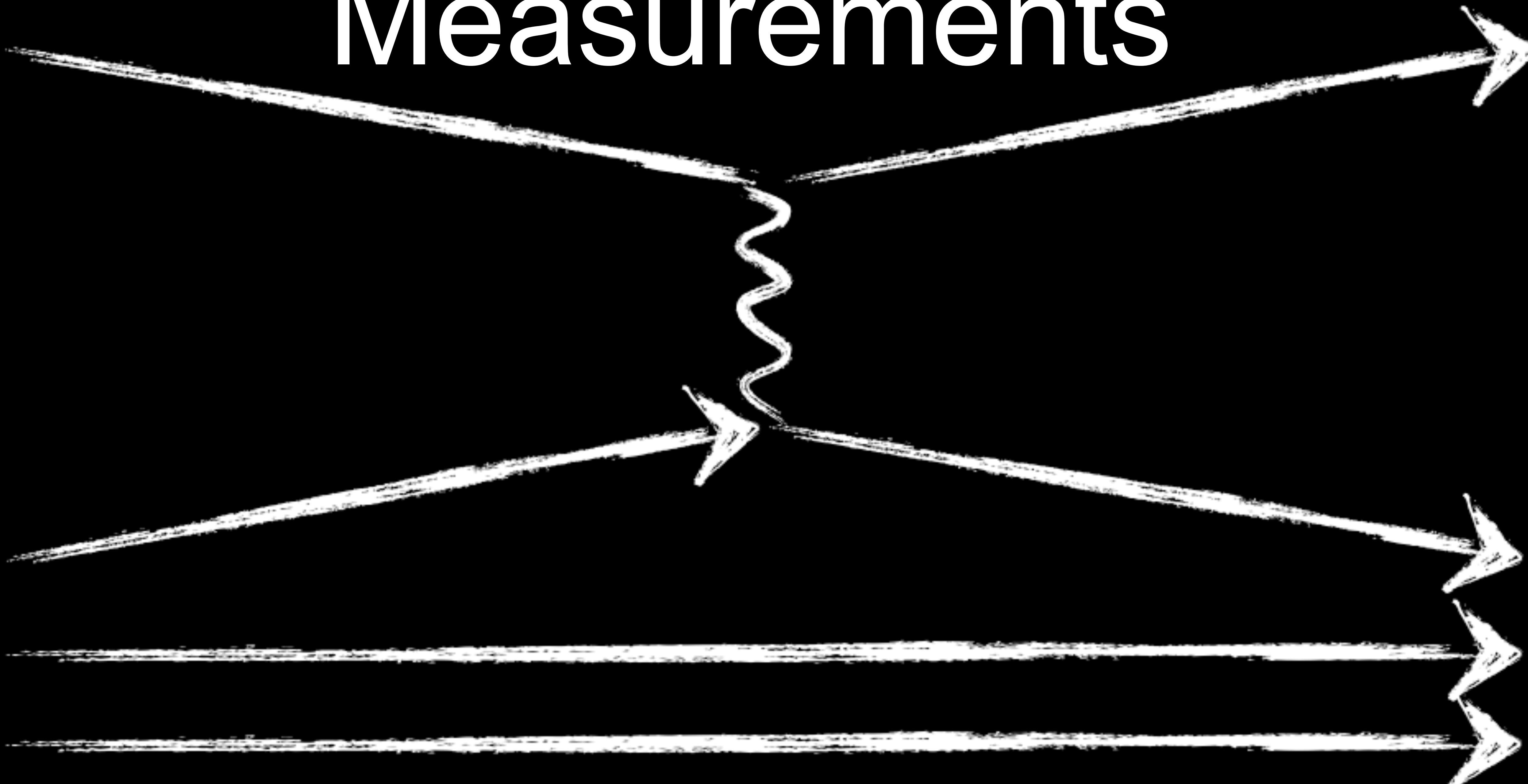
Quasi-Elastic Scattering Measurements



Morgan Wascko
Imperial College London

Neutrino 2010, 18 June 2010

Message

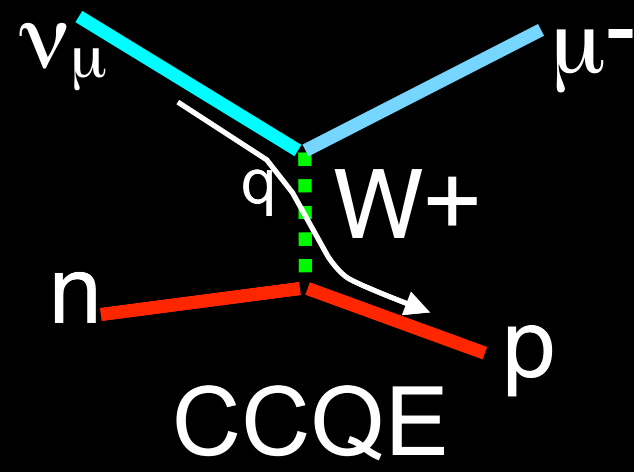
The precision of future oscillation measurements is limited by neutrino interaction uncertainties.

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
- Path Forward

Quasi-Elastic Scattering

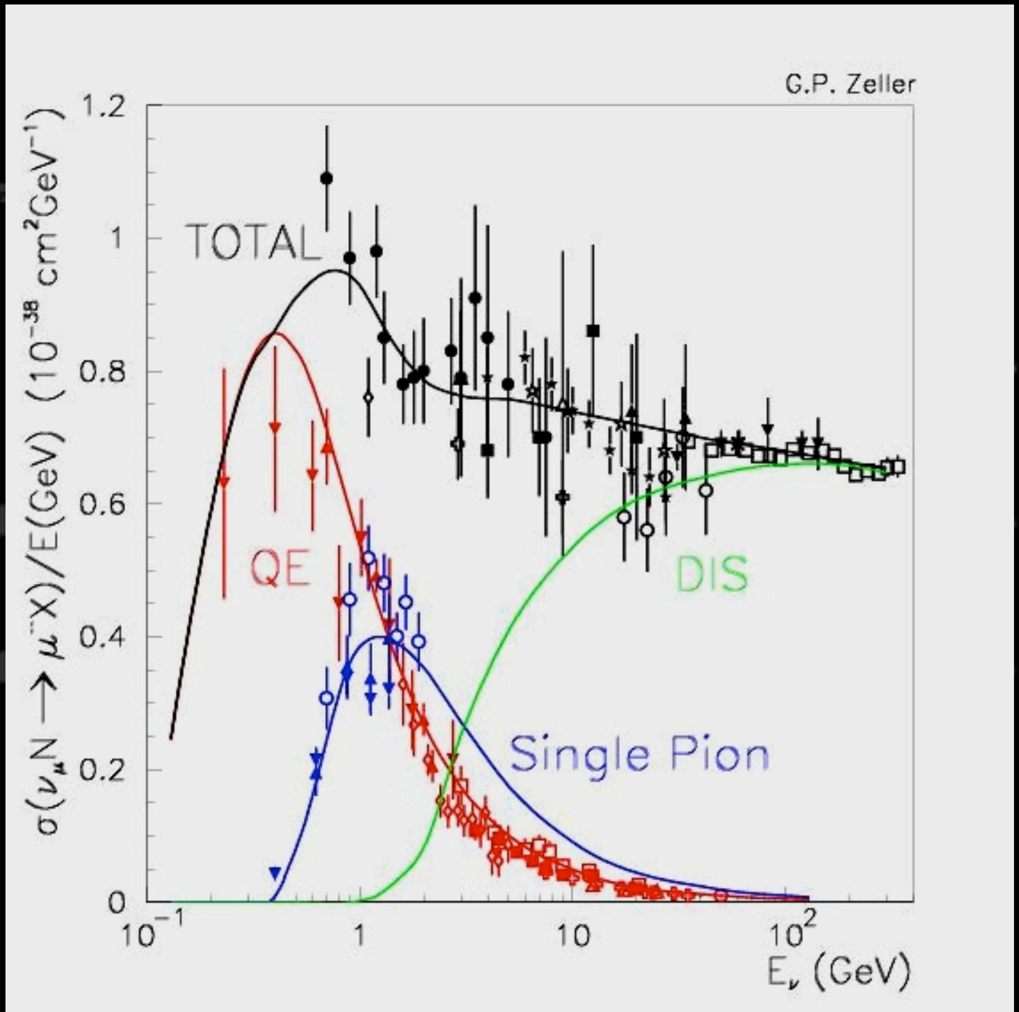


$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{Q^2}{M_A^2})^2}$$

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

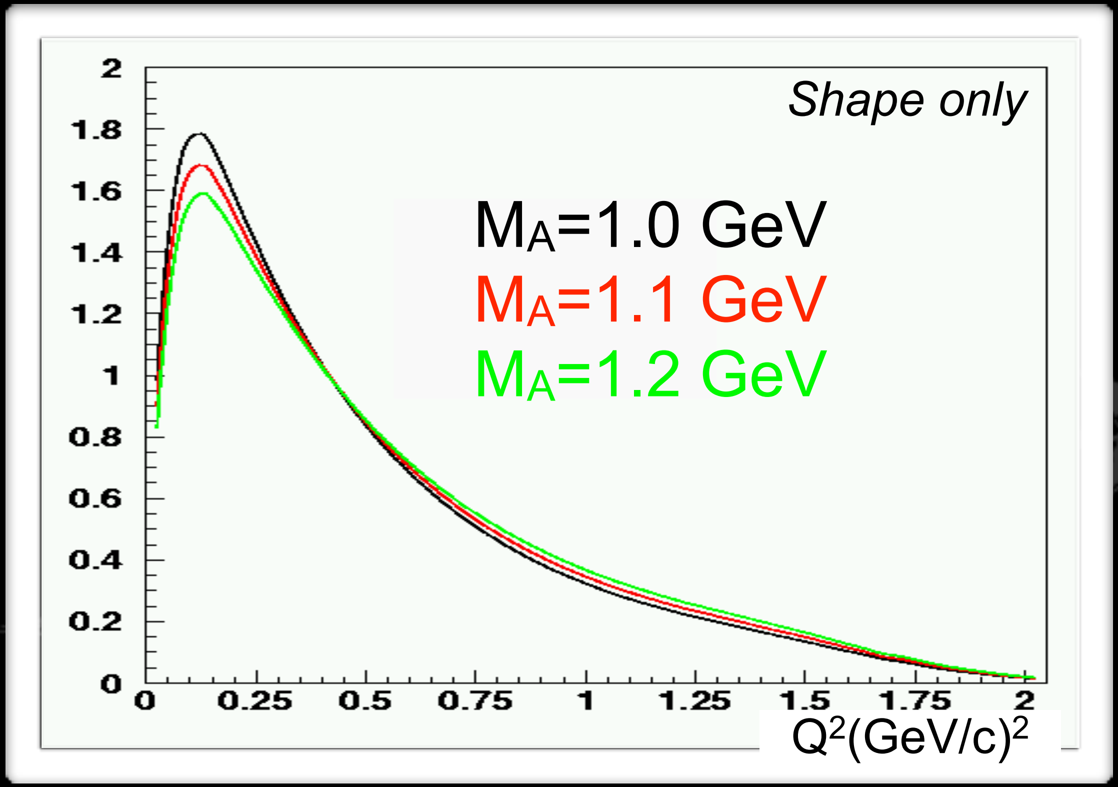
Theory covered by L. Alvarez Ruso

- 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
  - *See talk by D. Harris*



M_A fit results

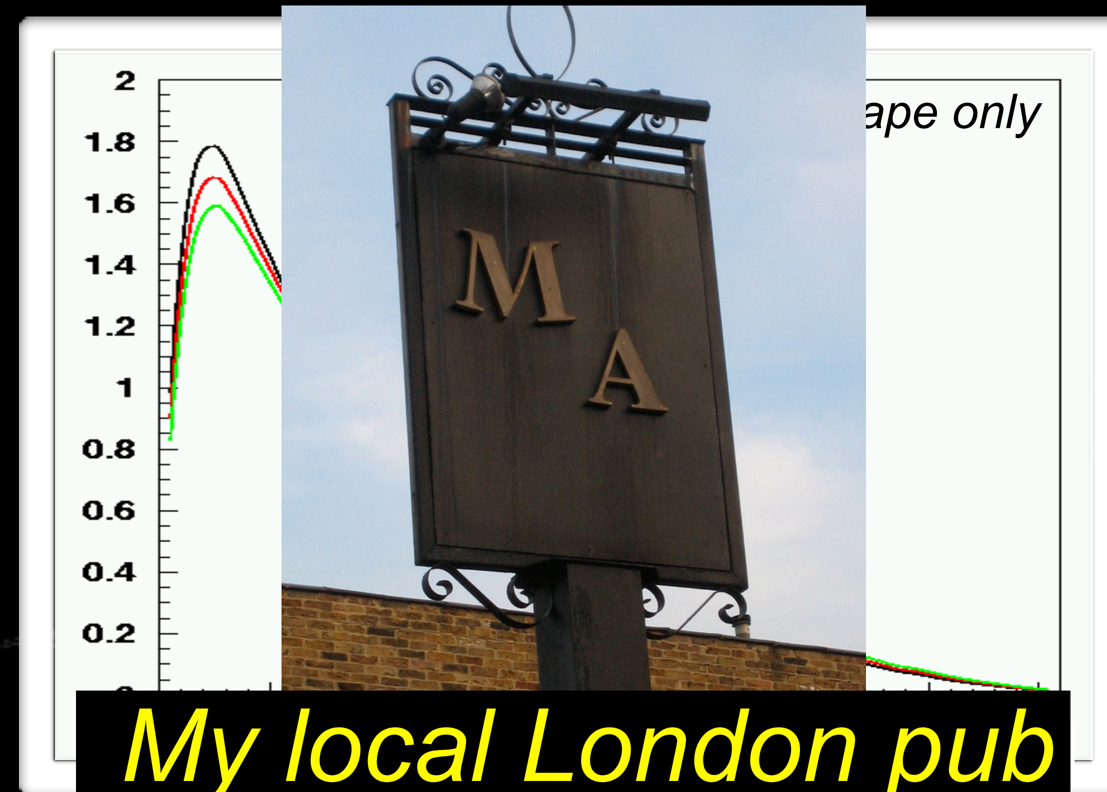
- Value of M_A changes scale & shape of Q^2 distribution
- Recent measurements at low energy on nuclear targets favour high value of M_A
  - But not at high energy!
- Also show increased suppression at low Q^2
- F_A: not dipole form factor?
  - Is M_A an effective parameter?



Courtesy of R. Gran

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

M_A fit results



My local London pub

Courtesy of R. Gran

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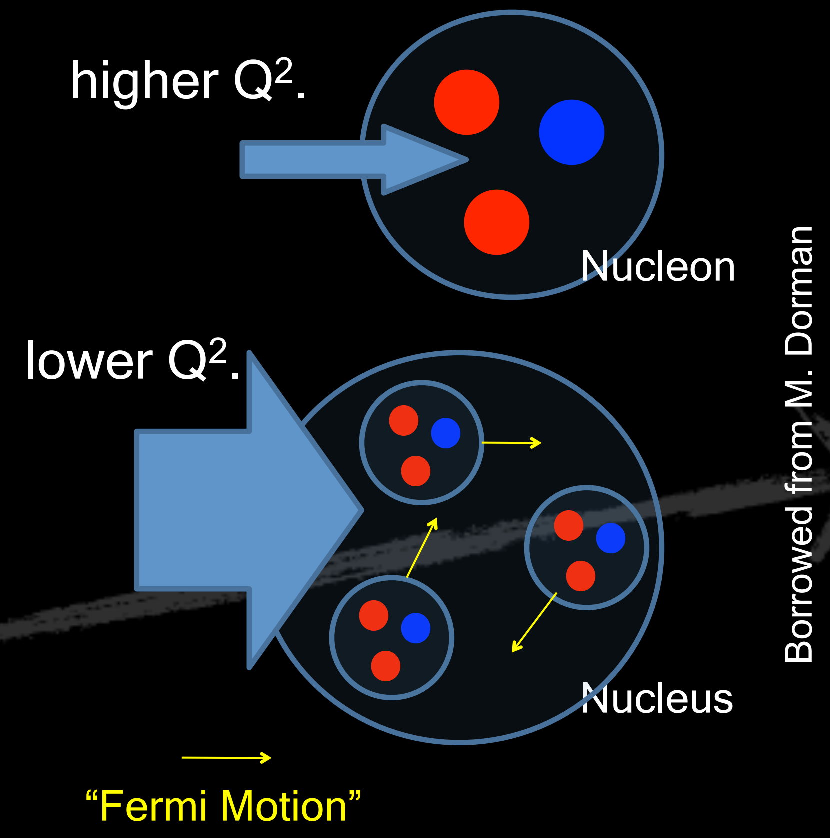
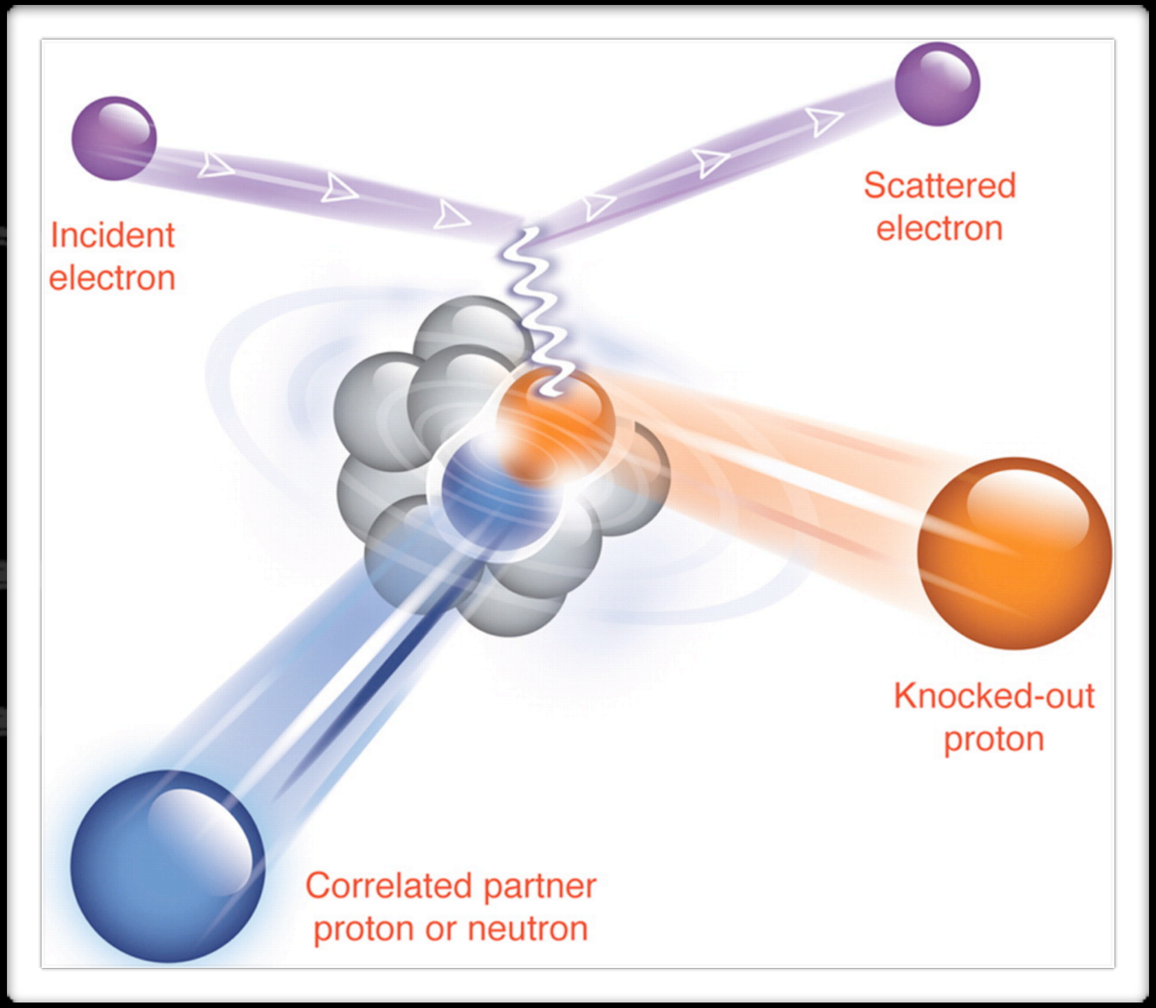
Impulse approximation

Nuclear effects covered by O. Benhar

- Assume interaction involves only one nucleon
  - $\lambda > 1$ 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?

