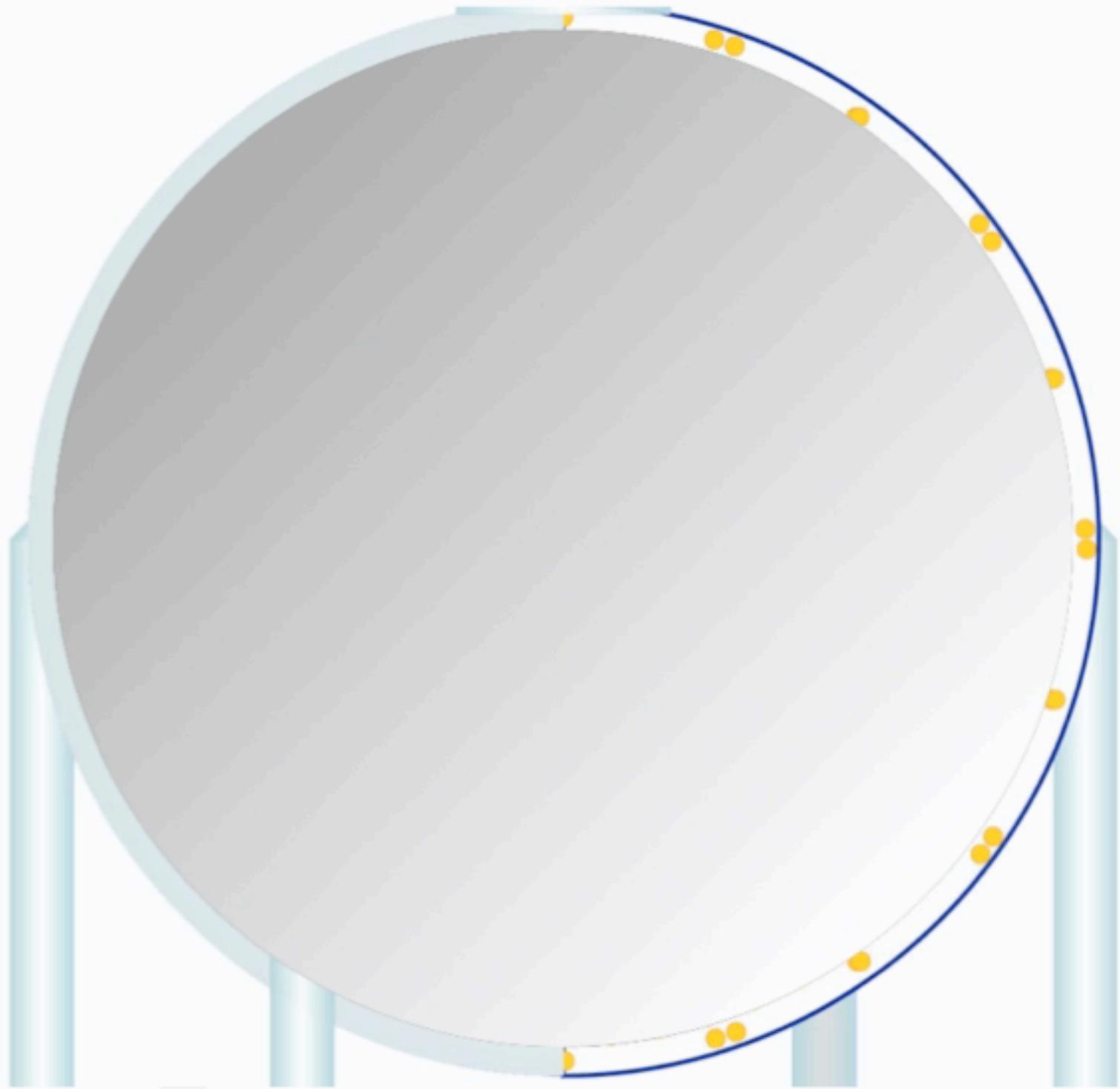
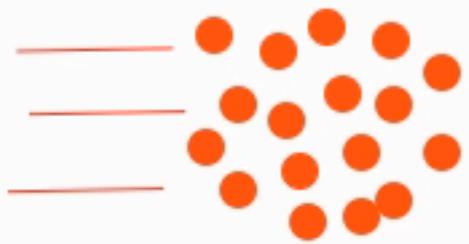


New Anti-Neutrino Cross Sections from MiniBooNE

$\bar{\nu}_\mu$

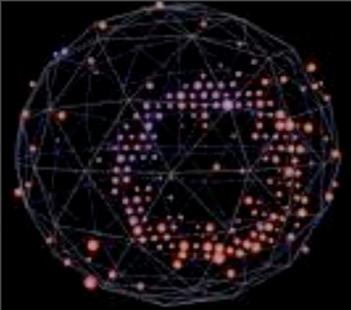


Joe Grange

University of Florida

Joint Experimental-Theoretical Seminar

11/30/12



Outline



Joe Grange

FNAL Joint Experimental-Theoretical Seminar

Nov. 30 2012

1. Introduction

ν cross sections in a single-detector oscillation exp't
recent σ interest from MiniBooNE neutrino-mode data

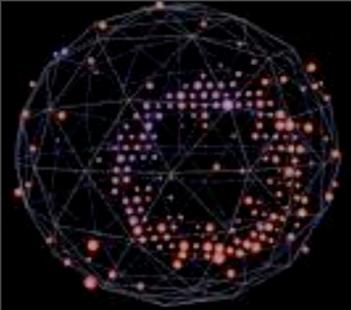
2. Anti-neutrino analyses

ν_μ background (wrong signs)

$\bar{\nu}_\mu$ CCQE σ (new!)

$\bar{\nu}_\mu$ NCE σ (new!)

3. Outlook and summary



I. Introduction

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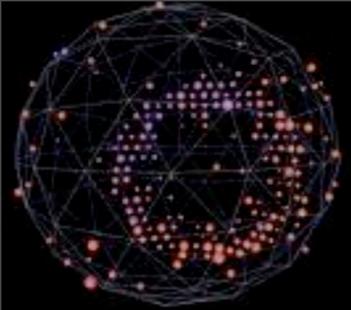
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MiniBooNE



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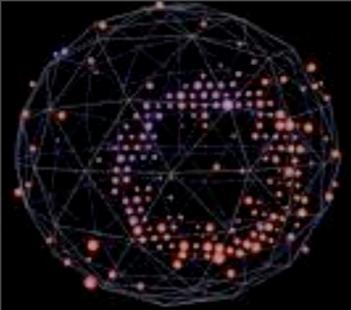
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- ▶ Primary physics goal: neutrino oscillations, designed to test an anomalous signal in data from LSND
- ▶ Along the way our secondary physics goals of ν cross sections have become increasingly interesting
- ▶ Successful 10-year run, HUGE data set in both neutrino and anti-neutrino running ([thanks AD!](#))



MiniBooNE crosses the finish line



Why do we care?



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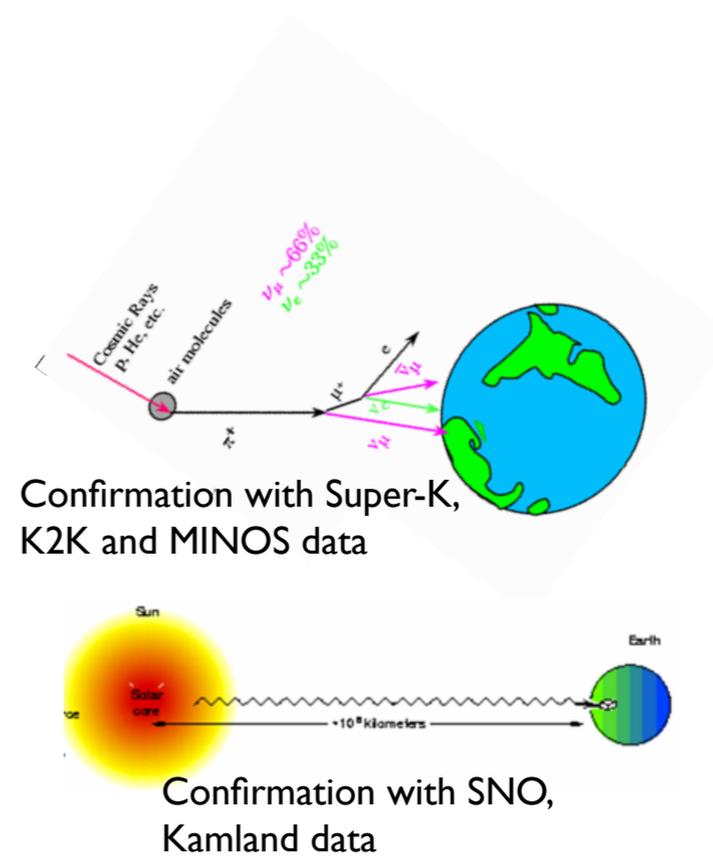
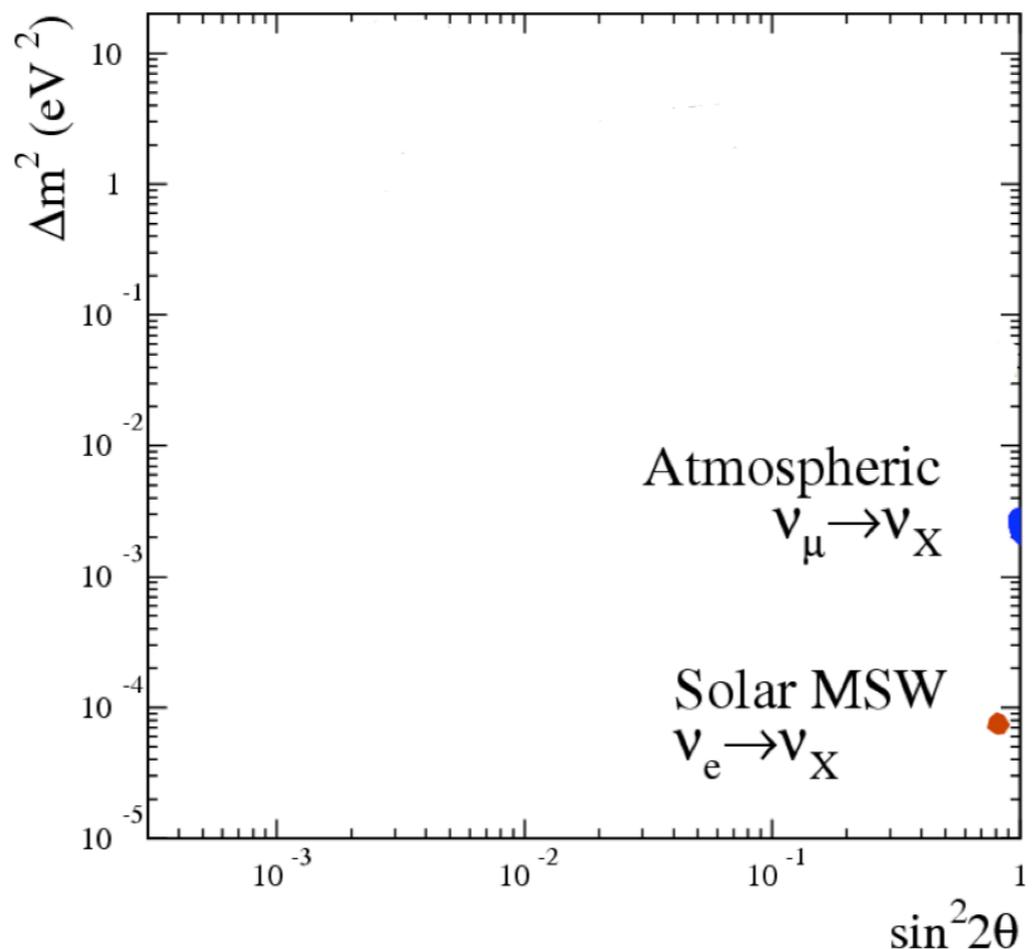
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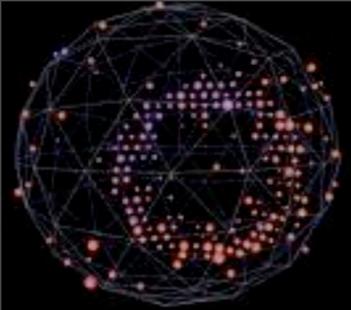
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- ▶ One of the few concrete results not predicted by the Standard Model: ν 's oscillate!



- ▶ 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





Why do we care?



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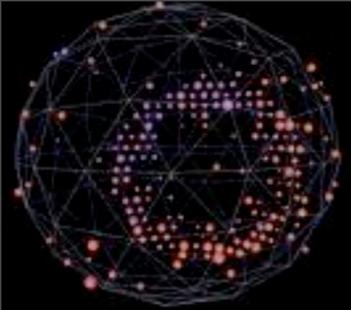
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- ▶ Two-neutrino approximation for ν_β to appear from a source of ν_α :

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

- ▶ (Of course) ν oscillations observed with analysis of ν interactions. To understand the rate ($\sim \theta$) and the energy dependence ($\sim \Delta m^2$) 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 $(\Delta m^2, \theta)$ of interest



Single-detector expt's



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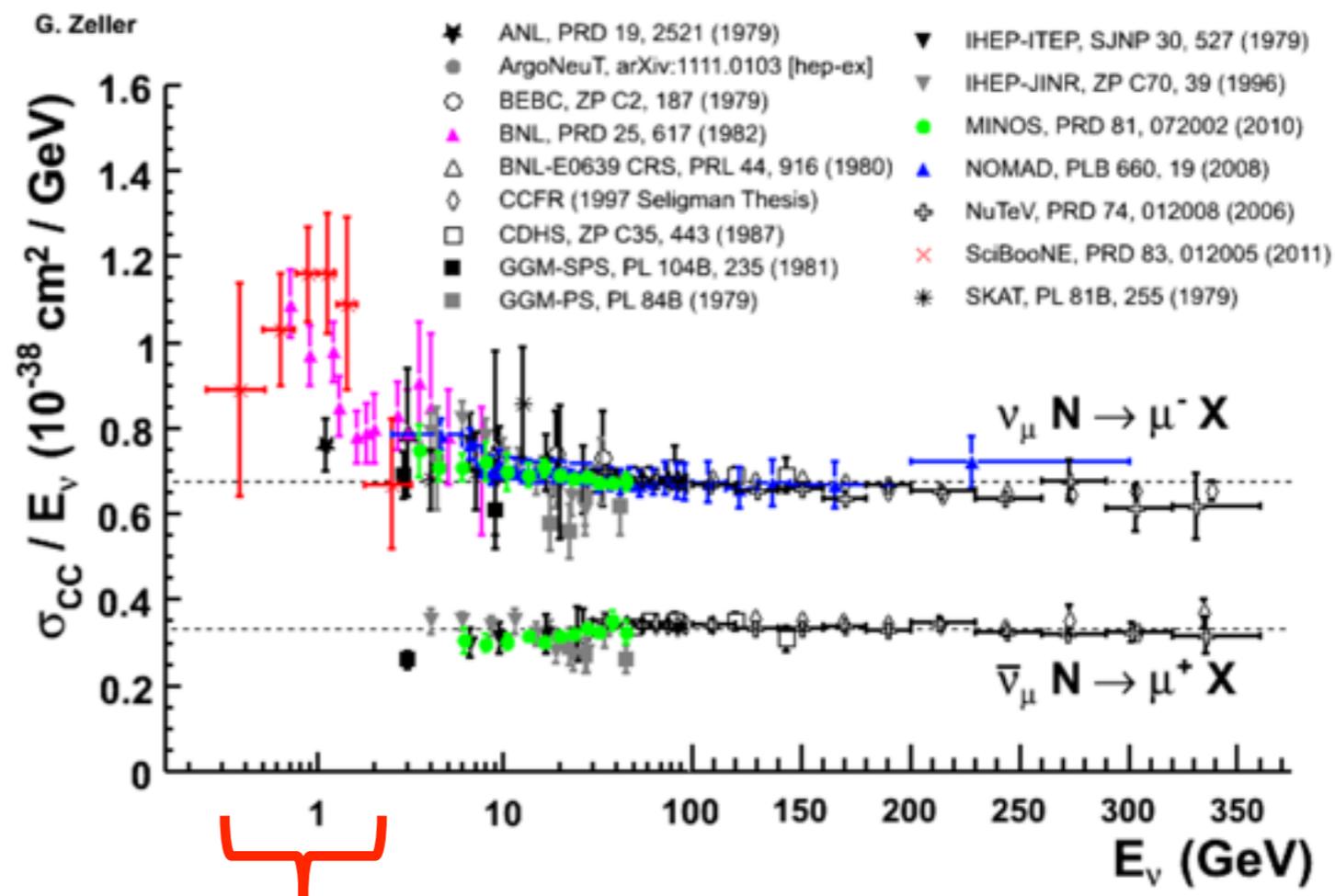
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- ▶ If second detector not available, can still make appearance (ν_e) measurements based on constraints from control sample (ν_μ)
 - MiniBooNE analysis strategy, also currently the favored LBNE phase 1 config.
- ▶ Single-detector expt's naturally more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

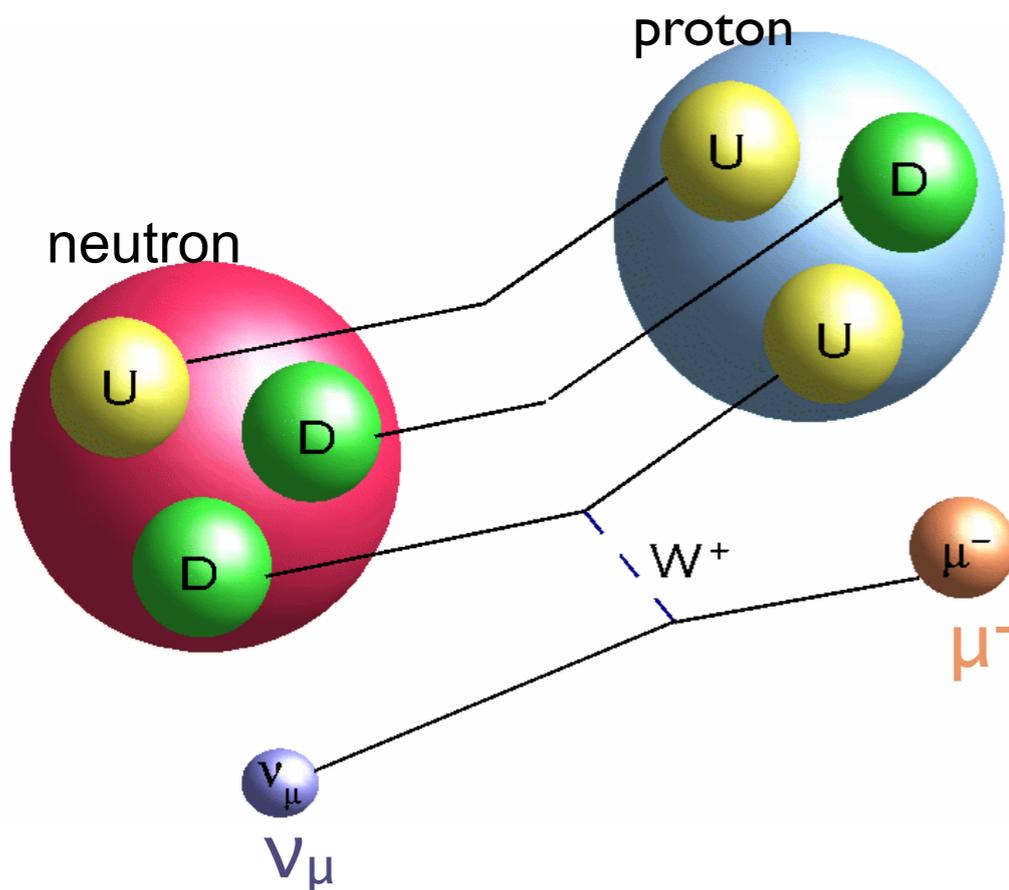
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- ▶ Due to simple multiplicity and ability to reconstruct ν energy based solely on lepton kinematics, charged current quasi-elastic interactions are the preferred channel for osc. measurements

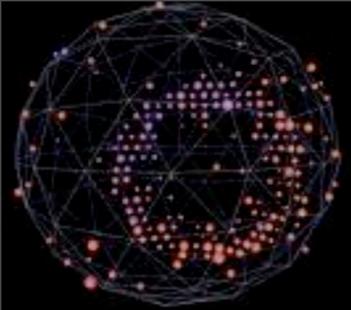


MiniBooNE only reconstructs outgoing μ

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

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

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



CCQE Expectations



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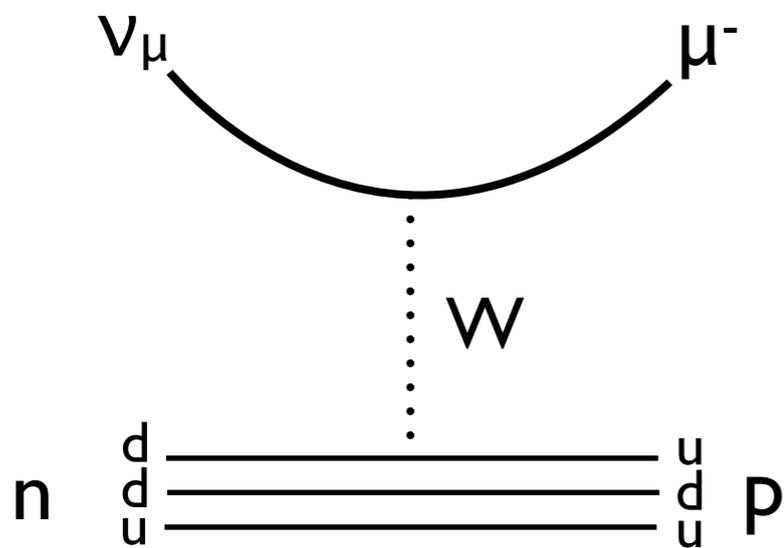
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- ▶ Expectation starts with calculation for free nucleons: Phys. Rep. 3, 261 (1972)

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

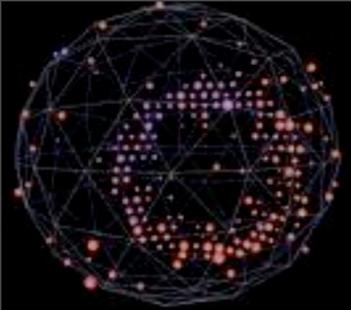
- ▶ Using CVC, vector and tensor form factors measured in (e,e') data

- ▶ 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



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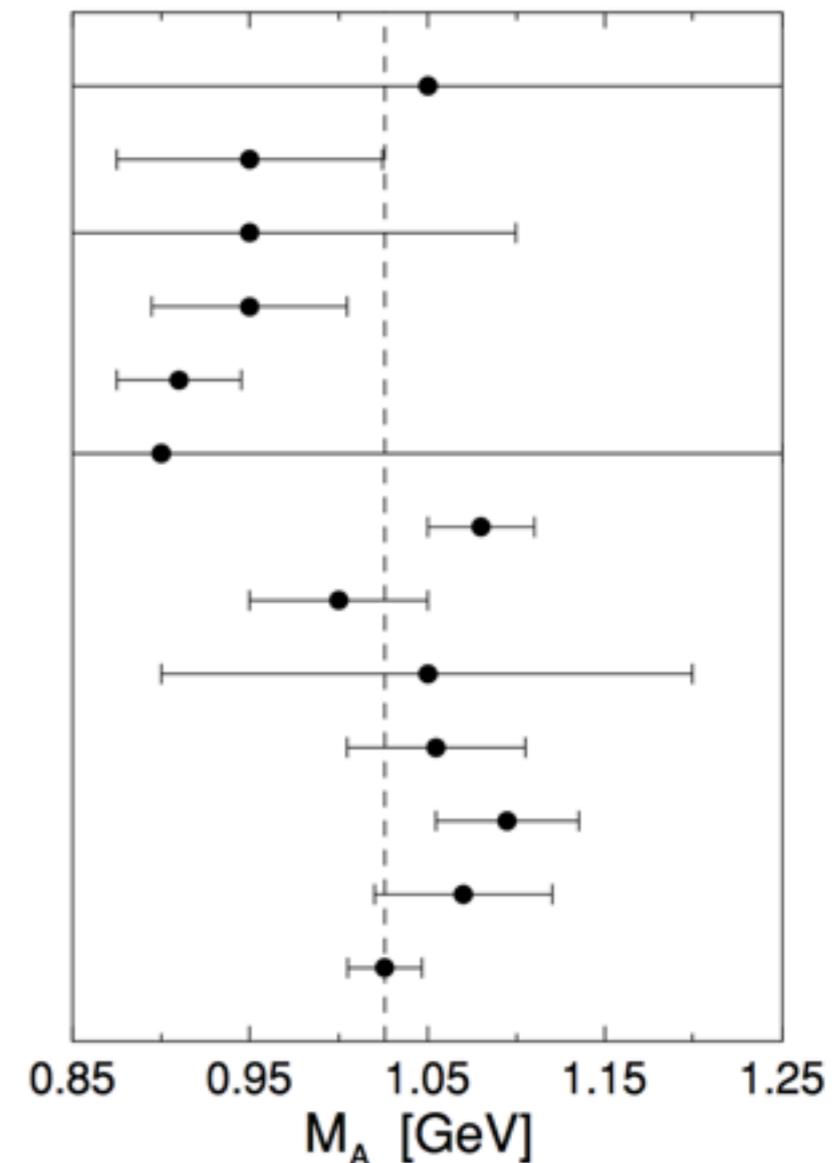
- ▶ M_A measured for decades in ν scattering on mostly $Z = 1$ targets with a variety of techniques
 - both total cross section and shape of Q^2 strongly influenced by M_A

★ H or ^2H

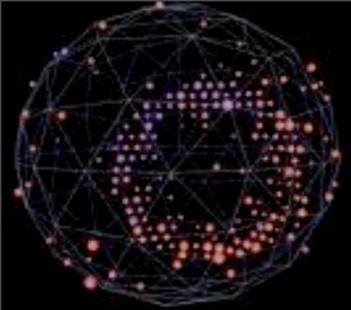
- ▶ Global average to these data find $M_A = 1.03 \pm 0.02$ GeV
 - fit driven by light-target expt's

- ▶ With discovery of ν oscillations (1998), suddenly require nuclear targets to get higher rates needed to nail osc. physics

- Argonne (1969)
- ★ Argonne (1973)
- CERN (1977)
- ★ Argonne (1977)
- CERN (1979)
- ★ BNL (1980)
- ★ BNL (1981)
- ★ Argonne (1982)
- ★ Fermilab (1983)
- ★ BNL (1986)
- ★ BNL (1987)
- ★ BNL (1990)
- Average



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



Put it in a nucleus - ^{12}C



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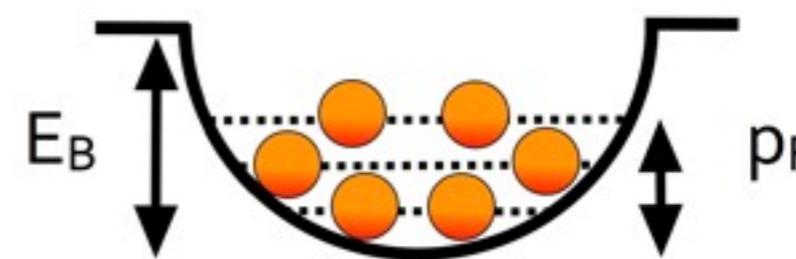
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▶ MiniBooNE (and everyone else) uses the Relativistic Fermi Gas model (RFG)

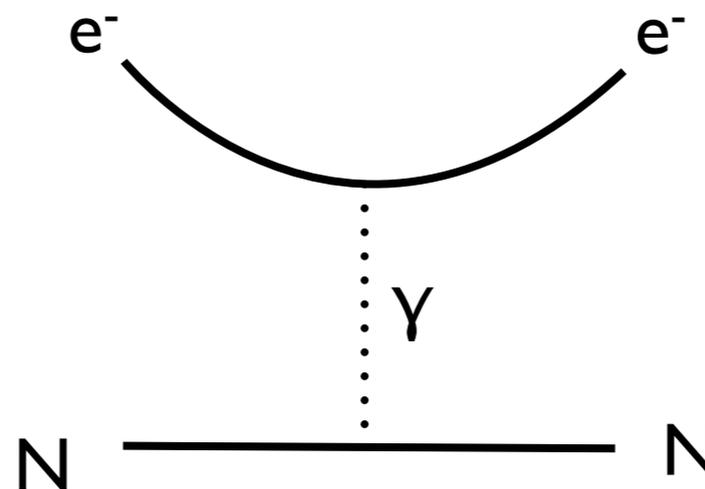
Nucl. Phys. B43, 605 (1972)

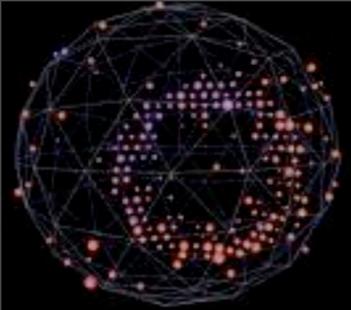
- Models nucleons as independent, quasi-free particles bound by a binding energy E_B
- All outgoing nucleons subject to Pauli blocking. Enforced by a global Fermi momentum p_F



G. Perdue

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





That's it!



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- ▶ 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!

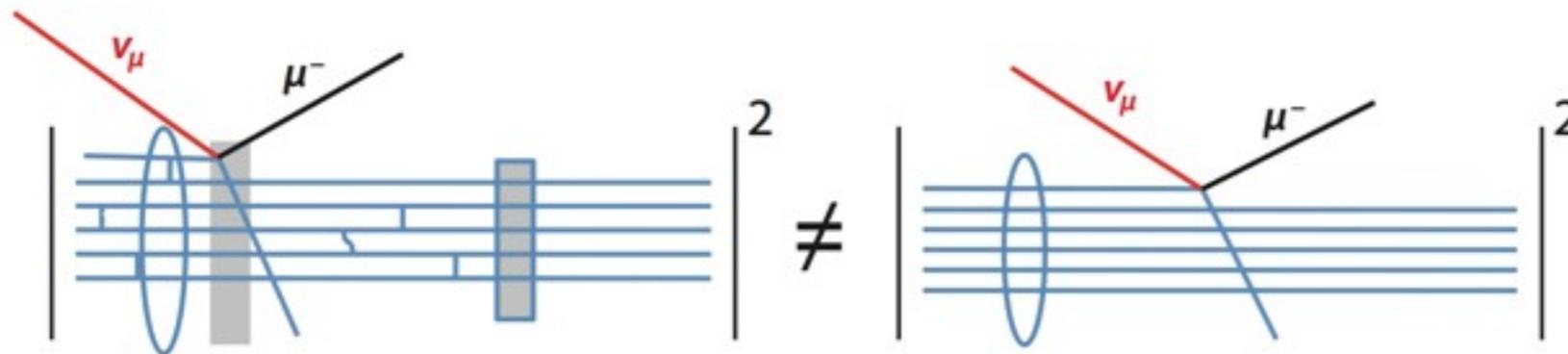
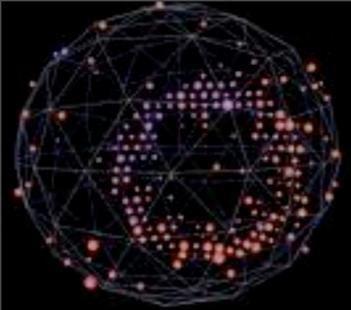


Fig. from Ann. Rev. Nucl. Part. Sci. 2011. 61:355–78

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



Early days of MiniBooNE

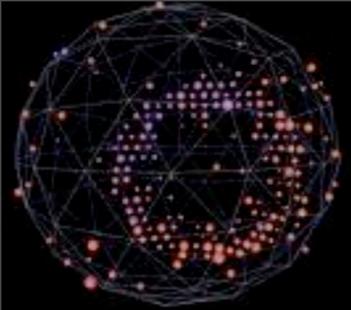


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- ▶ Subsequent to understanding detector response and verifying reconstruction algorithms on variety of calibration data, we found surprises in this ν_μ CCQE channel (recall understanding this interaction is crucial for the ν_e appearance analysis)
 1. Once a flux prediction obtained from dedicated hadroproduction data (more later), a 30% excess found relative to RFG
 2. Disagreement in μ kinematics



Early days of MiniBooNE



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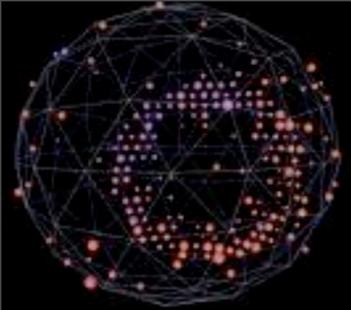
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In principle, this could be due to either flux or cross section mismodeling



Early days of MiniBooNE



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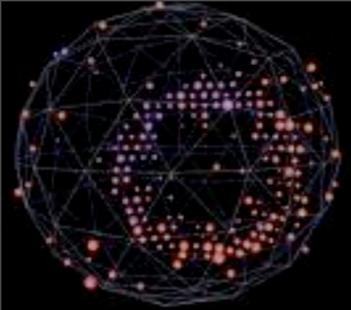
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1. Once a flux prediction obtained from dedicated hadroproduction data (more later), a 30% excess found relative to RFG

2. Disagreement in μ kinematics

Implies cross section is the likely culprit

In principle, this could be due to either flux or cross section mismodeling



μ kinematics

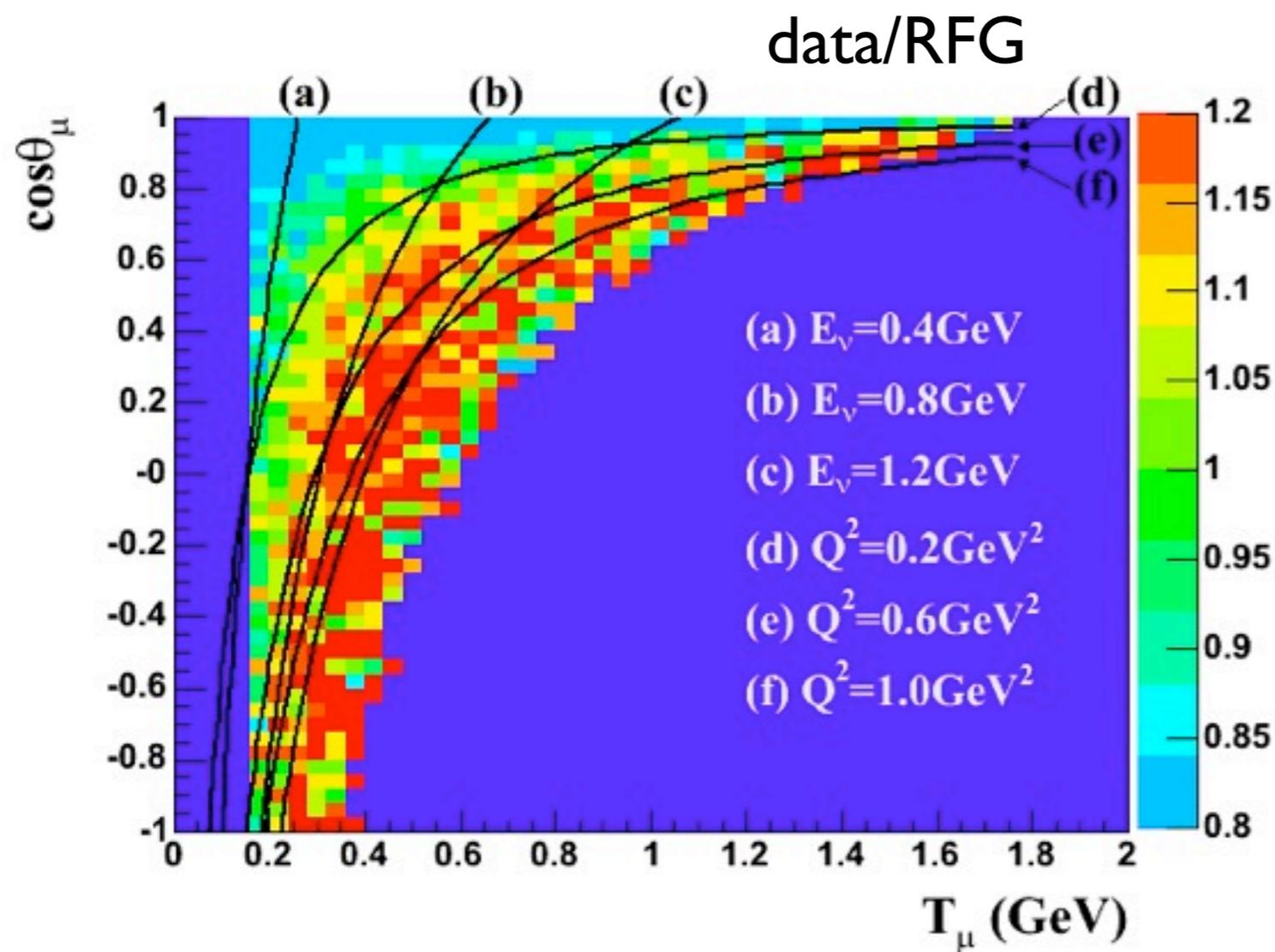


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- ▶ With more than 10x statistics of previous CCQE measurements *combined*, MiniBooNE can look at kinematics with unprecedented precision

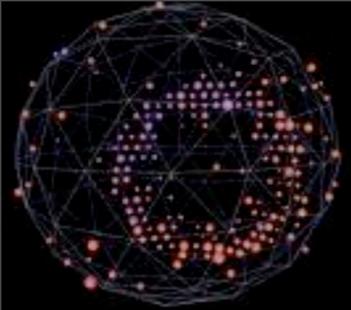


(broadly)

* $\Phi(E_\nu)$

* $\sigma(Q^2)$

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



μ kinematics

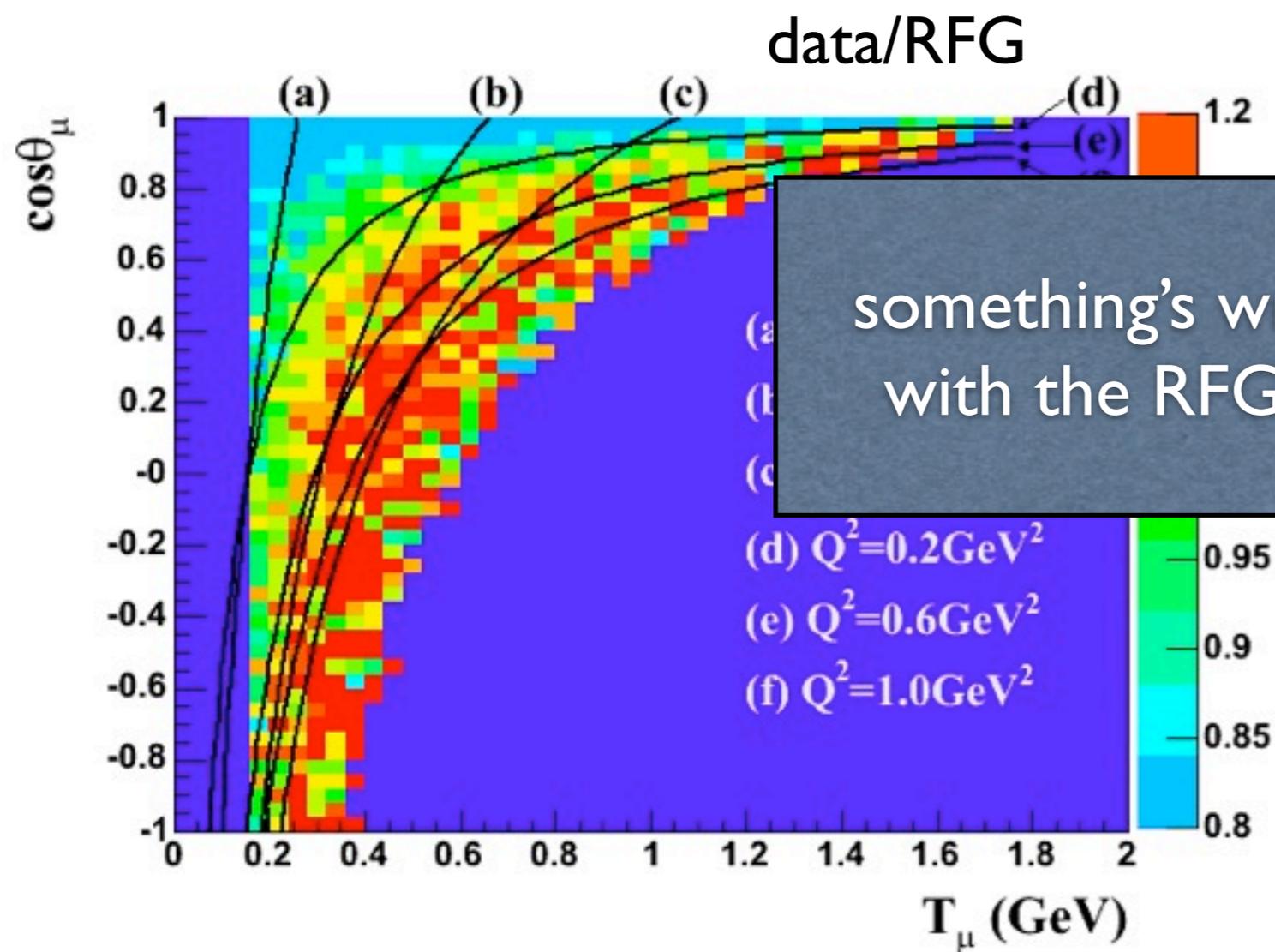


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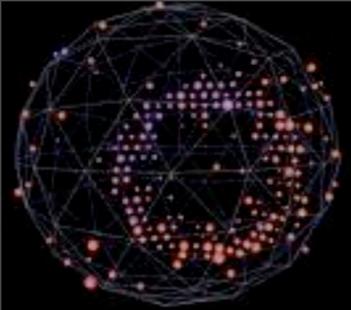
something's wrong with the RFG σ !

(broadly)

* $\Phi(E_\nu)$

* $\sigma(Q^2)$

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



Looking for alternatives

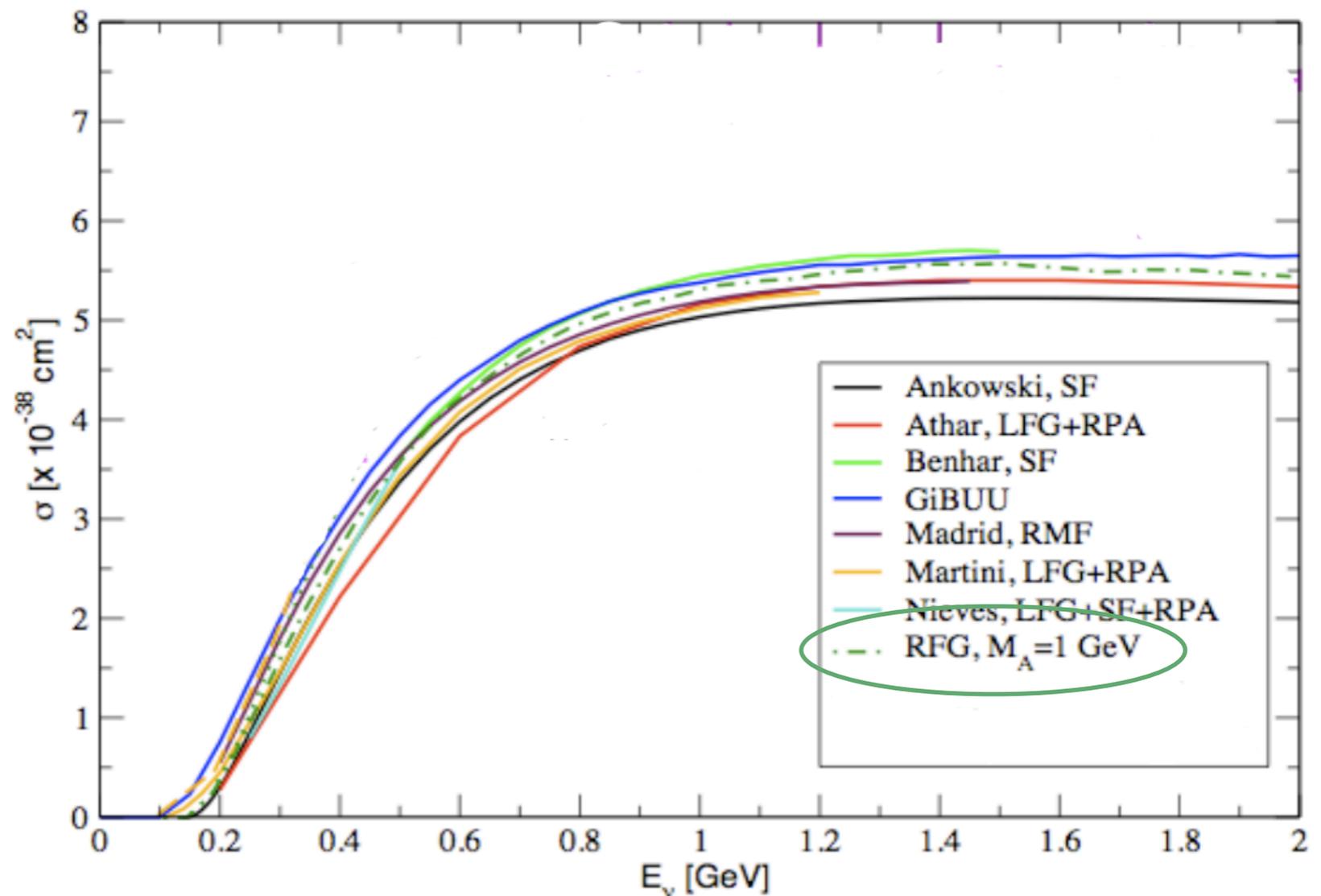


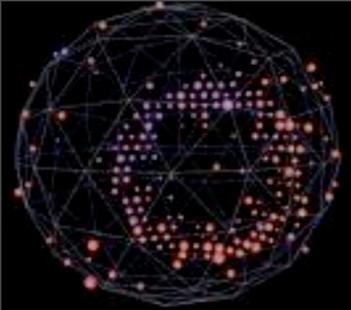
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- ▶ With the admission the RFG may be insufficient, we look to more modern calculations
- ▶ Find general theory consensus that RFG with $M_A \sim 1$ GeV is about right
 - at least for the total σ
- ▶ In fact, most modern models predict nuclear effects *suppress* the σ , not enhance it!





