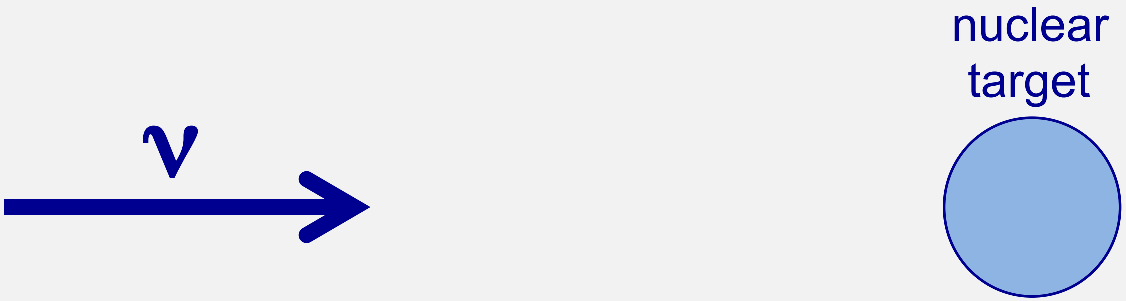
T2K NIWG,arXiv:1601.05592

MA is no longer 1.3 (GeV)

→ 1.15! (still not 1)

Fit type	$\chi^2/N_{\rm DOF}$	$M_{\rm A}$ (GeV/c^2)	2p2h (%)	$p_{\rm F}$ (MeV/c)
Unscaled	97.8/228	1.15±0.03	27±12	223±5
PGoF scaling		1.15±0.06	27±27	223±11

TABLE IX: The final errors for the RFG+rel.RPA+2p2h parameters. Note that the scaled errors should be used by any analyses which use these results.


ν
nuclear
target

Fun Timely Intellectual Adorable!

Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Neutrino Cross-Section Newsletter

Weak interaction

Nucleon correlation

EMC effect

electron scattering

Dark matter

Subscribe “Neutrino Cross-Section Newsletter”
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Please “like” our Facebook page, use hashtag #nuxsec

Neutrino-Nucleus Quasi-Elastic Cross-Section Measurements

Teppei Katori
Queen Mary University of London
ESNT workshop, CEA Saclay, Apr. 18, 2016

outline

1. **Neutrino oscillation physics**
2. **CCQE signal and background**
3. **Flux-integrated differential cross-section**
4. **CCQE results with lepton kinematics**
5. **CCQE results with hadron kinematics**
6. **Conclusion**

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1. Neutrino oscillation physics

2. CCQE signal and Background

3. Flux-integrated differential cross-section

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5. CCQE results with hadron kinematics

6. Conclusion

1. Neutrino physics is the future of particle physics

P5 (particle physics project prioritization panel) recommend neutrinos to DOE

Contents

CERN → LHC
Fermilab → Neutrino

Table 1
Summary of Scenarios

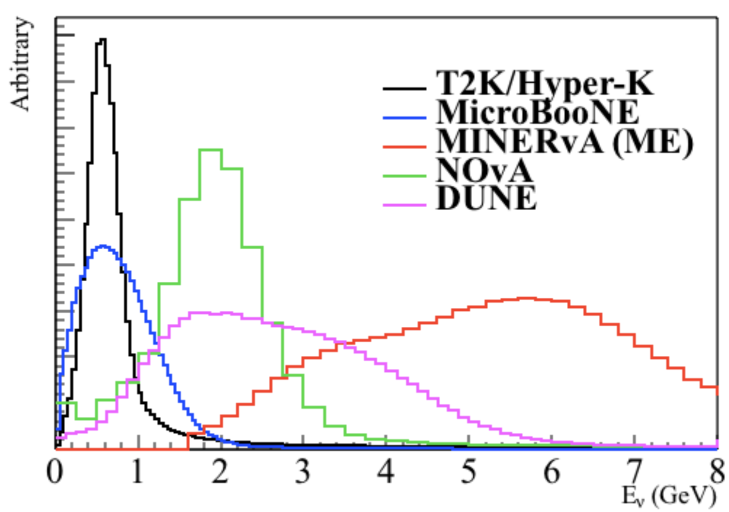
	Scenarios			Science Drivers					
Project/Activity	Scenario A	Scenario B	Senario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contri-butions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

1. CERN-USA, KEK-ICRR…

Political pacts are made to strengthen large collaborations…

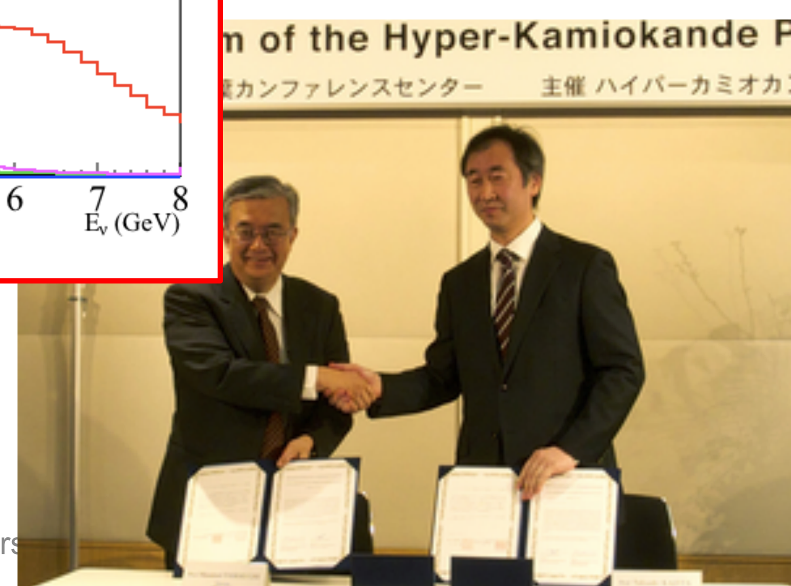
CERN - USA

DUNE (2025?)
LArTPC detector
argon target
wideband 1-4 GeV
(on-axis beam)



Hyper-Kamiokande (2026?)
Water Cherenkov detector
water target
narrowband 0.6 GeV
(off-axis beam)

KEK - ICRR



1. Neutrino Standard Model (νSM)

Next goal of particle physics

- After Higgs discovery, this is the only project with clear directionality
- Establish "SM + 3 active massive neutrinos"

Unknown parameters of νSM

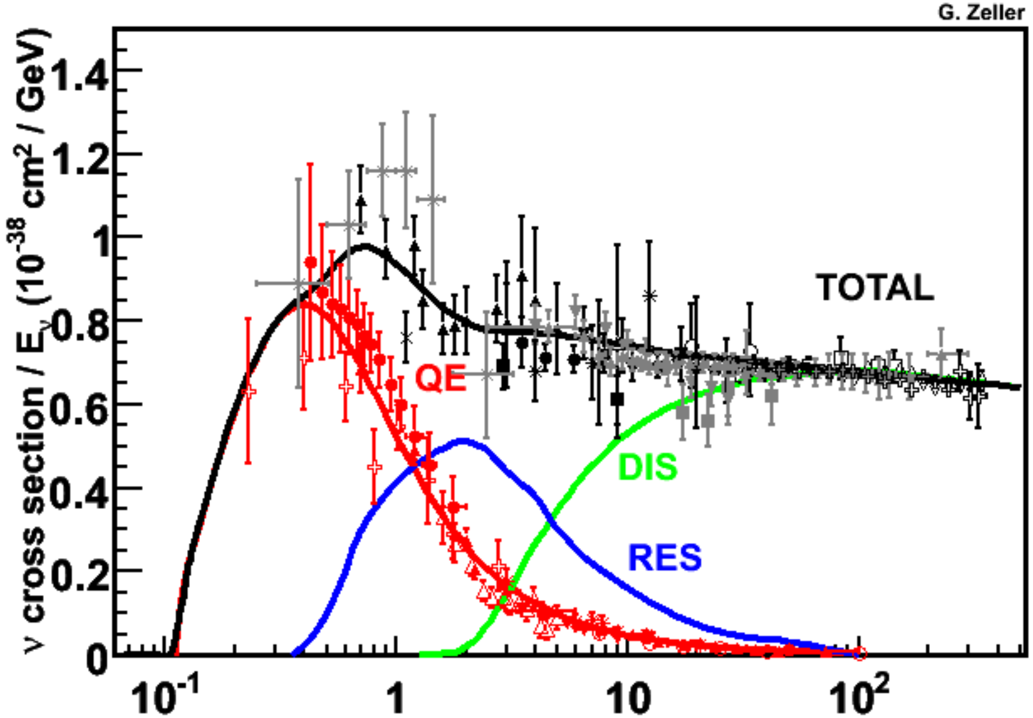
1. Dirac CP phase
2. θ_{23} (θ_{23}=40° and 50° are same for $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$)
3. normal mass ordering $m_1<m_2<m_3$ or inverted mass ordering $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase (x2)
6. Absolute neutrino mass

We need higher precision experiments around 1-10 GeV

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE



ν_μCC cross section per nucleon

$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

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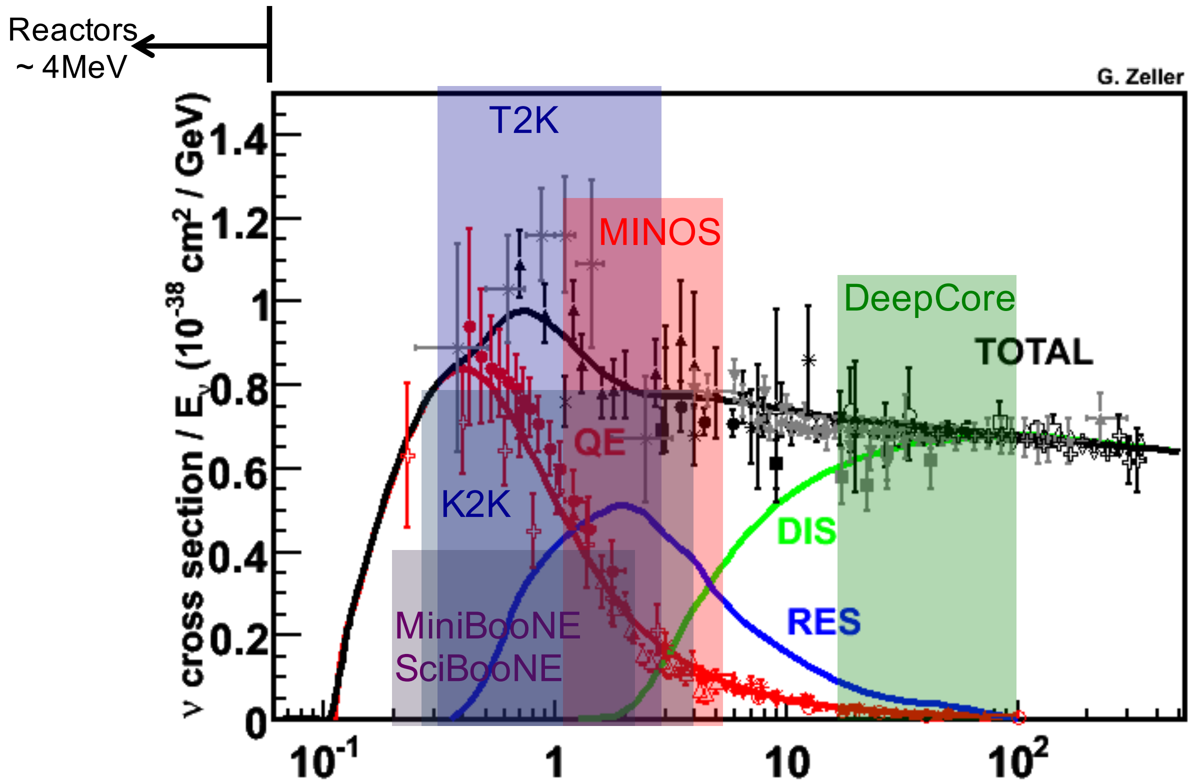

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Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

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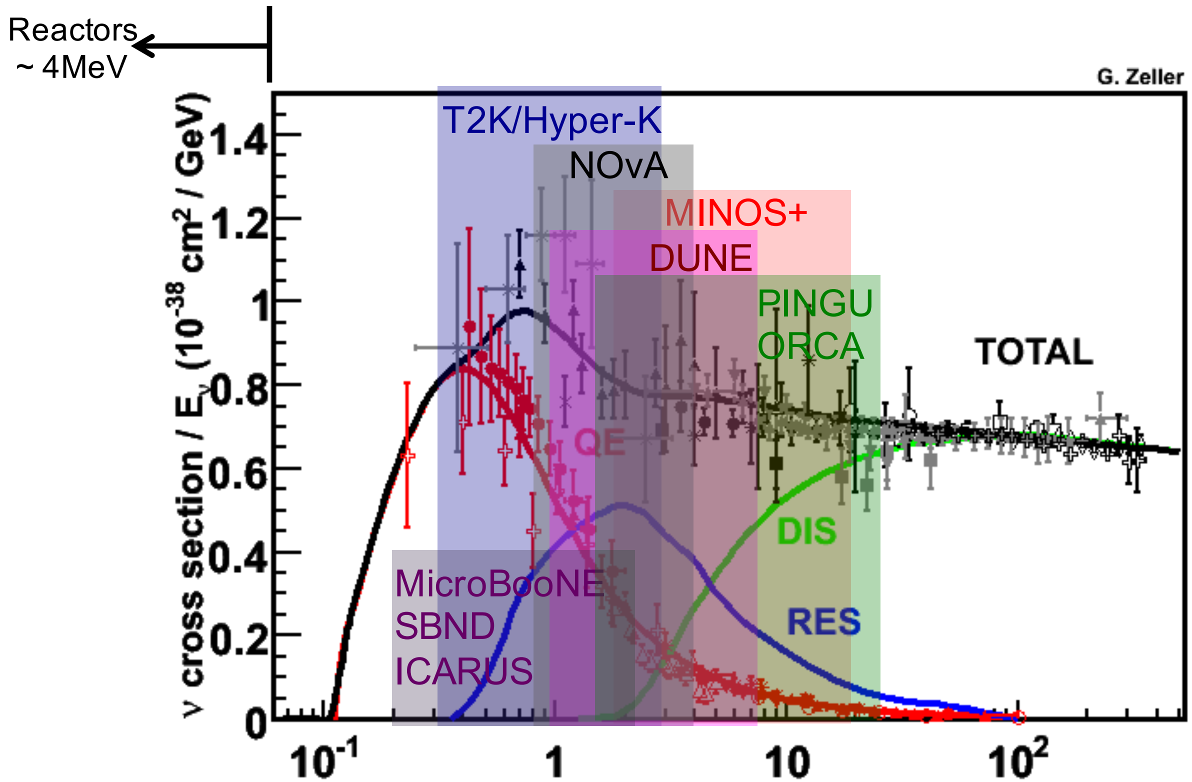

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1. Neutrino oscillation physics

2. CCQE signal and Background

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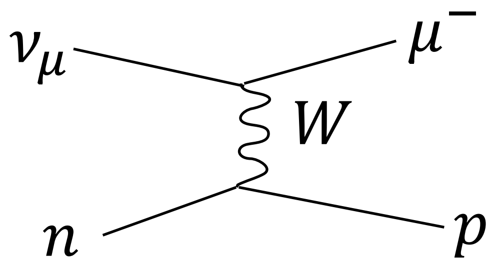
5. CCQE results with hadron kinematics

6. Conclusion

2. Charged Current Quasi-Elastic scattering (CCQE)

The simplest and the most abundant interaction around ~1 GeV.



$$\nu_\mu + n \rightarrow p + \mu^- \; (\nu_\mu + X \rightarrow X' + \mu^-)$$

It was essential to understand this channel in MiniBooNE

1. ν_μCCQE is the largest events (~40%)

2. ν_μCCQE data is used to understand CCQE model, then same model is used for ν_eCCQE measurement (=oscillation measurement)

3. ν_μCCQE data is used to understand ν_μ beam and ν_e contamination prediction error (=oscillation background)

MiniBooNE,PRD81(2010)092005

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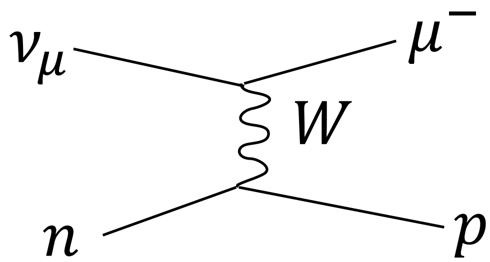

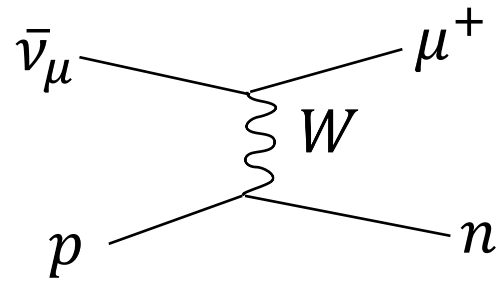

Neutrino-CCQE reaction

- neutron target
  → nuclear target

$$\nu_\mu + n \rightarrow p + \mu^-$$
$$(\nu_\mu + X \rightarrow X' + \mu^-)$$

Antineutrino-CCQE reaction

- proton target
  → nuclear target or free proton (hydrogen)

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$
$$\begin{pmatrix} \bar{\nu}_\mu + X \rightarrow X' + \mu^+ \\ \bar{\nu}_\mu + H \rightarrow n + \mu^+ \end{pmatrix}$$

- lower cross-section
- confusion of nuclear target vs. free proton

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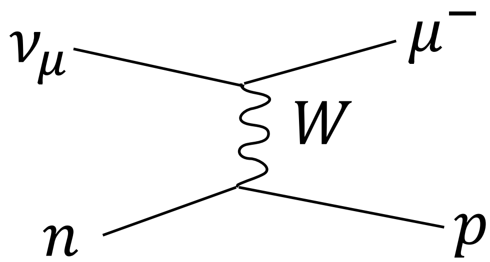

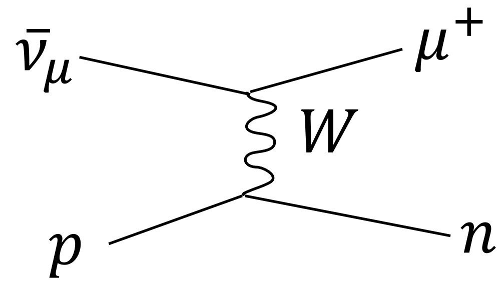

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- lower cross-section
- confusion of nuclear target vs. free proton

Antineutrino beam

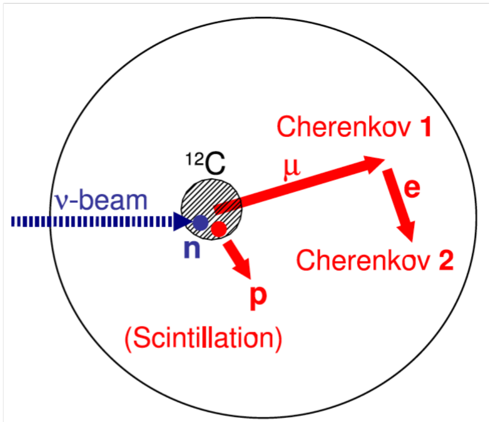
- lower flux than neutrino beam (primary proton makes more π^+ than π^-)
- higher background contamination than neutrino beam
  → ν_μ in $\bar{\nu}_\mu$ beam (wrong sign "WS" background)

→ Antineutrino experiments are harder

2. Selection of CCQE

Cherenkov neutrino detector

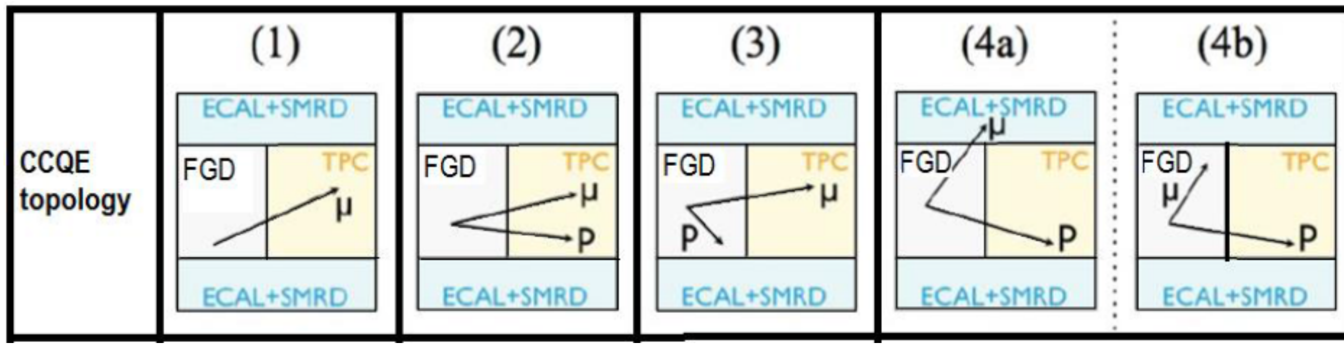
- 1 lepton track



- 4π coverage
- not good to measure multi-tracks
- good calorimetric measurement

Tracker neutrino detector

- 1 lepton track (and 1 proton track)



- multi-track measurements
- vertex activity measurement (high resolution)
- efficiency depends on topology

Liquid argon TPC neutrino detector

- It claims to have all features

(4π coverage, calorimetric, multi-track, vertex activity)

2. Selection of CCQE

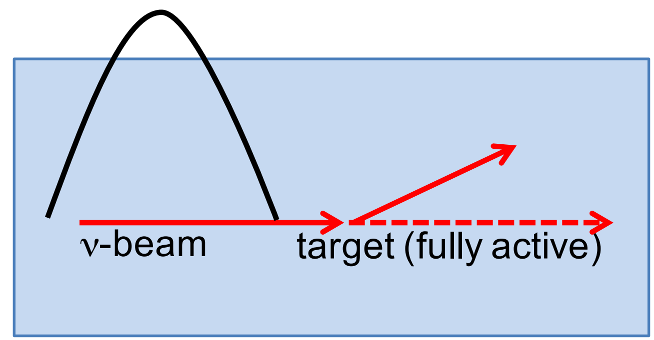
Cherenkov neutrino detector

- 1 lepton track
- 4π coverage
- not good to measure multi-tracks
- good calorimetric measurement

Tracker neutrino detector

- 1 lepton track (and 1 proton track)
- multi-track measurements
- efficiency depends on topology
- vertex activity measurement (high resolution)

In general, neutrino experiments use active target with wideband beam. QE is selected by outgoing lepton track



