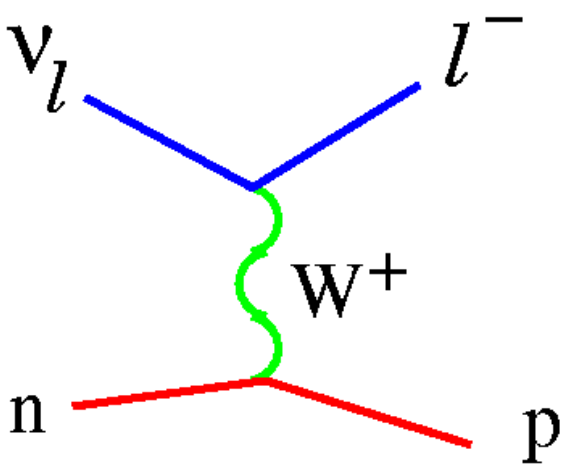
Charged Current Quasi-Elastic Interactions at MiniBooNE with Your σ Monte Carlo

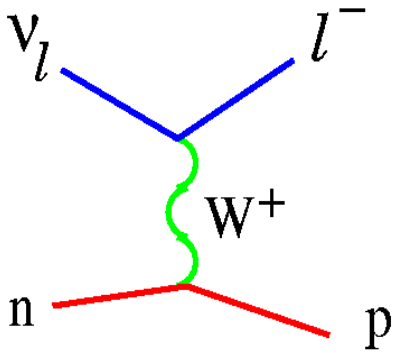
Jocelyn Monroe, Columbia University

- CCQE interactions
- CCQE Predictions in NUANCE, NEUGEN & NEUT Monte Carlos
- Measuring quasi-elastic interactions at MiniBooNE



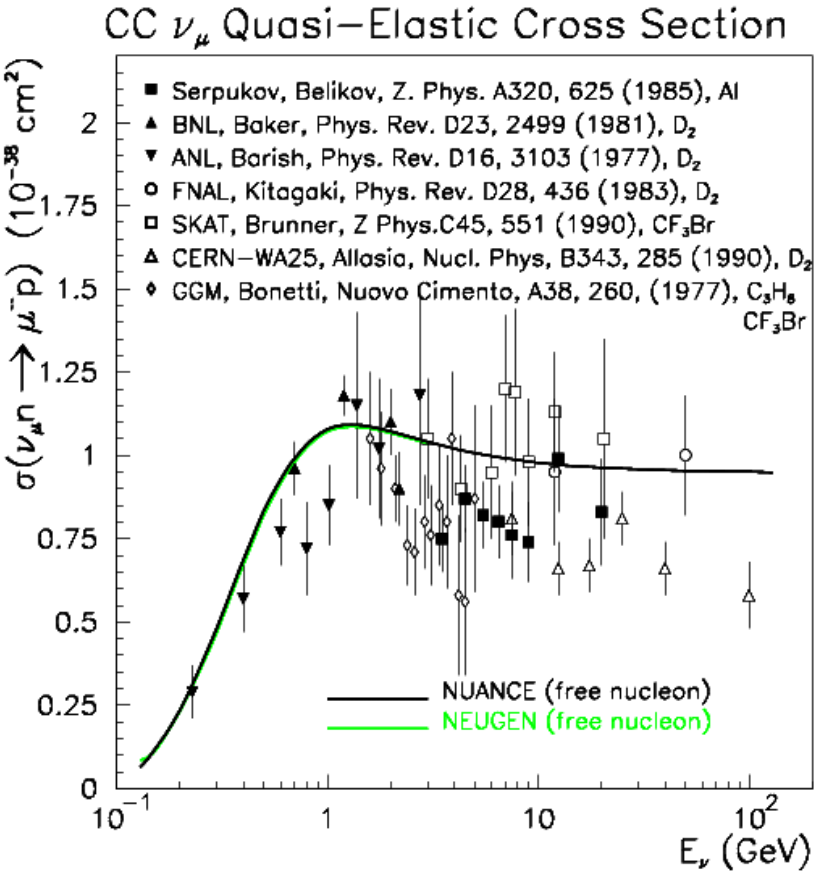
Charged Current Quasi-Elastic Interactions

- Simple kinematics: measure lepton energy, angle ⇒ calculate ν energy (then fit for oscillations)



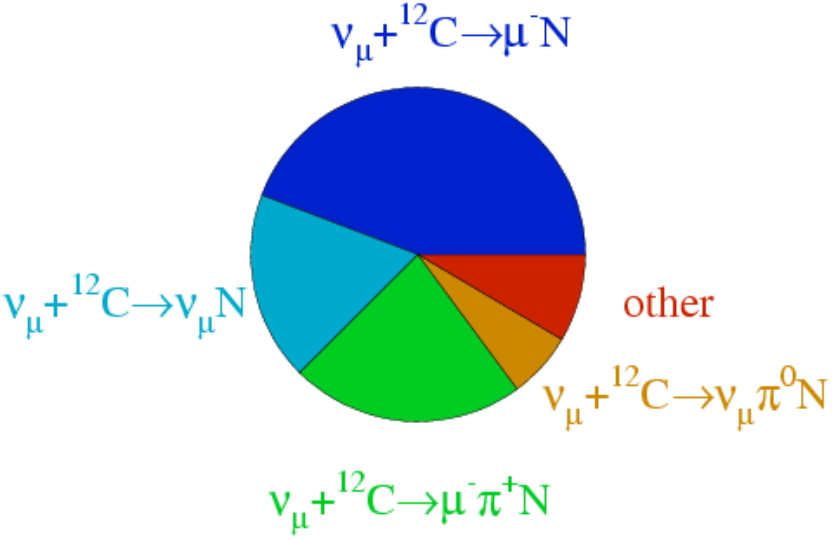
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

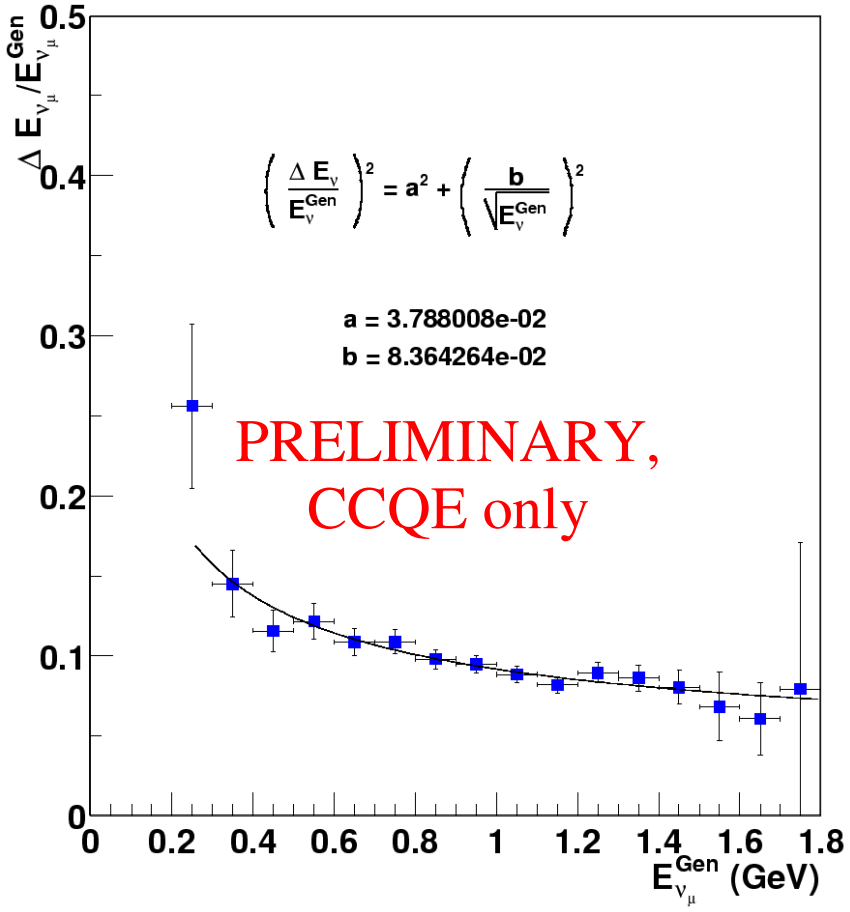
- Fairly well known cross section at low ν energy (important error contribution to oscillation searches)



