QE kinematics

1. Introduction
2. MiniBooNE pahse space study
3. T2K phase space study
4. Conclusion

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Queen Mary University of London
Valencia Neutrino Interaction T2K meeting (VANISh)
University of Valencia, Valencia, Spain, Apr. 3, 2014

1. Introduction

2. MiniBooNE phase space study

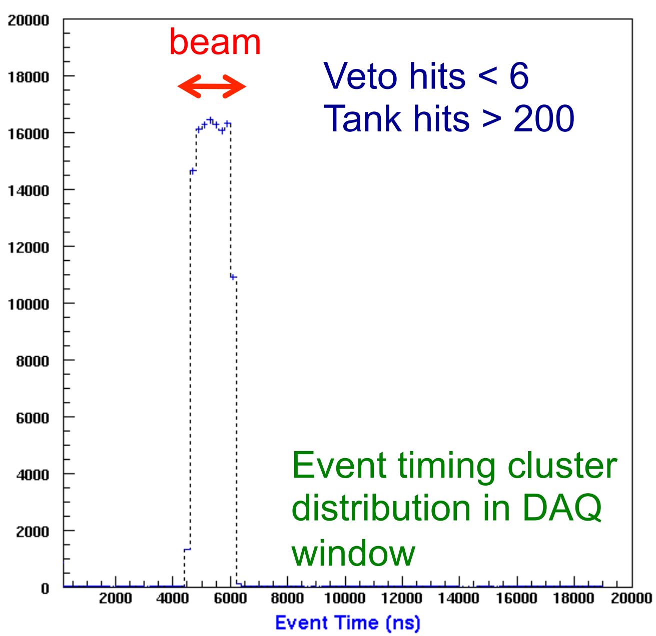
3. T2K phase space study

4. Conclusion

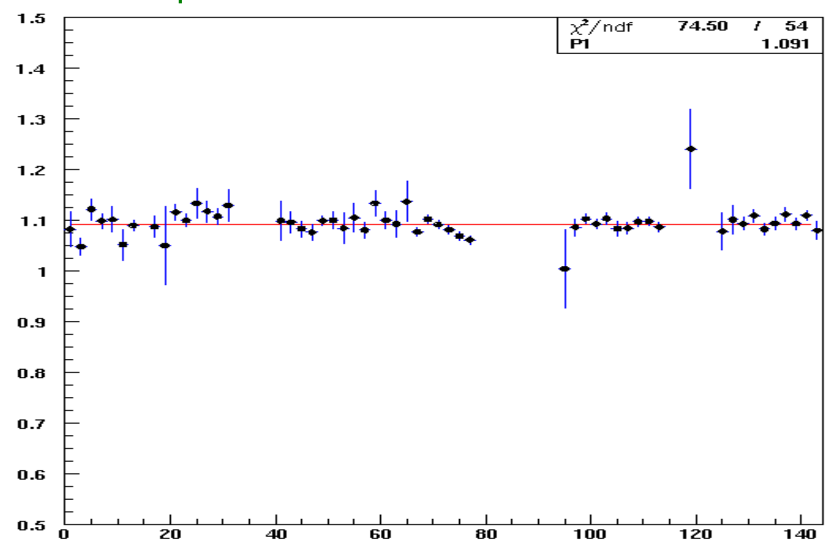
1. Introduction

MiniBooNE detector

- 800 MeV (700 MeV) neutrinos from Booster neutrino beamline at Fermilab.
- 12m diameter (10m fiducial) spherical Cherenkov detector filled with mineral oil (CH_2).
- CC interaction is isolated by veto hits <6 and tank hits > 200.
- Ring pattern is used for particle ID.
- Roughly 1 neutrino interaction per minute for 5E16 proton per hour (neutrino mode).



Event per 1E15POT vs Week



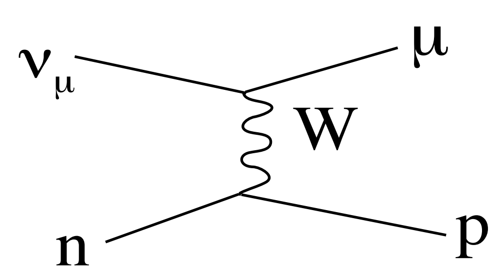
1. Introduction

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

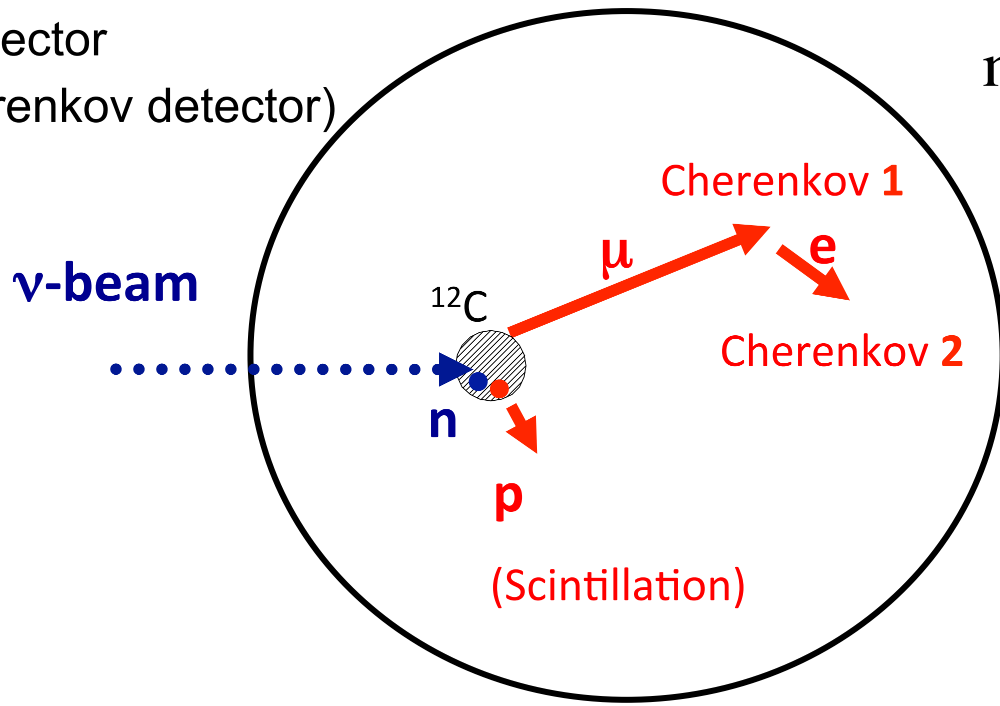
$$\nu_\mu + n \rightarrow p + \mu^-$$

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



MiniBooNE detector

(spherical Cherenkov detector)



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

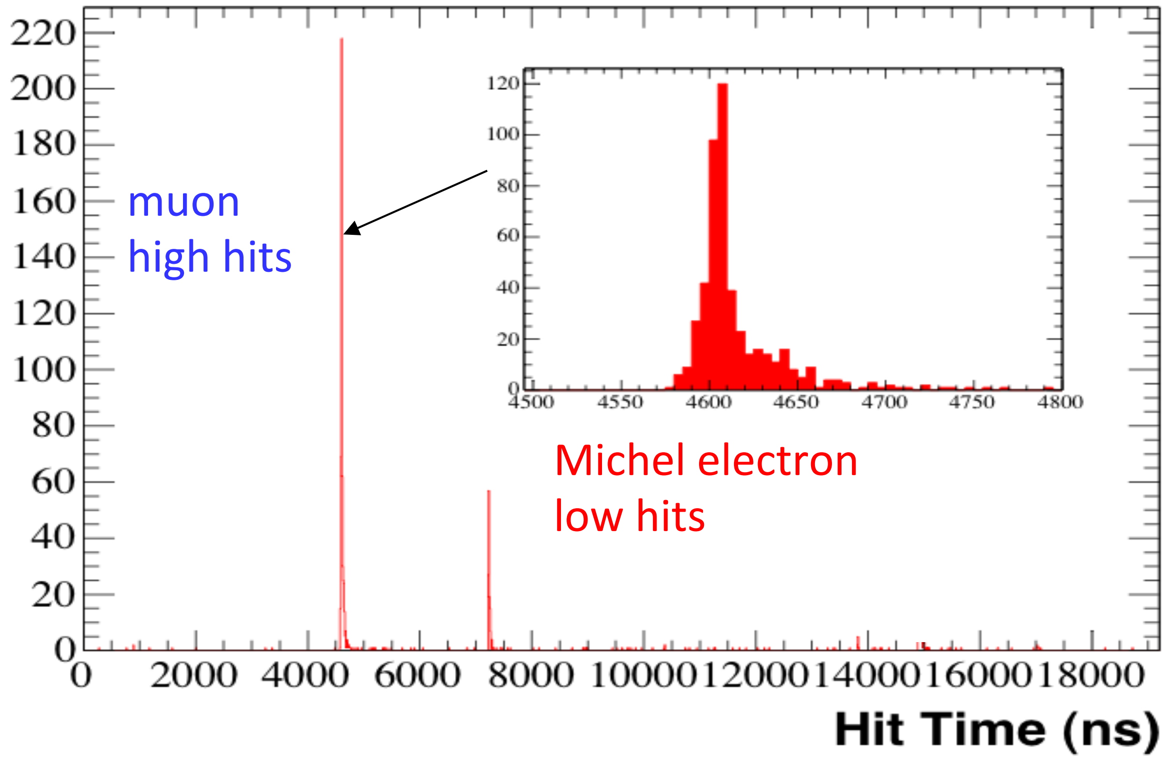
1. Introduction

MiniBooNE CCQE definition

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

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

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



1. Introduction

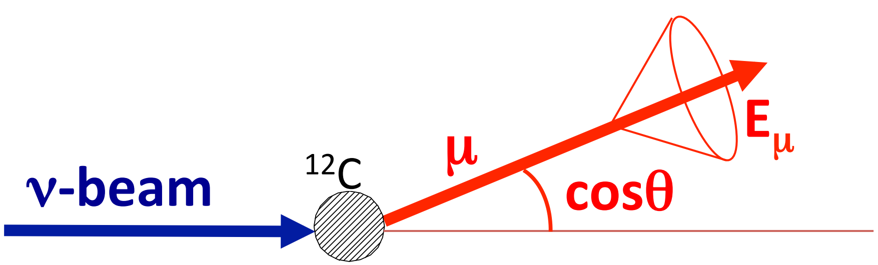
MiniBooNE CCQE observables

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

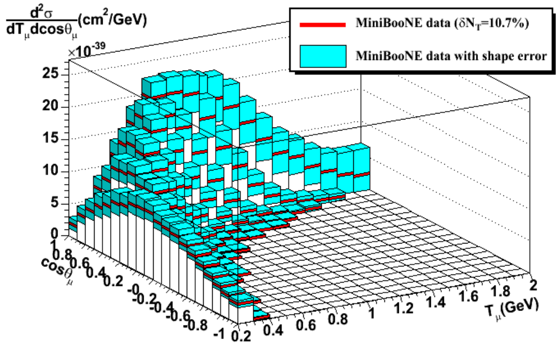
Energy of the neutrino E_ν^{QE} and 4-momentum transfer Q^2_{QE} can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest ("QE assumption")

