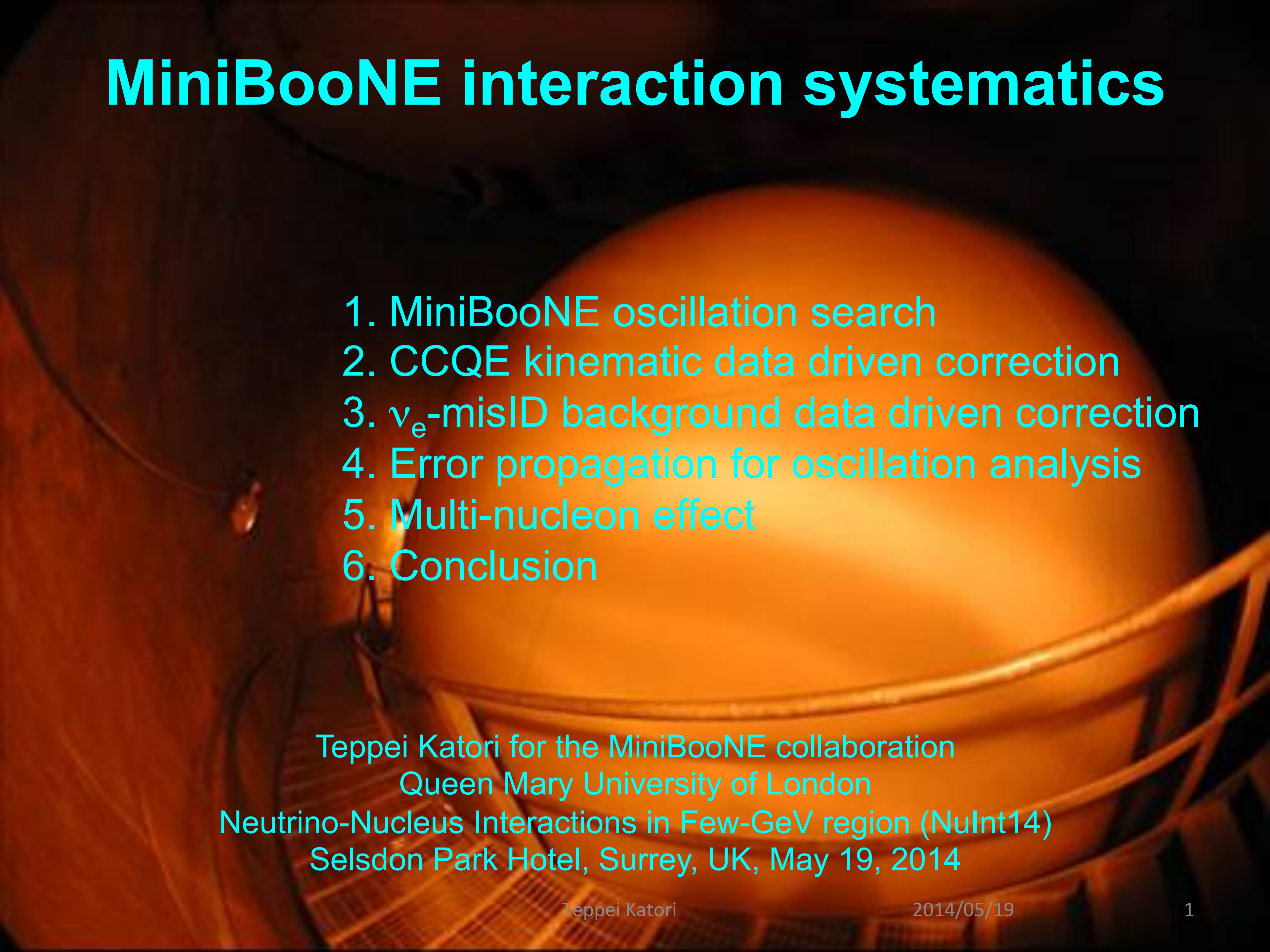
MiniBooNE interaction systematics



1. MiniBooNE oscillation search
2. CCQE kinematic data driven correction
3. ν_e-misID background data driven correction
4. Error propagation for oscillation analysis
5. Multi-nucleon effect
6. Conclusion

Teppei Katori for the MiniBooNE collaboration
Queen Mary University of London

Neutrino-Nucleus Interactions in Few-GeV region (NuInt14)
Selsdon Park Hotel, Surrey, UK, May 19, 2014

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1. MiniBooNE neutrino oscillation search experiment

Blind analysis

Since MiniBooNE uses a blind analysis, oscillation candidate (ν_e-box) cannot be accessed before box opening.

Goal of MiniBooNE experiment cross section group

- Understand ν_eCCQE kinematics of before box opening
- Understand ν_e-misID background in ν_e-box before box opening
- Propagate associated interaction systematic errors to the final oscillation fit

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + e^- (\text{Cherenkov})$$

$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow n + e^+ (\text{Cherenkov})$$

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MiniBooNE collaboration,PRL100(2008)032301