Charged Current Quasi-Elastic Interactions

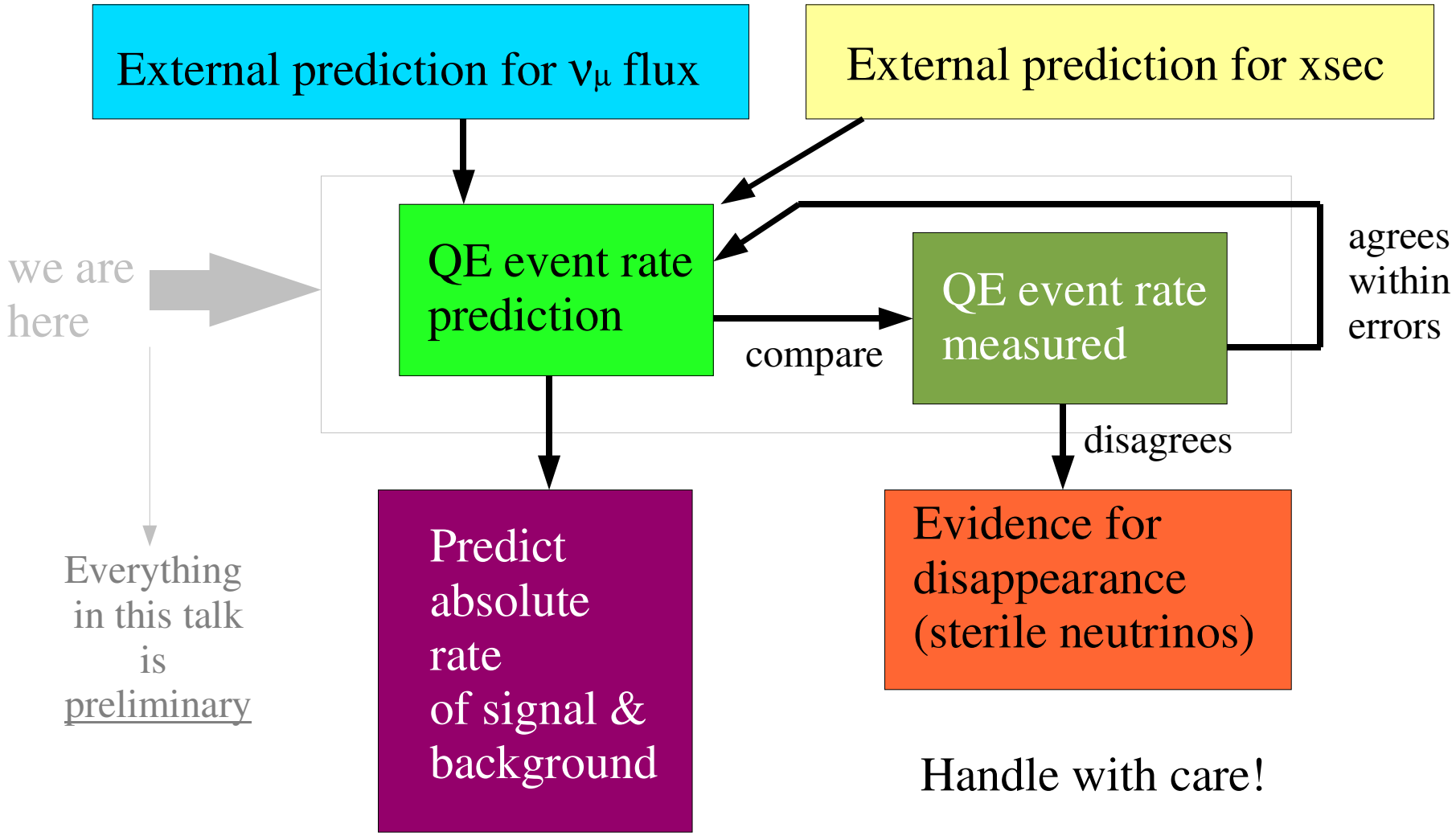
- MiniBooNE has a lot of ν_μ CCQE events (about 100k so far, 500k eventually)



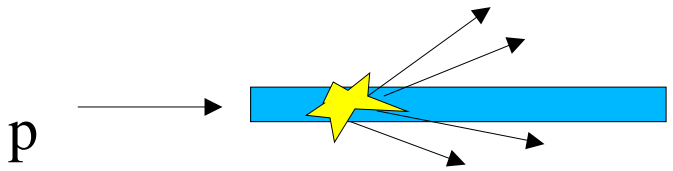


- Excellent ν energy resolution ~10%
  (ideal case, no non-CCQE background,
  BUT, *current* calibration and reconstruction!)

Modelling CCQE Interactions at MiniBooNE



External Prediction for ν_μ Flux

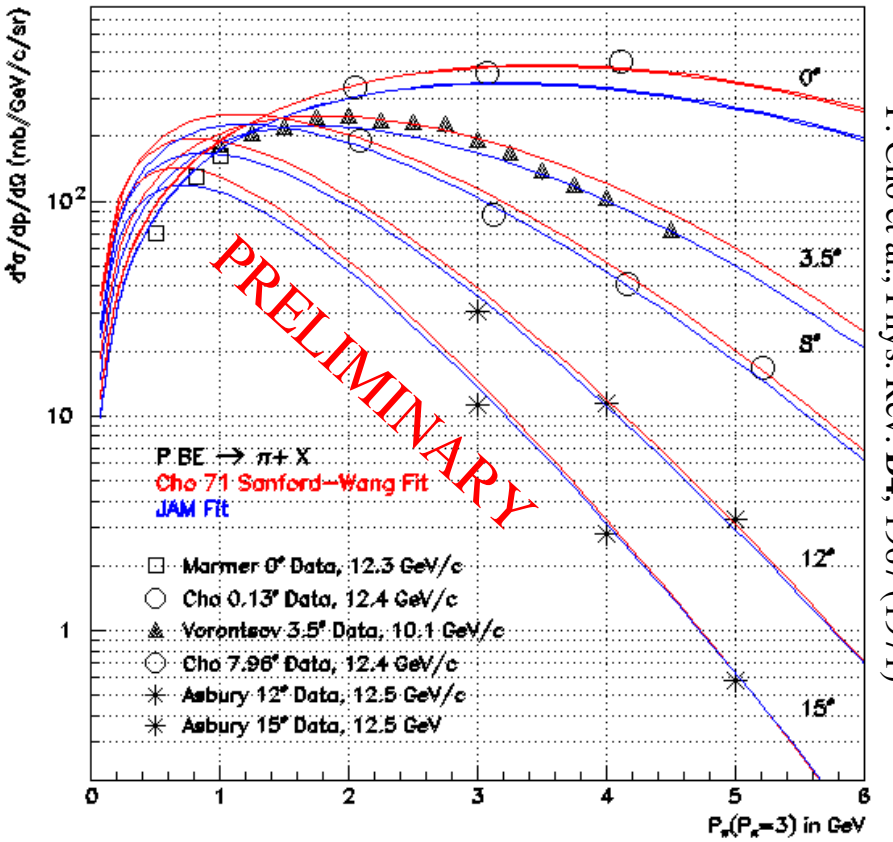


$$\pi^+ / K^+ \rightarrow \mu^+ \nu_\mu \quad \& \quad K^+ / K^0_L \rightarrow \pi\, e\, \nu_e$$
$$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$$

- Production of secondaries in Be target modelled via
  - GFLUKA or MARS
  - Sanford-Wang parametrization:
    generic form in p, p_T w/ kinematic cutoff

    fit to p Be -> π^+ X data ("JAM")
    $10 < p_{proton} < 23$ GeV/c
    $\Rightarrow$ requires extrapolation to 8 GeV

$$\frac{d^2\sigma}{dp\,d\Omega} = W_1 p_\pi^{W_2}\left(1-\frac{p_\pi}{p_{proton}}\right) \; x$$
$$\exp\left(\frac{-W_3 p_\pi^{W_4}}{p_{proton}^{W_5}} - W_6\theta_\pi\left(p_\pi - W_7 p_{proton}\cos^{W_8}\theta_\pi\right)\right)$$



Y. Cho et al., Phys. Rev. **D4**, 1967 (1971)

External Prediction for ν_μ Flux

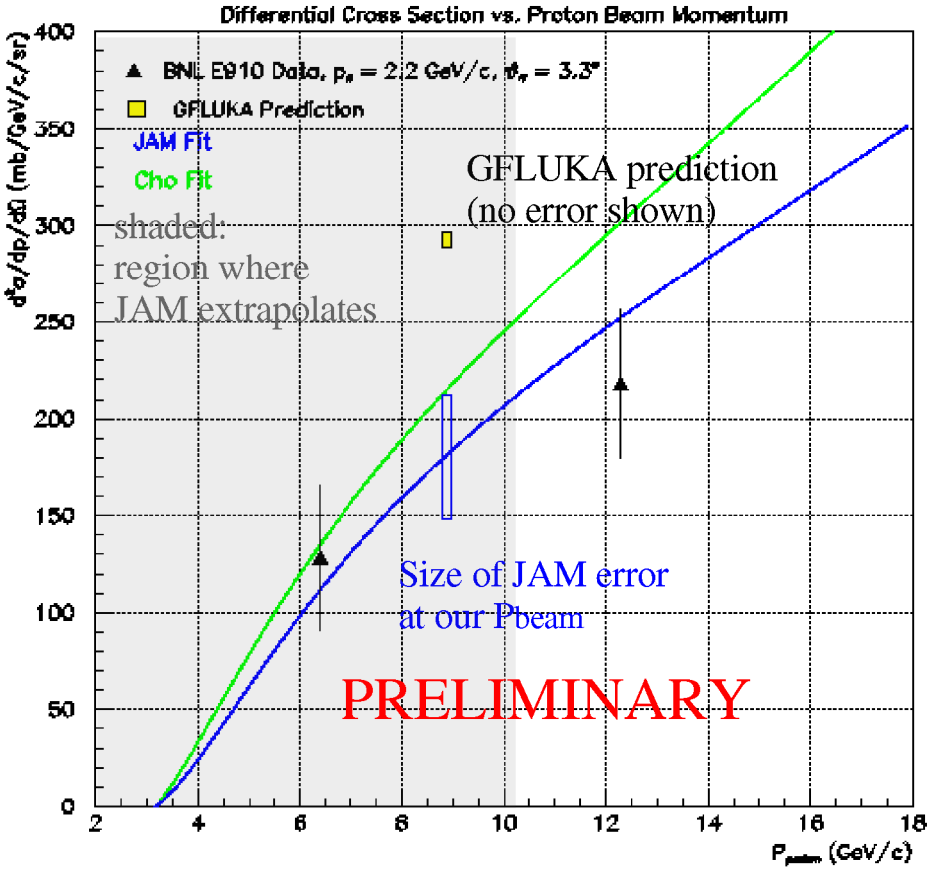
BNL E910, recent (1990's) data on Be target

- 4π detector, high statistics
- 6.3, 12.4, 17.5 GeV/c proton beam momenta
- $0 \leqslant \theta_\pi \leqslant 18^o$
- $0 < p_\pi < 6$ GeV/c
- Requires we interpolate
- Not included in "JAM" Sanford-Wang fit, but in good agreement

Combined fit results coming soon!

