Neutrino Interaction Physics

Lecture 1: Introduction of neutrino interactions
1. Cross sections
2. Standard Model
3. ν-e scattering cross section

Lecture 2: Charged-current quasi-elastic (CCQE) interaction
4. Conservation of vector current (CVC)
5. Nucleon current
6. Introduction to CCQE interaction
7. CCQE scattering cross section

Lecture 3: Overview of neutrino cross sections
8. Neutrino cross section experiments
9. Neutrino cross section measurements

Teppei Katori
Queen Mary University of London
Summer lecture series, Yokohama National University, Japan, Aug. 1-3, 2018

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References – Books

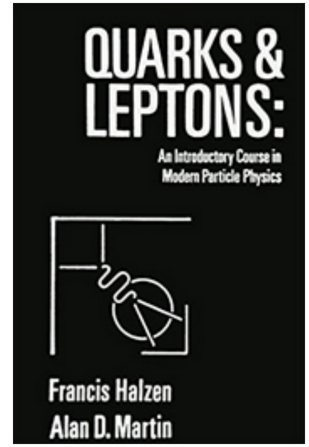
Quarks and Leptons (Q&L, Halzen and Martin)
- classic
- show many calculations
- solutions for all exercises

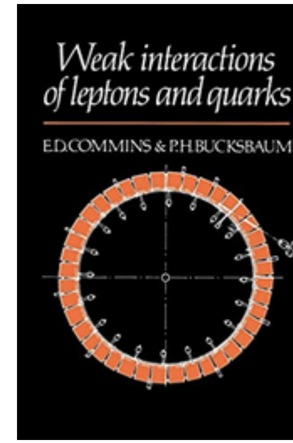
Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- classic
- show more details of weak interaction calculations
- too many typos

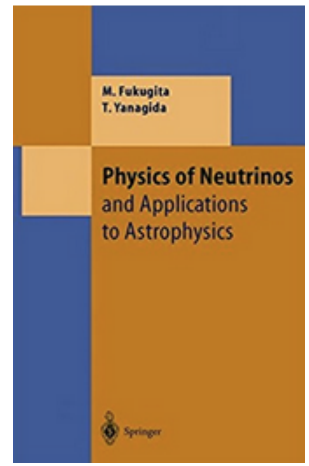
Physics of Neutrinos (Fukugita and Yanagida)
- modern
- very intense
- from solar neutrinos to SUSY

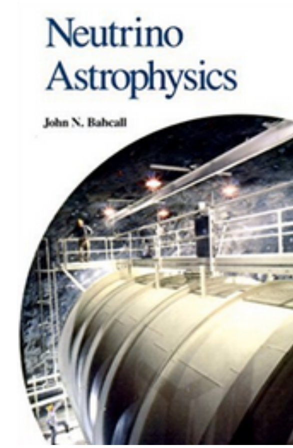
Neutrino astrophysics (Bahcall)
- more likely a novel, honorable mentioning

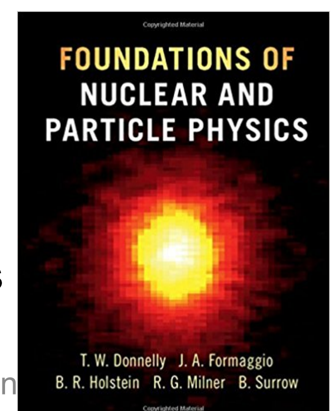
Foundation of Nuclear and Particle Physics (2017)
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- Texbook to fill the gap between nuclear and particle physics











References – Review papers

"From eV to EeV: Neutrino cross sections across energy scales"
 - Authors: Formaggio and Zeller (MicroBooNE spokesperson)
 - Rev.Mod.Phys.84(2012)1307, https://arxiv.org/abs/1305.7513
 - very good summary of neutrino cross sections

"Neutrino-Nucleus Cross Sections for Oscillation Experiments"
 - Authors: Katori (me) and Martini (Martini model)
 - JPhysG45(2017)1, https://arxiv.org/abs/1611.07770
 - my paper, a review both theoretical and experimental views

"NuSTEC White Paper: Status and Challenges of Neutrino-Nucleus Scattering"
 - Authors: NuSTEC colaboration
 - PPNP100(2018)1, https://arxiv.org/abs/1706.03621
 - state-of-the-art list of topics in nuxsec community

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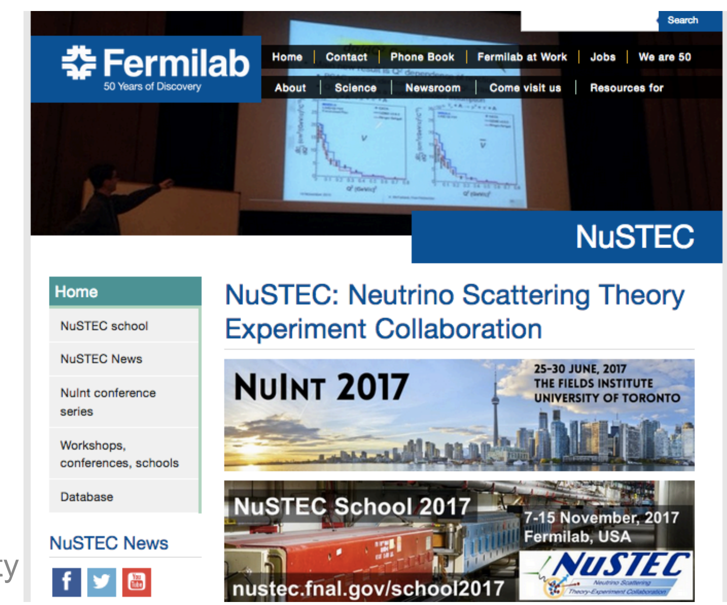


Outline

1. Introduction to cross sections
2. Standard Model and Feynman diagrams
3. ν-e scattering cross section
4. Conservation of vector current (CVC)
5. Nucleon current
6. CCQE interaction
7. CCQE scattering cross section
8. Neutrino cross section experiments
9. Neutrino cross section measurements

Outline

1. Introduction to cross sections
- Lecture loosely based on Q&L, section 4.3
- CMS cross section formula, Q&L, 4.35
- Lab frame cross section formula, original
- dipole form factor formula, original

2. Standard Model and Feynman diagrams
- Lecture loosely based on Q&L, chapter 13

3. ν-e scattering cross section
- Lecture from Fukugita&Yanagida, section 3.10

4. Conservation of vector current (CVC)
- Lecture from Commins and Bucksbaum, section 4.9

5. Nucleon current
- Skipped this time, lecture from Commins and Bucksbaum, section 8.3

Outline

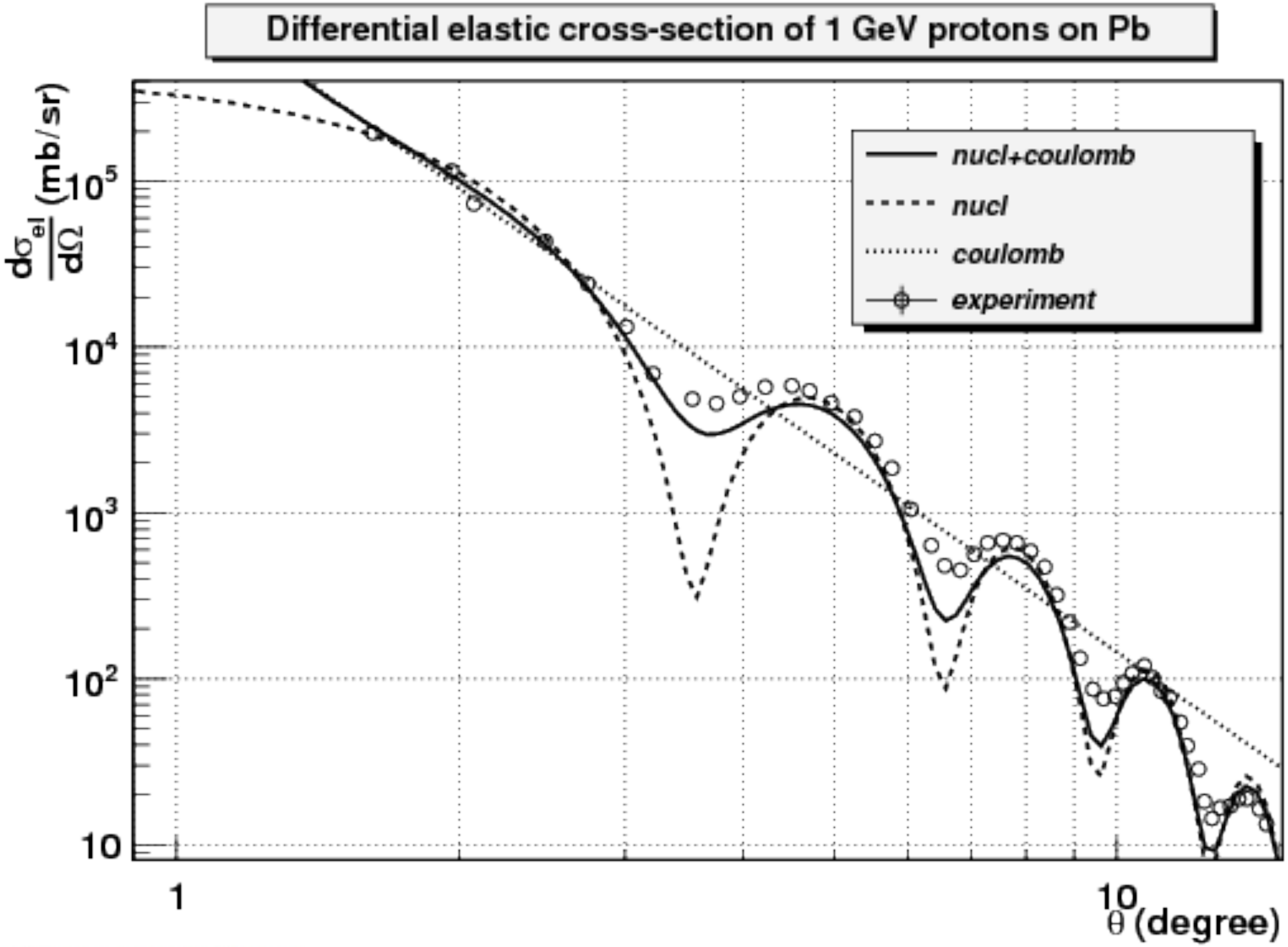
6. CCQE interaction
- Original

7. CCQE scattering cross section
- Lectures and calculations from 3 main papers
- Llewellyn Smith, http://inspirehep.net/record/67183
- Tony Mahn's NOvA technote, http://nova-docdb.fnal.gov/cgi-bin/ShowDocument?docid=28289
- my PhD thesis, Appendix C, http://inspirehep.net/record/806696

8. Neutrino cross section experiments
- Original, based on my talk at IPMU
http://pprc.qmul.ac.uk/~katori/talk/2017/TK_XS_IPMU_17.pdf

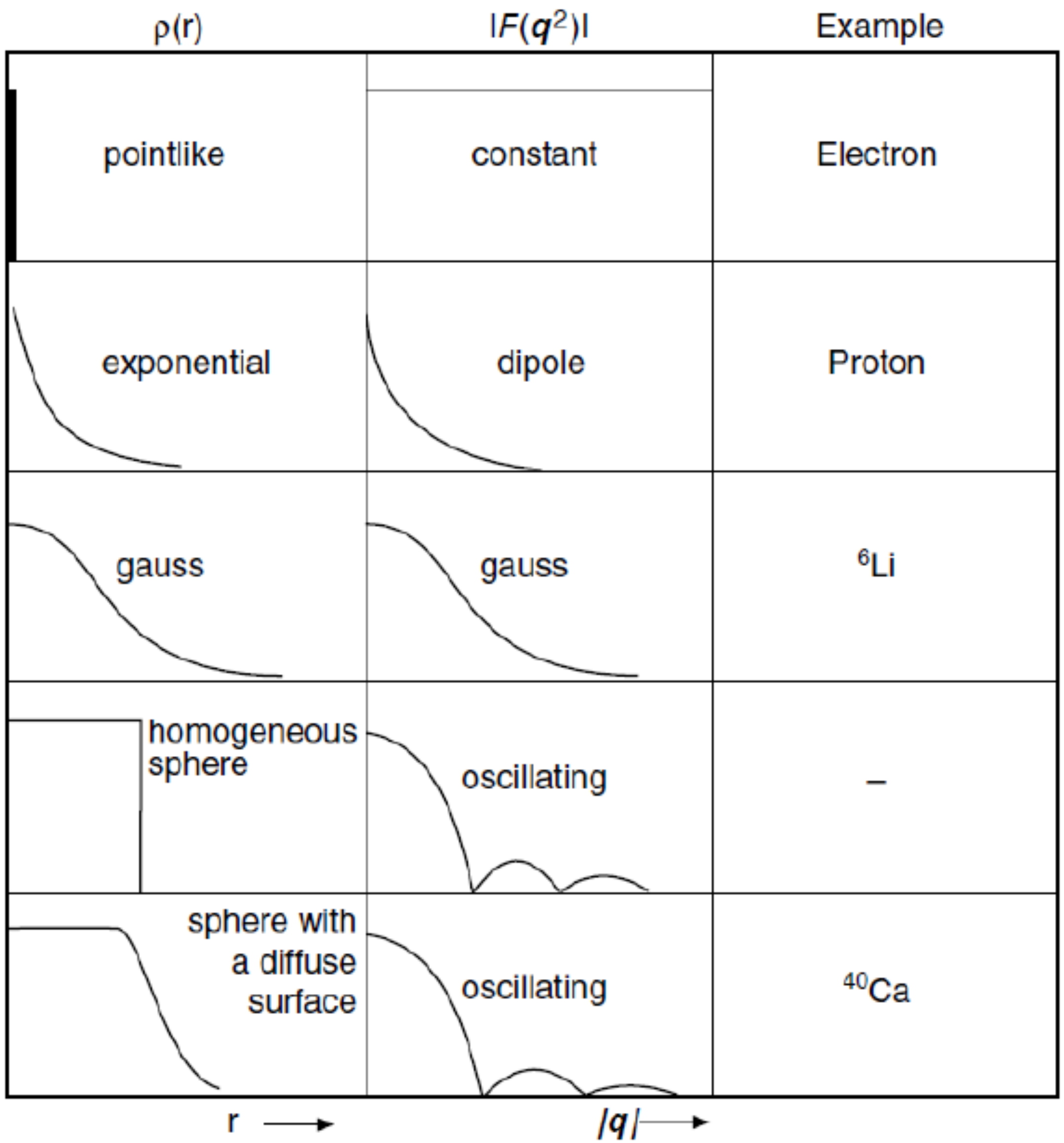
9. Neutrino cross section measurements
- Original, based on my lecture at Fermilab (old)
http://pprc.qmul.ac.uk/~katori/talk/2010/TK_XS_110510.pdf

1. e+Pb → e+Pb elastic scattering



1. Form Factors

Fourier transformation
charge distribution ←→ form factor



$$\Gamma^\mu = \gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu} q_\nu F_2 + \frac{q^\mu}{M} F_S - \gamma^\mu \gamma_5 F_A - \frac{i}{2M}\sigma^{\mu\nu} q_\nu \gamma_5 F_T - \frac{q^\mu}{M}\gamma_5 F_P$$