Finding a “solution” within the RFG



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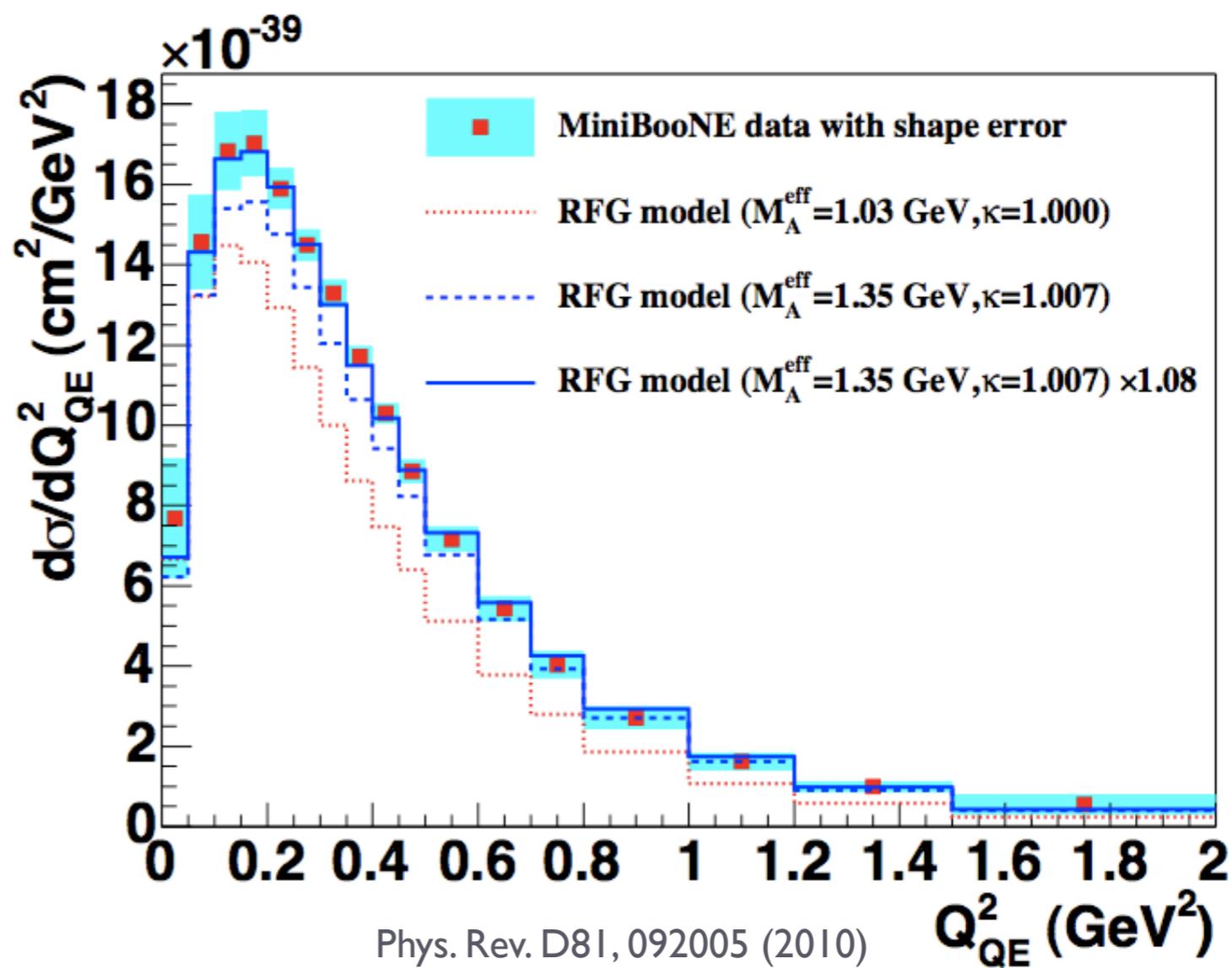
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- ▶ Need to reproduce observed ν_μ CCQE in simulation to obtain a reliable ν_e CCQE prediction

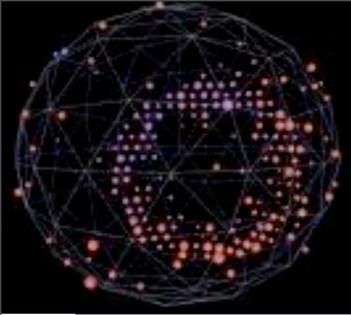
➔ Tuned M_A and an empirical Pauli blocking scale κ

$$M_A = 1.35 \pm 0.17 \text{ GeV}$$

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



$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE} (E_\mu - p_\mu \cos \theta_\mu) \quad 19$$



Axial Mass Tension

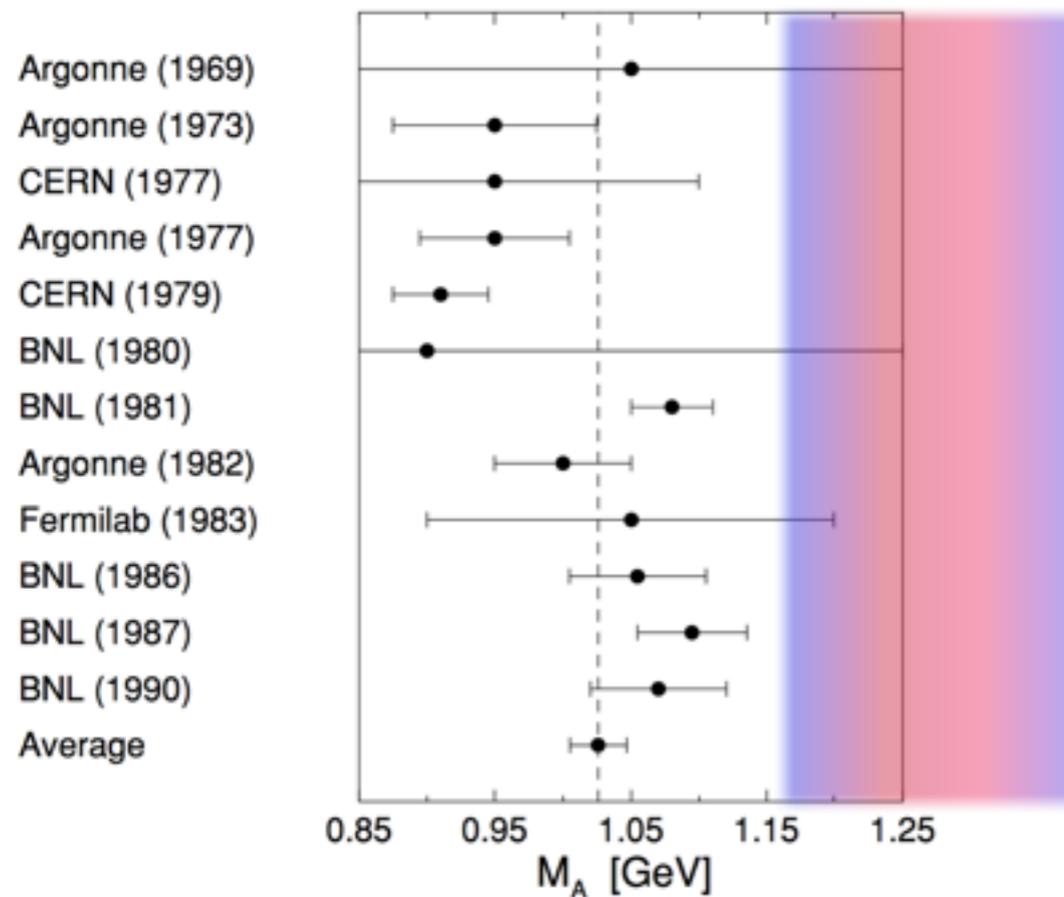


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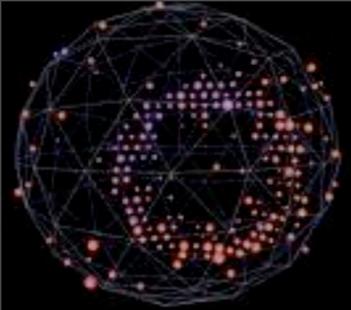
- ▶ $M_A \sim 1.3$ GeV clearly disagrees with previous data, but MiniBooNE not alone in finding this tension



Maybe the physics model is wrong?

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

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



New interaction?



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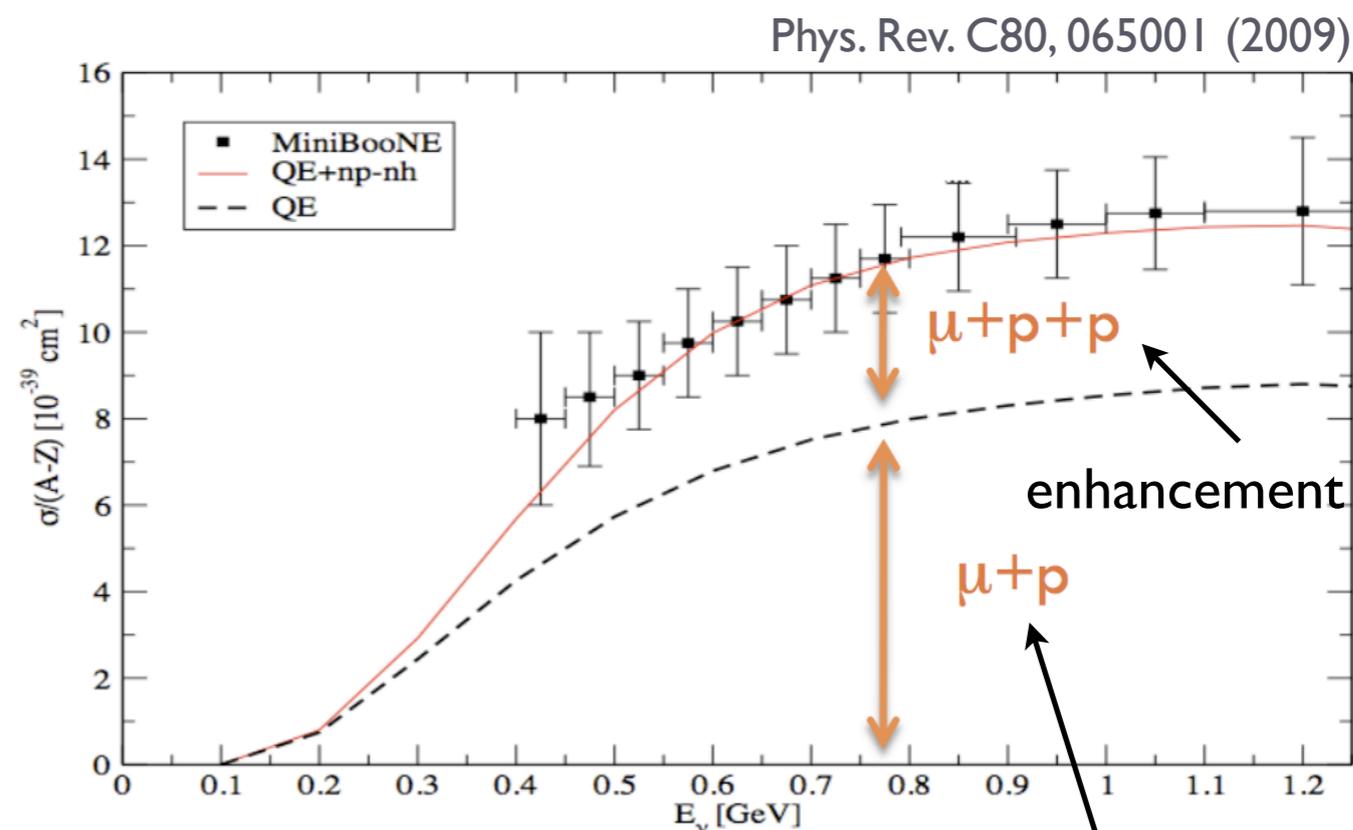
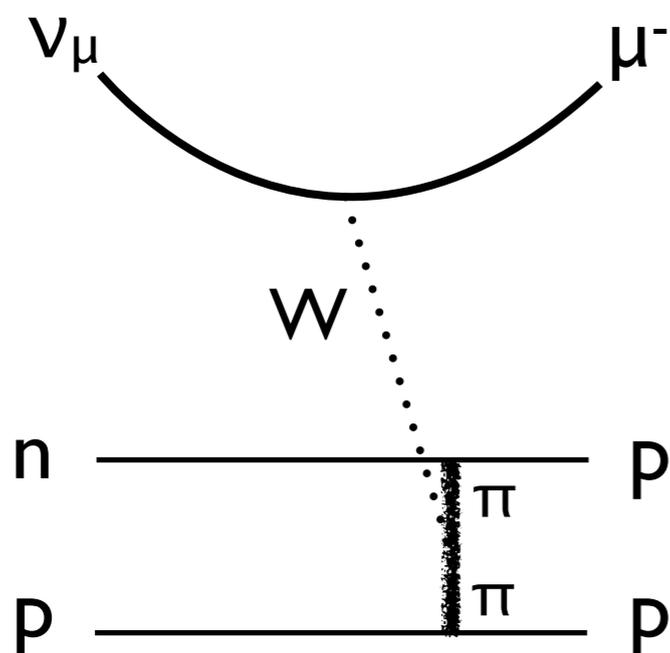
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- ▶ 2009, first group to propose unification of apparently discrepant data sets Martini *et al.*

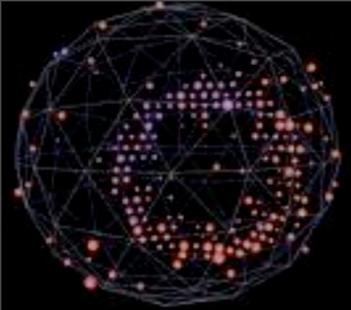
- ▶ Nuclear correlation effects in ^{12}C result in a large enhancement



not present in light target experiments and indistinguishable from “true CCQE” in MiniBooNE
 - no selection on outgoing nucleons



“True CCQE”: $M_A \sim 1 \text{ GeV}$



Old interaction! Observed in (e,e') data for decades

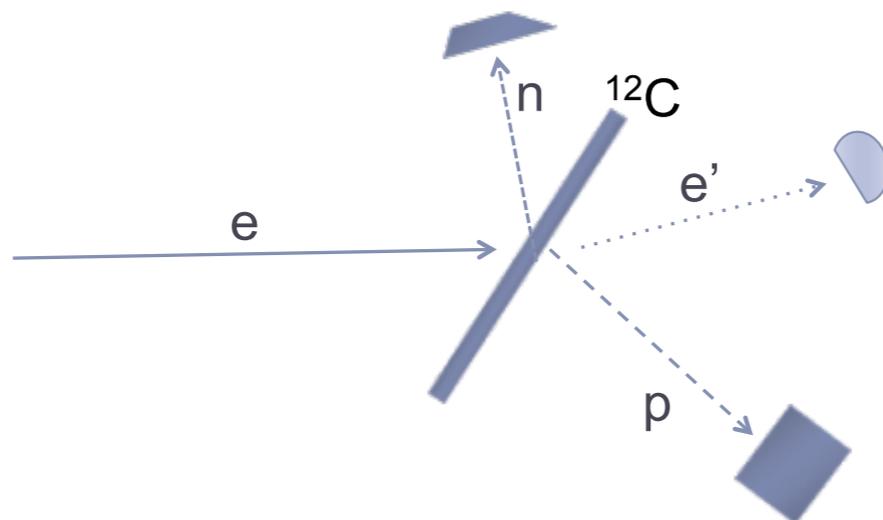


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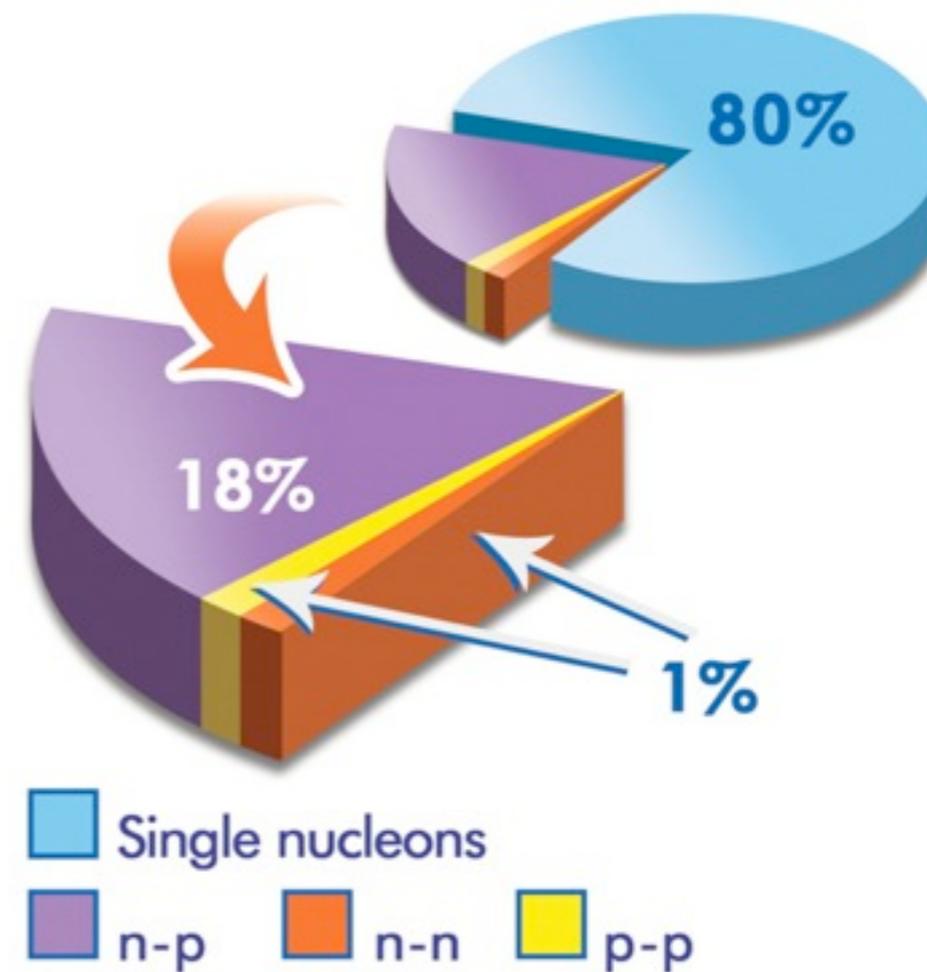
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- ▶ JLAB observed analogous process in electron scattering data



- ▶ 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?



Science 320, 1476 (2008)

Complications: job security?

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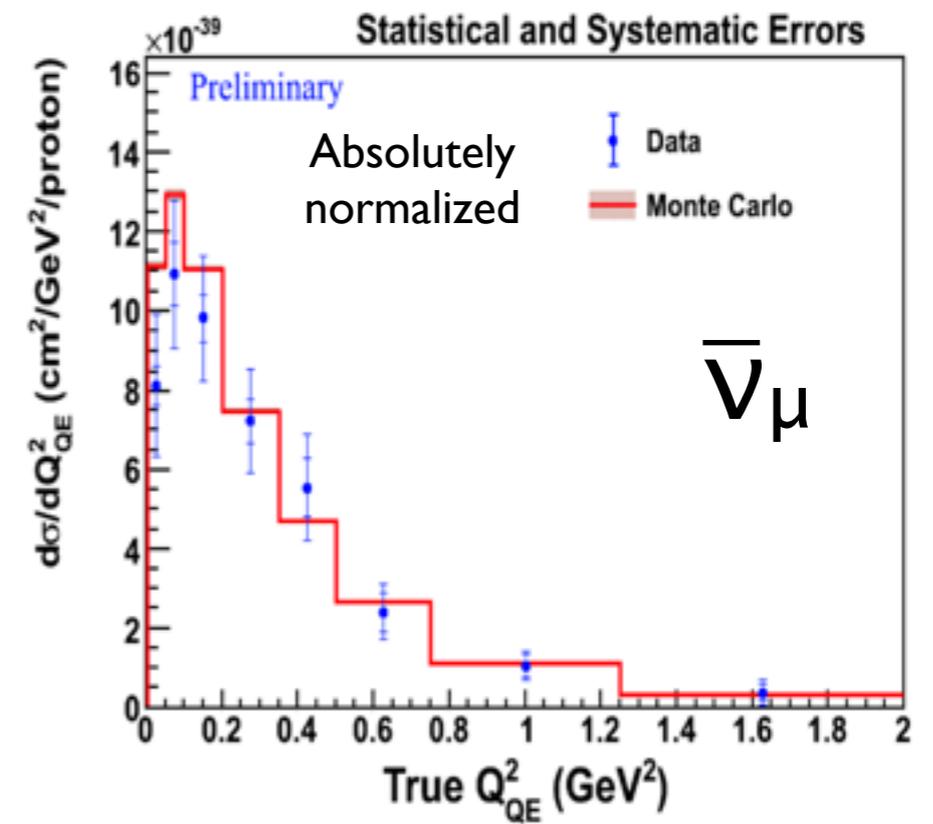
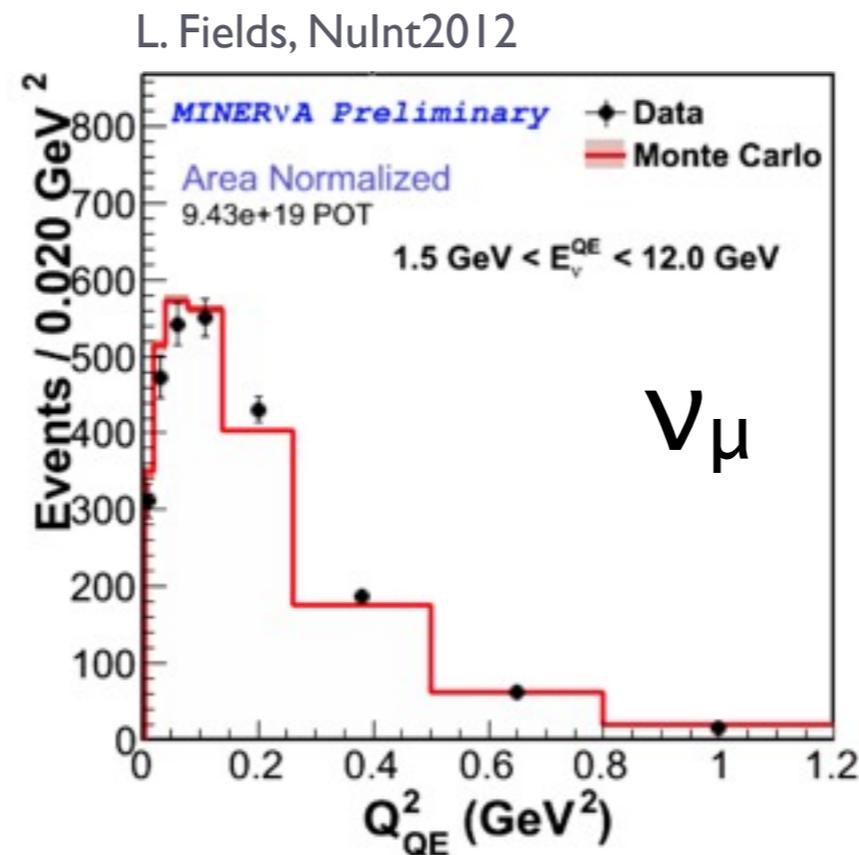
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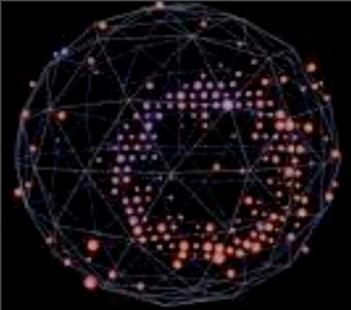
- ▶ No hint of this process in recent ^{12}C experiment NOMAD: measured $M_A \sim 1$ GeV with $\sim 5\%$ error for both ν_μ and $\bar{\nu}_\mu$

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



- ▶ Trouble in comparing results: different energy ranges, different detector technologies, selection criteria, etc.

- have seen only a few calculations for correlated scattering > 2 GeV



Since 2009



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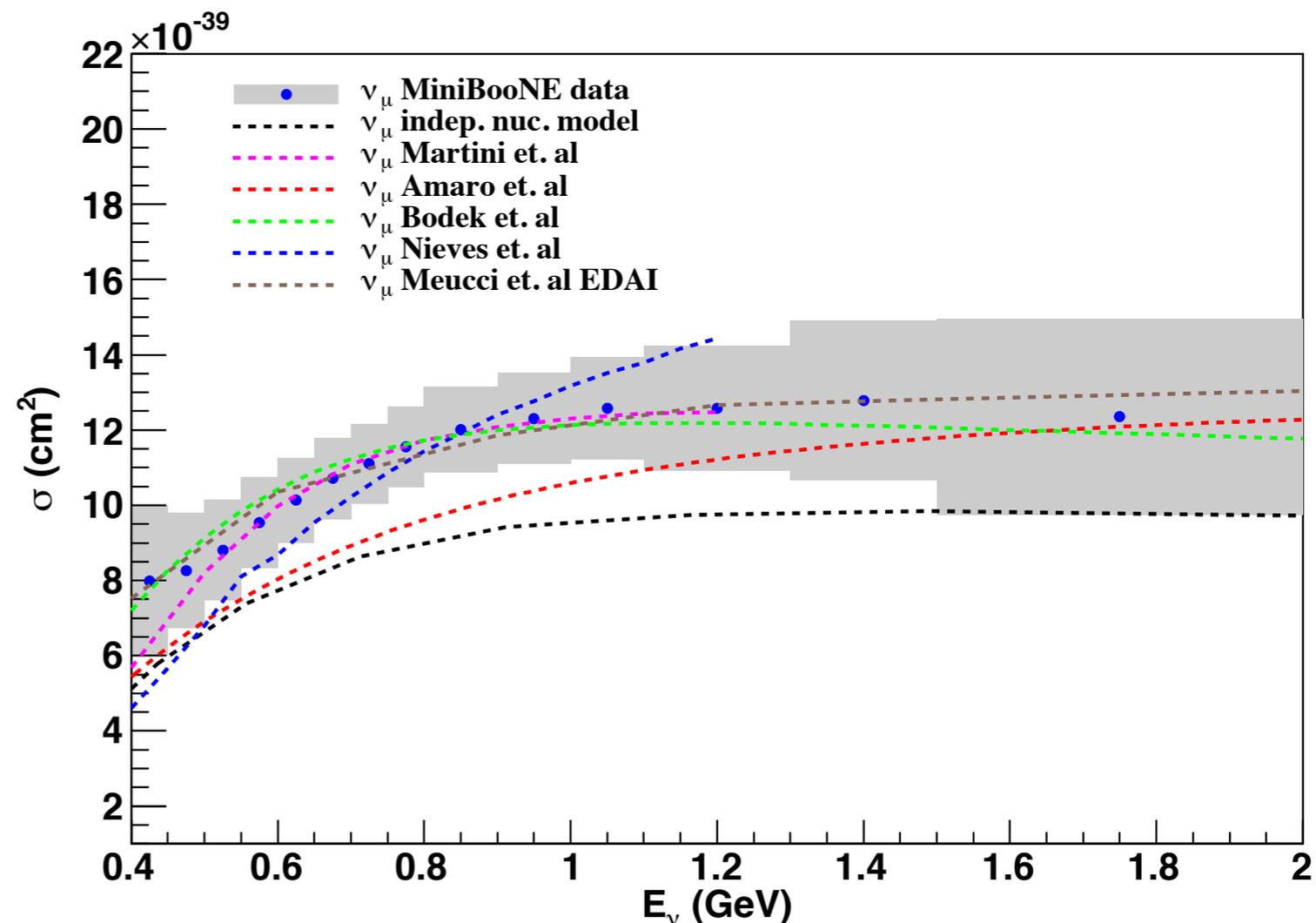
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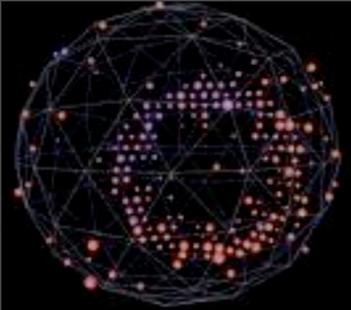
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- ▶ Confirmation from independent groups that *something like* the multi-nucleon mechanism can account for observed enhancement
 - variety of different approaches represented here: parametrizations, extrapolations, and *ab initio* calculations

- ▶ 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?





Since 2009



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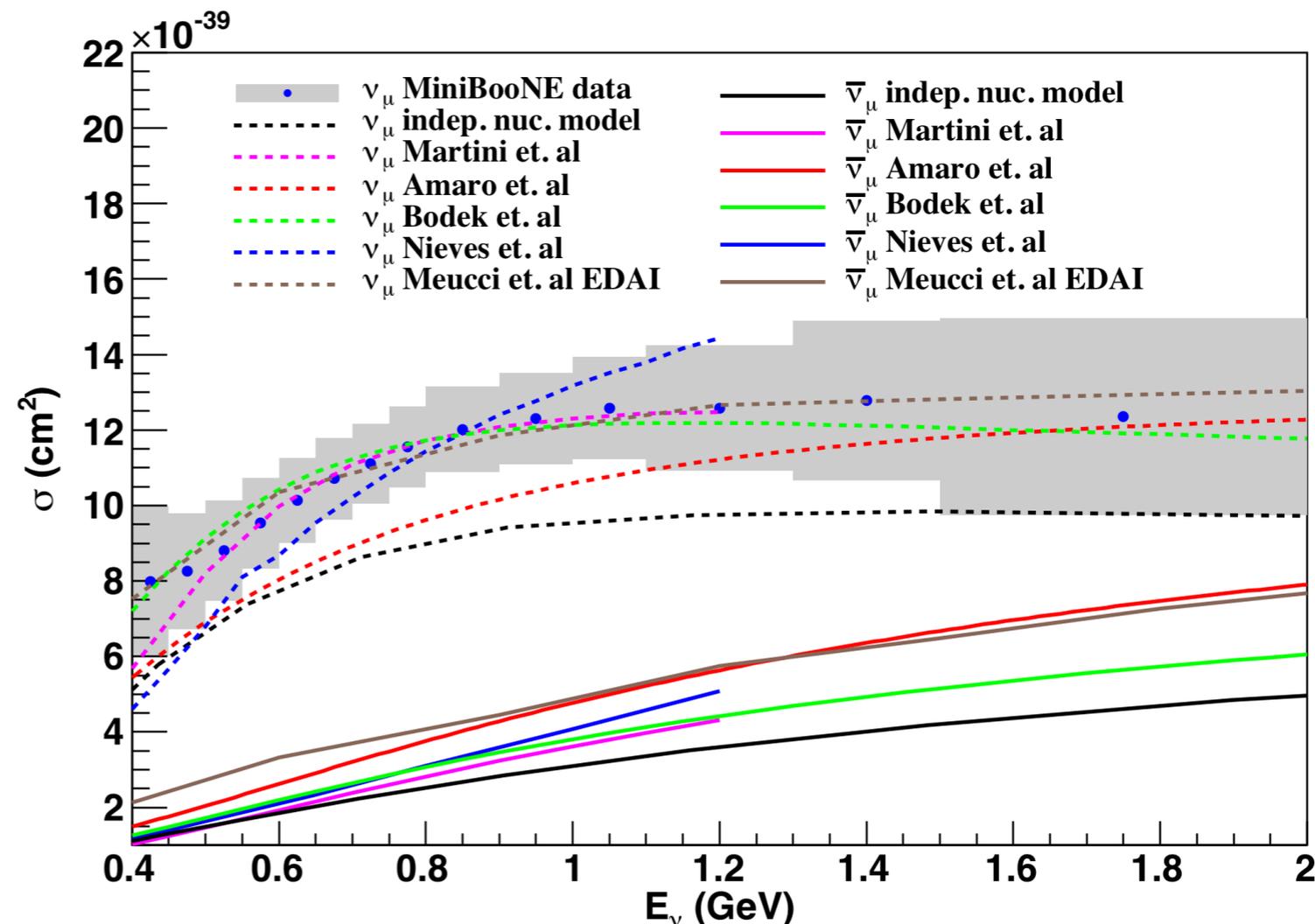
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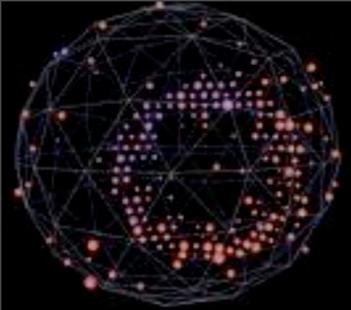
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- probes a different mix of axial, vector σ pieces. How might this new process contribute to anti-neutrino CCQE in MiniBooNE?
- $\bar{\nu}_\mu$ predictions differ by as much as factor of two!





Another historical $\bar{\nu}$ factor 2 cross section



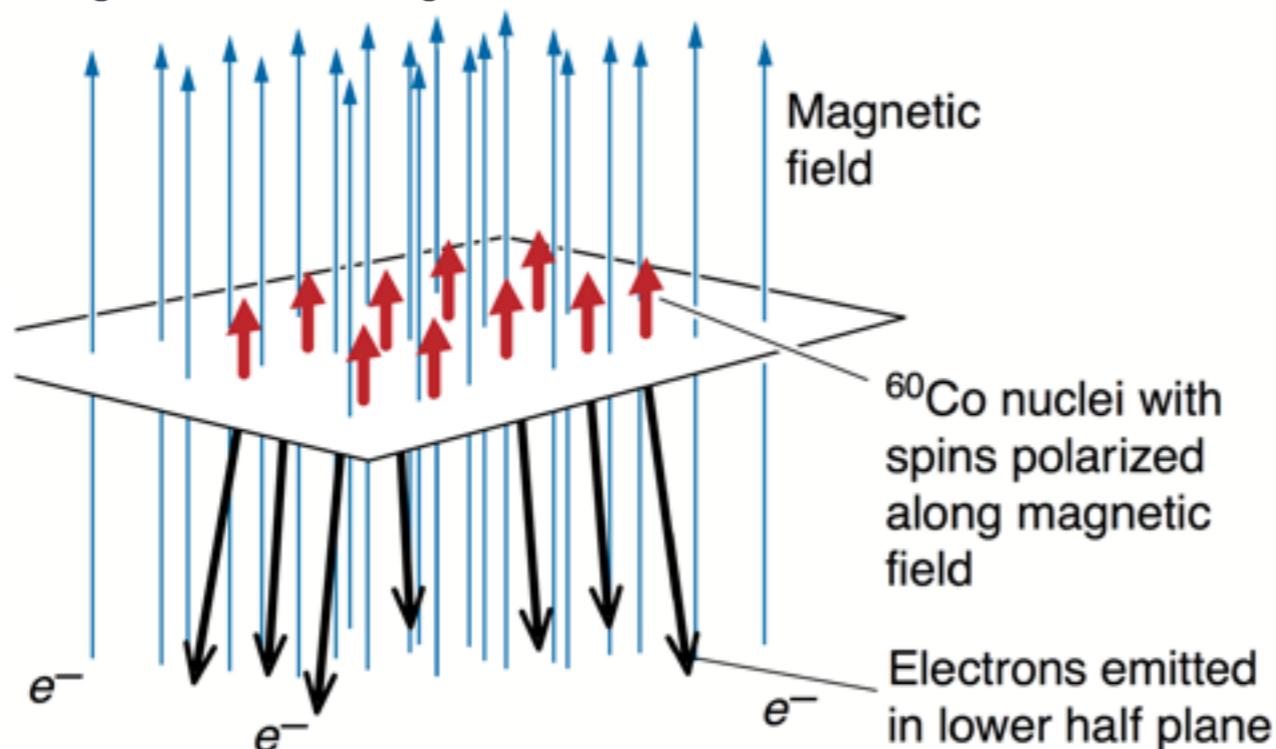
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- ▶ Parity violation in weak interaction discovered same year as the ν
 - immediately implied reduction of ν cross sections by factor 2

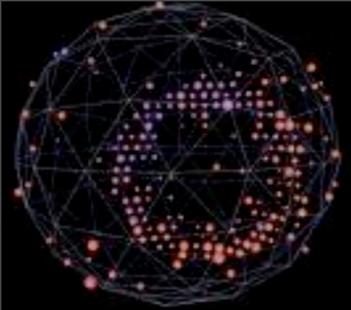
Fig. from *Celebrating the Neutrino*, LANL



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: $\sigma(T_\mu, \theta_\mu)$



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- ▶ 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!

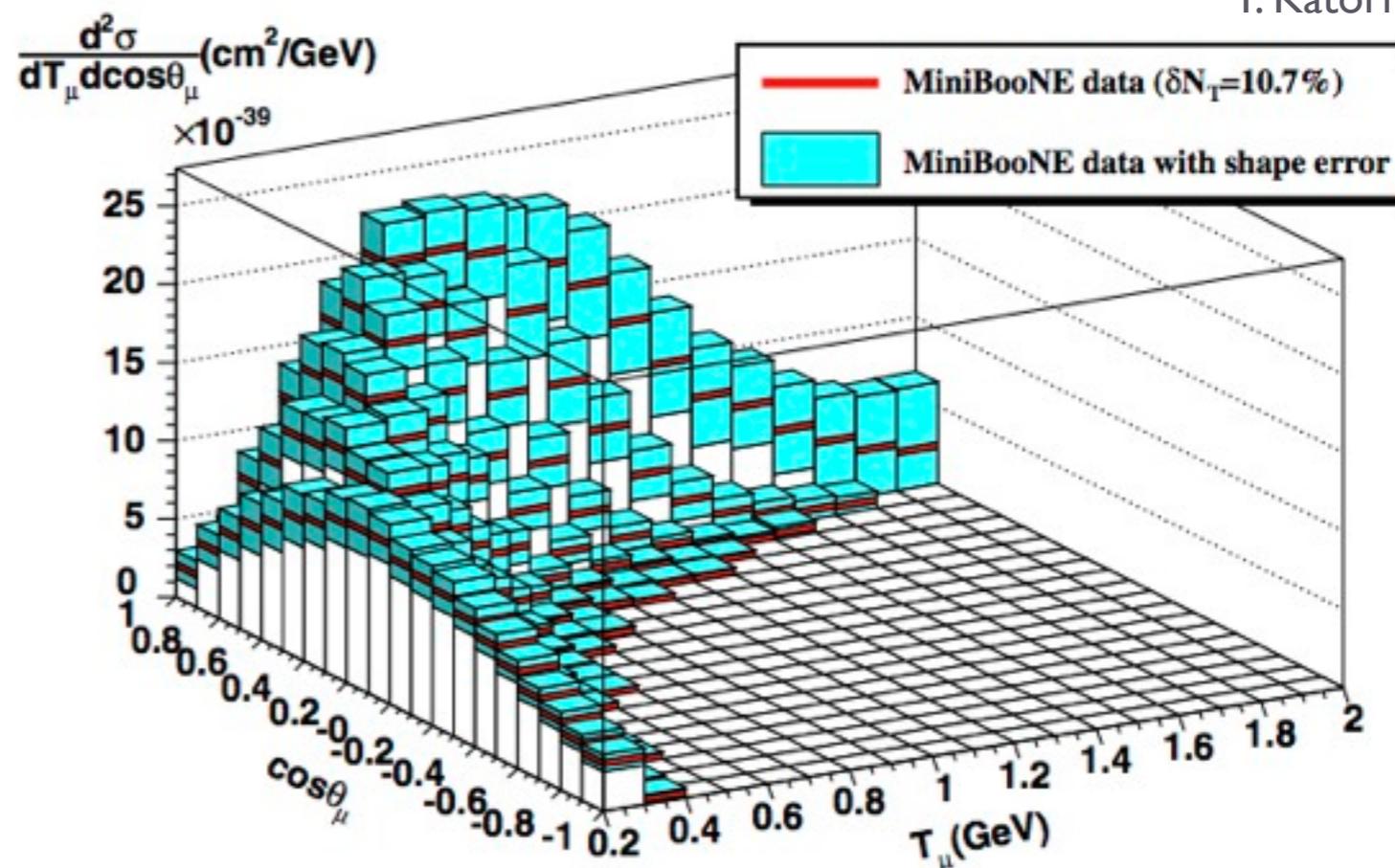
- ▶ Much better idea: report *what we measure*, double-differential

$$\sigma(T_\mu, \theta_\mu)$$

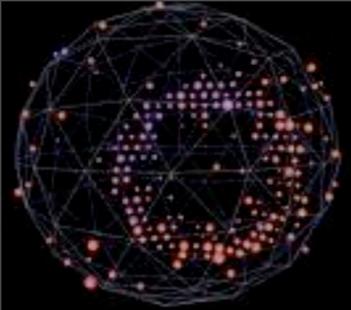
- also fully exploits MiniBooNE's unprecedented statistics

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

T. Katori



Phys. Rev. D81, 092005 (2010)



1. Introduction

ν cross sections in a single-detector oscillation exp't
recent σ interest from MiniBooNE neutrino-mode data

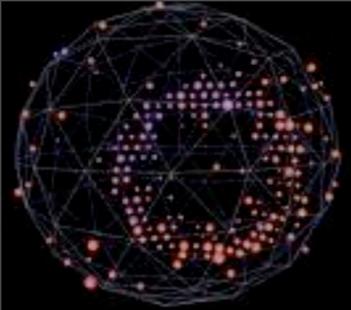
2. Anti-neutrino analyses

ν_μ background (“wrong signs”)

$\bar{\nu}_\mu$ CCQE σ (new!)

$\bar{\nu}_\mu$ NCE σ (new!)