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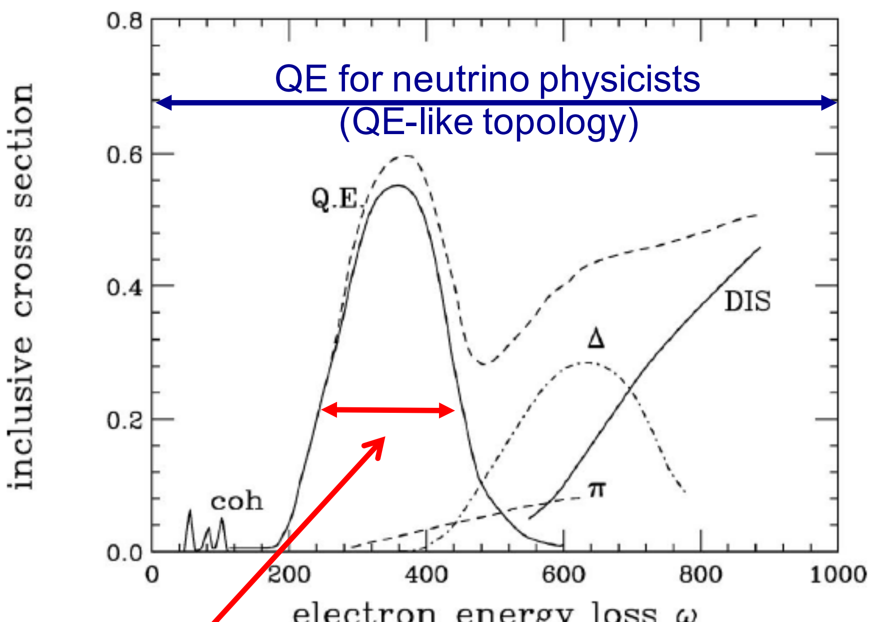
- not good to measure multi-tracks
- good calorimetric measurement

Tracker neutrino detector

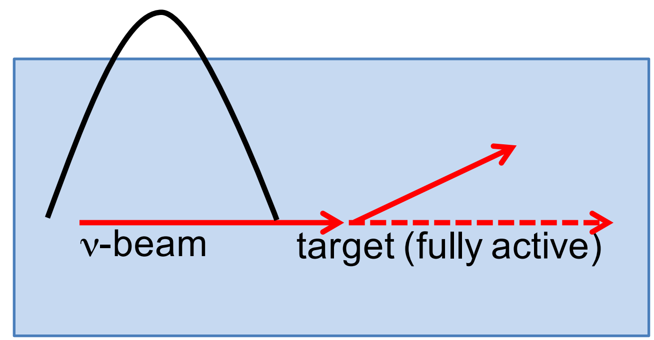
- 1 lepton track (and 1 proton track)
- multi-track measurements
- efficiency depends on topology
- vertex activity measurement (high resolution)

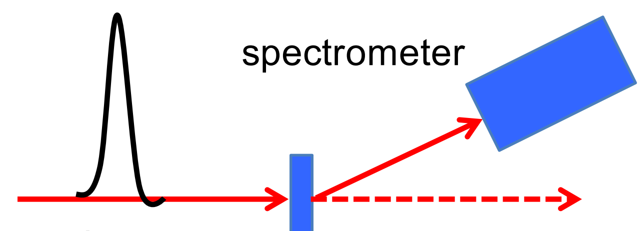
Selection of QE by electron scattering

- QE peak



QE for nuclear physicists (genuine QE)





Selection of QE ≠ Definition of QE in neutrino experiments

2. misID and intrinsic background of CCQE

misID

- fail to identify signal topology as signal (small)
- identify wrong topologies as signal topology

(failed to reconstruct π^- track and fail to reject π^- track)

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  - Intrinsic Beam background
  - Intrinsic interaction background

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Intrinsic
- interactions with same topology with signal
  - Intrinsic Beam background
  - Intrinsic interaction background

ex) ν_μCCQE measurement
- ν_μCCQE measurement but interactions not by ν_μ ($\overline{\nu_\mu}$, ν_e, $\overline{\nu_e}$)
- need to rely on simulation to subtract (intrinsic background)
- usually not important for ν-mode, but it is significant in $\bar{\nu}$-mode (WS events)

2. misID and intrinsic background of CCQE

misID
- fail to identify signal topology as signal (small)
- identify wrong topologies as signal topology

(failed to reconstruct π^- track and fail to reject π^- track)

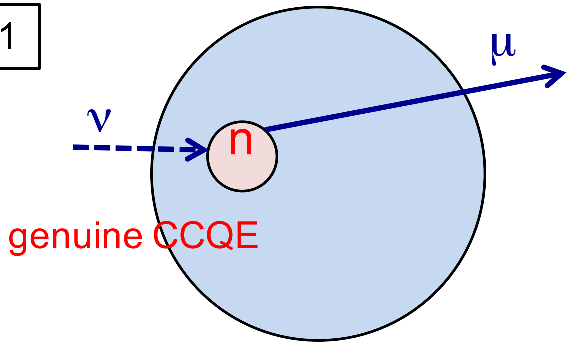
Intrinsic
- interactions with same topology with signal
  - Intrinsic Beam background
  - Intrinsic interaction background

ex) ν_μCCQE measurement
- interactions with same topology with signal

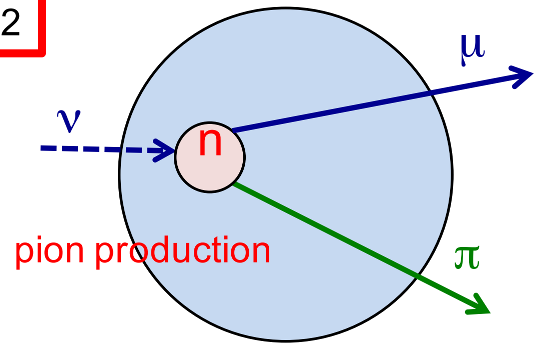
Background depends on how to define signal
i) Genuine QE (QE in e-scattering experiment)
ii) CCQE-like (MiniBooNE, MINERvA)
iii) CC0π (T2K)

2. Background

1

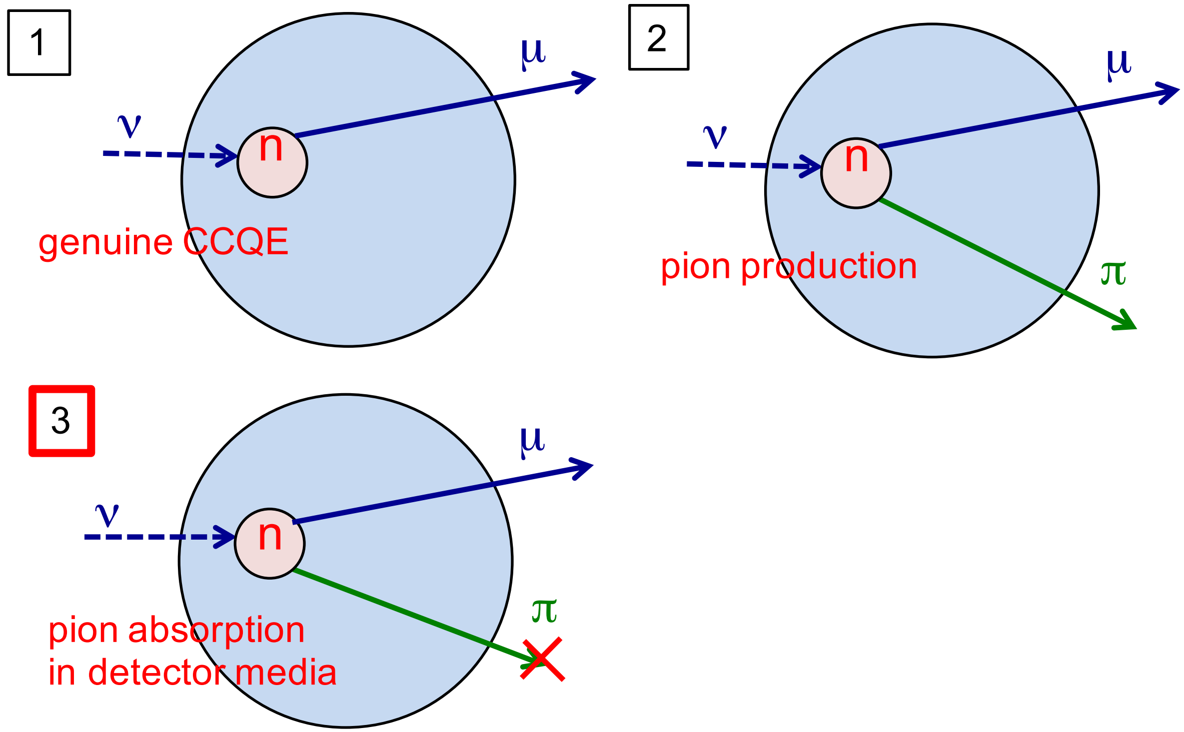


2



(2) is different topology from (1), and it is rejected by selection.
→ not background

2. Background



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If the detector fail to find π and fail to reject, (3), it is misID background and need to be estimated by simulation

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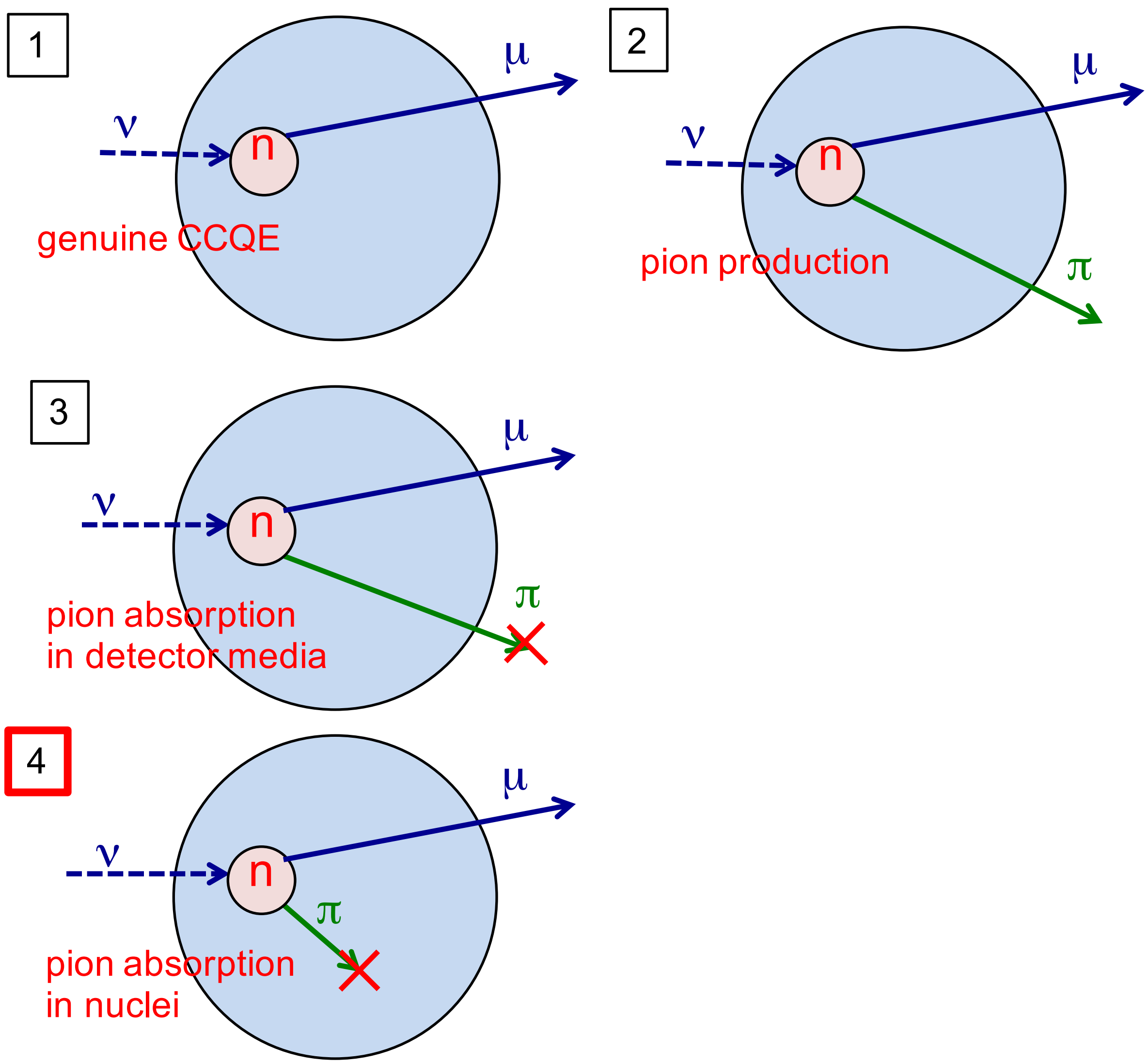

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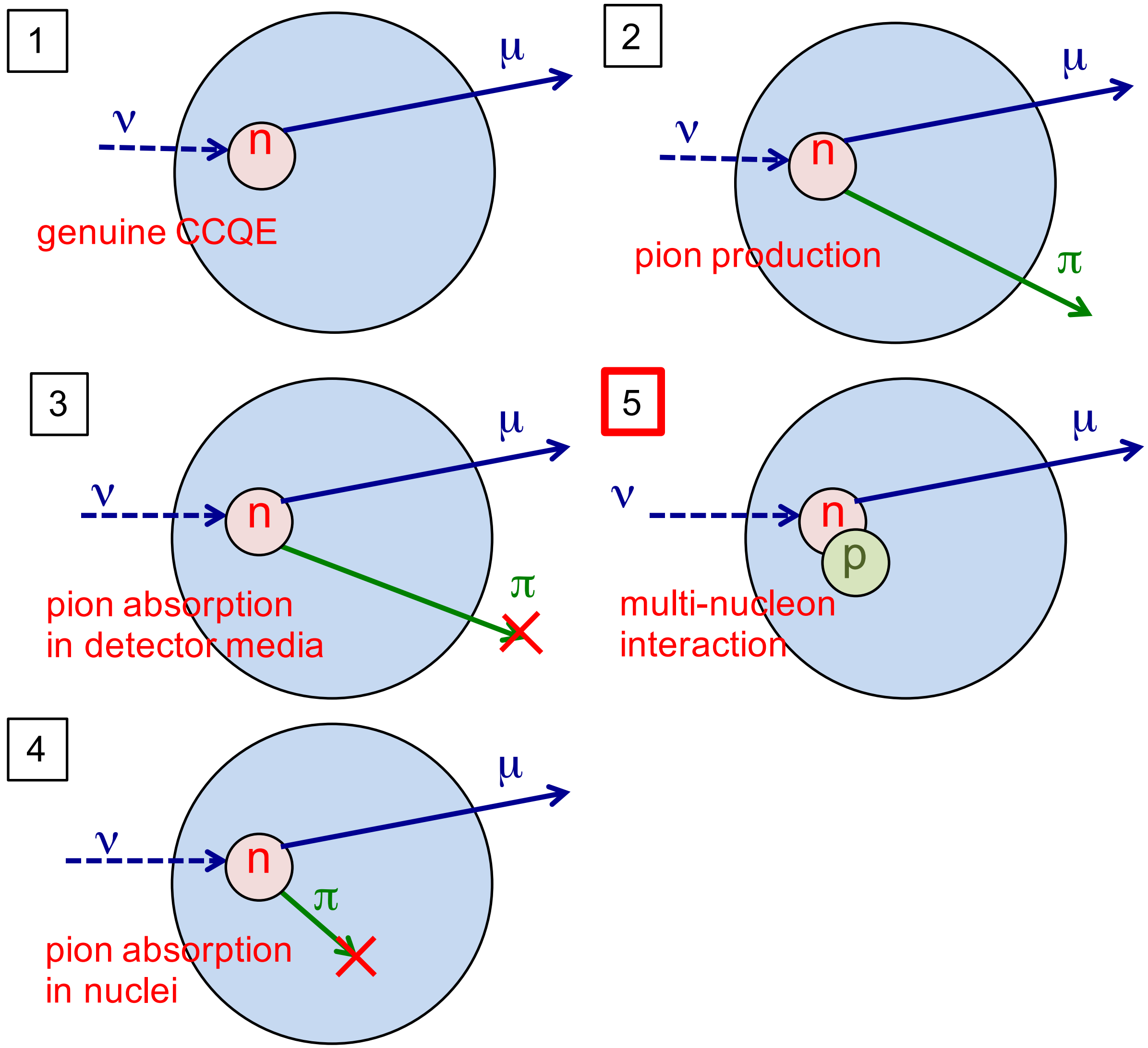
(4) has same topology with (1), so it is signal for topology dependent signal definition, but it was defined as intrinsic background in MiniBooNE and simulated and subtracted

2. Background



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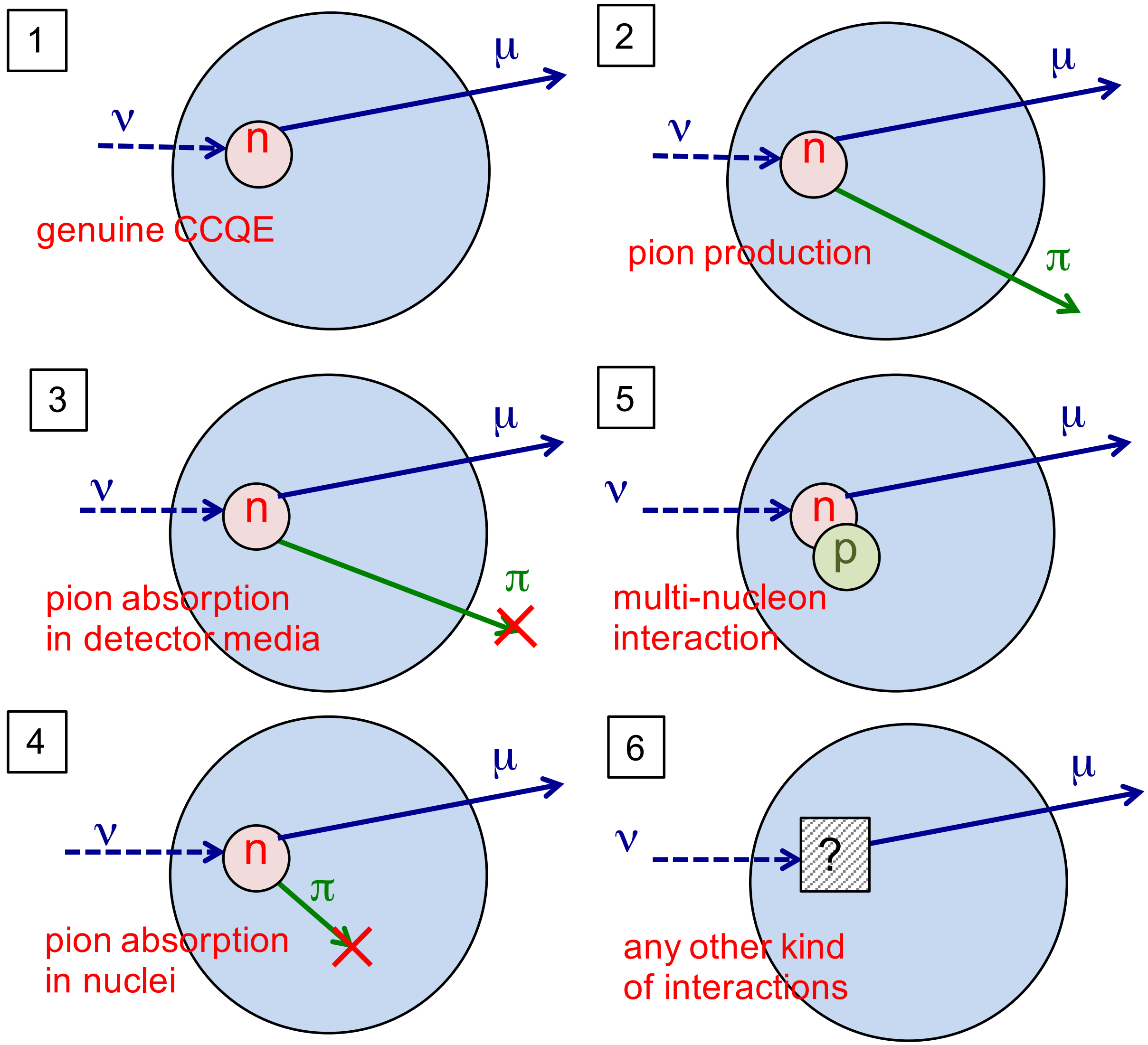
But (5) have same topology with (1), so they are signal for topology dependent signal definition, and it is not simulated and not subtracted from MiniBooNE (it's signal)

2. Background



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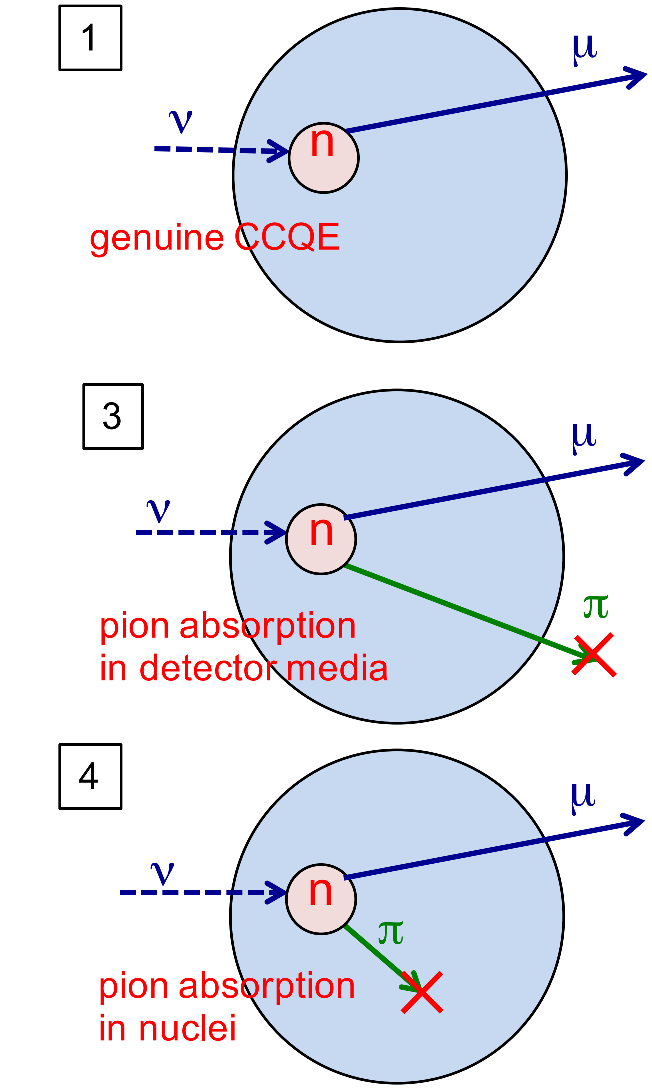
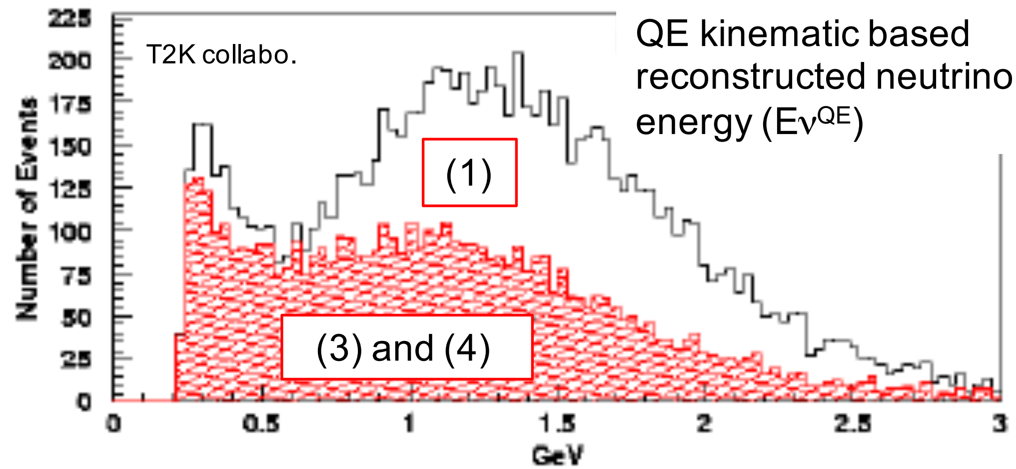
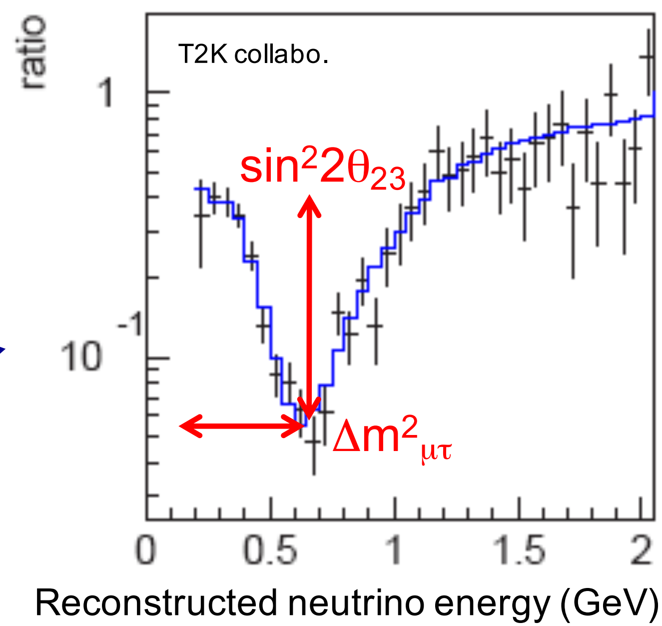
Genuine CCQE = (1)
CCQE-like = (1), (5), (6)
CC0π = (1), (4), (5), (6)

