BREAKTHROUGH PRIZE

"Year of Neutrinos"

2016 Fundamental Physics Breakthrough Prize
- Koichiro Nishikawa (K2K and T2K)
- Atsuto Suzuki (KamLAND)
- Kam-Biu Luk (Daya Bay)
- Yifang Wang (Daya Bay)
- Art McDonald (SNO)
- Yoichiro Suzuki (Super-Kamiokande)
- Takaaki Kajita (Super-Kamiokande)

The Nobel Prize in Physics 2015
Takaaki Kajita, Arthur B. McDonald

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

NuSTEC News

Nucleon correlation

EMC effect

electron scattering

Dark matter

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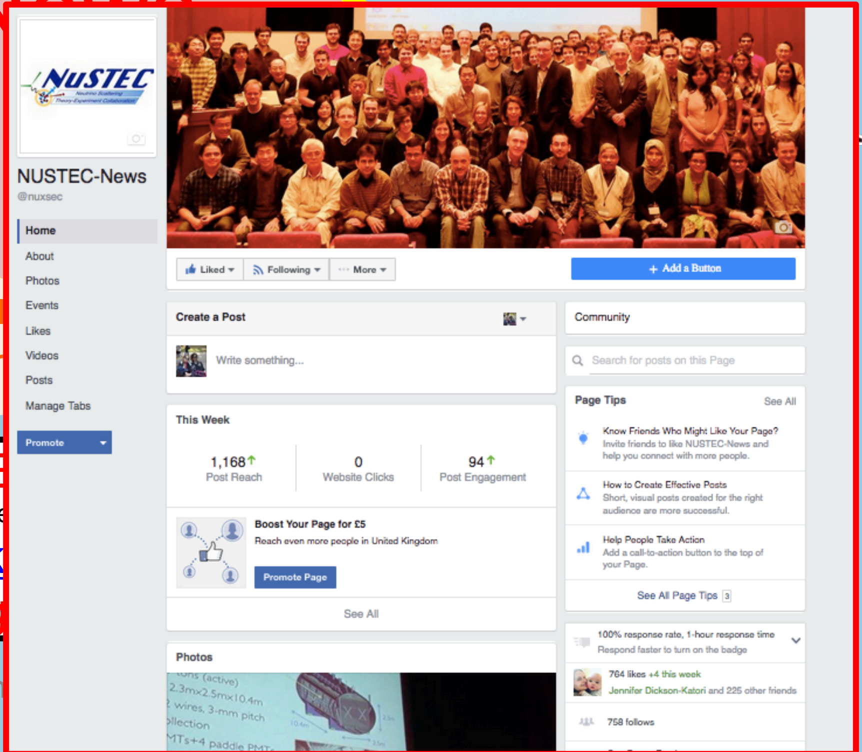

Physics of Neutrino Interactions around 1-10 GeV

Teppei Katori
Queen Mary University of London
HEP seminar, Yokohama National University, Japan, Aug. 3, 2018

outline

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TK and Martini, JPhysG45(2018)013001

Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1

Physics of Neutrino Interactions around 1-10 GeV

Further reading

HEP semi... 3, 2018

outline

1. Neutrino Interaction Physics
2. Neutrino scattering experiments
3. Charged-Current Quasi-Elastic (CCQE) interaction
4. Resonance single pion production
5. Shallow inelastic scattering (SIS)
6. Conclusions

IOP Publishing Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001 (98pp) https://doi.org/10.1088/1361-6471/aa8bf7

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

[1] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

[2] ESNT, CEA, IRFU, Service de Physique Nucléaire, Université de Paris-Saclay, F-91191 Gif-sur-Yvette, France

[3] Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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Progress in Particle and Nuclear Physics

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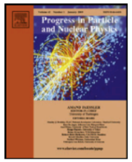

Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

L. Alvarez-Ruso[a], M. Sajjad Athar[b], M.B. Barbaro[c], D. Cherdack[d], M.E. Christy[e], P. Coloma[f], T.W. Donnelly[g], S. Dytman[h], A. de Gouvêa[i], R.J. Hill[j,f], P. Huber[k], N. Jachowicz[l], T. Katori[m], A.S. Kronfeld[f], K. Mahn[n], M. Martini[o], J.G. Morfín[f,*], J. Nieves[a], G.N. Perdue[f], R. Petti[p], D.G. Richards[q], F. Sánchez[r], T. Sato[s,t], J.T. Sobczyk[u], G.P. Zeller[f]

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

1. Neutrino interaction physics

2. Neutrino scattering experiments

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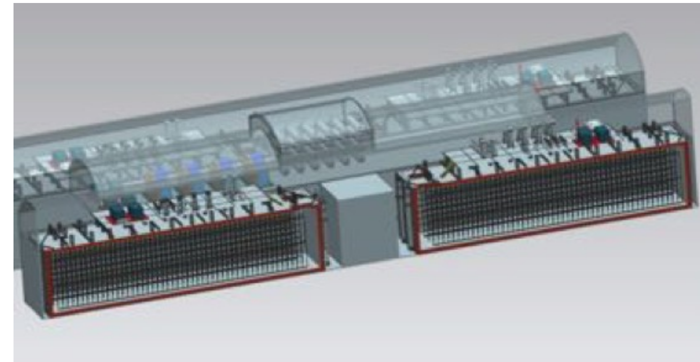
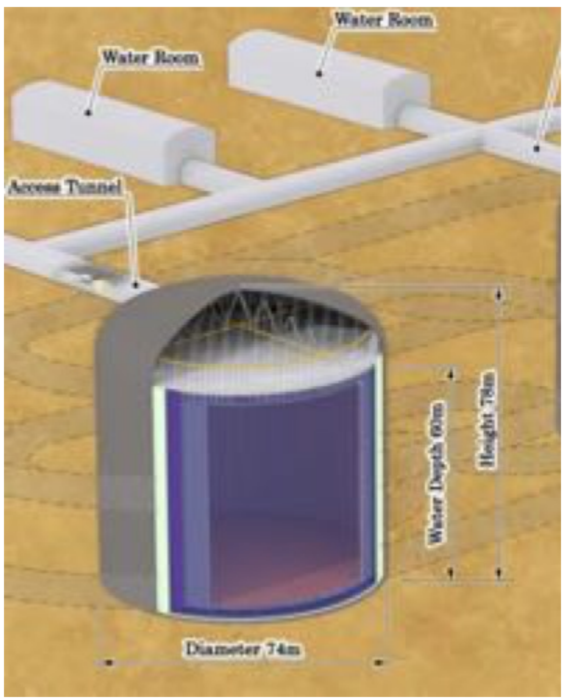
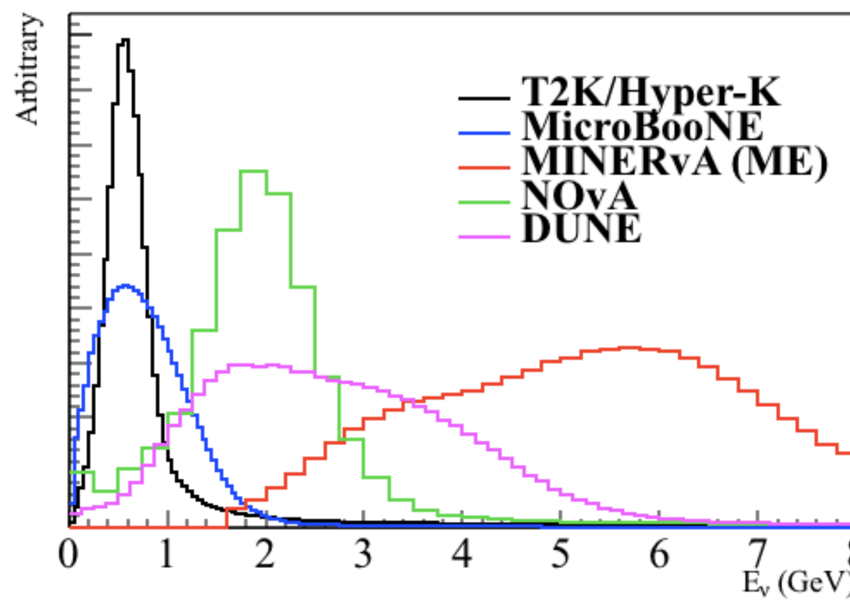
1. Hyper-Kamiokande and DUNE

HyperK
- ~2026? in Japan
- Water target
- Narrow band 0.6 GeV
- Low resolution

DUNE
- ~2025? in USA
- Argon target
- wide band 1-4 GeV
- High resolution







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

1. Next goal of high energy physics

Establish Neutrino Standard Model (νSM)
- 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
6. absolute neutrino mass

(4–6: not relevant to neutrino oscillation experiment(?))

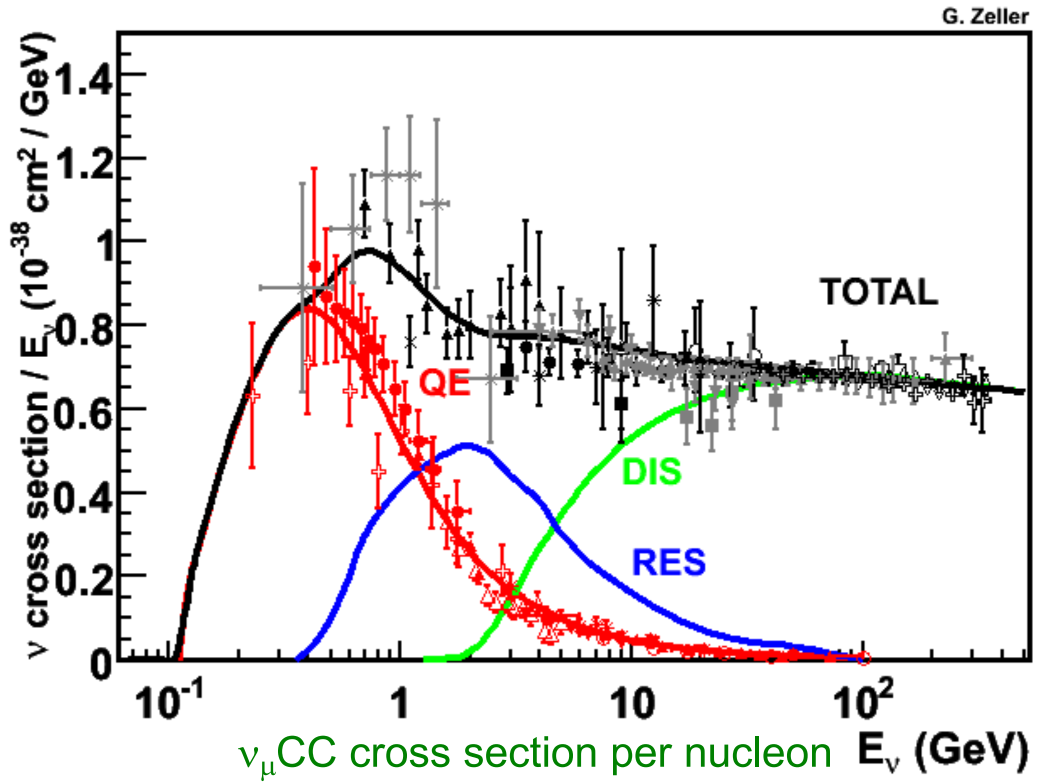
We need higher precision experiments around 1-10 GeV.

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

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

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

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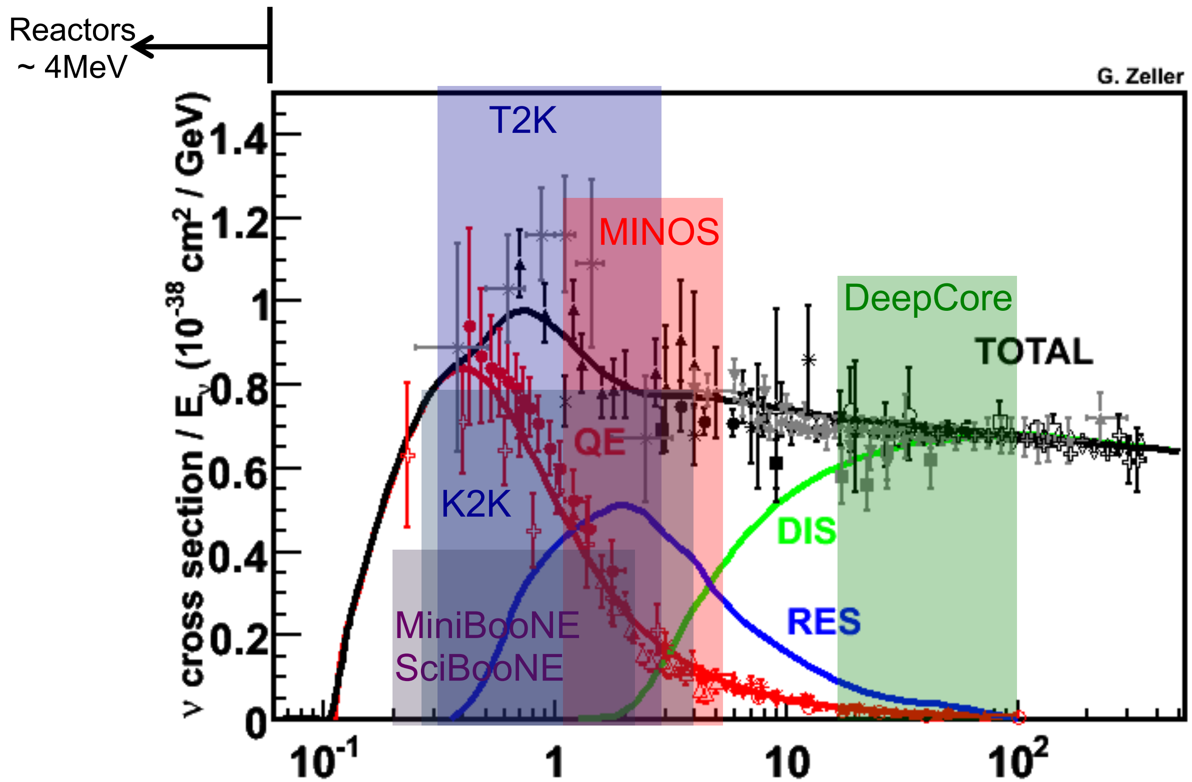

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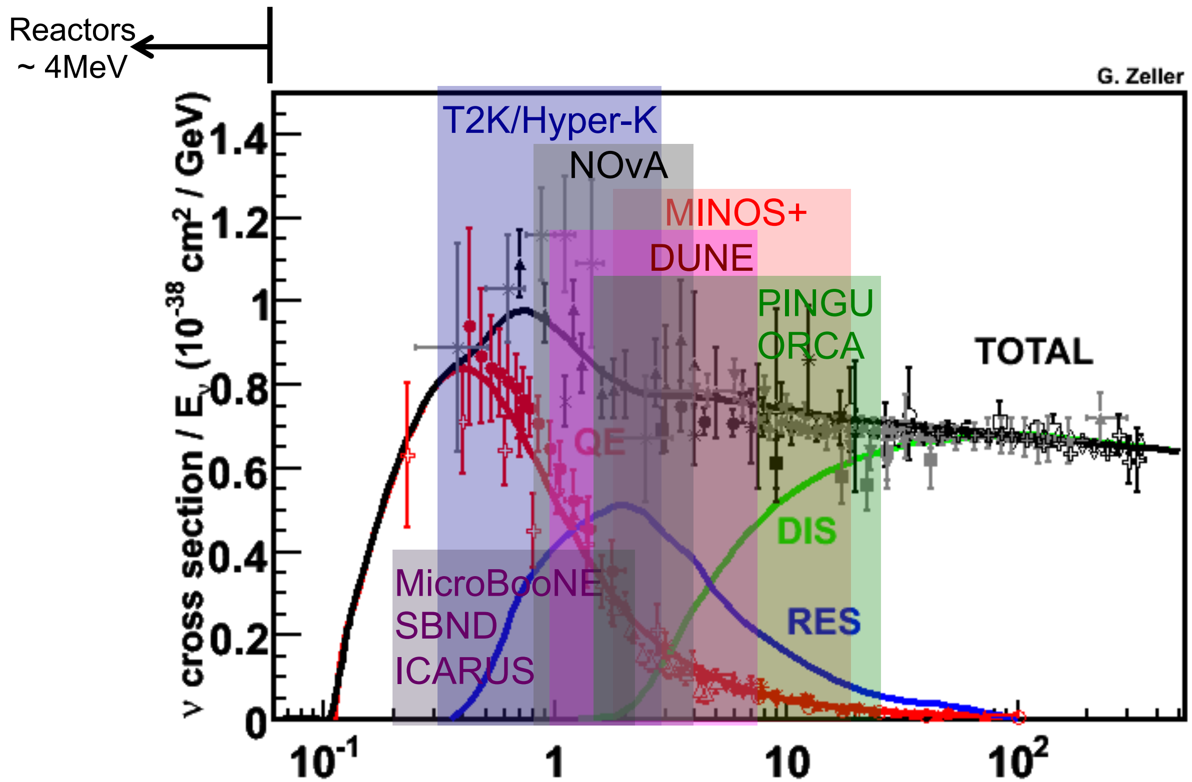

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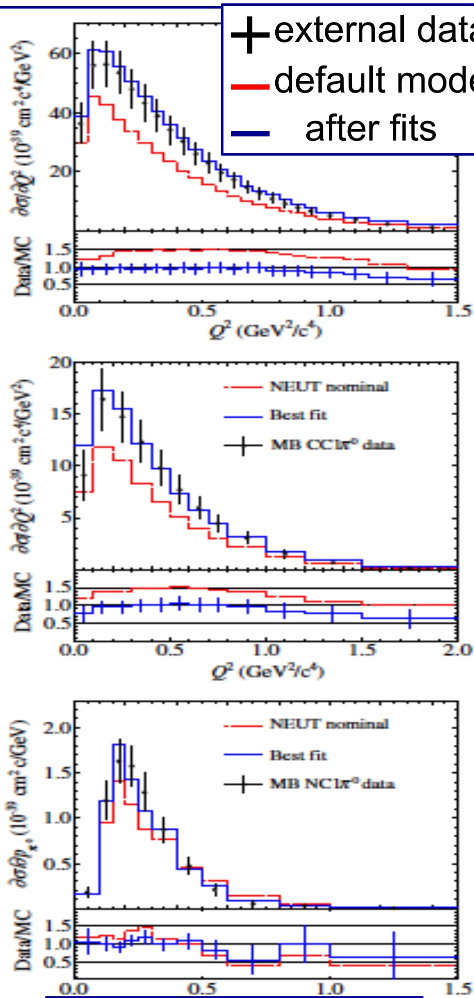
1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics

T2K collaboration, PRL118(2017)151801

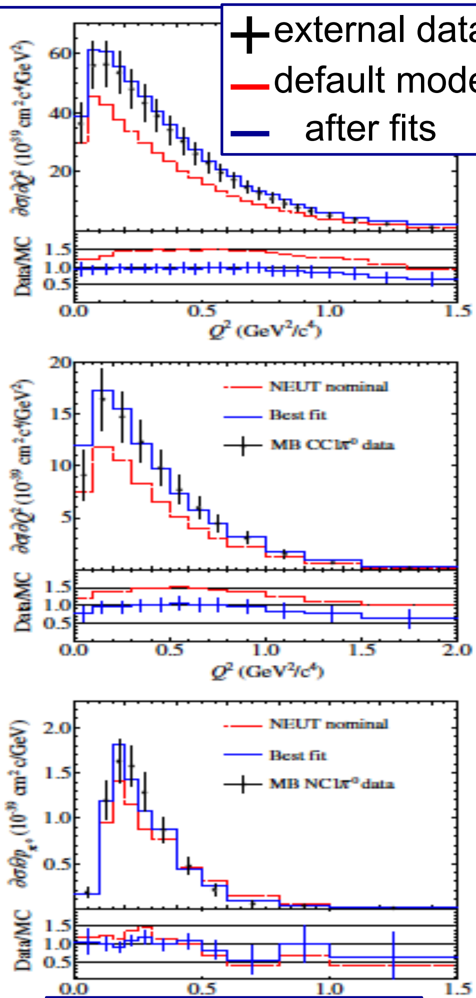
1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

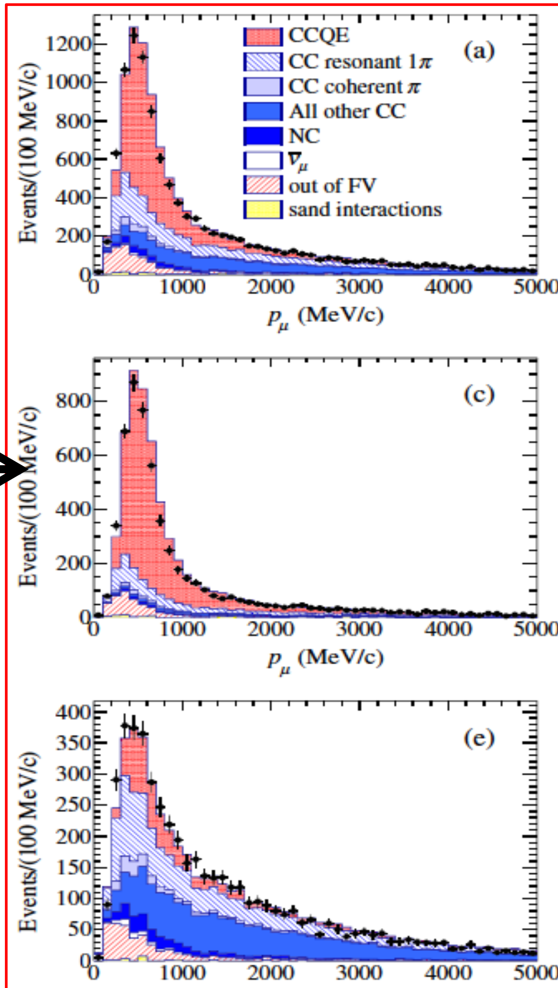
Internal constraint

Near detector
oscillation non-sensitive channels



External data fit

→



T2K ND280 data fit

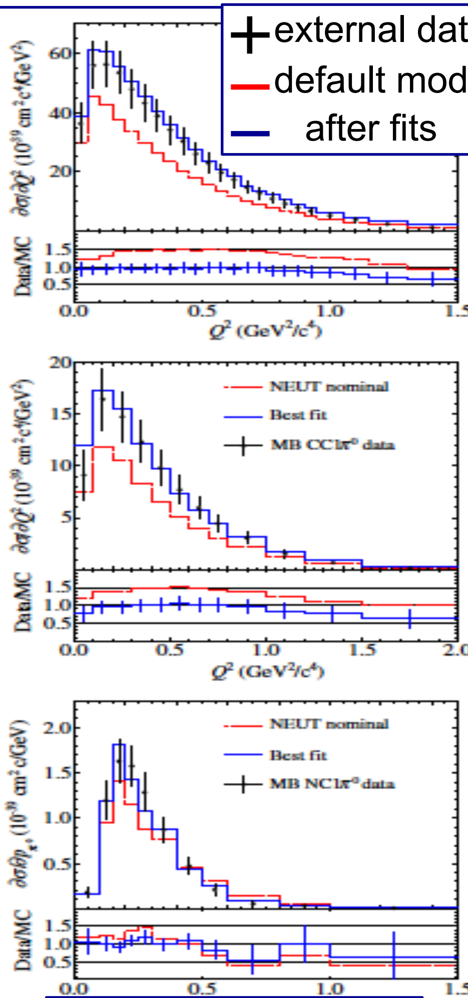
Constraint from internal data find actual size of cross-section errors

1. e.g.) T2K oscillation experiments

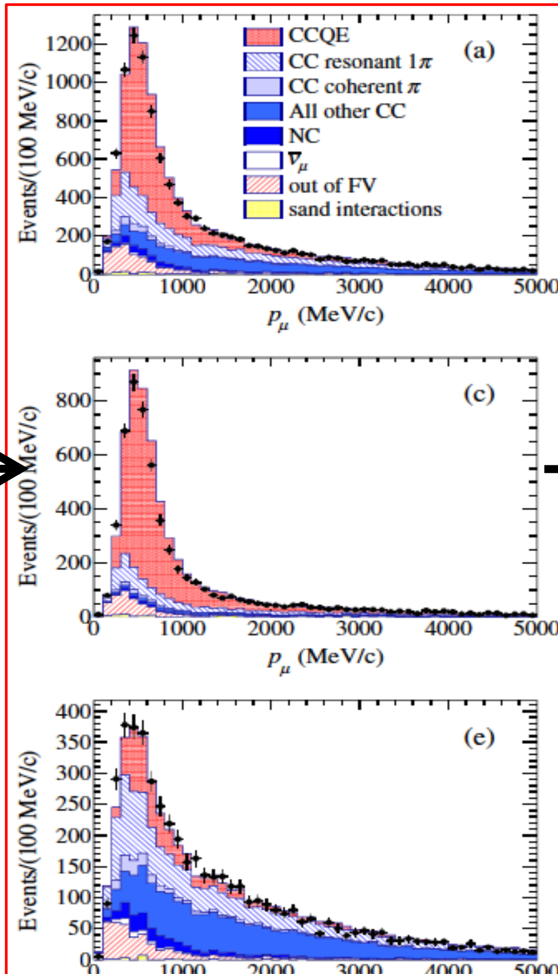
External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint
Near detector
oscillation non-sensitive channels

Neutrino interaction model is a large systematics of neutrino oscillation experiment

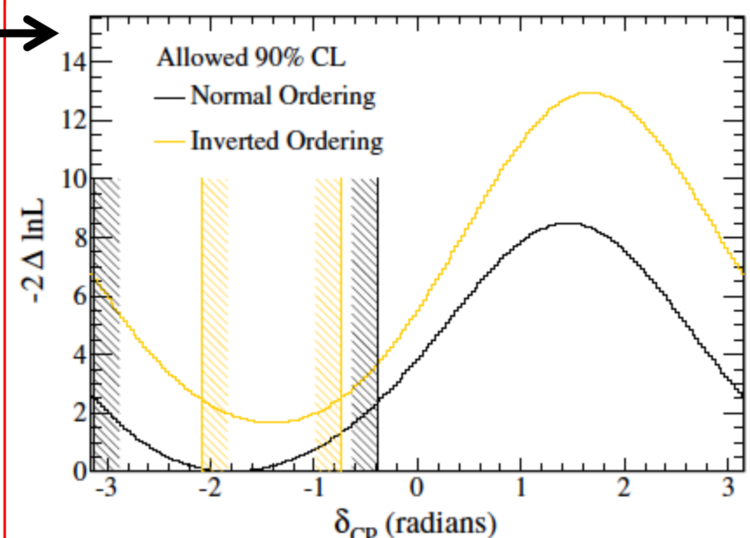


External data fit



T2K ND280 data fit

Source (%)	ν_μ	ν_e	$\bar{\nu}_\mu$	$\bar{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
Super-Kamiokande detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2



oscillation result

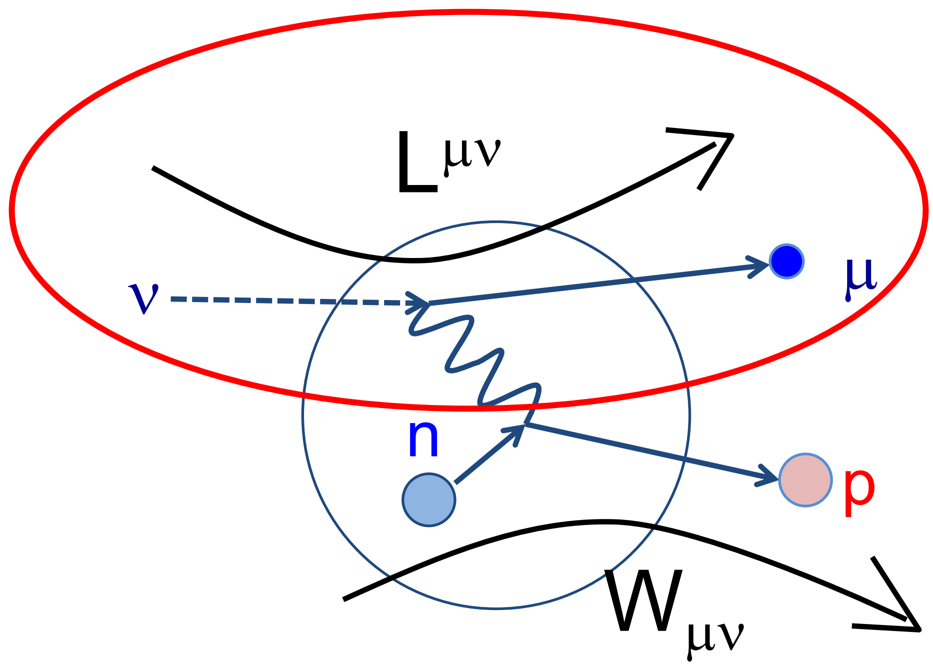
1. Neutrino cross-section formula

Cross-section
- product of Leptonic and Hadronic tensor

$$d\sigma \sim L^{\mu\nu}W_{\mu\nu}$$

Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)



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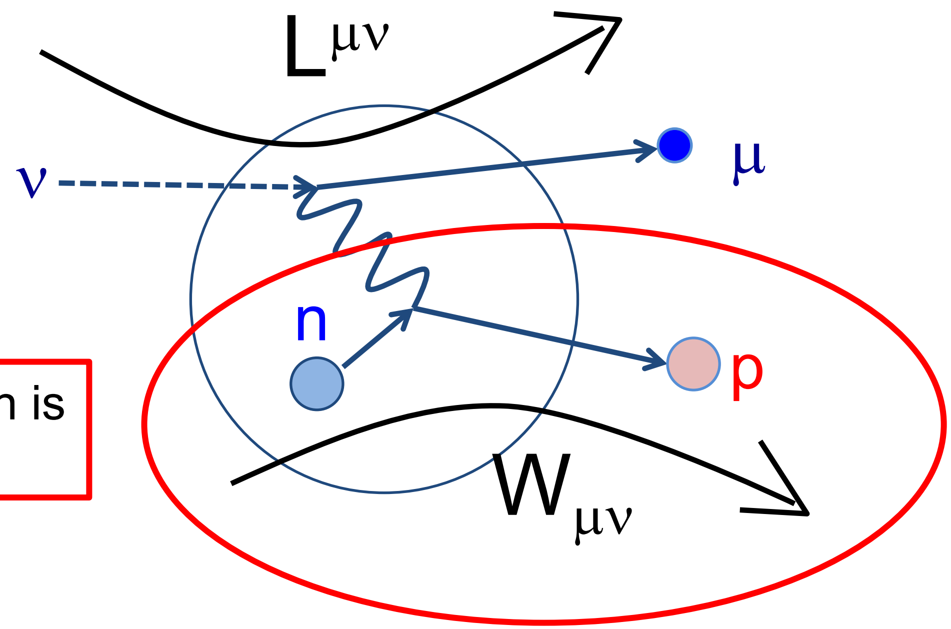

All complication of neutrino cross-section is how to model the hadronic tensor part

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

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Neutrino–nucleus cross sections for oscillation experiments

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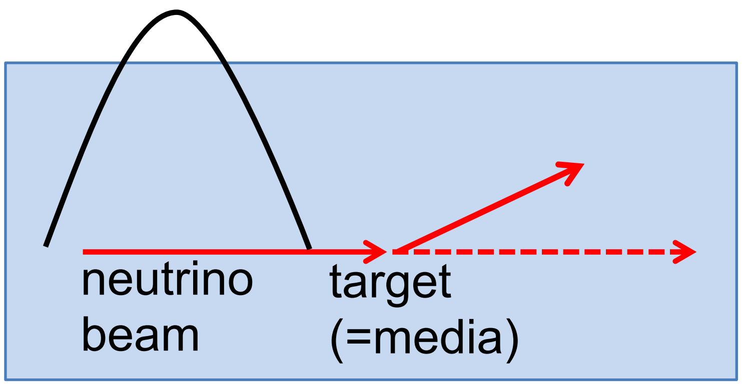
2. Three rules of neutrino interaction physics

Three rules of neutrino interaction physics

1. Incomplete measurements
2. Incomplete kinematics
3. Unknown target

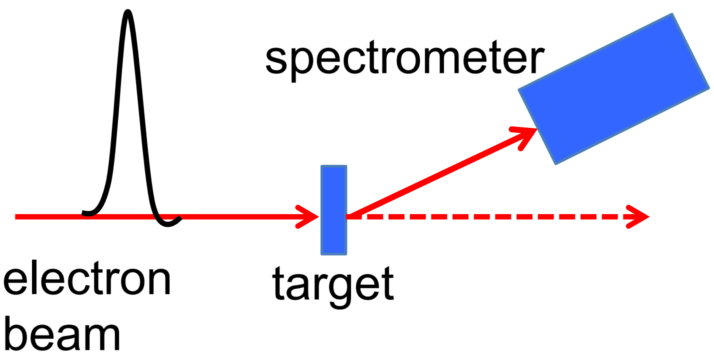
Neutrino scattering

- Coarse instrumentation
- Wideband beam
- Heavy nuclear target



Electron scattering

- Precise spectrometer
- Well defined beam energy, known flux
- It can study reactions with variety of targets



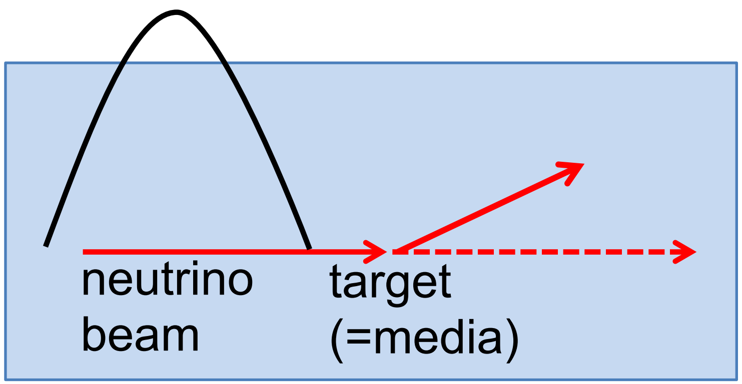
2. Rule 1: Detector performance is poor

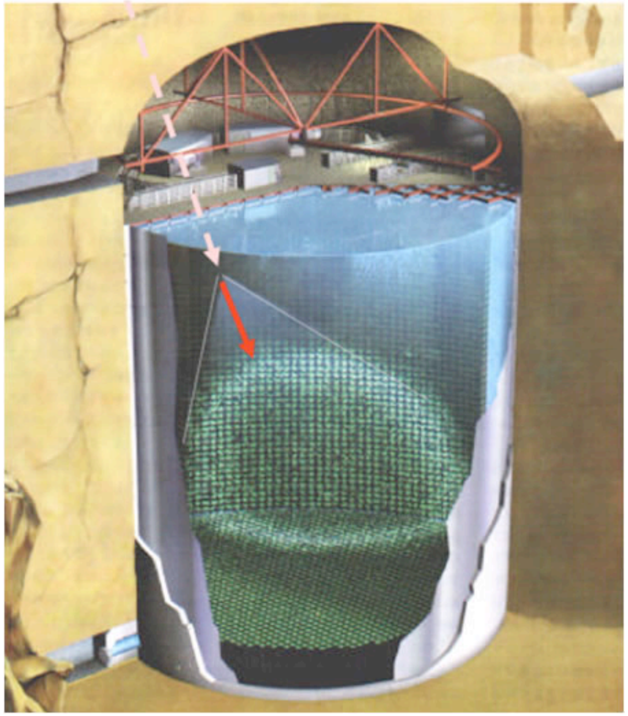
Three rules of neutrino interaction physics

1. Incomplete measurements
2. Incomplete kinematics
3. Unknown target

In order to maximize interaction rate, detector volume is large, coarsely instrumented
→ Poor final hadron state measurements

Neutrino scattering
- Coarse instrumentation
- Wideband beam
- Heavy nuclear target





TK, Martini, JPhysG45(2017)1

2. Rule 2: Beam energy is unknown

Three rules of neutrino interaction physics

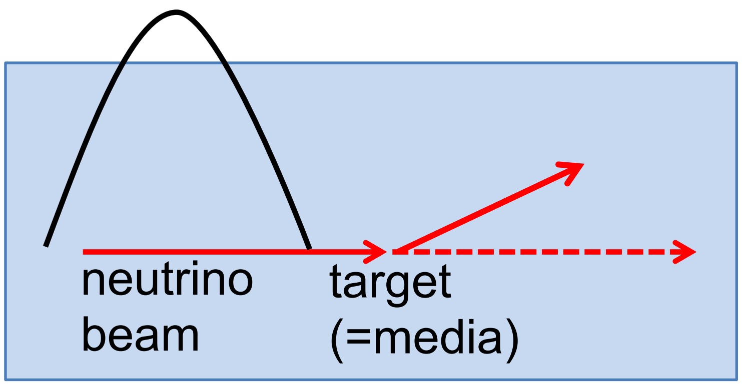
1. Incomplete measurements
2. Incomplete kinematics
3. Unknown target

Incoming neutrino energy is not known.

Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

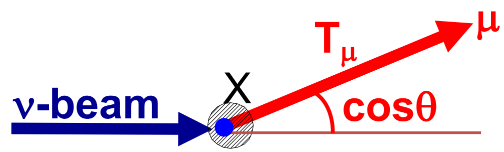
Neutrino scattering

- Coarse instrumentation
- Wideband beam
- Heavy nuclear target



1. Kinematics energy reconstruction

- Need to assume 2-body kinematics



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

2. Calorimetric energy reconstruction

- Need to measure all outgoing particles

$$E_\nu^{Cal} = E_\mu + \sum_{i=1}^{all} E_{had}^i$$

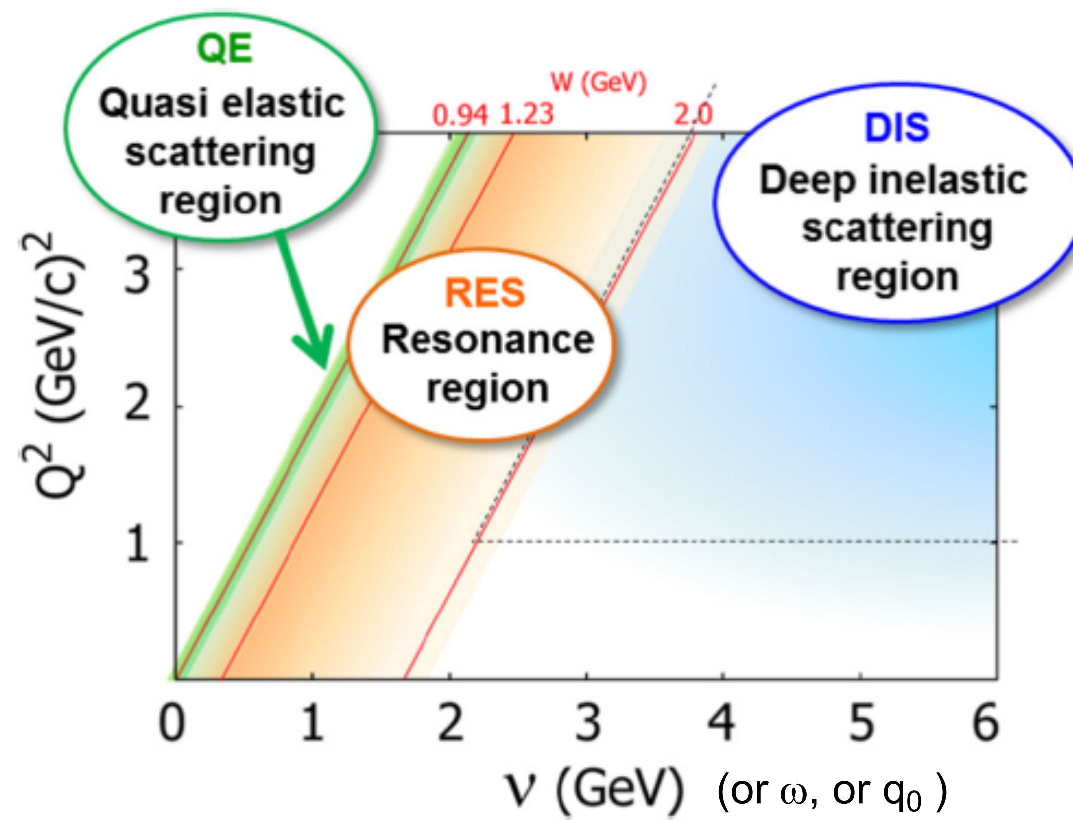
2. Rule 3: More interactions with unknown materials

Three rules of neutrino interaction physics

1. Incomplete measurements
2. Incomplete kinematics
3. Unknown target

Each sub-field of nuclear physics (non-perturbative QCD) is well-developed in limited kinematics, but we are not good at connecting all of them!

Rep. Prog. Phys. **80** (2017) 056301



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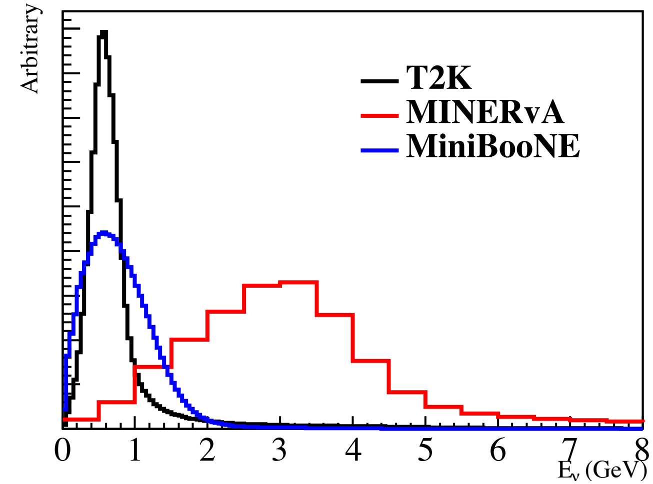
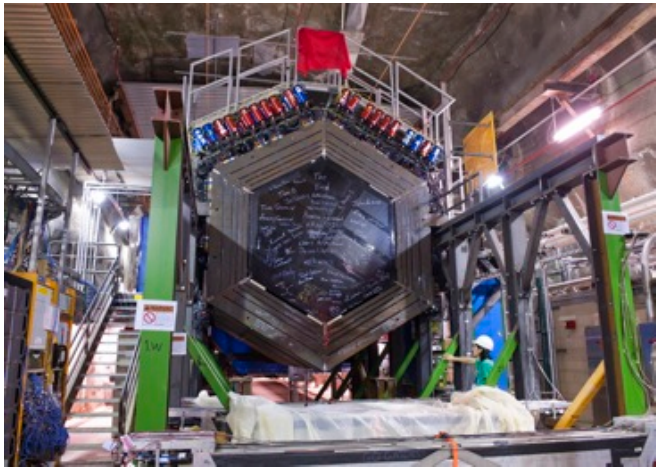
2. MiniBooNE



Mineral oil (CH_2) Cherenkov detector

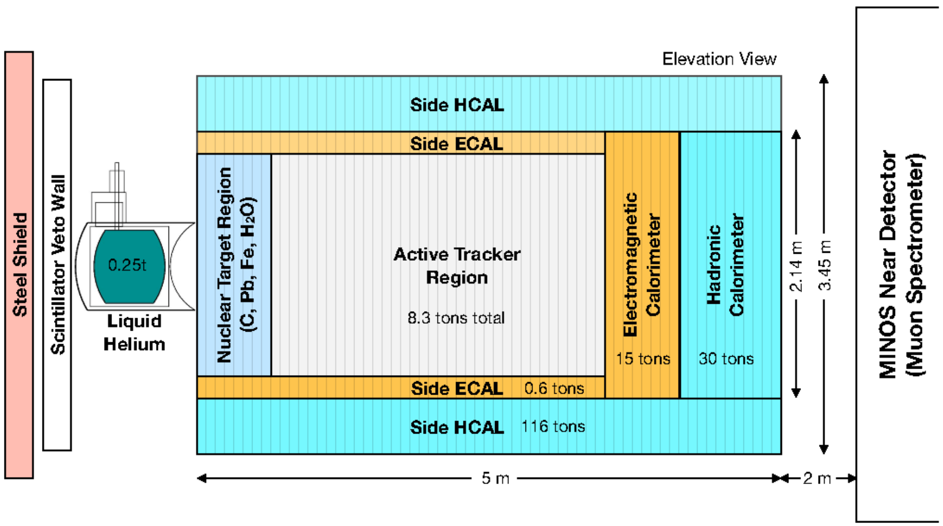
- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Designed for short baseline oscillation experiment
- Kinematic neutrino energy reconstruction
- Some calorimetric (scintillation)

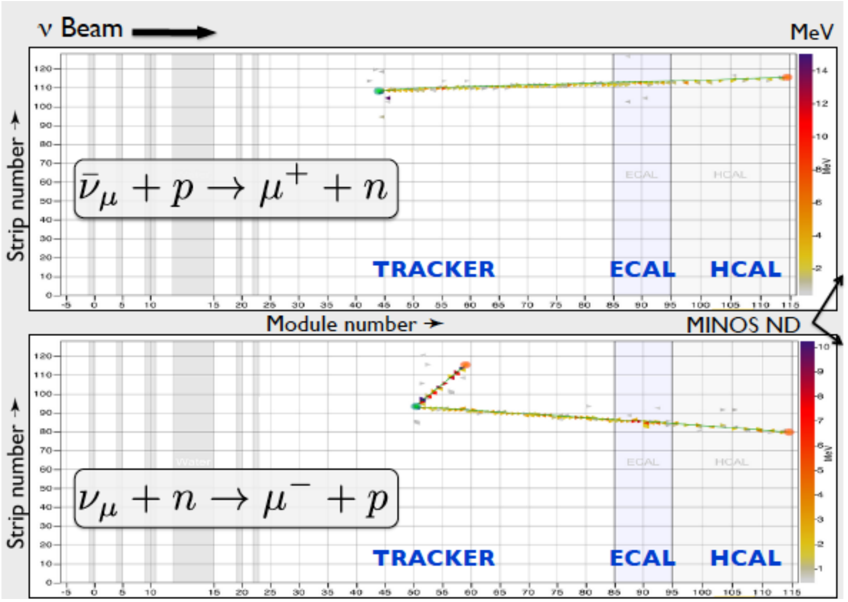
2. MINERvA



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)

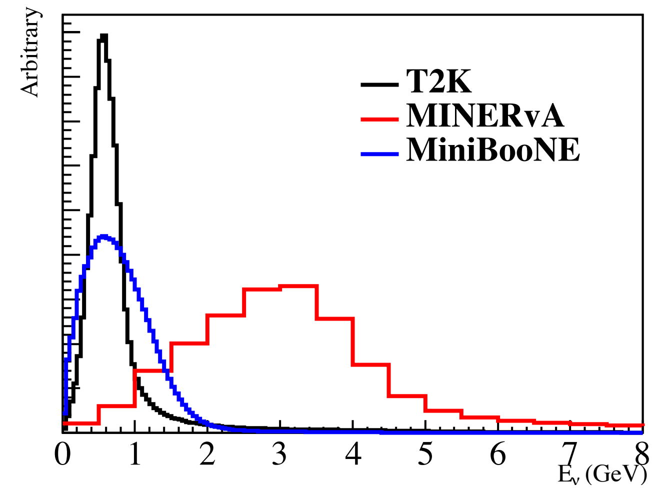


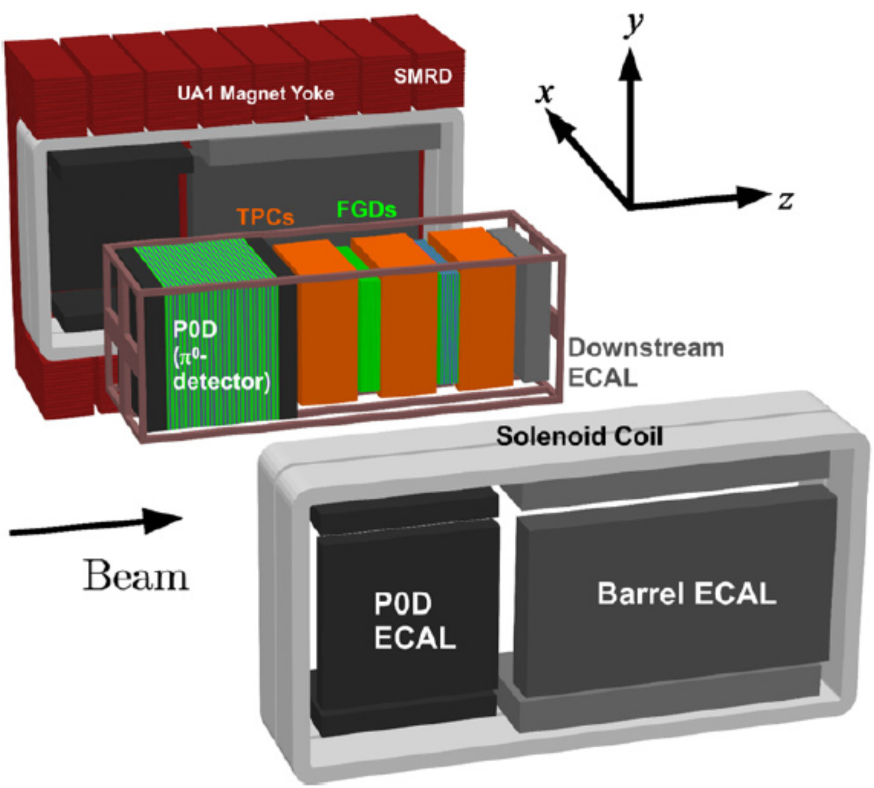


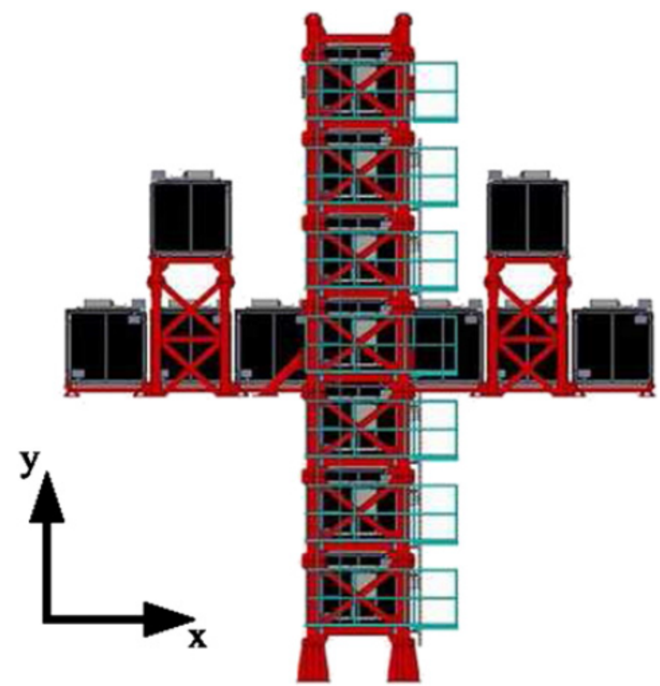
T2K, NIMA659(2011)106

2. T2K near detectors

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)







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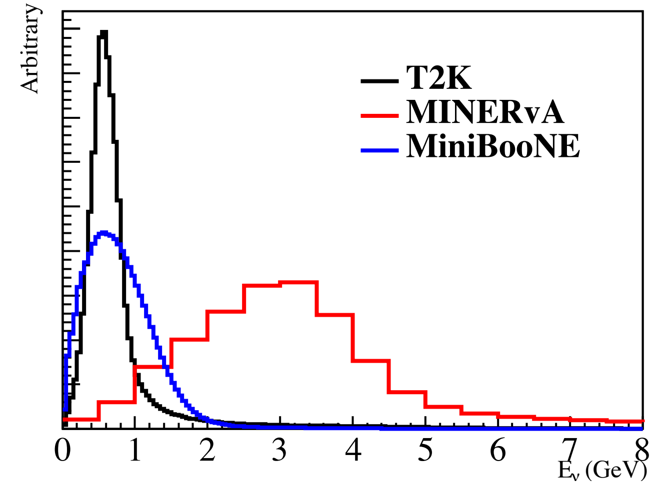
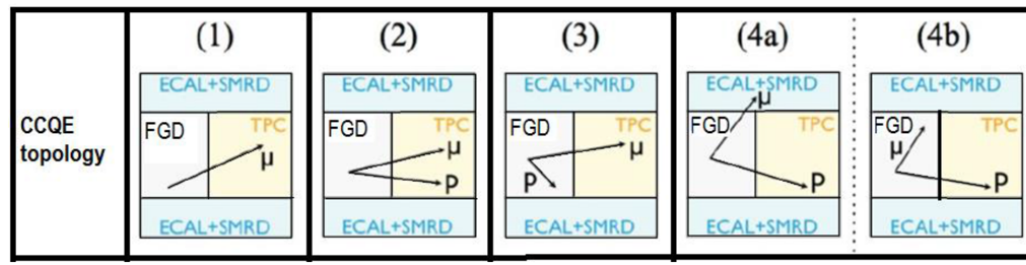
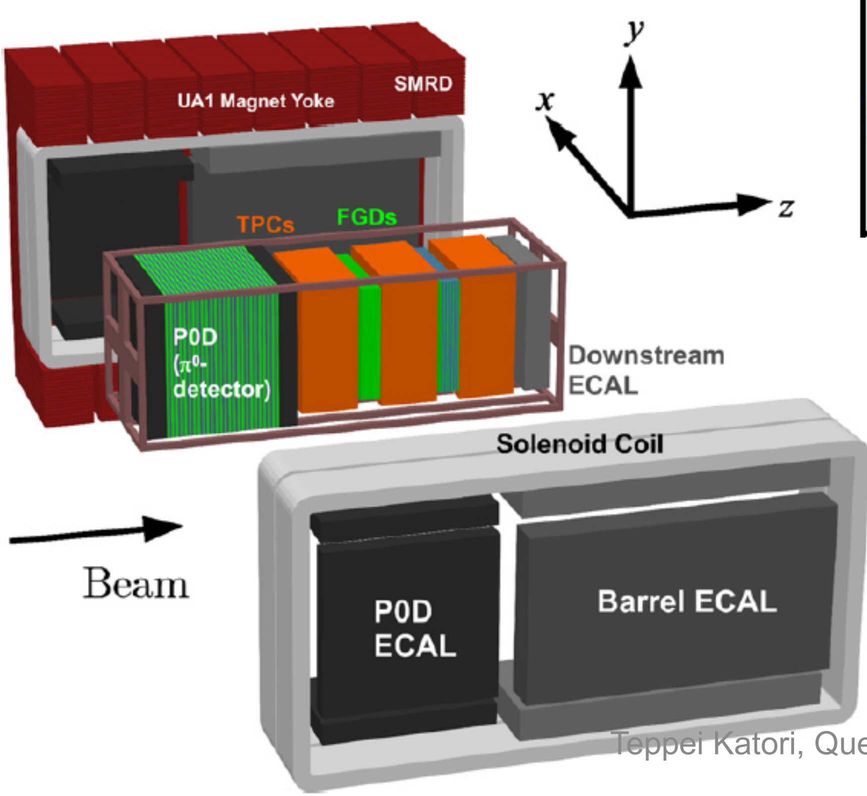
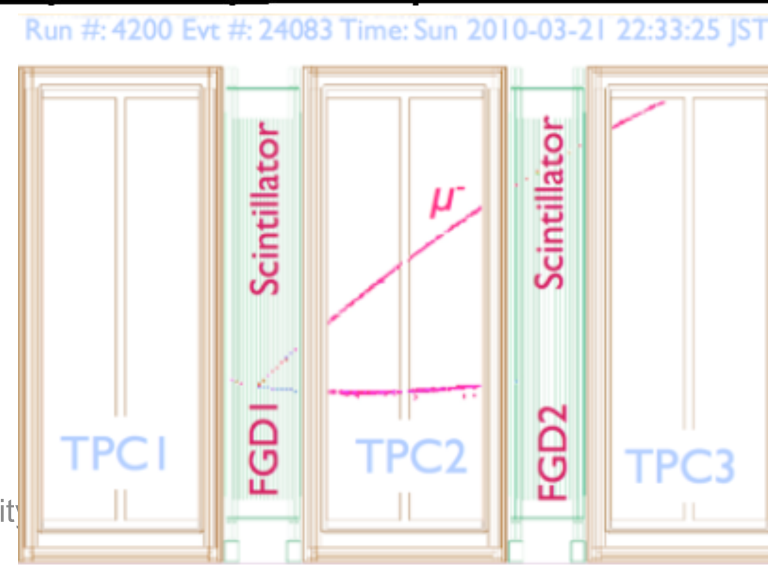


neutrino CC0π double differential cross sections

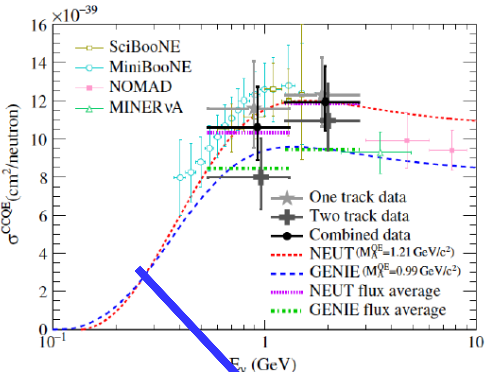


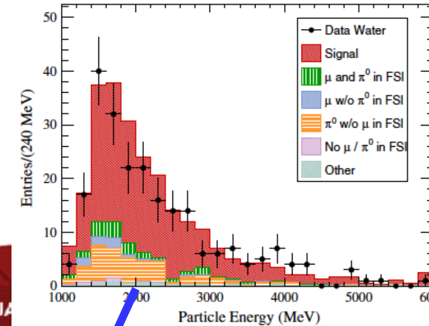


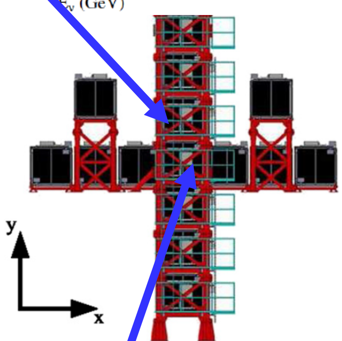


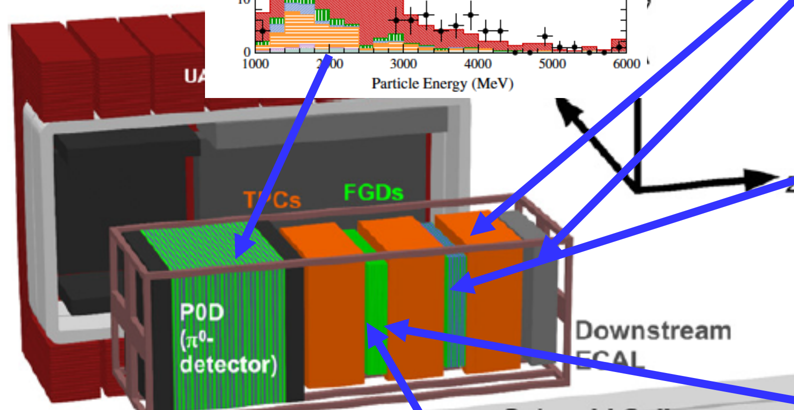
T2K,PRD91(2015)112002;91(2015)112010;93(2016)112012;95(2017)012010, WAGASCI, PoS(EPS-HEP2015)292
PRL113(2014)241803, Brailsford, PhD thesis (Imperial, 2015), Hamilton, PhD thesis (Imperial, 2016)

2. T2K near detectors

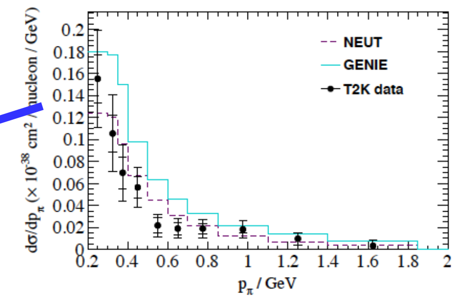


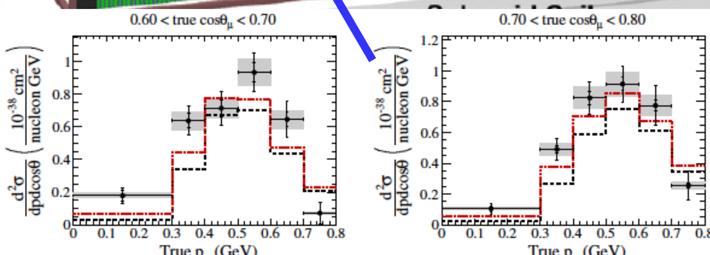


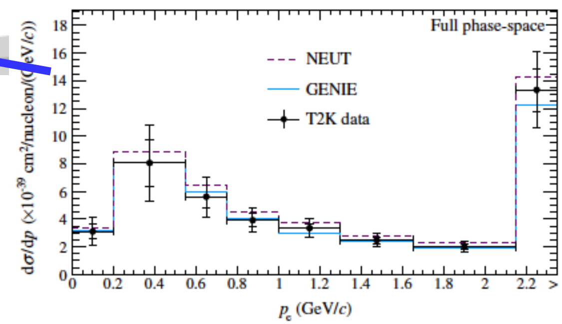




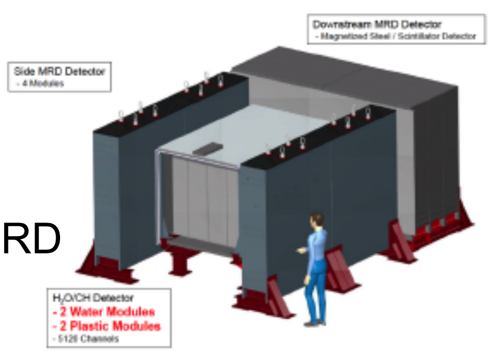
Target dependent measurement
- Ar (TPC gas)
- Pb (ECal)
etc

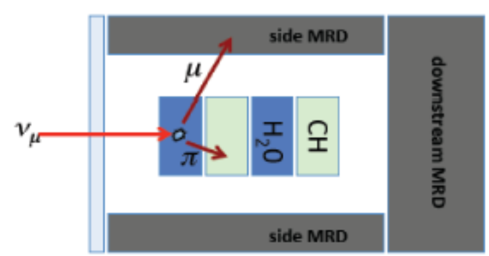


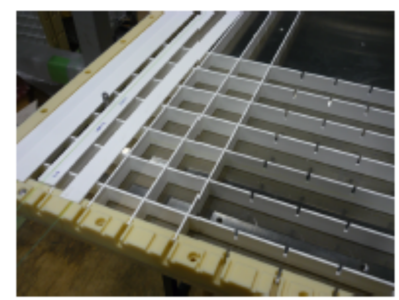




WAGASCI
- YNU initiative
- Water target
- x-y-z tracker
- magnetized MRD



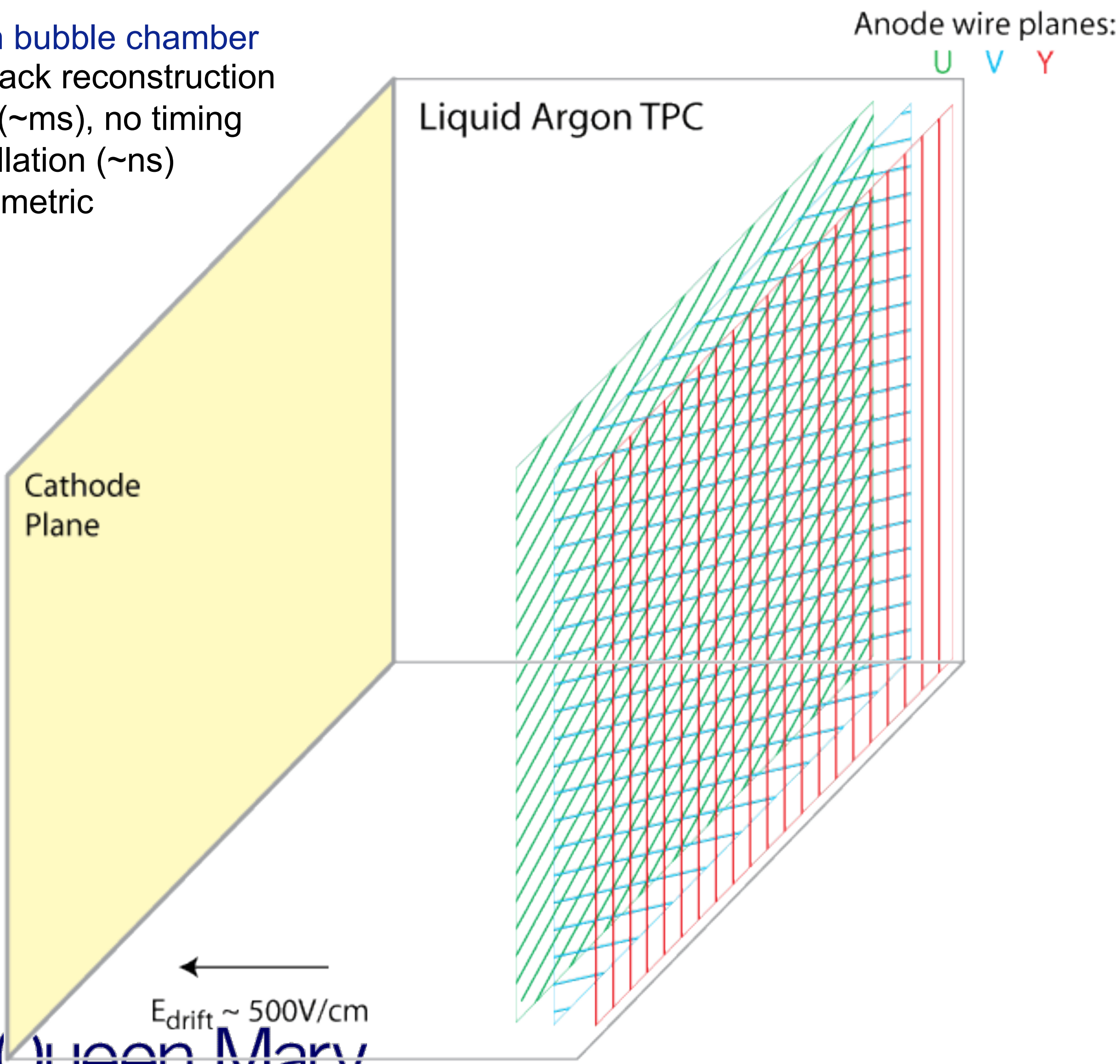




2. Liquid Argon Time Projection Chamber (LArTPC)

Modern bubble chamber

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



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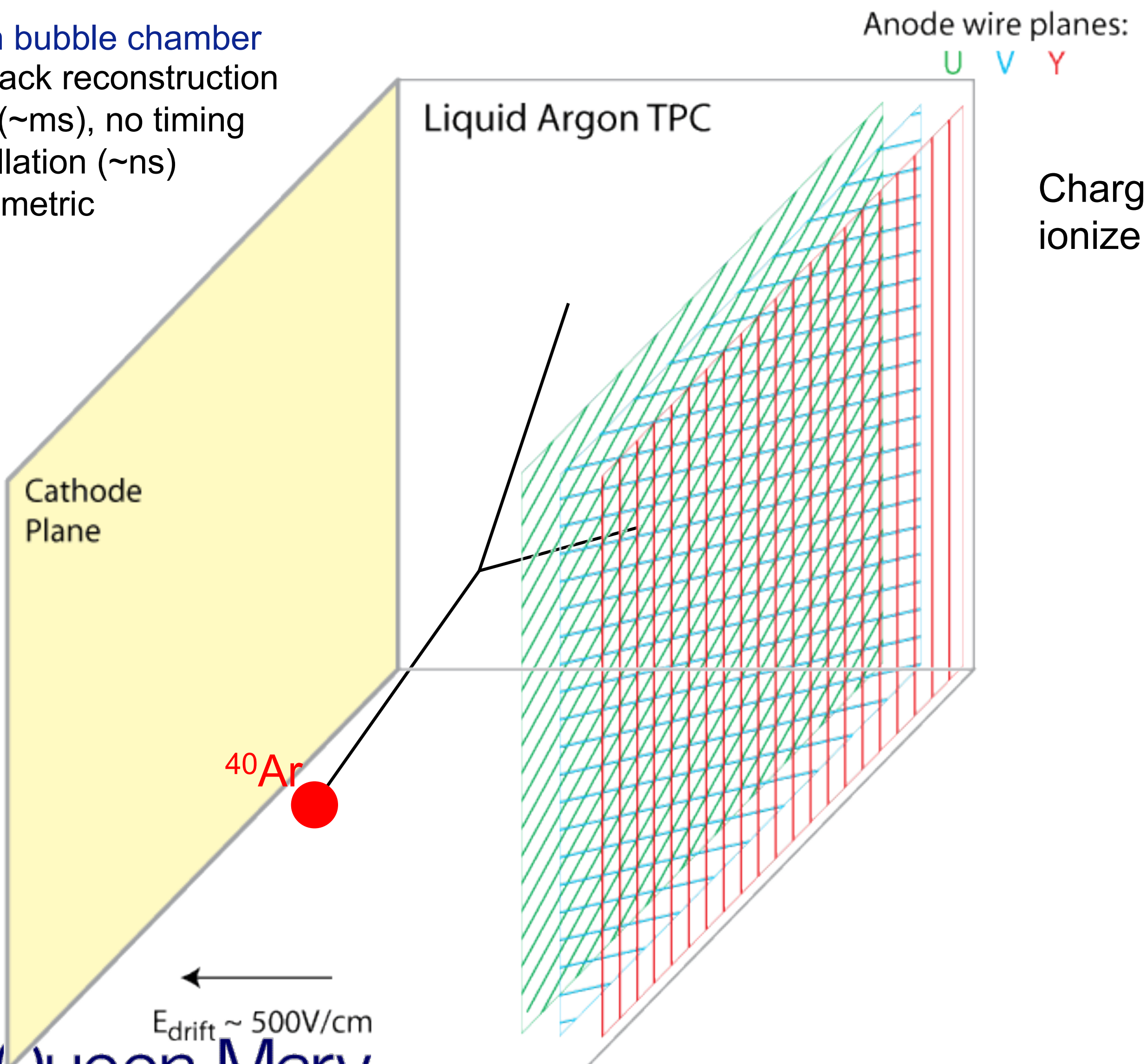