3. Outlook and summary



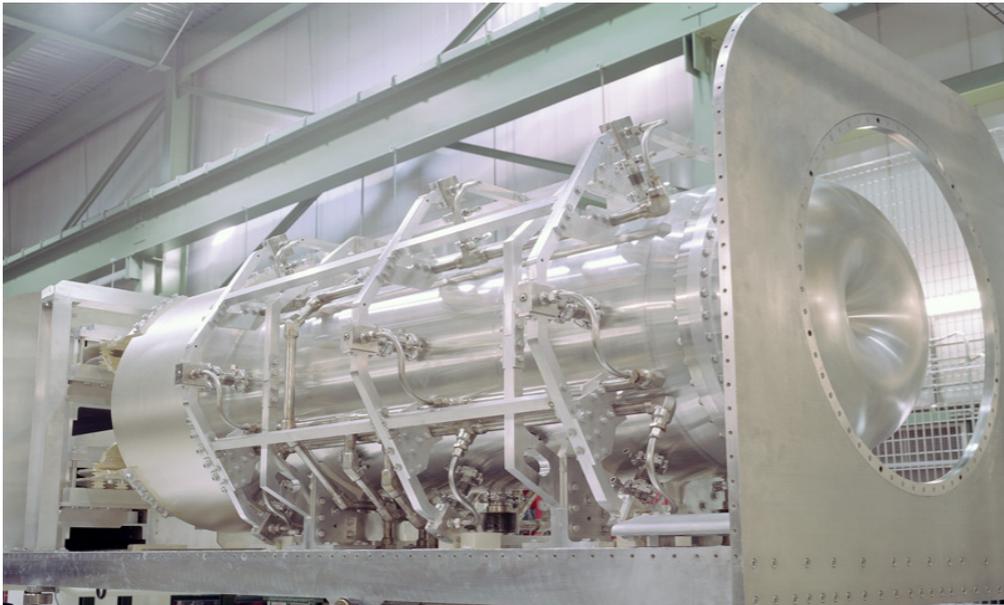
Booster neutrino beam



Joe Grange

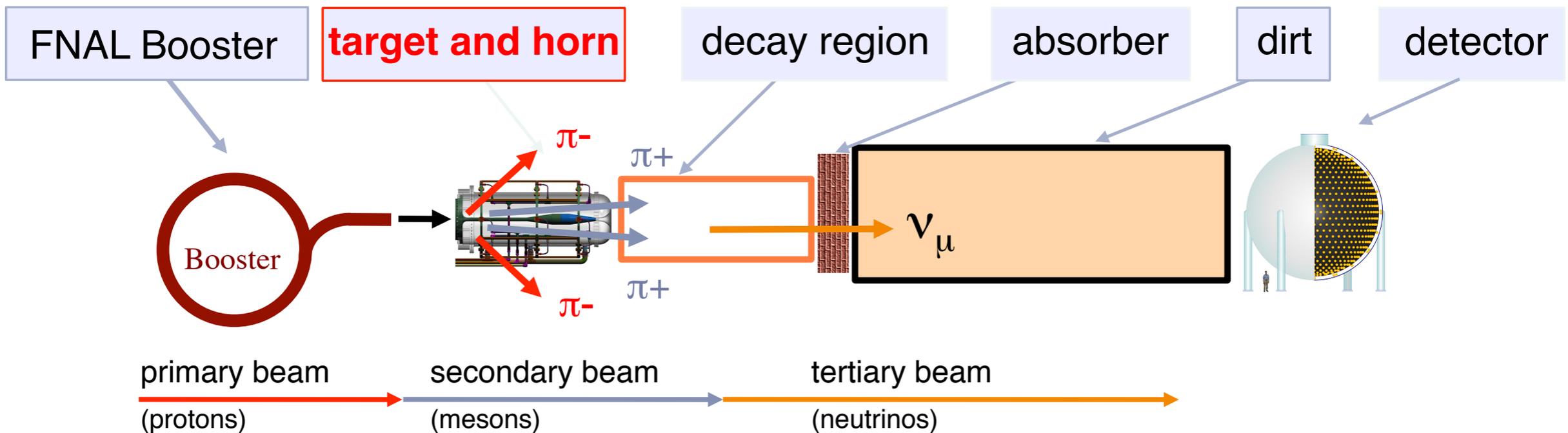
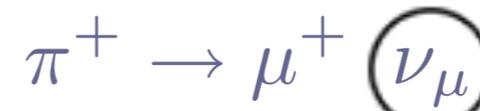
FNAL Joint Experimental-Theoretical Seminar

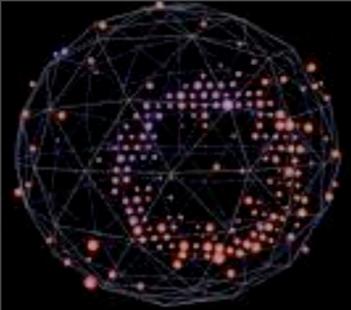
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Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent

mesons





Neutrino flux



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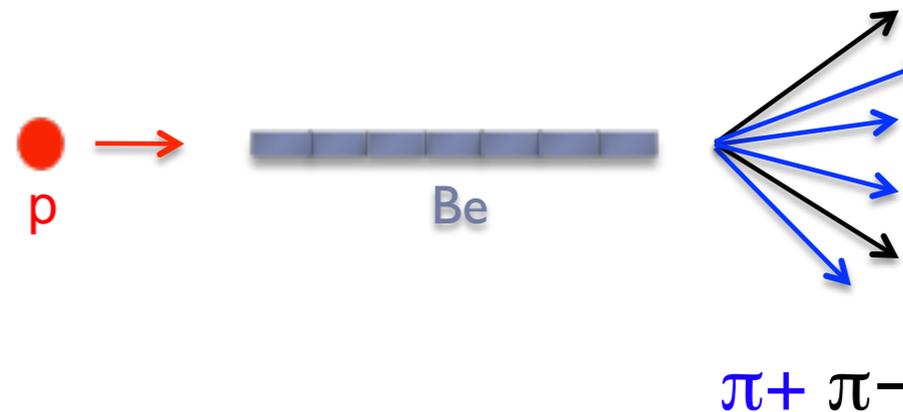
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▶ With measurements of

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

can predict ν , anti- ν flux at detector



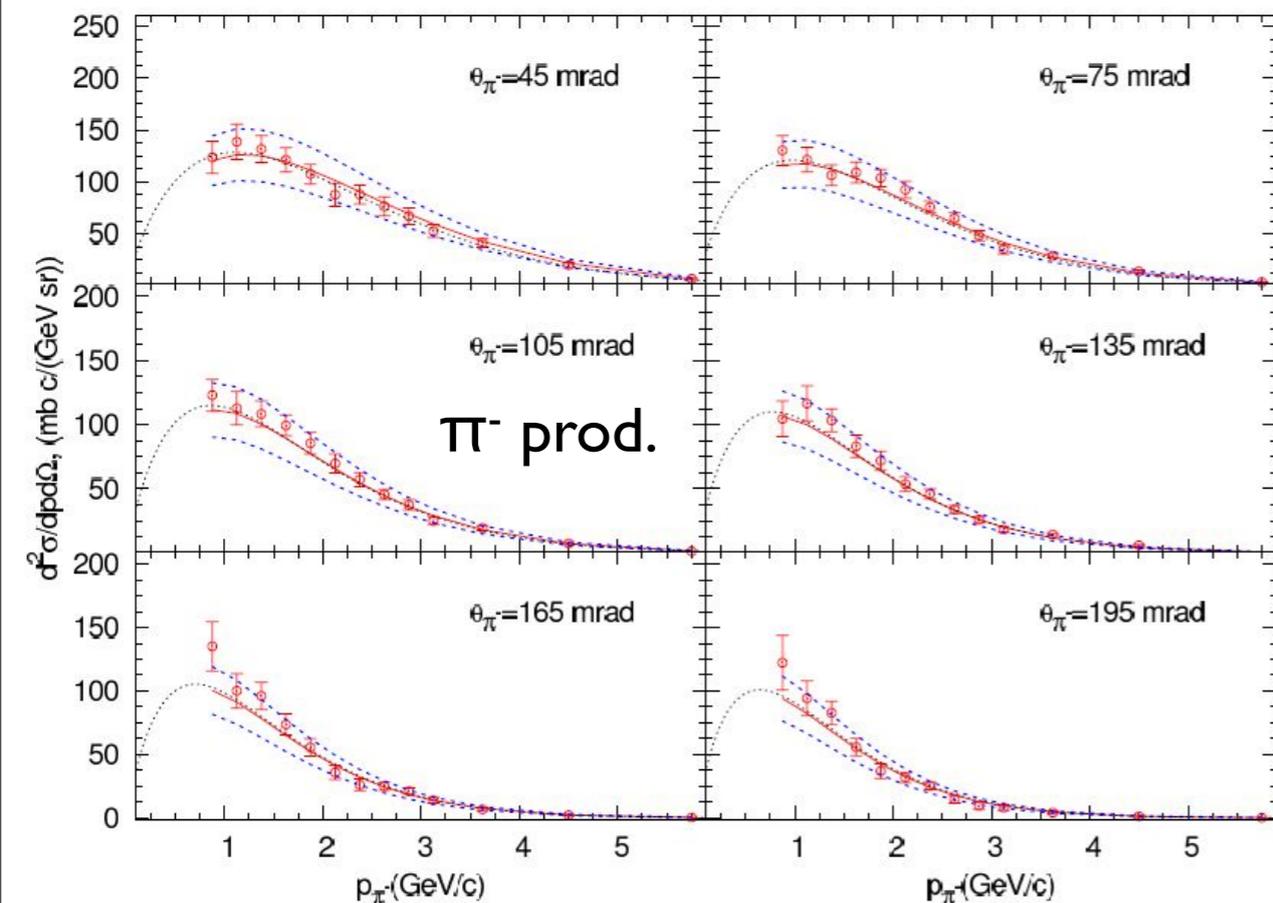
▶ Dedicated π production data taken by HARP experiment (CERN)

- “thin target” results used (5% λ), thick target data also taken and actively being analyzed

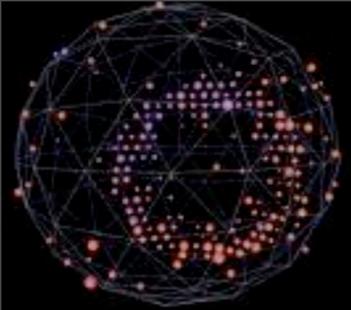
▶ Spline fit to these data (along with beamline geometry simulation) brings ν flux uncertainty to ~9%

- 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)



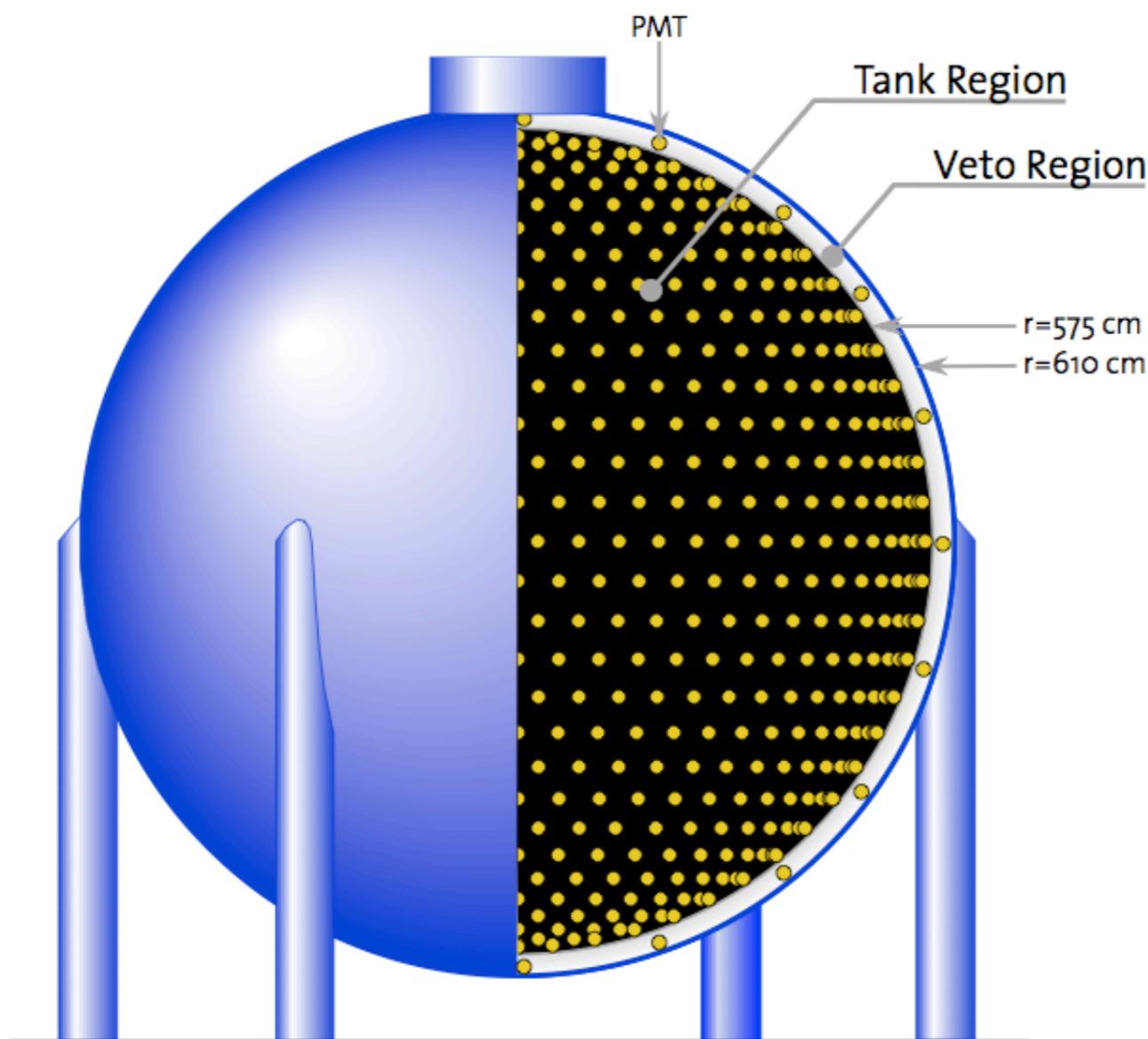
Detector



Joe Grange

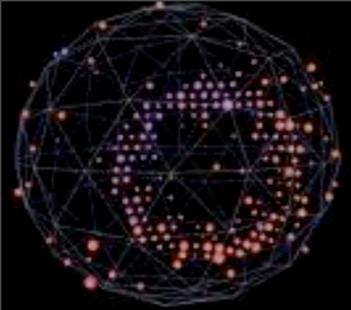
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Nucl. Instr. Meth. A599, 28 (2009)

- ▶ 6.1 m 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)



V-mode rate

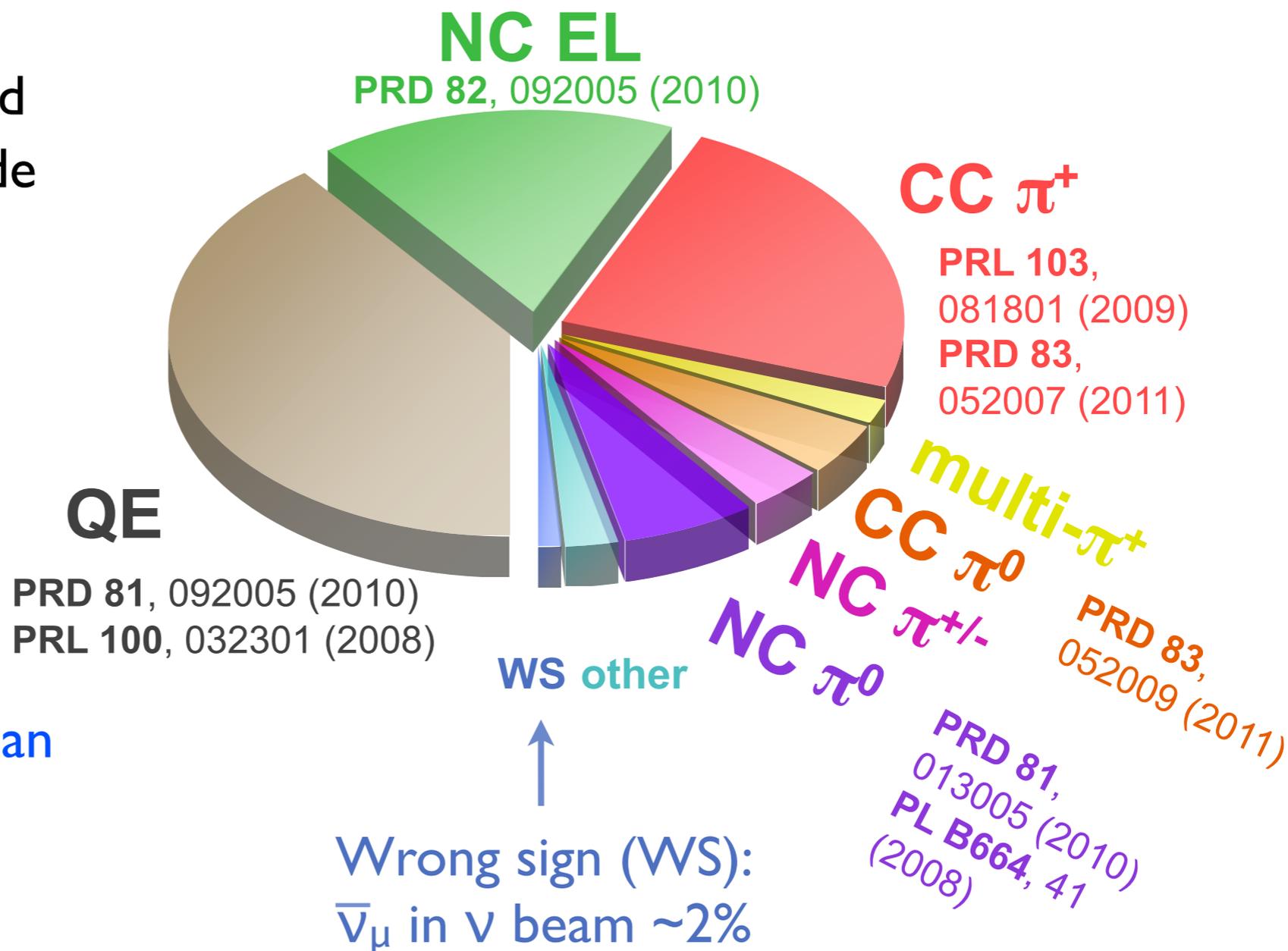


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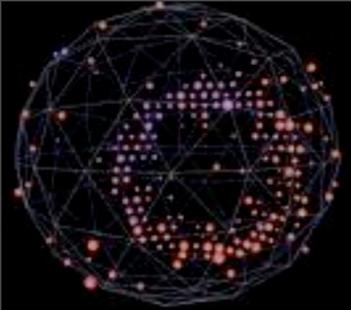
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- ▶ MiniBooNE has published ~90% of the total V-mode rate



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



$\bar{\nu}$ -mode rate

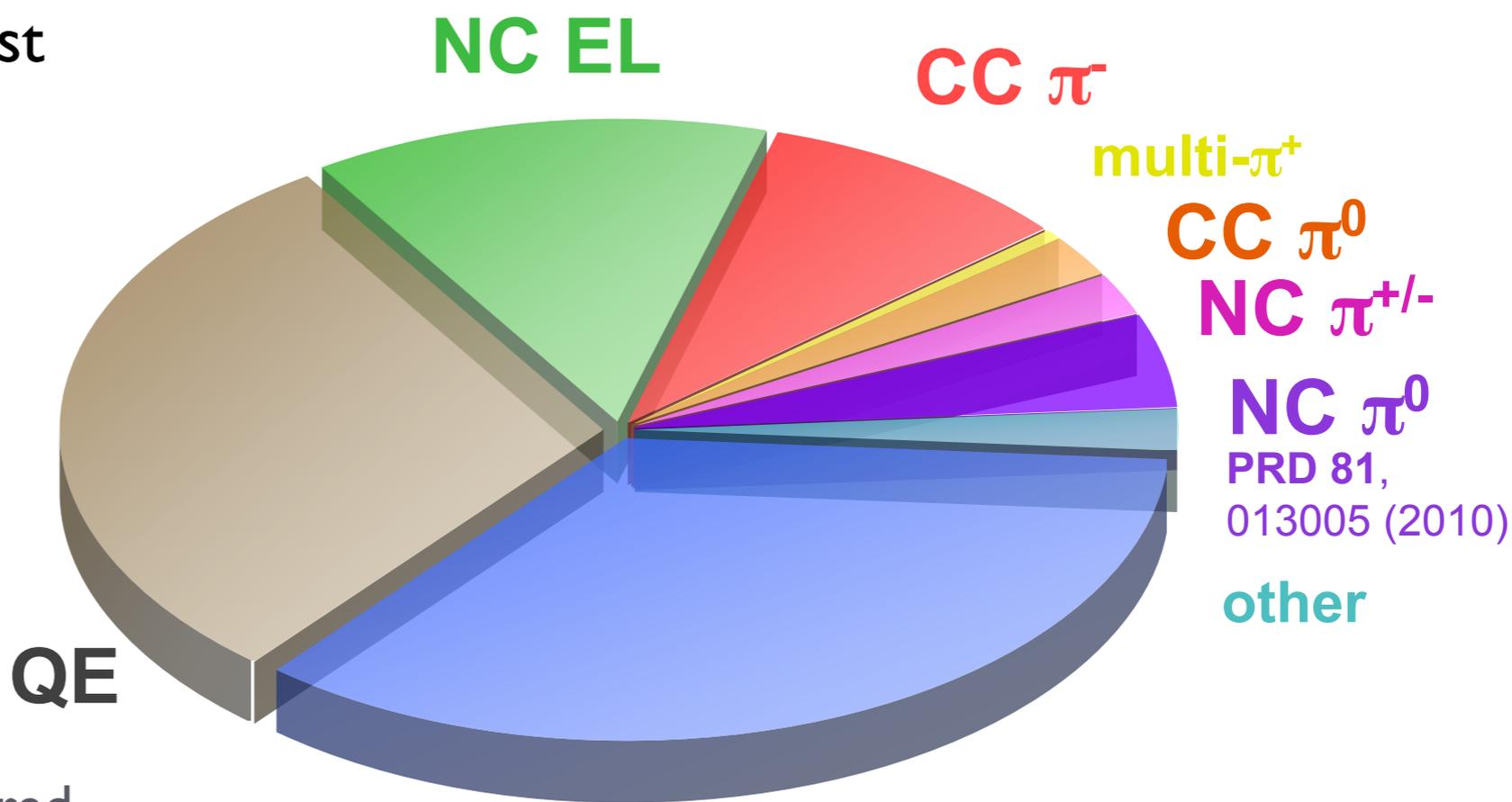


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- ▶ Before able to make precision $\bar{\nu}_\mu$ σ 's, must deal with largest background: wrong-sign ν_μ



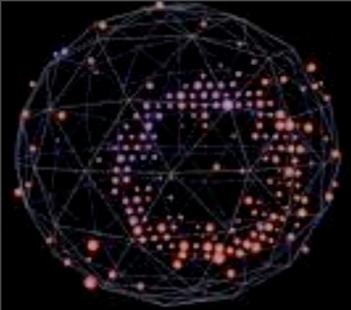
- ▶ Unprecedented $\bar{\nu}$ statistics
 - 1.0×10^{21} POT in an unexplored energy region

QE

WS ν

PRD 84, 072005 (2011)

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



Wrong-sign background

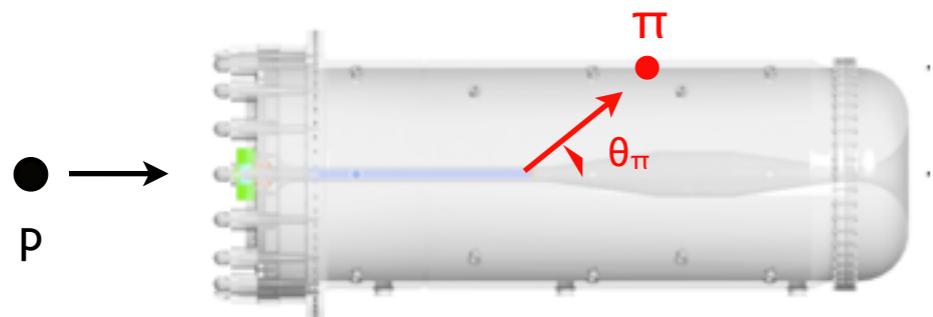


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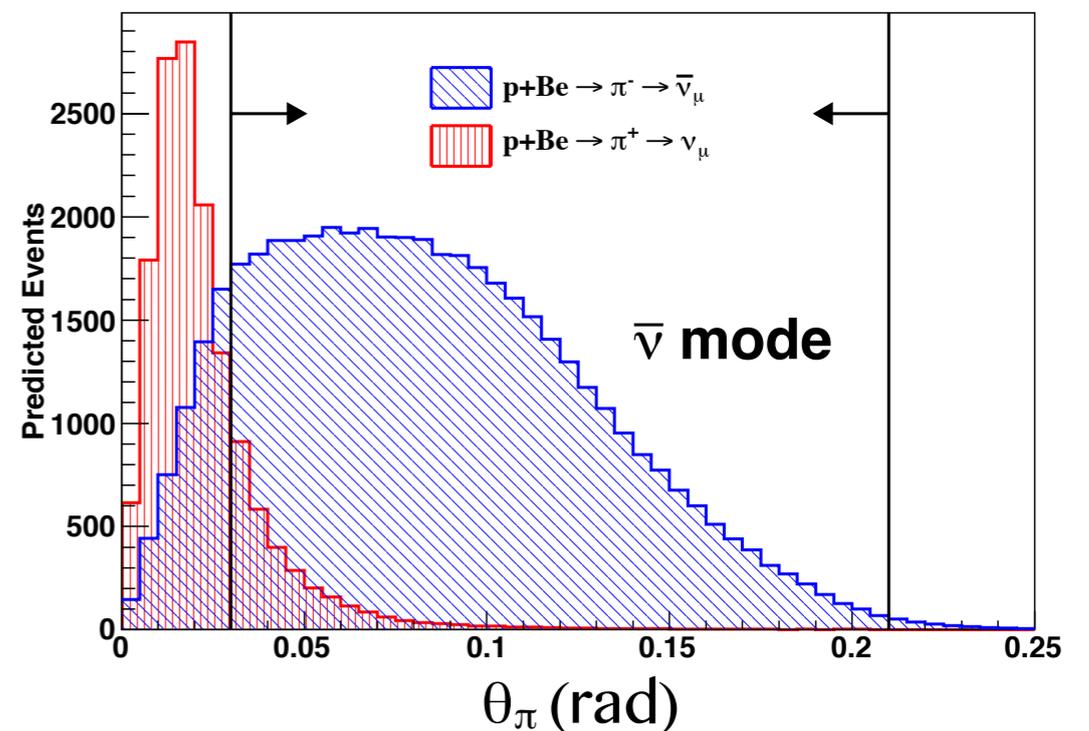
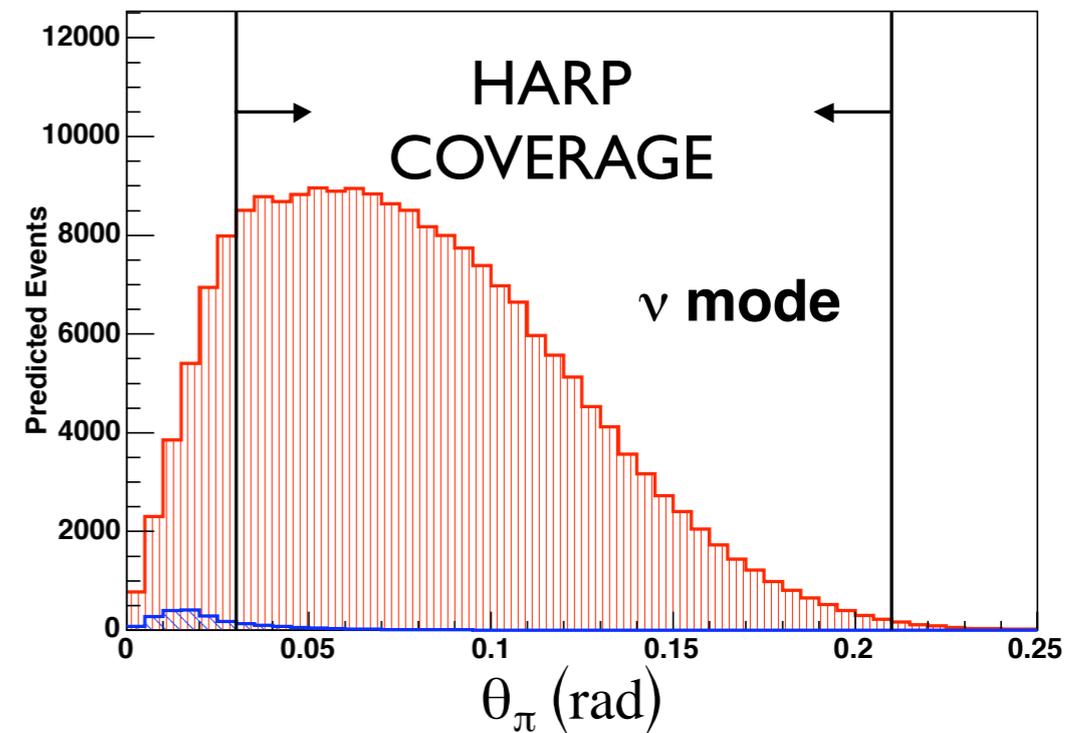
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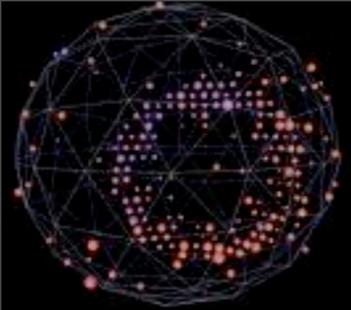
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- ▶ Even worse: ν_μ parent π^+ production in $\bar{\nu}$ mode (“wrong signs”) mostly not constrained by HARP measurements
 - overall rate highly uncertain!



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





Wrong-sign background

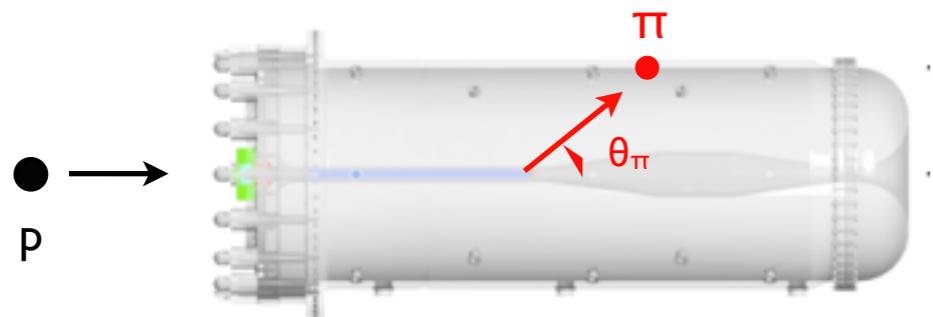


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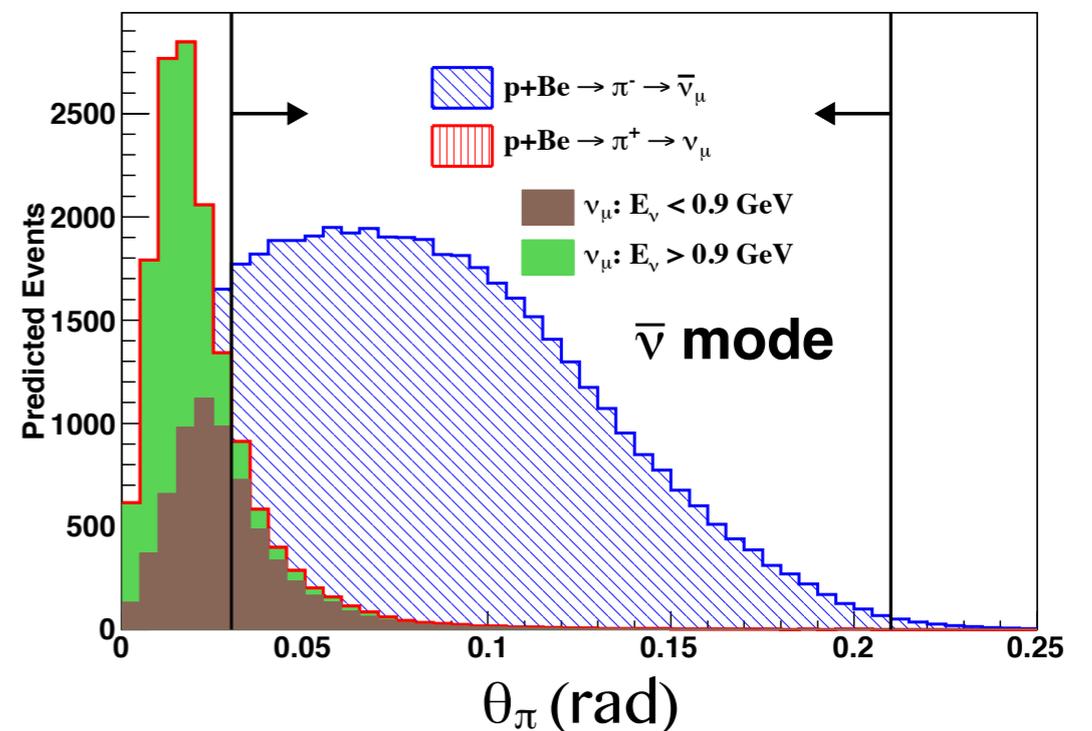
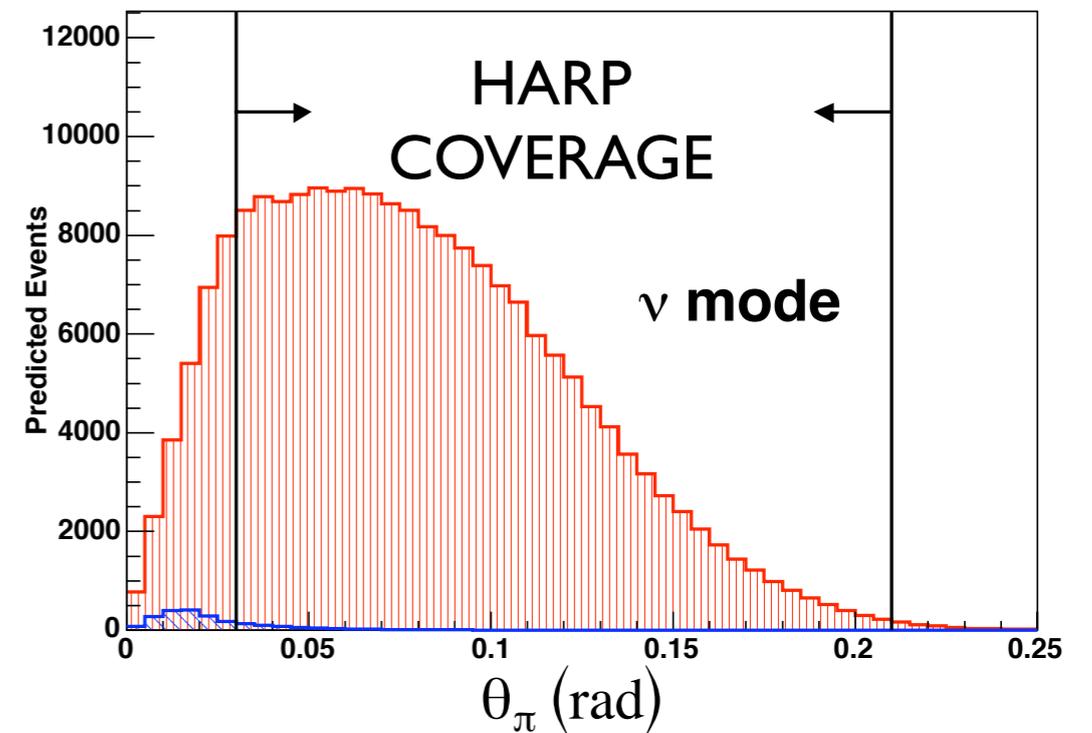
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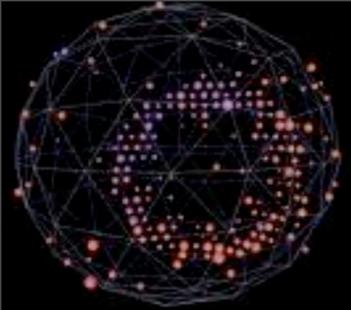
Nov. 30 2012

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 - overall rate highly uncertain!



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 - need to check flux spectrum!





Wrong-sign measurements



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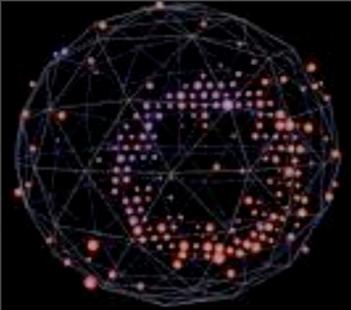
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- ▶ Other detectors employ magnetic field to separate CC $\nu_\mu / \bar{\nu}_\mu$
 - MiniBooNE unmagnetized, must use statistical techniques
- ▶ Never been done before, had to get creative! General strategy:
 1. exploit asymmetries between ν_μ , anti- ν_μ interactions in the detector
 2. apply measured σ 's from neutrino-mode data (CCQE, CC π^+)

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

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



Three ν_μ flux measurements



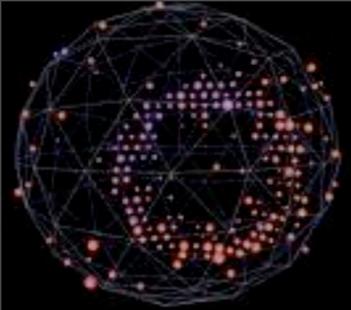
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▶ Three complementary measurements based on:

1. ν_μ CC π^+ sample (exploits π^- nuclear capture)
2. μ -only and $\mu+e$ rates (exploits μ^- nuclear capture)
3. backward scattering region in CCQE sample (dominated by ν_μ)



Three ν_μ flux measurements



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▶ Three complementary measurements based on:

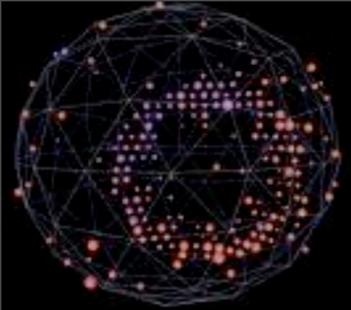
1. ν_μ CC π^+ sample (exploits π^- nuclear capture)
2. μ^- -only and μ^+e rates (exploits μ^- nuclear capture)
3. backward scattering region in CCQE sample (dominated by ν_μ)

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 π^+ sample



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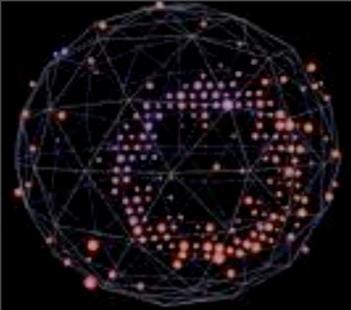
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- ▶ From lepton and charge conservation, single- π production (mostly via Δ resonance) results in π^+ for ν_μ , π^- for $\bar{\nu}_\mu$

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

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



CC π^+ sample



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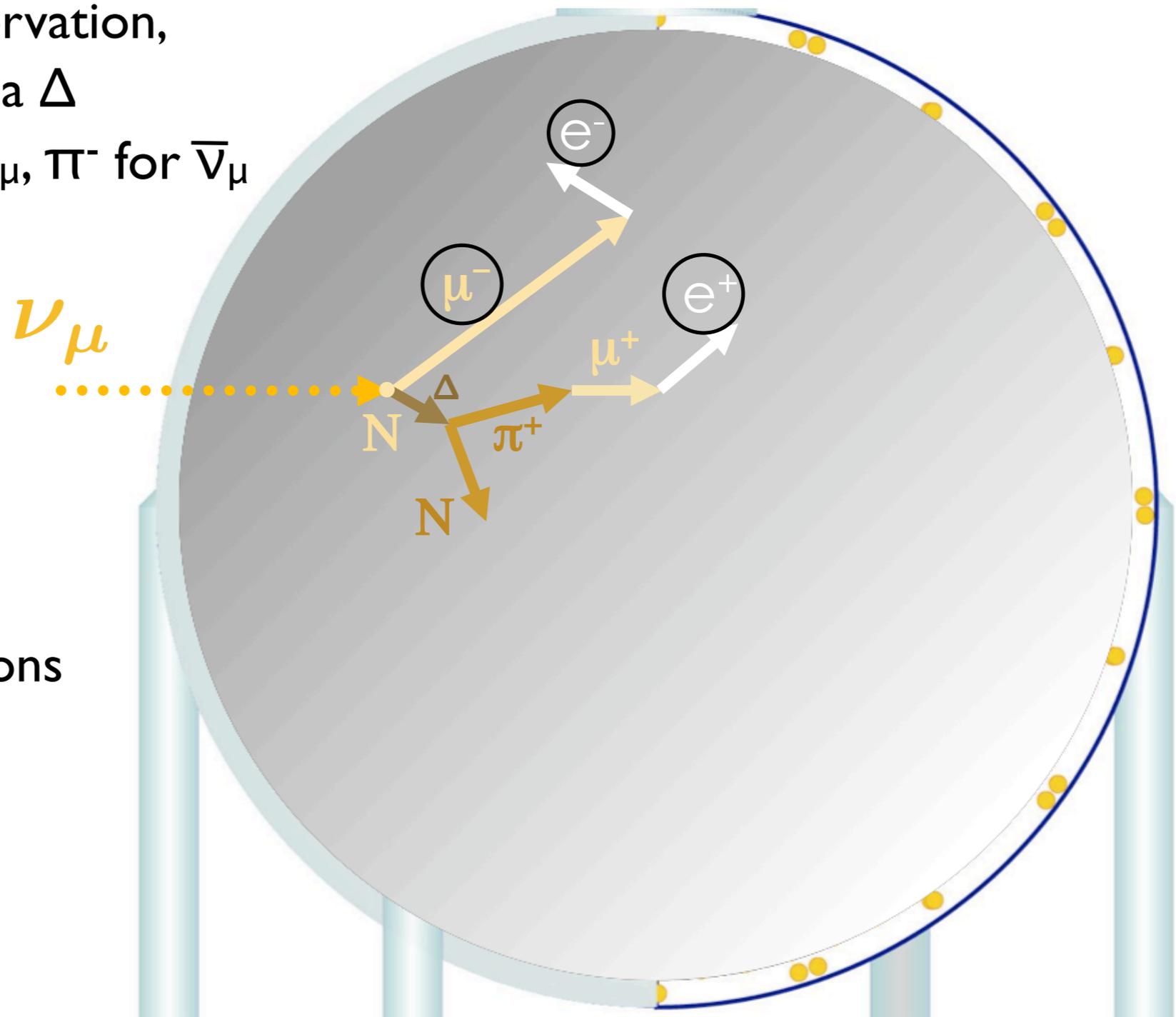
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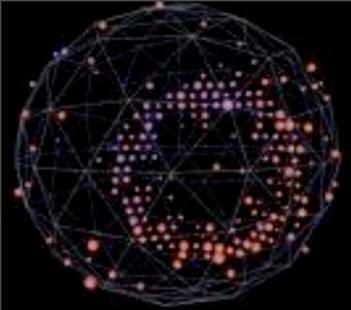
$$\nu_\mu N \rightarrow \mu^- \pi^+ N$$

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

- ▶ ν_μ process leads to three leptons above Cherenkov threshold

1. primary μ
2. decay positron
3. decay electron





CC π^+ sample



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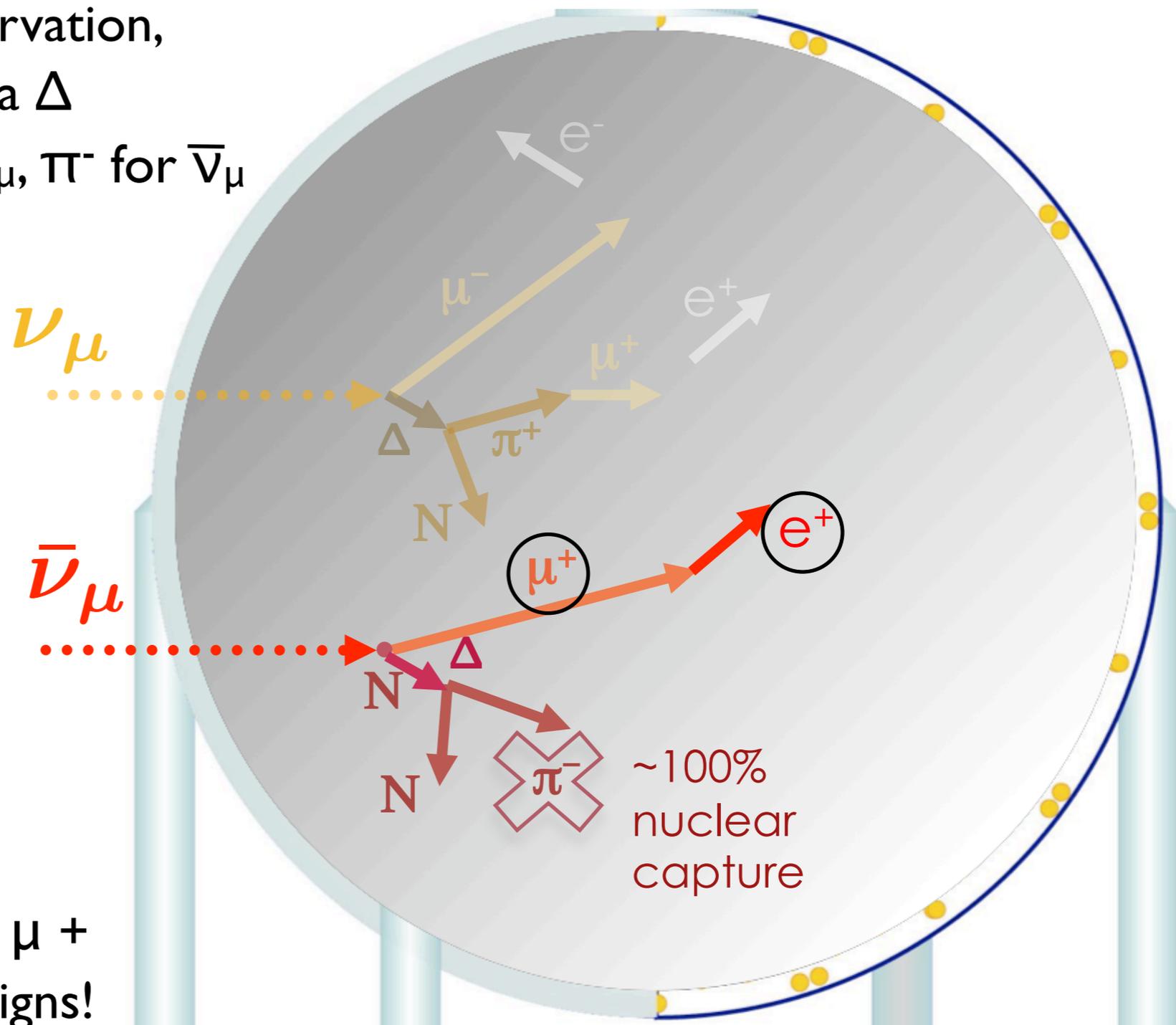
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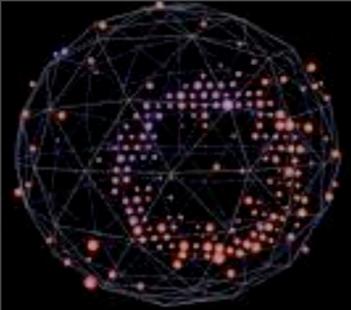


- ▶ Due to π^- nuclear capture ($\sim 100\%$), $\bar{\nu}_\mu$ single π process only has two

1. primary μ
2. decay positron

- ▶ Can do simple rate analysis on $\mu + 2e$ sample to measure wrong signs!