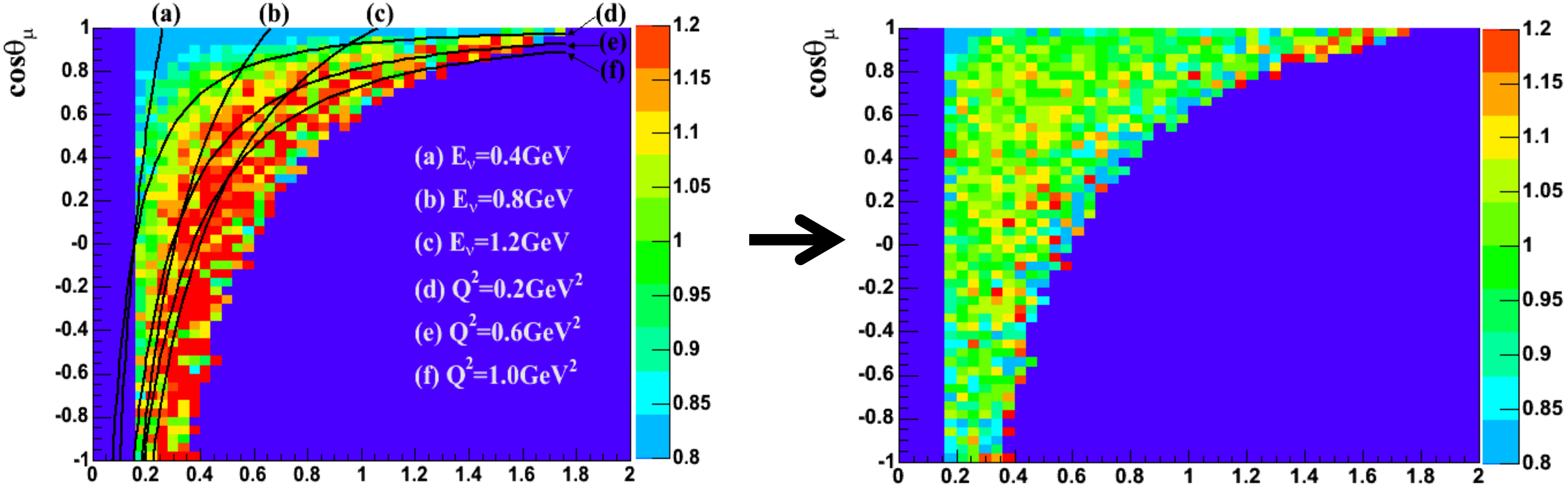
2. MiniBooNE ν_μCCQE measurement

Due to the blind analysis, ν_eCCQE candidate (ν_e-box) cannot be accessed

Assuming lepton universality, ν_eCCQE is identical with ν_μCCQE interaction, except lepton mass effect.

ν_μCCQE data was used to tune the CCQE model. Tuned effective relativistic Fermi gas (RFG) model successfully describe ν_μCCQE data in al kinematic space.

Data-MC ratio of T_μ-cosθ_μ plane for MiniBooNE CCQE



Relativistic Fermi gas (RFG) model in NUANCE

Effective RFG model

Benhar et al,PRD72(2005)053005
Caballero et al,PRL95(2005)252502

2. CCQE errors

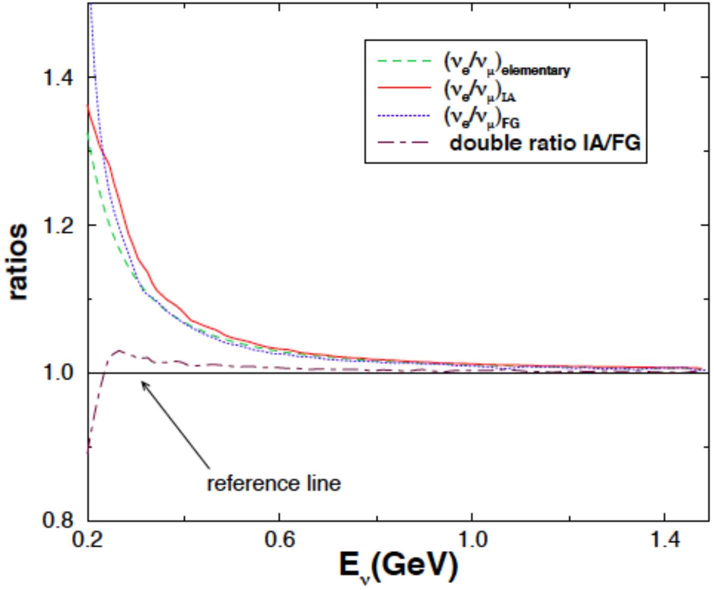
1. Effective RFG model errors

Effective M_A and Pauli blocking parameter "κ", are extracted from fit, with errors.

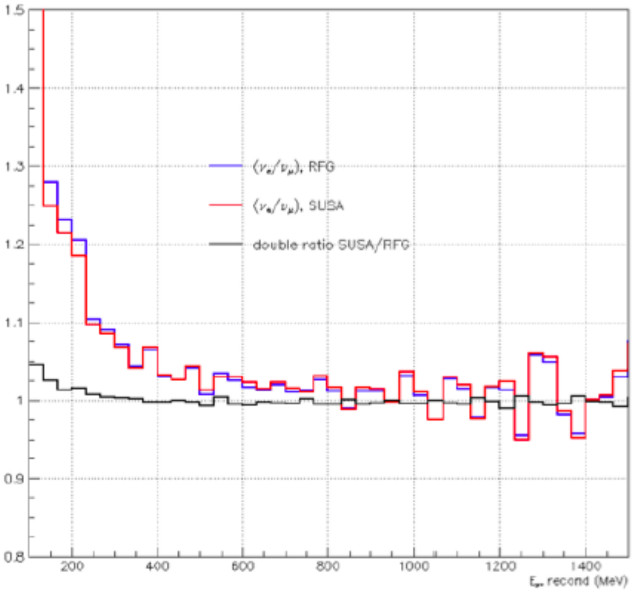
2. ν_e to ν_μ uncertainty

The ν_e to ν_μ cross section ratio was compared with other models. The error is assigned to cover all possible difference between effective RFG and other models.

comparison with SF



comparison with SuSA



Benhar et al,PRD72(2005)053005
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2. CCQE errors

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Effective M_A and Pauli blocking parameter "κ", are extracted from fit, with errors.

2. ν_e to ν_μ uncertainty

The ν_e to ν_μ cross section ratio was compared with other models. The error is assigned to cover all possible difference between effective RFG and other models.

3. High energy CCQE uncertainty

Effective RFG model tuned from ν_μCCQE is effective up to ~2 GeV. To extend this to higher energy, additional energy dependent error was added.

4. CCQE normalization

Effective RFG underestimates ν_μCCQE data. Normalization error (10%) was added.

5. neutrino to antineutrino uncertainty

Effective RFG model is tuned to neutrino CCQE. Although it describe anti-neutrino CCQE shape well, but not normalization. Normalization error (10%) was added.

These errors are propagated to final oscillation analysis (Later).