1. Form Factors

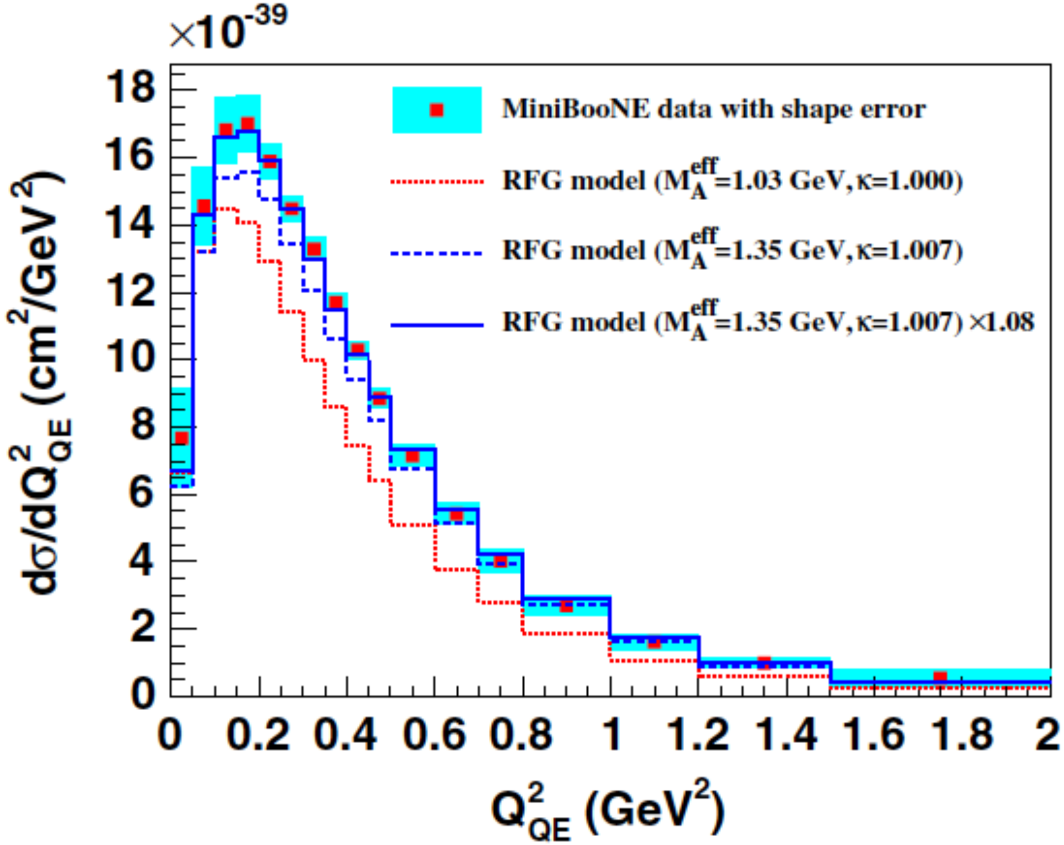


FIG. 14 (color online). Flux-integrated single differential cross section per target neutron for the ν_μ CCQE process. The measured values are shown as points with the shape error as shaded bars. Calculations from the NUANCE RFG model with different assumptions for the model parameters are shown as histograms. Numerical values are provided in Table IX in the appendix.

$$\Gamma^\mu = \gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu} q_\nu F_2 + \frac{q^\mu}{M} F_S - \gamma^\mu \gamma_5 F_A - \frac{i}{2M}\sigma^{\mu\nu} q_\nu \gamma_5 F_T - \frac{q^\mu}{M}\gamma_5 F_P$$

2. Current algebra

$$g_{\mu\nu}g^{\mu\nu} = 4\ , \quad \gamma^5\gamma^5 = \mathrm{I}\ , \quad \{\gamma^5, \gamma^\mu\}_+ = 0\ , \quad tr\{\mathrm{I}\} = 4, \quad tr\{ABC\} = tr\{BCA\}$$

$$\mathbf{tr}\{\gamma_\mu\} = 0\ , \quad \text{and moreover} \quad \mathbf{tr}\{\text{odd number of Dirac } \gamma \text{ matrices}\} = 0\ .$$

$$\mathbf{tr}\{\gamma_\mu\gamma_\nu\} = 4\, g_{\mu\nu} \quad \text{which implies} \quad \mathbf{tr}\{\not{p}\not{q}\} = 4\, p\cdot q\ .$$

$$\mathbf{tr}\{\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\} = 4\, [g_{\mu\nu}\, g_{\rho\sigma} - g_{\mu\rho}\, g_{\nu\sigma} + g_{\mu\sigma}\, g_{\nu\rho}]\ .$$

$$\mathbf{tr}\{\gamma_5\} = 0\ , \quad \mathbf{tr}\{\gamma_5\gamma_\mu\} = 0\ , \quad \mathbf{tr}\{\gamma_5\gamma_\mu\gamma_\nu\} = 0\ , \quad \mathbf{tr}\{\gamma_5\gamma_\mu\gamma_\nu\gamma_\rho\} = 0\ .$$

$$\mathbf{tr}\{\gamma_5\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\} = 4\, i\, \epsilon_{\mu\nu\rho\sigma}\ .$$

Neutrino Cross Section Experiments

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TK and Martini, JPhysG45(2018)013001
Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1

1. Neutrino Interaction Physics

2. MiniBooNE

3. T2K near detector

4. MINERvA

5. LArTPC

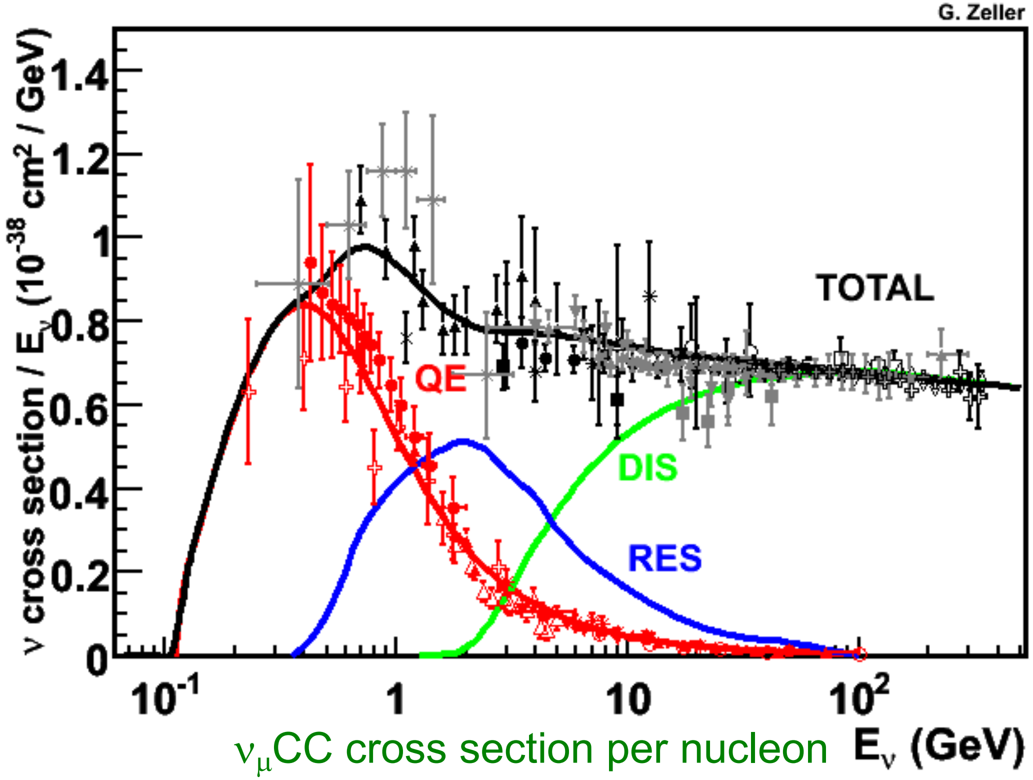
6. Conclusion

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



ν_μCC cross section per nucleon

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

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

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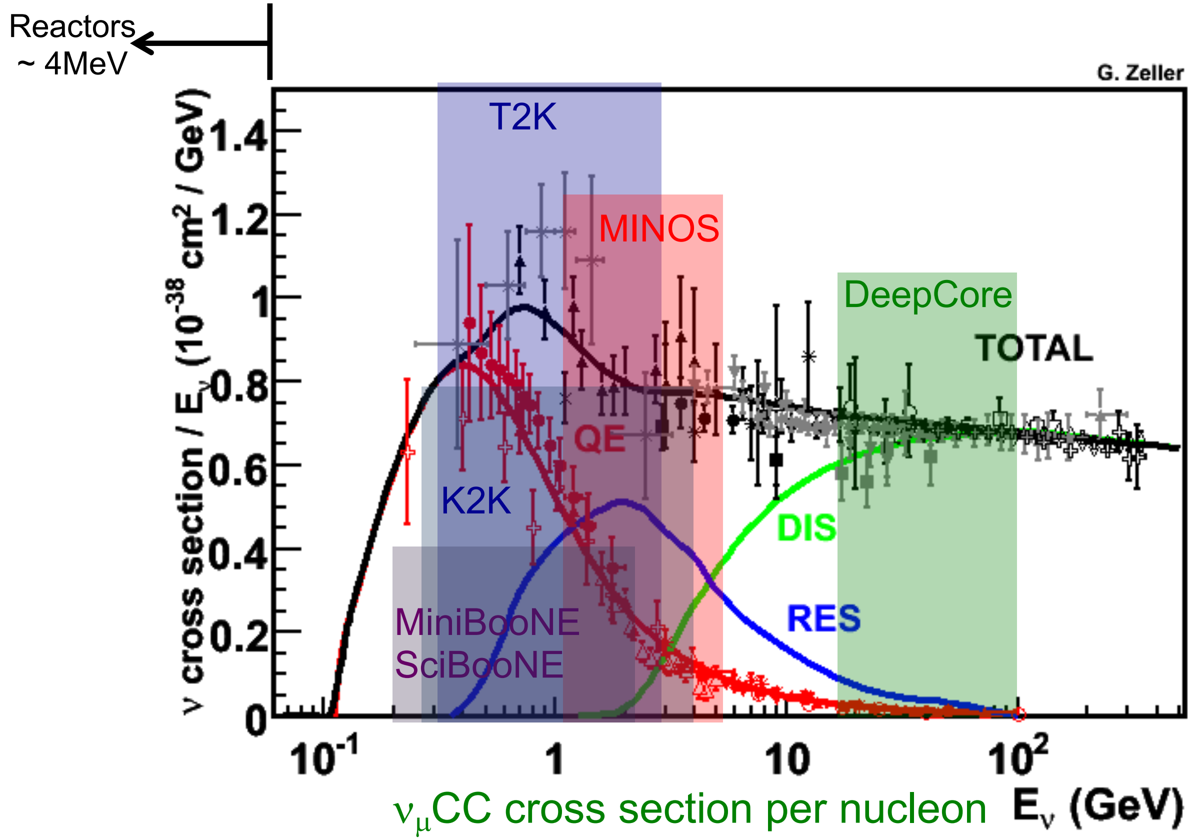

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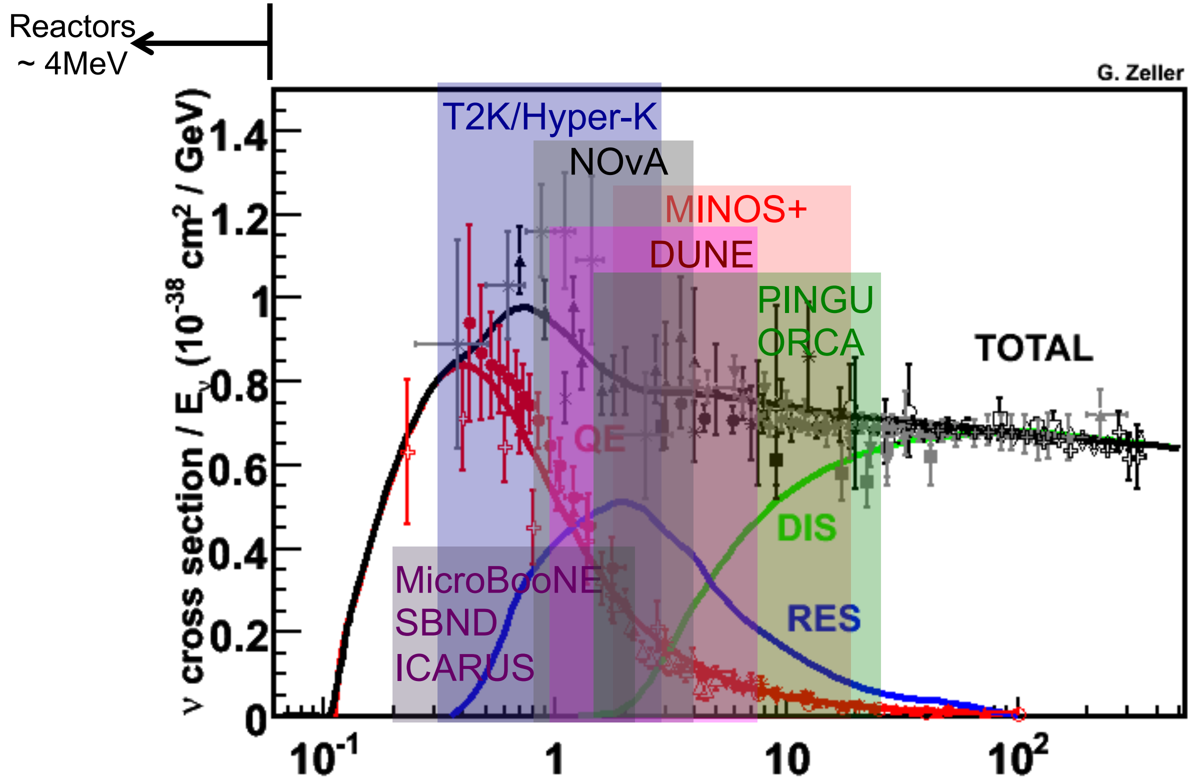

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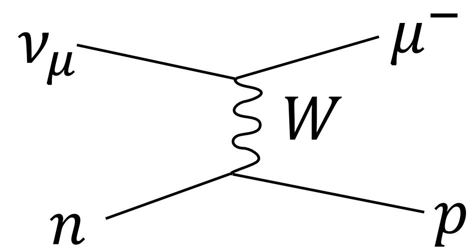
$$P_{\mu \to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. K2K