μ^- capture measurement



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

- ▶ Sample composition:

observe μ only



observe $\mu+e$

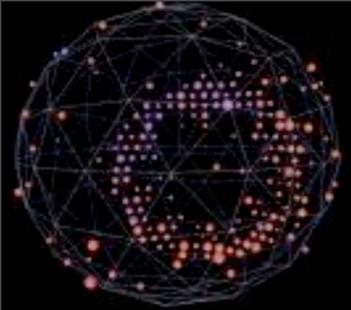


ν_μ $\bar{\nu}_\mu$

- ▶ 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

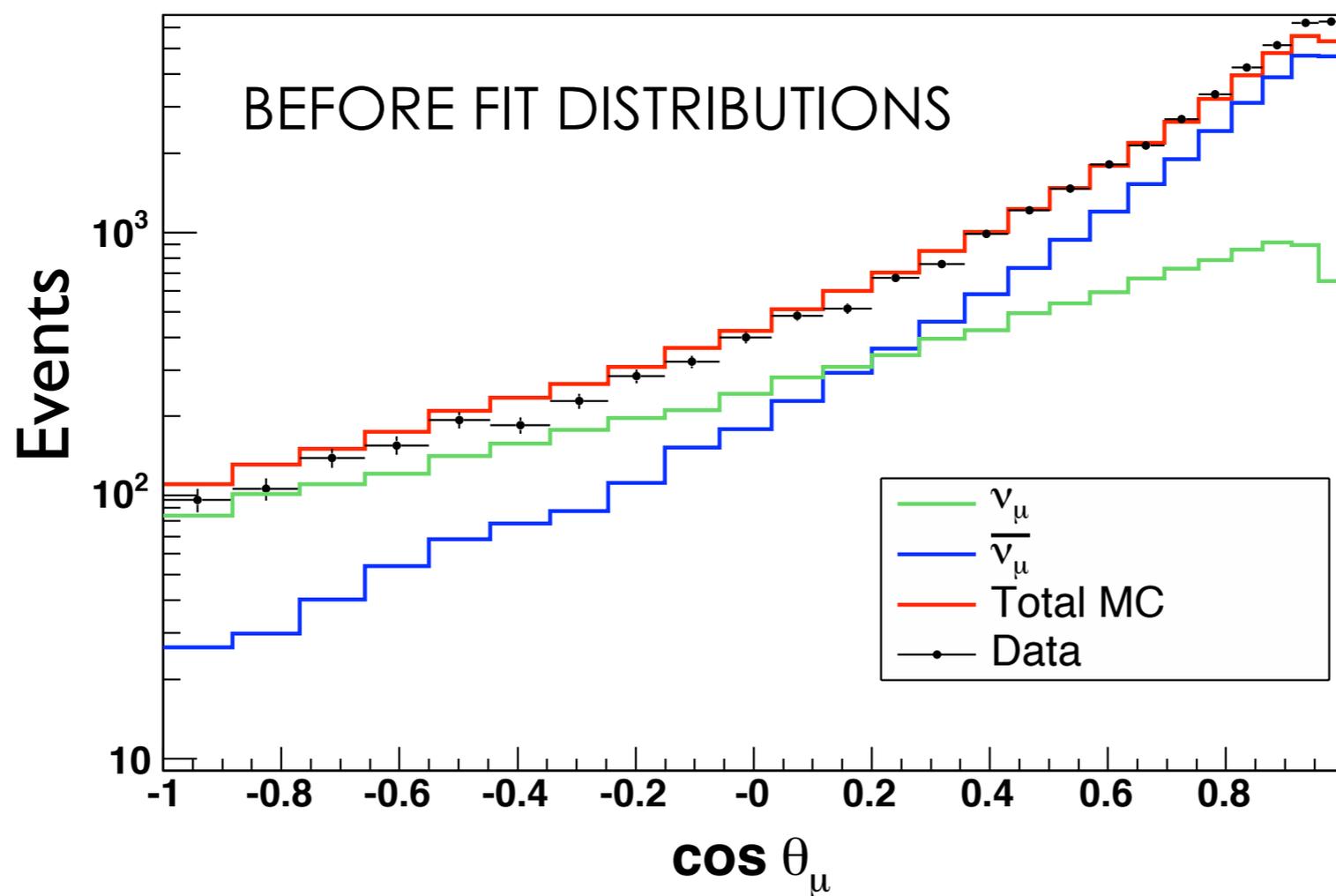


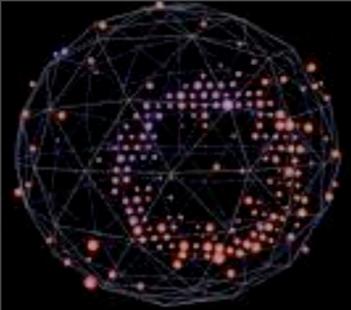
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- ▶ Due to axial-vector interference term in CCQE σ , $\bar{\nu}_\mu$ events expected to be much more forward-going compared to ν_μ
 - perform simple fit to data in reconstructed energy bins





CCQE angular fits



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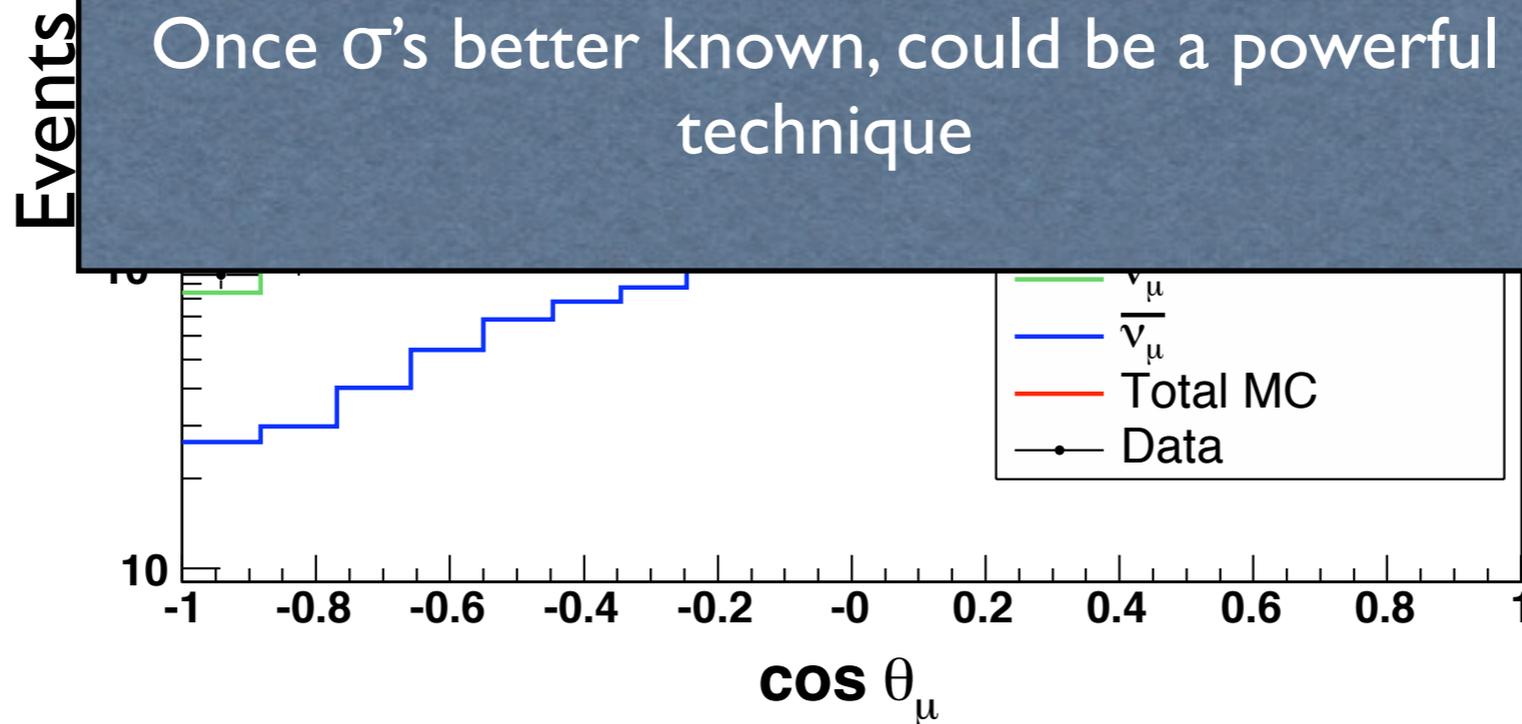
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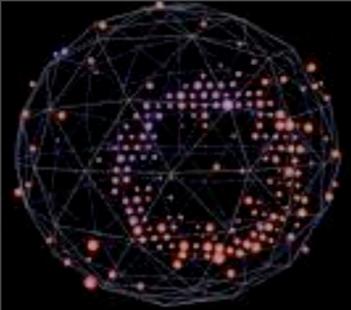
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- ▶ Due to axial-vector interference term in CCQE σ , $\bar{\nu}_\mu$ events expected to be much more forward-going compared to ν_μ
 - perform simple fit to data in reconstructed energy bins

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

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





Wrong-sign flux results

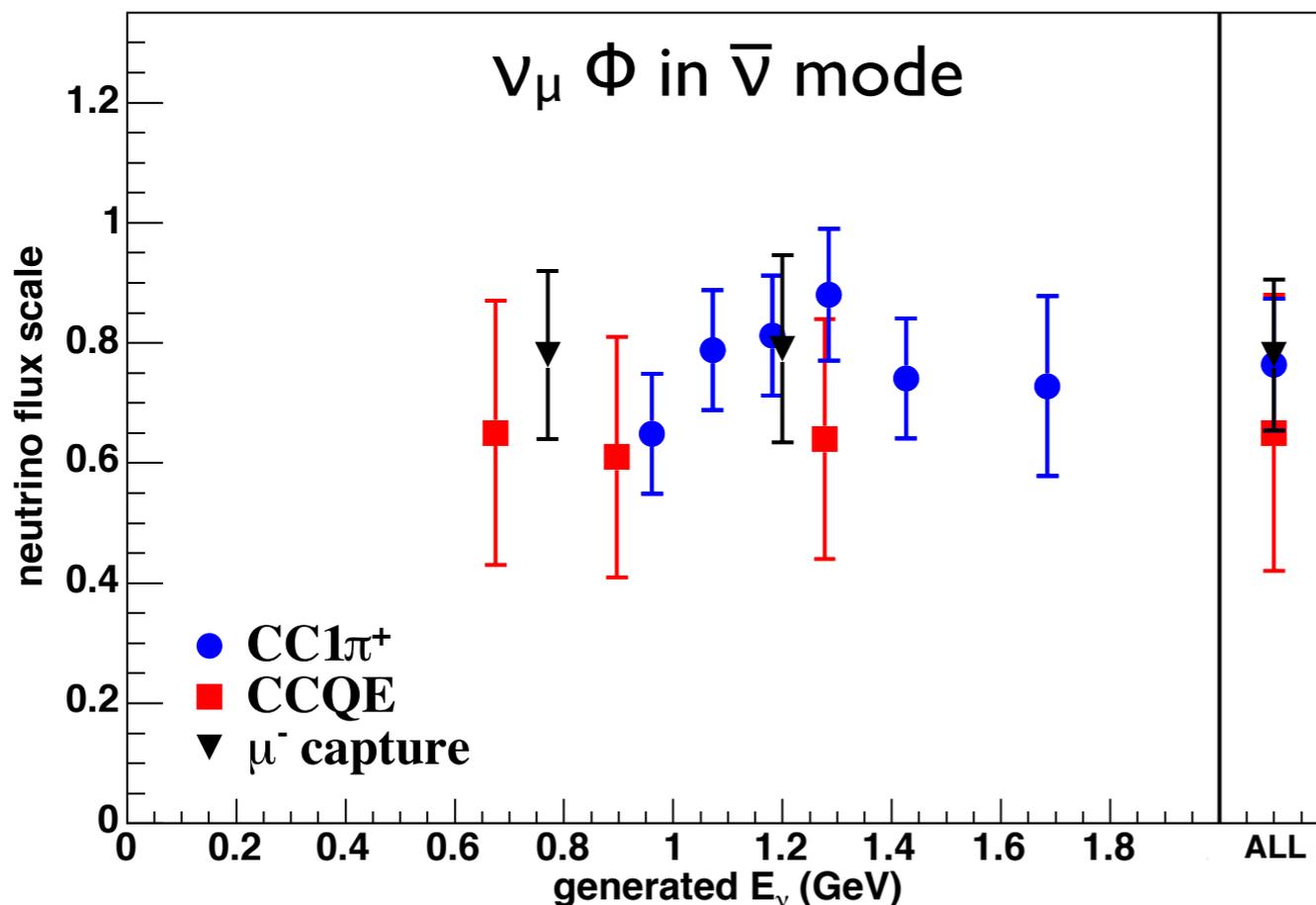


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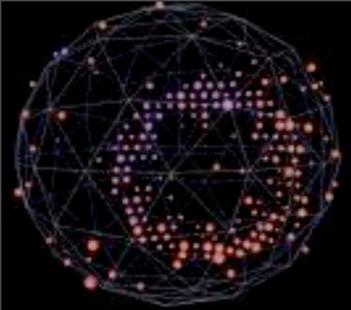
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- ▶ Results binned in energy as finely as allowed by statistics
 - nominal prediction ~20% high in normalization, simulated spectrum appears adequate



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



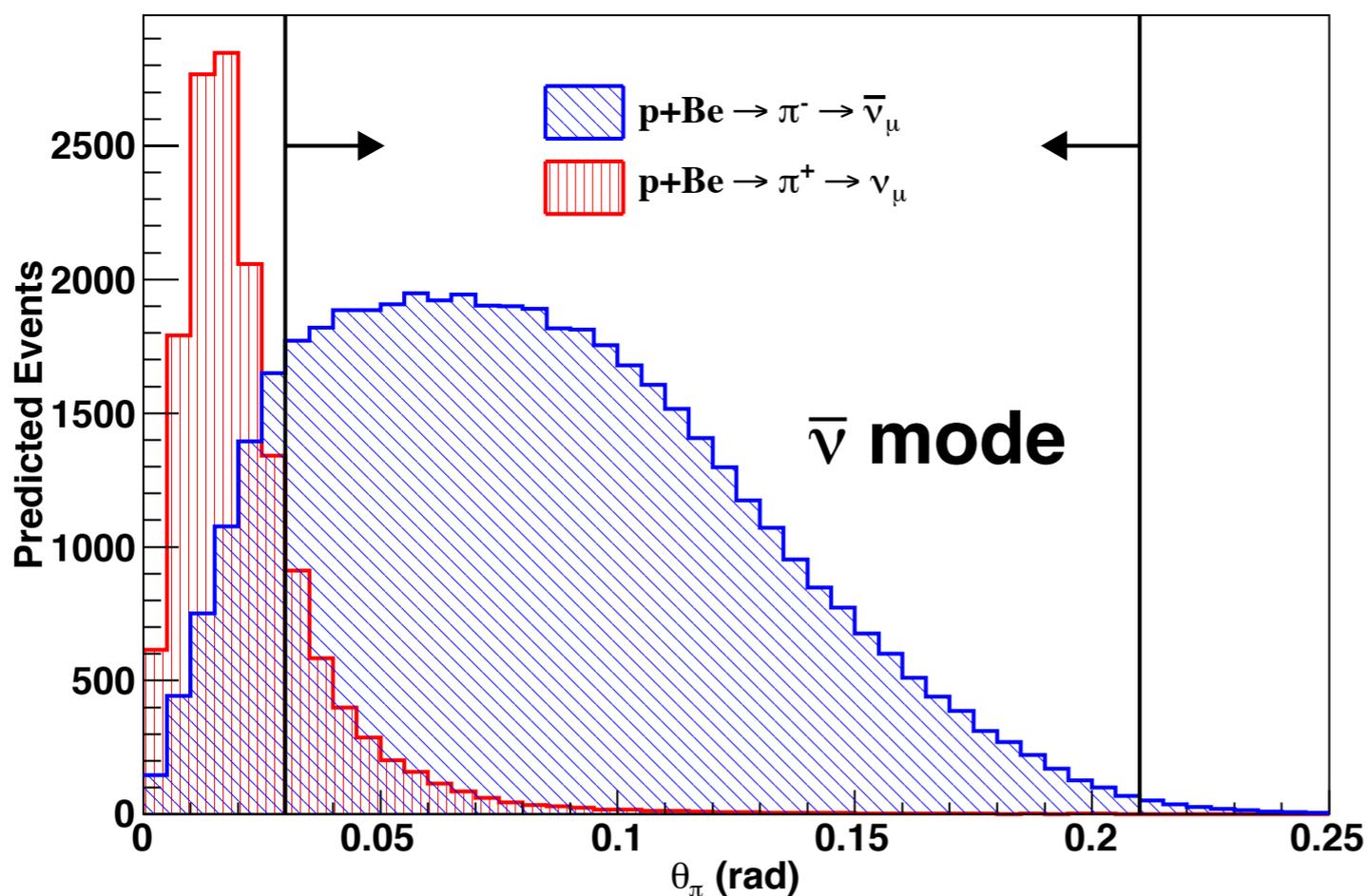
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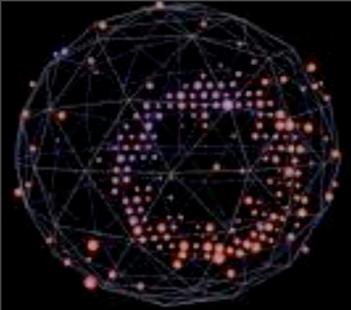
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- ▶ Wrong signs constrained to a sub-dominant uncertainty in all $\bar{\nu}$ mode analyses
- ▶ Let's move to $\bar{\nu}$ events, where we *can* exploit HARP data

(arrows indicate HARP coverage)



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



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



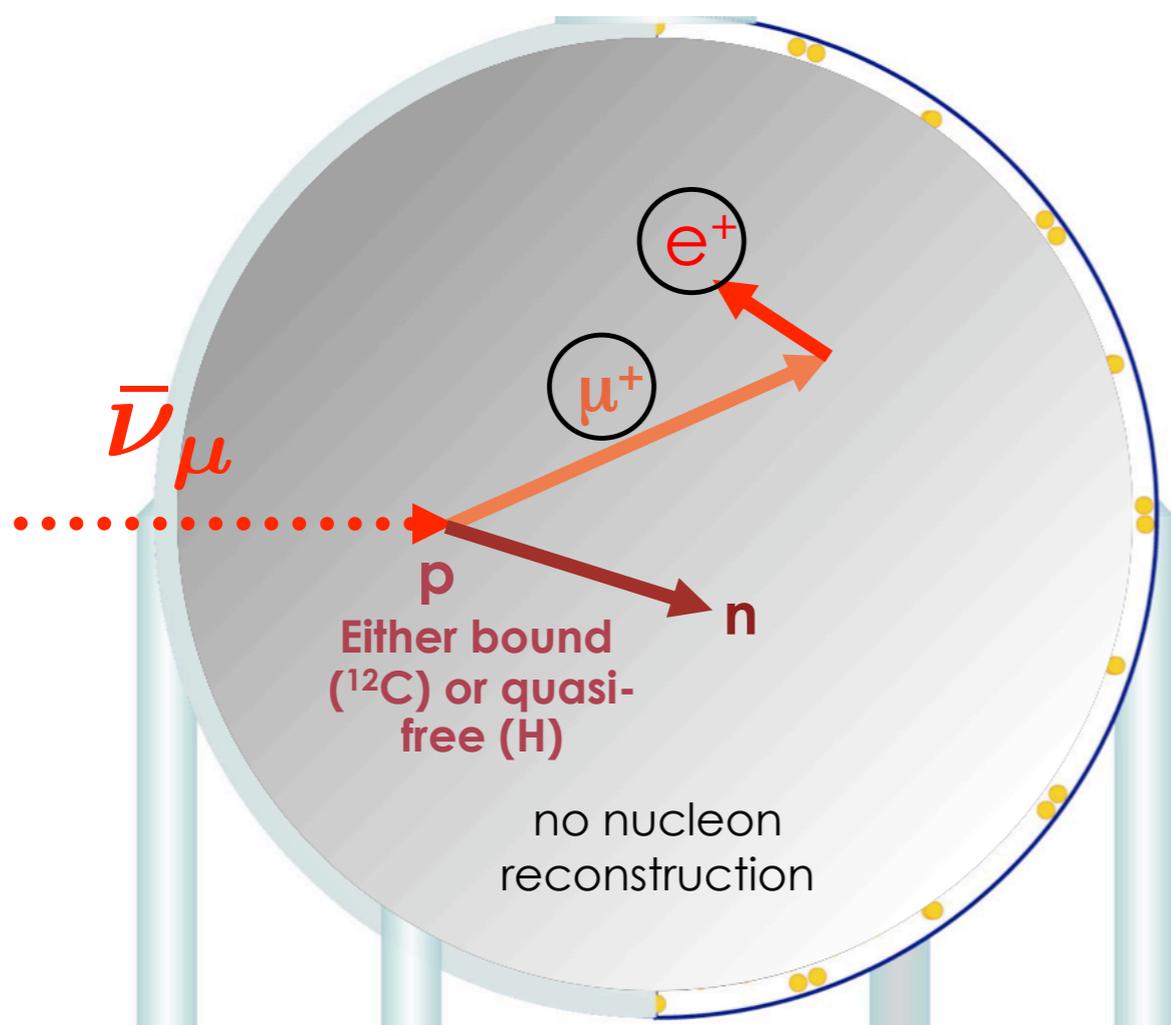
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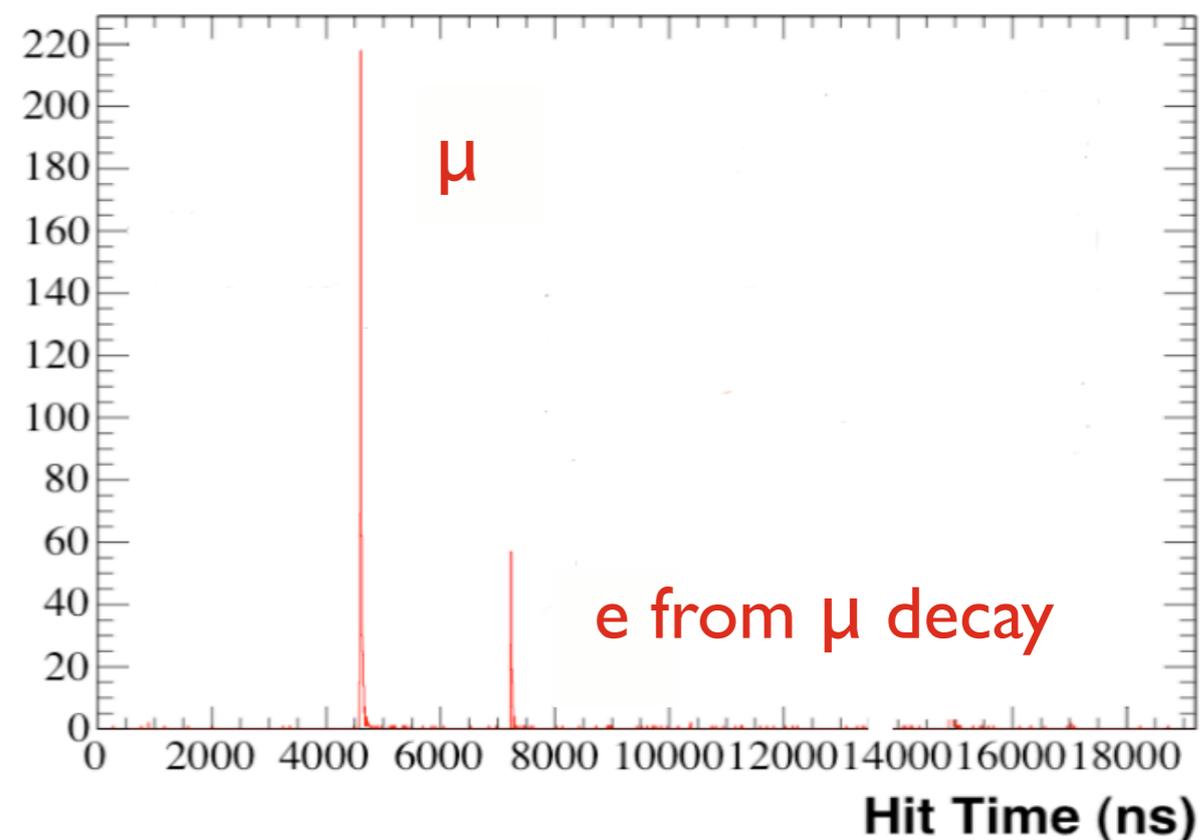
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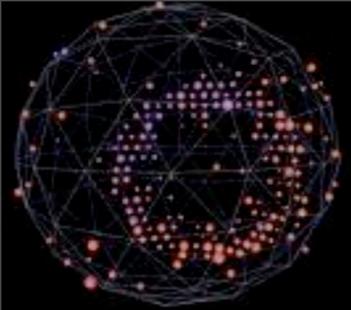
- ▶ $\bar{\nu}_\mu$ CCQE only involves protons: MiniBooNE medium CH_2 , so sample is mix of bound and free scattering

- unlike ν_μ analysis: all n targets housed in ^{12}C



typical event - two "subevents"





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

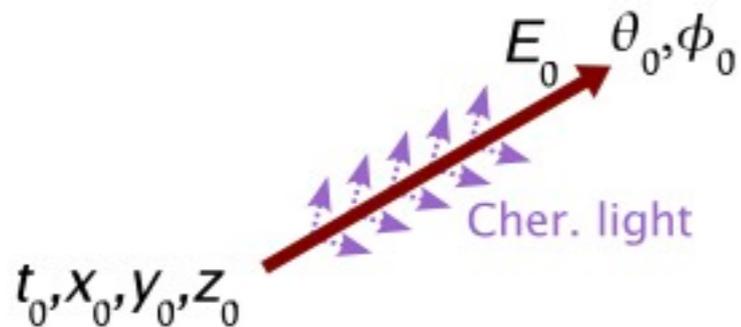


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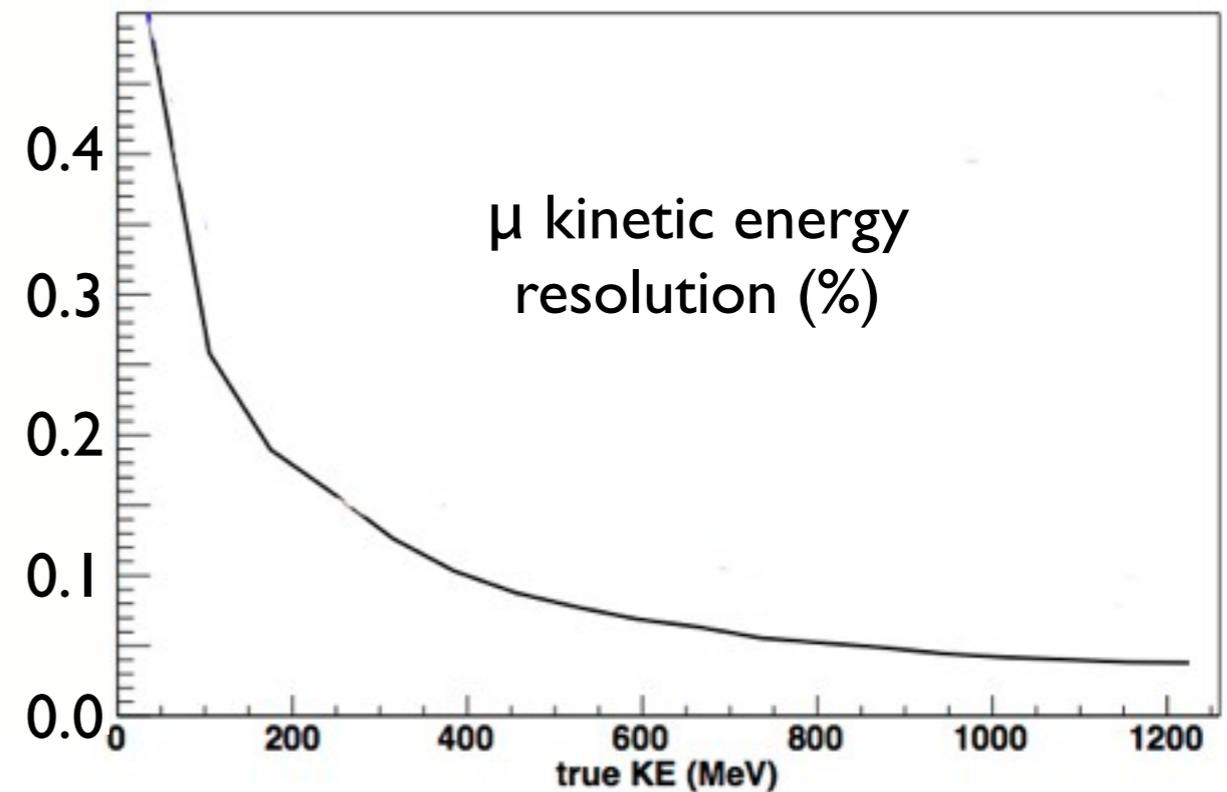
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- ▶ μ kinematics identified by fitting PMT hit topology and timing

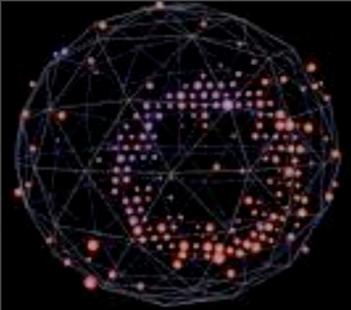


- ▶ μ 's leave distinctive Cherenkov ring, reconstruction performs well



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

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



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

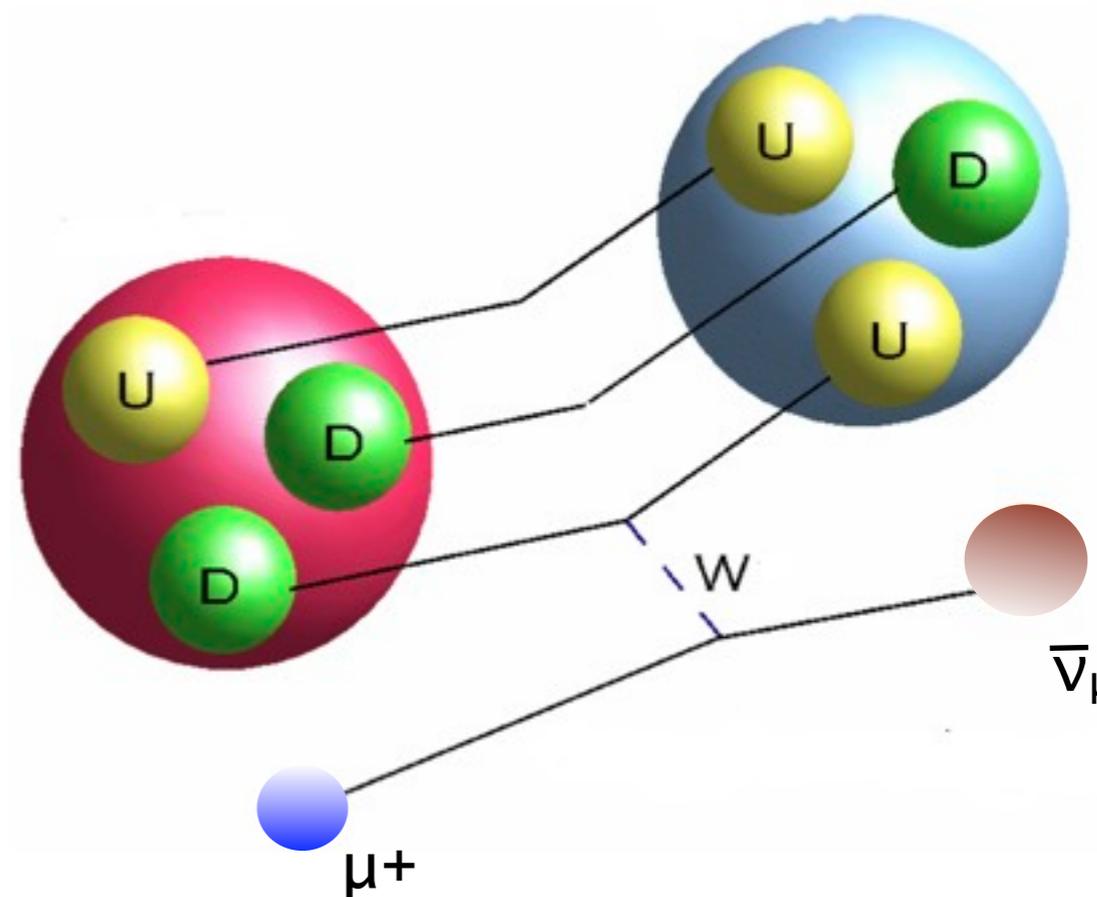


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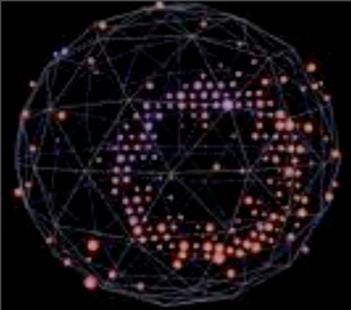
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1. Two subevents
 - consistent with prompt μ + decay e
2. In time with ν beam
3. $T_\mu > 200$ MeV
 - removes beam-unrelated e's
4. 2nd subevent vertex consistent prompt particle
 - based on observed μ kinematics
5. μ/e separation PID
 - single-pion bkg's 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



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- ▶ **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
$\nu_\mu + p \rightarrow \mu^+ + n$ (p from ^{12}C)	43%
$\nu_\mu + p \rightarrow \mu^+ + n$ (p from H_2)	17%
All ν_μ	20%
CC π^-	14%

Cross-section calculation, uncertainties

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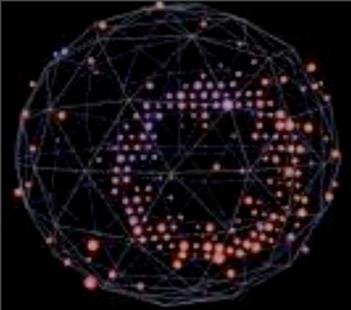
- ▶ Calculation identical to ν_μ CCQE σ analysis

independent of physics model!

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

Diagram illustrating the components of the cross-section calculation:

- unfolding matrix** points to U_{ij}
- reco data** points to d_j
- reco bkg** points to b_j
- bin widths** points to ΔT_μ
- detection efficiency** points to ϵ_i
- int. flux** points to Φ
- nucleon targets** points to T



Uncertainty summary



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

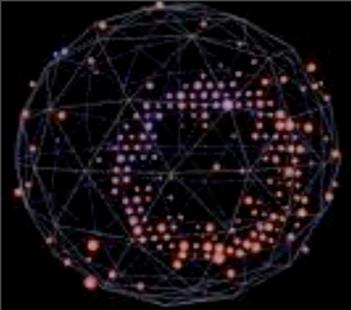
$$\frac{d^2 \sigma^k}{dT_\mu d(\cos \theta_\mu)} = \frac{\sum_j U_{ij}^k (d_j - b_j^k)}{\Delta T_\mu \Delta(\cos \theta_\mu) \epsilon_i^k \Phi^k T^k}$$

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



Results: double-differential on CH₂



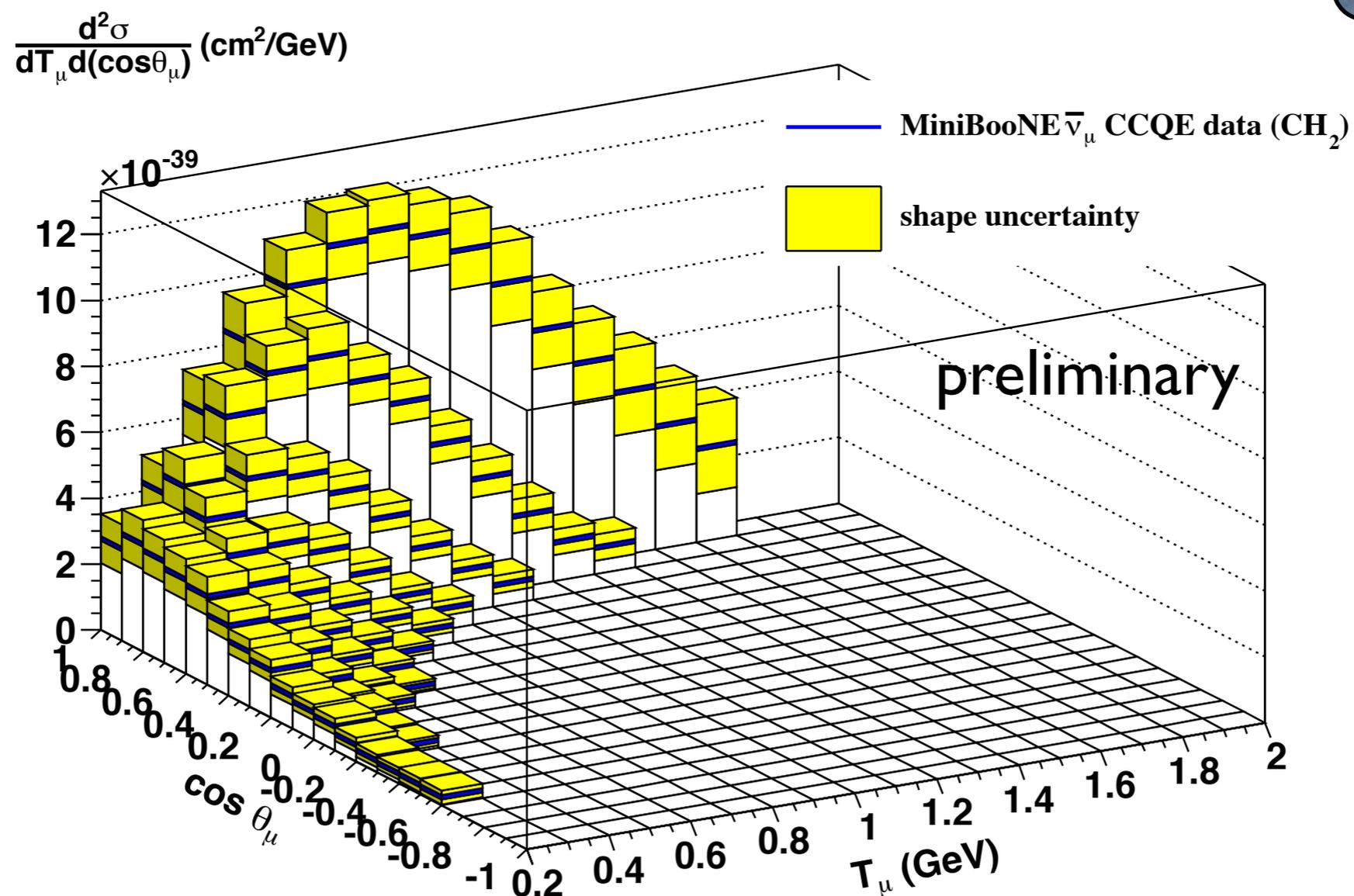
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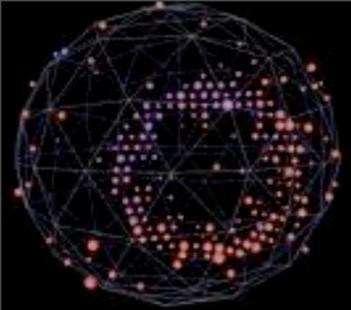
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- ▶ Least model-dependent measurement possible with MiniBooNE data. Independent of CCQE interaction assumptions

2nd time publicly shown





Results: double-differential on CH₂

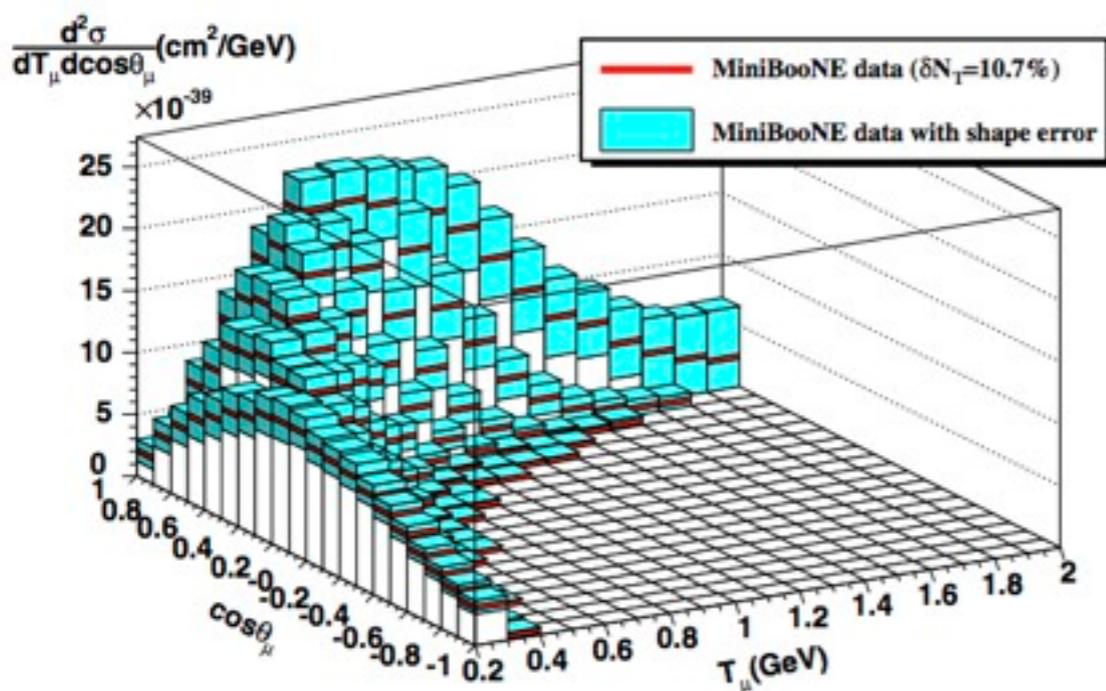


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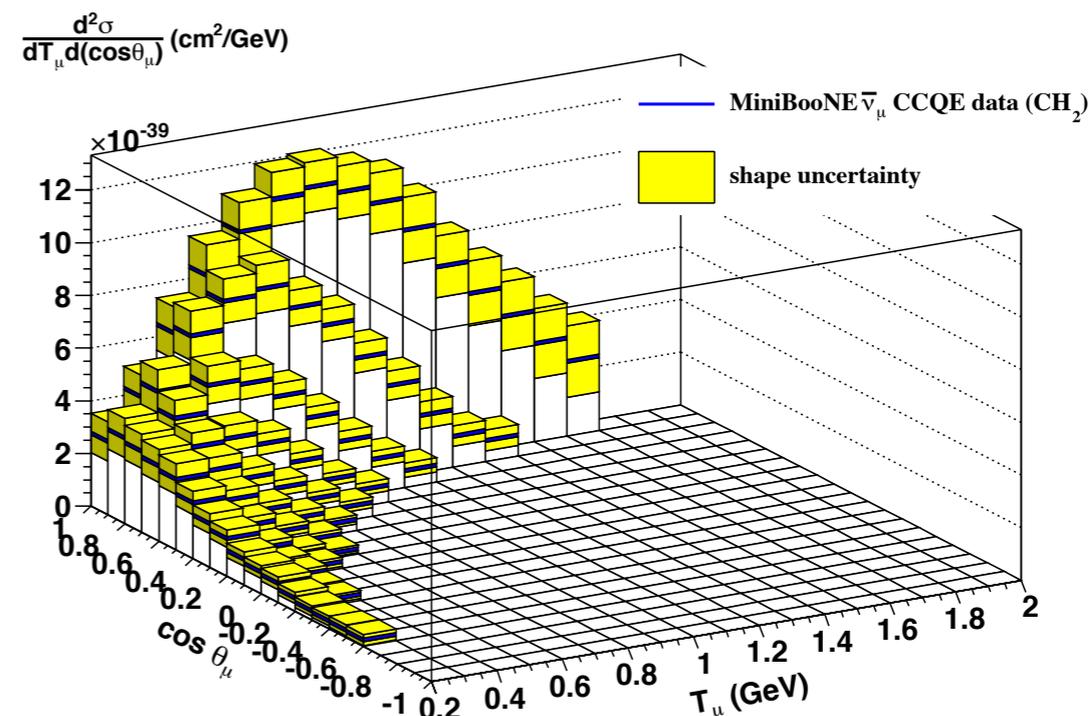
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- ▶ First time in ν history we've been able to make this kind of comparison
- ▶ $\bar{\nu}_\mu$ CCQE much more forward-going compared to ν_μ