Charged particle tracks ionize Argon atoms

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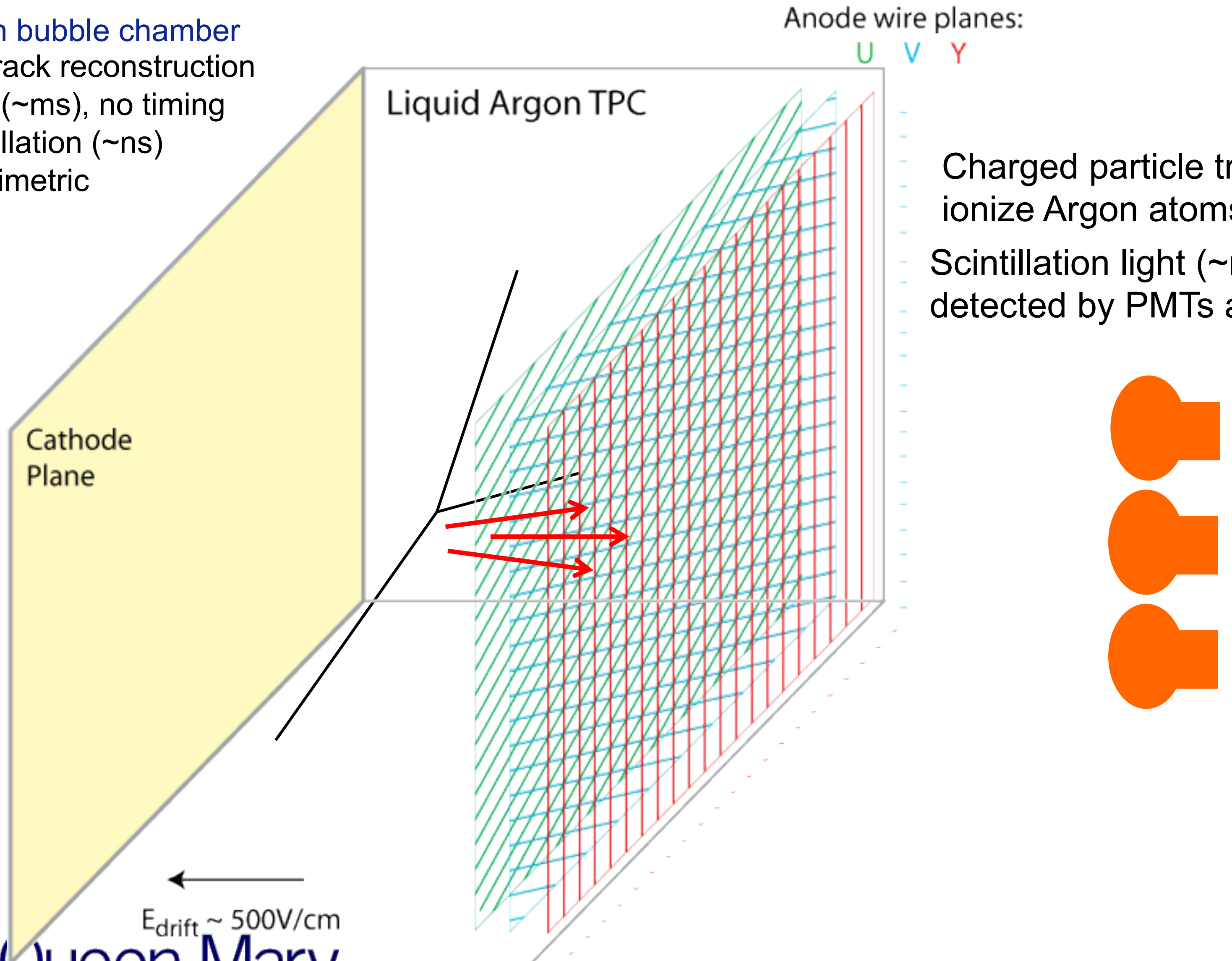

Charged particle tracks ionize Argon atoms

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

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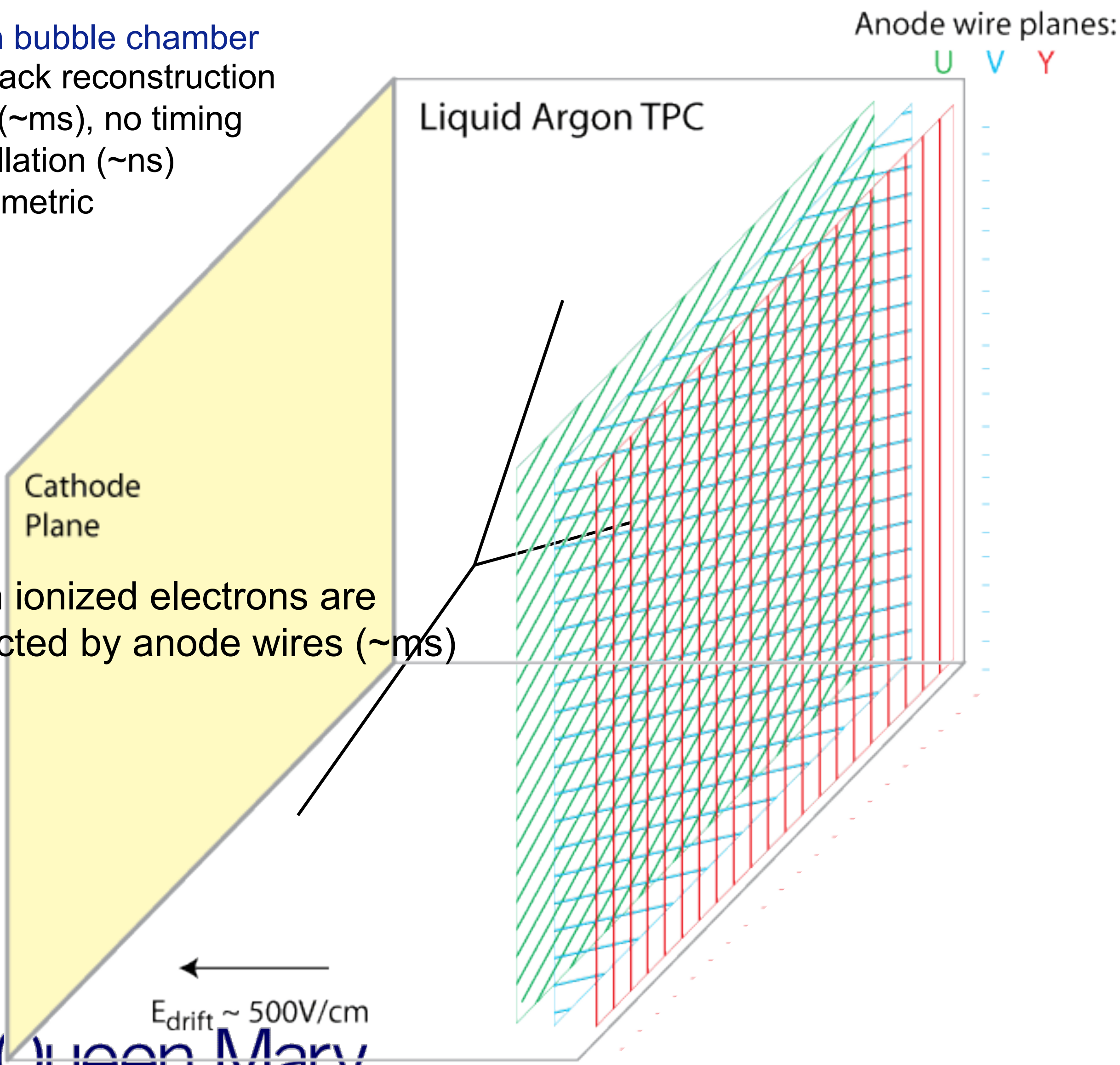

Then ionized electrons are collected by anode wires (~ms)

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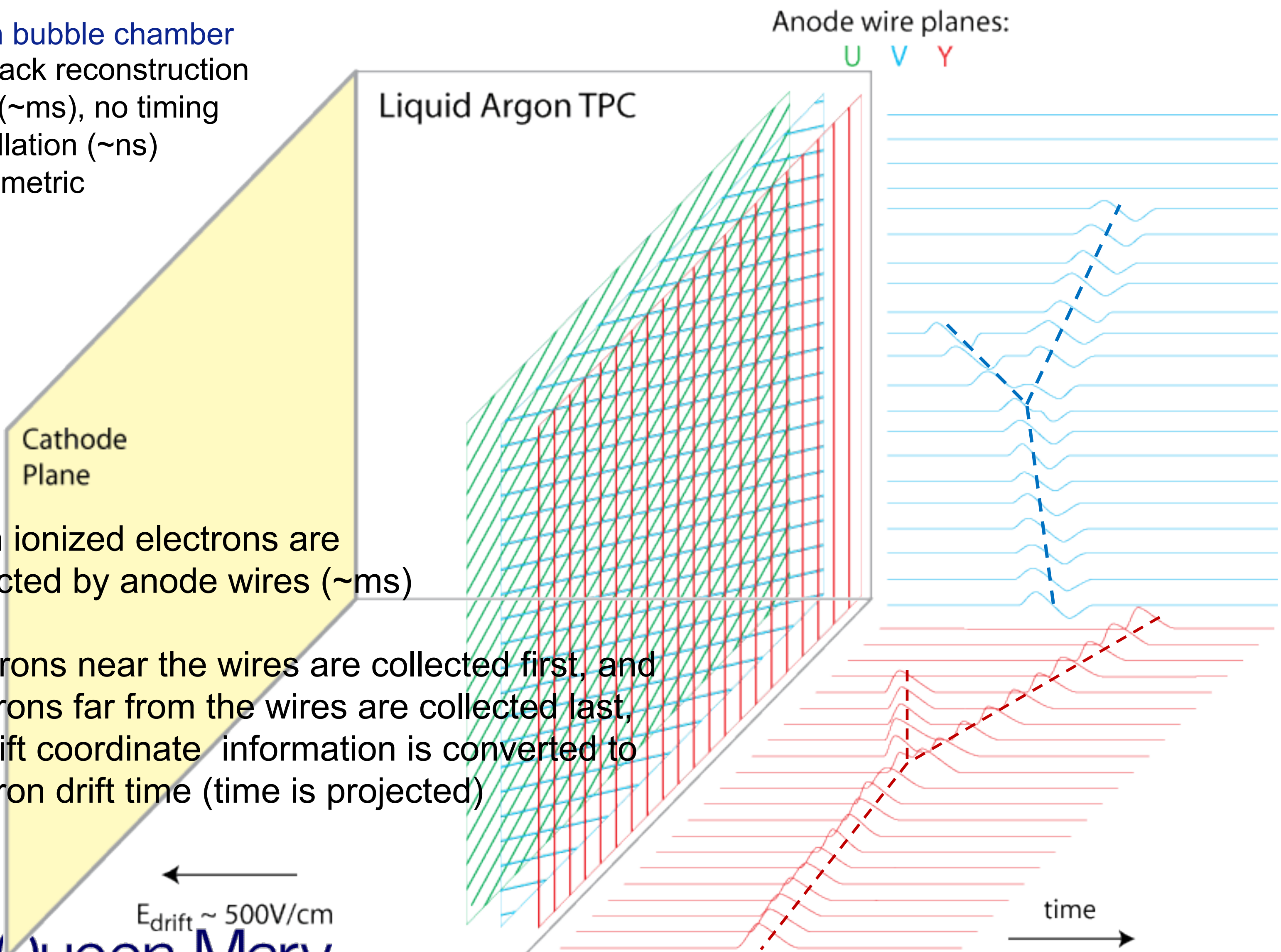


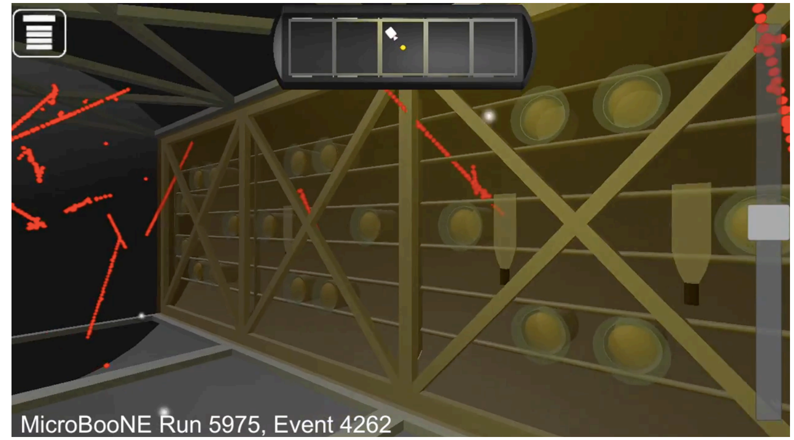
Then ionized electrons are collected by anode wires (~ms)

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)

T2K, arXiv:1805.06887

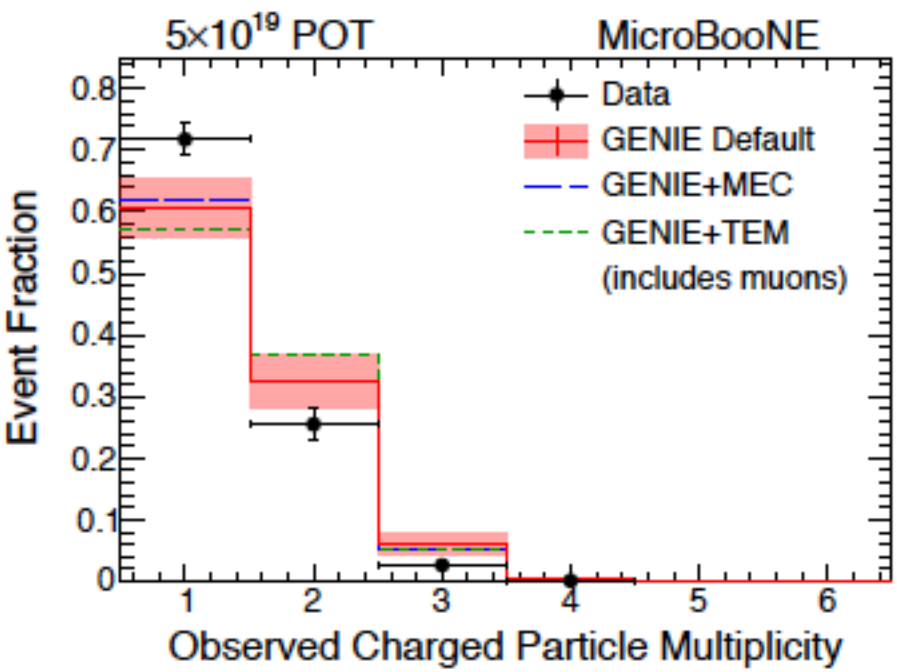
2. MicroBooNE

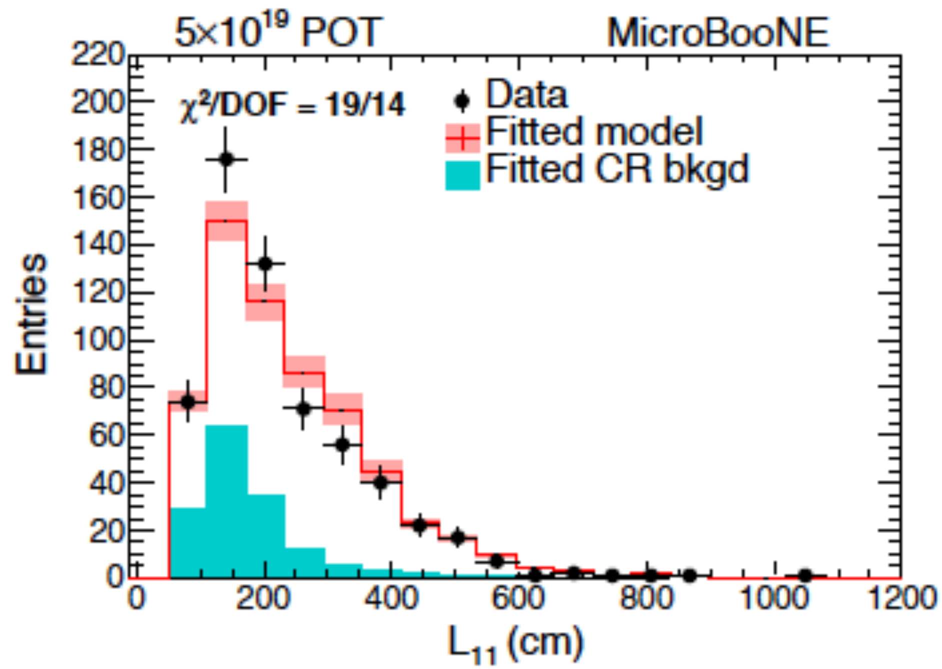
VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- MicroBooNE data event display app



86 ton LArTPC

- technology for DUNE experiment
- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- ArgoNeuT, SBND, protoDUNE, LArIAT…

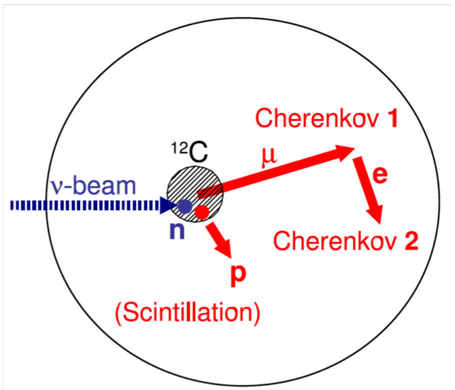




2. Type of neutrino detectors

Cherenkov neutrino detector

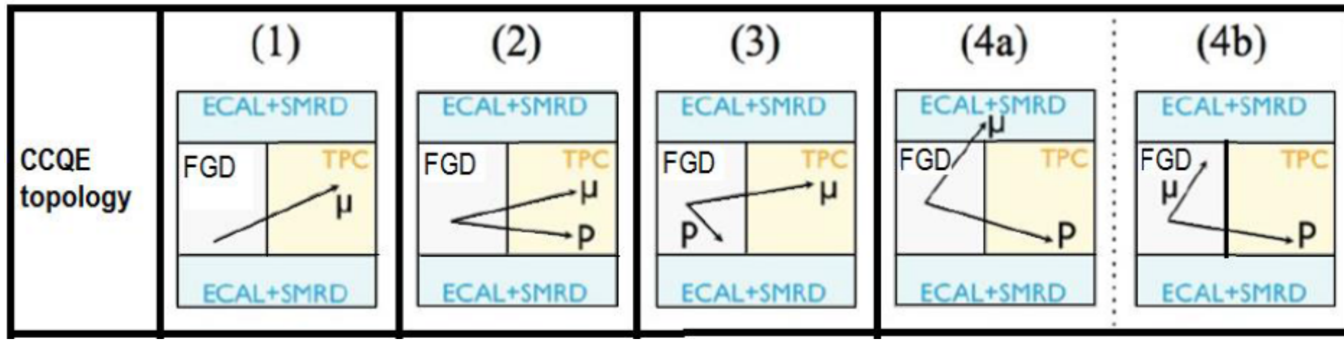
- MiniBooNE
- Super-Kamiokande



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

Tracker neutrino detector

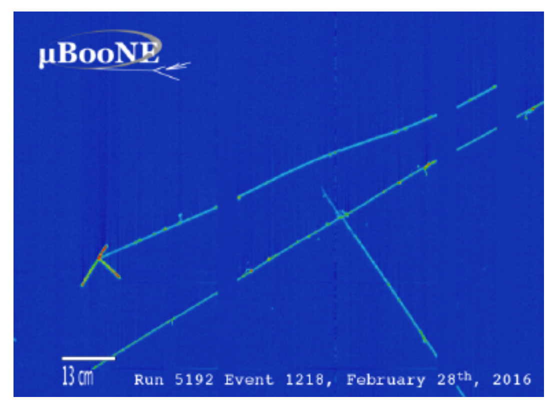
- K2K, T2K near detectors
- MINERvA



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

Liquid argon TPC neutrino detector

- MicroBooNE, ArgoNeuT, SBND
- 4π coverage (Cherenkov)
- multi-track, vertex activity (segmented tracker)
- calorimetric (scintillator)
- no timing (~ms)



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

1. Neutrino interaction physics

2. Neutrino scattering experiments

3. Charged-Current Quasi-Elastic (CCQE) interaction

4. Resonance Single Pion Production

5. Shallow Inelastic Scattering (SIS)

6. Conclusions

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001 (98pp) https://doi.org/10.1088/1361-6471/aa8bf7

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

[1] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[2] ESNT, CEA, IRFU, Service de Physique Nucléaire, Université de Paris-Saclay, F-91191 Gif-sur-Yvette, France
[3] Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium

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journal homepage: www.elsevier.com/locate/ppnp

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Review

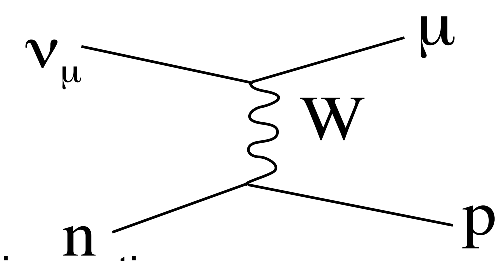
NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

L. Alvarez-Ruso[a], M. Sajjad Athar[b], M.B. Barbaro[c], D. Cherdack[d], M.E. Christy[e], P. Coloma[f], T.W. Donnelly[g], S. Dytman[h], A. de Gouvêa[i], R.J. Hill[j,f], P. Huber[k], N. Jachowicz[l], T. Katori[m], A.S. Kronfeld[f], K. Mahn[n], M. Martini[o], J.G. Morfín[f,*], J. Nieves[a], G.N. Perdue[f], R. Petti[p], D.G. Richards[q], F. Sánchez[r], T. Sato[s,t], J.T. Sobczyk[u], G.P. Zeller[f]

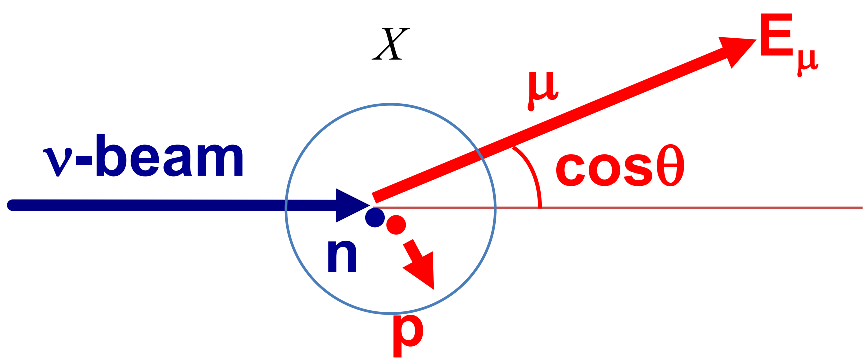
3. Charged Current Quasi-Elastic scattering (CCQE)

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

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



Neutrino energy is reconstructed from the observed lepton kinematics
"QE assumption"
1. assuming neutron at rest
2. assuming interaction is CCQE



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

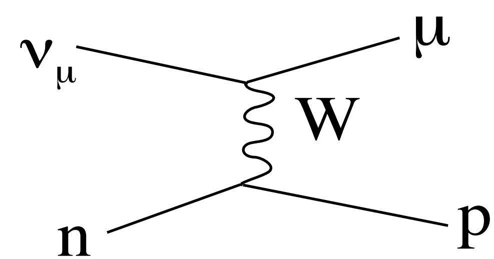
CCQE is the single most important channel of neutrino oscillation physics
T2K, NOvA, microBooneE, Hyper-Kamiokande, DUNE (2nd maximum)…etc

3. CCQE puzzle

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

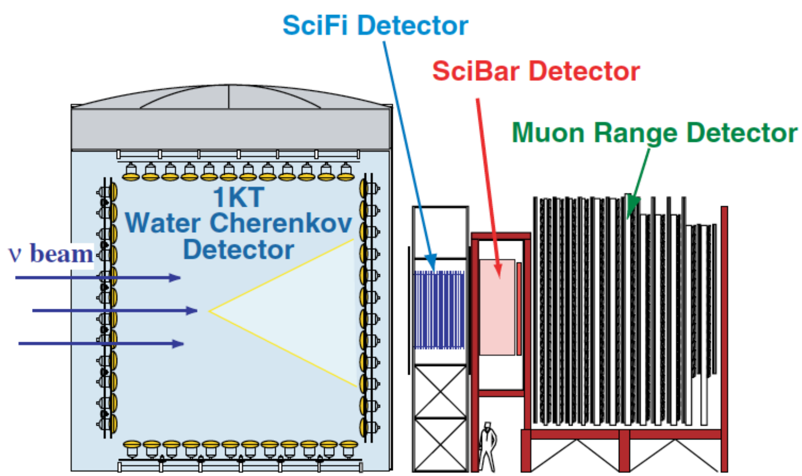
CCQE puzzle

1. low Q2 suppression → Low forward efficiency? (detector)
2. high Q2 enhancement → MA>1.0 GeV? (physics)
3. large normalization → ??? (flux?)