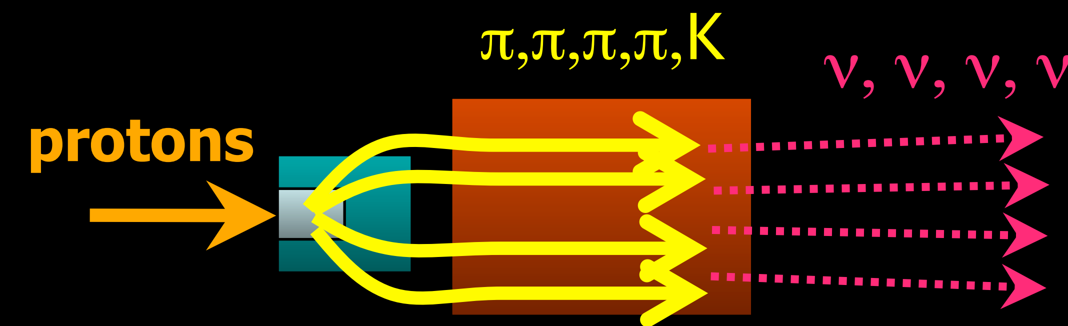




Science Vol.320. no.5882, pp.1476

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)

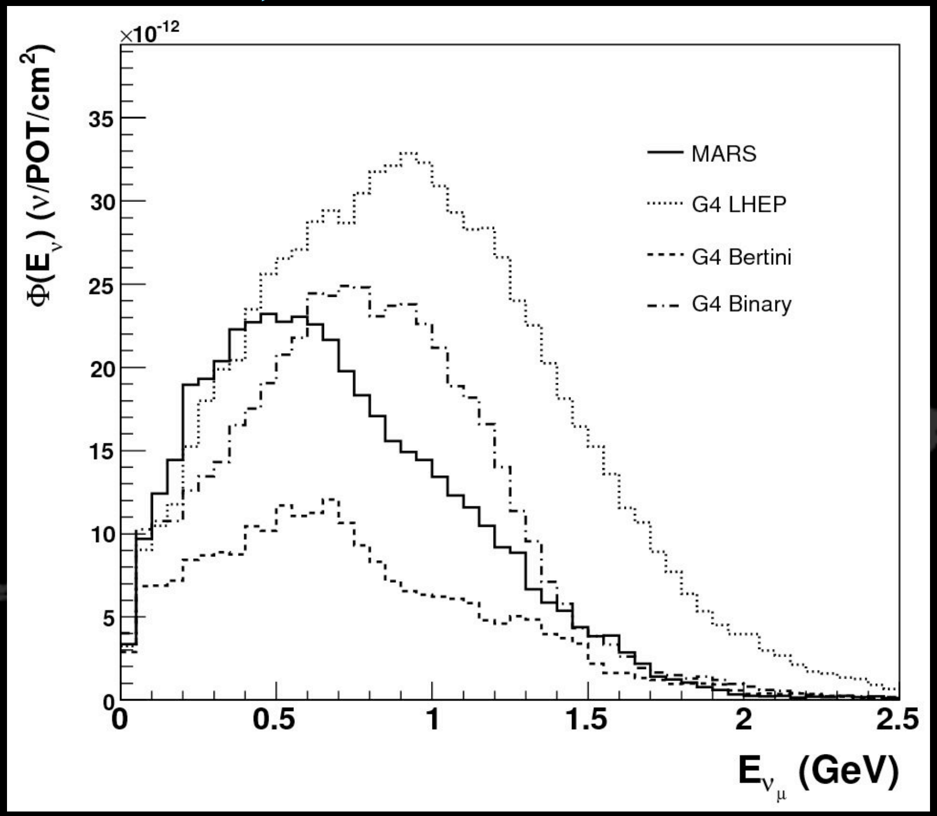
Further Reading:
NOMAD: NIMA 515 (2003) 800-828
NuMI: AIP Conf.Proc.967:49-52,2007
*MiniBooNE: Phys.Rev.D**79** 072002 (2009)*
General: Phys.Rept.439:101-159,2007

Hadron Production

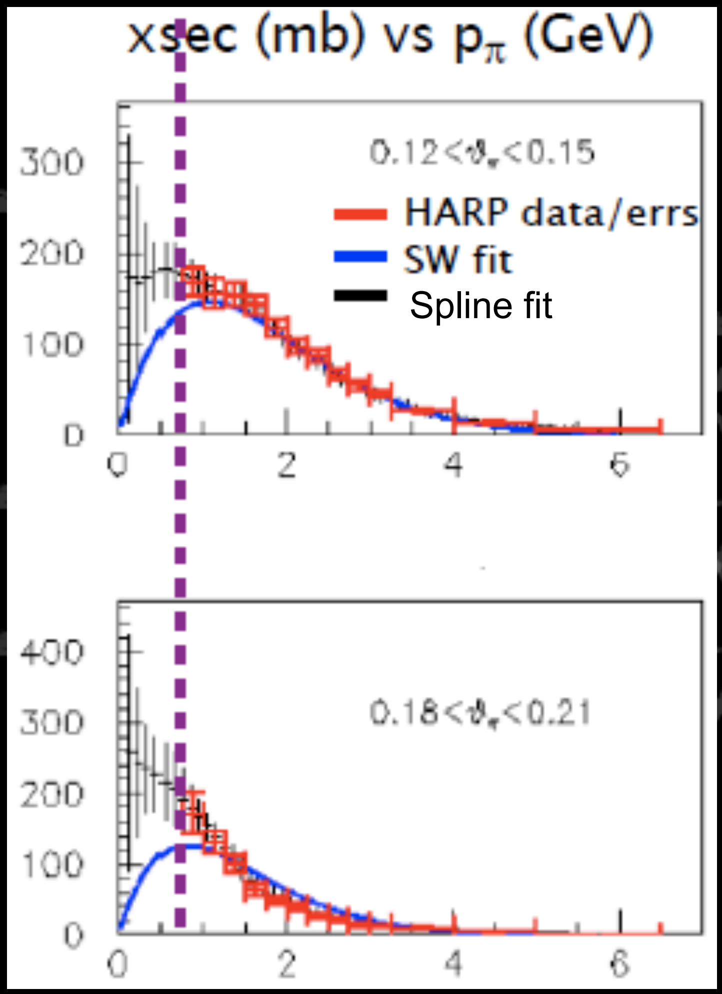
Measurements covered by A Blondel

- 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



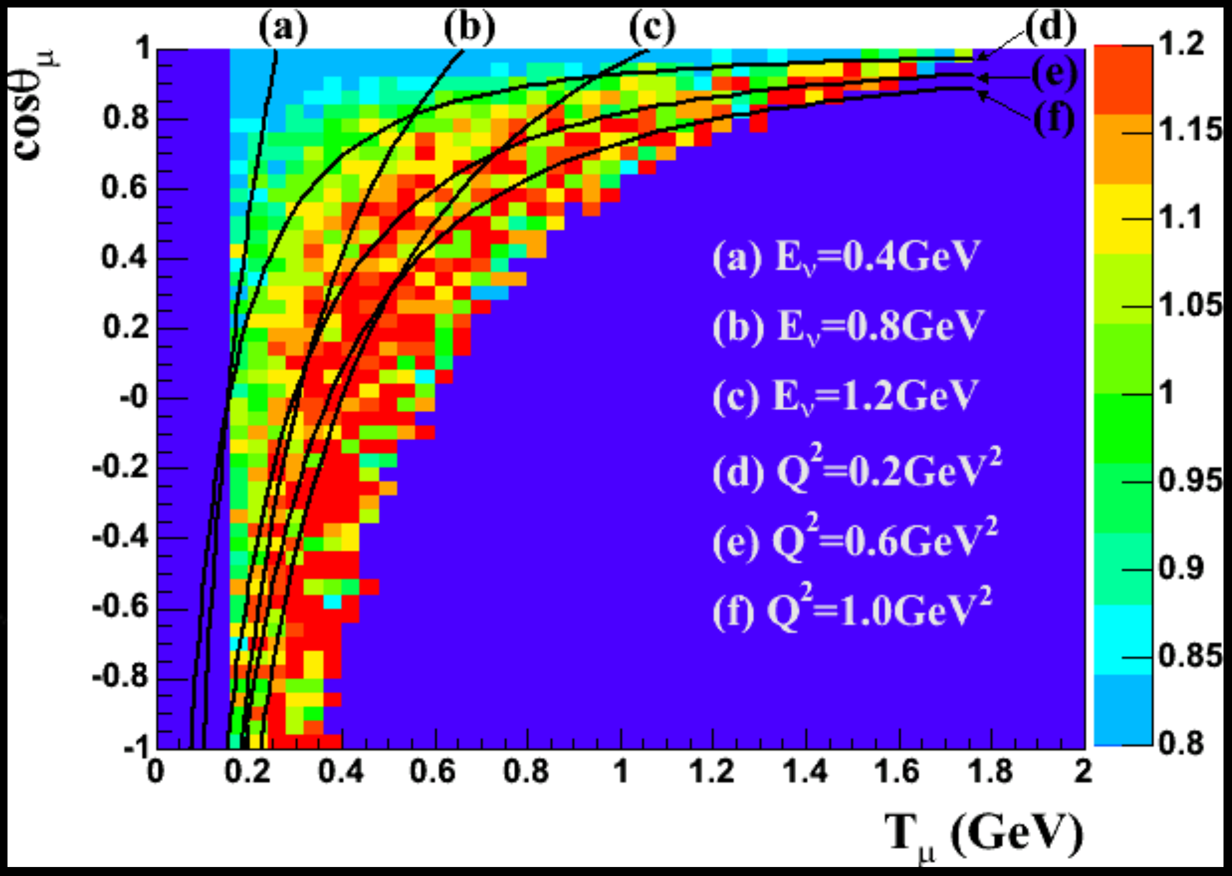
S. Brice



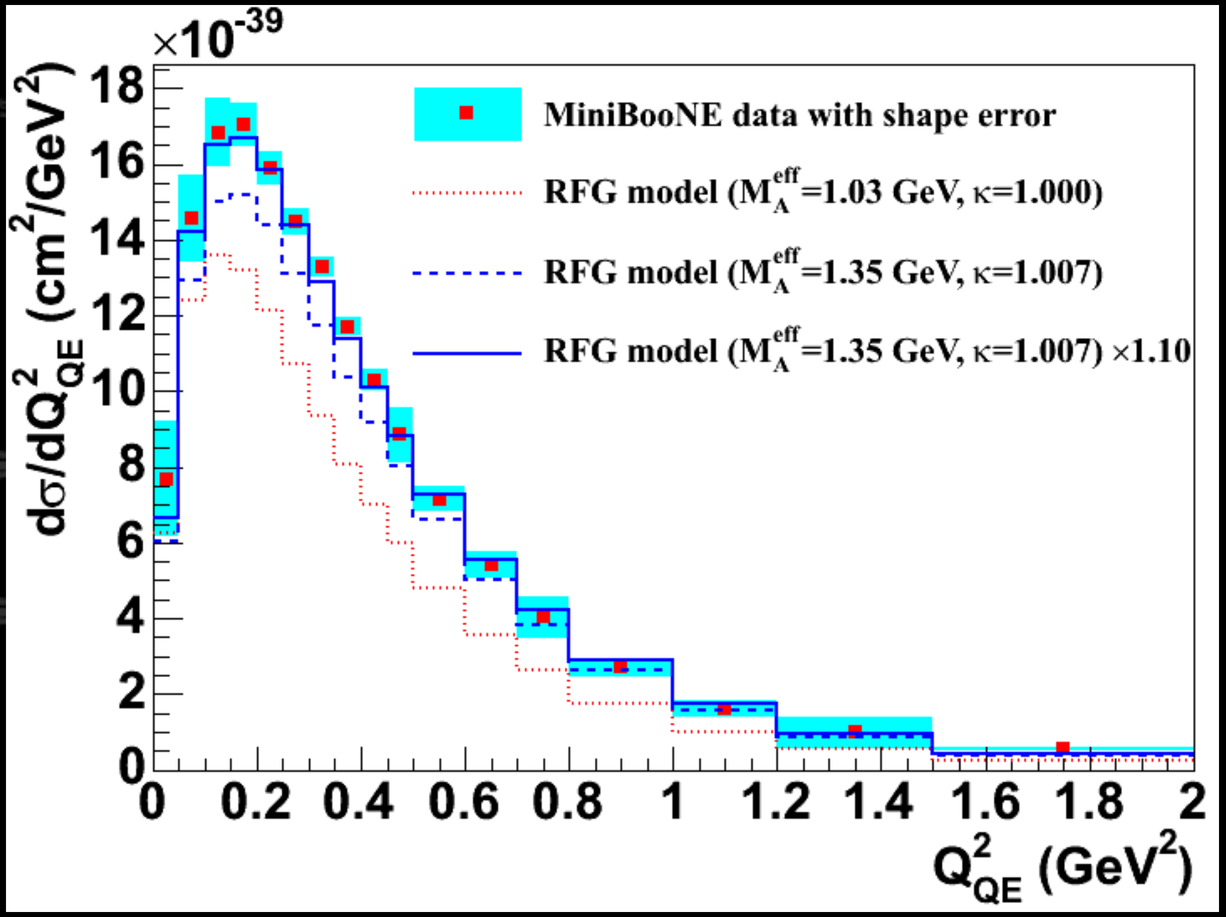
MiniBooNE

T. Katori

- 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!



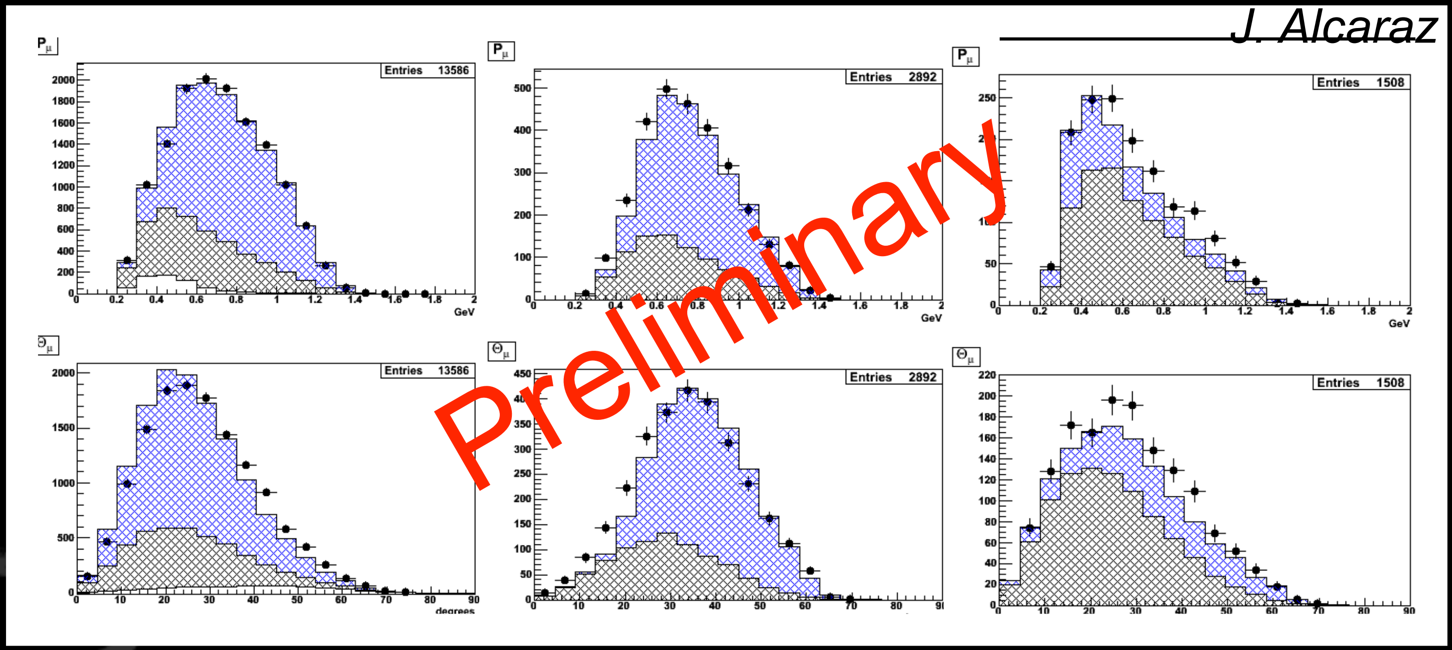
*PhysRevD **81** 092005 (2010)*



SciBooNE

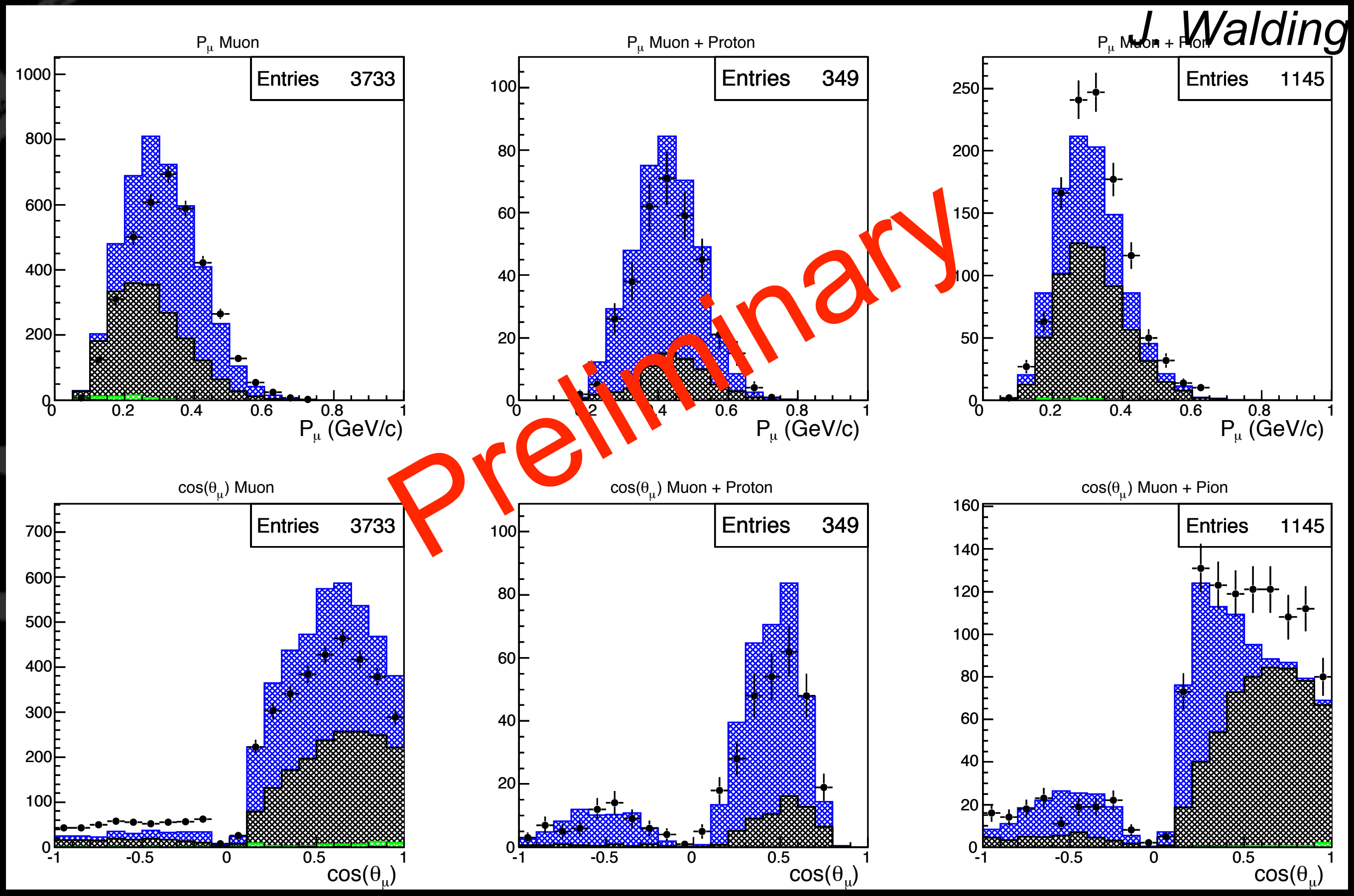
- Fine-grained vertex detector
  - Carbon target
- Sensitivity to secondary tracks
  - simultaneously fit μ, μ+p, $\mu+\pi$ samples
  - Extract $\sigma_{QE}(E_\nu)$
- Also producing POT normalised cross-sections
- Similar discrepancies as seen by MiniBooNE