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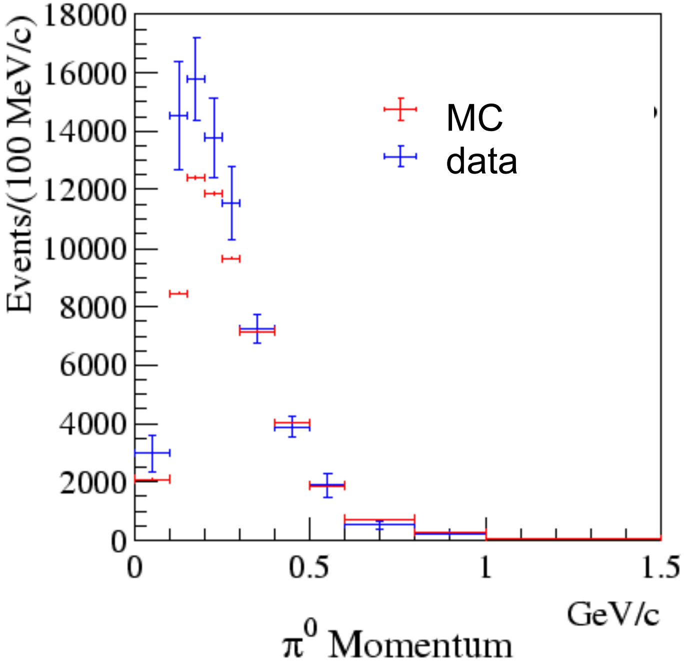
MiniBooNE collaboration,PLB100(2008)032301

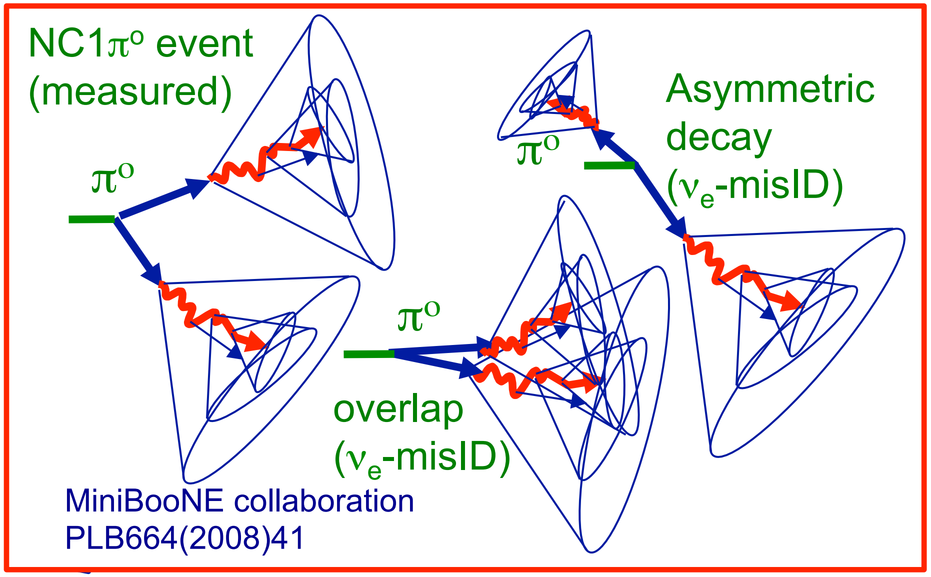
3. NC1π° data driven correction

NC1π° is the major misID background. There are various ways to lose 1 photon to become ν_e-misID background.

The prediction of NC1π°. interaction rate is the biggest error to predict this background in ν_e-box.

We performed NC1π° measurement, and measured π° kinematics is used to constrain π° origin ν_e-misID events in ν_e-box.





MiniBooNE collaboration
PLB664(2008)41

Zhang and Serot, PLB719(2013)409, PRC86(2012)015501
Wang et al, PRC89(2014)015503, arXiv:1304.2702

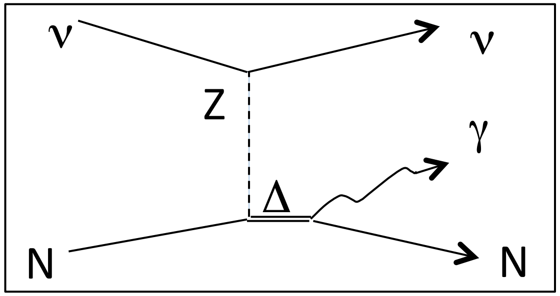
3. Radiative Δ-decay data driven correction

Radiative Δ-decay (NC1γ) is an additional ν_e-misID channel.

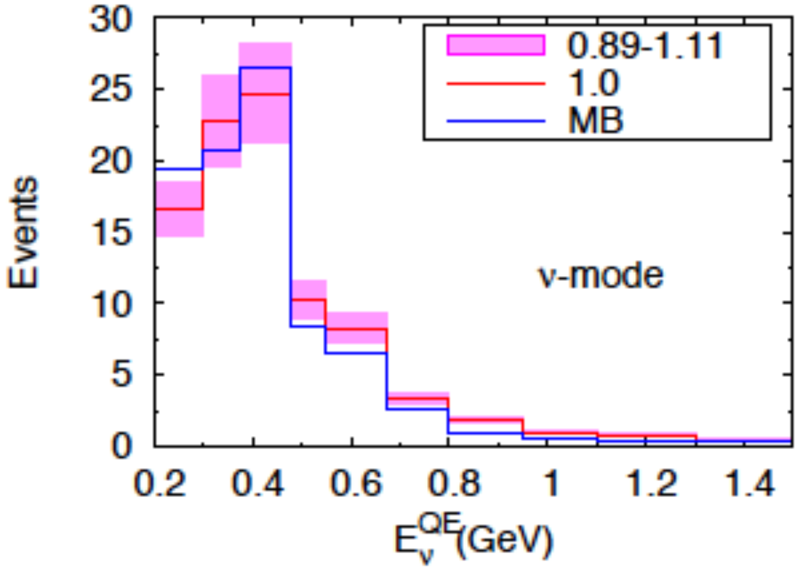
This process is also estimated from measured NC1π^o rate, with taking account W-dependence and pion escaping probability.

This naive estimation is consistent with recent state-of-the-art nuclear calculation of single gamma production.

