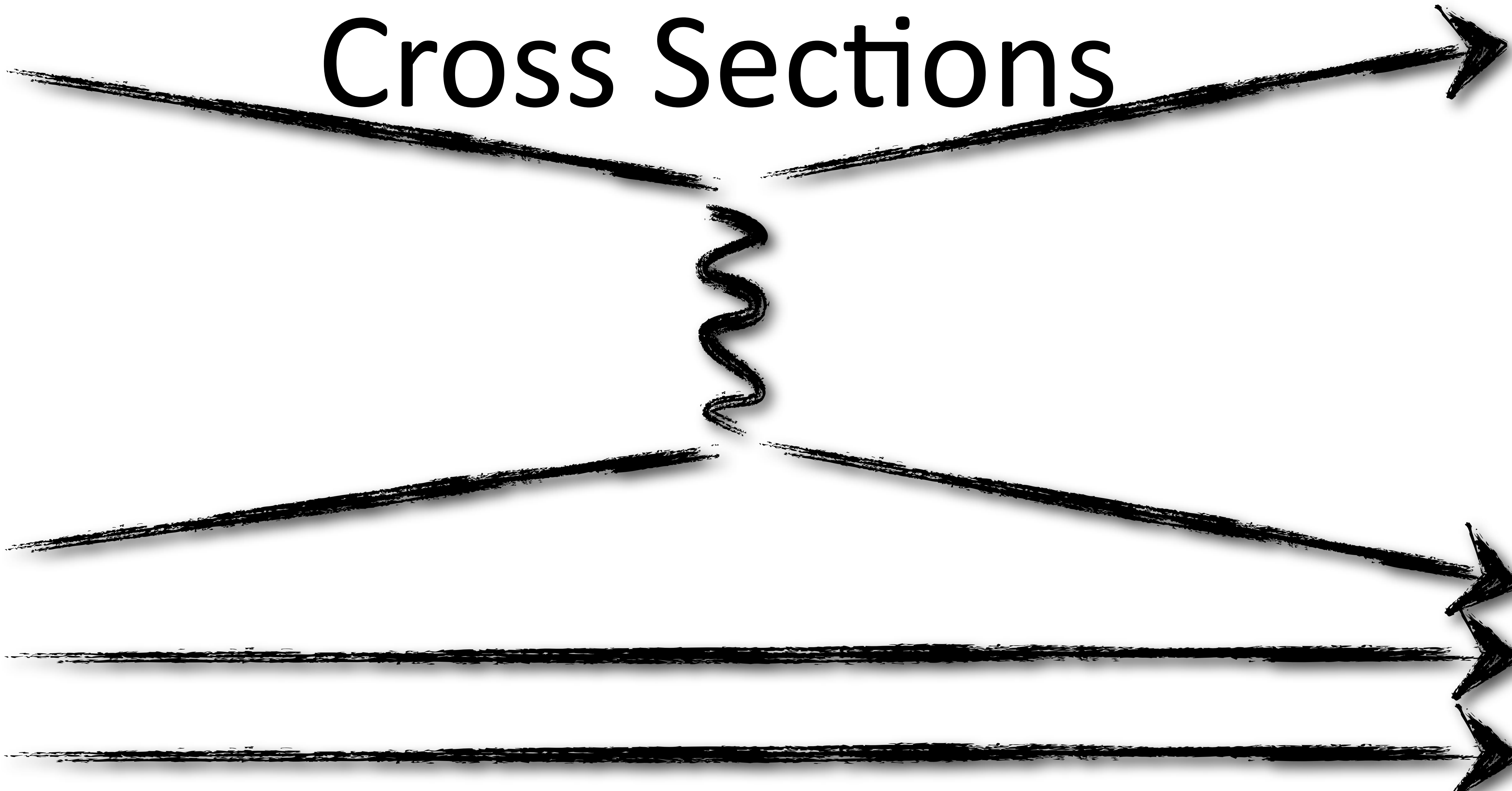
Introduction to

Neutrino Interaction Cross Sections



Morgan Wascko

International Neutrino Summer School 2011

2011 07 23

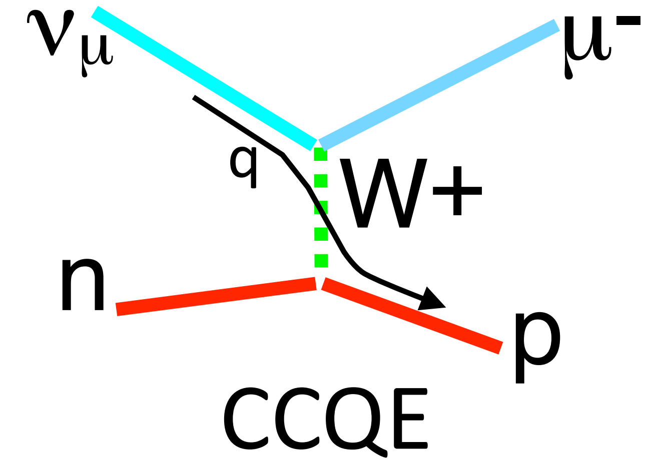
Outline

- Introduction to cross section calculations
- Focus on charged current quasi-elastic scattering
- Introduction to cross section experiments
  - Connections to neutrino oscillations
- Focus on CCQE

Lecture 1

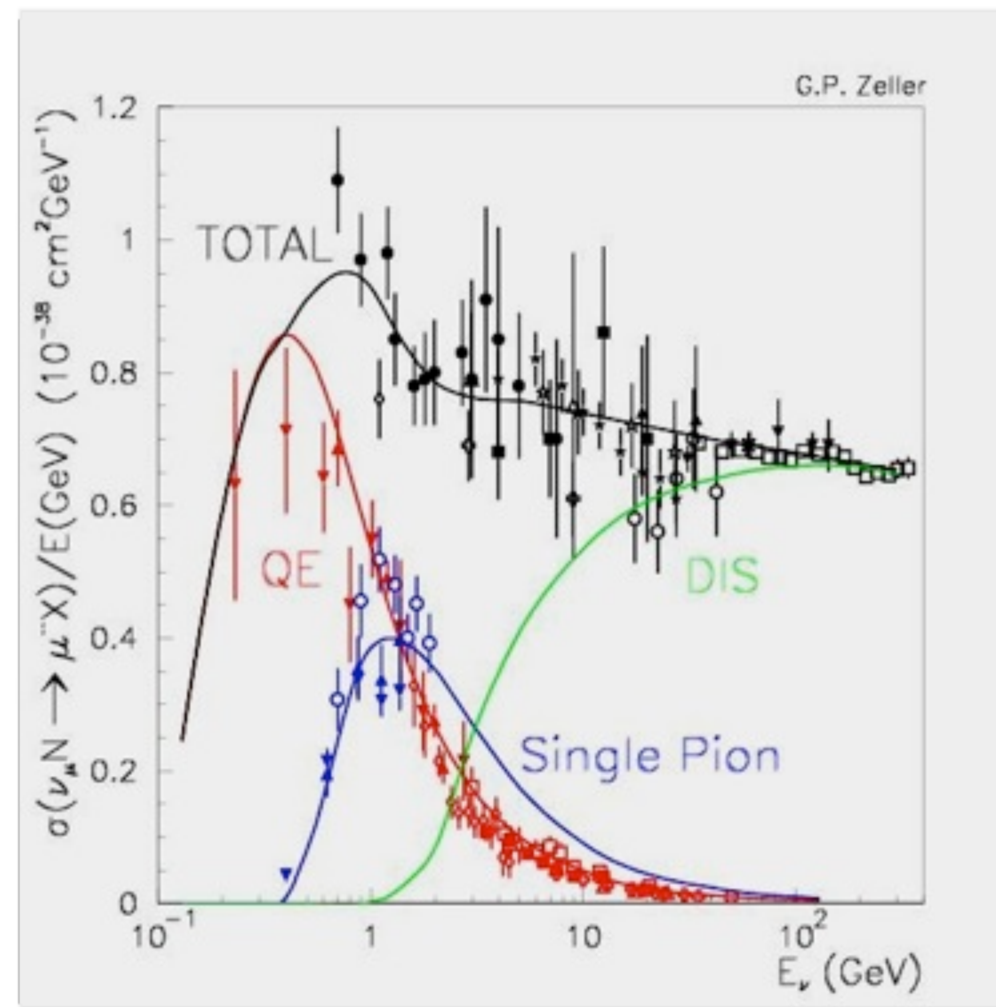
Lecture 2

Quasi-Elastic Scattering



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

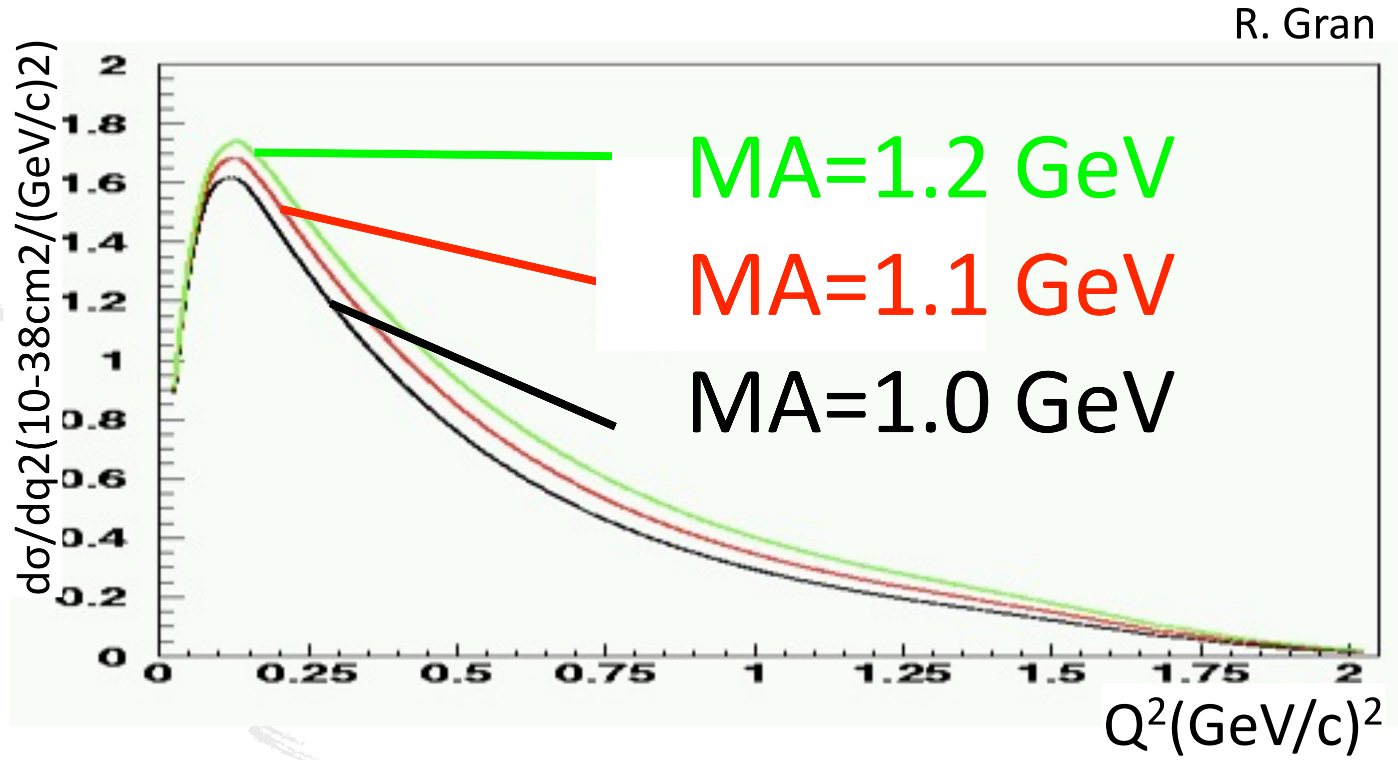
(where $Q^2 = -q^2$)



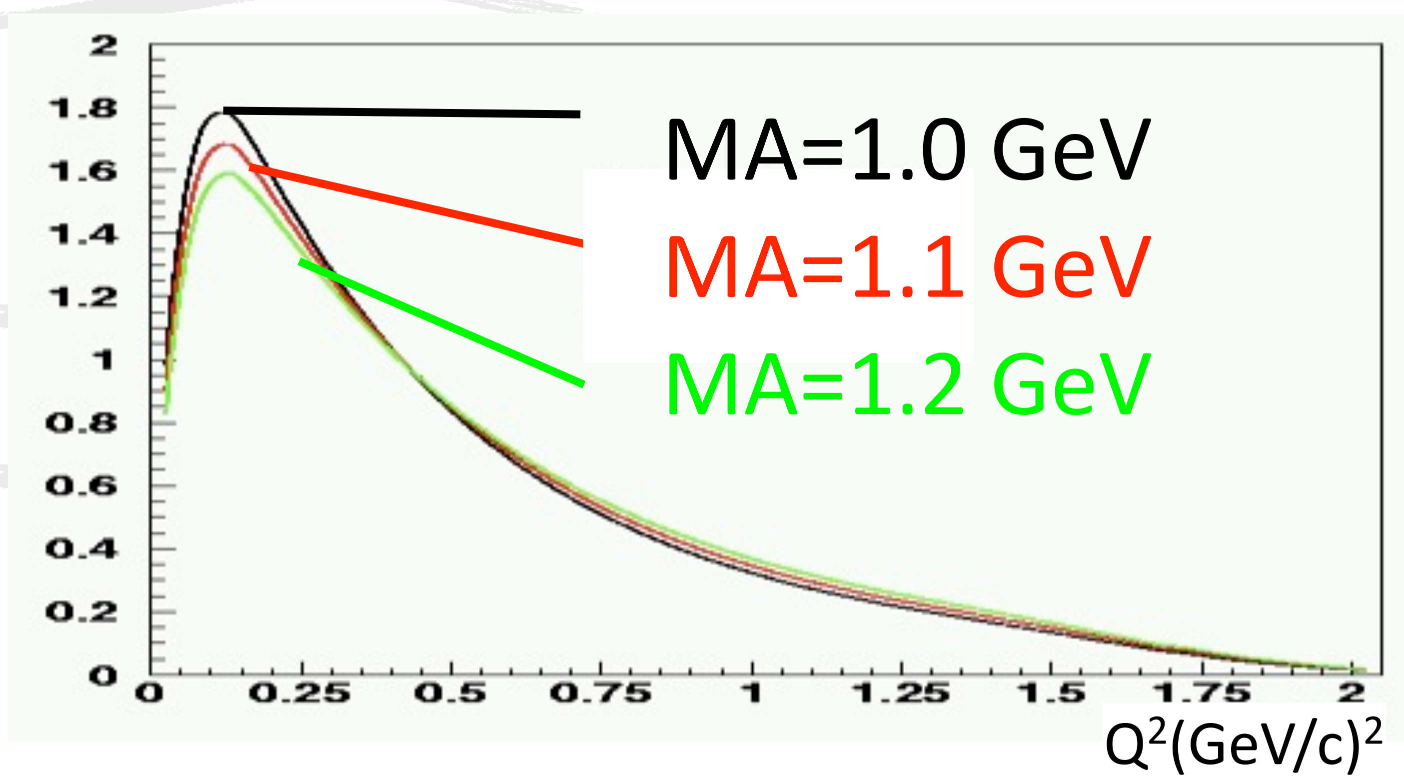
- Described by Llewellyn-Smith formalism
- Form-factors parameterise nucleon weak charge distributions
  - F_V measured by electron scattering, F_P negligible due to kinematics, F_A assumed to be dipole
- Important for accelerator ν beams
  - Dominant process near 1 GeV
  - Simple energy reconstruction

Importance of M_A

Absolute Cross-section (includes normalisation)

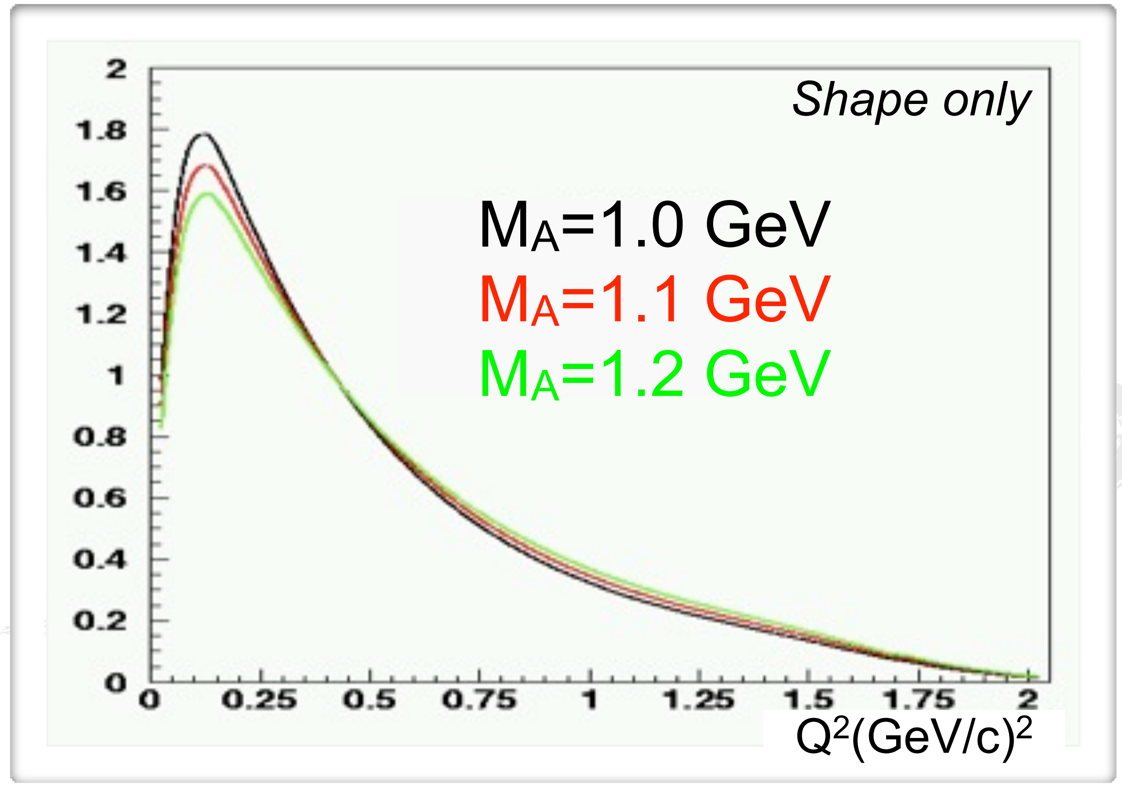


Shape only



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

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My local London pub

Courtesy of R. Gran

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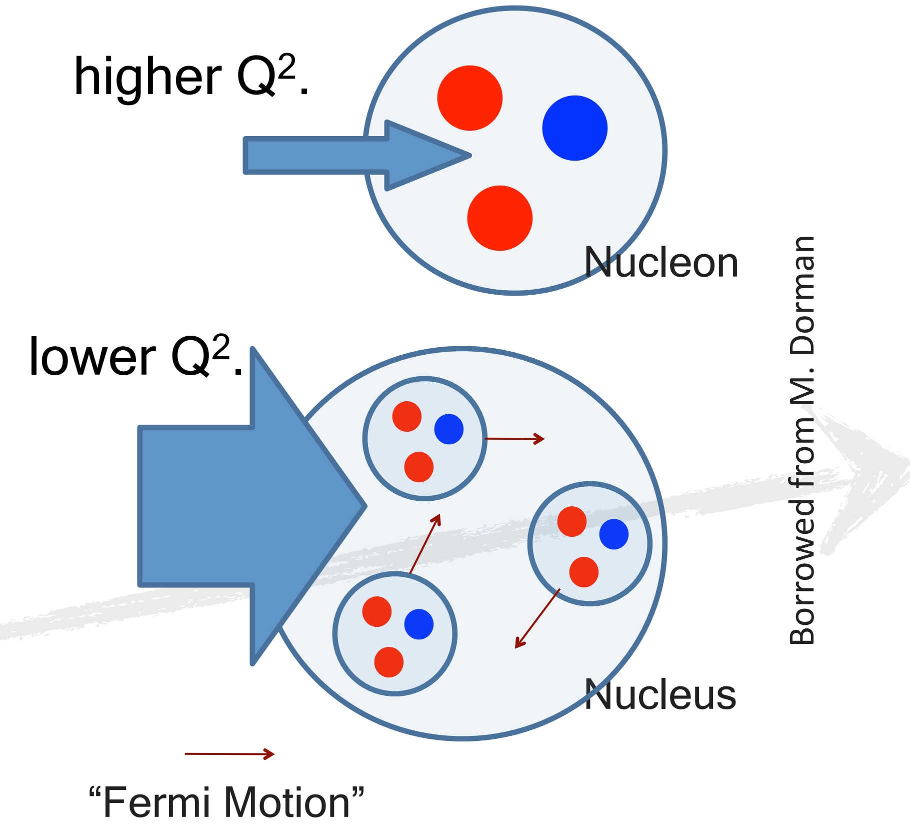
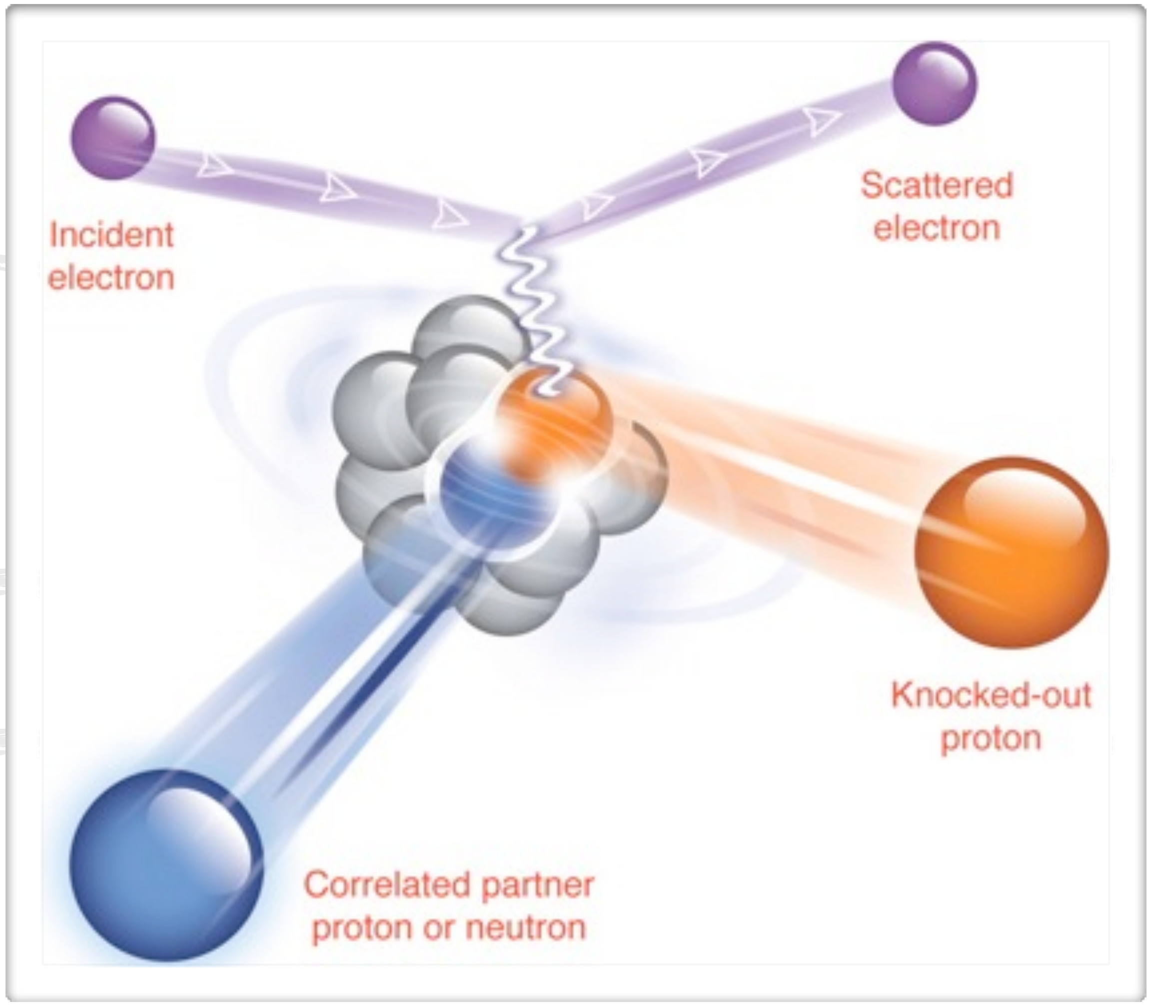
Impulse approximation



- 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?