$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$

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



1. Overview of MiniBooNE xs measurements



MiniBooNE collaboration,
PRD81(2010)092005

CCQE (CC0π)
PRD81(2010)092005
FERIMILAB-THESIS-2008-64

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

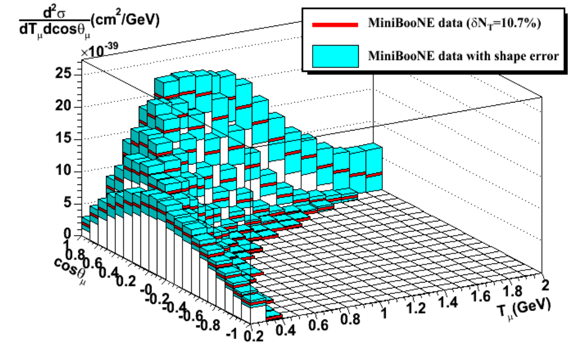
$$(\nu_\mu + {}^{12}C \rightarrow X + \mu^-)$$

Signal definition: 1 μ + 0 π + N protons

Why we measure
- Test CCQE models

Why MiniBooNE measure
- Largest sample (~40%) to test detector efficiency, veto efficiency, event uniformity, timing, etc
- Best sample to study ν_eCCQE kinematics (=oscillation signal)
- ν_μCCQE to constraint ν_e from μ-decay in oscillation sample

It is important to measure CCQE!



MiniBooNE collaboration, PRD81(2010)092005

1. Overview of MiniBooNE xs measurements

MiniBooNE CCQE basics

- high statistics
- high purity
- error dominated by flux (as usual)

integrated protons on target		5.58×10^{20}
energy-integrated ν_μ flux		$2.88 \times 10^{11}\ \nu_\mu/\mathrm{cm}^2$
CCQE candidate events		146070
CCQE efficiency ($R < 550$ cm)		26.6%
background channel	events	fraction
NCE	45	<0.1%
$CC1\pi^+$	26866	18.4%
$CC1\pi^0$	3762	2.6%
$NC1\pi^\pm$	535	0.4%
$NC1\pi^0$	43	<0.1%
other ν_μ	328	0.2%
all non-ν_μ	1977	1.4%
total background	33556	23.0%

source	normalization error (%)
neutrino flux prediction	8.66
background cross sections	4.32
detector model	4.60
kinematic unfolding procedure	0.60
statistics	0.26
total	10.7

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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?

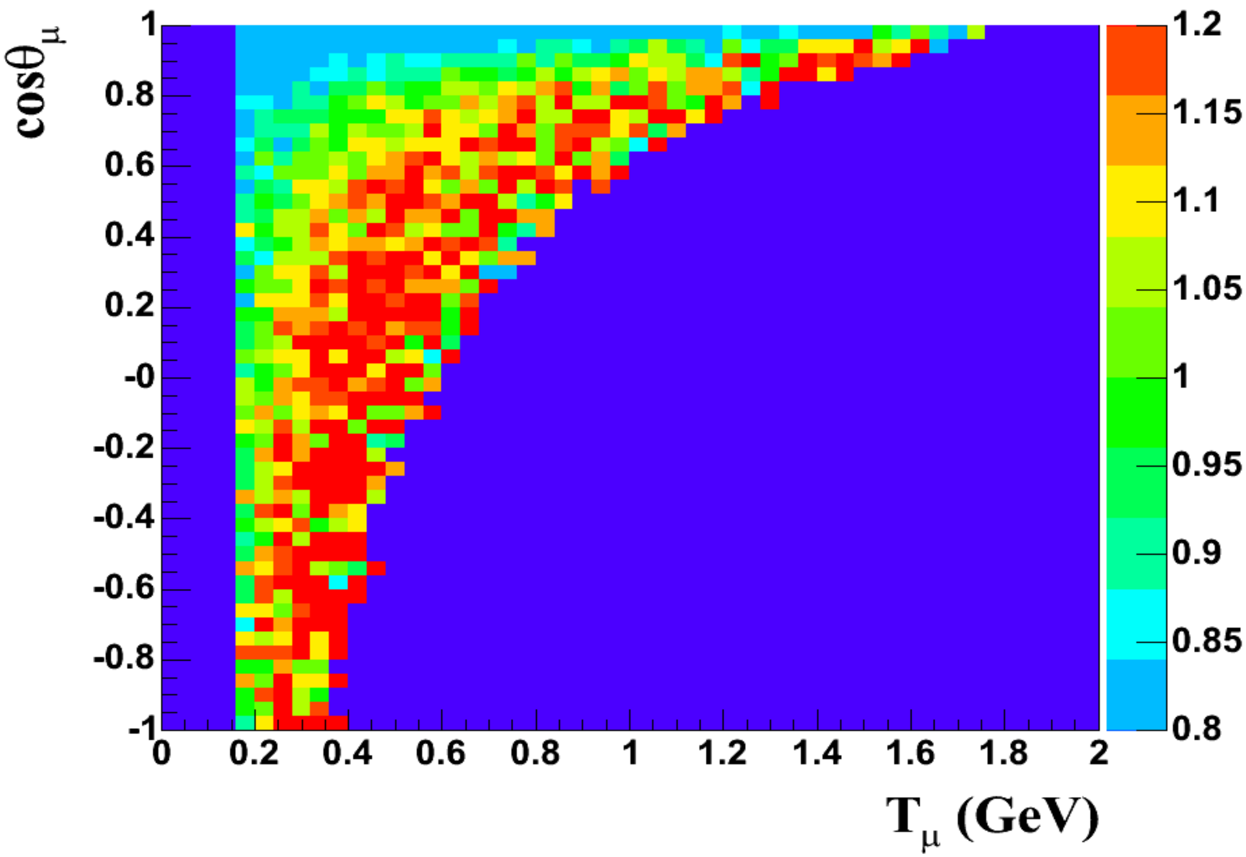
MiniBooNE collaboration,
PRL.100(2008)032301

2. MiniBooNE phase space

$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$

CCQE kinematic space (T_μ-$\cos\theta_\mu$ plane) in MiniBooNE

Since observables are muon energy (T_μ) and angle ($\cos\theta_\mu$), these 2 variables completely specify the kinematic space.



Data-MC ratio for T_μ-$\cos\theta_\mu$ plane (arbitrary normalization). MiniBooNE MC doesn't describe data very well.

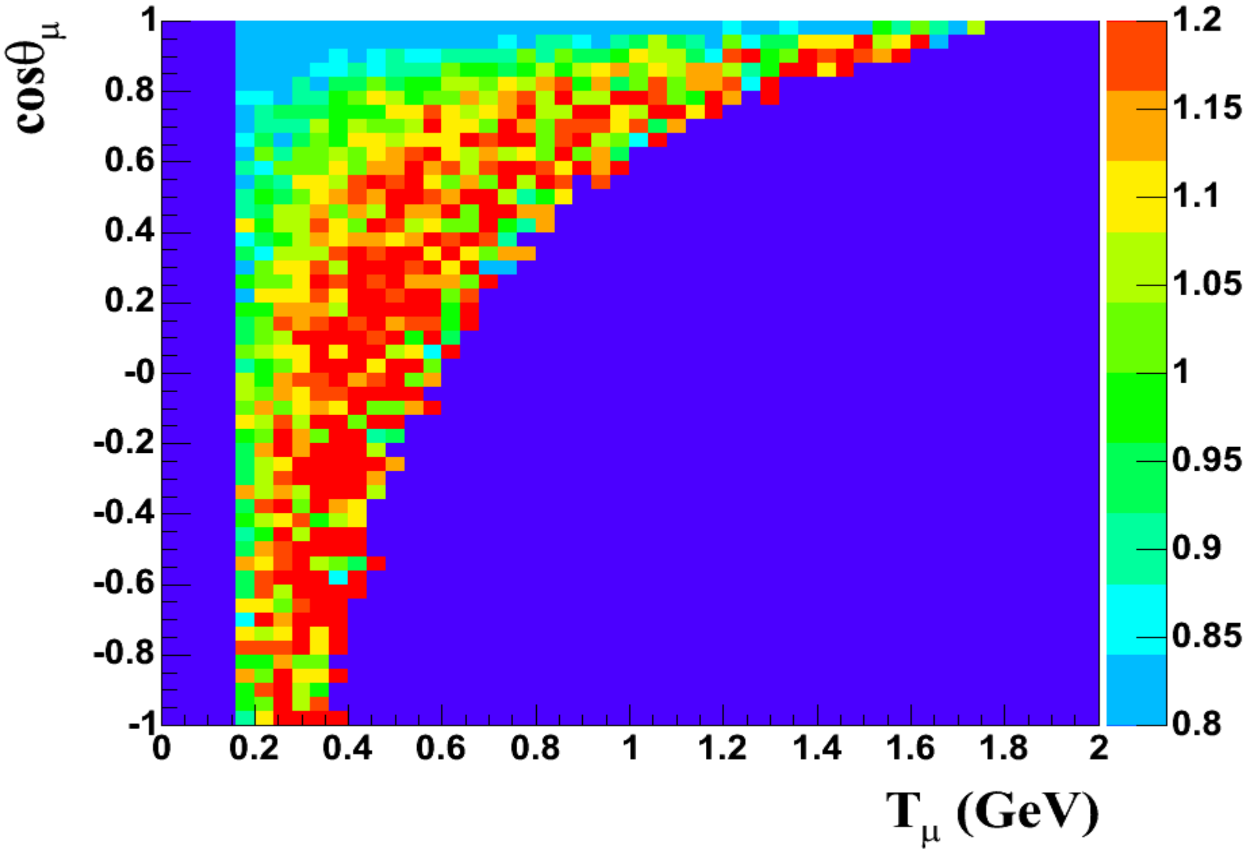
We would like to improve our simulation, but how?