μ μ+p $\mu+\pi$



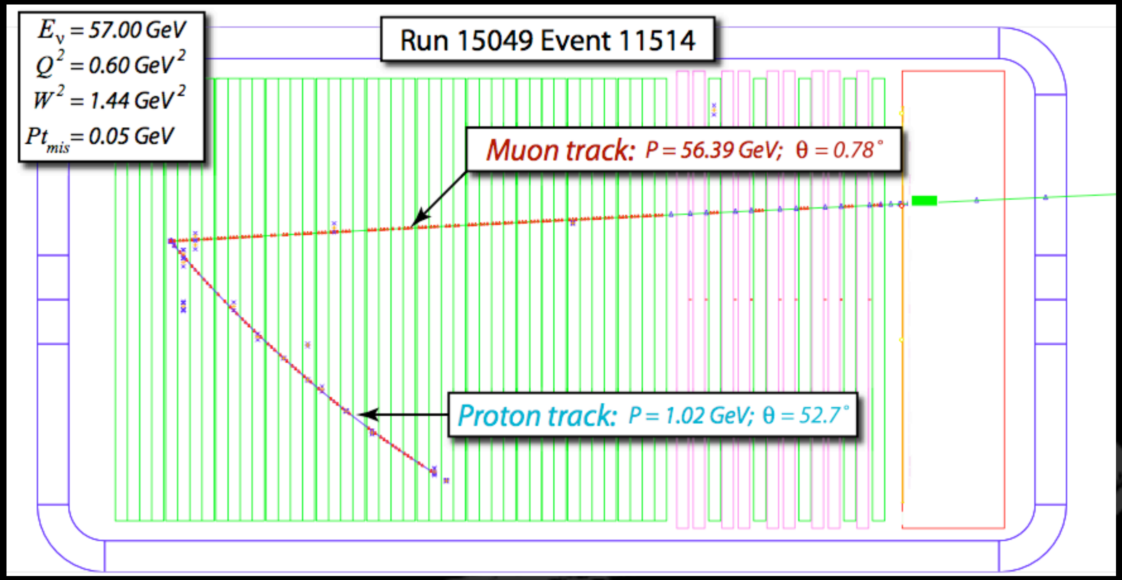
CCQE signal ; Backgrounds

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

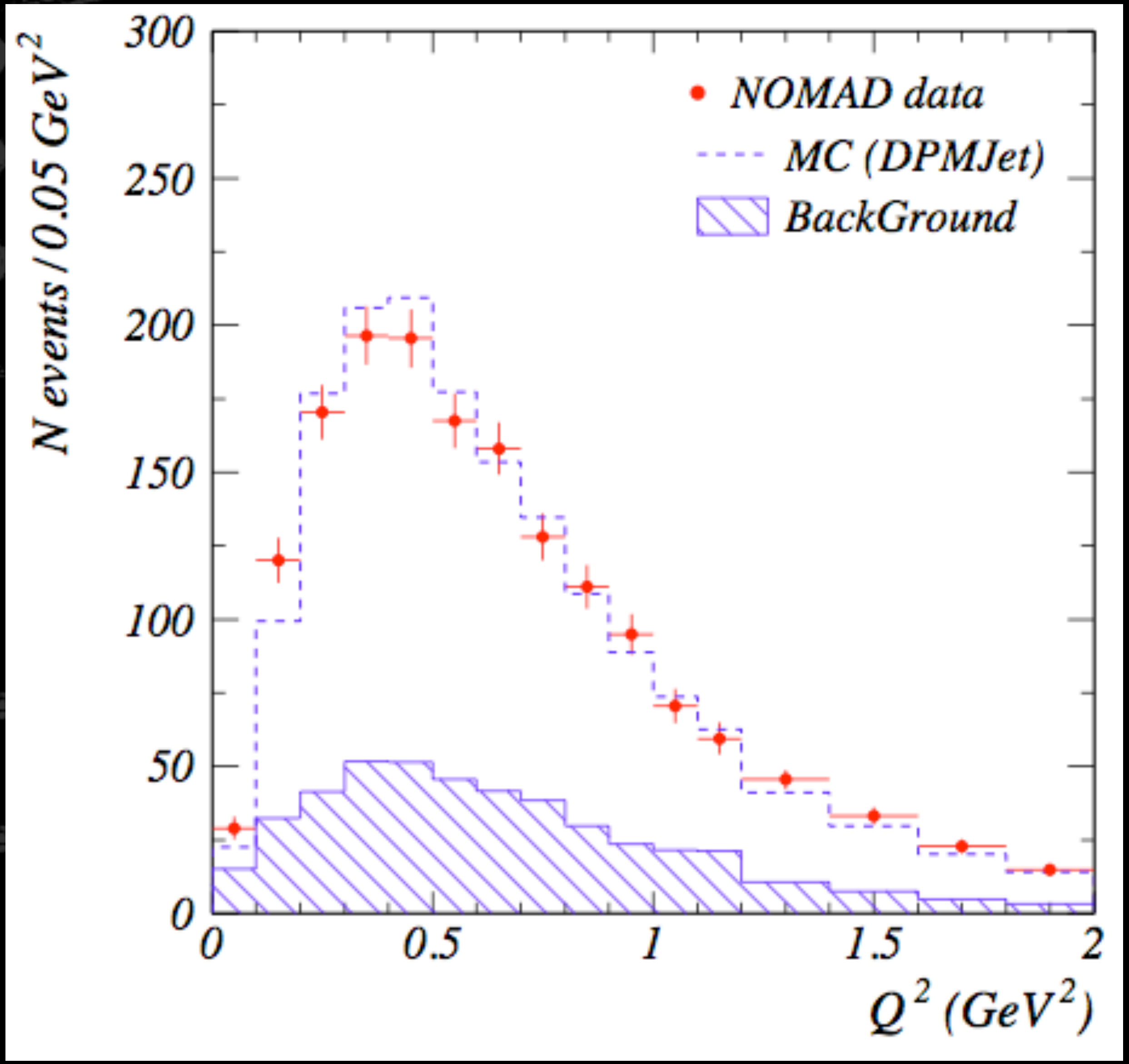


NOMAD

- 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

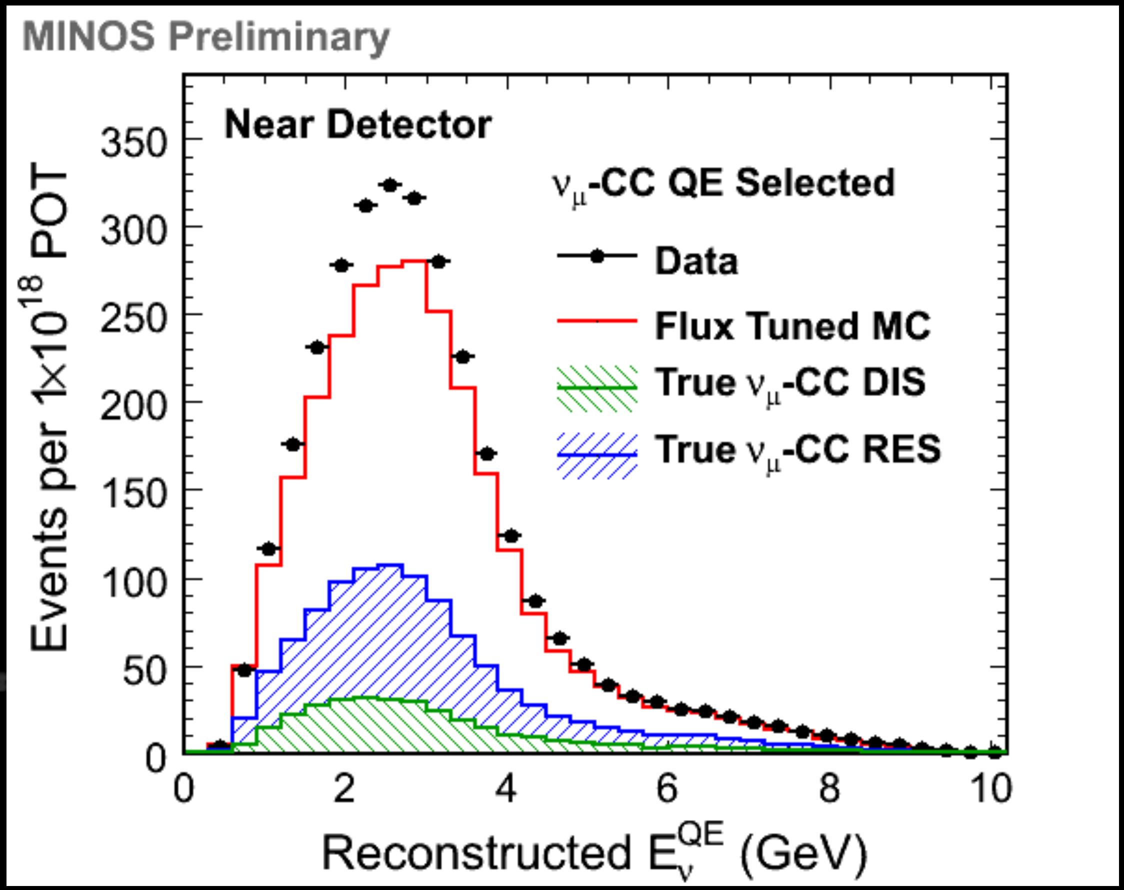


Eur.Phys.J.C63:355-381,2009

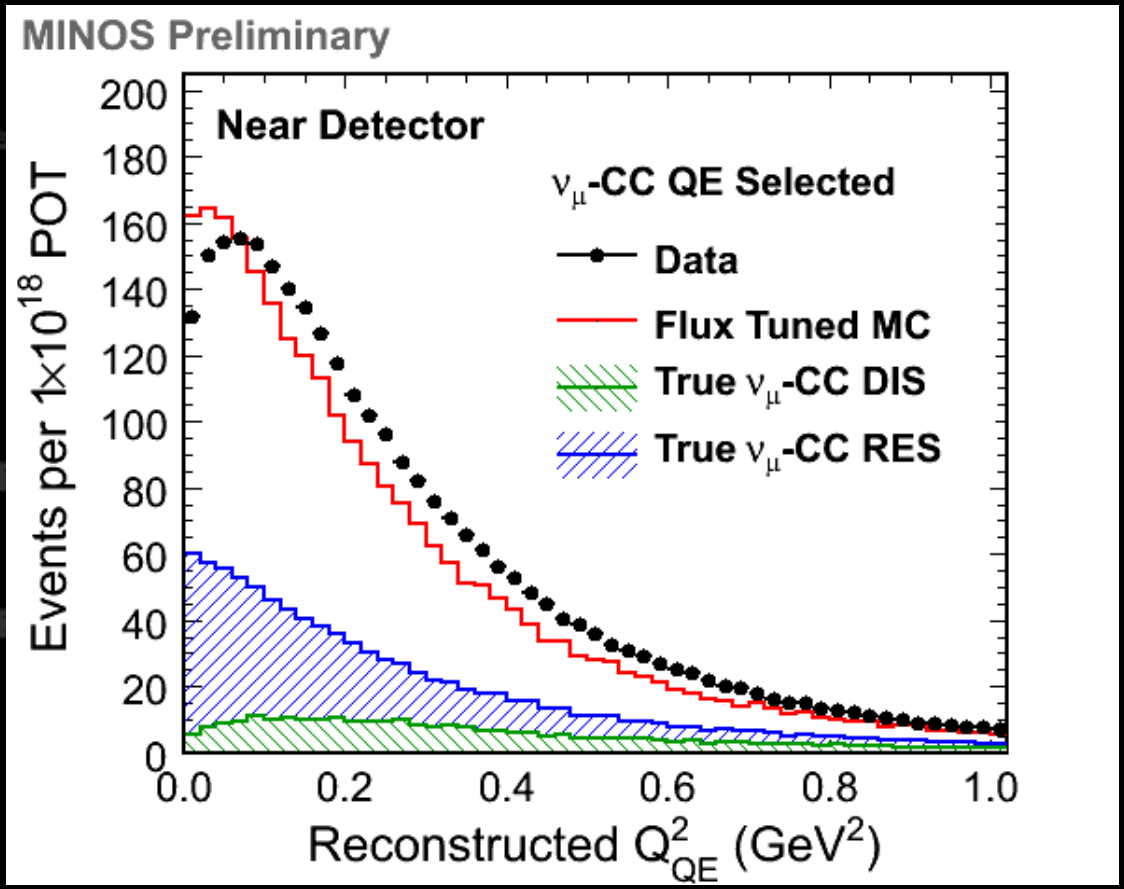


MINOS

- 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.

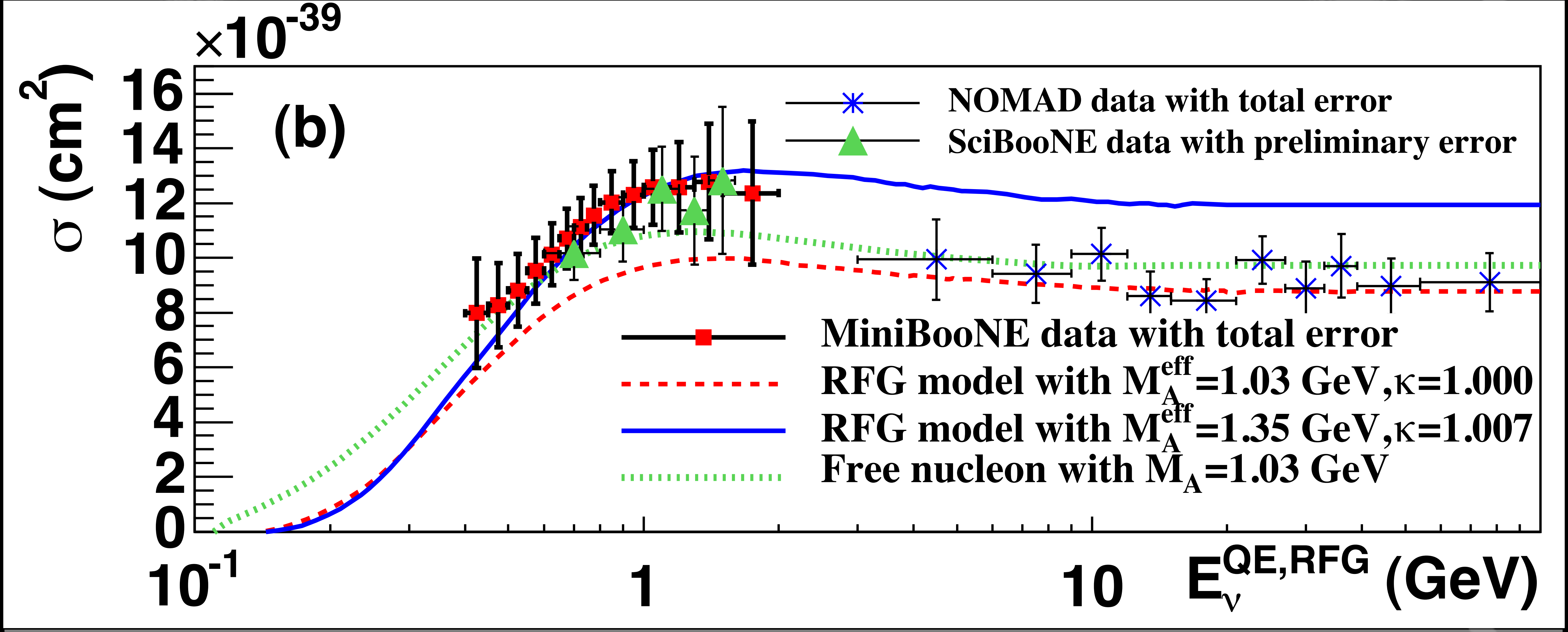


AIP Conf.Proc.1189:133-138,2009

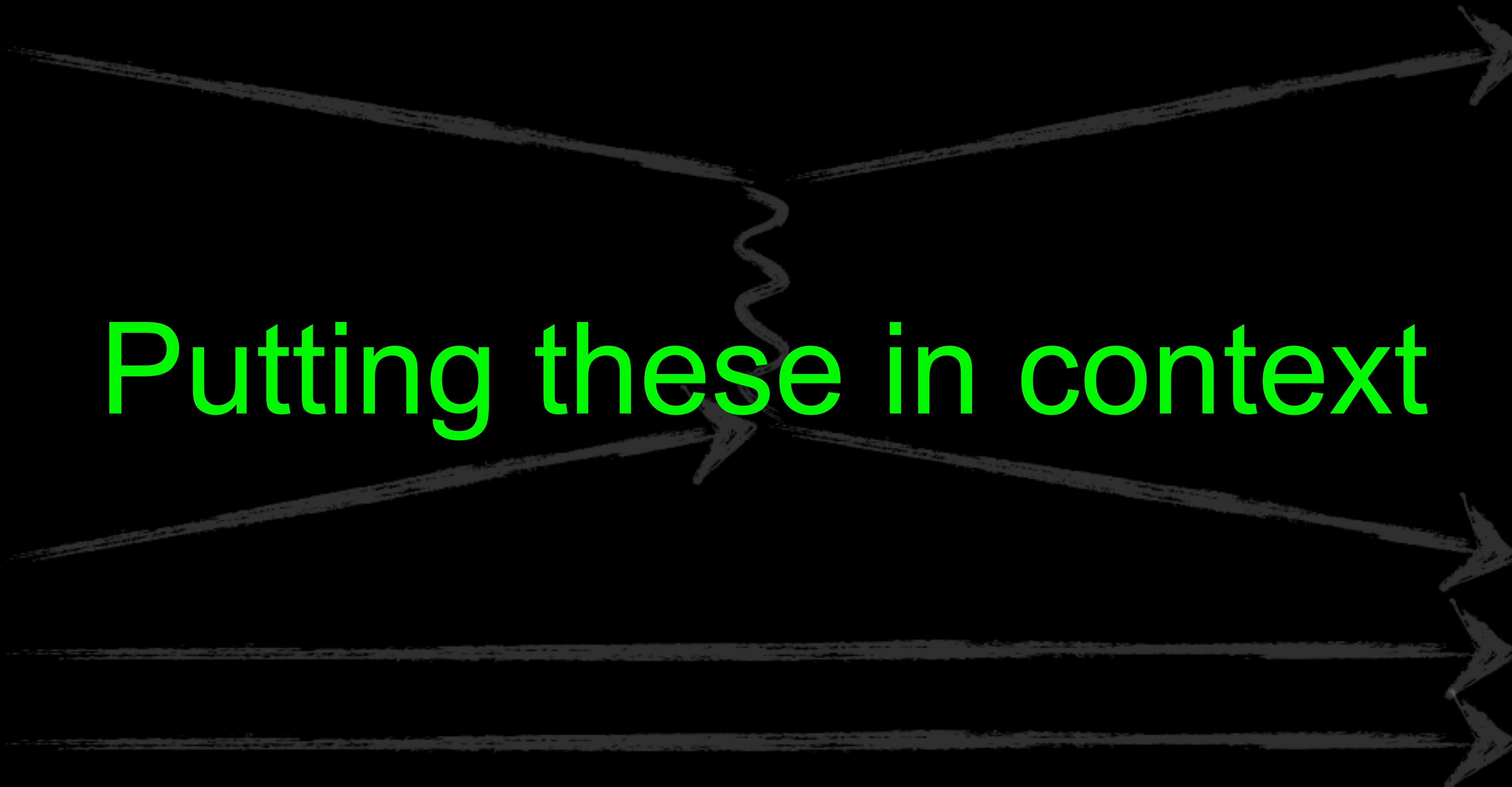


CCQE comparisons

Plot courtesy of Teppei Katori (MIT)



Putting these in context

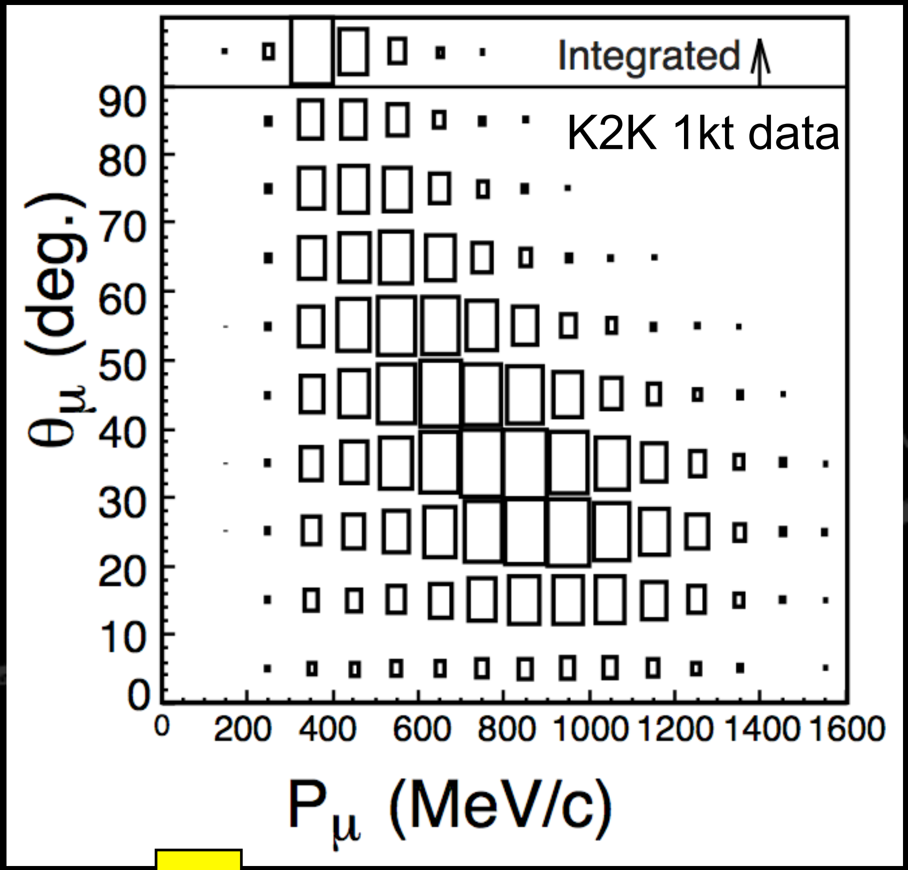


What do we need?