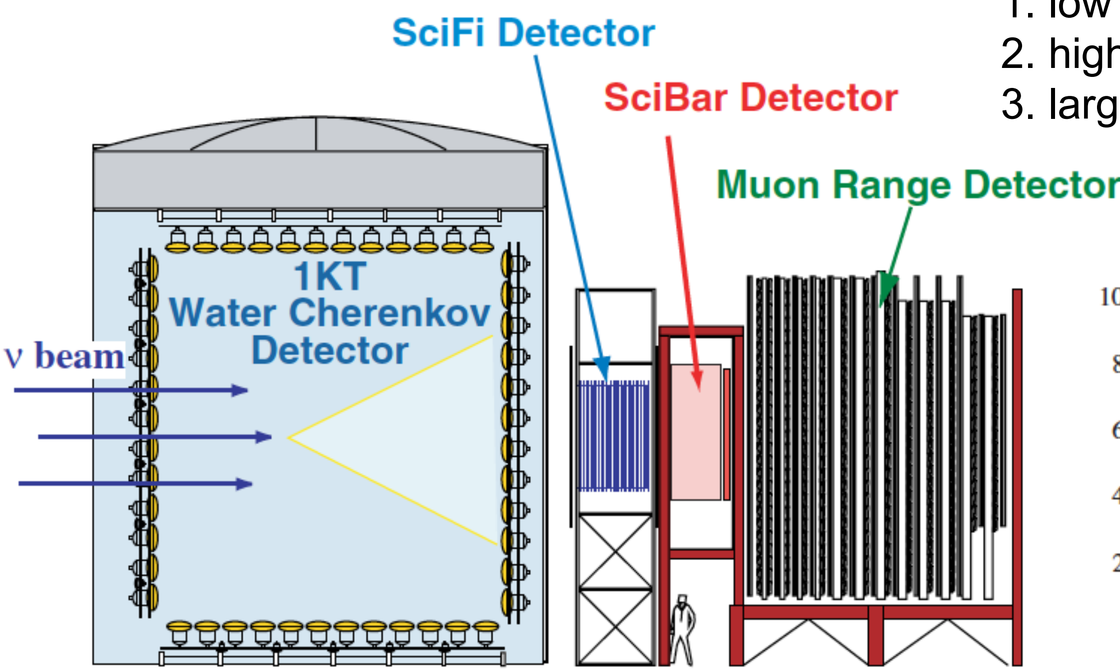


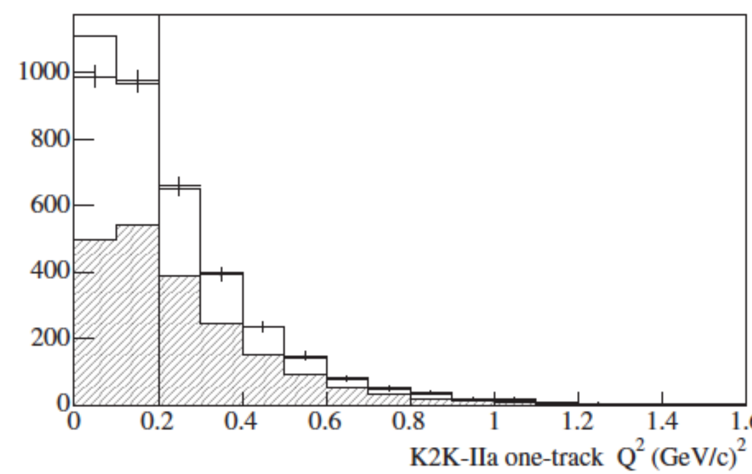
Scintillation tracker

- Tracker, <E>~1.3 GeV
- The first long baseline oscillation experiment
- Modern neutrino interaction experiment to "discover" Origin of all neutrino interaction problems…

CCQE puzzle

1. low Q2 suppression → Pauli blocking?
2. high Q2 enhancement → MA=1.2 GeV?
3. large normalization → Beam normalization?





Cross section models are really wrong!
→ we need more experiments to improve models

1. Neutrino Interaction Physics

2. MiniBooNE

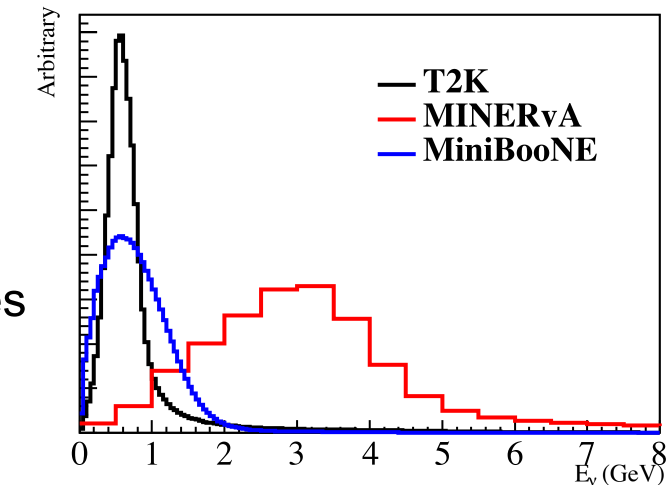
3. T2K near detector

4. MINERvA

5. LArTPC

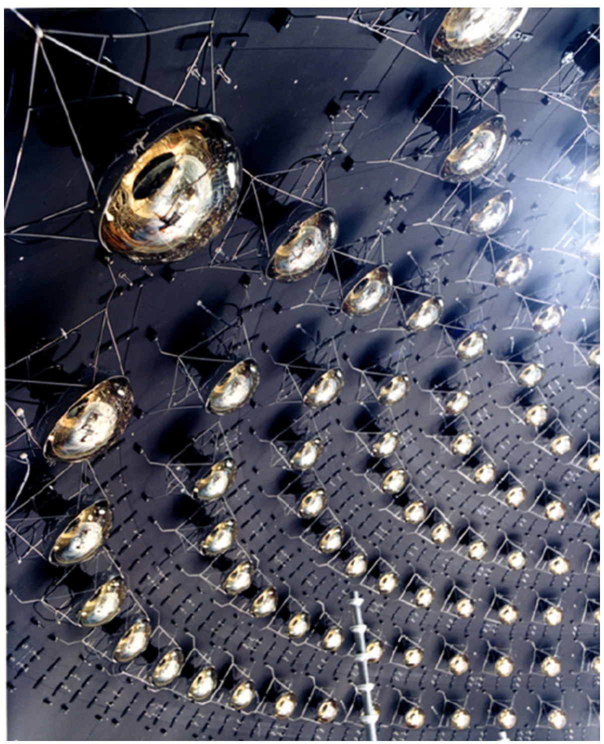
6. Conclusion

2. MiniBooNE

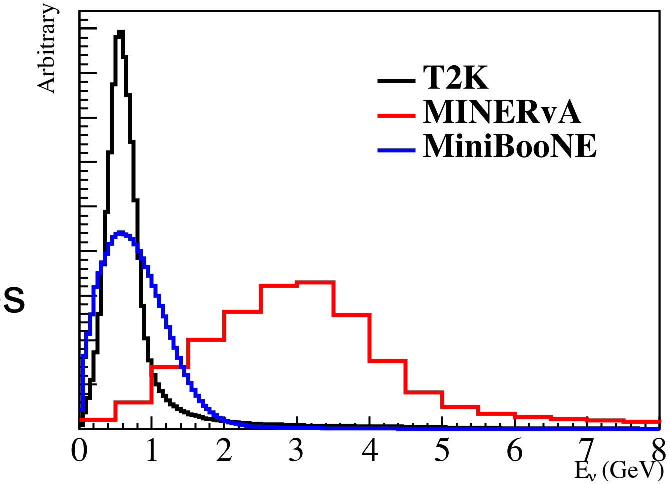


Mineral oil (CH_2) Cherenkov detector

- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Measure Cherenkov radiations from charged particles
- Some calorimetric (scintillation)



2. MiniBooNE



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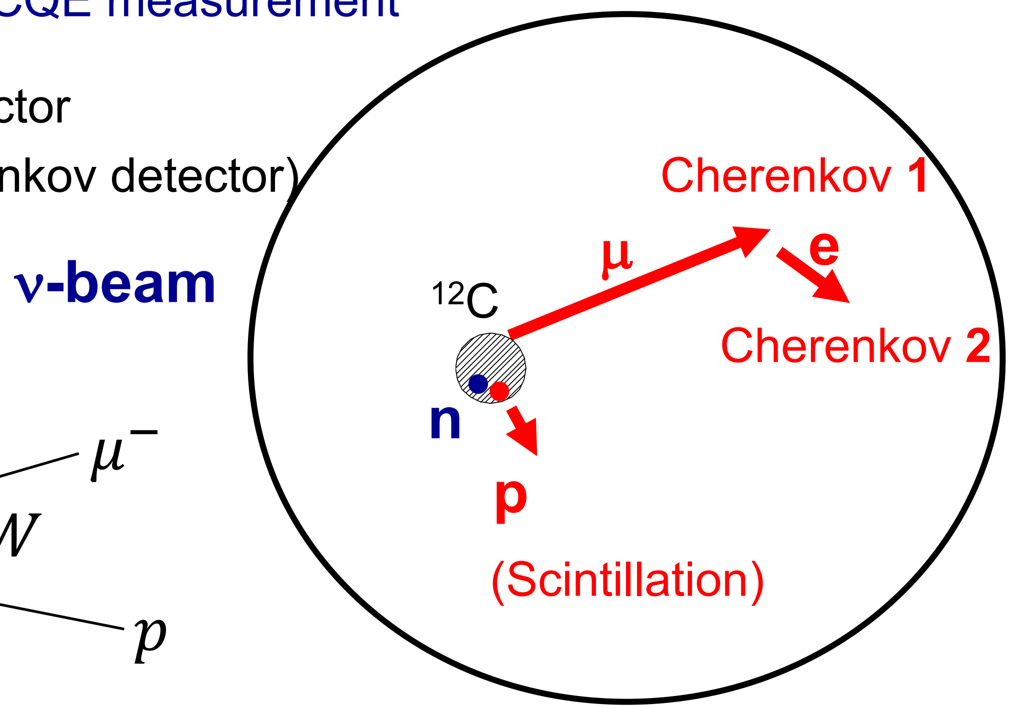
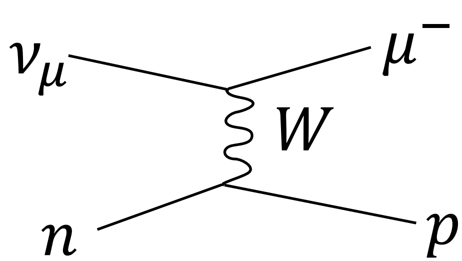
MiniBooNE CCQE measurement

MiniBooNE detector

(spherical Cherenkov detector)

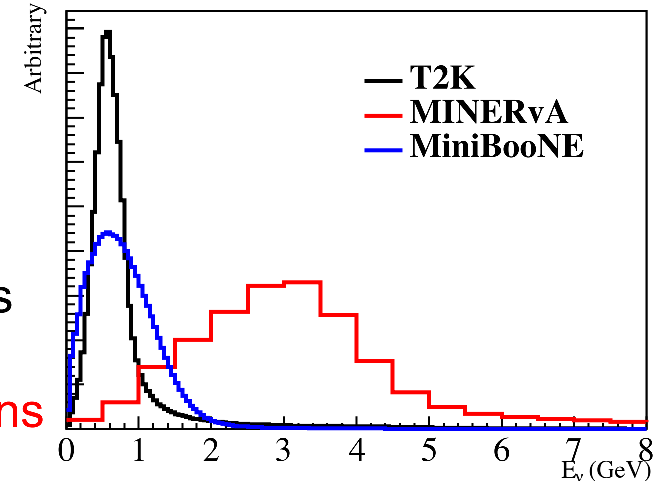




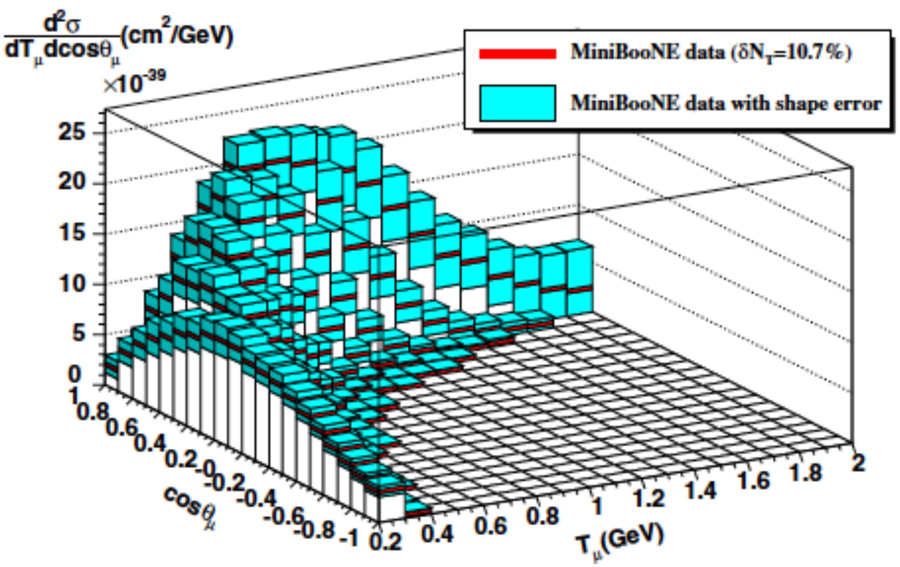
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

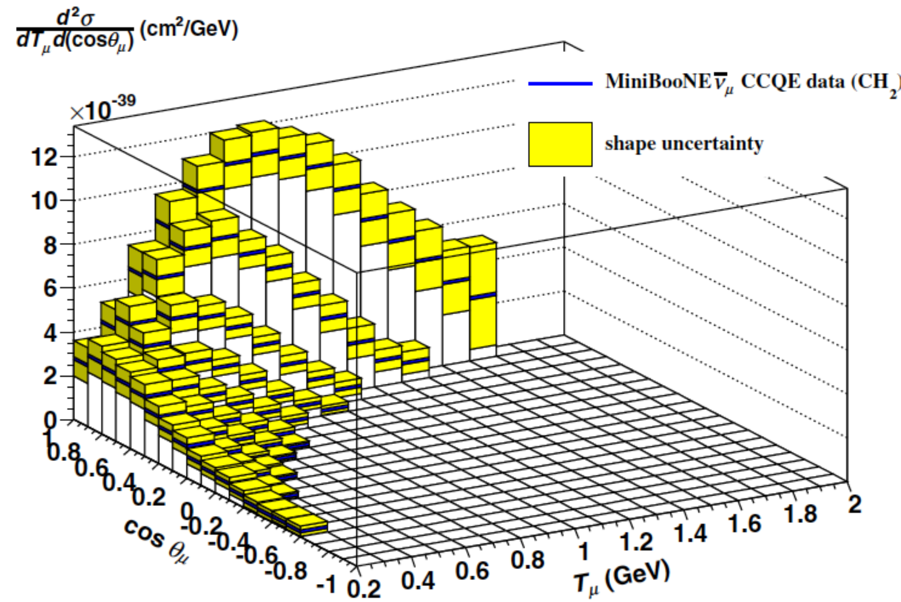
2. MiniBooNE

Mineral oil (CH_2) Cherenkov detector
- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Measure Cherenkov radiations from charged particles
- Some calorimetric (scintillation)
- Measured first flux-integrated differential cross sections
- Solved CCQE puzzle



neutrino and anti-neutrino CCQE-like double differential cross sections





TK and Martini, JPhysG45(2018)013001
Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1