2. Intrinsic background and energy reconstruction





QE kinematic based reconstructed neutrino energy ($E\nu^{QE}$)



To perform neutrino oscillation experiments, we do need predictions of (3), (4), (5), (6).

$$\Phi(E_\nu)\times P(L,E_\nu)\times\sigma(q,\omega)\times\varepsilon(observables)=R$$

1. Neutrino oscillation physics

2. CCQE signal and Background

3. Flux-integrated differential cross-section

4. CCQE results with lepton kinematics

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3. Flux-integrated differential cross-section

We want to study the cross-section model, but we don't want to implement every models in the world in our simulation…

We want theorists to use our data, but flux-unfolding (model-dependent process) loses details of measurements…

3. Flux-integrated differential cross-section

We want to study the cross-section model, but we don't want to implement every models in the world in our simulation…

We want theorists to use our data, but flux-unfolding (model-dependent process) loses details of measurements…

Now, all modern experiments publish flux-integrated differential cross-section
→ Can anybody invent a sexy name for this quantity?
(Flussintegrierterdifferentiellerwirkungsquerschnitt®?)
→ Detector effect corrected event rate
→ Theorists can reproduce the data with neutrino flux tables from experimentalists
→ Minimum model dependence, useful for nuclear theorists

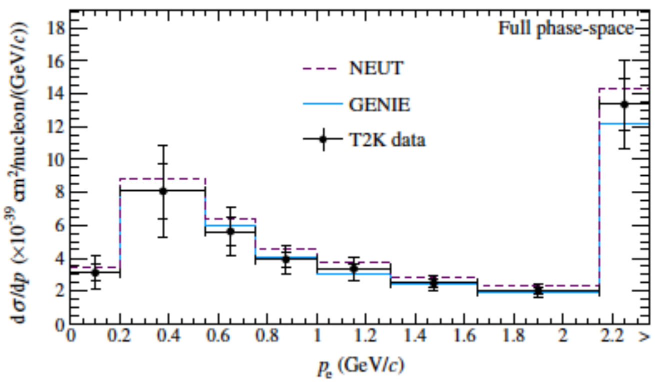
These data play major roles to study/improve neutrino interaction models by theorists

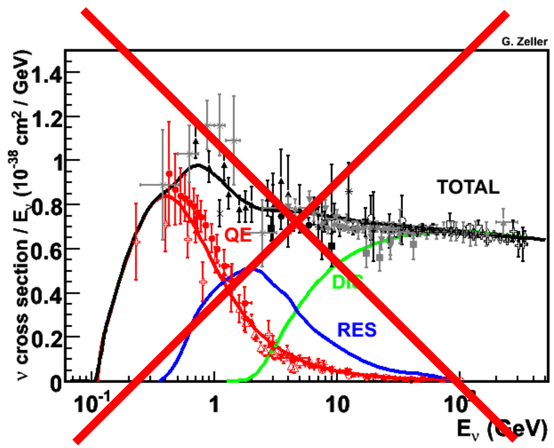
Fluss-integrierter Differentieller Wirkungsquerschnitt® is a copyrighted trademark of the T2K experiment

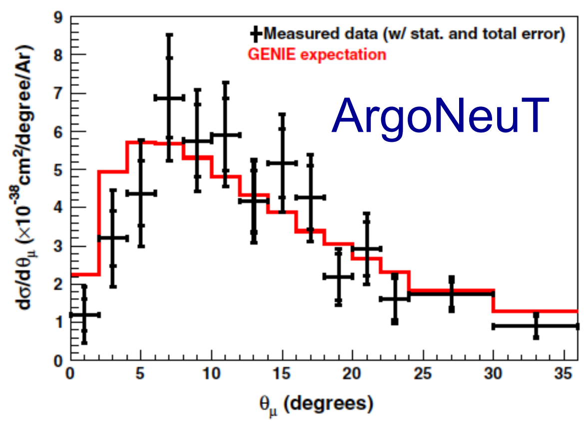
3. Flux-integrated differential cross-section

Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

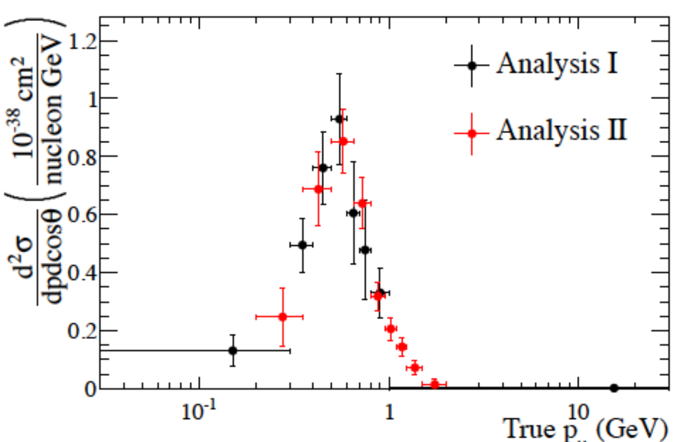
T2K

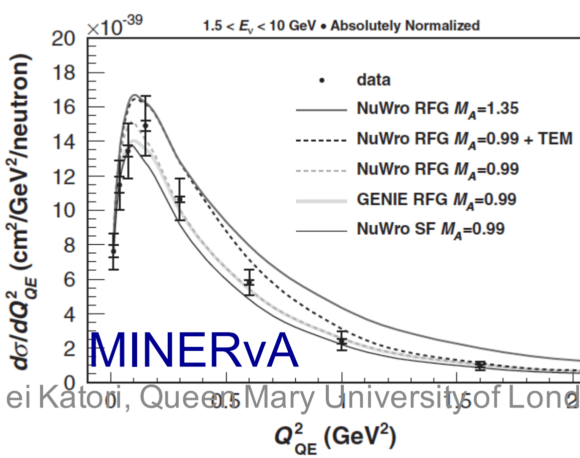




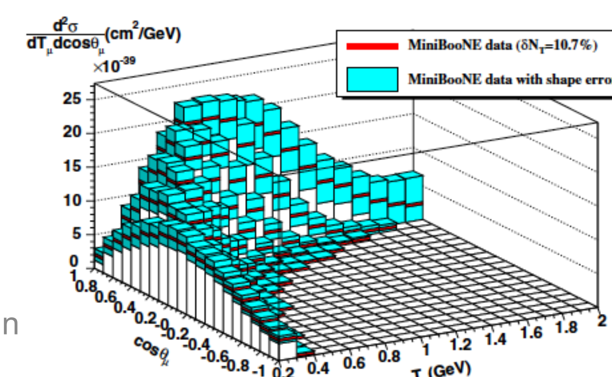


0.80 < true cosθ$_\mu$ < 0.85





MiniBooNE



3. Flux-integrated differential cross-section

Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

→ Now PDG has a summary of neutrino cross-section data! (since 2012)

$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$

Theorists

Experimentalists

$$\frac{d^2\sigma}{dT_l cos\theta} = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

Flux-integrated differential cross-section data allow theorists and experimentalists talk first time in modern neutrino interaction physics history

3. Flux-integrated differential cross-section

$$\left(\frac{d^2\sigma}{dT_l cos\theta}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

d_j = data vector of measured variables
b_j = background vector
U_{ij} = unsmearing transformation to true variables
ε_i = efficiency correction
Φ = integrated neutrino flux
T = total target number
$(\Delta T_l, \Delta cos\theta)_i$ = bin width

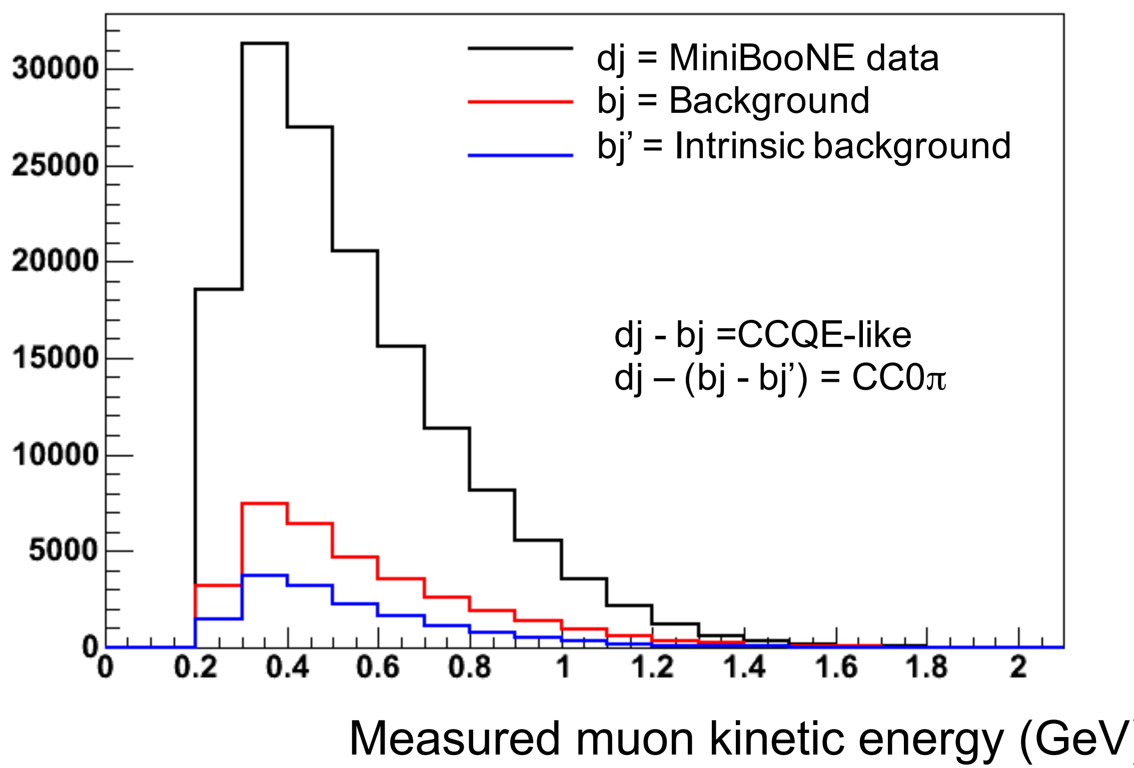
3. Flux-integrated differential cross-section

$$\left(\frac{d^2\sigma}{dT_l cos\theta}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

Data vector is a function of measured variables, and background vector depends on how to define "signal"

d_j = data vector of measured variables
b_j = background vector
U_{ij} = unsmearing transformation to true variables
ε_i = efficiency correction
Φ = integrated neutrino flux
T = total target number
$(\Delta T_l, \Delta cos\theta)_i$ = bin width

MiniBooNE CCQE candidate muon kinetic energy distribution



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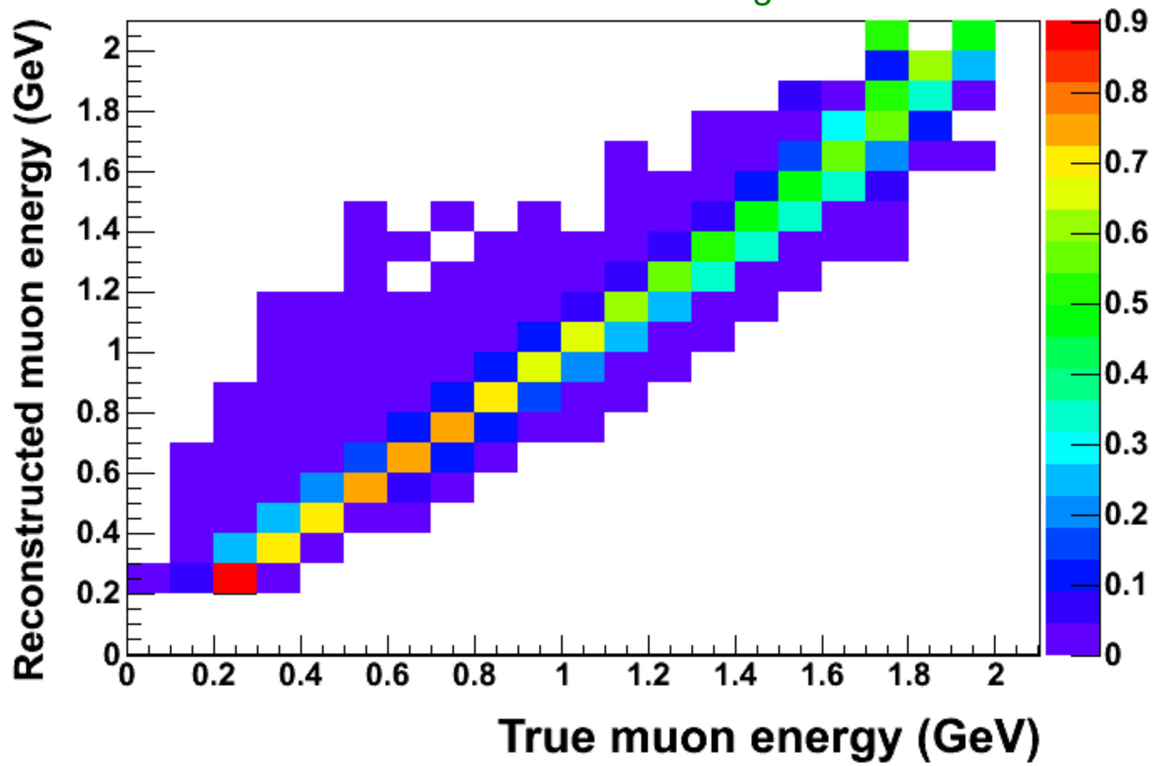
T = total target number
$(\Delta T_l, \Delta cos\theta)_i$ = bin width

Unsmearing process convert measured distribution to true distribution
j-index = measured distribution
i-index = true distribution

"Detector effect unfolding" include 2 processes
- unsmearing
- efficiency correction

Unfolding removes the detector effect from the distribution

MiniBooNE CCQE candidate unsmearing matrix



3. Flux-integrated differential cross-section

$$\left(\frac{d^2\sigma}{dT_l cos\theta}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i}$$

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b_j = background vector
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ε_i = efficiency correction
Φ = integrated neutrino flux
T = total target number
$(\Delta T_l, \Delta cos\theta)_i$ = bin width

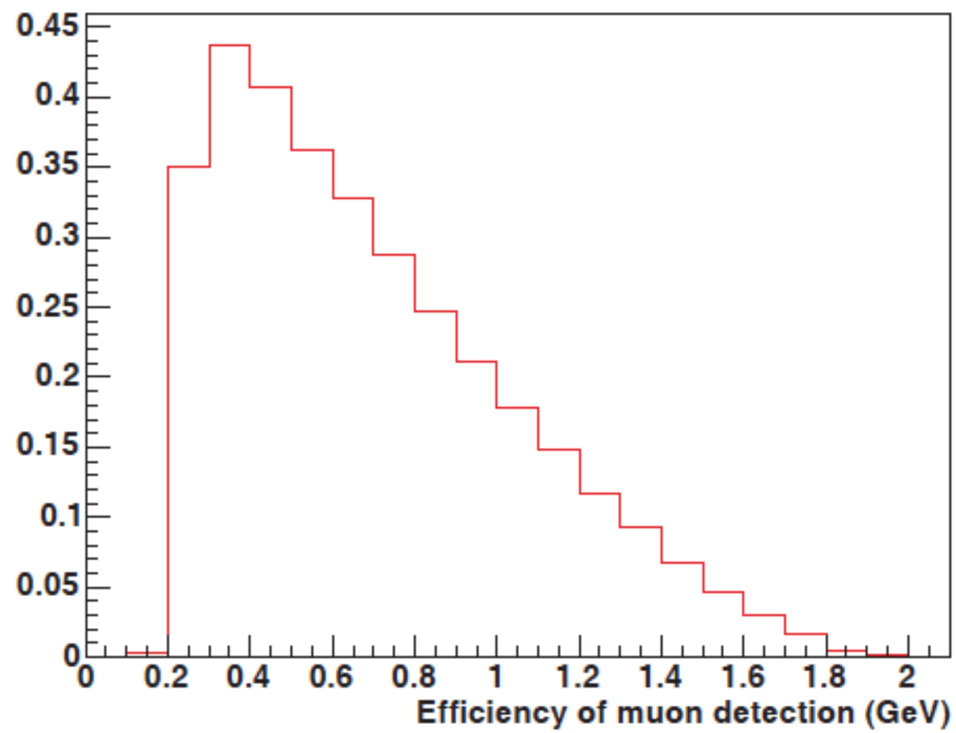
Efficiency is defined from before and after the cuts of MC sample of signal topology

$$\varepsilon_i = \frac{N_i^{after\ cut}}{N_i^{before\ cut}}$$

"Detector effect unfolding" include 2 processes
- unsmearing
- efficiency correction

Unfolding removes the detector effect from the distribution

MiniBooNE CCQE candidate efficiency

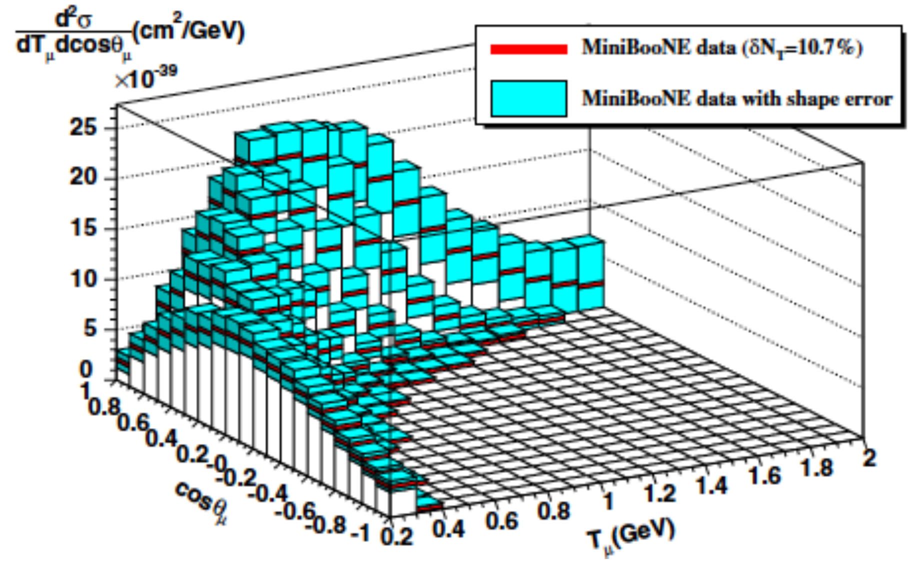


3. Flux-integrated differential cross-section

$$\left(\frac{d^2\sigma}{dT_l cos\theta}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\boxed{\Phi \cdot T} \cdot \varepsilon_i \cdot \boxed{(\Delta T_l, \Delta cos\theta)_i}}$$

d_j = data vector of measured variables
b_j = background vector
U_{ij} = unsmearing transformation to true variables
ε_i = efficiency correction
Φ = integrated neutrino flux
T = total target number
$(\Delta T_l, \Delta cos\theta)_i$ = bin width

After correcting normalizations, theory and data are comparable (flux is the largest normalization error)



Experimentalists

Theorists

$$\frac{\sum_j U_{ij}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot (\Delta T_l, \Delta cos\theta)_i} = \frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu - E_l} \Phi(E_\nu)$$

1. Neutrino oscillation physics

2. CCQE signal and Background

3. Flux-integrated differential cross-section

4. CCQE results with lepton kinematics

5. CCQE results with hadron kinematics

6. Conclusion

4. Bubble chamber era

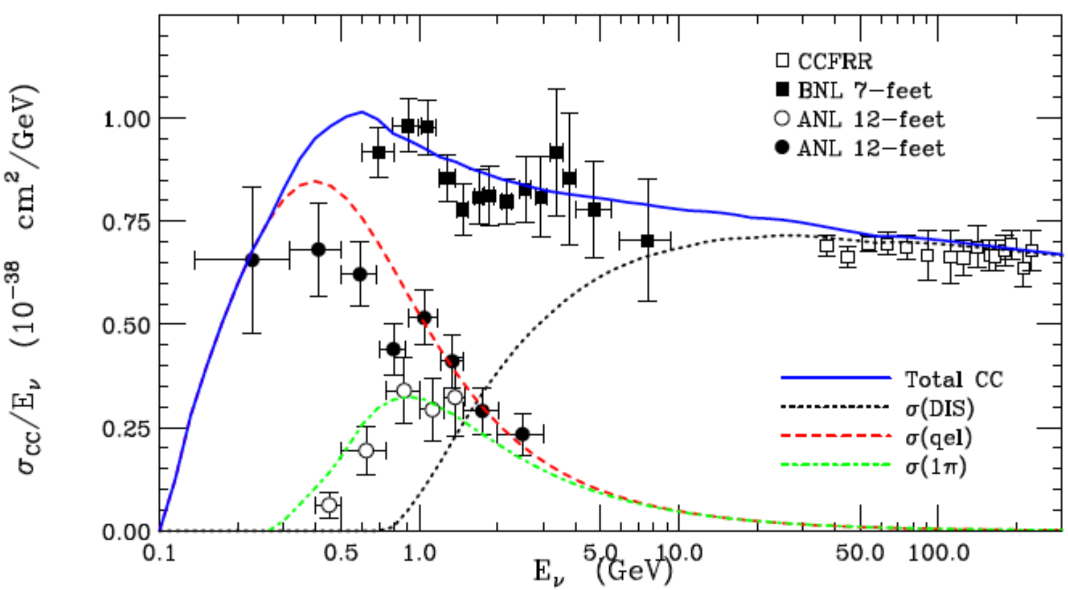
Bubble chamber deuteron data are consistent with M_A~1 GeV
- In general, very poor job to measure the absolute cross-section

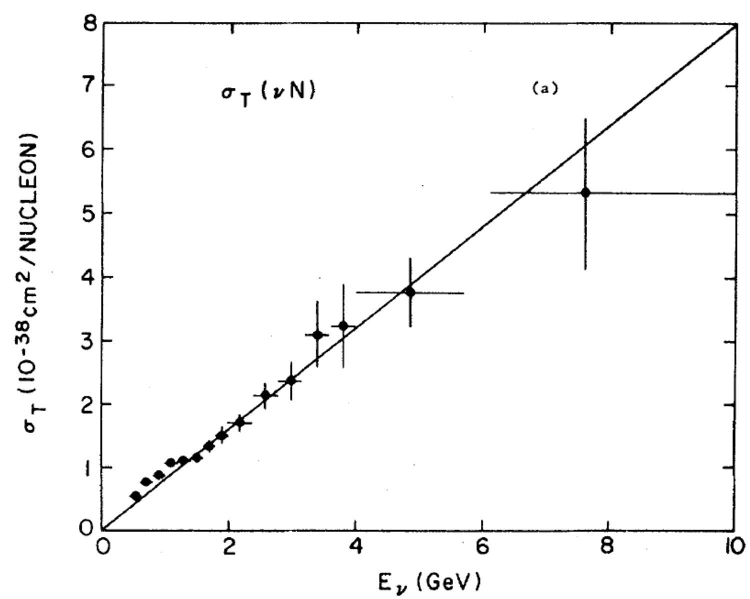
(1) Measure interaction rate
(2) Divide by known cross section to get flux
(3) use this flux, measure cross-section from measured interaction rate

What you get? the known cross section!

