Revision of my talk on

Measuring Quasi-Elastic Scattering

from Neutrino 2010

Morgan Wascko
Imperial College London

FNAL PPD Neutrino Discussion, 16 September 2010

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Embedded links throughout slides

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Message

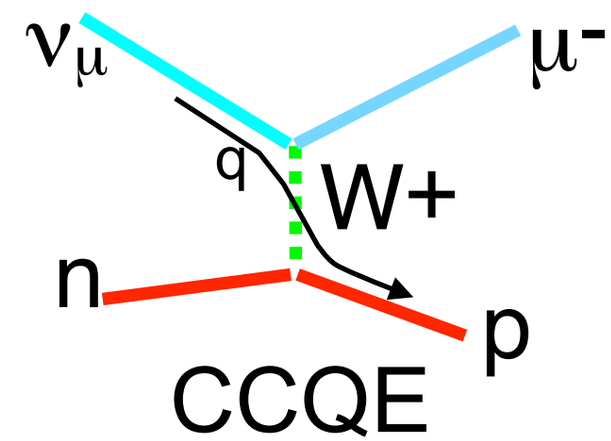
The precision of future oscillation measurements is limited by neutrino interaction uncertainties.

The solution is model independent cross-section measurements from the current generation of experiments.

Outline

- Phenomenological introduction
- Recent measurements (since Nu2008)
  - MiniBooNE, SciBooNE, NOMAD, MINOS
    - Flux predictions, uncertainties
- Importance to oscillations
- Quick mention: neutral currents & antineutrinos
- Discussion of path forward

Quasi-Elastic Scattering

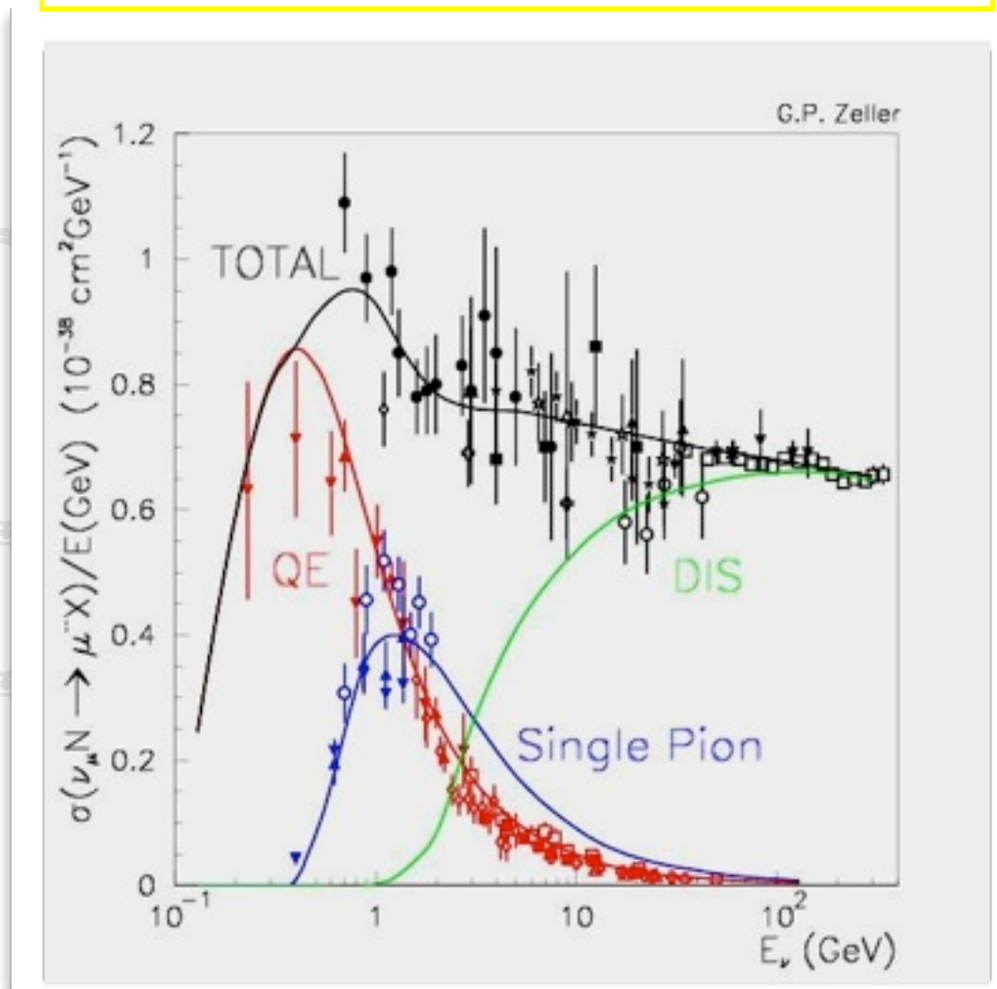


Theory talk by L. Alvarez Ruso

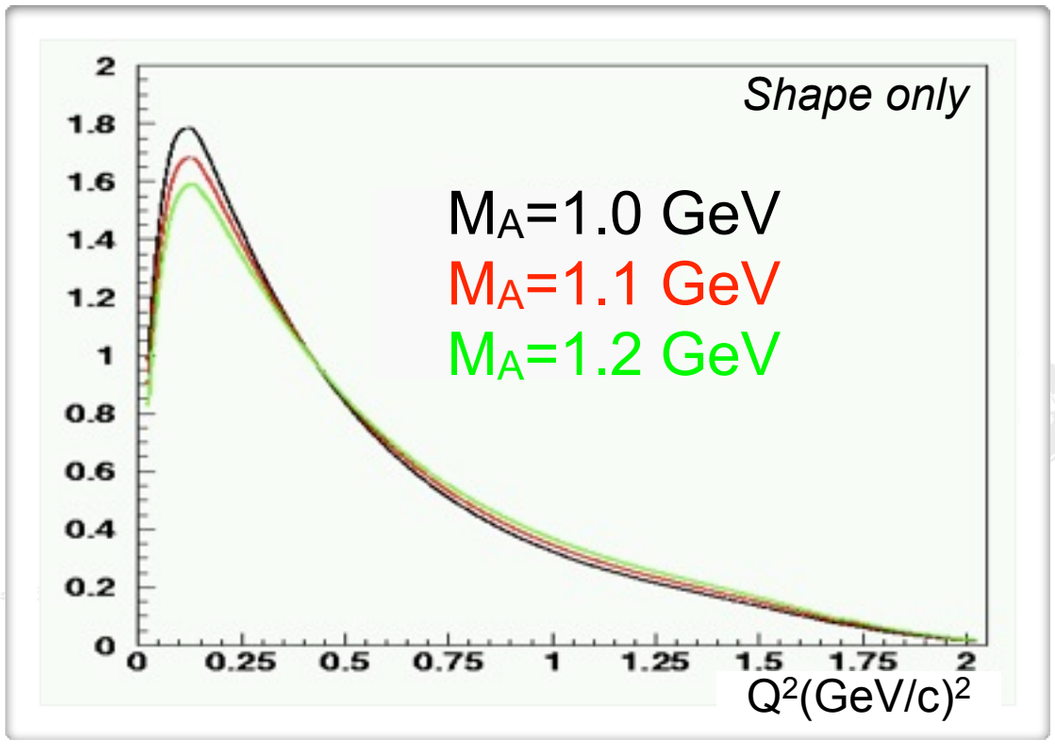
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{Q^2}{M_A^2})^2}$$

(where $Q^2 = -q^2$)

- Described by Llewellyn-Smith formalism
- Form-factors parameterise nucleon weak charge distributions
  - F_V measured by electron scattering, F_P negligible due to kinematics, F_A assumed to be dipole
- Important for accelerator ν beams
  - Dominant process near 1 GeV
  - Simple energy reconstruction



M_A fit results



Courtesy of R. Gran

- Value of M_A changes scale & shape of Q^2 distribution
- Recent measurements at low energy on nuclear targets favour high value of M_A
  - But not at high energy!
- Also show increased suppression at low Q^2
- F_A: not dipole form factor?
  - Is M_A an effective parameter?

Experiment	M_A Value (GeV)
World Average (n,p)	1.03±0.03
K2K SciFi (O)	1.20±0.12
K2K SciBar (C)	1.14±0.10
MiniBooNE (C)	1.35±0.17
MINOS (Fe)	1.19±0.17
NOMAD (C)	1.05±0.06

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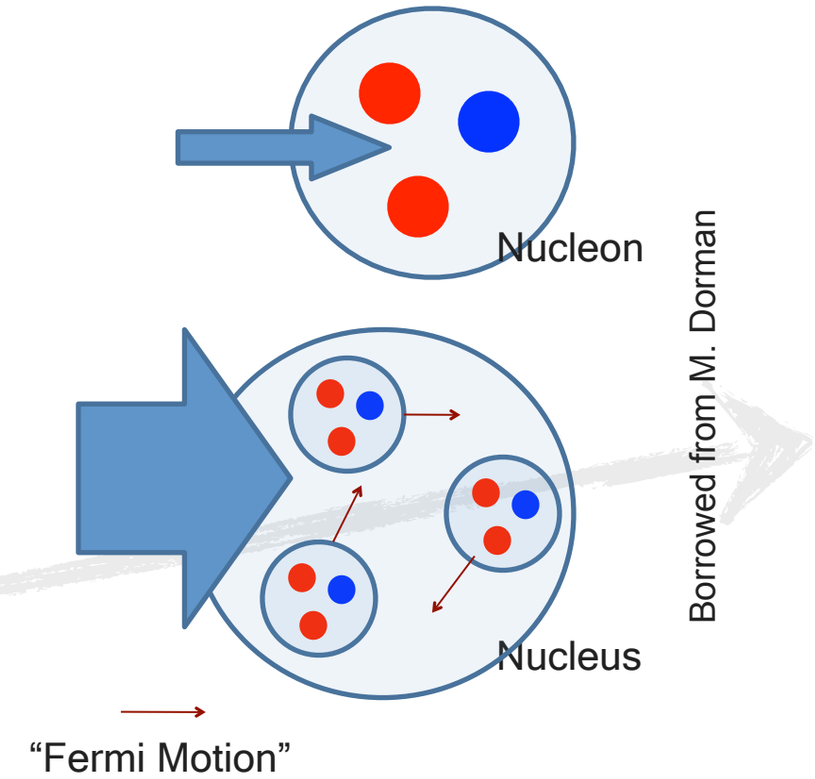
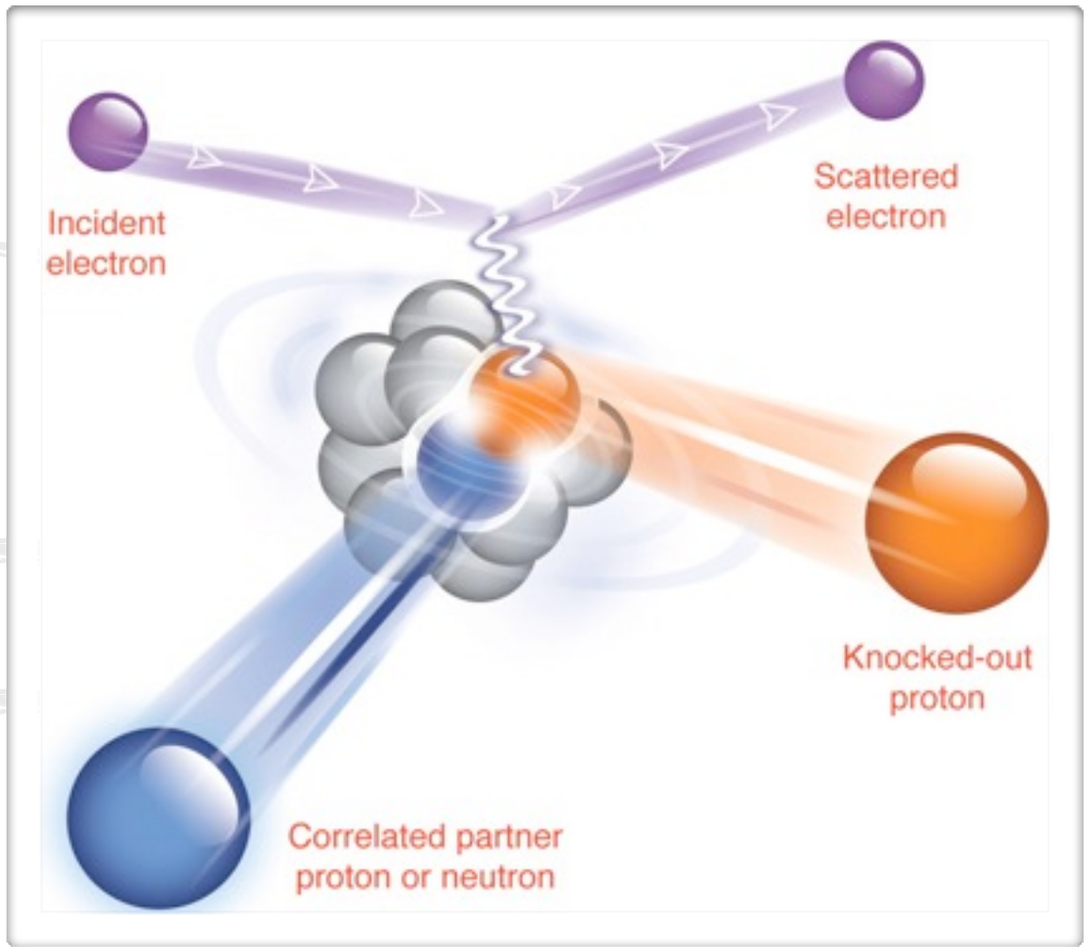
Impulse approximation

Nuclear effects covered by O. Benhar

- Assume interaction involves only one nucleon
  - λ>1 fm for Q^2<1(GeV/c)^2
- Neutrino experiments assume quasi-free interactions
  - Are nucleons actually quasi-free? If not, could we tell?
- Can low Q^2 region be described by impulse approximation?





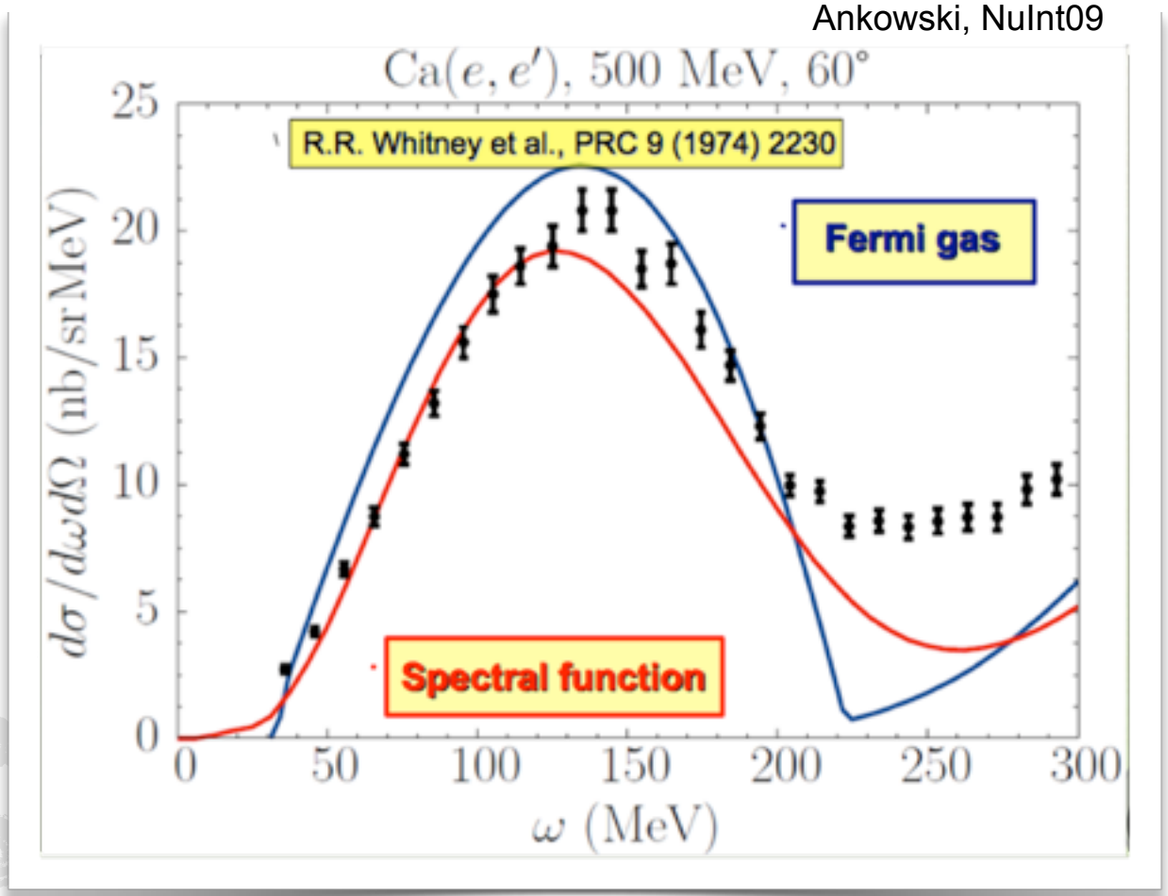
Science Vol.320. no.5882, pp.1476

Nuclear Models

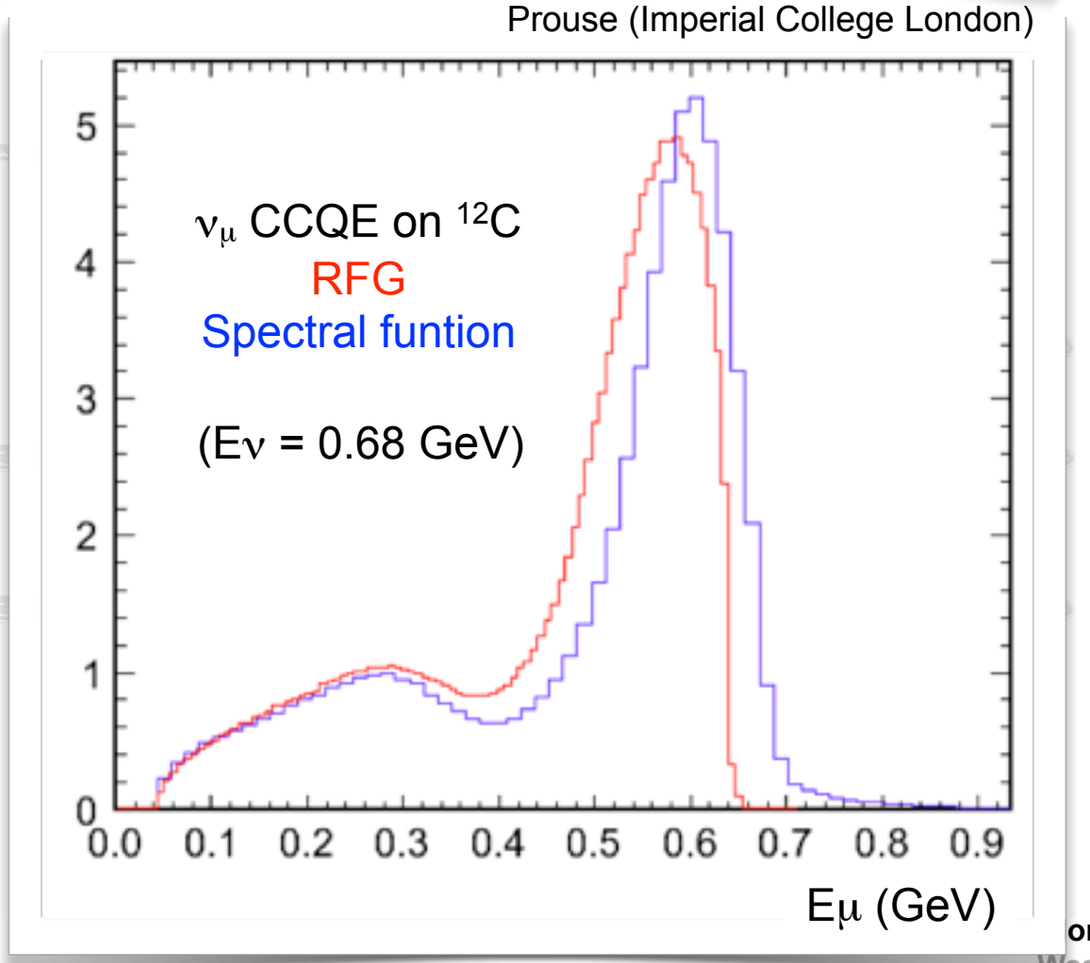
- Most experiments use RFG
- Most theorists prefer something else
- Effects neutrino energy reconstruction!