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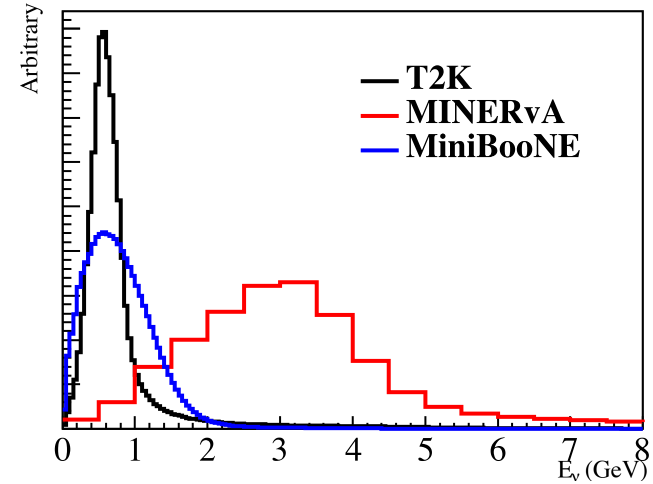
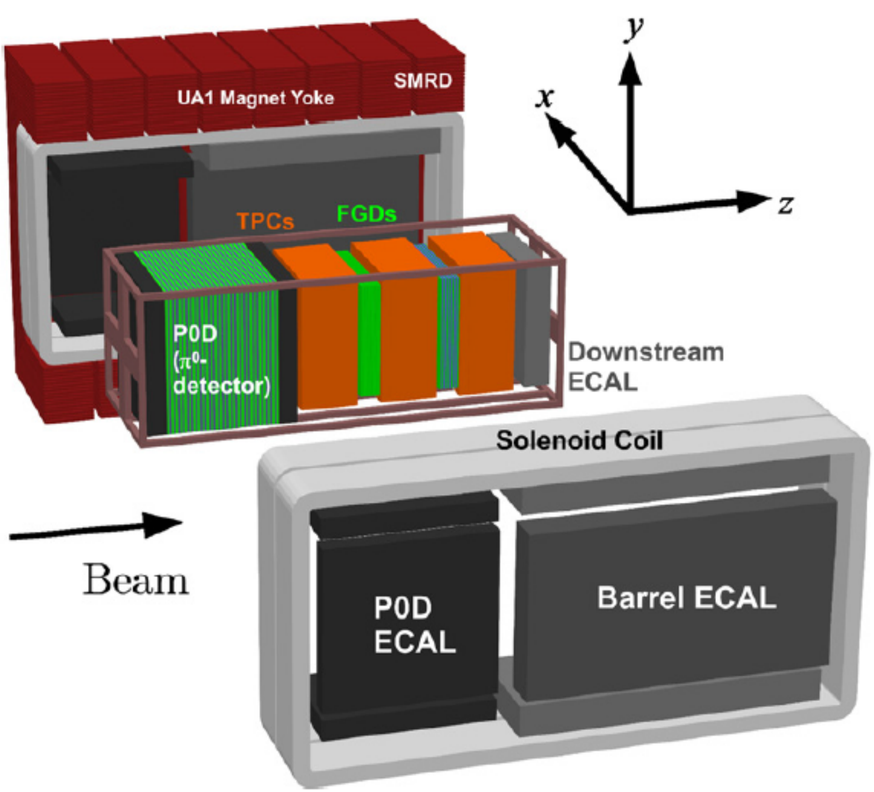
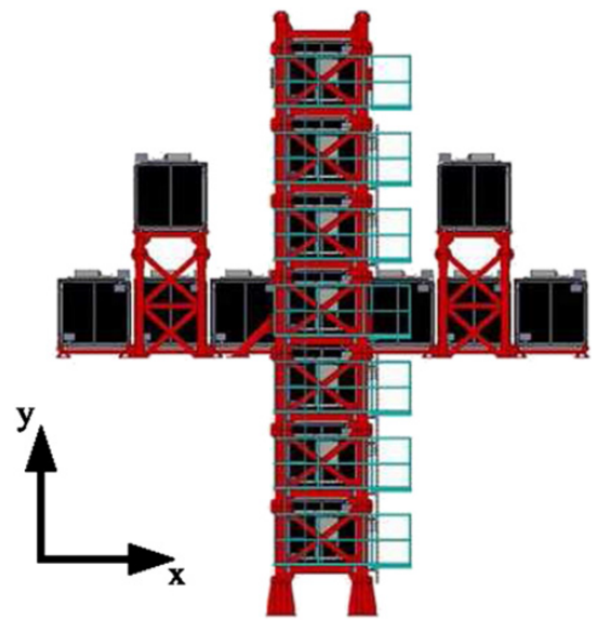
3. T2K near detector

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

- Plastic scintillation trackers (except gas TPC)
- 0.2T magnet for momentum measurement
- <E>~600 MeV off-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)







T2K, NIMA659(2011)106

3. T2K near detector

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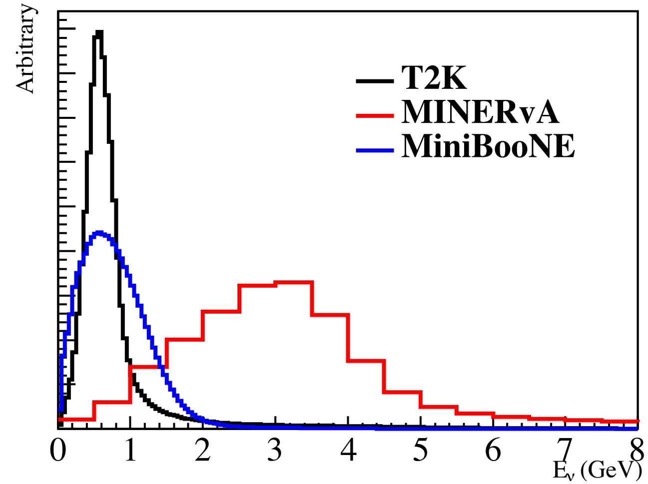
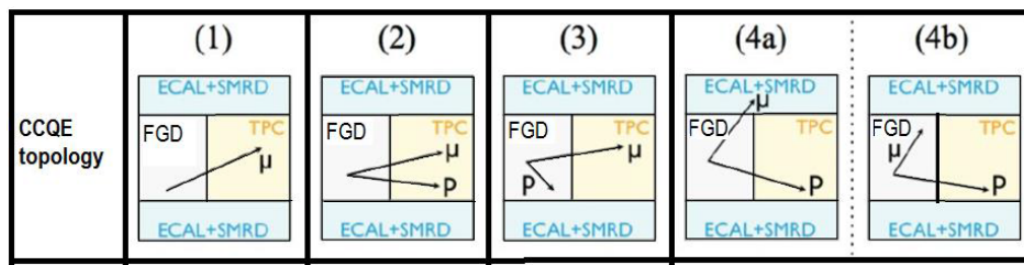
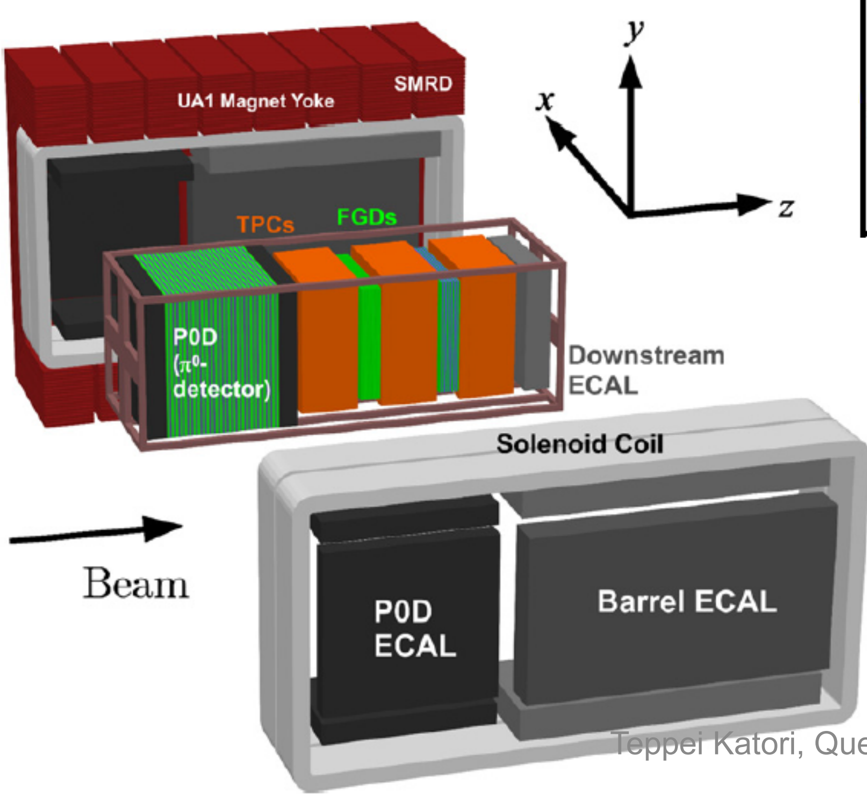
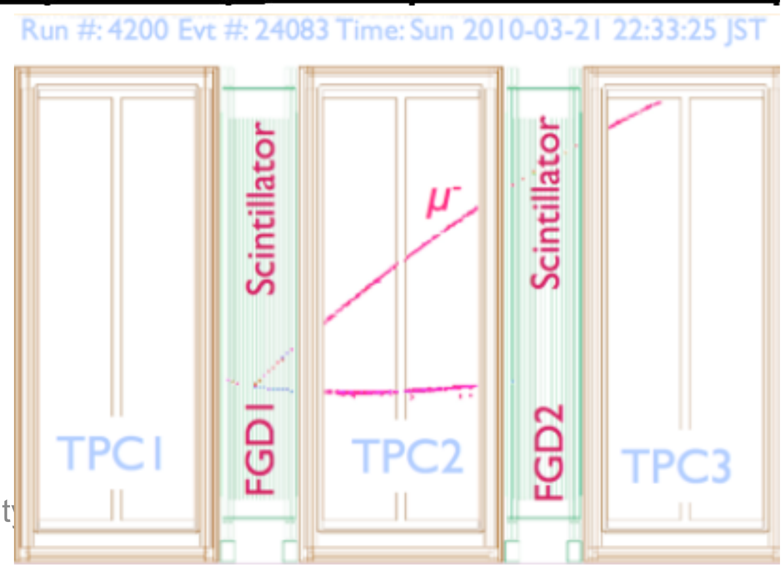


neutrino CC0π double differential cross sections







T2K,PRD93(2016)112012

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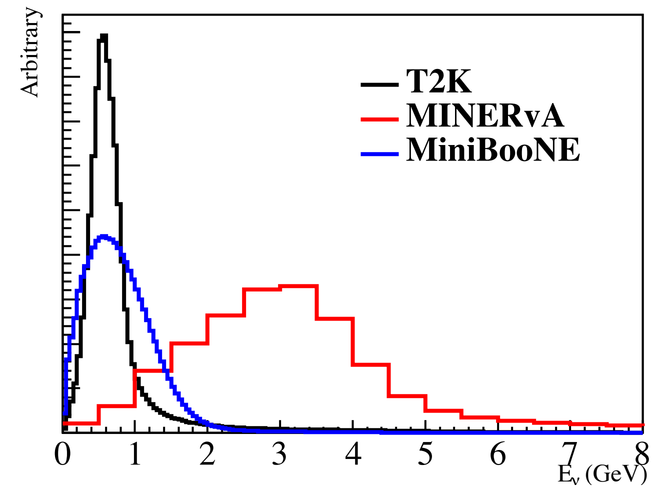
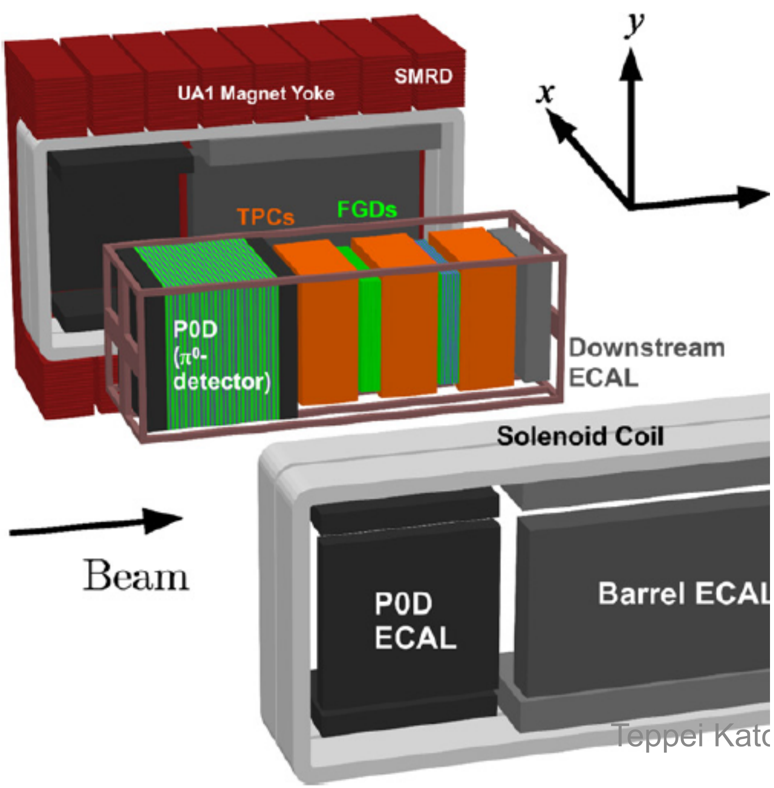
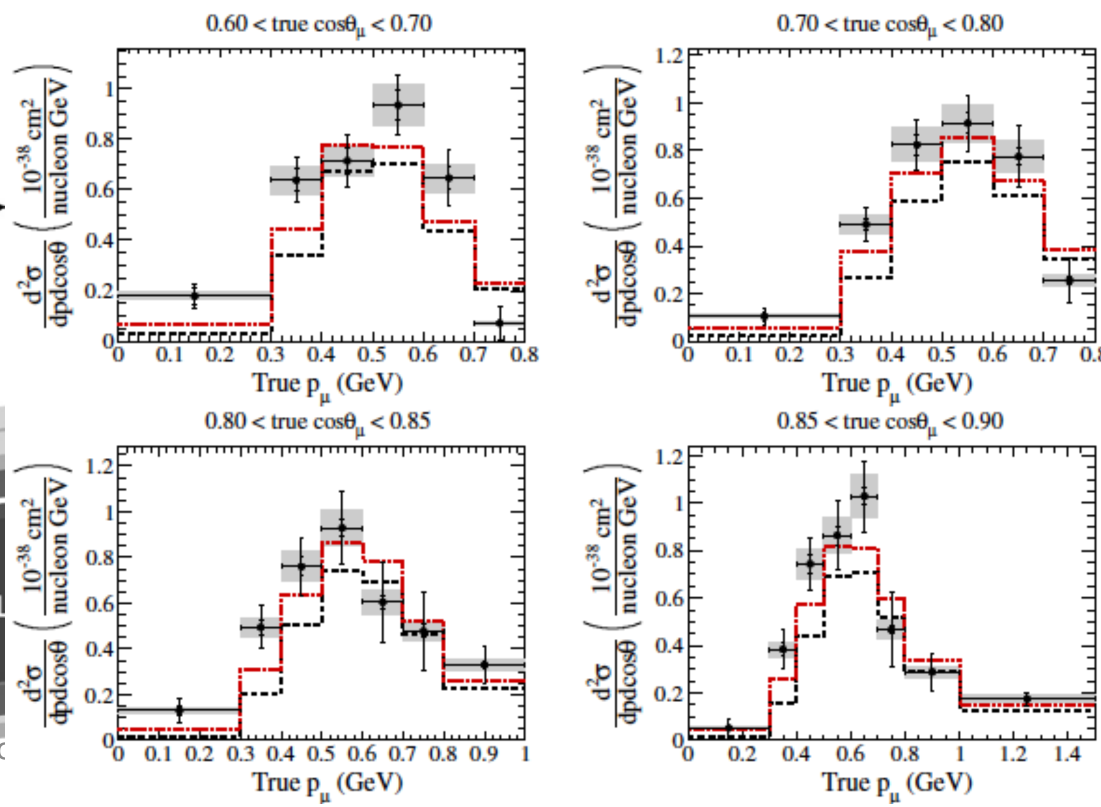