Phys. Rev. D [redacted] (1982)

The distribution of events in neutrino energy for the 3C $\nu d \to \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \to \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]

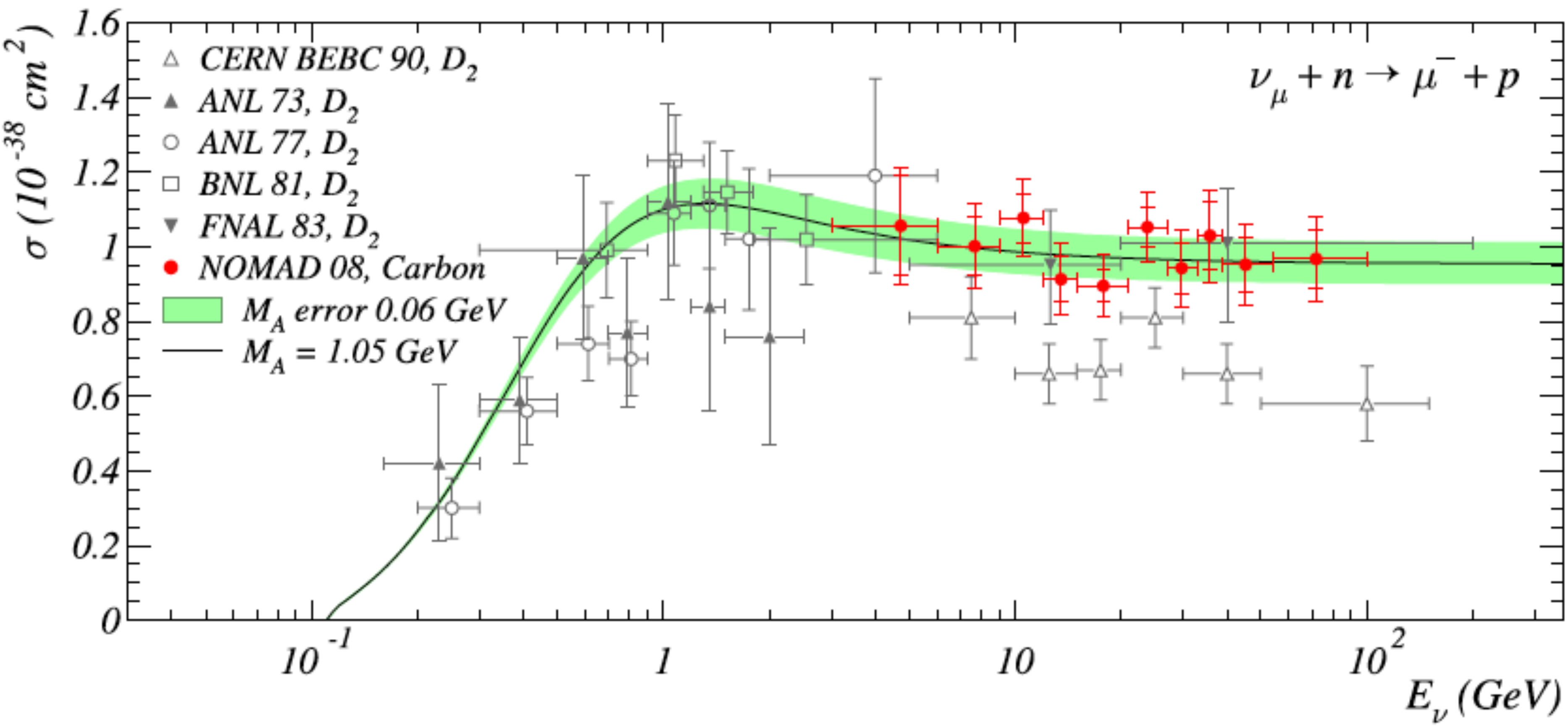




4. NOMAD

Magnetized tracker

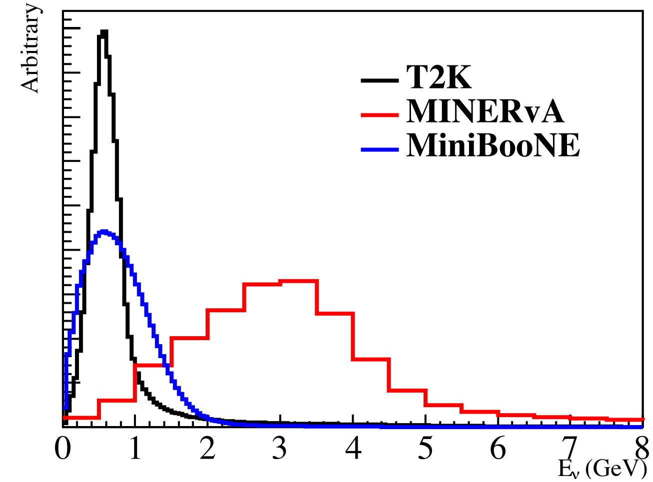
- <E> ~ 17 GeV
- flux normalization is checked by DIS and IMD events
- 1 track (73%) and 2 track (27%) are merged to report the total cross section.
- Formation zone (=FSI) was tuned to merge.

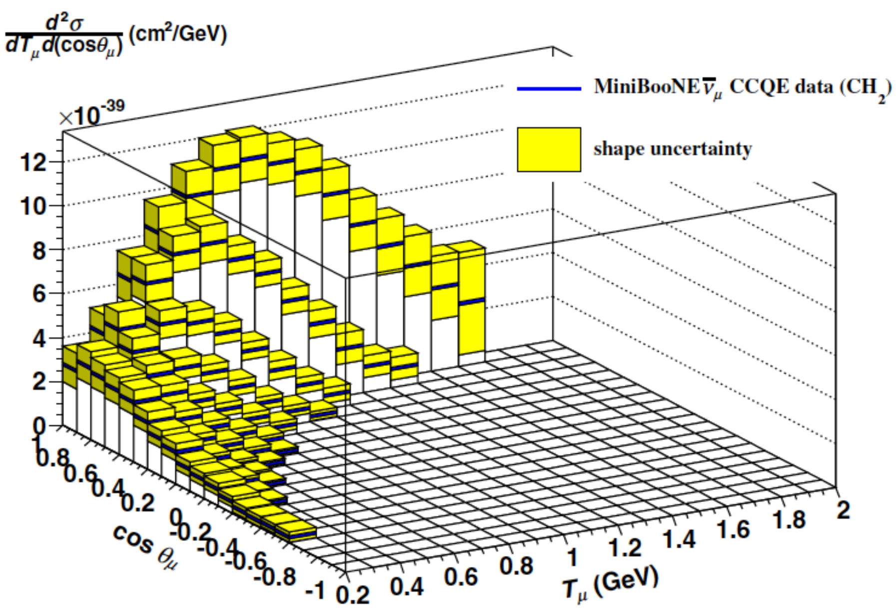


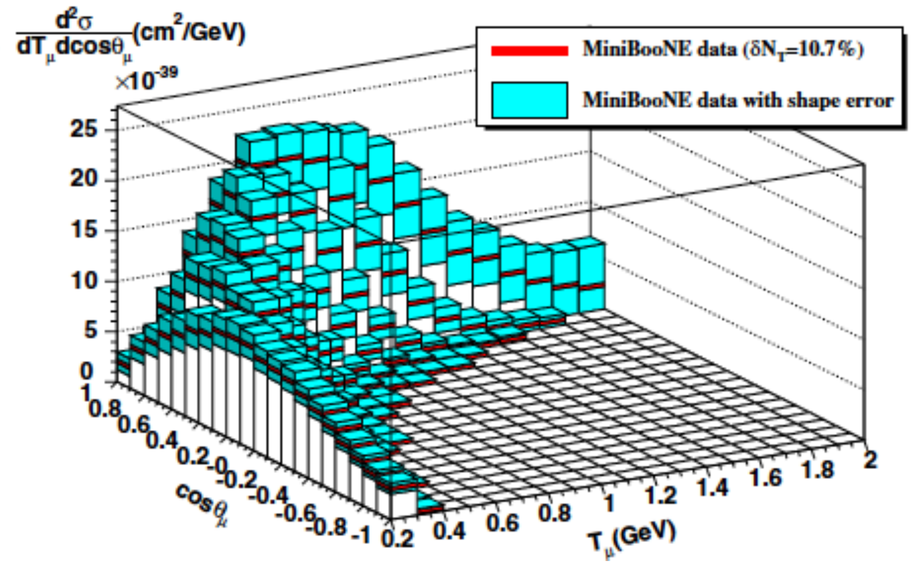
4. MiniBooNE

Mineral oil (CH_2) Cherenkov detector

- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Highest amount of information of lepton kinematics
- Large normalization error (10.7%)
- Covariance matrix is not published







MiniBooNE, PRL100(2008)032301,PRD81(2010)092005:88(2013)032001
Ankowski et al,PRD82(2010)013002

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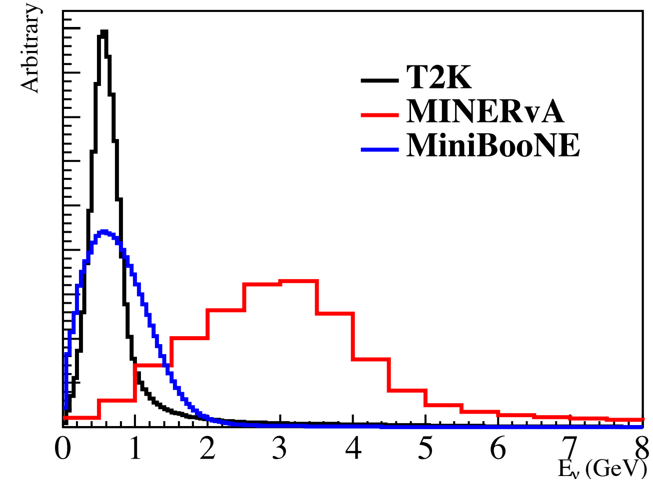
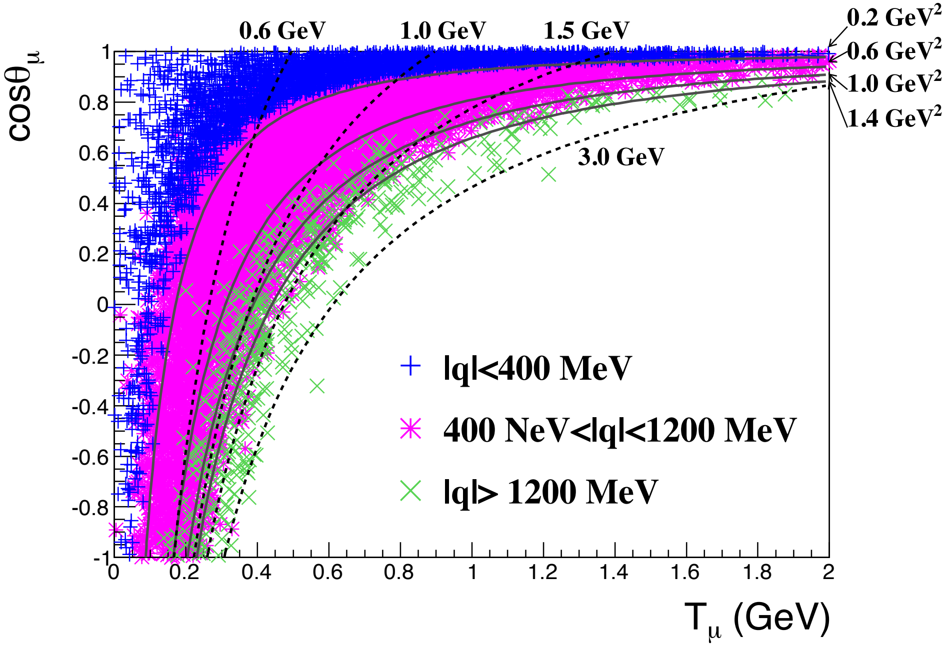
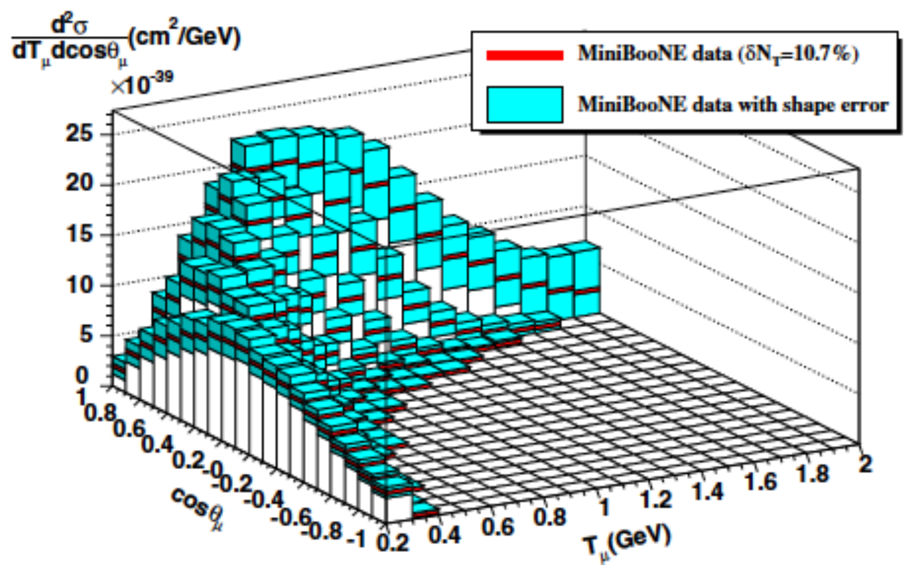


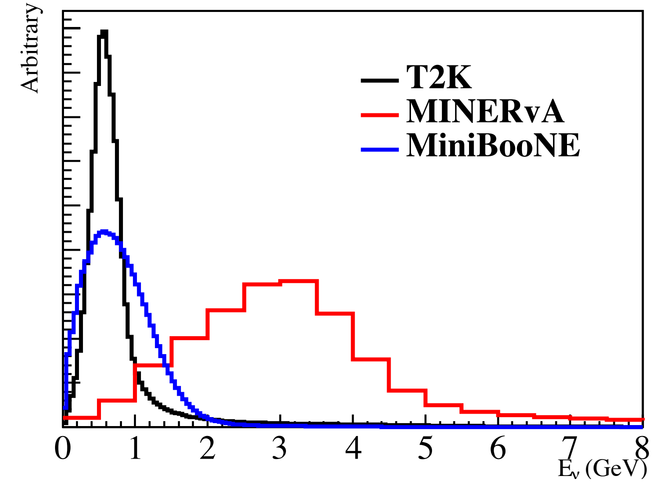
MiniBooNE CCQE phase space





T2K,PRD92(2015)112003,arXiv:1602.03652

4. T2K

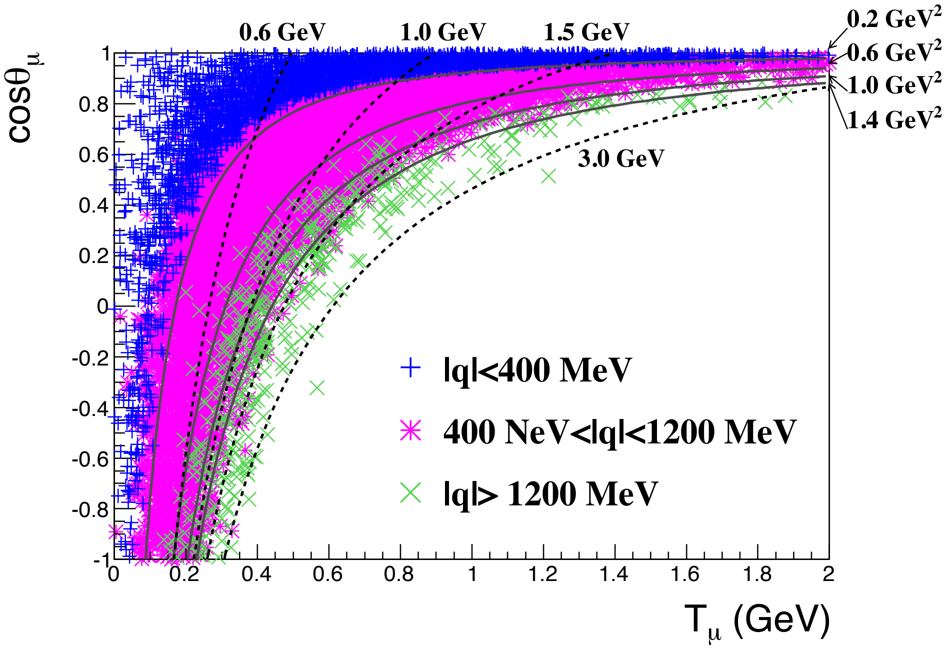


INGRID, FGD, P0D, ECal, TPC, SMRD, Super-K

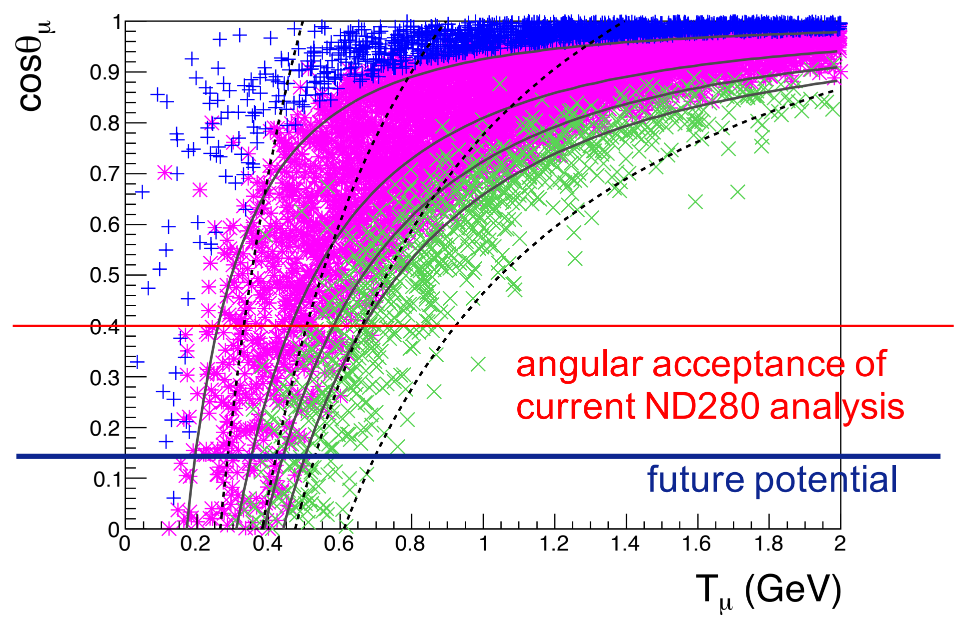
- <E>~600 MeV on-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)
- Covariance matrix is published for double differentia
- Kinematic phase space is similar with MiniBooNE

(~20% of events are |q|<400 MeV)

MiniBooNE CCQE phase space

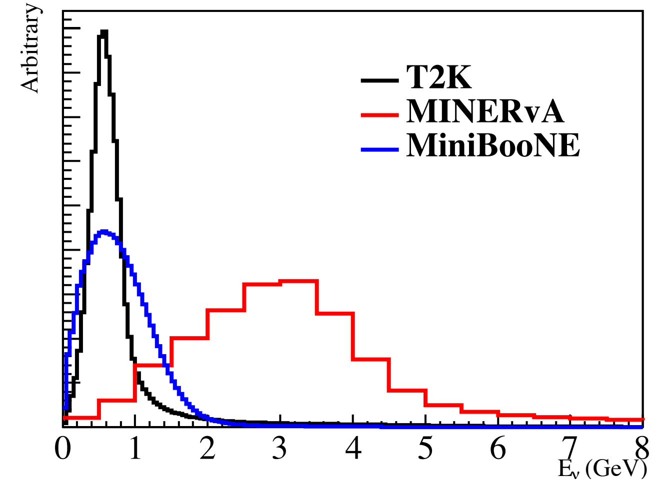


T2K CCQE phase space



T2K,PRD92(2015)112003,arXiv:1602.03652
Martini et al,PRC81(2010)045502,Amaro et al,PRL108(2012)152501

4. T2K



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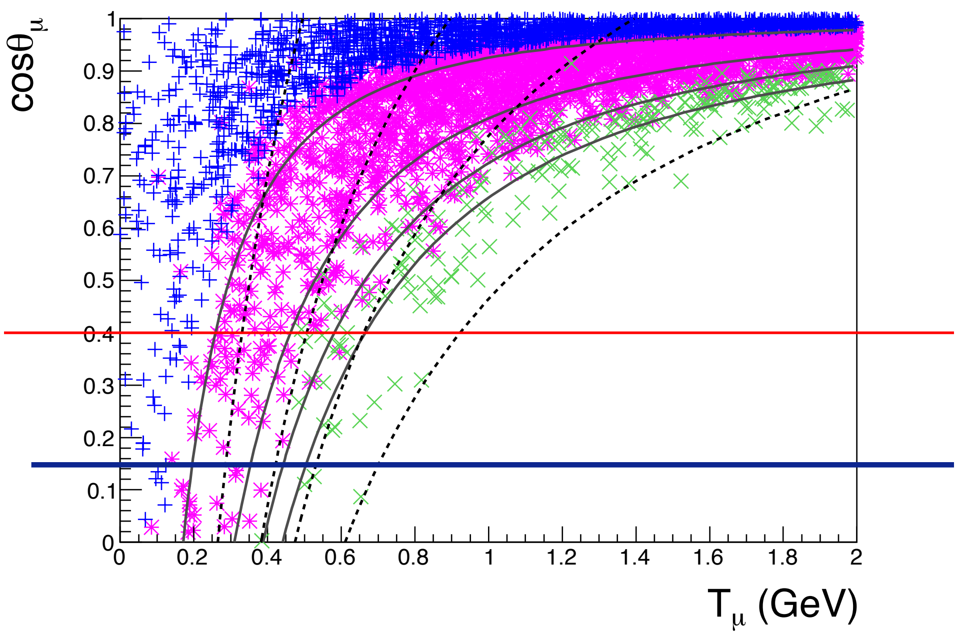
- <E>~600 MeV on-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)
- Covariance matrix is published for double differential
- Kinematic phase space is similar with MiniBooNE