Near future:

Measure σ (p Be $\rightarrow \pi^+ X$) at 8 GeV at HARP with high statistics and MiniBooNE target



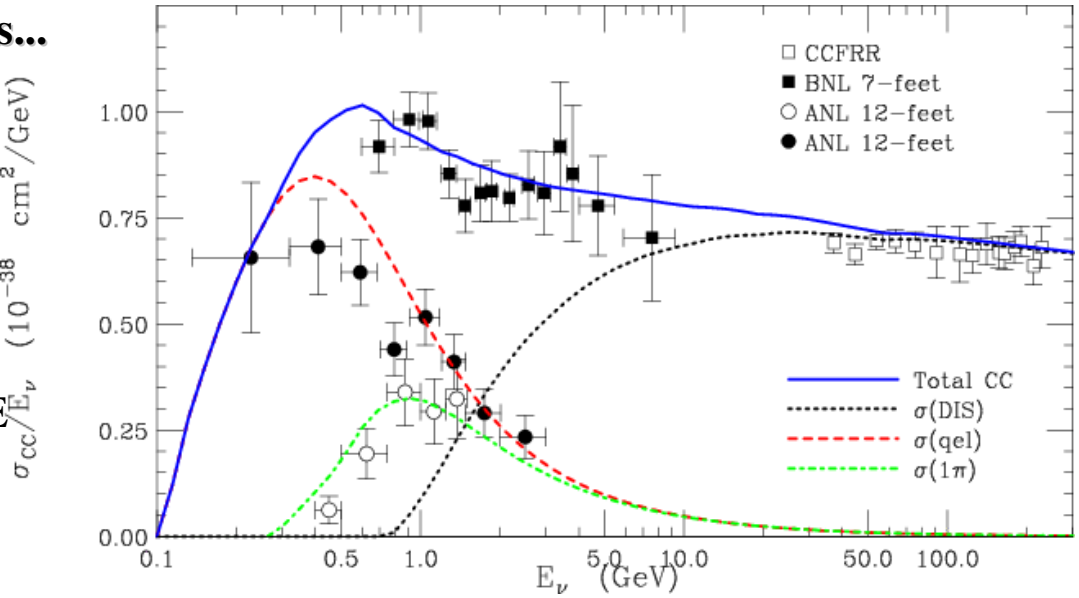
External Prediction for σ(CCQE)

Many low E ν cross section Monte Carlos...

Common theoretical inputs:
- Llewellyn Smith free nucleon QE xsec
- Rein-Sehgal resonance cross sections
- standard DIS formula for high Q^2

Nontrivial differences:
- implementation of Fermi gas model for QE
- joining of resonance and DIS regions
- treatment of nuclear effects (FSI)

P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



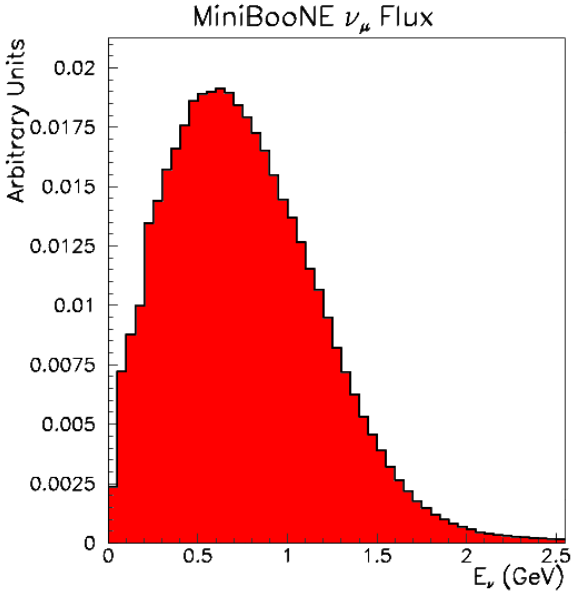
NUANCE v2: dipole form-factors, Smith & Moniz Fermi gas model, $m_A = 1.0$ (GeV/c^2)

NUANCE v3: non-dipole form factors, new π absorption model tuned on π data, $m_A = 1.03$ (GeV/c^2)

NEUT: dipole form factors, Smith & Moniz Fermi gas model, $m_A = 1.1$ (GeV/c^2)

NEUGEN: dipole form factors, π absorption tuned on ν data, Bodek-Ritchie modified Fermi gas model, no nucleon rescattering, $m_A = 1.032$ (GeV/c^2)

Monte Carlo σ(CCQE) Comparisons



NUANCE v2
NUANCE v3
NEUGEN
NEUT

MiniBooNE Detector Monte Carlo (Geant3.21)

MiniBooNE Analysis Framework (reconstruction, etc.)

Compare reconstructed distributions

All Monte Carlo sets are produced consistently:

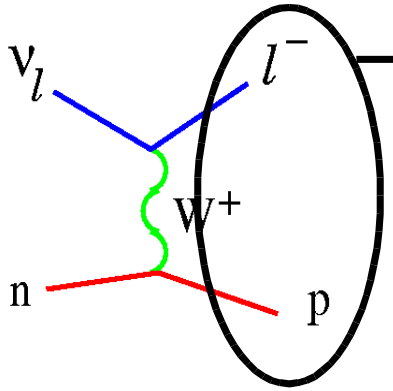
- same ν flux (MiniBooNE)
- different cross section Monte Carlos (different Fermi gas models, FSI & m_A)
- same detector Monte Carlo (MiniBooNE)
- same analysis (MiniBooNE CCQE selection)

CCQE Prediction: Monte Carlo Comparisons

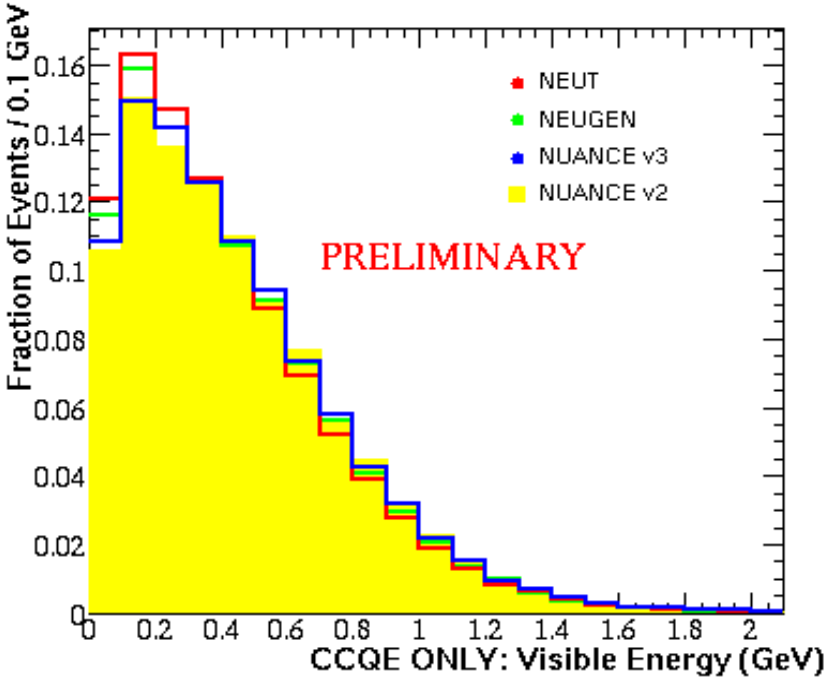
Cuts: require CCQE only

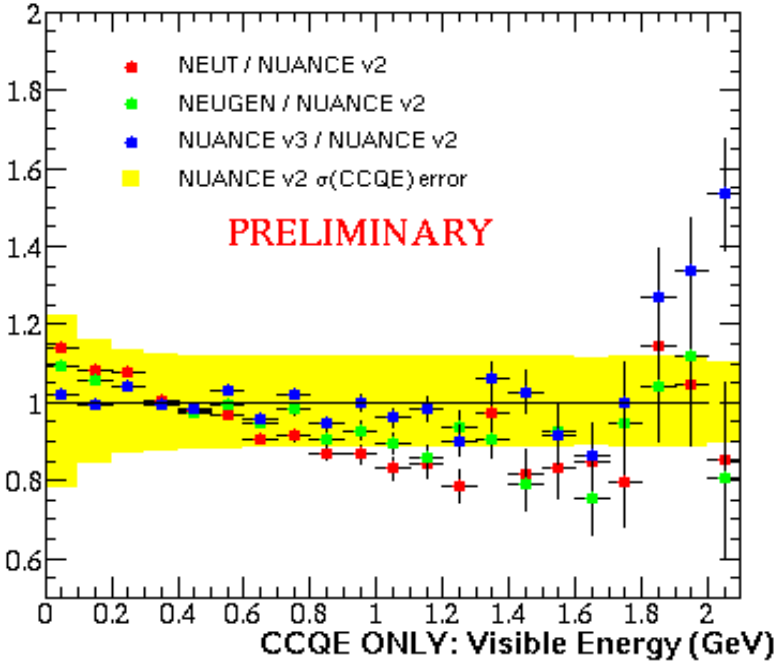
Error band: CCQE σ only

~10% differences at low visible energy between Monte Carlos



measure visible energy (mostly Cerenkov from μ, + a little scintillation light from proton)