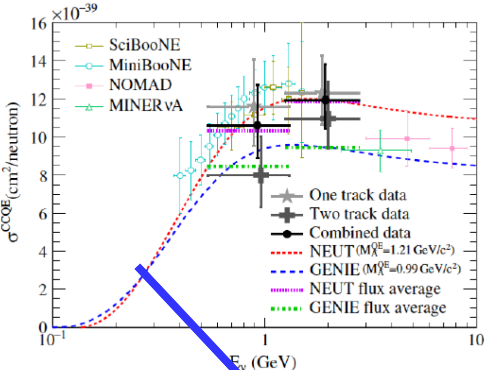


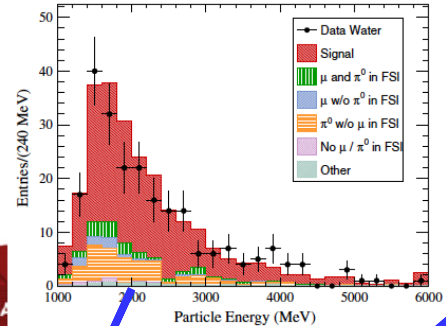
neutrino CC0π double differential cross sections

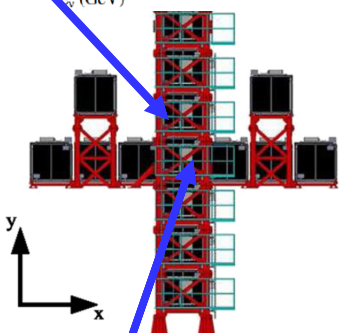


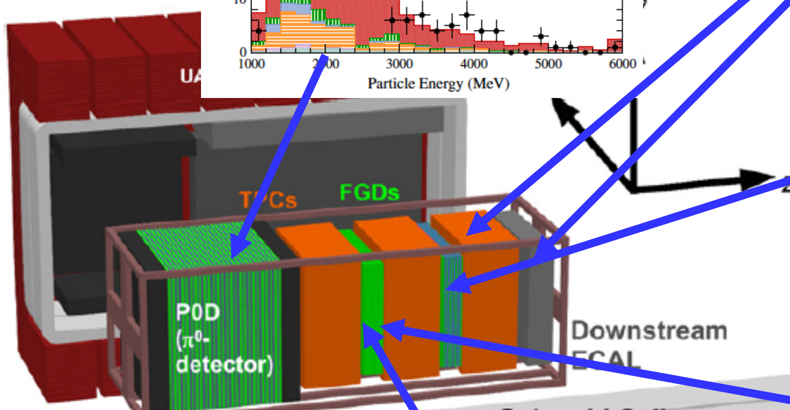
T2K,PRD91(2015)112002;91(2015)112010;93(2016)112012;95(2017)012010, WAGASCI, PoS(EPS-HEP2015)292
PRL113(2014)241803, Brailsford, PhD thesis (Imperial, 2015), Hamilton, PhD thesis (Imperial, 2016)

3. T2K near detectors



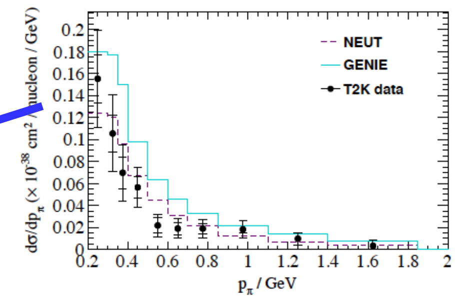


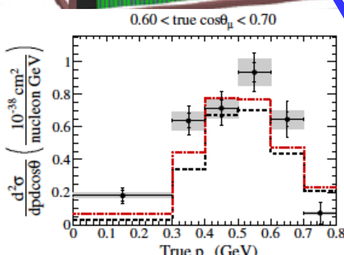


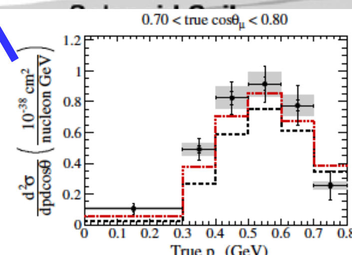


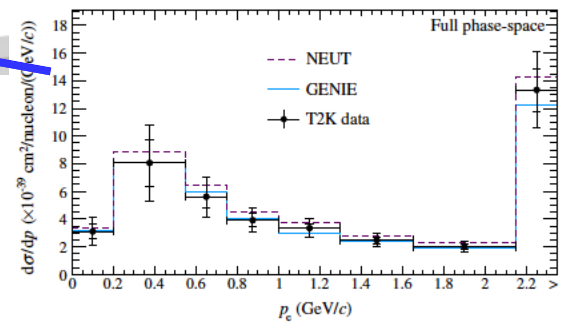
Target dependent measurement
- Ar (TPC gas)
- Pb (ECal)

etc

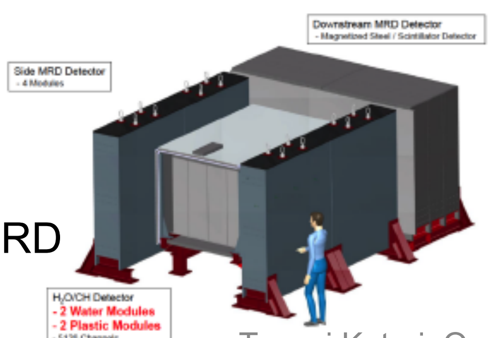


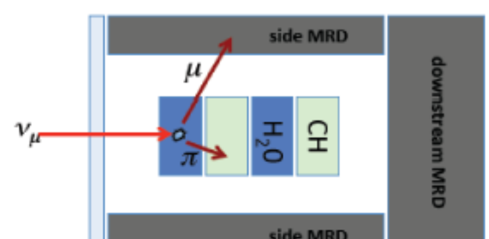


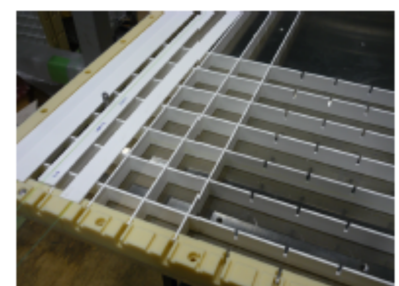




WAGASCI
- YNU initiative
- Water target
- x-y-z tracker
- magnetized MRD

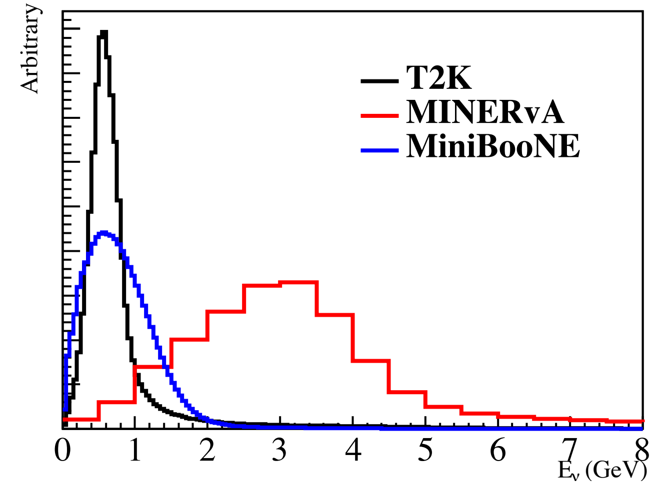






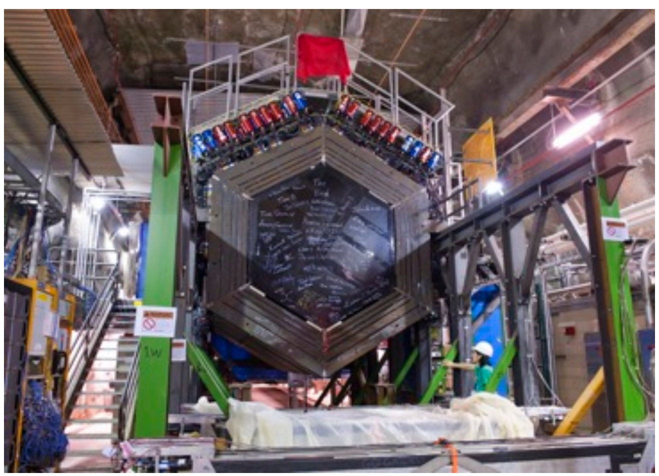
TK and Martini, JPhysG45(2018)013001
Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1

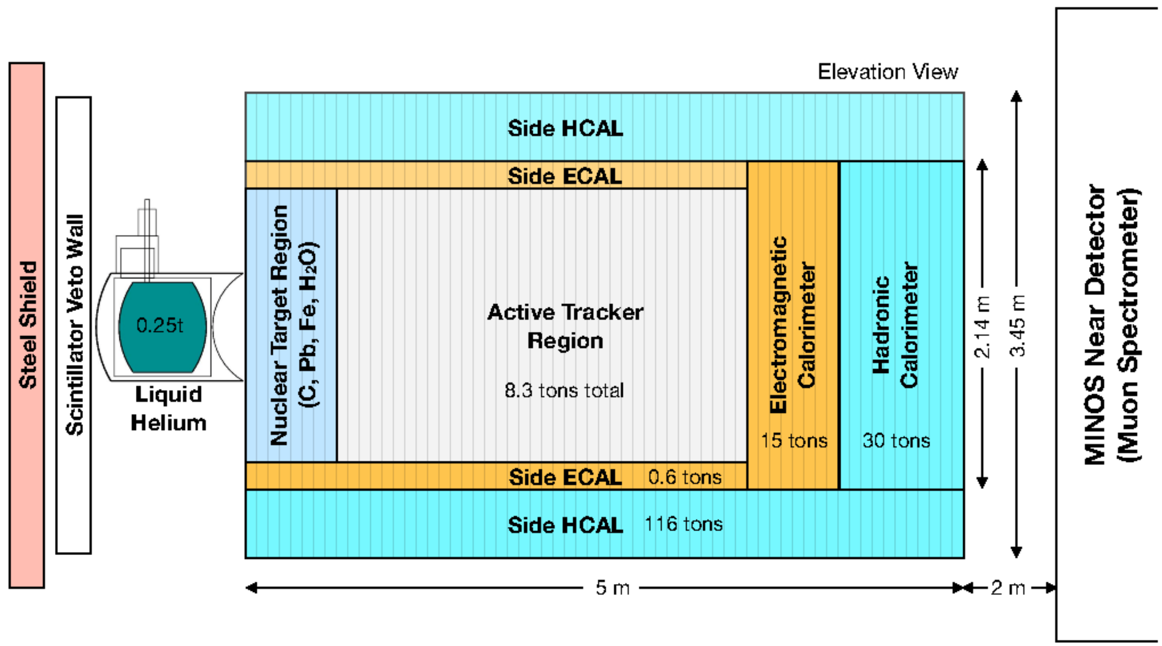
4. MINERvA



Scintillation tracker

- <E>~3.5 GeV on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)





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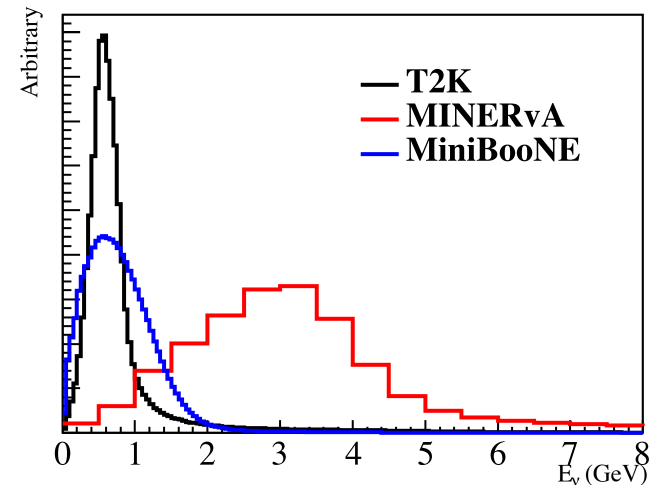

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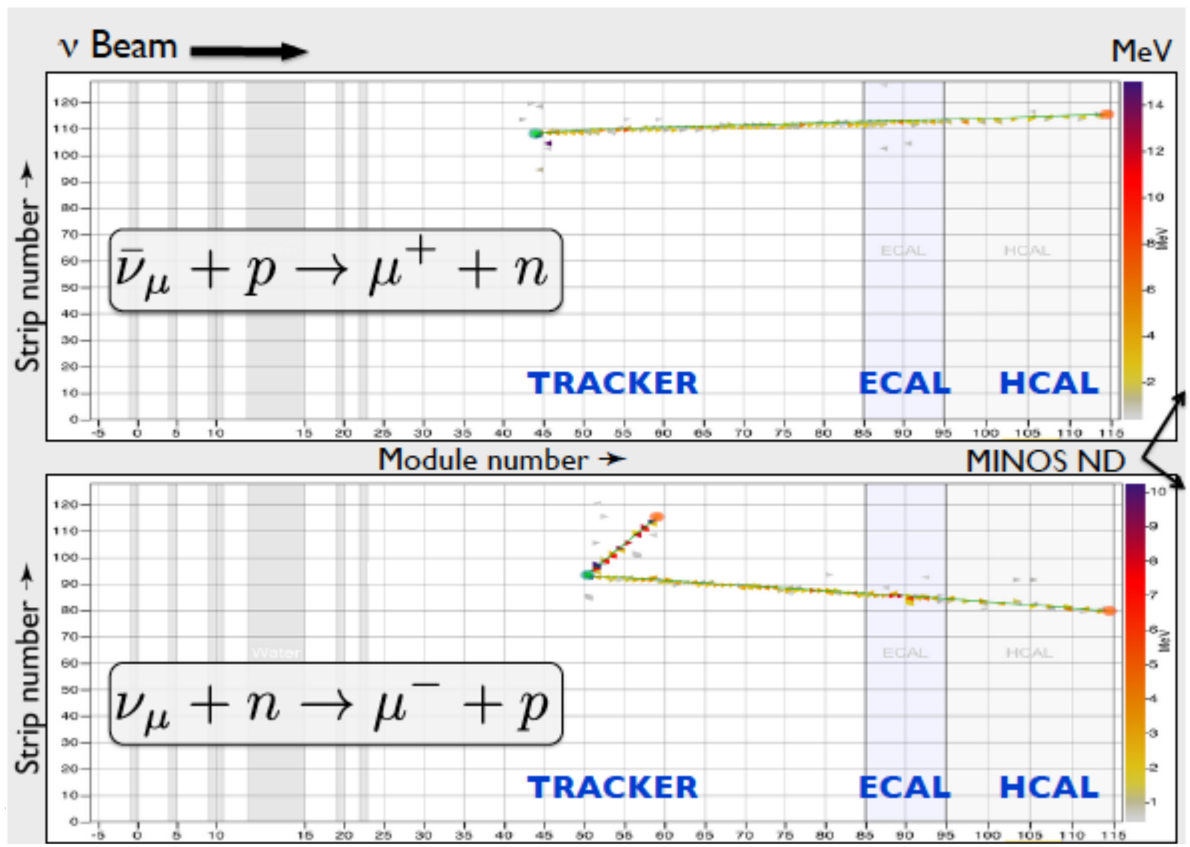

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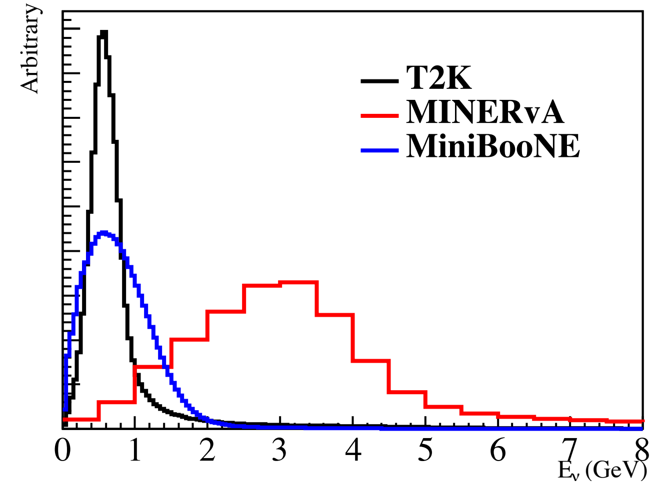
4. MINERvA