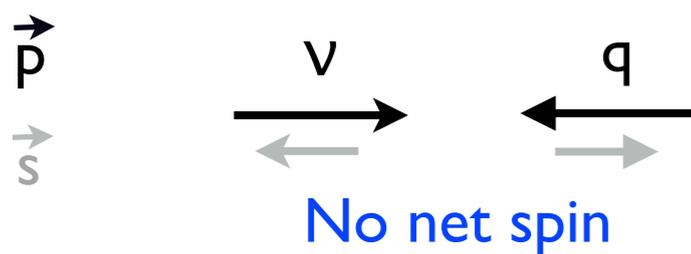


ν_μ CCQE

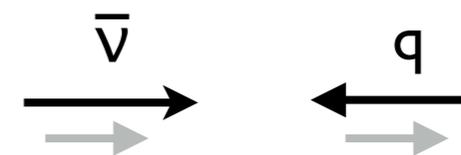


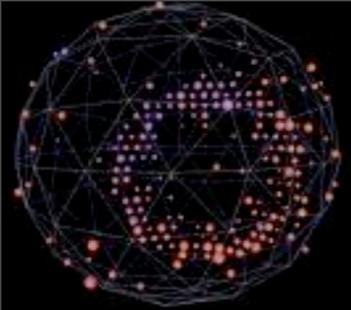
$\bar{\nu}_\mu$ CCQE

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



(in COM frame)





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

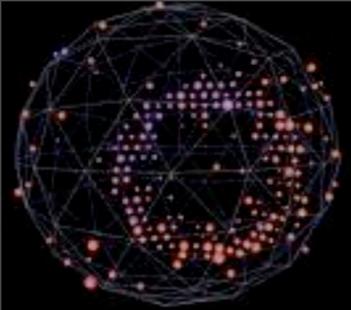


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- ▶ To facilitate comparisons with theoretical calculations, CCQE on hydrogen subtracted to form ^{12}C -only σ (using $M_A = 1.02$ GeV)
 - introduces model dependence, also larger errors due to lower sample purity



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

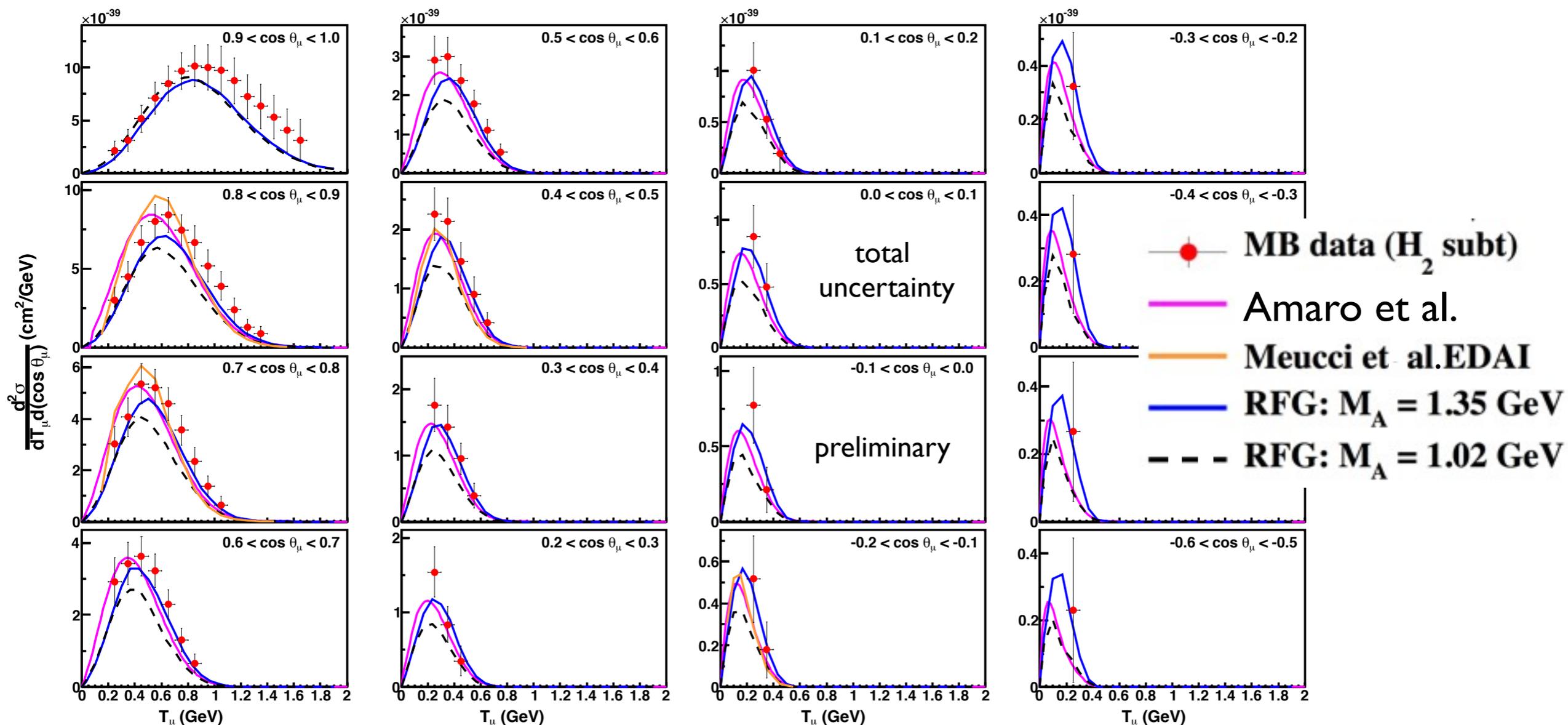


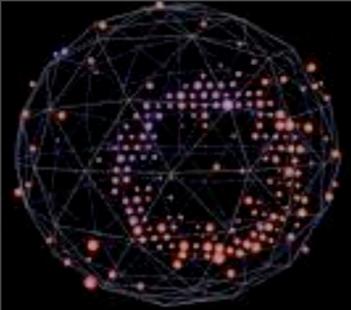
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$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only



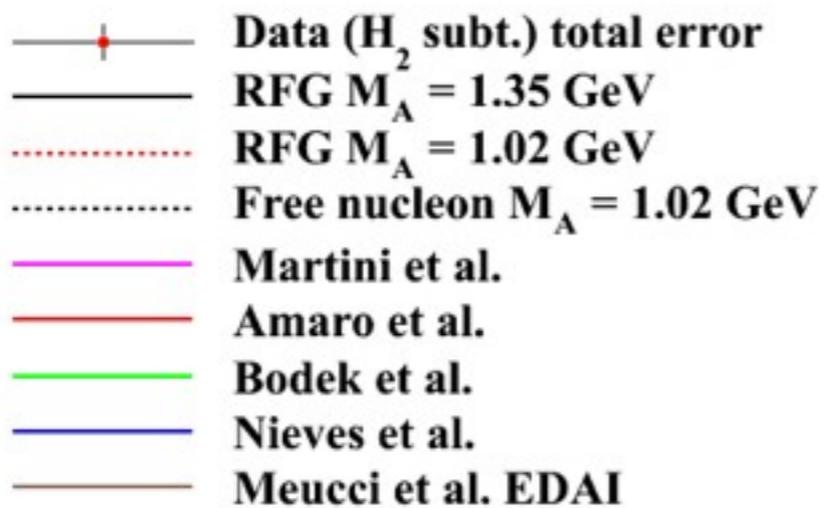
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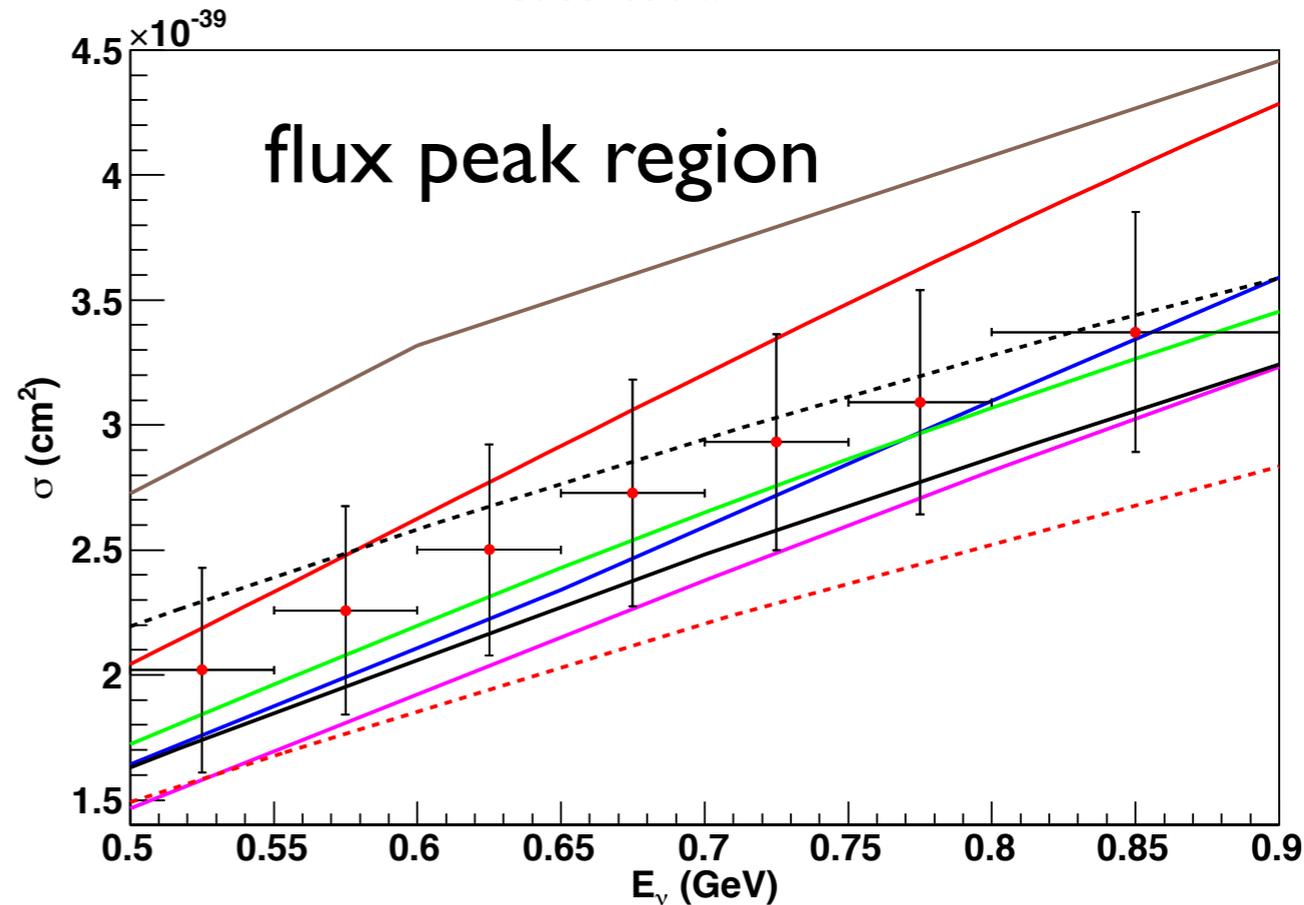
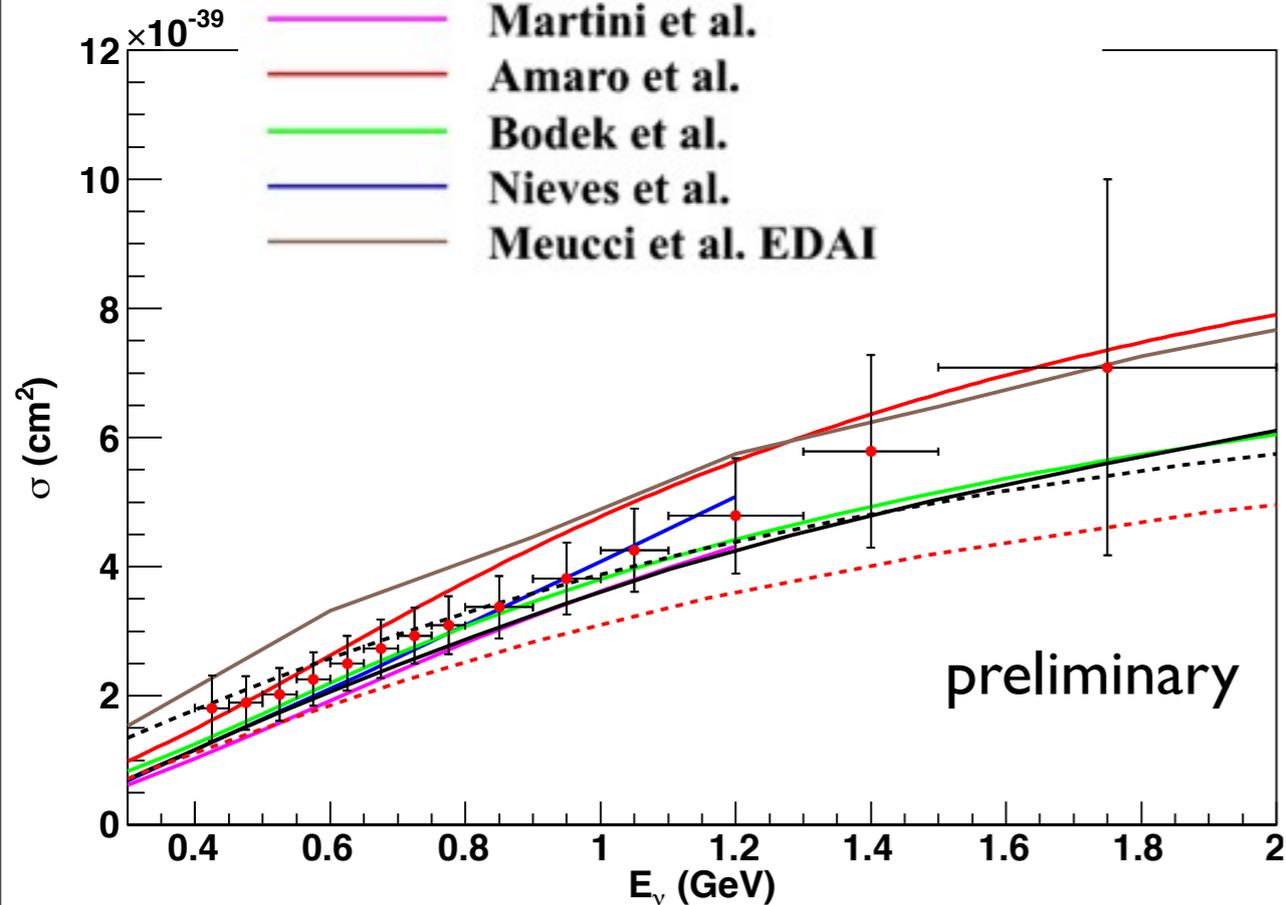
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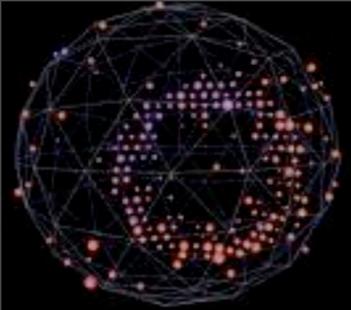
▶ Total $\sigma(E_\nu)$ results: WARNING MODEL DEPENDENT

- 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)





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



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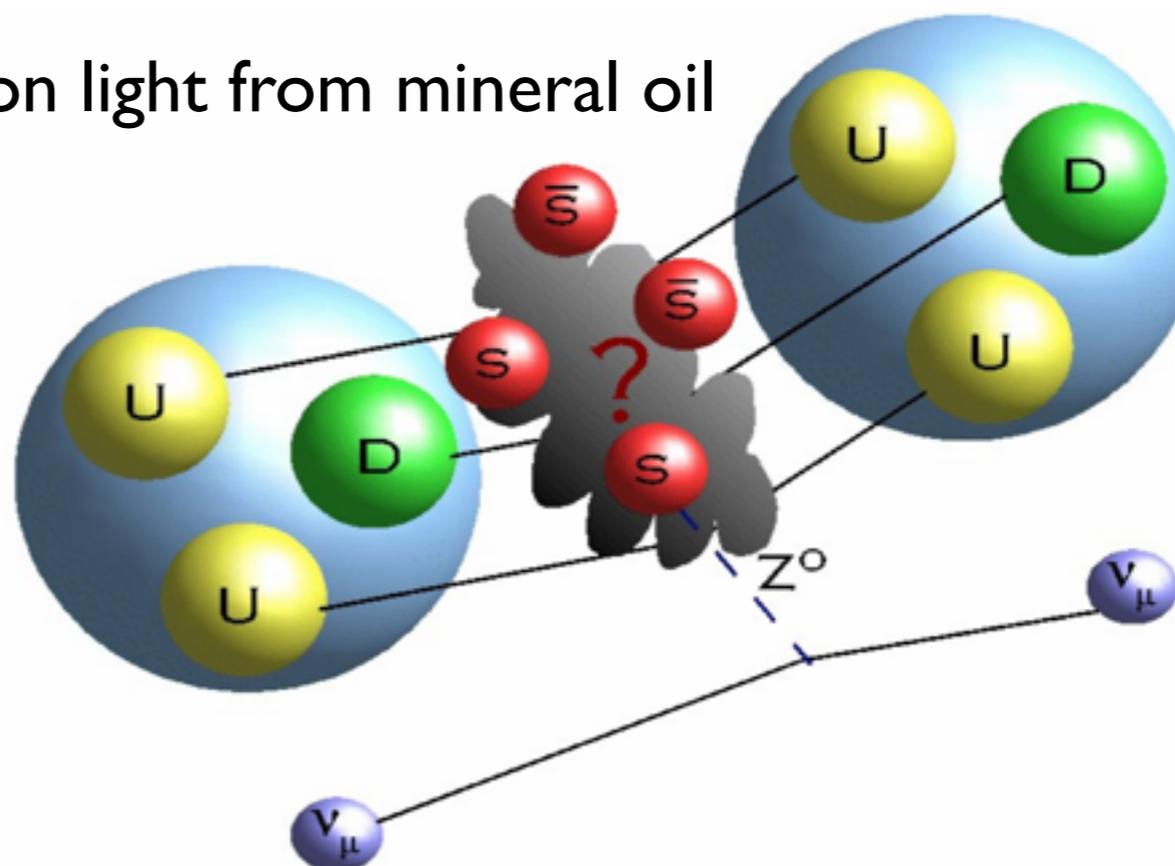
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- ▶ CCQE reconstruction based only on μ observations, NCE offers access to the hadronic side of the neutral-current version of this process

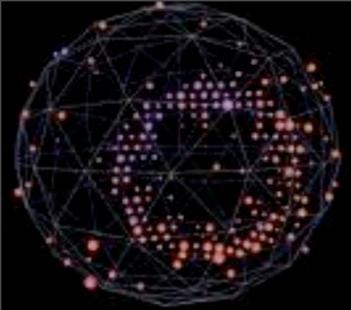
$$\nu_{\mu} N \rightarrow \nu_{\mu} N$$

- ▶ 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



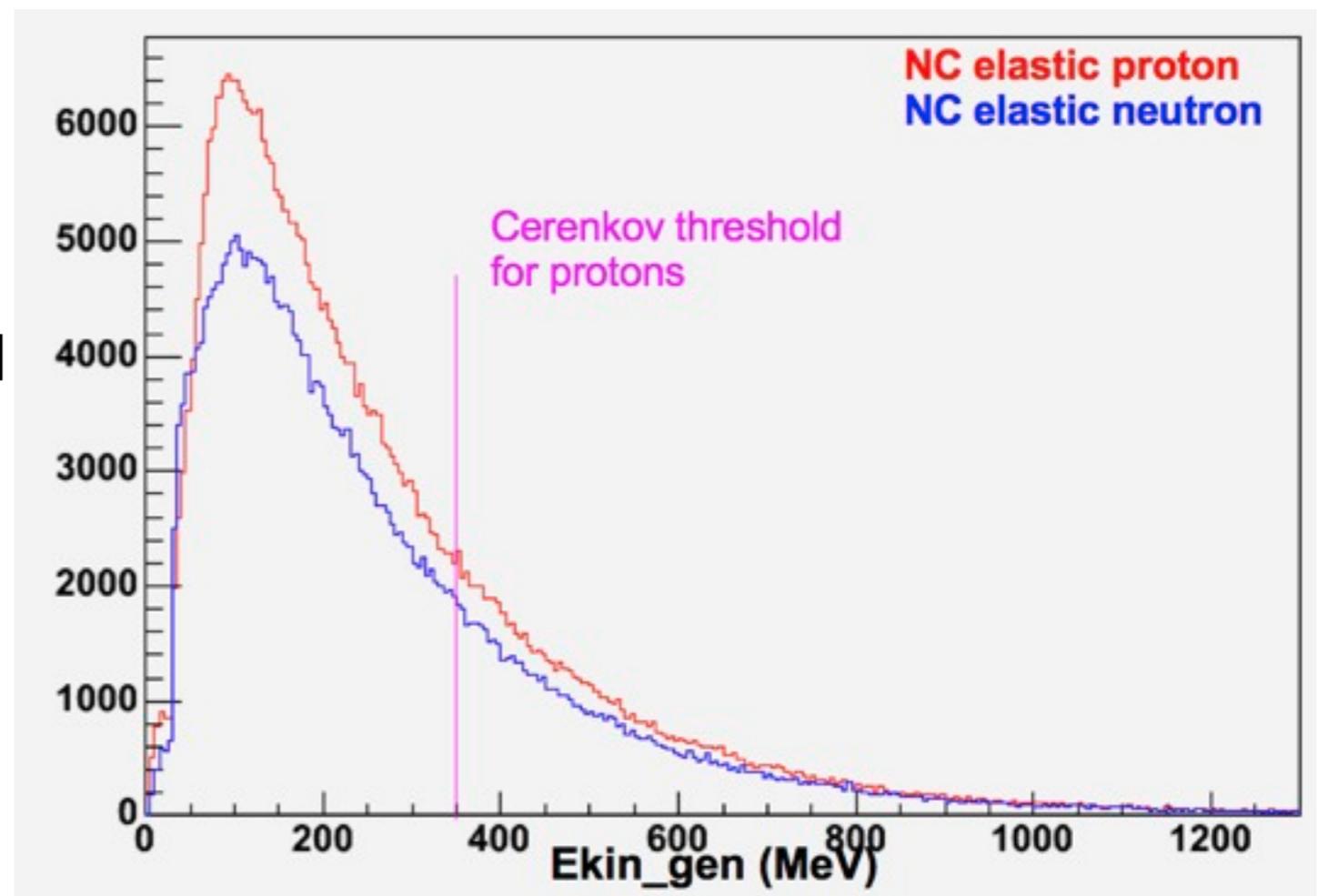
Joe Grange

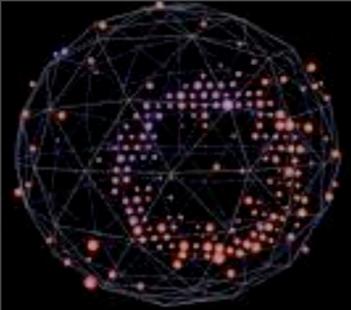
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- ▶ We measure sum of n+p NC interactions: identical isotropic scintillation signature for bulk of spectra
- ▶ Some separation above Cherenkov threshold (350 MeV)

- ▶ Dedicated fitter identifies kinematics via PMT hit charge and time-likelihood maximization
 - position res. ~ 0.7 m
 - energy res. $\sim 20\%$





Event selection

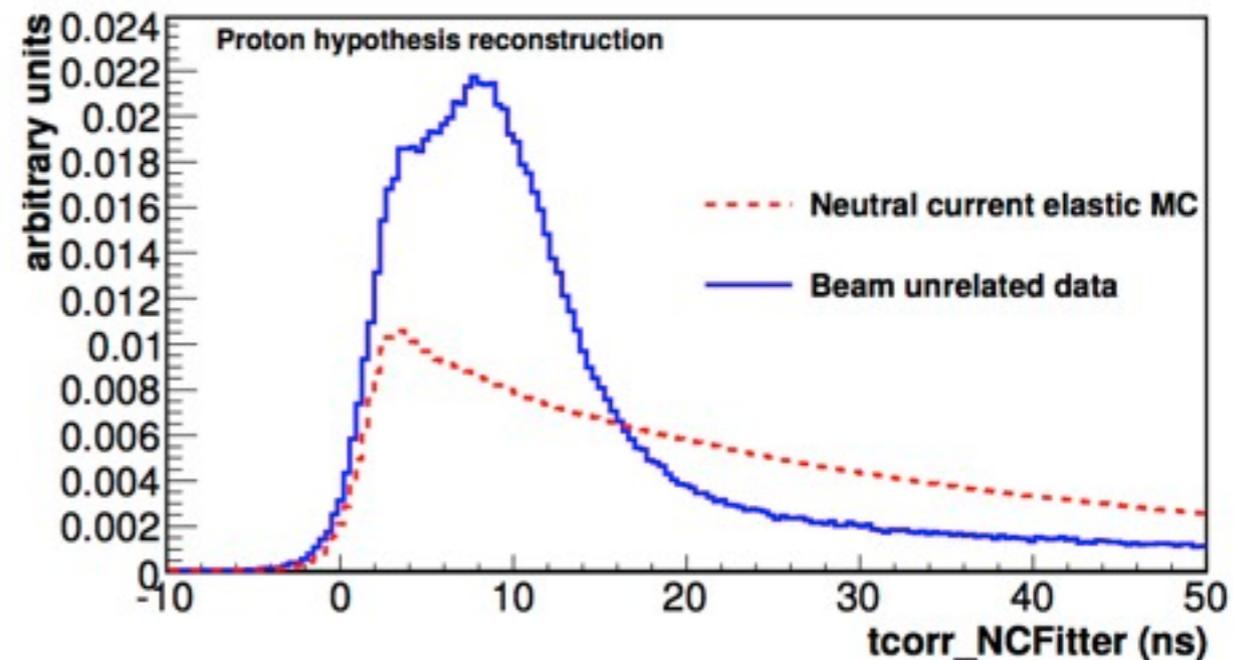


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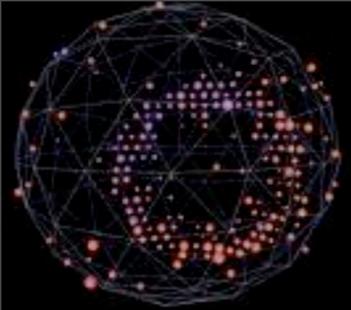
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1. One subevent
 - ▶ removes decaying particles (μ , π)
2. In time with ν beam
3. Low veto activity
 - ▶ ensures containment, rejects incoming
4. Signal PMT hits > 12
 - ▶ reconstructible event
5. Cut on time $\ln(L_e/L_p)$
 - ▶ rejects beam-unrelated 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



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▶ **61k** events pass selection

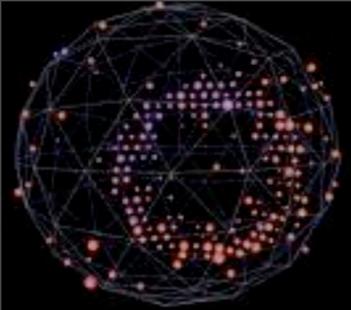
- more than an order of magnitude larger than all other published $\bar{\nu}_\mu$ NCE data sets

Constrained by wrong-sign measurements

Dedicated background measurement

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

Irreducible bkg:
NC π with no final-state π



Dirt background

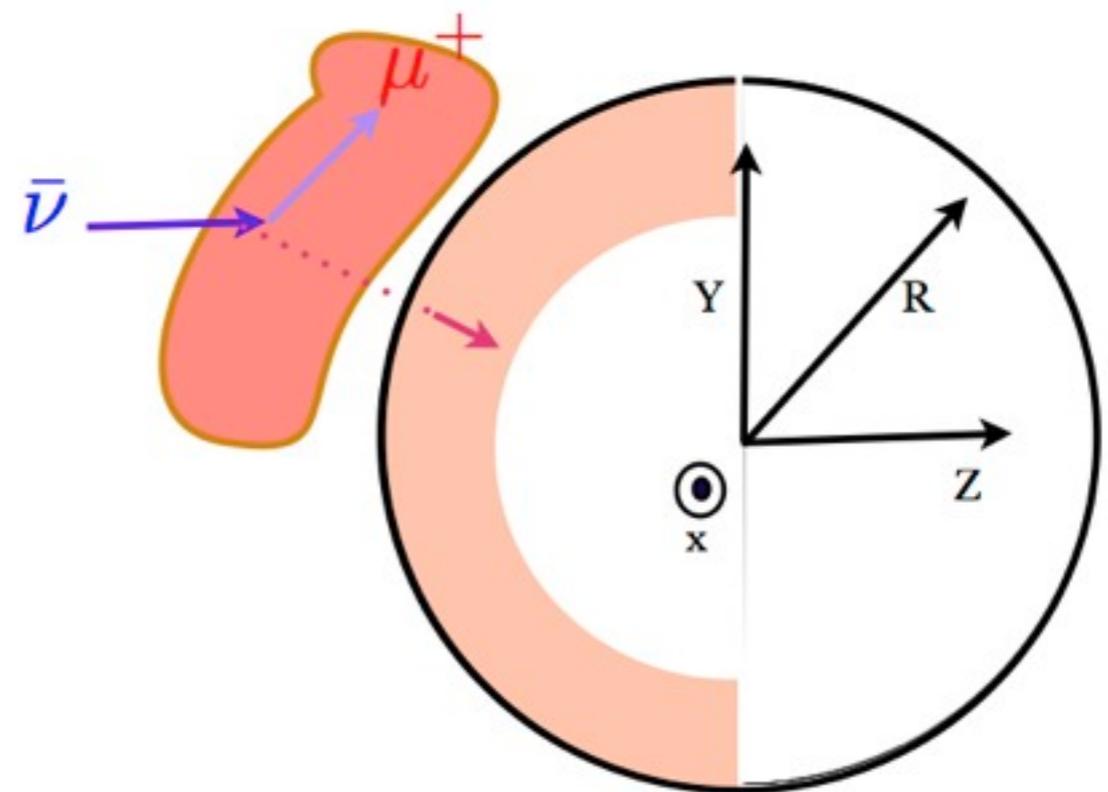


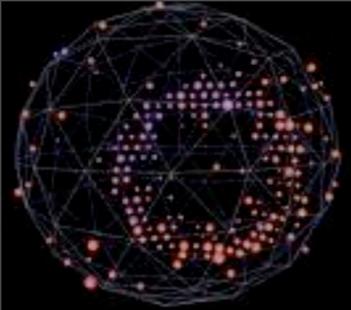
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- ▶ “Dirt”: events produced external to the detector, do not deposit energy in veto, lead to PMT activity
- ▶ Tend to pile up at:
 - high radius
 - upstream half of detector
 - low energy
- ▶ Form dirt-enriched samples based on these correlations





Dirt background



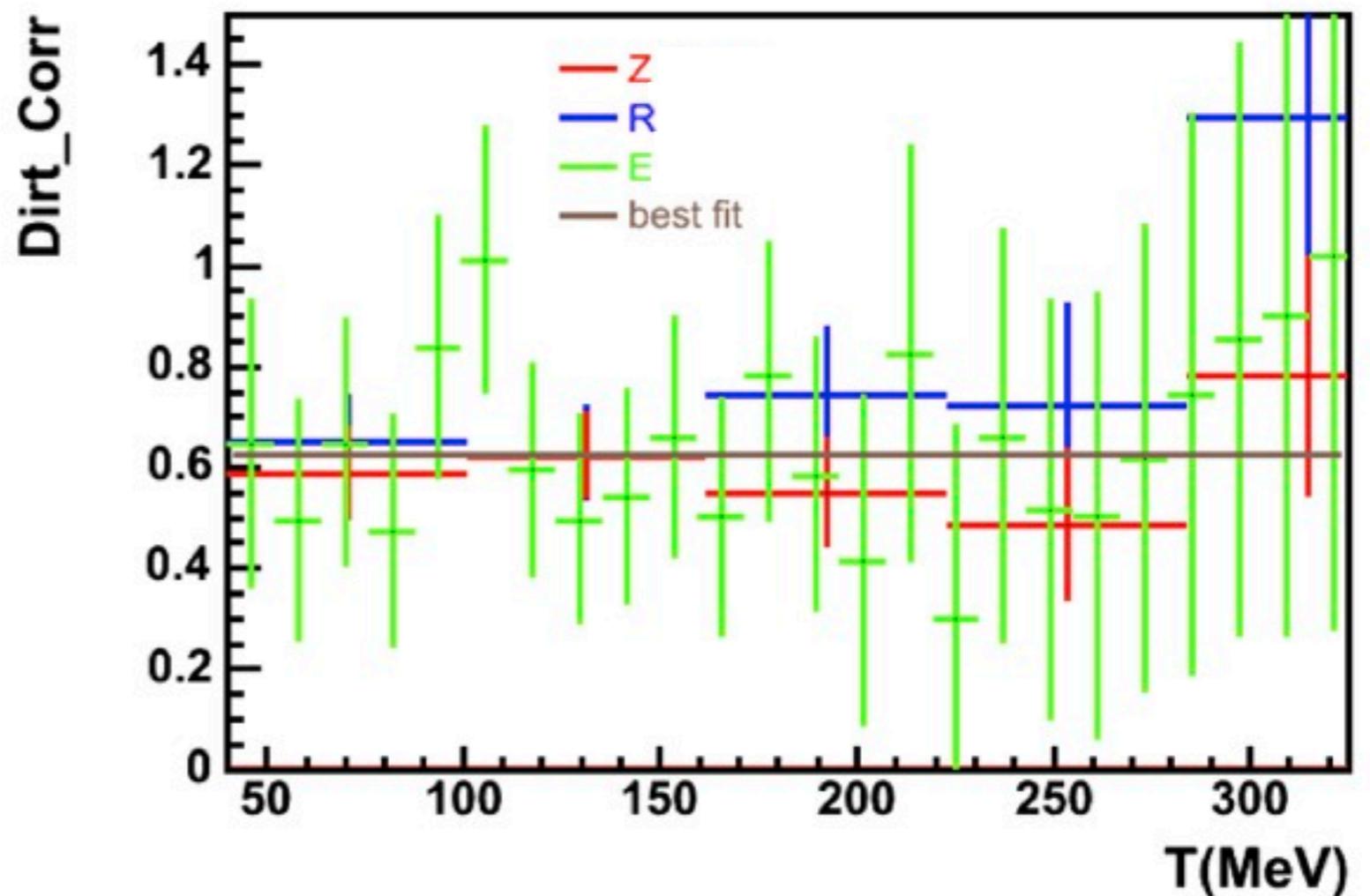
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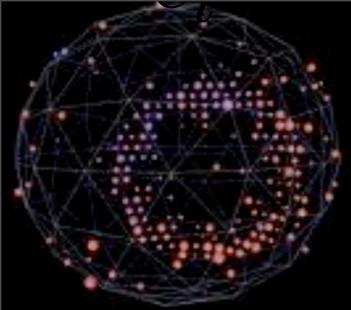
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► Many, many measurements:

- 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



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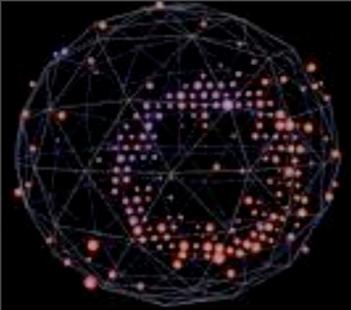
- ▶ Main result is $d\sigma/dQ^2$. Can calculate Q^2 based on nucleon energy **assuming** interaction with an independent, at-rest target

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

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



Systematic uncertainties



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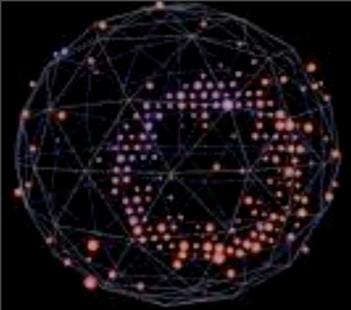
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$$\frac{d\sigma^k}{dQ^2} = \frac{\sum_j U_{ij}^k (d_j \times \frac{s_j^k}{s_j^k + b_j^k})}{\Delta Q^2 \epsilon_i^k \Phi^k T}$$

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



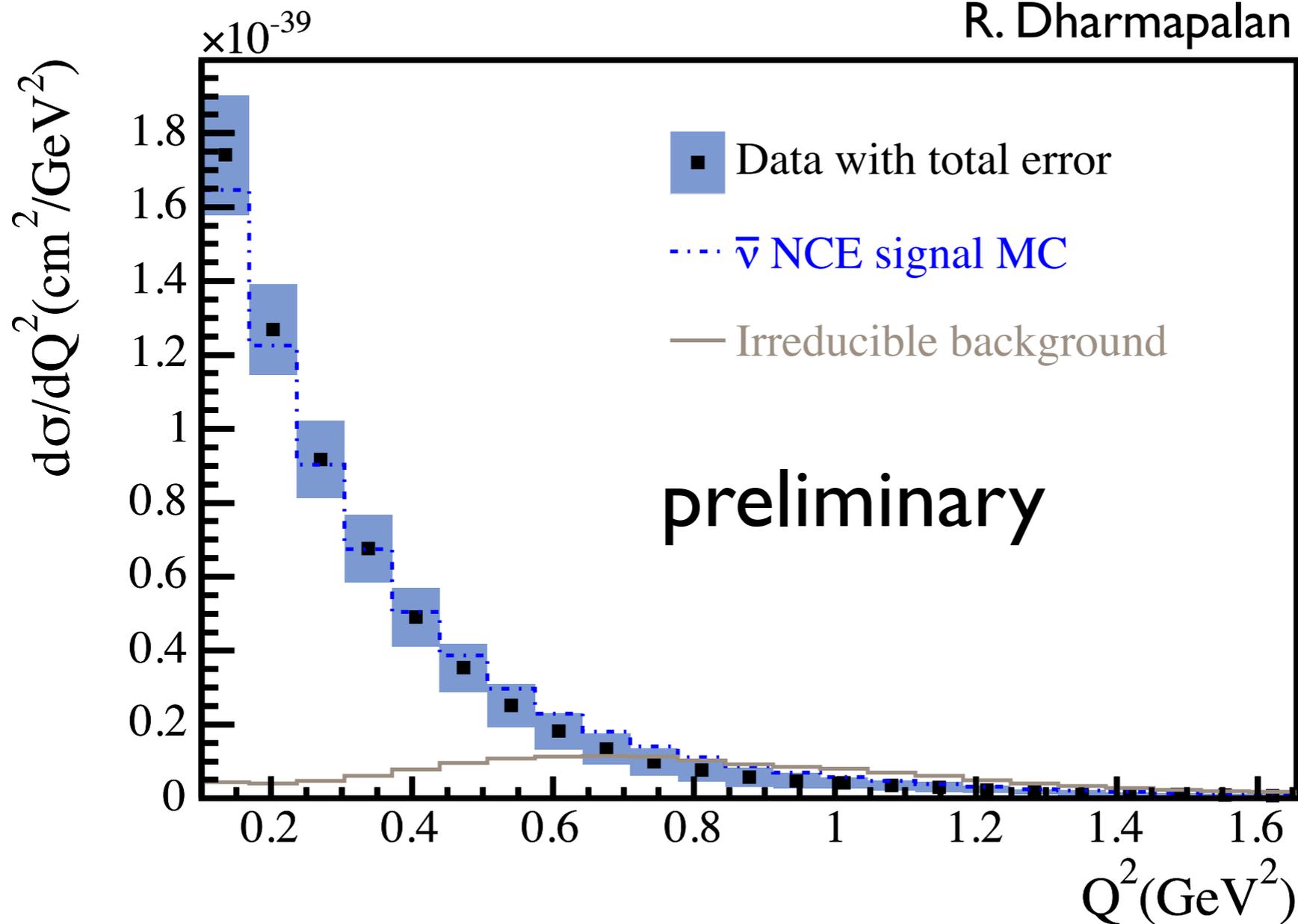
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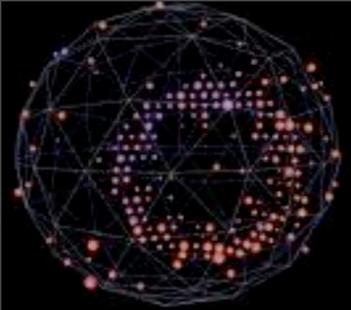
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R. Dharmapalan

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

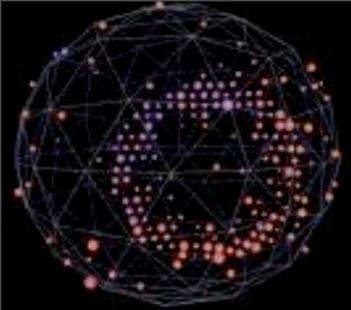
2. Anti-neutrino analyses

ν_μ background (wrong signs)

$\bar{\nu}_\mu$ NCE σ (new!)

$\bar{\nu}_\mu$ CCQE σ (new!)

4. Outlook and summary



Future experimental tests



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- ▶ 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!)

★ - MINERvA (A-dependence!)