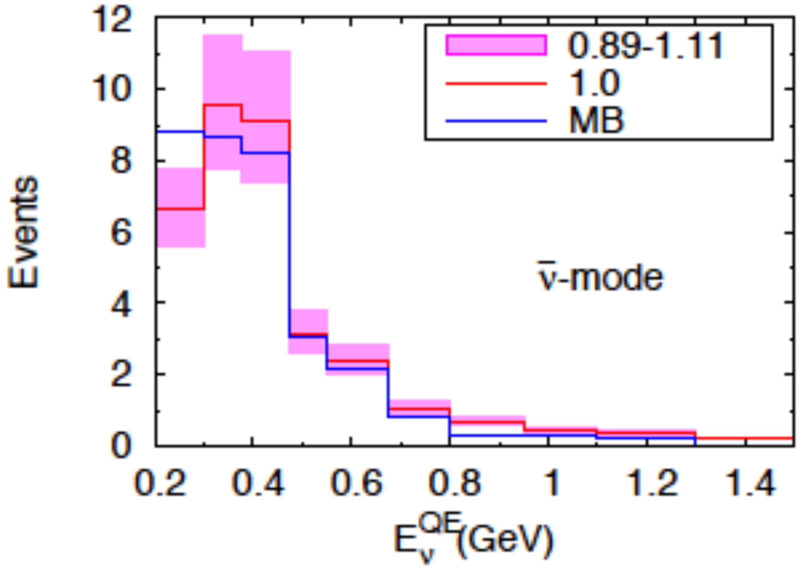
radiative Δ-decay



NCγ event prediction (neutrino mode)



NCγ event prediction (antineutrino mode)



1. MiniBooNE neutrino oscillation search
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Roe,NIMA570(2007)159

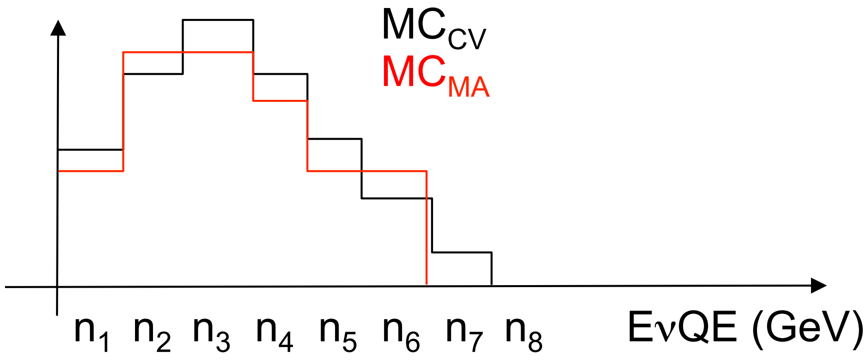
4. Unisim method

$$M_{ij}^{MA} = \left(N_i^{CV} - N_i^{MA}\right)\left(N_j^{CV} - N_j^{MA}\right)$$

CCQE error in oscillation search

Traditionally;

- Standard MC is made from M_A with its central value (MC_{CV})
- M_A is shifted 1σ and new MC is generated (MC_{MA})
- ν_e-candidate distribution is made using from MC_{CV} and MC_{MA}
- Difference of MC_{CV} and MC_{MA} is used to construct an Error matrix
- This exercise is repeated to all systematics
- All error matrices are added to construct total error matrix
- This total error matrix is used for the final oscillation fit



Roe,NIMA570(2007)159

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Problem of unisim method

- M_A and κ (effective Pauli blocking parameter) are extracted simultaneously from the ν_μCCQE data, so there is a correlation. Unisim method doesn't propagate the correlation, this in general, overestimate total errors.

Roe,NIMA570(2007)159

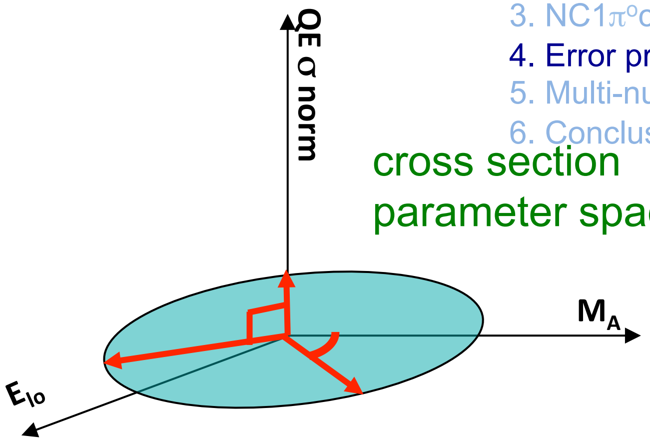
4. Multisim method

ex) cross section uncertainties

M_AQE	6%
κ (Pauli blocking)	2%
QE σ norm	10%

correlated

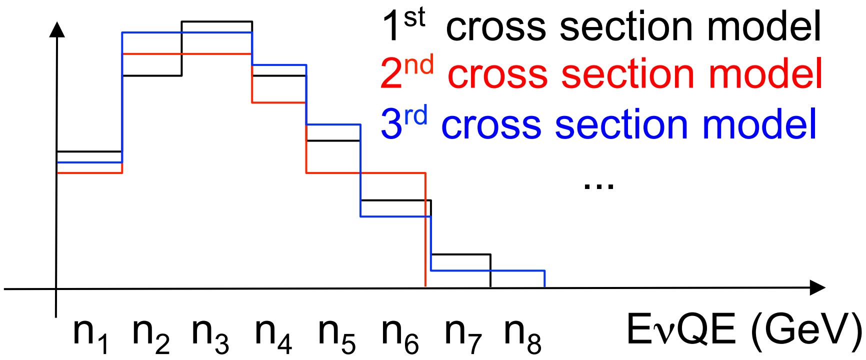
uncorrelated



cross section parameter space

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

cross section error for EνQE



We repeat this exercise many times to create smooth error matrix for EνQE

Roe,NIMA570(2007)159

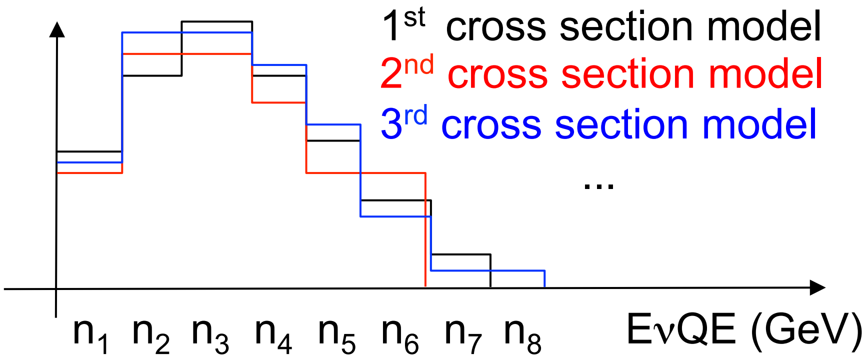
4. Multisim method

Output cross section error matrix for EνQE

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

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

cross section error for EνQE



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Roe,NIMA570(2007)159

4. Multisim method

MiniBooNE cross section uncertainties

M_AQE	6%
κ (Pauli)	2%
QE σ norm	10%
QE σ shape	function of Eν
ν_e/ν_μ QE σ	function of Eν
anti-ν_μ/ν_μ	10%