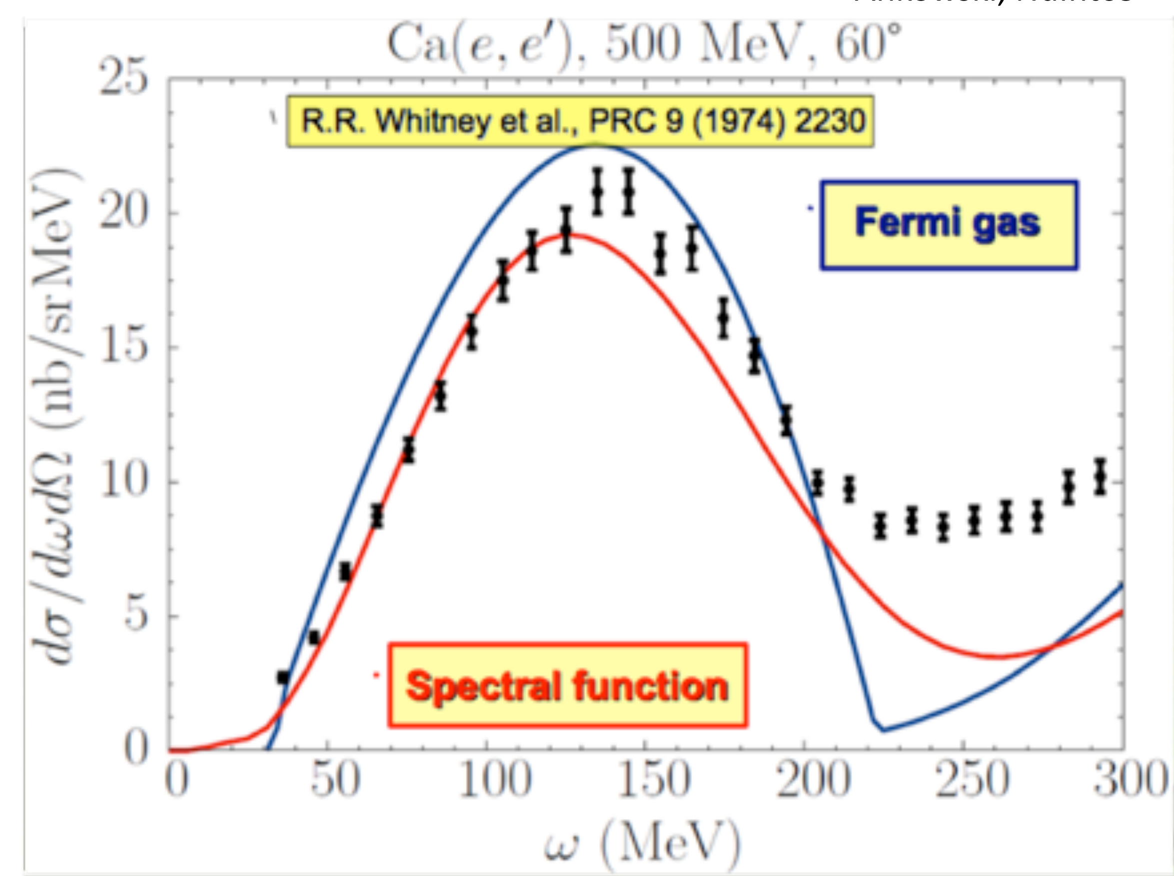
Science Vol.320. no.5882, pp.1476

Nuclear Models

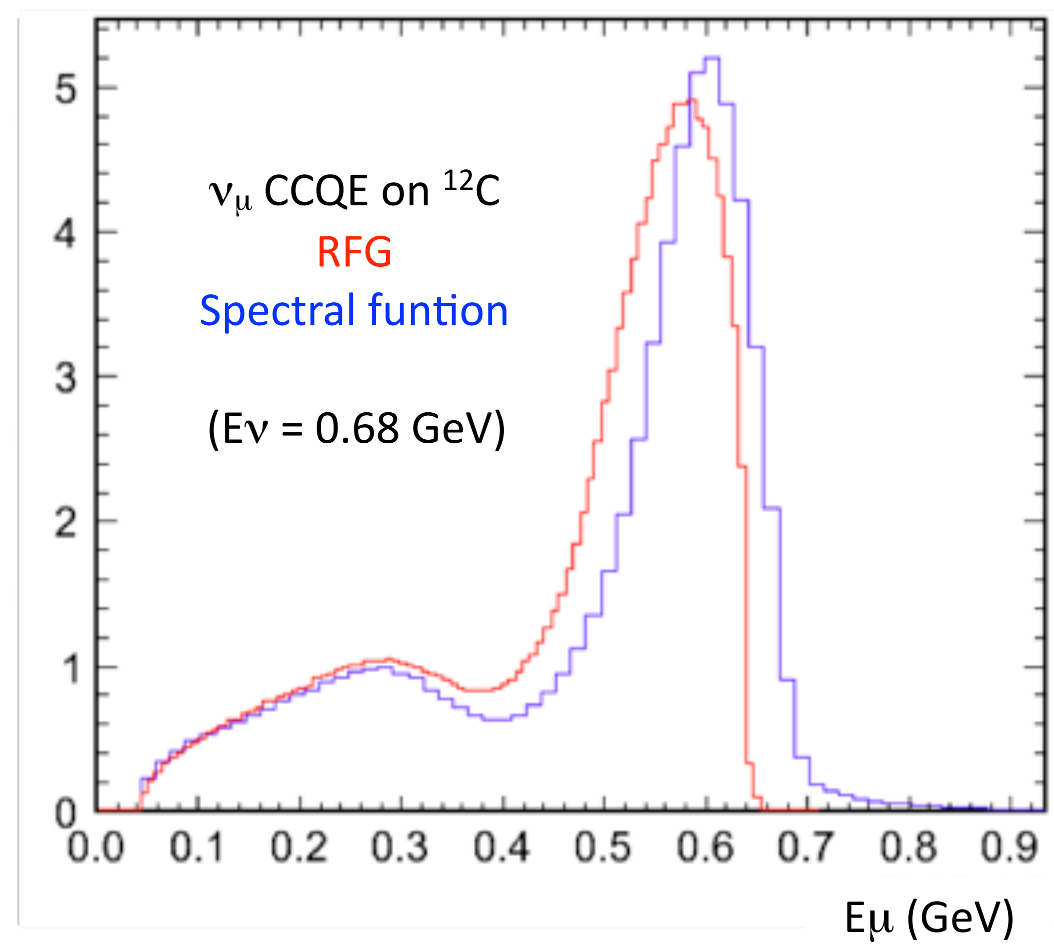
- Most experiments use RFG
- Most theorists prefer something else
- Effects neutrino energy reconstruction!

➡ Impacts oscillation experiment!

Ankowski, NuInt09



Prouse (Imperial College London)



Recent Measurements

Measuring a cross section

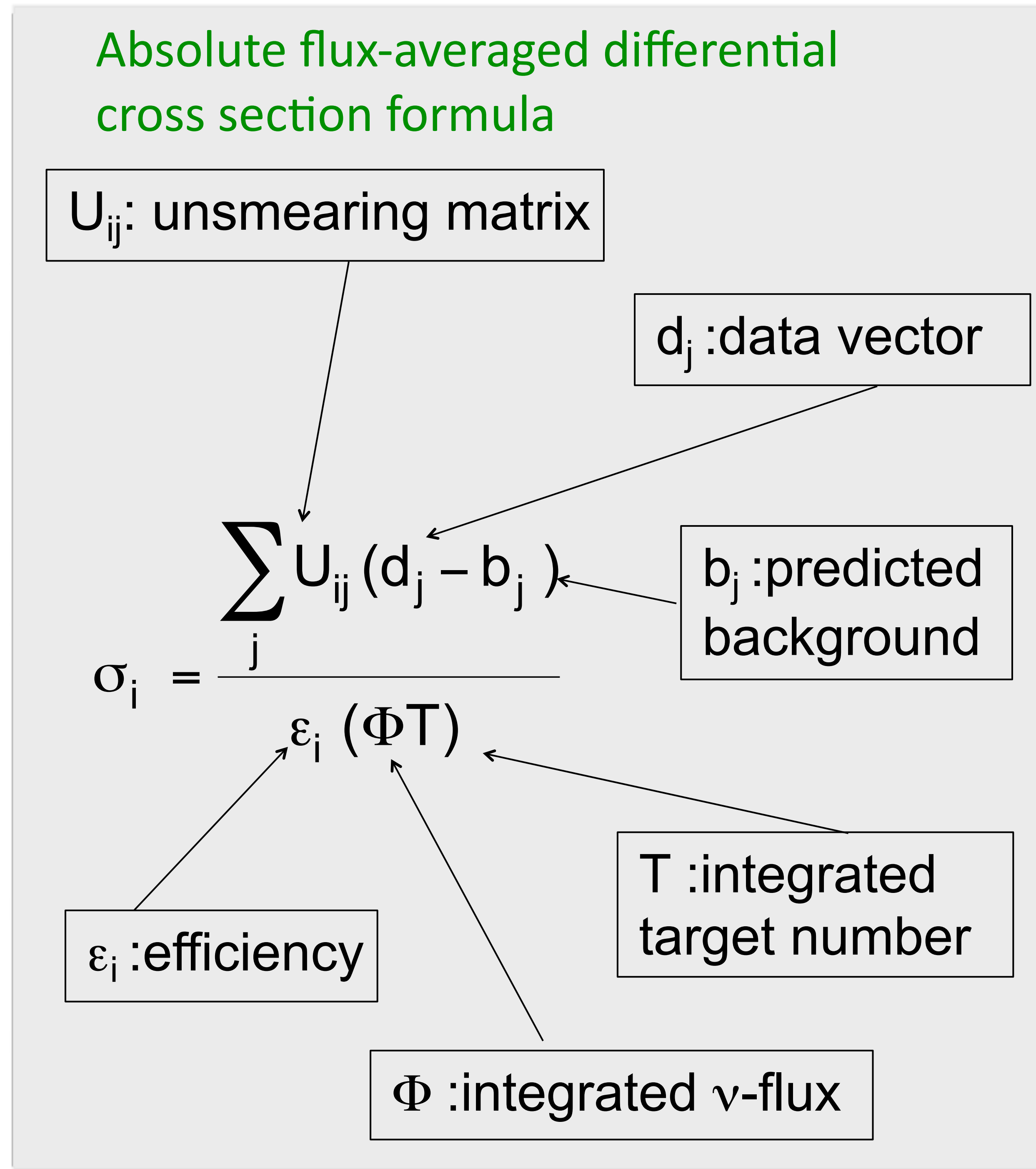
- We actually measure an event rate.
- No problem, we can solve for the cross section.
- Need to correct for background events, detector efficiencies, smearing.
- Need to calculate neutrino flux!

$$N(E,Q^2) = \Phi_\nu(E) \times \sigma_\nu(E,Q^2) \times N_t$$

$$\sigma_\nu(E,Q^2) = N(E,Q^2) / (\Phi_\nu(E) \times N_t)$$

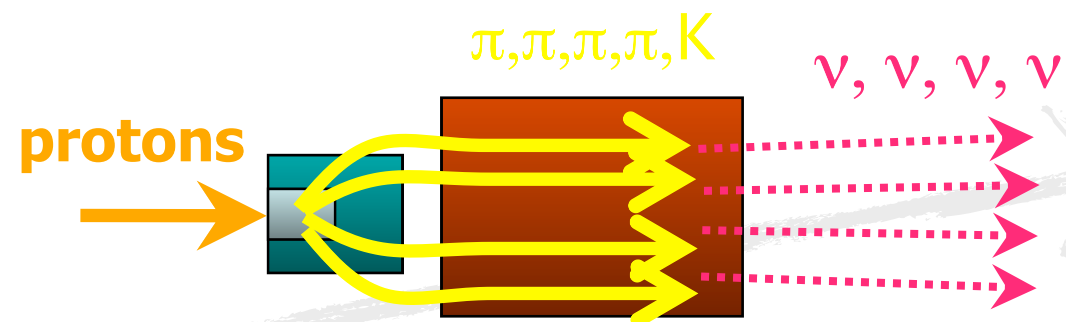
Measuring a cross section

- We actually measure an event rate versus E_ν or Q^2.
- No problem, we can solve for the cross section.
- Need to correct for background events, detector efficiencies, smearing.
- Need to calculate neutrino flux!



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

Flux Predictions



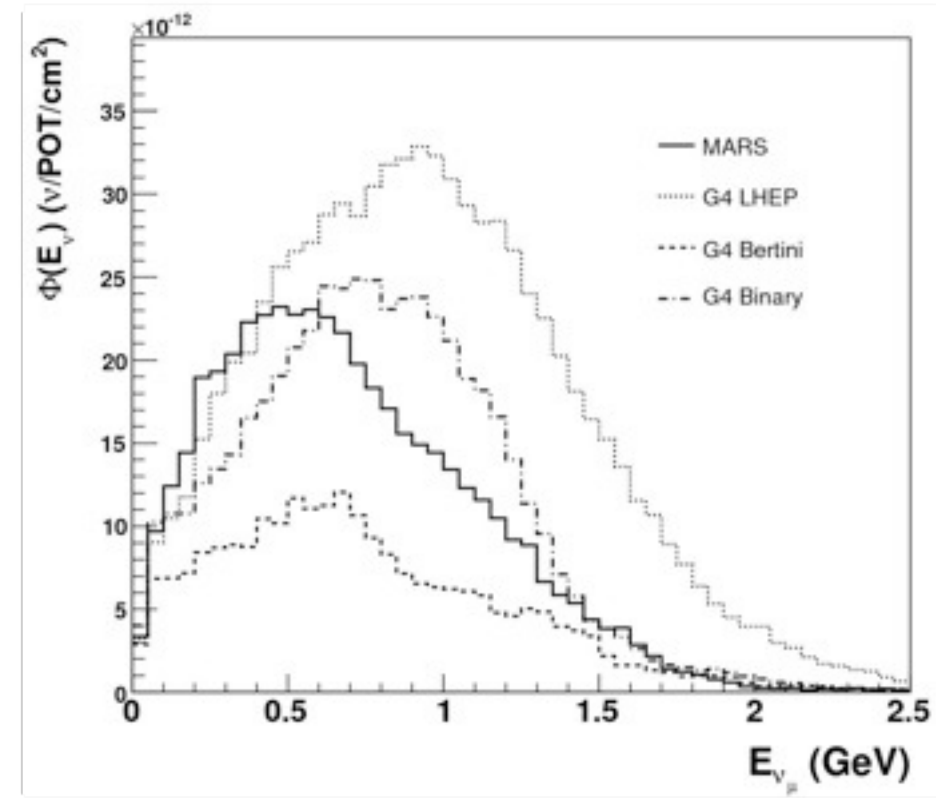
Beam	E_p (GeV)	target	$\langle \delta\Phi/\Phi \rangle$	E range	$\langle E_\nu \rangle$	Hadron prod.exp.
CERN WANF	450	Be	7%	3-100	24.3	SPY (CERN)
NuMI	120	C	~20%?	1-20	4	MIPP (FNAL)
BooNEs	8	Be	9%	0.2-3	0.8	HARP (CERN)

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

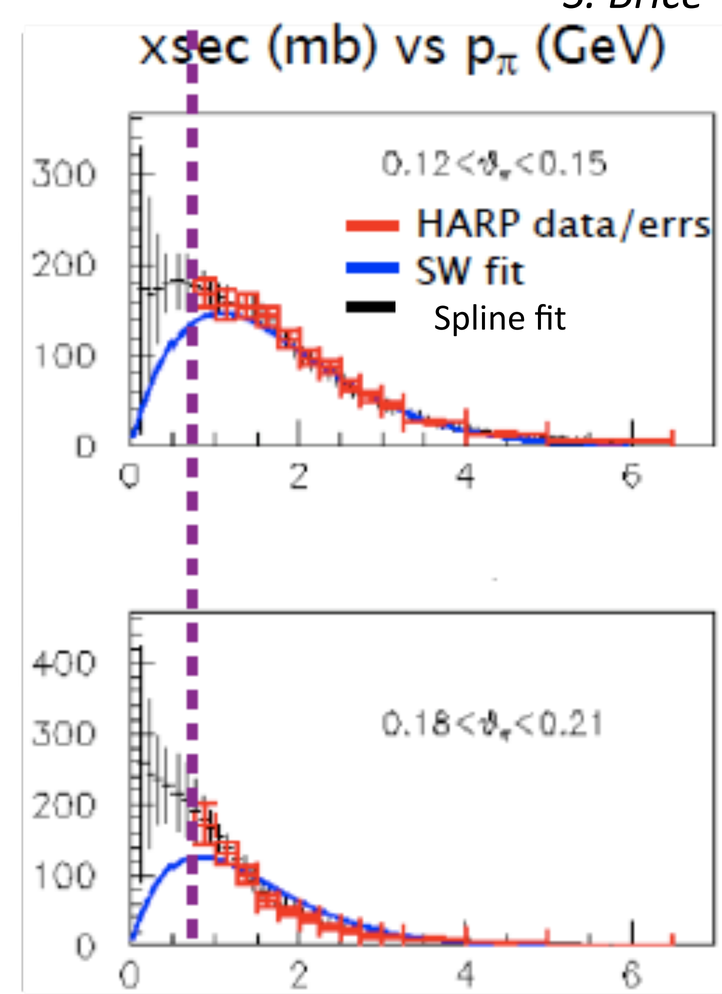
Hadron Production

- *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.