➡Impacts oscillation experiment!

Ankowski, NuInt09

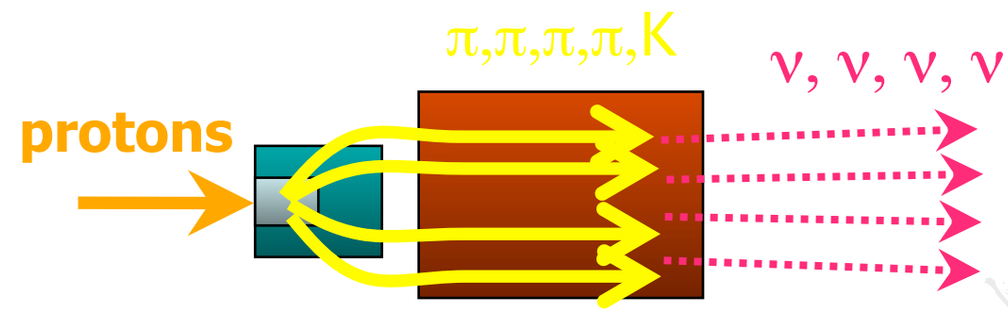


Prouse (Imperial College London)



Recent Measurements

Flux Predictions



Flux measurements covered by M. Bishai, S. Kopp

Beam	E_p (GeV)	target	$\langle \delta\Phi/\Phi \rangle$	E range	$\langle E_\nu \rangle$	Hadron prod.exp.
CERN WANF	450	Be	7%	3-100	24.3	SPY (CERN)
NuMI	120	C	~20%?	1-20	4	MIPP (FNAL)
BooNEs	8	Be	9%	0.2-3	0.8	HARP (CERN)

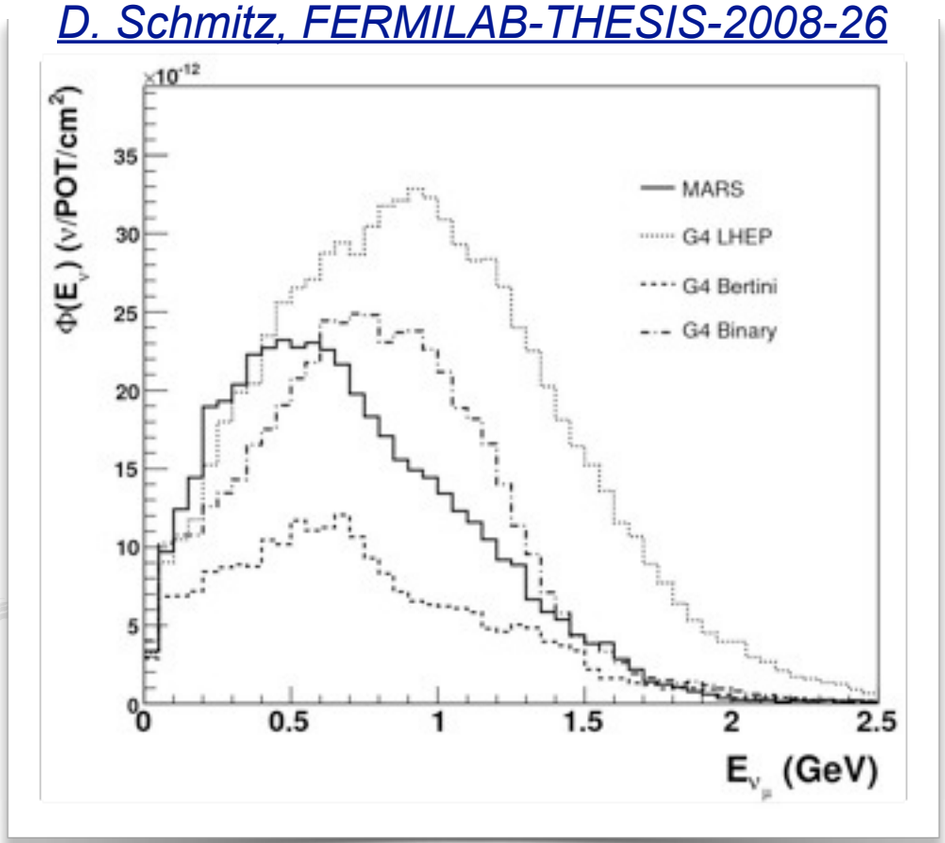
Further Reading:
NOMAD: NIMA 515 (2003) 800-828
NuMI: AIP Conf.Proc.967:49-52,2007
*MiniBooNE: Phys.Rev.D**79** 072002 (2009)*
General: Phys.Rept.439:101-159,2007

Hadron Production

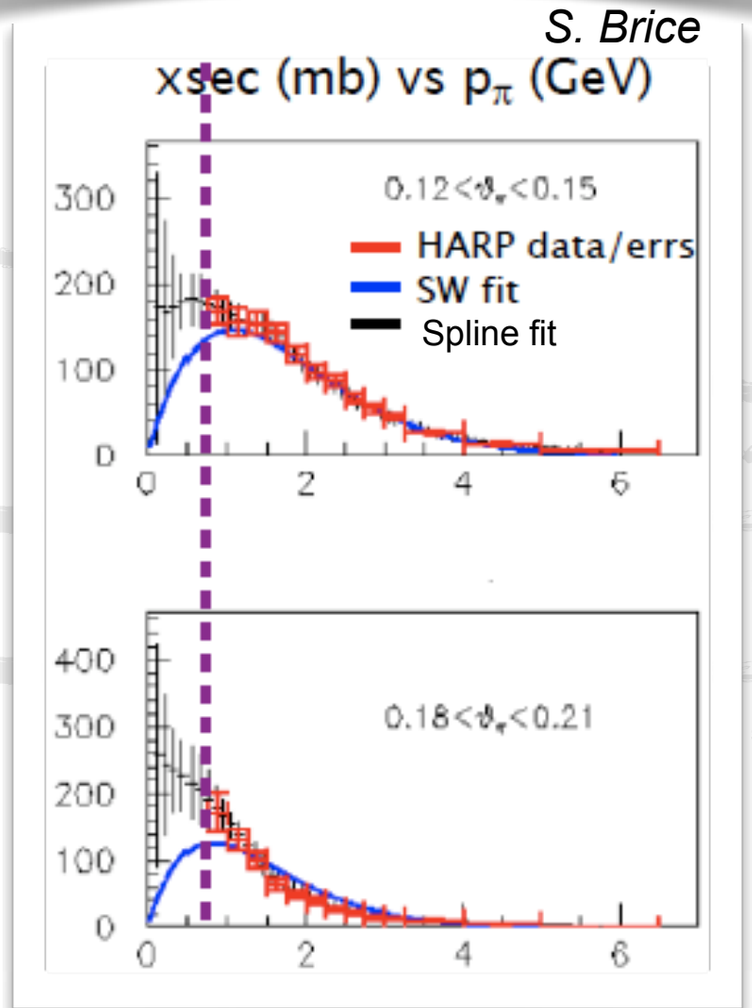
Measurements covered by A Blondel

- MiniBooNE example
- Range of MC flux predictions with different hadron models
  - 8 GeV protons on beryllium
- HARP pBe→π^+X data with MiniBooNE fits
  - Spline fit reduces integrated uncertainty from 17% to 9%
- Of course, hadron production isn't magic
  - Still need primary & secondary beam monitoring, etc.

D. Schmitz, FERMILAB-THESIS-2008-26



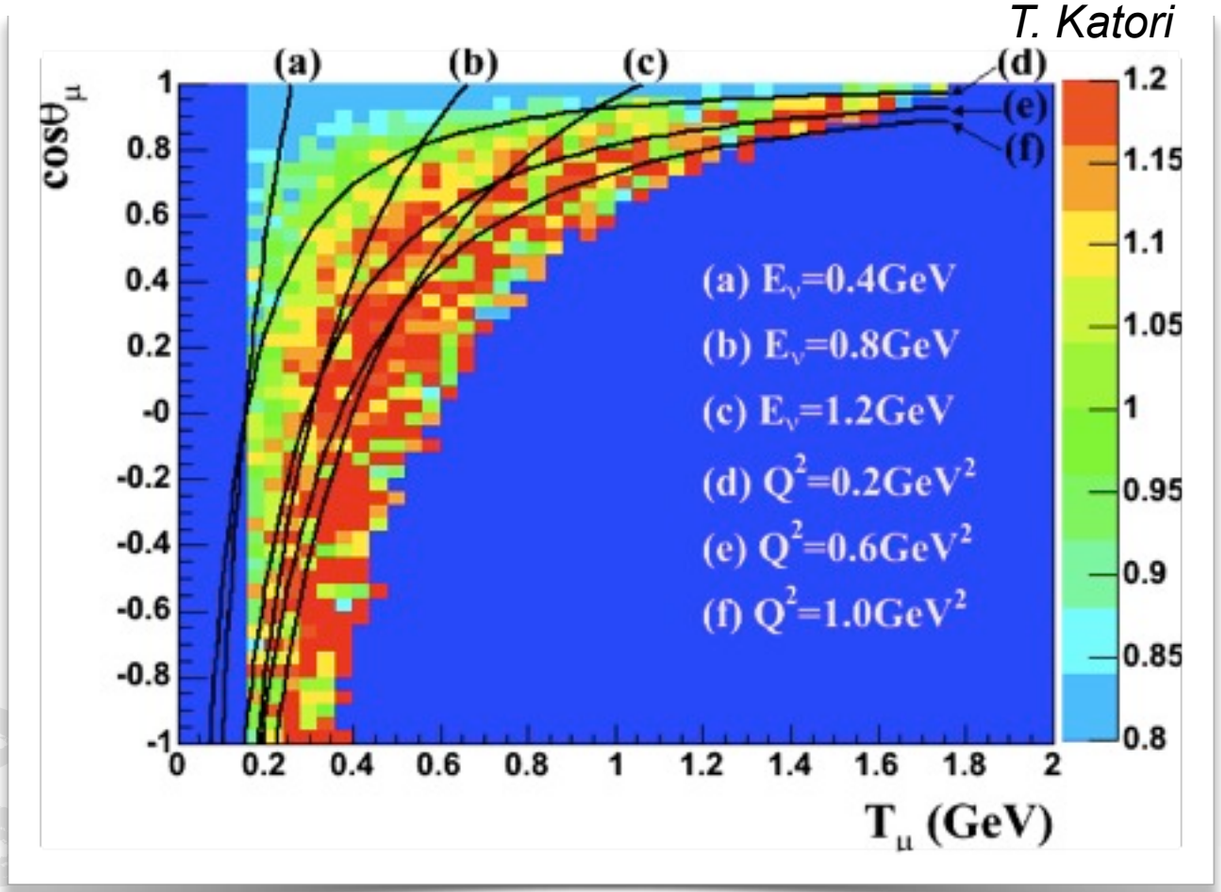
S. Brice



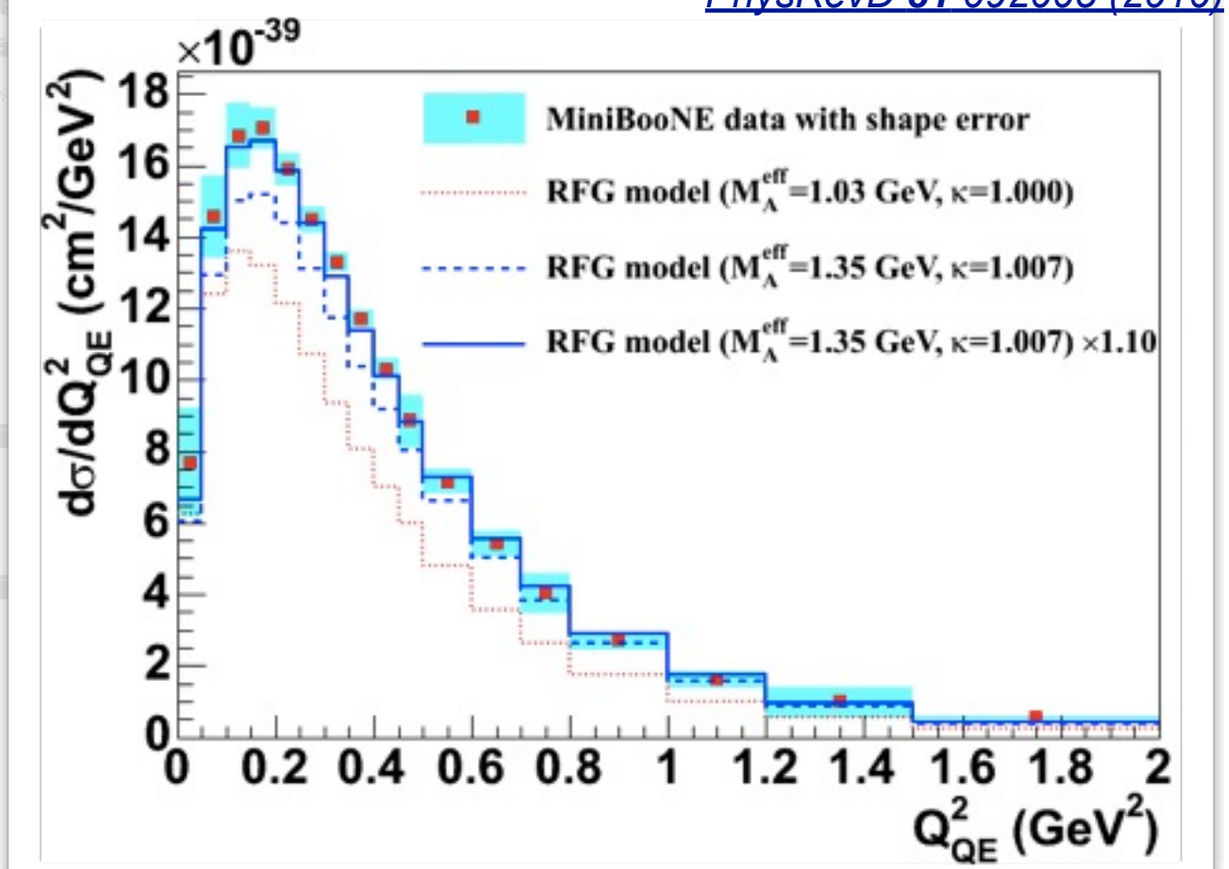
MiniBooNE

- Open volume Cherenkov detector
  - Carbon target
- CCQE selection: require clean μ ring with matched decay electron
  - 1.4E5 events after cuts!
- Q^2 shape fits for M_A
  - discrepancies at high & low Q^2!
  - M_A=1.35±0.17 GeV
- Low Q^2 deficit addressed with $CC\pi^+$ BG with data constraint
  - *M. Tzanov will discuss CCπ*
- First POT normalised cross-section!