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- <E>~3.5 GeV on-axis beam
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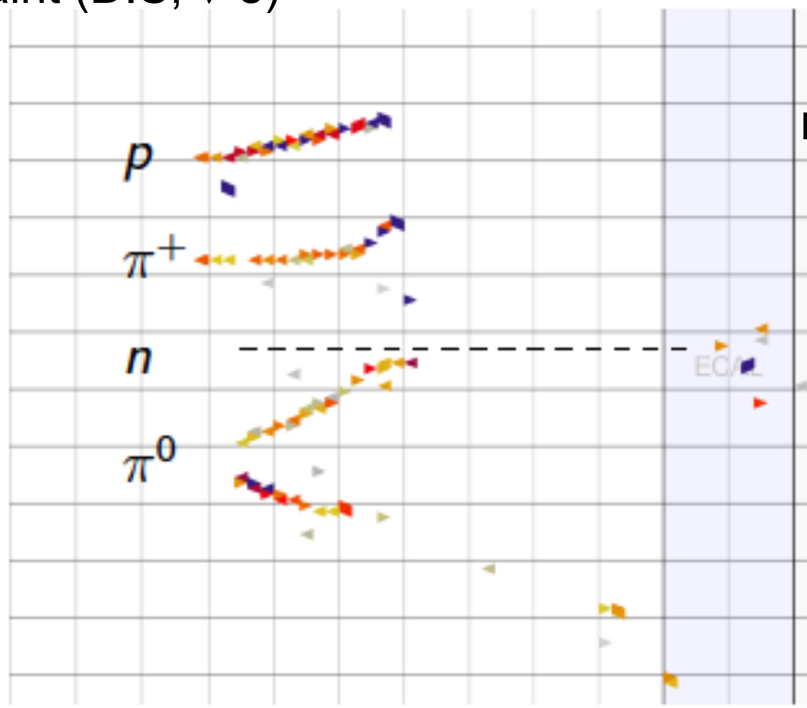
Kinetic energy

Kinetic energy

0

Total energy



Beam test + better(?) scintillator
→ good hadron measurement
→ kinematics is completely fixed

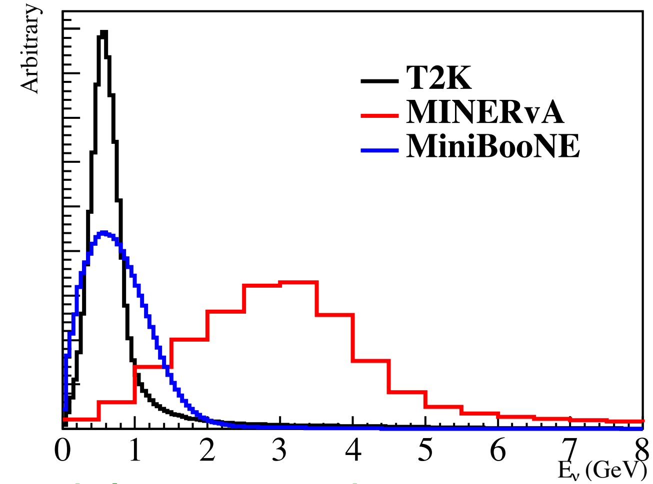
model-dependent

visible hadron energy
↓
total hadron energy
↓
Eν
↓
Q2

On average, we see *available* hadronic energy $E_{avail} \neq q_0$:

$$E_{avail} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

4. MINERvA



Scintillation tracker

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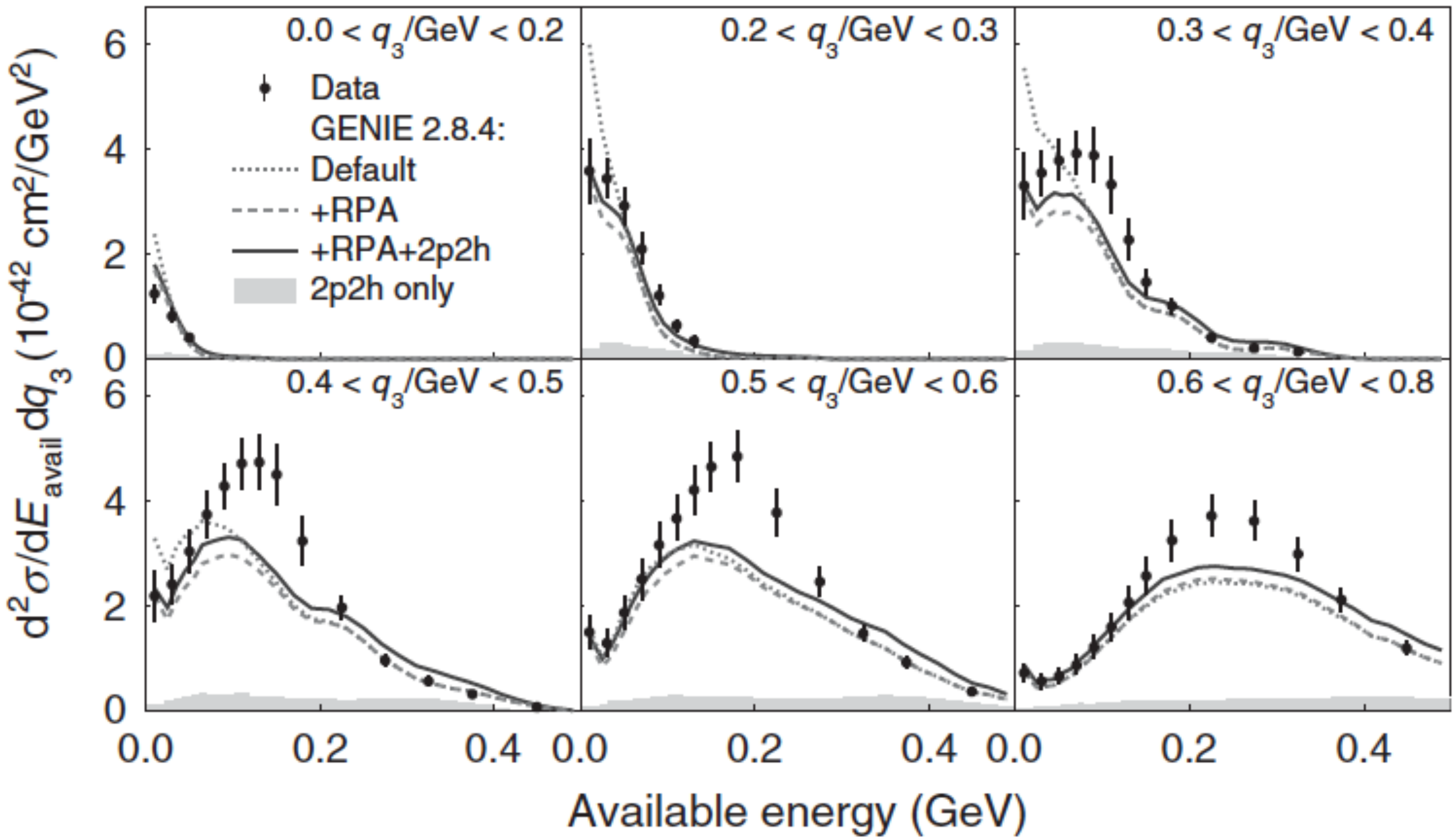
Flux-unfolded double differential cross section

Directly comparable with nuclear theories



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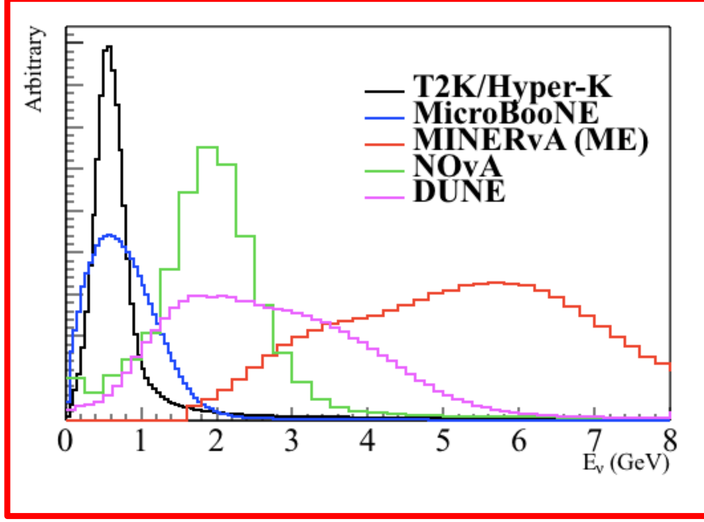
MINERvA,PRD94(2016)052005
Rodrigues et al.,EPJC76(2016)474

4. Pion puzzle

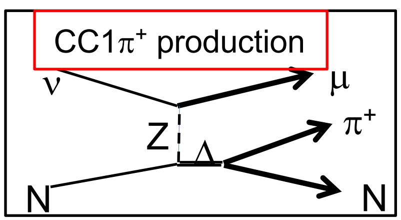


After CCQE puzzle, pion puzzle is the next biggest problem…

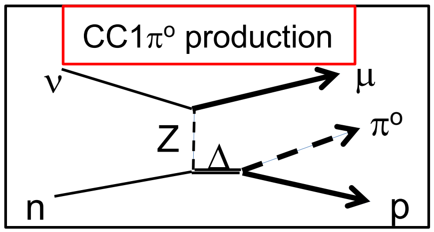
MINERvA $\nu_\mu CC1\pi^+$ vs. $\overline{\nu_\mu} CC1\pi^o$

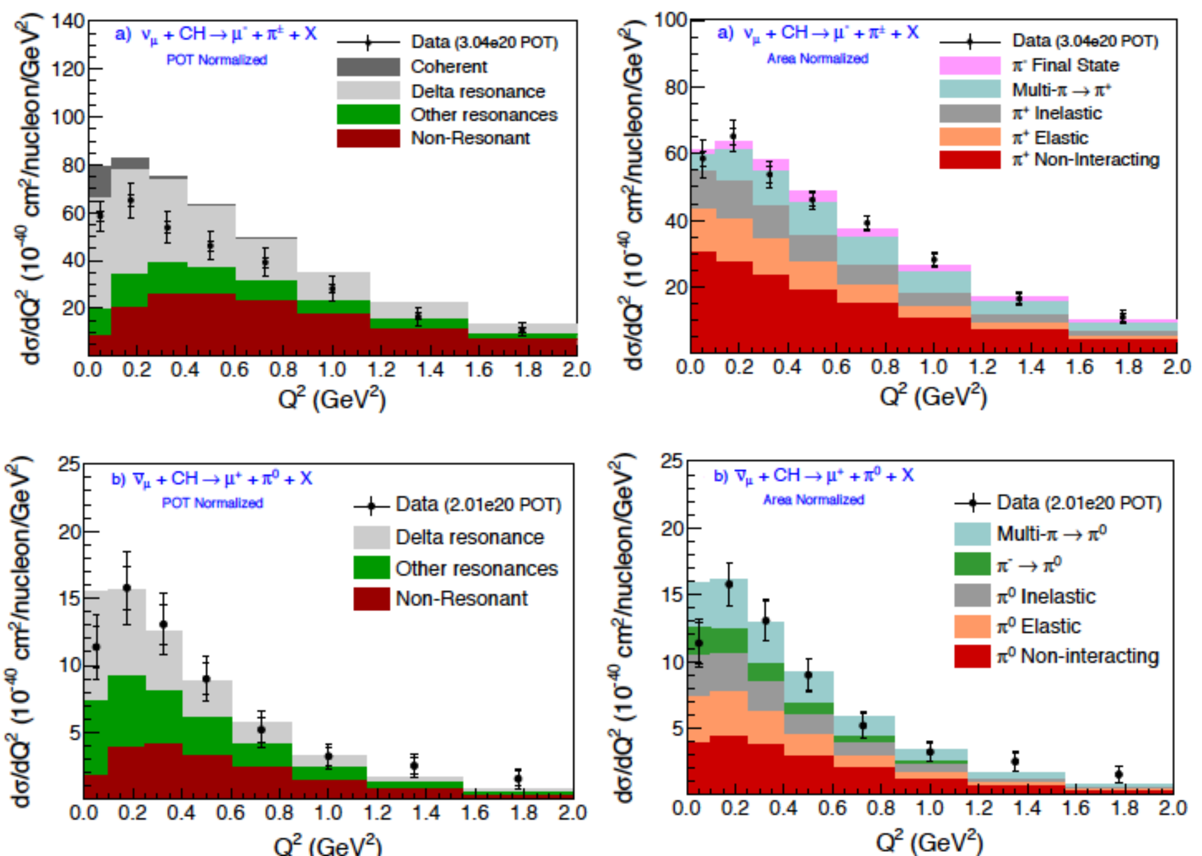
- simultaneous fit of 2 samples to understand structures of neutrino scatterings and pion propagations.