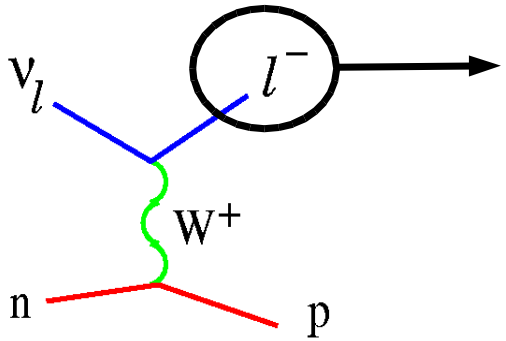


CCQE Prediction: Monte Carlo Comparisons

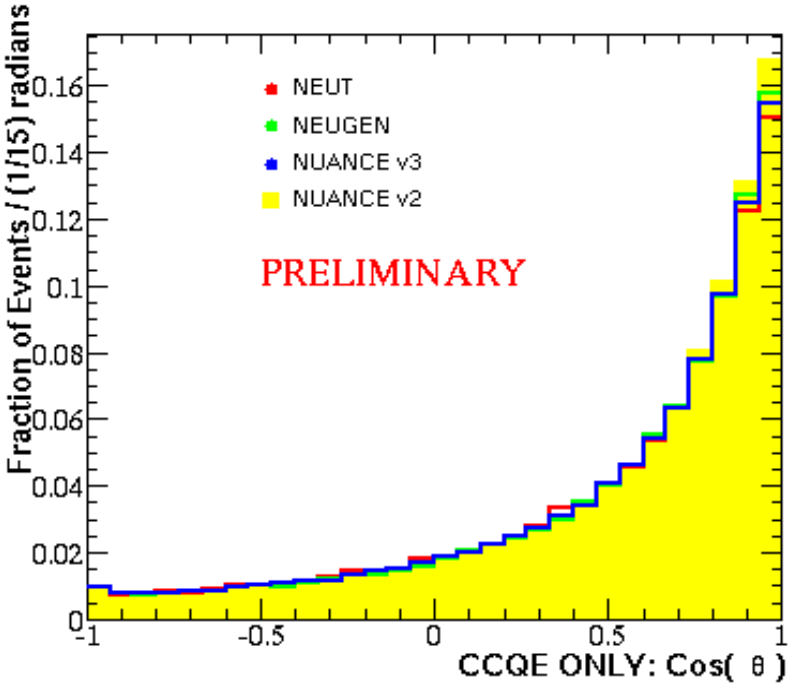
Cuts: require CCQE only

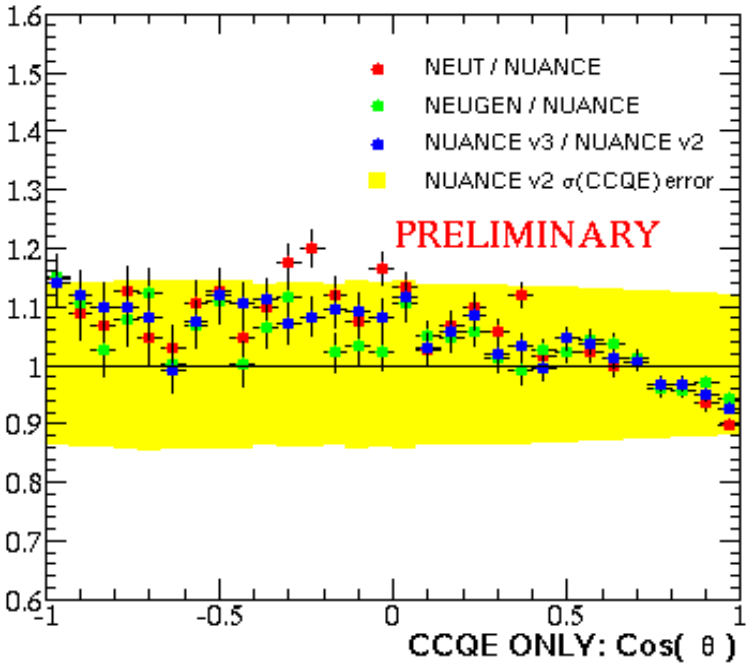
Error band: CCQE σ only

cos(θ) = 1: 5-10% lower in NUANCE v3
NEUT, NEUGEN, cf. NUANCE v2



reconstruct μ direction
from Cerenkov light,
cos(θ) = 1 ~ low Q^2



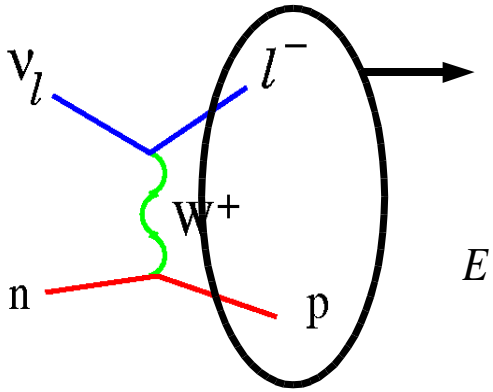


CCQE Prediction: Monte Carlo Comparisons

Cuts: require CCQE only

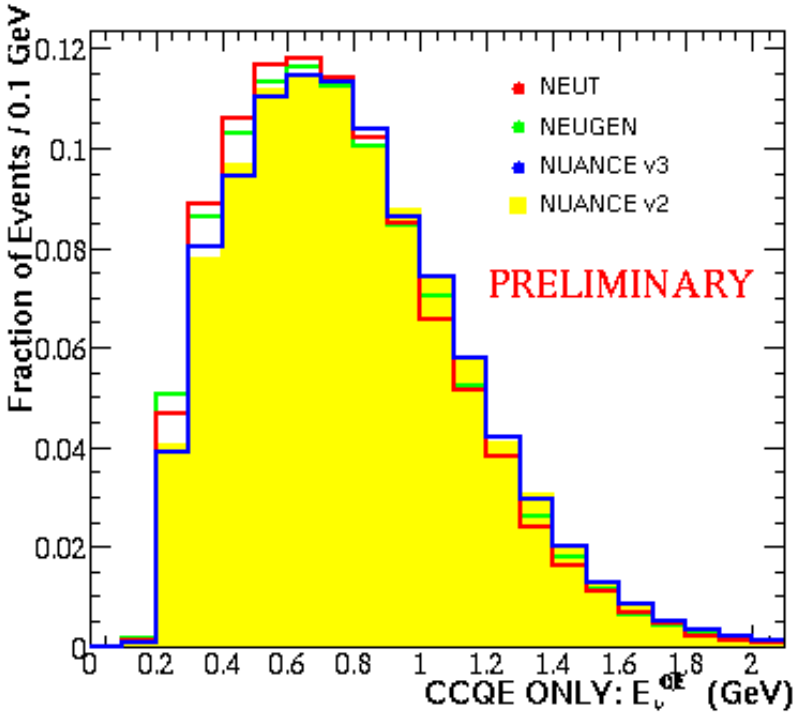
Error band: CCQE σ only

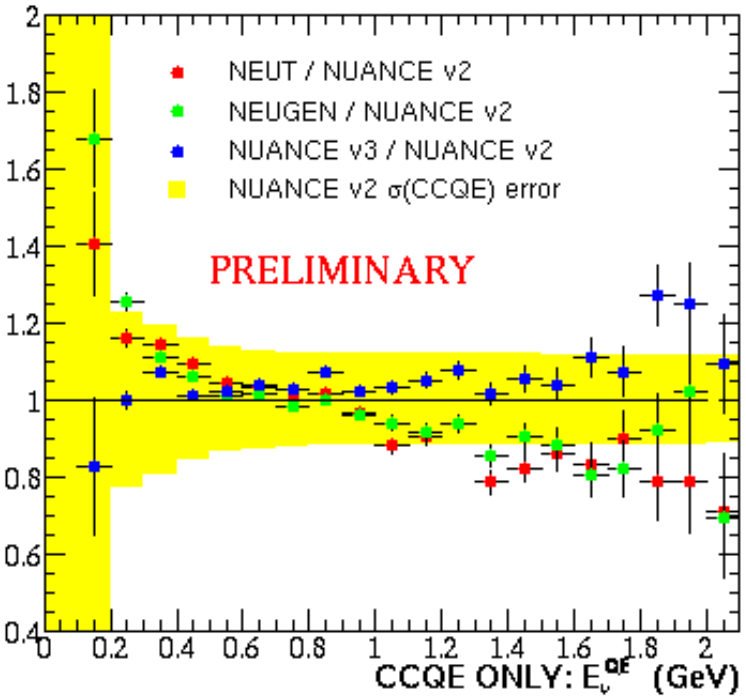
NEUT, NEUGEN systematically softer spectrum than NUANCE v2, v3



use measured μ visible energy and angle to reconstruct E_ν^{QE}

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_p E_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$



