Charged Current Interaction measurements in MiniBooNE

hep-ex/XXX

Teppei Katori for the MiniBooNE collaboration
Indiana University
NuInt 07, Fermilab, May., 31, 07

Charged Current Interaction measurements in MiniBooNE

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outline

1. CCQE events in MiniBooNE
2. Prediction for CCQE events
3. CCQE data-MC comparison
4. Fit results
5. Anti-neutrino CCQE events
6. Conclusion

1. CCQE events in MiniBooNE

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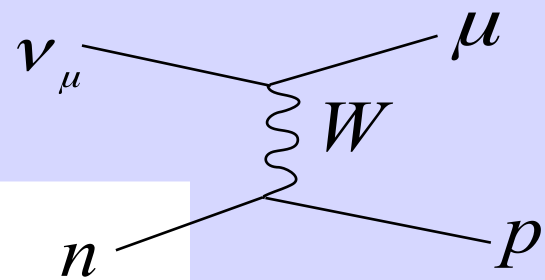
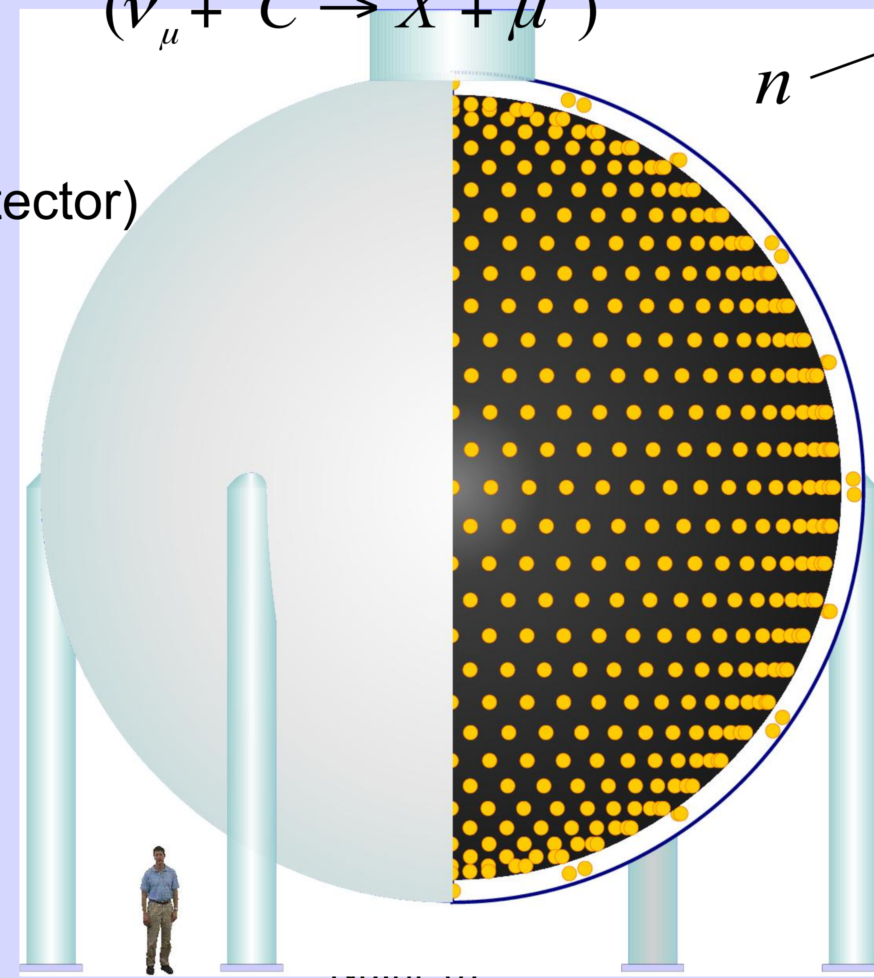
ν_μ charged current quasi-elastic (ν_μ CCQE) interaction is the most abundant (~40%) and the fundamental interaction in MiniBooNE detector

$$\nu_\mu + n \rightarrow p + \mu^-$$

$$(\nu_\mu + {}^{12}C \rightarrow X + \mu^-)$$



MiniBooNE detector
(spherical Cherenkov detector)



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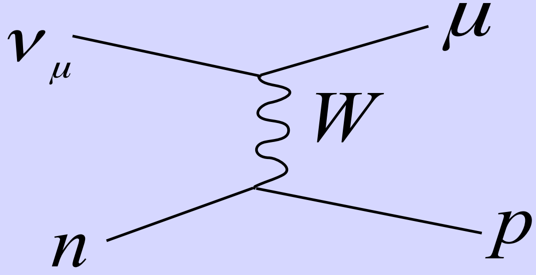

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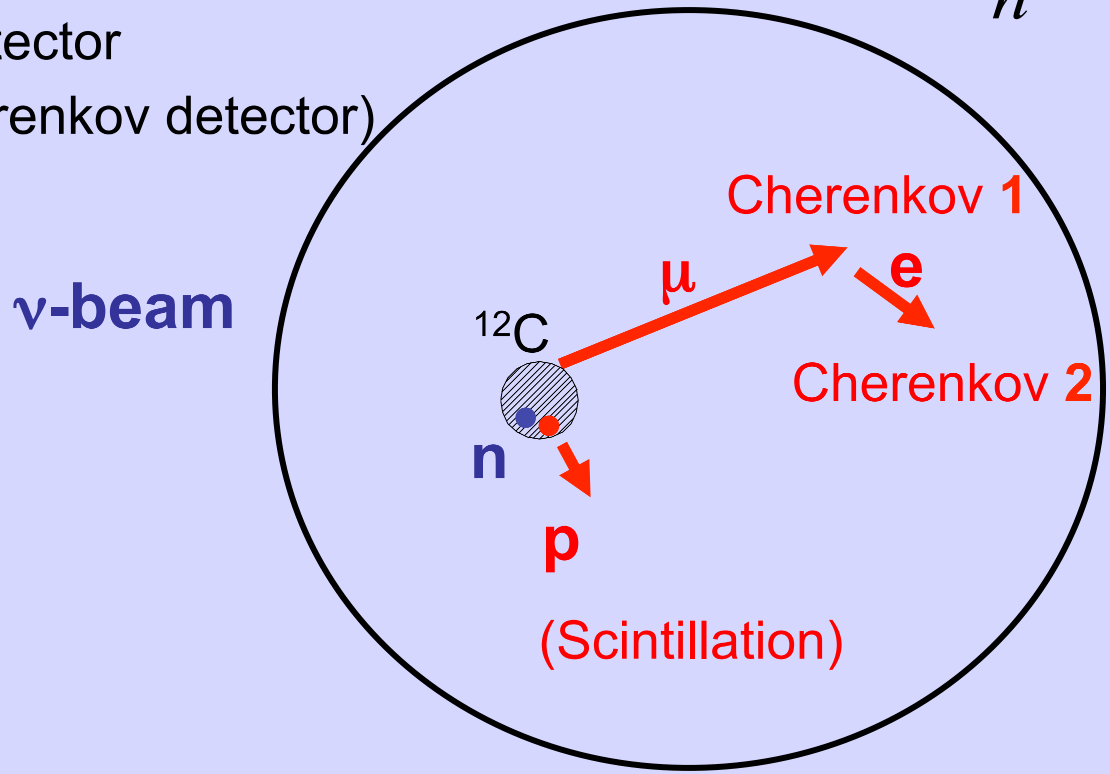
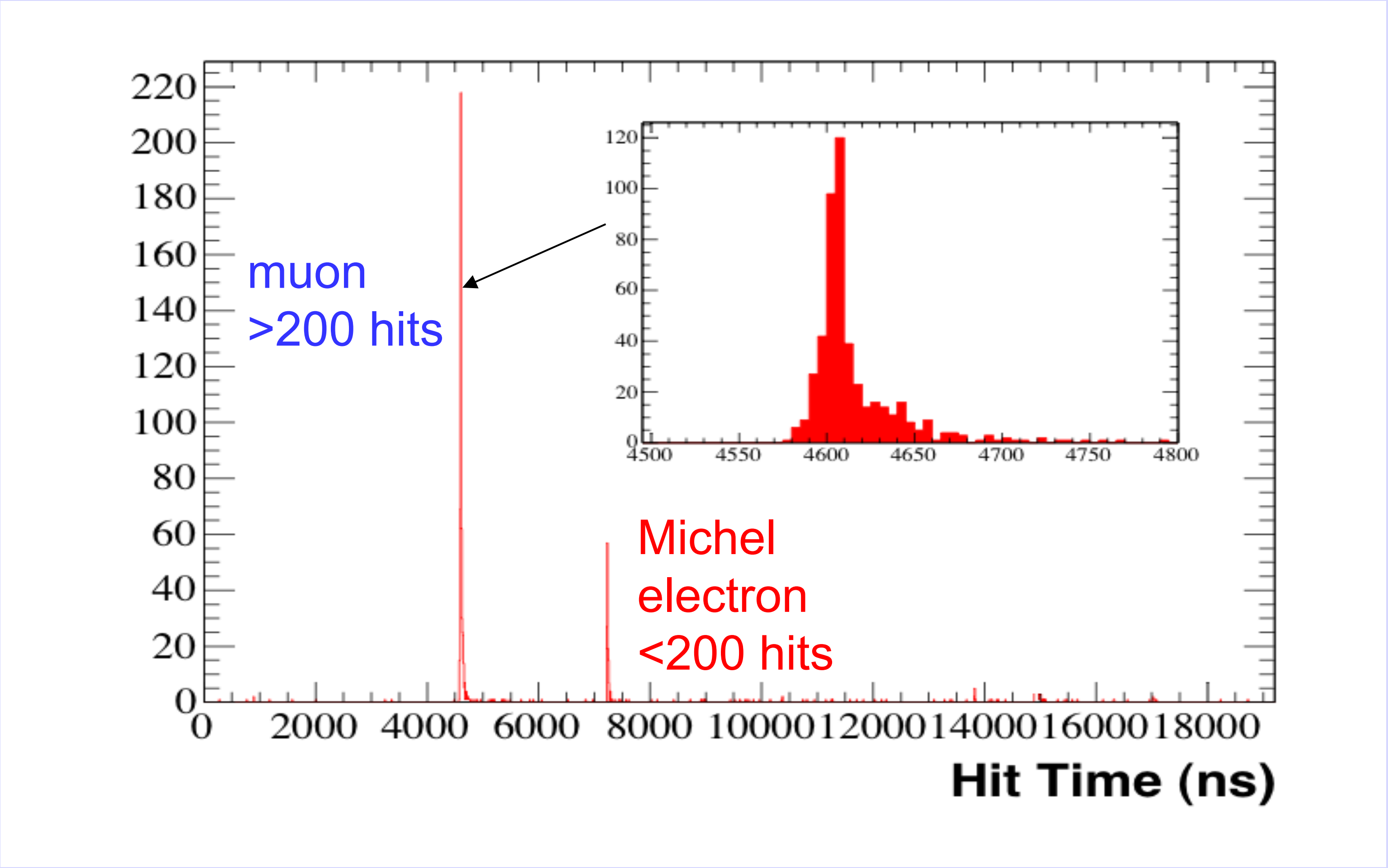


muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

1. CCQE events in MiniBooNE

ν_μ CCQE interactions (ν+n $\rightarrow$ μ+p) has characteristic two "subevent" structure from muon decay

$$\nu_\mu + n \rightarrow \boxed{\mu} + p \qquad \mu \rightarrow \nu_\mu + \bar{\nu}_e \boxed{+ e}$$



35.0% cut efficiency

197,308 events with 5.58E20POT

1. CCQE events in MiniBooNE

Cut and efficiency summary

total 2 subevents	54.2%
muon in beam window (4400ns < Time < 6400ns)	52.9%
muon veto hits < 6 and Michel electron veto hits < 6	46.4%
muon tank hits > 200 and Michel electron tank hits < 200	41.6%
fiducial reconstruction for muon	41.3%
muon and electron distance < 100cm	35.0%

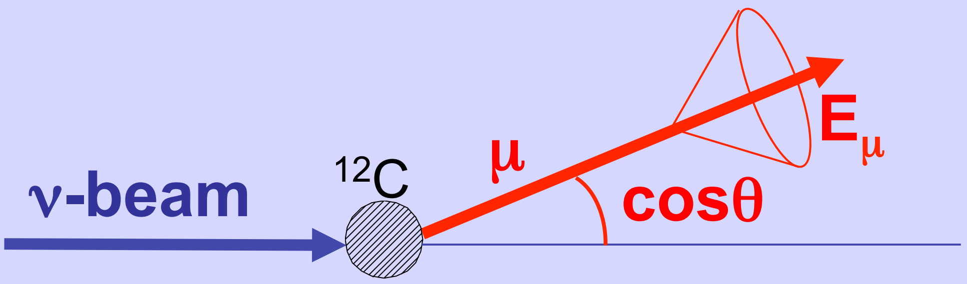
1. CCQE events in MiniBooNE

All kinematics are specified from 2 observables, muon energy E_μ and muon scattering angle θ

Energy of the neutrino E_ν and 4-momentum transfer Q^2 can be reconstructed by these 2 observables