T. Katori



PhysRevD **81** 092005 (2010)

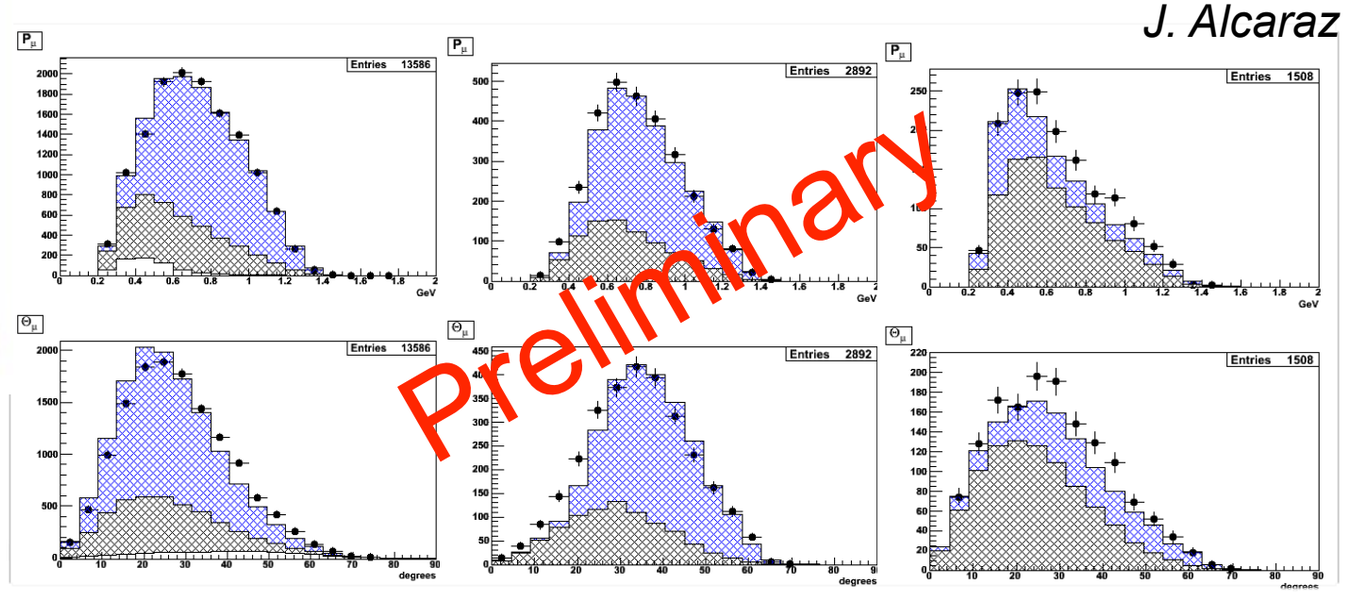


SciBooNE

- Fine-grained vertex detector
  - Carbon target
- Sensitivity to secondary tracks
  - simultaneously fit μ, μ+p, $\mu+\pi$ samples
  - Extract $\sigma_{QE}(E_\nu)$
- Also producing POT normalised cross-sections
- Similar discrepancies as seen by MiniBooNE

μ μ+p $\mu+\pi$

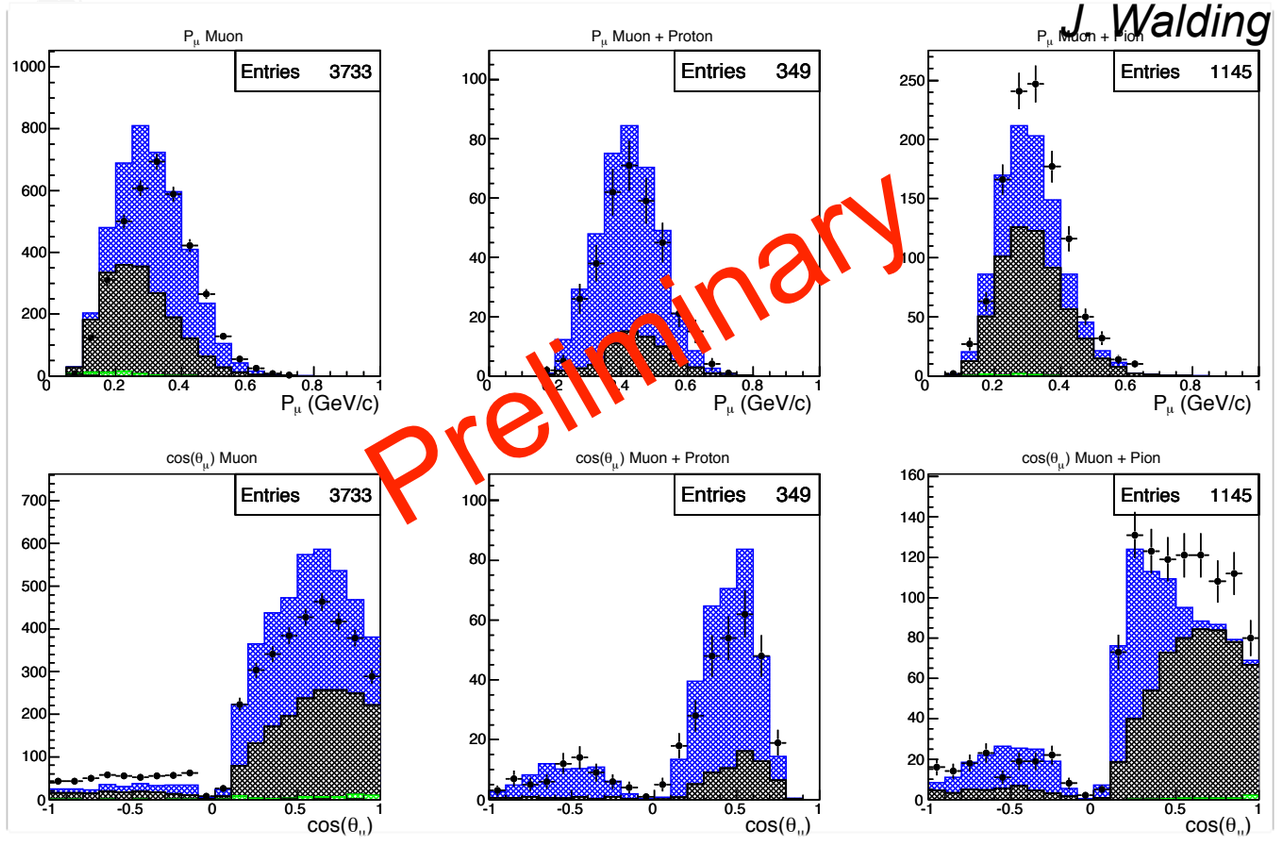
J. Alcaraz



CCQE signal ; Backgrounds

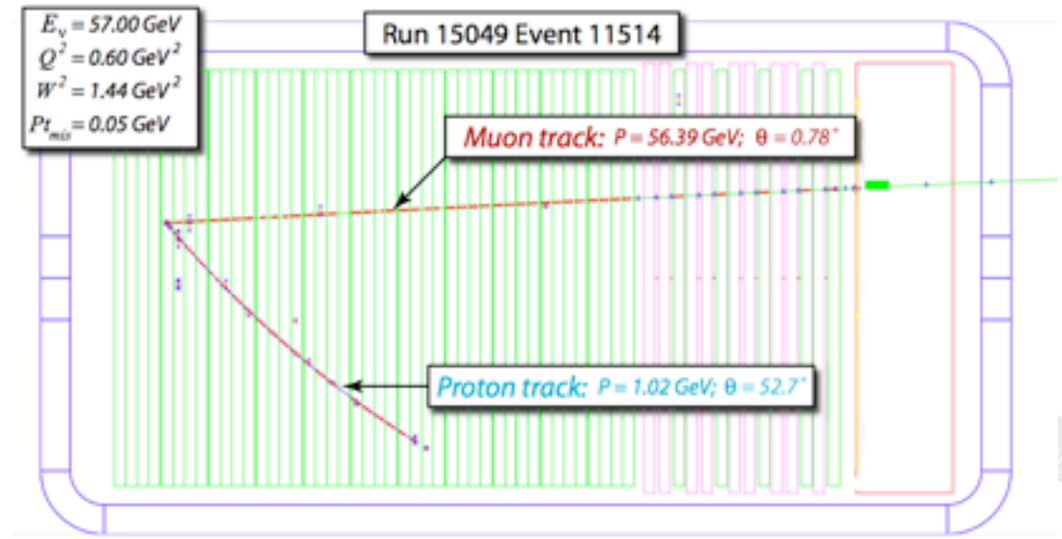
AIP Conf.Proc.1189:145-150,2009

J. Walding

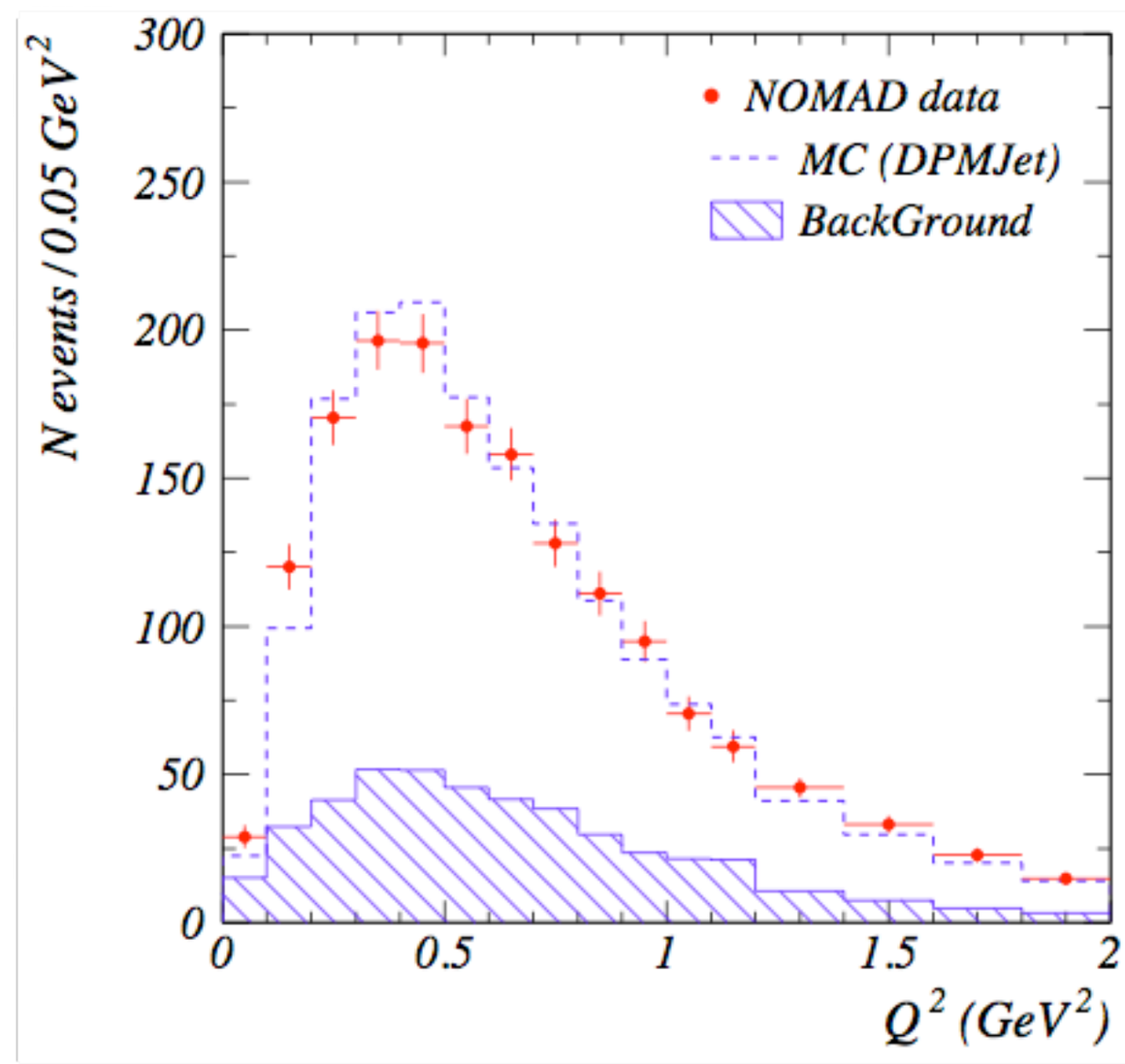


NOMAD

- Drift chambers in magnetic field
  - "Mainly carbon" target
- Select ν_μ and $\bar{\nu}_\mu$ CCQE events using strict PID and final state cuts
- Extract σ_{QE} with cross section ratios (DIS)
  - Use extracted σ_{QE} to infer value of M_A
  - Also fit Q^2 shape to check M_A
- M_A=1.05±0.06 GeV



Eur.Phys.J.C63:355-381,2009



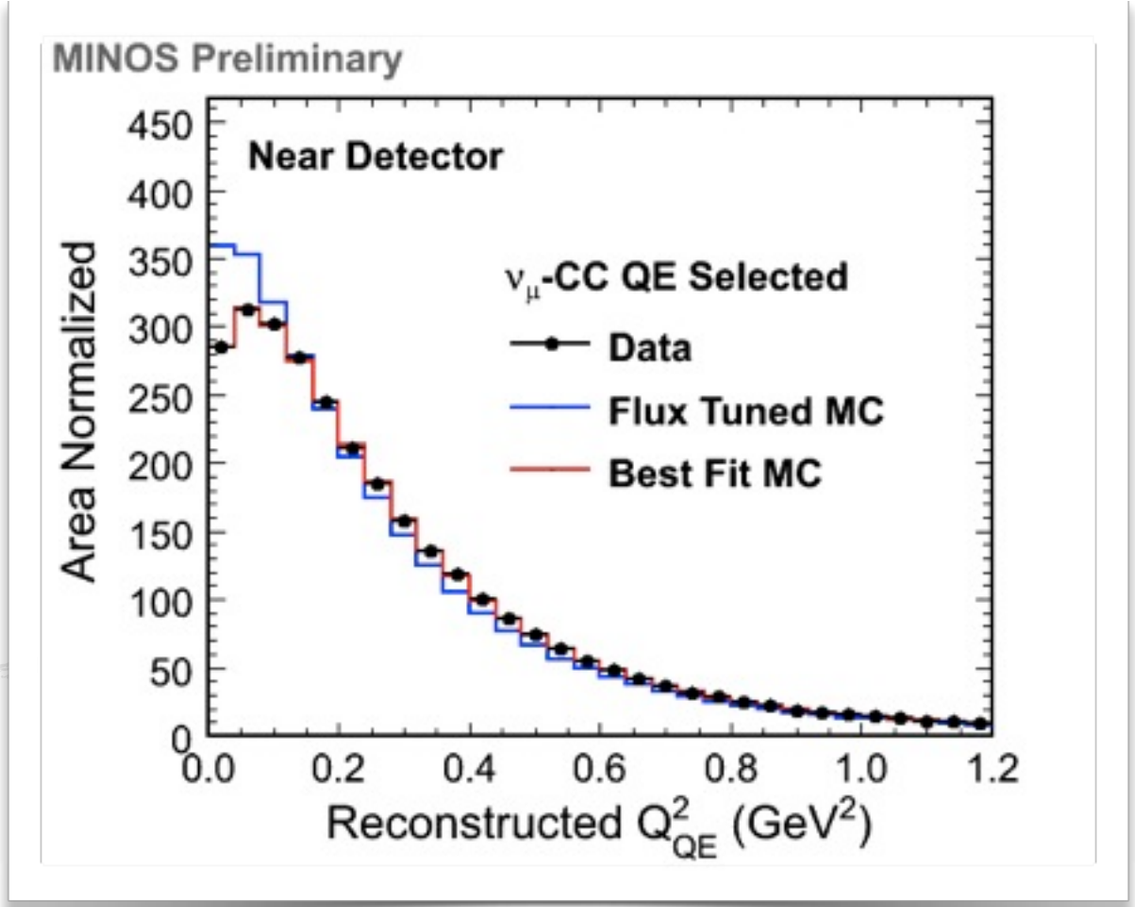
MINOS

- Iron calorimeter with magnetic field
  - Intense flux ⇒ high statistics
  - (Already published CC inclusive σ_νs [Phys.Rev.D 81, 072002 (2010)])

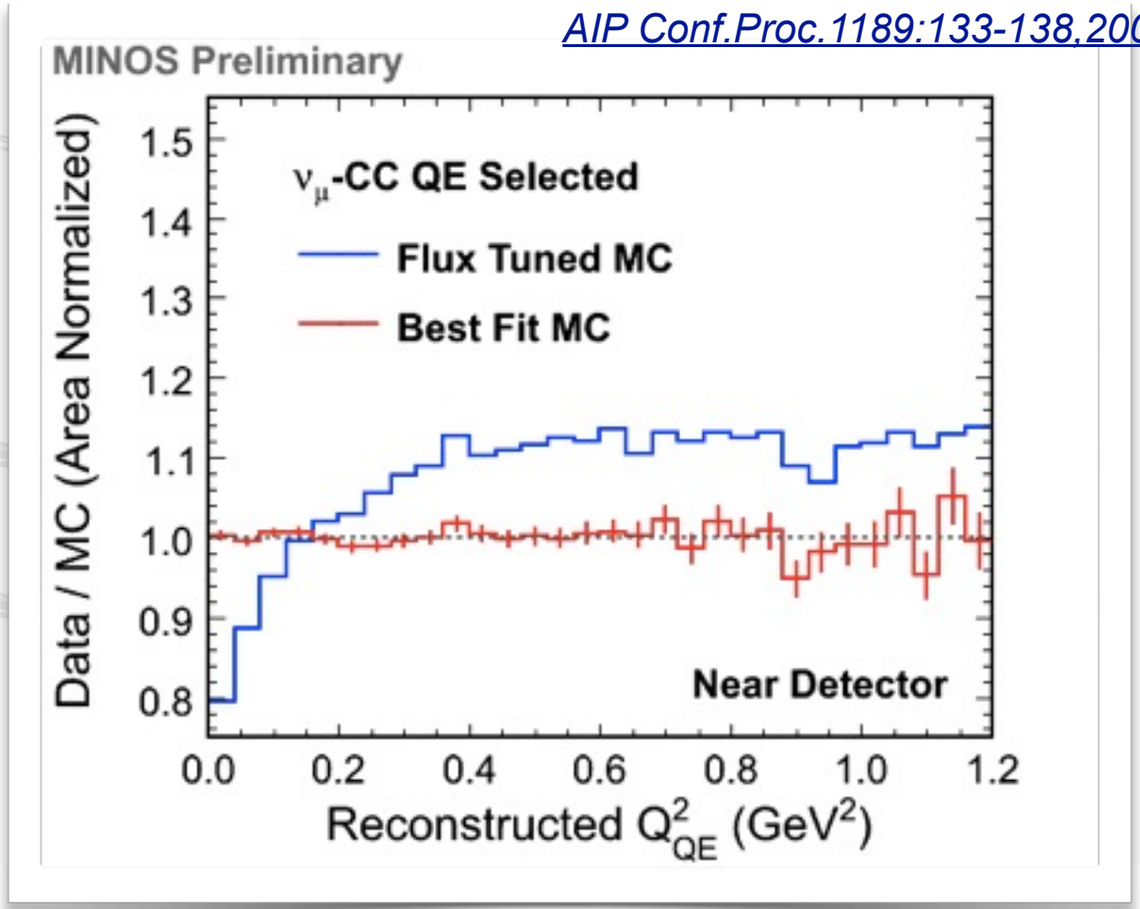
- Select ν_μ events with low hadronic shower energy

- Fit Q^2 distribution for M_A
  - M_A=1.19±0.17 GeV

- Non-dipole F_A fits ongoing.