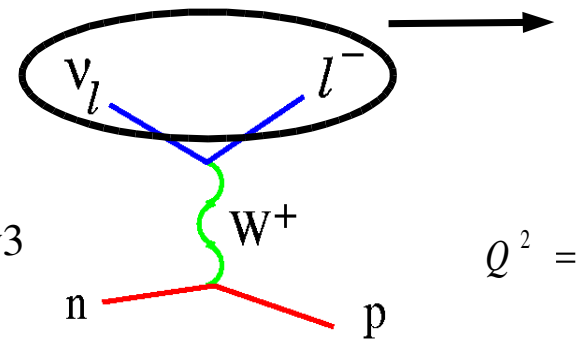


CCQE Prediction: Monte Carlo Comparisons

Cuts: require CCQE only

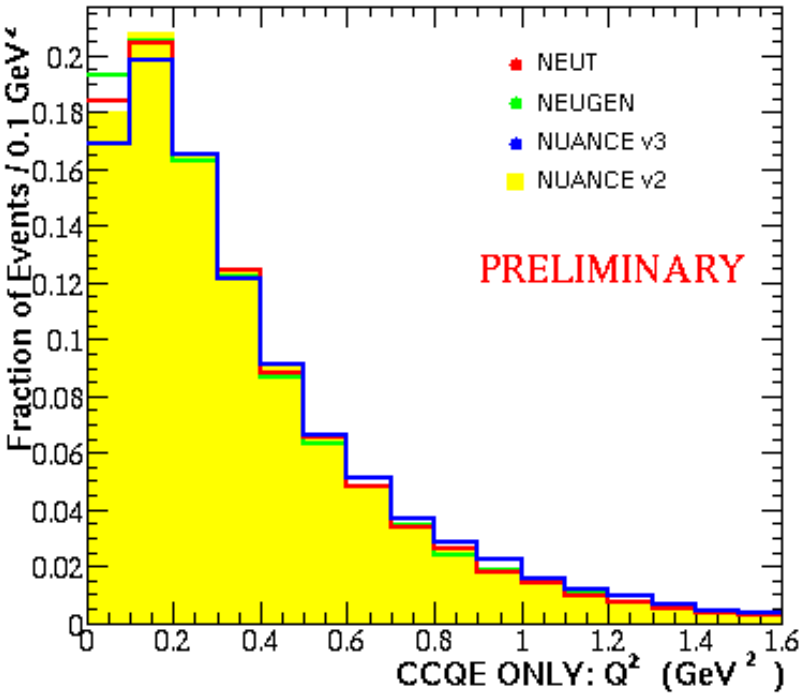
Error band: CCQE σ only

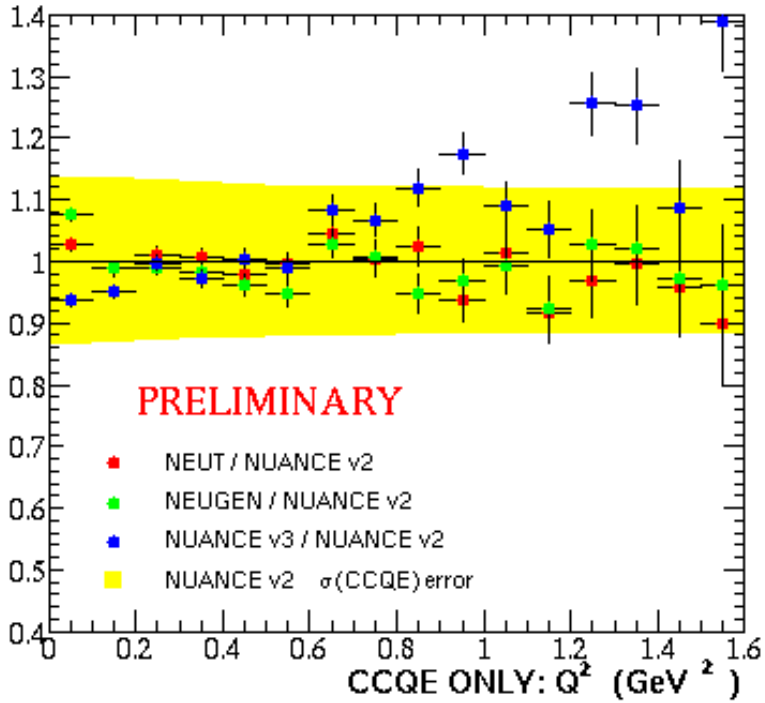
± ~8% difference in Q^2 for NUANCE v3
NEUT, NEUGEN, cf. NUANCE v2



reconstruct Q^2 from μ
direction, momentum, & E_ν^{QE}

$$Q^2 = 2E_\nu E_\mu (1 - \beta_\mu \cos\theta_\mu) - m_\mu^2$$

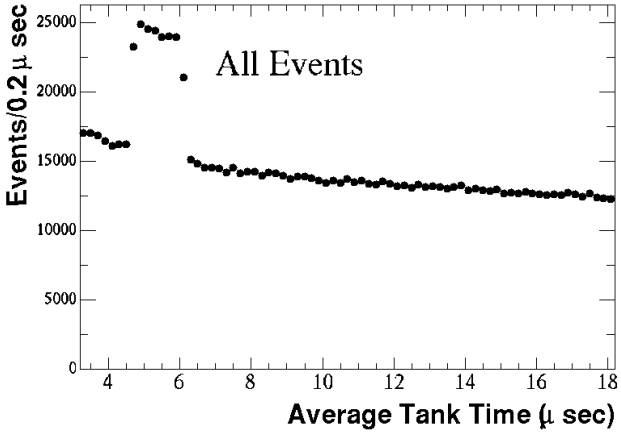


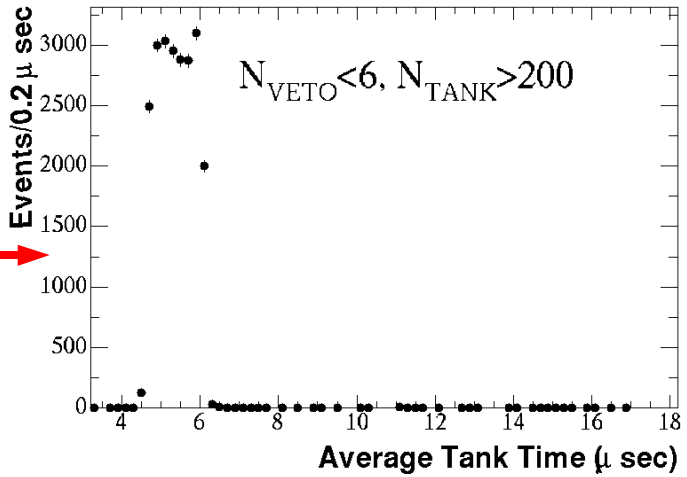


CCQE Event Selection at MiniBooNE

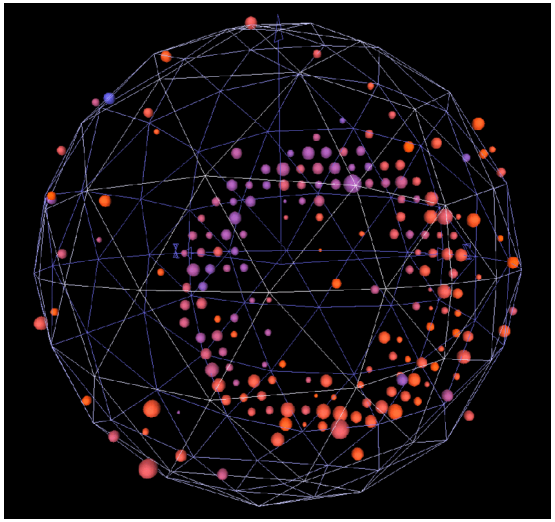
Signal: $\nu_\mu n \rightarrow \mu^- p$ ..... time passes ..... $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

1. Simple cuts:
eliminate cosmic rays, beam-induced bgnd
- #Tank hits > 100
- #Veto hits < 6





2. Intermediate cuts:
ensure good energy reconstruction, select events with 1 μ decay
- reconstructed R < 500 cm.
- 0 < #subevents < 3



3. CCQE PID cuts: Fisher discriminant
- event topology
- fraction of prompt (Čerenkov) vs. late (scintillation) light
- fraction of "on-ring" charge

CCQE Event Selection: MC Comparisons

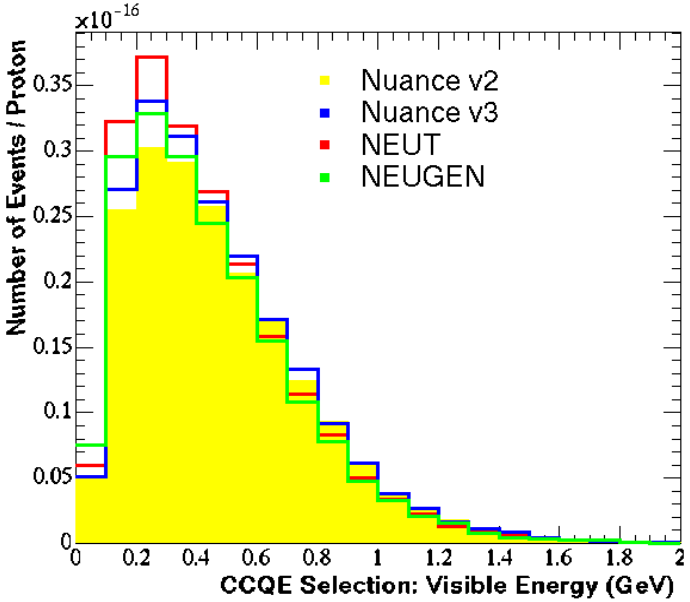
Same CCQE cuts, different Monte Carlos ...

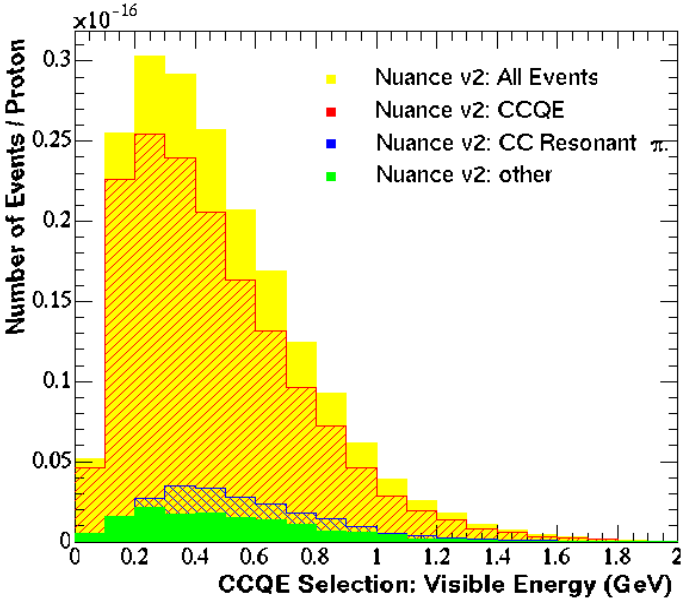
- Absolute normalization

Monte Carlo	CCQE (%)	Efficiency of cuts (%)	(Rate / proton after cuts) / v2
NUANCE v2	38.7	24.8	1.0
NUANCE v3	39.8	24.8	1.05
NEUT	38.0	24.5	1.07
NEUGEN	38.0	25.2	1.0

- After CCQE event selection: signal purity

Monte Carlo	CCQE (%)	Resonant 1 π (%)	total (%) background
NUANCE v2	83	14	17
NUANCE v3	80	16	20
NEUT	78	13	22
NEUGEN	80	16	20