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

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - p_\mu \cos\theta_\mu)$$



2. Prediction for CCQE events

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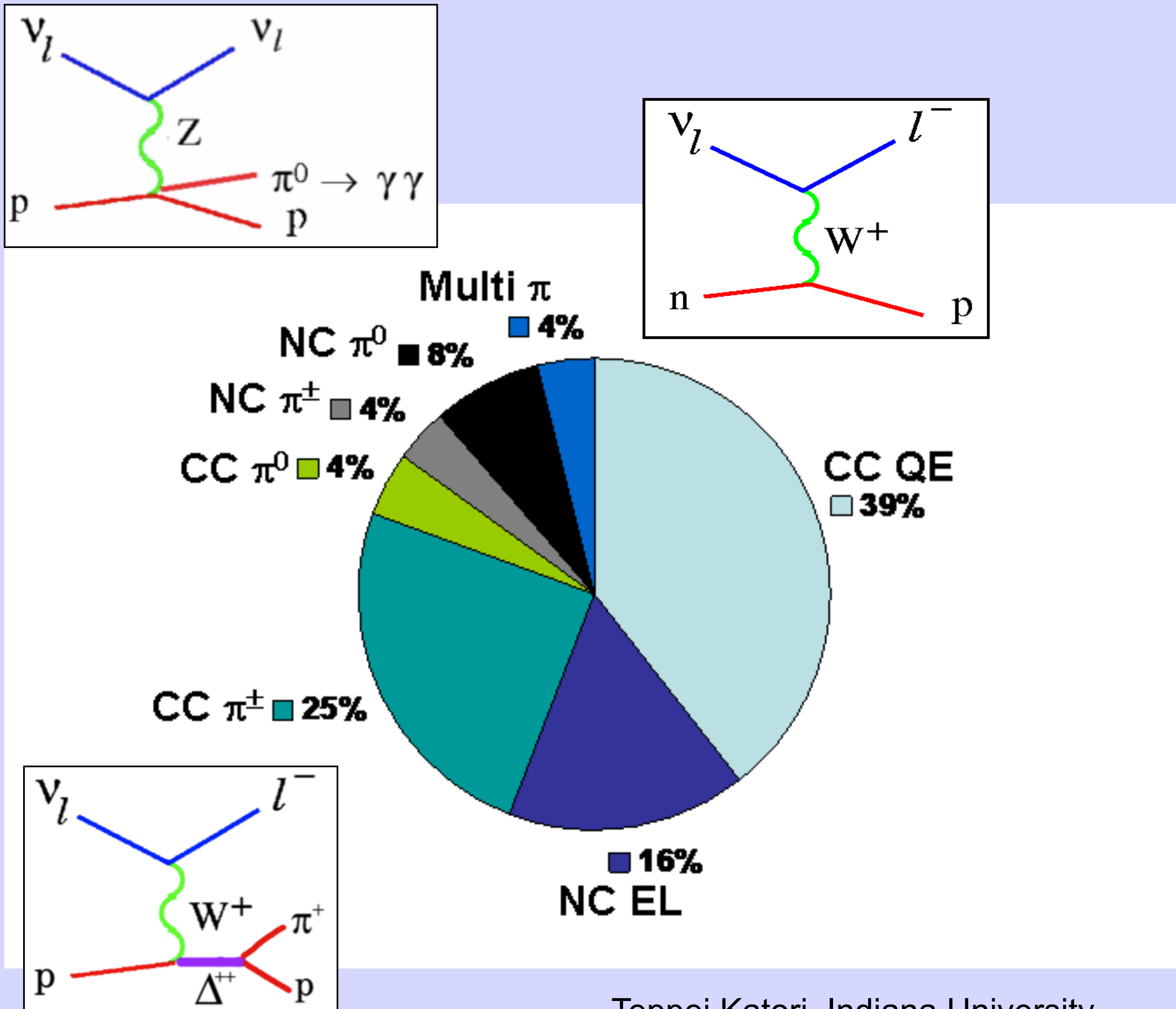

Predicted event rates (NUANCE Monte Carlo)

Casper, Nucl.Phys.Proc.Suppl. 112 (2002) 161

2. Prediction for CCQE events

Smith and Moniz, Nucl.,Phys.,B43(1972)605

Relativistic Fermi Gas (RFG) Model

Carbon is described by the collection of incoherent Fermi gas particles.
All details come from hadronic tensor.

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k}, \vec{q}, w) T_{\mu\nu} dE$$: hadronic tensor

$f(\vec{k}, \vec{q}, w)$: nucleon phase space density function

$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P)$: nucleon tensor

$F_A(Q^2) = g_A/(1 + Q^2/M_A^2)^2$: Axial form factor

Ehi : the highest energy state of nucleon = $\sqrt{(p_F^2 + M^2)}$

Elo : the lowest energy state of nucleon = $\sqrt{(p_F^2 + M^2)} - w + E_B$

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$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k},\vec{q},w) T_{\mu\nu} dE : \text{hadronic tensor}$$

$$f(\vec{k},\vec{q},w) : \text{nucleon phase space density function}$$

$$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P) : \text{nucleon tensor}$$

$$F_A(Q^2) = g_A/(1+Q^2/\boxed{M_A^2})^2 : \text{Axial form factor}$$

$$Ehi : \text{the highest energy state of nucleon} = \sqrt{(\boxed{p_F^2}+M^2)}$$

$$Elo : \text{the lowest energy state of nucleon} = \sqrt{(\boxed{p_F^2}+M^2)} - w + \boxed{E_B}$$

3 parameters are especially important to control nuclear effect of Carbon;

M_A = 1.03GeV : axial mass

P_F = 220MeV : Fermi momentum

E_B = 34MeV : binding energy

3. CCQE data-MC comparison

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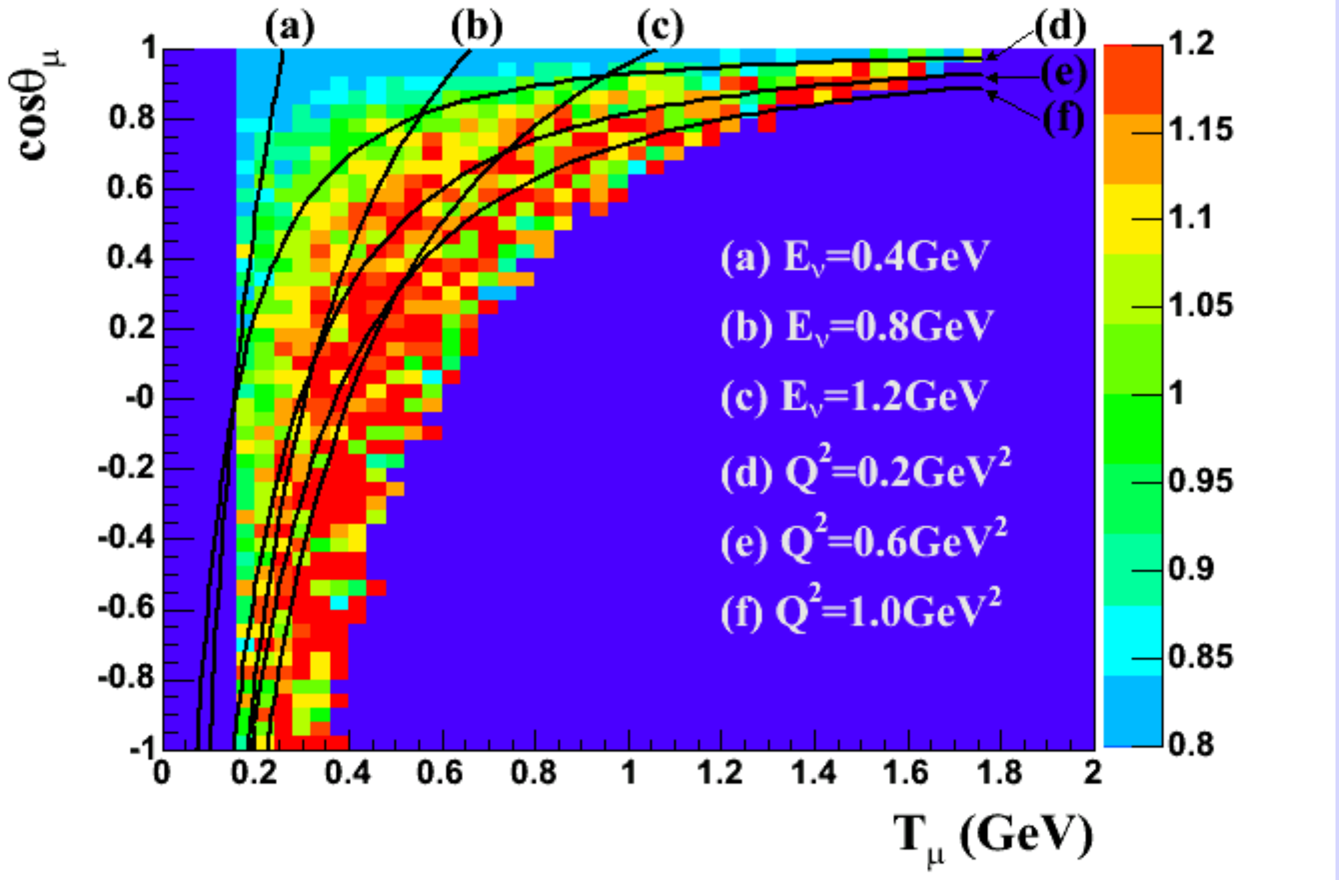
CCQE kinematics phase space

The data-MC agreement is not great

Since data-MC disagreements align on the Q^2 lines, not $E\nu$ lines, the source of data-MC disagreement is not the neutrino beam prediction, but the neutrino cross section prediction.

data-MC ratio from RFG model



3. CCQE data-MC comparison

CCQE kinematics phase space

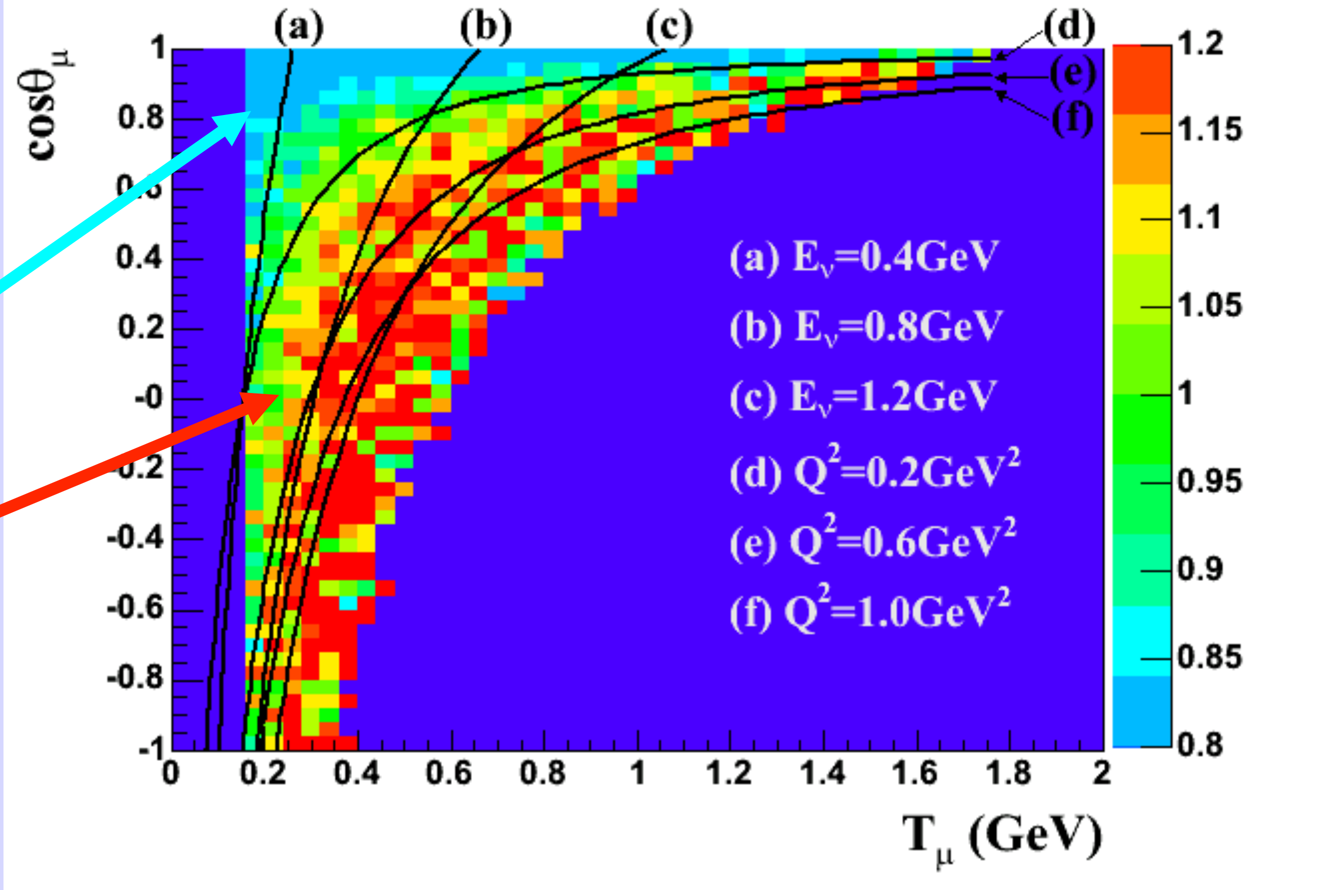
The data-MC agreement is not great

The data-MC disagreement is characterized by 2 features;

(1) data deficit at low Q^2 region

(2) data excess at high Q^2 region

data-MC ratio from RFG model



3. CCQE data-MC comparison

Nuclear model parameters are tuned from electron scattering data, thus the best explanations of observed data-MC disagreements are something one cannot measure from the electron scattering data

(1) data deficit at low Q^2 region
→ Pauli blocking

(2) data excess at high Q^2 region
→ Axial mass M_A

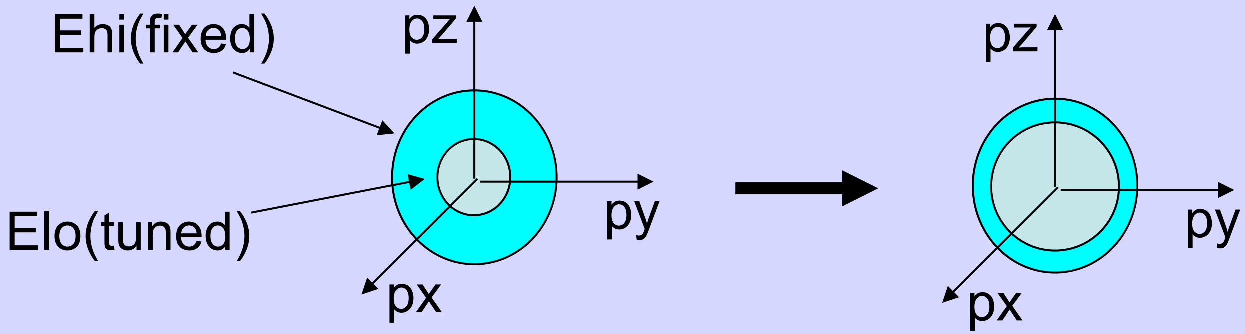
We tune the nuclear parameters in RFG model using Q^2 distribution;
M_A = tuned
P_F = fixed
E_B = fixed