★ - ArgoNeuT

★ - NOvA

- T2K

★ - MINOS

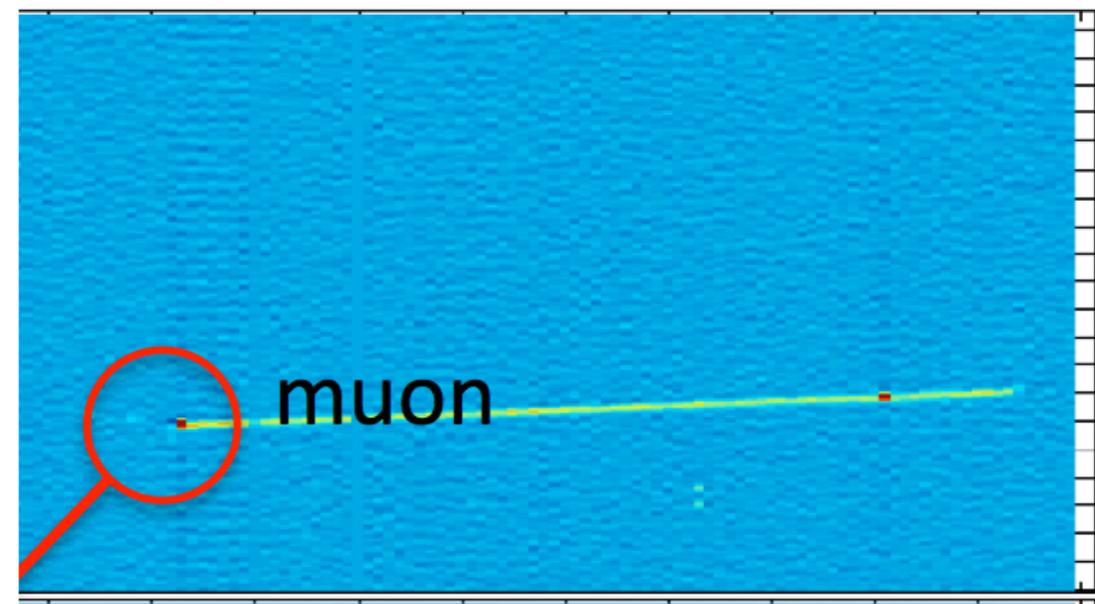
- ICARUS

★ - MicroBooNE

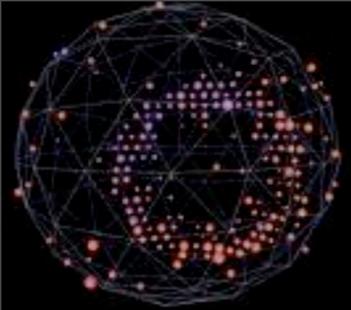
★ - SciBooNE

★ FNAL!

21 MeV proton!



K. Partyka for ArgoNeuT, NuInt 12



Summary

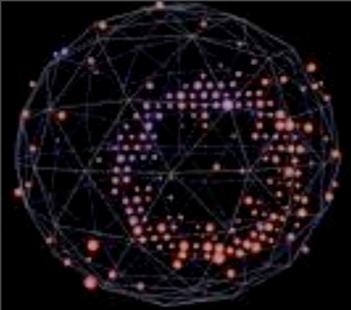


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- ▶ Experimental puzzle whose resolution may involve an unexpected interaction type may shed light on intranuclear dynamics
- ▶ New anti-neutrino NCE and CCQE σ results constrain many predictions for such a mechanism
- ▶ Resolution crucial to understand 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

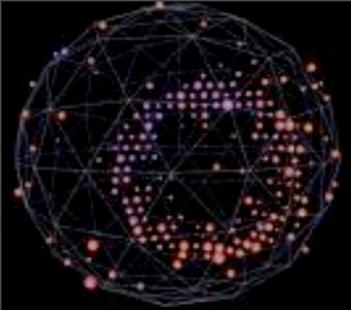


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Impact on oscillation physics?



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- ▶ Multiple theory groups claim the absence of multi-nucleon events in MiniBooNE MC significantly biases the ν_e oscillation results

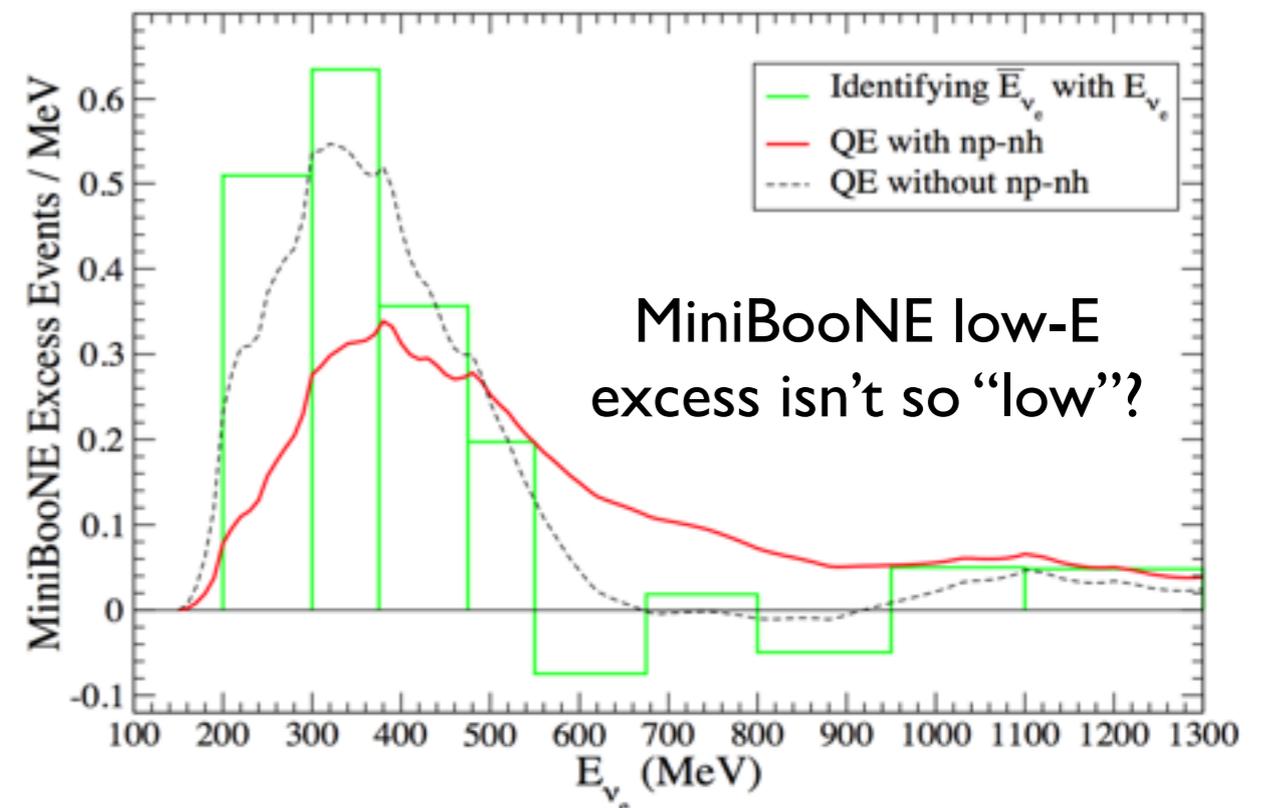
- proposed effect: current reconstruction biases events towards lower energy
 - ➔ would effect Δm^2 extraction, change compatibility of data with osc. hypothesis

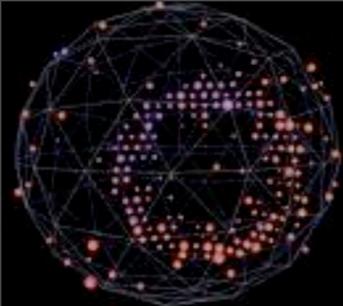
- ▶ Have done some preliminary analyses in MiniBooNE to estimate this effect

- 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 ν STORM

Martini et al. arXiv:1202.4745





Future experimental tests: MiniBooNE!



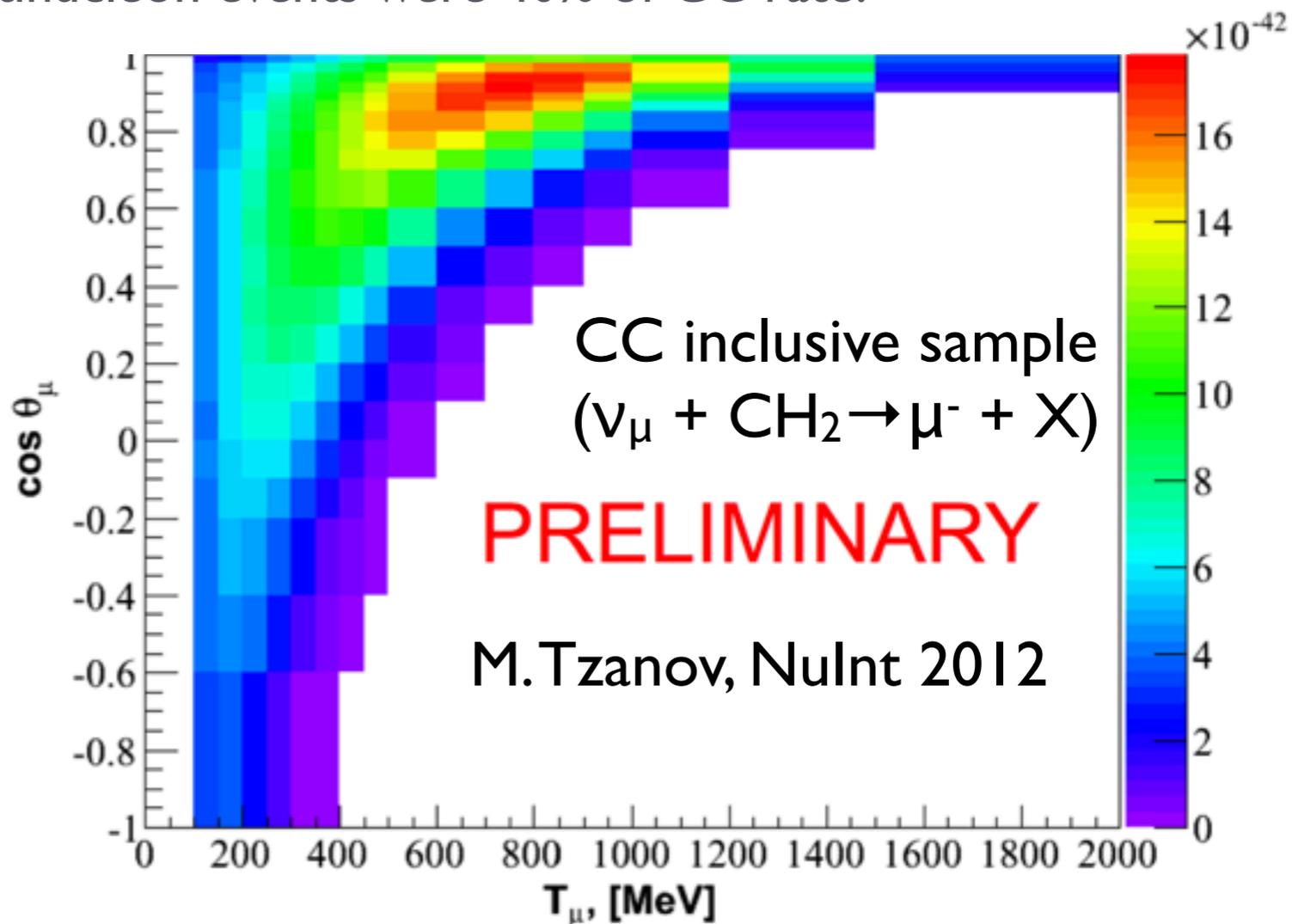
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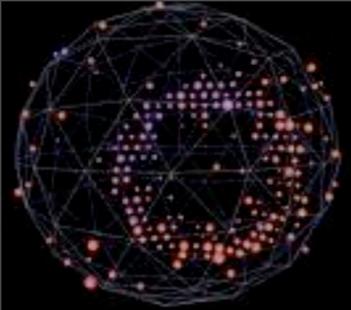
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- ▶ New hadronic late light fitter gives model-independent measurement of E_ν in CC inclusive measurement
 - Does reco. E_ν from hadronic light give larger values compared to that from lepton observations? Might expect so if multinucleon events were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

- ▶ Merging of μ and proton fitter.
 - if MiniBooNE uses “tracking style selection” ($I_\mu + I_p$), does the ν_μ CCQE “excess” go away?





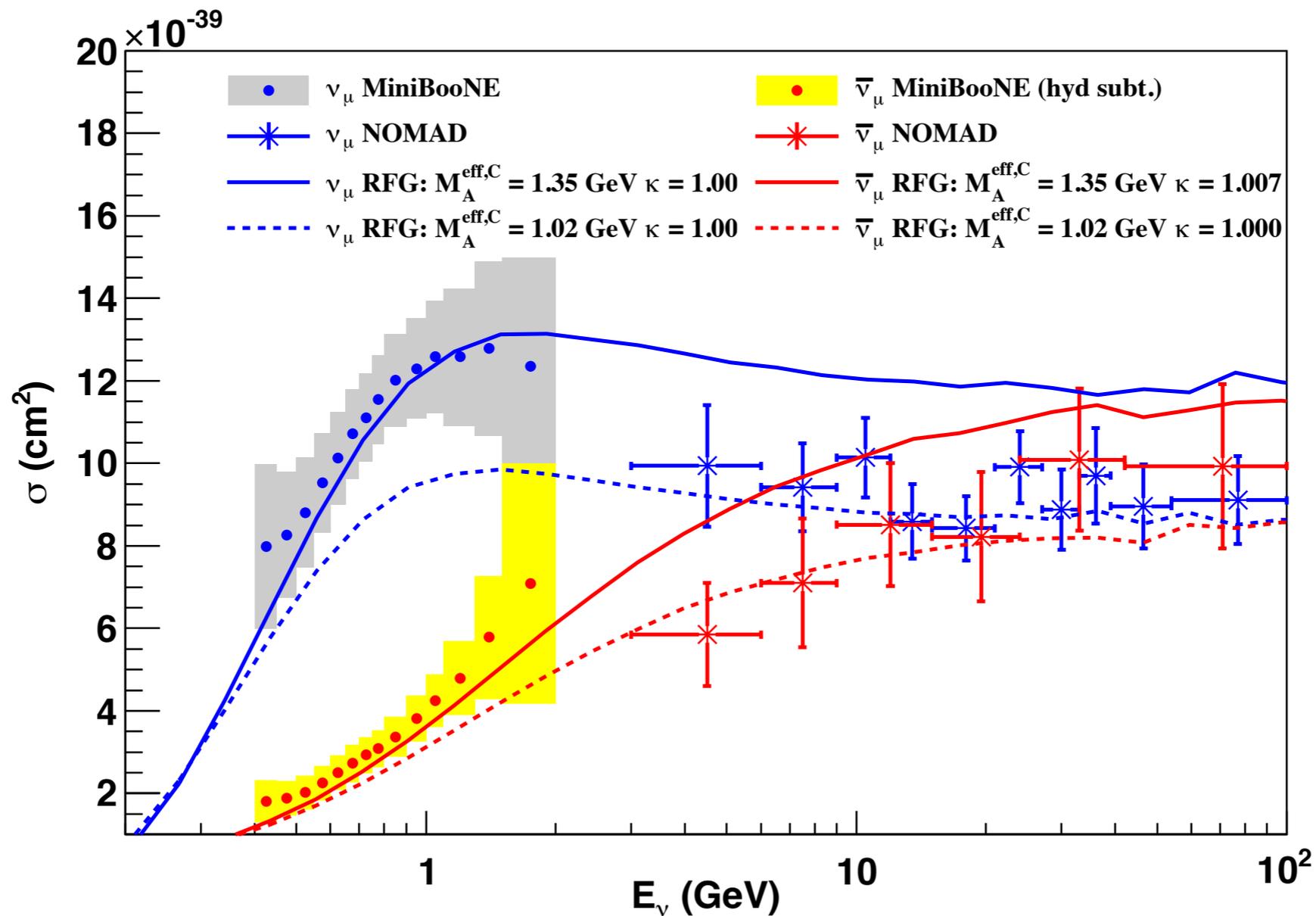
Comparison to NOMAD data

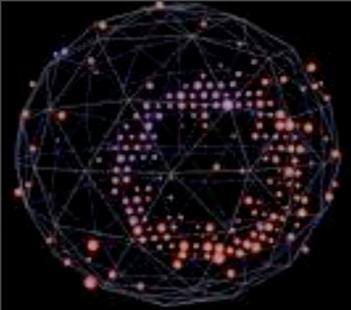


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$\bar{\nu}_\mu$ CCQE σ 's on ^{12}C only

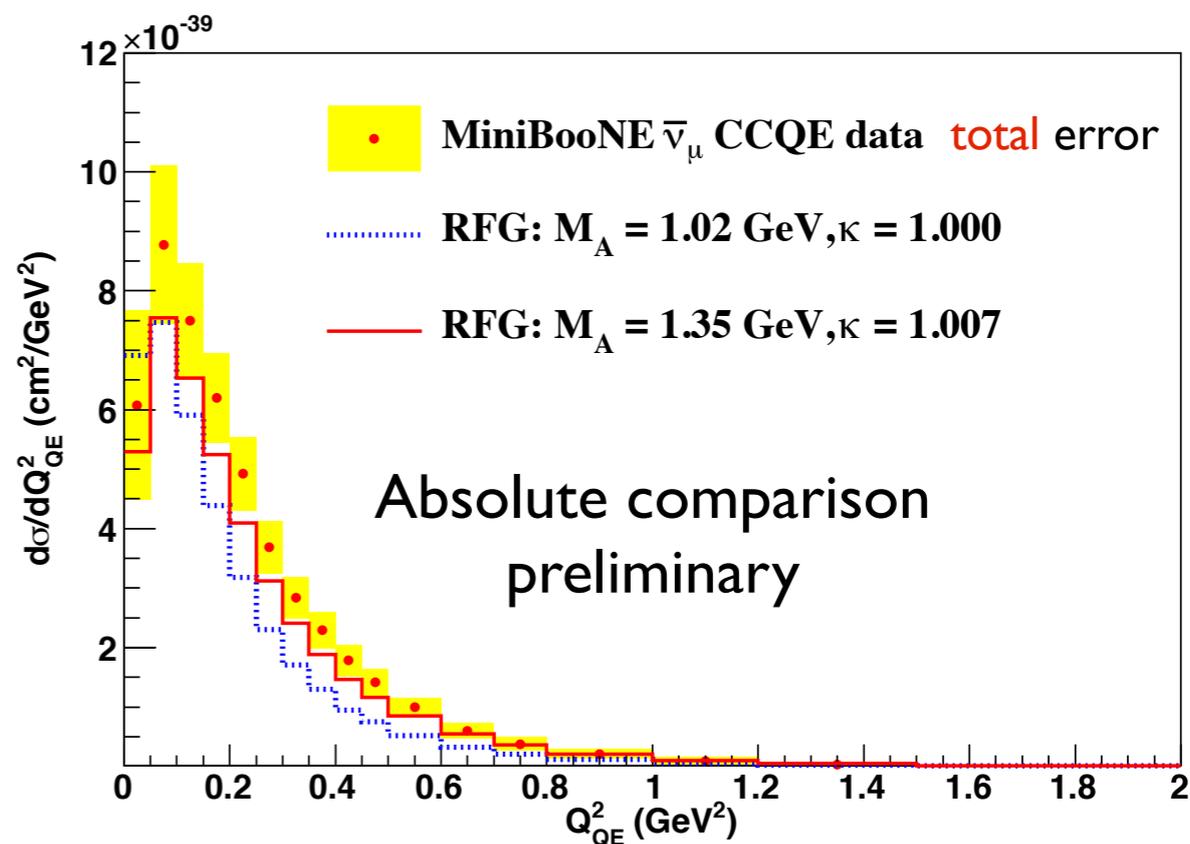
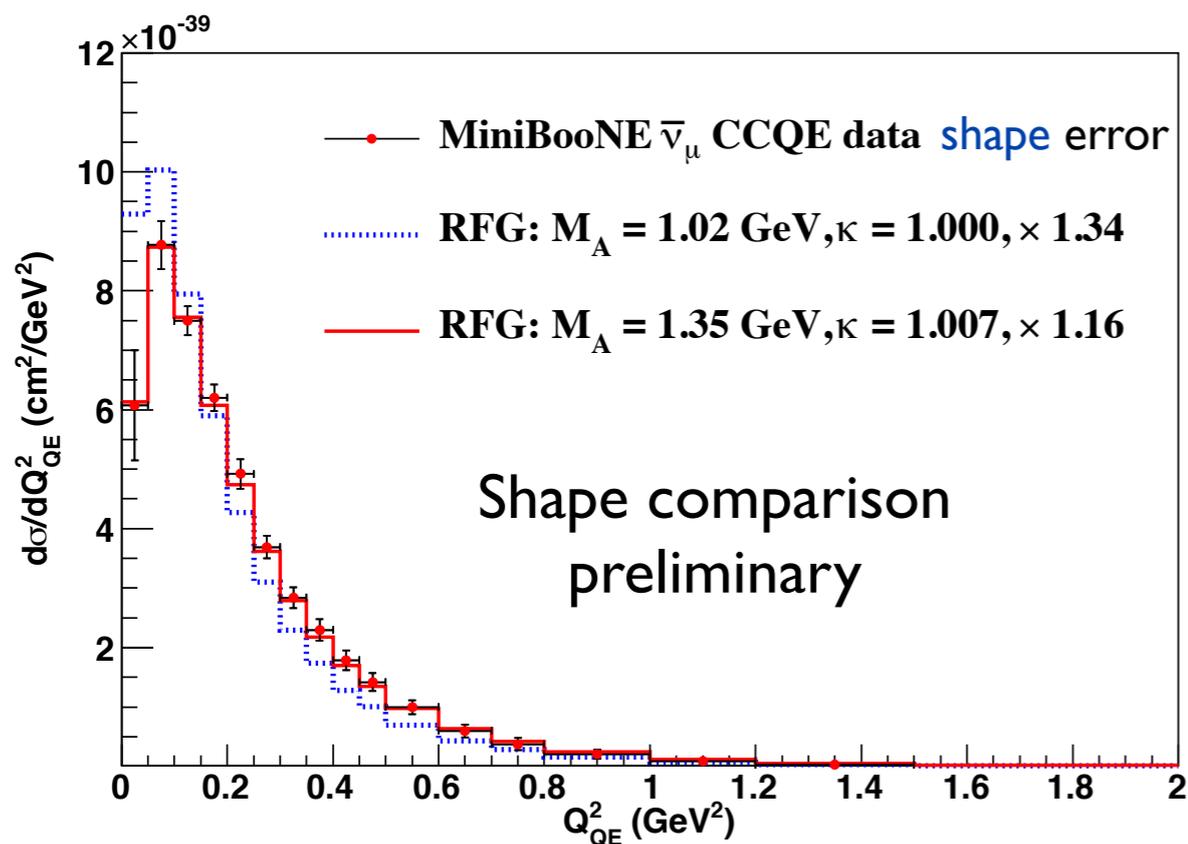


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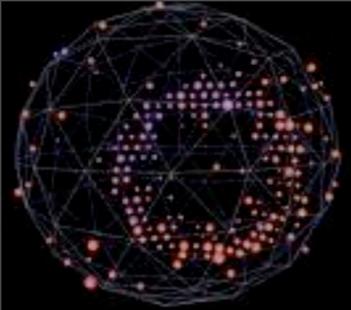
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- Under same assumptions on underlying interaction, can calculate “ Q^2_{QE} ”



- Again, data prefers higher normalization, harder spectrum compared to expectations with $M_A = 1.0 \text{ GeV}$



BooNE of data!



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▶ Robust MiniBooNE measurements:

ν_μ NCE

PRD 82, 092005 (2010)

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

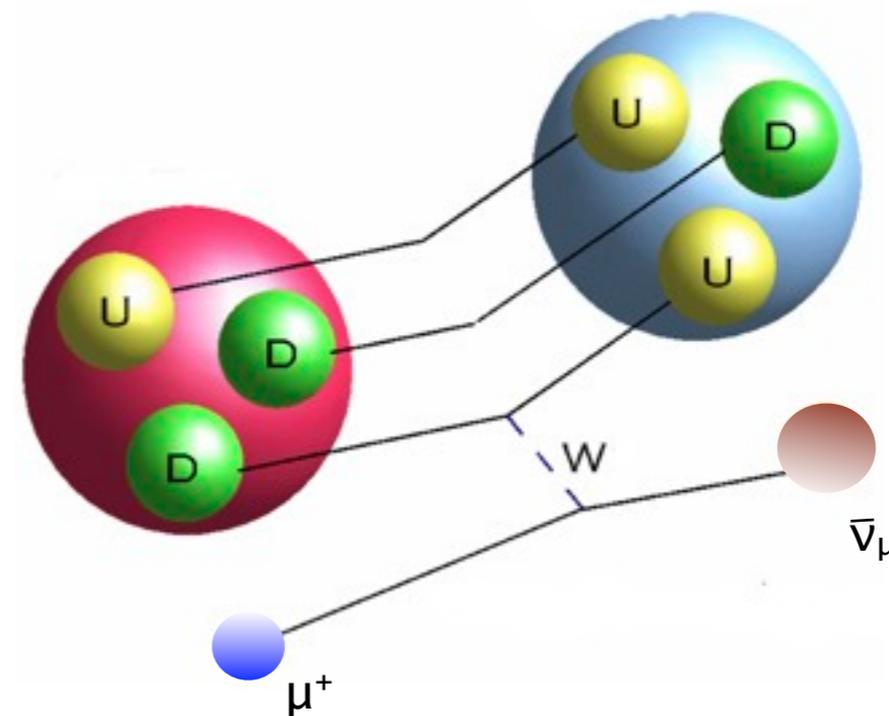
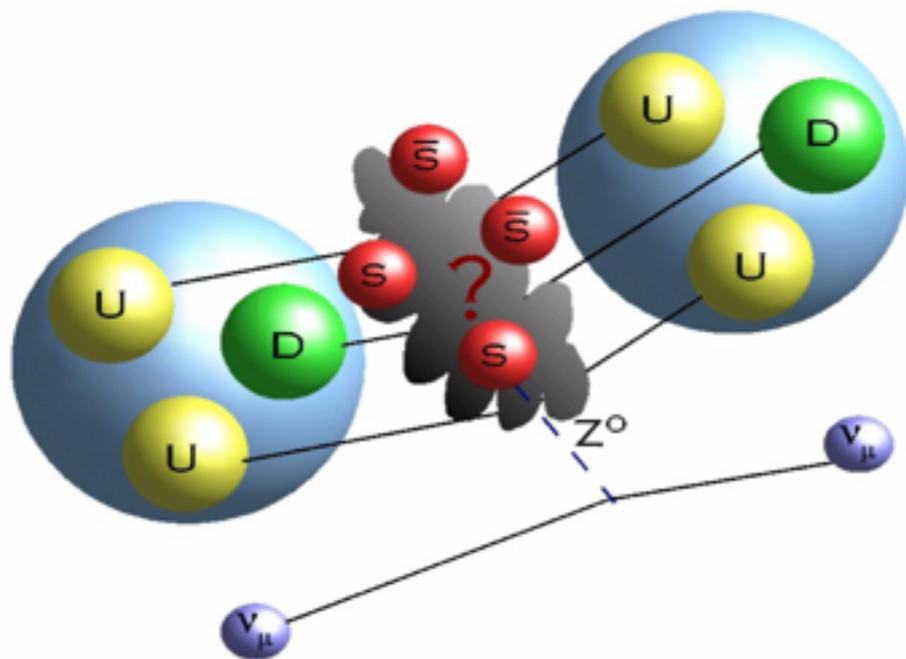
This work

ν_μ CCQE

PRD 81, 092005 (2010)

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

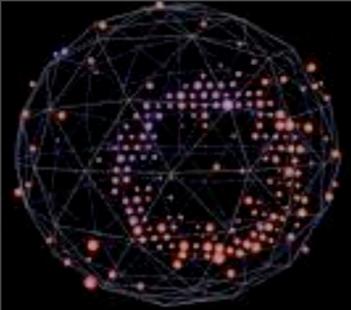
This work



▶ 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: $\bar{\nu}_\mu / \nu_\mu$

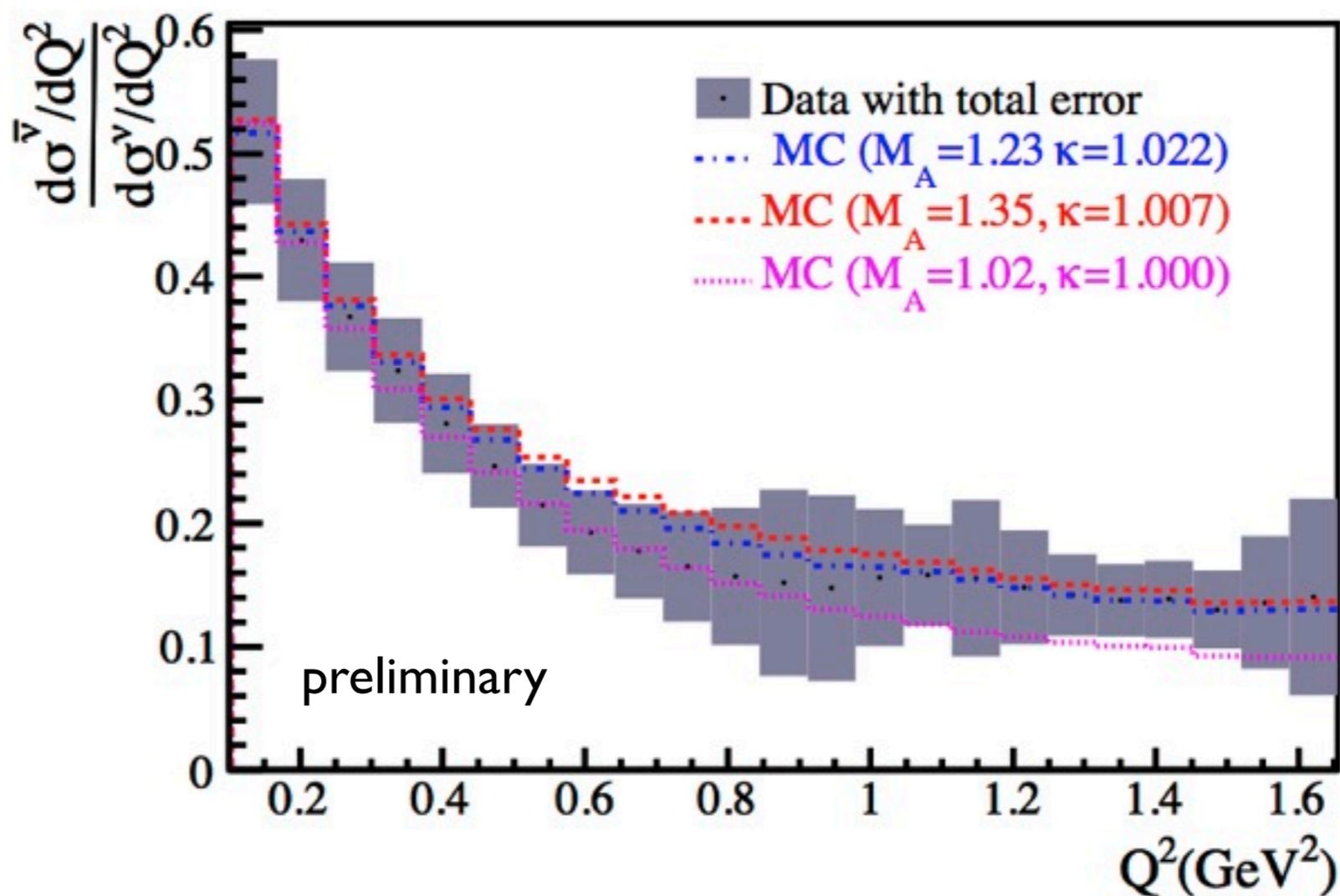


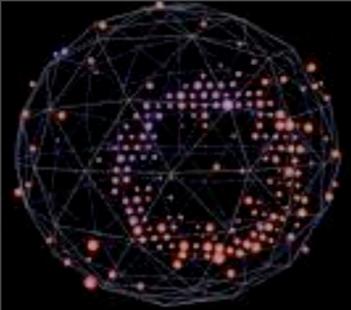
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- ▶ Carefully evaluated correlated uncertainties implemented
 - biggest gain in light propagation model





CCQE: $\nu_\mu / \bar{\nu}_\mu$



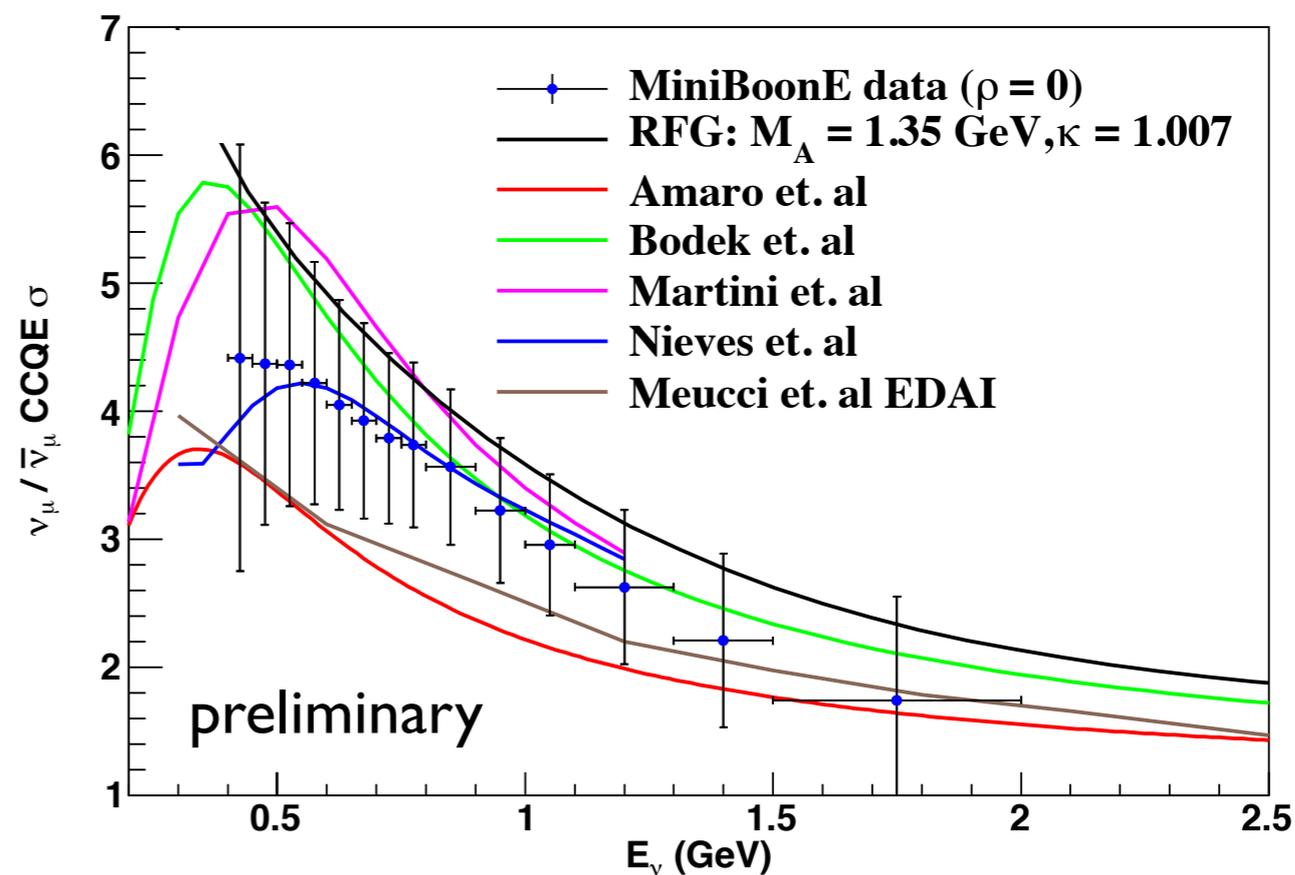
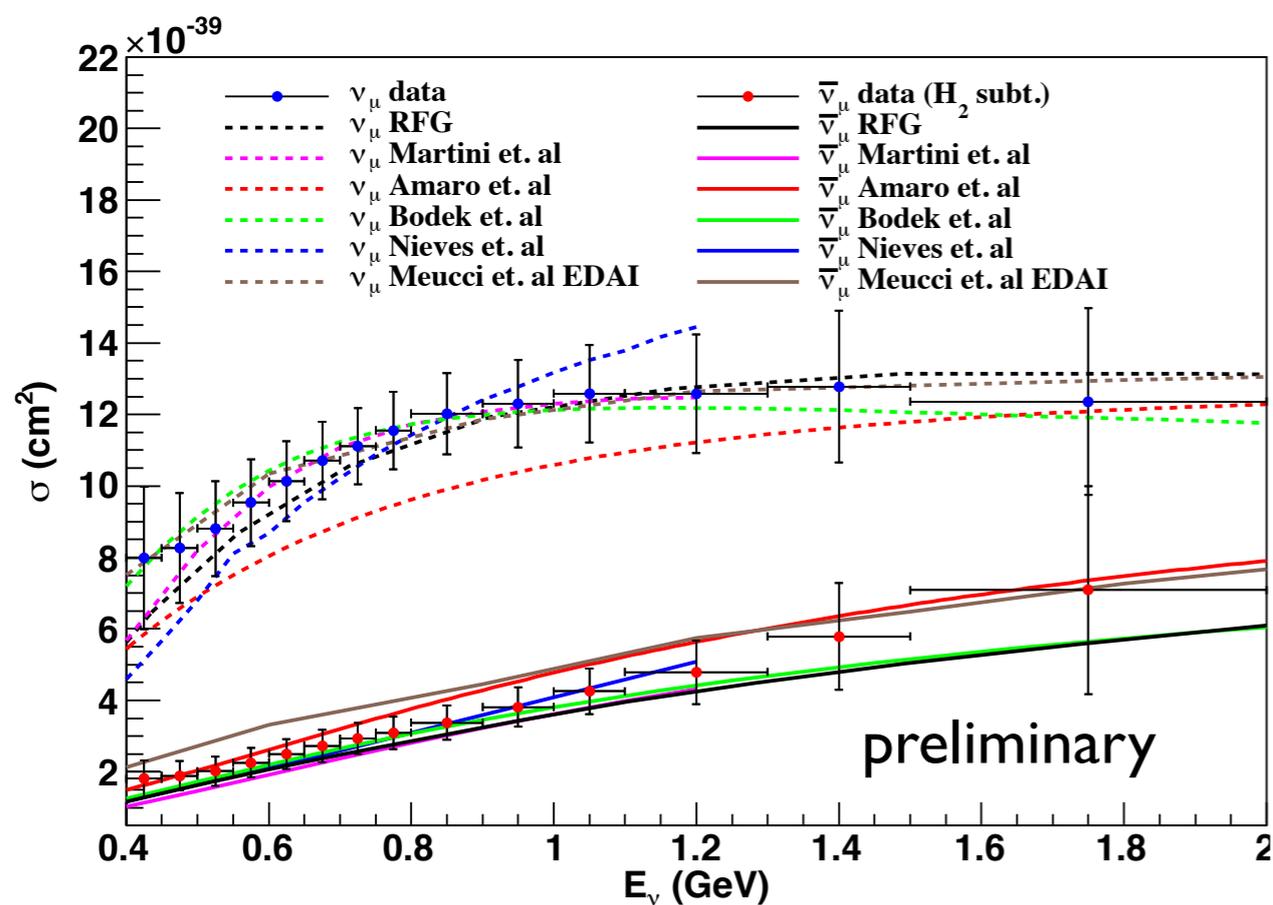
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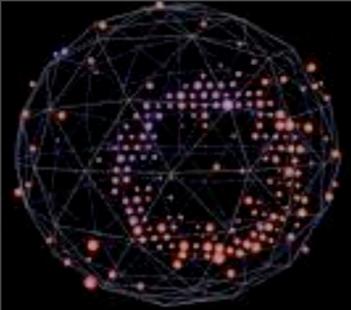
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► Correlations not yet evaluated

- ratio measurement will only get better





$\nu_\mu / \bar{\nu}_\mu \sigma$ predictions

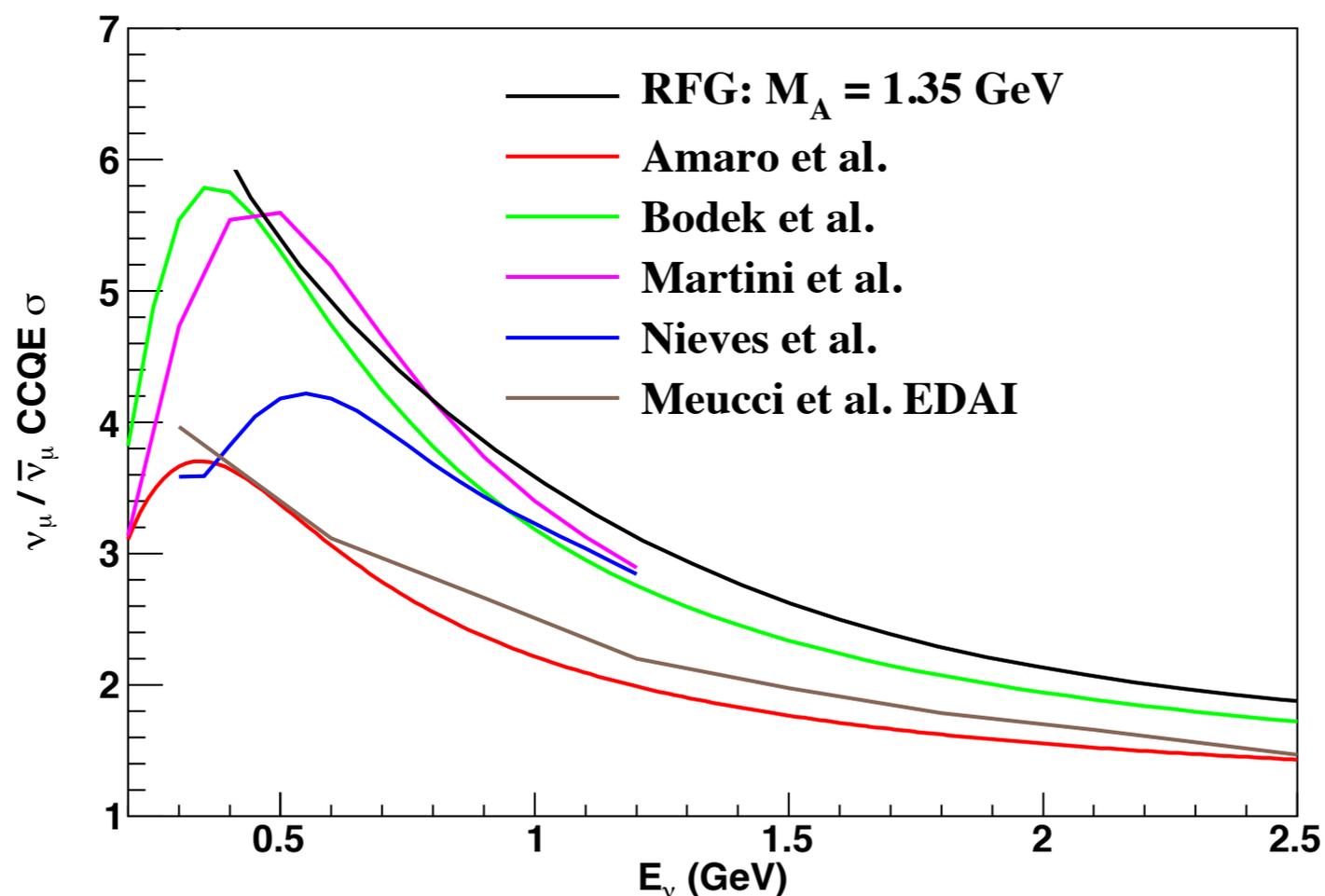


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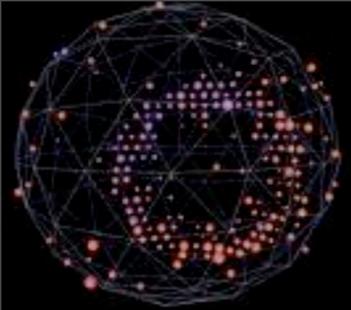
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- ▶ Next round of osc. experiments will need robust knowledge of both ν and $\bar{\nu}$ cross sections - current level of expectations for both:



- ▶ Worst-case scenario, could imagine lack of ν vs. $\bar{\nu}$ cross section knowledge show up as spurious \mathcal{CP} signal