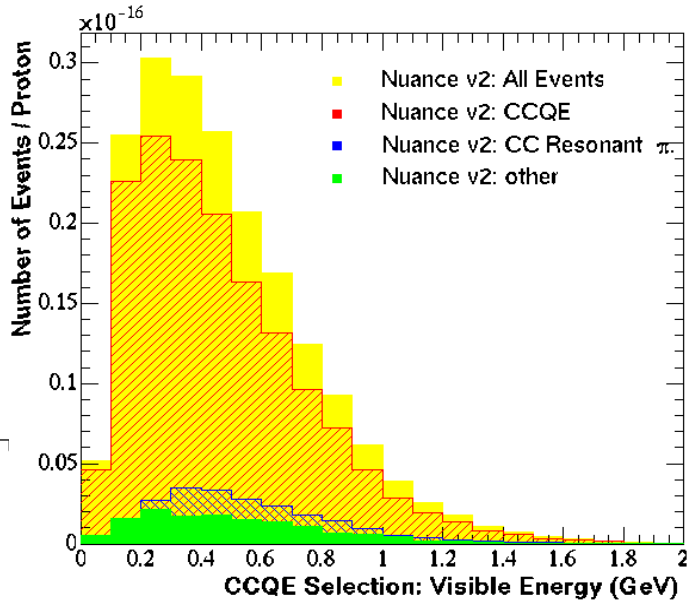


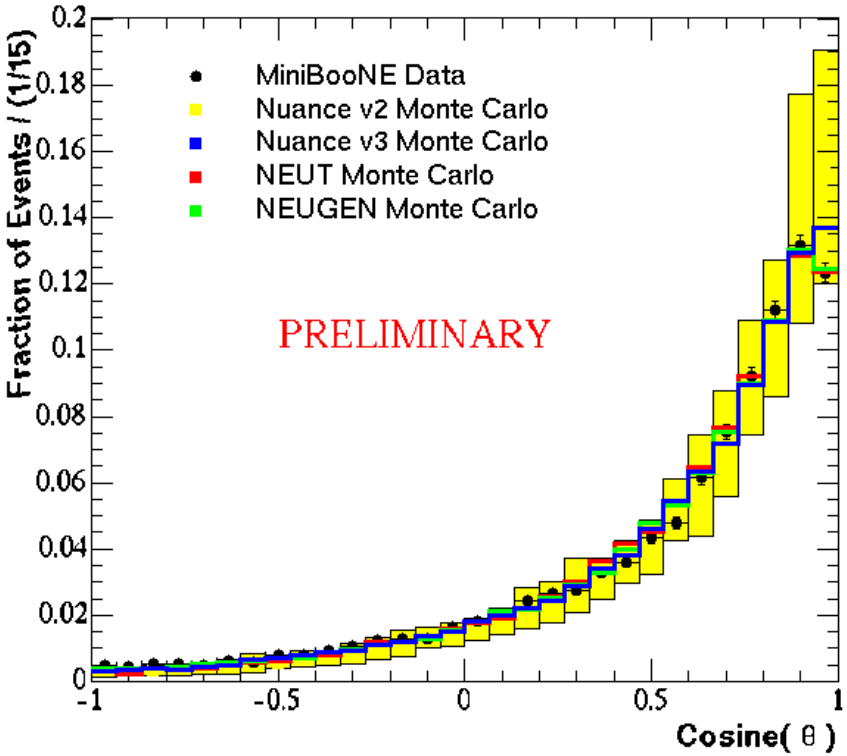
Data / MC Comparisons

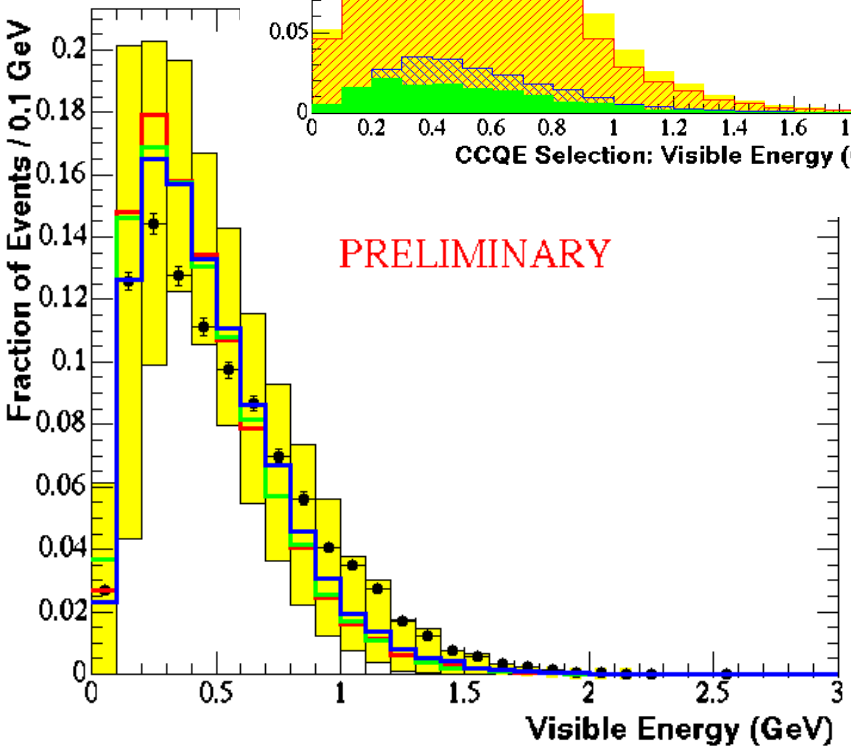
Cuts: ν_μ CCQE event selection, applied to all MC s

Errors: Flux, σ & Detector Optical Model (NUANCE v2)

- all distributions normalized to unit area
- error bands reflect current uncertainties, will shrink
- in general, cos (θ) measurement is better than T_μ
- largest background contamination in peak of T_μ distribution





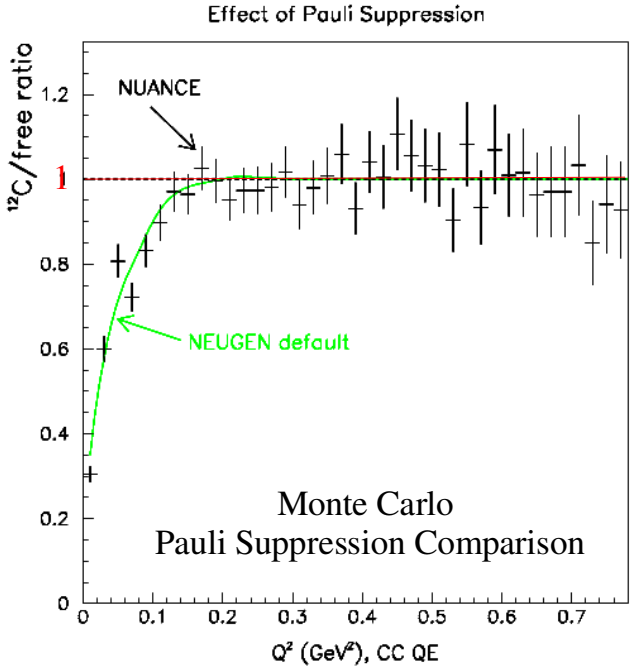


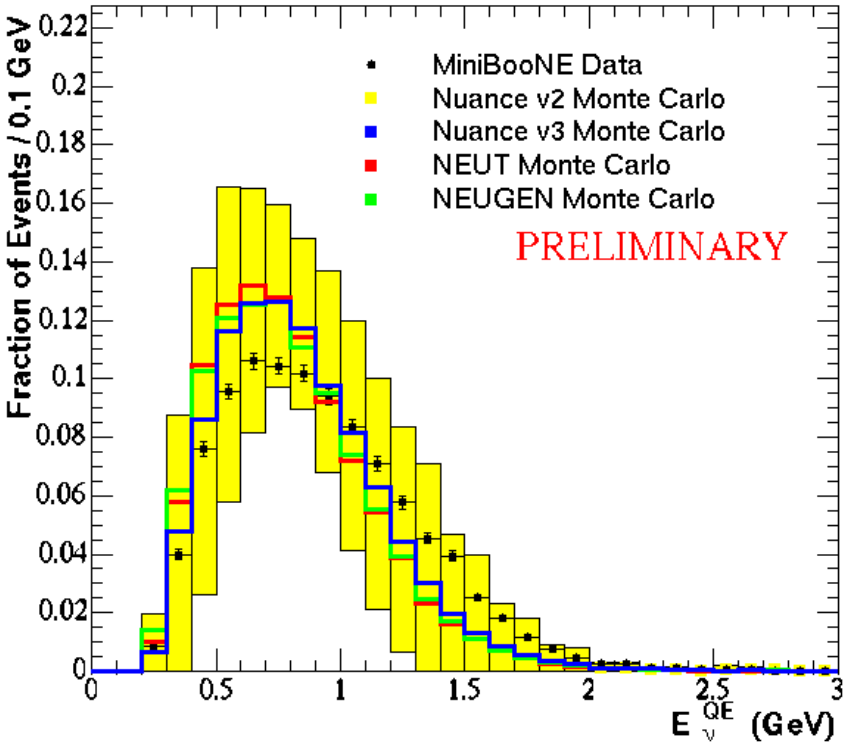
Data / MC Comparisons

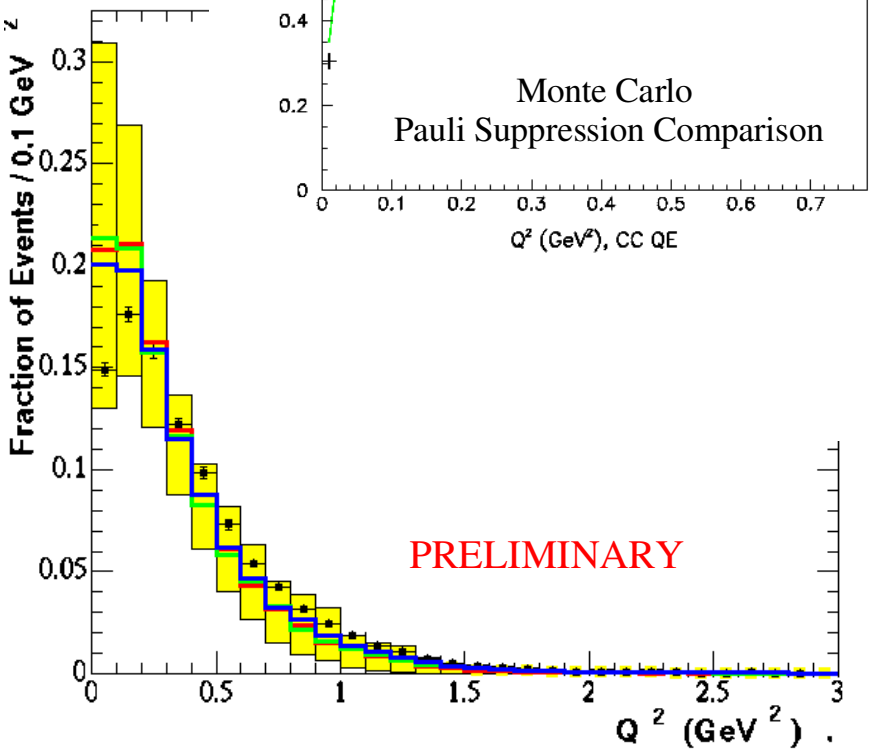
Cuts: ν_μ CCQE event selection, applied to all MC s