$\nu_\mu CC1\pi^+$ data has better shape agreement with GENIE



$\bar{\nu} CC1\pi^o$ data has better normalization agreement with GENIE





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TK and Martini, JPhysG45(2018)013001
Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1

1. Neutrino Interaction Physics

2. MiniBooNE

3. T2K near detector

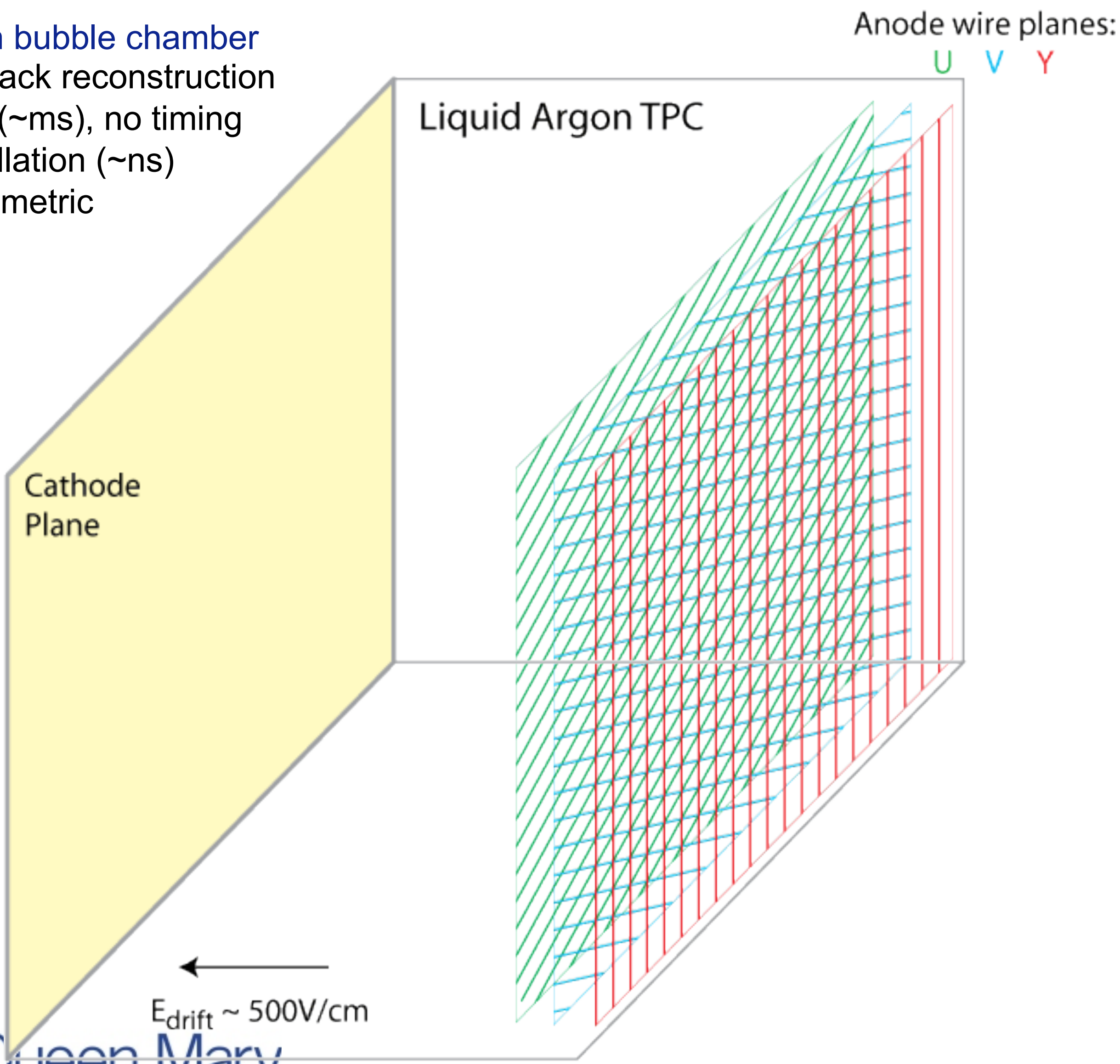
4. MINERvA

5. LArTPC

6. Conclusion

5. LArTPC

Modern bubble chamber
- 3-d track reconstruction
- slow (~ms), no timing
- scintillation (~ns)
- calorimetric



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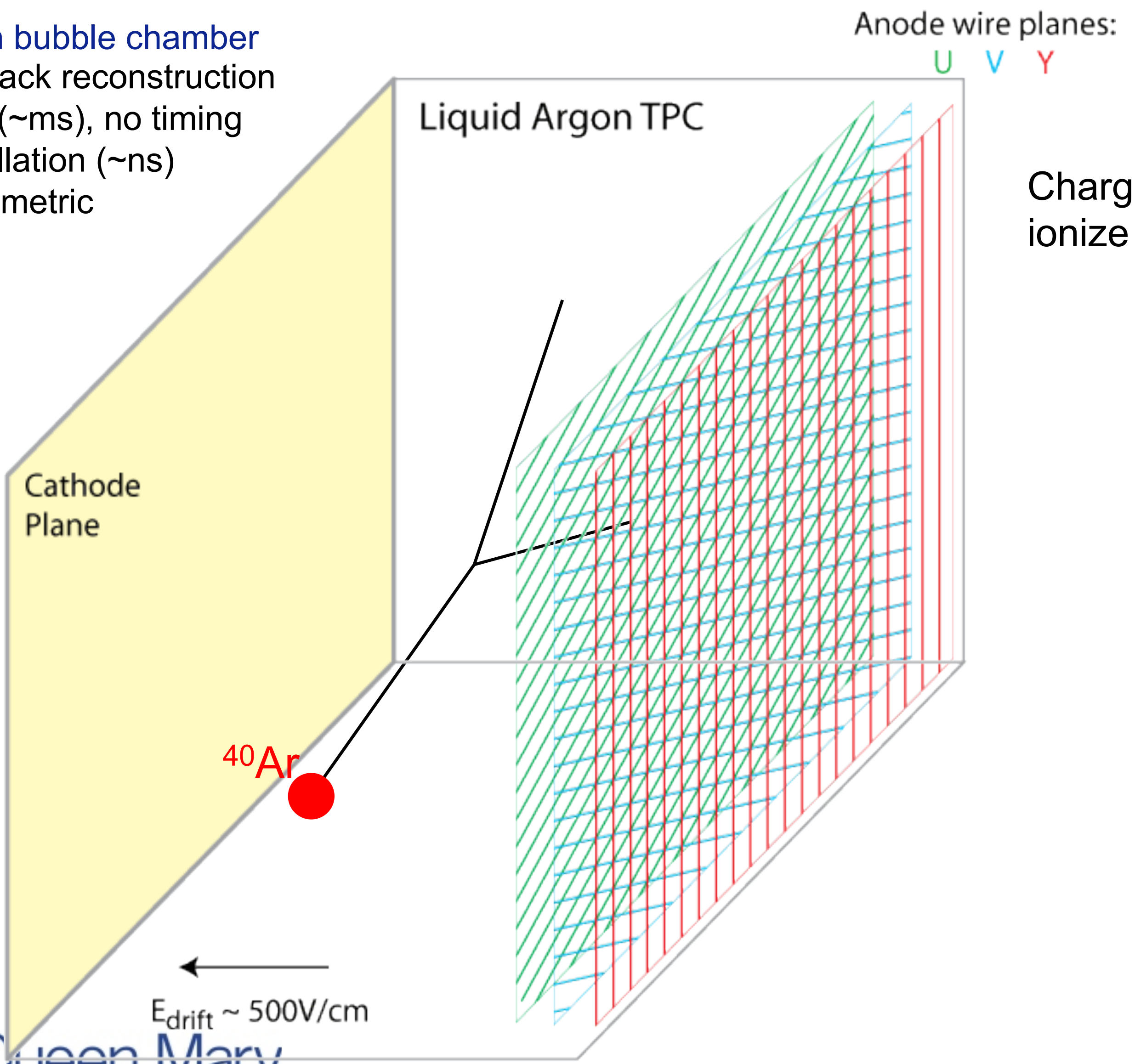

Charged particle tracks ionize Argon atoms

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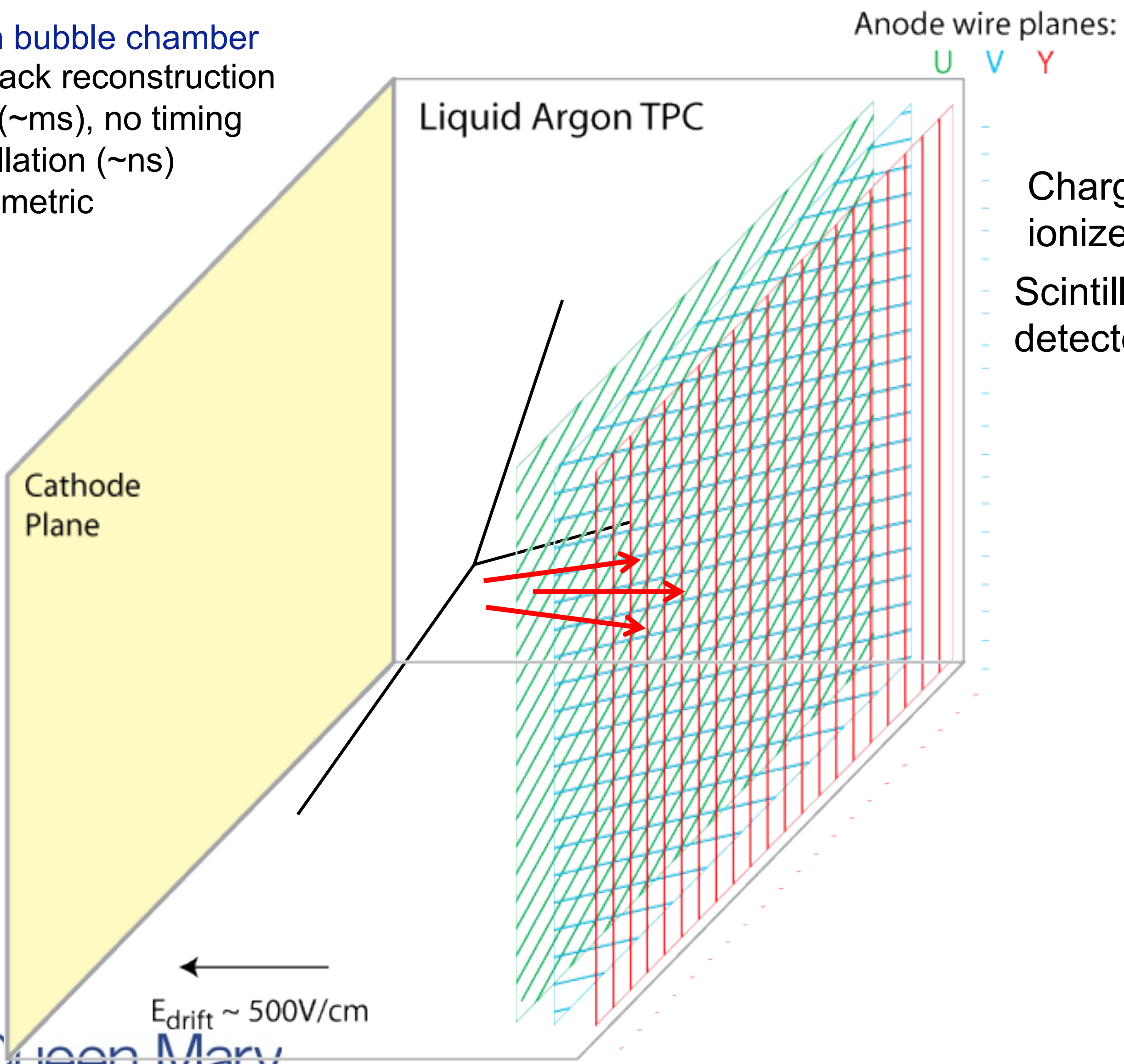
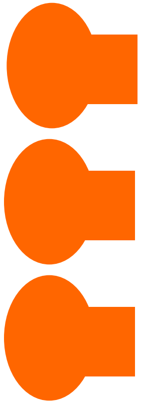


Charged particle tracks ionize Argon atoms

Scintillation light (~ns) is detected by PMTs at same time



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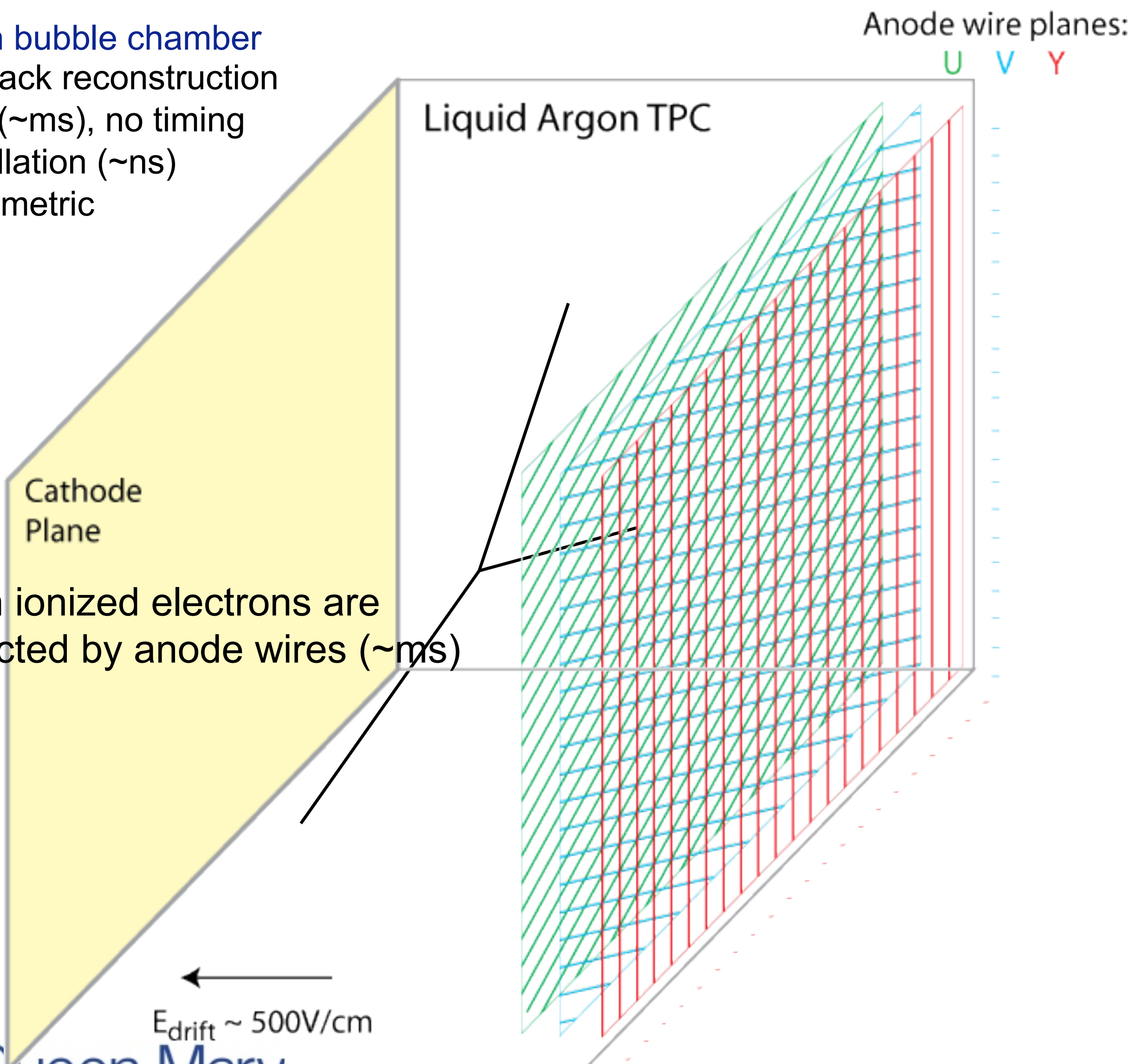

Then ionized electrons are collected by anode wires (~ms)