determined from
MiniBooNE
ν_μ QE data

NC π^o rate	function of π^o mom (~5%)
coh frac	14%
$\Delta \rightarrow N\gamma$ rate	12%

determined from
MiniBooNE
ν_μ NC π^o data

E_B	9 MeV
P_F	30 MeV
Δs	10%
$M_A1\pi$	25%
$M_AN\pi$	40%
$M_A$coh	25%
M_AQE(H)	9%
DIS σ	25%
π-abs	25%
π-charge ex.	30%
π-less Δ-decay	100%

determined
from other
experiments

Roe,NIMA570(2007)159

4. Multisim method

Input error matrix
keep all correlation
of systematics

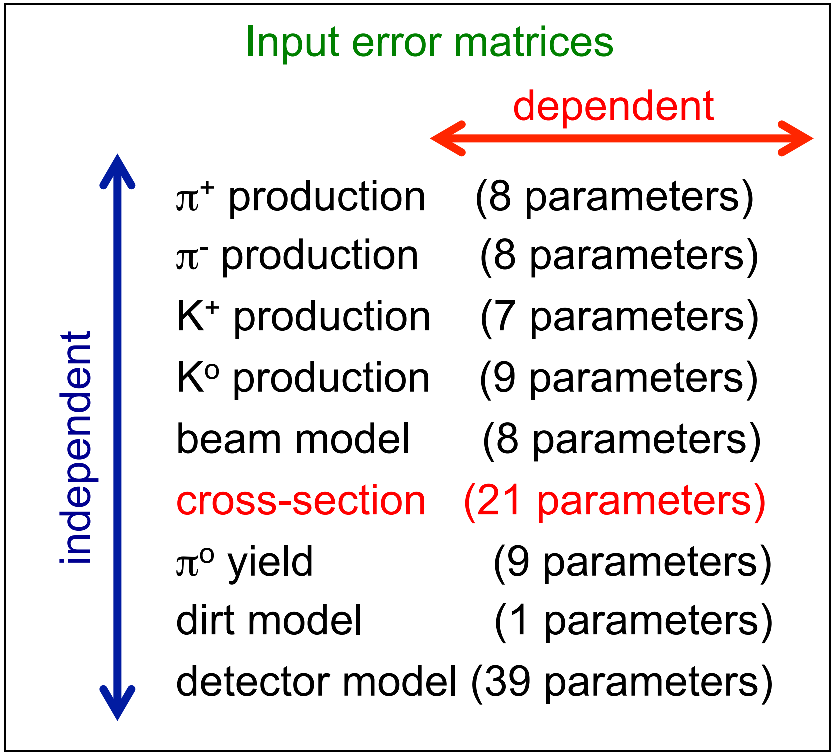
"multisim"
nonlinear error propagation →

Output error matrix
keep all correlation
of EνQE bins

The total error matrix is used for oscillation fit to extract the best fit Δm^2 and $\sin^2 2\theta$.

Total error matrix for oscillation fit

$$
\begin{aligned}
M(\text{total}) = & M(\pi^+ \text{ production}) \\
& + M(\pi^- \text{ production}) \\
& + M(\pi^+ \text{ production}) \\
& + M(K^+ \text{ production}) \\
& + M(K^o \text{ production}) \\
& + M(\text{beamline model}) \\
& + M(\text{cross-section}) \\
& + M(\pi^o \text{ yield}) \\
& + M(\text{dirt model}) \\
& + M(\text{detector model})
\end{aligned}
$$



Input error matrices

π^+ production	(8 parameters)
π^- production	(8 parameters)
K^+ production	(7 parameters)
K^o production	(9 parameters)
beam model	(8 parameters)
cross-section	(21 parameters)
π^o yield	(9 parameters)
dirt model	(1 parameters)
detector model	(39 parameters)

Queen Mary
University of London

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Martini et al,PRD85(2012)093012, Lalakulich et al,PRC86(2012)054606, Nieves et al,PRD85(2012)113008

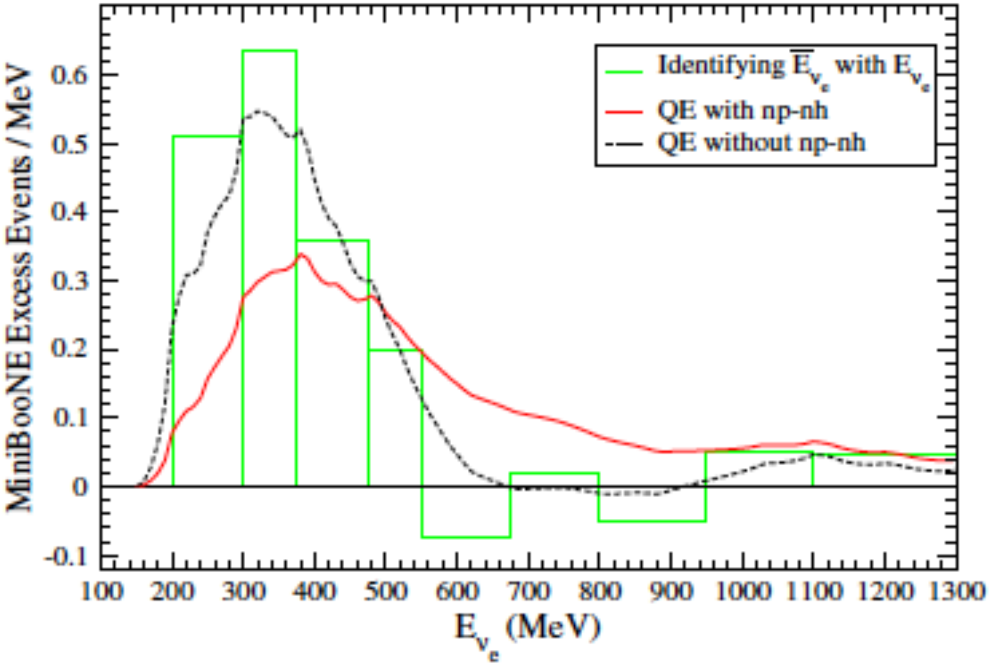
5. Energy reconstruction bias

Energy reconstruction bias due to multi-nucleon (np-nh) effect

It was pointed out np-nh effect is responsible to the MiniBooNE effective M_A.