CCQE: $\nu_\mu - \bar{\nu}_\mu$

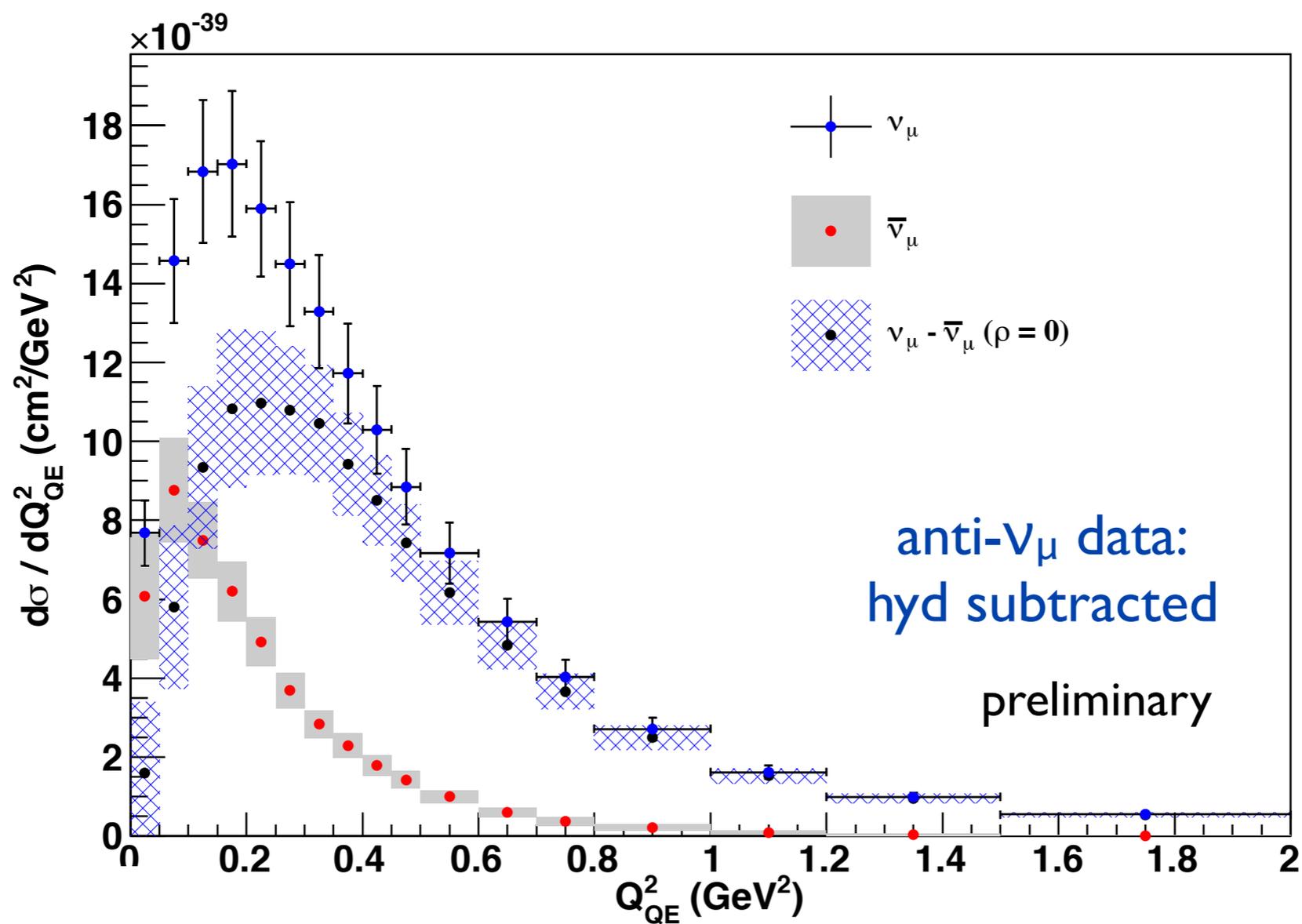


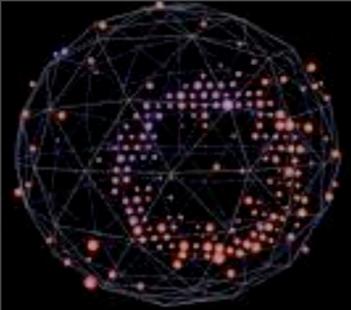
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- ▶ Difference as a function of Q_2^{QE}
 - again, correlations not yet taken into account





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



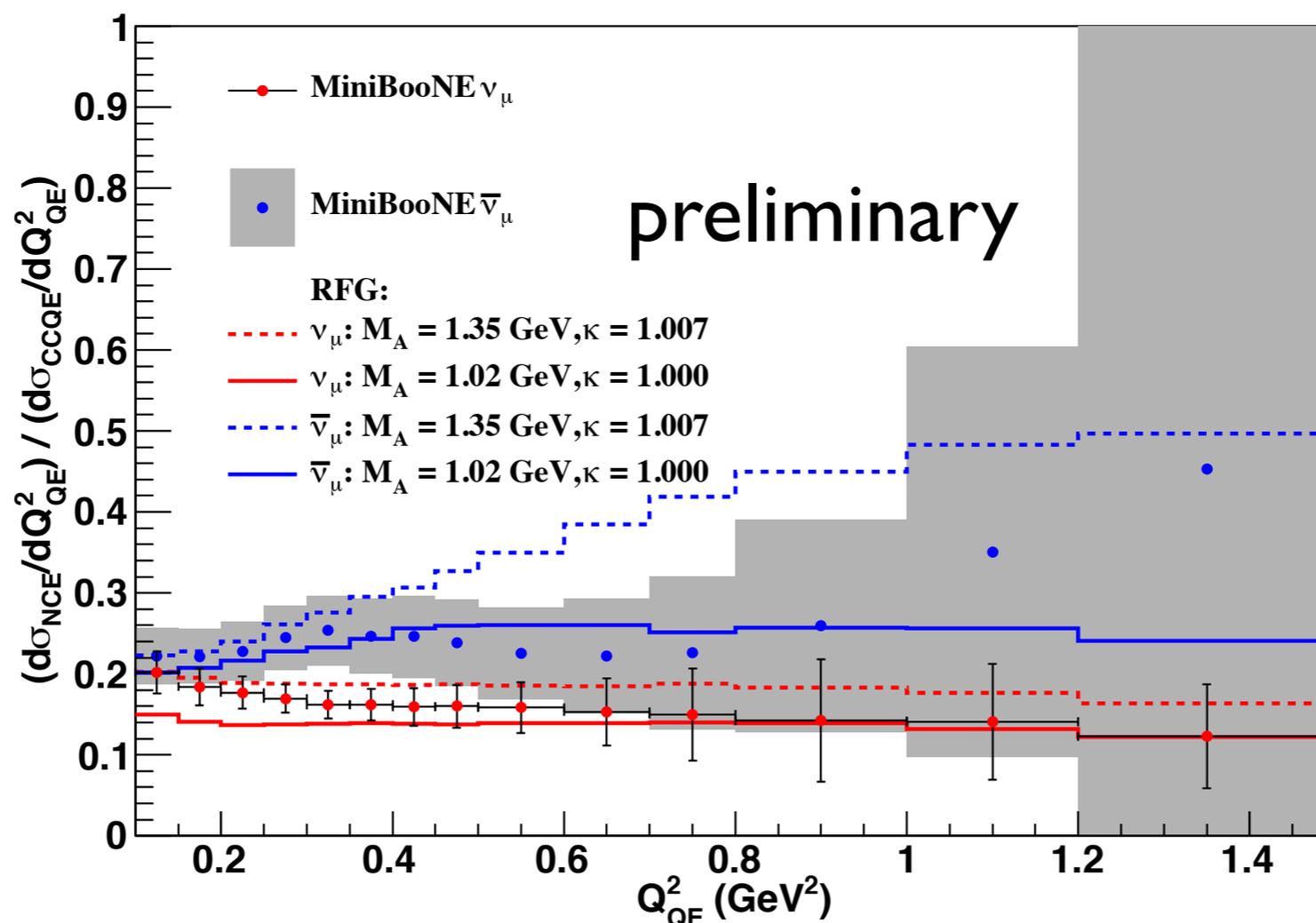
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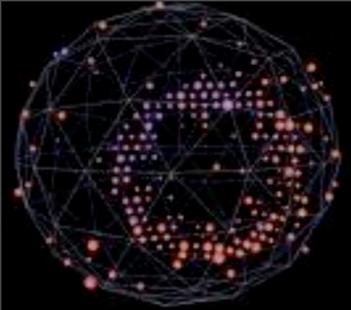
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- ▶ Recall exp't definitions of Q_{QE}^2 very different here: **hadronic** vs. **leptonic** observations

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



ν_μ ratio:
PRD 82,
092005 (2010)



NCE dirt background

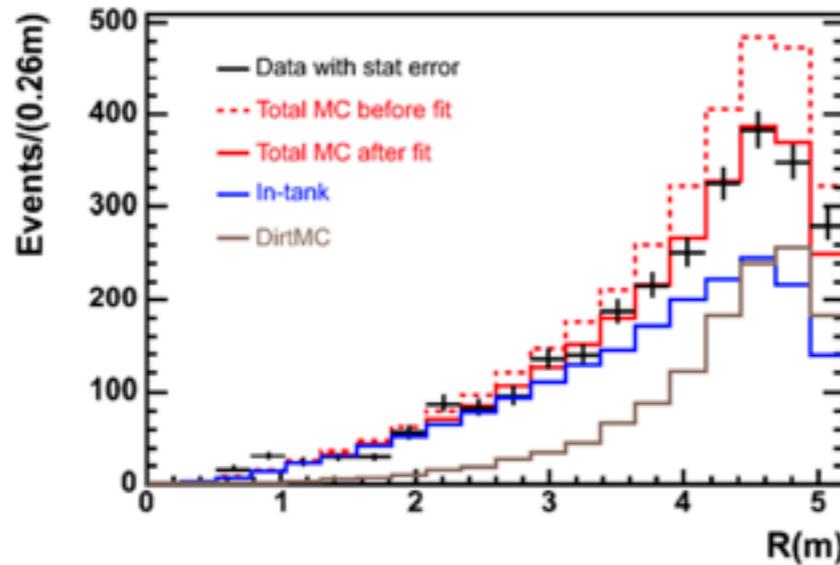


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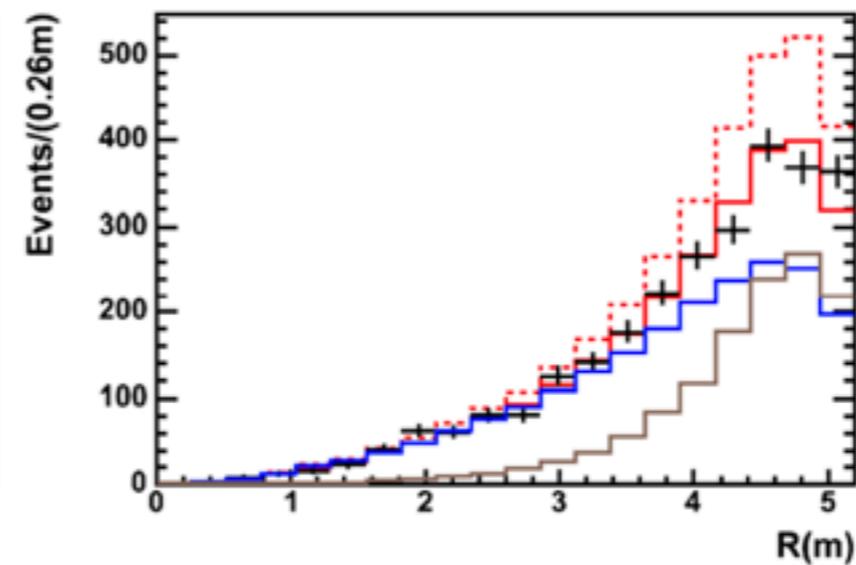
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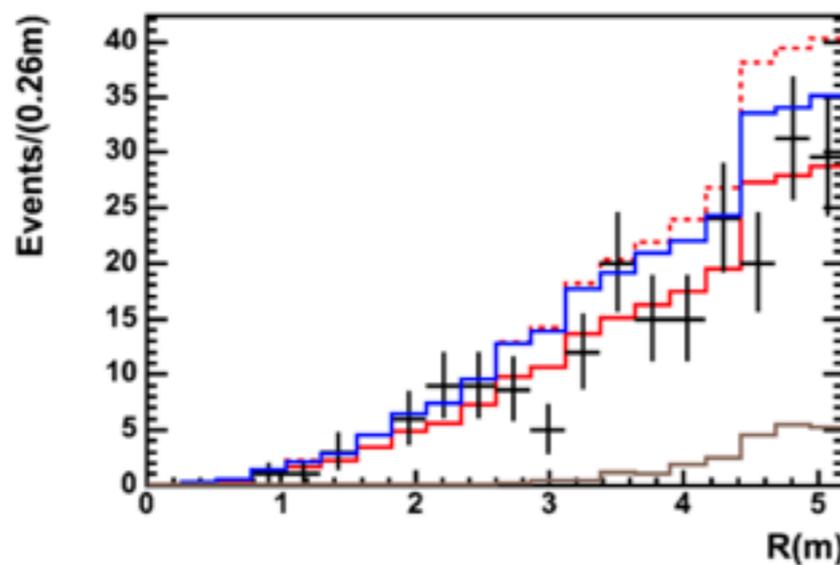
Example of radius fits in E bins



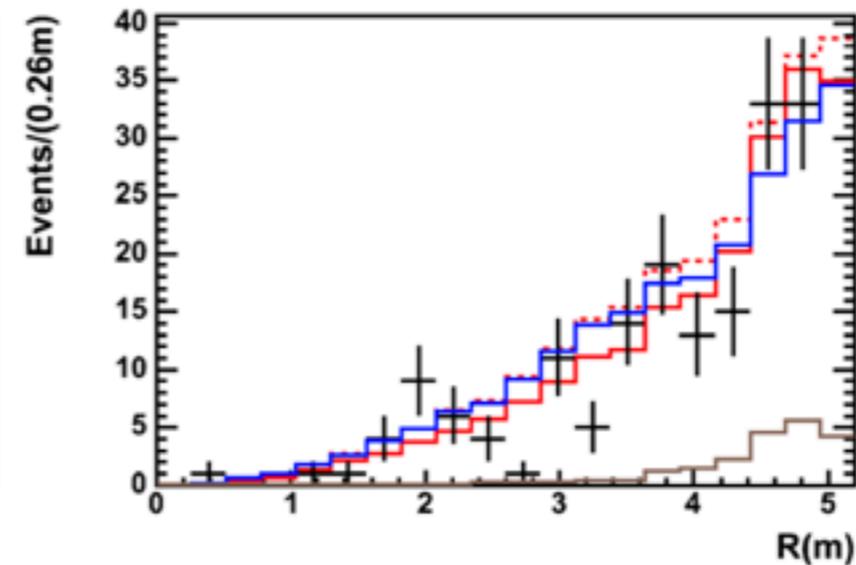
(a)



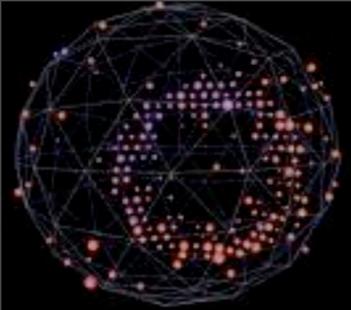
(b)



(c)



(d)



CH₂ comparison to RFG



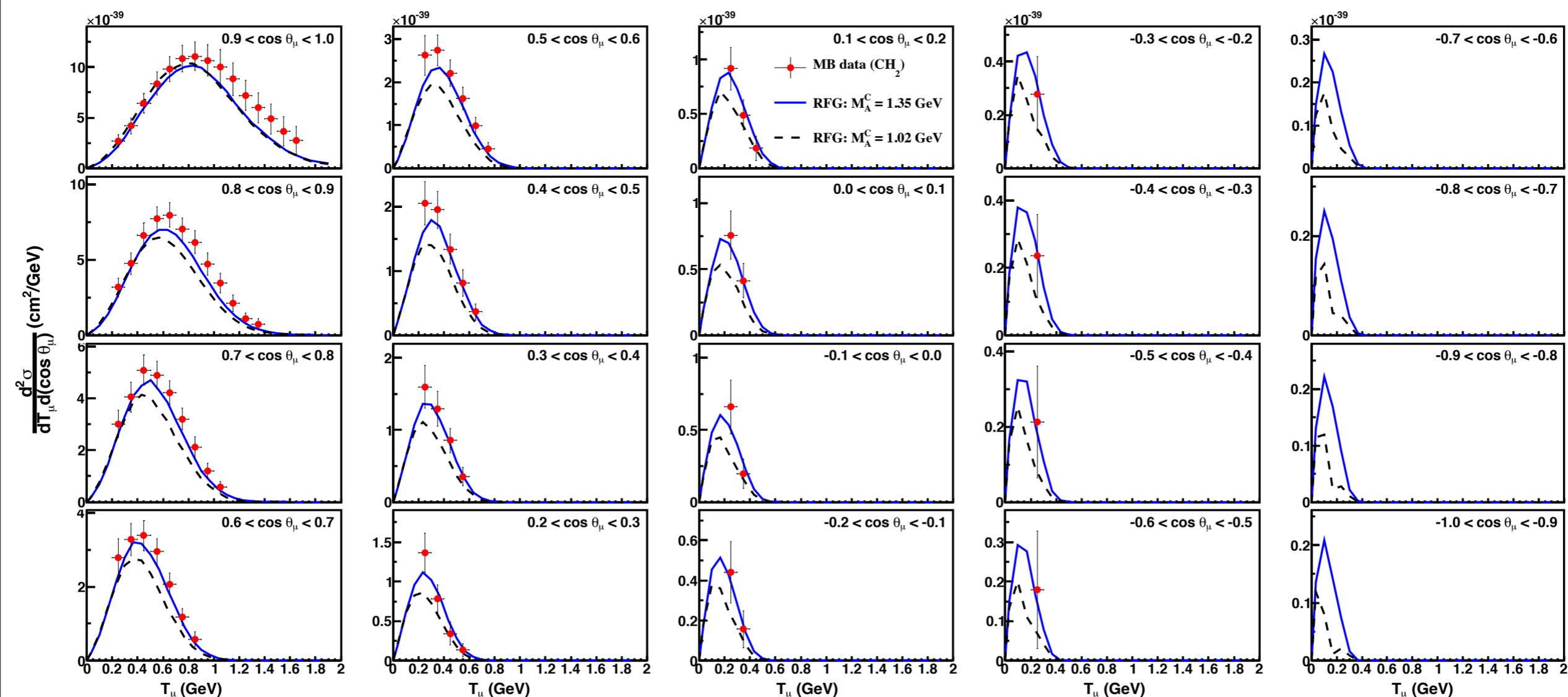
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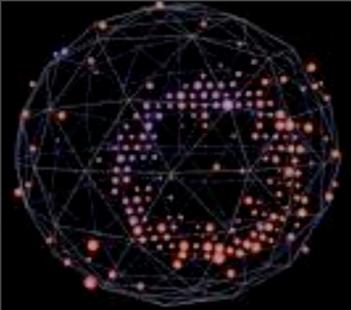
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- ▶ Data shape favors high effective axial mass
- ▶ Total uncertainty shown here

- data ~10% high of $M_A = 1.35$ GeV





What does κ do?

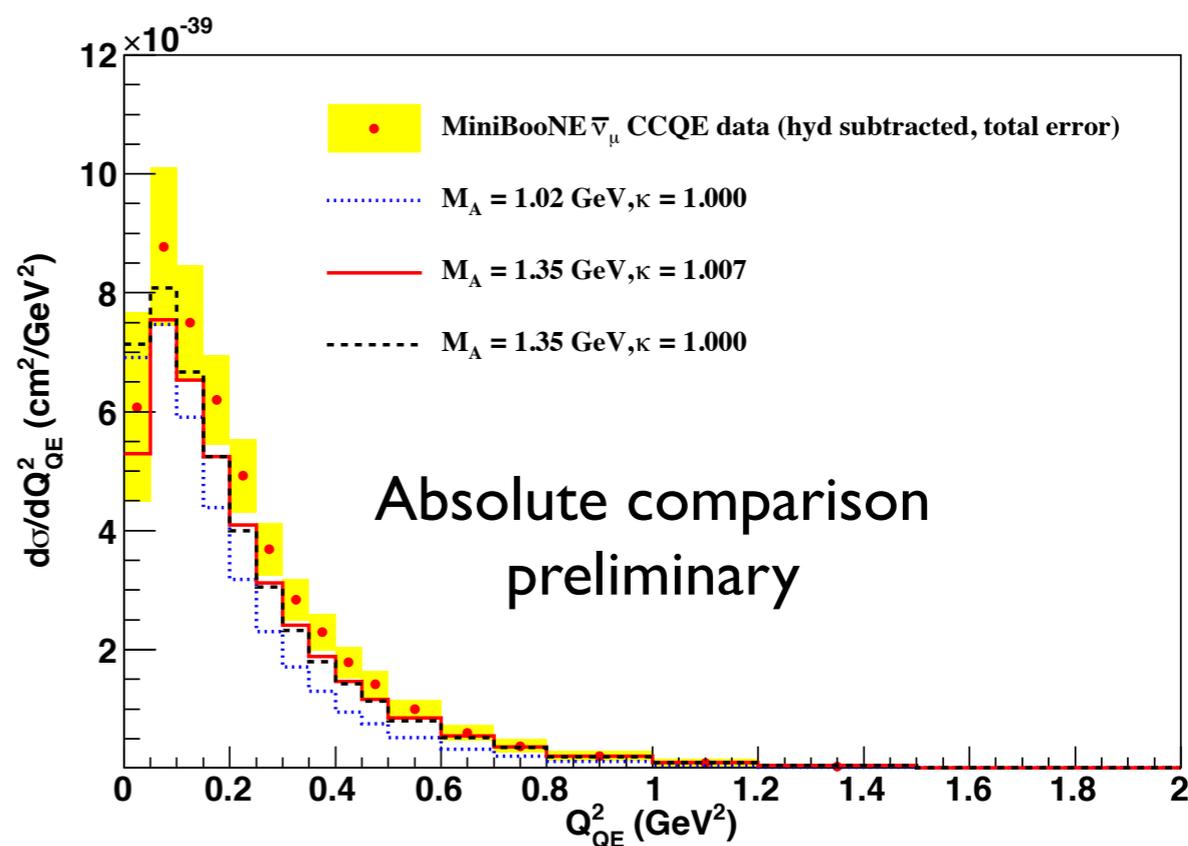
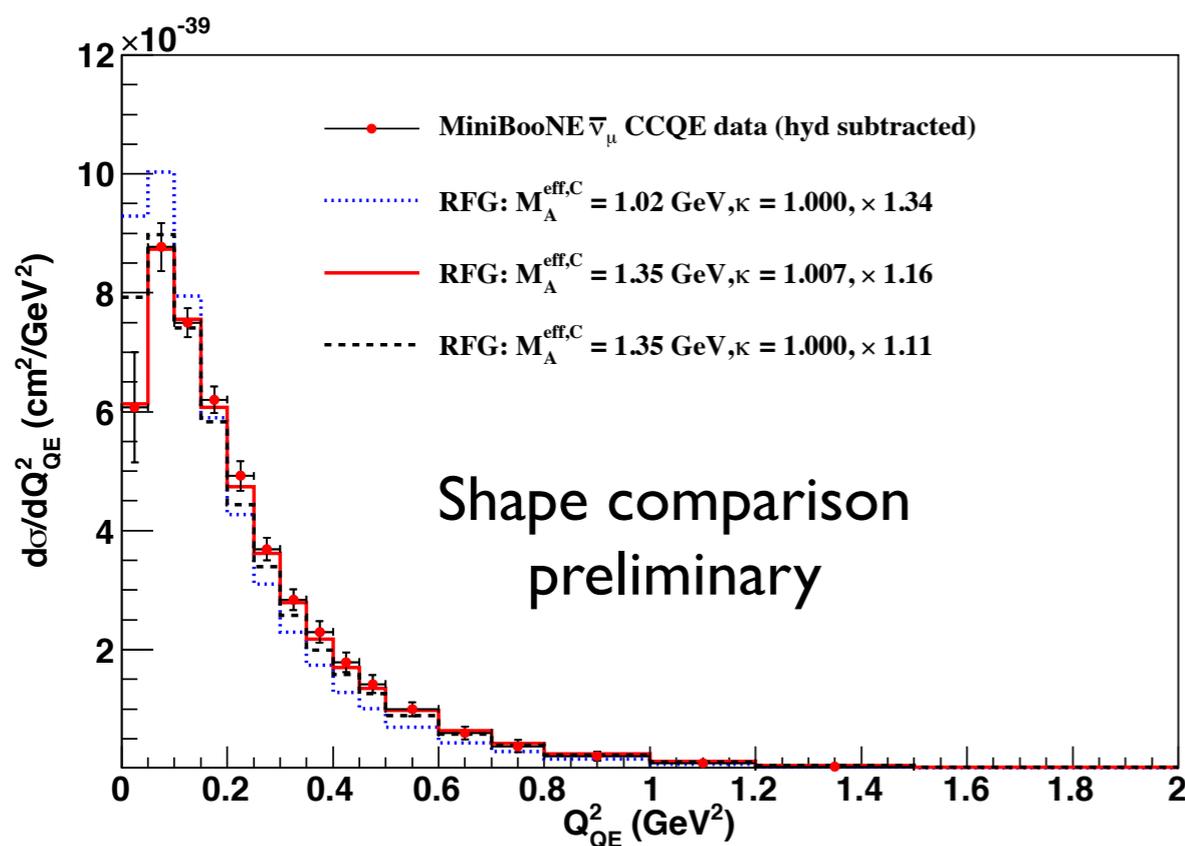


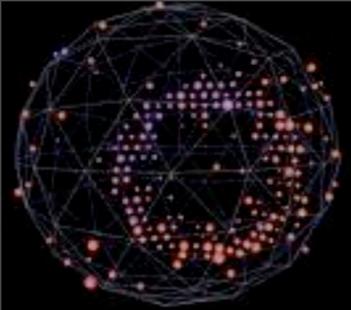
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- ▶ Small value of κ (1.007) does appreciably affect low Q^2_{QE}





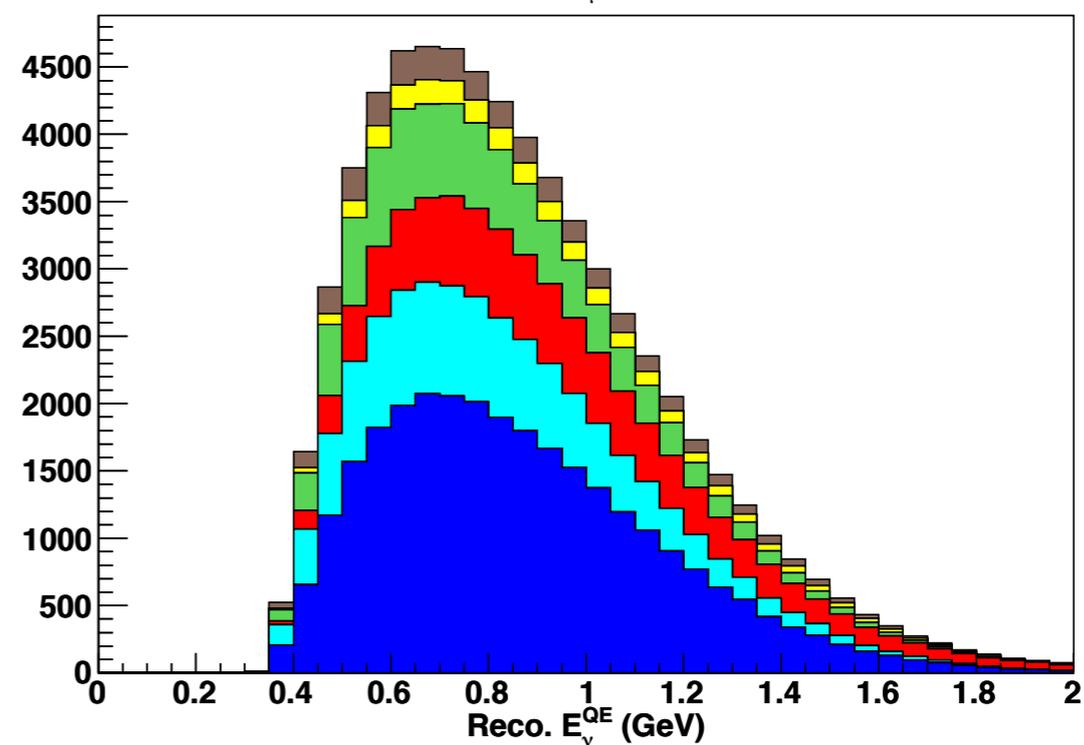
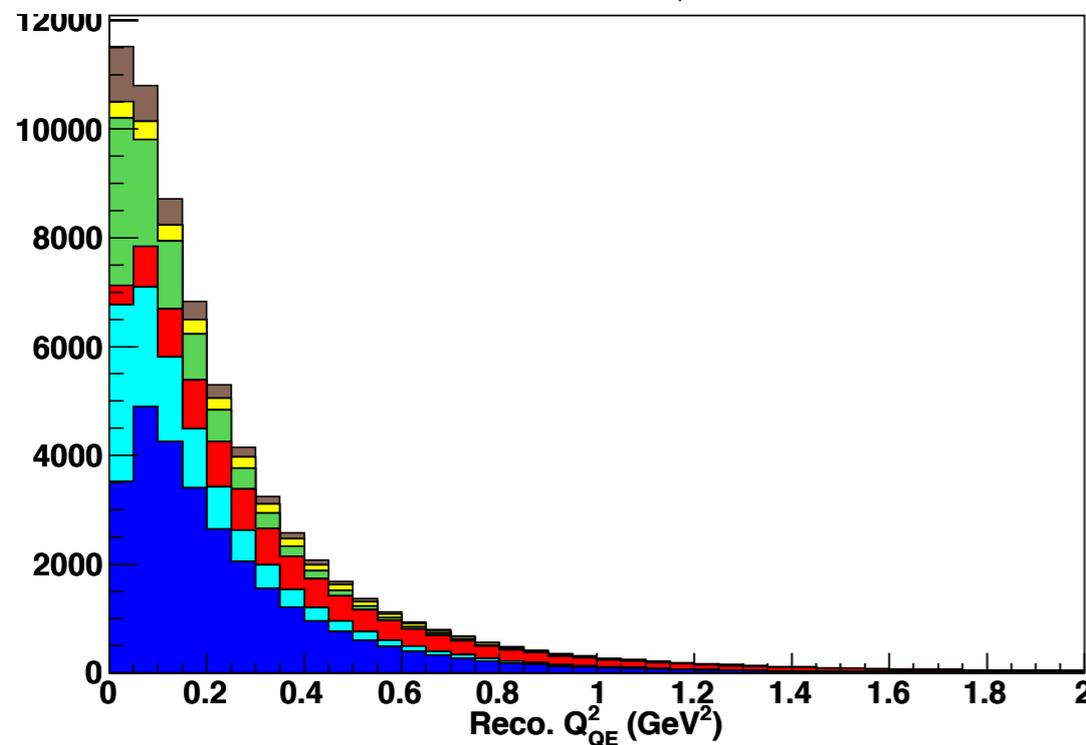
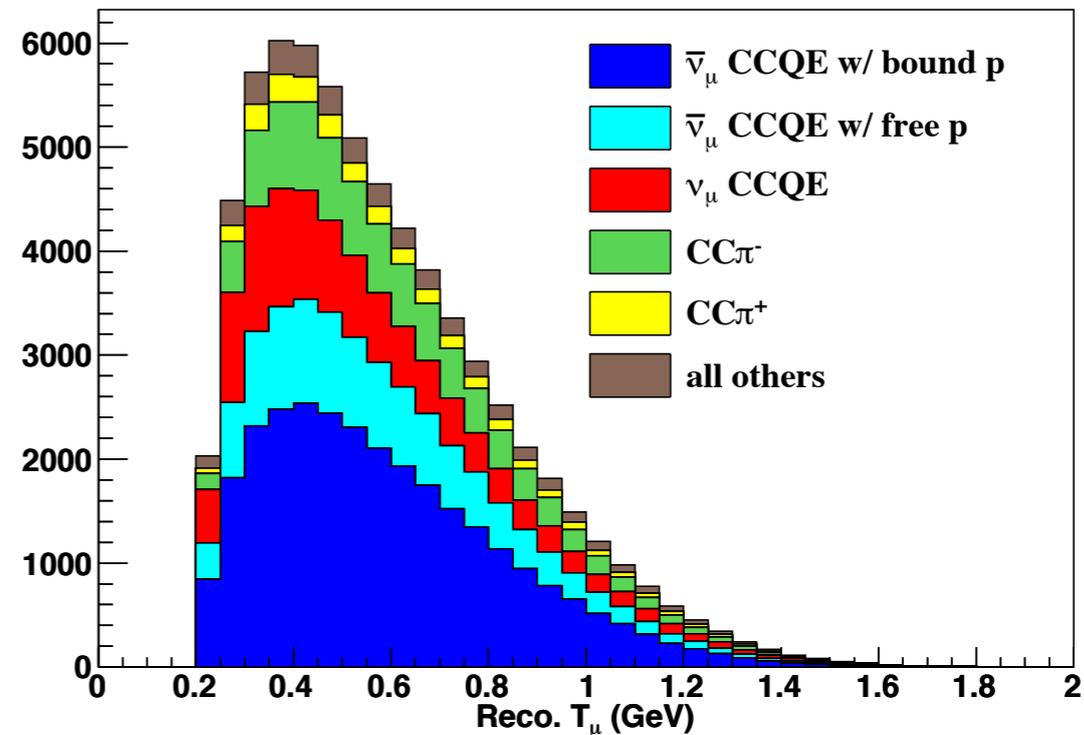
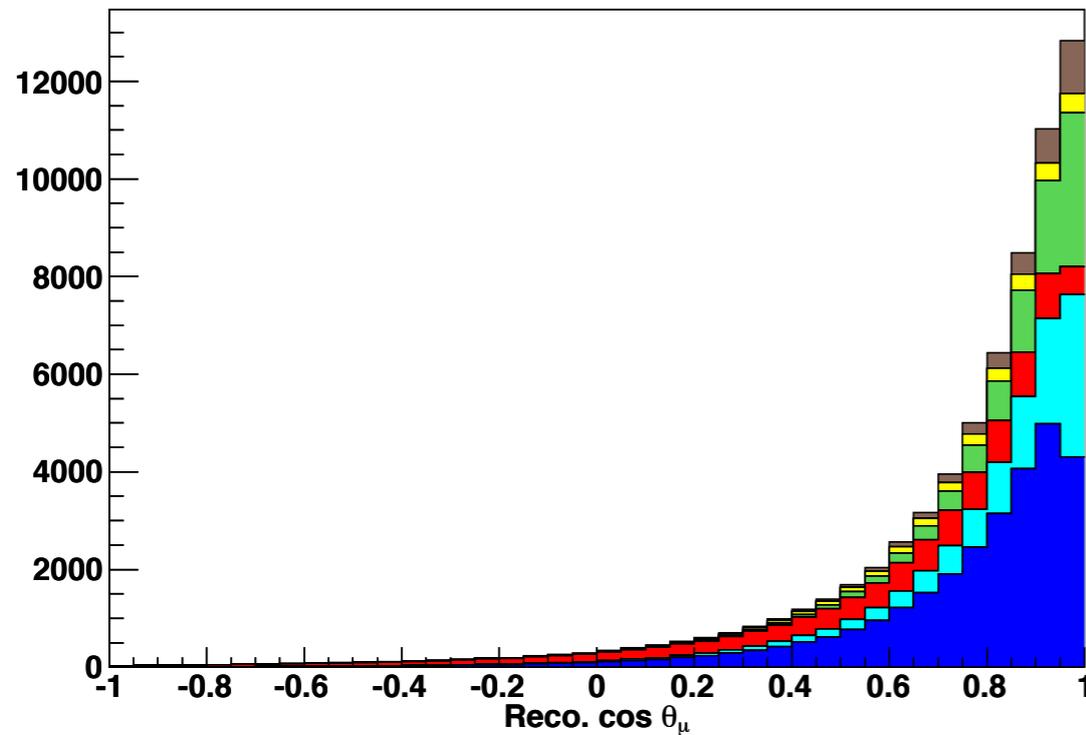
$\bar{\nu}_\mu$ sample composition

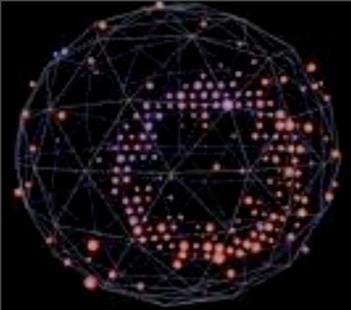


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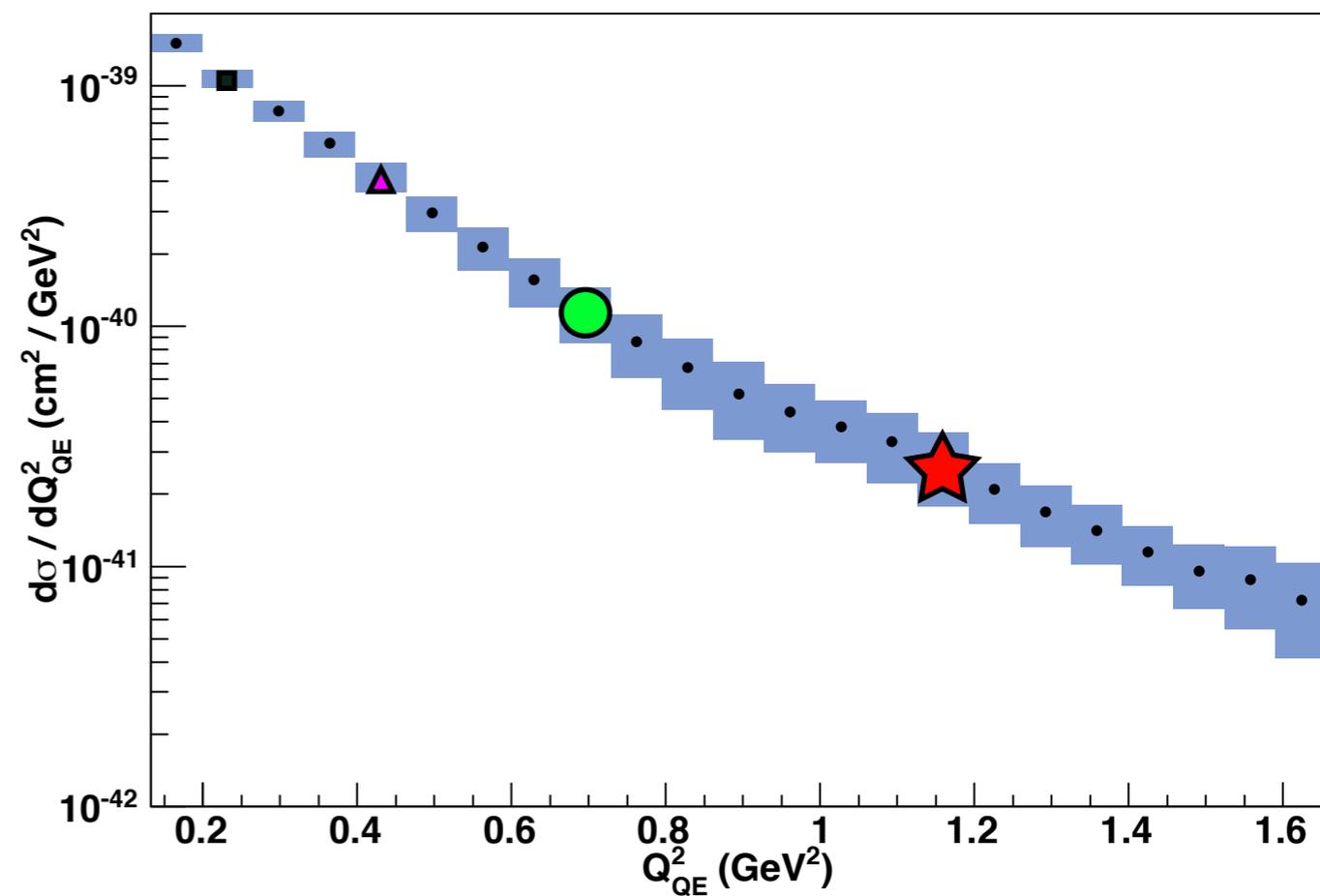
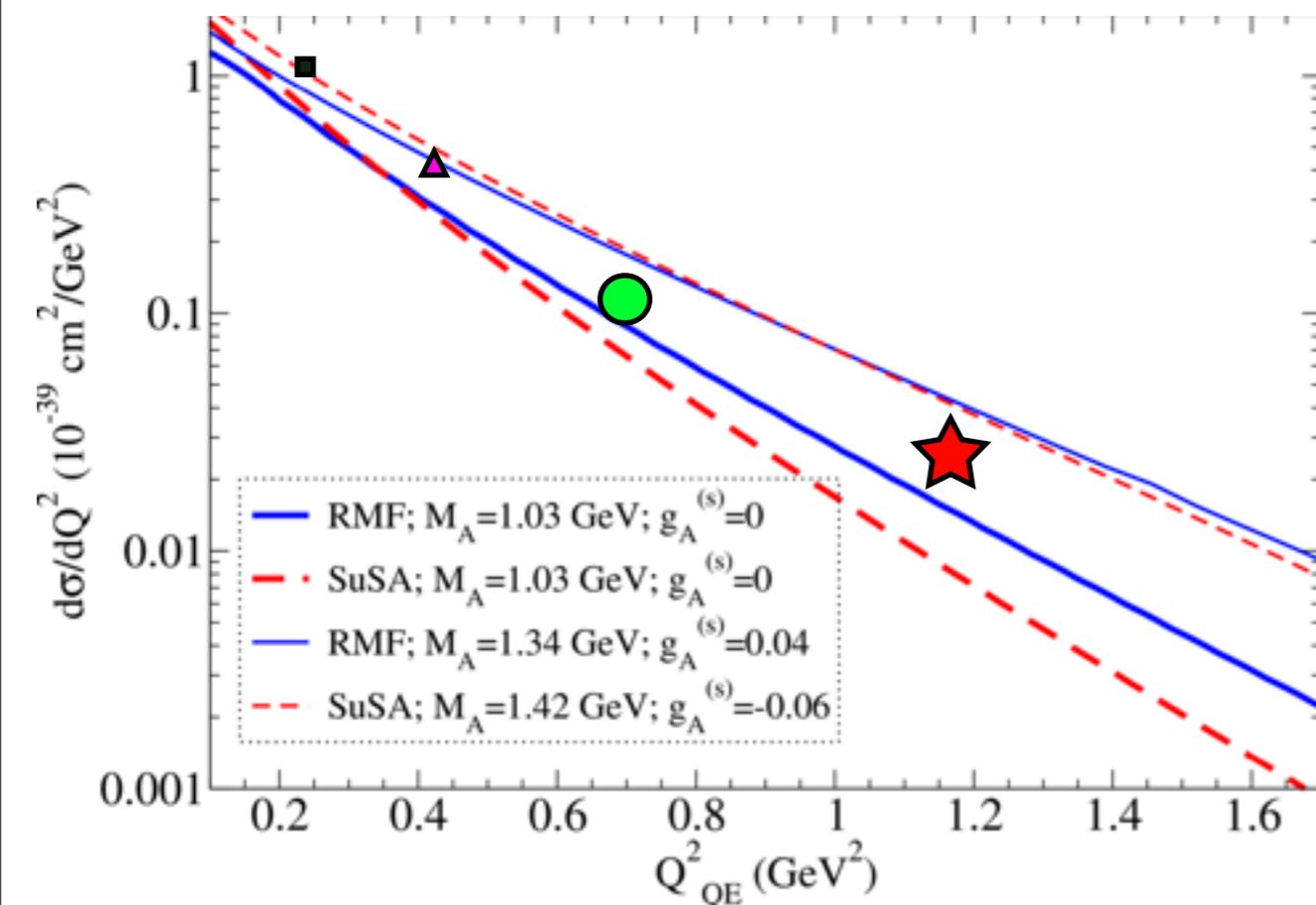
Anti- ν NCE recent calculation