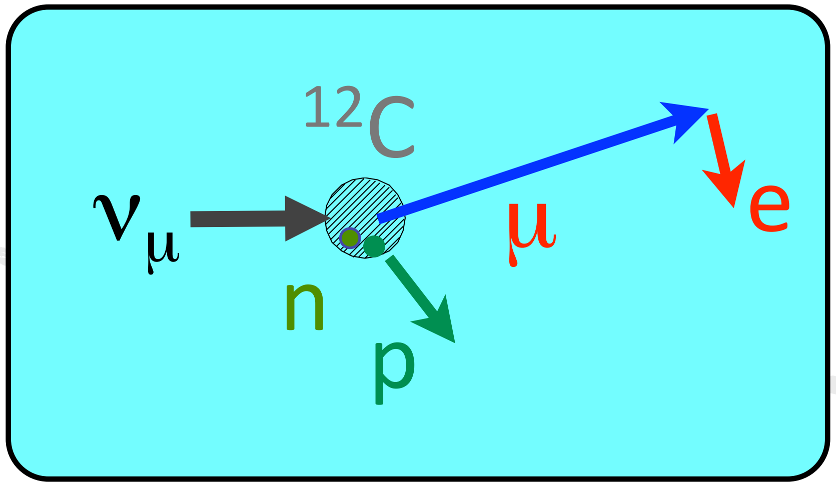
D. Schmitz, FERMILAB-THESIS-2008-26

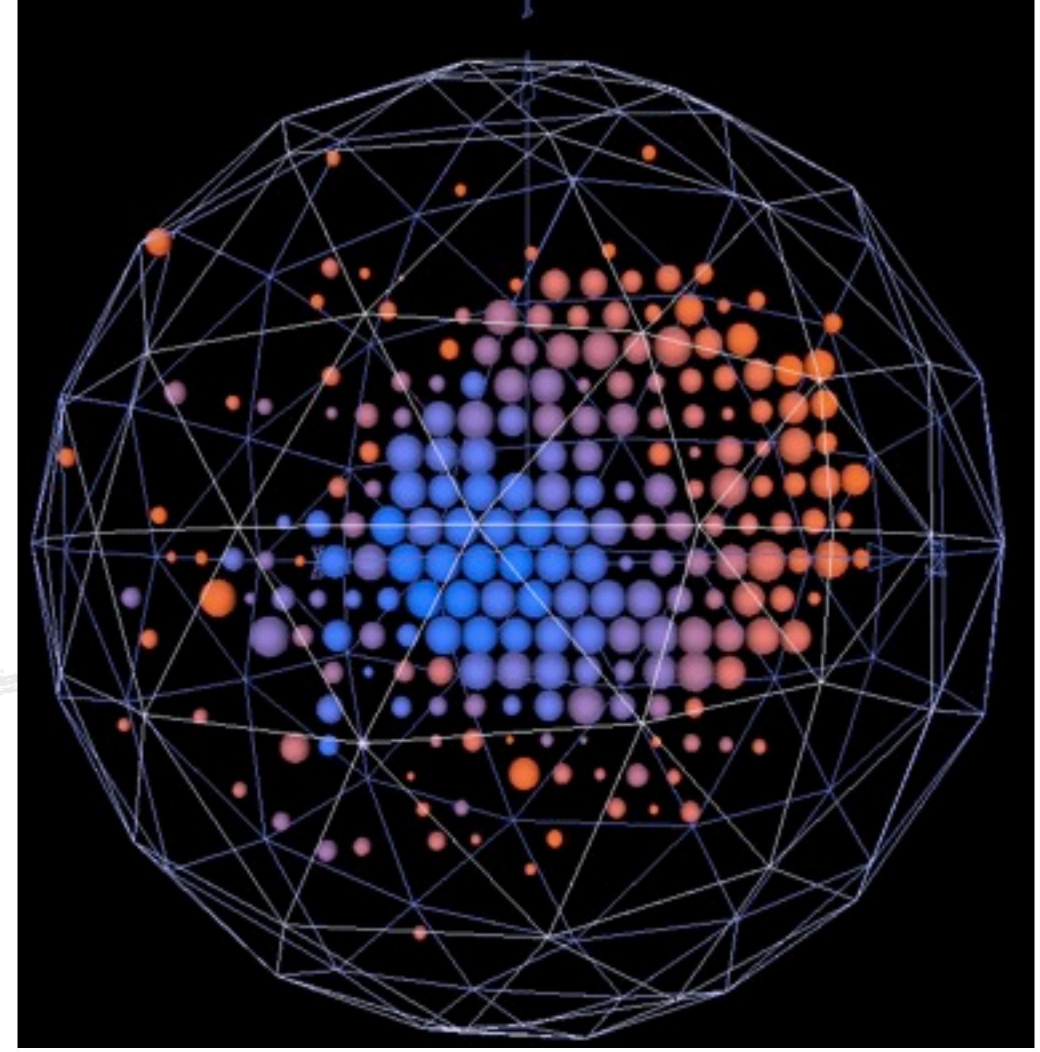


S. Brice



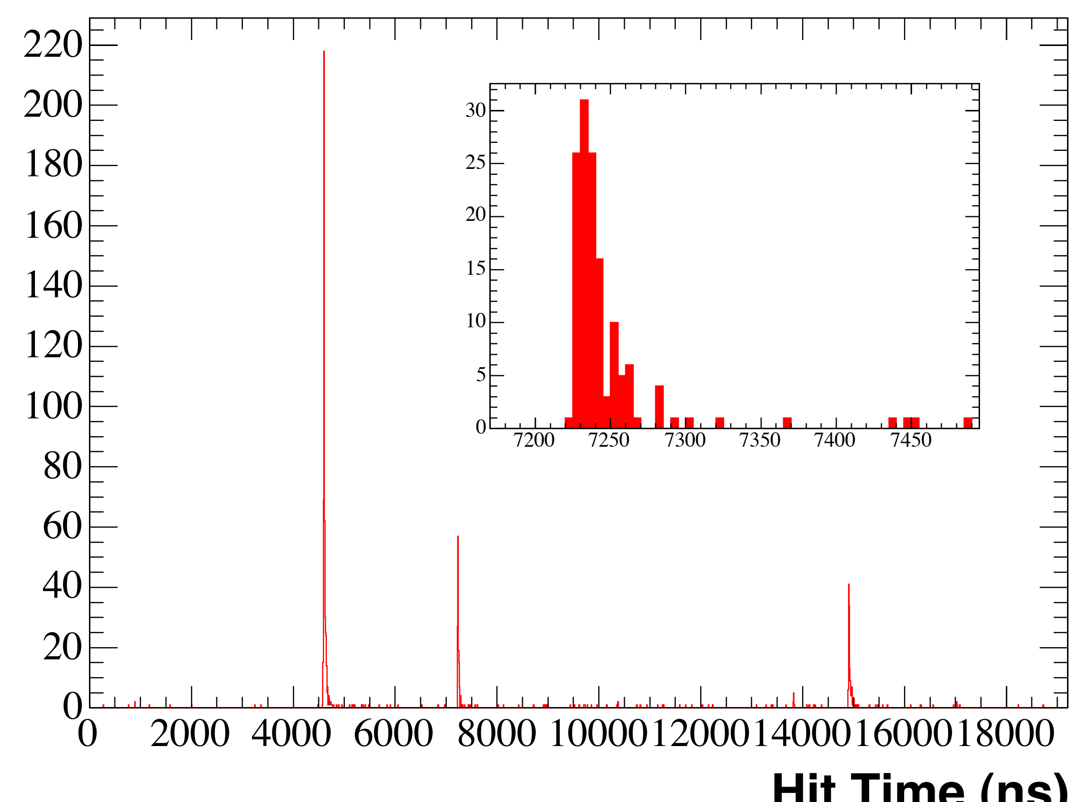
MiniBooNE



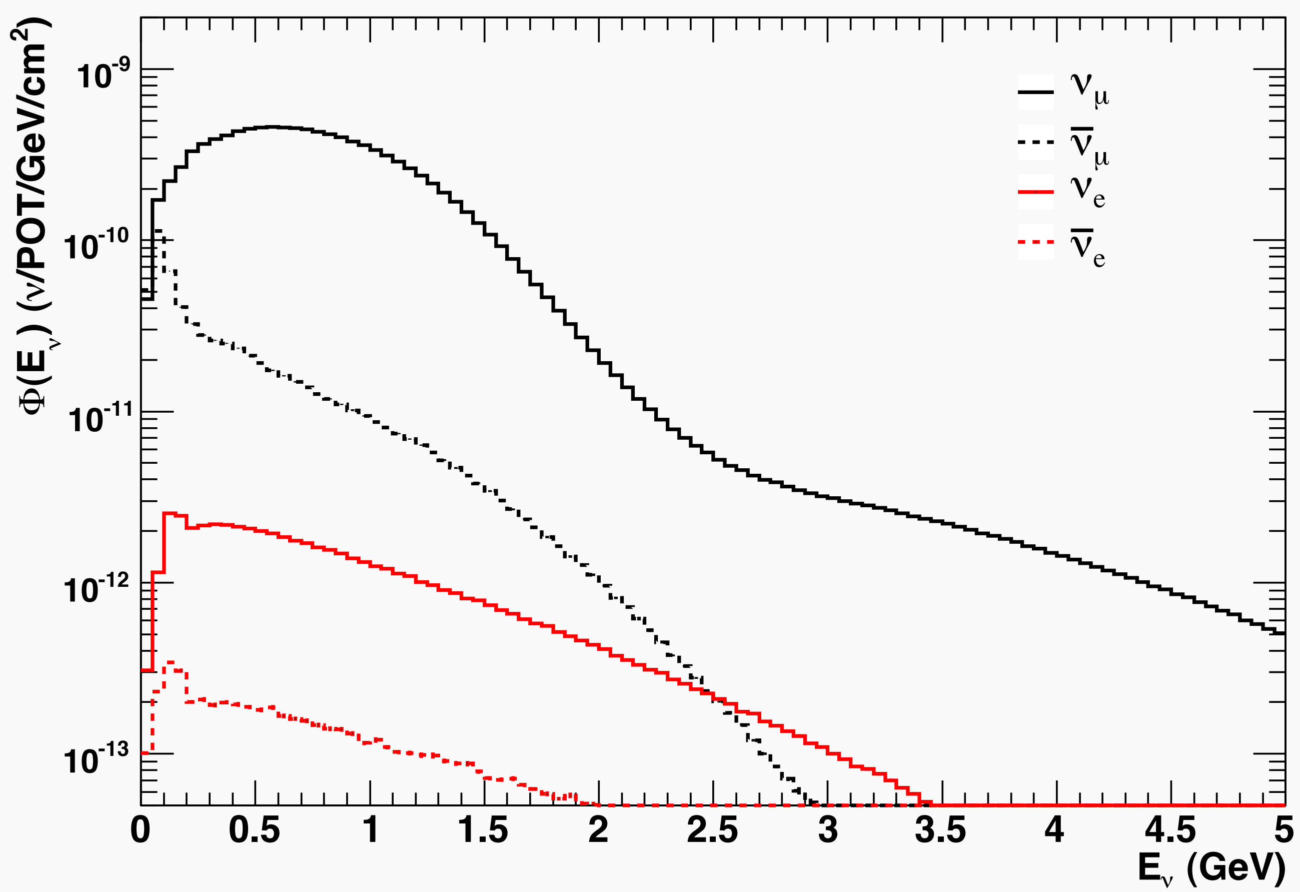


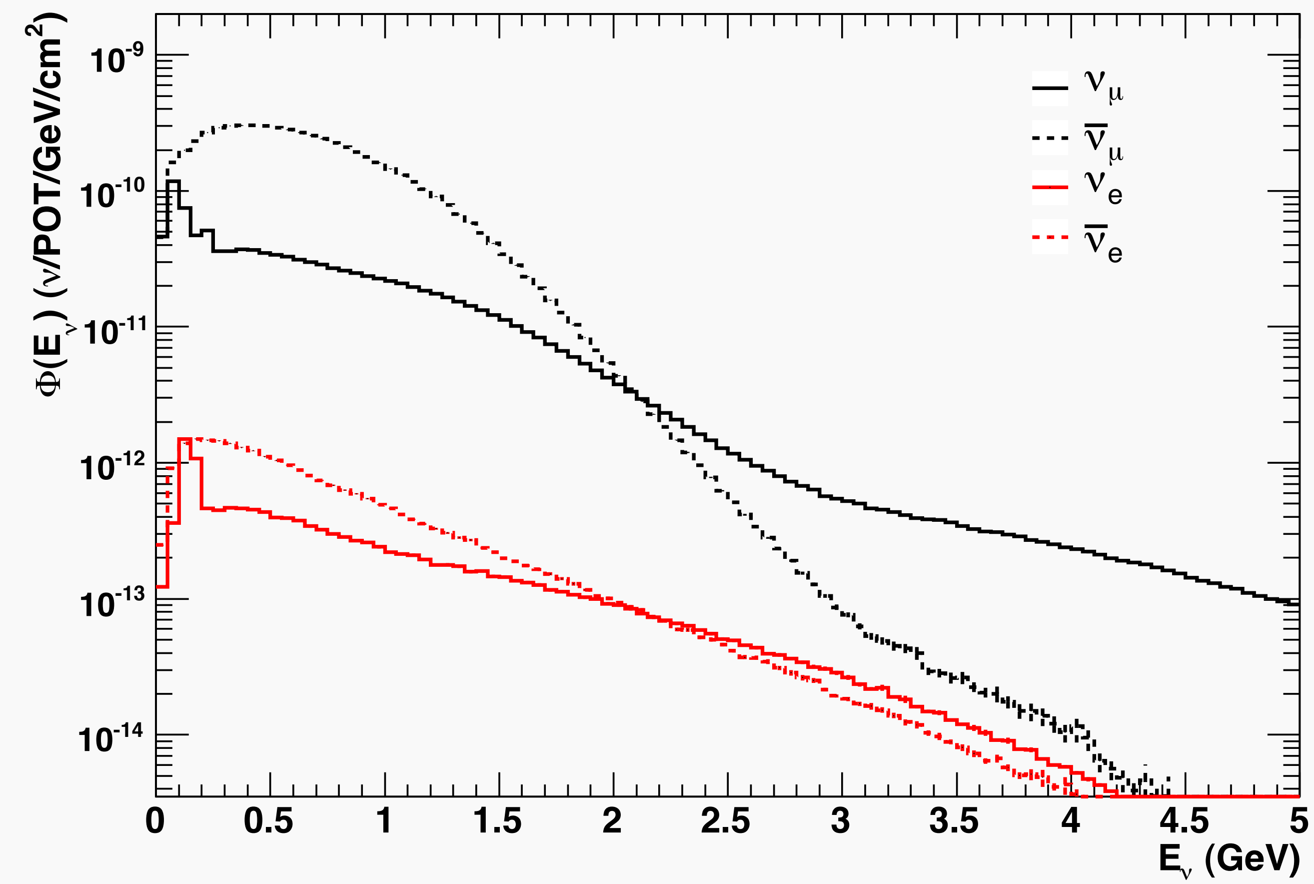
- PMT hits separated into time clusters (“subevents”)
- Reconstruct muon Cherenkov ring
  - First subevent
- Find decay electrons
  - Late subevents
- CCQE requires 1 late subevent

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



MB fluxes

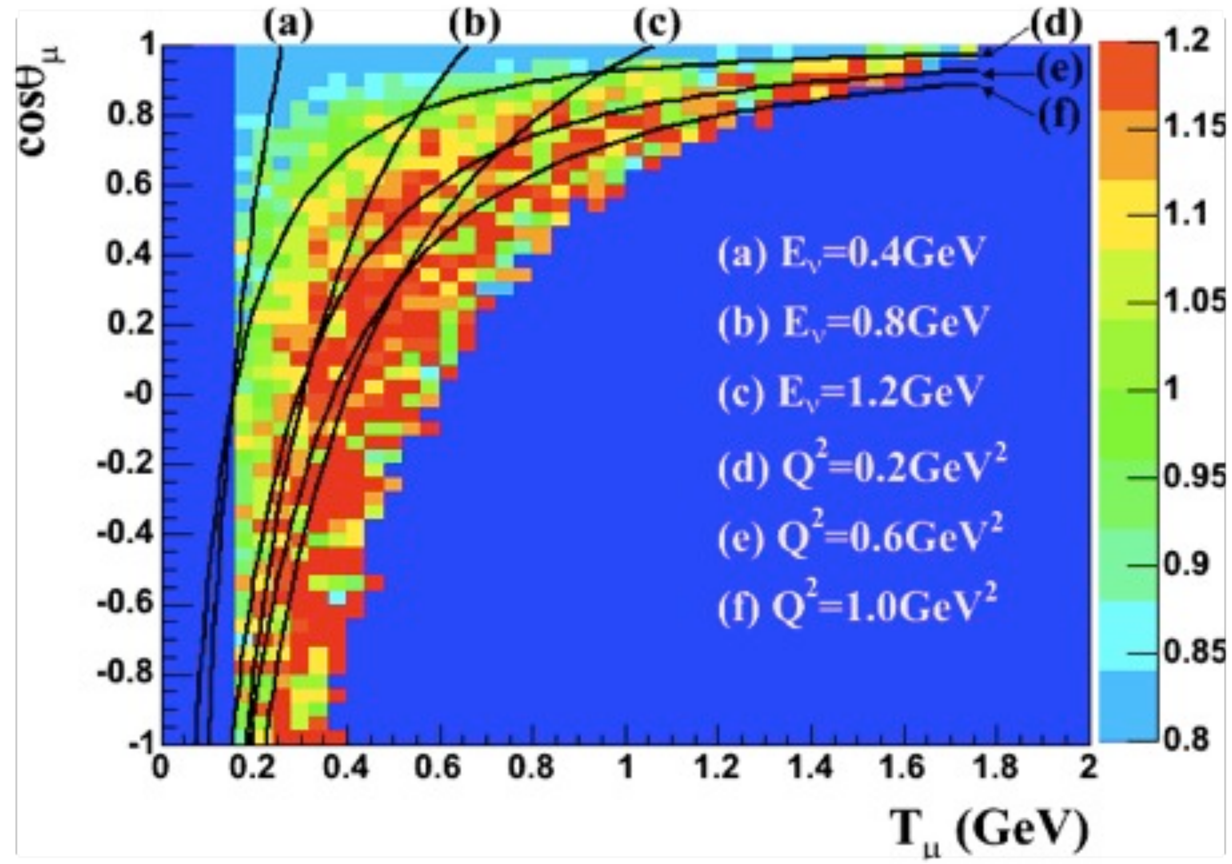

$\Phi(E_\nu)$ (ν/POT/GeV/cm^2)
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$


$\Phi(E_\nu)$ (ν/POT/GeV/cm^2)
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

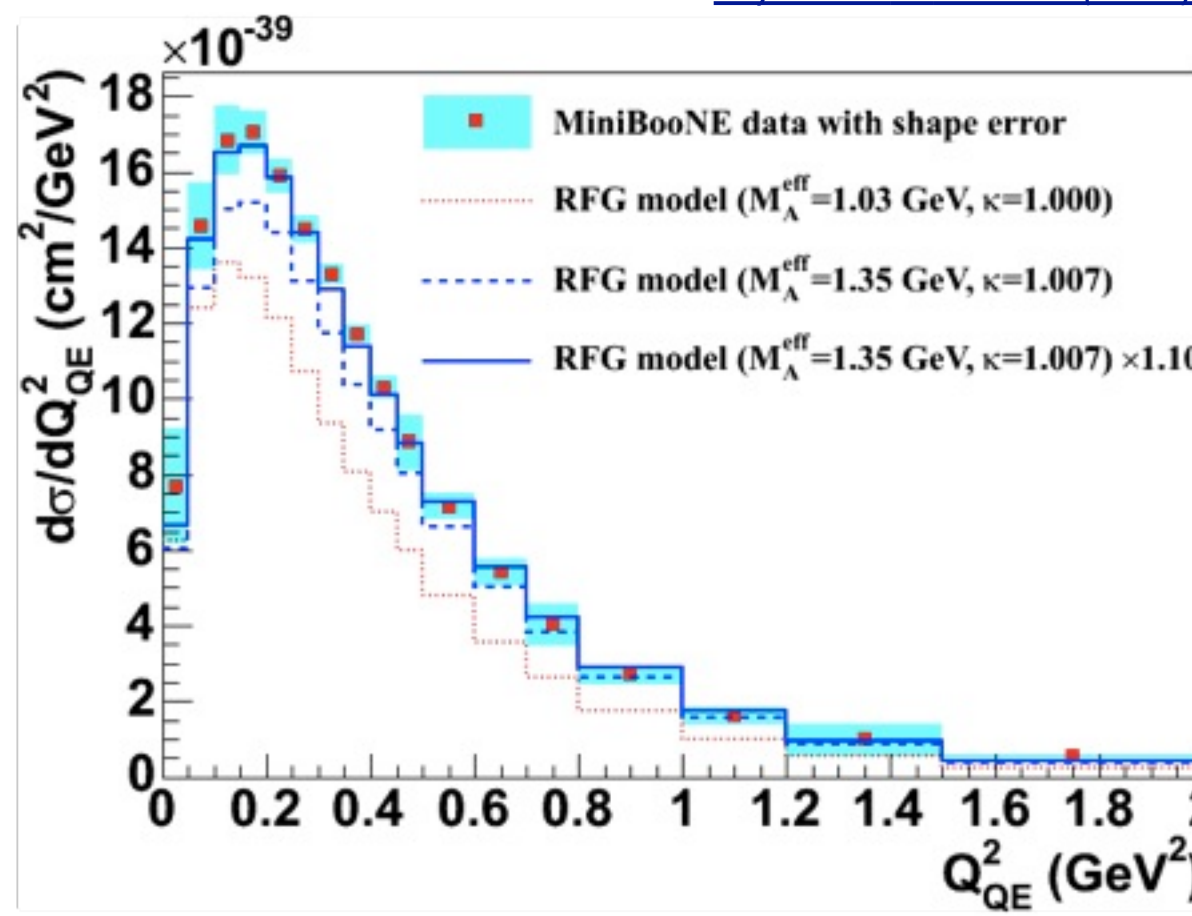
MiniBooNE

- 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
- First POT normalised cross-section!

T. Katori



PhysRevD **81** 092005 (2010)

