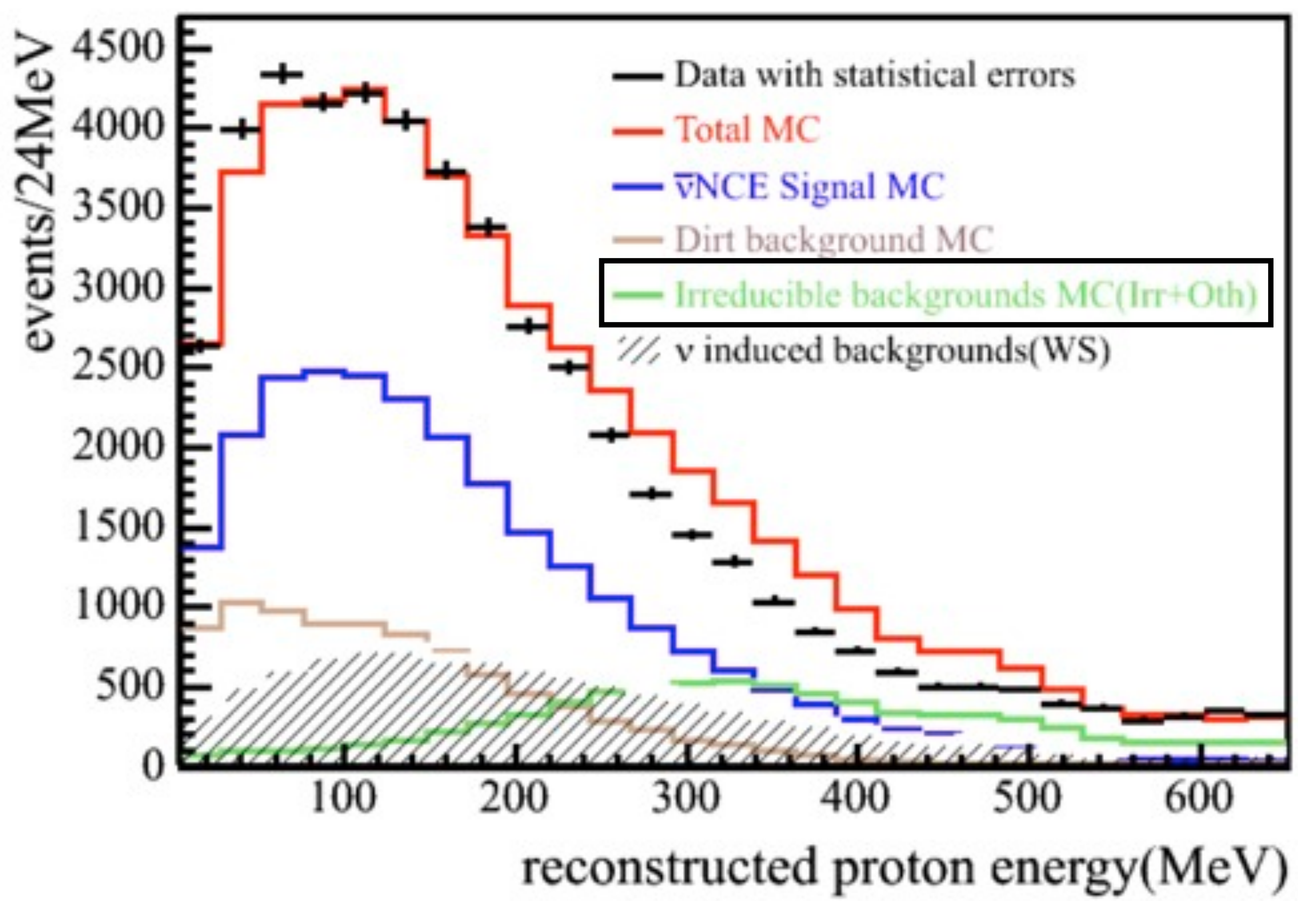
J. Nowak, NuInt09

Irreducible background

- Irreducible: NCπ with no final-state π, e.g.:

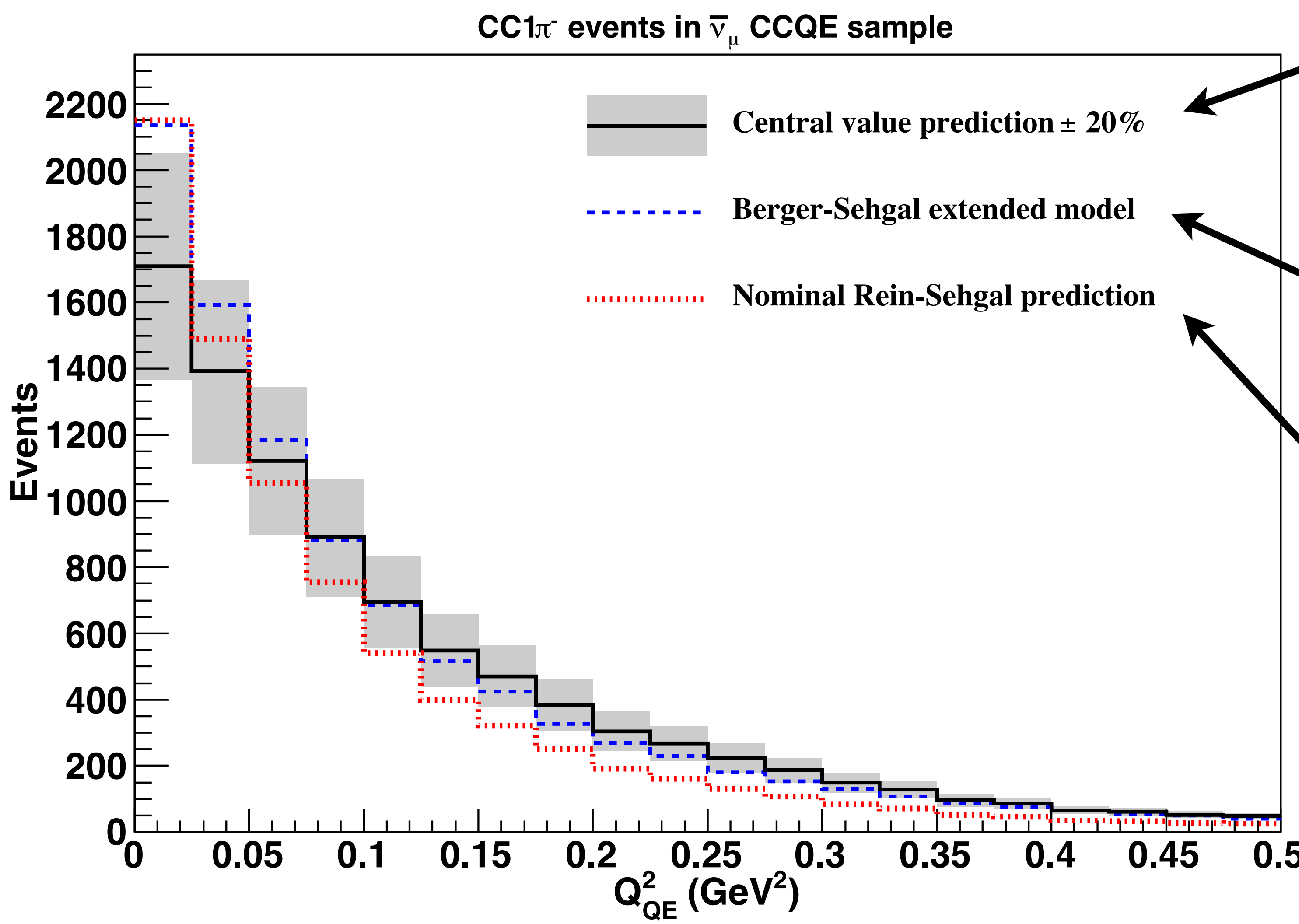
$$\bar{\nu}\, p \rightarrow \bar{\nu}\, p\, \not{\pi}^0$$
$$\bar{\nu}\, p \rightarrow \bar{\nu}\, n\, \not{\pi}^+$$
$$\bar{\nu}\, n \rightarrow \bar{\nu}\, n\, \not{\pi}^0$$
$$\bar{\nu}\, n \rightarrow \bar{\nu}\, p\, \not{\pi}^-$$

- Rely on MC to predict this background
  - 30 - 40% errors assigned
- Will also report what was subtracted to allow model-independent comparisons
  - following previous MiniBooNE conventions



CCπ⁻

- Comparison to MiniBooNE predictions



tuned to MiniBooNE CCπ⁺ data

improved prediction

Phys Rev D76, 113004 (2007)

pred. w/ no tuning

D. Rein and L. Sehgal, Ann. Phys. 133, 79 (1981)

- Level of agreement suggests 20% uncertainty is sufficient

Wrong-sign background