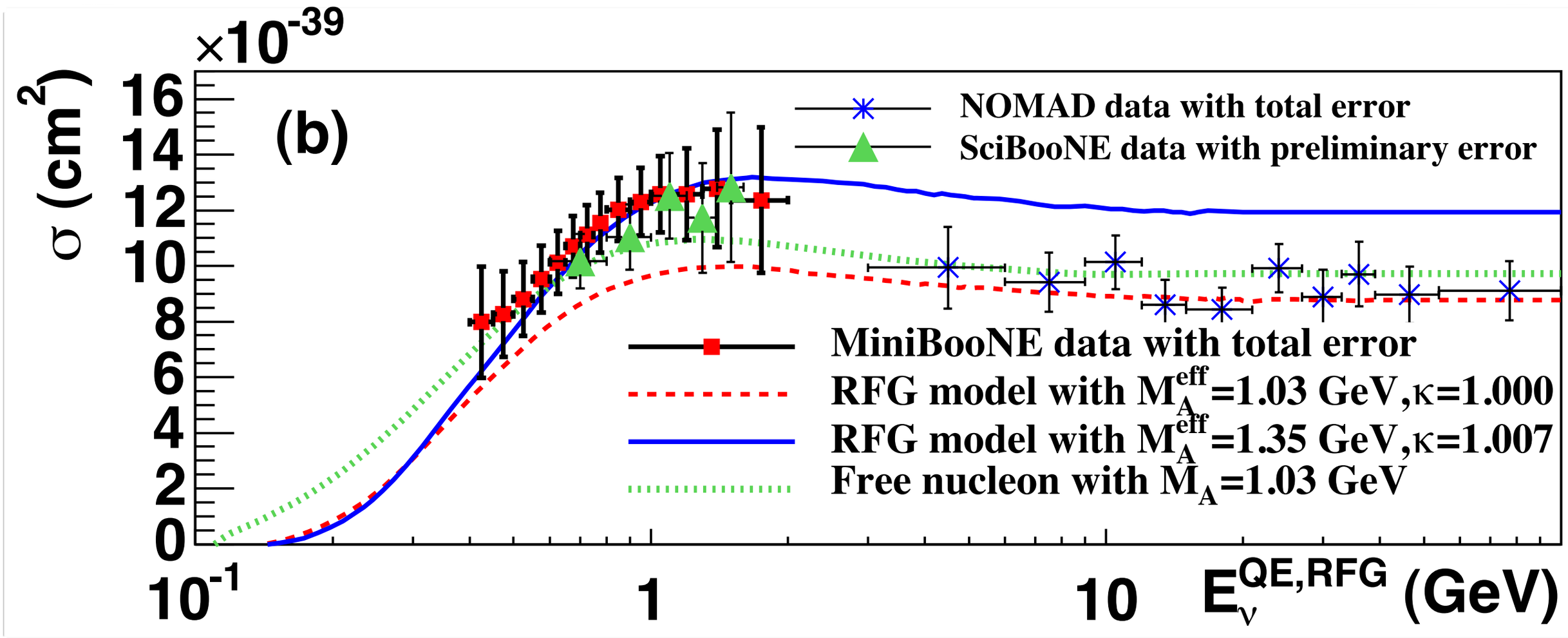


AIP Conf.Proc.1189:133-138,2009



CCQE comparisons

Plot courtesy of Teppei Katori (MIT)



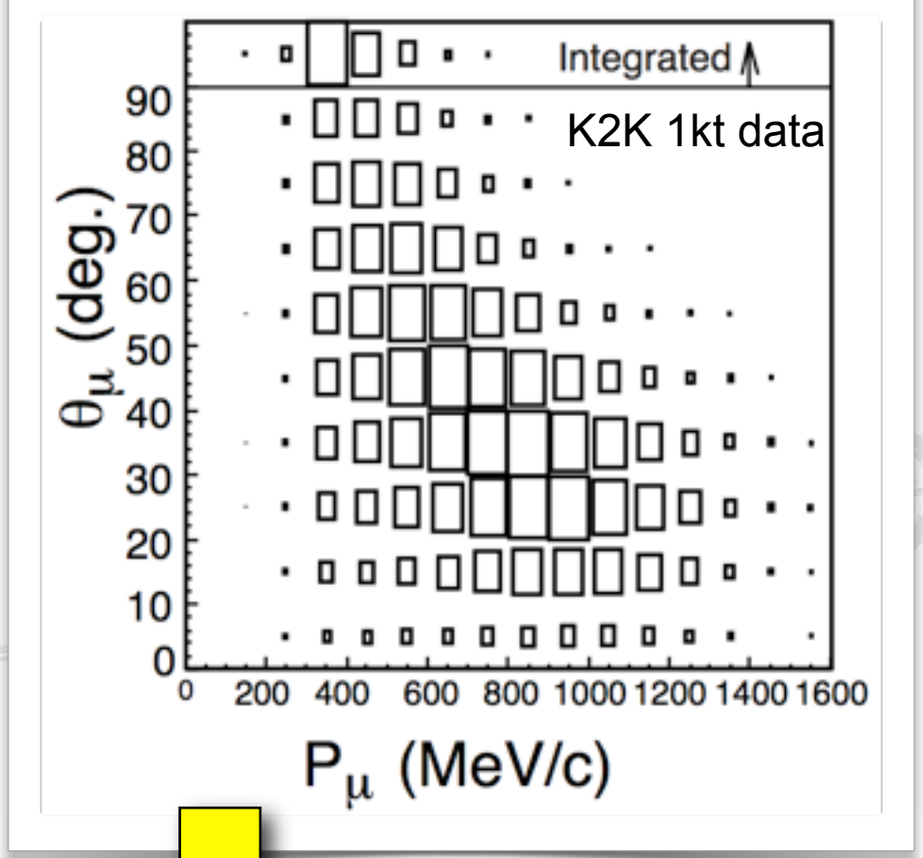
Putting these in context

What do we need?

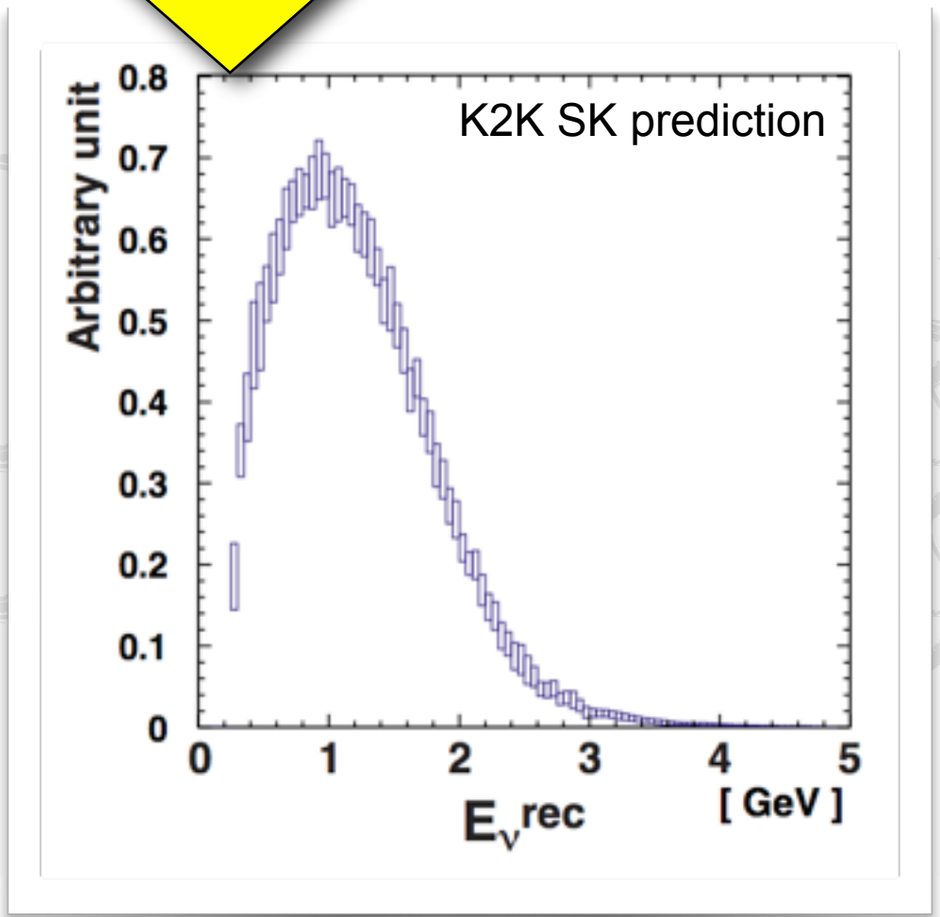
- Need to predict event rates and kinematics of final state particles
- Need to reconstruct neutrino energy accurately
- Need to accurately predict background contamination

➡Need precise neutrino-nucleus cross-sections

➡Need good models



*Phys.Rev.D **74** 072003 (2006)*



CCQE and Oscillations

- Current models cannot describe K2K, MiniBooNE, SciBooNE observations.
- Model dependence will always injected into data analysis
  - Energy, Q^2 reconstruction
  - Background subtraction
- Using current models will always give such uncertainties.
  - Need better models!

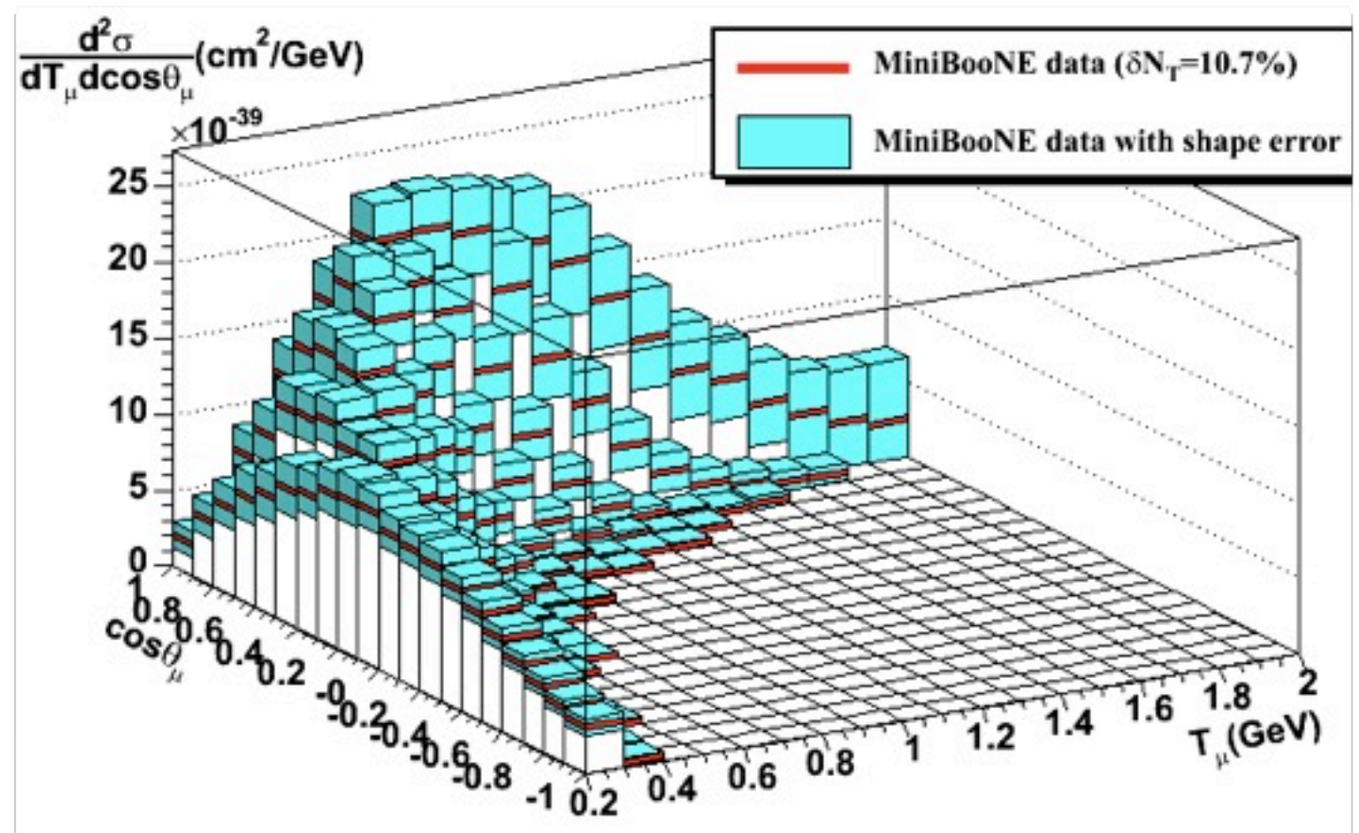
MiniBooNE ν_e appearance systematic uncertainties

Source	Error(%)
Flux from π+/μ+ decay	6.2
Flux from K+ decay	3.3
Flux from K0 decay	1.5
Target and beam models	2.8
ν-cross section	**12.3**
NC π0 yield	1.8
External interactions (“Dirt”)	0.8
Optical model	6.1
DAQ electronics model	7.5

Conrad & Louis, FNAL Wine and Cheese Apr 11 2007

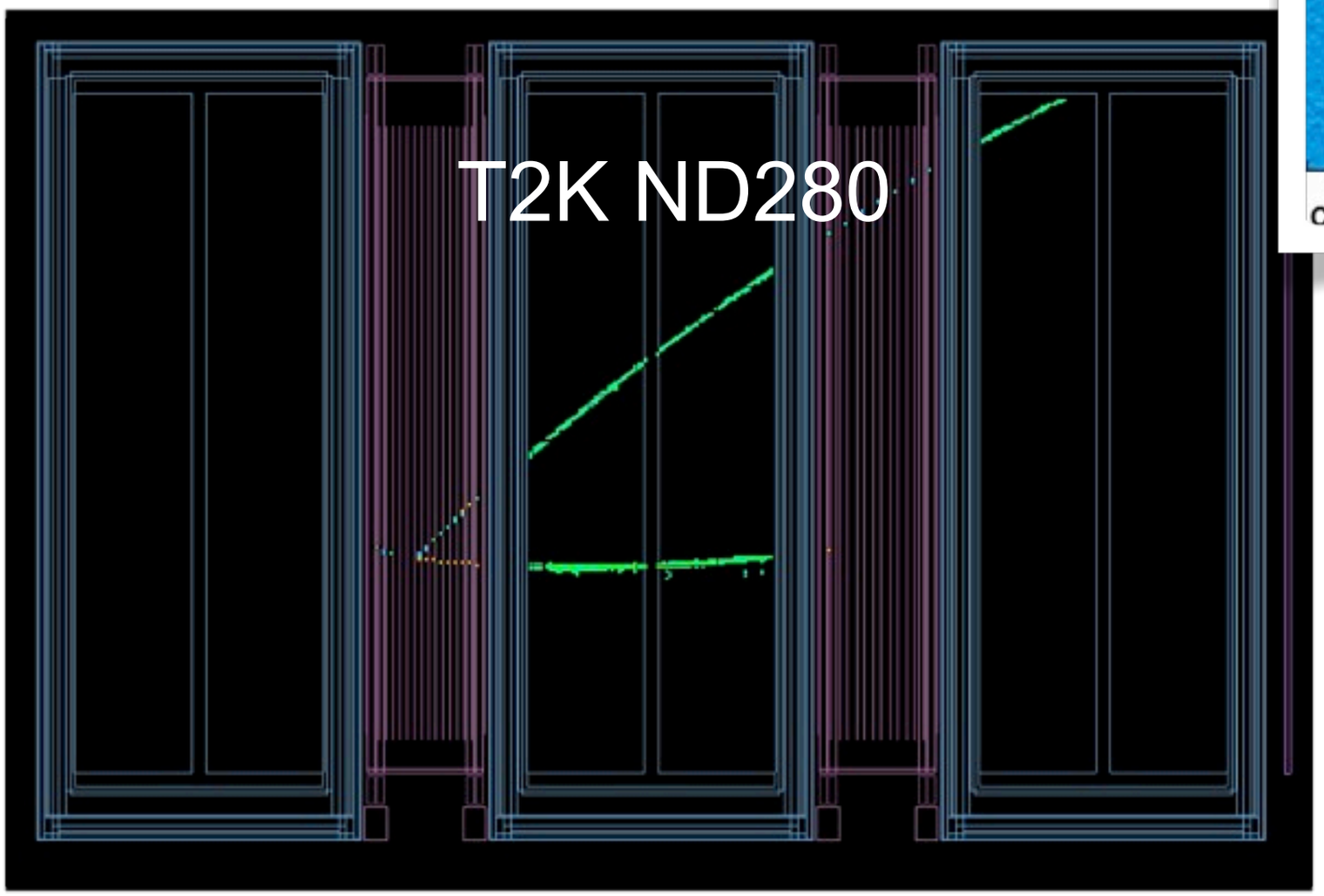
MiniBooNE's final ν_μ CCQE result

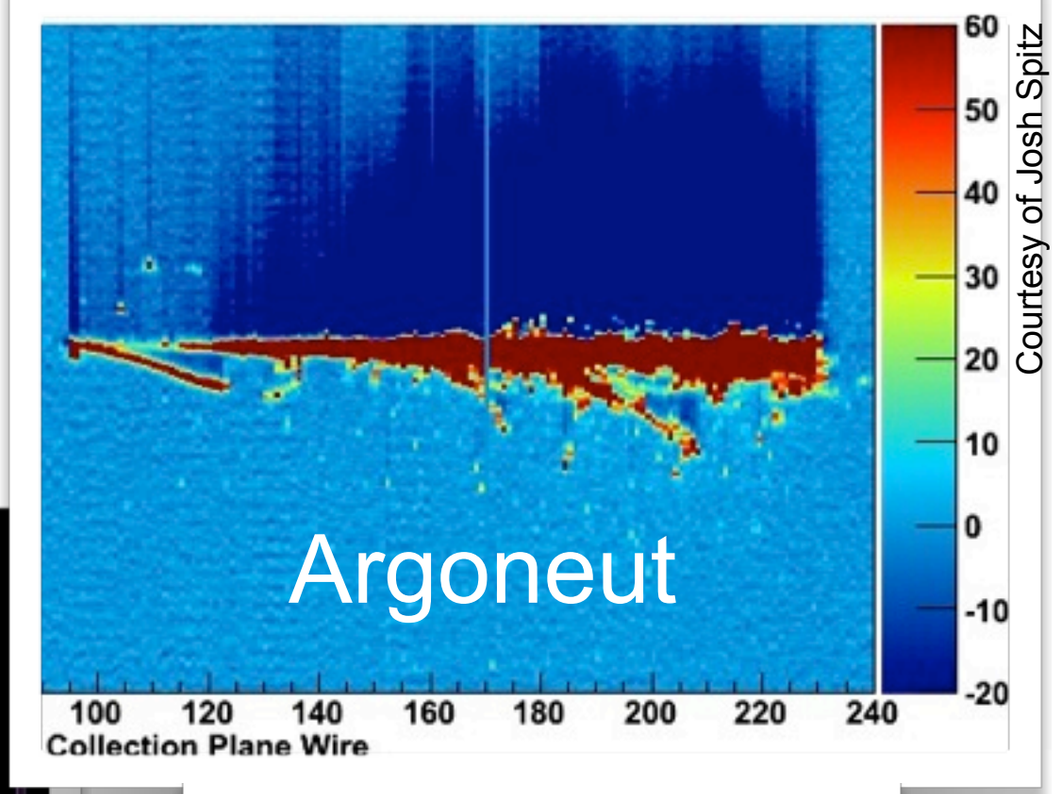
- Flux averaged double differential CCQE cross section
- Most complete, and least biased, information possible about the cross section based on the muon kinematics
  - Also being pursued for multi-particle final states
- Crucial input for theorists!