Errors: Flux, σ & Detector Optical Model (NUANCE v2)

- all distributions normalized to unit area
- interesting rollover at $Q^2 = 0$ not fully reproduced by any MC s
- deficiency in Pauli blocking models? Other nuclear effects?
- Or, artifact of data / MC disagreement? (but, within errors)







Summary & Conclusions

Summary: with $1.0 < m_A < 1.1$, dipole vs. non-dipole form factors, different Fermi gas models, and various FSI models ...

- 15% differences at low visible energy, -10% at $\cos(\theta) = 1$, ± 10% at low Q^2 relative to NUANCE v2 for CCQE (with no other cuts)
- NEUT and NEUGEN reproduce MiniBooNE data at $\cos(\theta) = 1$, but, no MC nails MiniBooNE's energy distribution (visible or reconstructed E_ν^{QE})
  Caveat: for generator level differences, see Session 6

"MC Agreement is better than expected!"
-Dave Casper & Hugh Gallagher

Conclusions: May be model deficiencies at low Q^2 (Pauli blocking, ν shadowing?), MiniBooNE data not yet conclusive (working on resolution) ... *lots to do* ...

Thank you! INFN for generous travel support, &
Dave Casper (NUANCE), Hugh Gallagher (NEUGEN) & Yoshinari Hayato (NEUT)

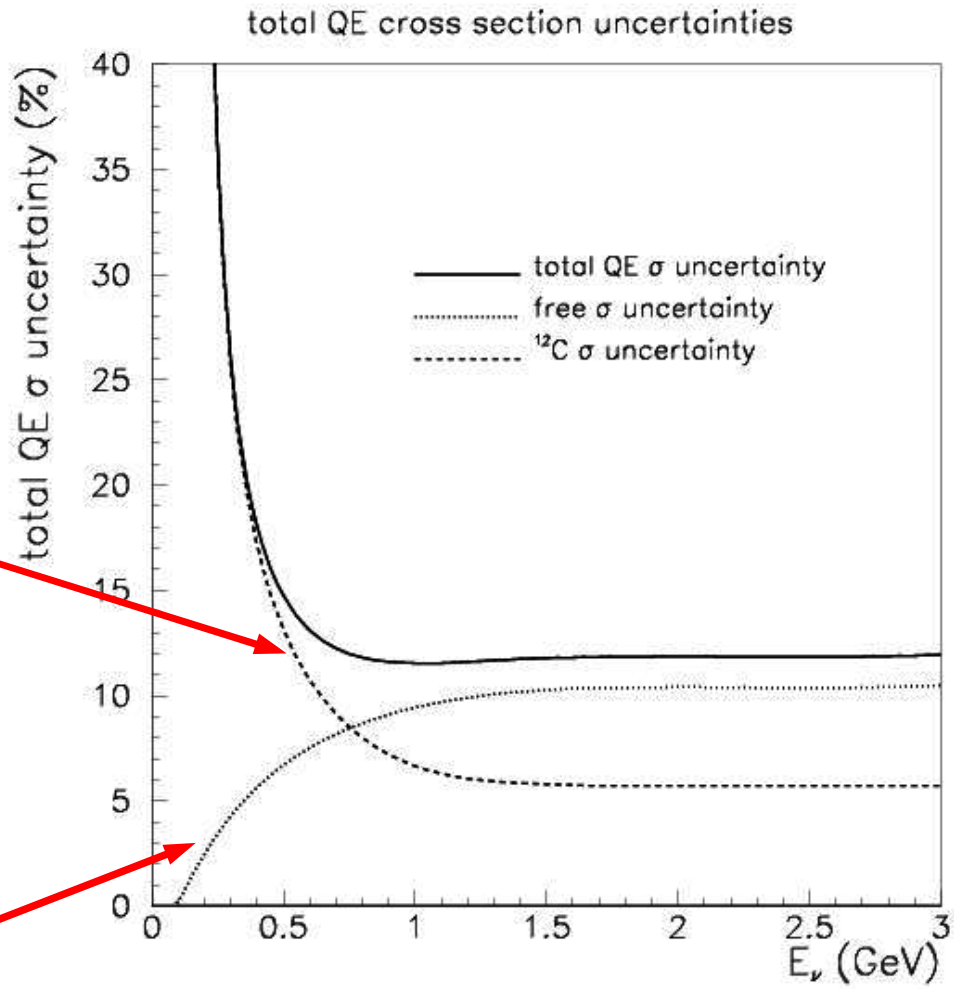
BACKUP SLIDES ...

MiniBooNE Cross Section Errors

QECC cross section uncertainties include:

- 60% uncertainty in Pauli suppression
  set in order to cover LSND σ_{QE} at low energy
- 5 MeV shift in cross section
  to estimate uncertainty in σ at threshold

- 10% uncertainty in m_A
  to cover range in m_A from light vs. heavy target ν data fits, as well as K2K choice



Non-Dipole Vector Form Factors (NUANCE v3)

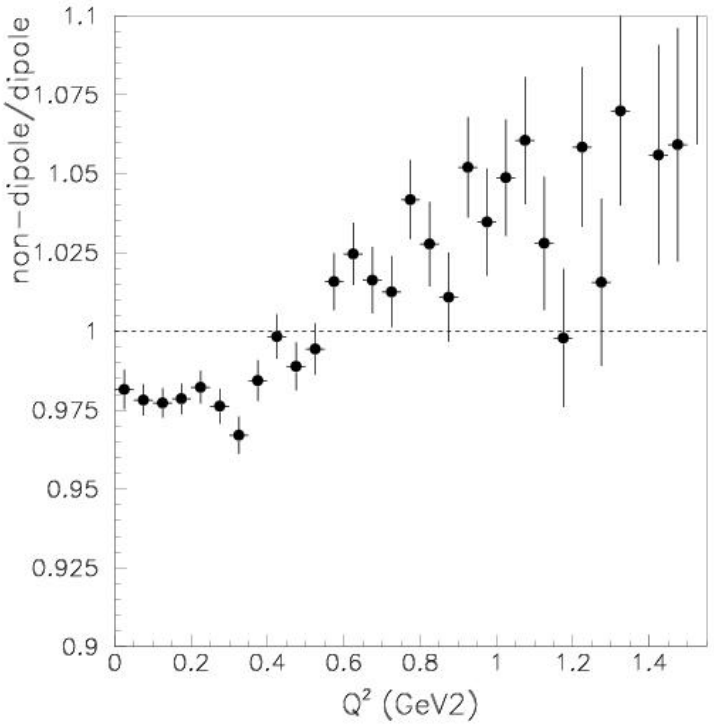
$$G_M^p(Q^2) = \mu_p/(1+0.35Q+2.44Q^2+0.5Q^3+1.04Q^4+0.34Q^5)$$

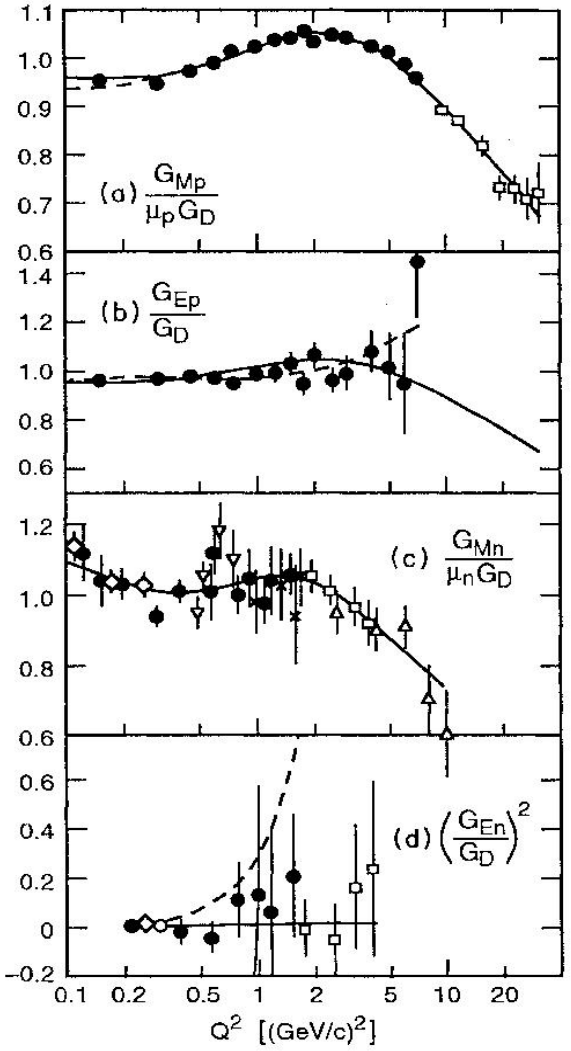
$$G_E^p(Q^2) = 1/(1+0.62Q+0.68Q^2+2.8Q^3+0.83Q^4)$$

$$G_M^n(Q^2) = \mu_n/(1-1.74Q+9.29Q^2-7.63Q^3+4.63Q^4)$$

$$G_e^n(Q^2) = -1.25\mu_n\tau/(1+18.3\tau)(1+Q^2/0.71)^2 \text{ , } \tau=Q^2/4M^2$$