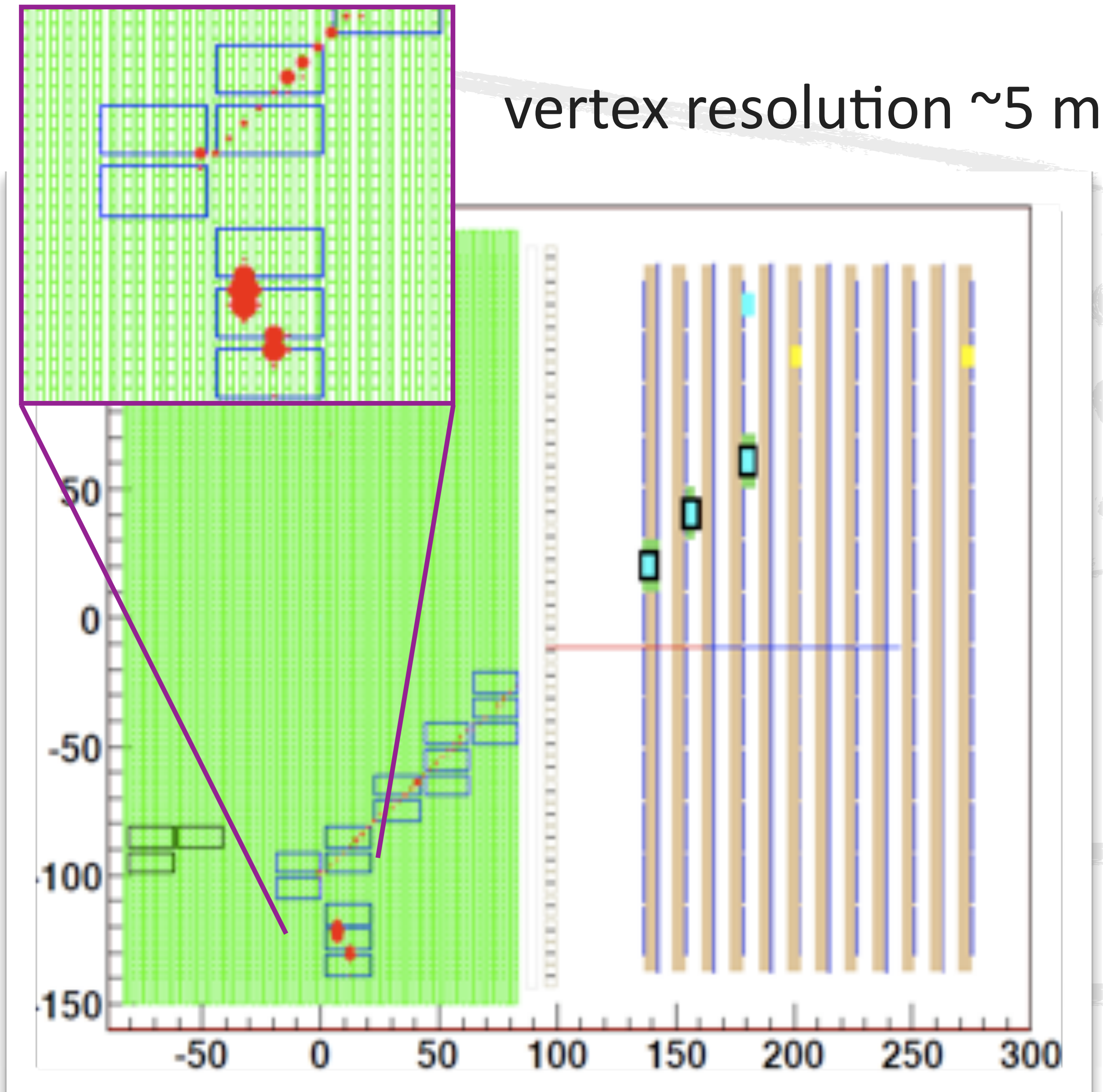


SciBooNE event displays

Real SciBooNE Data

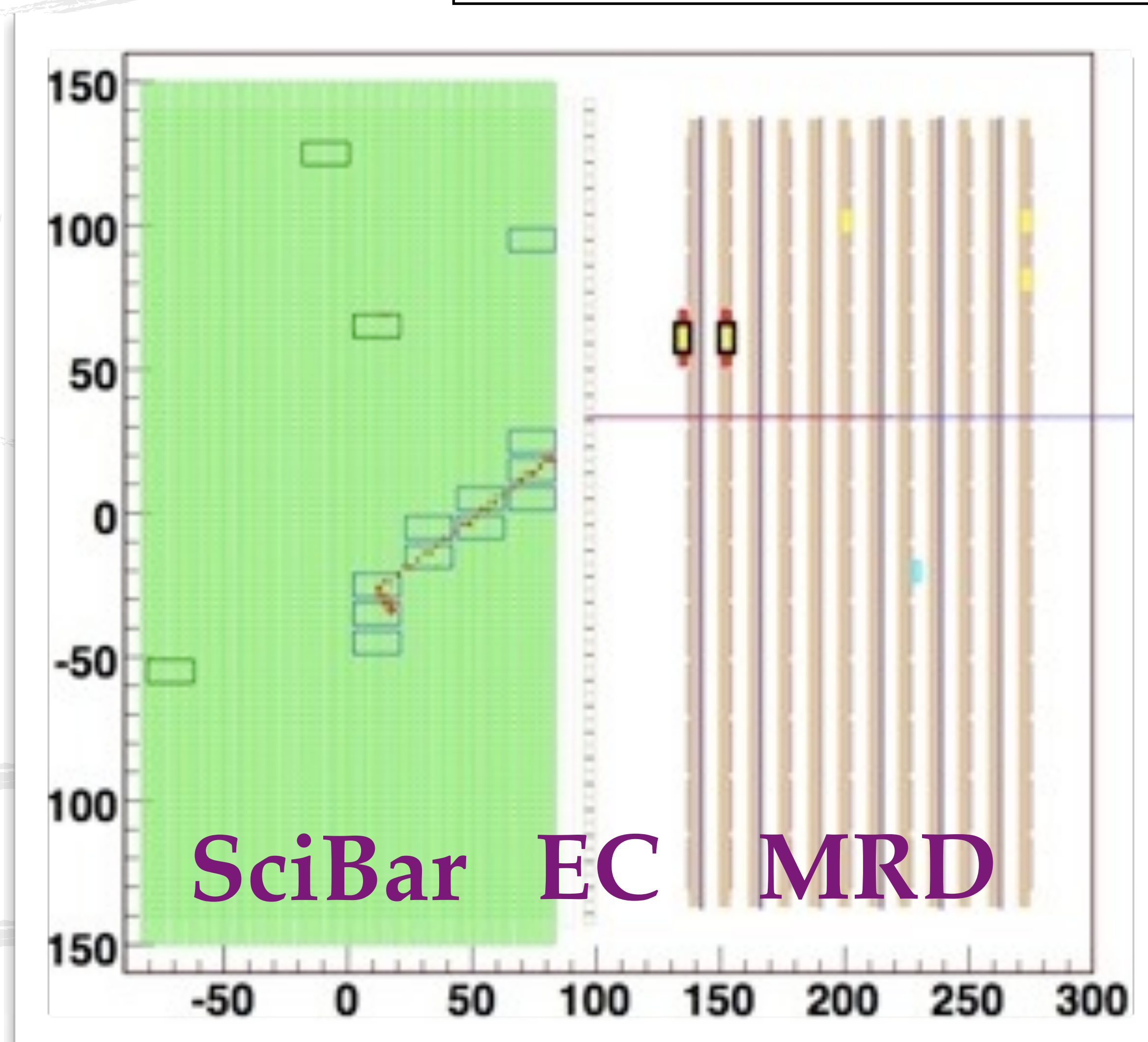
vertex resolution ~5 mm

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



anti-ν_μ CC-QE candidate

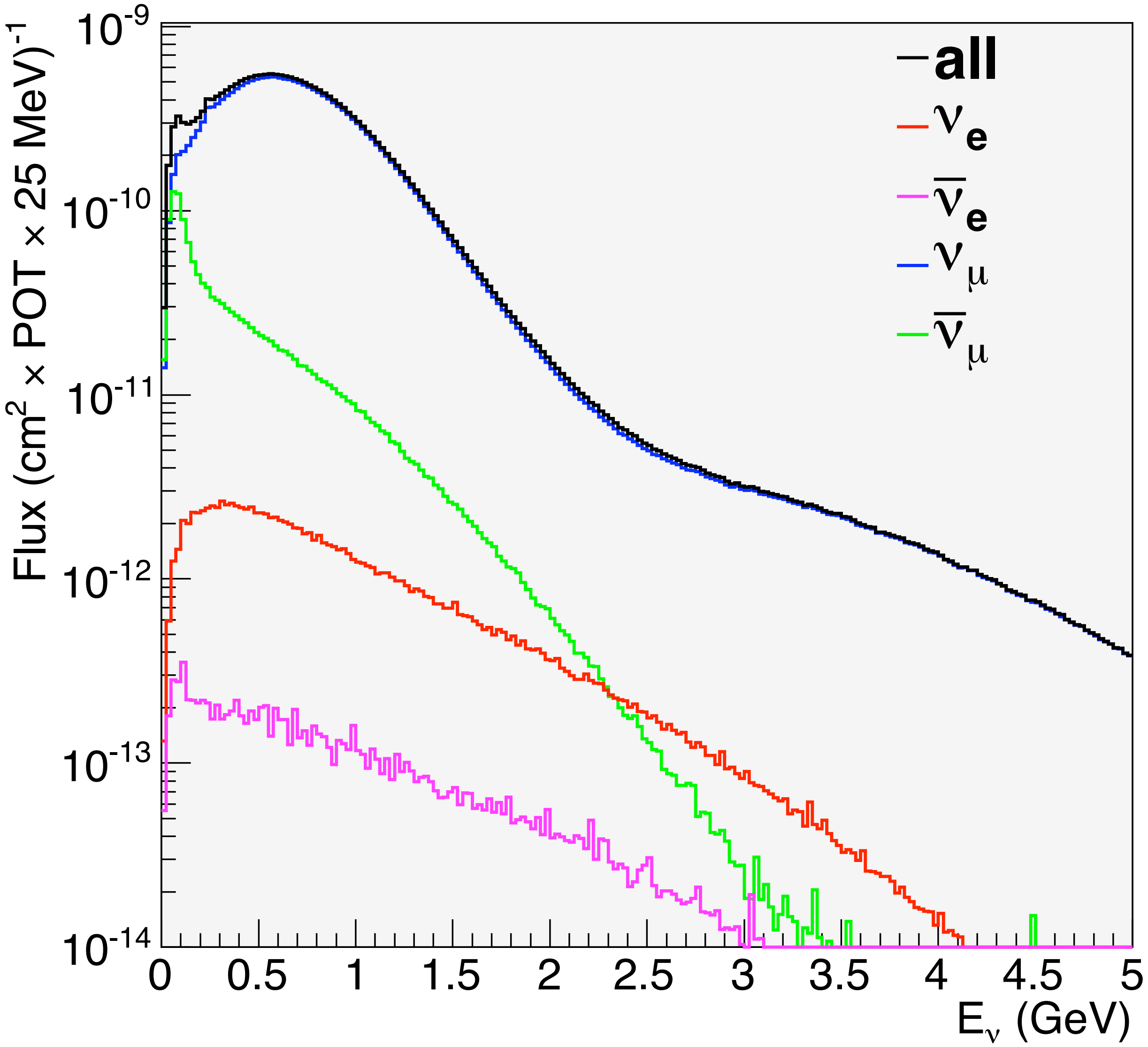
($\bar{\nu}_\mu + p \rightarrow \mu + n$)



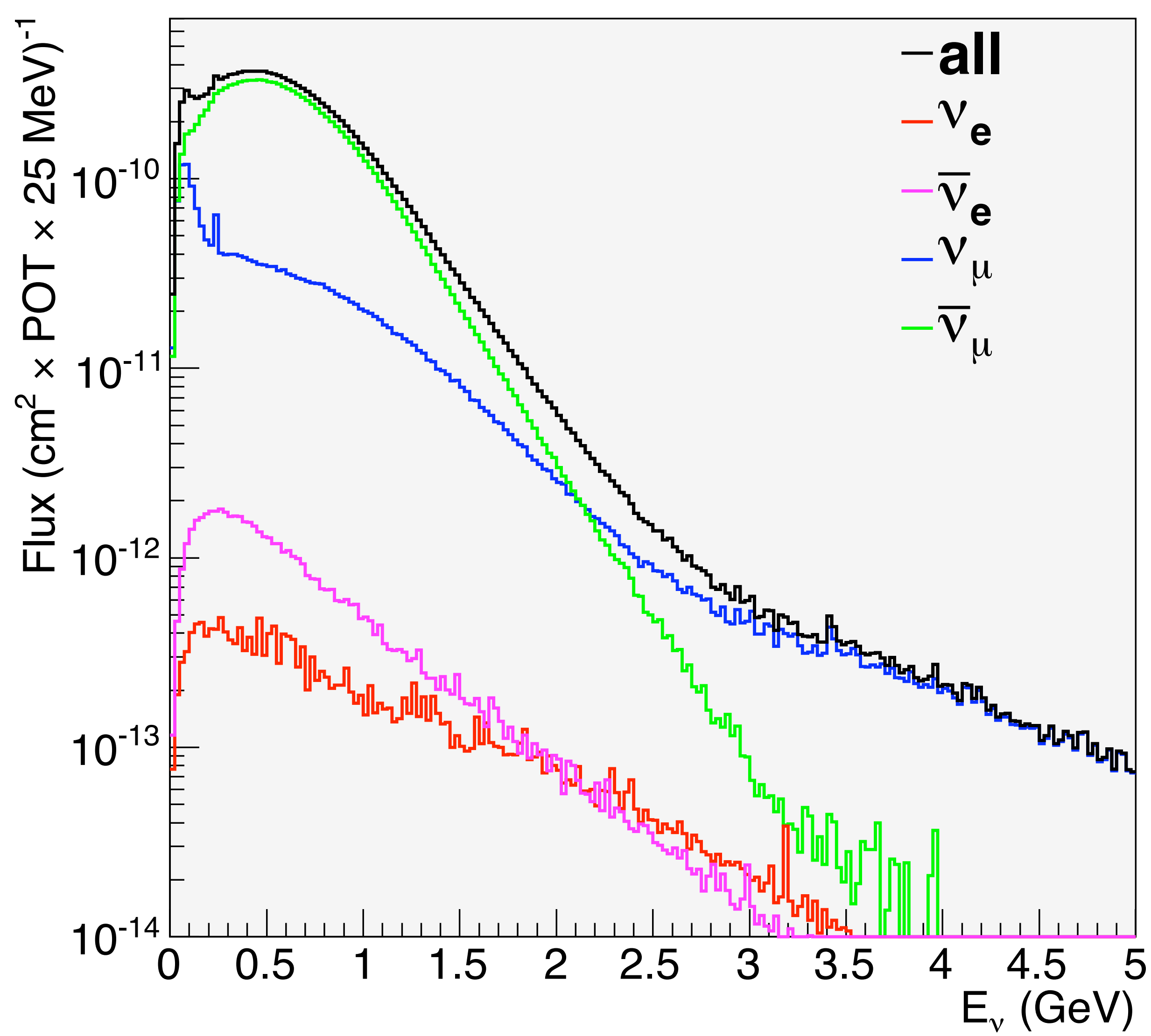
ν_μ CC-QE candidate

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

SB fluxes

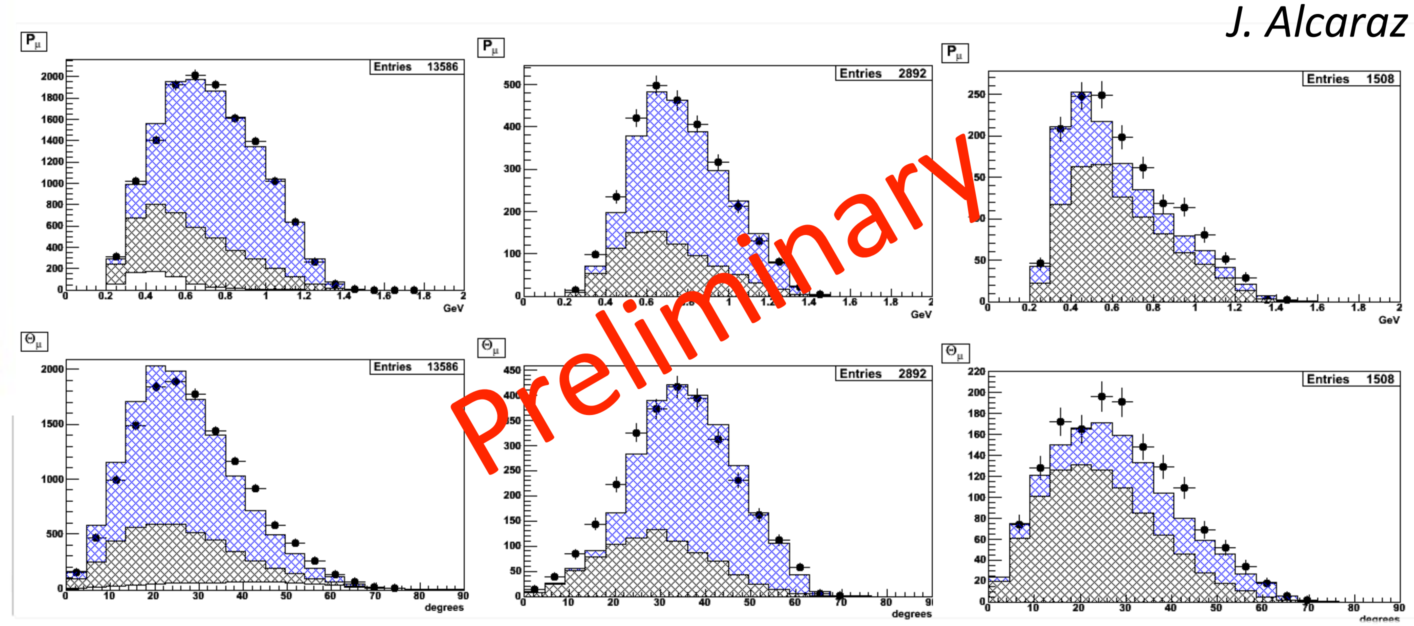


Flux (cm^2 × POT × 25 MeV)$^{-1}$
all
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$
E_ν (GeV)



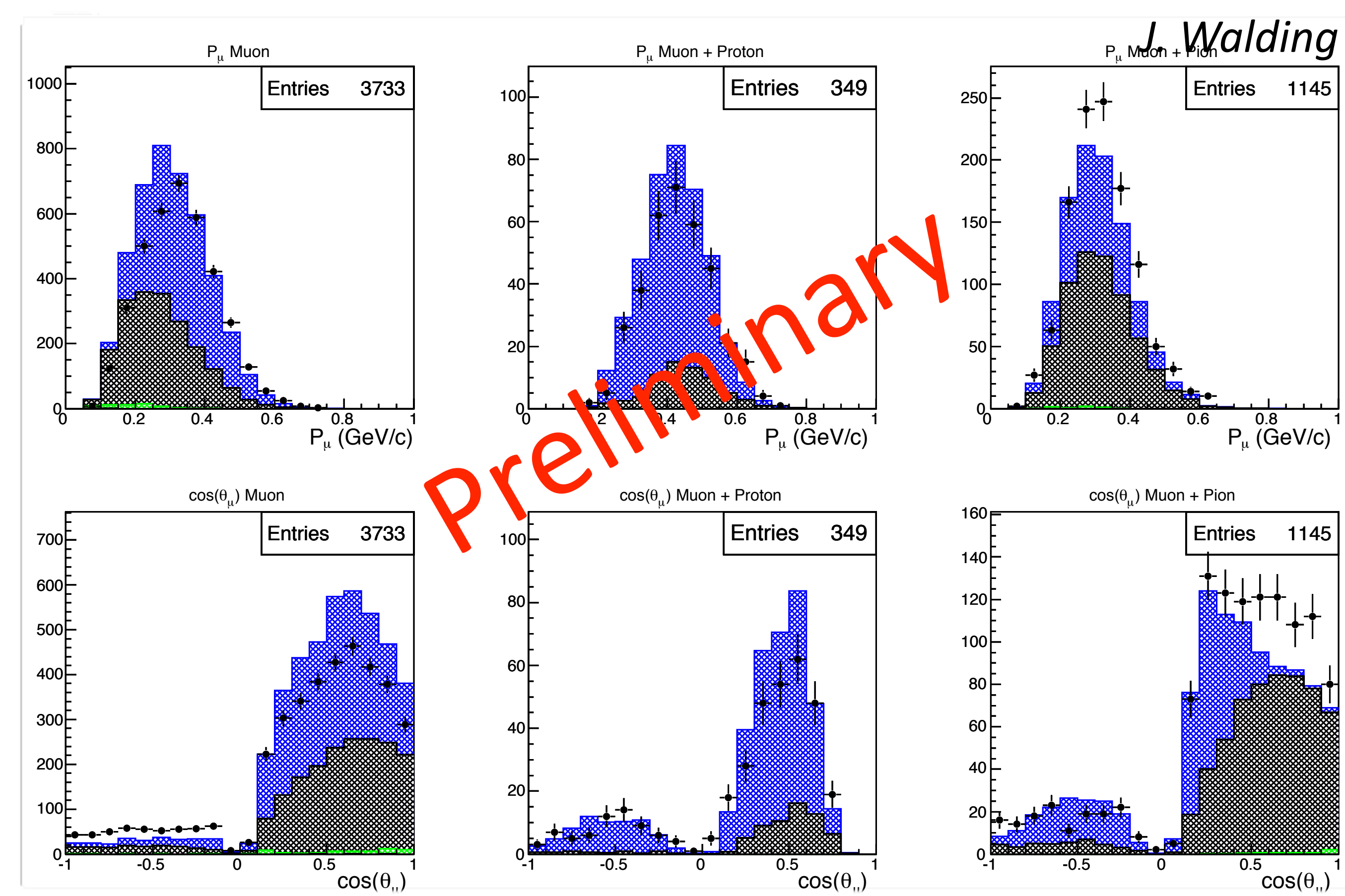
Flux (cm^2 × POT × 25 MeV)$^{-1}$
all
ν_e
$\bar{\nu}_e$
ν_μ
$\bar{\nu}_\mu$
E_ν (GeV)

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

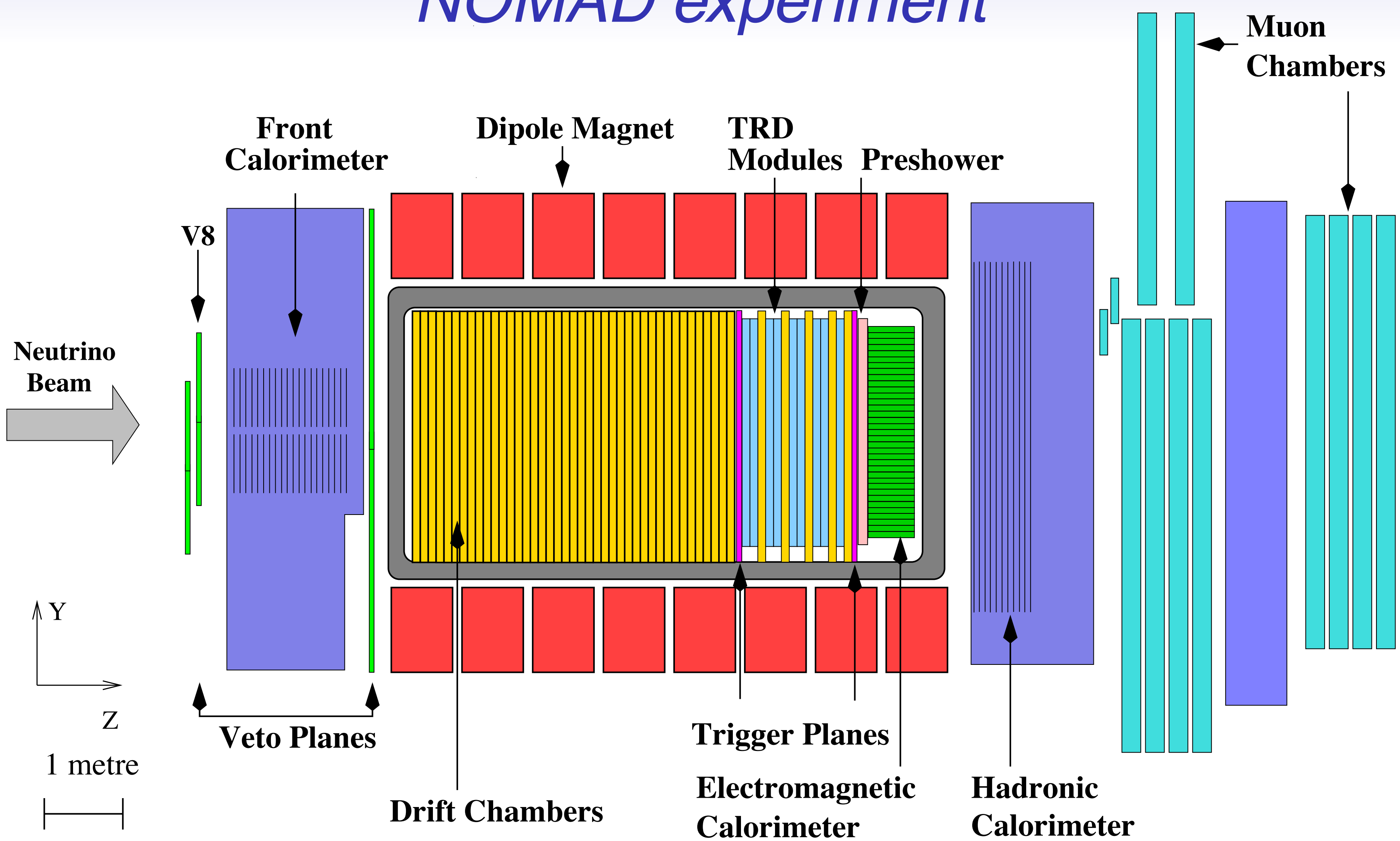


CCQE signal ; Backgrounds

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

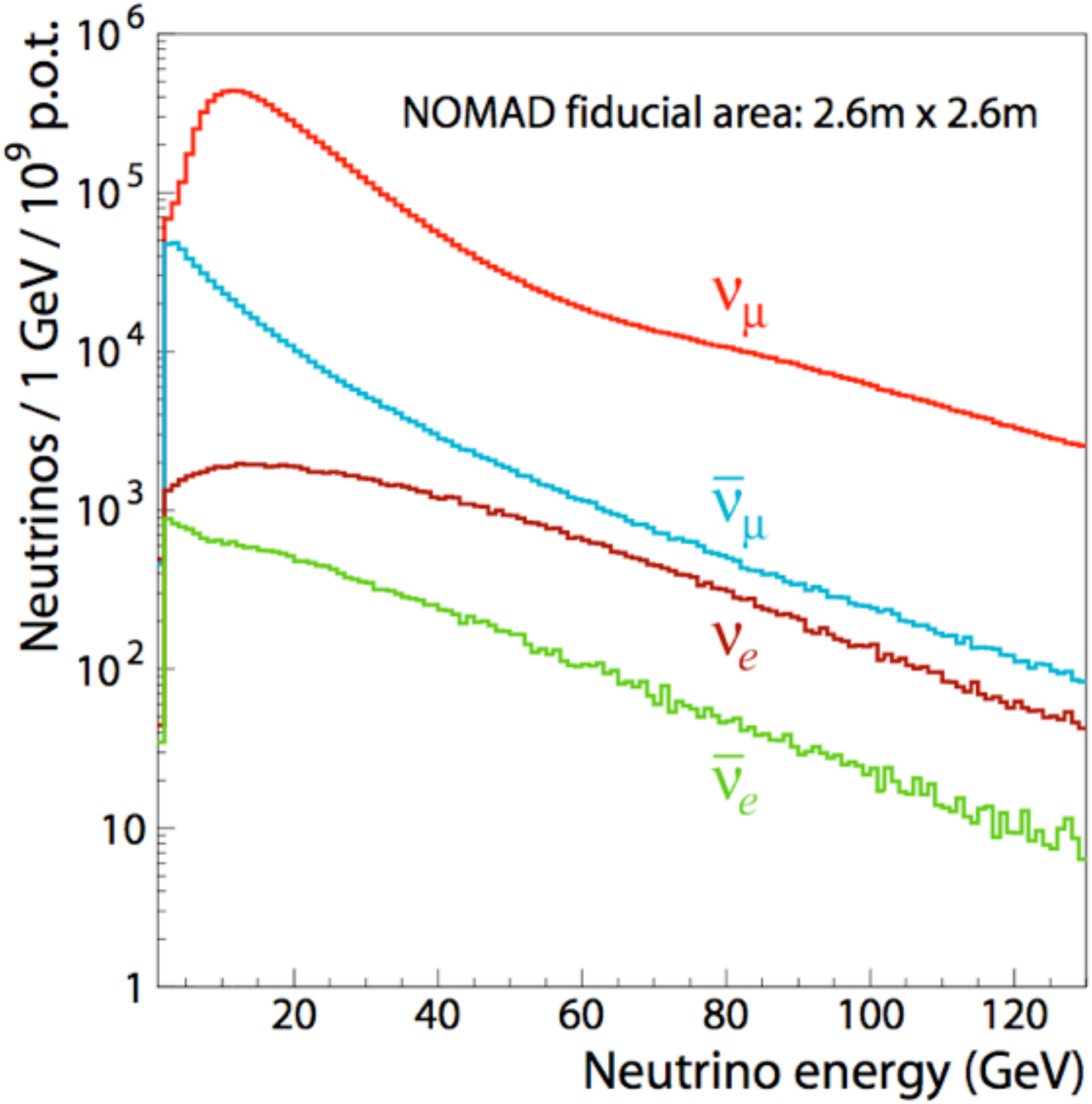


NOMAD experiment

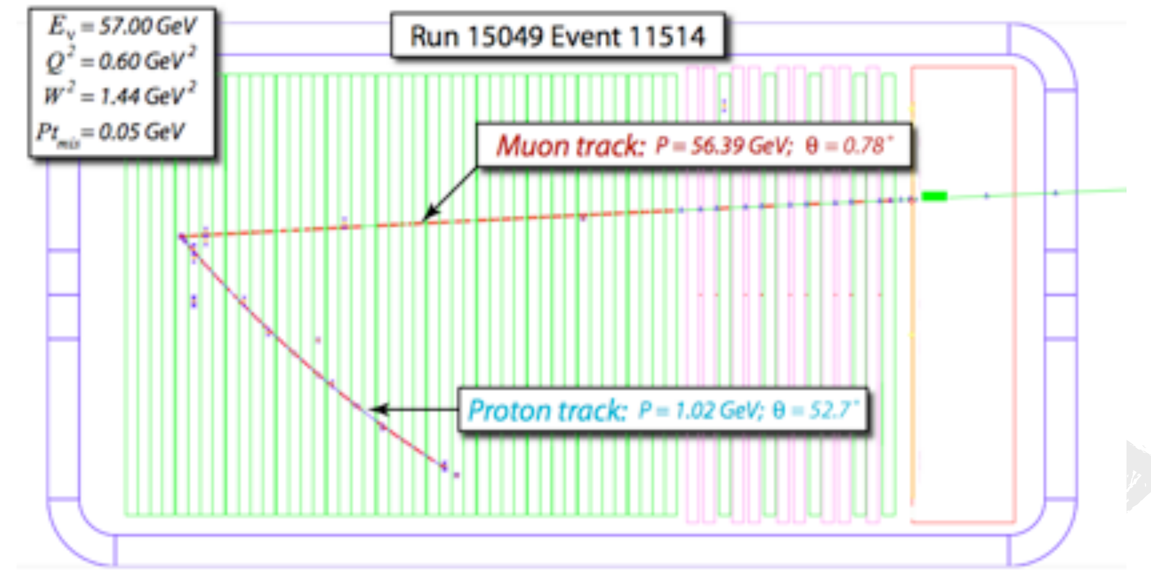


- Drift Chambers (target and momentum measurement) Position resolution $< 200\ \mu$m (small angle tracks) Momentum resolution $\sim 3.5\%$ ($p < 10$ GeV/c)
- Transition Radiation Detector for $e^{\pm}$ identification: π rejection $\sim 10^3$ for electron efficiency $\geqslant 90\%$
- Lead glass Electromagnetic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