What is more, np-nh effect in ν_eCCQE sample might cause significant bias in neutrino energy reconstruction.

MiniBooNE neutrino mode event excess distribution in EνQE



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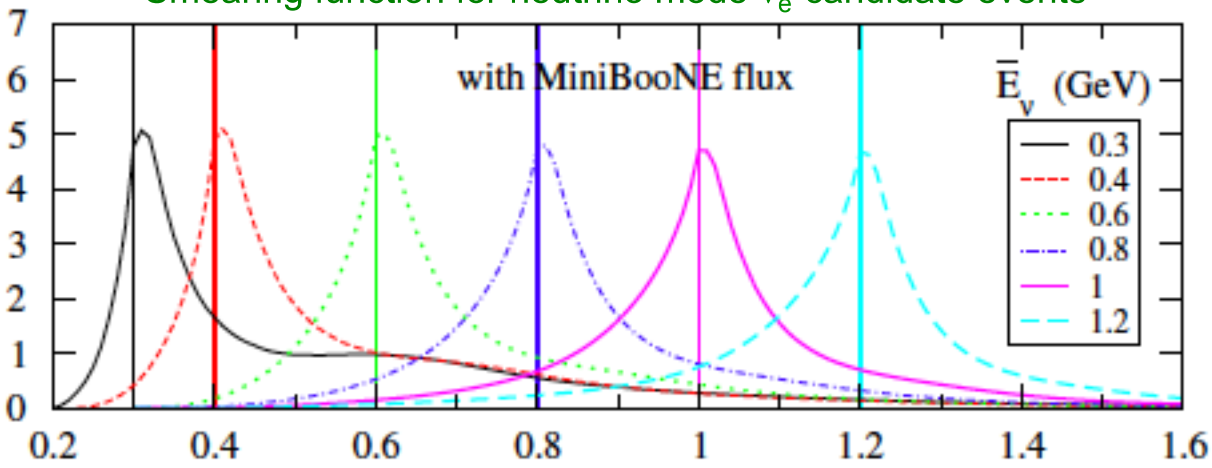
We mimic this effect by applying same probability function from Martini et al paper in our reconstructed ν_e energy distribution both data and MC, then fit again.

Smearing function for neutrino mode ν_e-candidate events



Martini et al,PRD85(2012)093012, Lalakulich et al,PRC86(2012)054606, Nieves et al,PRD85(2012)113008
MiniBooNE collaboration,PRL110(2013)161801

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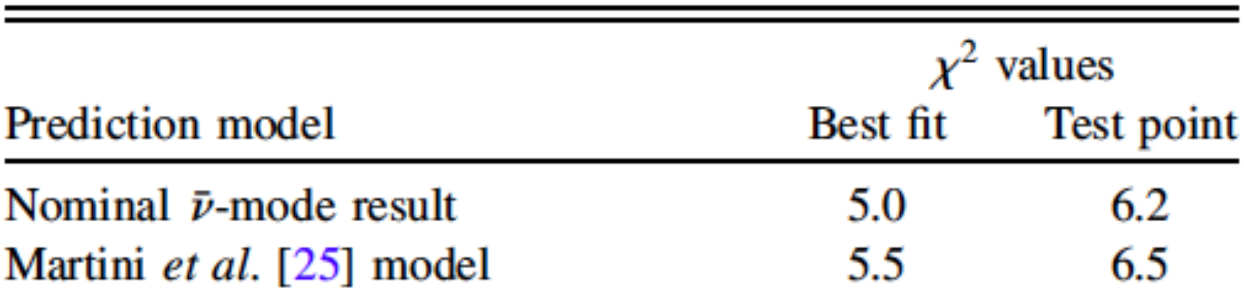
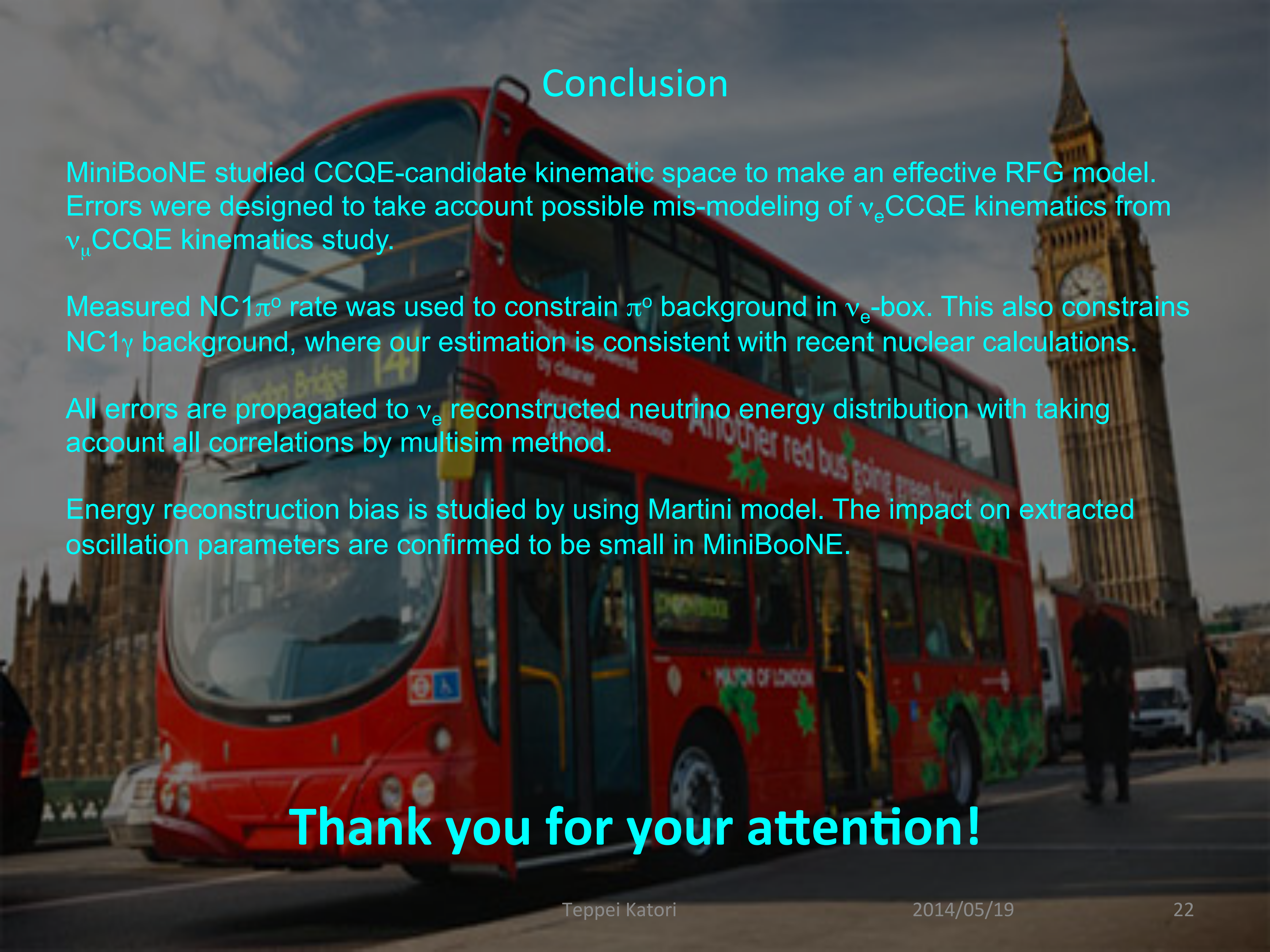
We mimic this effect by applying same probability function from Martini et al paper in our reconstructed ν_e energy distribution both data and MC, then fit again.