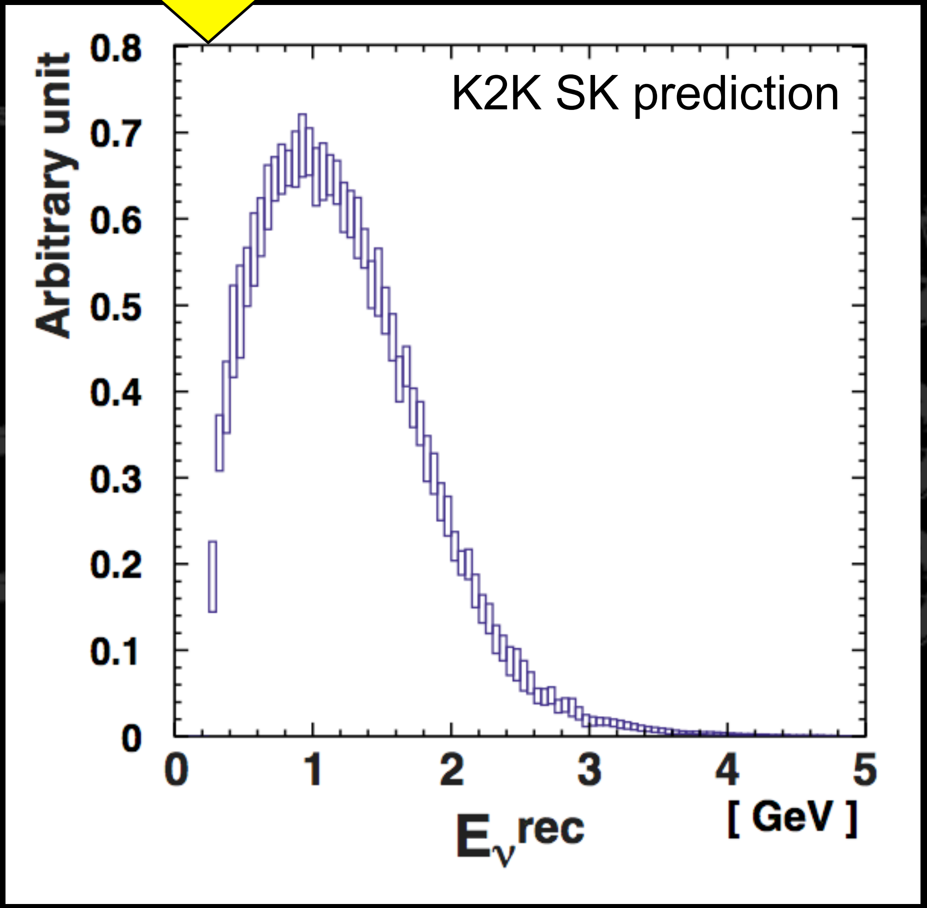
- Need to predict event rates and kinematics of final state particles
- Need to reconstruct neutrino energy accurately
- Need to accurately predict background contamination

➡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!

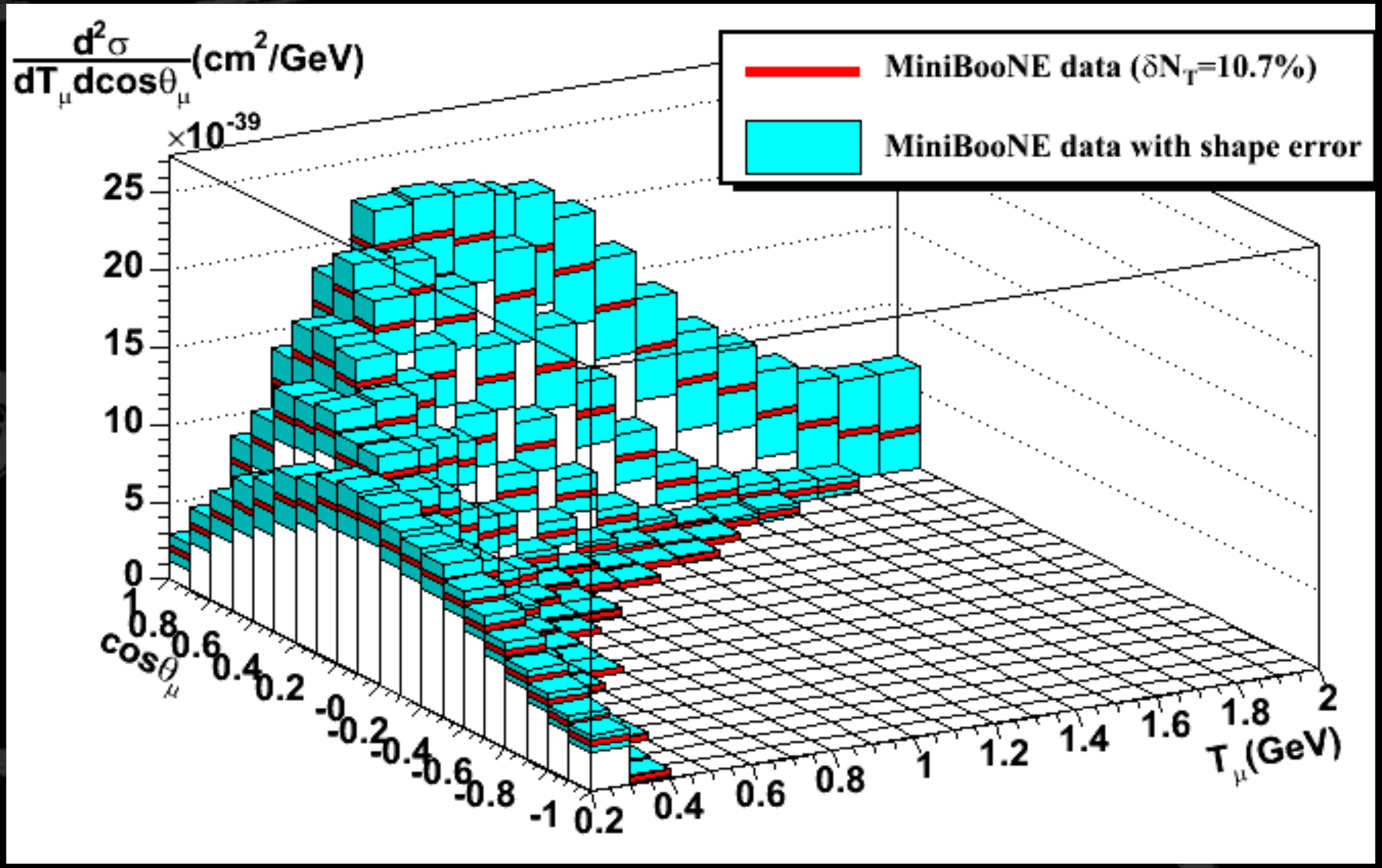
MiniBooNE ν_e appearance systematic uncertainties

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

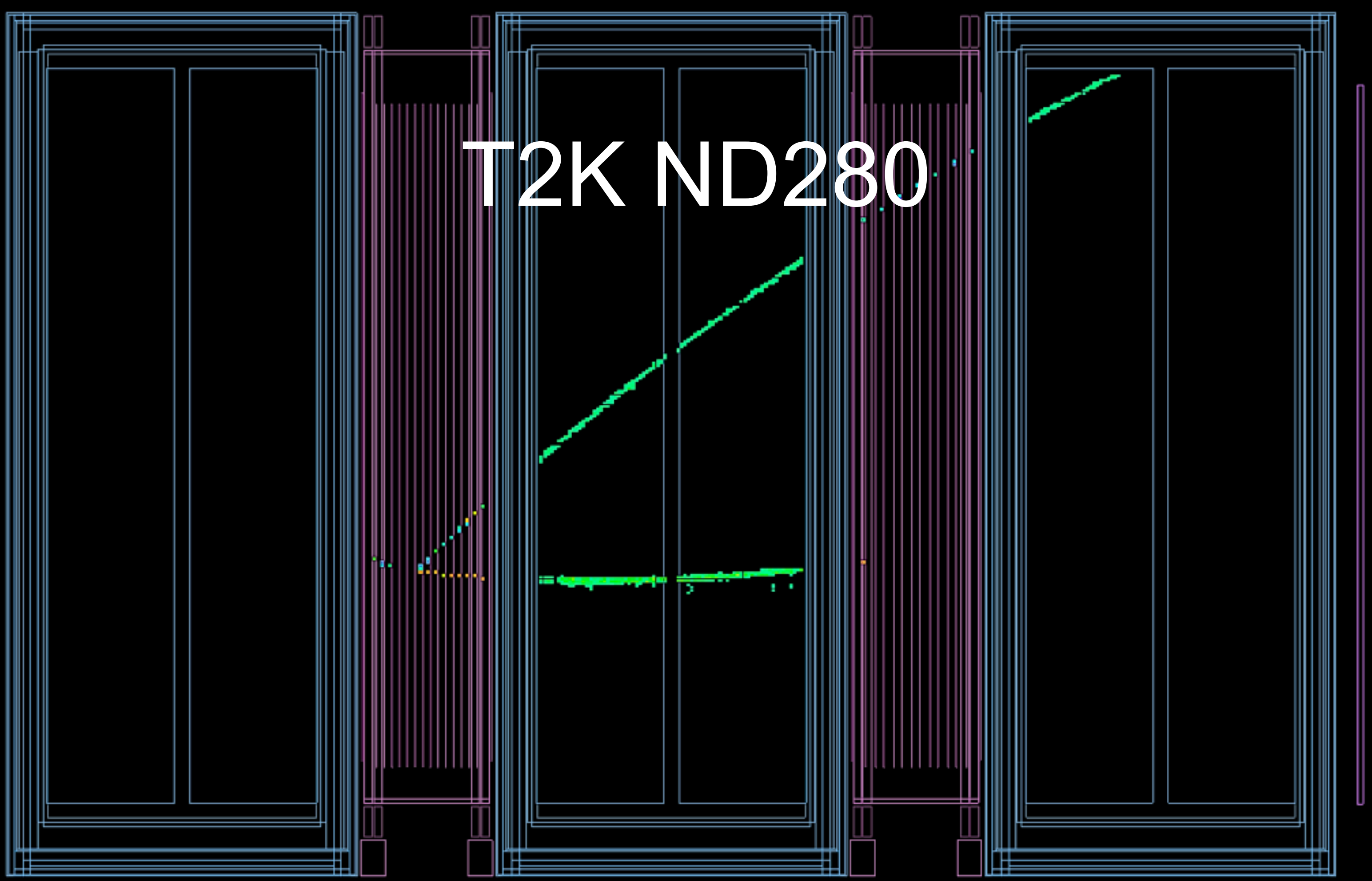
MiniBooNE's final ν_μ CCQE result

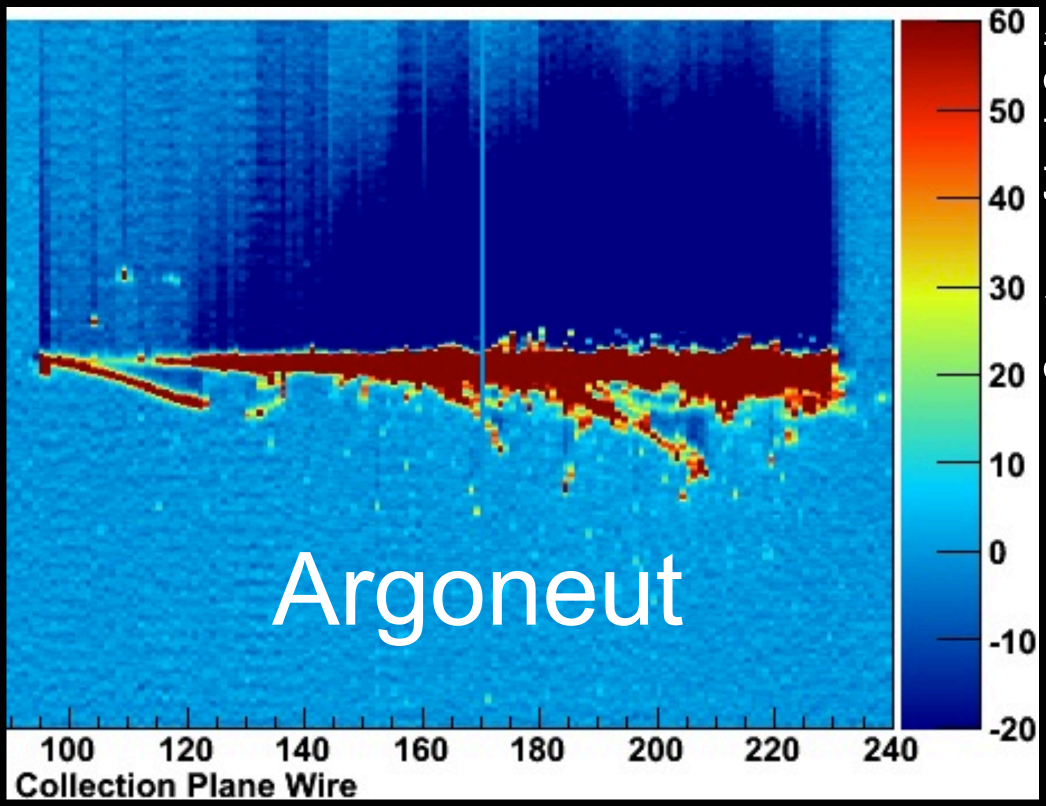
- Flux averaged double differential CCQE cross section
- Most complete, and least biased, information possible about the cross section based on the muon kinematics
  - Also being pursued for multi-particle final states
- Crucial input for theorists!

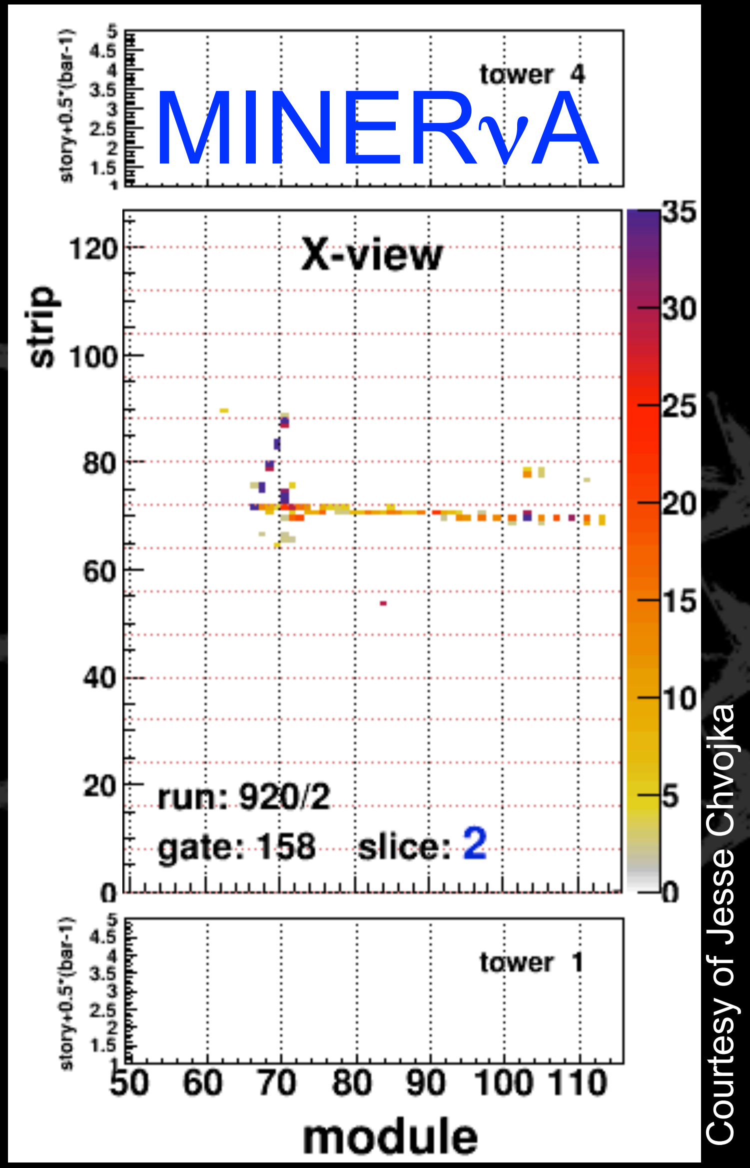


*PhysRevD **81** 092005 (2010)*

The Future

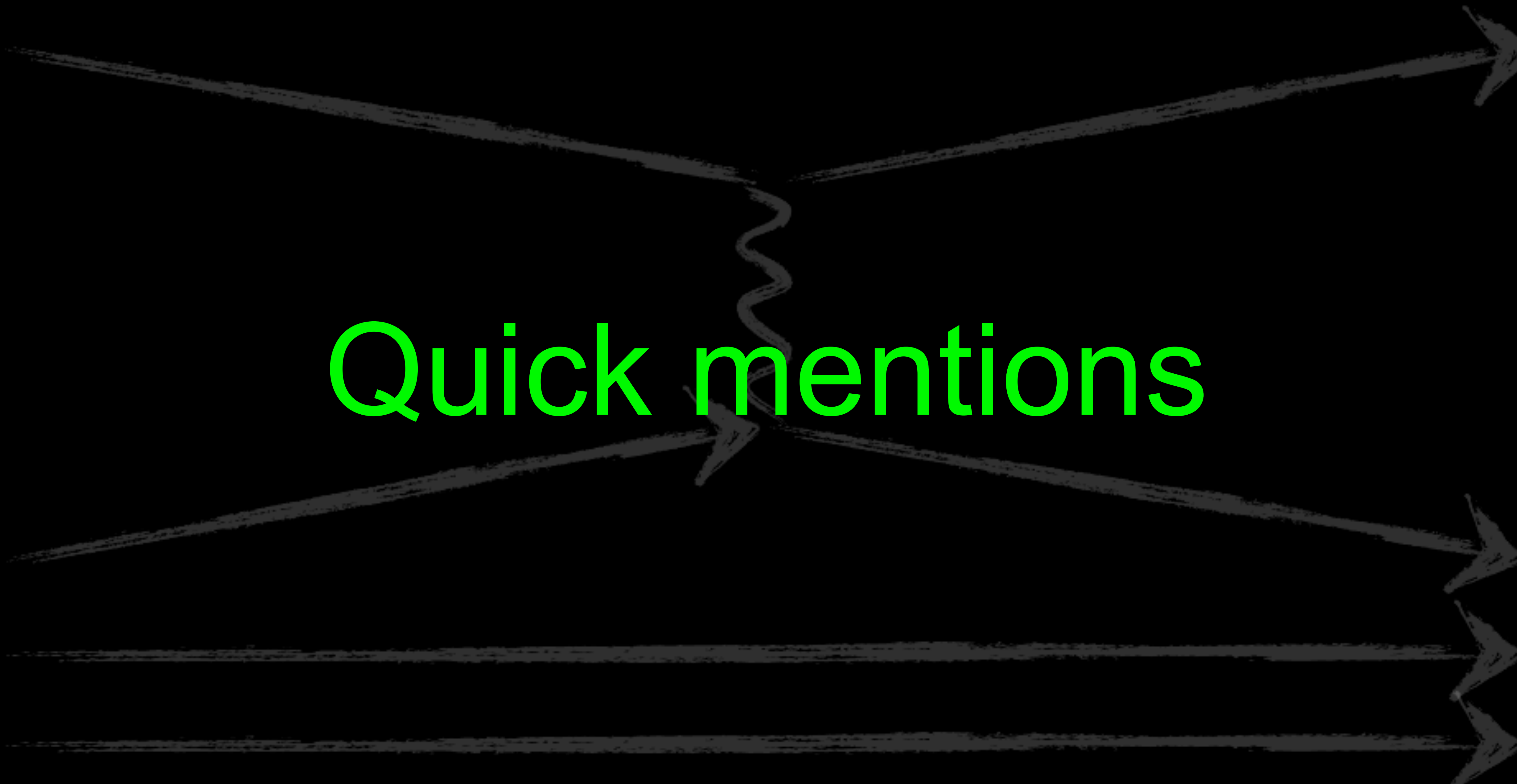




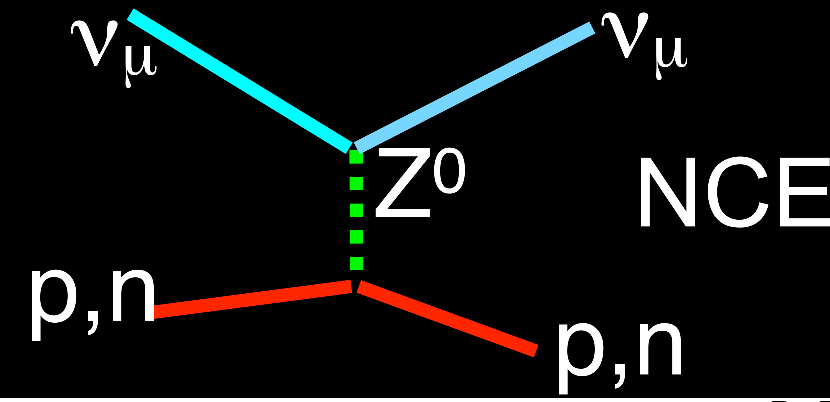


All data event displays - not MC!