3. CCQE data-MC comparison

Pauli blocking parameter "kappa" : κ

To enhance the Pauli blocking at low Q^2, we introduced a new parameter κ, which is the scale factor of lower bound of nucleon sea and controls the size of nucleon phase space

$$\mathrm{Elo} = \boxed{\kappa}\left(\sqrt{(p_F^2 + M^2)} - w + E_B\right)$$



This modification gives significant effect only at low Q^2 region

We tune the nuclear parameters in RFG model using Q^2 distribution;

M_A = tuned

P_F = fixed

E_B = fixed

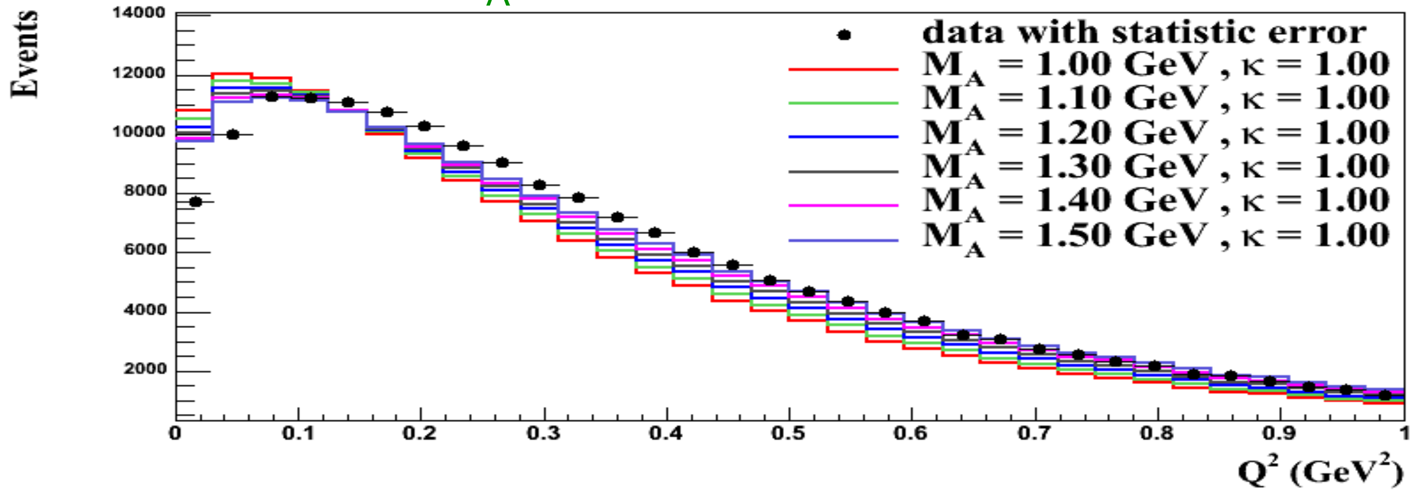
κ = tuned

3. CCQE data-MC comparison

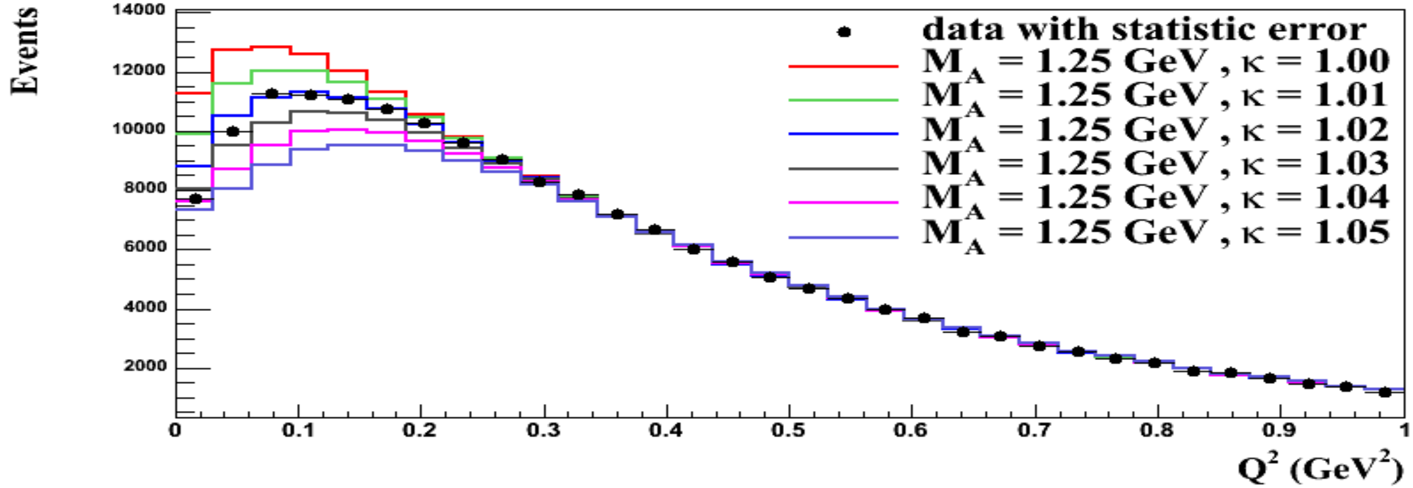
M_A and κ are simultaneously fit to the data

2% change of κ is sufficient to take account the data deficit at low Q^2 region

Q^2 distribution with M_A variation



Q^2 distribution with κ variation



4. Fit results

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Least χ^2 fit for Q^2 distribution

$$\chi^2 = (\text{data} - \text{MC})^T (M_{total})^{-1} (\text{data} - \text{MC})$$

χ^2 minimum is found by global scan of shape only fit with $0.0<Q^2(GeV^2)<1.0$

Input error matrices
keep the correlation of systematics

dependent

independent

π^+ production (8 parameters)
π^- production (8 parameters)
K^+ production (7 parameters)
K^0 production (9 parameters)
beam model (8 parameters)
cross section (20 parameters)
detector model (39 parameters)

The total output error matrix
keep the correlation of Q^2 bins

$$\begin{aligned} M_{total} = \; & M(\pi^+ \text{ production}) \\ & + M(\pi^- \text{ production}) \\ & + M(K^+ \text{ production}) \\ & + M(K^0 \text{ production}) \\ & + M(\text{beam model}) \\ & + M(\text{cross section model}) \\ & + M(\text{detector model}) \\ & + M(\text{data statistics}) \end{aligned}$$

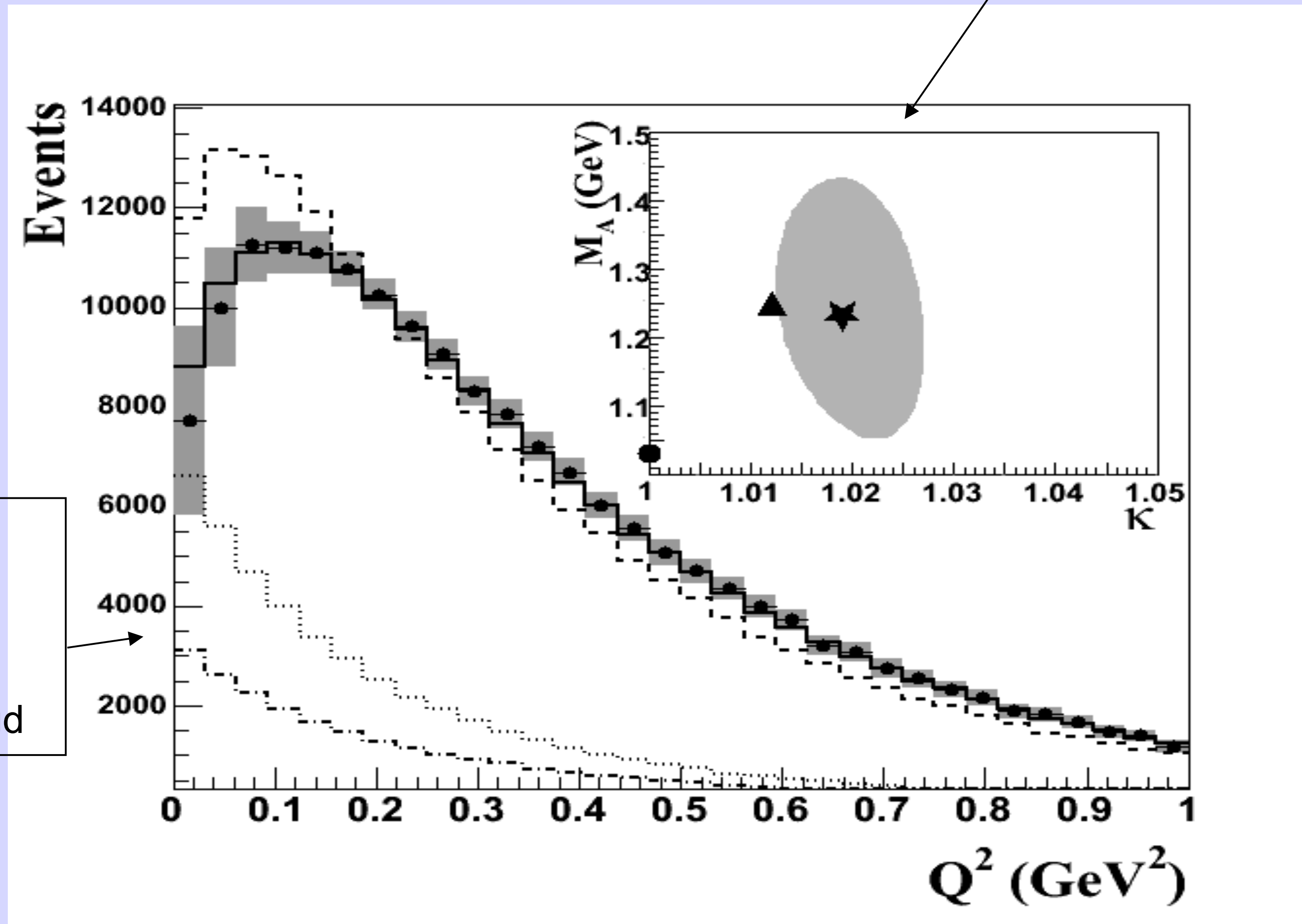
4. Fit results

M_A - κ fit result

$M_A = 1.23 \pm 0.20$(stat+sys)

$\kappa = 1.019 \pm 0.011$(stat+sys)

circle: before fit
star: after fit with 1-sigma contour
triangle: bkgd shape uncertainty



dots : data with error bar
dashed line : before fit
solid line : after fit
dotted line : background
dash-dotted :non-CCQElike bkgd

4. Fit results

Errors

The detector model uncertainty dominates the error in M_A

The error on κ is dominated by Q2 shape uncertainty of background events

	δM_A(GeV)	$\delta\kappa$
data statistics	0.03	0.003
neutrino flux	0.04	0.003
neutrino cross section	0.06	0.004
detector model	0.10	0.003
$CC\pi^+$ background shape	0.02	0.007
total error	0.20	0.011

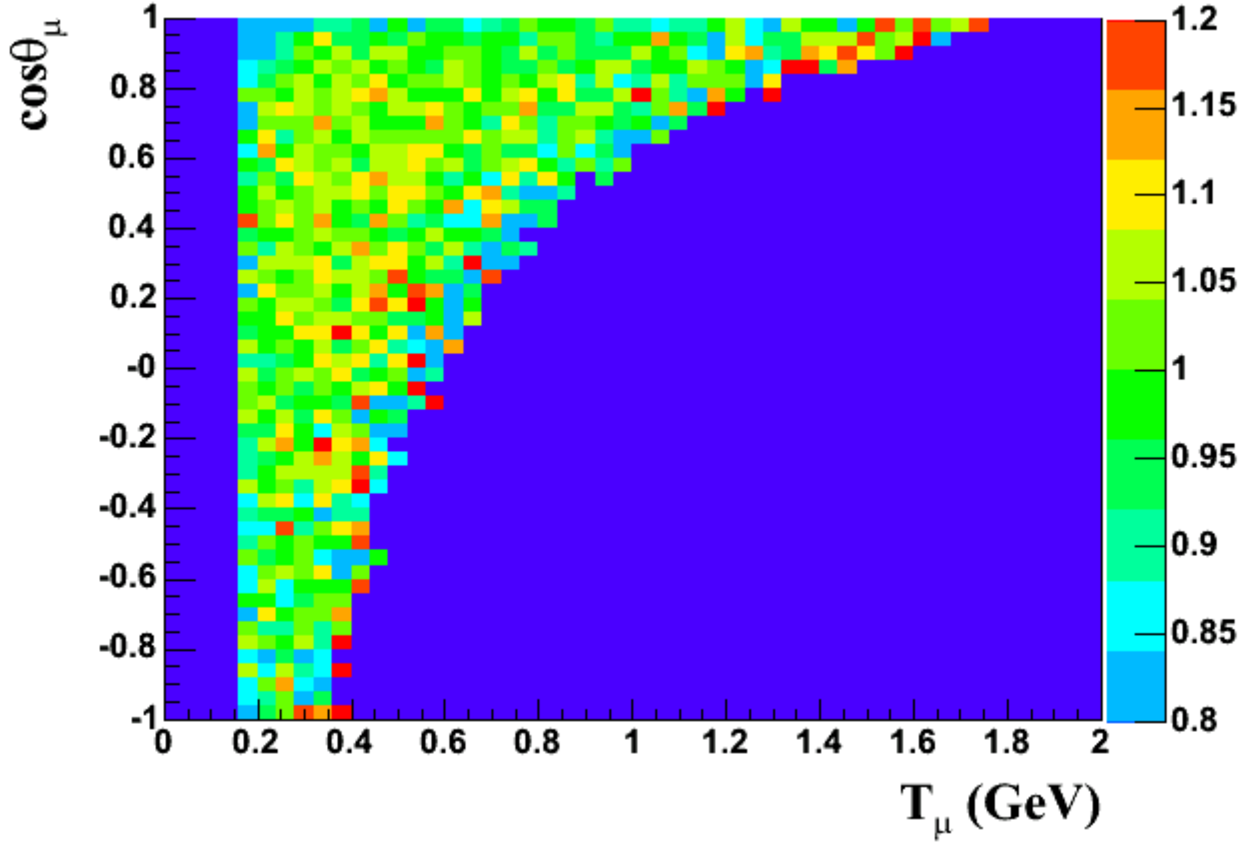
4. Fit results

M_A - κ fit result

M_A = 1.23 ± 0.20(stat+sys)