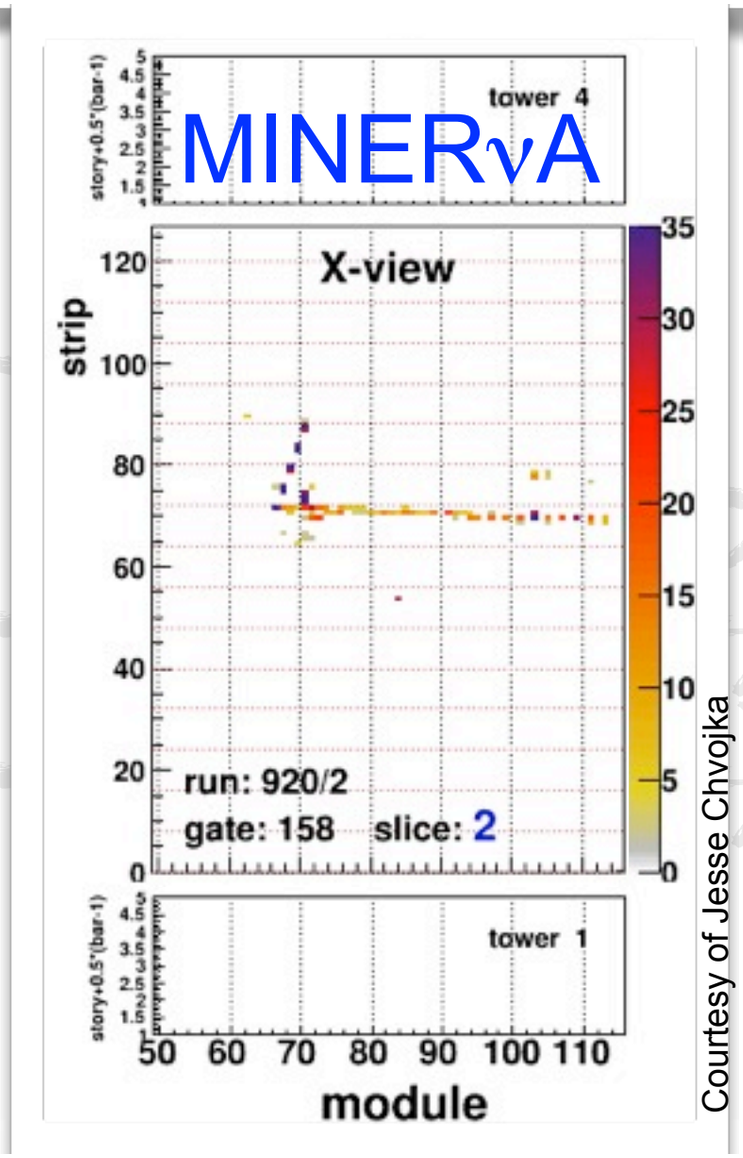
PhysRevD **81** 092005 (2010)

The Future





Courtesy of Josh Spitz

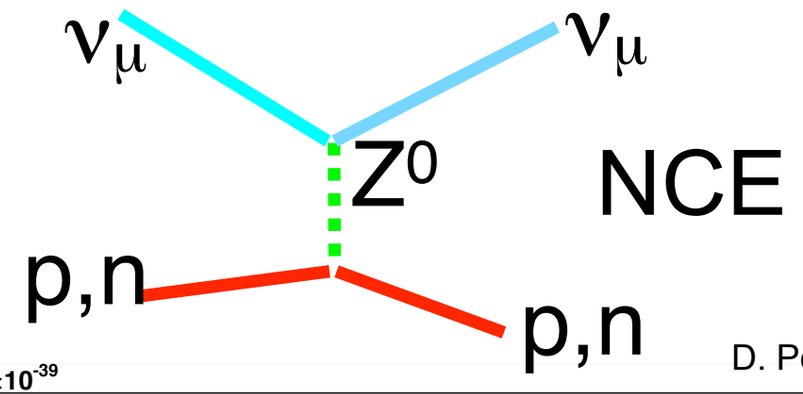


Courtesy of Jesse Chvojka

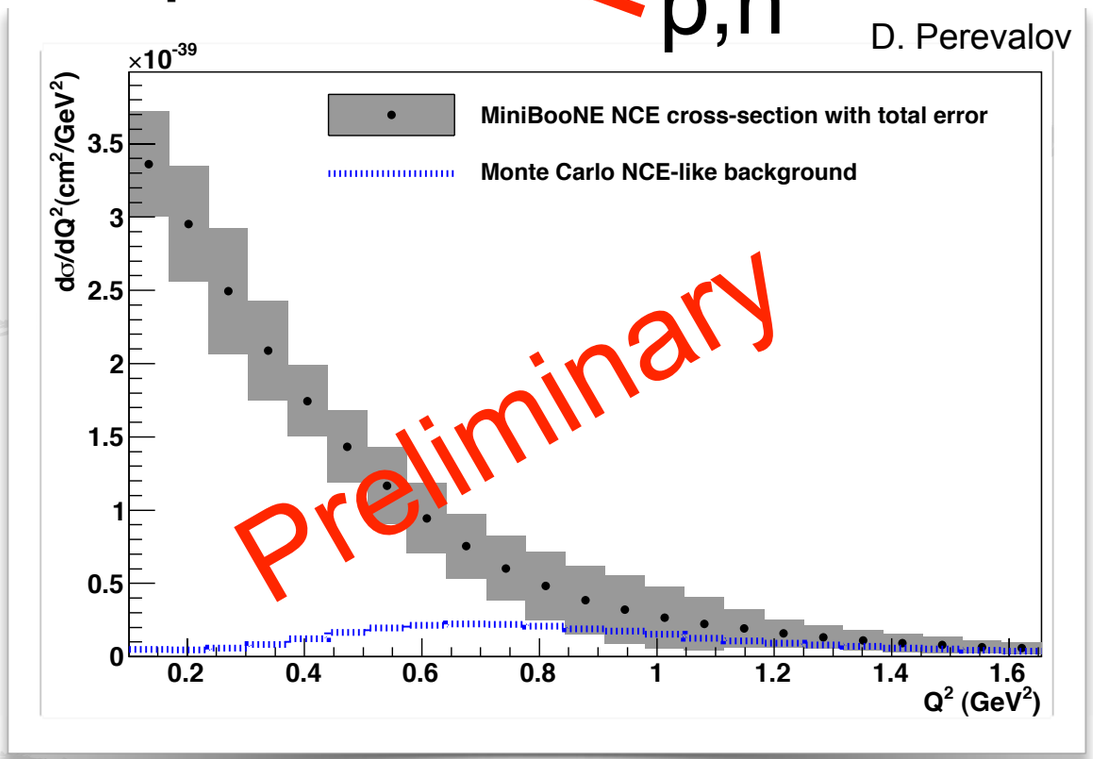
All data event displays - not MC!

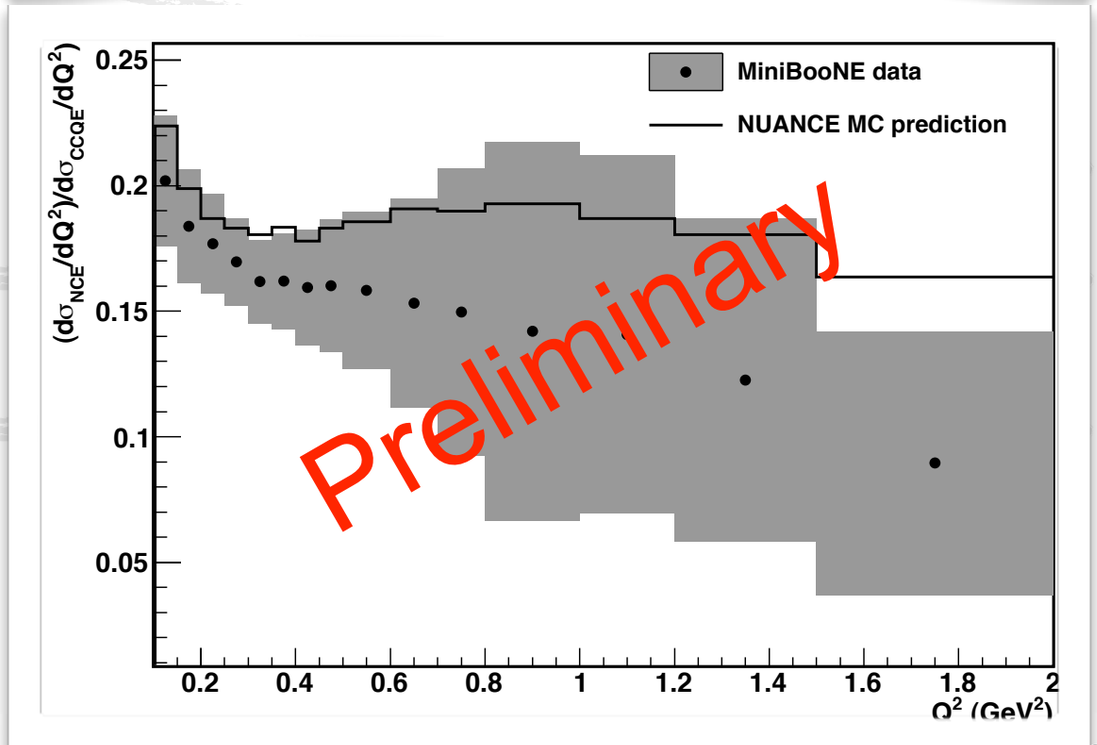
Quick mentions

MiniBooNE NC Elastic



- NCE event selection requires no decay electron, light patterns characteristic of protons
- Fit Q^2 distribution for M_A
  - 1.39±0.11 GeV
- Measured ratio of NC/CC in same detector with same flux
  - Gives access to Δs
    - Δs = -0.08±0.26
    - Highly correlated with M_A

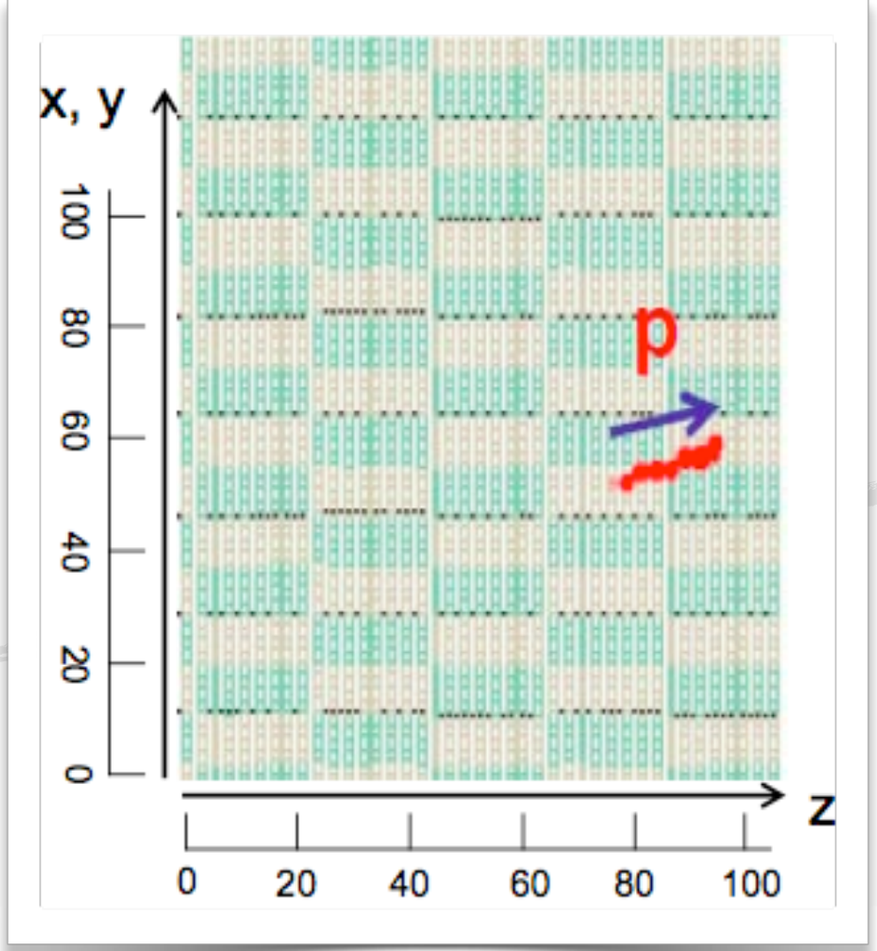


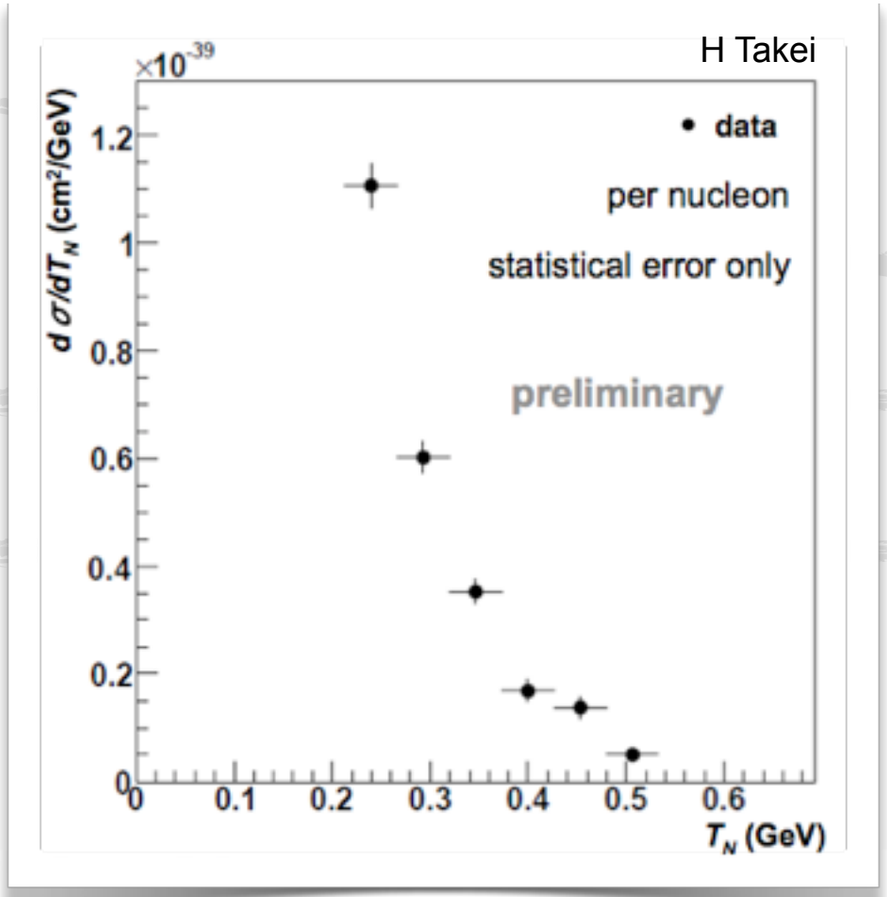


arXiv:1007.4730[hep-ex]

SciBooNE NC Elastic

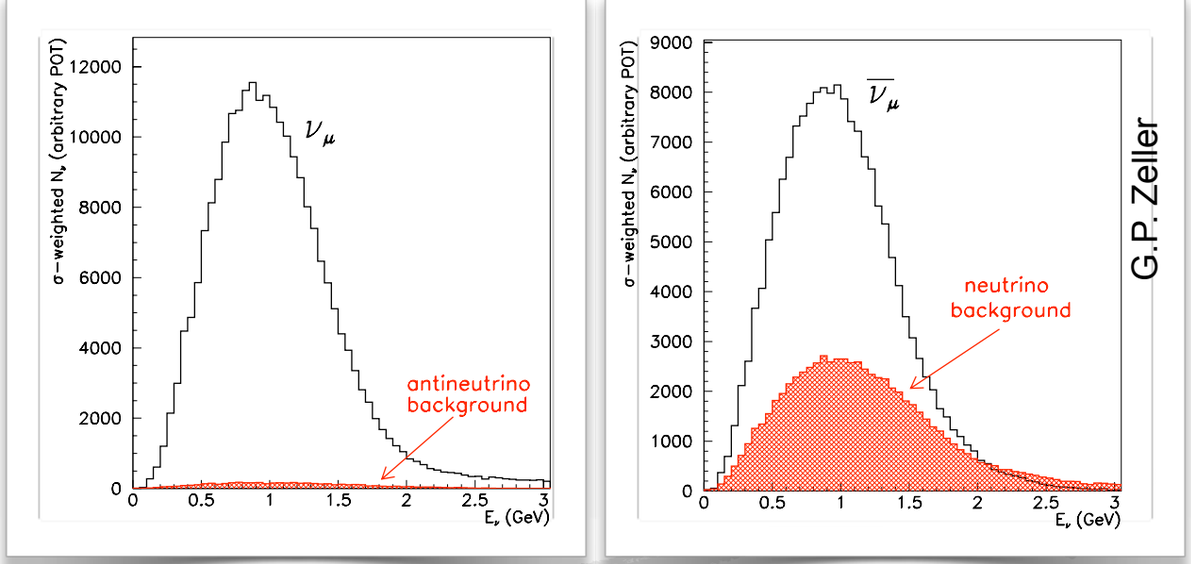
- Search for tracks with high ionisation
  - Recoil proton/neutron tracks
- Measure Q^2 directly from recoil nucleon
  - Different model dependence
  - Comparison to CCQE would be very valuable
- Analysis ongoing...