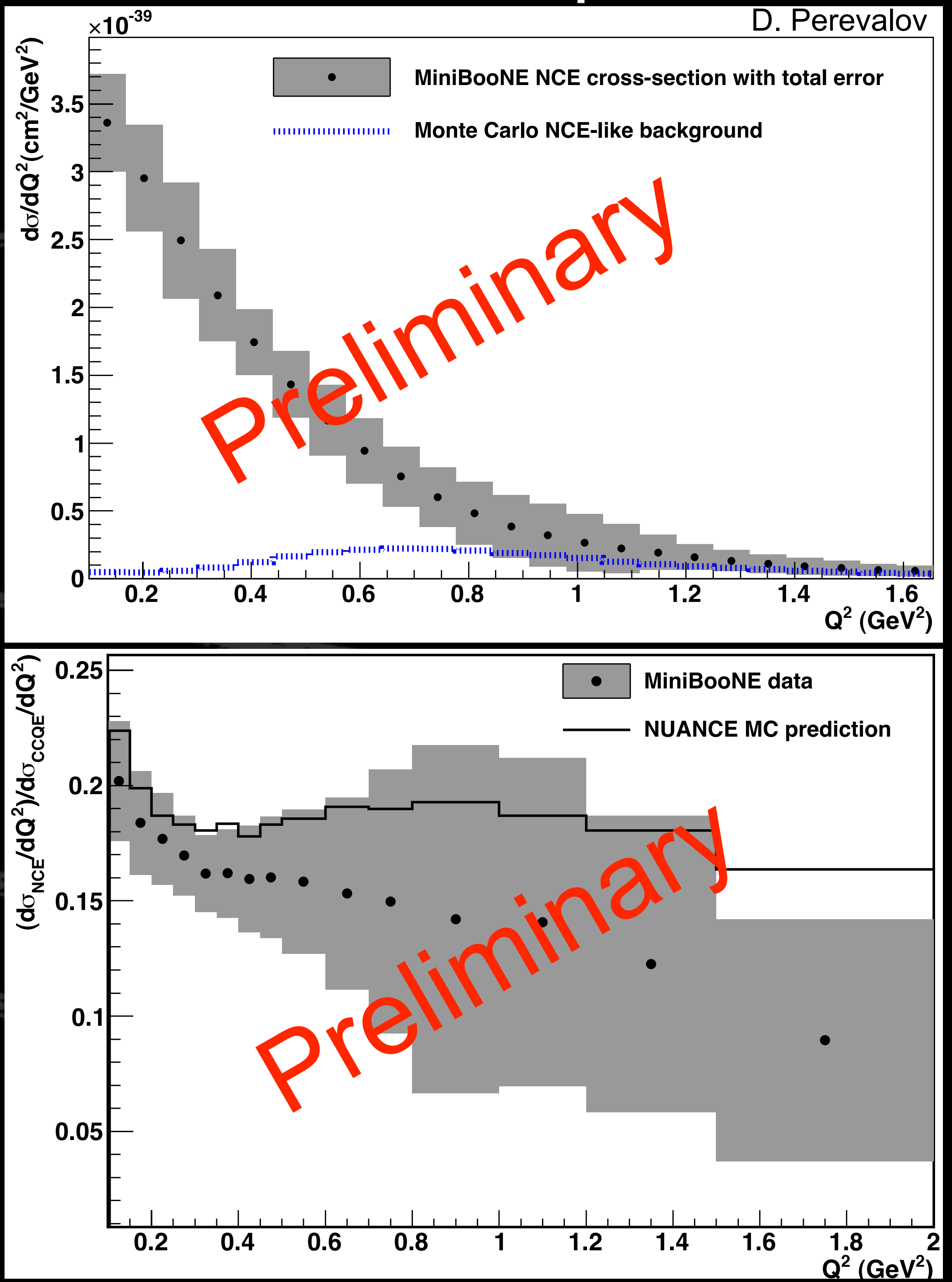
Quick mentions



MiniBooNE NC Elastic



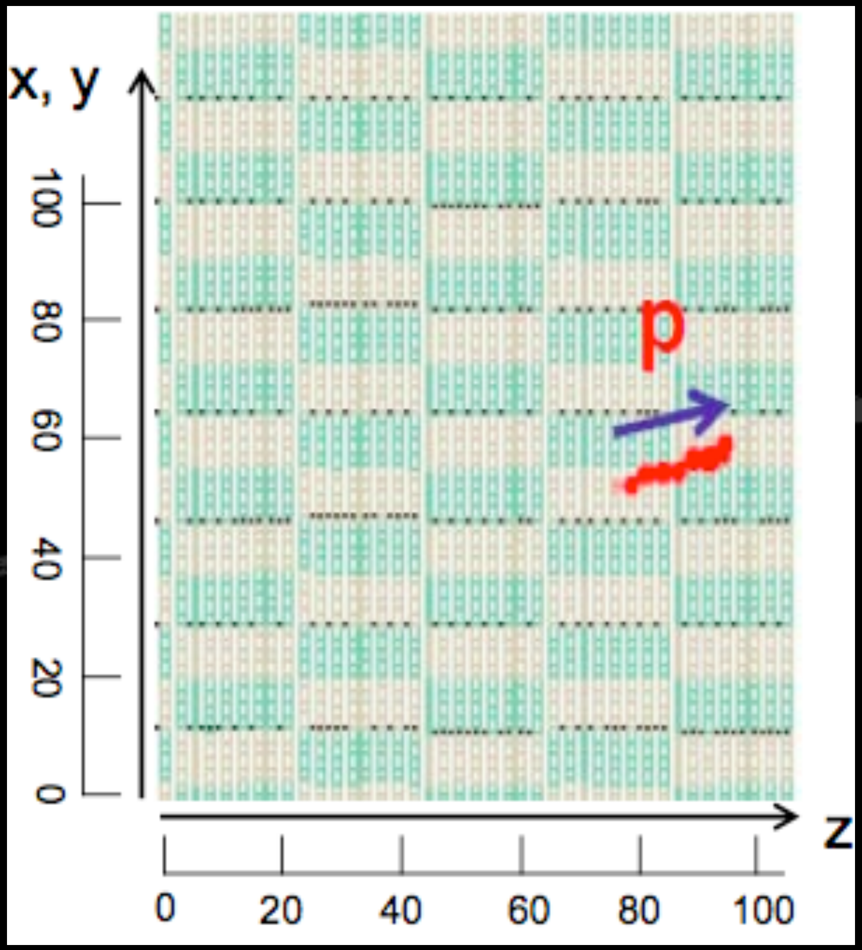
- NCE event selection requires no decay electron, light patterns characteristic of protons
- Fit Q2 distribution for MA
  - 1.39±0.11 GeV
- Measured ratio of NC/CC in same detector with same flux
  - Gives access to Δs
    - Δs = -0.08±0.26
    - Highly correlated with M_A

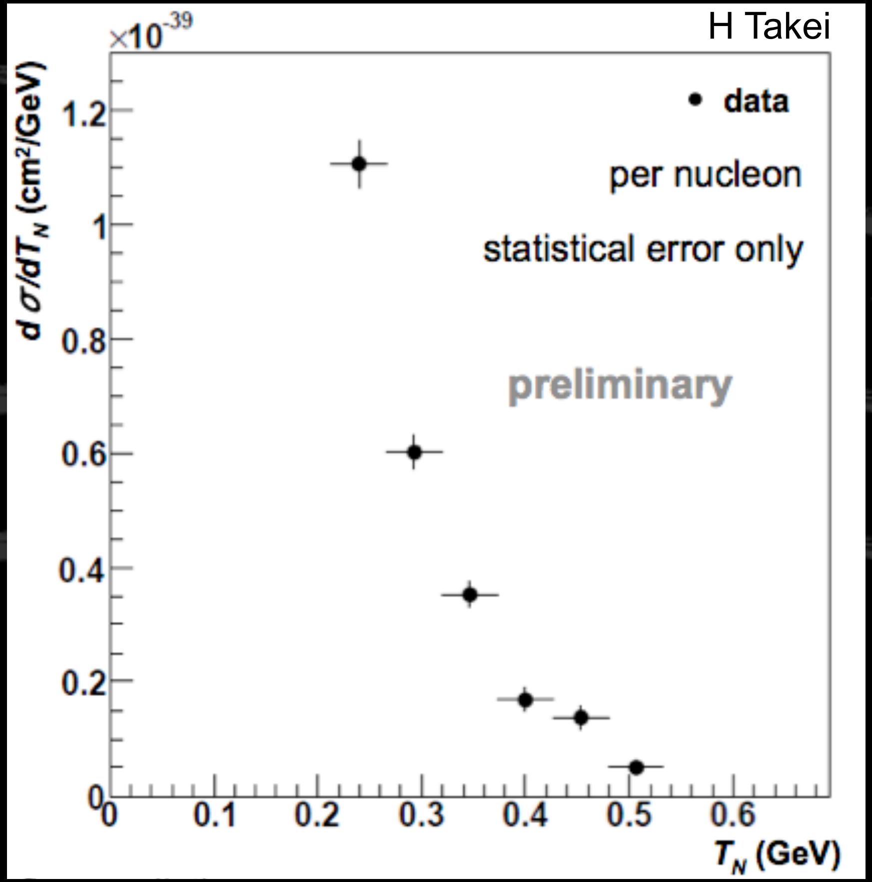


D Perevalov, FERMILAB-THESIS-2009-47

SciBooNE NC Elastic

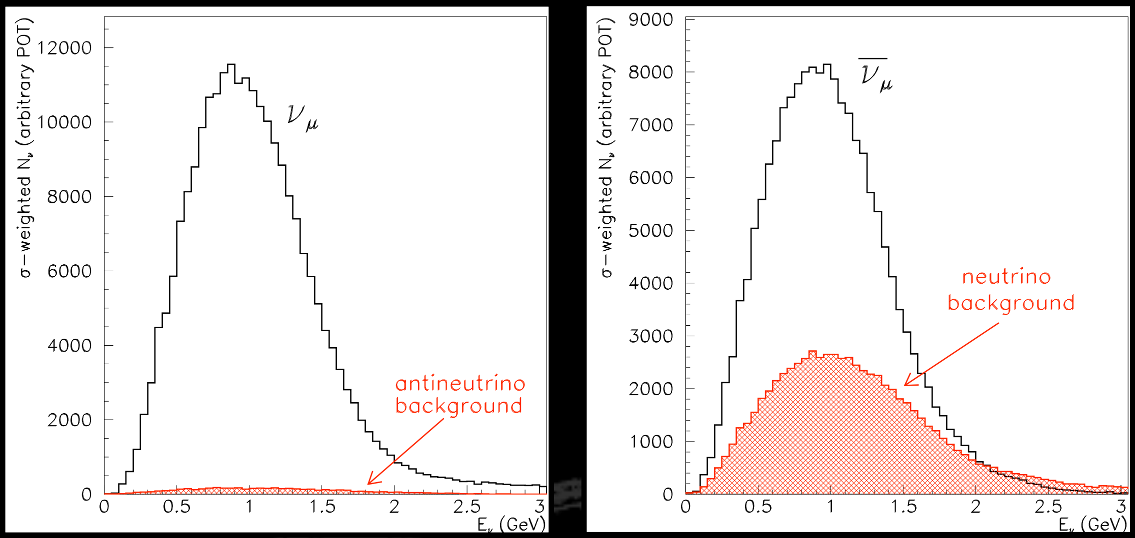
- Search for tracks with high ionisation
  - Recoil proton/neutron tracks
- Measure Q^2 directly from recoil nucleon
  - Different model dependence
  - Comparison to CCQE would be very valuable
- Analysis ongoing...





H. Takei, FERMILAB-THESIS-2009-19

MiniBooNE Antineutrinos



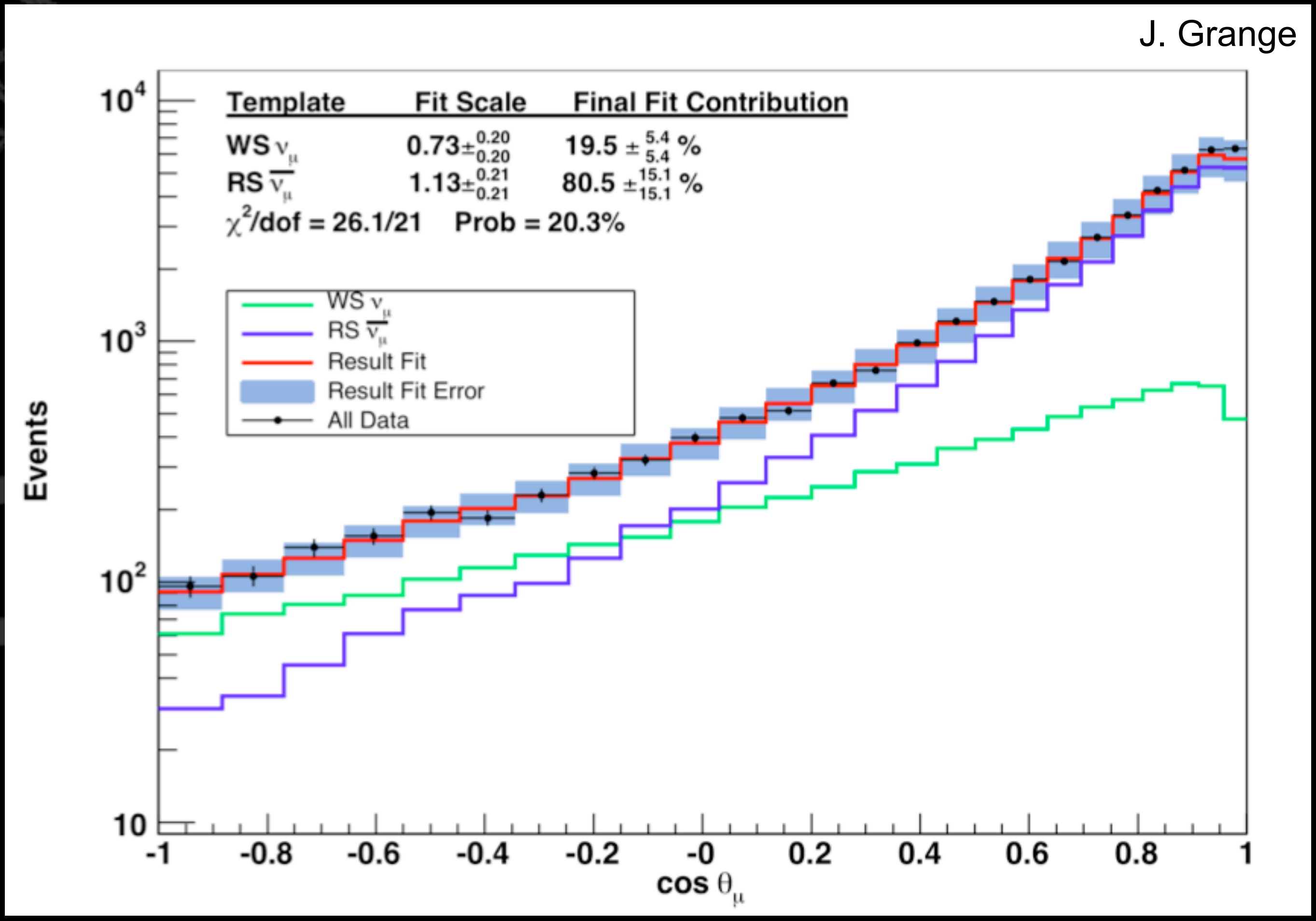
G.P. Zeller

- Very few measurements of nubar CCQE near 1 GeV

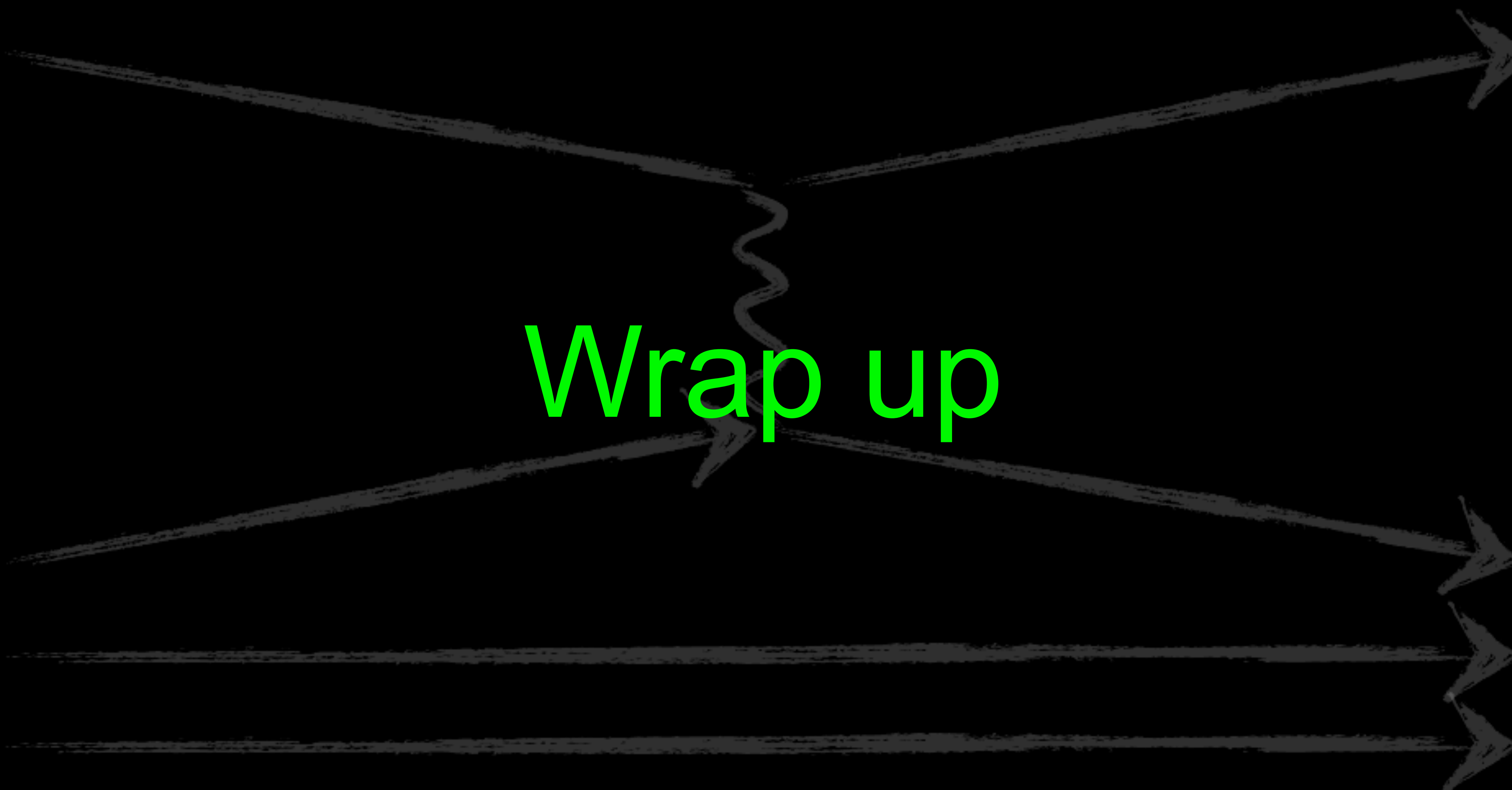
$$\frac{d\sigma^{QE}}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2) \times \left(\frac{s-u}{M^2}\right) + C(Q^2) \times \left(\frac{s-u}{M^2}\right)^2\right]$$