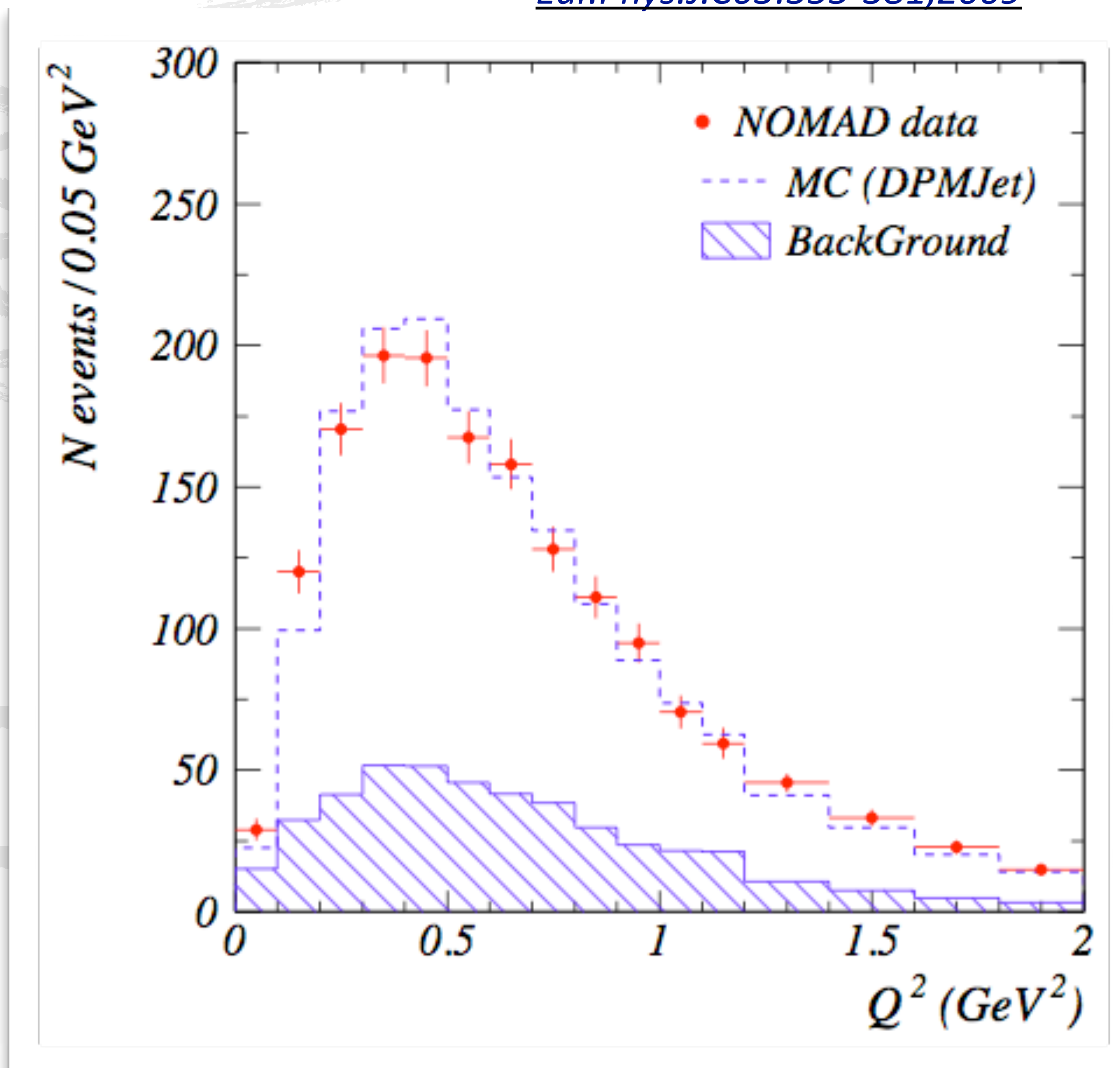
NOMAD fluxes



NOMAD



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

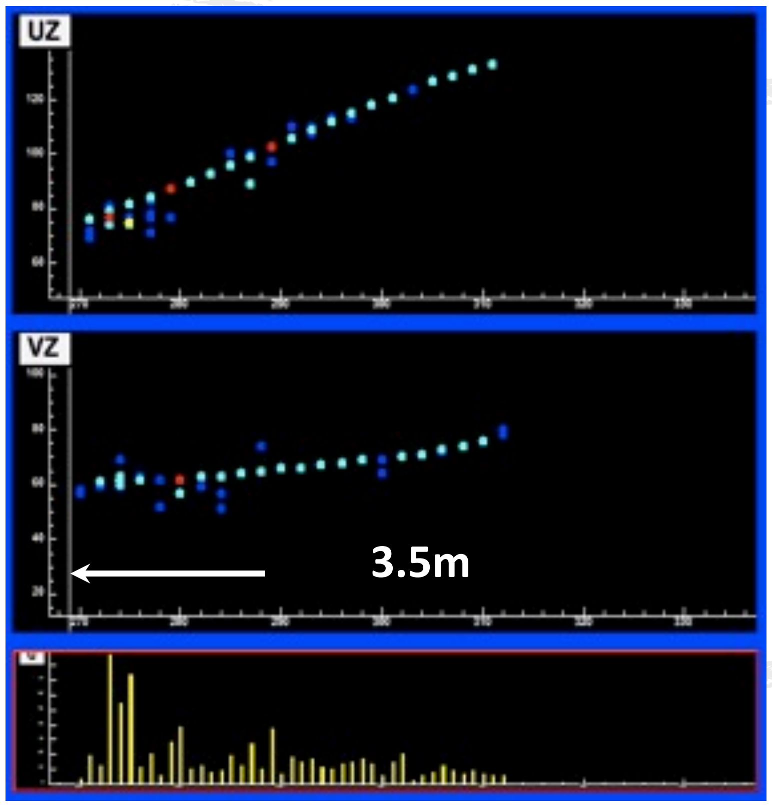


- Drift chambers in magnetic field
  - "Mainly carbon" target
- Select ν_μ and $\bar{\nu}_\mu$ CCQE events using strict PID and final state cuts
- Extract σ_{QE} with cross section ratios (DIS)
  - Use extracted σ_{QE} to infer value of M_A
  - Also fit Q^2 shape to check M_A
- M_A=1.05±0.06 GeV

M. Dorman, HEP Seminar at Imperial, 2009

Events in the MINOS Detectors

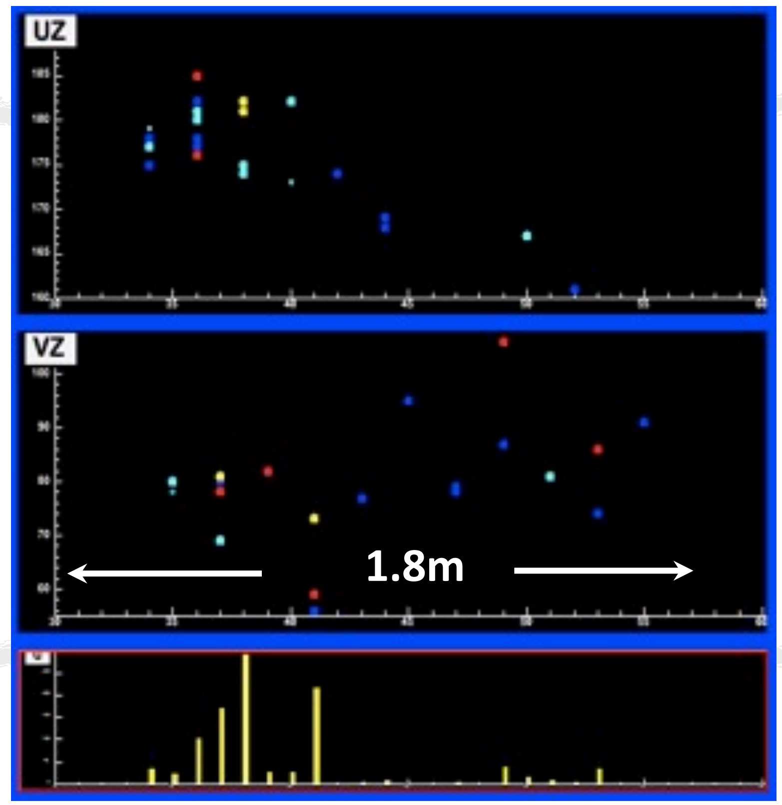
ν_μ CC Event



Long muon track with hadronic activity at the vertex.

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

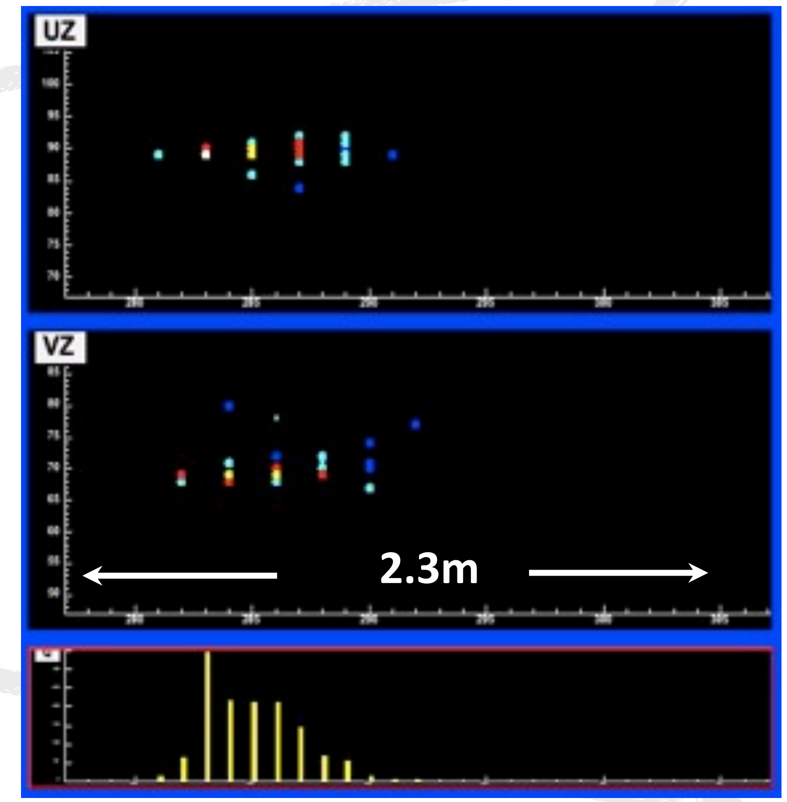
NC Event



Short event often with a diffuse shower.

What we use for the sterile neutrino analysis.

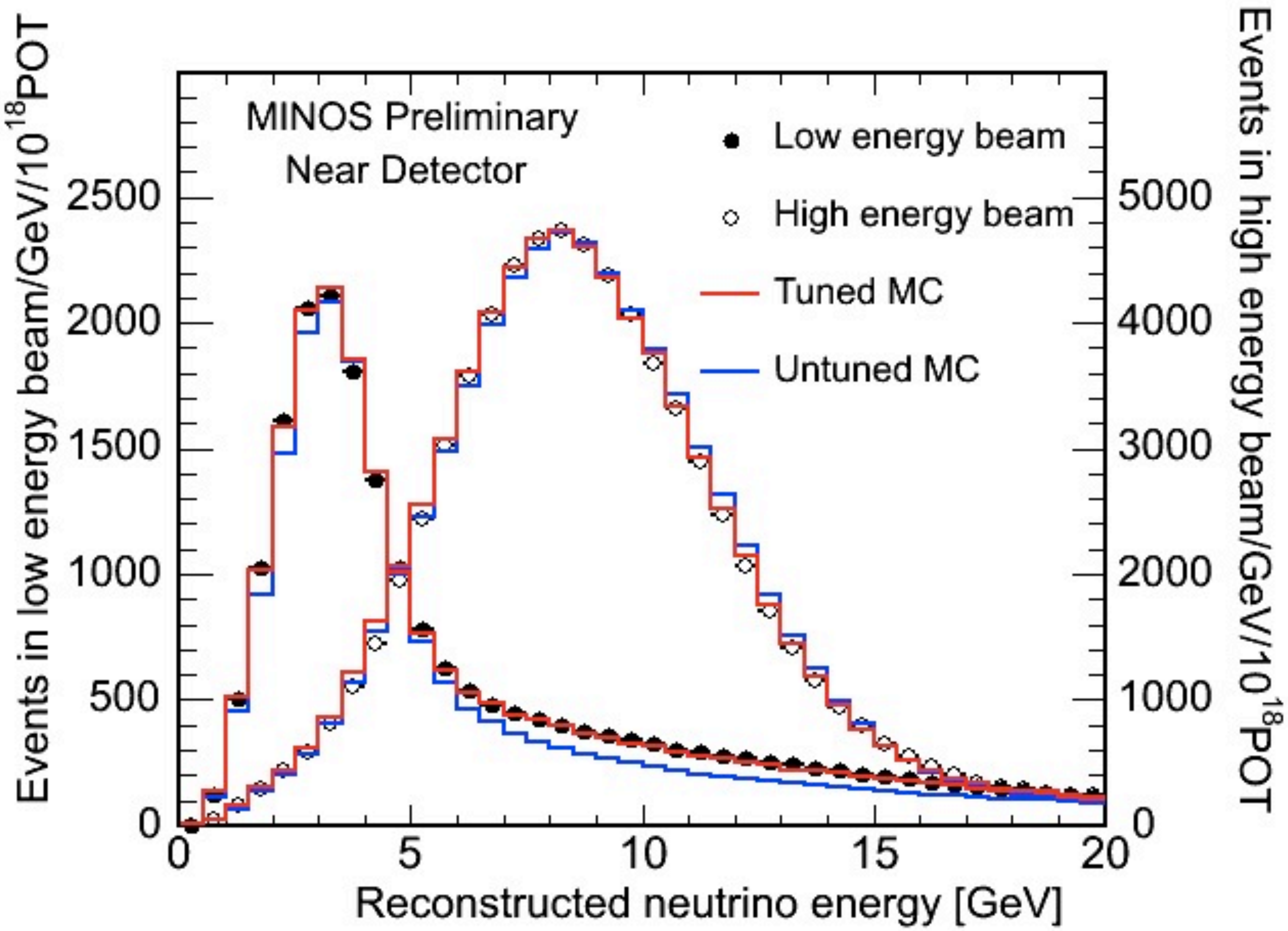
ν_e CC Event



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

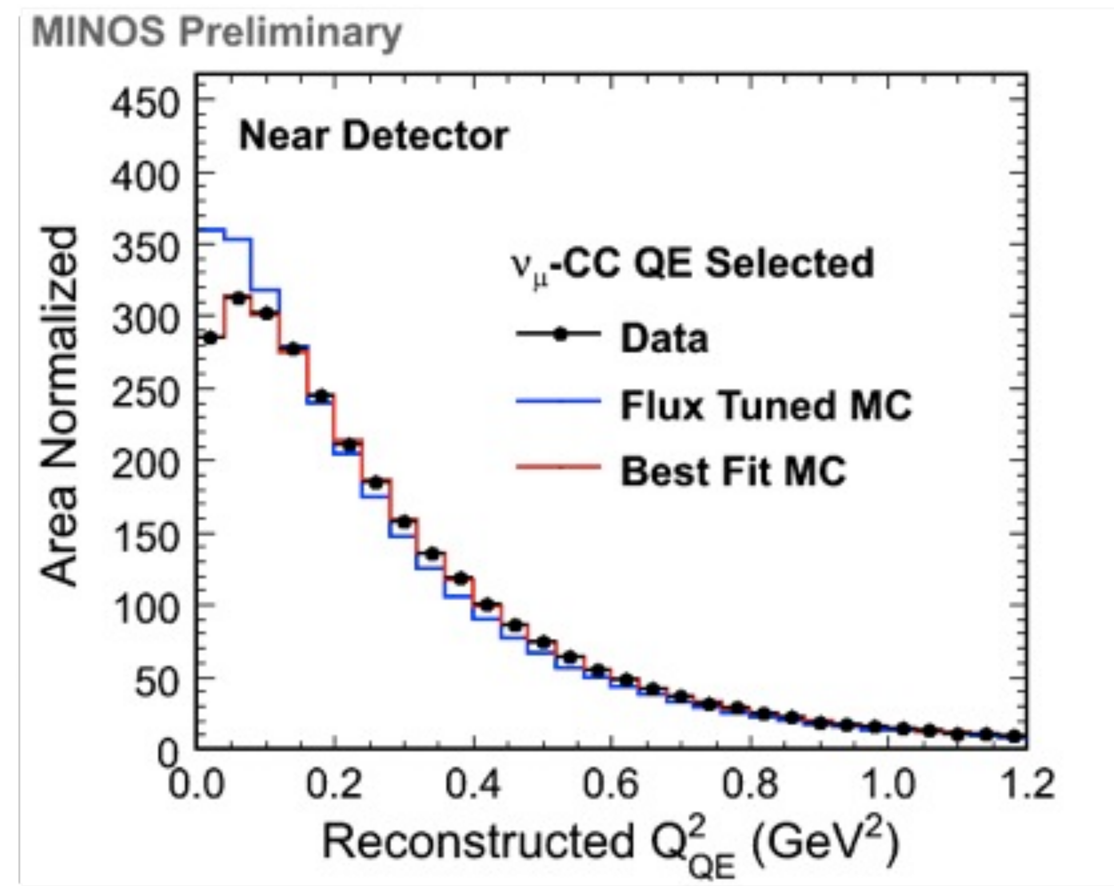
What we look for in the electron neutrino analysis.

MINOS fluxes

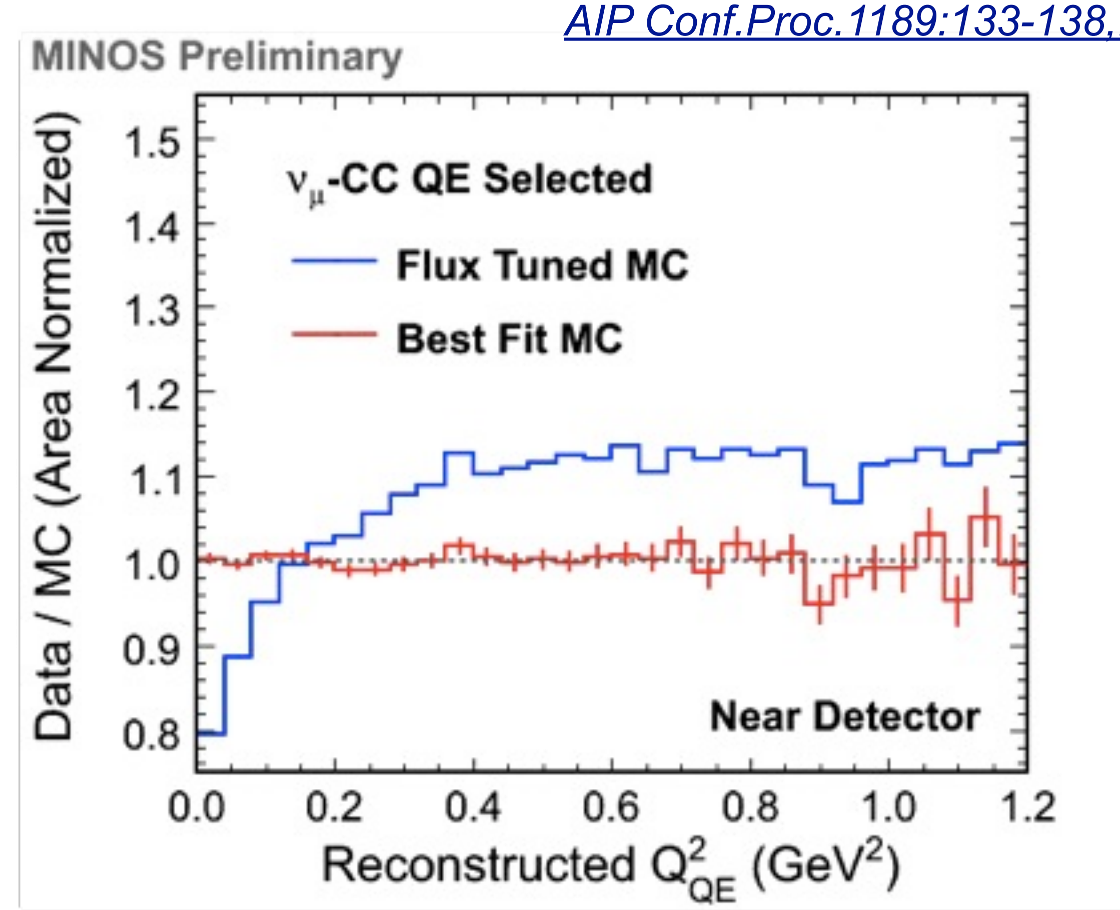


MINOS

- 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.