H. Takei, FERMILAB-THESIS-2009-19

MiniBooNE Antineutrinos

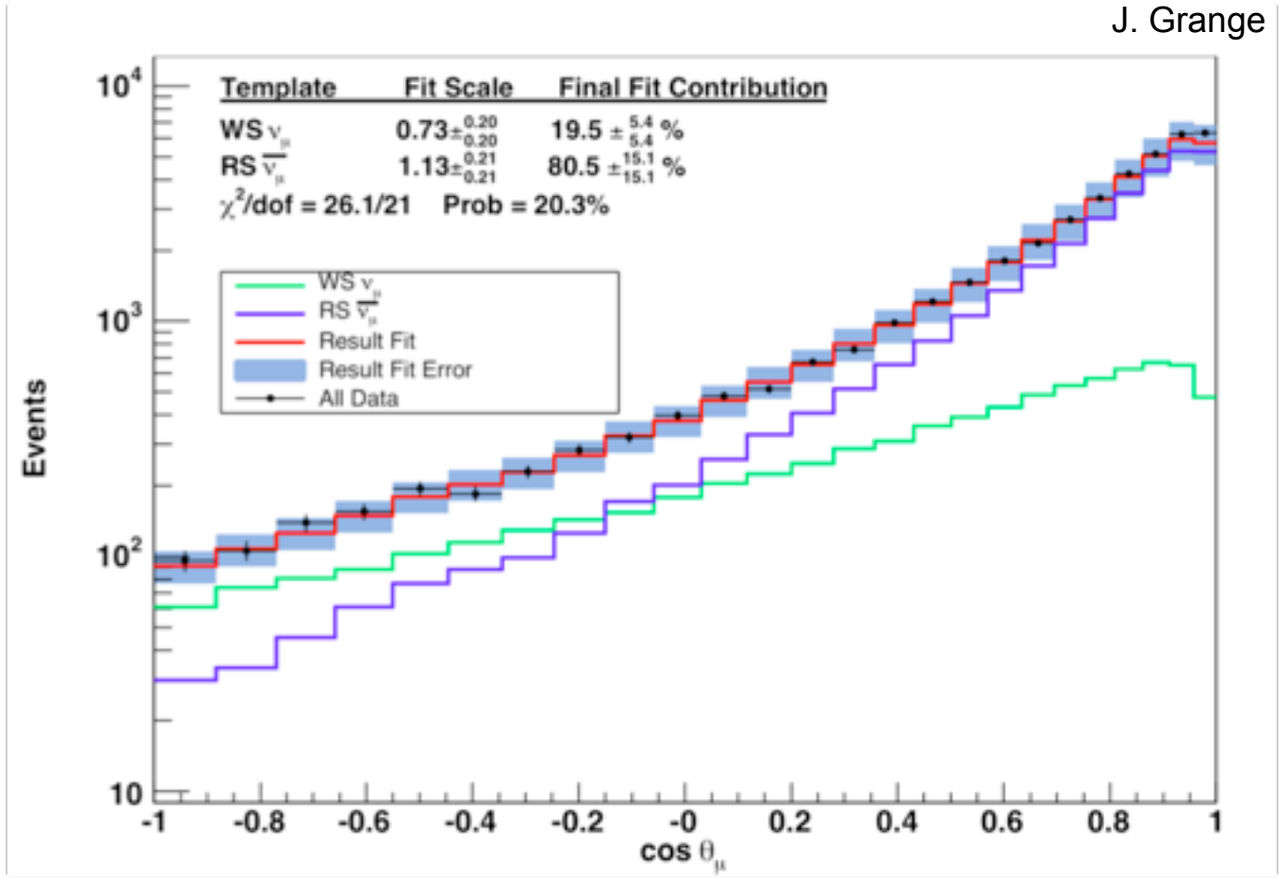


- Very few measurements of nubar CCQE near 1 GeV

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

+ for ν, - for $\bar{\nu}$

- Horn focussing leads to wrong sign (WS) backgrounds
  - neutrinos in antineutrino mode
- MiniBooNE has sophisticated analysis to constrain WS BGs
  - Different angular distributions
- *Poster by Joe Grange*



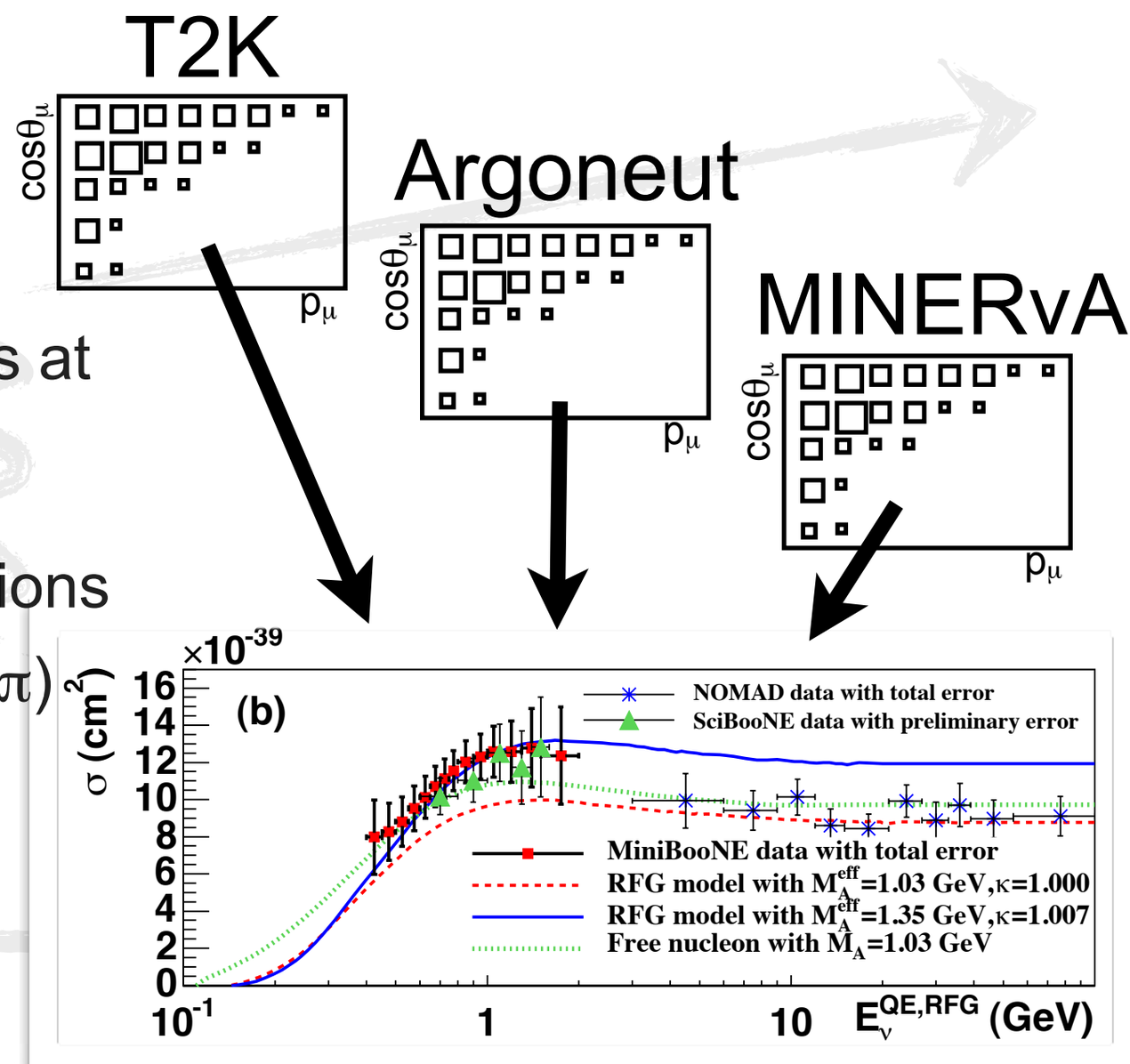
Wrap up

Summary of measurements

- Recent measurements of ν_μ CCQE scattering have much higher statistics and better controlled flux systematics than past.
- In 1 GeV region, experiments on nuclear targets show increased cross-section, harder Q^2 spectrum, and large suppression at low Q^2 (<0.2 GeV^2).
  - Higher M_A? Non-dipole F_A? Nuclear model? Impulse approximation? Many body effects?
- At higher energy, world average model with RFG seems to work fine.

Growing Consensus

- We need broad coverage
  - Model independent measurements at many energies, nuclei
- Move away from process cross-sections
  - σ(CCQE), σ(CC res π), σ(CC coh π)
- Instead measure final state particle cross-sections
  - σ(CC), $\sigma(\mu)$, $\sigma(\mu+p)$, $\sigma(\mu+\pi)$
    - (CC Inclusive measurements offer most robust confrontation of theory and experiment)



Same goes for NC...

What does model dependence mean?

- Distinguish between σ model and detector model
  - Any MC-derived quantity is, of course, model-dependent
- Restricting unsmearing, BG corrections, and efficiencies to detector MC quantities, not cross section processes is probably the best we can do
- This is why we push the idea of final state particle cross sections over process measurements

Absolute flux-averaged differential cross section formula

$$\sigma_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\varepsilon_i (\Phi T)}$$

U_{ij} :unsmearing matrix

d_j :data vector

b_j :predicted background

ε_i :efficiency

T :integrated target number

Φ :integrated ν-flux

Best way to present data?

- To get better models, we need theorists to use our data effectively
  - It's in our best interest to make that as easy as possible
- Typically, our goal is to produce cross section measurements
  - We use the detector MC to model the efficiency and smearing,
  - We then correct those effects with unfolding matrices and efficiency functions

Best way to present data?

- We could alternatively provide theorists with the tools to analyze our data the way that we do
  - For example, when fitting for M_A, we use the detector MC to make fake data sets, and modify the fake data sets until the MC matches data
    - For example, numbers of events in bins of p_μ, θ_μ
  - We obviously don't want to give away the detector MC, but we could provide efficiency functions (including smearing) with systematics and our measured data
  - The efficiency function could be applied to inclusive fake data samples, allowing theorists to perform analysis the way we do
    - Obviously need to provide fluxes, too, but we already do that.

Conclusions

- We observe discrepancies between CCQE data and models, & between experiments.
- Flux constraints are crucial for cross section measurements.
- Need model independent measurements so that new models can be tested.
  - MiniBooNE has published world's first absolutely normalised double differential cross section!
  - New measurements from Fermilab can and should provide the needed data for better models.

Searches for θ_{13} with accelerators depend on this.

Advertisement

मसूरी

NuInt11 will be held in March 2011 (Mar 12-16?) in Mussoorie India

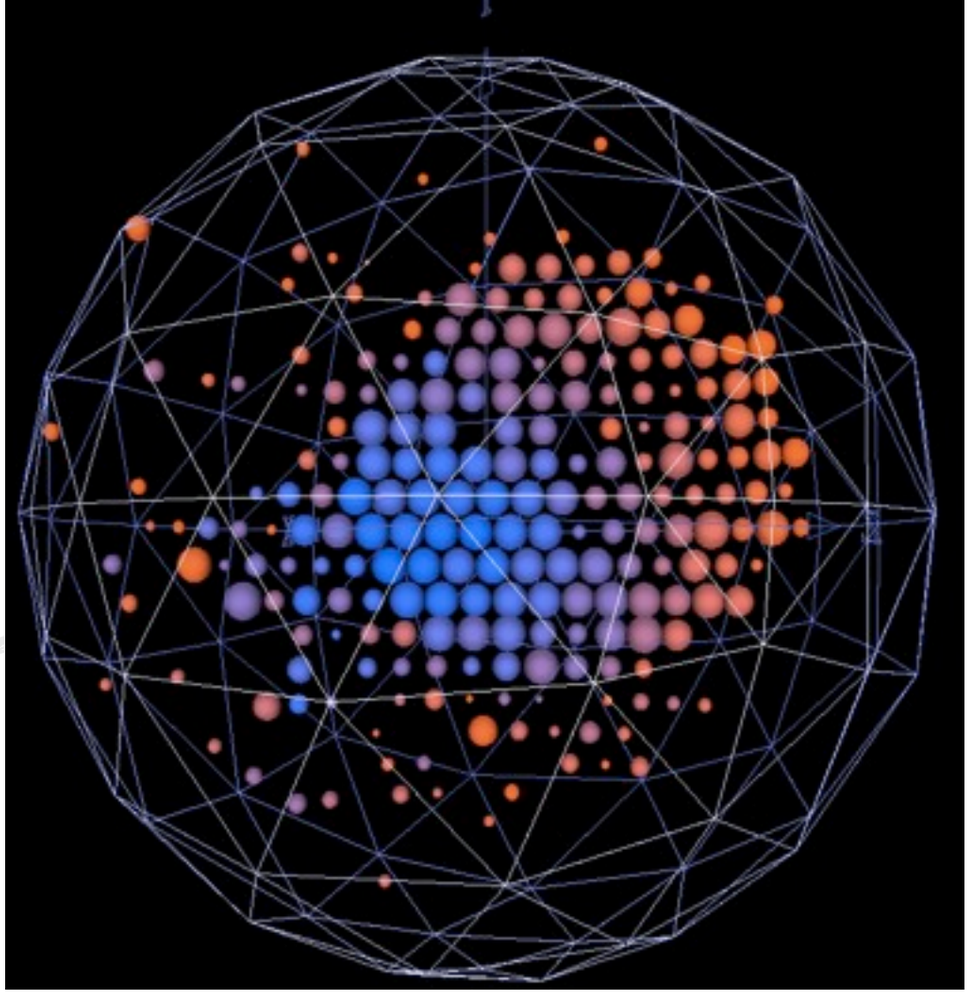
भारत गणराज्य

Aligarh Muslim University

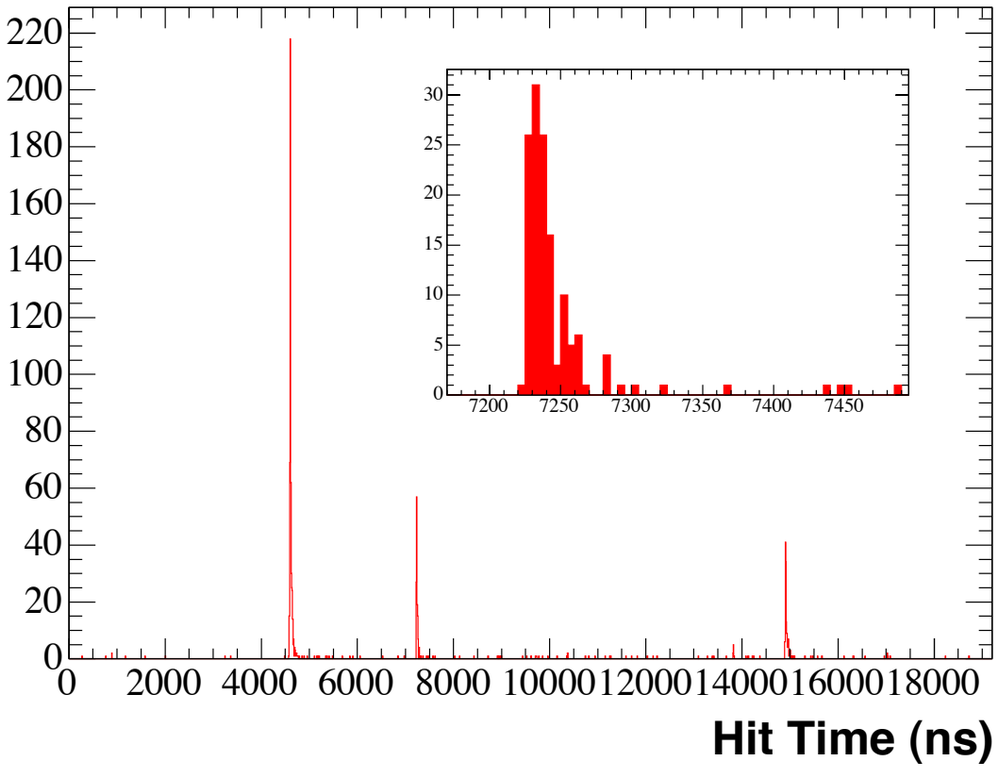
Thanks!

Backups

MiniBooNE Events



- PMT hits seprated into time clusters (“subevents”)
- Reconstruct muon Cherenkov ring
  - First subevent
- Find decay electrons
  - Late subevents
- CCQE requires 1 late subevent



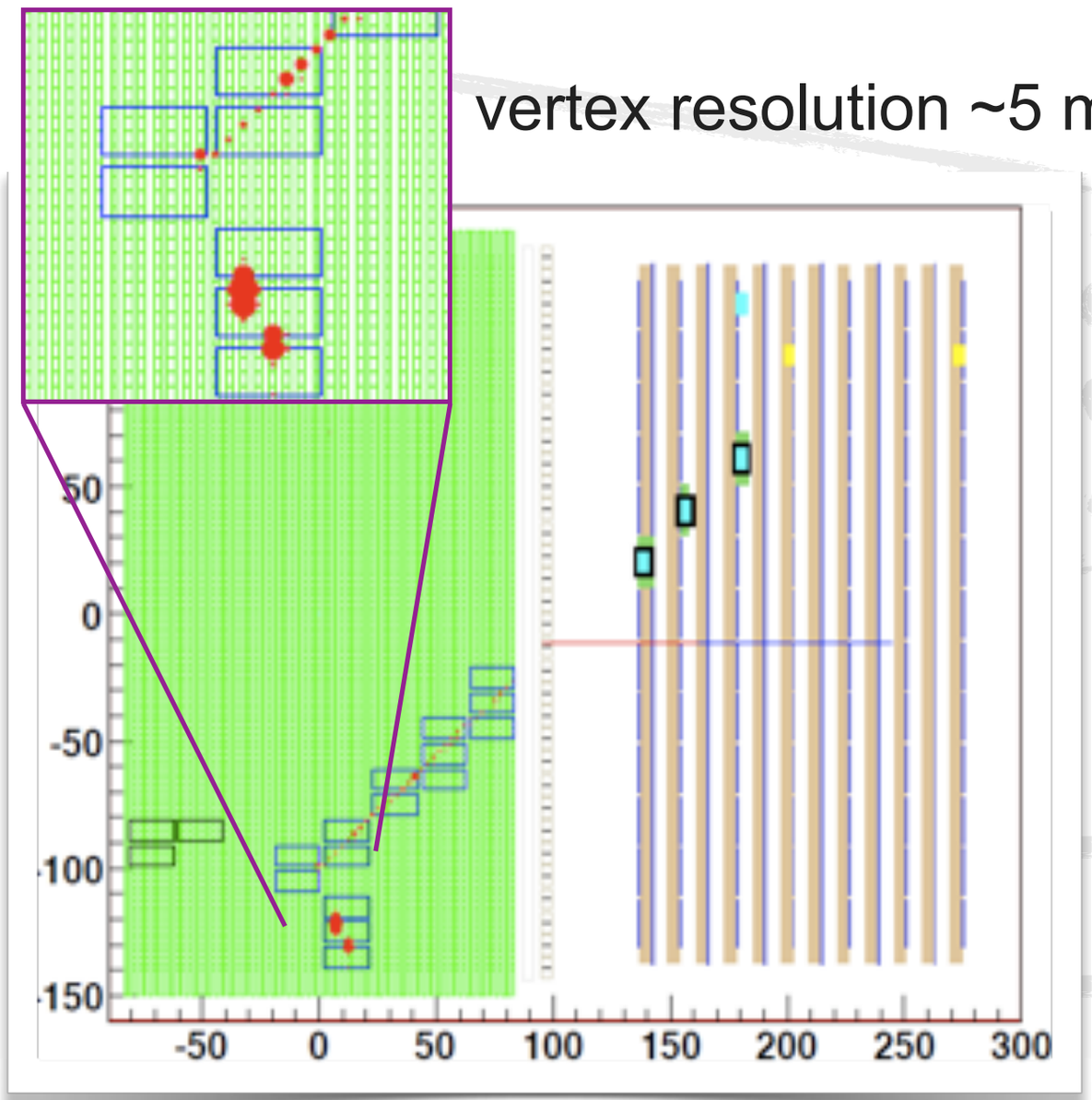
27% efficiency
77% purity
146,070 events
with 5.58E20POT