(~20% of events are |q|<400 MeV)

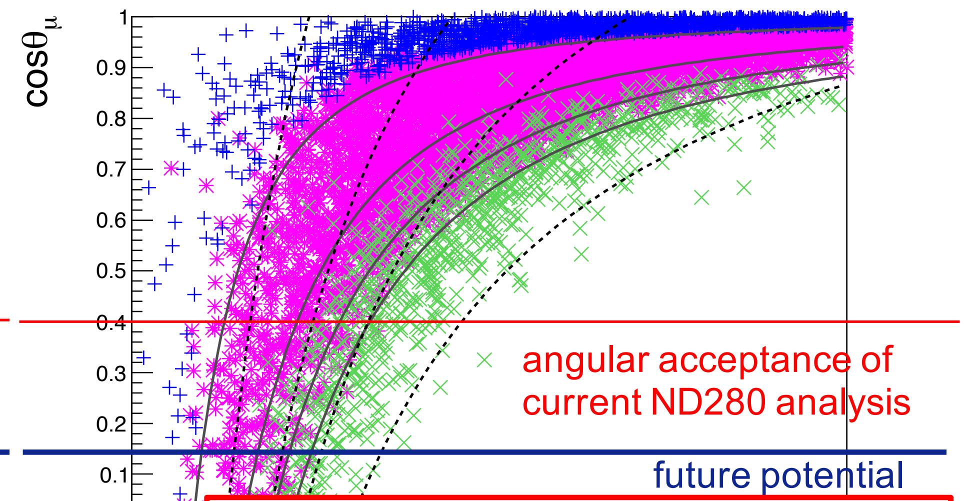
Anti-neutrino CCQE

- There will be larger fraction of low |q| events

T2K anti-CCQE phase space



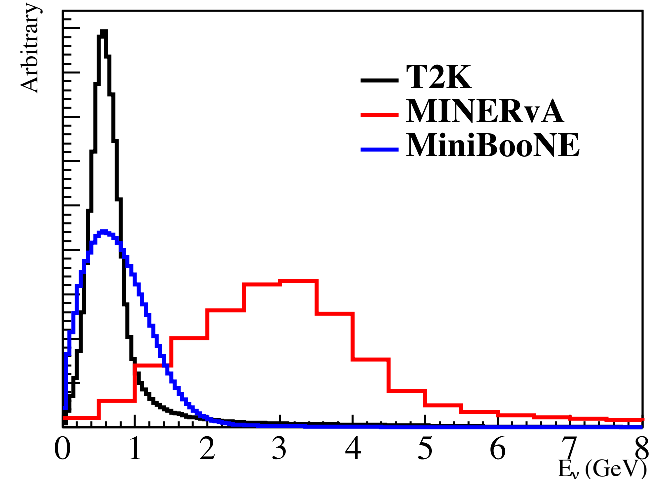
T2K CCQE phase space



RPA (MEC?) may be more important for anti-neutrino mode

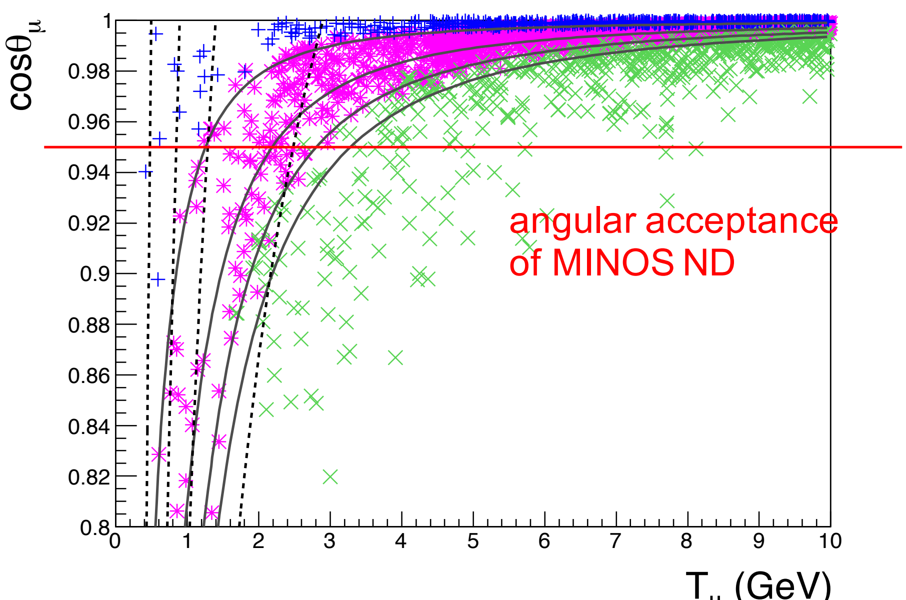
MINERvA, PRL111(2013)022501:022502
Megias et al,PRD89(2014)093002

3. MINERvA

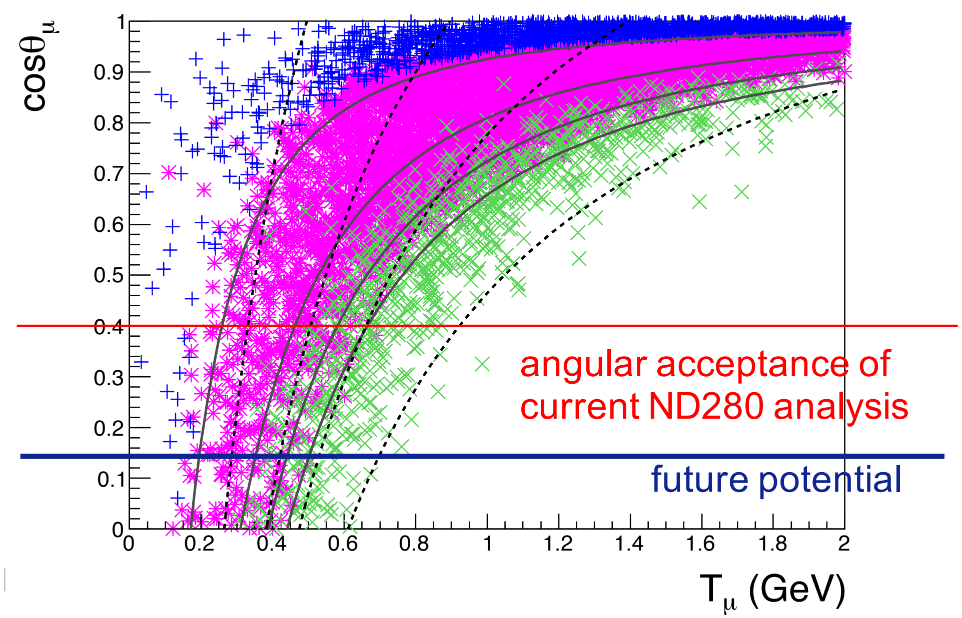


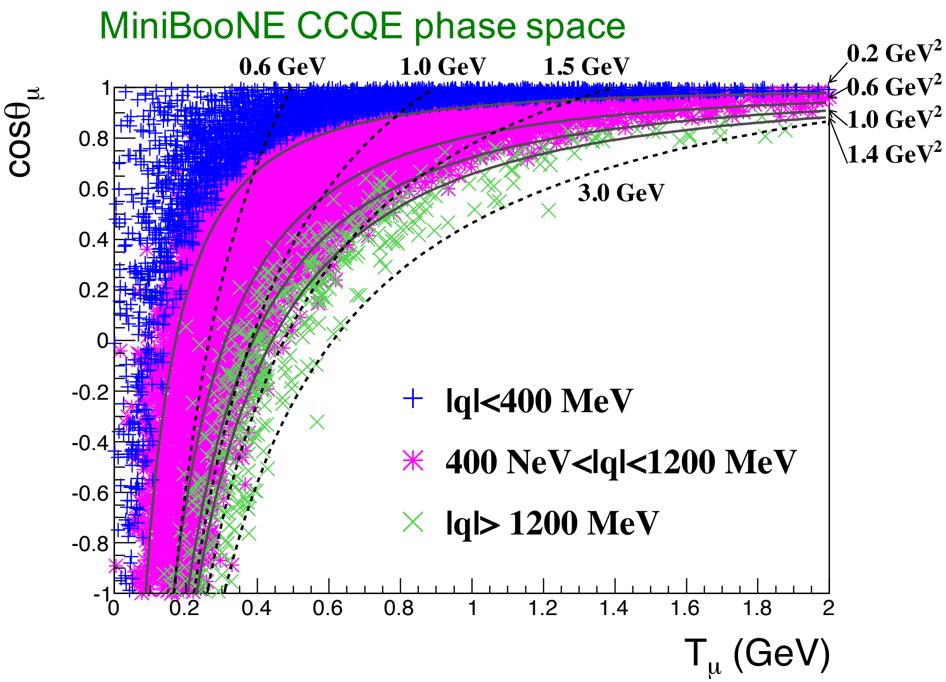
- <E>~3.5 GeV on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- flux changed recently (~10%)
- Kinematic phase space is similar with MB and T2K (~20% of events are |q|<400 MeV)

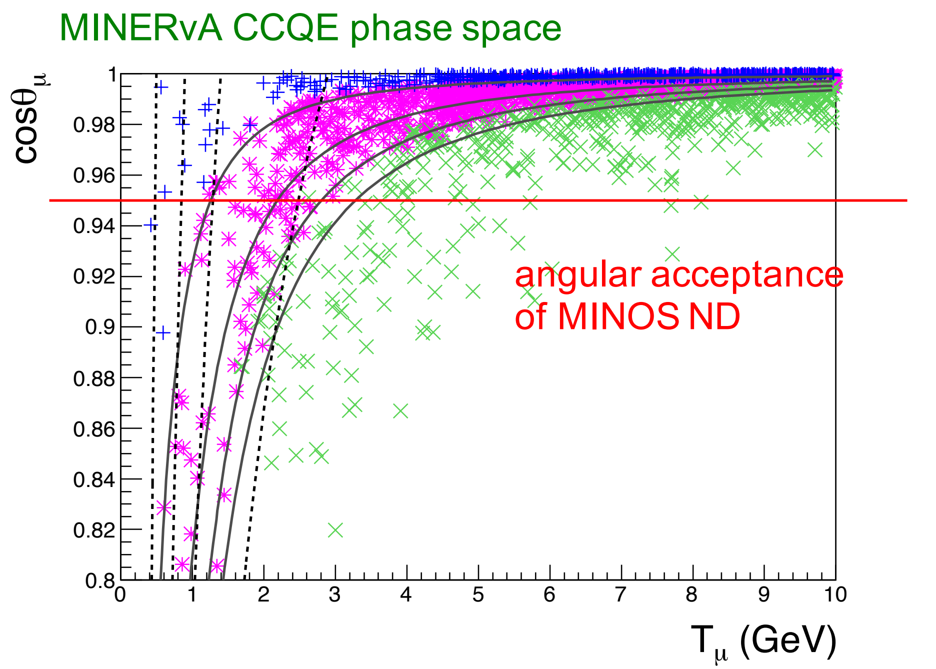
MINERvA CCQE phase space

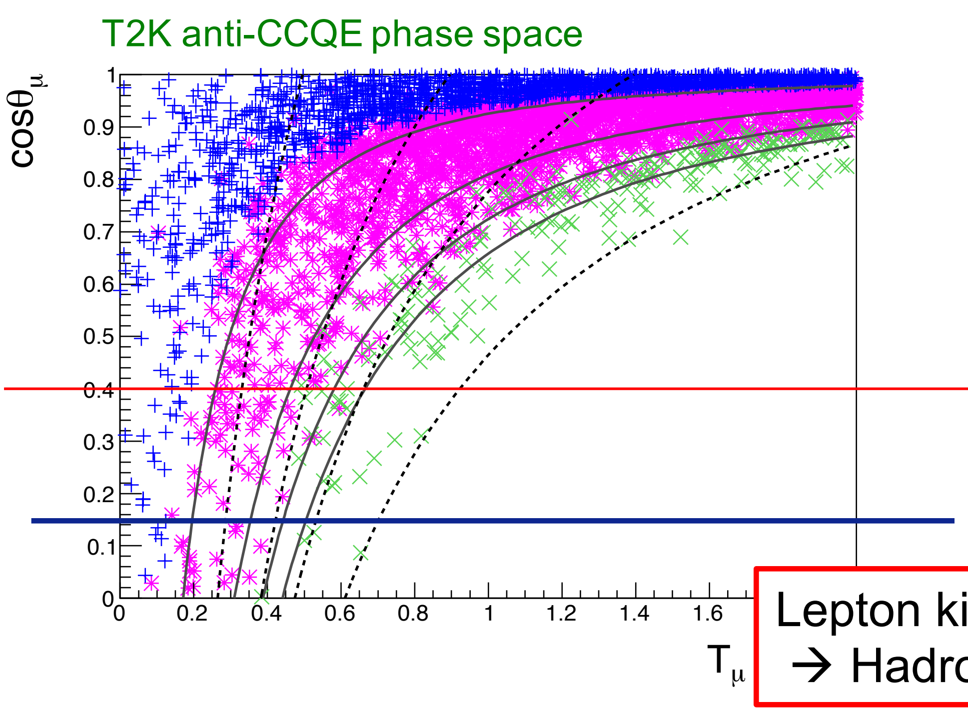


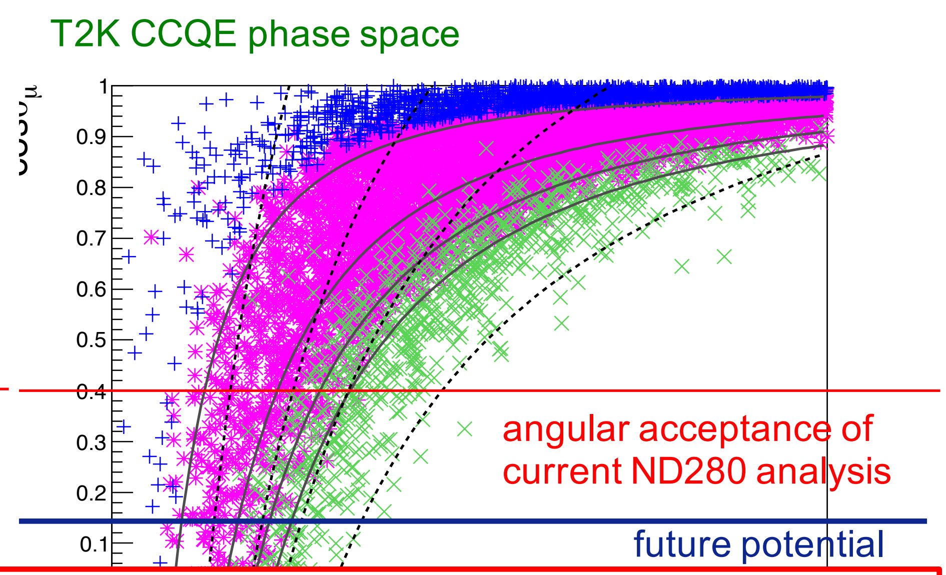
T2K CCQE phase space











Lepton kinematics are exploited in past experiments
→ Hadron kinematics

1. Neutrino oscillation physics

2. CCQE signal and Background

3. Flux-integrated differential cross-section

4. CCQE results with lepton kinematics

5. CCQE results with hadron kinematics

6. Conclusion

T2K,PRD91(2015)112002, T2K NIWG,arXiv:1601.05592
Lalakulich et al.,PRC86(2012)014614, Nieves et al, PRC83(2011)045501

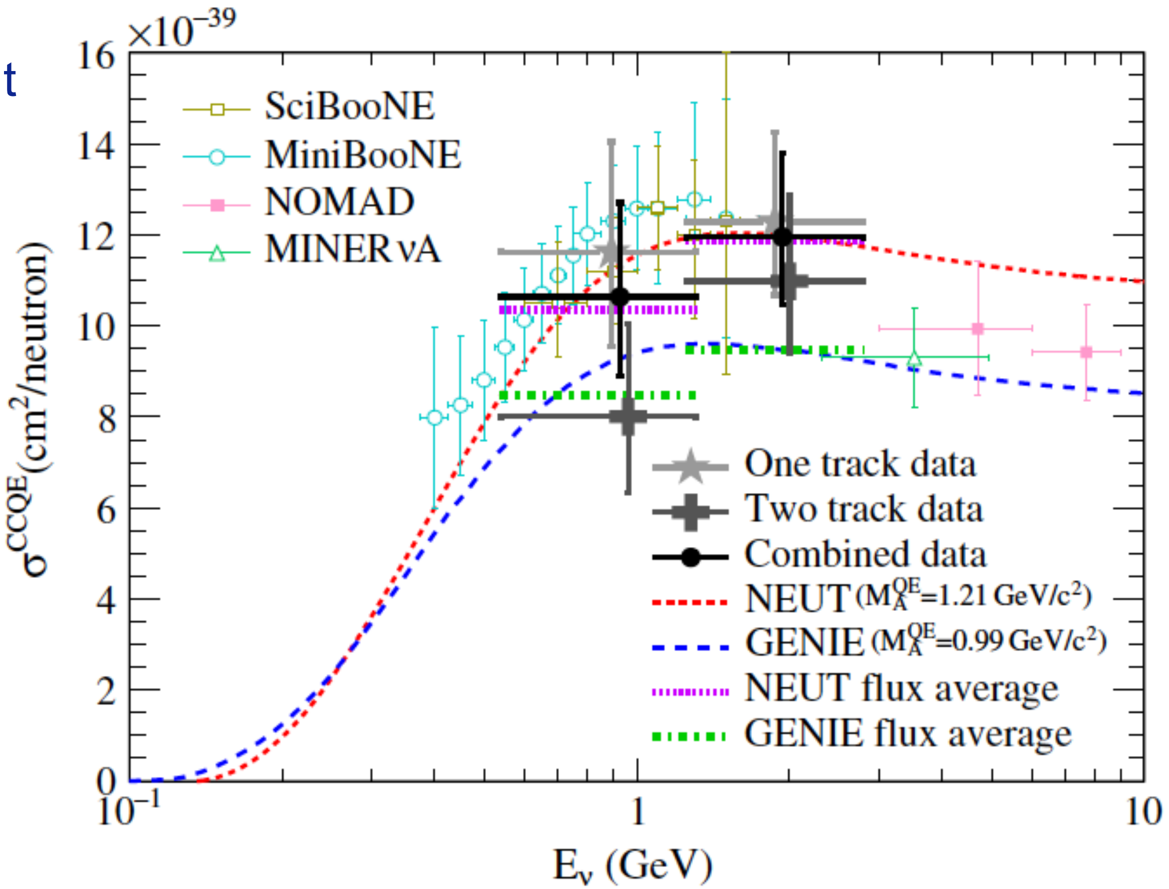
5. Hadron measurements for CCQE

T2K 2-track events

- 1-track and 2-track sample have different total cross sections
- If 2p2h is there, one would expect higher xs for 2-track?
- Maybe protons energy are too low to identify in FGD?
- Nieves model doesn't describe data

2p2h+RPA in neutrino experiment

- Correct idea
- It doesn't pass the precise test
  - not rigorous implementation
  - lack of theoretical errors
  - lack of covariance matrix

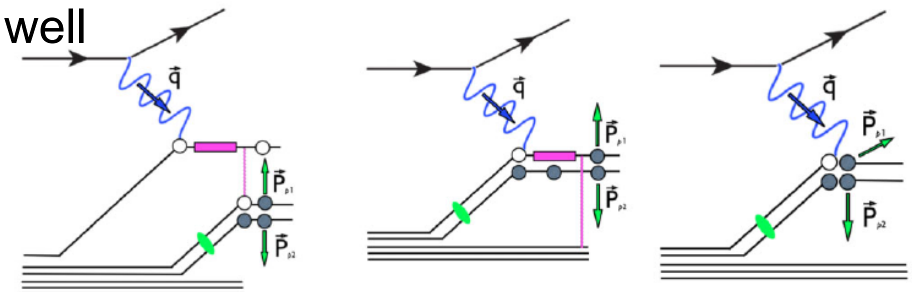


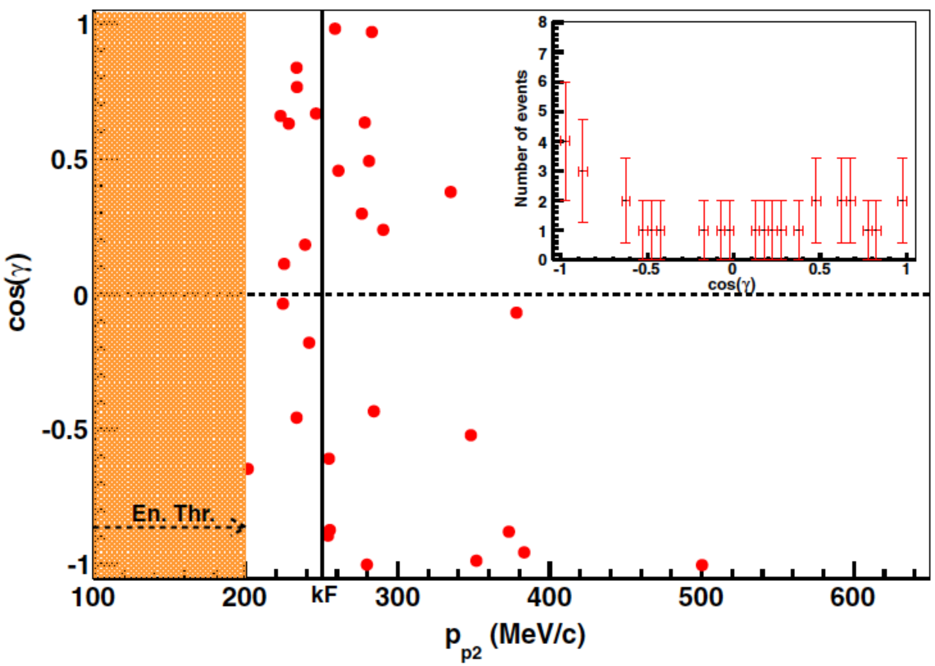
ArgoNeuT,PRD90(2014)012008, JLab Hall A,PRL99(2007)072501
Niewczas and Sobczyk,arXiv:1511.02502, Weinstein et al, arXiv:1604.02482