κ = 1.019 ± 0.011(stat+sys)

data-MC ratio after the fit



Although fit is done in Q^2 distribution, entire CCQE kinematics is improved

before

χ^2/dof = 79.5/53, $P(\chi^2)$ = 1%

↓

after

χ^2/dof = 45.1/53, $P(\chi^2)$ = 77%

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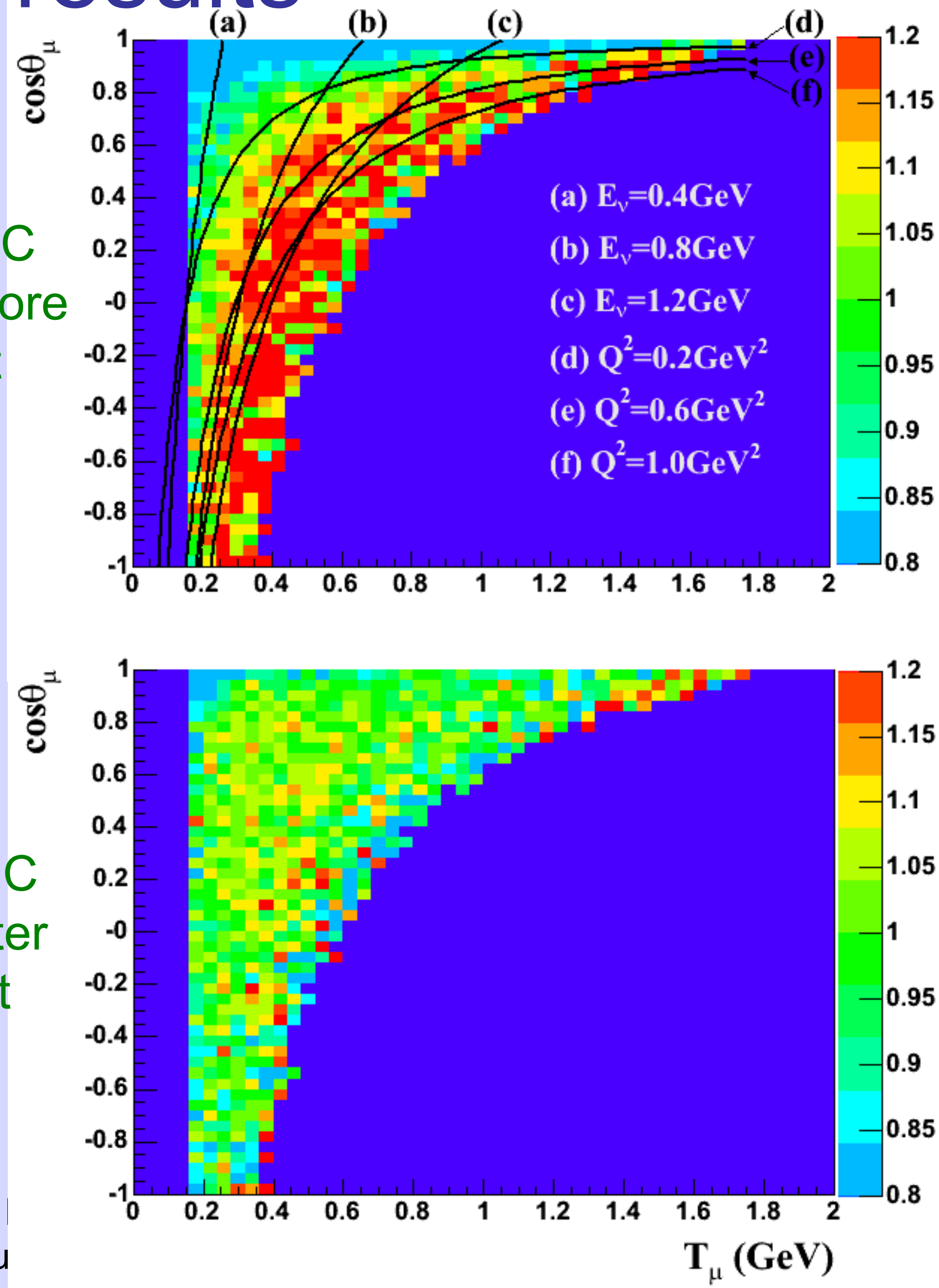
data-MC ratio before the fit

data-MC ratio after the fit

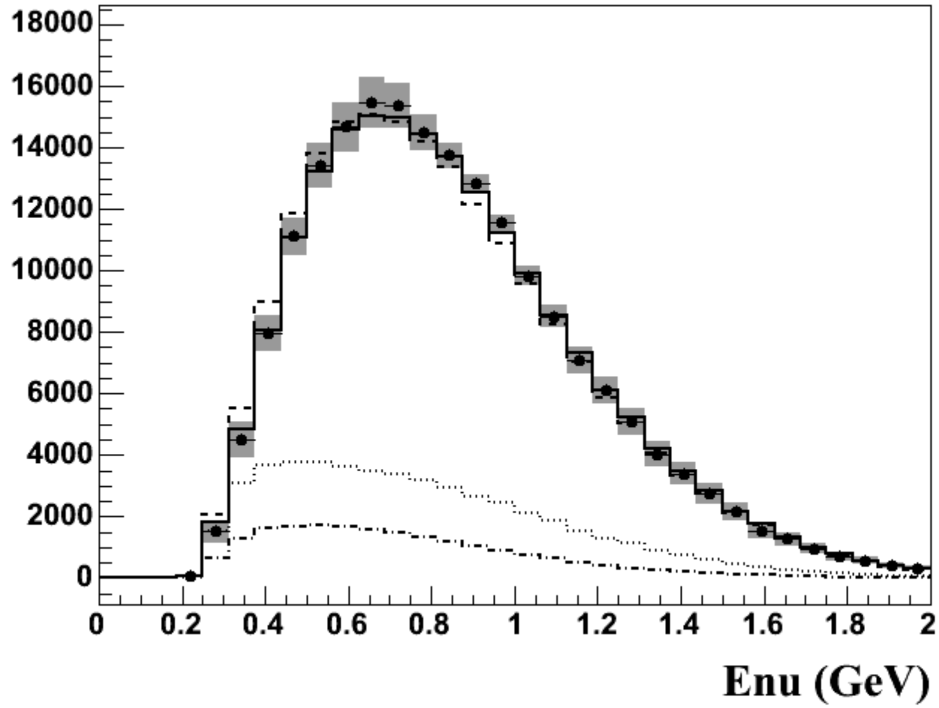


4. Fit results

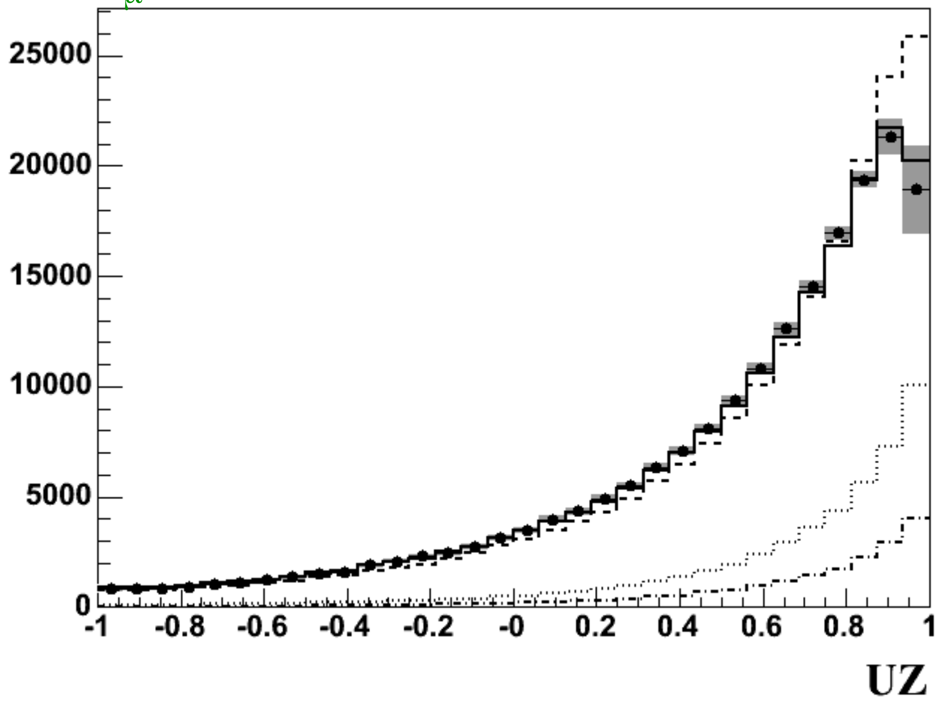
Other kinematics distribution also show very good data-MC agreement
(This is critical for MiniBooNE neutrino oscillation search experiment)

MiniBooNE collaboration,
arXiv:0704.1500 [hep-ex] (2007)

$E\nu$ distribution



$\cos\theta_\mu$ distribution



4. Fit results

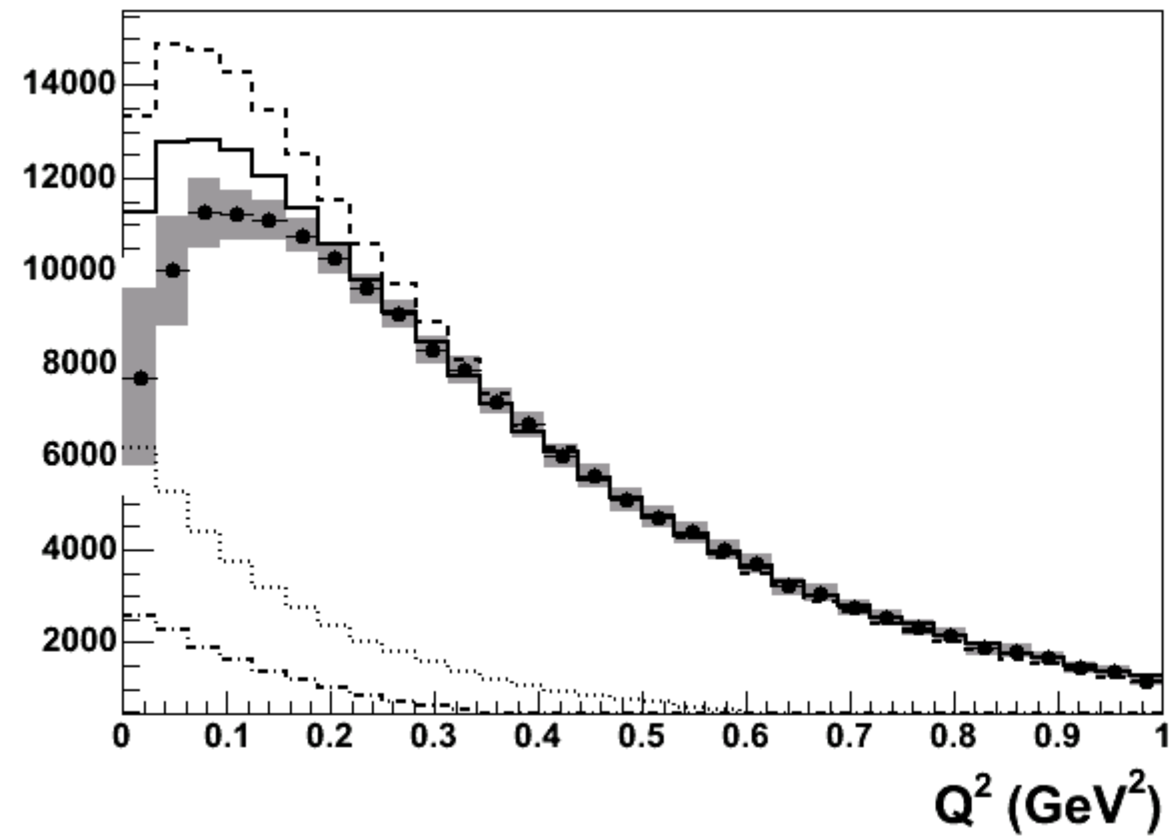
M_A only fit result
M_A = 1.25 ± 0.12(stat+sys)