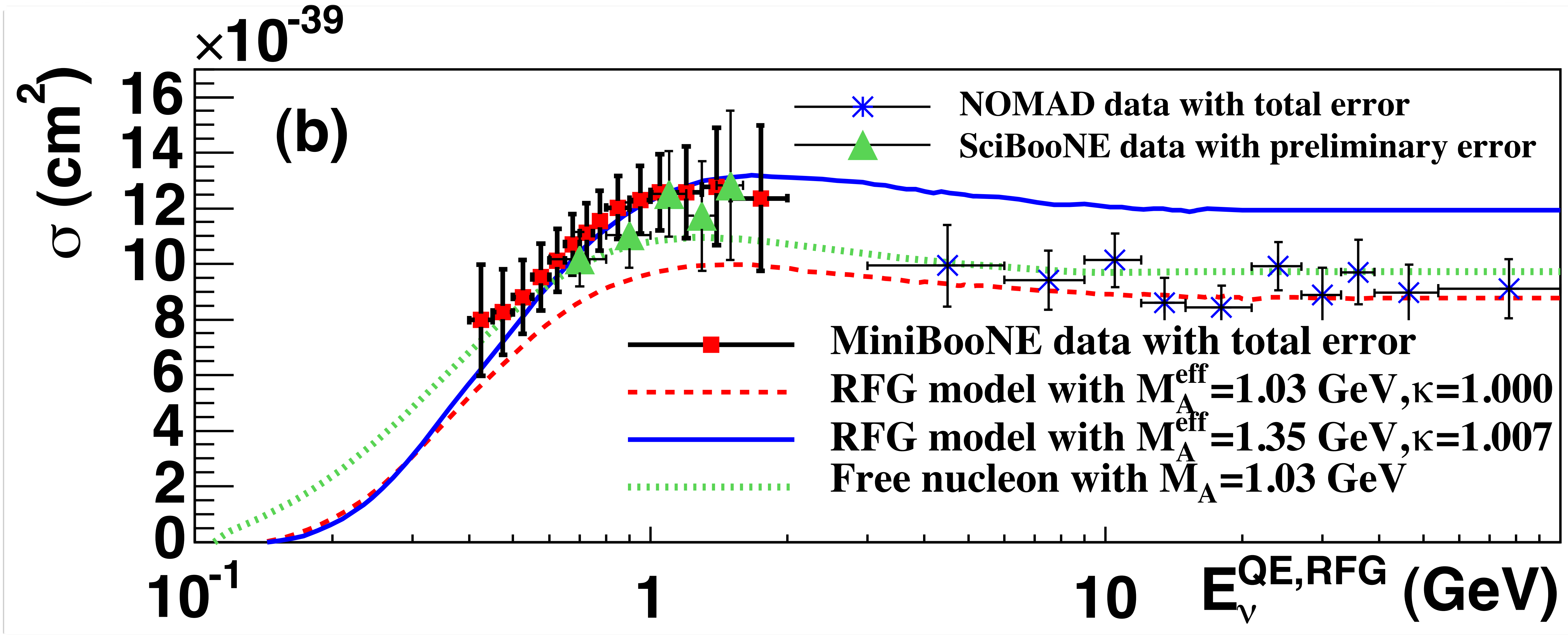


AIP Conf.Proc.1189:133-138,2009



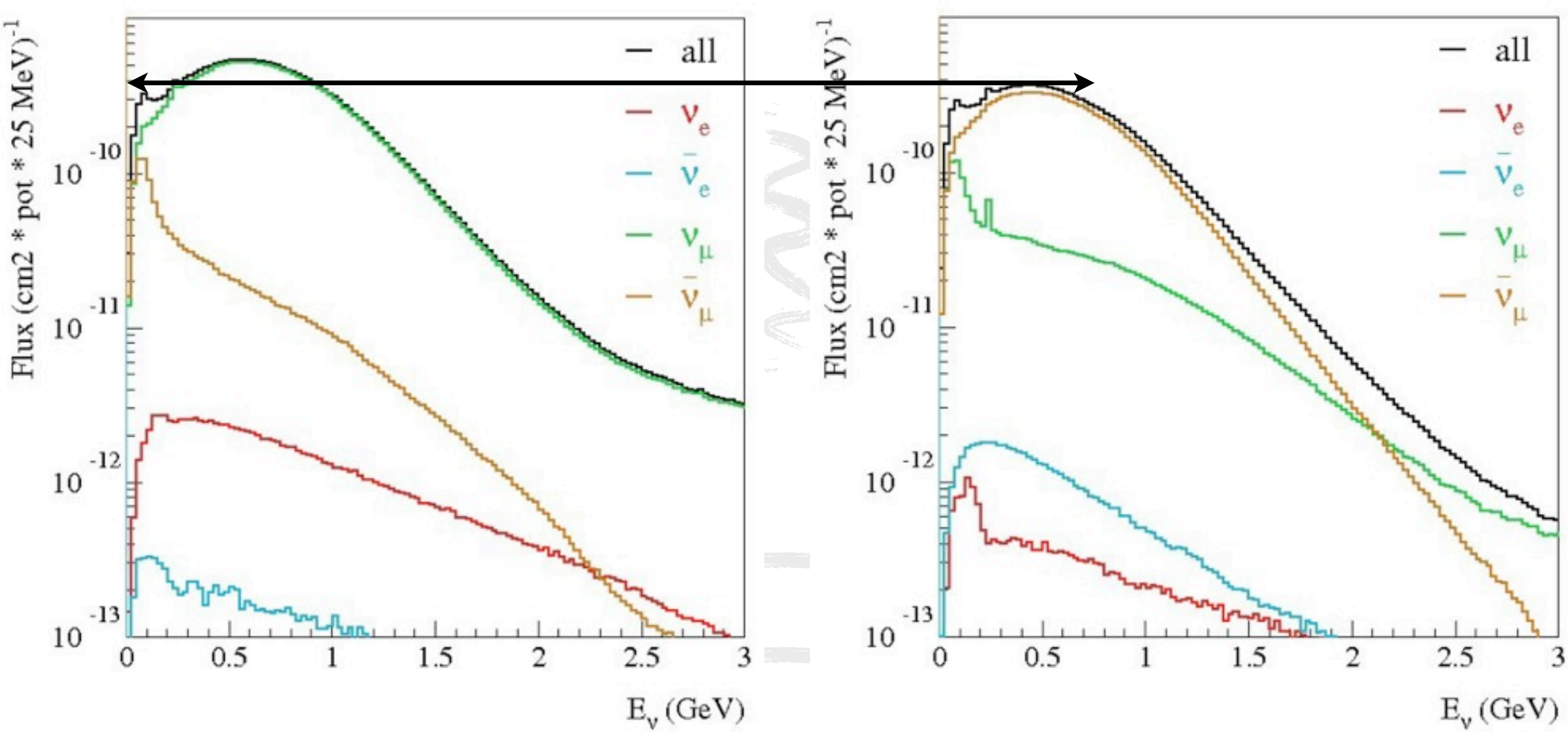
CCQE comparisons

Plot courtesy of Teppei Katori (MIT)

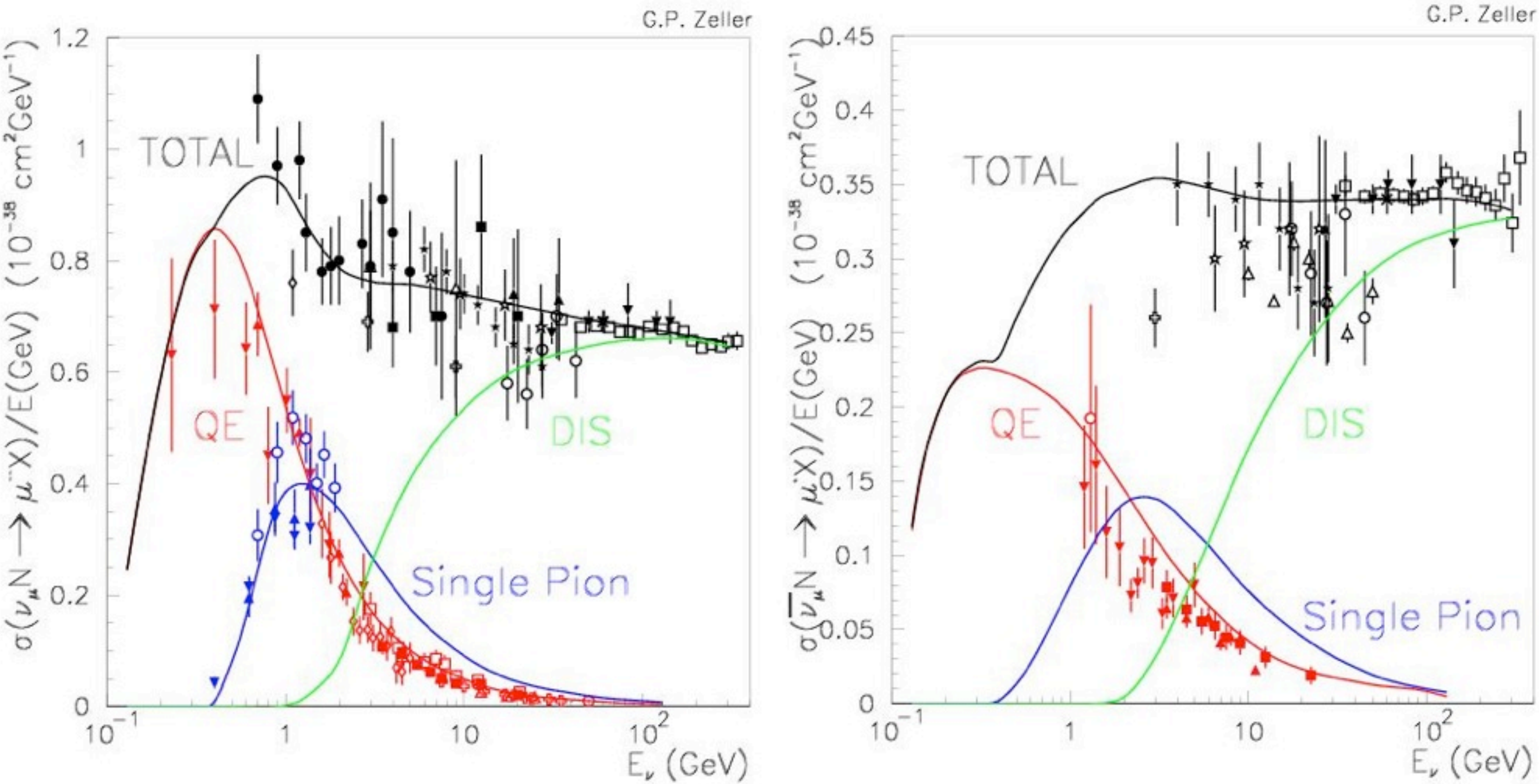


Antineutrino intro

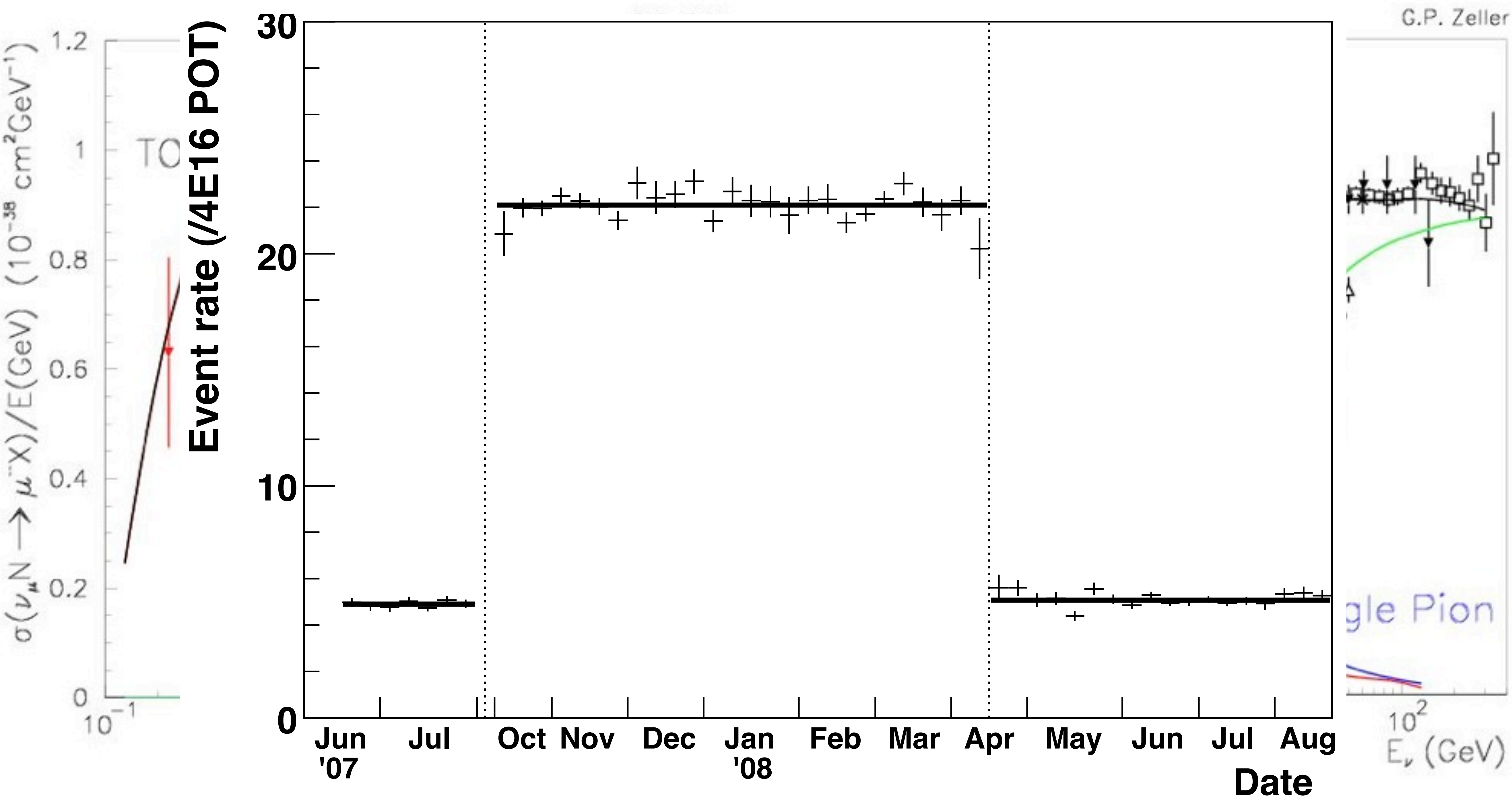
Size Matters



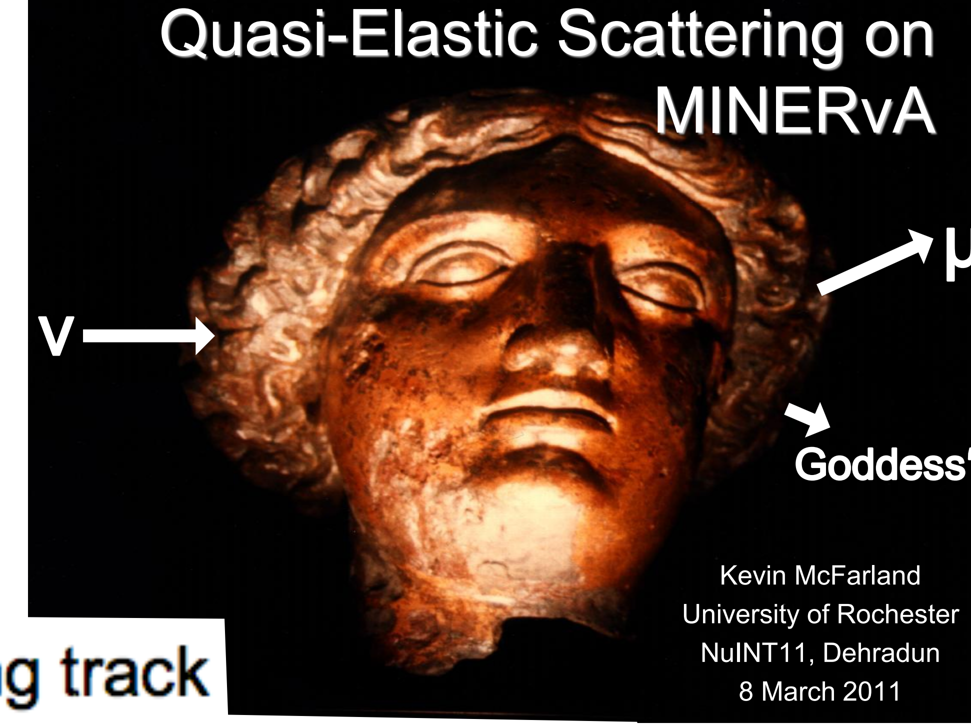
Size Matters



Size Matters

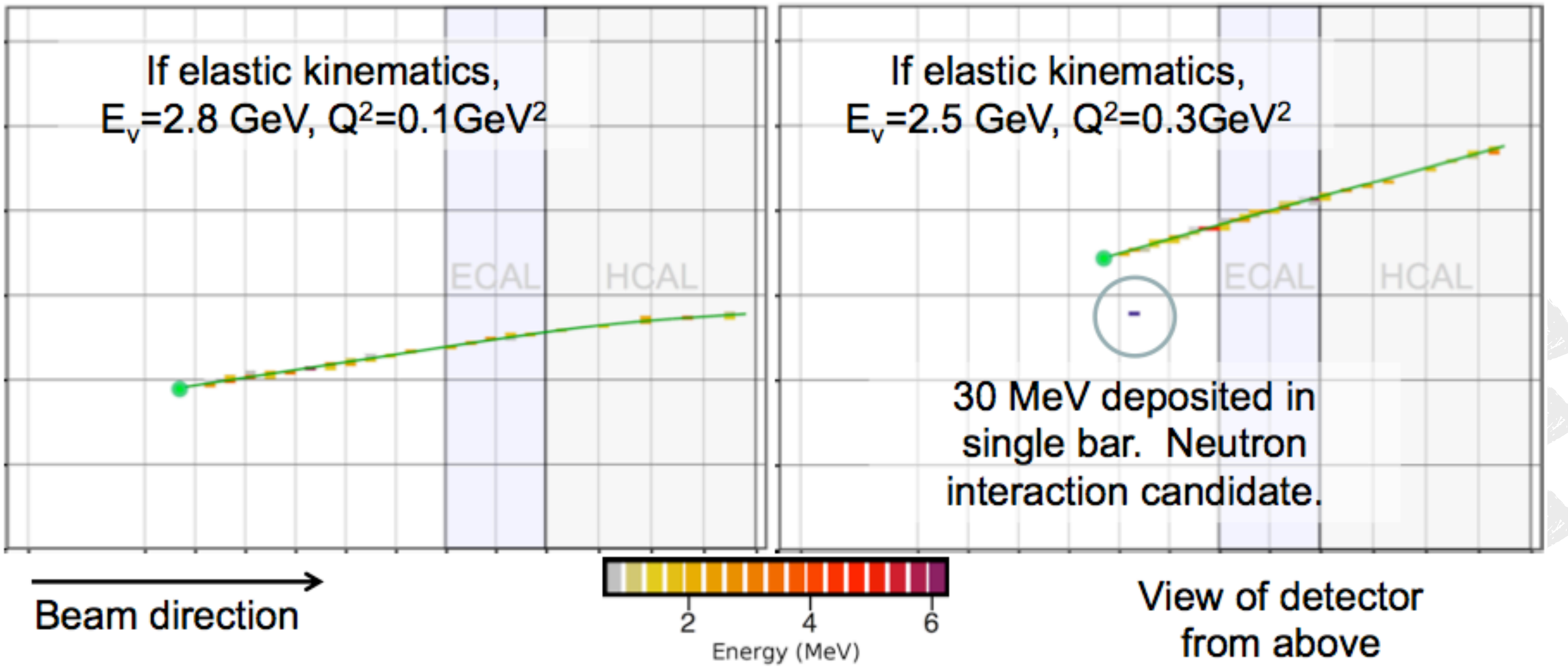


MINERvA

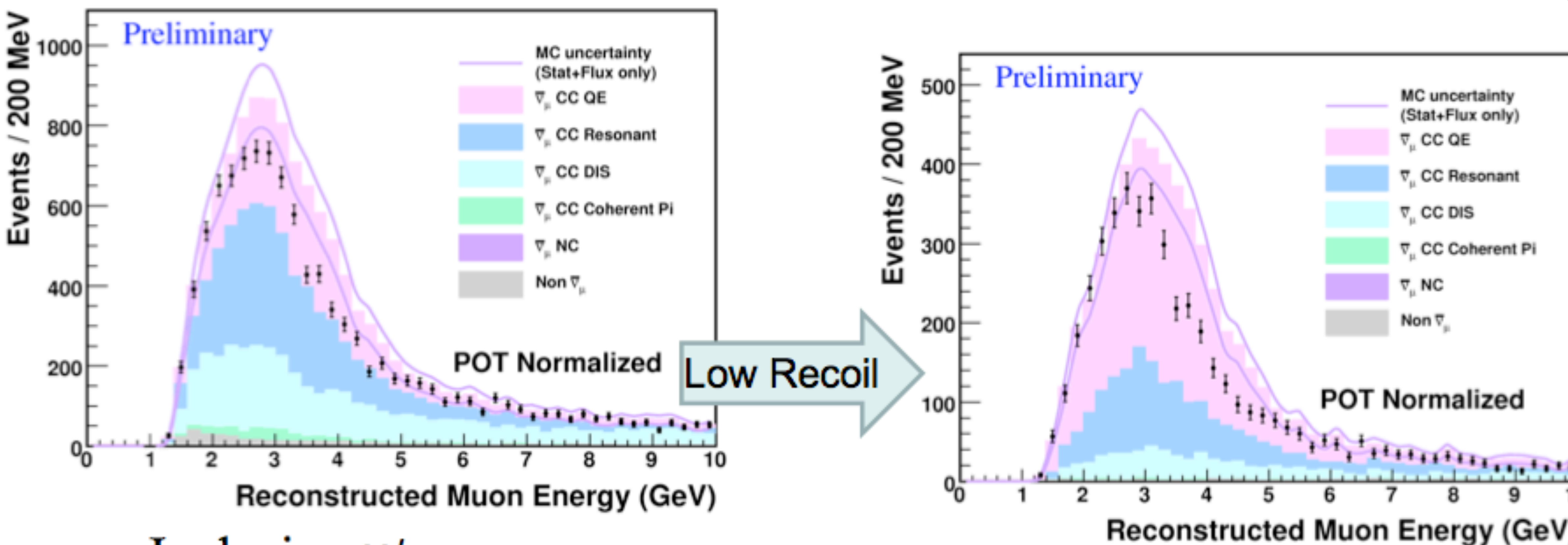


$\bar{\nu}_\mu p \to \mu^+ n$

- Muon is a long, penetrating track
- Neutron may or may not appear in the detector



MINERvA



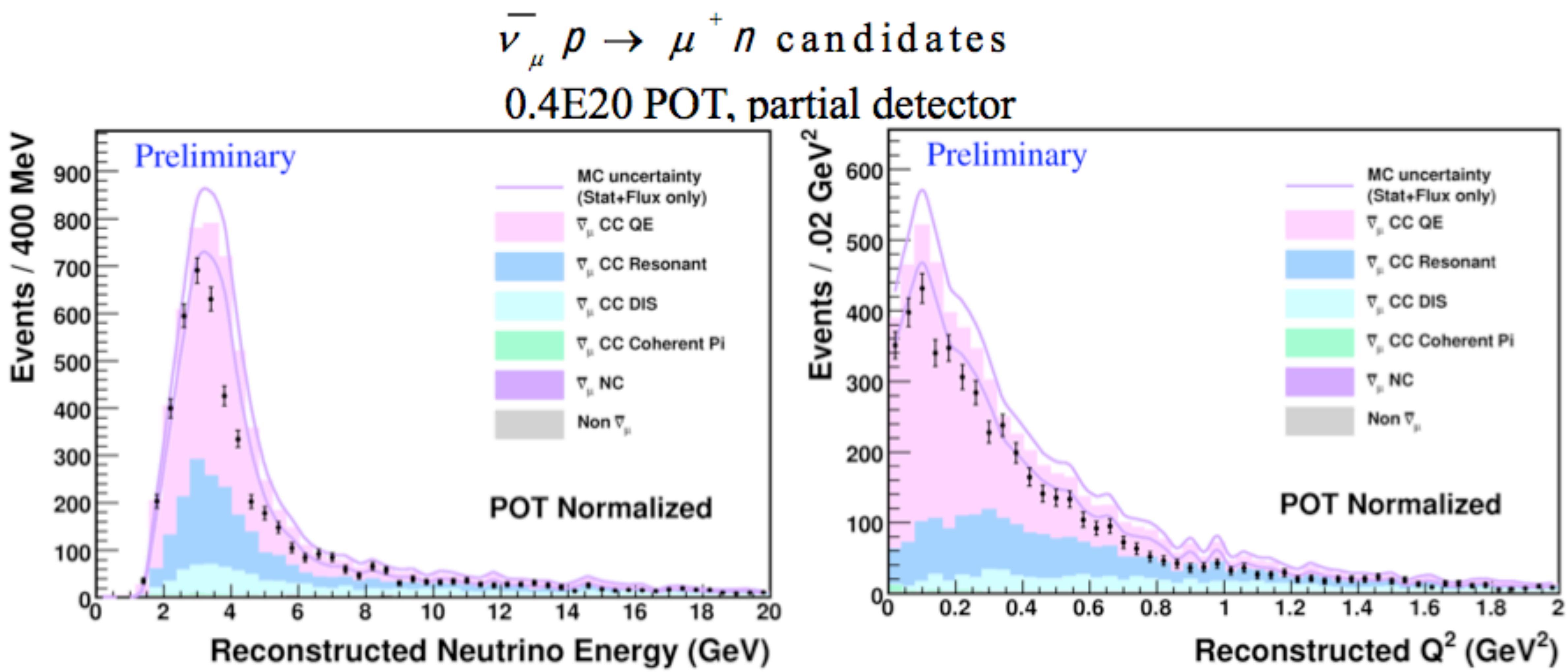
Inclusive μ^+

0.4E20 POT,
partial detector

$\bar{\nu}_\mu p \rightarrow \mu^+ n$ candidates

- Absolute normalization: protons + flux + cross-sections
- Recoil cut leaves Quasi-Elastic sample largely untouched, but reduces backgrounds significantly