The fit results are consistent without smearing. This confirms energy mis-reconstruction does not change the oscillation parameters extracted from MiniBooNE ν_e and anti-ν_e candidate data.



	χ^2 values	
Prediction model	Best fit	Test point
Nominal $\bar{\nu}$-mode result	5.0	6.2
Martini *et al.* [25] model	5.5	6.5



Conclusion

MiniBooNE studied CCQE-candidate kinematic space to make an effective RFG model. Errors were designed to take account possible mis-modeling of ν_eCCQE kinematics from ν_μCCQE kinematics study.

Measured NC1π^o rate was used to constrain π^o background in ν_e-box. This also constrains NC1γ background, where our estimation is consistent with recent nuclear calculations.

All errors are propagated to ν_e reconstructed neutrino energy distribution with taking account all correlations by multisim method.

Energy reconstruction bias is studied by using Martini model. The impact on extracted oscillation parameters are confirmed to be small in MiniBooNE.

Thank you for your attention!

backup

1. MiniBooNE neutrino oscillation search experiment

Signal is single isolated electron-like Cherenkov ring from electron (anti)neutrino CCQE interaction

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + e^-(\text{Cherenkov})$$

$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow n + e^+(\text{Cherenkov})$$

MiniBooNE does not observe out going nucleons in CC interactions, then CCQE is defined "1 charged lepton+0 pion+ N protons".

Neutrino energy reconstruction

Eν is reconstructed from measured kinematics (energy and angle) of charged lepton, by assuming CCQE interaction and target nucleon at rest (QE assumption)

ν_e-misID background

MiniBooNE Cherenkov detector cannot distinguish electron (positron) and gamma ray. Then the major ν_e-misID background is single gamma ray from NC interactions, such as NC π^o production (NC1π^o) and NC single gamma production (NC1γ)

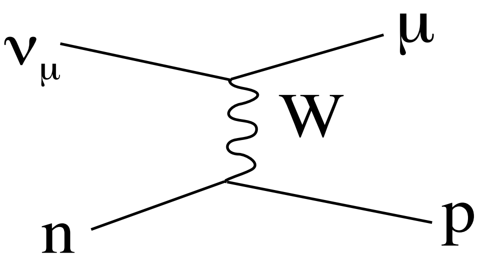
2. MiniBooNE ν_μCCQE measurement

MiniBooNE CCQE definition

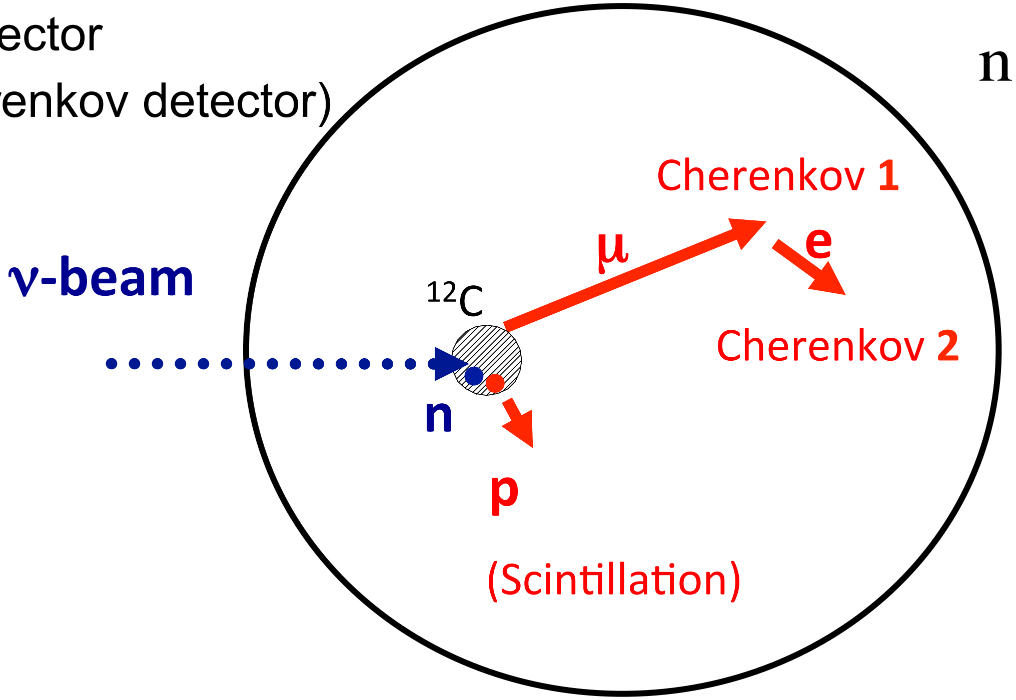
ν_μ charged current quasi-elastic (ν_μCCQE) interaction is an important channel for the neutrino oscillation physics and the most abundant (~40%) interaction type in MiniBooNE detector

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

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



MiniBooNE detector
(spherical Cherenkov detector)