fit with fixing κ for $0.25<Q^2(GeV^2)<1.0$

good agreement above $0.25GeV^2$ but gross disagreement at low Q^2 region

This fit cannot improve entire CCQE phase space

Q^2 distribution



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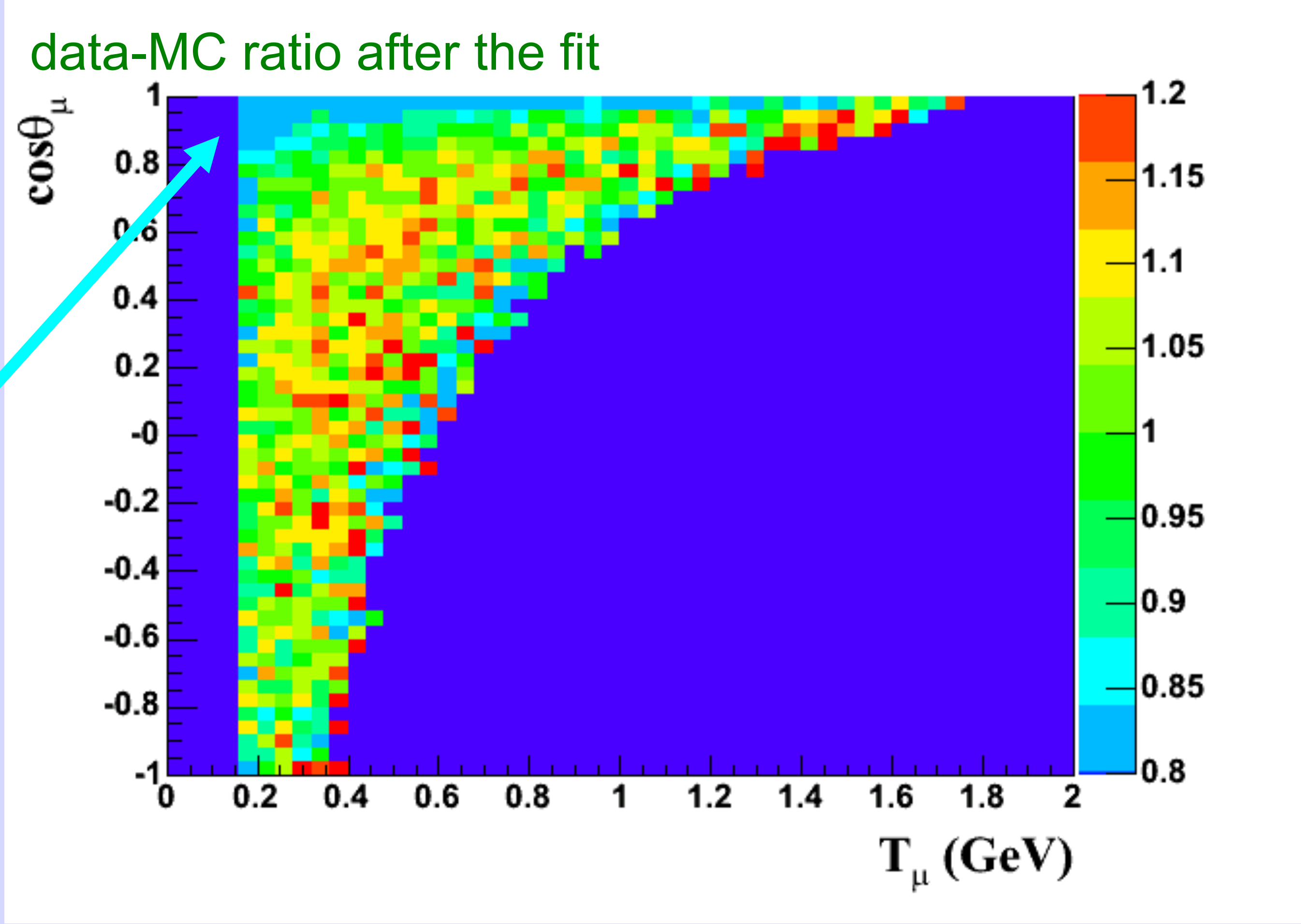

5. Anti-neutrino CCQE events

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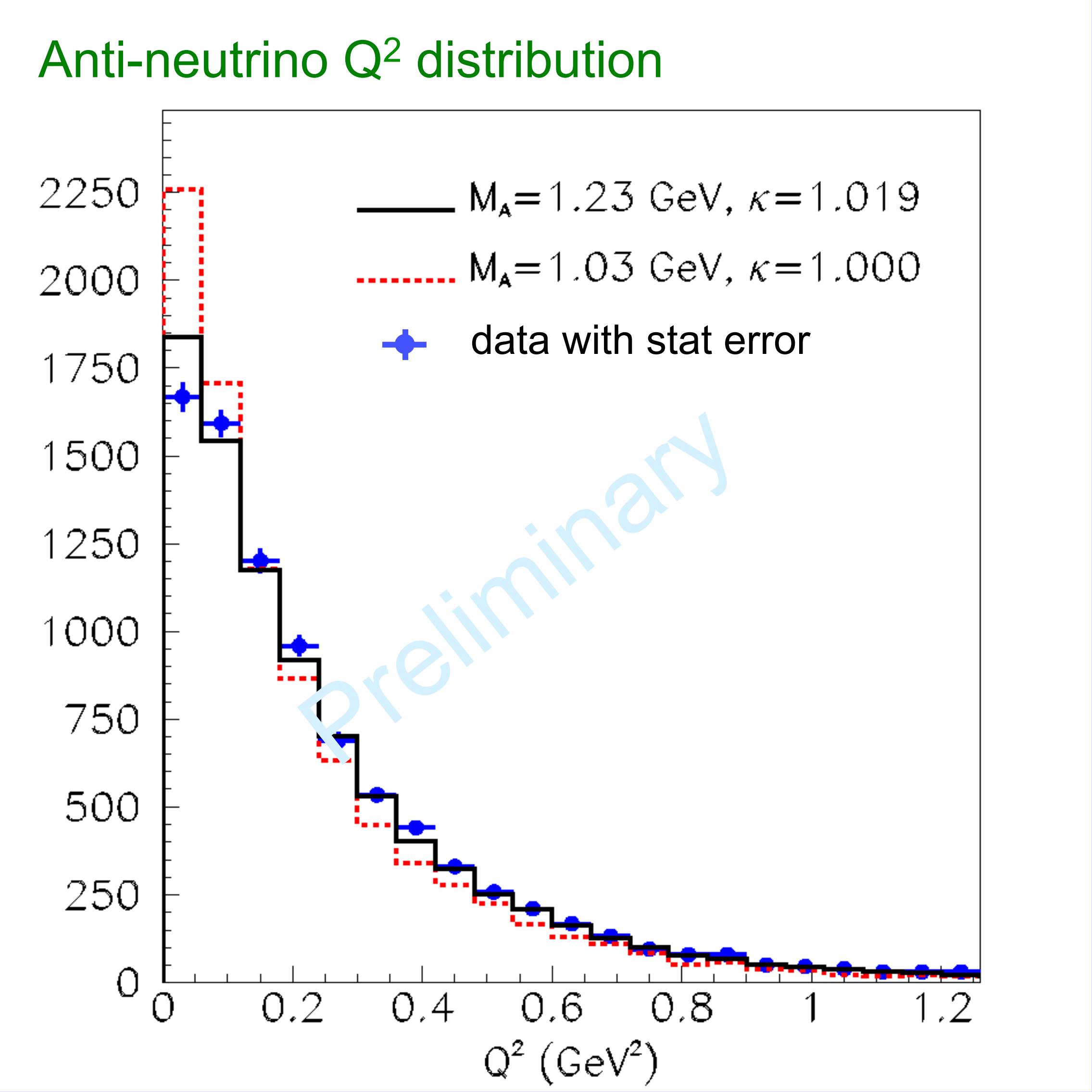
Anti-neutrino Q^2 distribution

MiniBooNE anti-neutrino CCQE
8772 events
(1651 total for pre-MiniBooNE data)

We use same cut with neutrino mode

The values of M_A and κ extracted from neutrino mode are employed to anti-neutrino MC, and they describe data Q^2 distribution well.



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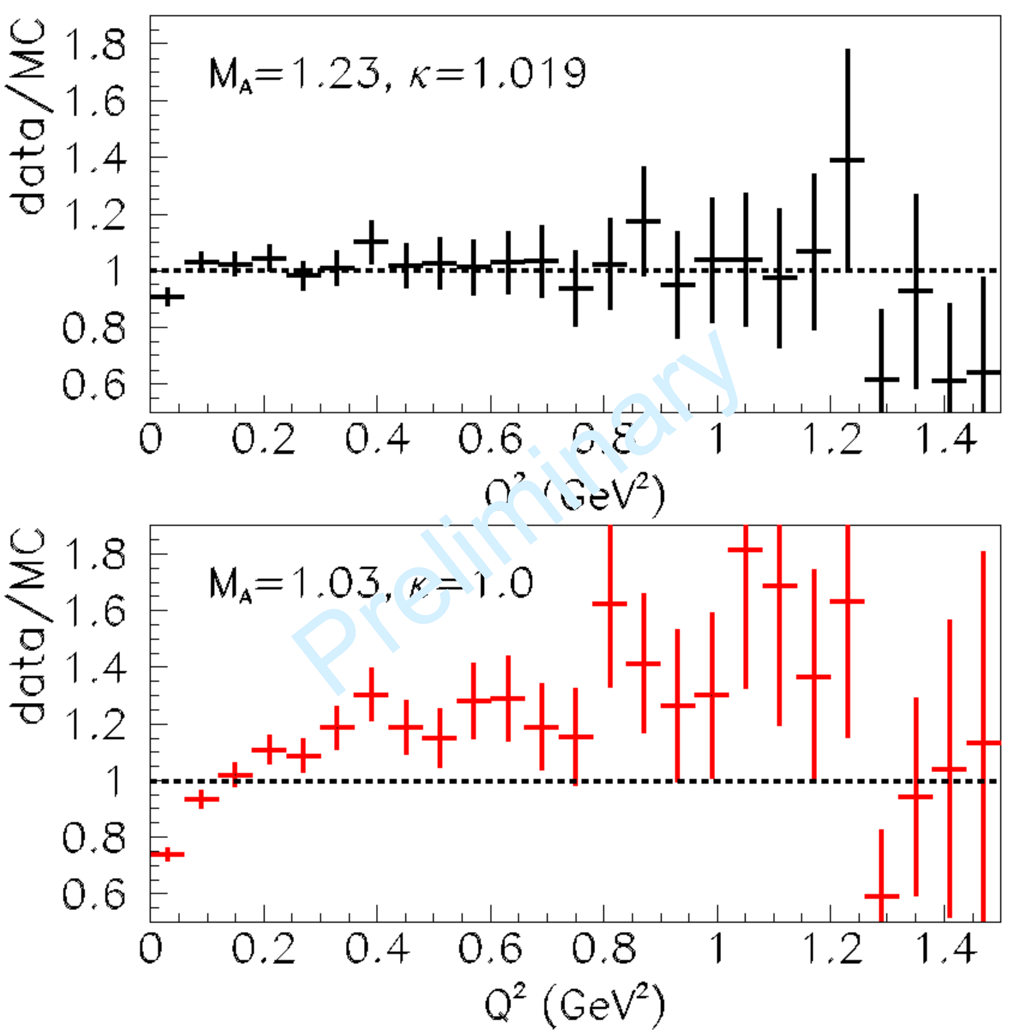
Anti-neutrino Q^2 distribution data-MC ratio



5. Anti-neutrino CCQE events

Anti-neutrino CCQE kinematics

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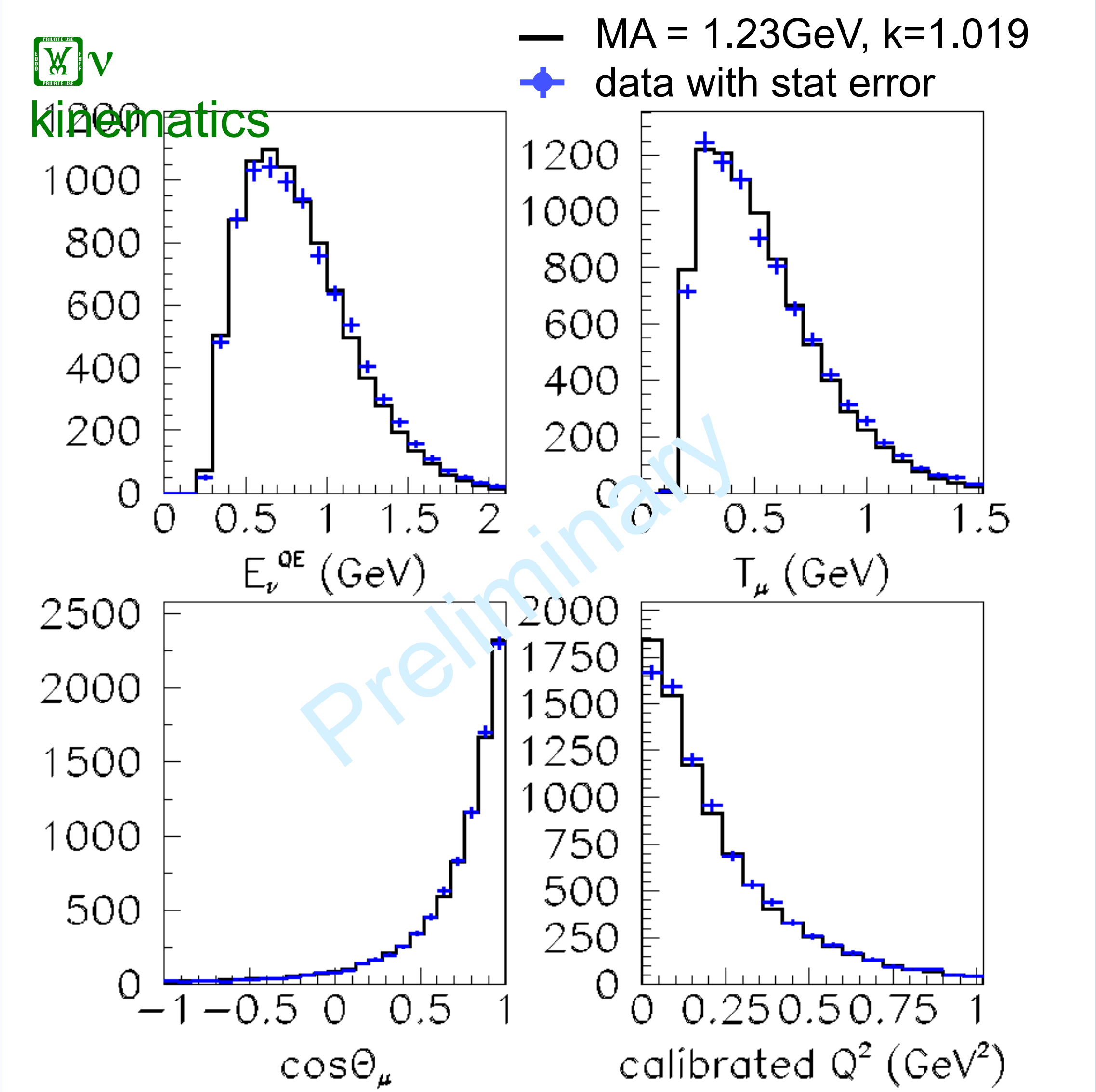
Anti-neutrino CCQE kinematics variables are described by the MC well, too.