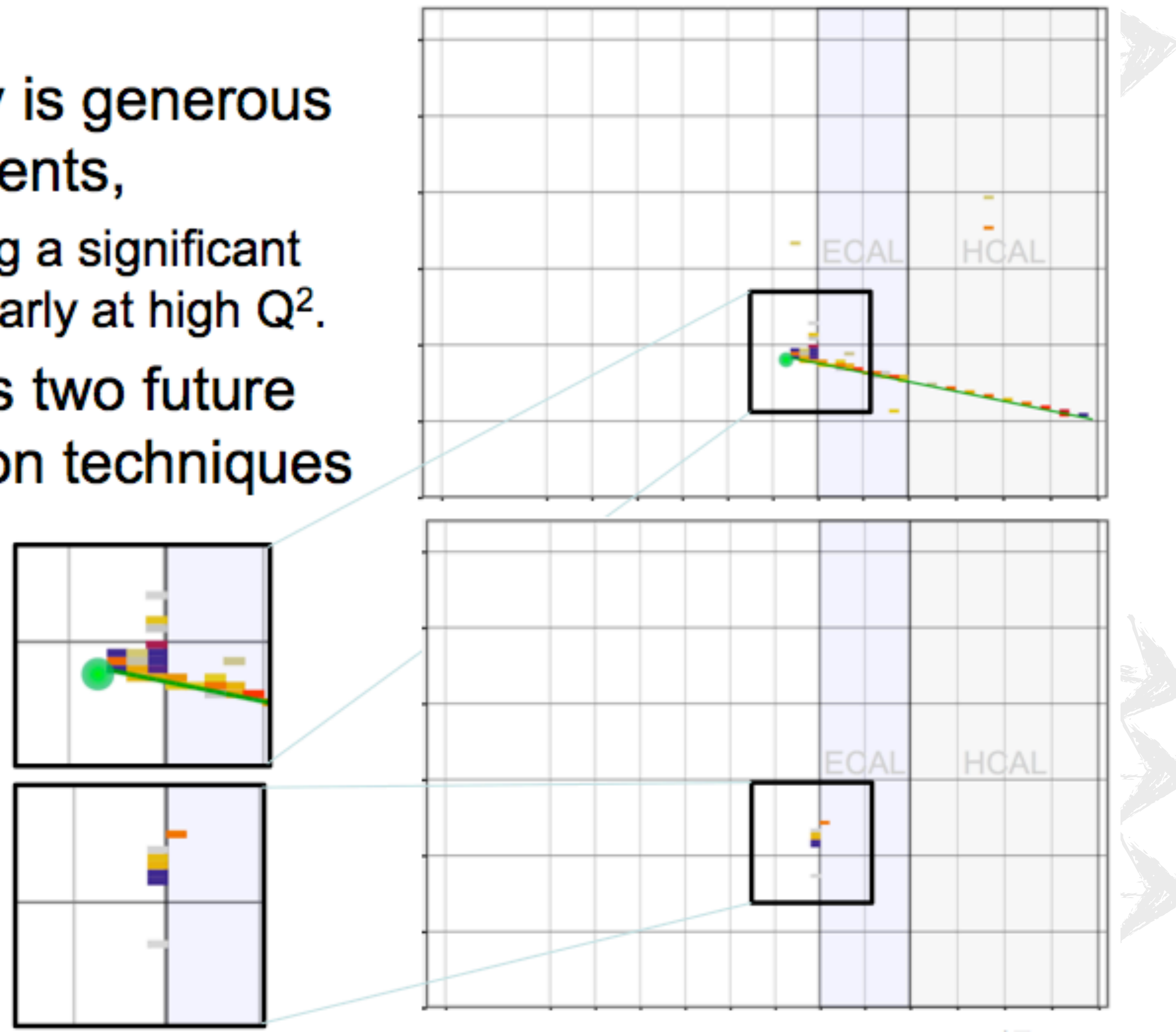
MINERvA



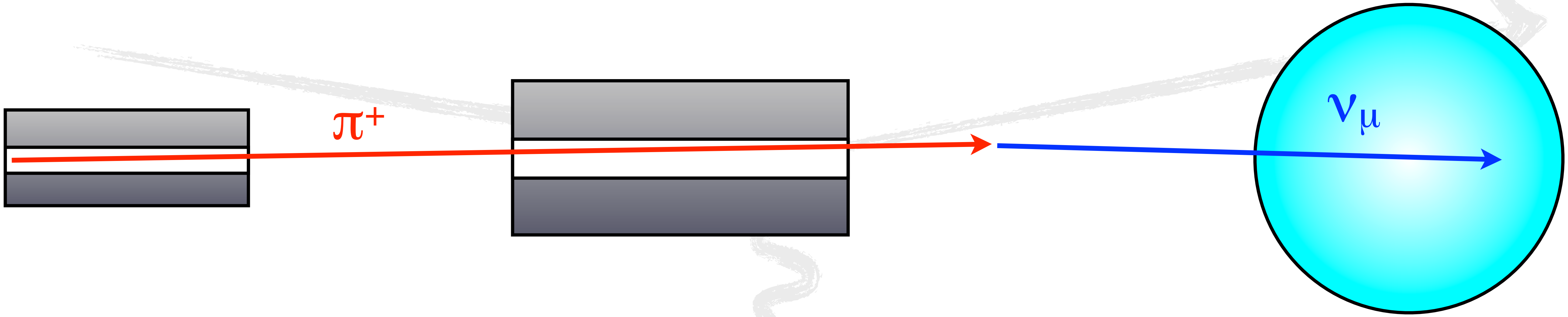
- Reminder: absolute predictions from flux simulation, GENIE 2.6.2, MINERvA simulation
- Event deficit is flat in Q^2 and not flat in E_ν

Ways to improve purity

- The current strategy is generous in keeping signal events,
  - at the price of leaving a significant background, particularly at high Q^2.
- This event illustrates two future background reduction techniques
  - Recoil energy near the track
  - Michel electron veto to remove $\pi^{\pm}$



Wrong sign BGs



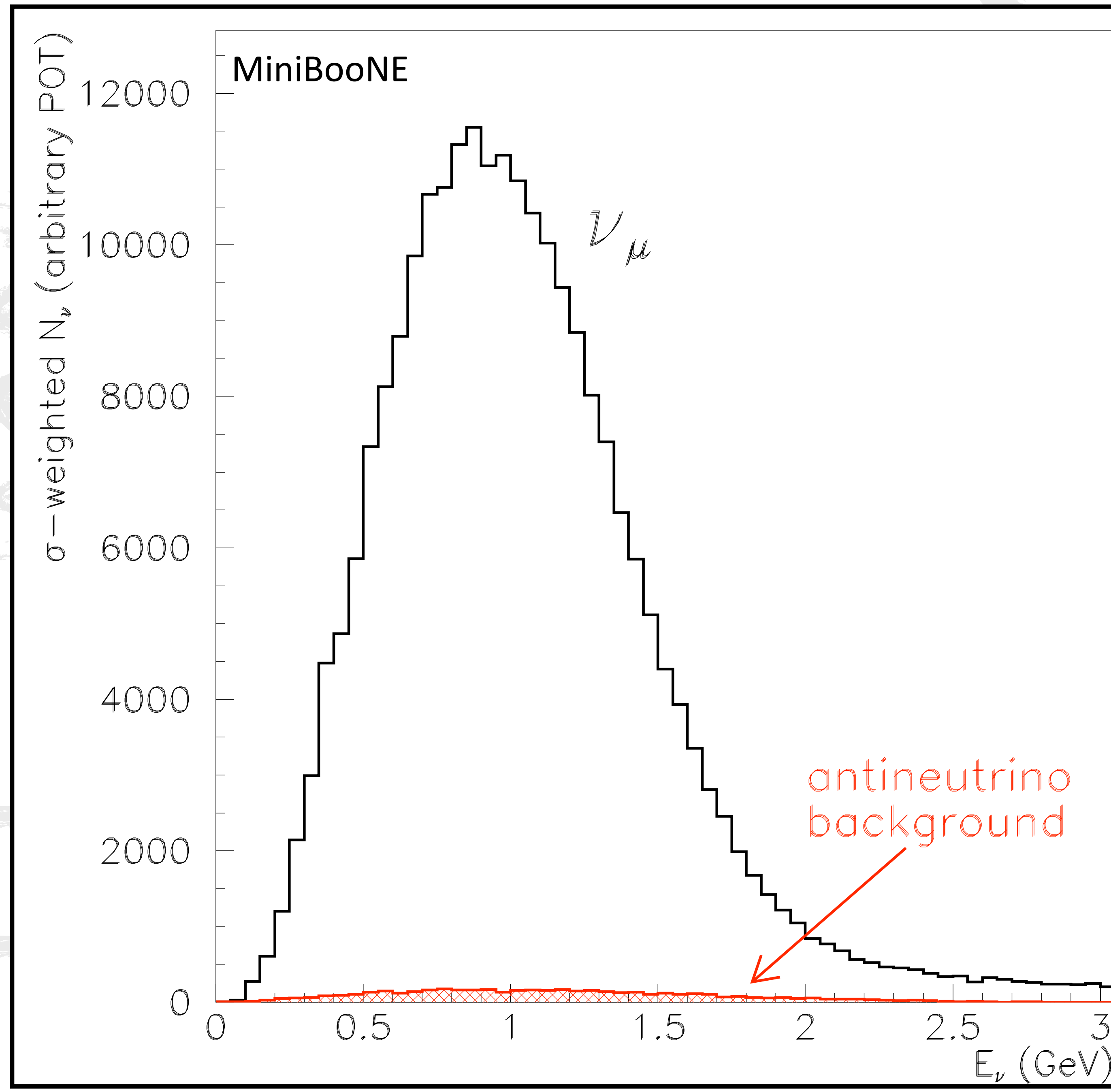
Neutrino horns cannot focus (or sign-select) pion passing *inside* the inner conductor.

More π+ produced than π-, so unfocused beam is predominantly ν_μ not $\bar{\nu}_\mu$.

Wrong Sign BGs

- In neutrino running, wrong sign backgrounds are very small (2%)
- In antineutrino running they are much larger (~30%)
- Cherenkov calorimeters cannot distinguish μ^- from μ^+
- Need a way to extract the WS BGs!

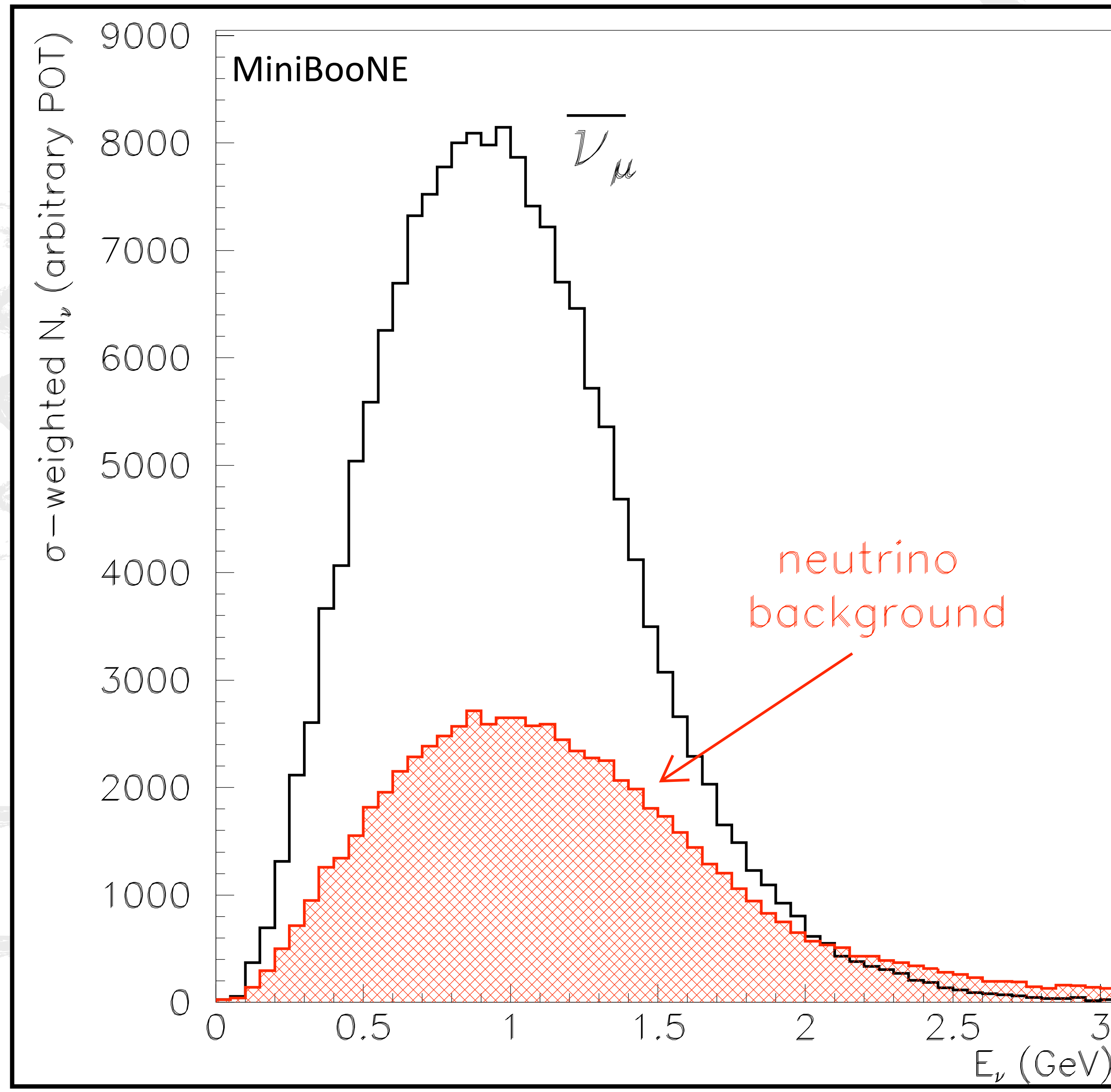
Gang of Four



Wrong Sign BGs

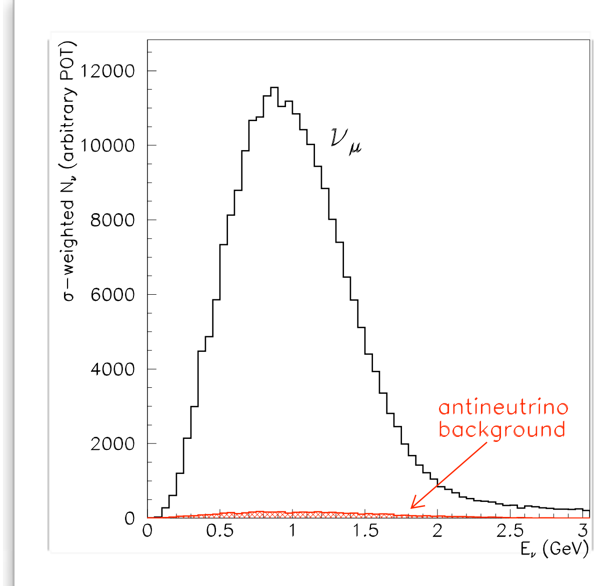
- In neutrino running, wrong sign backgrounds are very small (2%)
- In antineutrino running they are much larger (~30%) for BooNEs
- Cherenkov calorimeters cannot distinguish μ^- from μ^+ (event by event)
- Need a way to extract the WS BGs!

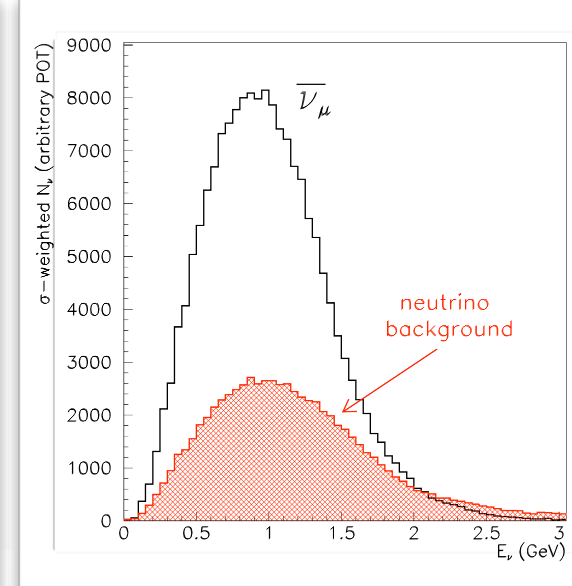
Gang of Four



MiniBooNE Antineutrinos

- Very few measurements of nubar CCQE near 1 GeV
- Horn focussing leads to wrong sign (WS) backgrounds
  - neutrinos in antineutrino mode
- MiniBooNE has sophisticated analysis to constrain WS BGs
  - Different angular distributions



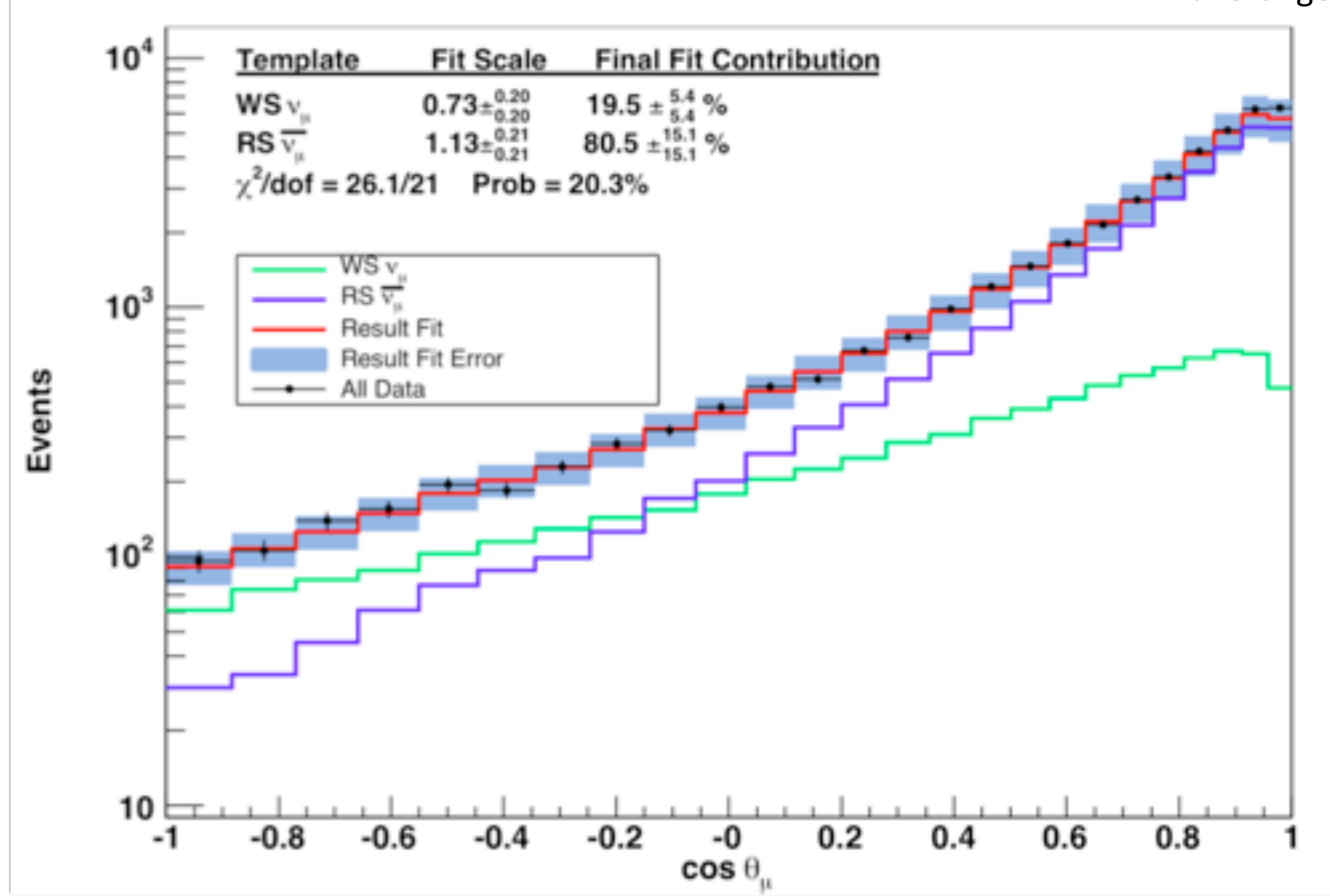


G.P. Zeller

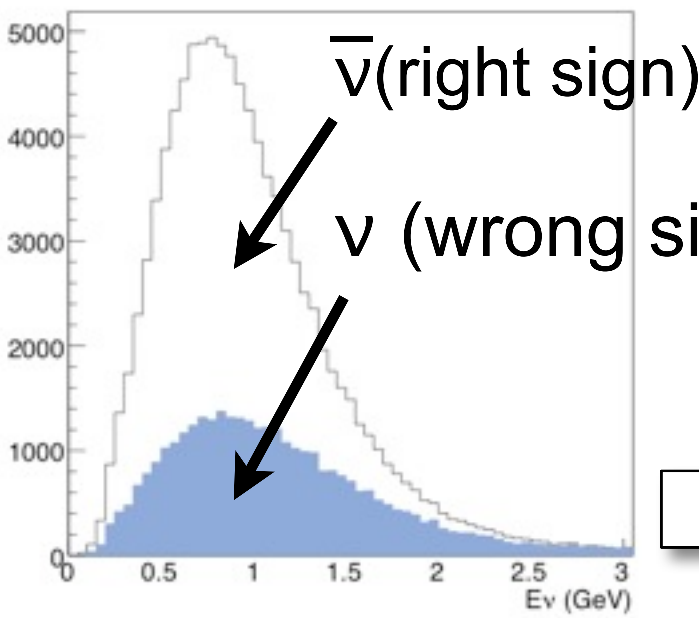
$$\frac{d\sigma^{QE}}{dQ^2} = \frac{M^2 G_F^2 |V_{ud}|^2}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2)\times\left(\frac{s-u}{M^2}\right) + C(Q^2)\times\left(\frac{s-u}{M^2}\right)^2\right]$$