+ 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

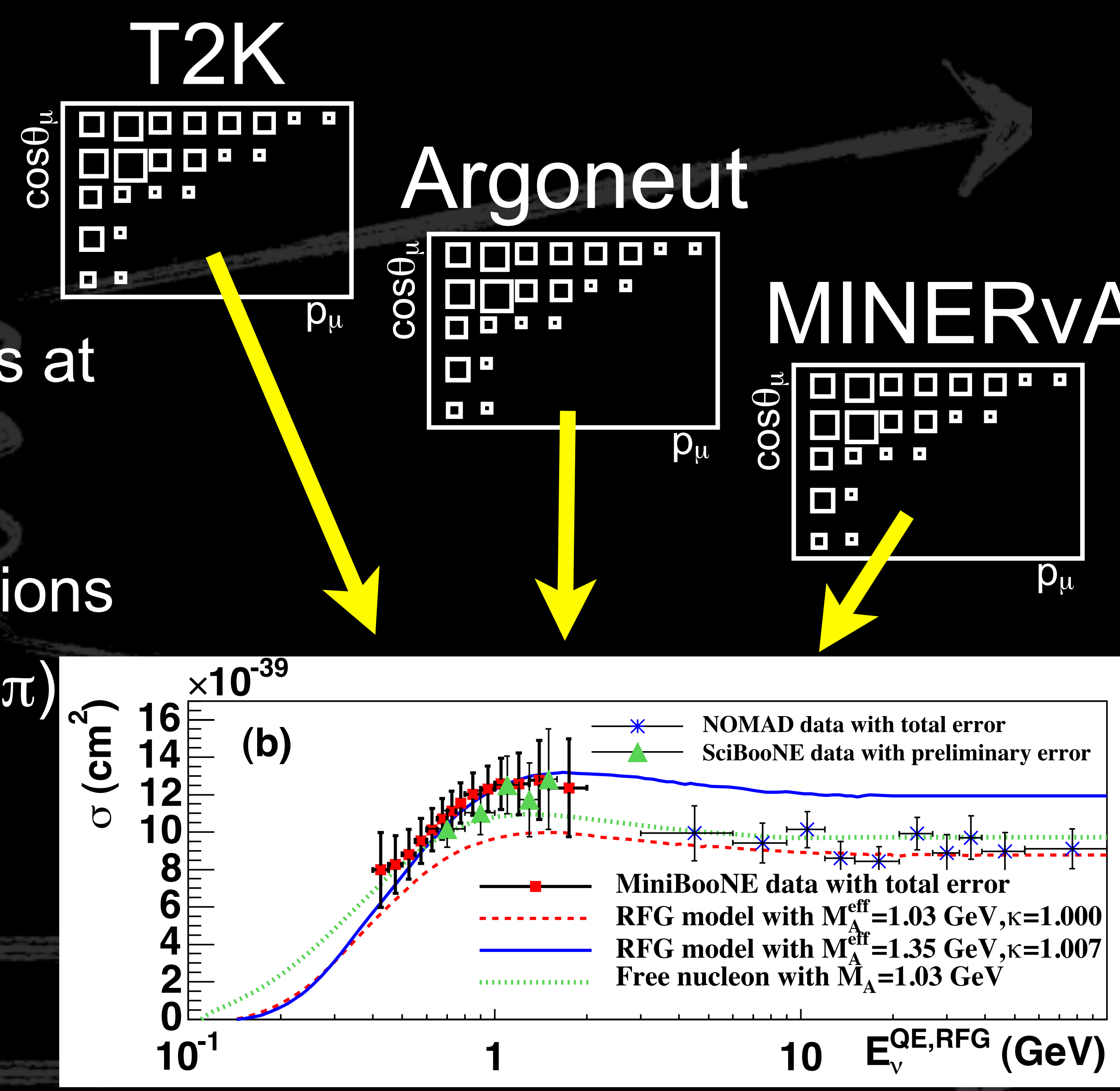


Summary

- 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), σ(μ), σ(μ+p), σ(μ+π)
    - (CC Inclusive measurements offer most robust confrontation of theory and experiment)



Same goes for NC...

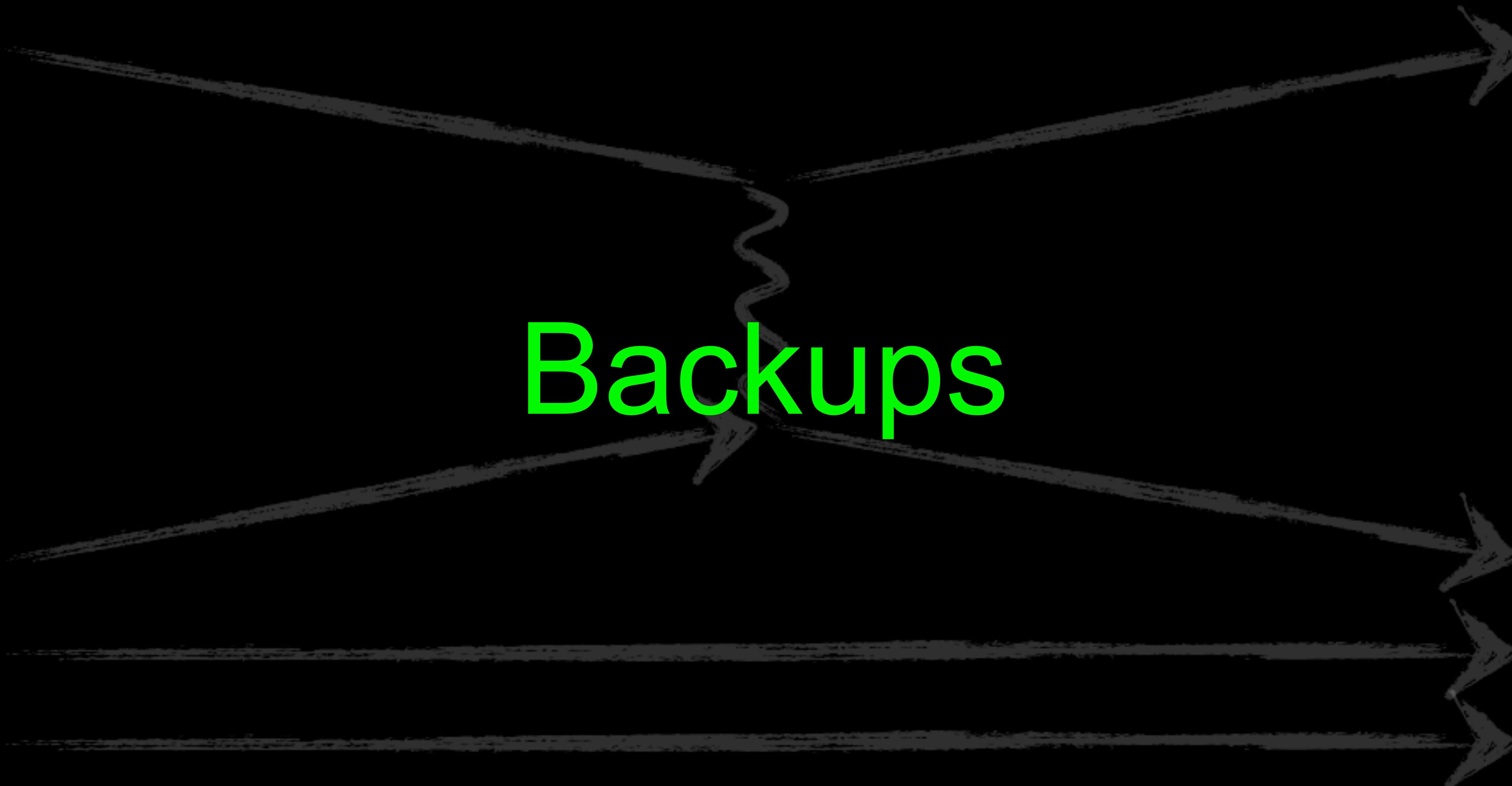
Conclusions

- 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!

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

Thanks!

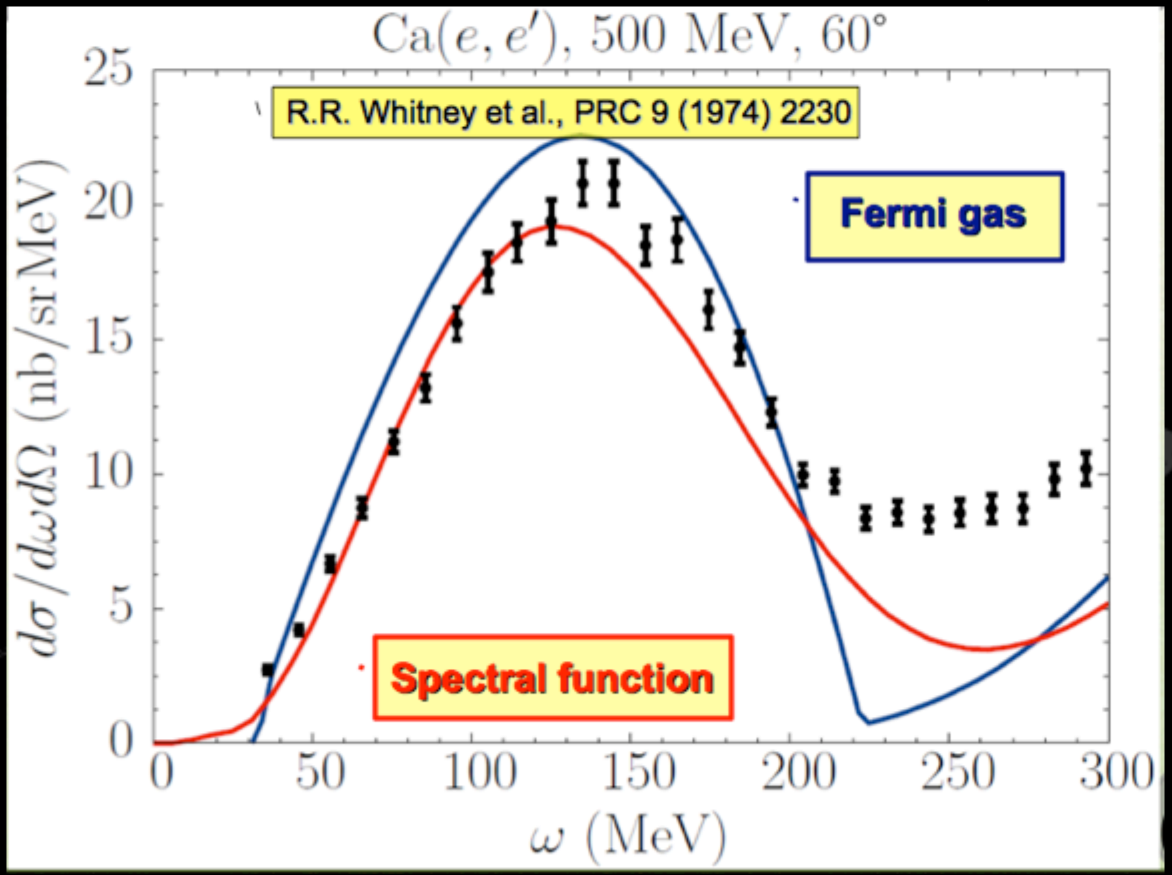
Backups



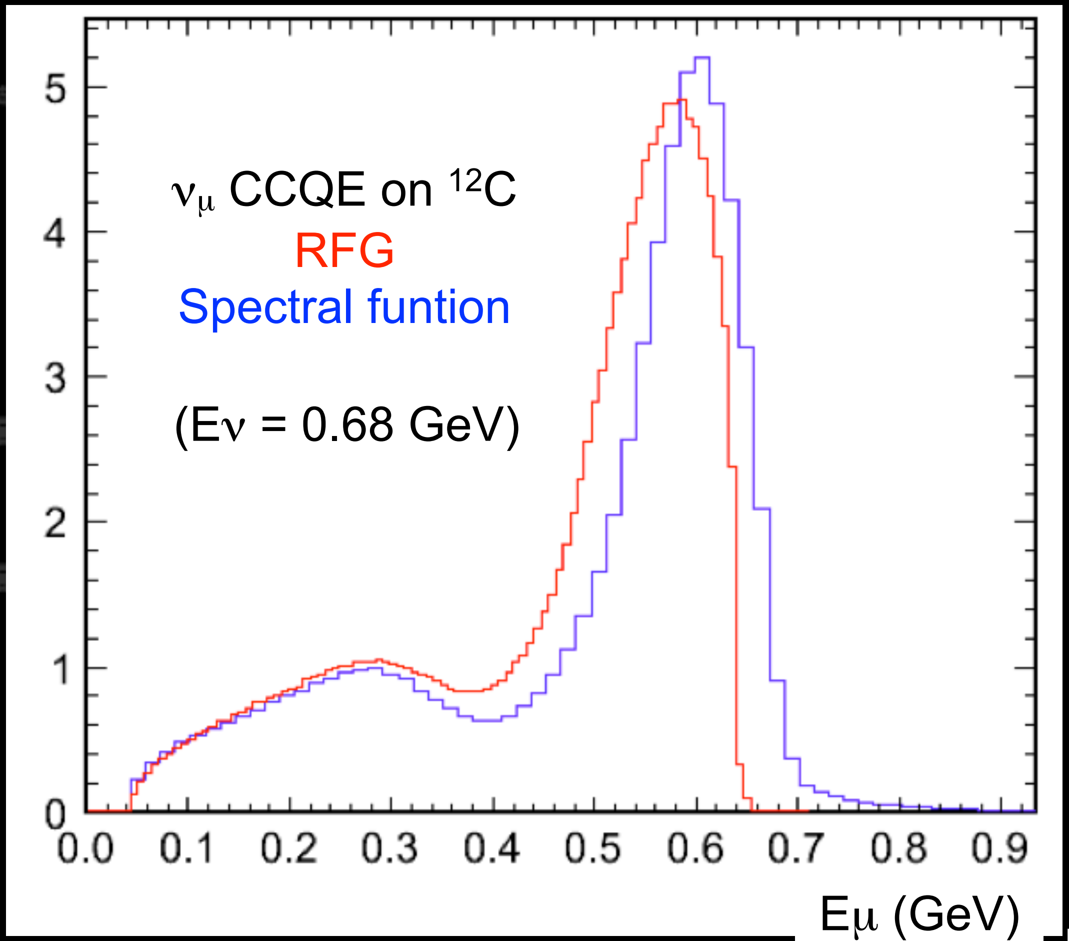
Nuclear Models

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

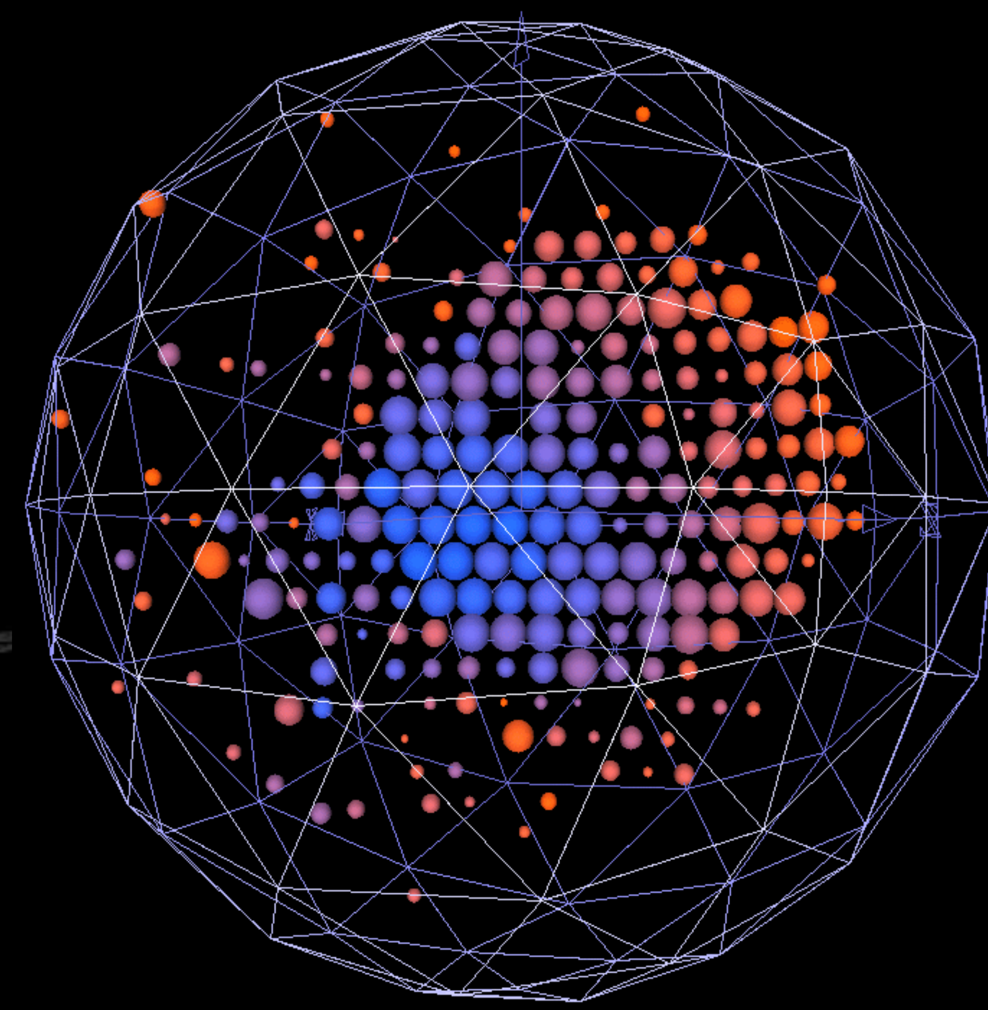
Ankowski, NuInt09



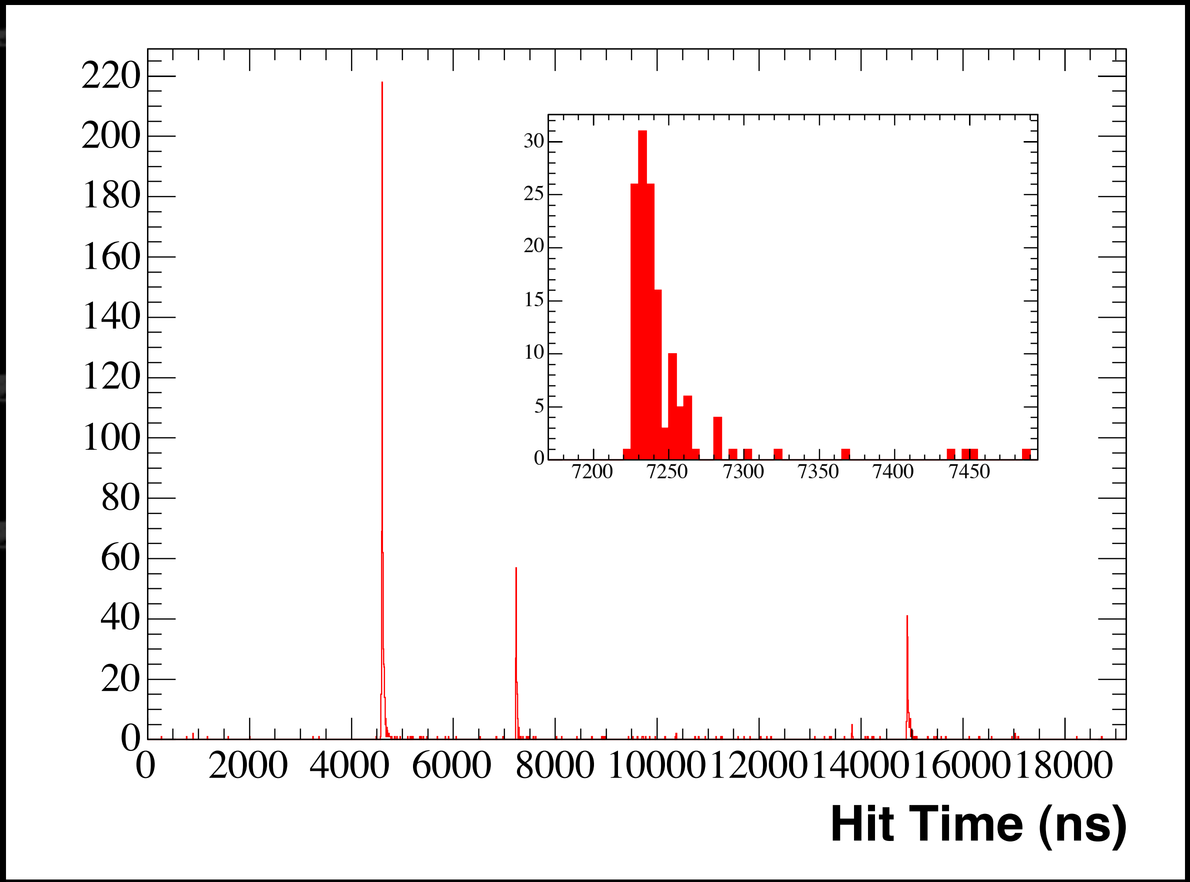
Prouse (Imperial College London)