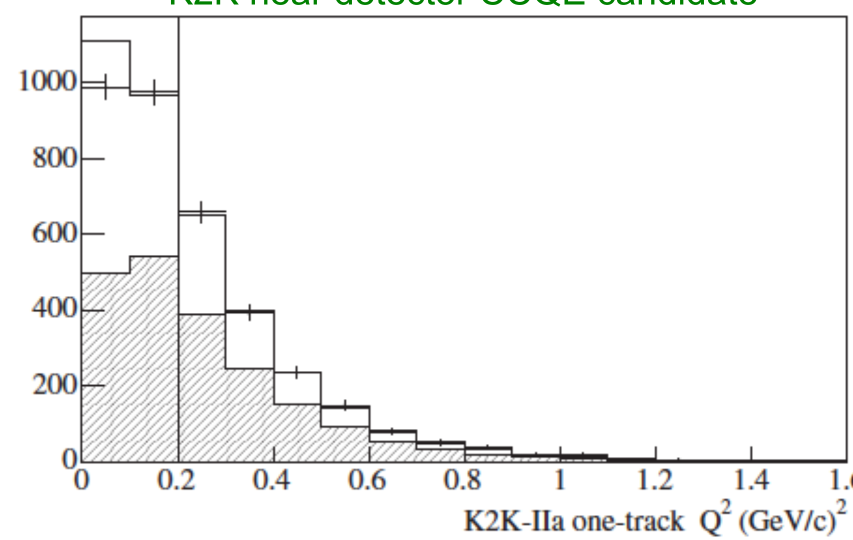


K2K

- Scintillation tracker
- <E>~1.3 GeV
- The first long baseline neutrino oscillation experiment



K2K near detector CCQE candidate



K2K, PRD74(2006)052002,PRD74(2006)072003

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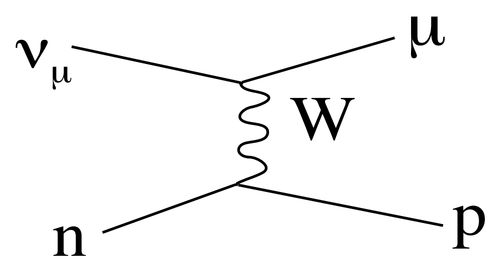
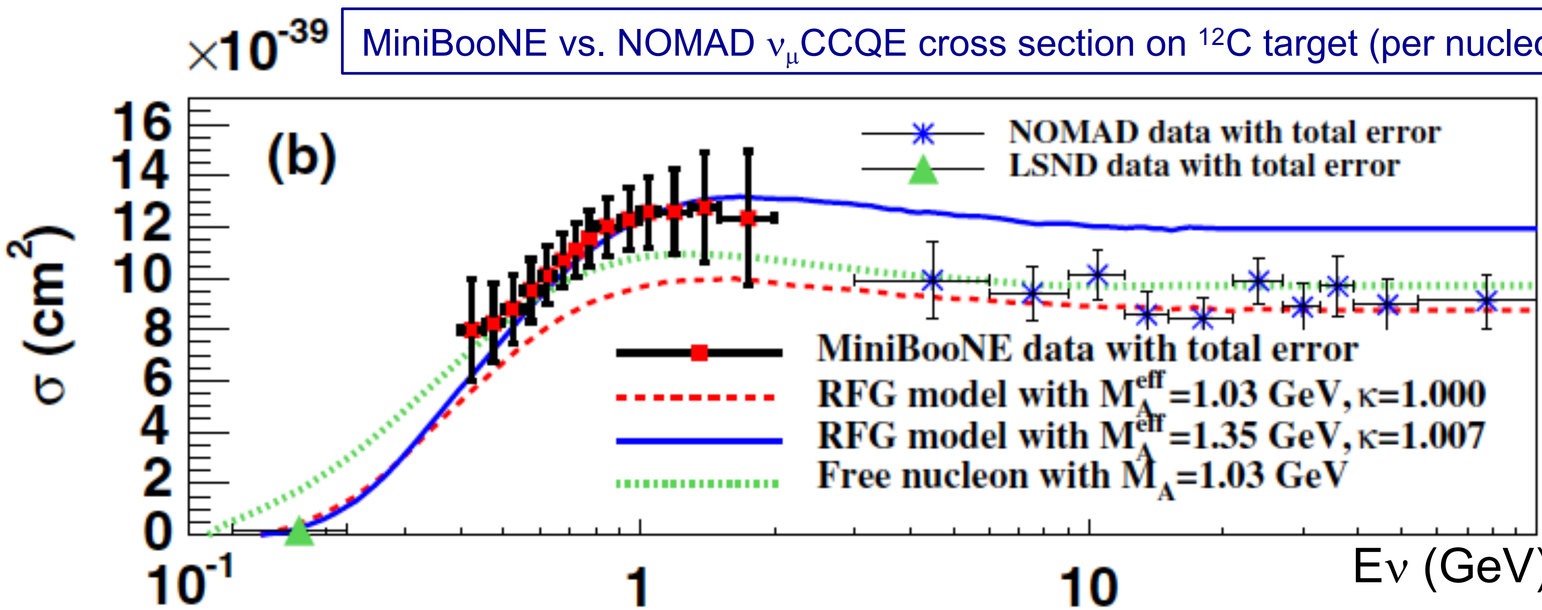


CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality = precise prediction for neutrino CCQE cross-section...?
  → Data disagree with theory both shape (both low Q^2 and high Q^2) and normalization



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) lose 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) lose details of measurements…

Now, all modern experiments publish flux-integrated differential cross-section
→ Detector efficiency corrected event rate
→ Theorists can reproduce the data with neutrino flux tables from experimentalists
→ Minimum model dependent, useful for nuclear theorists

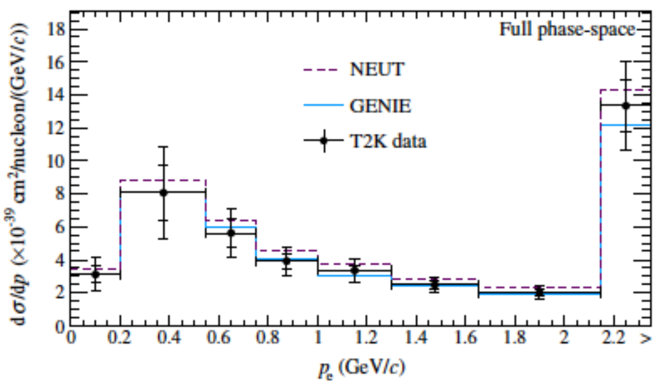
These data play major roles to study/improve neutrino interaction models by theorists

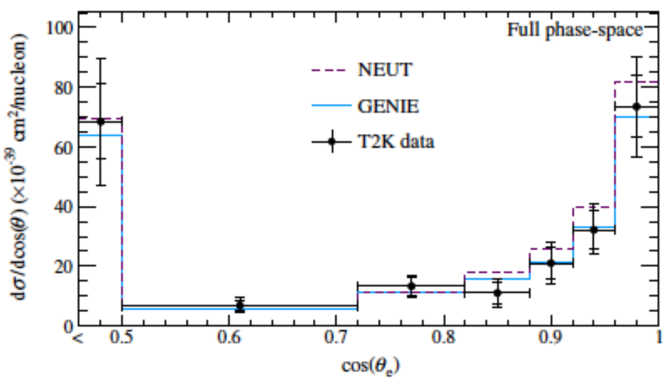
3. Flux-integrated differential cross-section

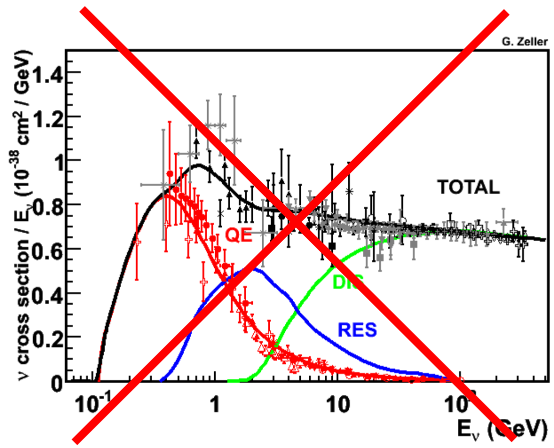
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

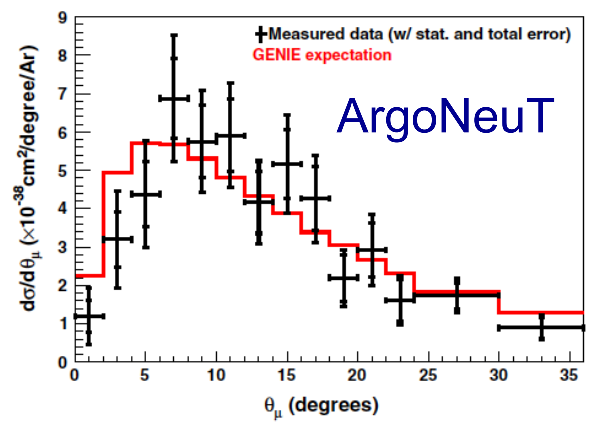
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

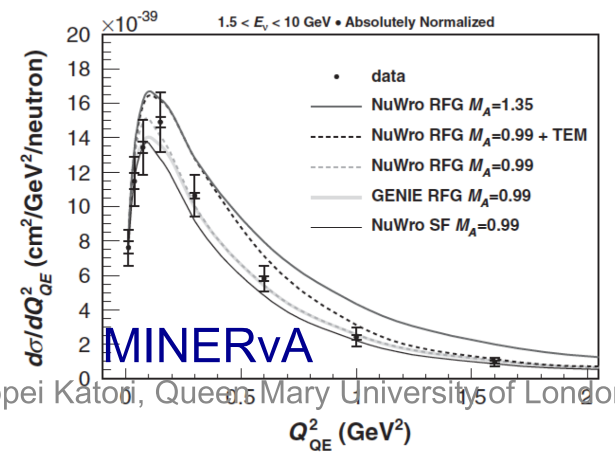
T2K



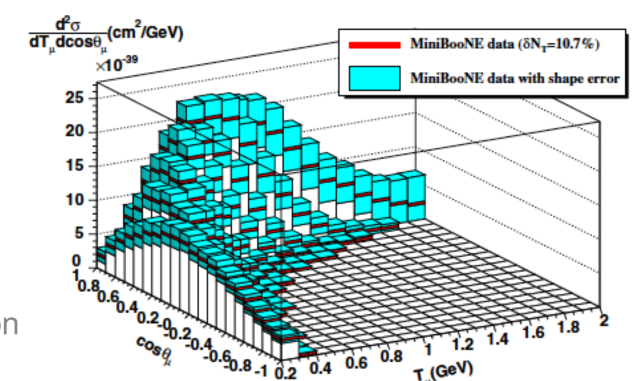








MiniBooNE



3. Flux-integrated differential cross-section

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

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 neutrino interaction physics history

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3. The solution of CCQE puzzle

Presence of 2-body current

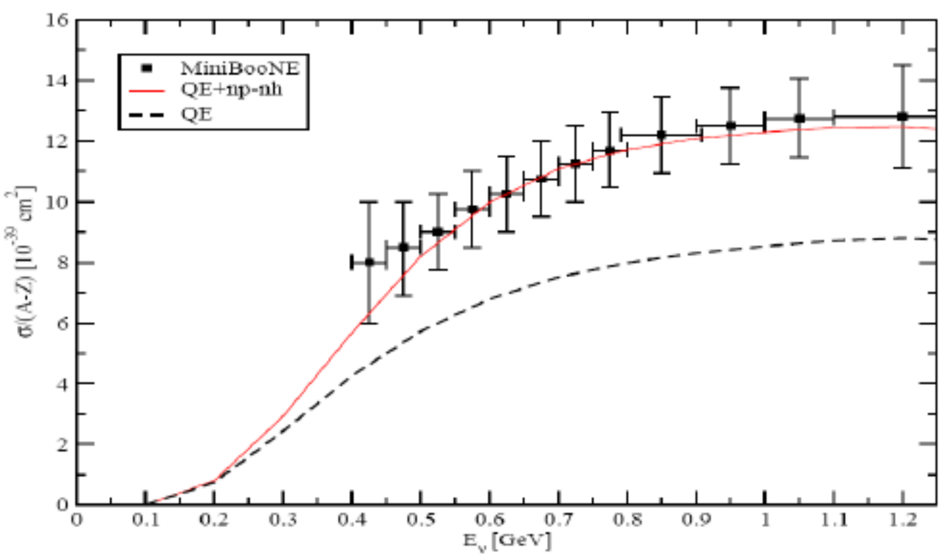
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

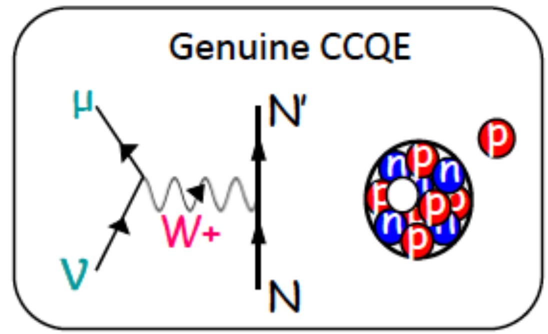
What experimentalists call “CCQE” is not genuine CCQE!

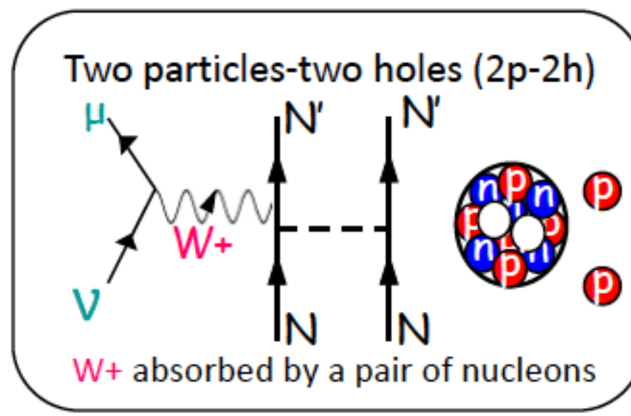
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







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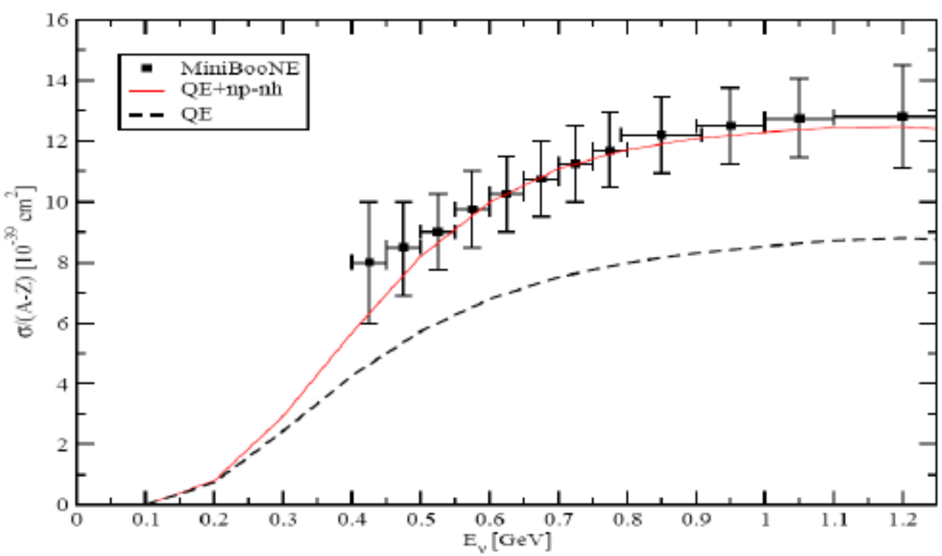
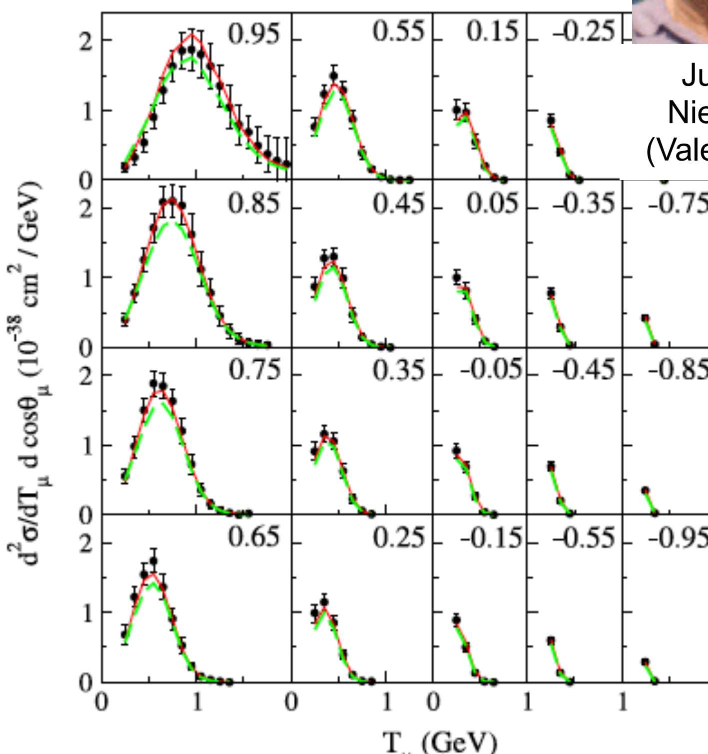


The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)



Valencia model vs. MiniBooNE CCQE double differential cross-section data

Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72

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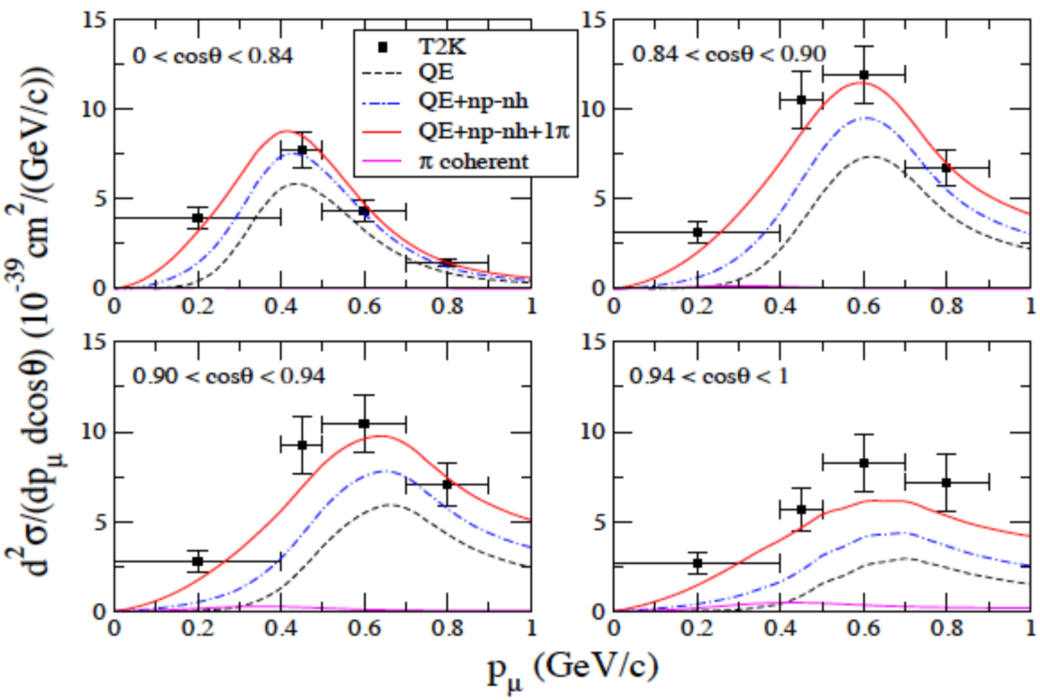

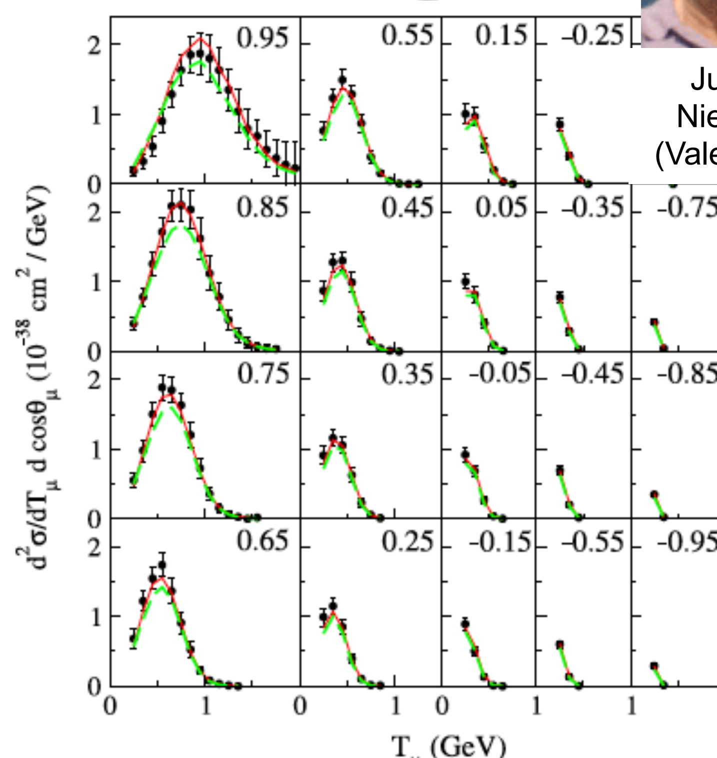

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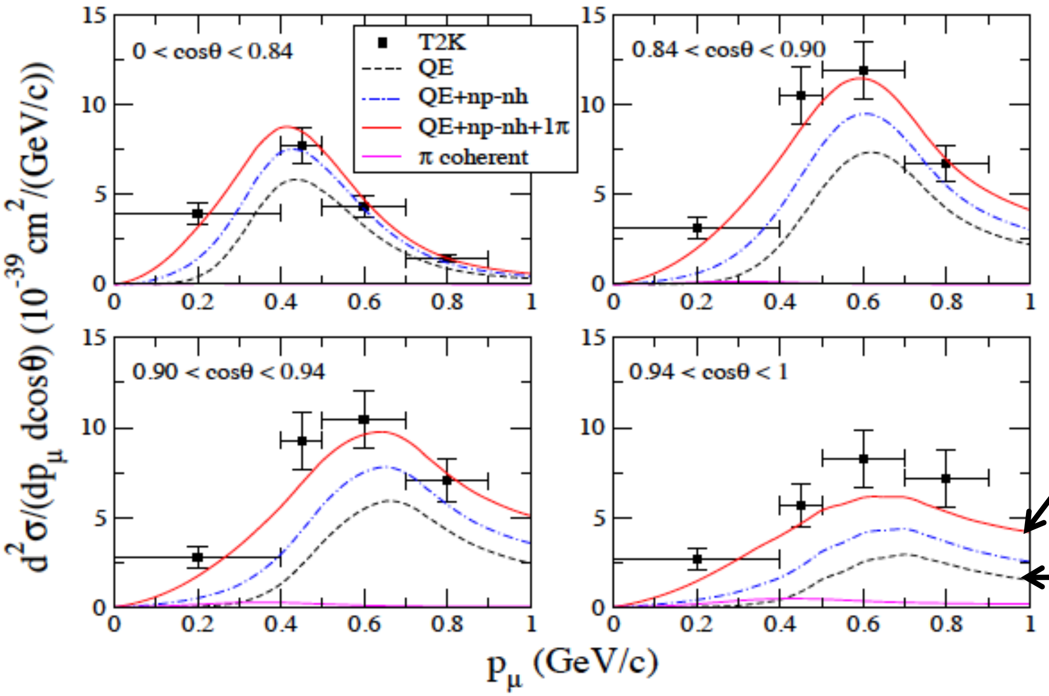
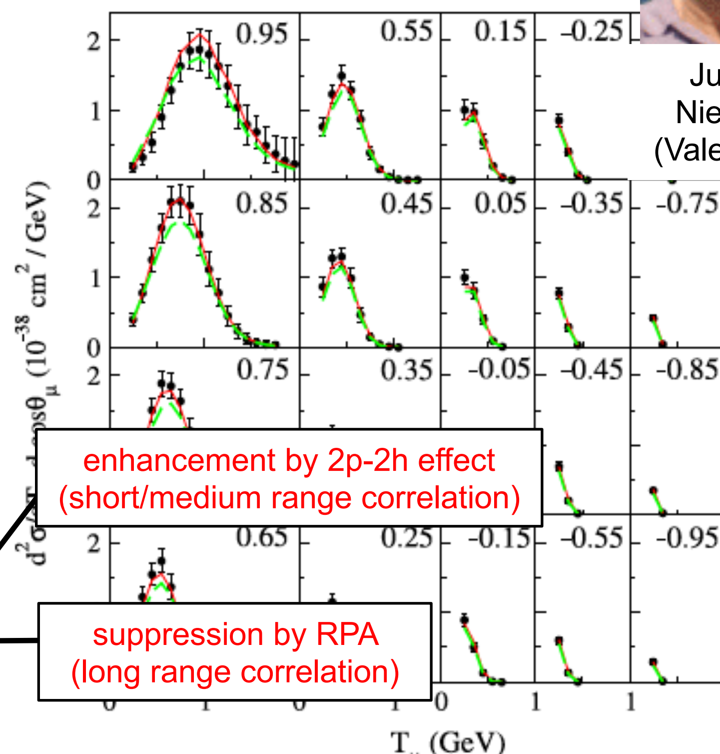




enhancement by 2p-2h effect (short/medium range correlation)

suppression by RPA (long range correlation)

Valencia model vs. MiniBooNE CCQE double differential cross-section data

Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRL112(2014)182502, PRC91(2015)062501

3. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato (Argonne)

Ab-initio calculation

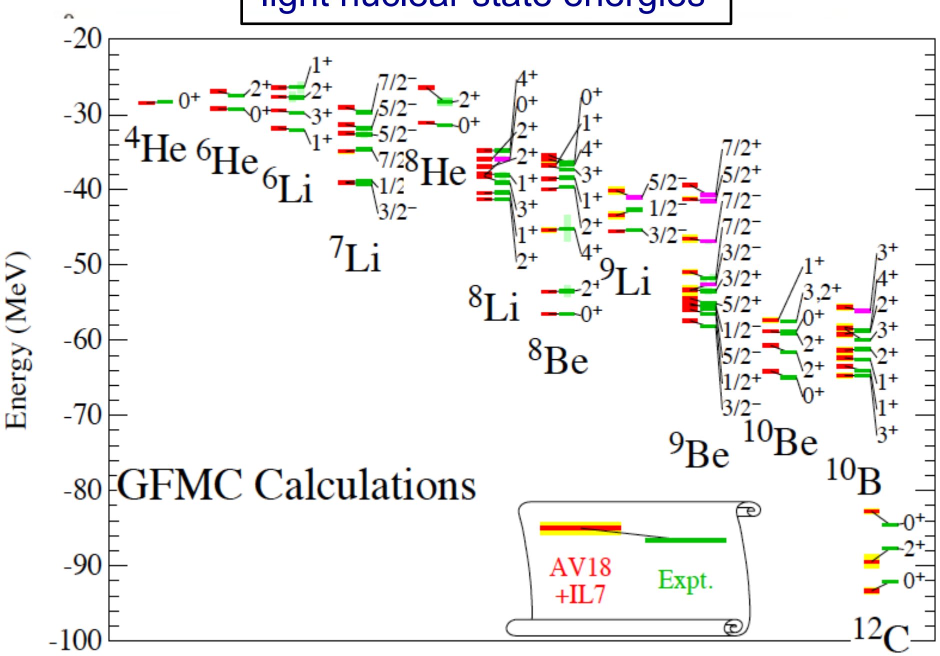
- Green's function Monte Carlo (GFMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}^{A}\left[1 + U_{ij} + \sum_{k\neq i,j}^{A}\tilde{U}_{ijk}^{TNI}\right]|\Psi_J\rangle$$

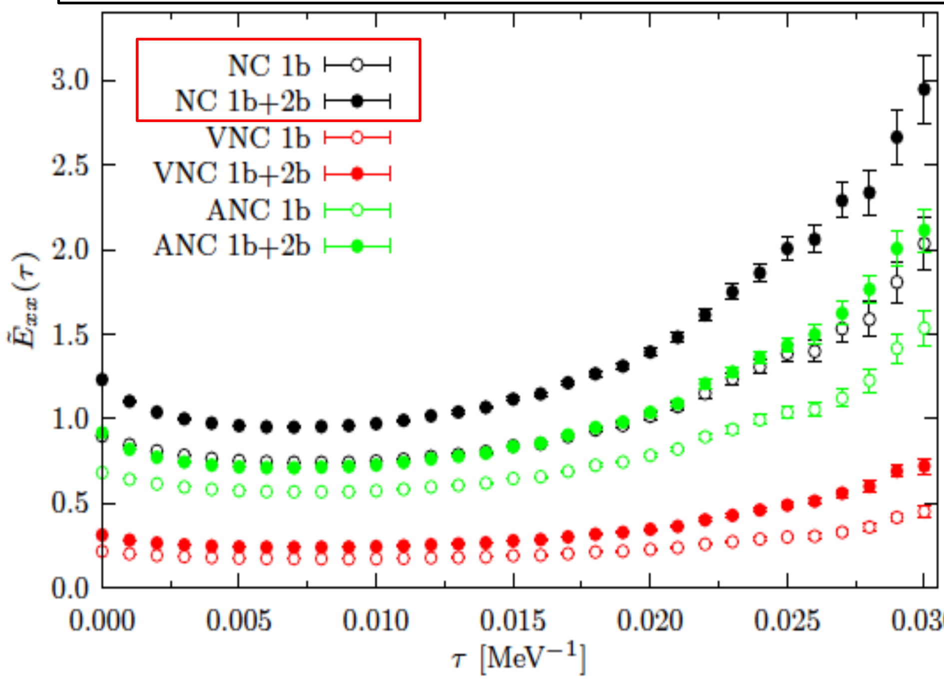
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



Neutrino NCQE scattering in ^{12}C response function



Frankfurt et al,IJMPA23(2008)2991, JLab HallA, Science320(2008)1476
Sobczyk, Neutrino2014, Piasetzky et al, PRL106(2011)052301

3. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato (Argonne)

Ab-initio calculation

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- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

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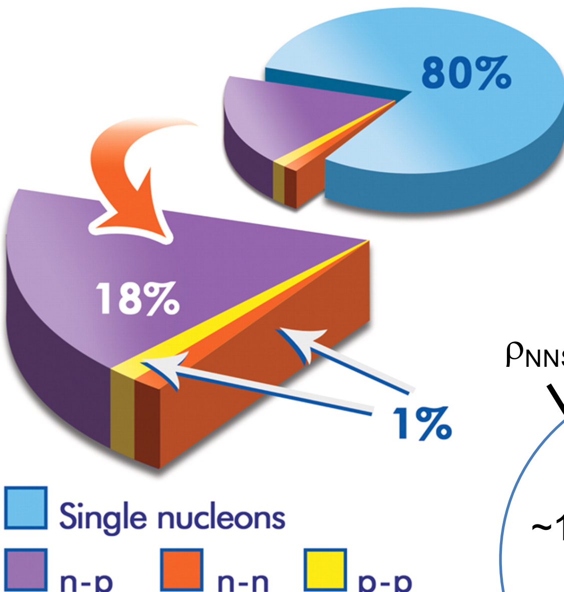
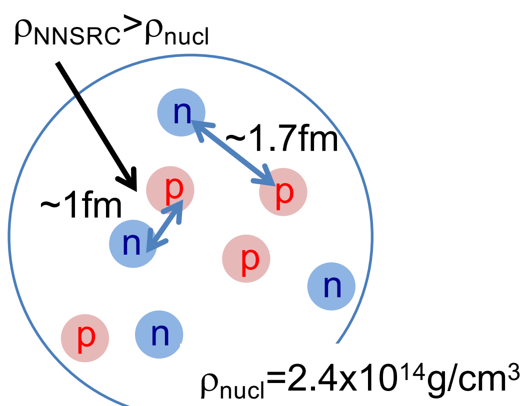
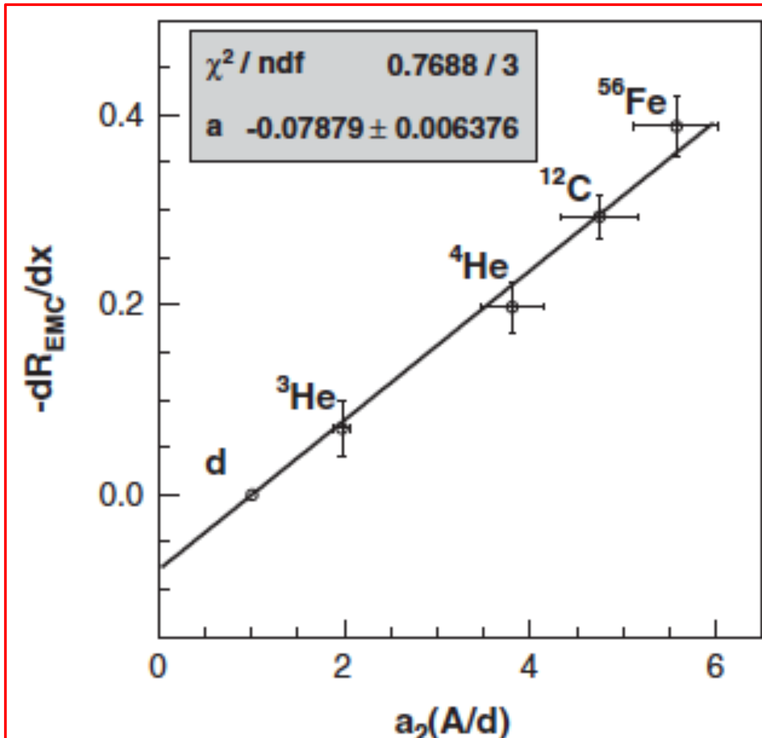


Physics of SRC

- neutrino interaction
- 0νββ
- astrophysics
- EMC effect
- etc





Queen Mary University of London

Nucleon correlation is a very hot topic in Particle Physics!

3. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation

- Valencia MEC model is available in NEUT
- Implemented in GENIE, officially ready for GENIE v2.12

This moment…

- Valencia MEC model does not fit global neutrino data simultaneously (within generators)
- lepton-hadron correlations (STVs) from T2K and MINERVA reveal new information

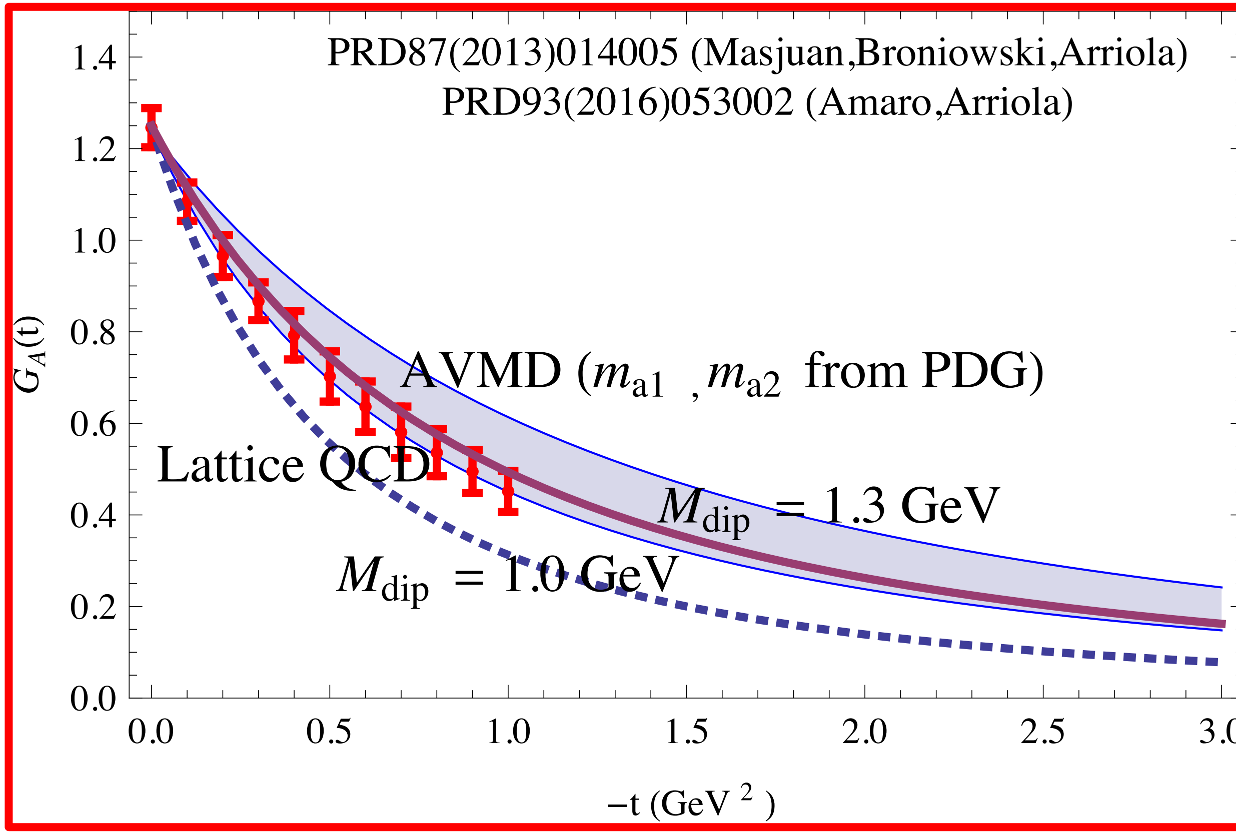
large M_A error → large nucleon correlation error

We have good theorists who make models,
and good experimentalists who measure data,
but we are still lacking people between them.

3. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation?
- Lattice QCD prefers large MA
- Some top down axial form factor model prefers harder spectrum (~large MA)

The community is still confused with neutrino-nucleon scattering theory. It looks we are bit far from building a correct neutrino-nucleus scattering model.



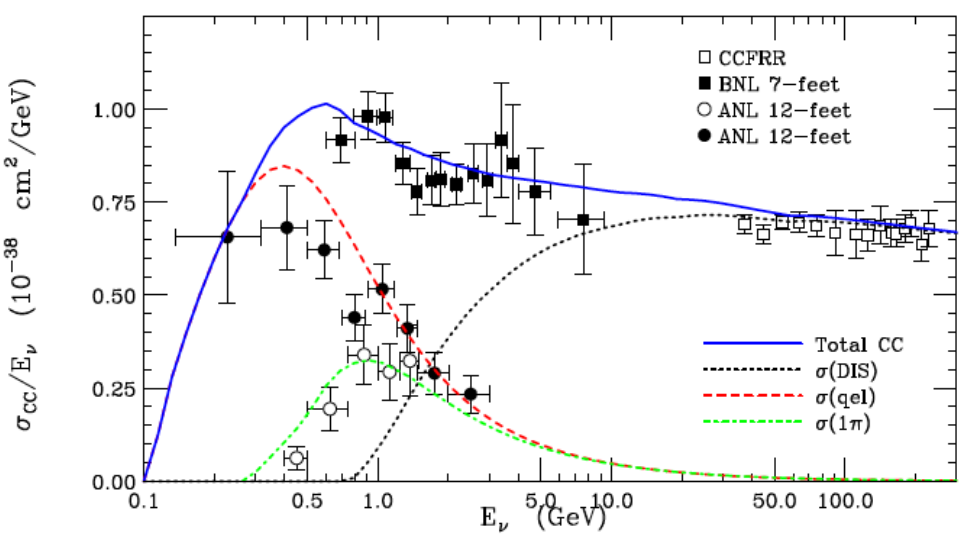
3. Dark age of neutrino interaction physics

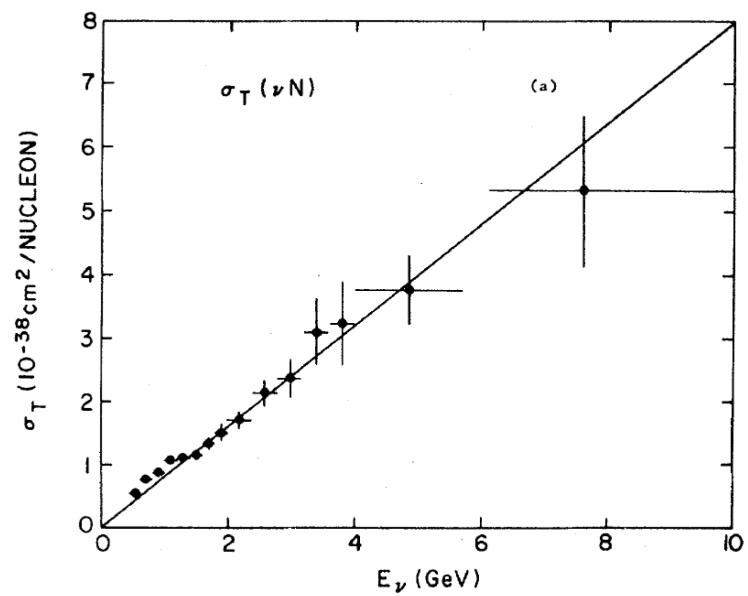
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate

What you get? OF COURSE the cross section you assume!

Phys. Rev. D [redacted]

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]





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

1. Neutrino interaction physics
2. Neutrino scattering experiments
3. Charged-Current Quasi-Elastic (CCQE) interaction
4. **Resonance Single Pion Production**
5. Shallow Inelastic Scattering (SIS)
6. Conclusions

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001 (98pp) https://doi.org/10.1088/1361-6471/aa8bf7

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

[1] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[2] ESNT, CEA, IRFU, Service de Physique Nucléaire, Université de Paris-Saclay, F-91191 Gif-sur-Yvette, France
[3] Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium

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Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp
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Review

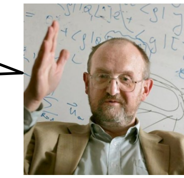
NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

Check for updates

L. Alvarez-Ruso[a], M. Sajjad Athar[b], M.B. Barbaro[c], D. Cherdack[d], M.E. Christy[e], P. Coloma[f], T.W. Donnelly[g], S. Dytman[h], A. de Gouvêa[i], R.J. Hill[j,f], P. Huber[k], N. Jachowicz[l], T. Katori[m], A.S. Kronfeld[f], K. Mahn[n], M. Martini[o], J.G. Morfín[f,*], J. Nieves[a], G.N. Perdue[f], R. Petti[p], D.G. Richards[q], F. Sánchez[r], T. Sato[s,t], J.T. Sobczyk[u], G.P. Zeller[f]

4. Open question of neutrino interaction physics

The new data raised doubts in the areas well understood. The list of new puzzles is quite long and seems to be expanding…



Jan Sobczyk (Wroclaw)

CCQE puzzle
- Low Q2 suppression, high Q2 enhancement, high normalization

ANL-BNL puzzle
- Normalization difference between ANL and BNL bubble chamber pion data

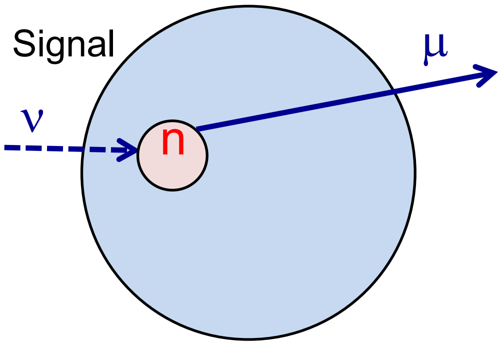
Coherent pion puzzle
- Is there charged current coherent pion production?

Pion puzzle
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models

Baryon resonance, pion production by neutrinos

4. non-QE background

non-QE background → shift spectrum

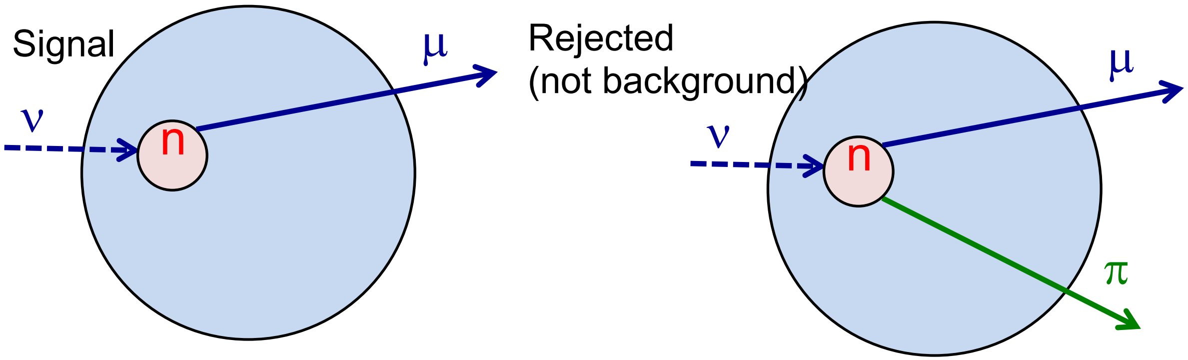


Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

4. non-QE background

non-QE background → shift spectrum



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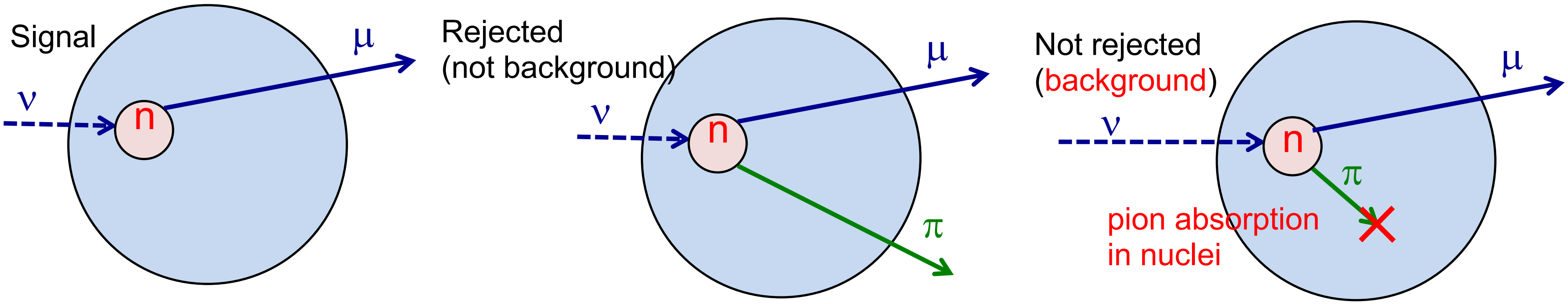

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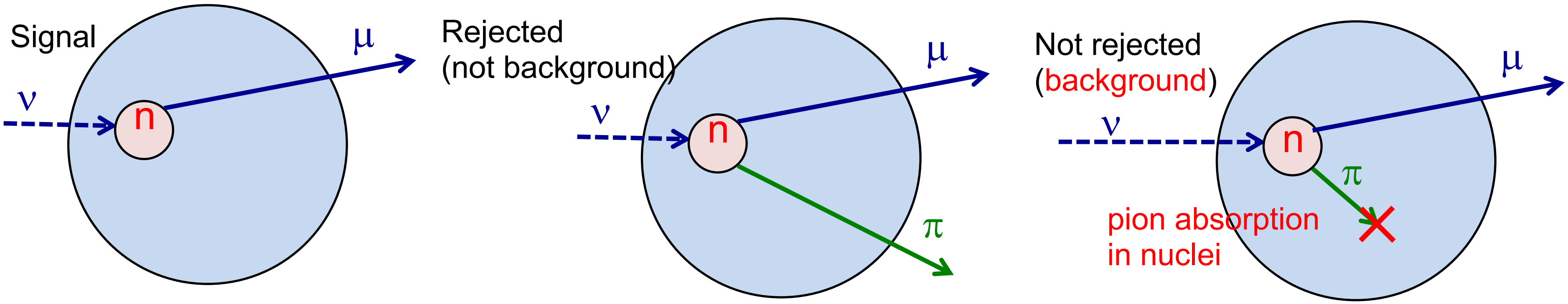
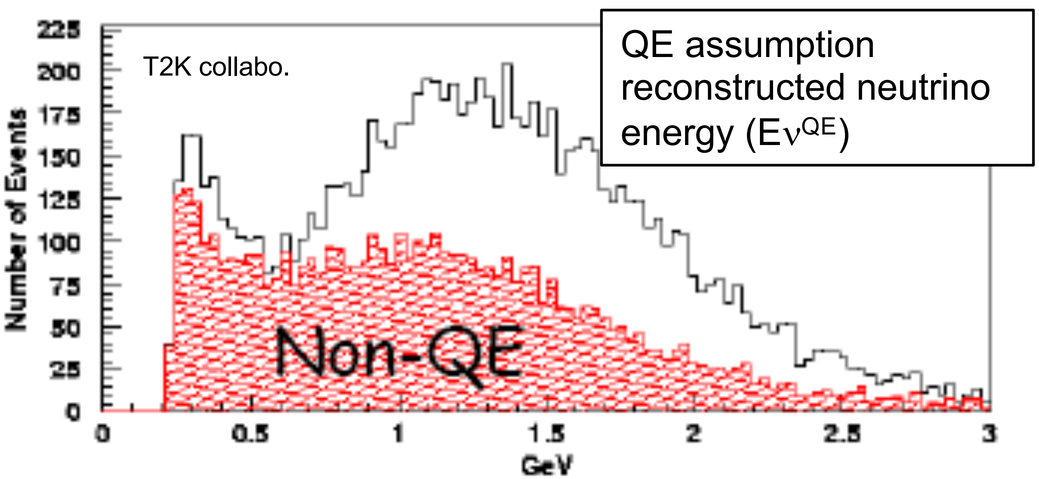
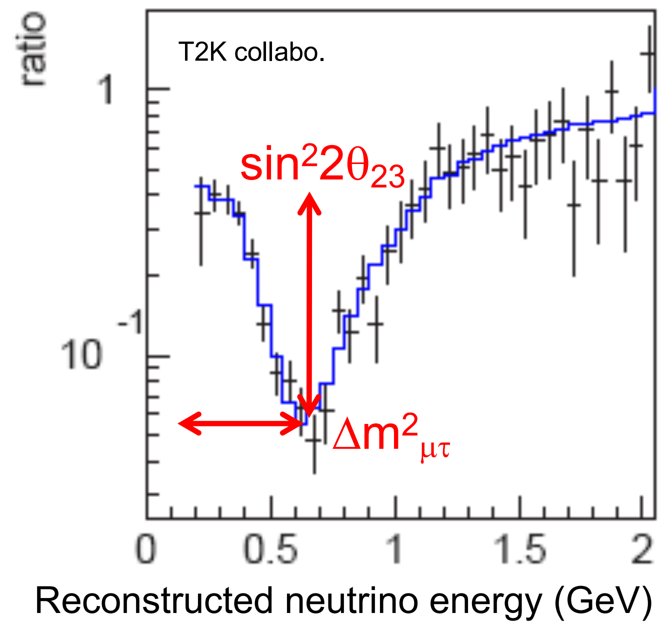
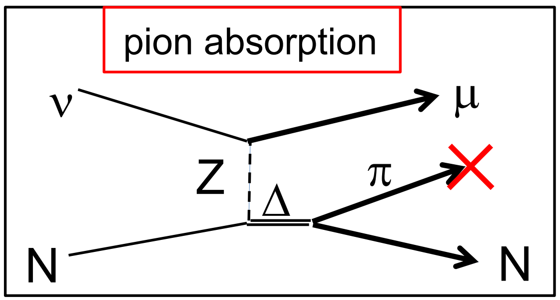




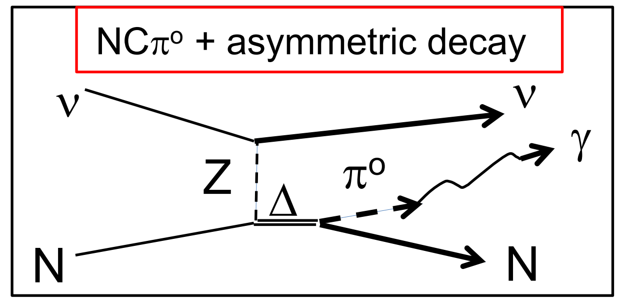


4. Baryon resonance backgrounds for oscillation physics

Pion production for ν_μ disappearance search
- Source of mis-reconstruction of neutrino energy

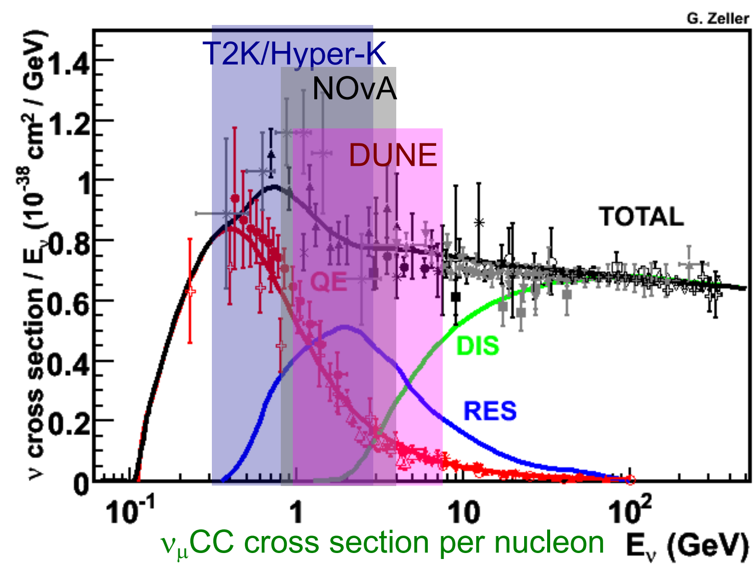


Neutral pion production in ν_e appearance search
- Source of misID of electron



In T2K, understanding of baryon resonance and pion production is important mainly as oscillation background.

However in NOvA and DUNE, pion production channels are main signal events!



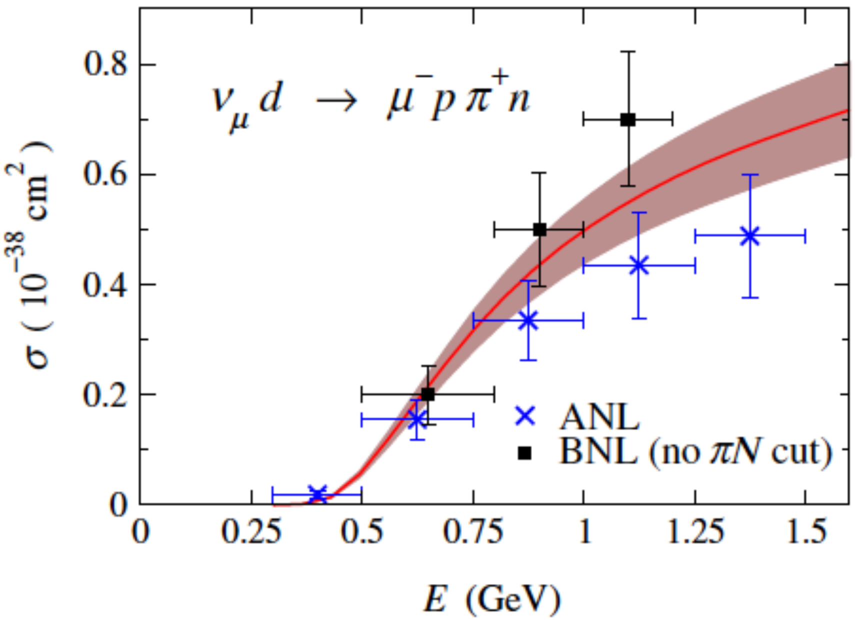
Hernandez et al,PRD87(2013)113009
Alvarez-Ruso et al,PRC89(2014)015503

4. ANL-BNL puzzle

Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25%.

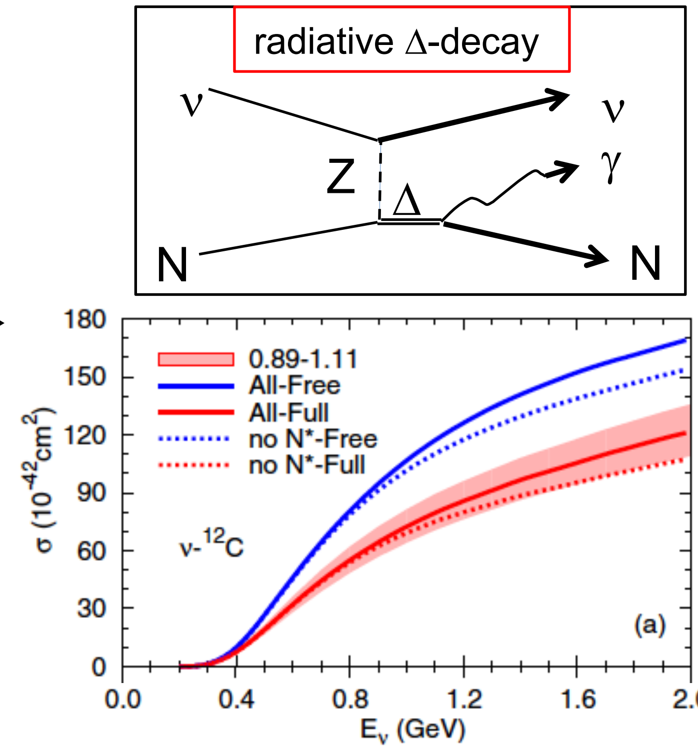
→ this propagates to every interactions with baryon resonance

ANL vs. BNL



→

e.g.) NCγ production model



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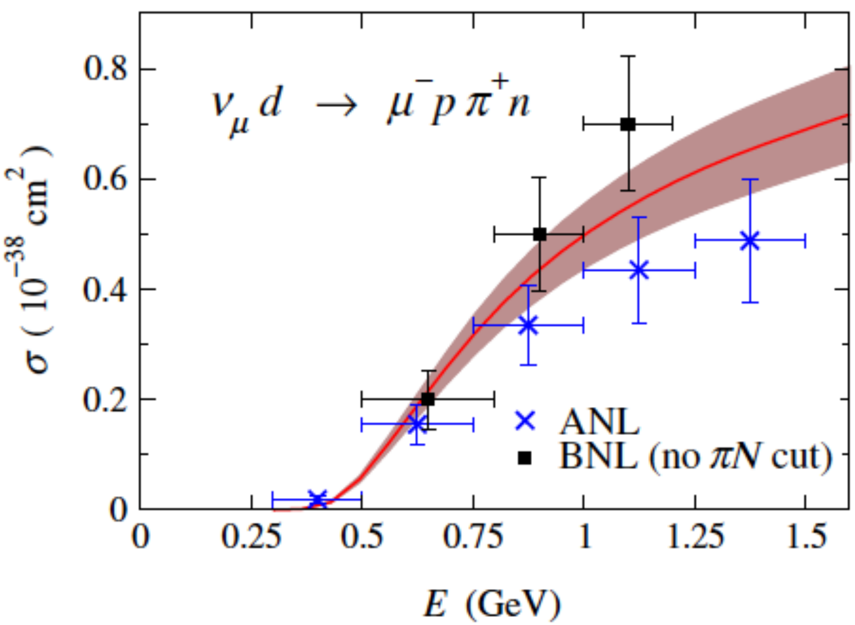
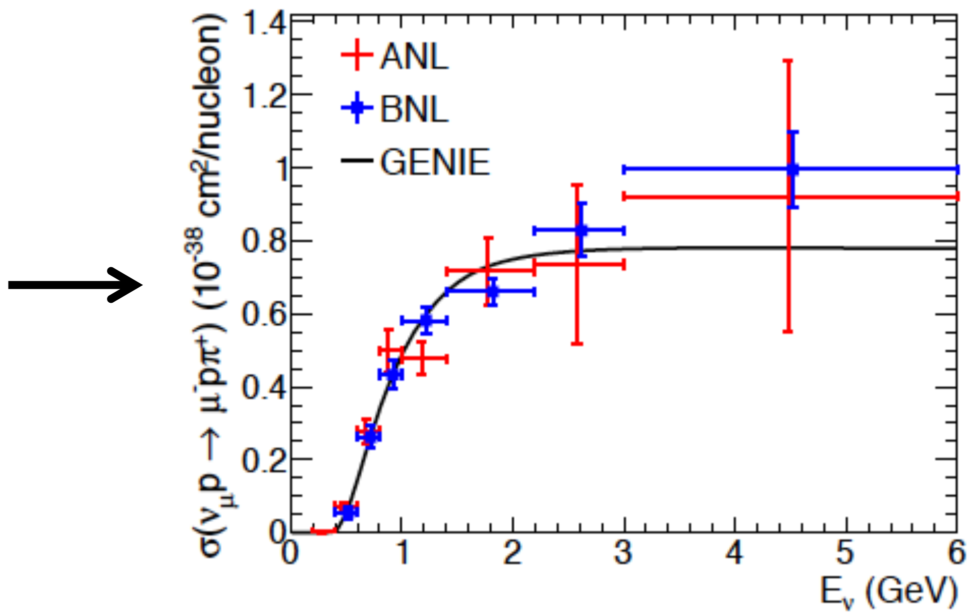
Reanalysis by Sheffield-Rochester group found a normalization problem on BNL

ANL vs. BNL





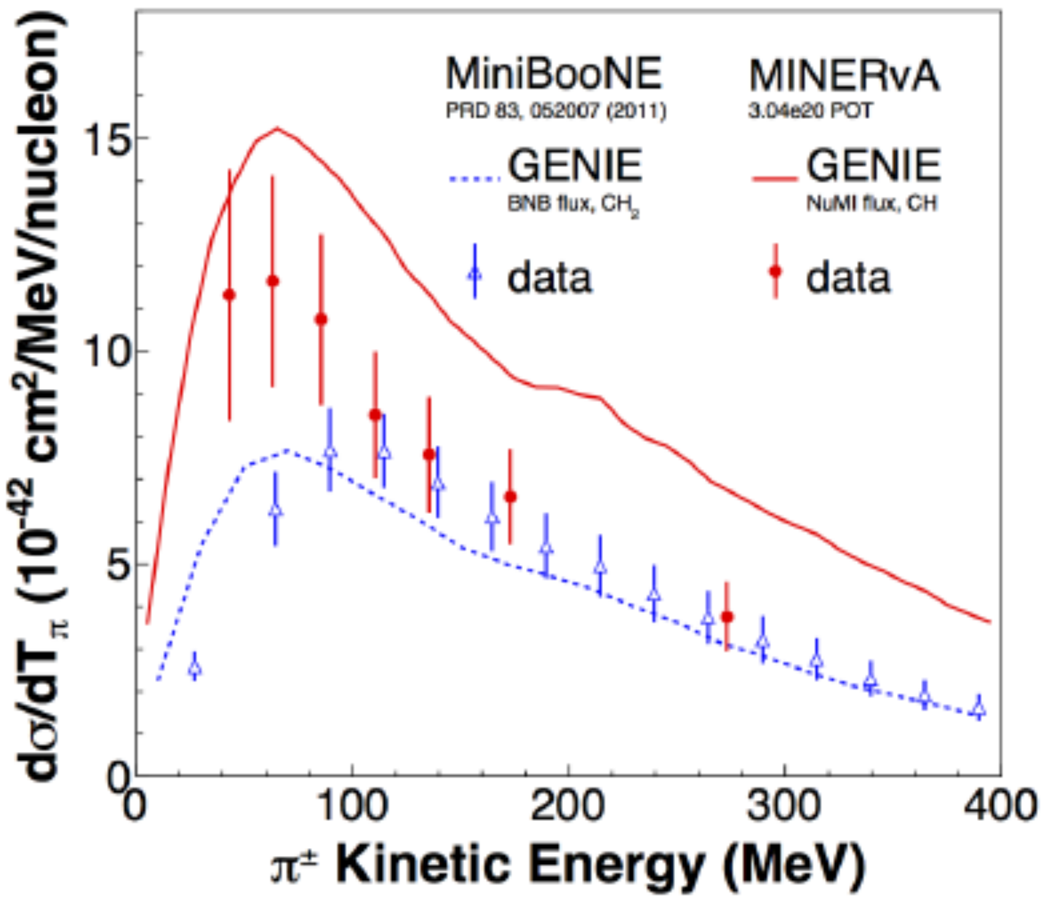
4. Pion puzzle

Data from MiniBooNE and MINERvA and simulation are all incompatible

Flux-integrated differential cross-section are not comparable (unless 2 experiments use same neutrino beam)

Two data set are related by a model (=GENIE neutrino interaction generator).

MINERvA data describe the shape well, but MiniBooNE data have better normalization agreement…



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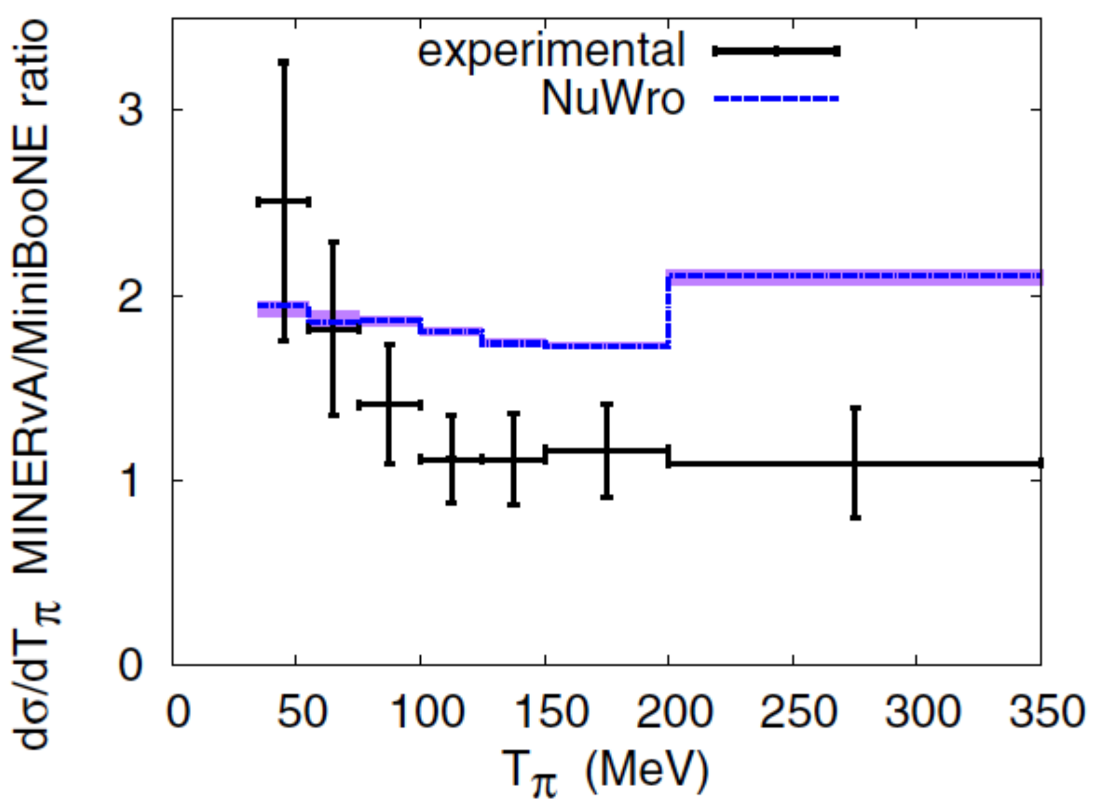


MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

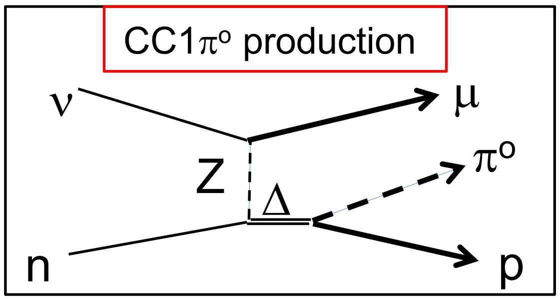
4. Pion puzzle

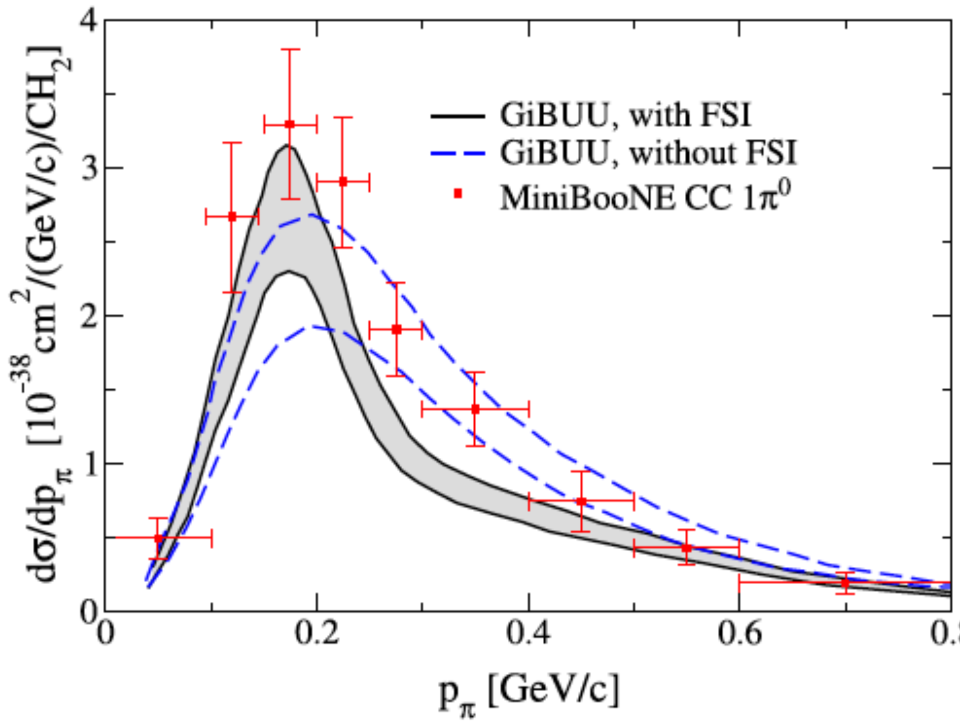
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation





ex) Giessen BUU transport model

- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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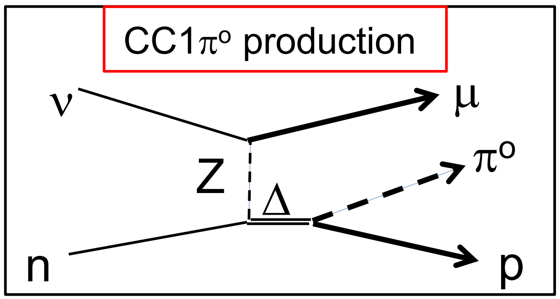