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

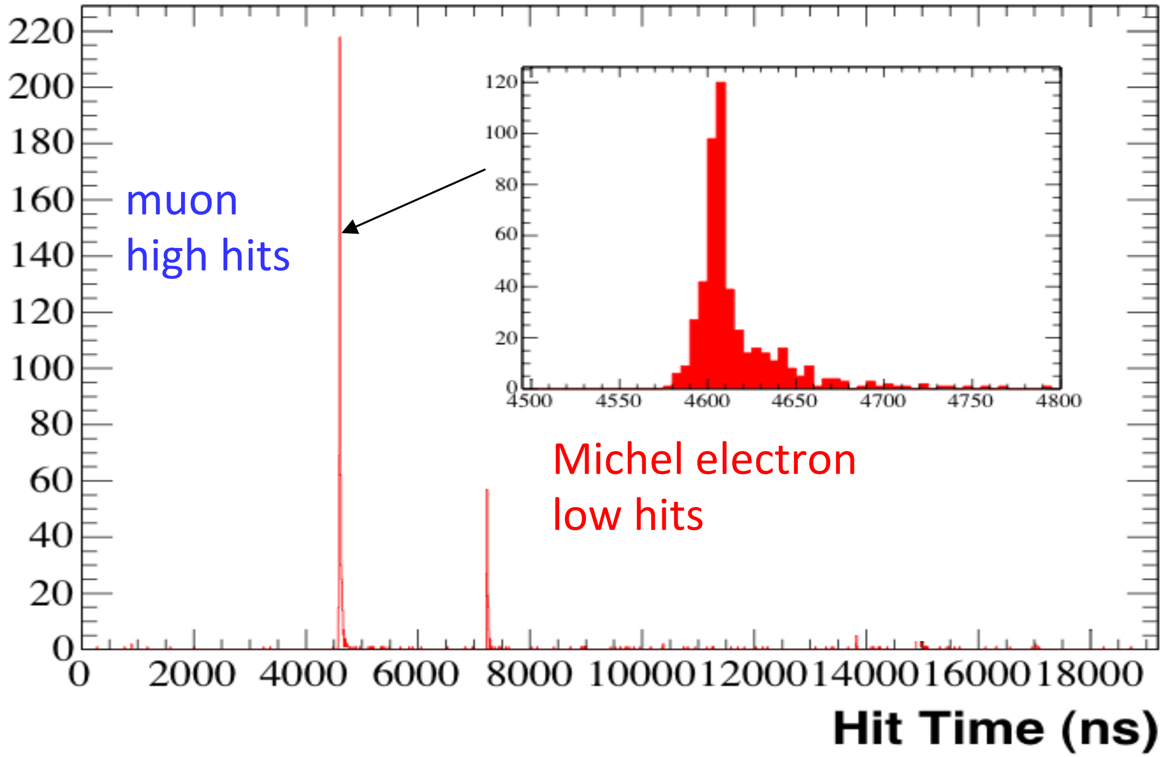
2. MiniBooNE ν_μCCQE measurement

MiniBooNE CCQE definition

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

$$\nu_\mu + n \rightarrow \overset{1}{\boxed{\mu^-}} + p \rightarrow \nu_\mu + \overline{\nu}_e + \overset{2}{\boxed{e^-}} + p$$

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



2. Neutrino experiment

Experiment measure the interaction rate R,

$$R \sim \int \Phi \times \sigma \times \varepsilon$$

- Φ : neutrino flux
- σ : cross section
- ε : efficiency

When do you see data-MC disagreement, how to interpret the result?

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

2. Relativistic Fermi Gas (RFG) model

Nucleus is described by the collection of incoherent Fermi gas particles.

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

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

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

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

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

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

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

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

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

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

MiniBooNE tuned following 2 parameters using Q^2 distribution by least χ^2 fit;

M_A = effective axial mass

κ = effective Pauli blocking parameter

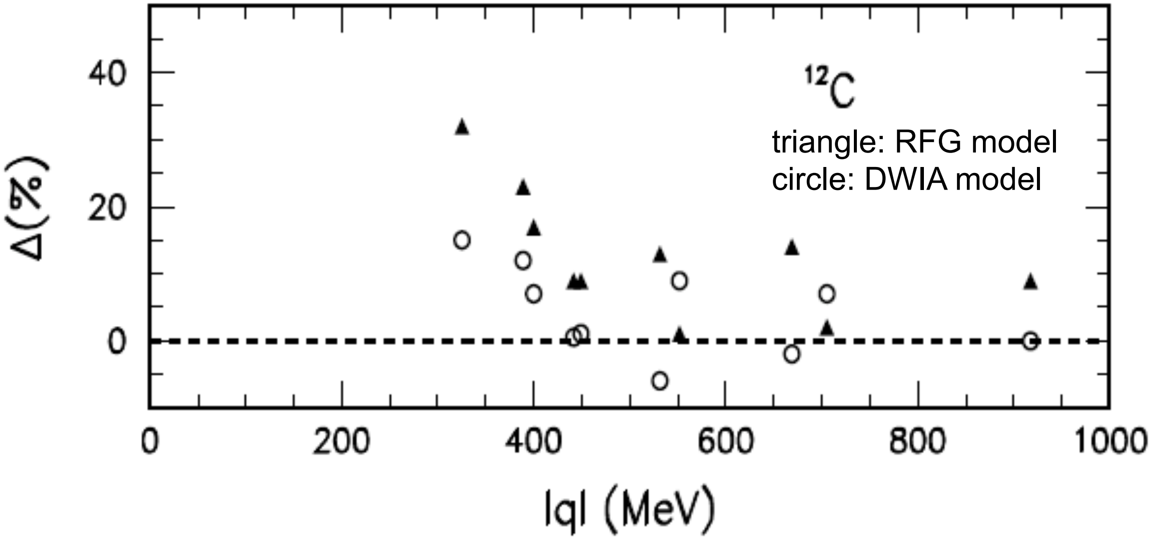
Butkevich and Mikheyev,PRC72(2005)025501

2. Relativistic Fermi Gas (RFG) model

Relativistic Fermi Gas (RFG) Model
Nucleus is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

In low |q|, The RFG model systematically over predicts cross section for electron scattering experiments at low |q| (~low Q^2)

Data and predicted xs difference for ^{12}C



Butkevich and Mikheyev,PRC72(2005)025501

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RFG prediction-(e,e') data ratio in Q^2 (GeV^2)