6. Conclusion

MiniBooNE has large CCQE data set around 1GeV region

MiniBooNE successfully employee RFG model with appropriate parameter choices for M_A and κ

This new model can describe entire CCQE phase space well

The best fit parameters for MiniBooNE CCQE data are;

$$M_A = 1.23 \pm 0.20(\text{stat+sys})$$
$$\kappa = 1.019 \pm 0.011(\text{stat+sys})$$

Our new model also works well in anti-neutrino data

MiniBooNE is currently taking the data with anti-muon neutrino beam

MiniBooNE collaboration

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermi National Accelerator Laboratory
Indiana University

Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

Thank you for your attention!

10. Back up

4. Fit results

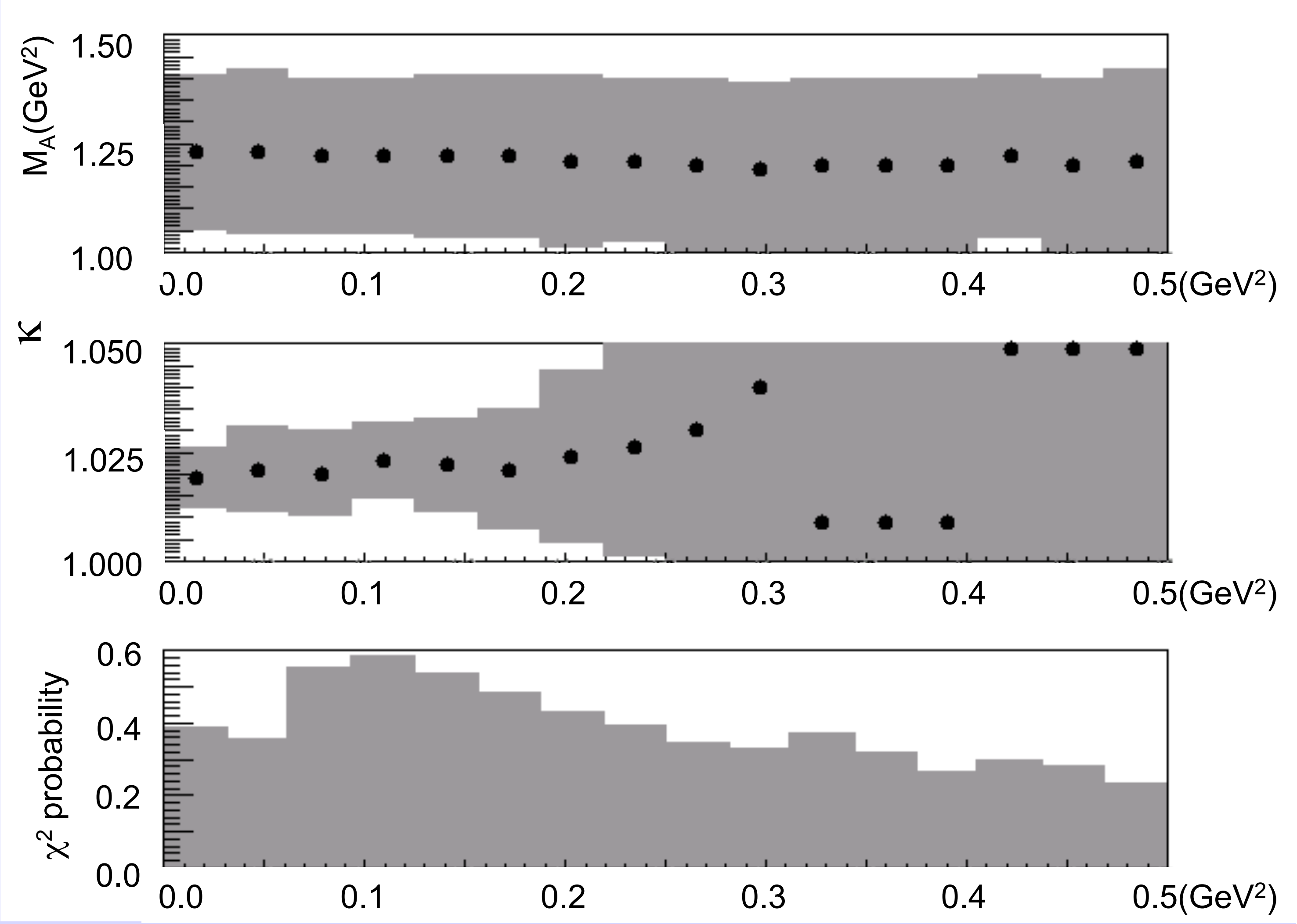
Fit result with varying Q^2min, Q^2min < Q^2 < 1.0GeV^2

Fit is repeated with changing the Q^2min

Fit quality (χ^2 probability) is good even Q^2min =0.0GeV^2

MA is stable in wide range of Q^2min

Since κ is only important for low Q^2 region, it has no power for fit for high Q^2



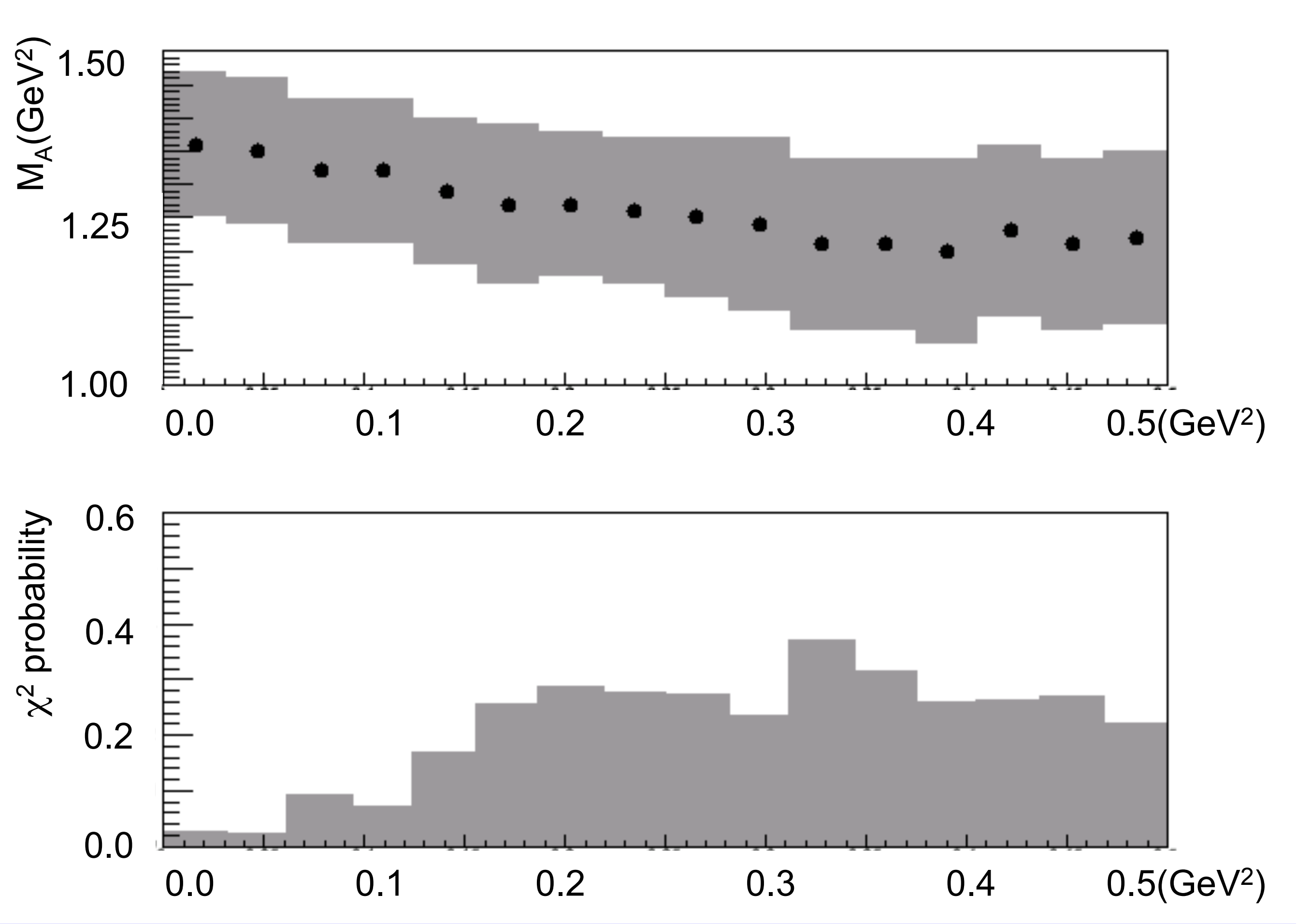
4. Fit results

M_A only fit with varying Q^2min, Q^2min < Q^2 < 1.0GeV^2

Fit is repeated with changing the Q^2min

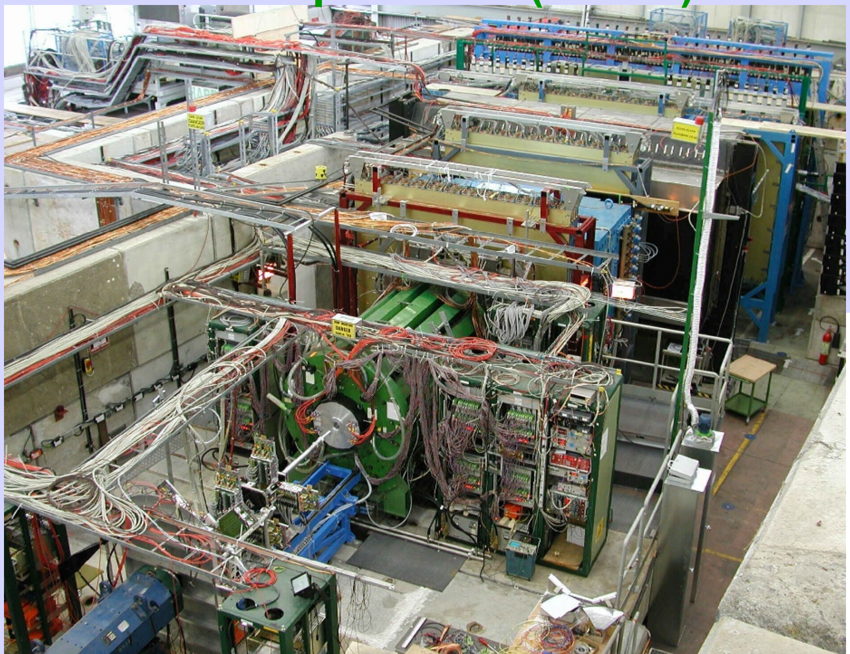
Fit quality (χ^2 probability) is low for Q^2min < 0.2GeV^2

MA is stable in wide range of Q^2min for Q^2min > 0.2GeV^2

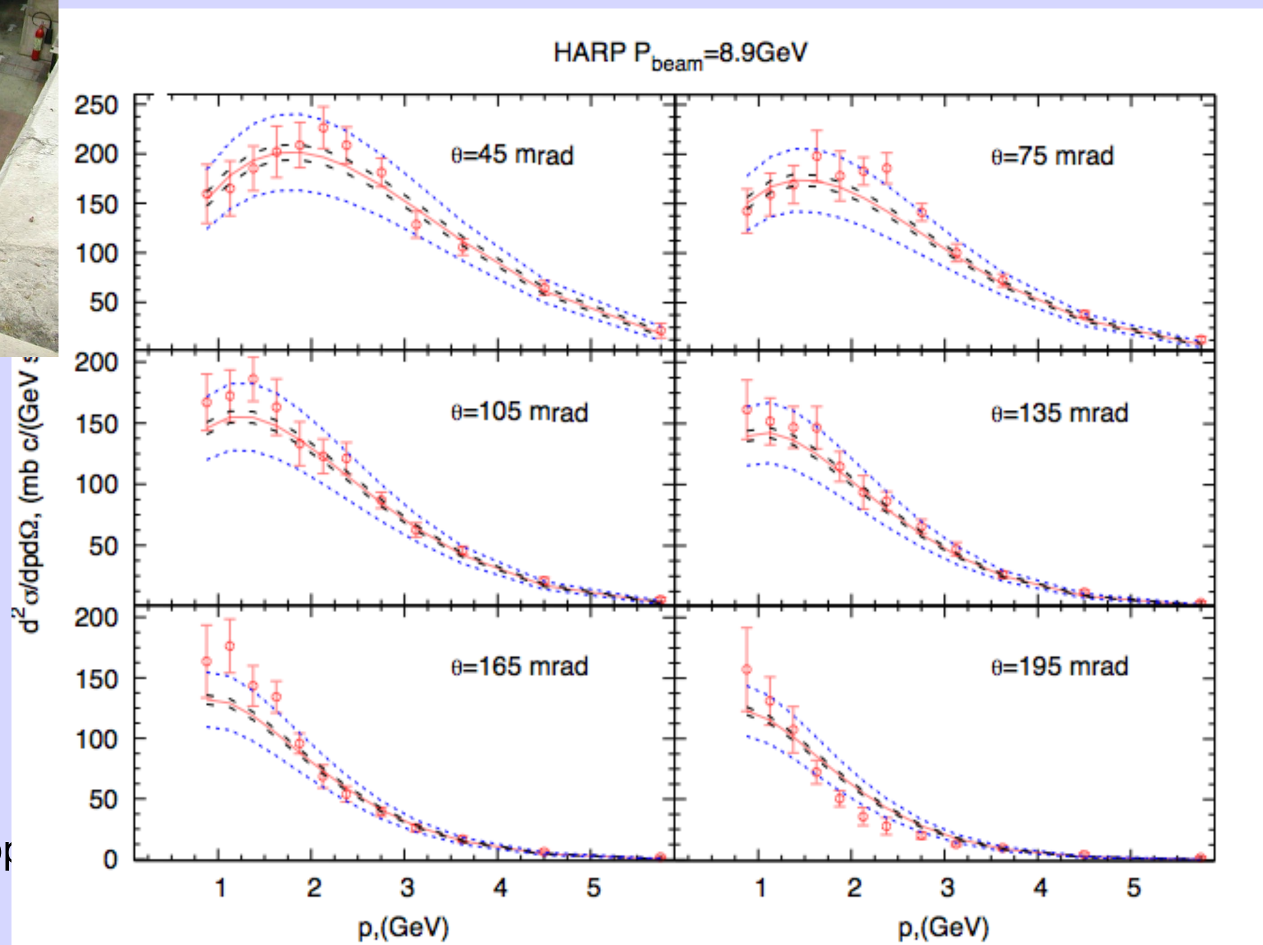


3. Neutrino beam

HARP experiment (CERN)