MiniBooNE collaboration,
PRL.100(2008)032301

2. MiniBooNE phase space

Without knowing flux, you cannot modify cross section model

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

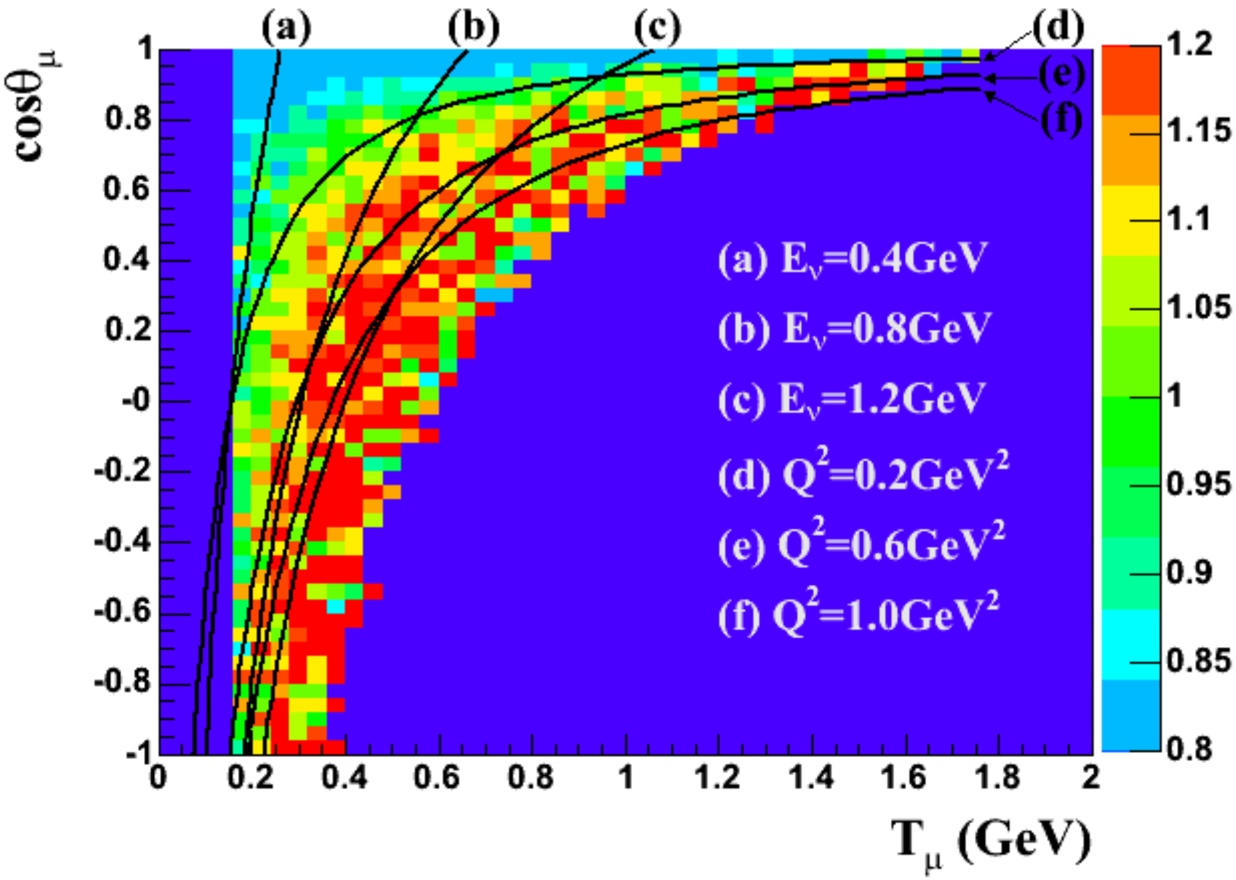


MiniBooNE collaboration,
PRL.100(2008)032301

2. MiniBooNE phase space

Without knowing flux, you cannot modify cross section model

$$R(E_\nu, Q^2) \sim \int \Phi(E_\nu) \times \sigma(Q^2)$$



The data-MC disagreement follows equal Q^2- lines, not equal E_ν-lines.

→ Something wrong in cross section model, not flux model.

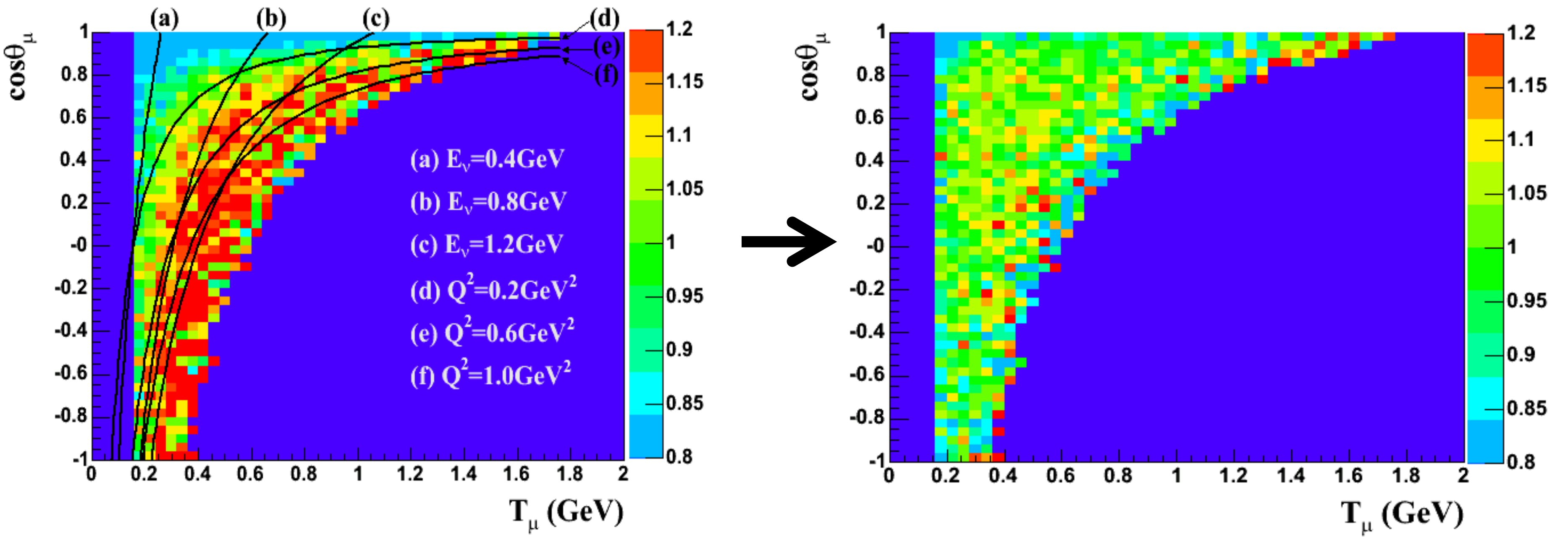
MiniBooNE collaboration,
PRL.100(2008)032301

2. MiniBooNE phase space

Without knowing flux, you cannot modify cross section model

$$R(E_\nu, Q^2) \sim \int \Phi(E_\nu) \times \sigma(Q^2)$$

After tuning cross section parameters, data and MC agree.



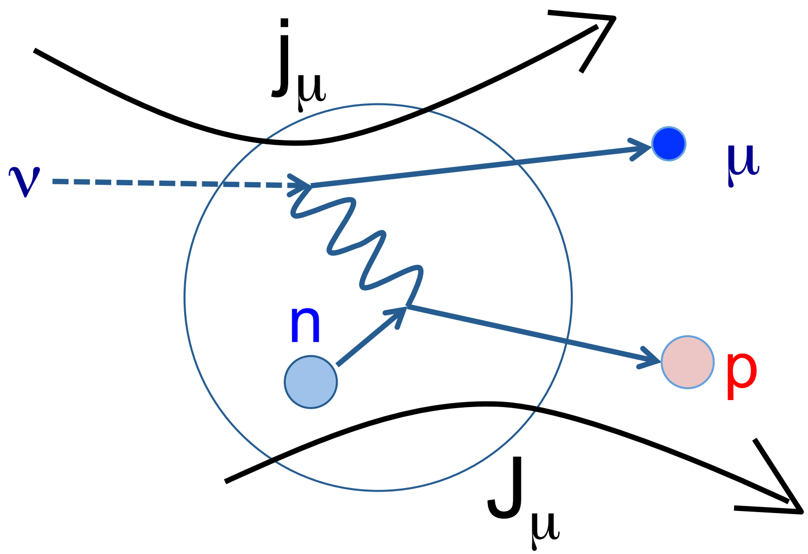
2. Cross section formula

Cross section formula

- product of Leptonic and hadronic tensor

$$d\sigma = \frac{\overline{|M^2|}}{F} dLips, \quad dLips = \frac{dQ^2}{16\pi M E_\nu}$$

$$\overline{|M^2|} = \frac{G_F^2}{4} \sum_{spin} J_\mu J_\nu^\dagger j^\mu j^{\nu\dagger} = \frac{G_F^2 \cos^2\theta_c}{4} W_{\mu\nu} L^{\mu\nu}$$



Question:
→ how to model $W_{\mu\nu}$?

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

2. Smith-Moniz formalism

Nucleus is described by the collection of incoherent nucleons.

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

Elo : the lowest energy state of nucleon

Although Smith-Moniz formalism offers variety of choice, one can solve this equation analytically if the nucleon space is simple.

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.

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

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

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

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

M_A = effective axial mass

κ = effective Pauli blocking parameter

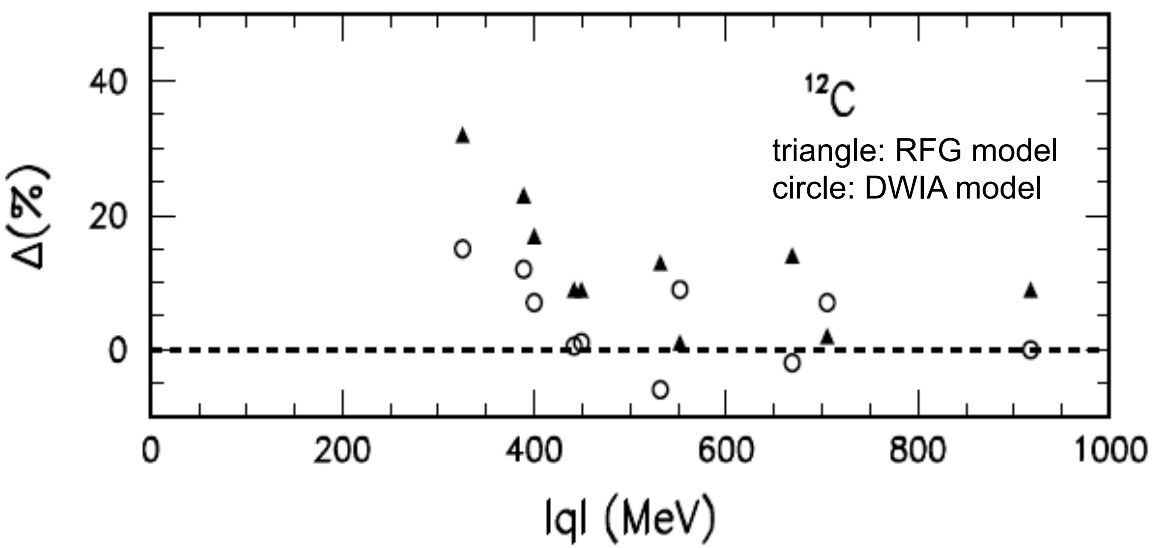
Butkevich and Mikheyev, PRC72(2005)025501