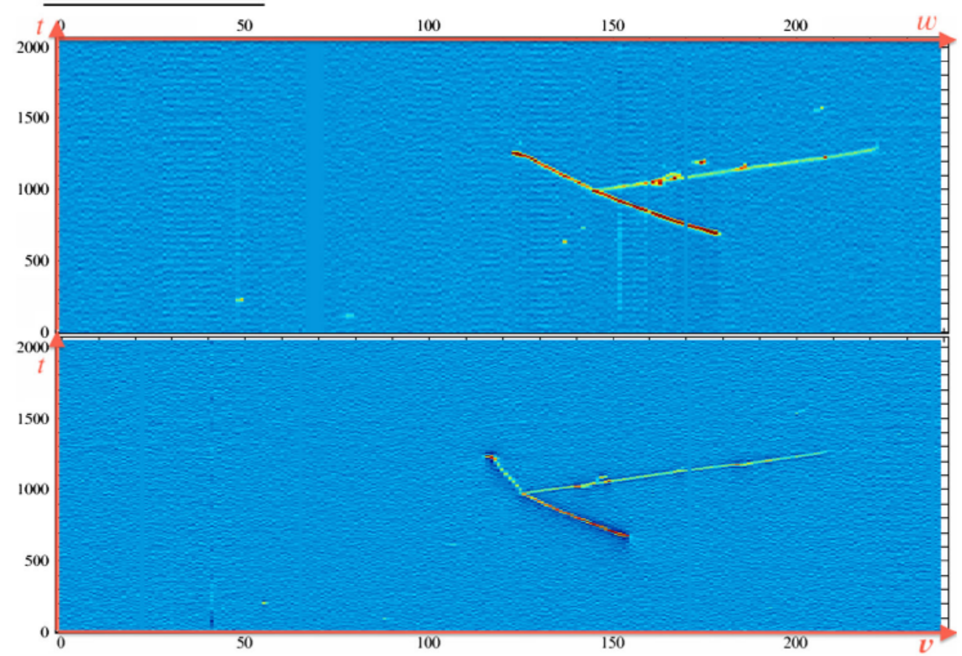
5. Hadron measurements for CCQE

ArgoNeuT hammer event

- 2 proton knockout from argon nucleus
- sometimes they make back-to-back configuration (hammer event)
- It looks like back-to-back in SRC interaction by e-scattering
- can be explained by Δ excitation
- We don't know FSI for argon target very well



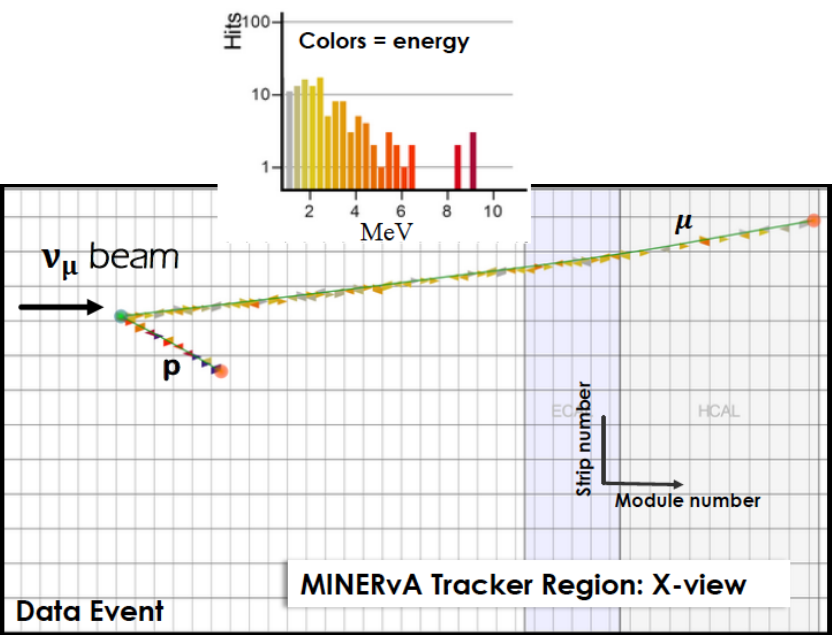


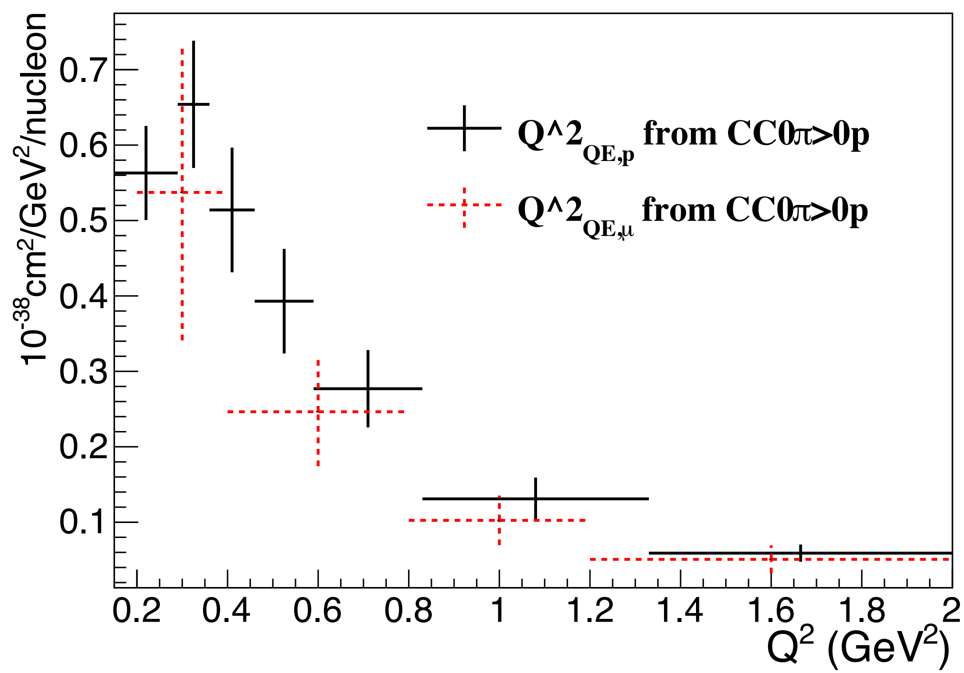


5. Hadron measurements for CCQE

MINERvA 2-track events

- signal = "1 muon and at least 1 proton and no pions (CC0π>p)"
- Q^2 is reconstructed from both muon and proton kinematics and they agree
- Large background tuning and subtraction



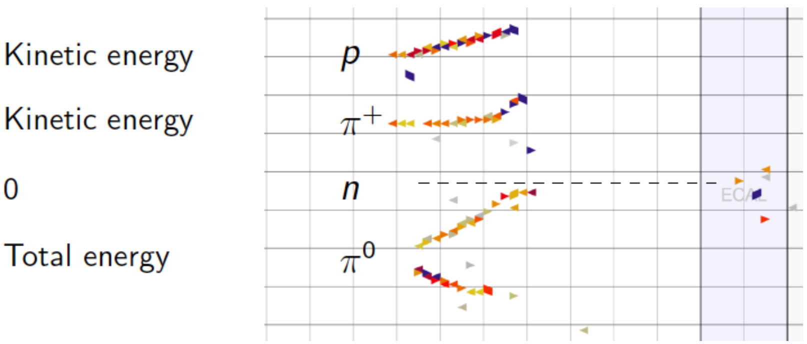


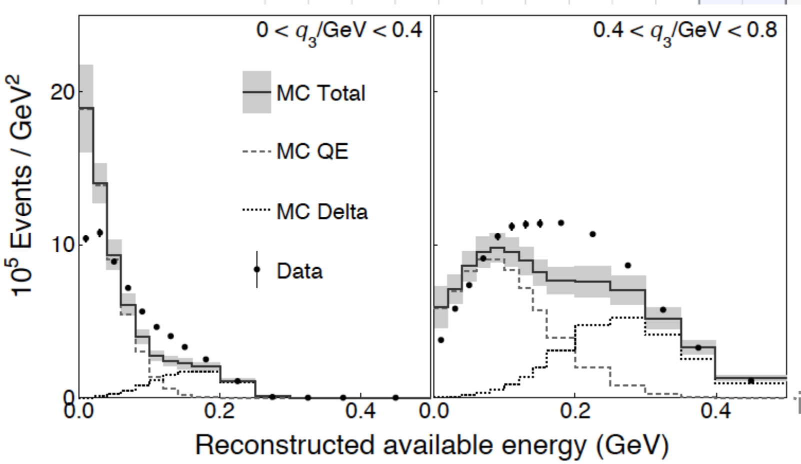
Queen Mary
University of London

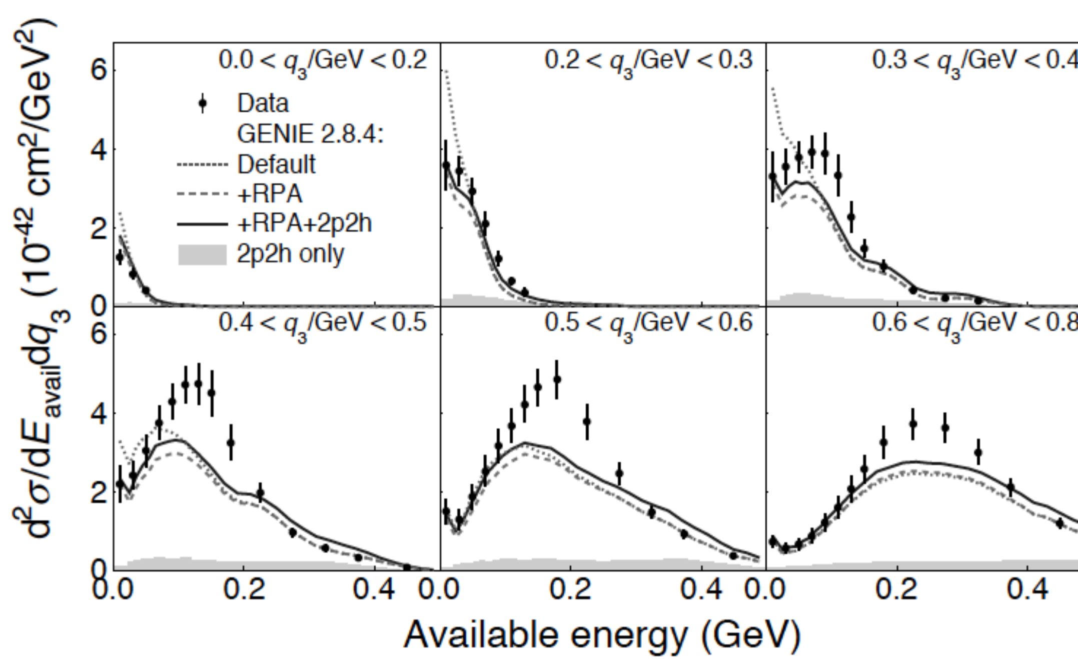
5. Hadron measurements for CCQE

MINERvA ω-q plot

- E_{avail} = ∑(Proton and p± KE) + (Total E of other particles except neutrons) ~ ω
- Eν, Q^2, W are reconstructed from here → effective variables
- First neutrino experiment to shop the "dip" region
- Nieves models underestimates cross section in the dip region



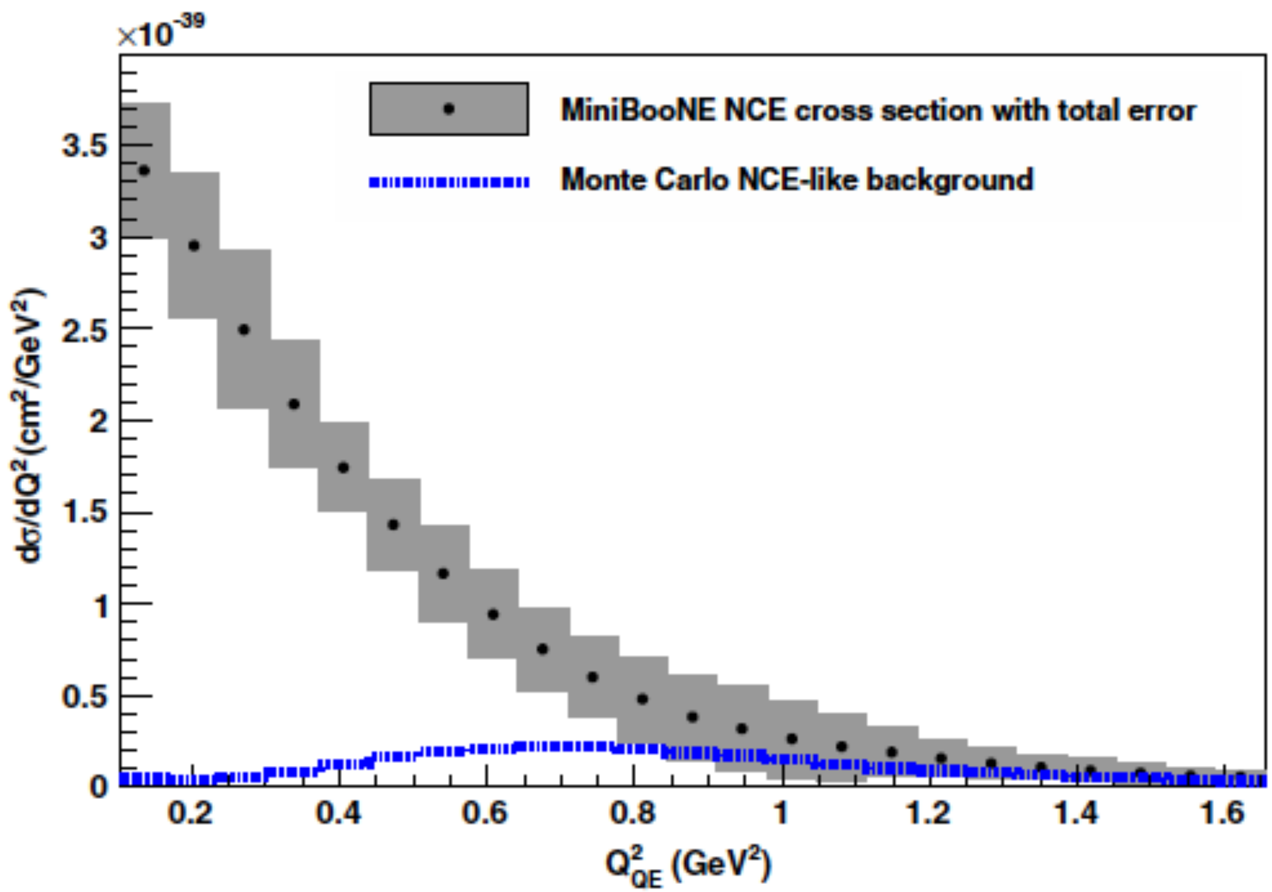




5. Hadron measurements for CCQE

MiniBooNE NCEL measurement

- Calorimetric energy reconstruction
- Larger normalization
- Hard to separate proton-NCEL and neutron-NCEL

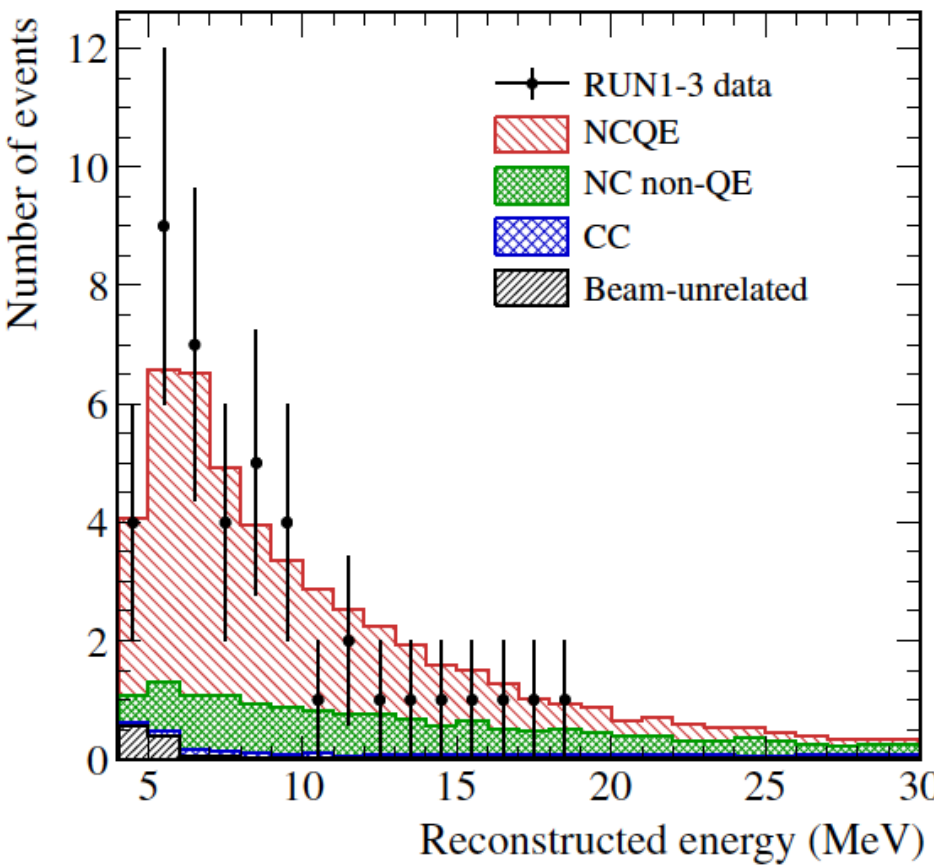


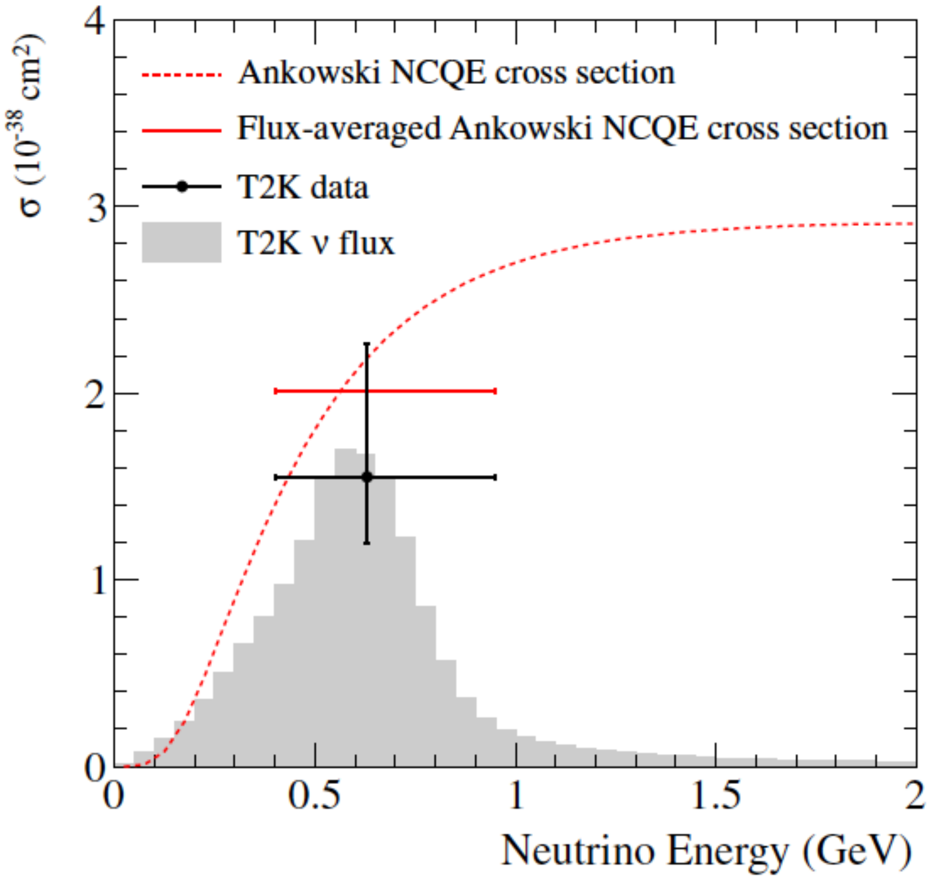
T2K,PRD90(2014)072012
Ankowski et al, PRL108(2012)052505

5. Hadron measurements for CCQE

Super-K NCQE measurement

- Measure de-excitation gamma from NC interaction
- Agree with prediction





5. Hadron measurements for CCQE

We don't expect dramatically better QE measurement with leptons
- normalization error is dominated by flux prediction
- shape error is dominated by flux and background prediction

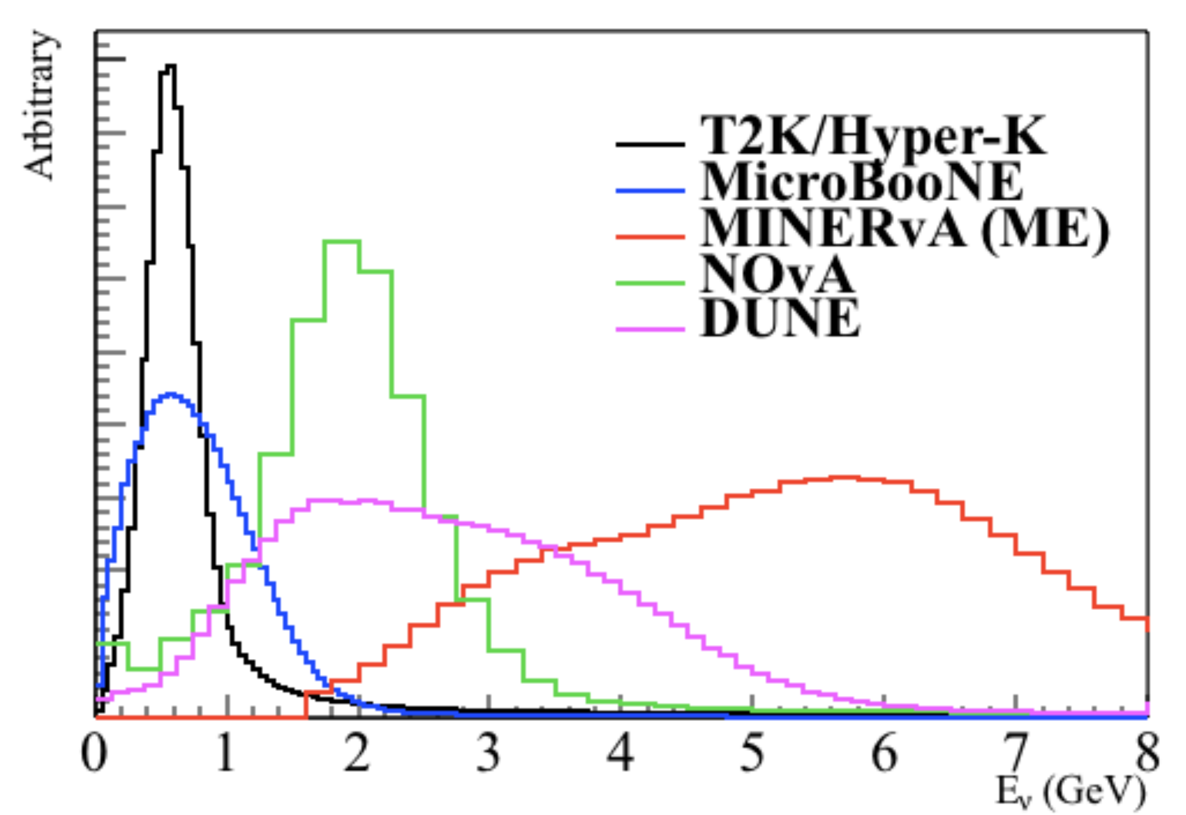
Hadron kinematics are the next step to study CCQE, but there are many problems

Theory

1. FSIs (especially for large A)
2. Hadron final state simulation from 2p2h+RPA interactions
3. large W contribution (resonance → SIS → DIS)
- Hadronization

Experiment

4. Hadron propagation in the detector media (secondary interaction)
5. Detector efficiency of low energy short track hadrons



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(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please “like” our Facebook page, use hashtag #nuxsec

6. Conclusion

Tremendous amount of activities, new data, new theories…
- NuInt15 at Osaka, Japan

http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46

Neutrino physics in 1-10 GeV will be important next 20 years.