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

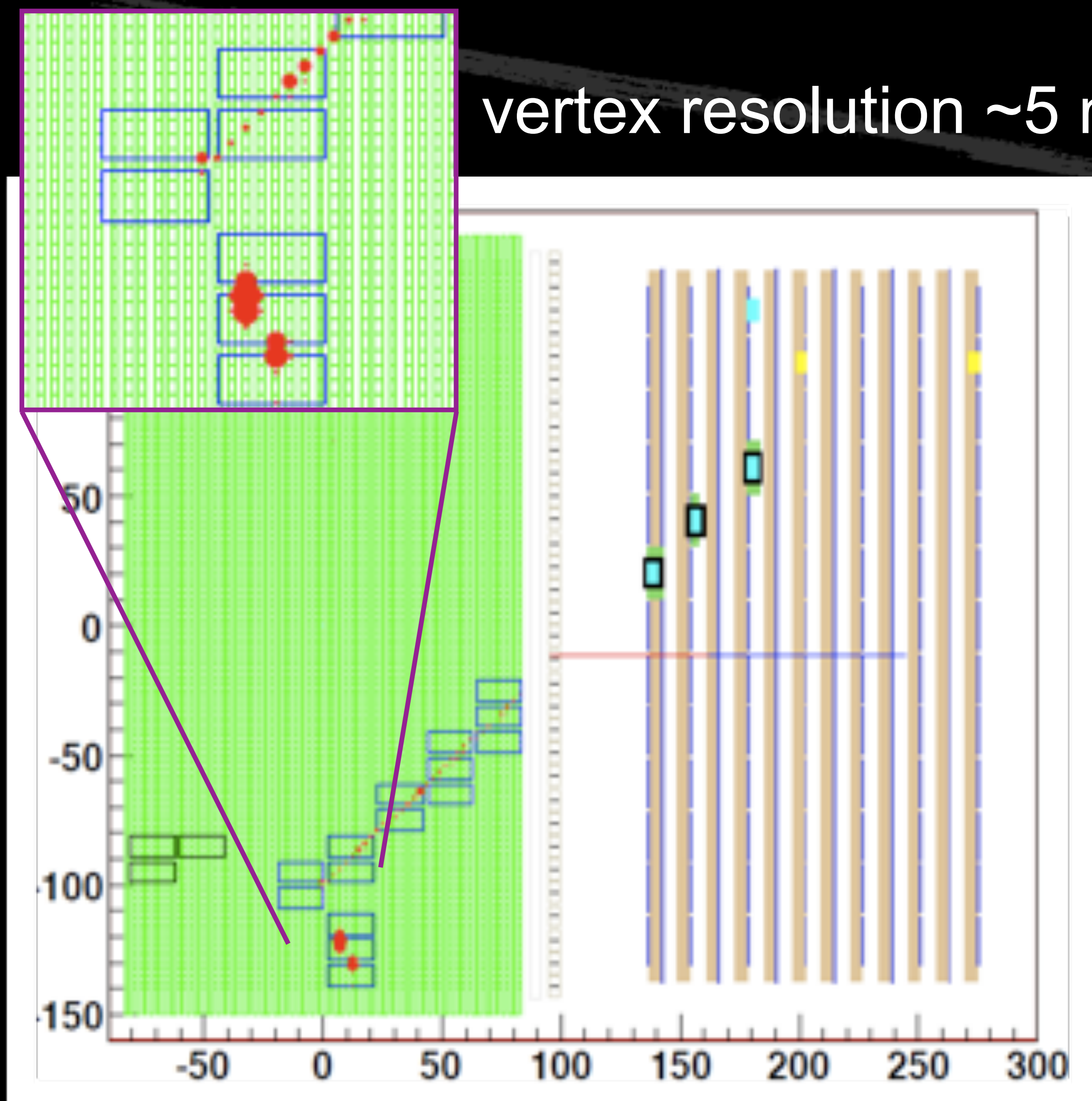


27% efficiency
77% purity
146,070 events
with 5.58E20POT

Neutrino event displays

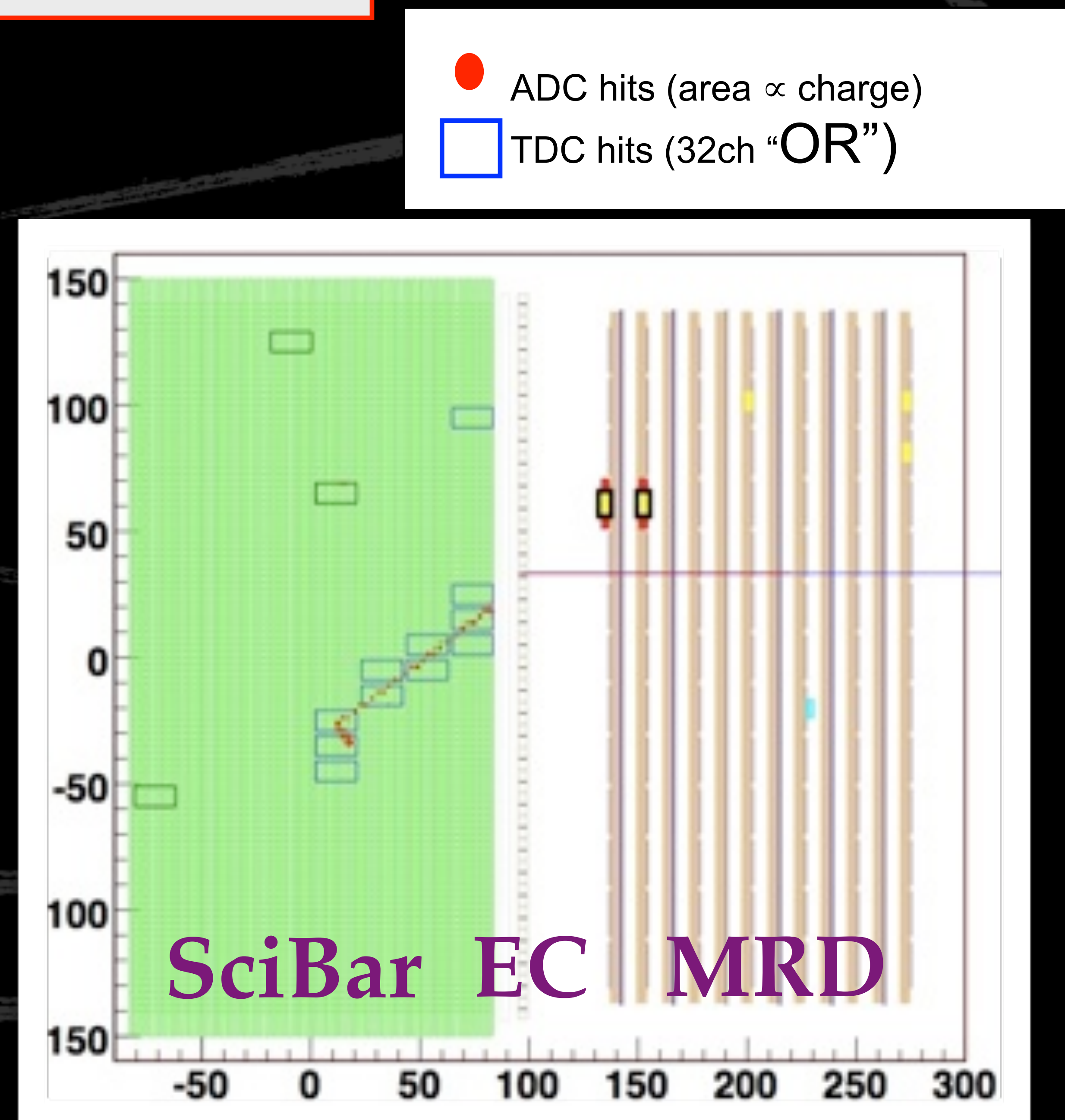
Real SciBooNE Data

vertex resolution ~5 mm



anti-ν_μ CC-QE candidate

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

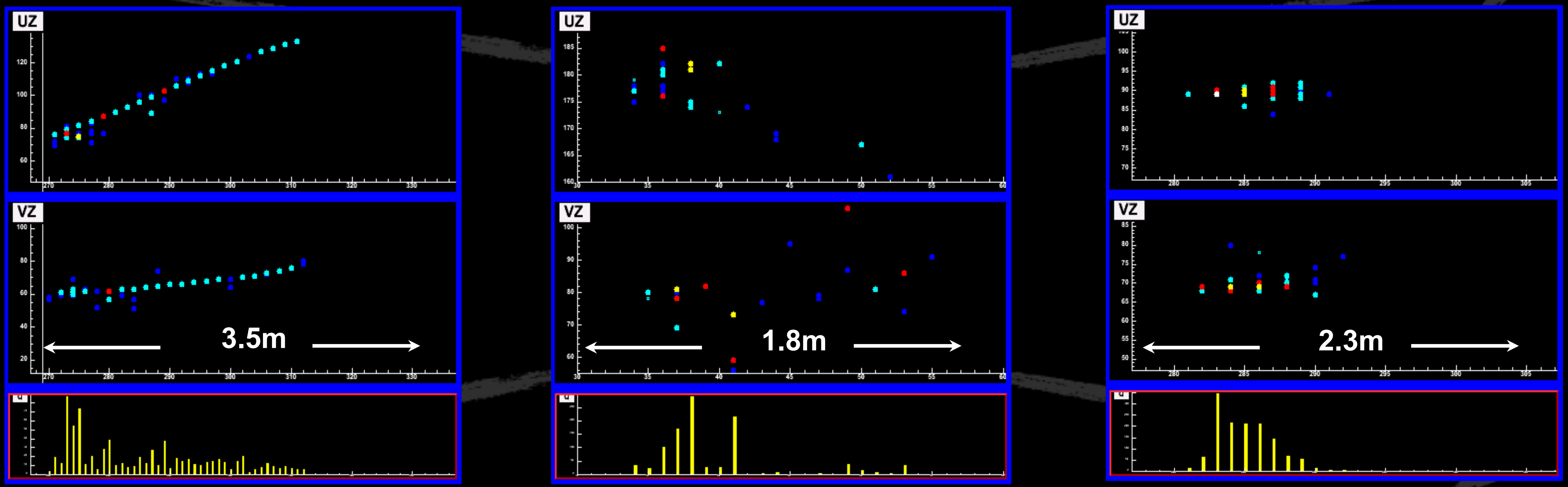


ν_μ CC-QE candidate

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

Events in the MINOS Detectors

ν_μ CC Event — NC Event — ν_e CC Event



ν_μ CC Event: Long muon track with hadronic activity at the vertex.

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

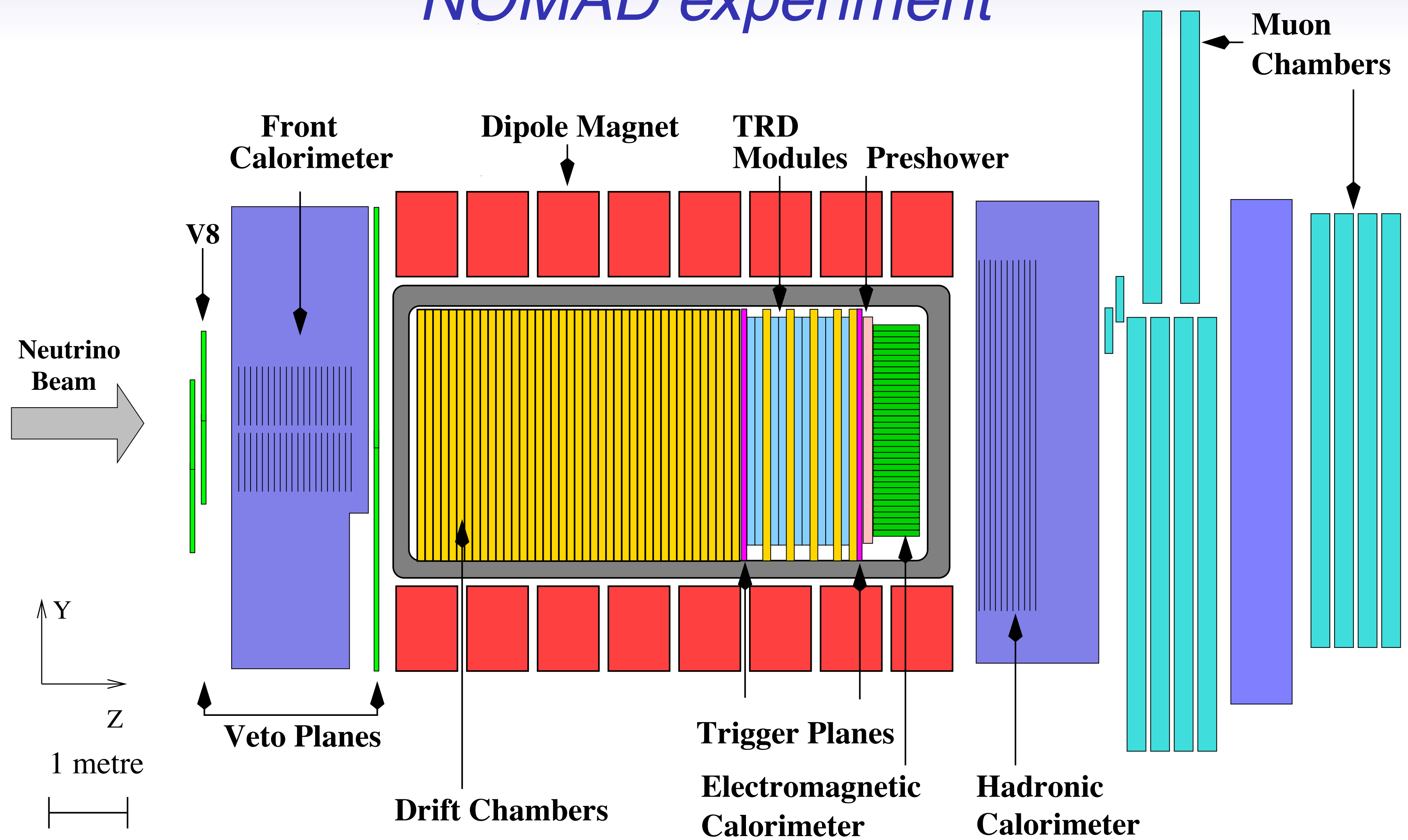
NC Event: Short event often with a diffuse shower.

What we use for the sterile neutrino analysis.

ν_e CC Event: Short event with a compact, EM-like shower profile.

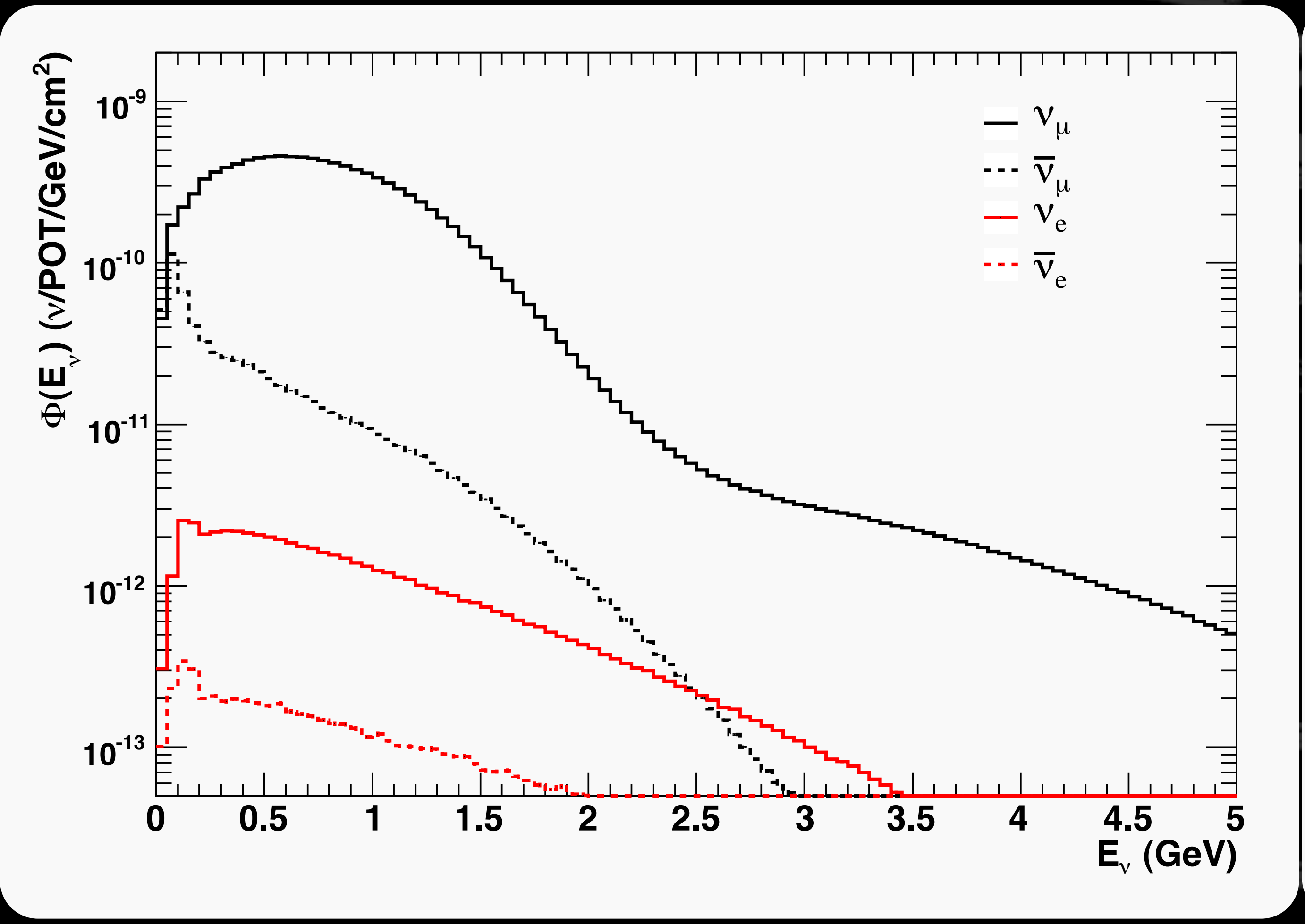
What we look for in the electron neutrino analysis.