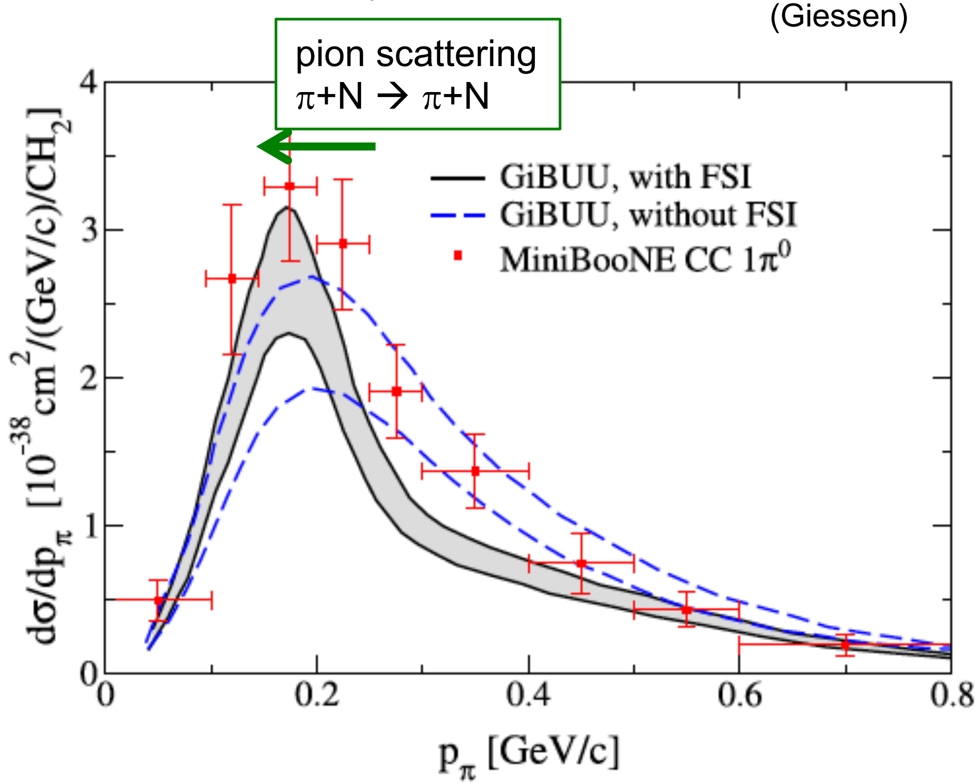

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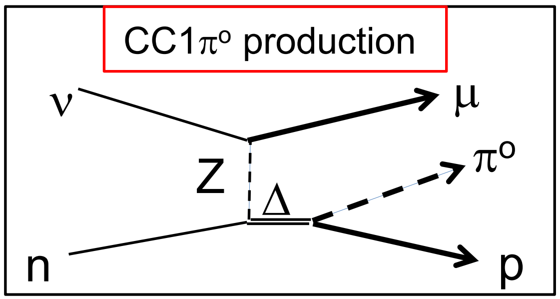

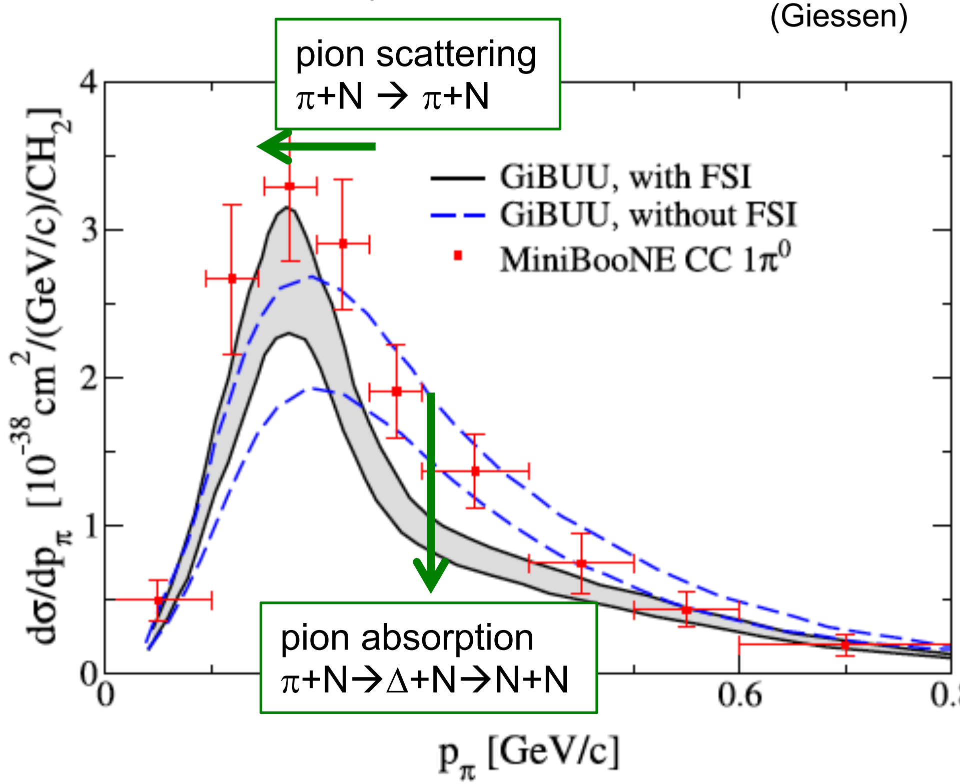

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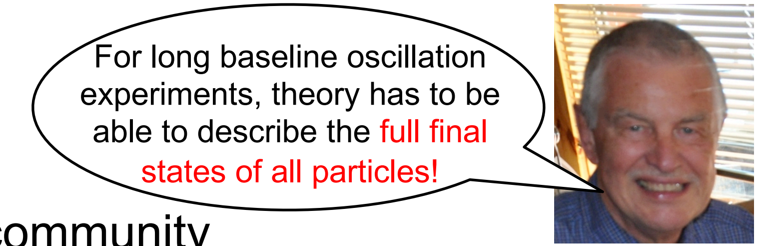

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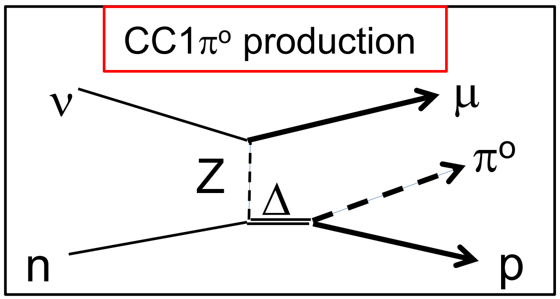
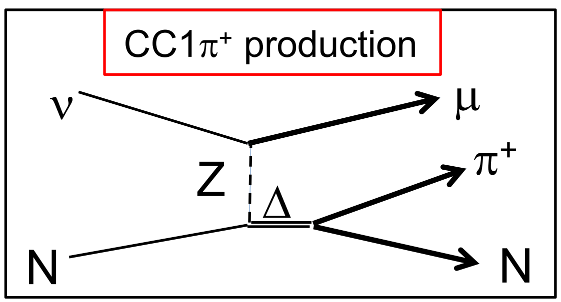
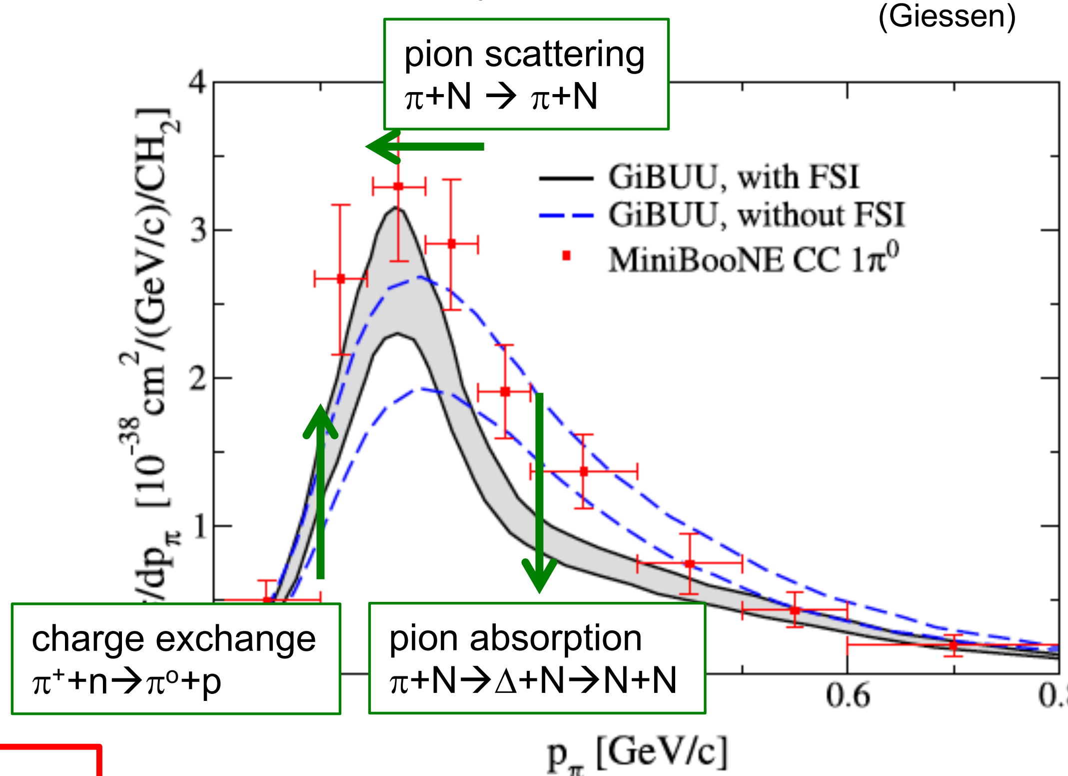






The simulation need to be good at both primary pion production model and final state interaction model!

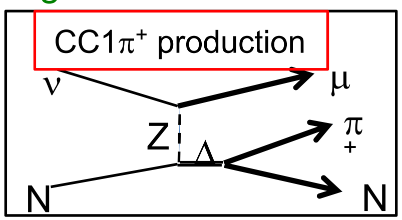
ex) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

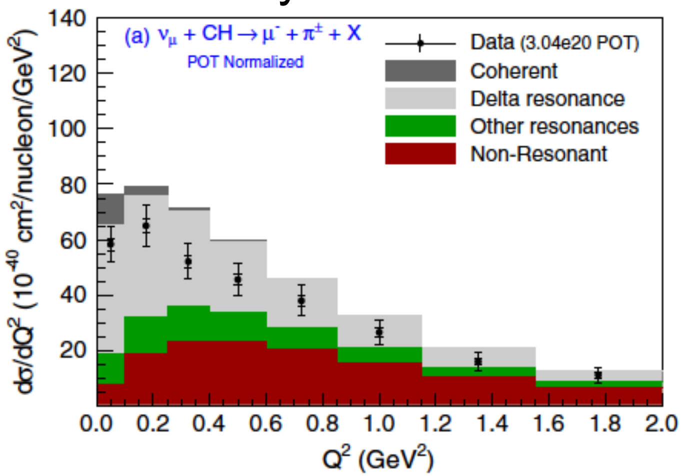
4. MINERvA FSI and cross section model tuning (2016)

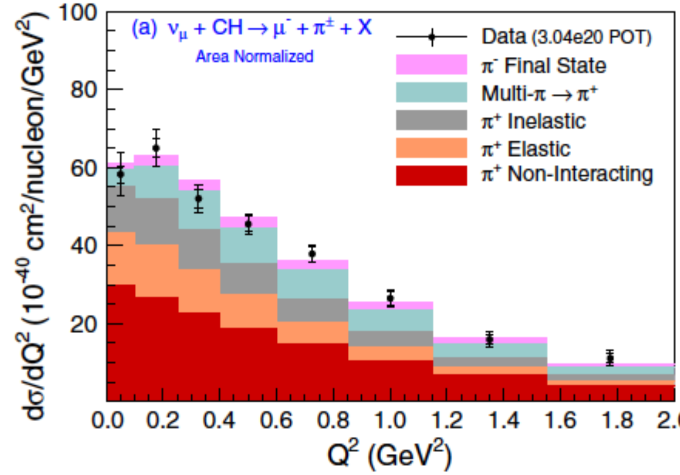
MINERvA CC1π^+, $\bar{\nu}$CC1π^o, νCC1π^o data simultaneous fit

- this moment, there is no clear way to tune MC from data…

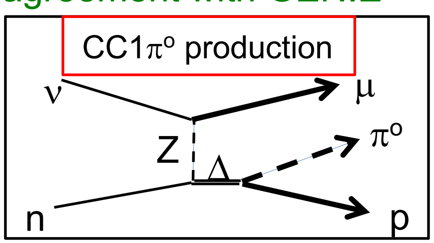
ν_μCC1π^+ data has better shape agreement with GENIE

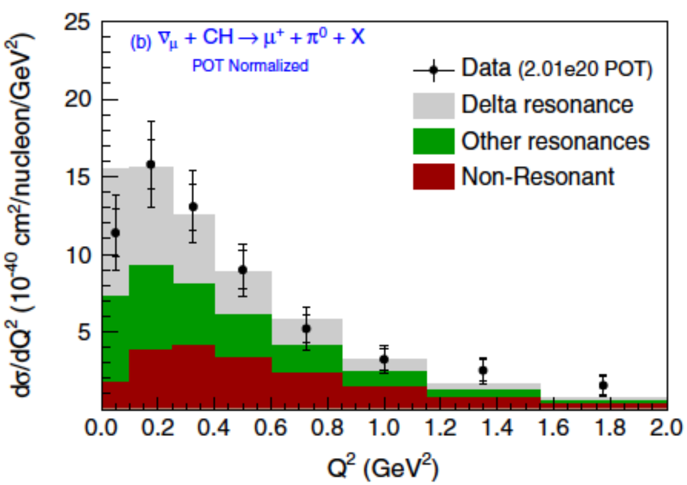


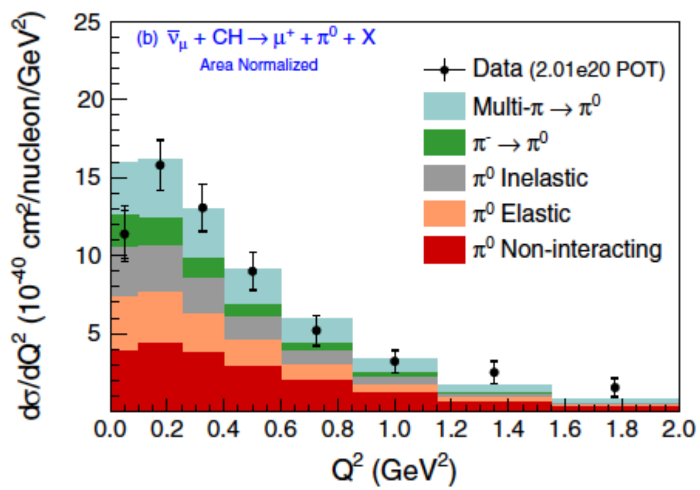




$\bar{\nu}$CC1π^o data has better normalization agreement with GENIE







4. Summary of resonance region for oscillation

Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25% (ANL-BNL puzzle).

→ origin of 20-30% error on M_A^{RES}

Recent fit on re-analyzed ANL-BNL data shows on $C^A{}_5(0)$ error is 6%. This would give ~6-10% error on M_A^{RES} for experimentalist.

However, M_A^{RES} includes all errors associated with SPP data ($C^A{}_5(0)$, M_A^{RES}, nuclear effect, etc). Unless pion puzzle is solved (MiniBooNE-MINERvA data tension), M_A^{RES} error stays ~20-30%.

Nucleon correlations (2p2h, SRC, RPA) introduce new contribution in QE-like final state measurement. Then nucleon correlations should contribute to pion production too…?

1. Neutrino interaction physics

2. Neutrino scattering experiments

3. Charged-Current Quasi-Elastic (CCQE) interaction

4. Resonance Single Pion Production

5. Shallow Inelastic Scattering (SIS)

6. Conclusions

IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001 (98pp) https://doi.org/10.1088/1361-6471/aa8bf7

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

[1] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
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Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

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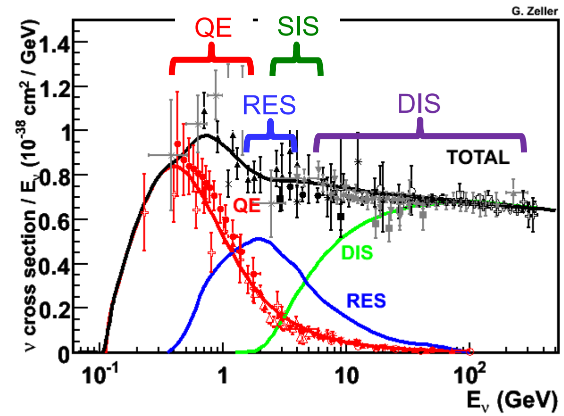
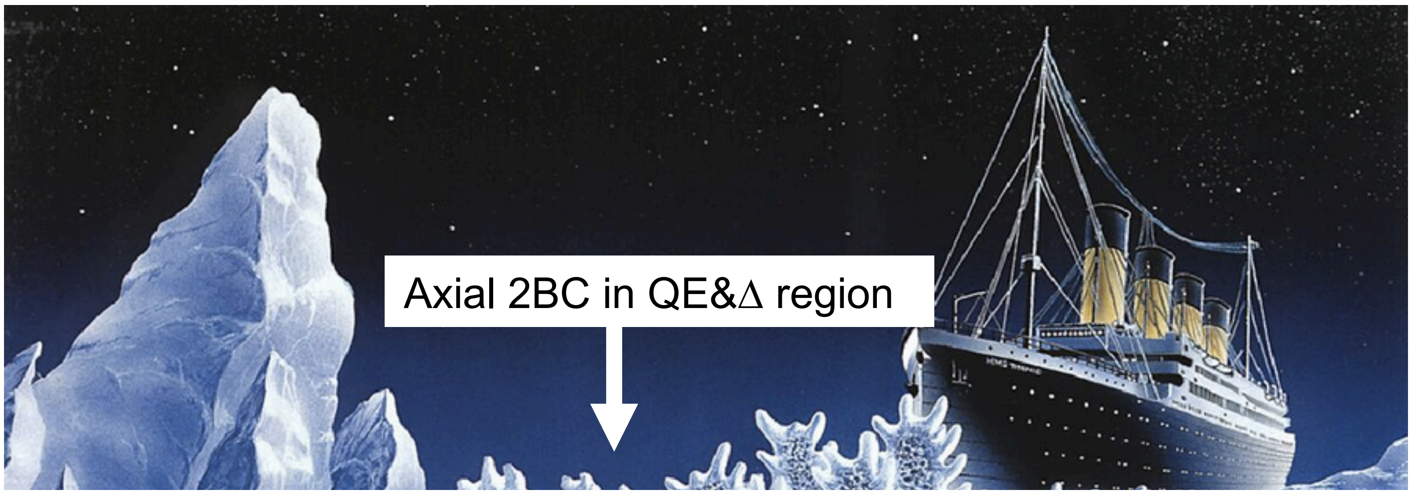
5. Beyond QE and Delta peak

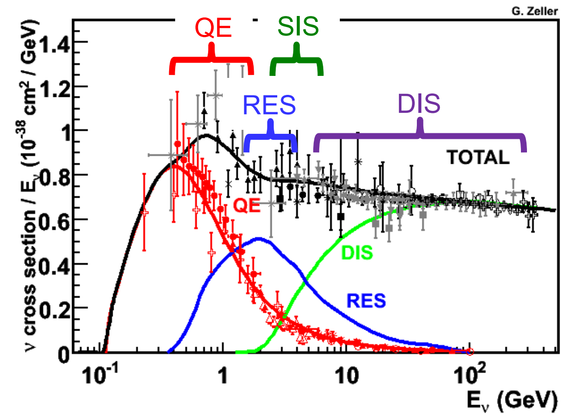


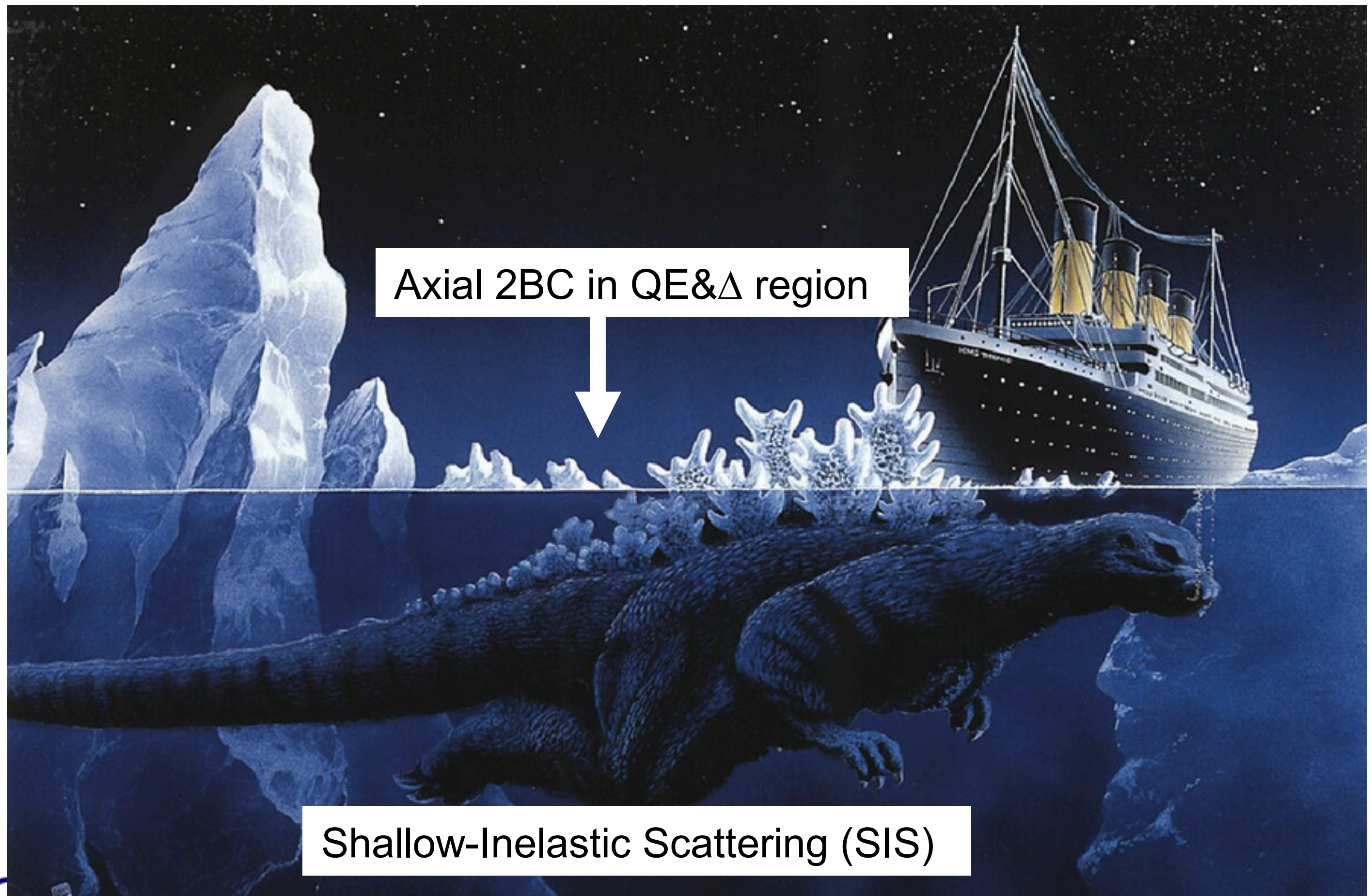
Axial 2-body current in QE and Delta regions may be a tip of the iceberg…



5. Beyond QE and Delta peak

Axial 2-body current in QE and Delta regions may be a tip of the iceberg…, or maybe a tip of gozilla!



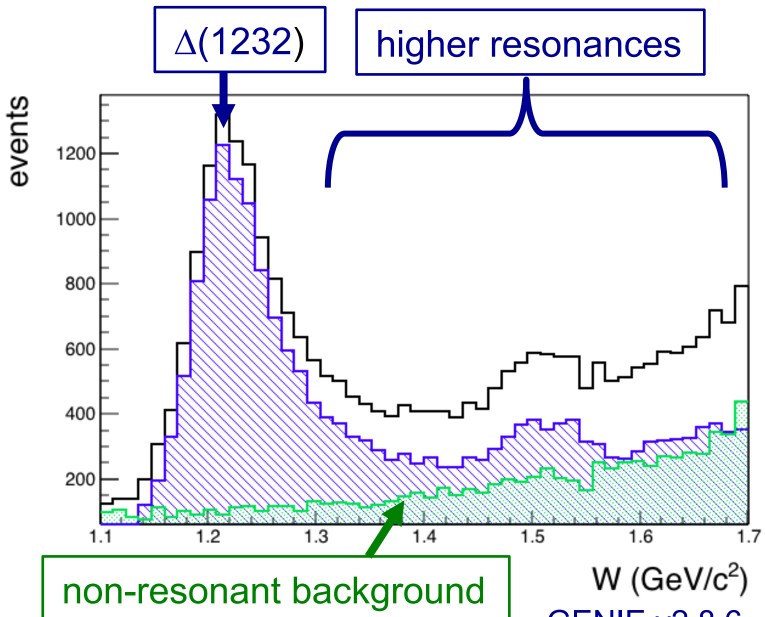


Traditionally called "transition" region

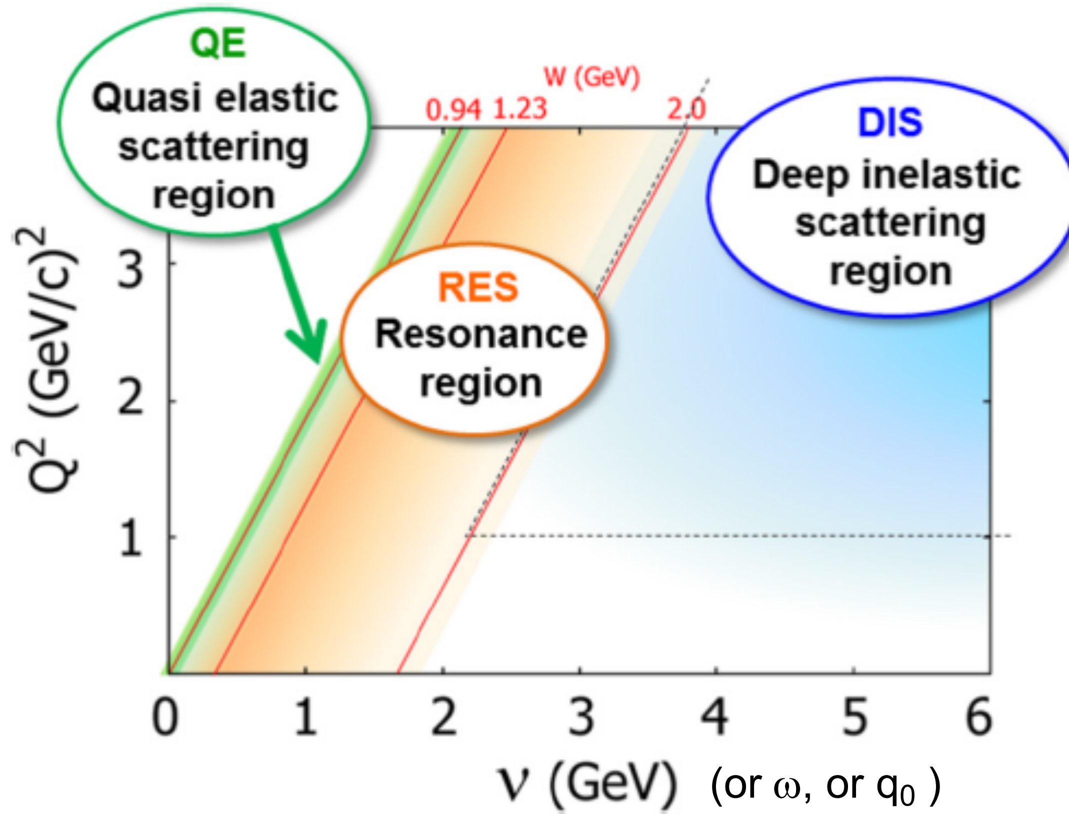
5. Sallow Inelastic Scattering (SIS) physics

Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS



Rep. Prog. Phys. 80 (2017) 056301

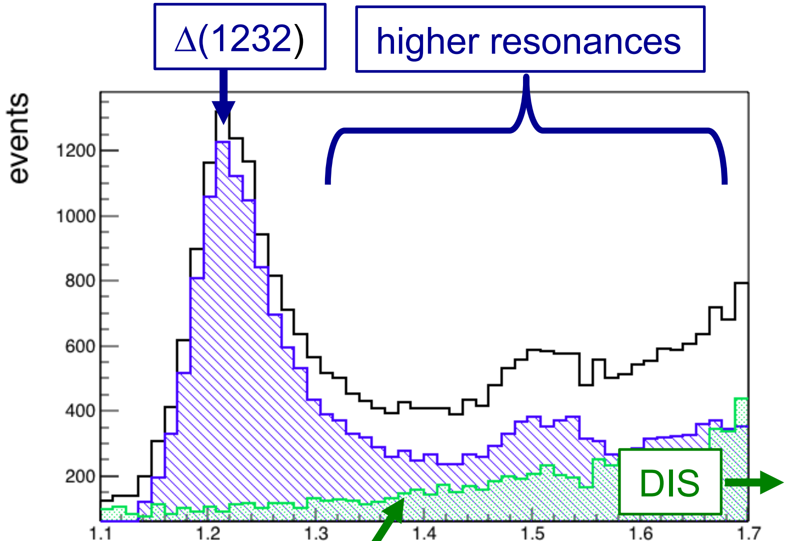


MiniBooNE,PRD83(2011)052007;052009, Lalakulich and Mosel,PRC87(2013)014602
Hernandez,Nieves,Vincent Vacas,PRD87(2013)113009

5. Physics of Δ resonance

Basic ingredients

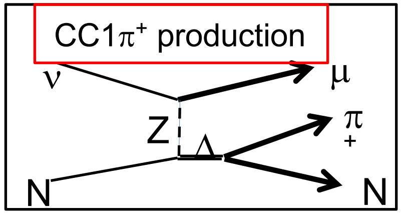
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2, low W DIS
5. Nuclear dependent DIS

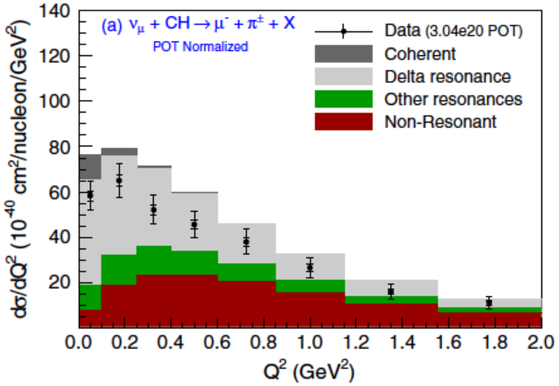


MINERvA CC1π⁺, $\bar{\nu}$CC1π°, νCC1π° data simultaneous fit

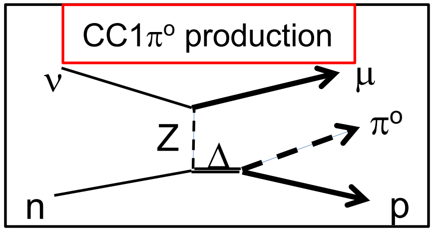
- this moment, there is no clear way to tune MC from data…

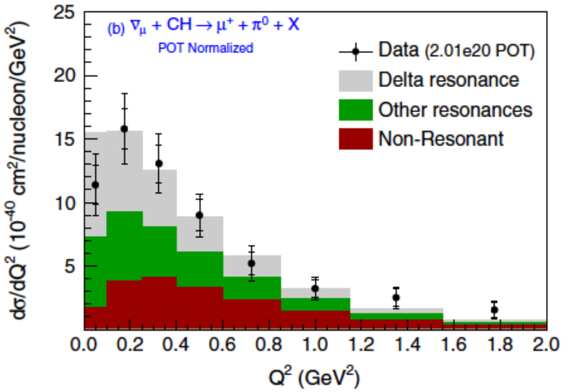
ν_μCC1π⁺ data





$\bar{\nu}$CC1π° data





5. Physics of higher resonances

DCC model vs. electro-pionproduction data

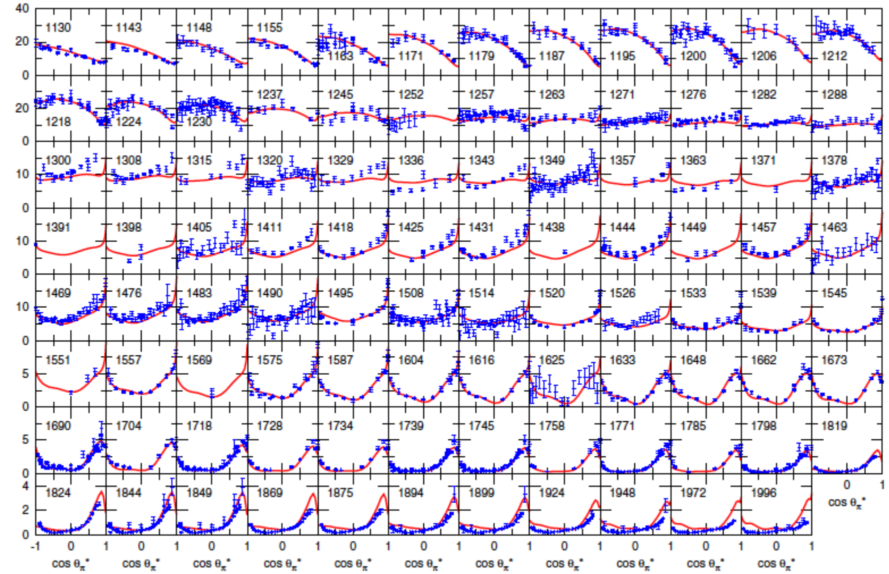


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega^*_\pi$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