We need models work in all phase space. This moment, RPA based calculation is successful. Neutrino experiment is always “inclusive” in terms of electron scattering.

Flux-integrated differential cross section is the way to communicate between theorists and experimentalists.

It looks unlikely that any new lepton measurements provide new information of CCQE. Role of hadron information is getting more important.

Thank you for your attention!

Subscribe “Neutrino Cross-Section Newsletter”
(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please “like” our Facebook page, use hashtag #nuxsec

6. Conclusion

Neutrino oscillation

electron scattering

nuclear many-body problem

Weak interaction

EMC effect

Nucleon correlation

Neutrino Interaction Physics

Spin physics

Dark matter

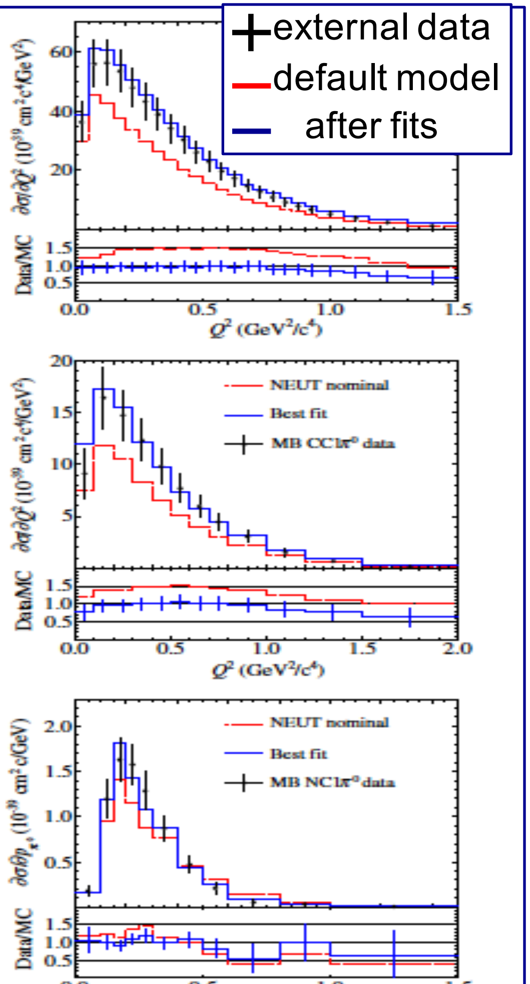
Heavy ion collision

Thank you for your attention!

Backup

1. T2K oscillation experiments

External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics

T2K, PRD88(2013)032002,PRL112(2014)061802

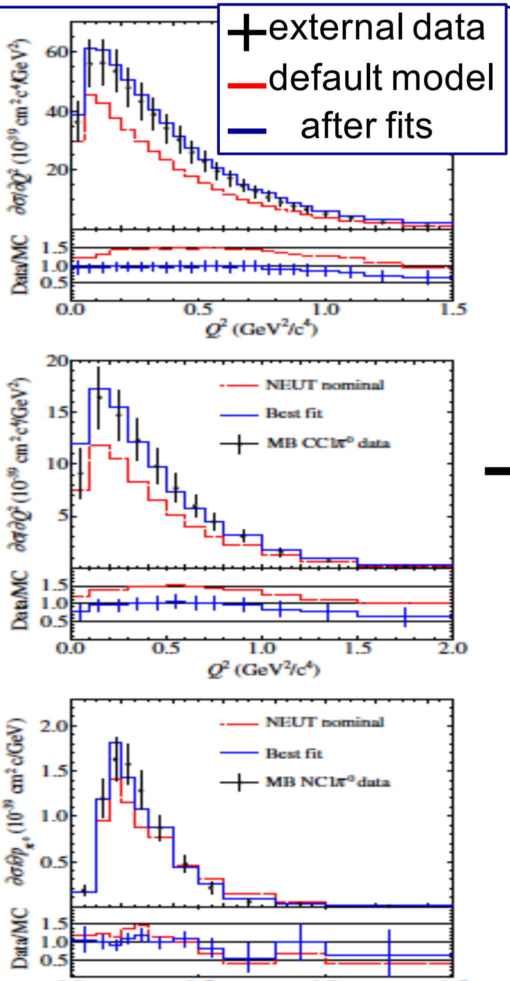
1. T2K oscillation experiments

External constraint

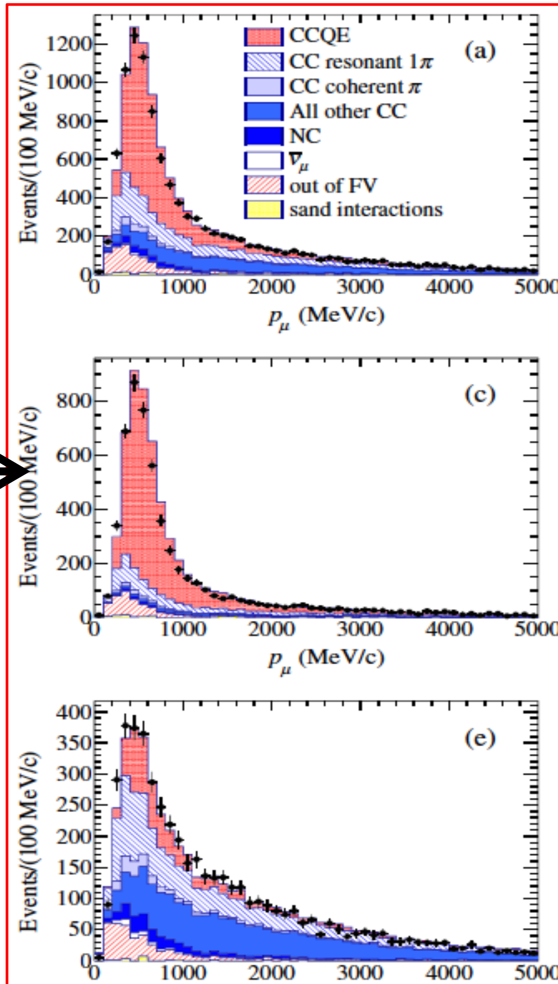
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint

Near detector
oscillation non-sensitive channels



External data fit



T2K ND280 data fit

Constraint from internal data find actual size of cross-section errors

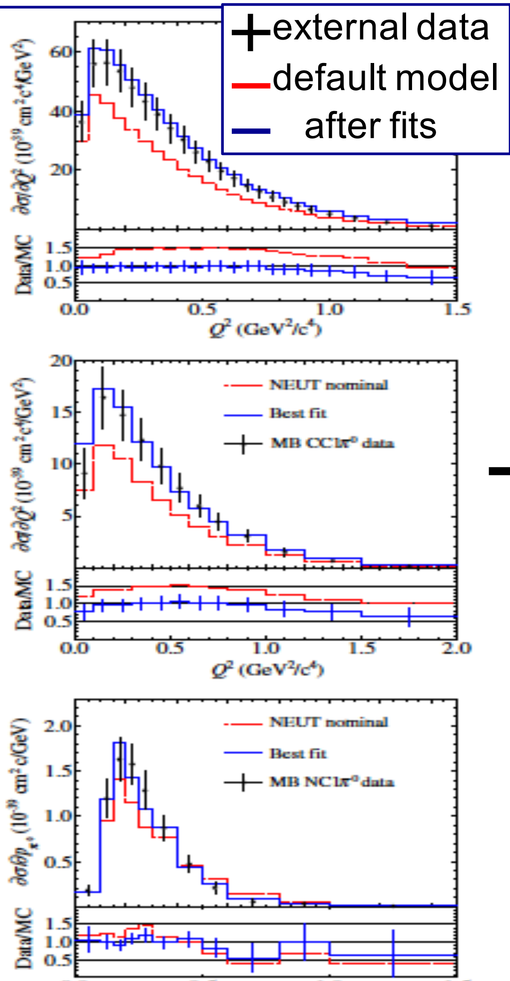
T2K, PRD88(2013)032002,PRL112(2014)061802,PRD91(2015)072010

1. T2K oscillation experiments

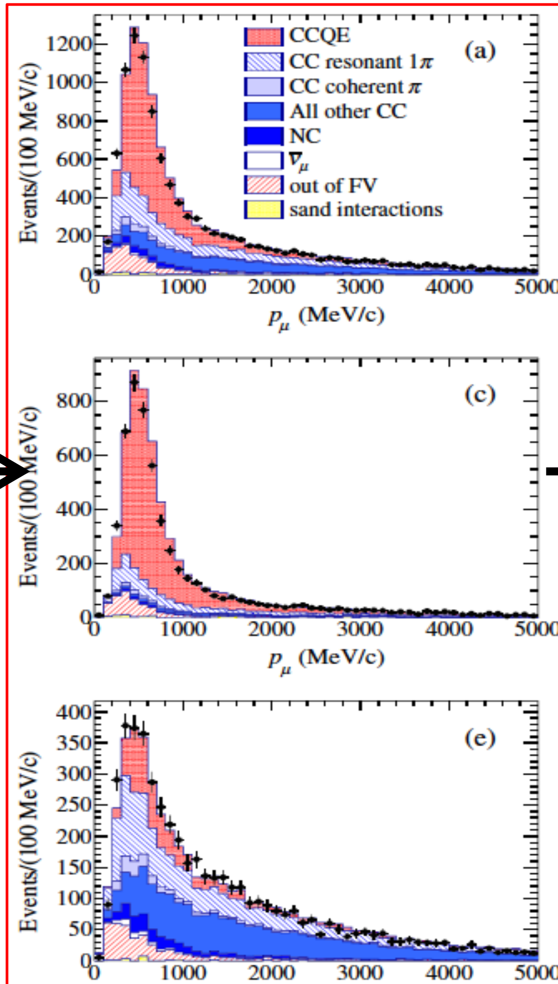
External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint
Near detector
oscillation non-sensitive channels

Neutrino interaction model is a large systematics of neutrino oscillation experiment

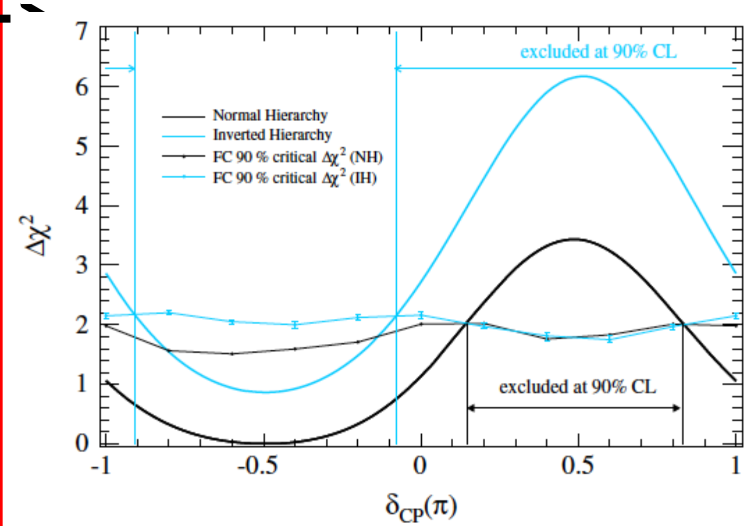


External data fit



T2K ND280 data fit

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI + SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%



oscillation result

1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Simulation (theory)

1. Neutrino oscillation experiment

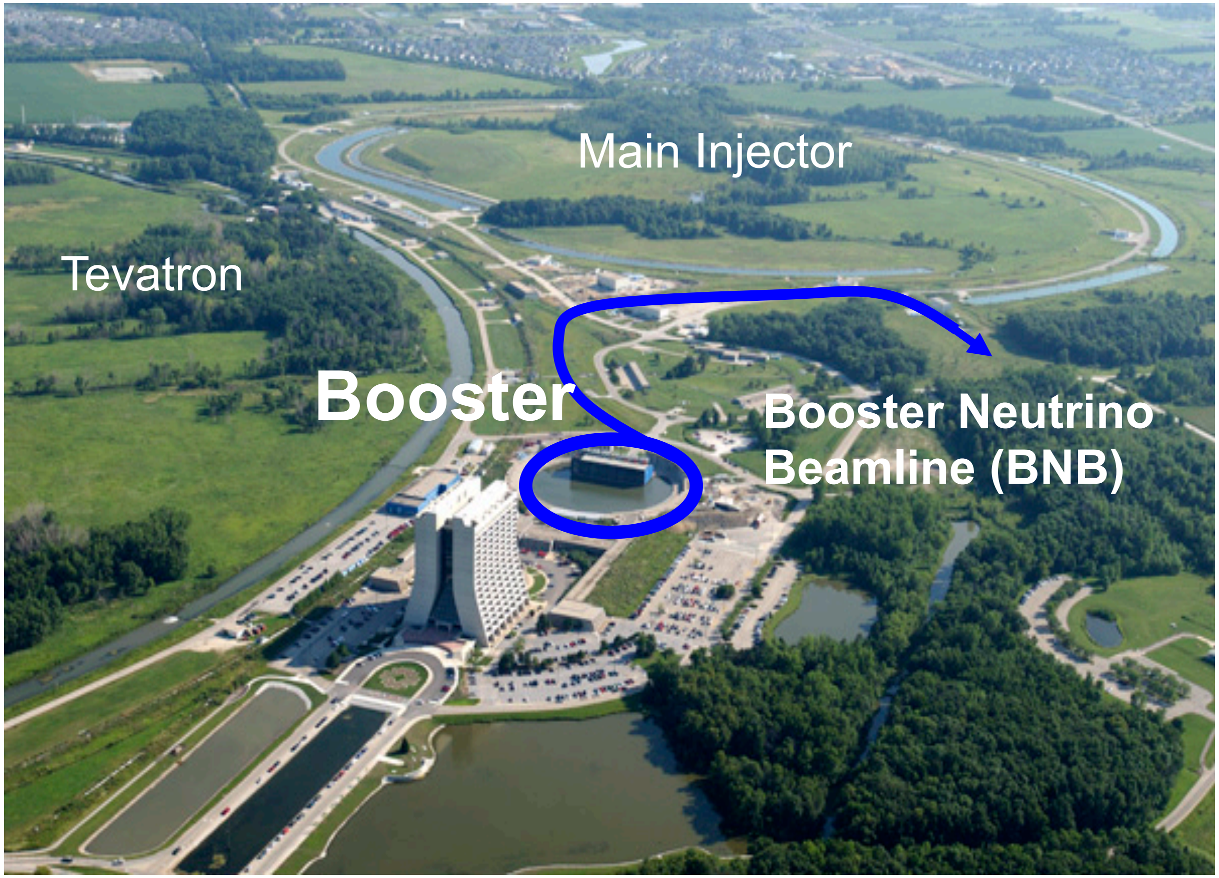
Neutrino interaction model dependence goes to red boxes

Data (nature)

Simulation (theory)

Produce neutrino beam

Fermilab accelerator complex



1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

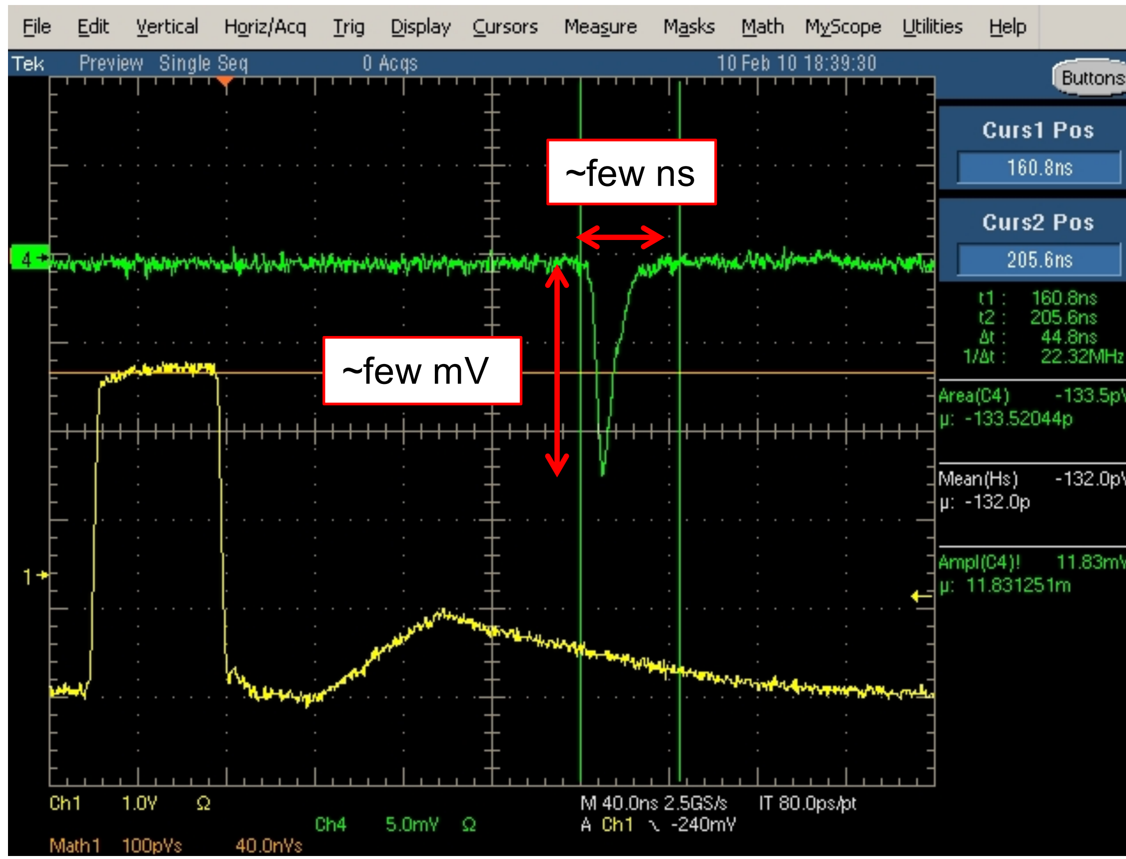
↓

Interaction in the detector makes electric signals

observed electric signal

Simulation (theory)

Typical PMT pulse



1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

↓

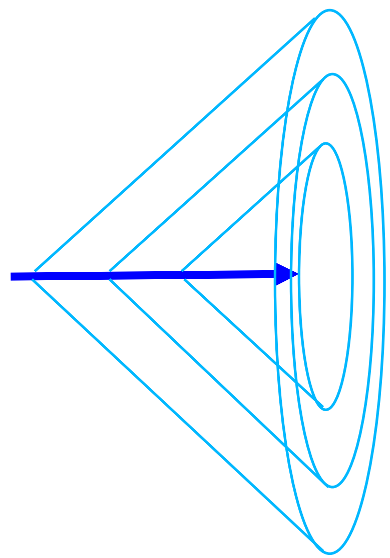
observed electric signal — Interaction in the detector makes electric signals

↓

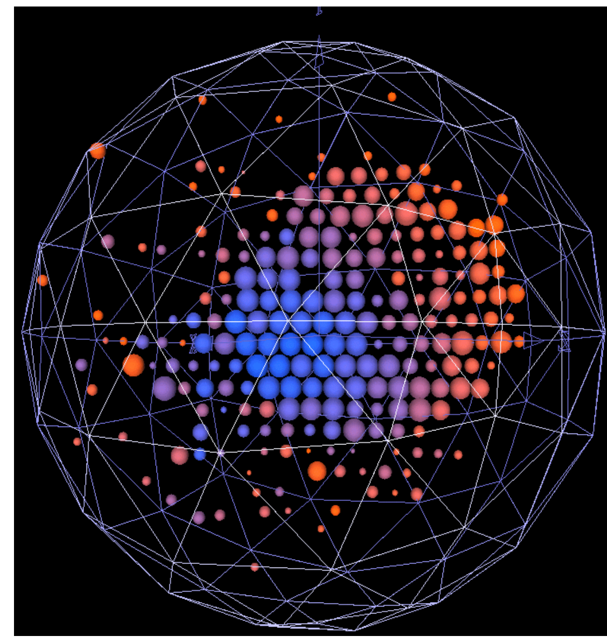
E_μ^{recon} — Particle kinematics are reconstructed from electric signals

Simulation (theory)

muon (sharp edge Cherenkov ring)



MiniBooNE event display of muon candidate event



1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

Data (nature)

Produce neutrino beam

↓

observed electric signal — Interaction in the detector makes electric signals

↓

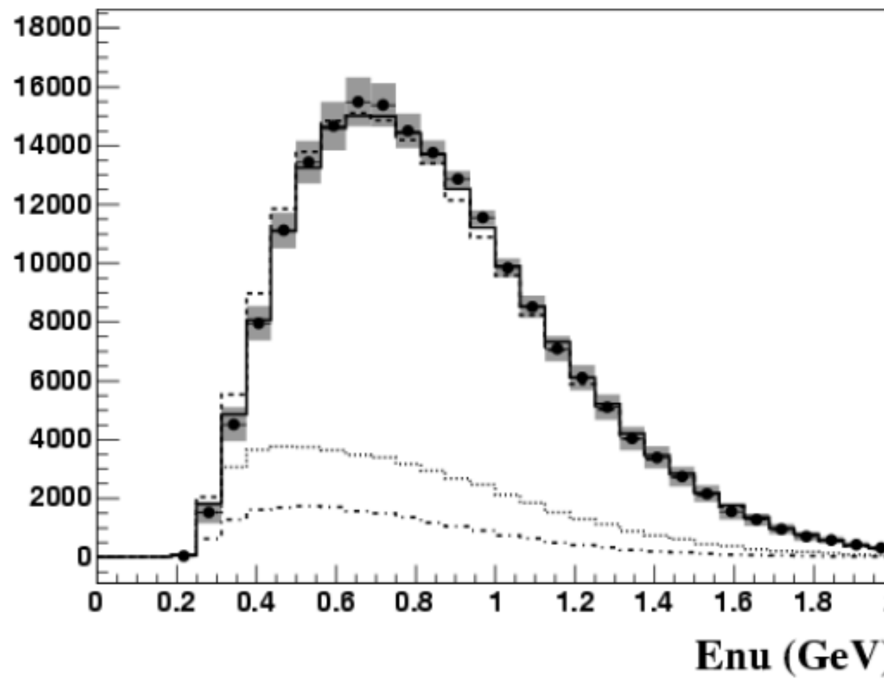
$E\mu^{recon}$ — Particle kinematics are reconstructed from electric signals

↓

$E\nu^{recon}$ — Neutrino energy is reconstructed from charged particle kinematics

Simulation (theory)

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



1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

$\Phi(E_\nu)$

Data (nature)

Produce neutrino beam

↓

observed electric signal — Interaction in the detector makes electric signals

↓

E_μ^{recon} — Particle kinematics are reconstructed from electric signals

↓

E_ν^{recon} — Neutrino energy is reconstructed from charged particle kinematics

Simulation (theory)

Simulate neutrino beam

E_ν^{true}

1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

$\Phi(E_\nu)\times P(L,E_\nu)$

Data (nature)

Produce neutrino beam

observed electric signal — Interaction in the detector makes electric signals

E_μ^{recon} — Particle kinematics are reconstructed from electric signals

E_ν^{recon} — Neutrino energy is reconstructed from charged particle kinematics

Simulation (theory)