Neutrino event displays

Real SciBooNE Data

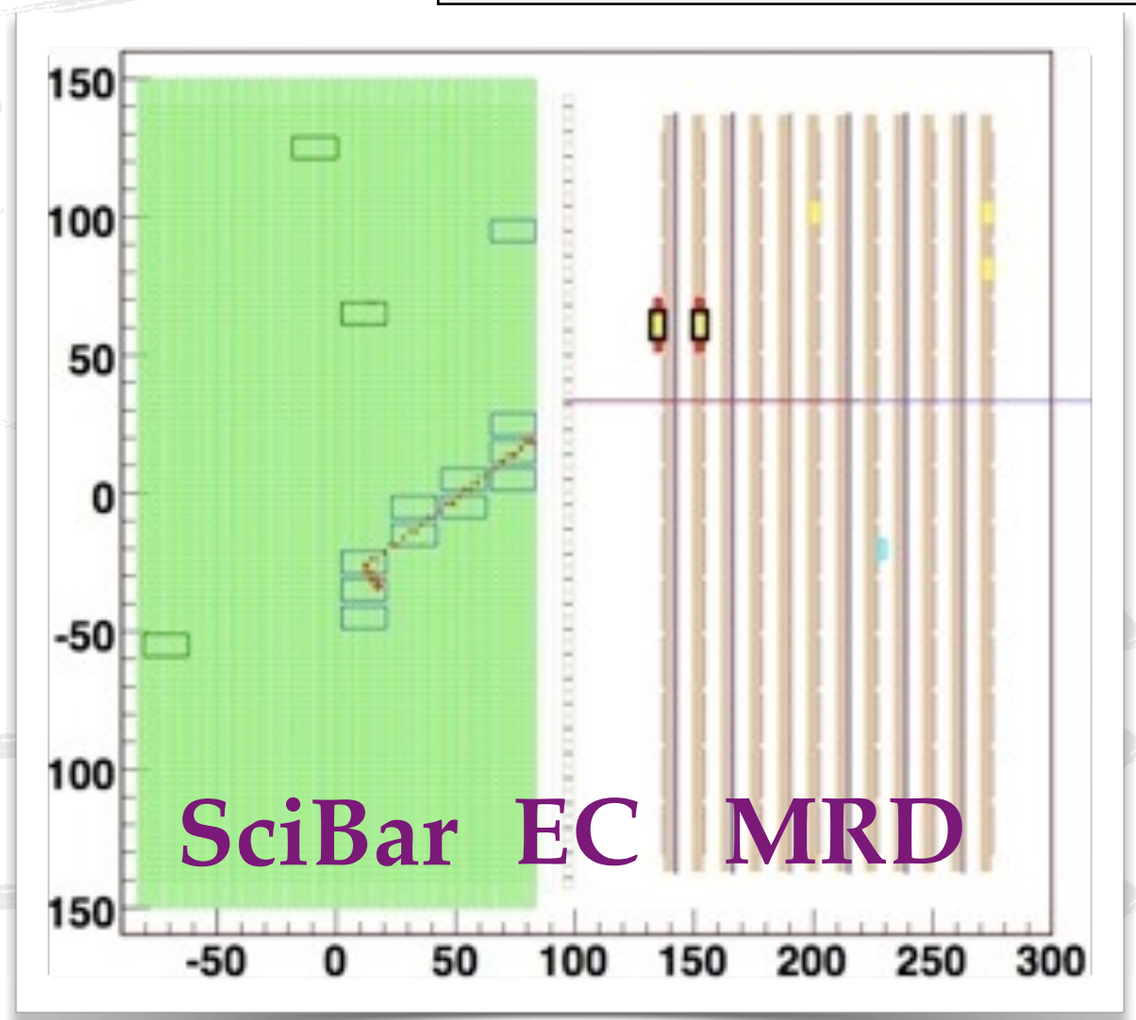
ADC hits (area ∝ charge)
TDC hits (32ch "OR")

vertex resolution ~5 mm



anti-ν_μ CC-QE candidate

($\bar{\nu}_\mu + p \rightarrow \mu + n$)

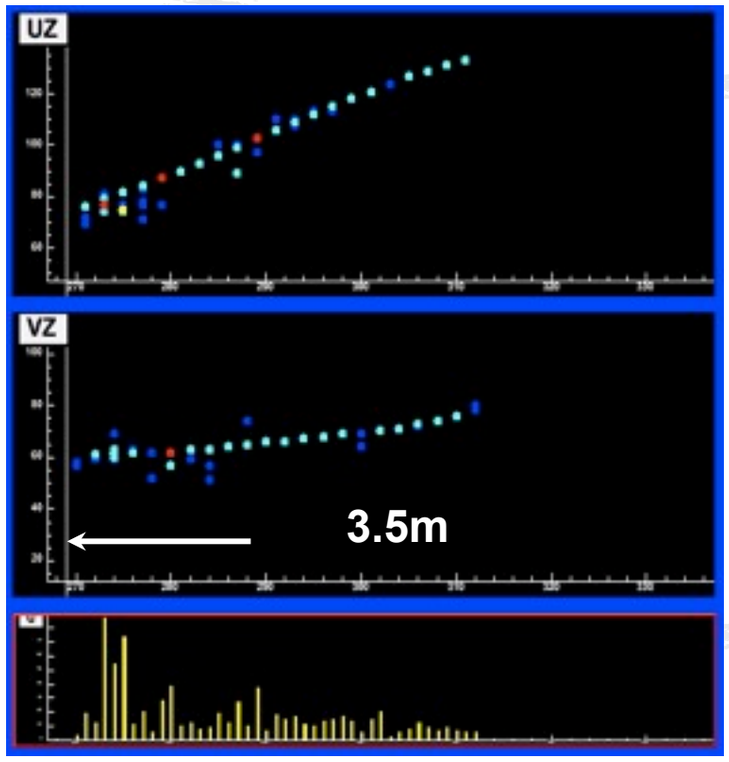


ν_μ CC-QE candidate

($\nu_\mu + n \rightarrow \mu + p$)

Events in the MINOS Detectors

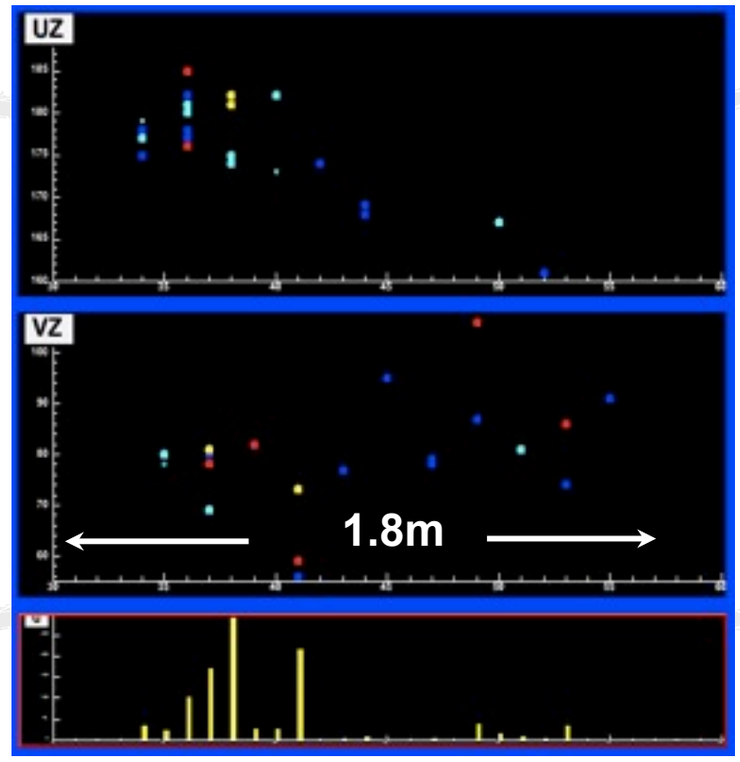
ν_μ CC Event



Long muon track with hadronic activity at the vertex.

What we look for in the muon neutrino / anti-neutrino analyses.

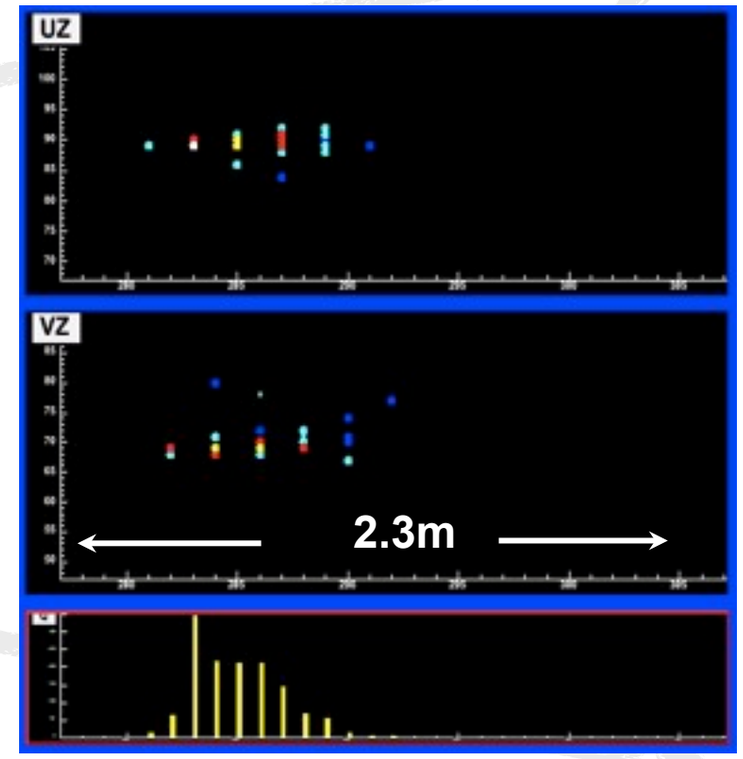
NC Event



Short event often with a diffuse shower.

What we use for the sterile neutrino analysis.

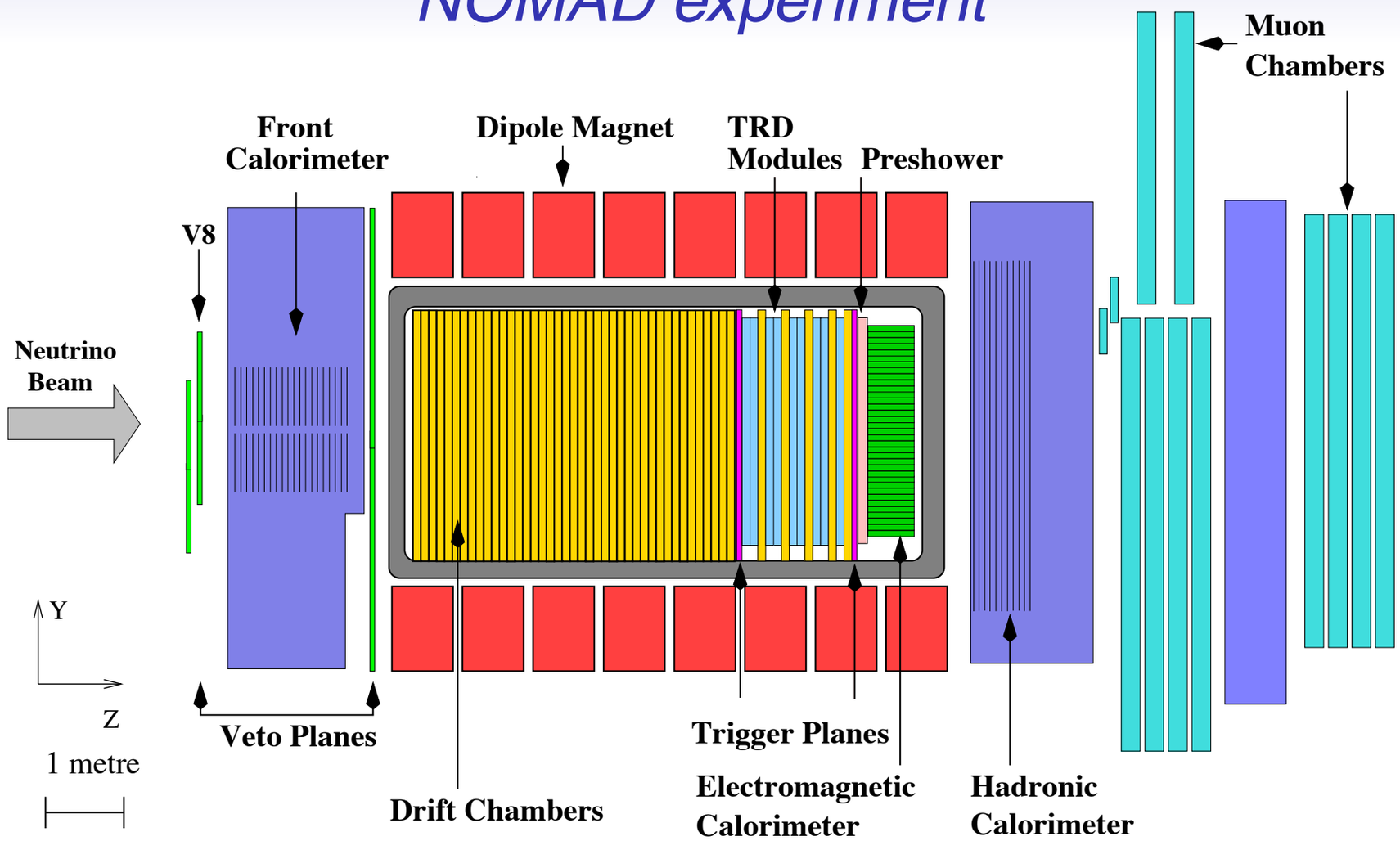
ν_e CC Event



Short event with a compact, EM-like shower profile.

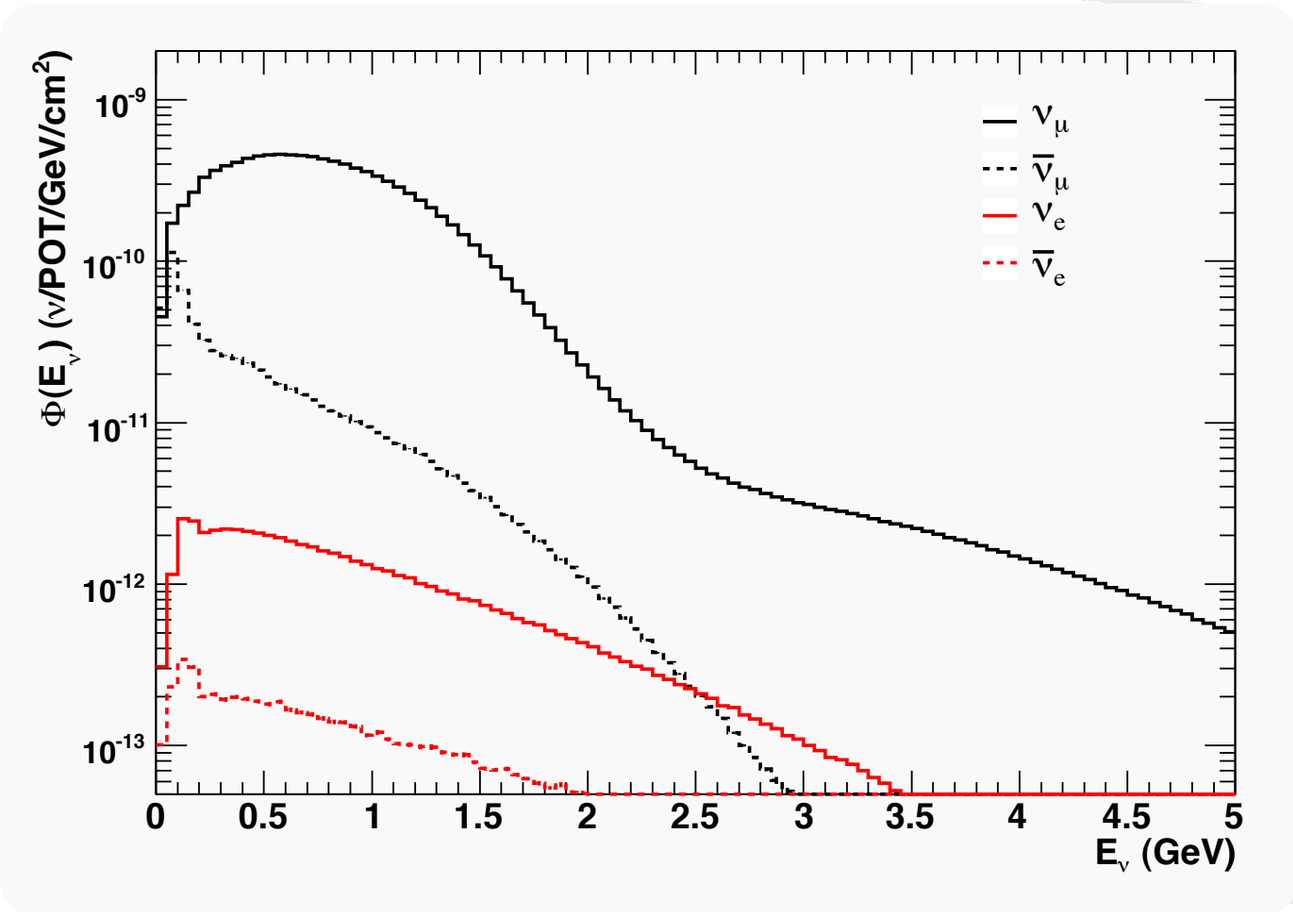
What we look for in the electron neutrino analysis.