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



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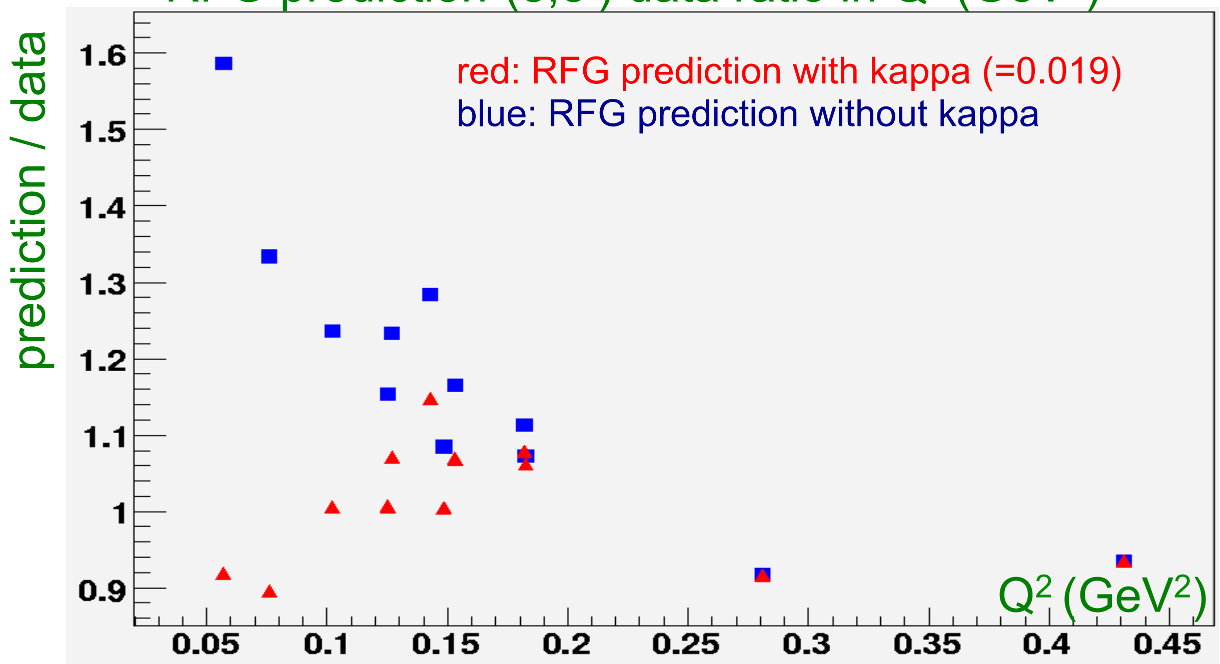
RFG prediction-(e,e') data ratio in Q^2 (GeV^2)



2. Summary

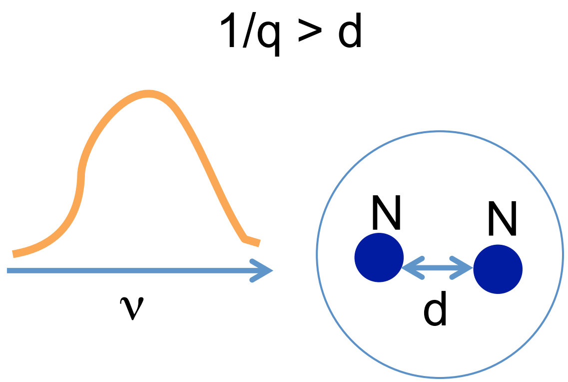
MiniBooNE studied kinematic space to disentangle flux and cross section effect.

Multi-dimentional distribution is very powerful to test underlining models (or find mistake)

Ankowski, Benhar, Farina,
PRD82(2010)013002

3. MiniBooNE phase space study

Violation of impulse approximation



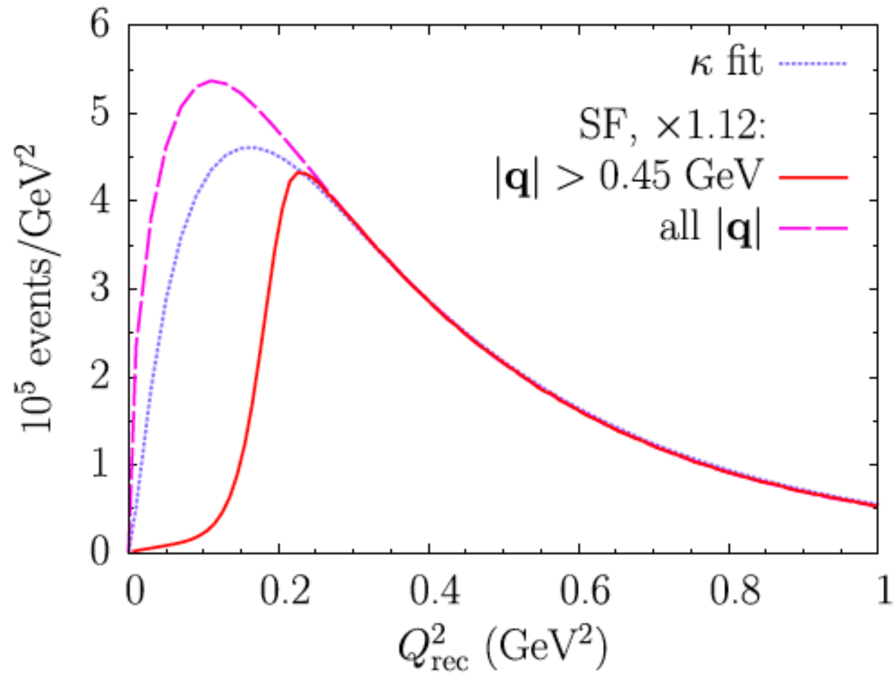


FIG. 6 (color online). Comparison of the MiniBooNE parametrization of the data (dotted line), labeled as the κ fit, to the spectral function calculation (dashed line). The solid line depicts the contribution to the latter from the region where the IA is expected to be valid. The SF results are multiplied by a factor 1.12 to make them match the κ fit.

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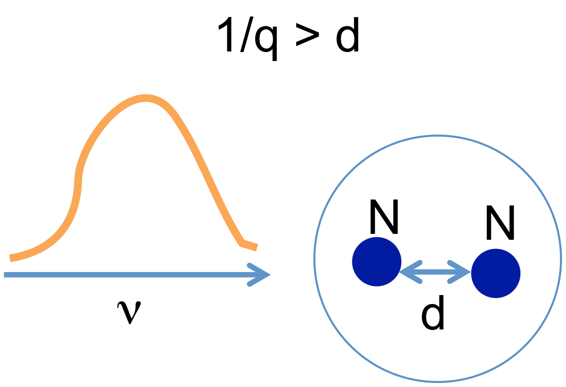
Juszczak,Sobczyk,Zmuda
PRC82(2010)045502