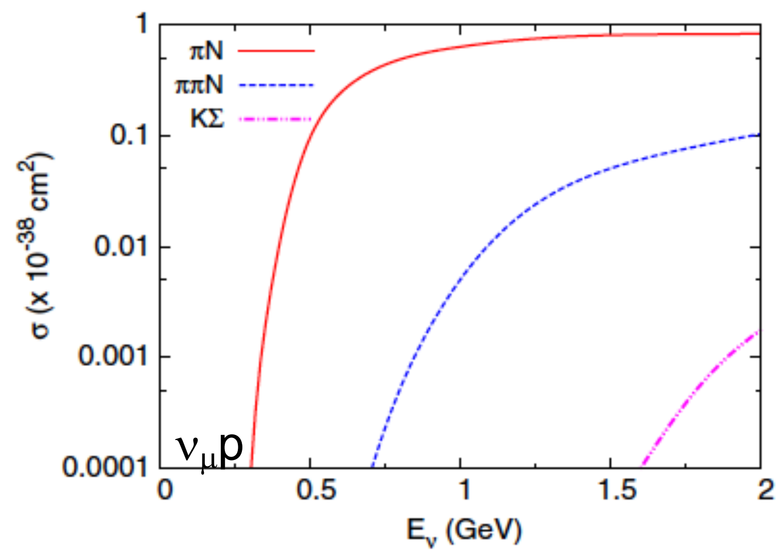
Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

DCC model

- Total amplitude is conserved
- Channels are coupled (pN, ppN, etc)
- 2 pion productions ~10% at 2 GeV
- not yet available in generators

Role of high W resonances in neutrino experiments is not understood (and probably modeled incorrectly)



Nakamura et al,Rep.Prog.Phys.80(2017)056301

5. Physics of higher resonances

Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

DCC model

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DCC model vs. electro-pionproduction data

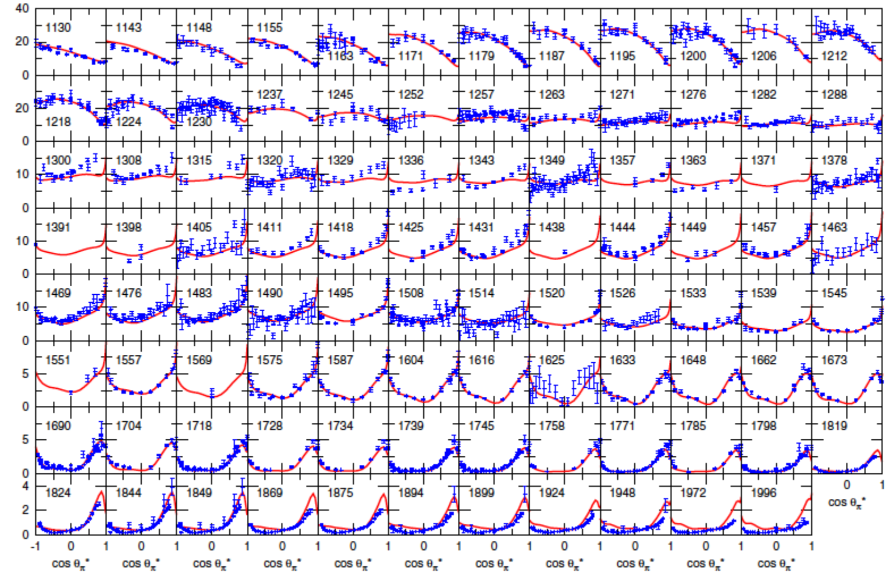
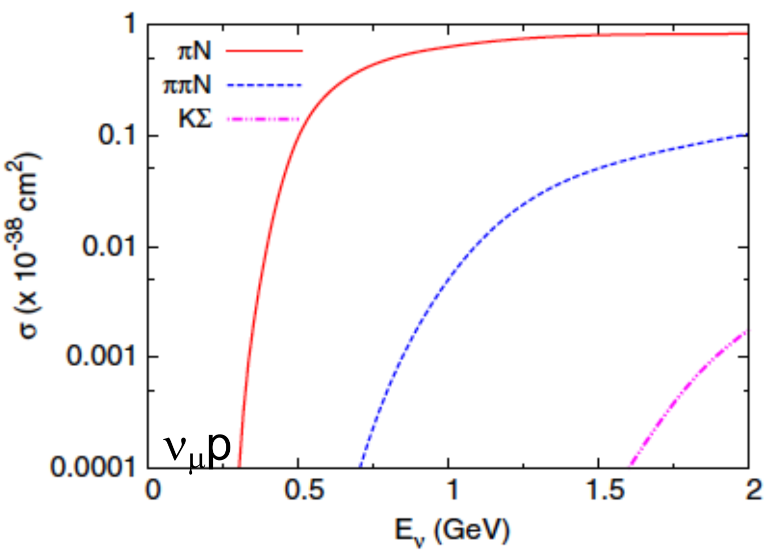
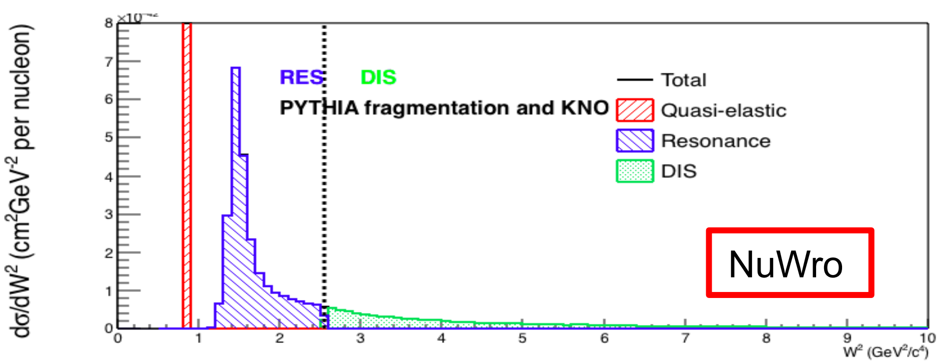


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

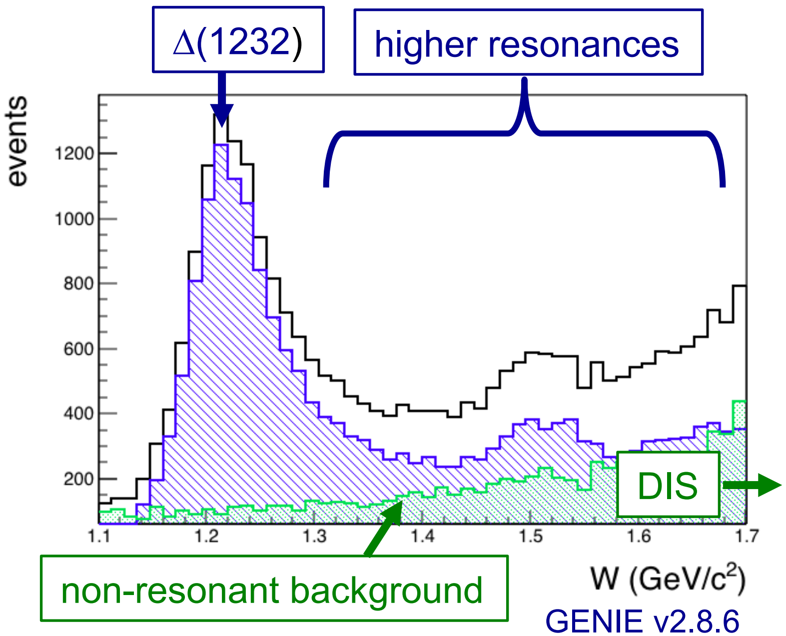




5. Physics of non-resonant background

Basic ingredients

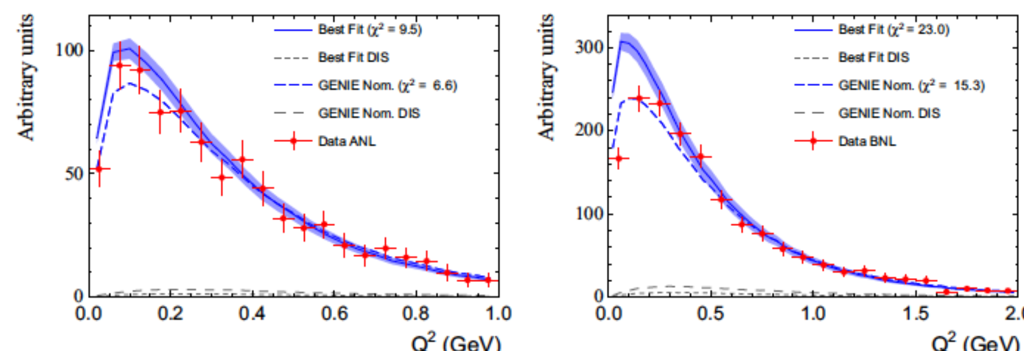
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS



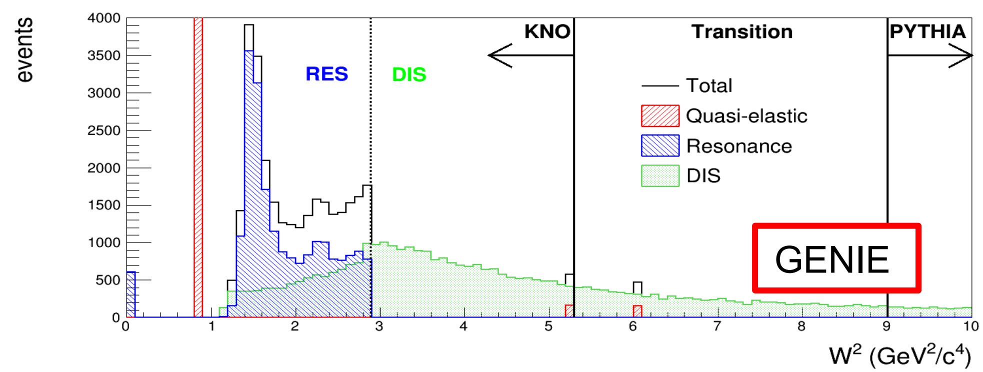
Non-resonant component and resonances are incoherently added (=wrong, but easy to simulate).

Non-resonant background is identified to be DIS at higher W.

Non-resonant background in GENIE needs to be reduced more than 50%.



(c) ANL Q^2 (d) BNL Q^2



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Bloom and Gilman, PRL25(1970)1140
Graczyk et al,NPA781(2007)227, Lalakulich et al, PRC75(2007)015202

5. Quark-Hadron Duality

Nachtmann variable $\xi = \dfrac{2x}{\left(1 + \sqrt{1 + \dfrac{4x^2M^2}{Q^2}}\right)}$

Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

GRV98 LO PDF + Bodek-Yang correction

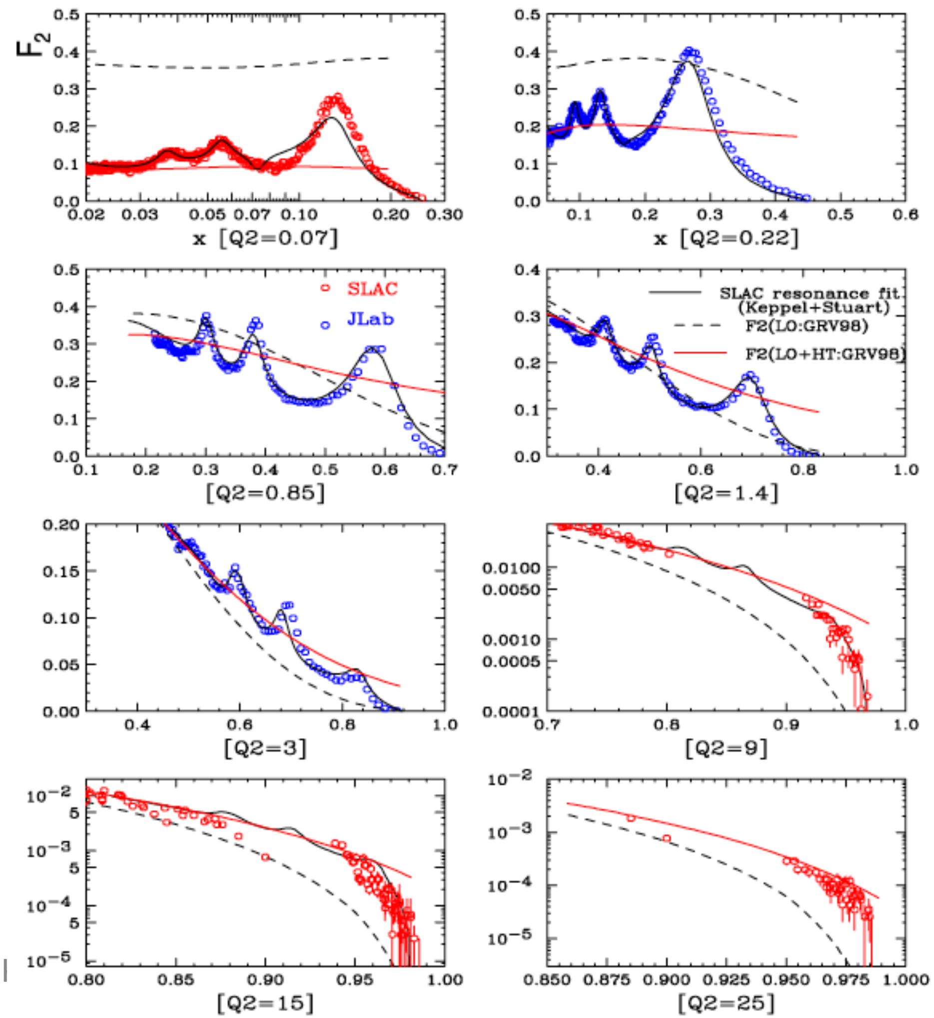
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

$$\xi \to \xi_\omega = \frac{2x\left(1 + \dfrac{M_f^2 + B}{Q^2}\right)}{\left(1 + \sqrt{1 + \dfrac{4x^2M^2}{Q^2}}\right) + \dfrac{2Ax}{Q^2}}$$

$$K_{valence}(Q^2) = [1 - G_D^2(Q^2)] \cdot \left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}\right)$$

$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_{s1}}$$

Proton F2 function GRV98-BY correction vs. data



HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028
nCTEQ, PRD80(2009)094004

5. Neutrino nuclear-dependent DIS processes

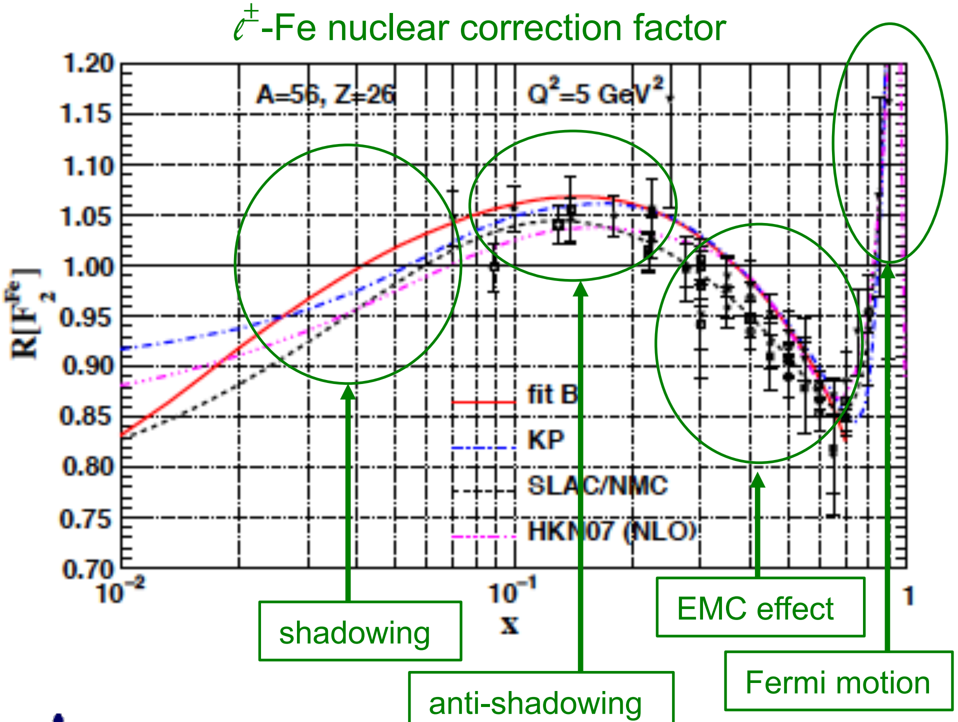
Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

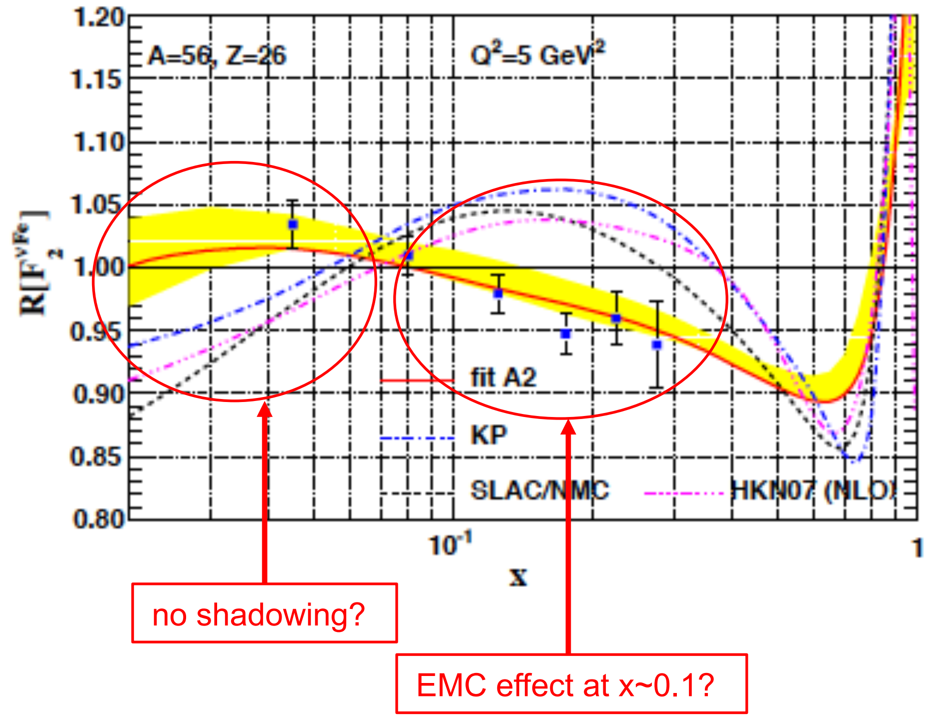
Nuclear PDF

- Shadowing, EMC effect, Fermi motion
- Theoretical origin is under debate
- Various models describe charged lepton data
- Neutrino data look very different

$\ell^{\pm}$-Fe nuclear correction factor



ν-Fe nuclear correction factor



MINERvA,PRD93(2016)071101
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028 ,nCTEQ, PRD80(2009)094004

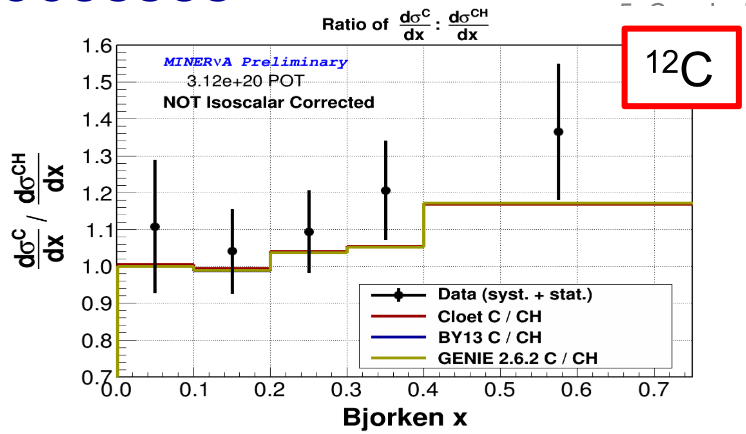
5. Neutrino nuclear-dependent DIS processes

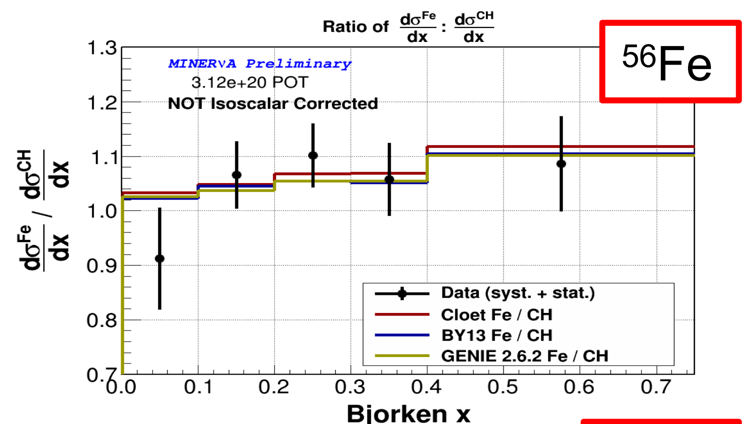
Basic ingredients

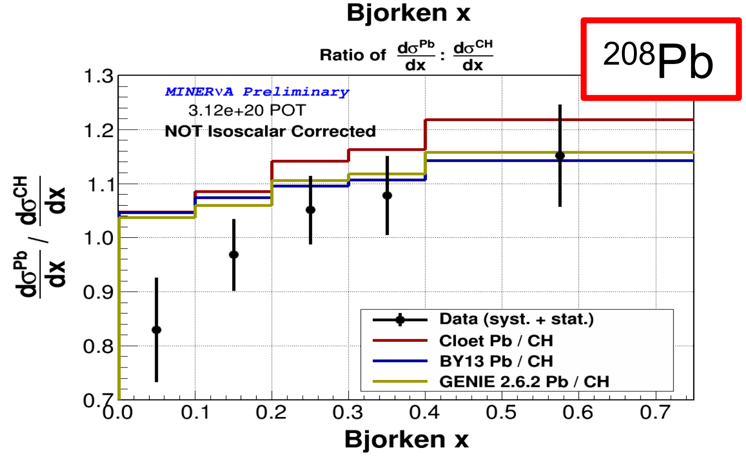
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

MINERvA DIS target ratio data (C, Fe, Pb)

- Neutrino nuclear-dependent DIS effects may be different from charged lepton sector
- Why we care? Because neutrino beam is like a "shower", and it interacts with all materials surrounding the vertex detector. MC needs to simulate neutrino interactions (and particle propagations) for all inactive materials.







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5. SIS physics, summary

Basic ingredients

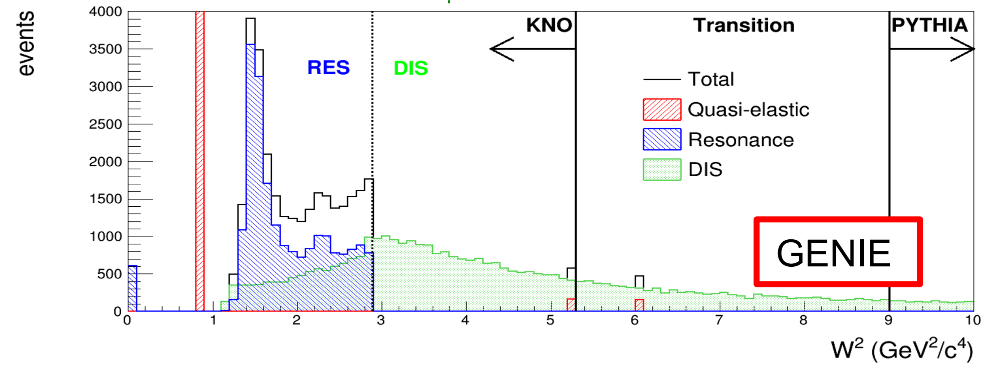
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2, low W DIS
5. Nuclear dependent DIS

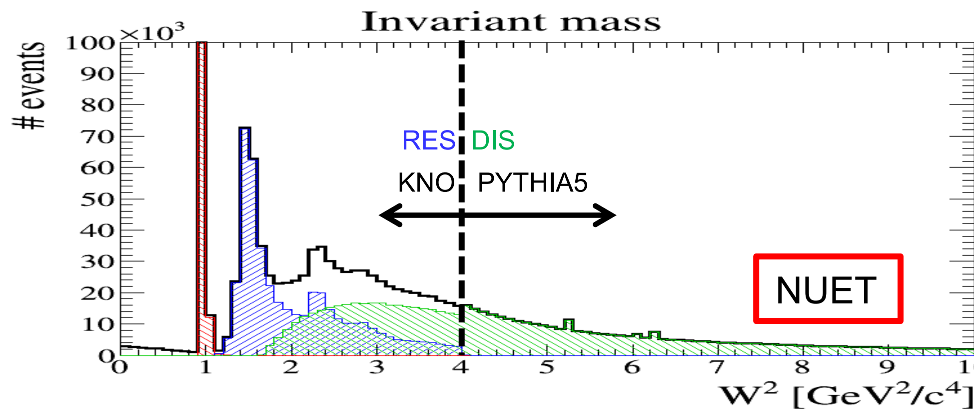
Generators show large disagreement for SIS models, also none of them look right.

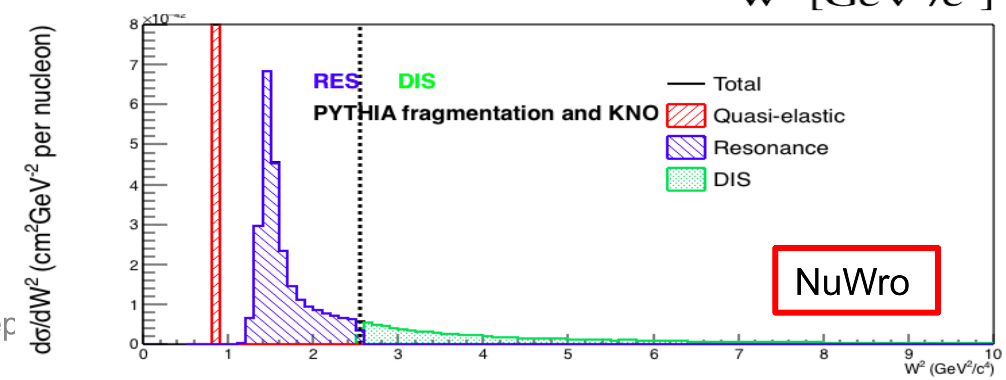
Each sub-field has been developed in a limited kinematics. And it is not easy to combine them together. The challenge we (=neutrino physics) have is a new kind.

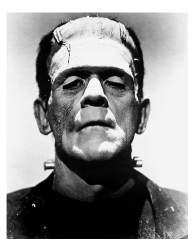
SIS is the home of Frankenstein models!

Neutrino interaction generator comparison (atmospheric ν_μ-H_2O CC interaction)









Neutrino Shallow and Deep-Inelastic scattering, GSSI, Oct 11-13

http://nustec.fnal.gov/nuSDIS18/

A dedicated workshop for physics related to DUNE, NOvA, HyperK, etc

- generator developments, impact on oscillation analyses
- higher resonance and non-resonance contributions
- low Q2 low W DIS
- nuclear modifications and nuclear-dependent PDFs
- neutrino hadronization problem

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

1. Neutrino interaction physics

2. Neutrino scattering experiments

3. Charged-Current Quasi-Elastic (CCQE) interaction

4. Resonance Single Pion Production

5. Shallow Inelastic Scattering (SIS)

6. Conclusions

IOP Publishing Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. 45 (2018) 013001 (98pp) https://doi.org/10.1088/1361-6471/aa8bf7

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

[1] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[2] ESNT, CEA, IRFU, Service de Physique Nucléaire, Université de Paris-Saclay, F-91191 Gif-sur-Yvette, France
[3] Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium

Progress in Particle and Nuclear Physics 100 (2018) 1–68
Contents lists available at ScienceDirect
Progress in Particle and Nuclear Physics
journal homepage: www.elsevier.com/locate/ppnp

Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

L. Alvarez-Ruso [a], M. Sajjad Athar [b], M.B. Barbaro [c], D. Cherdack [d], M.E. Christy [e], P. Coloma [f], T.W. Donnelly [g], S. Dytman [h], A. de Gouvêa [i], R.J. Hill [j,f], P. Huber [k], N. Jachowicz [l], T. Katori [m], A.S. Kronfeld [f], K. Mahn [n], M. Martini [o], J.G. Morfín [f,*], J. Nieves [a], G.N. Perdue [f], R. Petti [p], D.G. Richards [q], F. Sánchez [r], T. Sato [s,t], J.T. Sobczyk [u], G.P. Zeller [f]

Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…

nuclear many-body problem

Spin physics

Weak interaction

Neutrino oscillation

Dark matter

Neutrino Interaction Physics

EMC effect

Nucleon correlation

electron scattering

Heavy ion collision

Queen Mary University of London

NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

http://nustec.fnal.gov/

NuSTEC promotes the collaboration and coordinates efforts between
- theorists, to study neutrino interaction problems
- experimentalists, to understand nu-A and e-A scattering problems
- generator builders, to implement, validate, tune, maintain models

Theorists
Luis Alvarez Ruso (co-spokesperson, IFIC, Spain)
Mohammad Sajjad Athar (Aligarh Muslim University, India)
Maria Barbaro (University of Turin, Italy)
Omar Benhar (Sapienza University of Rome, Rome, Italy)
Richard Hill (University of Kentucky and Fermilab, USA)
Patrick Huber (Center for neutrino physics, Virginia Tech, USA)
Natalie Jachowicz (Ghent University, Belgium)
Andreas Kronfeld (Fermilab, USA)
Marco Martini (IRFU Saclay, France)
Toru Sato (Osaka, University, Japan)
Rocco Schiavilla (Old Dominion Univ. and Jefferson Lab, USA)
Jan Sobczyk (nuWro representative, University of Wroclaw, Poland)

Experimentalists
Sara Bolognesi (CEA-IRFU, France)
Steve Brice (Fermilab, USA)
Raquel Castillo Fernández (Fermilab, USA)
Dan Cherdack (Colorado State University, USA)
Steve Dytman (University of Pittsburgh, USA)
Andy Furmanski (University of Manchester, UK)
Yoshinari Hayato (NEUT representative, ICRR, Japan)
Teppei Katori (Queen Mary University of London, UK)
Kendall Mahn (Michigan State University, USA)
Camillo Mariani (Center for neutrino physics, VirginiaTech, USA)
Jorge G. Morfin (co-spokesperson, Fermilab, USA)
Ornella Palamara (Fermilab, USA)
Jon Paley (Fermilab, USA)
Roberto Petti (University of South Carolina, USA)
Gabe Perdue (GENIE representative, Fermilab, USA)
Federico Sanchez (IFAE, University of Barcelona, Spain)
Sam Zeller (Fermilab, USA)

NuSTEC white paper

https://arxiv.org/abs/1706.03621

- It addresses all topics of neutrino-nucleus scattering around 1-10 GeV.

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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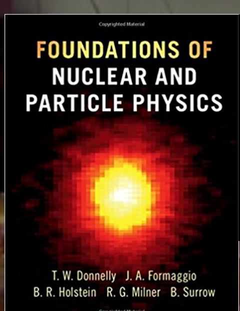
NuSTEC school

NuSTEC
NuSTEC Training in Neutrino-Nucleus Scattering Physics
Nov.8-14, 2015, Okayama, Japan

NuSTEC school, Fermilab, USA (Nov. 7-15, 2017)

- NuSTEC school is dedicated for students/postdocs to learn physics of neutrino interactions, both for theorists, and experimentalists

1. The Practical Beauty of Neutrino-Nucleus Interations (1 hour)	- Dr. Gabe Perdue (Fermilab)
2. Introduction to electroweak interactions on the nucleon (3 hours)	- Prof. Richard Hill (University of Kentucky and Fermilab)
3. Introduction to ν-nucleus scattering (3 hours)	- Prof. Wally Van Orden (Old Dominion University&JLab, VA)
4. Strong and electroweak interactions in nuclei (3 hours)	- Dr. Saori Pastore (Los Alamos National Lab., NM)
5. Approximate methods for nuclei (I) (2 hours)	- Dr. Artur Ankowski (Virginia Tech, VA)
6. Approximate methods for nuclei (II) (2 hours)	- Prof. Natalie Jachowicz (Ghent University, Belgium)
7. Ab initio methods for nuclei (2 hours)	- Dr. Alessandro Lovato (Argonne National Lab, IL)
8. Pion production and other inelastic channels (3 hours)	- Prof. Toru Sato (Osaka University, Japan)
9. Exclusive channels and final state interactions (3 hours)	- Dr. Kai Gallmeister (Goethe University Frankfurt, Germany)
10. Inclusive e- and ν-scattering in the SIS and DIS regimes (3 hrs)	- Prof. Jeff Owens (Florida State University, FL)
11. Systematics in neutrino oscillation experiments (3 hours)	- Dr. Sara Bolognesi (CEA Saclay, France)
12. Generators 1: Monte Carlo methods and event generators (3 rs)	- Dr. Tomasz Golan (Univ. Wroclaw, Poland)
12. Generators 2: Nuisance (2 hours)	- Dr. Patrick Stowell (Univ. Sheffield, UK)



Foundation of Nuclear and Particle Physics

- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- The first textbook on this subject!