Modeling Production of Secondary Pions
- 5% λ Beryllium target
- 8.9 GeV proton beam momentum



Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024

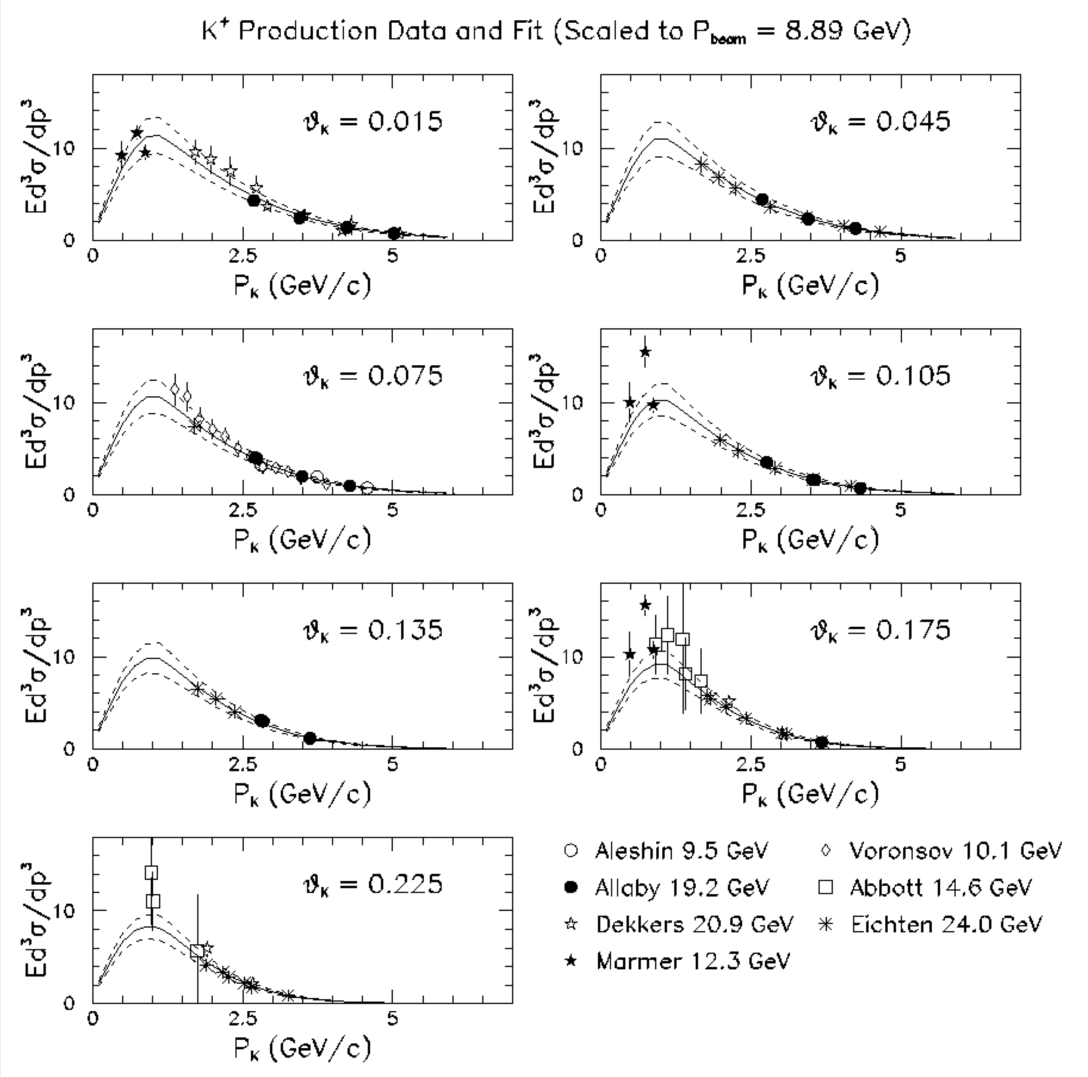
3. Neutrino beam

Modeling Production of Secondary Kaons

K^+ Data from 10 - 24 GeV. Uses a Feynman Scaling Parameterization.

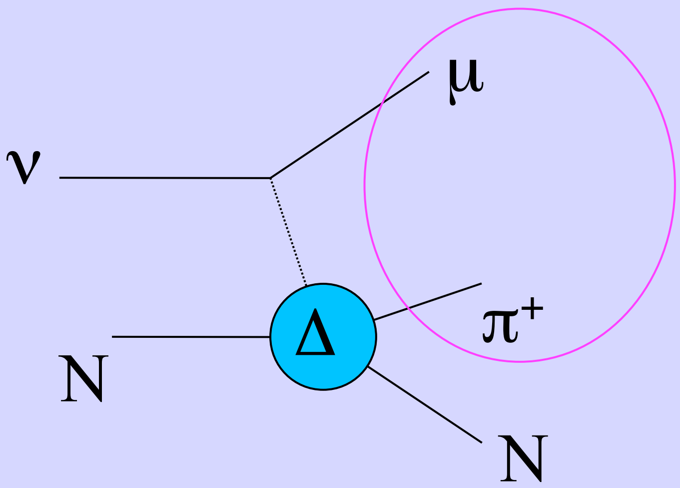
K^0 data are also parameterized.

In situ measurement of K^+ from LMC agrees within errors with parameterization

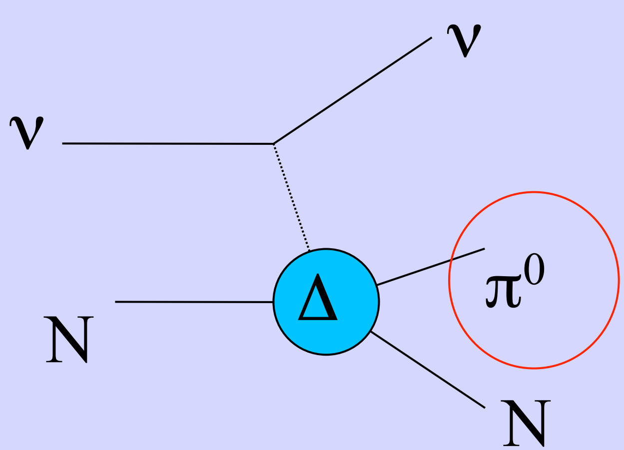


5. Cross section model

25%



8%



(also decays to a single photon with 0.56% probability)

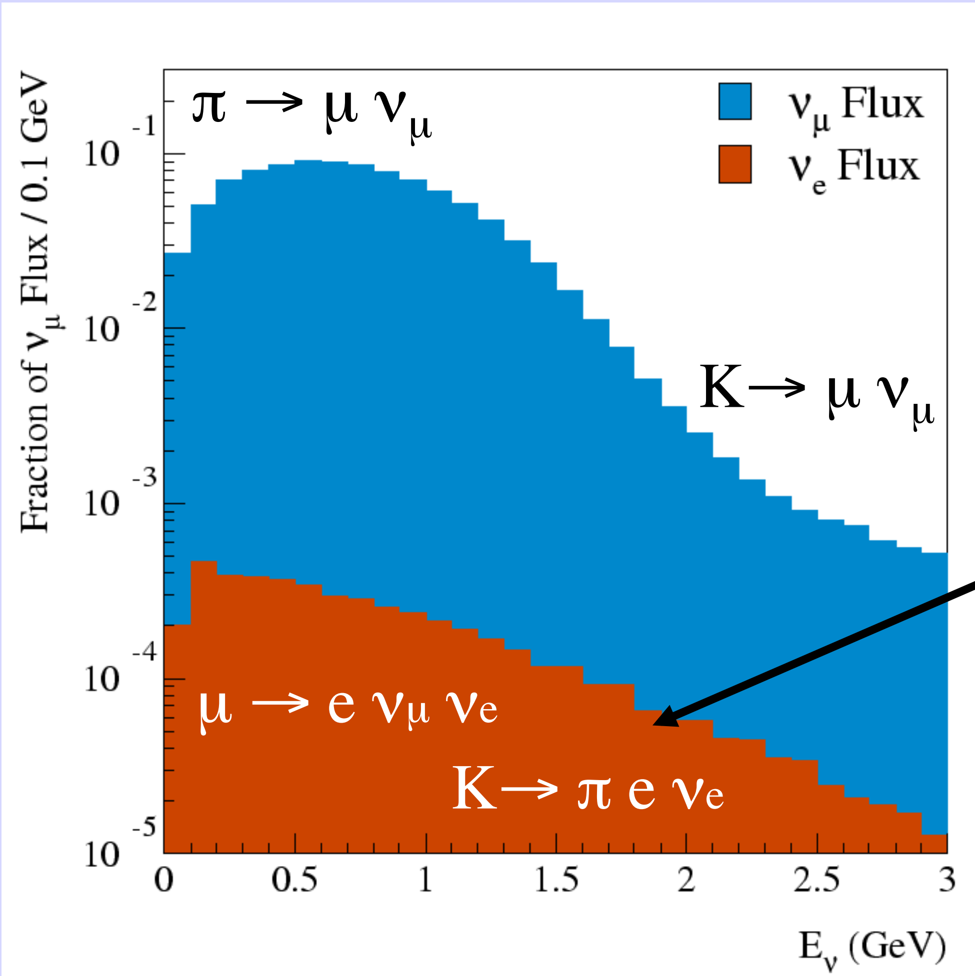
Events producing pions

$CC\pi^+$
Easy to tag due to 3 subevents. Not a substantial background to the oscillation analysis.

$NC\pi^0$
The π^0 decays to 2 photons, which can look "electron-like" mimicking the signal...

<1% of π^0 contribute to background.

6. Blind analysis



"Intrinsic" ν_e + ν_e sources:

$\mu^+ \rightarrow e^+\, \nu_\mu\, \nu_e$	(52%)
$K^+ \rightarrow \pi^0\, e^+\, \nu_e$	(29%)
$K^0 \rightarrow \pi\, e\, \nu_e$	(14%)
Other	(5%)

Since MiniBooNE is blind analysis experiment, we need to constraint intrinsic ν_e background without measuring directly

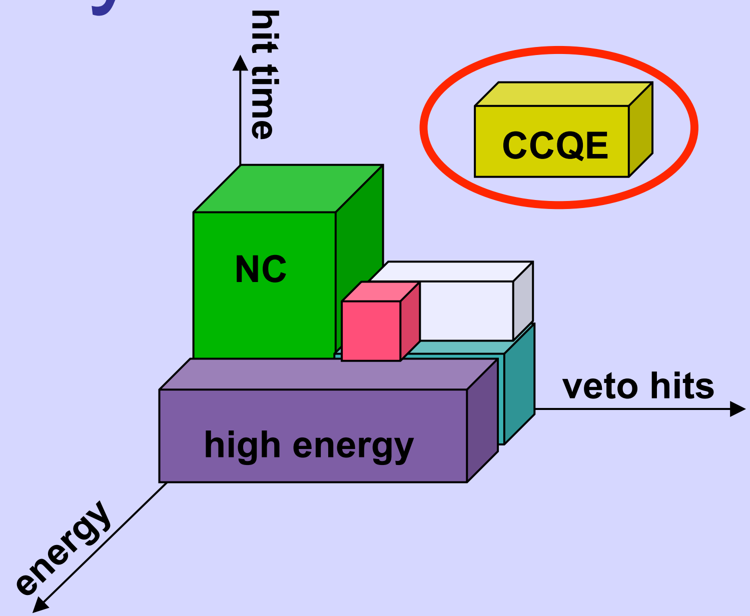
(1) μ decay ν_e background
(2) K decay ν_e background

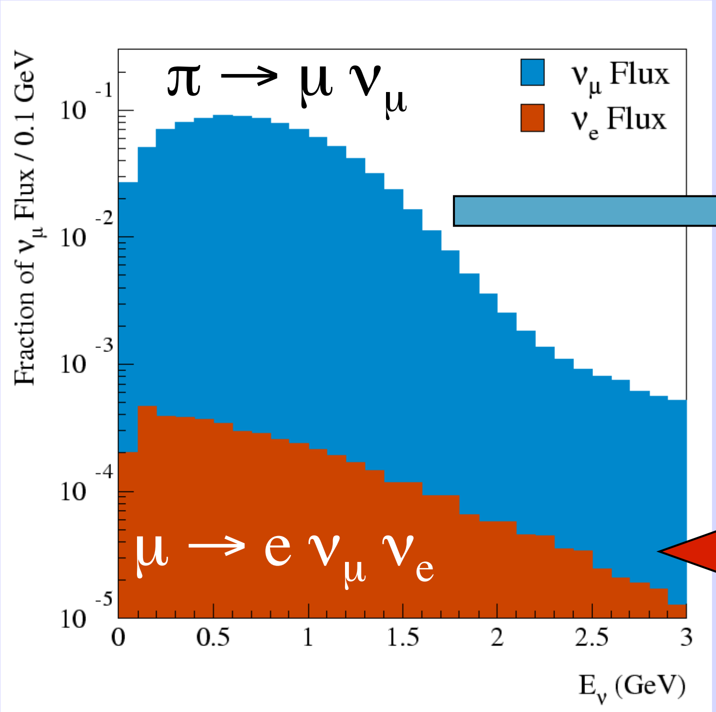
ν_e/ν_μ = 0.5%
Antineutrino content: 6%

6. Blind analysis

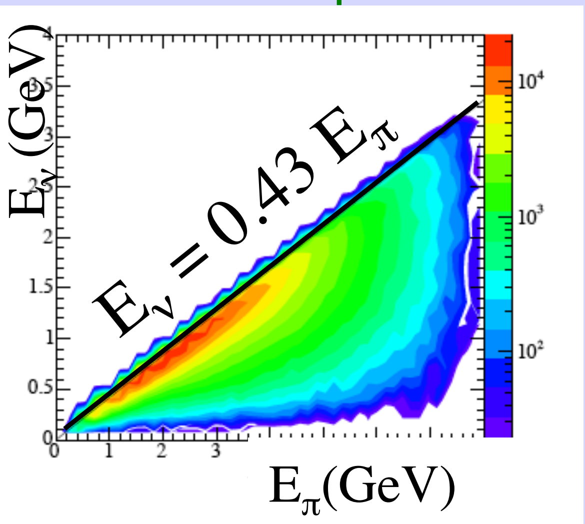
(1) measure ν_μ flux from ν_μCCQE event to constraint ν_e background from μ decay

ν_μCCQE is one of the open boxes.
Kinematics allows connection to π flux, hence intrinsic ν_e background from μ decay is constraint.