3. MiniBooNE phase space study

Violation of impulse approximation



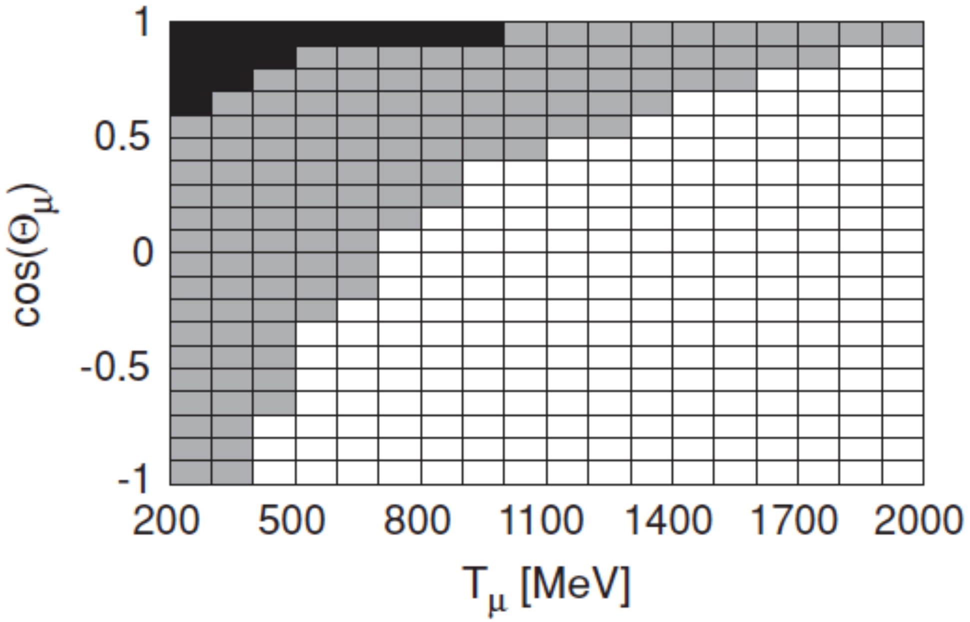
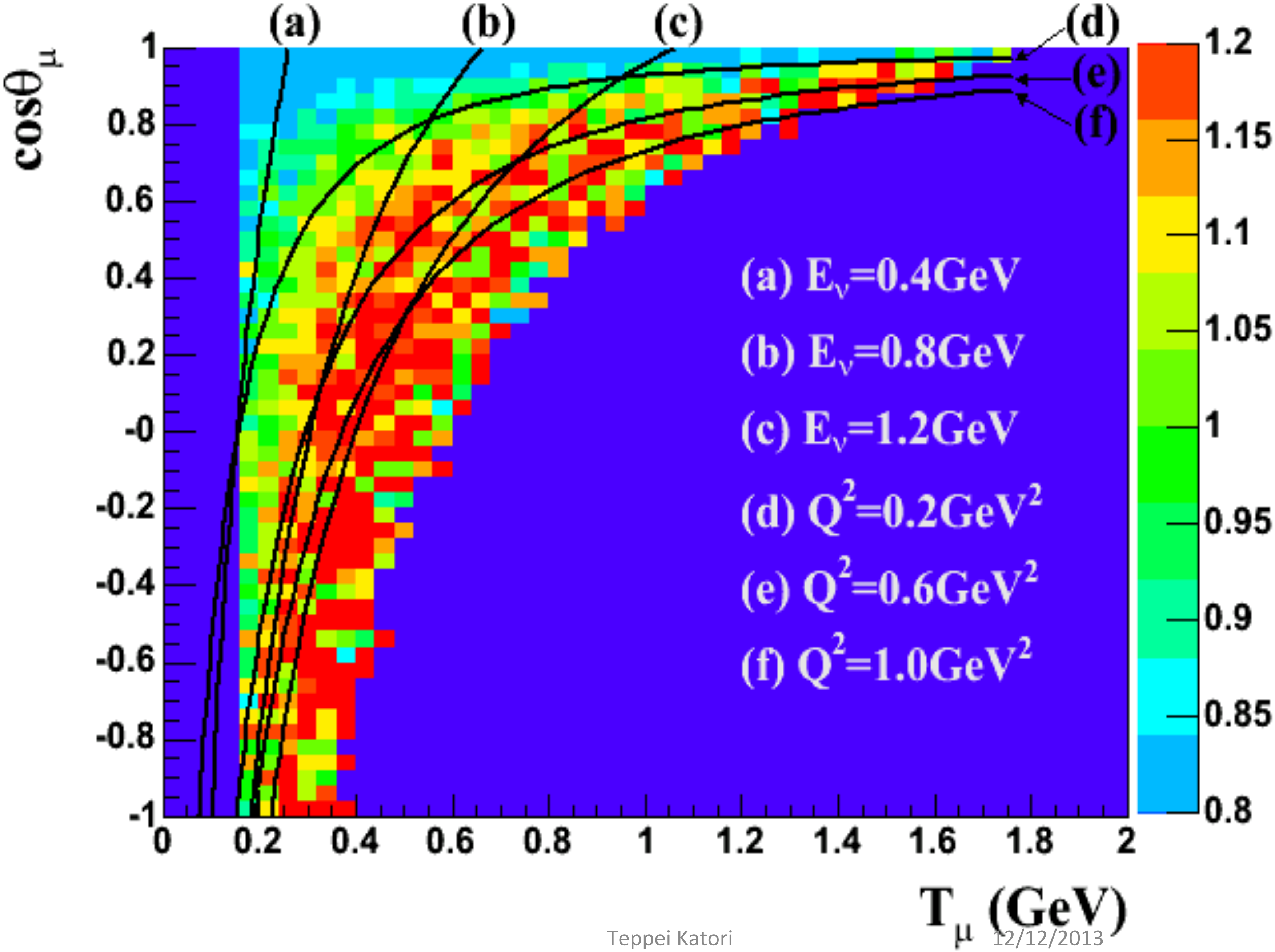
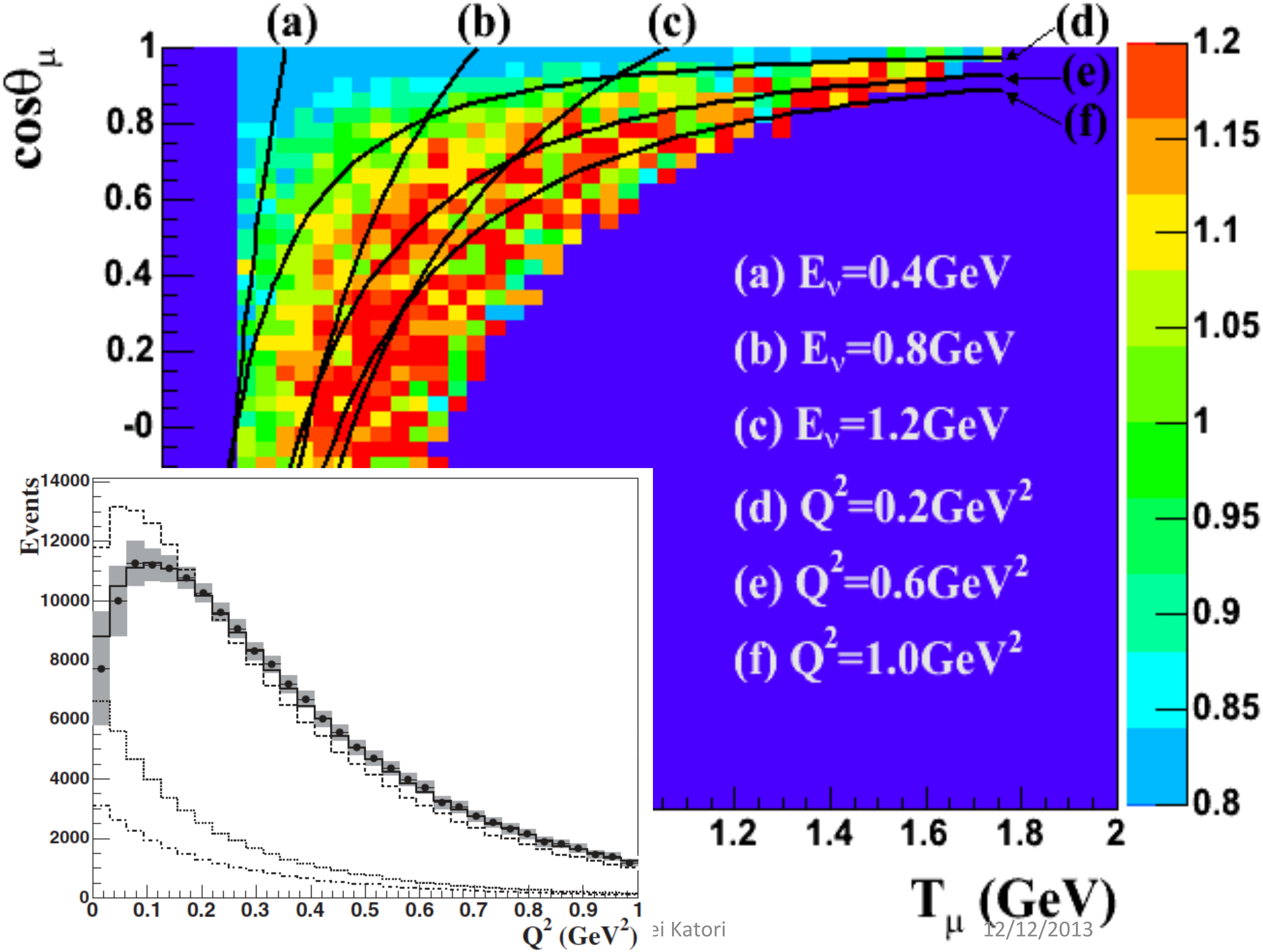


FIG. 3. Bins excluded from the fitting procedure for $q_{cut} =$ 400 MeV/c are shown in black. Bins with a nonzero cross section measured by MiniBooNE are shown in gray.