NOMAD experiment

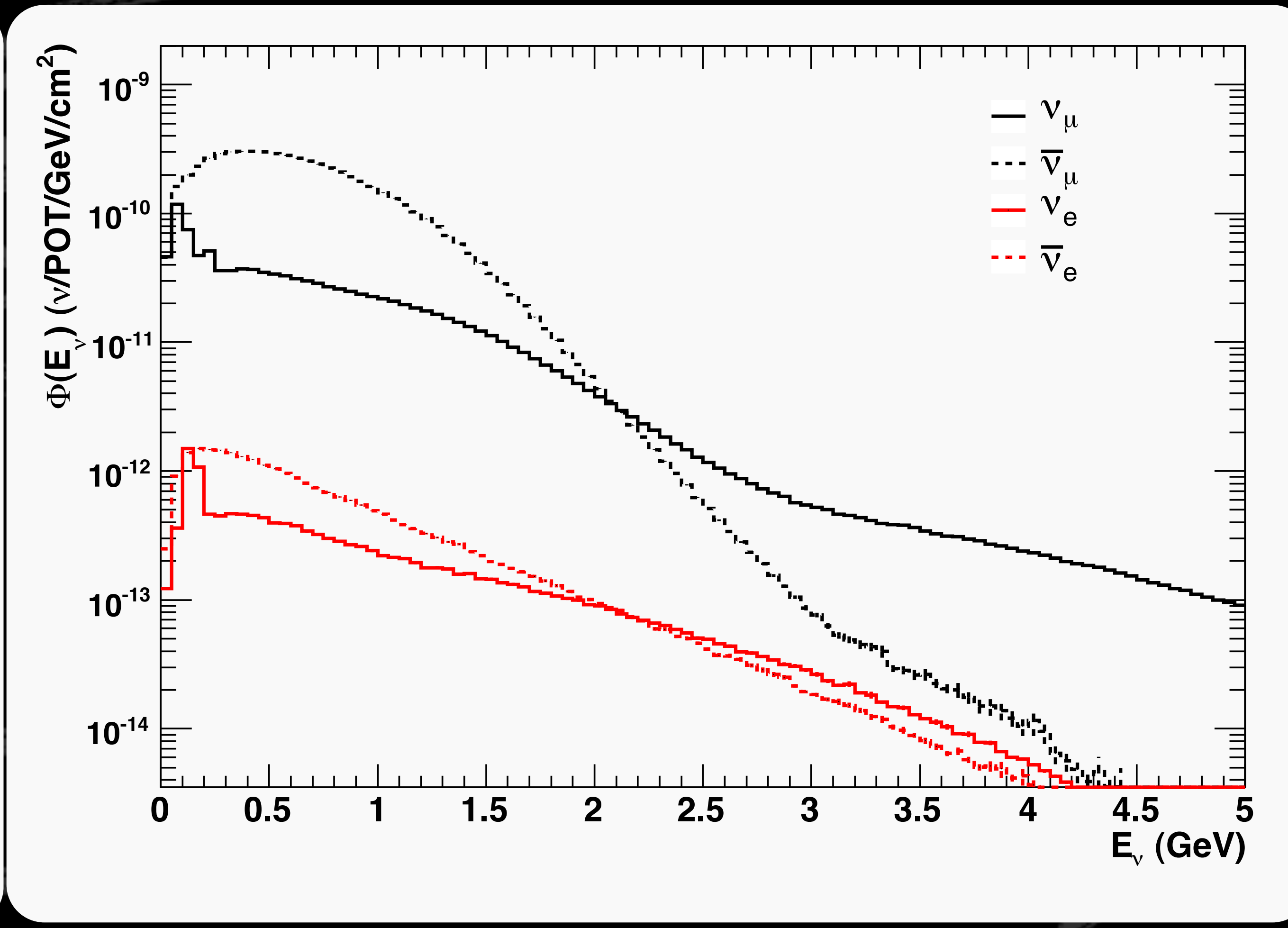


- Drift Chambers (target and momentum measurement) Position resolution $< 200\ \mu$m (small angle tracks) Momentum resolution $\sim 3.5\%$ ($p < 10$ GeV/c)
- Transition Radiation Detector for $e^{\pm}$ identification: π rejection $\sim 10^3$ for electron efficiency $\geqslant 90\%$
- Lead glass Electromagnetic Calorimeter $\frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{(3.22 \pm 0.07)\%}{\sqrt{E\ (\text{GeV})}}$
- 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

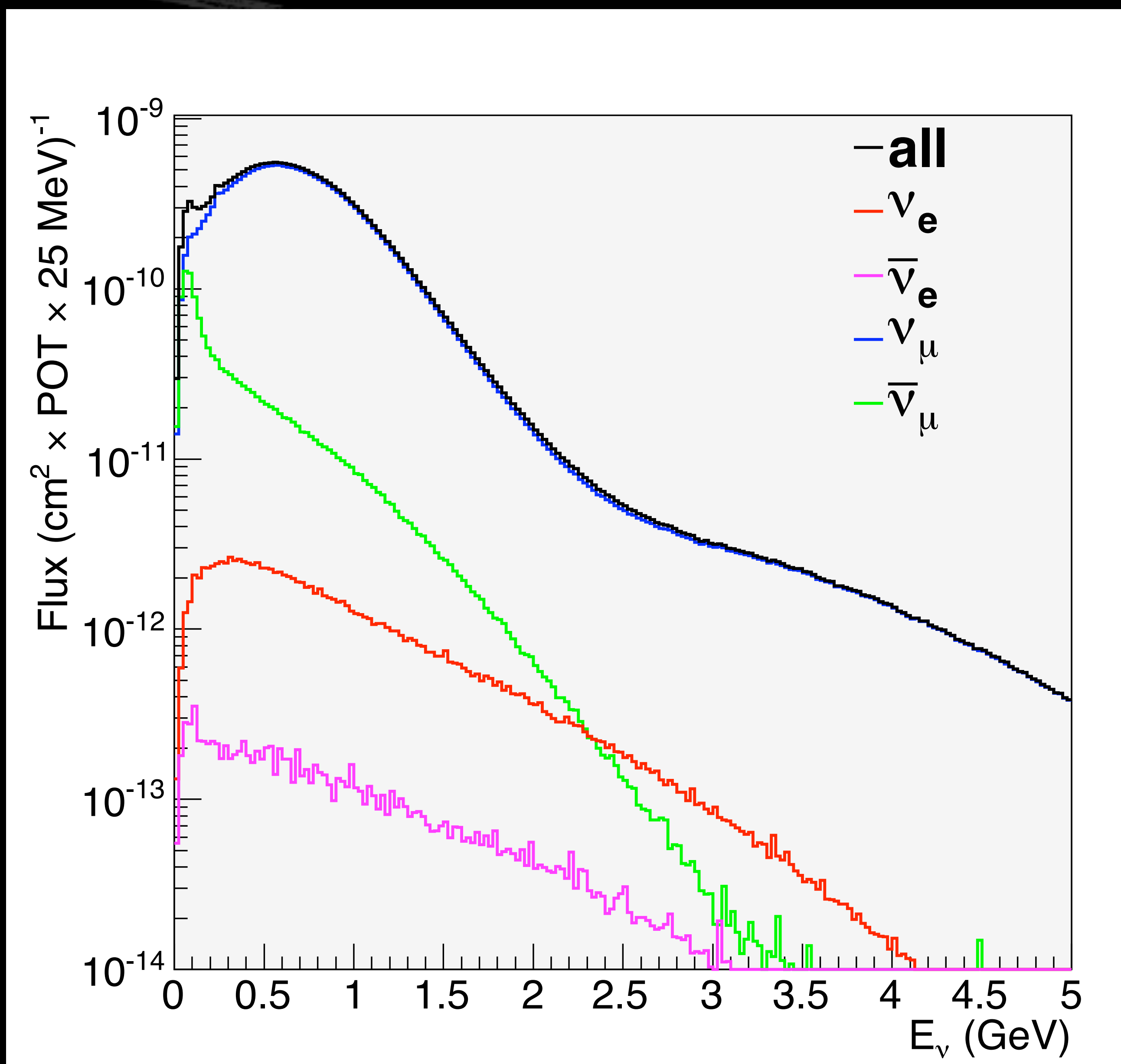


$\Phi(E_\nu)$ (ν/POT/GeV/cm^2)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
E_ν (GeV)

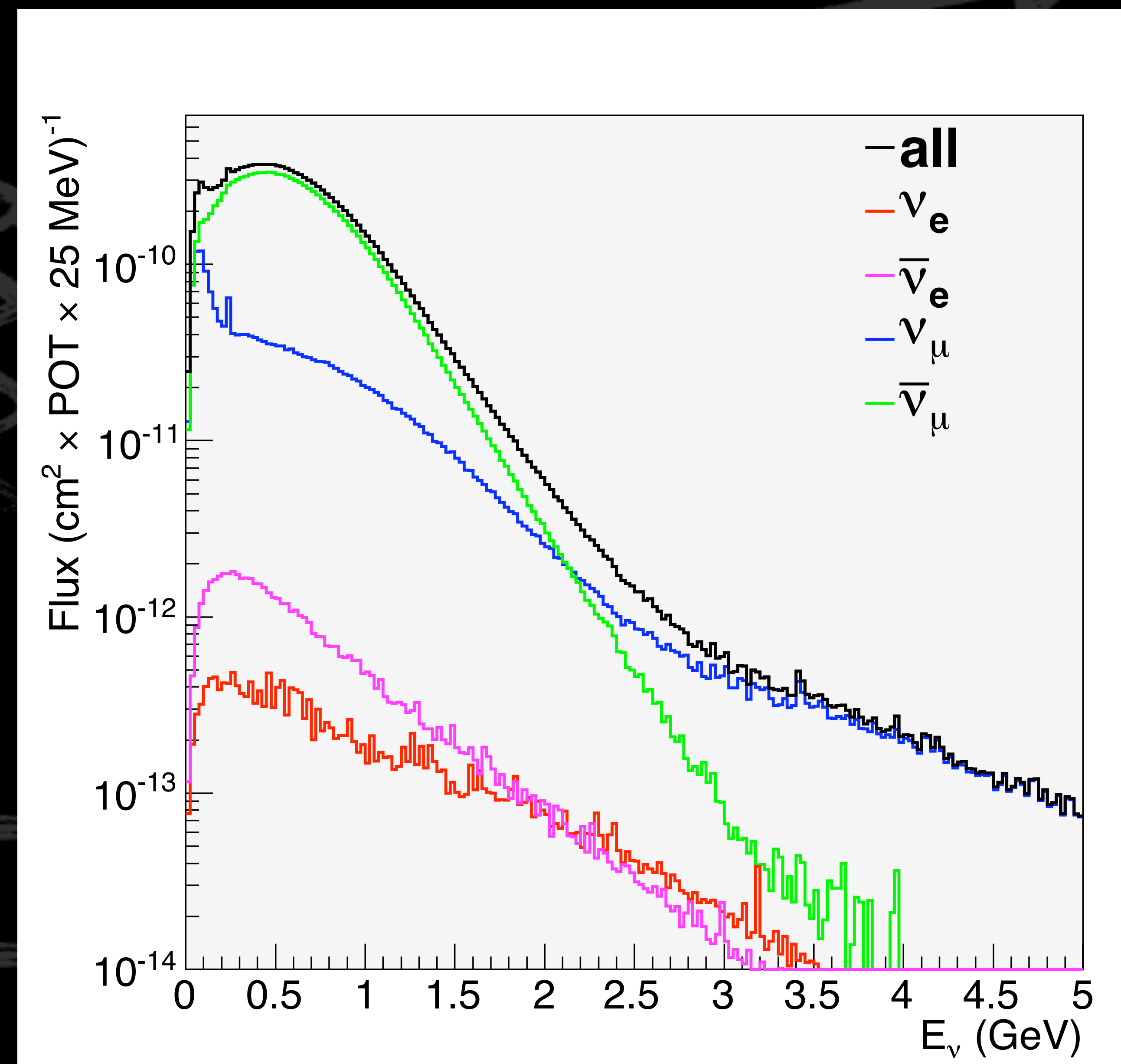


$\Phi(E_\nu)$ (ν/POT/GeV/cm^2)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
E_ν (GeV)

SB fluxes

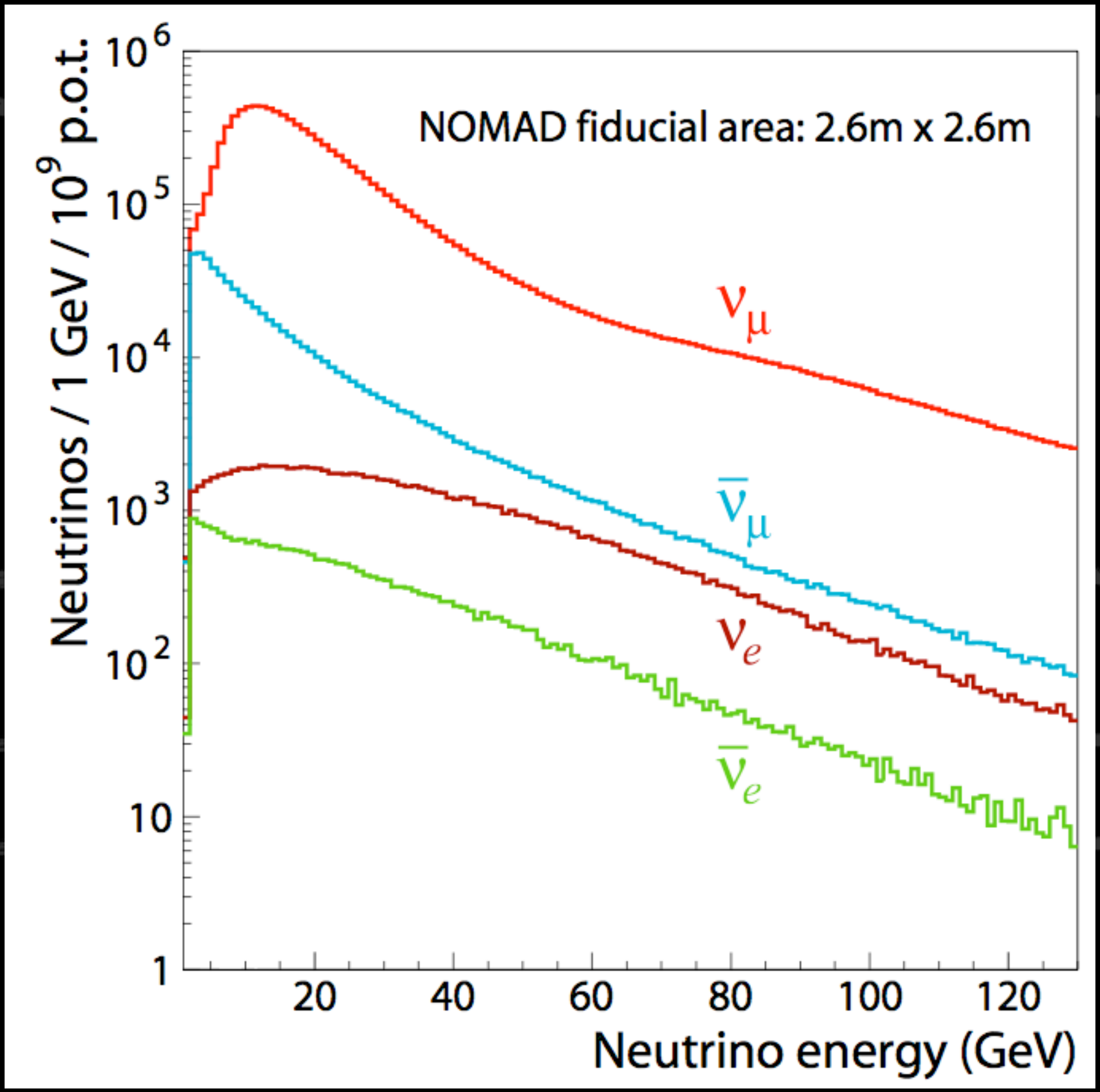


Flux (cm^2 × POT × 25 MeV)$^{-1}$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
E_ν (GeV)
all
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$

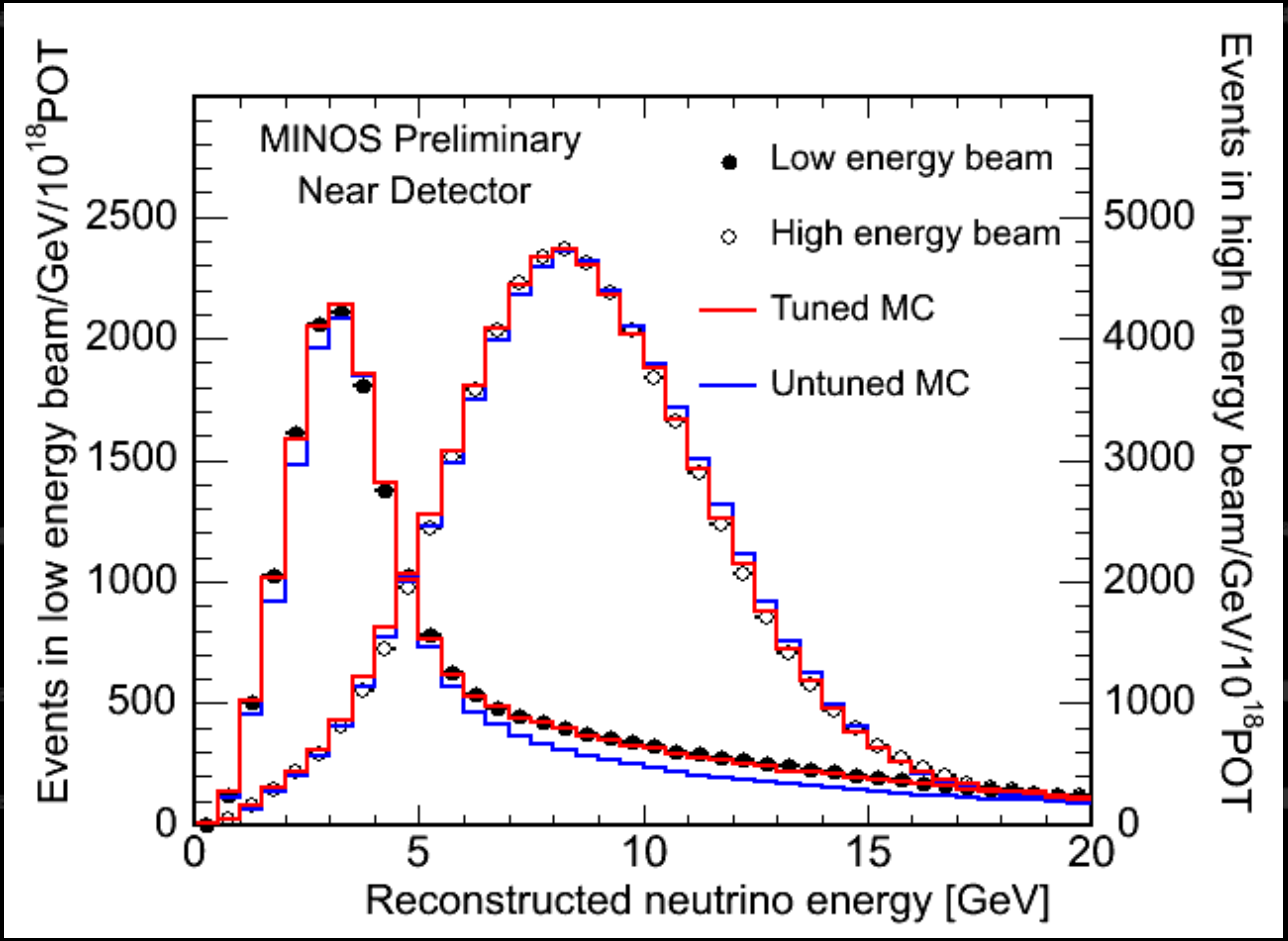


Flux (cm^2 × POT × 25 MeV)$^{-1}$
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5
E_ν (GeV)
all
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$

NOMAD fluxes



MINOS fluxes



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