5. LArTPC

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- 3-d track reconstruction
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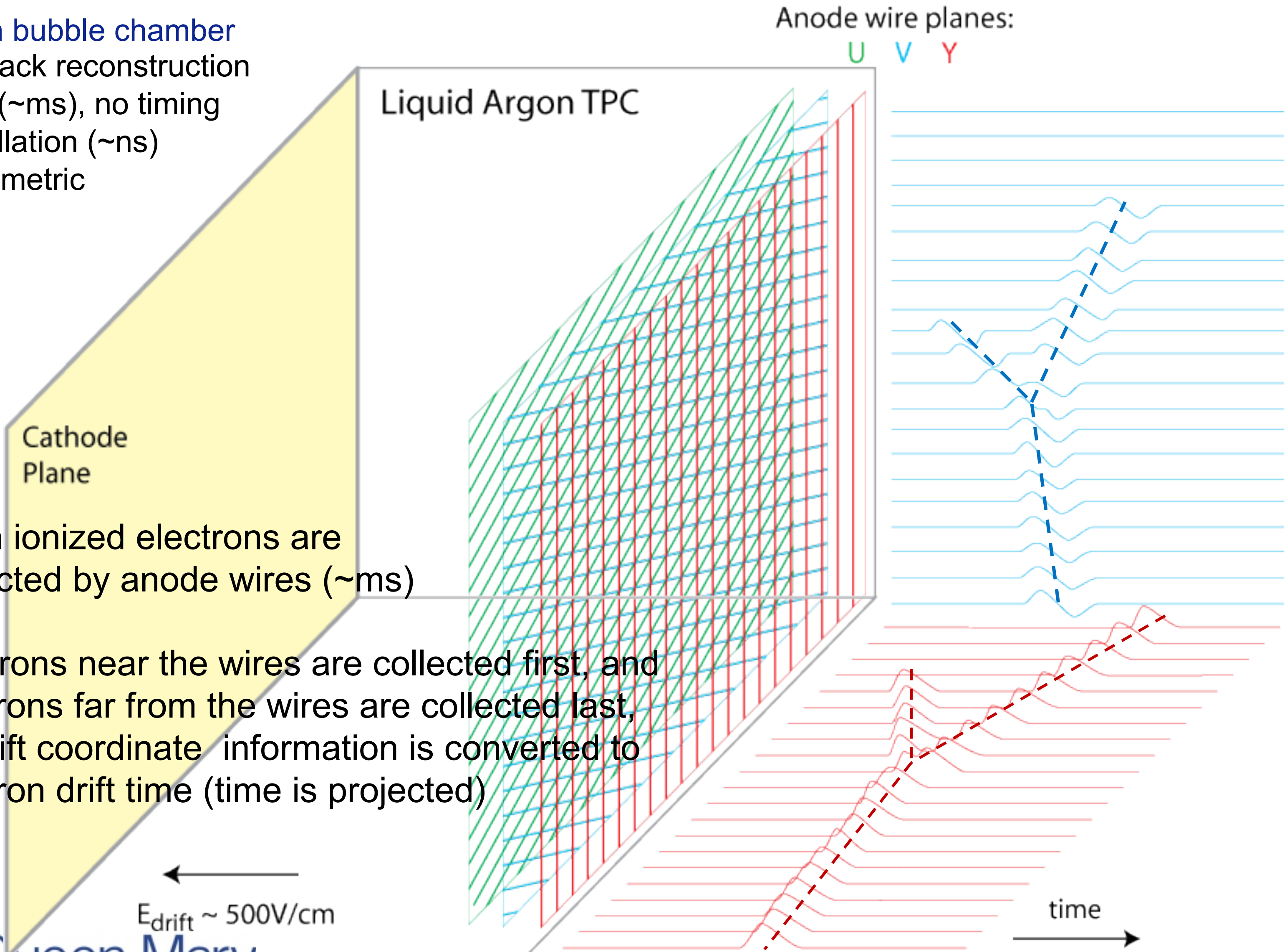
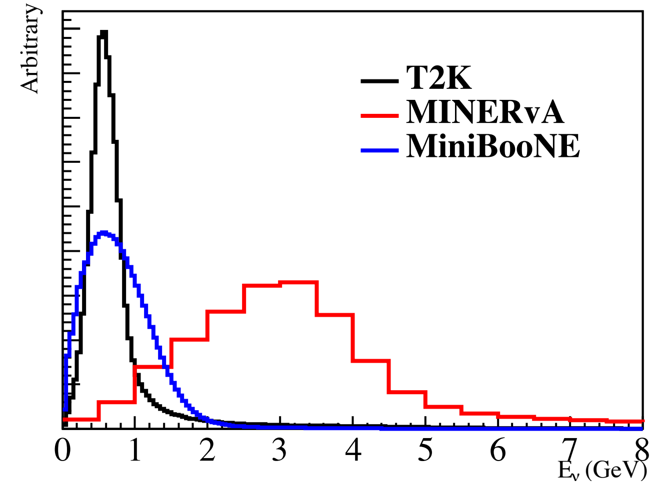


Then ionized electrons are collected by anode wires (~ms)

Electrons near the wires are collected first, and electrons far from the wires are collected last, so drift coordinate information is converted to electron drift time (time is projected)

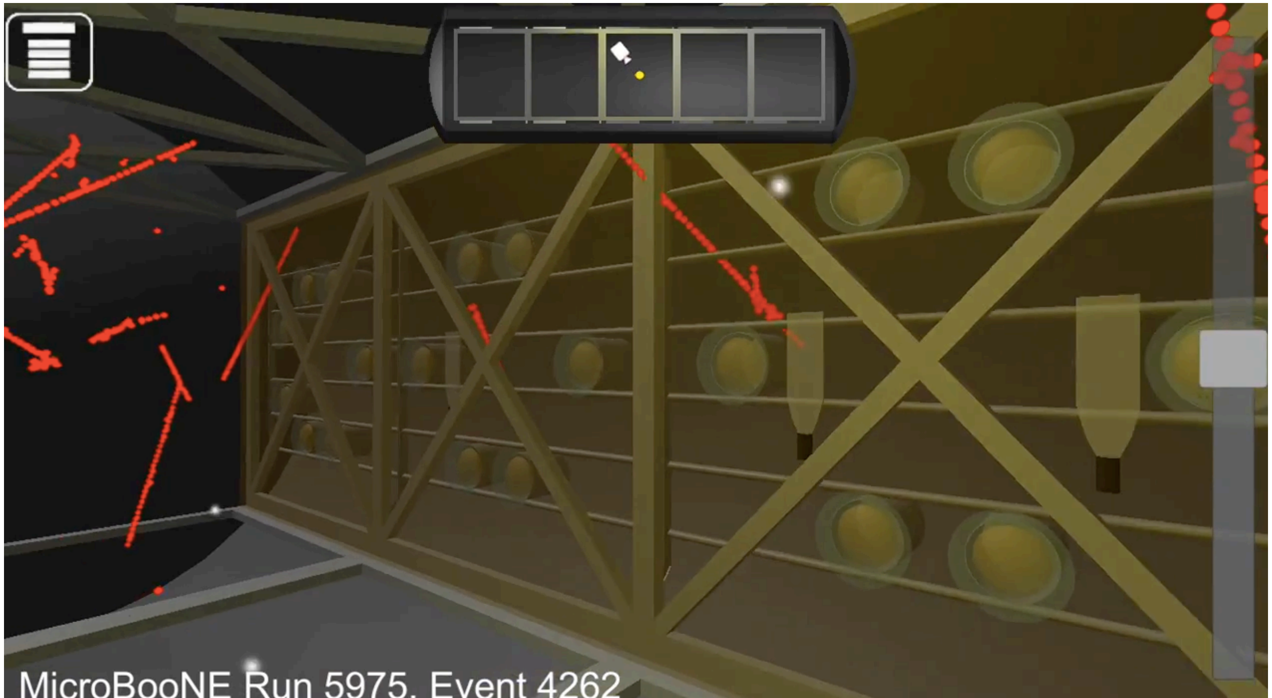
MicroBooNE,arXiv:1612.05824
VENu, http://venu.physics.ox.ac.uk/

5. MicroBooNE



86ton LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system
- ArgoNeuT, SBND, protoDUNE, LArIAT…



VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- smart phone app to take a look MicroBooNE data

TK and Martini, JPhysG45(2018)013001
Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1

1. Neutrino Interaction Physics

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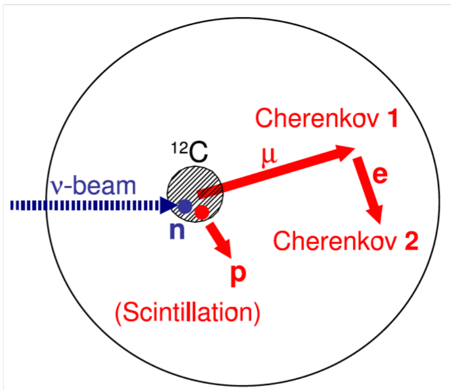
6. Conclusion

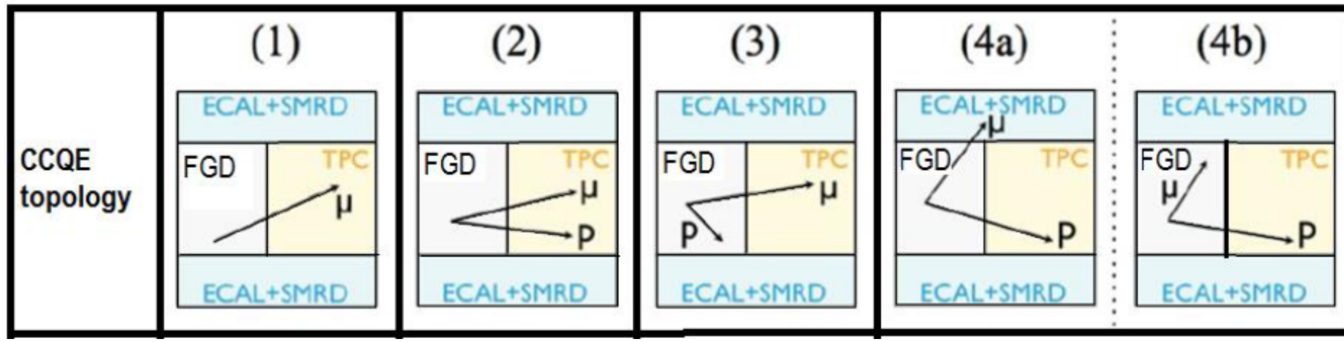
1. Type of neutrino detectors

Cherenkov neutrino detector
- MiniBooNE
- Super-Kamiokande



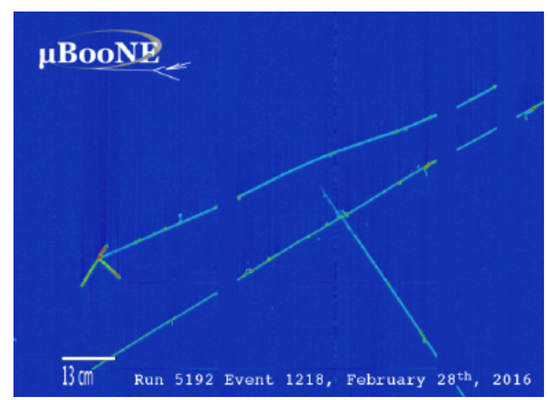
- 4π coverage
- not good to measure multi-tracks
- calorimetric measurement (scintillation)

Tracker neutrino detector
- K2K, T2K near detectors
- MINERvA



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

Liquid argon TPC neutrino detector
- MicroBooNE, ArgoNeuT, SBND, ICARUS
- 4π coverage (Cherenkov)
- multi-track, vertex activity (segmented tracker)
- calorimetric (scintillator)
- no timing (~ms)



Neutrino Cross Section Measurements

Lecture 1: Introduction of neutrino interactions
1. Cross sections
2. Standard Model
3. ν-e scattering cross section

Lecture 2: Charged-current quasi-elastic (CCQE) interaction
4. Conservation of vector current (CVC)
5. Nucleon current
6. Introduction to CCQE interaction
7. CCQE scattering cross section

Lecture 3: Overview of neutrino cross sections
8. Neutrino cross section experiments
9. Neutrino cross section measurements

Teppei Katori
Queen Mary University of London
Summer lecture series, Yokohama National University, Japan, Aug. 1-3, 2018

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Introduction

Goal of neutrino cross section measurement

- Goal is to measure cross section with minimum model-dependence. This is what theorists want to study their models.

Model-independent cross-section is

- the dependence of simulation is minimum.
- no assumption on kinematics (cf neutrino energy reconstruction assume CCQE interaction)
- detector efficiency must be corrected (so it is detector model-dependent)

Flux-integrated differential cross-sections satisfies above criteria

Formula of flux-integrated differential cross-section

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\varepsilon_i(\Phi T)\Delta x_i}$$

Neutrino flux-integrated differential cross-section measurements

Flux-integrated differential cross section formula

i :true index
j : reconstructed index

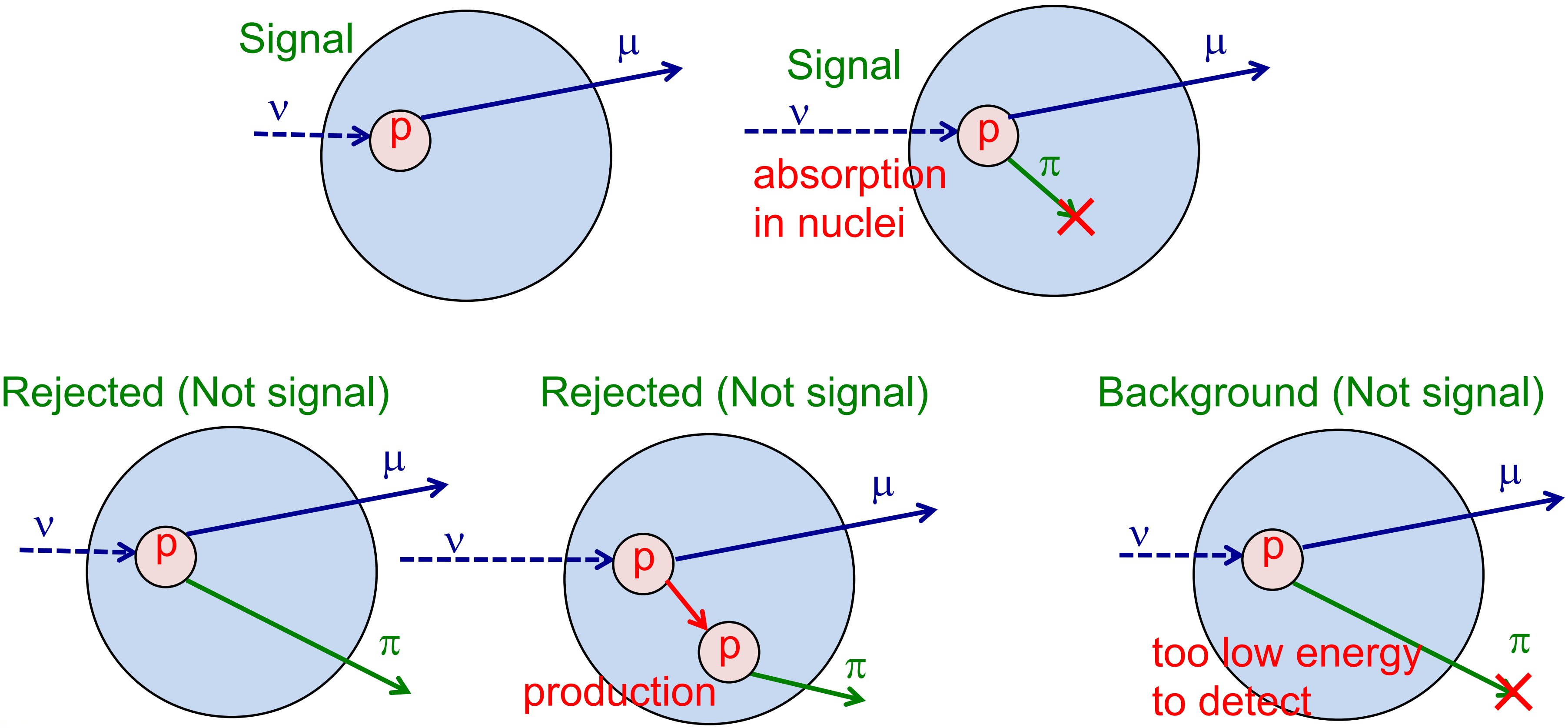
1 Signal definition
2 Background removing
3 Unsmearing
4 Efficiency correction
5 Flux correction
6 Target number correction

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(d_j - b_j)}{\varepsilon_i(\Phi T)\Delta x_i}$$

- U_{ij} :unsmearing matrix
- b_j :predicted background
- d_j :data vector
- Δx_i :bin width
- ε_i :efficiency
- T :integrated target number
- Φ :integrated ν-flux

Topology based signal definition

ex) CC0π = " 1 μ + 0 π + N protons"
"CCQE" is the primary process, but not exactly what we measure through experiment.
Nuclear effect (pion absorption in nuclei, for example) make exactly same topology of CC0π from pion production channels.



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