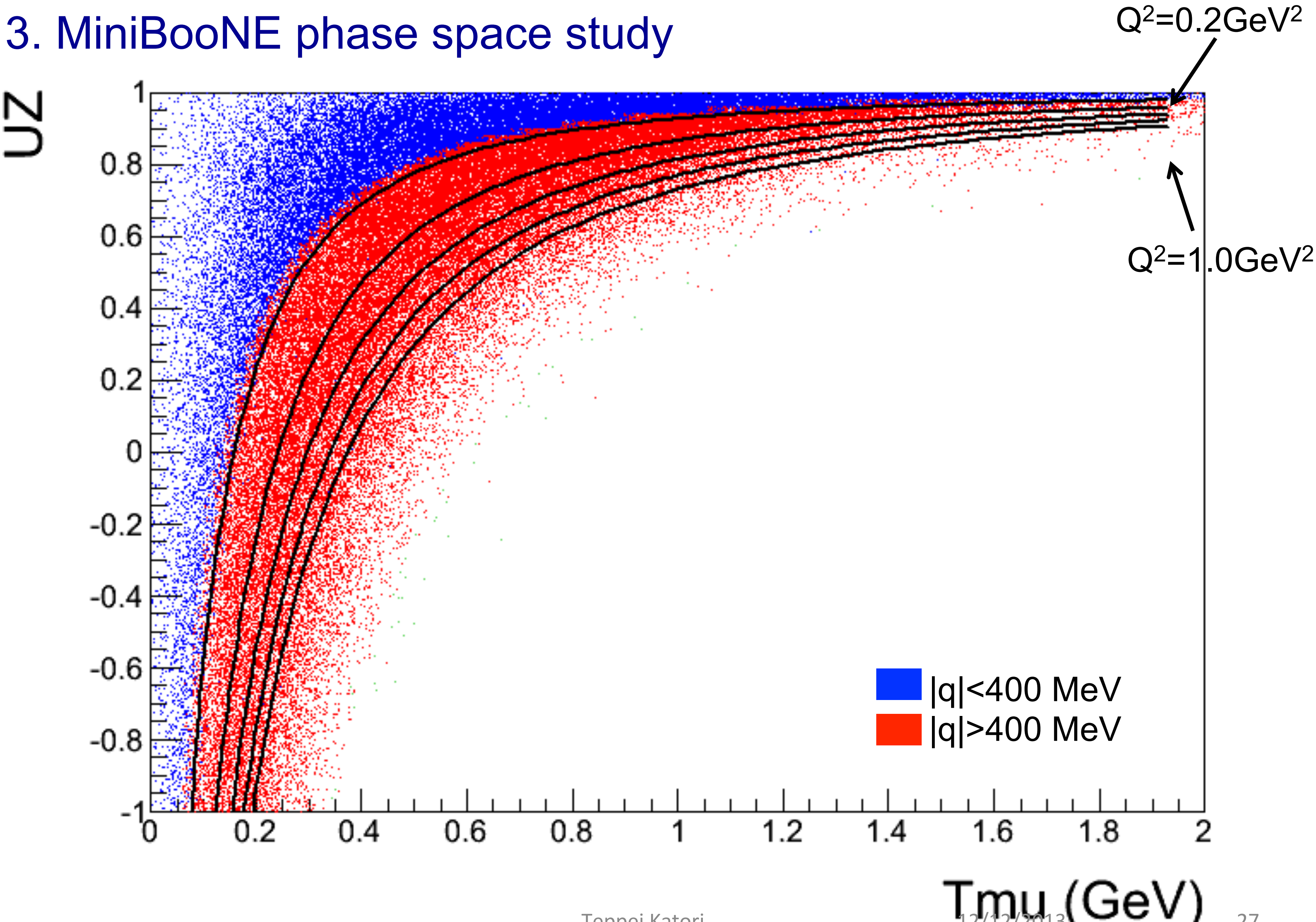
MiniBooNE,PRL100(2008)032301



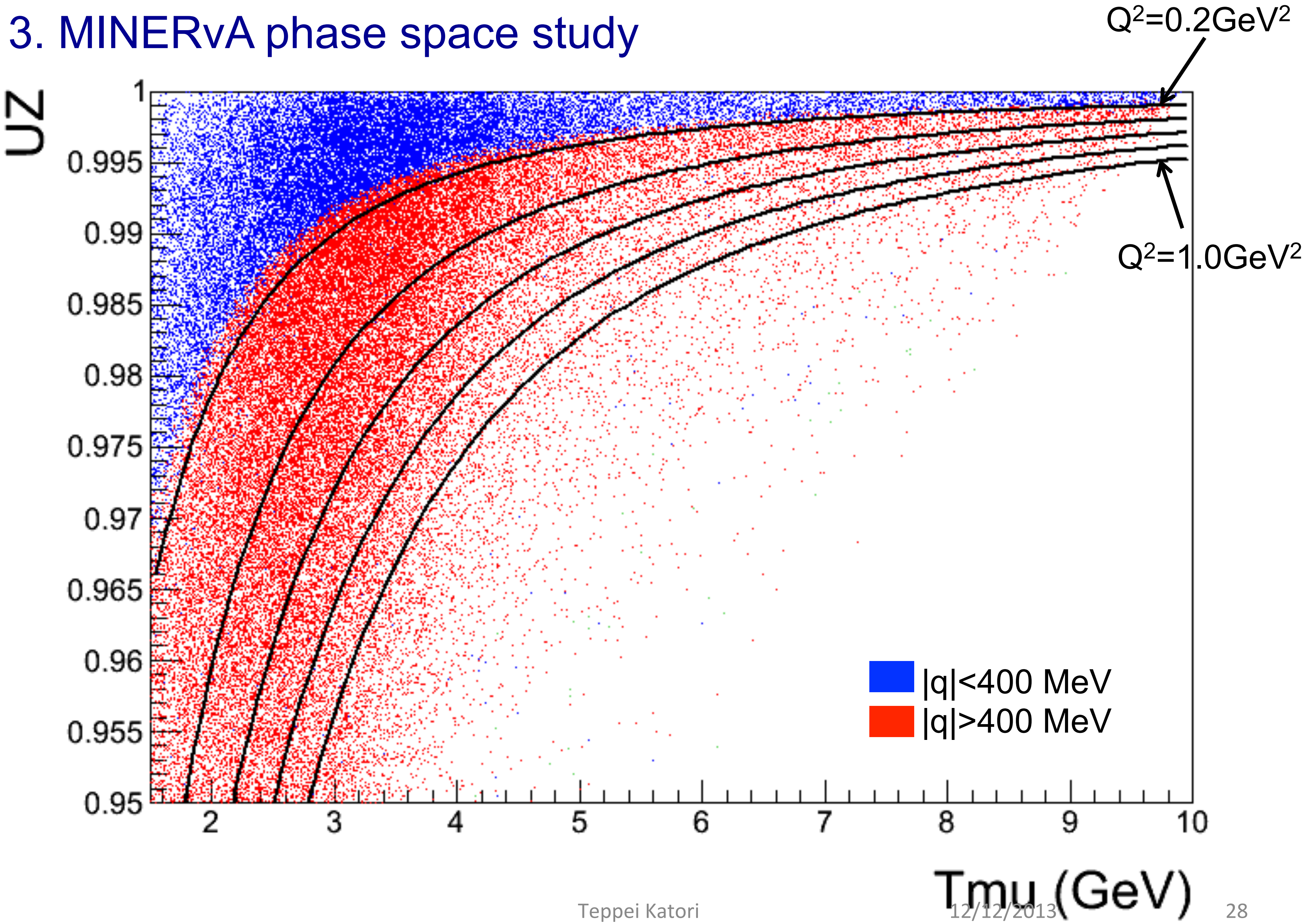
MiniBooNE,PRL100(2008)032301



3. MiniBooNE phase space study

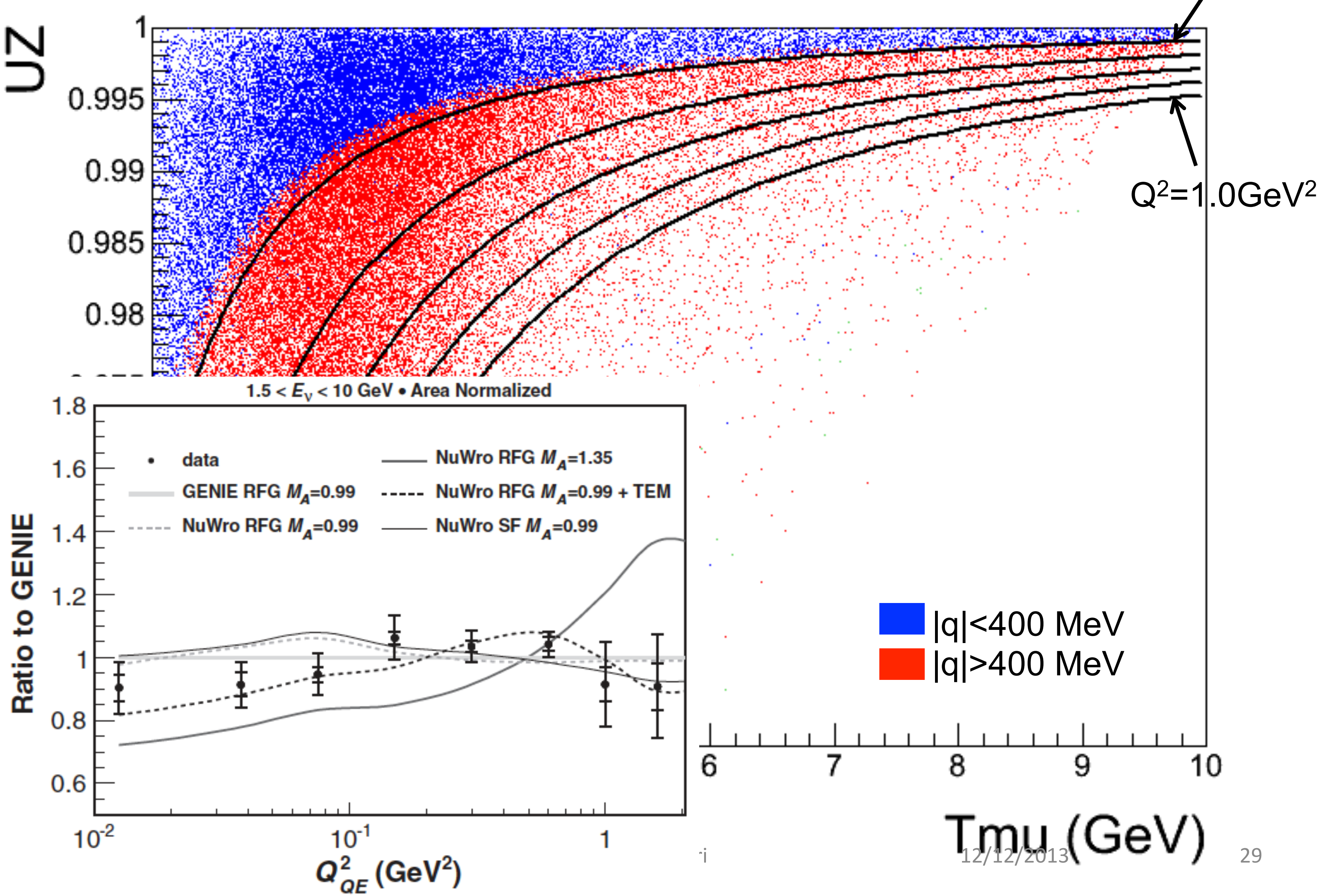


3. MINERvA phase space study

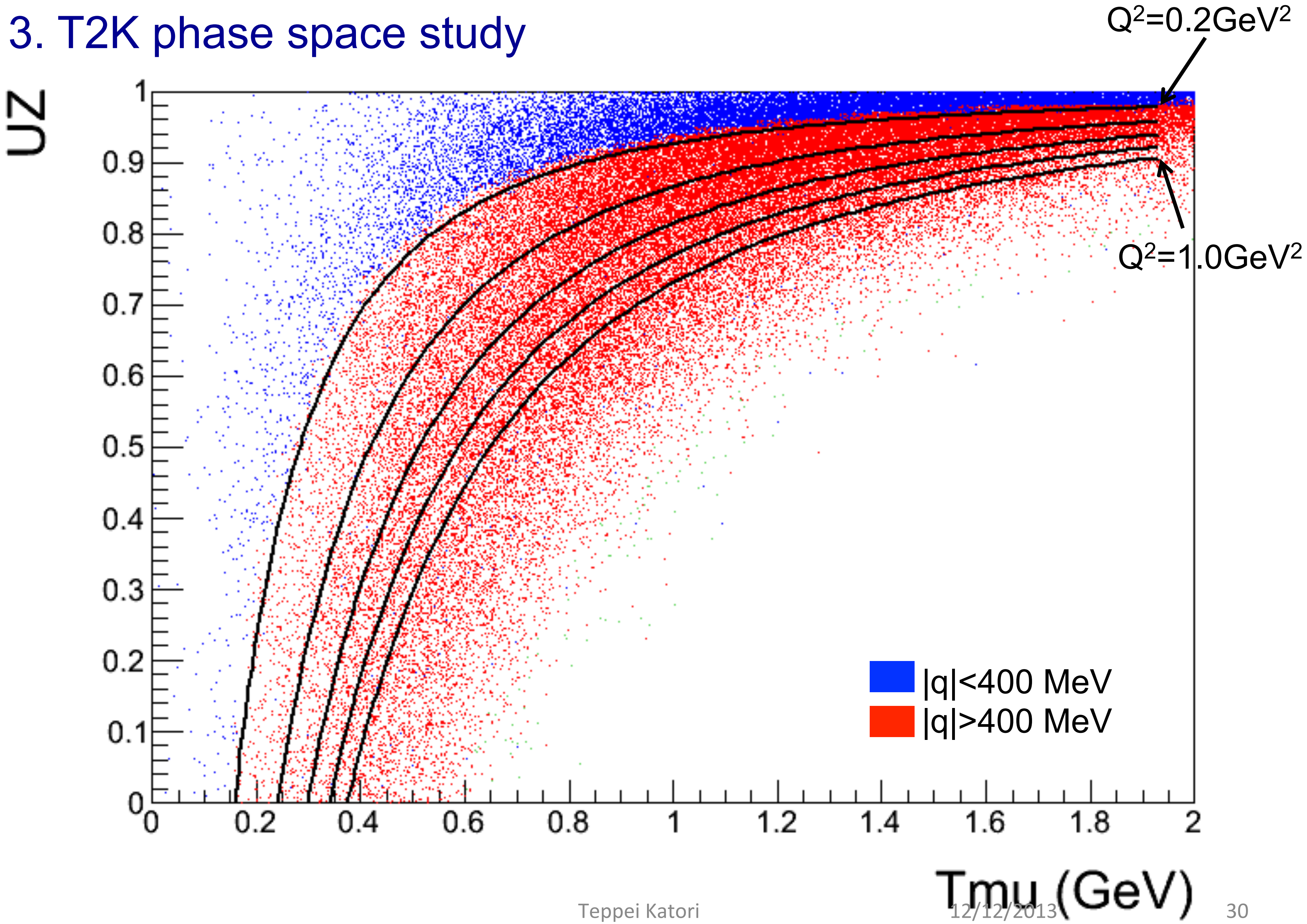


MINERvA,PRL111(2013)022502