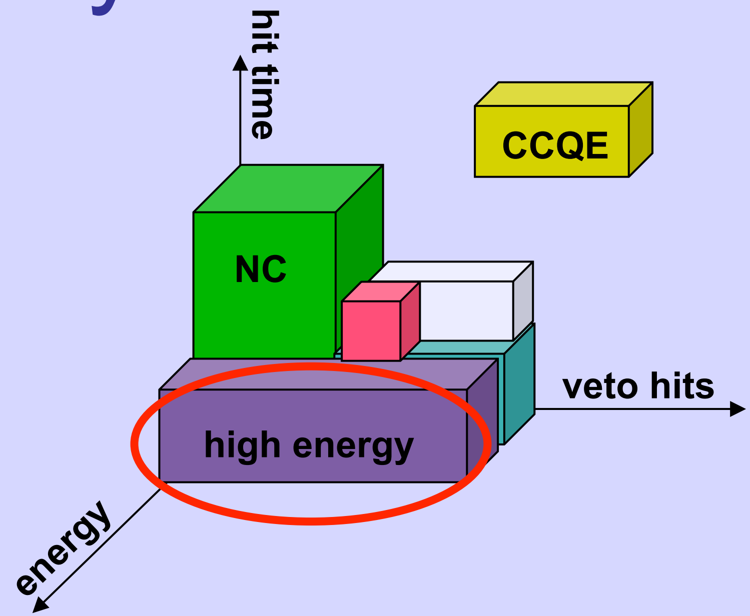
Eν-Eπ space

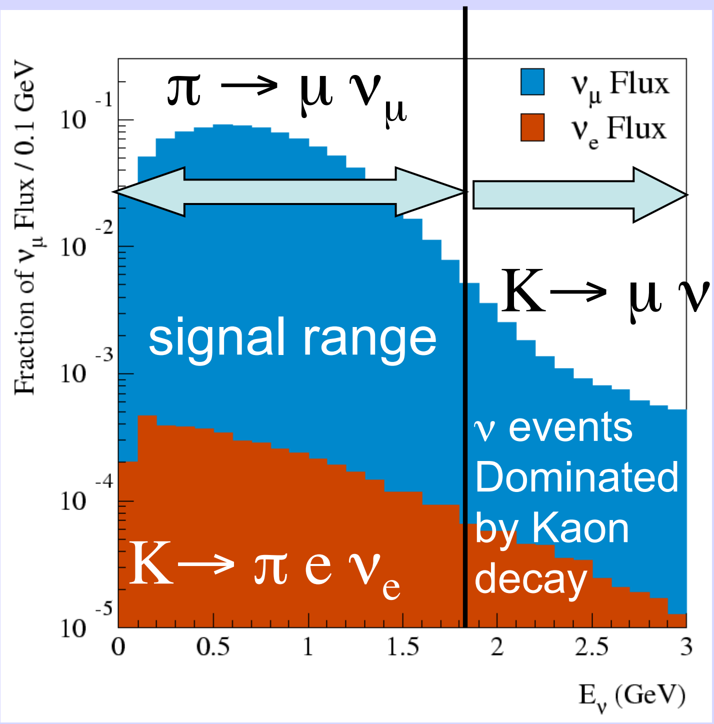


6. Blind analysis

(2) measure high energy ν_μ events to constraint ν_e background from K decay

At high energies, above "signal range" ν_μ and "ν_e -like" events are largely due to kaon decay





example of open boxes;
- ν_μCCQE
- high energy event
- CCπ^+
- NC elastics
- NC π^o
- NC electron scattering
- Michel electron

etc....

7. Error analysis

Handling uncertainties in the analyses:

What we begin with...

For a given source
of uncertainty,

Errors on a wide range
of parameters
in the underlying model

... what we need

For a given source
of uncertainty,

Errors in bins of
E_ν^{QE}
and information on
the correlations
between bins

Input error matrix
keep the all correlation
of systematics

"multisim"
nonlinear error propagation

Output error matrix
keep the all correlation
of E_ν^{QE} bins

7. Multisim

Multi-simulation (Multisim) method

many fake experiments with different parameter set give the variation of correlated systematic errors for each independent error matrix

total error matrix is the sum of all independent error matrix

B.P.Roe,
Nucl.,Instrum.,Meth,A570(2007)157

Input error matrices

dependent

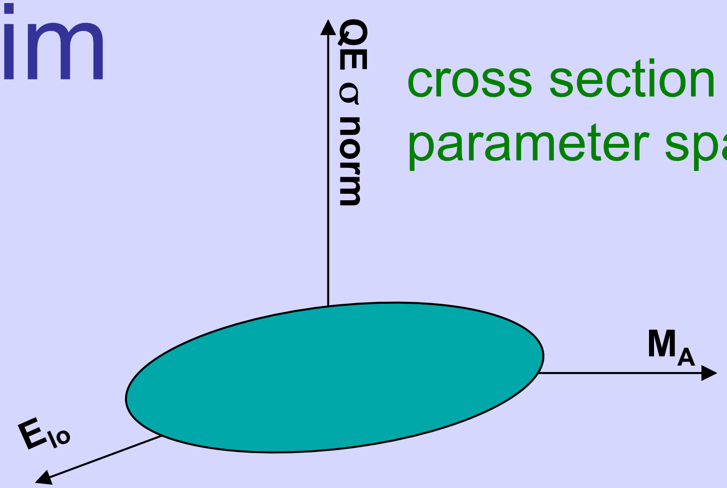
independent

π^+ production (8 parameters)
π^- production (8 parameters)
K^+ production (7 parameters)
K^0 production (9 parameters)
beam model (8 parameters)
cross section (20 parameters)
detector model (39 parameters)

7. Multisim

ex) cross section uncertainties

M_A^{QE}	6%	correlated
E_{lo}^{sf}	2%	
QE σ norm	10%	uncorrelated

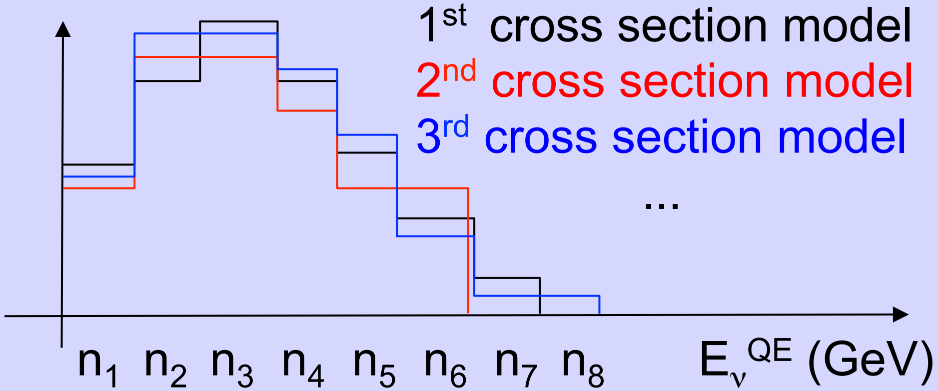


cross section parameter space

Input cross section error matrix

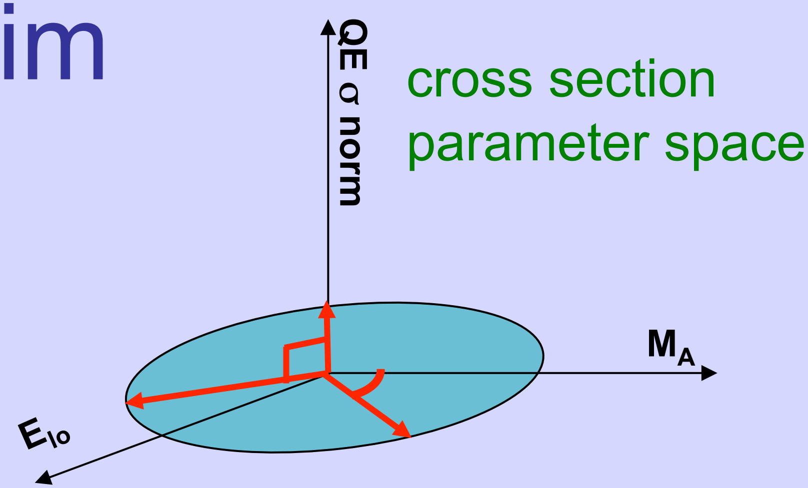
$$M_{input}(xs) = \begin{pmatrix} \mathrm{var}(M_A) & \mathrm{cov}(M_A, E_{lo}) & 0 \\ \mathrm{cov}(M_A, E_{lo}) & \mathrm{var}(E_{lo}) & 0 \\ 0 & 0 & \mathrm{var}(\sigma - norm) \end{pmatrix}$$

cross section error for E_ν^{QE}



repeat this exercise many times to create smooth error matrix for E_ν^{QE}

7. Multisim



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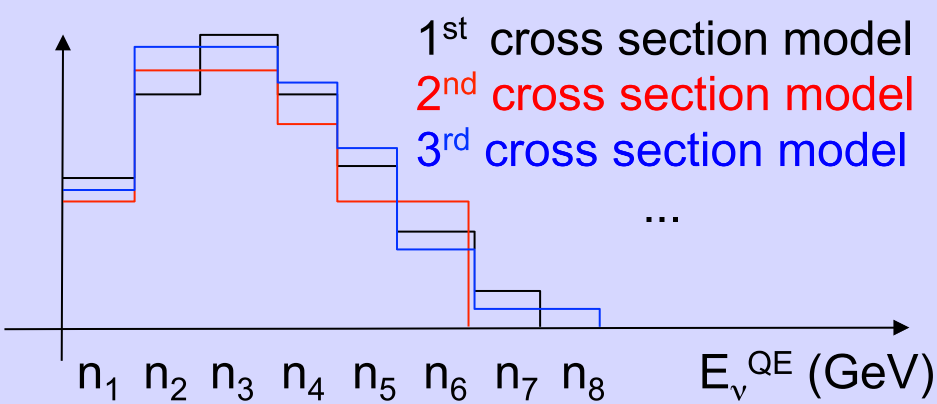
cross section error for E_ν^{QE}



repeat this exercise many times to create smooth error matrix for E_ν^{QE}

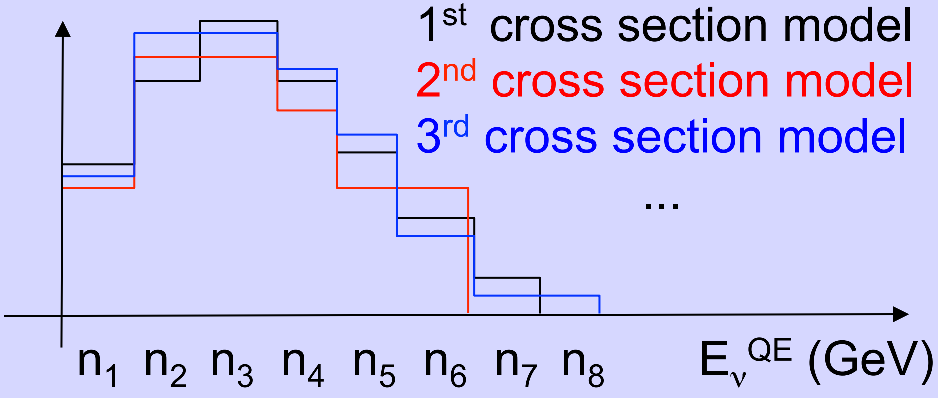
7. Multisim

Output cross section error matrix for E_ν^{QE}

$$\left[M_{output}(xs)\right]_{ij} \approx \frac{1}{S}\sum_{k}^{S}\left(N_i^k(xs) - N_i^{MC}\right)\left(N_j^k(xs) - N_j^{MC}\right)$$

$$M_{output}(xs) = \begin{pmatrix} \mathrm{var}(n_1) & \mathrm{cov}(n_1,n_2) & \mathrm{cov}(n_1,n_3) & \cdots \\ \mathrm{cov}(n_1,n_2) & \mathrm{var}(n_2) & \mathrm{cov}(n_2,n_3) & \cdots \\ \mathrm{cov}(n_1,n_3) & \mathrm{cov}(n_2,n_3) & \mathrm{var}(n_3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

cross section error for E_ν^{QE}



Oscillation analysis use output error matrix for χ^2 fit;

$$\chi^2 = (\mathrm{data} - \mathrm{MC})^T (M_{output})^{-1} (\mathrm{data} - \mathrm{MC})$$

7. Multisim

ex) cross section uncertainties

M_A^{QE}	6%	determined from MiniBooNE ν_μ QE data
E_{lo}^{sf}	2%	
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	

NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	±25%	
$\Delta \to N\gamma$ rate	function of γ mom + 7% BF	

E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

etc...