Effect on Q^2 distribution of generated QE events:



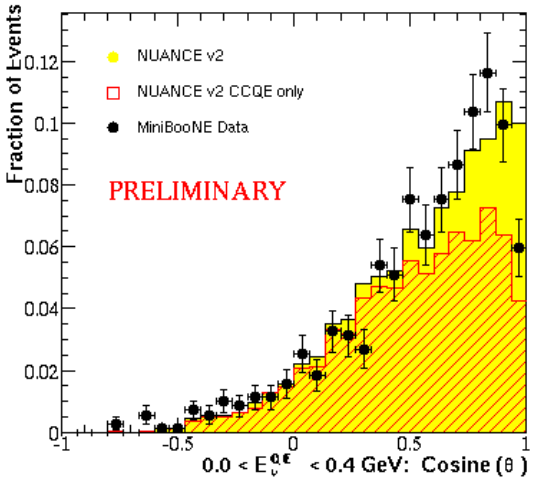


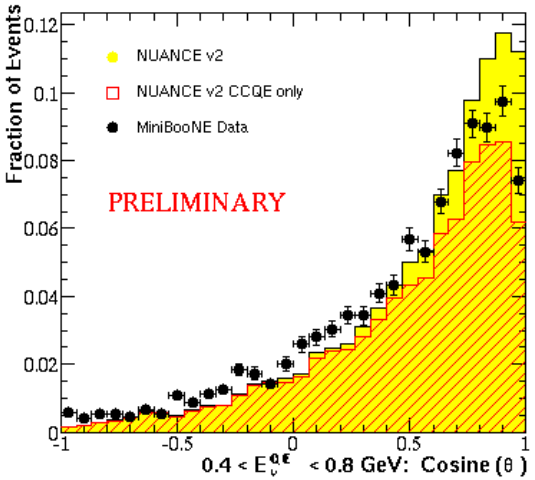
P.E. Bosted,
Phys. Rev. **C51**, 409 (1995)

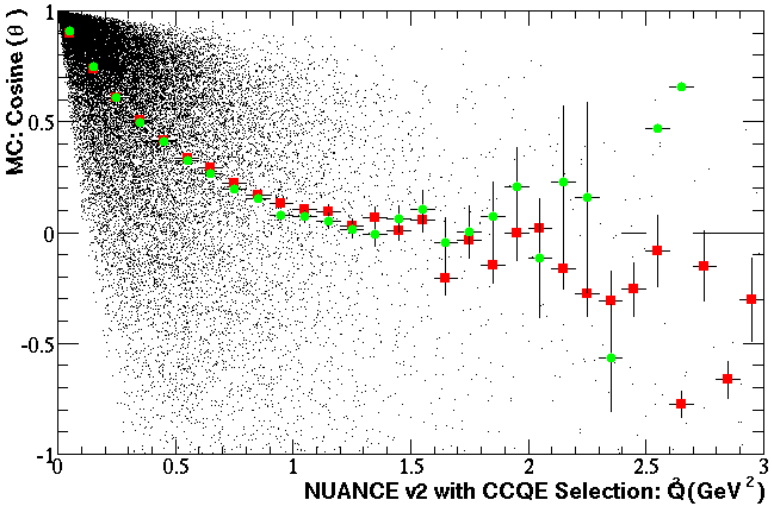
Data / MC Comparisons

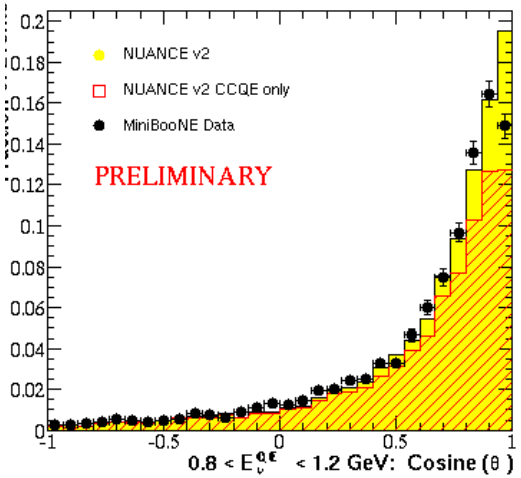
Look for Cos(θ) = 1 suppression vs E_ν

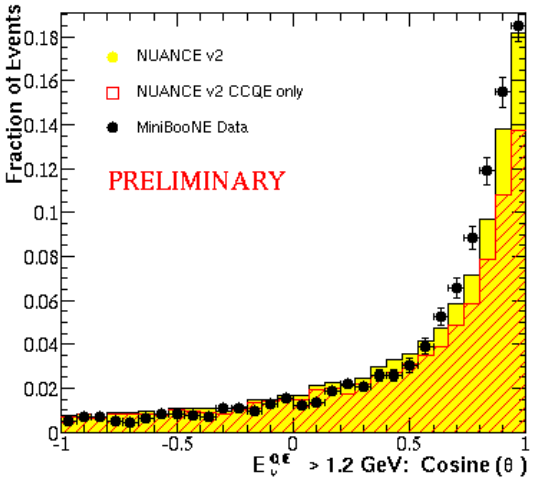
- why? great cos(θ) resolution (3°)
- cos(θ) = 1 probes $0 < Q^2 < 0.3$ GeV^2
- good reconstructed / generated MC agreement in this region
- Pauli blocking is most relevant here
- note that signal purity changes vs E_ν!









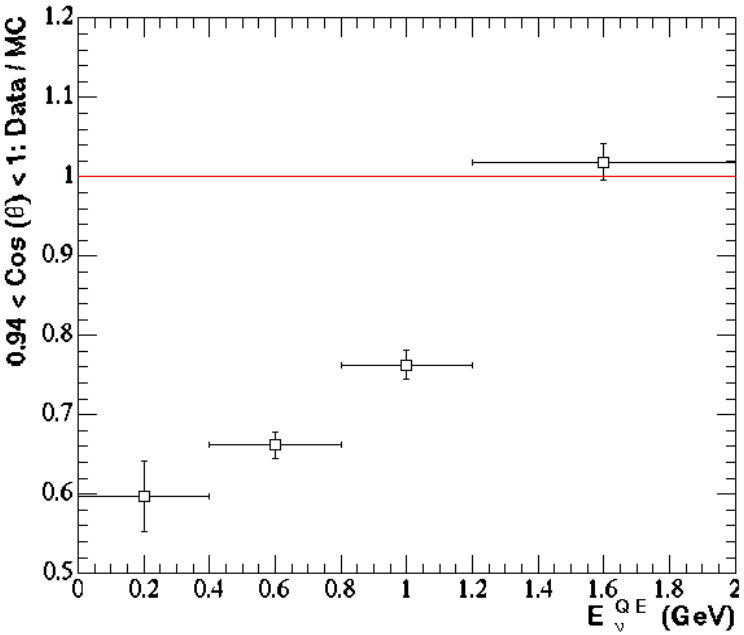


Data / MC Comparisons

Look for Cos(θ) = 1 suppression vs E_ν

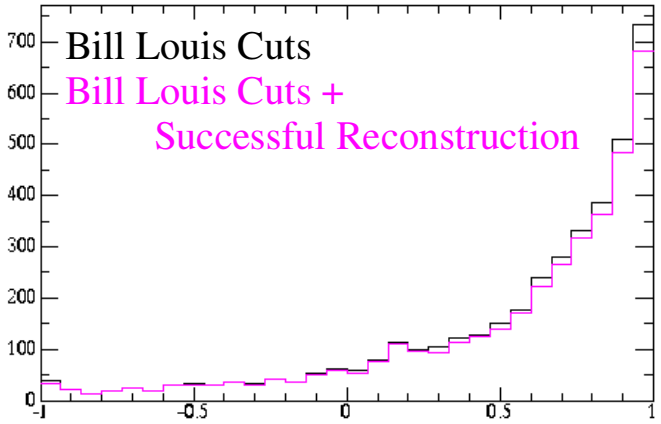
(with ν_μ CCQE event selection)

- cos(θ) = 1 probes $0 < Q^2 < 0.3$ GeV^2
- (data / MC) ratio in cos(θ) ~ 1 bin decreases with E_ν (reconstructed)
- is this consistent with Pauli blocking model deficiencies?

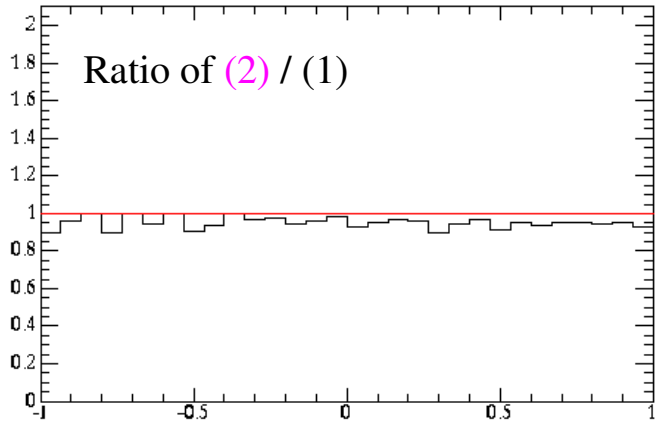


Reconstruction Artifact?

(not obviously in MC, may be different in data)



MC: Generated cos(θ)



MC: Generated cos(θ)