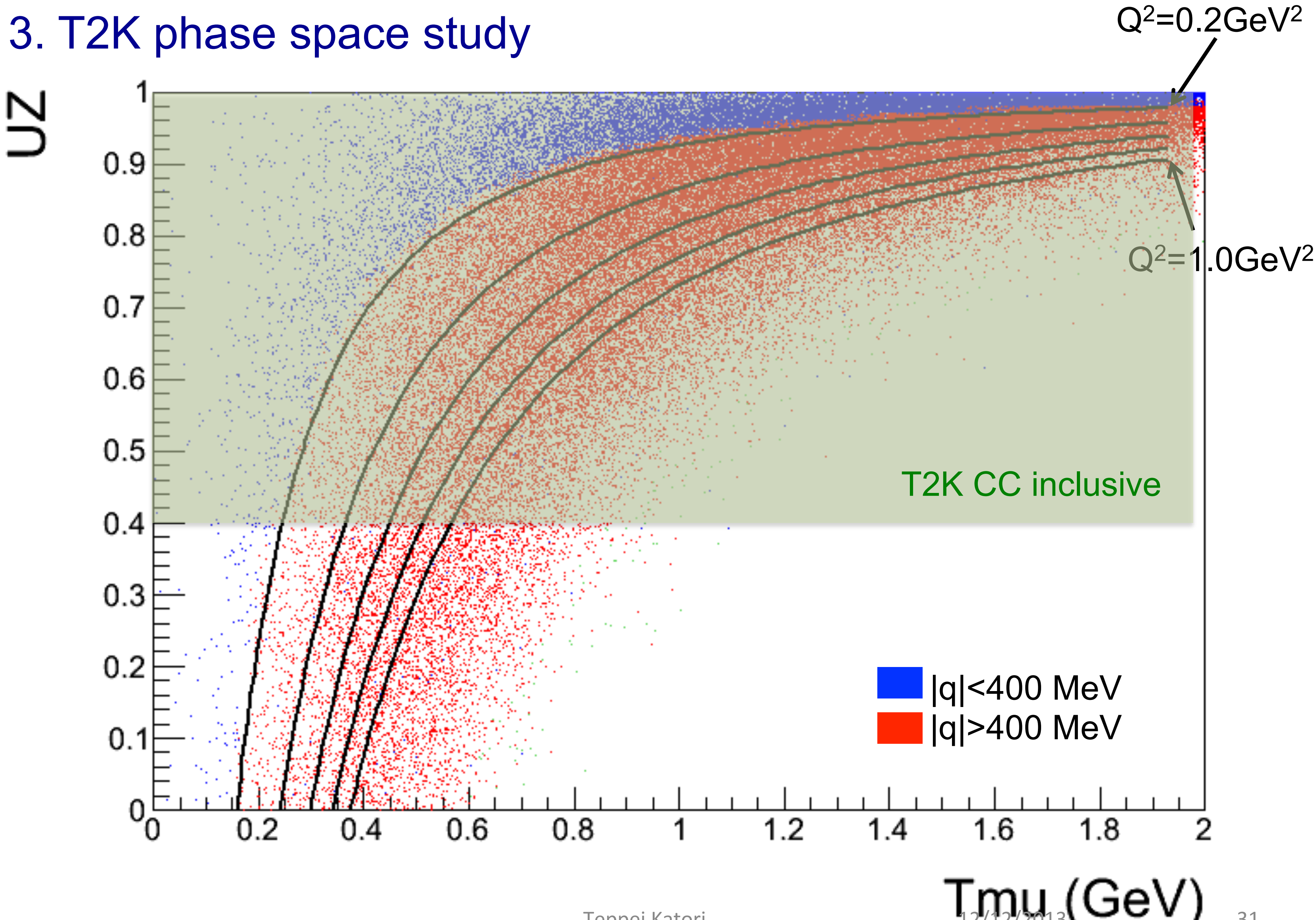
3. MINERvA phase space study



3. T2K phase space study



3. T2K phase space study



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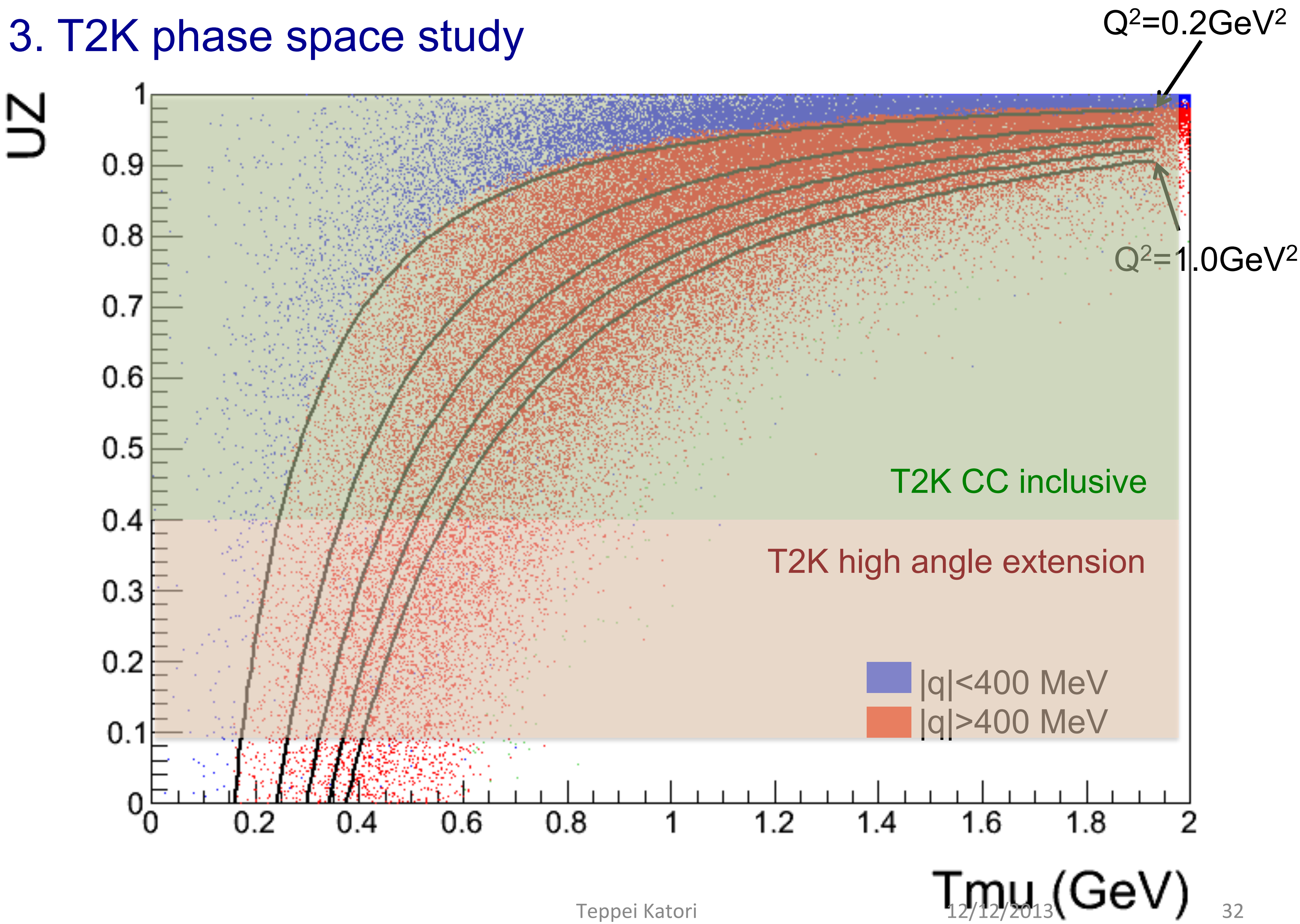

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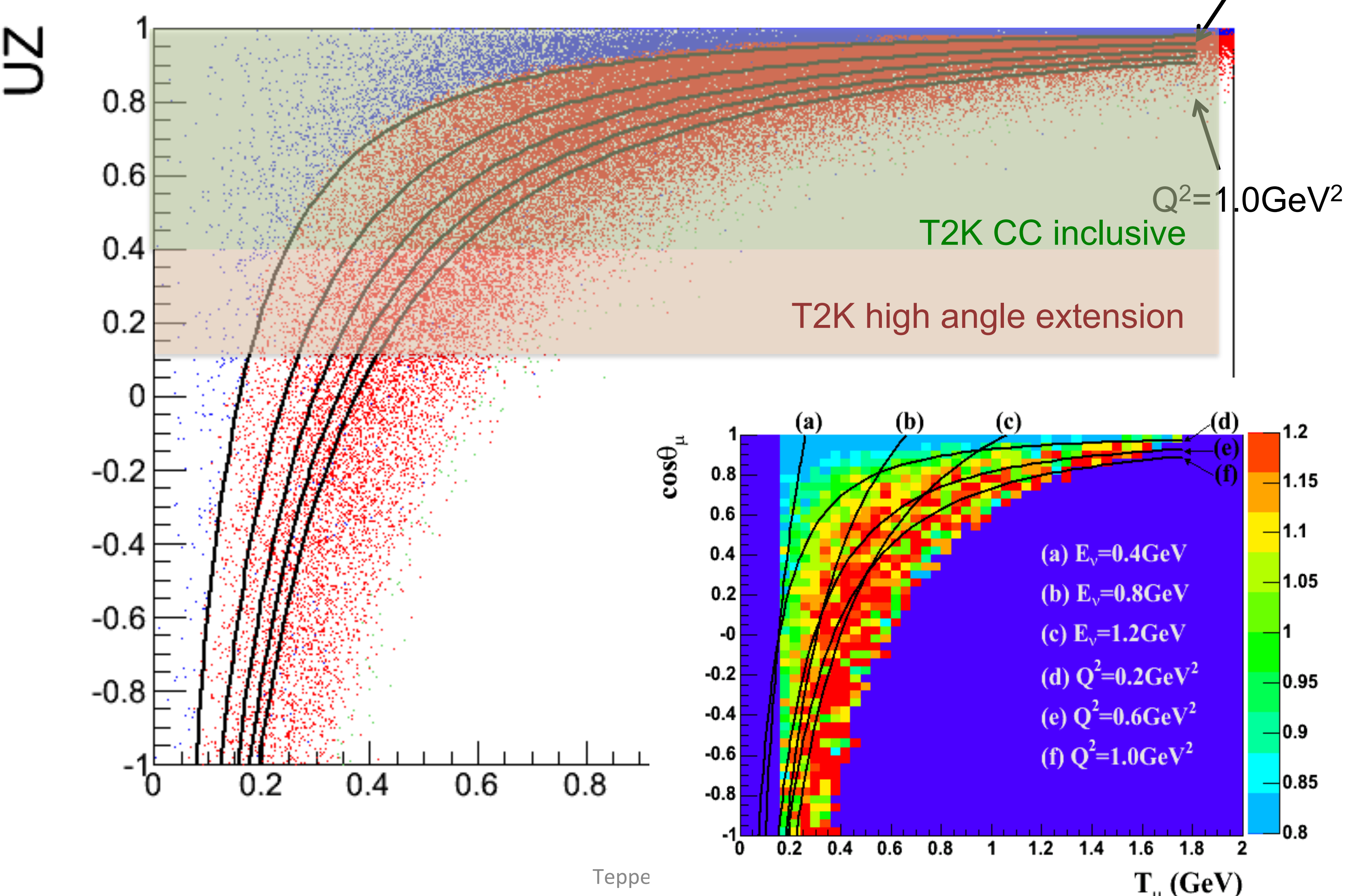