+ for ν, - for $\bar{\nu}$

J. Grange

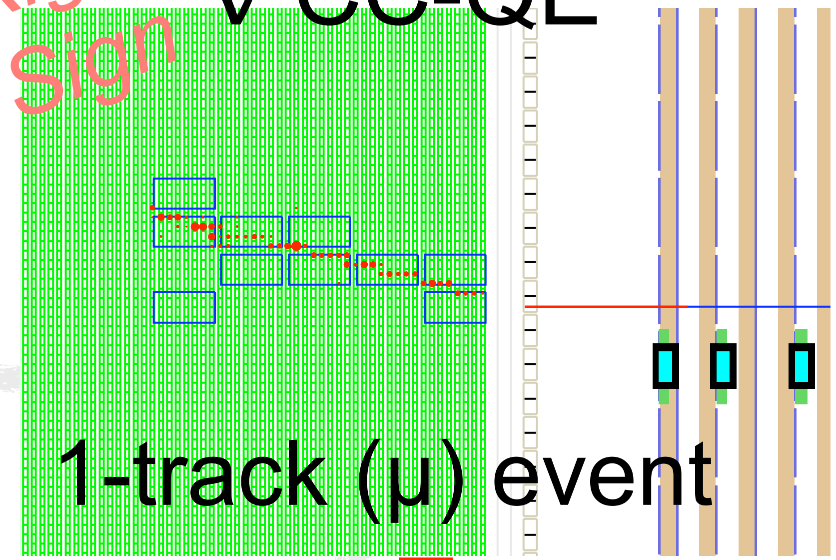


SciBooNE $\bar{\nu}$ and ν samples



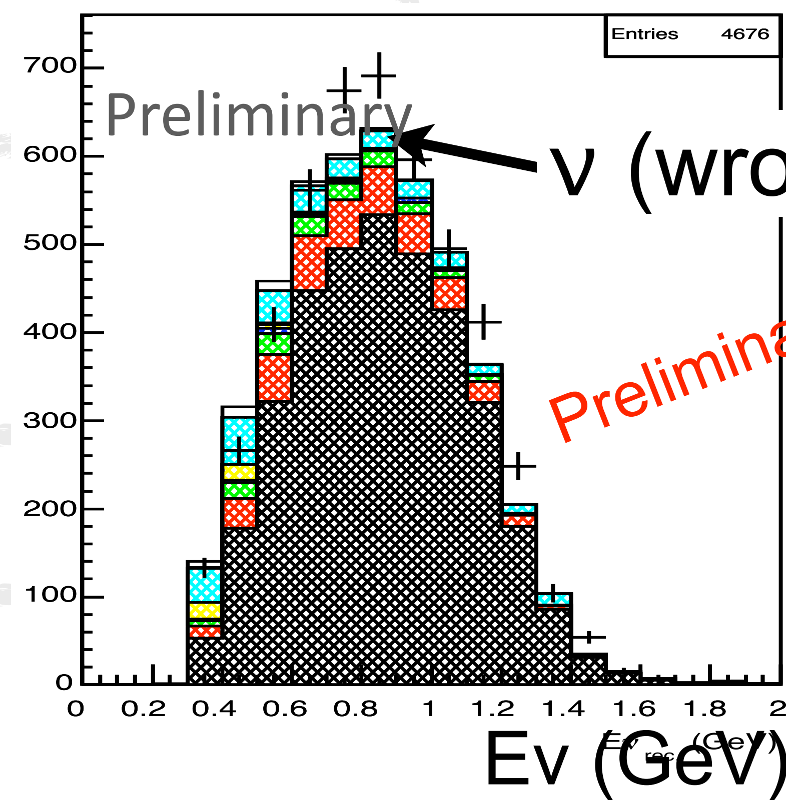
ν (wrong sign) ~30% background in MRD stopped sample

Right Sign $\bar{\nu}$ CC-QE



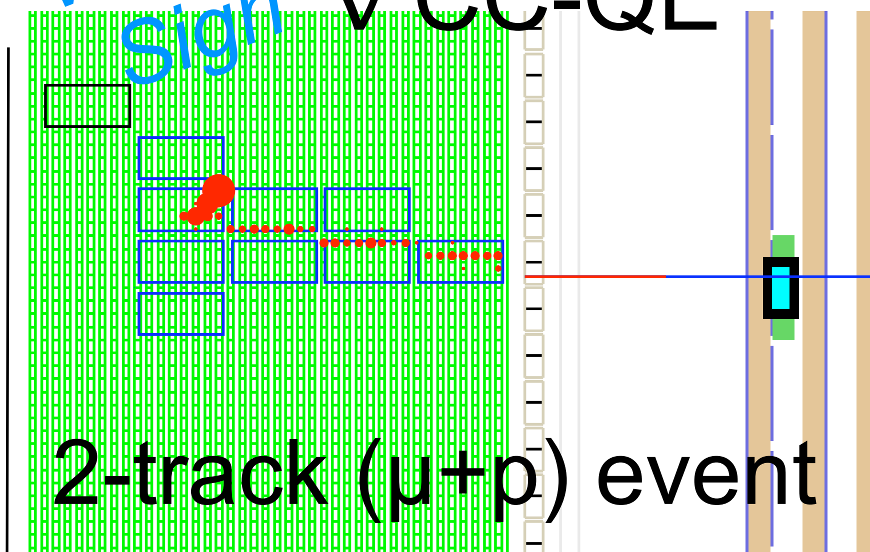
~90% $\bar{\nu}$ purity

($\bar{\nu}$ CC-QE: 80%)



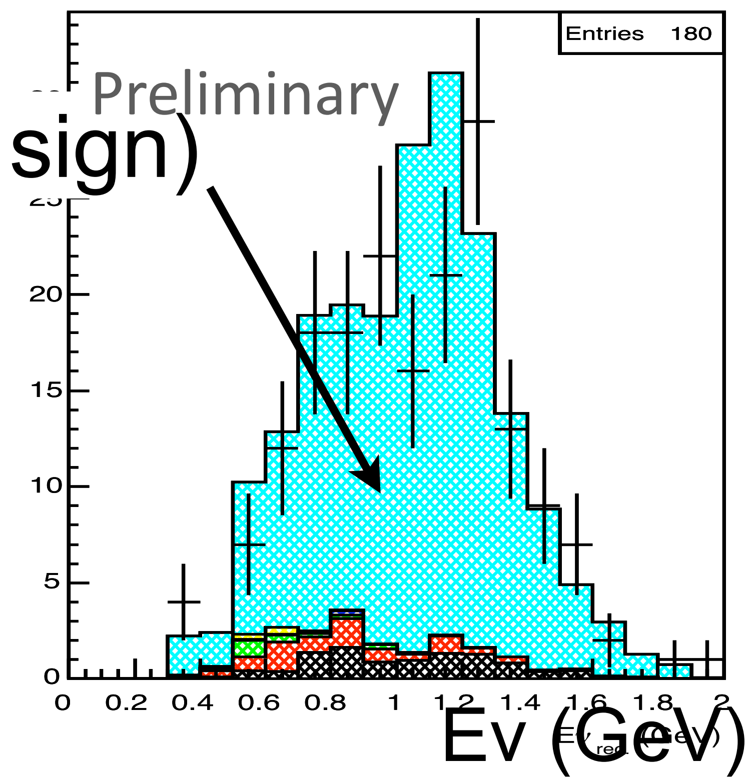
1-track w/o activity sample

Wrong Sign ν CC-QE

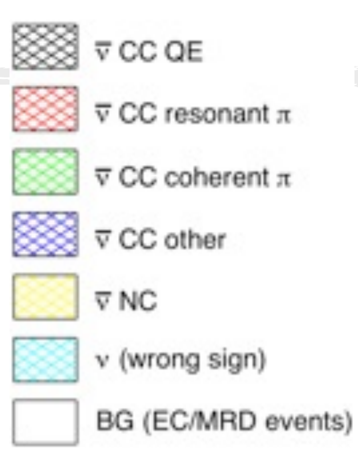


~90% ν purity

(ν CC-QE: 75%)



2-track QE-like sample



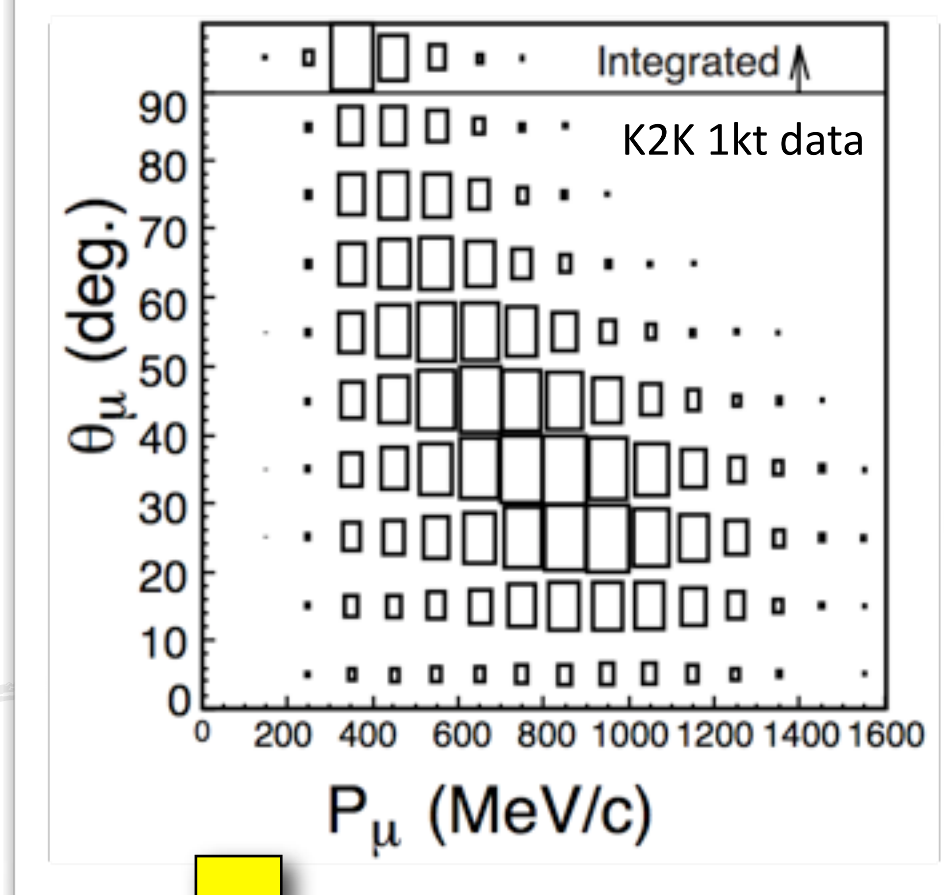
Putting these in context

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



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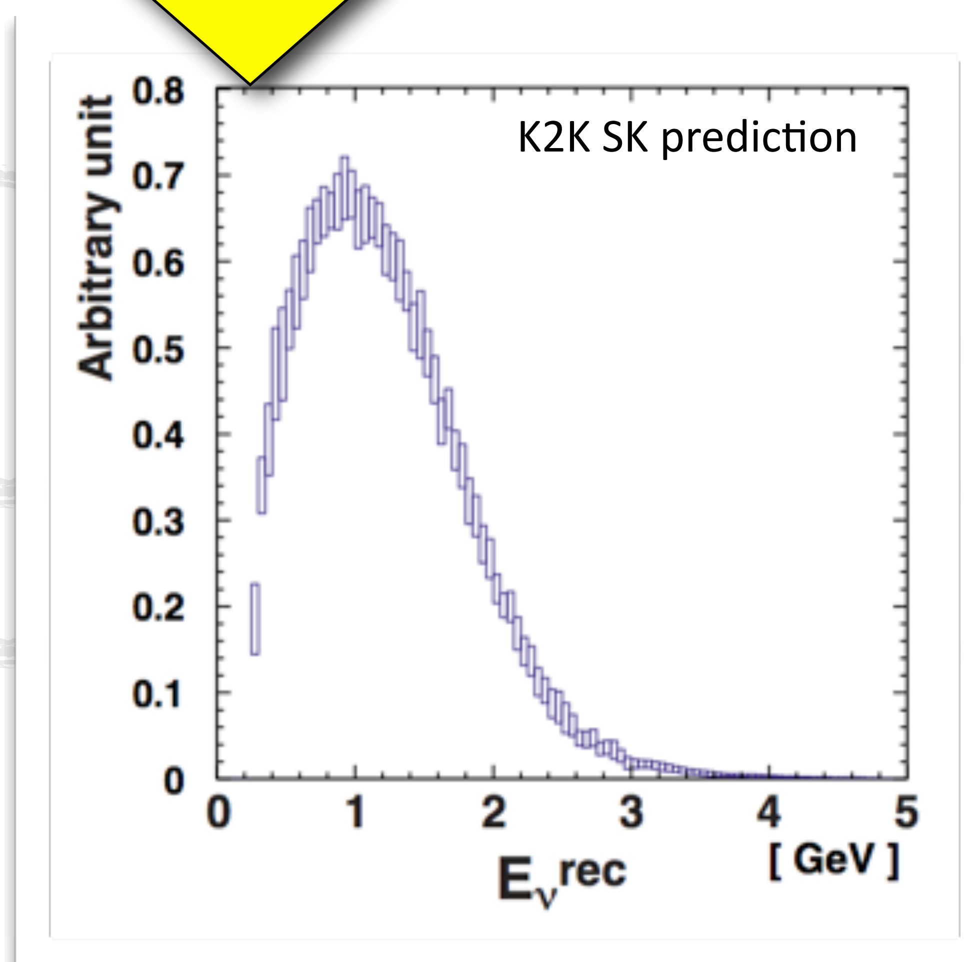


CCQE and Oscillations

- 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!

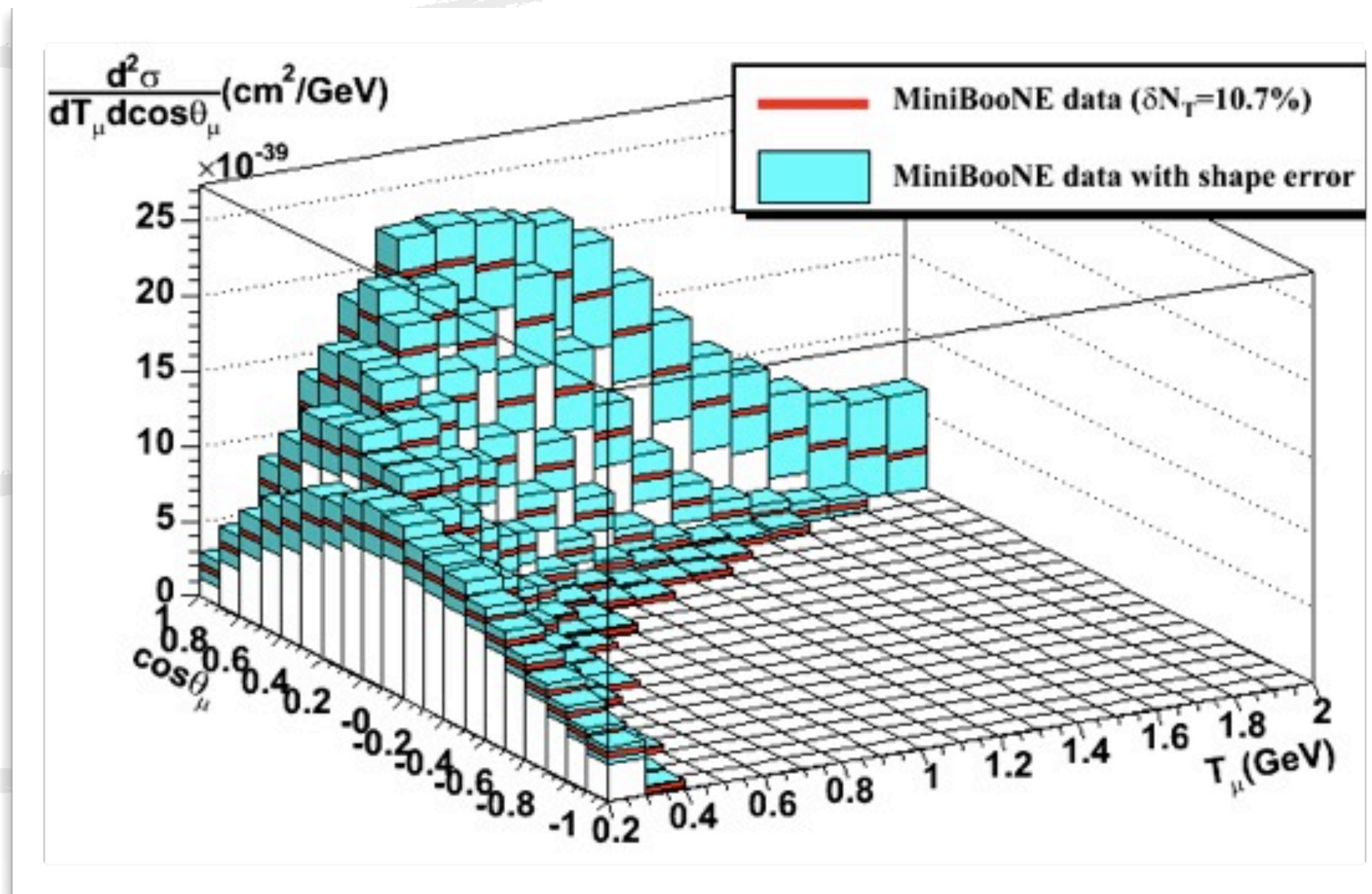
MiniBooNE ν_e appearance systematic uncertainties

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)

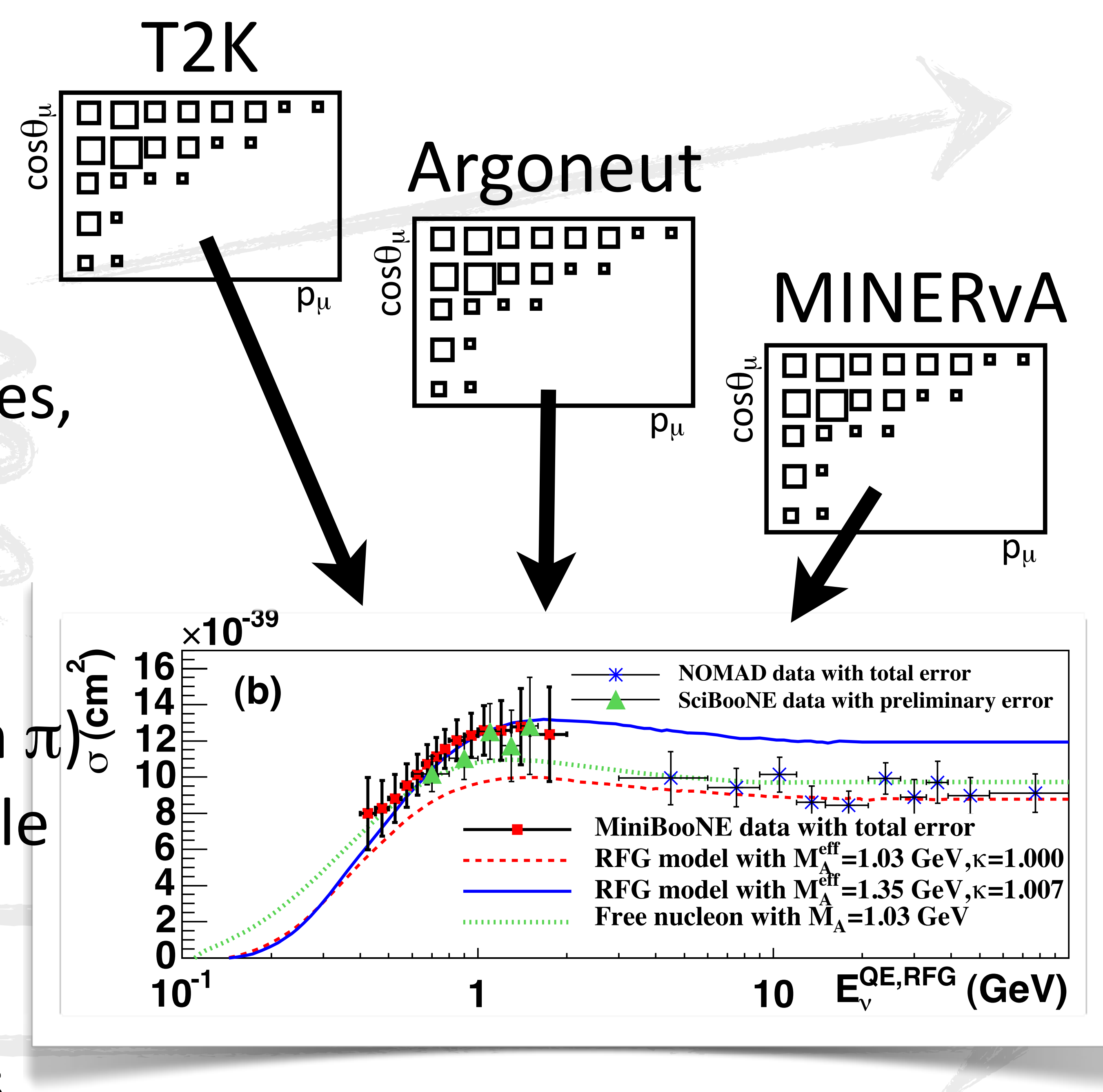
Wrap up

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

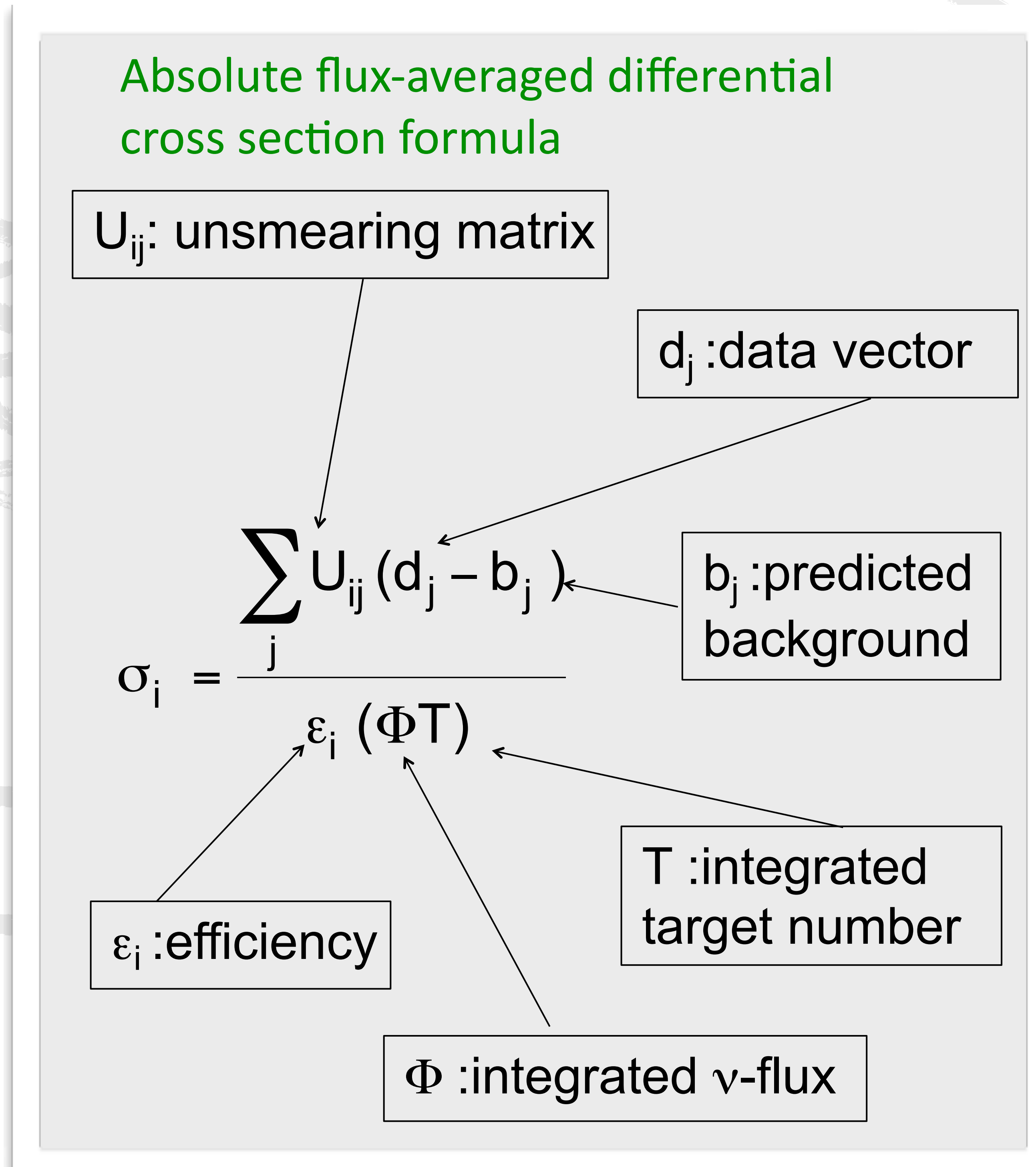
- We need broad coverage
  - Model independent measurements at many energies, nuclei
- Move away from process cross-sections
  - σ(CCQE), σ(CC res π), σ(CC coh π)
- Instead measure final state particle cross-sections
  - σ(CC), σ(μ), σ(μ+p), σ(μ+π)
    - (CC Inclusive measurements offer most robust confrontation 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



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.

CCQE 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.

Conclusions

- Cross section measurements are needed to interpret neutrino oscillation data.
- New measurements are revealing problems left unseen by previous experiments.
  - These problems have consequences for oscillation experiments.
- New data analysis philosophies are needed so we can improve theoretical models.
- Observing CP violation relies on this!!

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