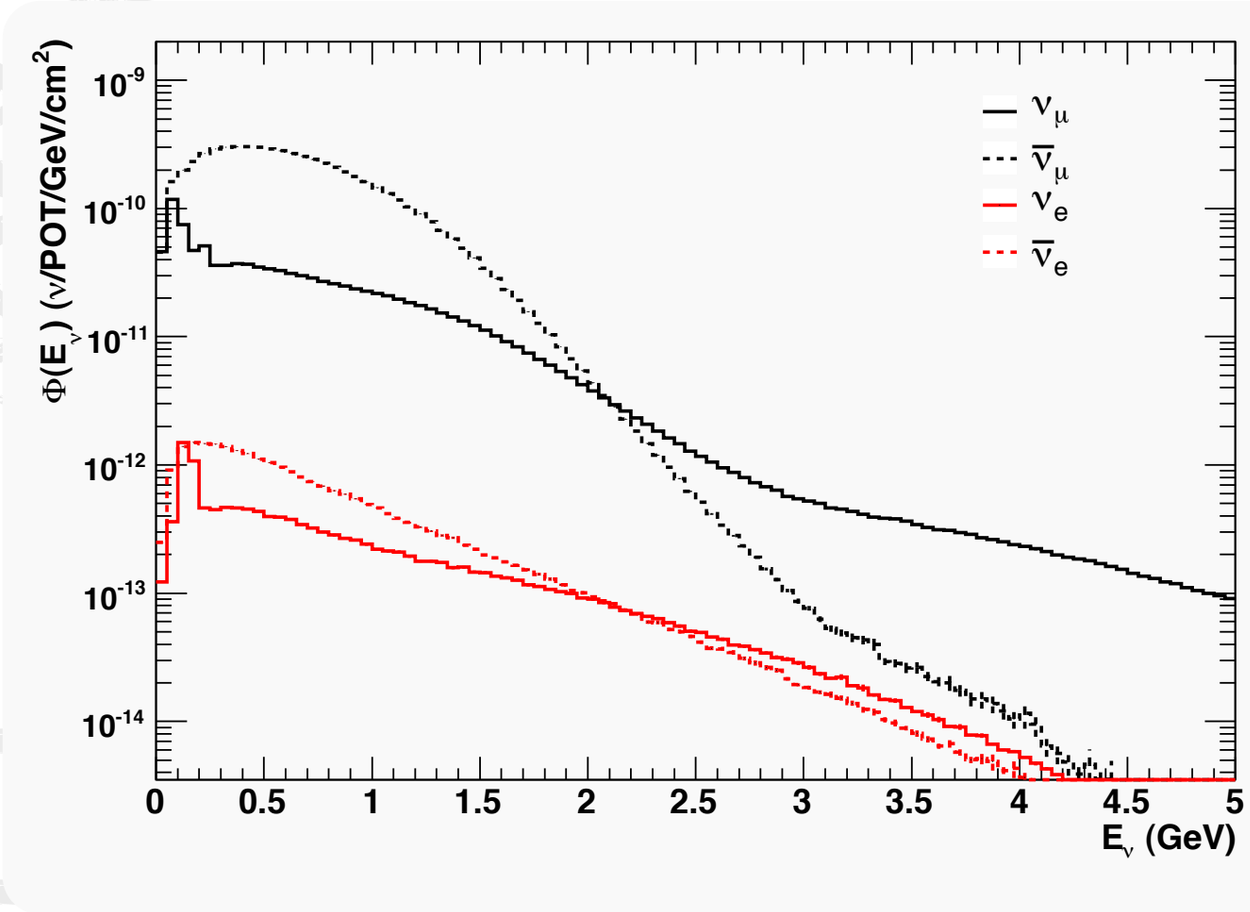
NOMAD experiment



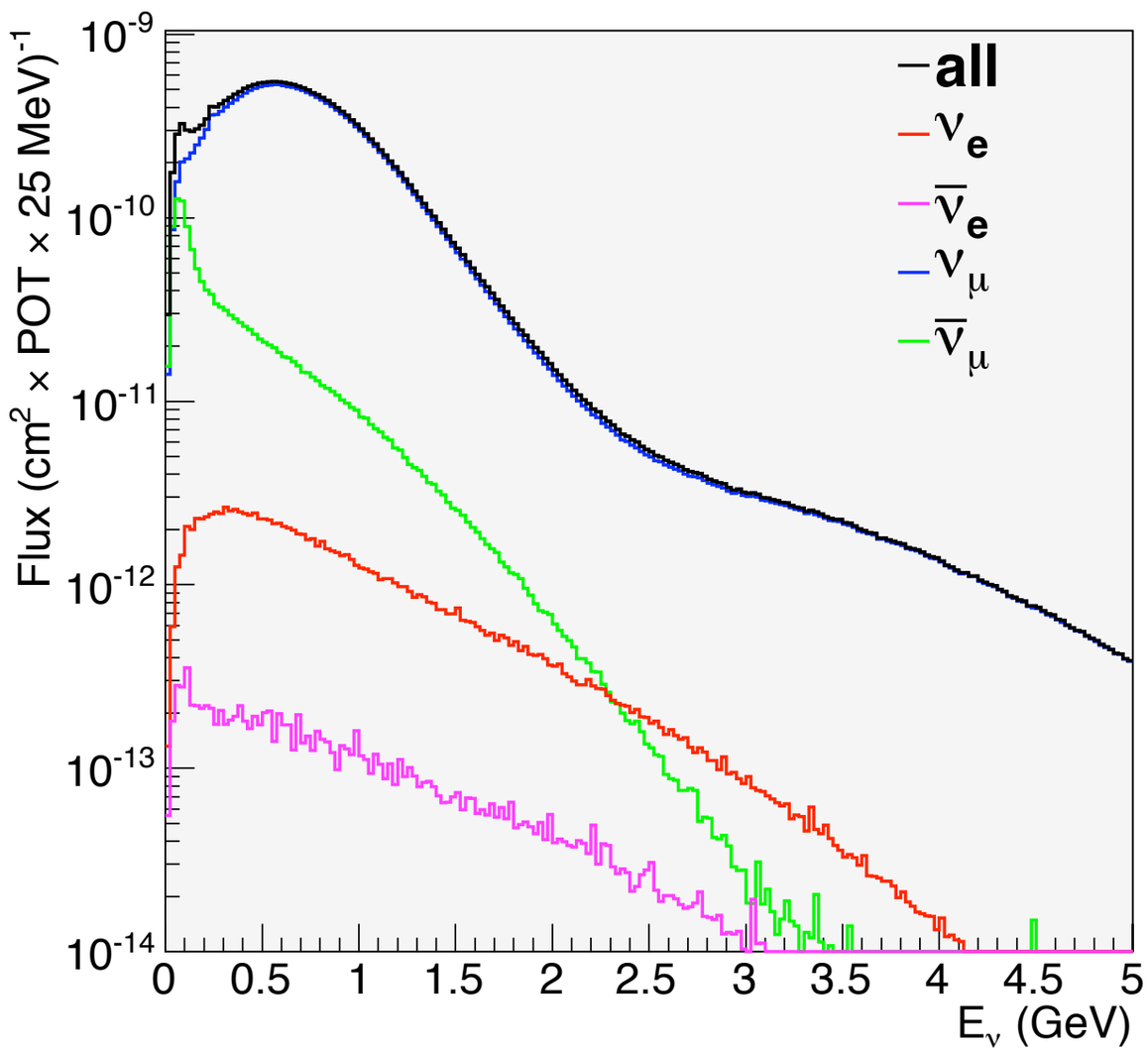
- Drift Chambers (target and momentum measurement) — Position resolution $< 200\ \mu$m (small angle tracks); Momentum resolution $\sim 3.5\%$ ($p < 10$ GeV/c)
- Transition Radiation Detector for $e^{\pm}$ identification: π rejection $\sim 10^3$ for electron efficiency $\geqslant 90\%$
- Lead glass Electromagnetic Calorimeter $\dfrac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \dfrac{(3.22 \pm 0.07)\%}{\sqrt{E\ (\mathrm{GeV})}}$
- Muon Chambers for $\mu^{\pm}$ identification: efficiency $\approx 97\%$ ($p_{\mu} > 5$ GeV/c)
- Hadronic Calorimeter for n and K_L^0 veto

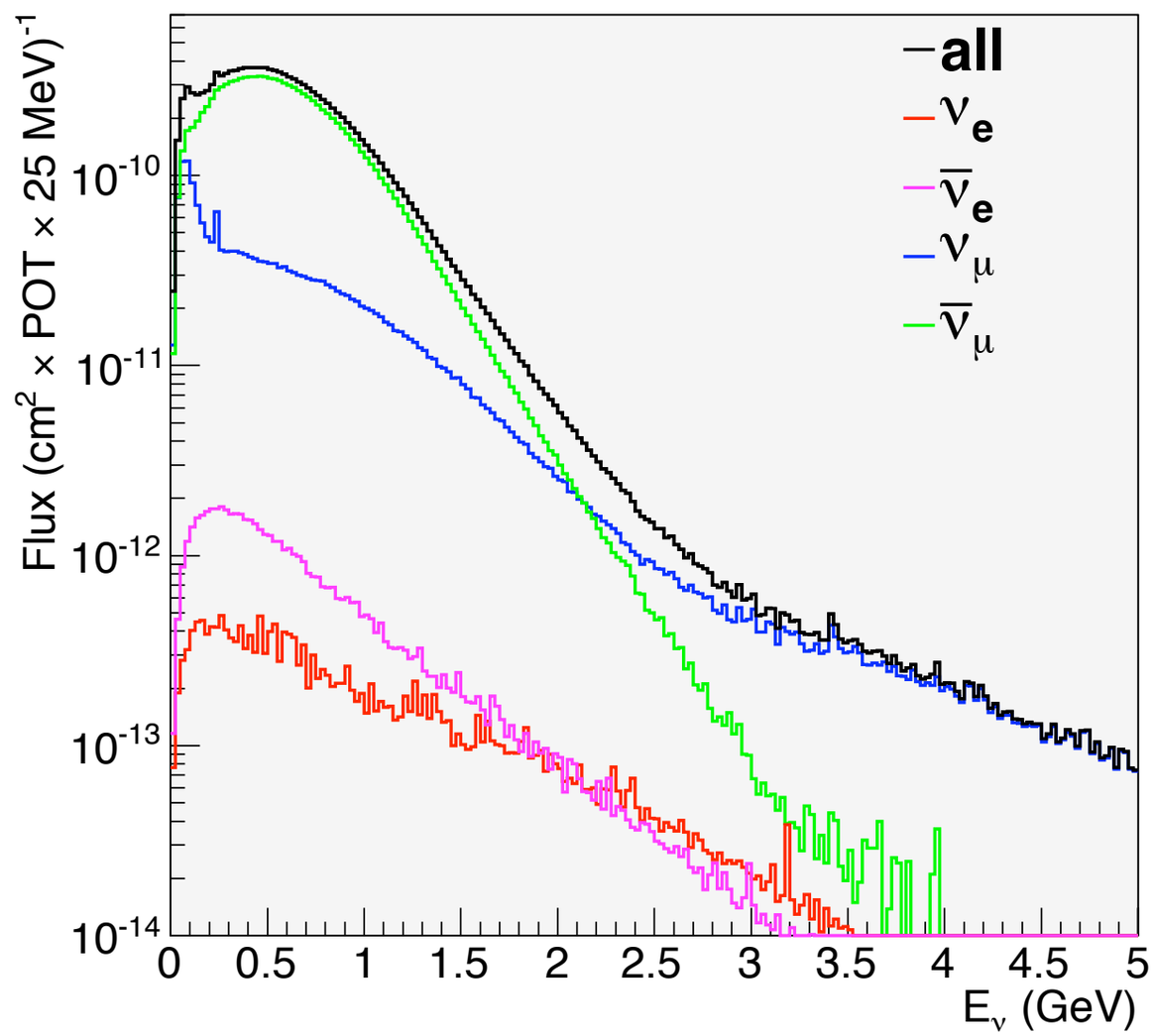
MB fluxes


$\Phi(E_\nu)$ (ν/POT/GeV/cm^2)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

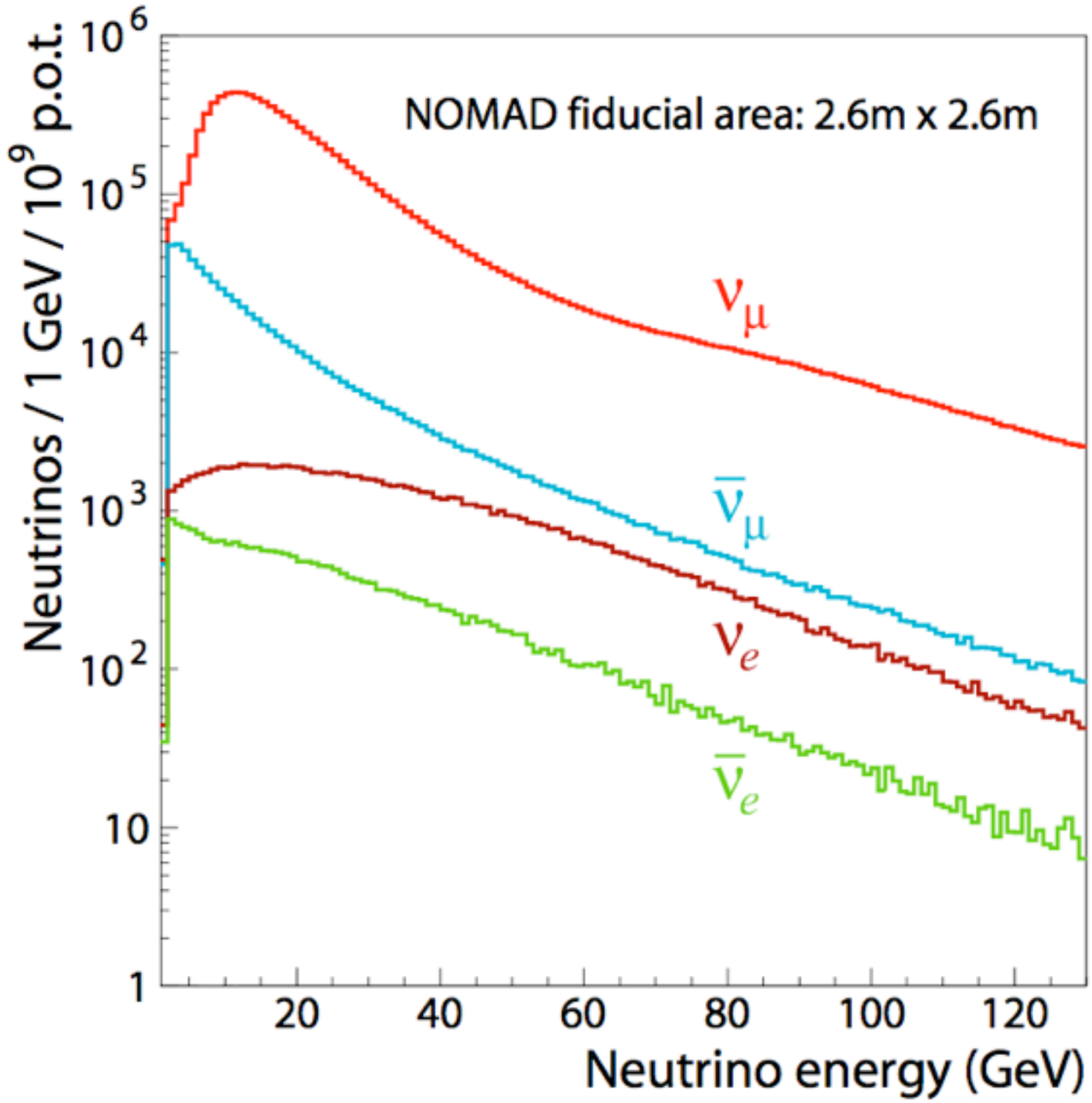
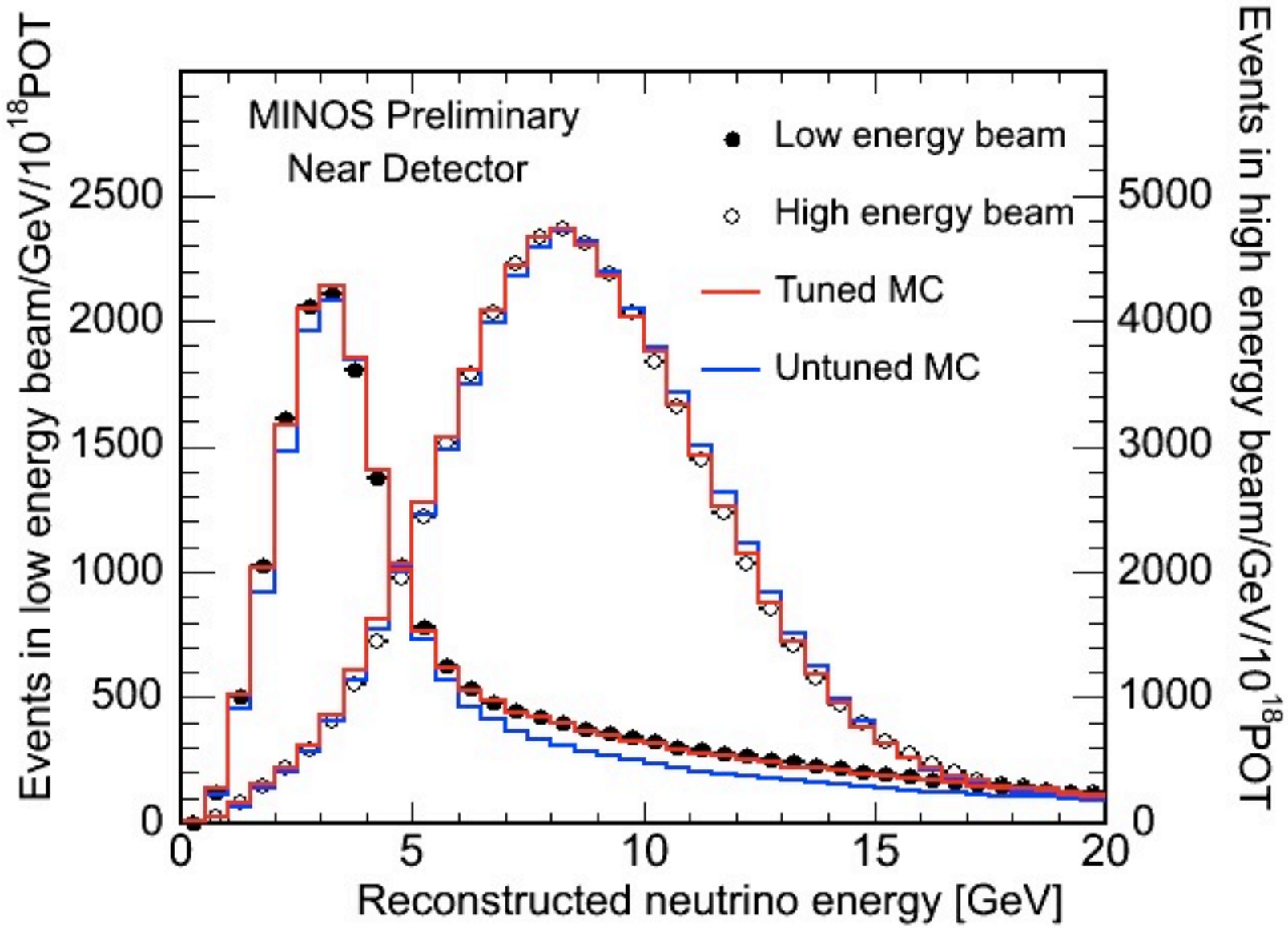

$\Phi(E_\nu)$ (ν/POT/GeV/cm^2)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

SB fluxes


Flux (cm^2 × POT × 25 MeV)$^{-1}$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
E_ν (GeV)
all
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$


Flux (cm^2 × POT × 25 MeV)$^{-1}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
E_ν (GeV)
all
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$

NOMAD fluxes



MINOS fluxes