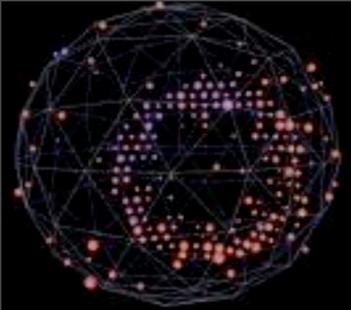


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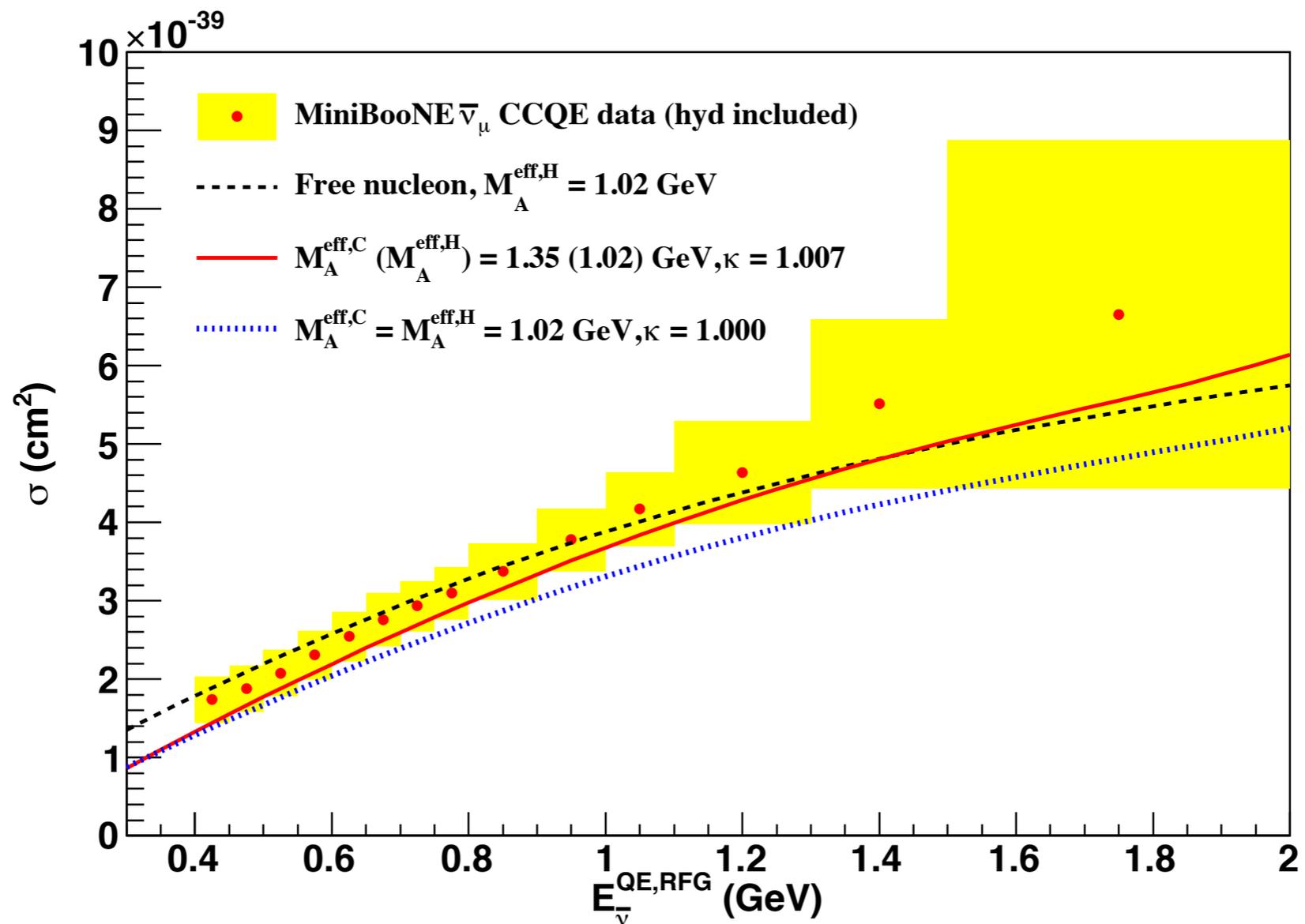
Total σ : CH₂

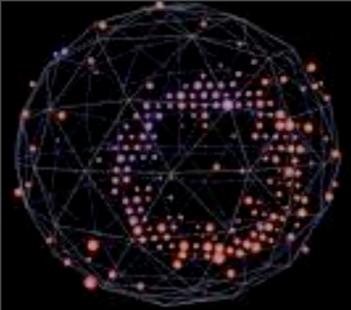


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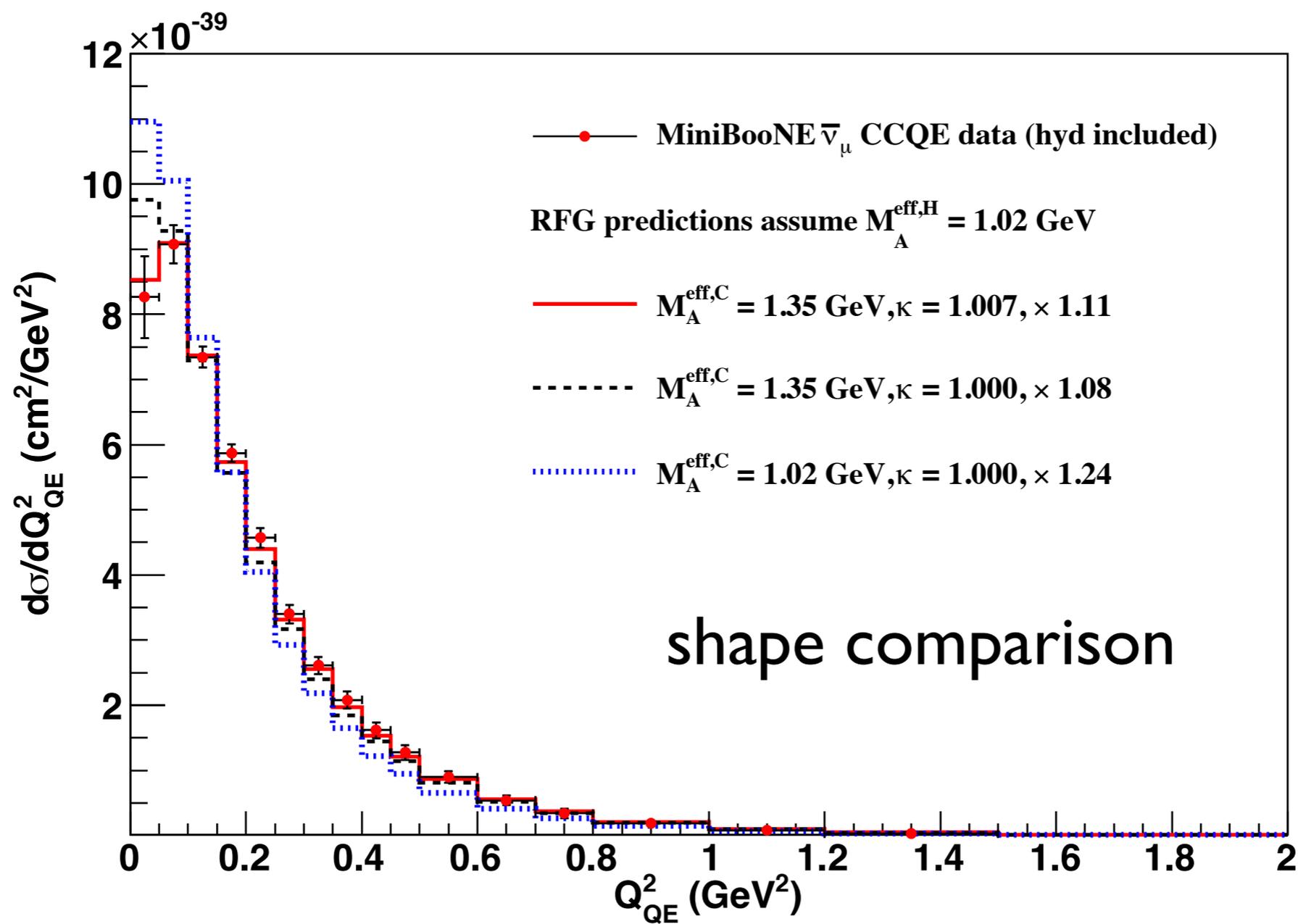
Single-differential $d\sigma/dQ^2_{QE}$: CH_2

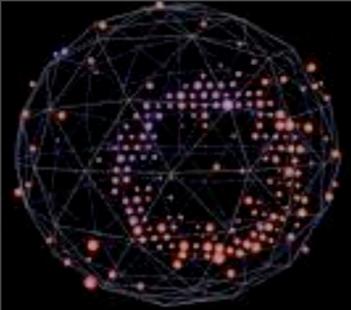


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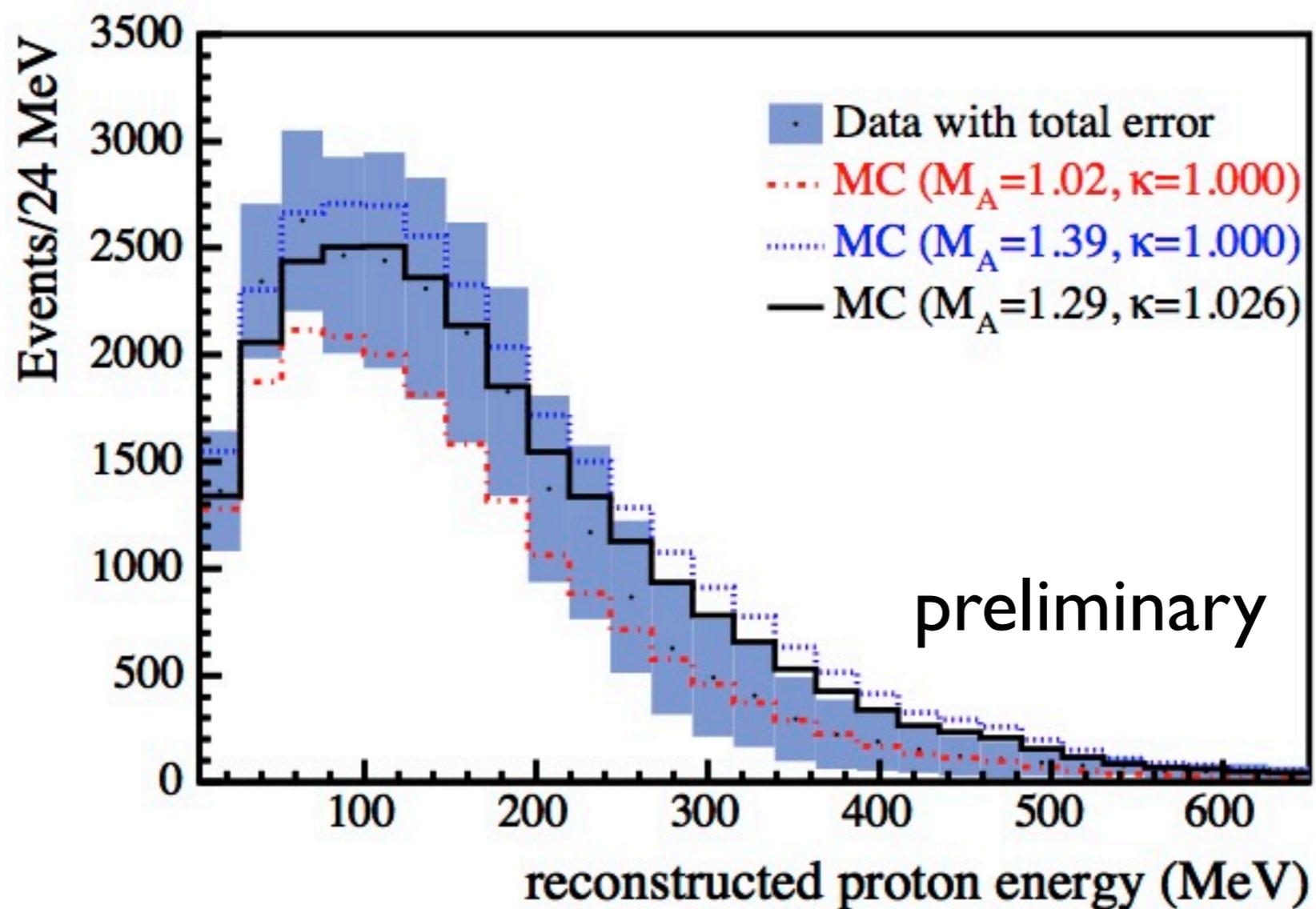
More model comparisons



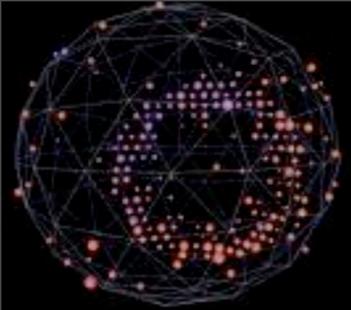
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- ▶ Not much shape sensitivity to model parameters



CC π^+ measurement



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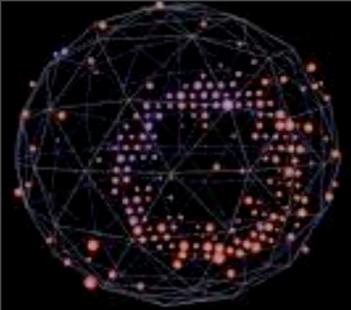
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- ▶ Simply require two decay electrons after prompt μ , get a sample of $\sim 80\%$ ν_μ (wrong sign) interactions

- ▶ 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

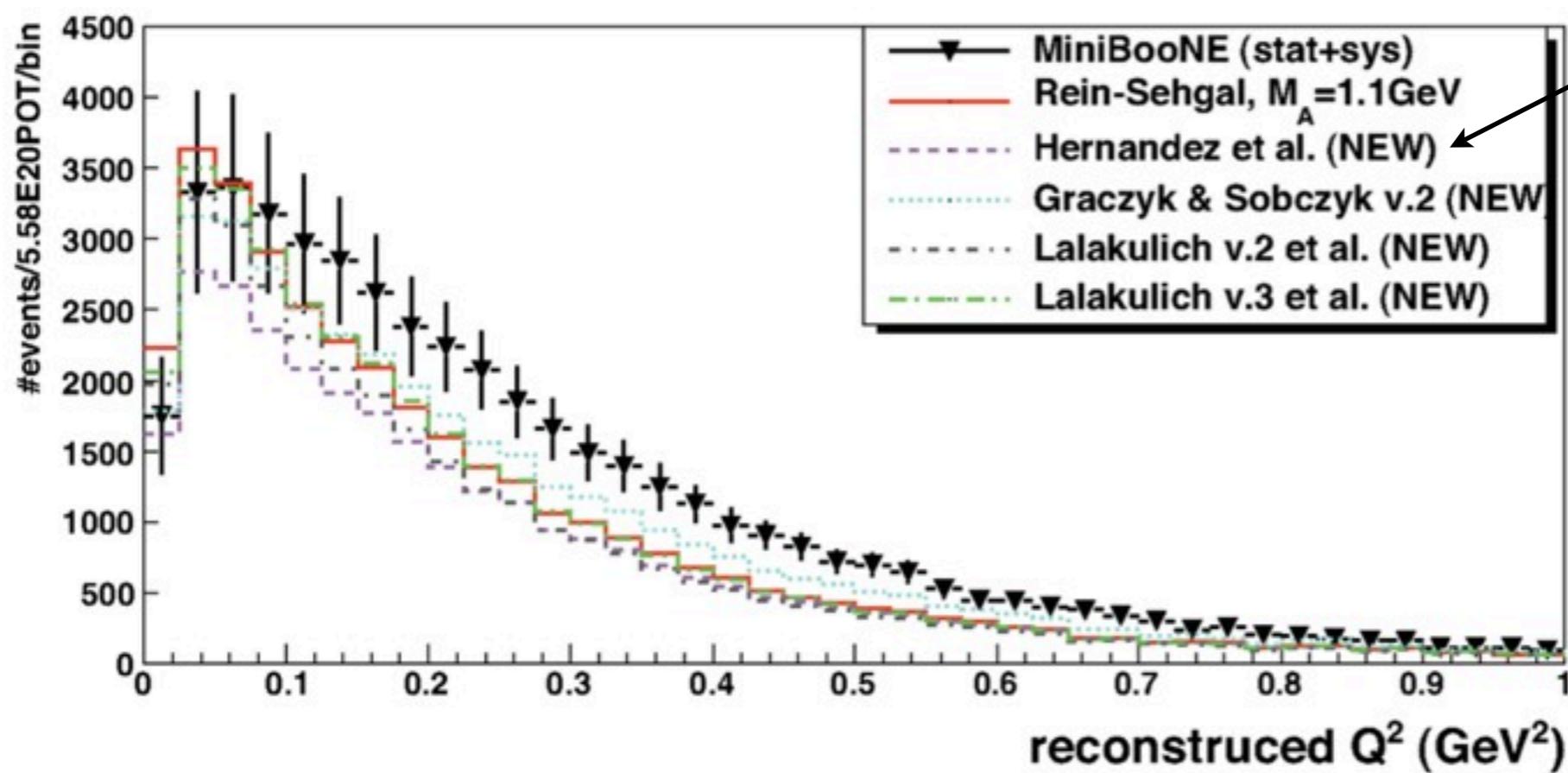


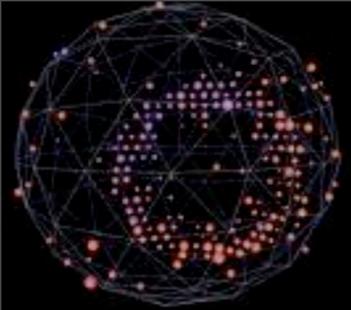
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Phys. Rev. D **76**, 033005 (2007).





Consistency in neutral current elastic channel



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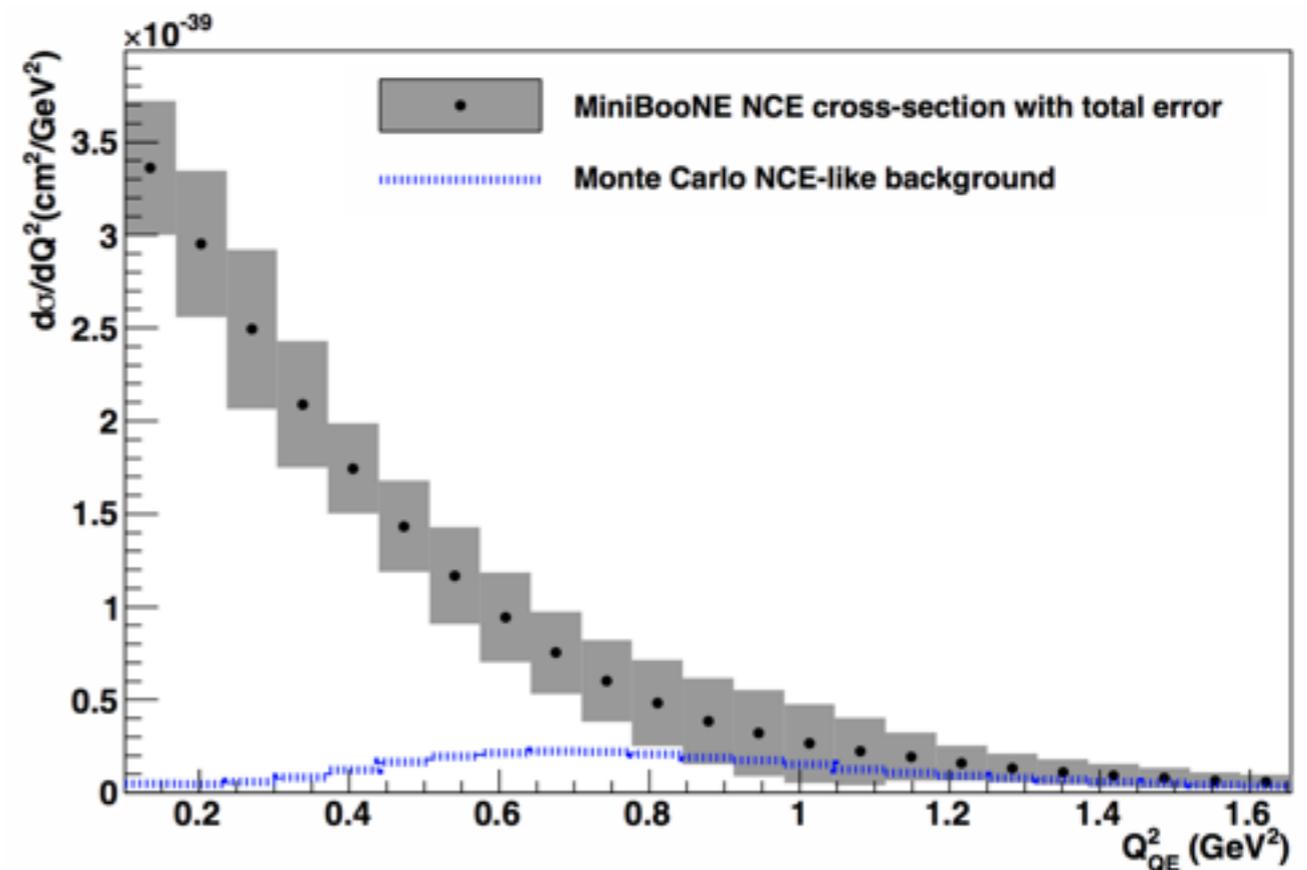
- ▶ Neutral current elastic: similar formalism to CCQE,

$$\nu_{\mu}N \rightarrow \nu_{\mu}N$$

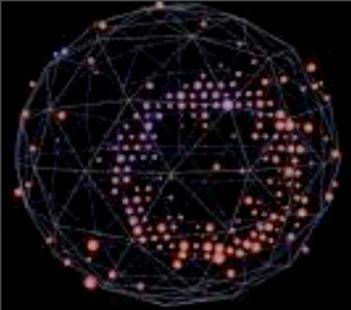
- ▶ Also sensitive to M_A : fit to observations of nuclear recoil energy shape find $M_A = 1.39 \pm 0.11$ GeV

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

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

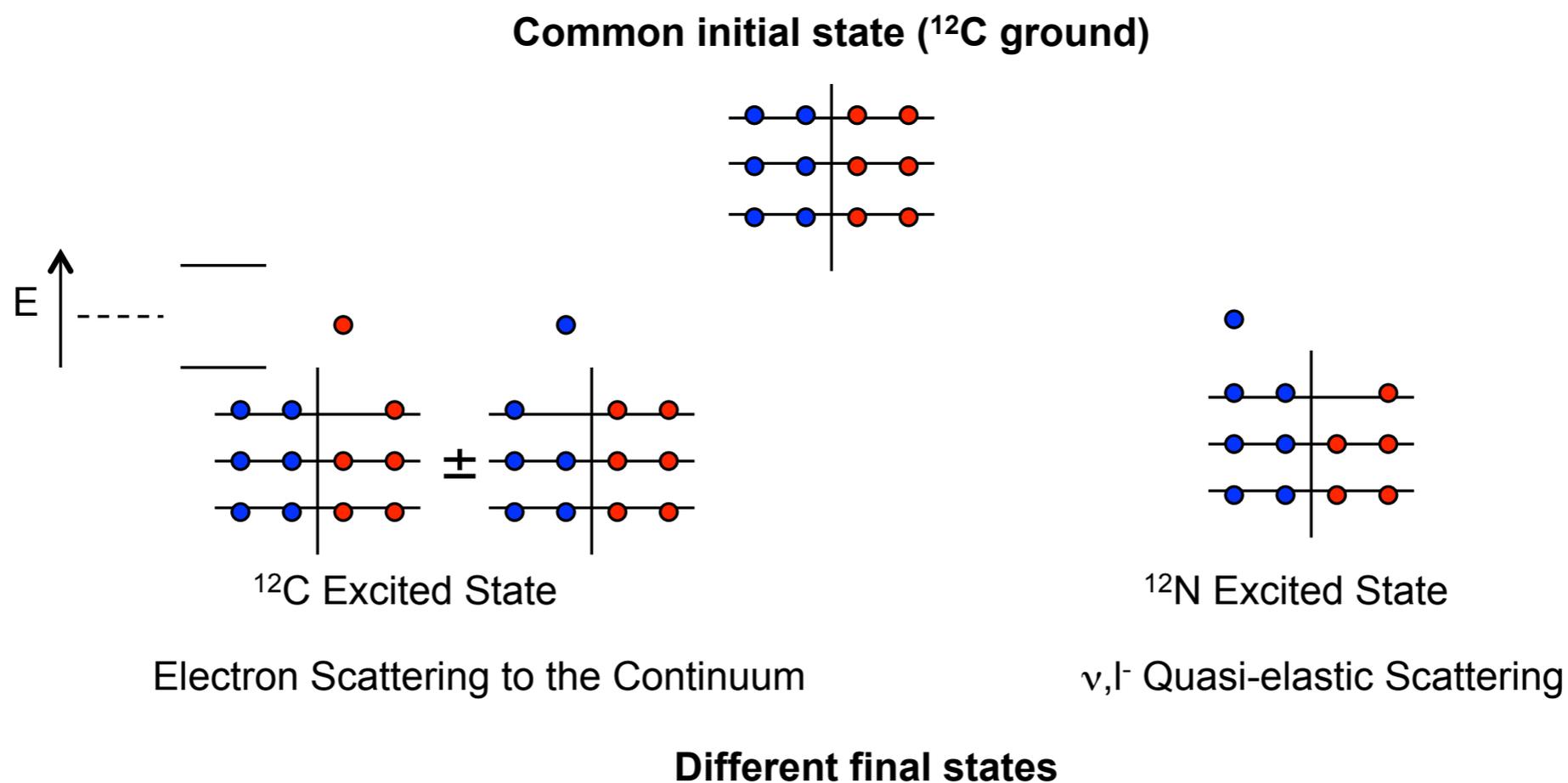


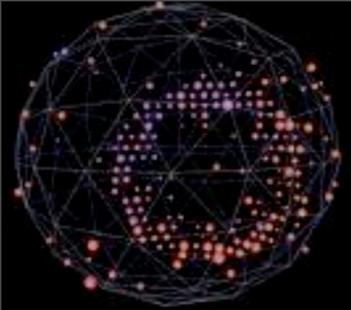
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- ▶ E_B for neutrino charged-current ($\nu + N \rightarrow l^\pm + N'$) interactions distinct from neutral-current ($e + N \rightarrow e + N$) E_B , as separation energy between final, initial states are different





How much different?



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

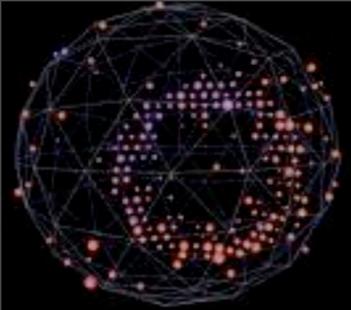
$$E_S(\text{MeV}) = \frac{28(A - 2Z)^2}{A}$$

- ▶ $E_S = 9 \text{ MeV}$ for $A = 12, Z = 7$
 - (CC interactions with $n \rightarrow p$, e.g. ν_μ CCQE)

- ▶ $E_B = 25 + 9 \text{ MeV} = 34 \text{ MeV}$

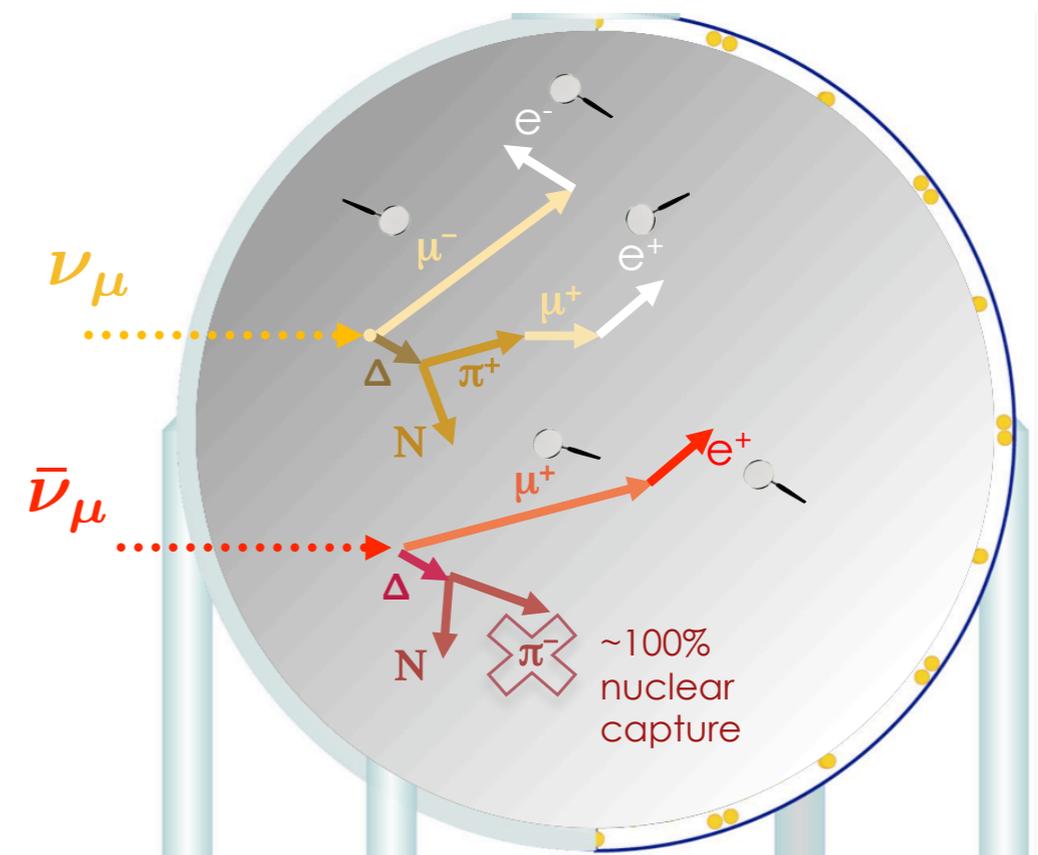
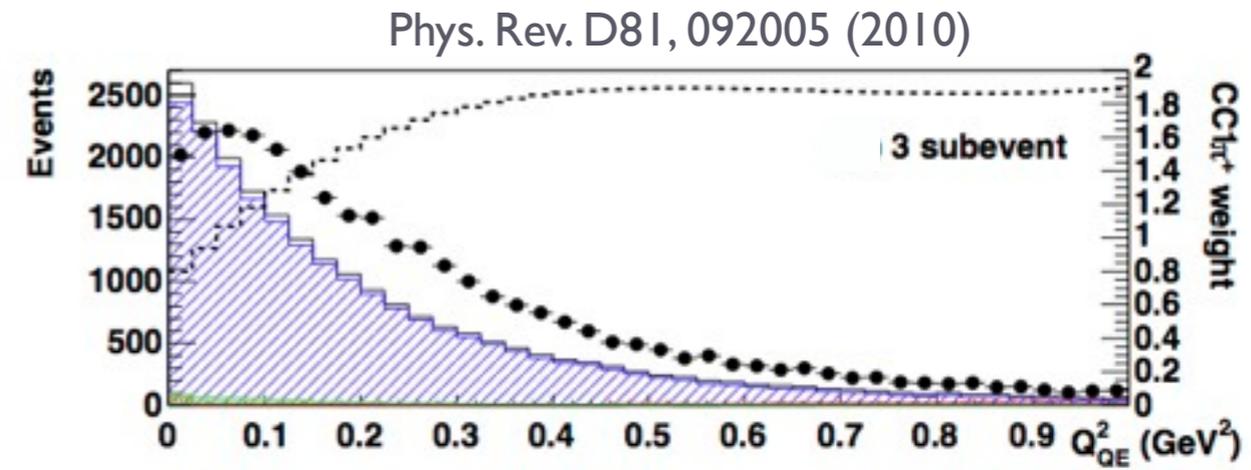
(e,e') data symmetry splitting

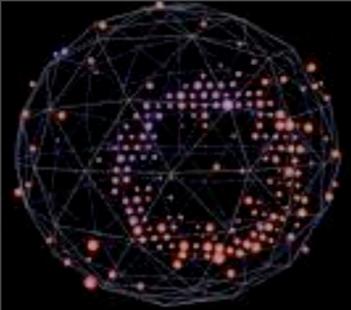
↑ ↑



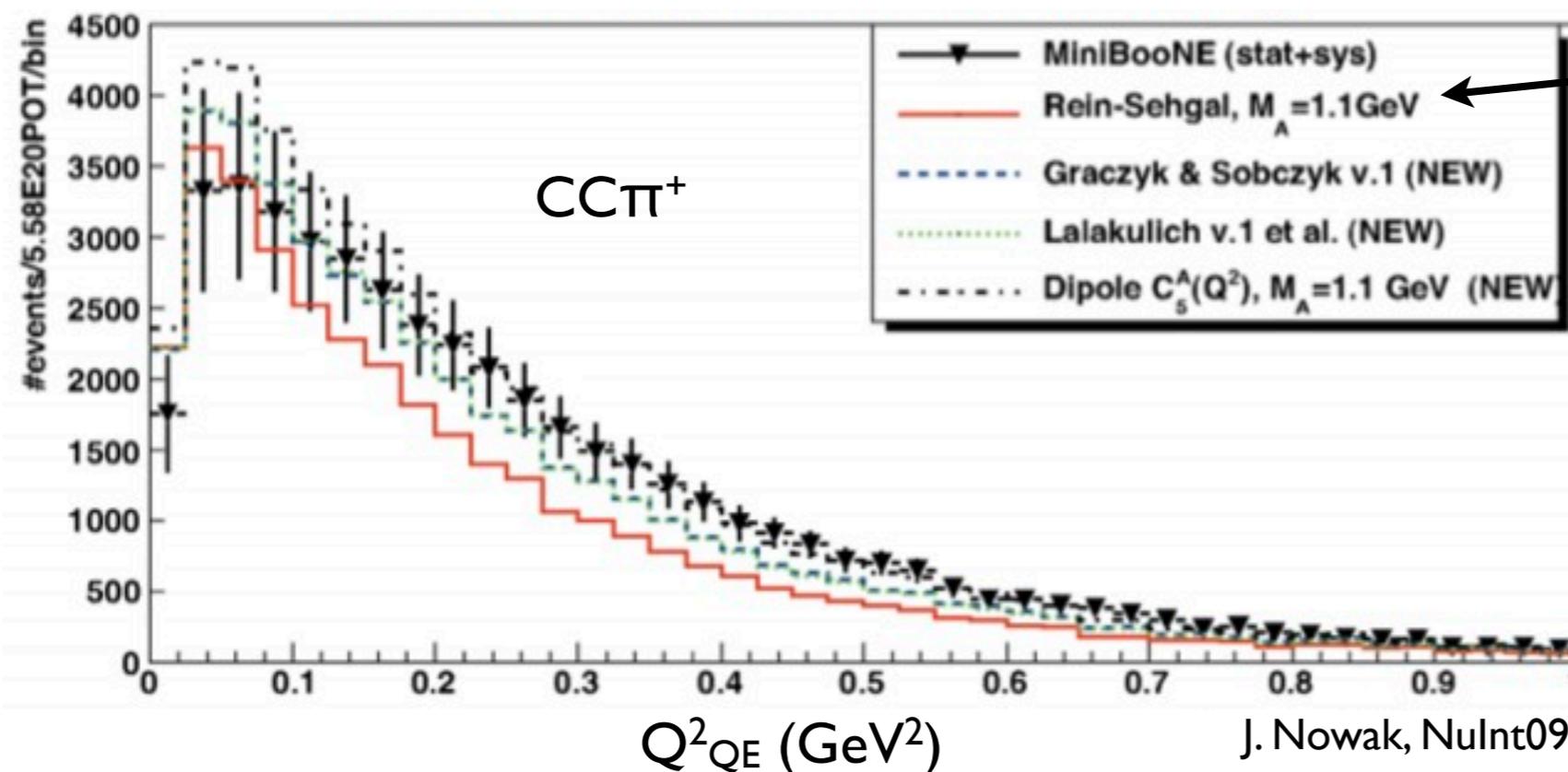
- ▶ Single- π bkg for ν_μ CCQE analysis: ID'd CC π^+ events using 2-Michel tag
 - empirically constrained their rate + shape, apply to bkg prediction

- ▶ Not possible in anti- ν mode: single-pion mechanism CC π^- , stopped π^- absorbed in medium $\sim 100\%$, 2nd Michel not produced



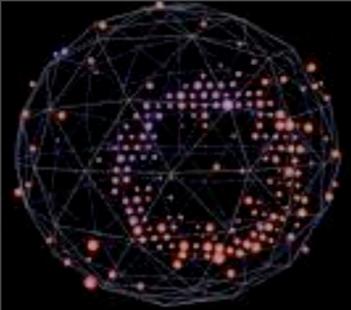


- ▶ Apply the same constraint measured in CCT π^+ sample to CCT π^- events
 - uncertain extrapolation!
- ▶ Can do better: use improved π -production model that agrees with MB CCT π^+ data as cross-check
 - improvements include muon mass effects (absent in nominal model)



Nominal prediction

Improved calculation



Irreducible background

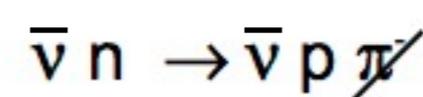
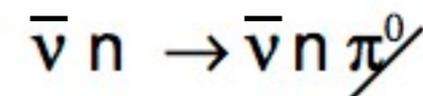
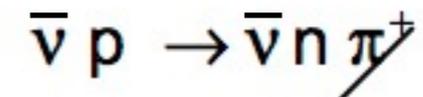
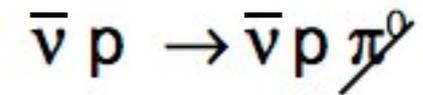


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▶ Irreducible: $N\bar{C}\pi$ with no final-state π , e.g.:

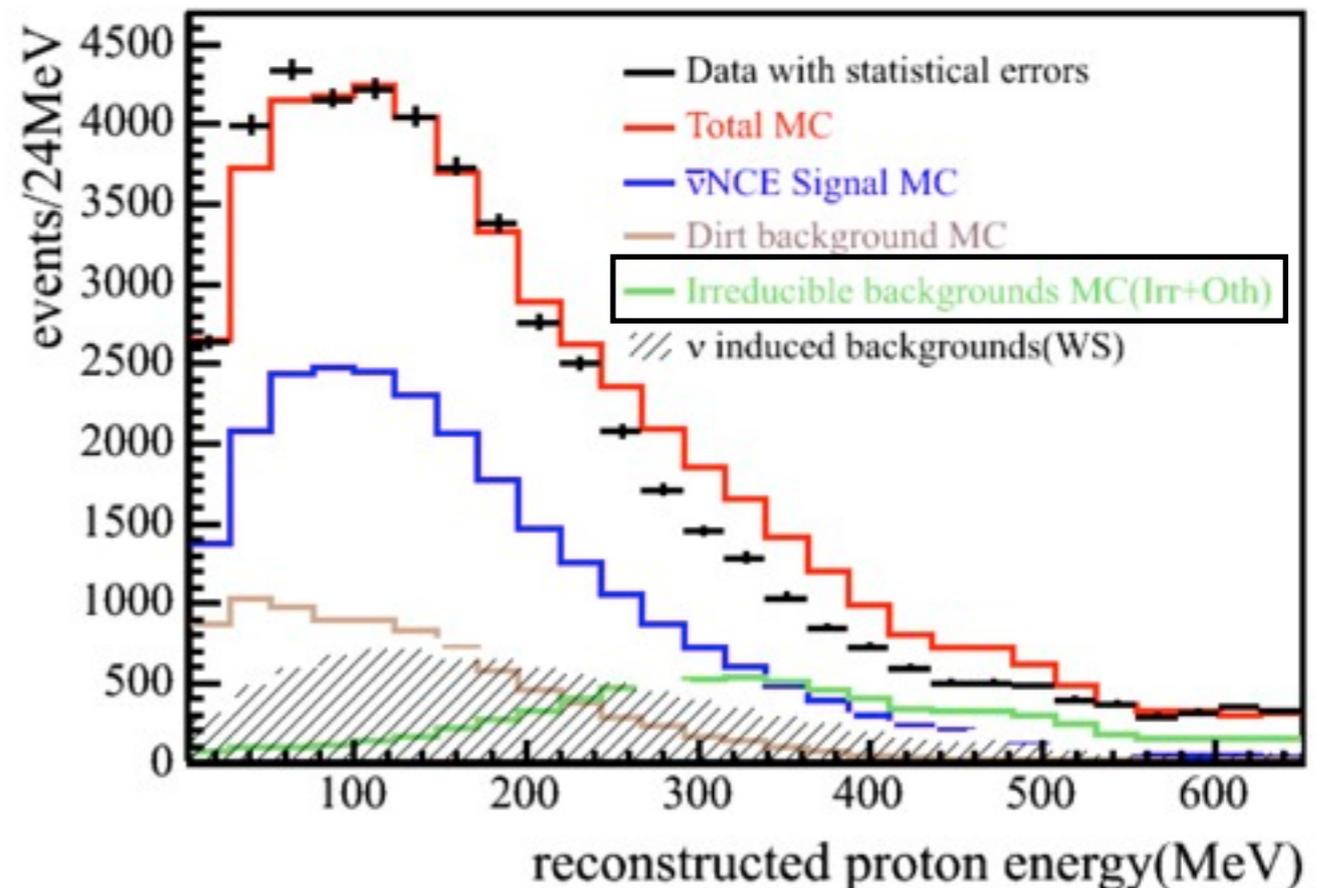


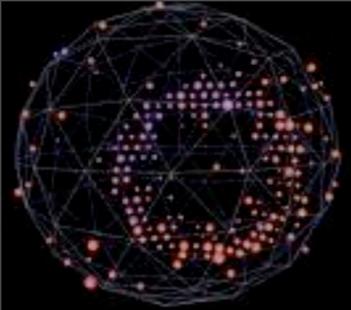
▶ **Rely on MC** to predict this background

- 30 - 40% errors assigned

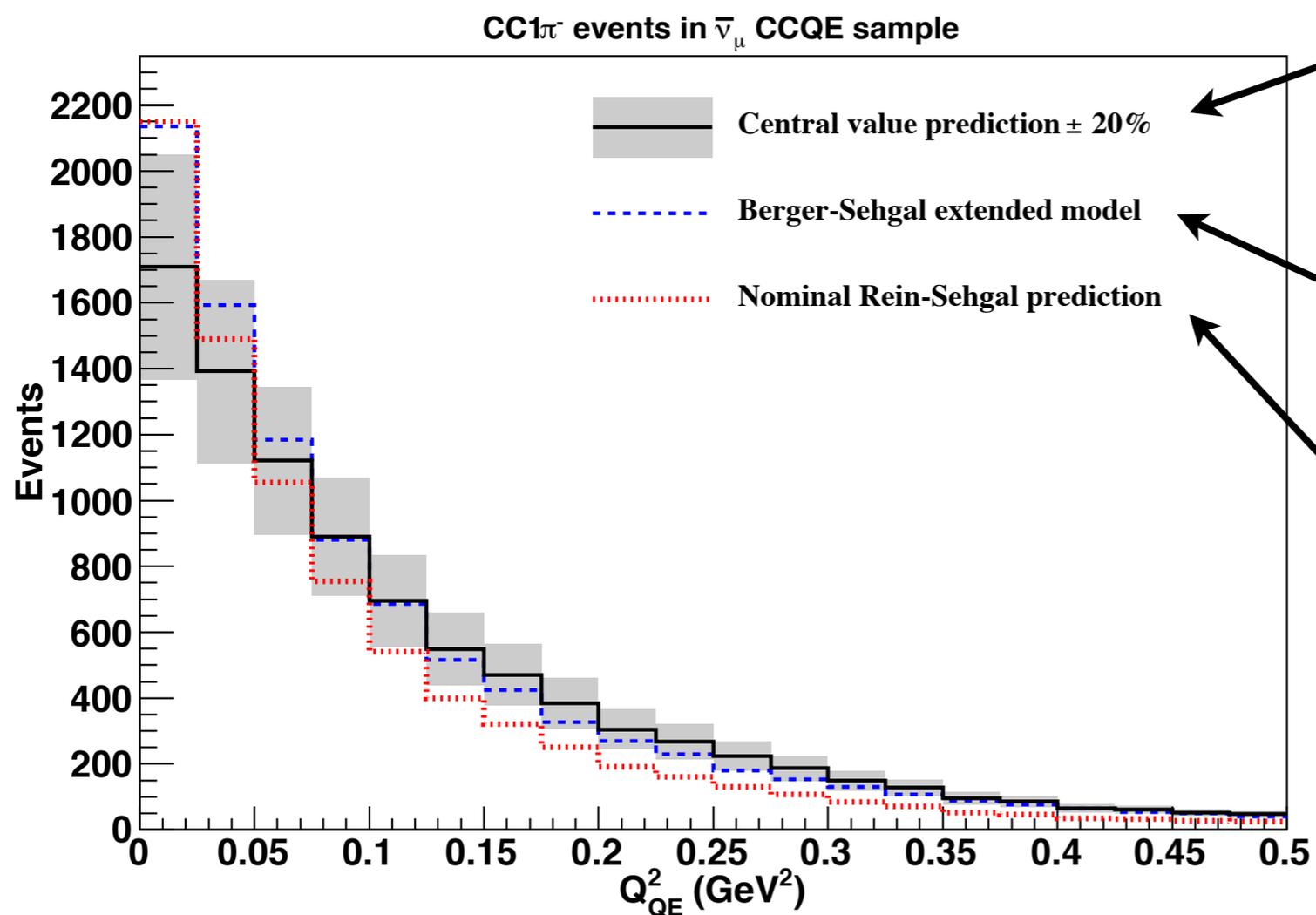
▶ Will also report what was subtracted to allow model-independent comparisons

- following previous MiniBooNE conventions





▶ Comparison to MiniBooNE predictions



tuned to MiniBooNE
CC π^+ 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