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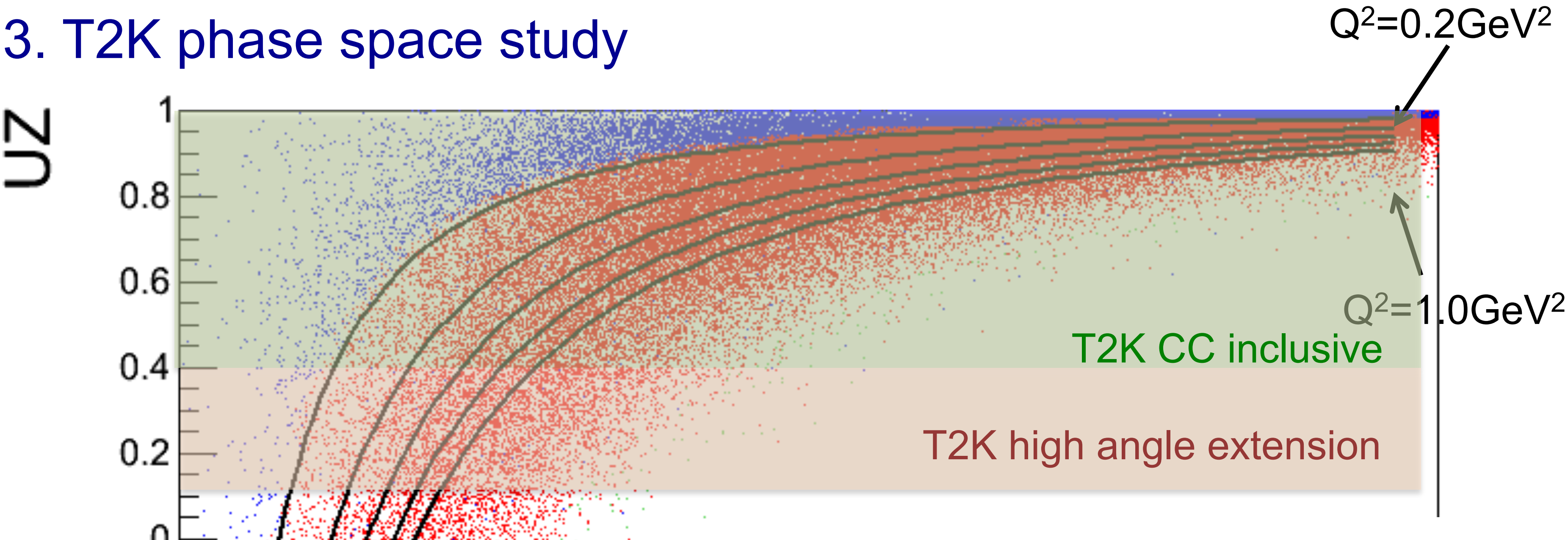
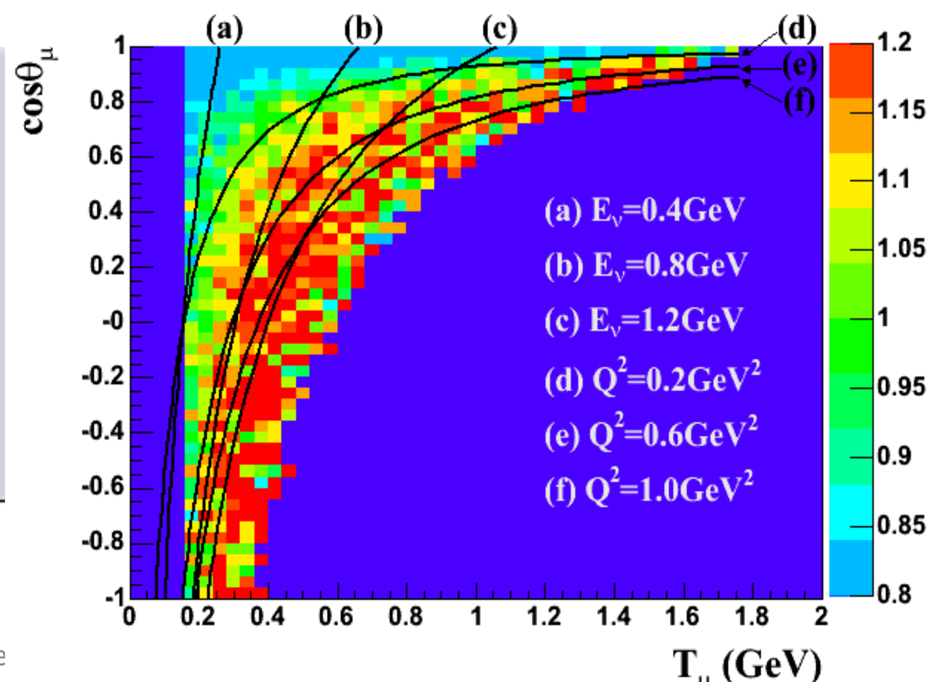




4. Conclusion

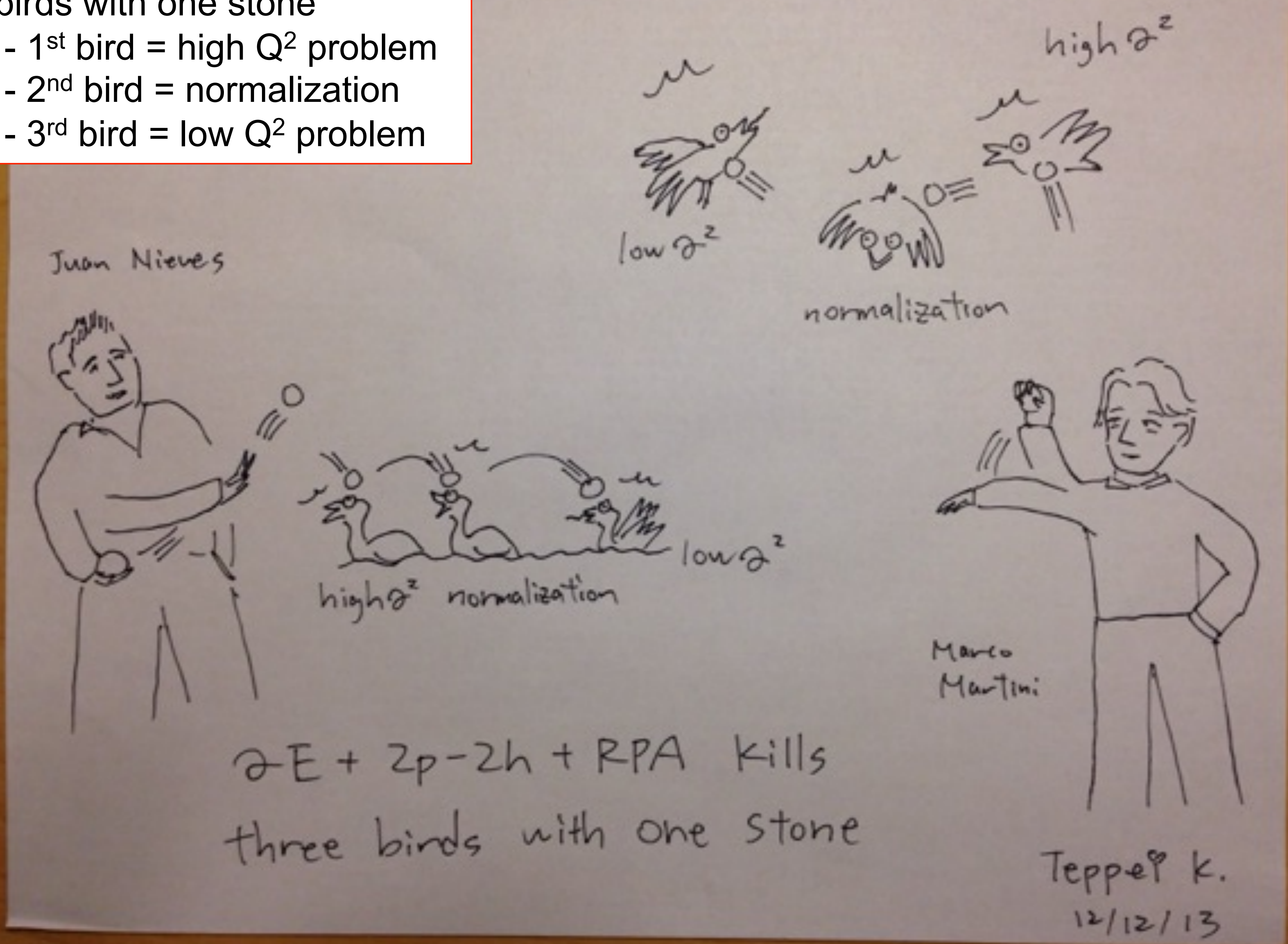
Theoretically MB/MINERvA/T2K phase space overlap each other. However Fermi motion and unknown effect can make Q^2 distribution strange. So measuring wider muon kinematic space seems to me the best test to check MB result.

Low Q^2 region ($Q^2<0.2$ GeV^2) corresponds to low 3 momentum transfer, where impulse approximation breaks down (including SF?).

Theoretical models working in low Q^2 region is essential (Nieves, Martini).

QE+2p-2h+RPA kills three birds with one stone

- 1st bird = high Q^2 problem
- 2nd bird = normalization
- 3rd bird = low Q^2 problem



Sachs, Phys.Rev.126(1962)2256

3. MiniBooNE phase space study

Violation of Sachs interpretation

- Dipole form factor is motivated by spherically symmetric exponential charge distribution.

$$\rho(r) = \rho_0 \exp(-Mr) \overset{Fourier}{\longleftrightarrow} G(|q|^2) \sim \frac{1}{\left(1+\frac{|q|^2}{M^2}\right)^2}.$$

This interpretation works only up to |q|<M~1GeV.
→ deviation from dipole form factor is necessary at high Q^2?