NuInt17, Toronto, Canada (June 25-30, 2017)

https://nuint2017.physics.utoronto.ca/

Topics include;

- T2K CC inclusive 4pi measurement
- Pion scattering data from LArIAT (argon) and DUET (carbon)
- New pion production models
- MINERvA pion data global fit
- MINERvA new study on 2p2h
- T2K measurements on Single Trsanverse Variables (STV)
- and more...

NuInt18, Gran Sasso Science Institute (GSSI), Italy, October 15-19, 2018
https://indico.cern.ch/event/703880/

Neutrino Shallow and Deep-Inelastic scattering, GSSI, Oct 11-13

http://nustec.fnal.gov/nuSDIS18/

A dedicated workshop for physics related to DUNE, NOvA, etc

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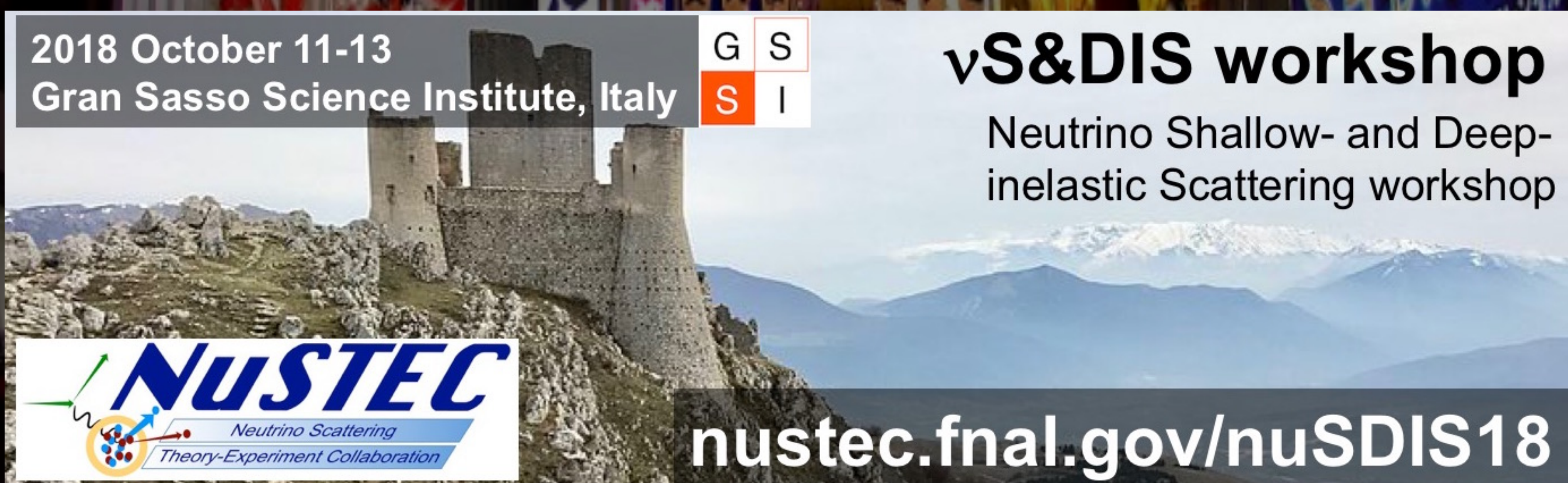
- low Q2 low W DIS
- nuclear modifications and nuclear-dependent PDFs
- neutrino hadronization problem



Register now!
http://nustec.fnal.gov/nuSDIS18/

Conclusion

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(or just send e-mail to me, katori@FNAL.GOV)

like "@nuxsec" on Facebook page, use hashtag #nuxsec

1 to 10 GeV neutrino interaction measurements are crucial to successful next-generation neutrino oscillation experiments (DUNE, Hyper-K)

CCQE: Presence of 2p-2h contribution is still a big discussion of the community.

Resonance region: Many tensions in existing data. It could be experimental errors, poor understanding of resonance and/or final state interaction models, and/or 2-body current in meson productions.

SIS physics: Very few activities but it is important for future DUNE experiment.

We need models working in all kinematic region. Neutrino experiment is incomplete final state particle measurements, incomplete kinematics, with unknown targets. This is different from electron scattering (nuclear physics) and collider physics (particle physics).

Conclusion

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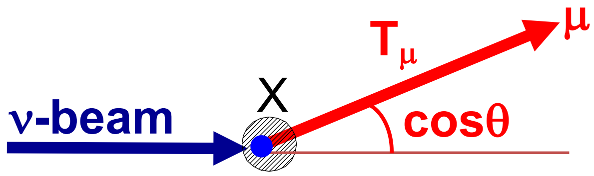
Neutrino Interaction Physics

- electron scattering
- nuclear many-body problem
- Weak interaction
- Neutrino oscillation
- EMC effect
- Nucleon correlation
- Spin physics
- Dark matter
- Heavy ion collision

Thank you for your attention!

Backup

2. Neutrino experiment



Experiment measure the interaction rate R,

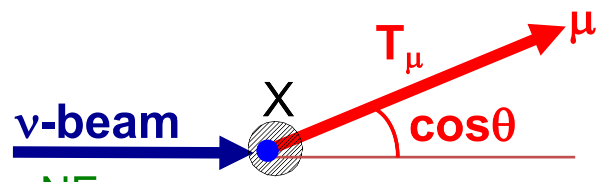
$$R \sim \int \Phi \times \sigma \times \varepsilon$$

- 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

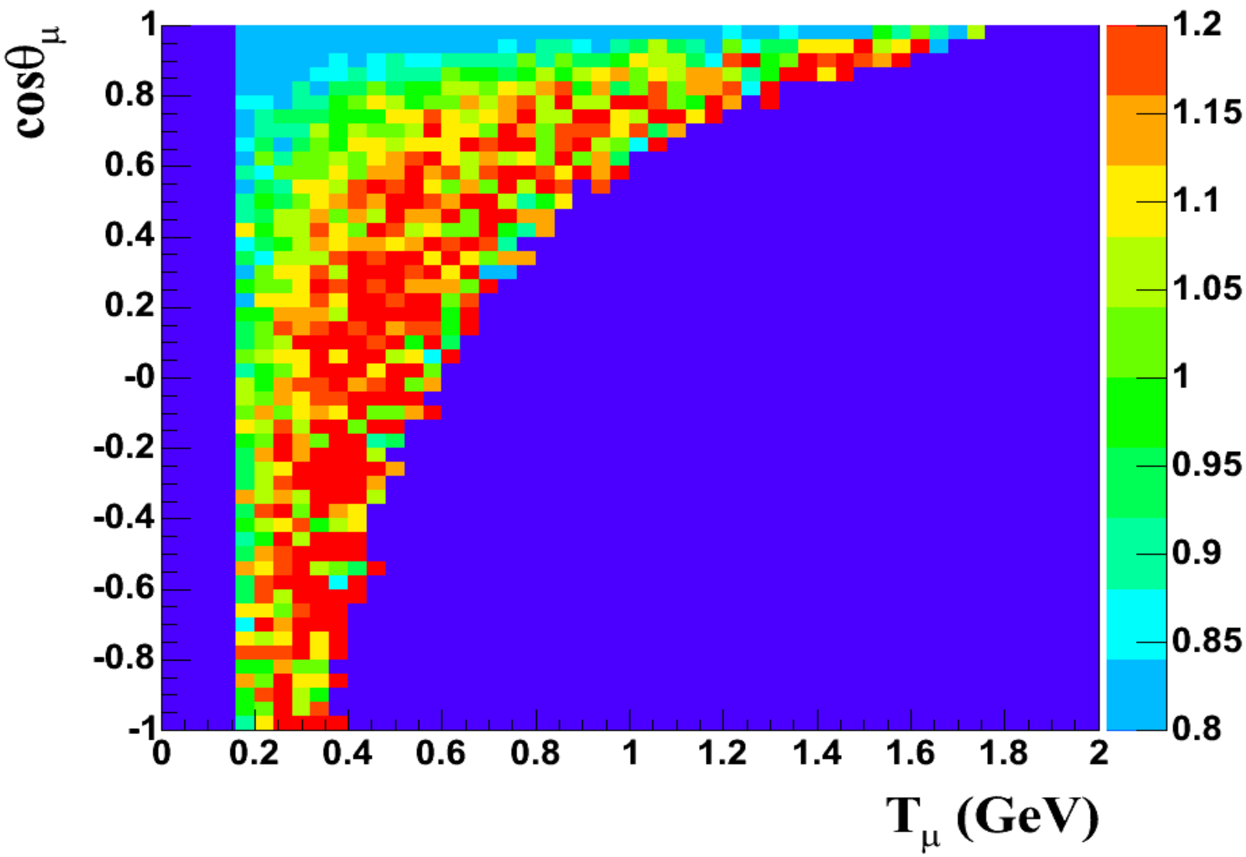
2. MiniBooNE phase space



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.

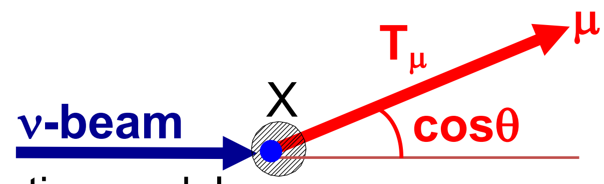
$$\frac{d\sigma^2}{dE\,d\Omega} \sim \frac{d\sigma^2}{dE\,d(\cos\vartheta)}$$



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?

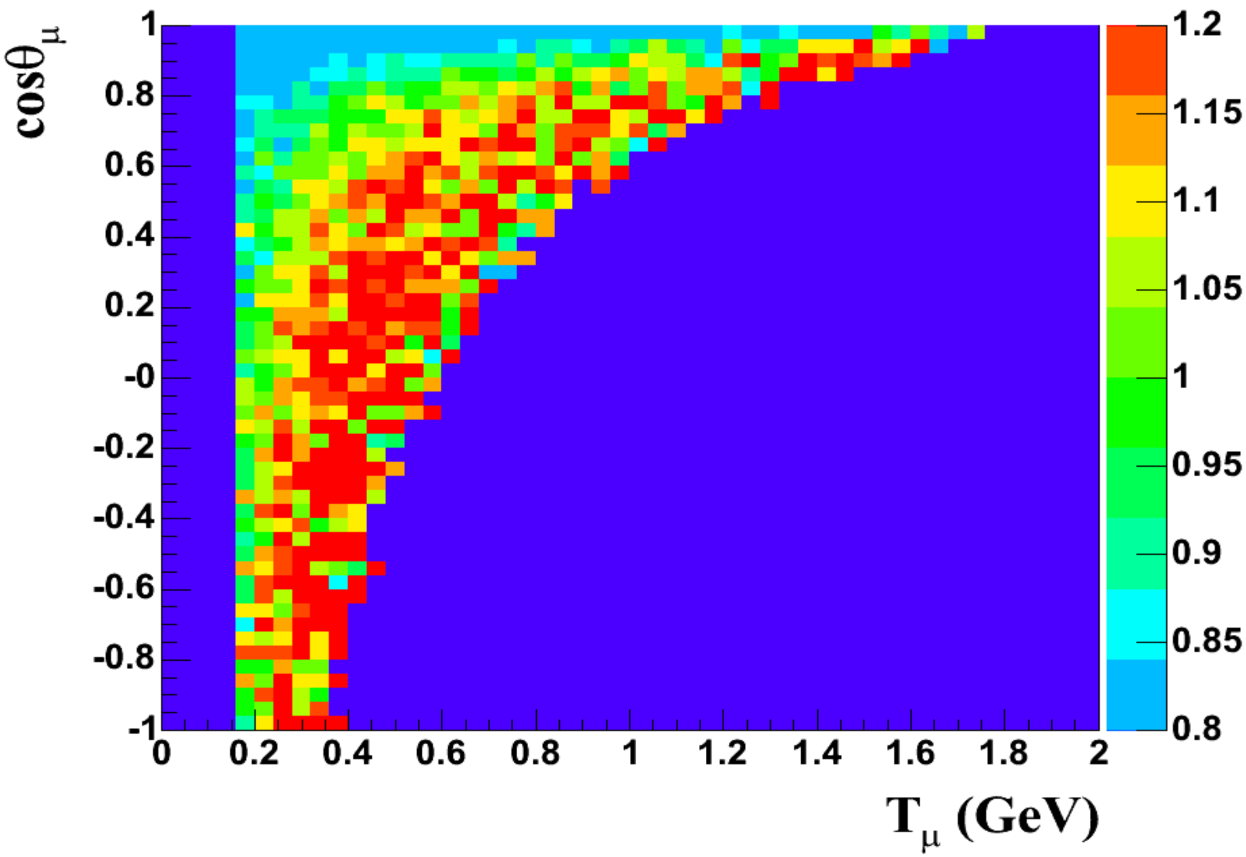
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

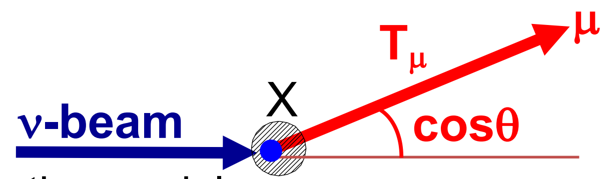
$$R \sim \int \Phi \times \sigma$$

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



MiniBooNE collaboration,PRL.100(2008)032301

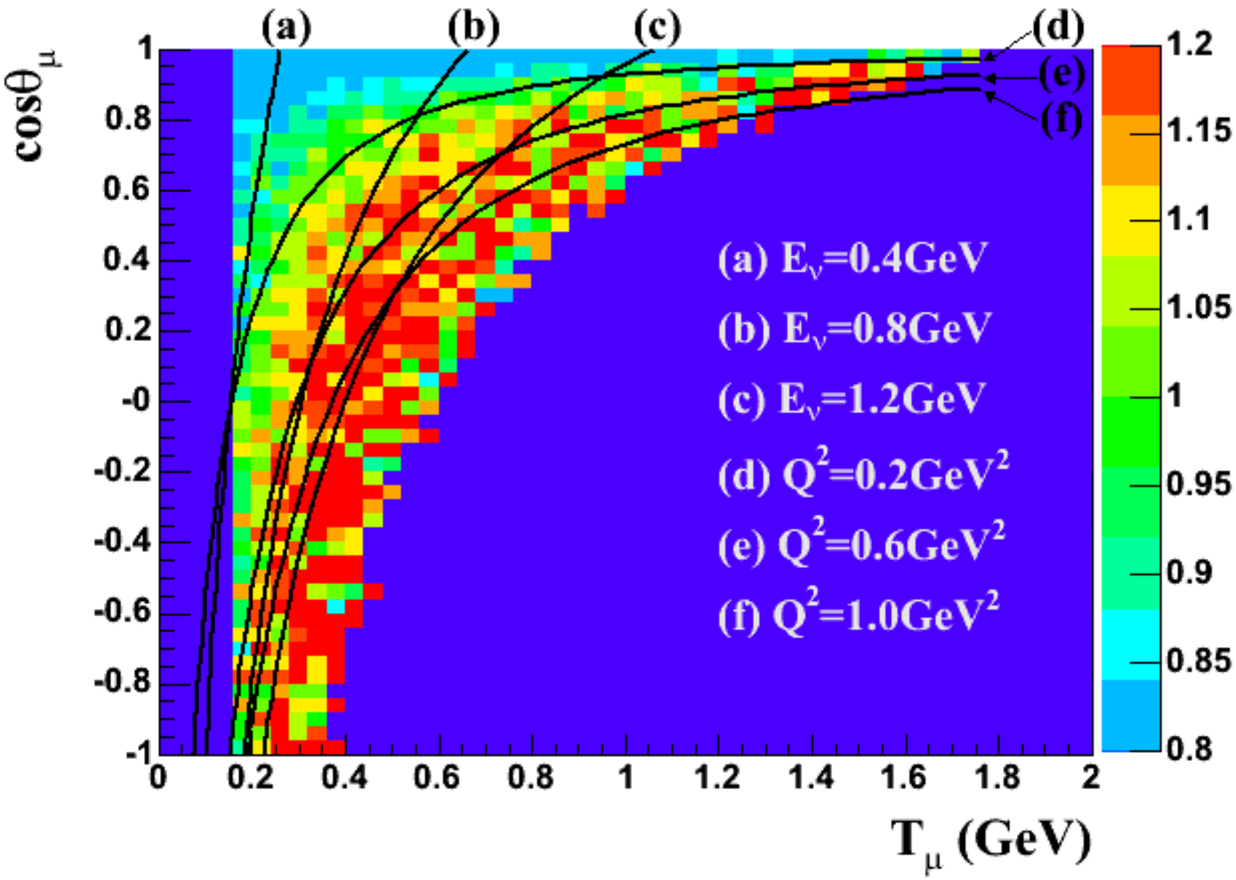
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

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

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

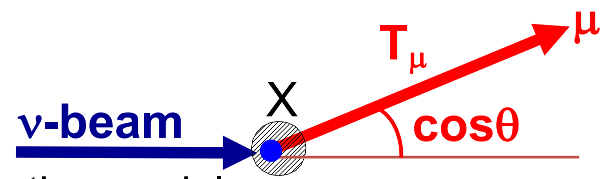


The data-MC disagreement follows equal Q^2- lines, not equal E_ν-lines.

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

MiniBooNE collaboration,PRL.100(2008)032301

2. MiniBooNE phase space

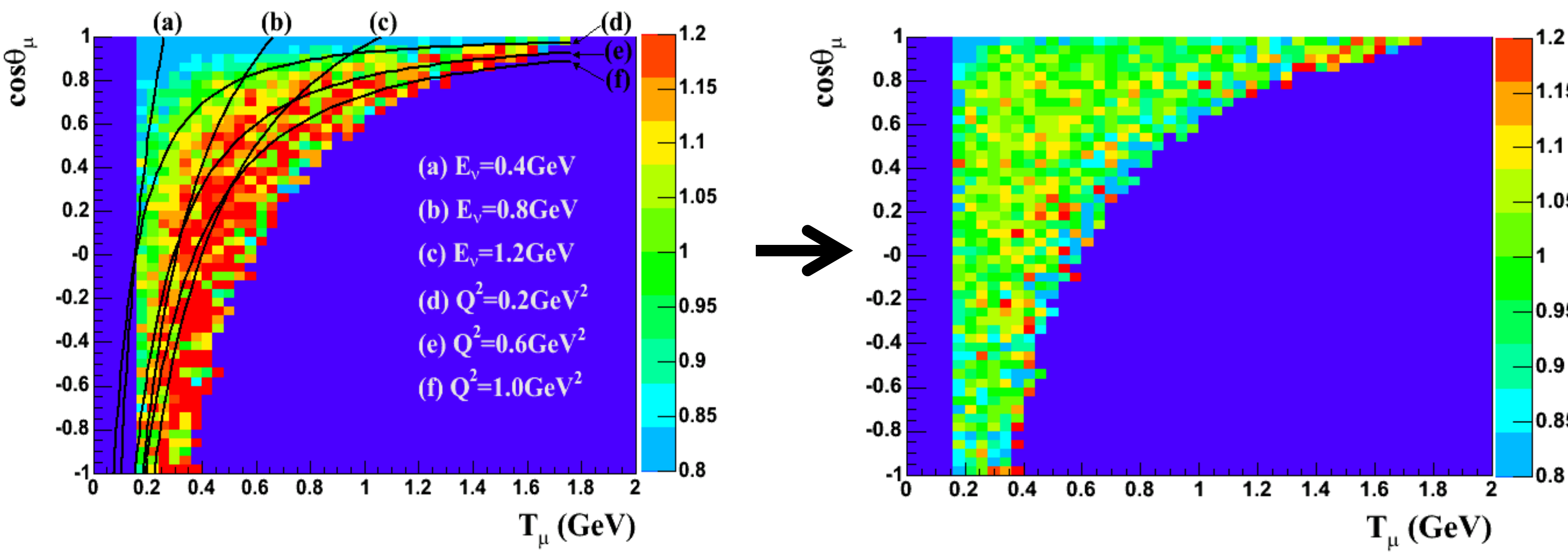


Without knowing flux, you cannot modify cross section model

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

After tuning cross section parameters, data and MC agree.

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



2. Smith-Moniz formalism

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

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

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

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

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

Ehi : the highest energy state of nucleon

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.

2. Relativistic Fermi Gas (RFG) model

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

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

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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

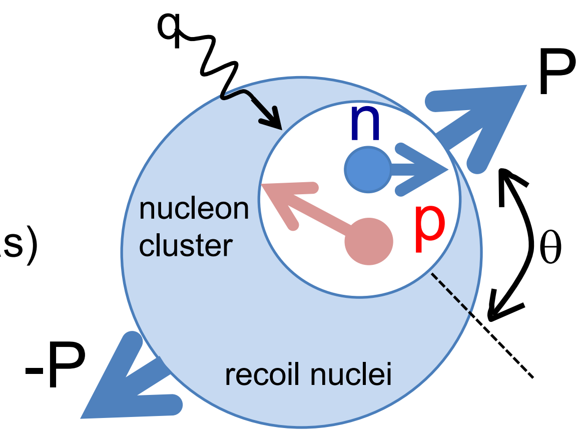
MiniBooNE tuned their axial mass to 1.3 GeV!

but axial mass is not 1.3 GeV!

Queen Mary
University of London

Sobczyk, PRD86(2012)015504, TK, arXiv:1304.6014
GENIE, arXiv:1510.05494

2. How to emit 2 nucleons from correlated pair?



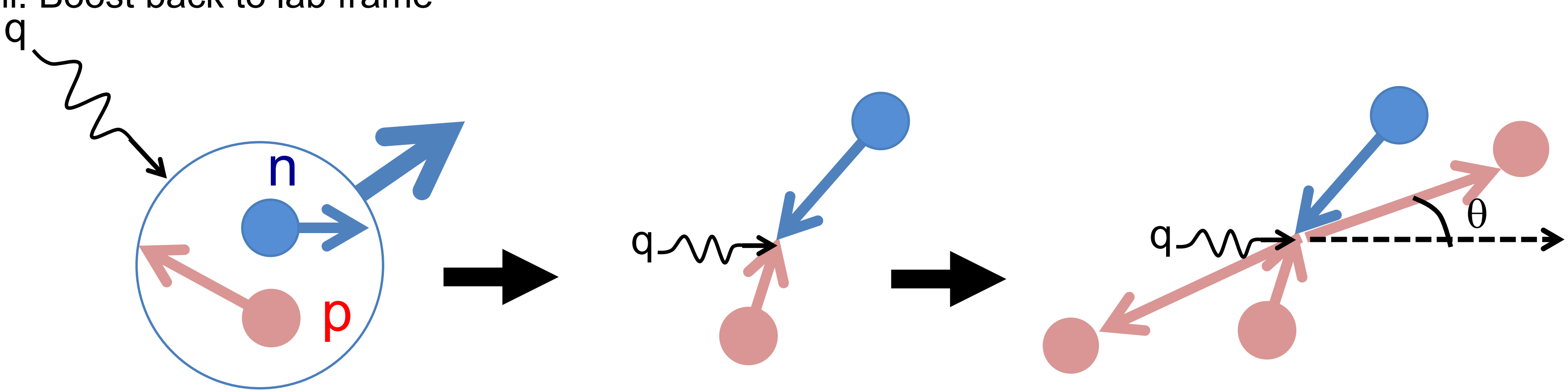
Default model for GENIE, NEUT, NuWro…

For a given Energy-Momentum transfer...

1. Choose 2 nucleons from specified kinematics (e.g., Fermi gas)
2. n-n, n-p, p-p pairs are allowed, if interaction is allowed
3. Energy-momentum conservation

Once 2 nucleons from on-shell are choosed

i. ω-q vector and nucleon cluster makes CM system (hadronic system)
ii. Isotropic decay (random θ and ϕ) of hadronic system creates 2 nucleon emission
iii. Boost back to lab frame



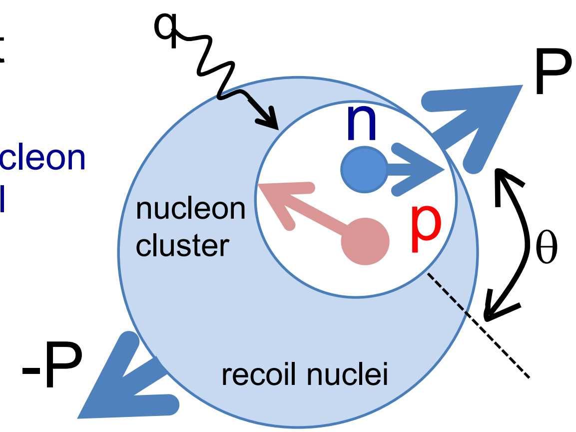
Is there correct way to model 2 nucleon emissions from a correlated nucleon pair?

Queen Mary
University of London

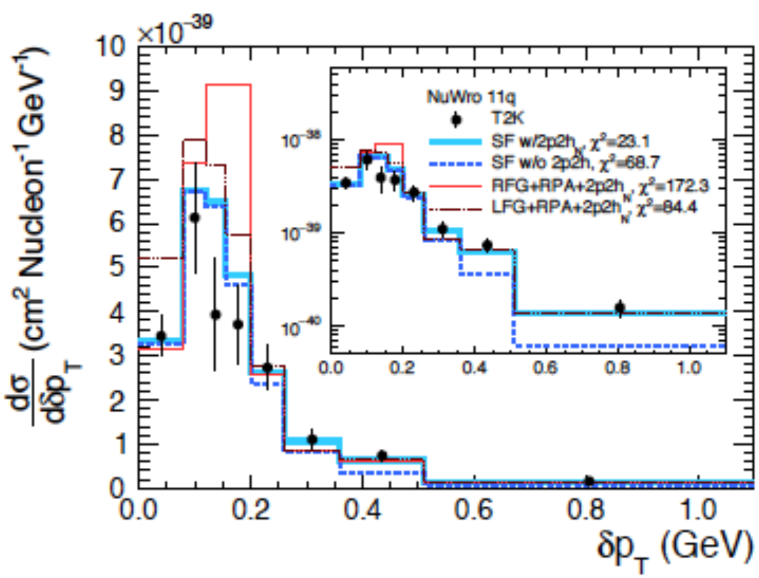
2. Hadron measurement for nuclear correlation

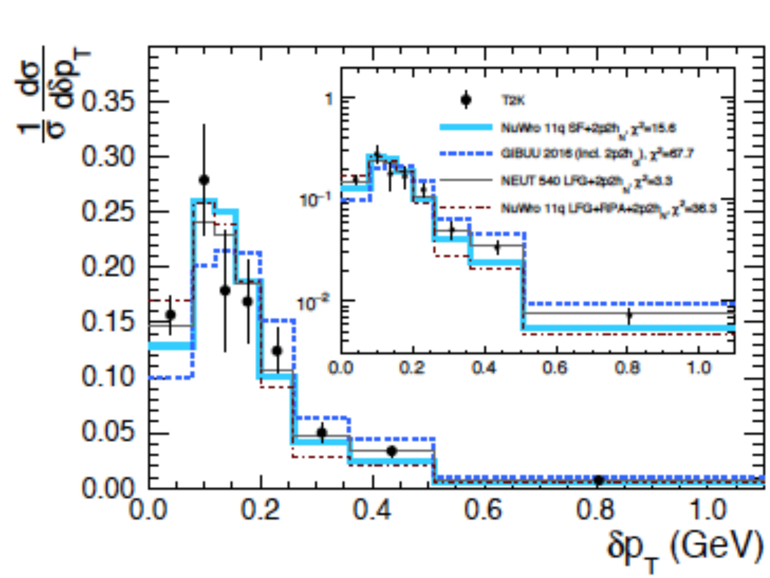
There is a strong belief in experimental community that hadron final states tell everything about 2p2h…

home-made nucleon emission model



We need prediction of hadronic final states from theorists





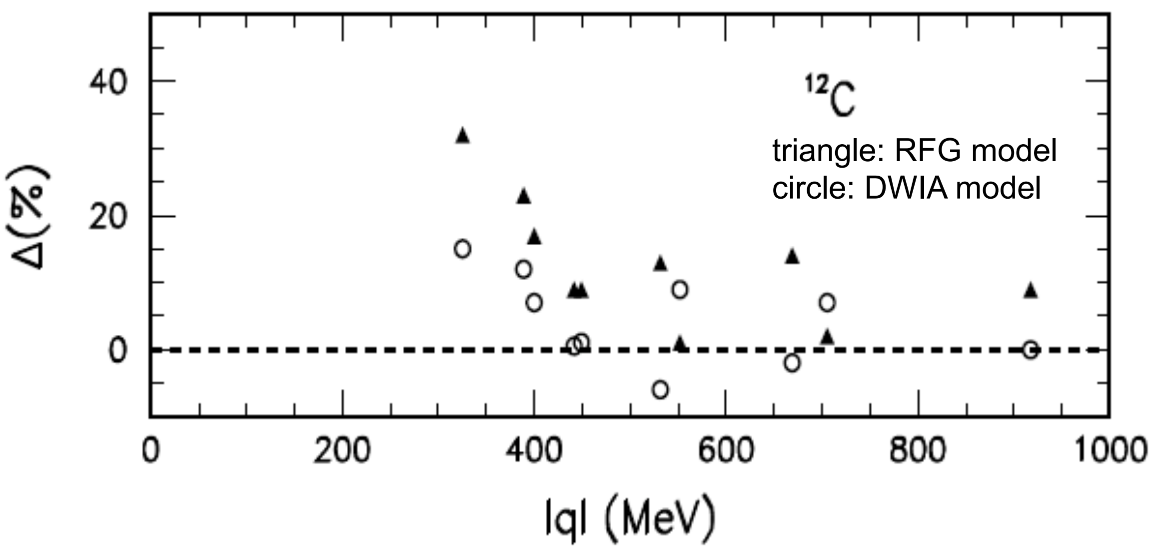
2. Relativistic Fermi Gas (RFG) model

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



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

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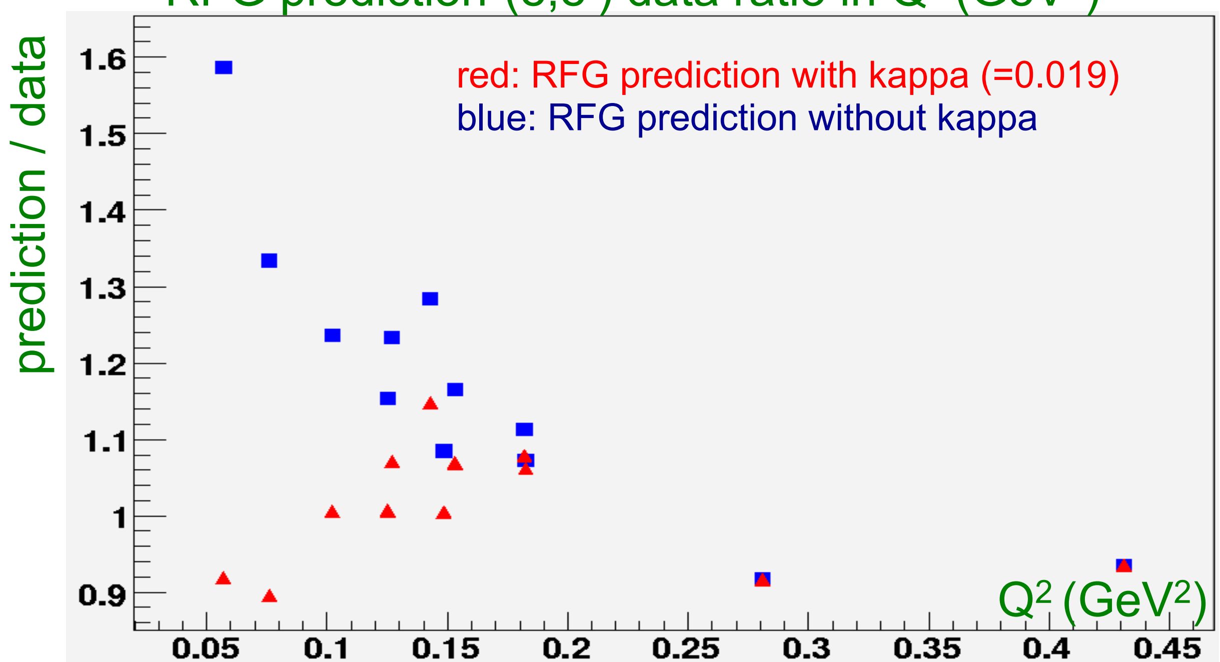
RFG prediction-(e,e') data ratio in Q^2 (GeV^2)



Ankowski et al, PRD92(2015)073014

1. Kinematic E reconstruction vs calorimetric E reconstruction

Calorimetric energy reconstruction suffers invisible hadrons (=neutrons)

It largely depends on neutrino interaction and hadron simulation
- multiplicity
- kinematics
- nuclear effect
  - re-scattering
  - charge exchange
  - baryonic resonance
  - nucleon correlation

etc