Simulate neutrino beam — E_ν^{true}

Add neutrino oscillation — E_ν^{true}

1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

$$\Phi(E_\nu)\times P(L,E_\nu)\times\sigma(q,\omega)$$

Data (nature)

- Produce neutrino beam
- ↓
- observed electric signal — Interaction in the detector makes electric signals
- ↓
- E_μ^{recon} — Particle kinematics are reconstructed from electric signals
- ↓
- E_ν^{recon} — Neutrino energy is reconstructed from charged particle kinematics

Simulation (theory)

- Simulate neutrino beam — E_ν^{true}
- ↓
- Add neutrino oscillation — E_ν^{true}
- ↓
- Simulate neutrino interaction to predict particle kinematics — E_μ^{true}

1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

$$\Phi(E_\nu)\times P(L,E_\nu)\times\sigma(q,\omega)\times\varepsilon(observables) = R$$

Data (nature)

- Produce neutrino beam
- Interaction in the detector makes electric signals — observed electric signal
- Particle kinematics are reconstructed from electric signals — E_μ^{recon}
- Neutrino energy is reconstructed from charged particle kinematics — E_ν^{recon}

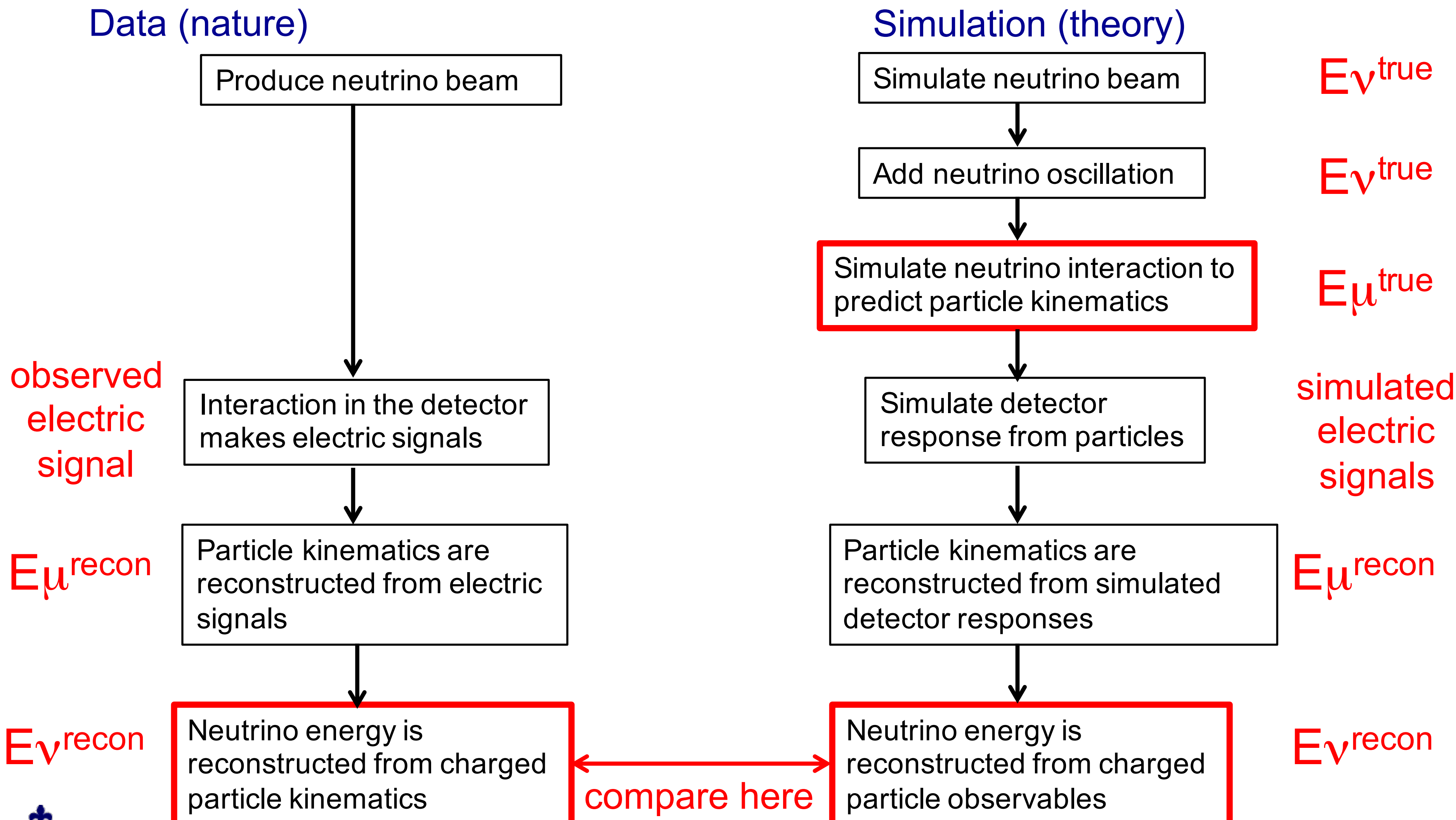
Simulation (theory)

- Simulate neutrino beam — E_ν^{true}
- Add neutrino oscillation — E_ν^{true}
- Simulate neutrino interaction to predict particle kinematics — E_μ^{true}
- Simulate detector response from particles — simulated electric signals
- Particle kinematics are reconstructed from simulated detector responses — E_μ^{recon}

1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

$$\Phi(E_\nu)\times P(L,E_\nu)\times\sigma(q,\omega)\times\varepsilon(observables) = R$$



T2K, PRD88(2013)032002

1. Neutrino oscillation experiment

Neutrino interaction model dependence goes to red boxes

$$\Phi(E_\nu)\times P(L,E_\nu)\times\sigma(q,\omega)\times\varepsilon(observables) = R$$

Data (nature)

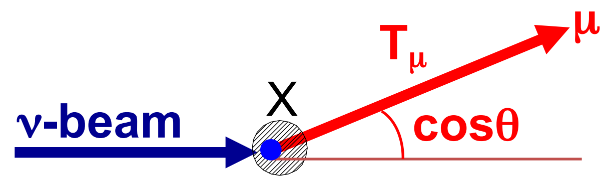
- Produce neutrino beam
- **Regardless reconstruct neutrino energy or not, neutrino interaction models are always a problem of oscillation experiments**
- Interaction in the detector makes electric signals — observed electric signal
- Particle kinematics are reconstructed from electric signals — E_μ^{recon}
- Neutrino energy is reconstructed from charged particle kinematics — E_ν^{recon}

Simulation (theory)

- Simulate neutrino beam — E_ν^{true}
- Add neutrino oscillation — E_ν^{true}
- Simulate neutrino interaction to predict particle kinematics — E_μ^{true}
- Simulate detector response from particles — simulated electric signals
- Particle kinematics are reconstructed from simulated detector responses — E_μ^{recon}
- Neutrino energy is reconstructed from charged particle observables — E_ν^{recon}

compare here

2. Neutrino experiment



Experiment measure the interaction rate R,

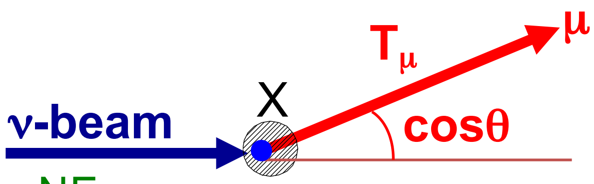
$$R \sim \int \Phi \times \sigma \times \varepsilon$$

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

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

$$R = \Phi(E_\nu) \times P(L, E_\nu) \times \sigma(q, \omega) \times \varepsilon(observables)$$

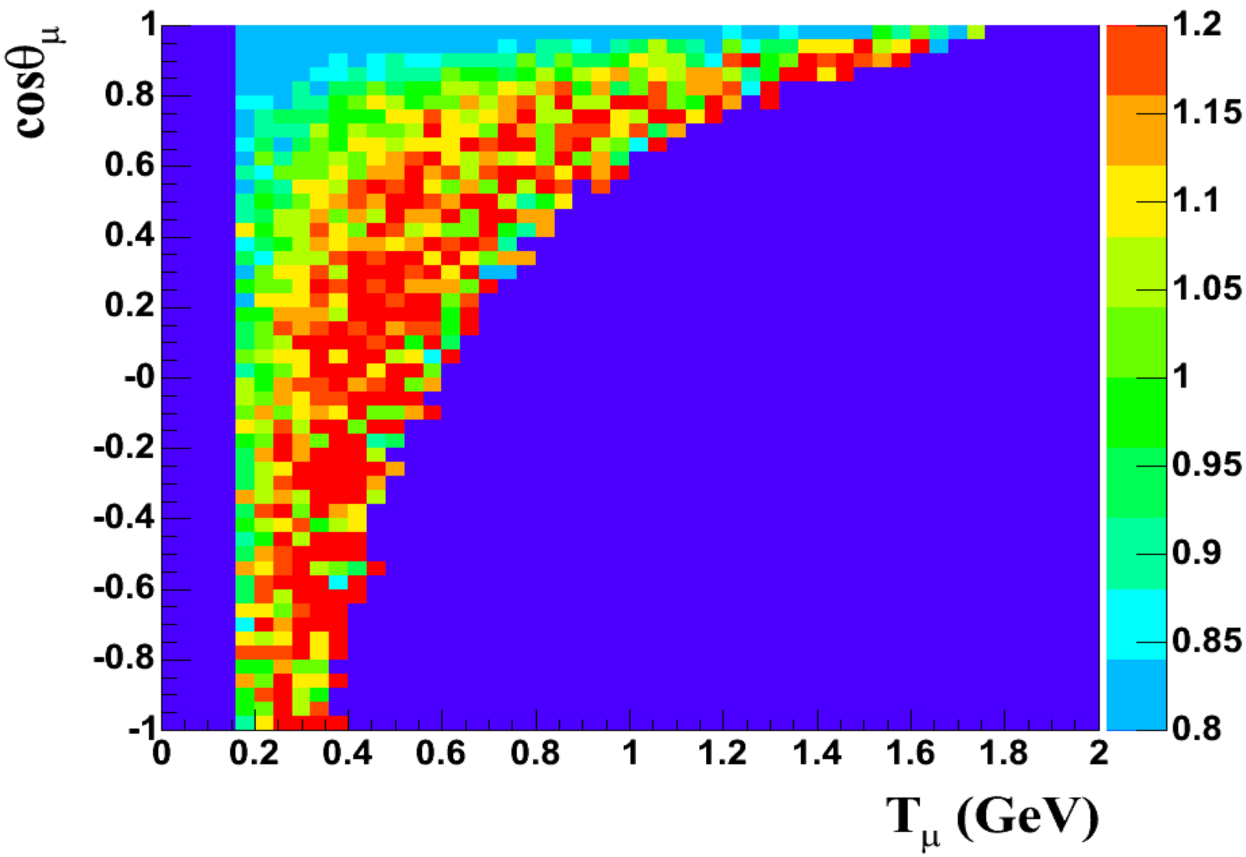
2. MiniBooNE phase space



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.

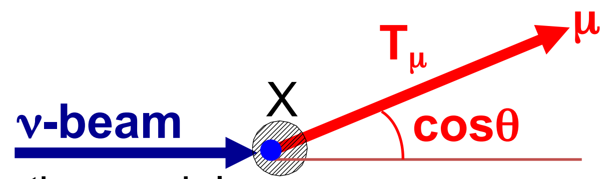
$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$



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?

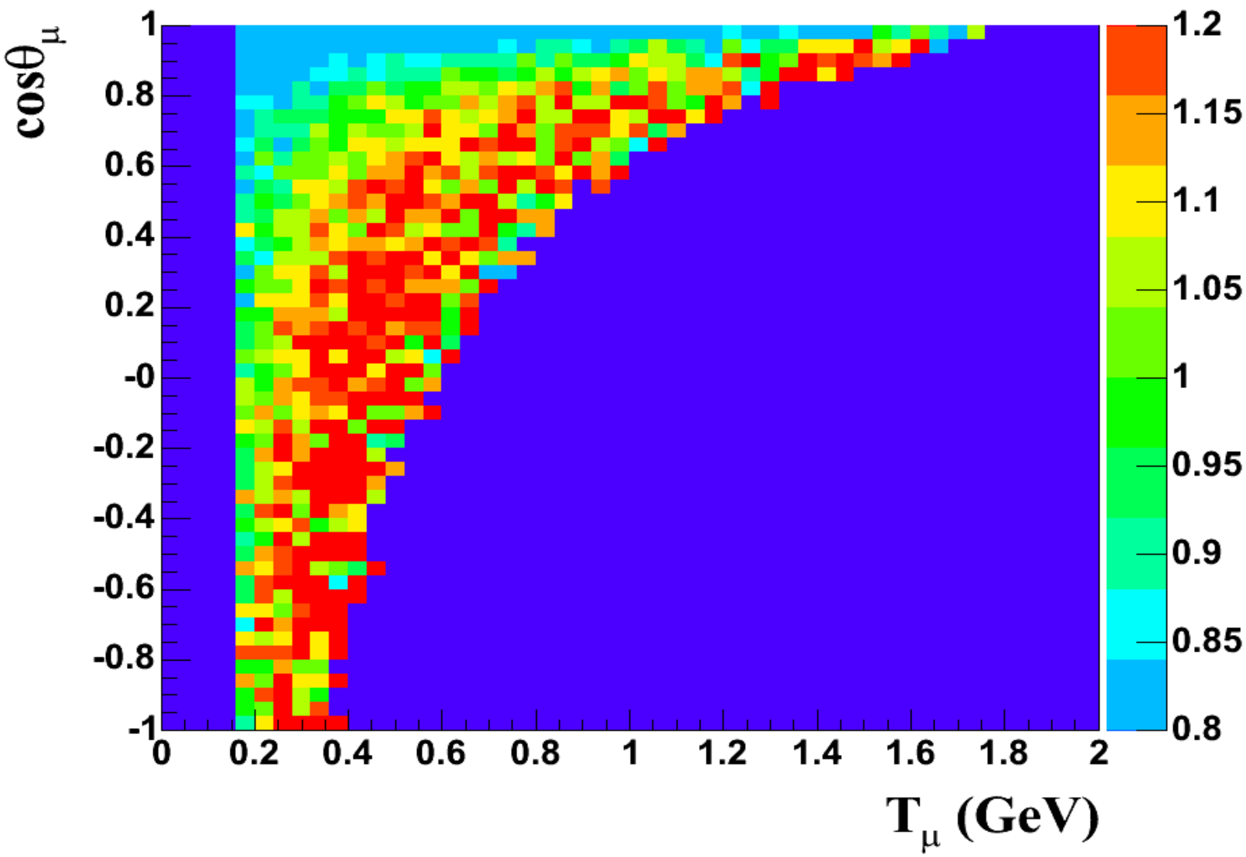
2. MiniBooNE phase space



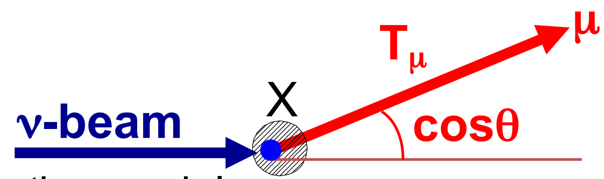
Without knowing flux, you cannot modify cross section model

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

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



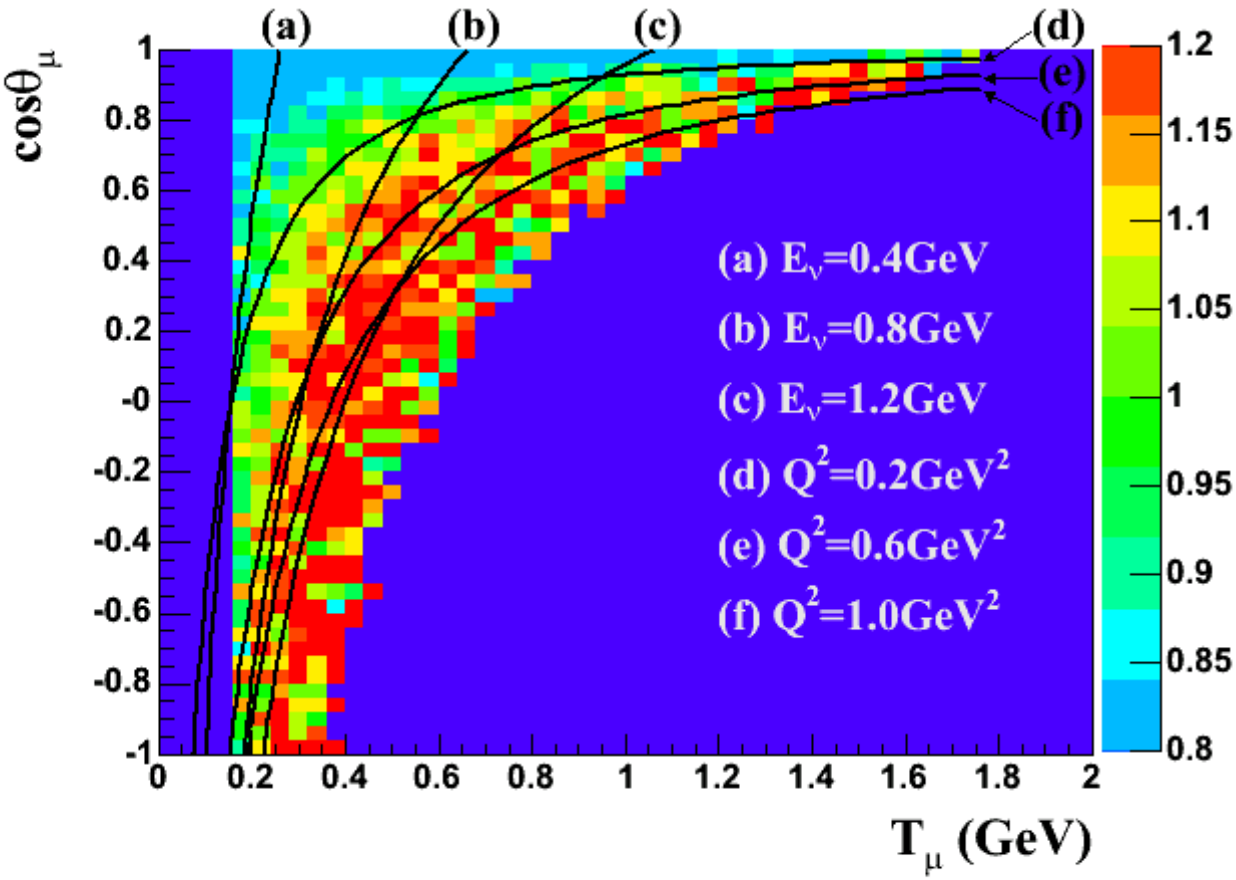
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

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

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

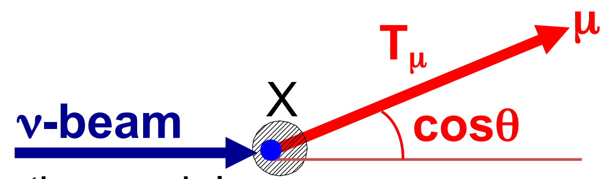


The data-MC disagreement follows equal Q^2- lines, not equal E_ν-lines.

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

MiniBooNE collaboration,PRL.100(2008)032301

2. MiniBooNE phase space

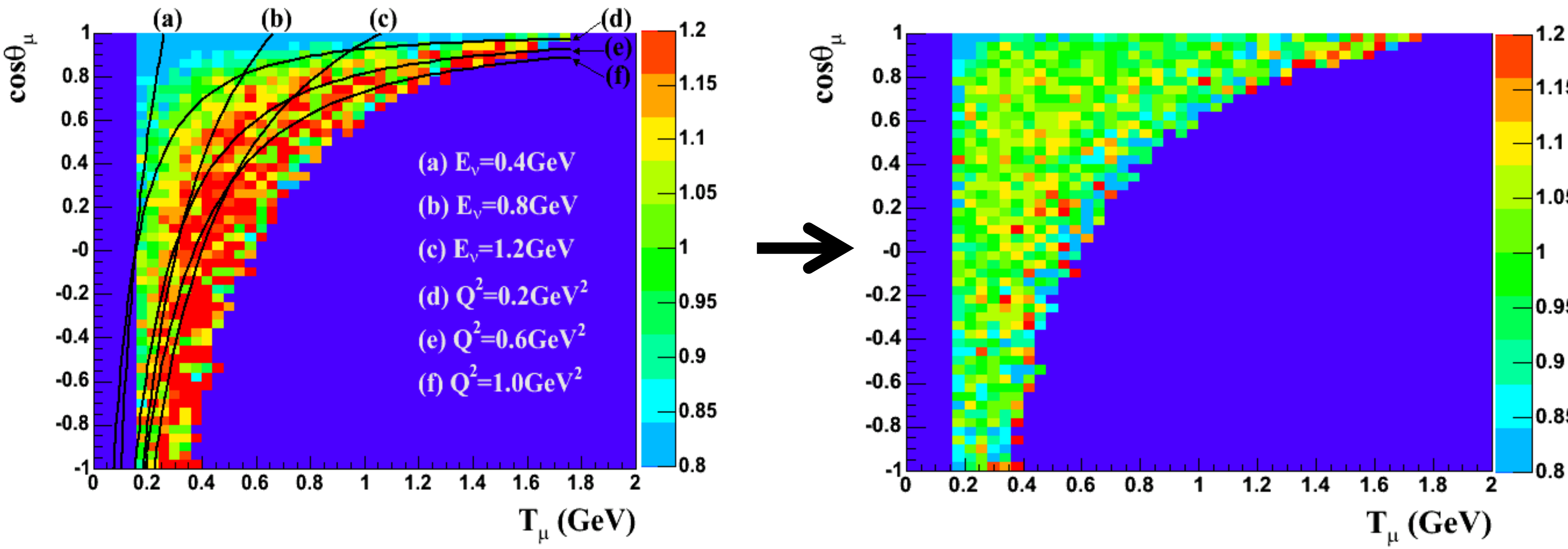


Without knowing flux, you cannot modify cross section model

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

After tuning cross section parameters, data and MC agree.

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



2. Noise, misID, and intrinsic background of CCQE

Noise
- recorded detector related errors as signal (often it's random)
→ small for GeV neutrino experiments

misID
- fail to identify signal topology as signal (small)
- identify wrong topologies as signal topology

(failed to reconstruct π^- track and fail to reject π^- track)

Intrinsic
- interactions with same topology with signal
  - Intrinsic Beam background
  - Intrinsic interaction background

ex) ν_μCCQE measurement
- interactions with same topology with signal

Background depends on how to define signal
i) Genuine QE (QE in e-scattering experiment)
ii) CCQE-like (MiniBooNE, MINERvA)
iii) CC0π (T2K)

5. Conclusion remarks from INT workshop 2013

"ν-A Interactions for Current and Next Generation Neutrino Oscillation Experiments", Institute of Nuclear Theory (Univ. Washington), Dec. 3-13, 2013

Toward better neutrino interaction models…

To experimentalists

- The data must be reproducible by nuclear theorists
- State what is exactly measured (cf. CCQE → 1muon + 0 pion + N nucleons)
- Better understanding of neutrino flux prediction

To theorists

- Understand the structure of 2-body current seen in electron scattering
- Relativistic model which can be extended to higher energy neutrinos
- Models should be able to use in neutrino interaction generator (cf. GENIE)
- Precise prediction of exclusive hadronic final state