Neutrino Interaction Physics

Lecture 1: Introduction of neutrino interactions (~3hr)
1. Introduction to cross sections
2. The Standard Model
3. ν-e scattering cross section

Lecture 2: Charged-current quasi-elastic (CCQE) interaction (~4hr)
4. Introduction to CCQE interaction
5. CCQE scattering cross section

Lecture 3: Overview of neutrino cross sections (~3hr)
6. Neutrino-nucleus interactions
7. Neutrino interaction physics around 1-10 GeV
8. Neutrino cross section experiments

Teppei Katori
King's College London
Summer lecture series, Nagoya University, Japan, July. 6-10, 2020

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Hi, my name is Teppei Katori (香取哲平)!

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PhD, Indiana University, Bloomington, USA (2008)
Postdoc, Massachusetts Institute of Technology, USA (2009-2013)
Assistant professor, Queen Mary University of London (2013-2019)
Associate professor, King's College London (2019 -)

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References - Lectures

Lecture slides (Lec. 7 and 8)
- https://nms.kcl.ac.uk/teppei.katori/teach/2020/20_Nagoya/TK_Lec_Nagoya20.pdf

Calculation slides
- https://nms.kcl.ac.uk/teppei.katori/teach/2020/20_Nagoya/TK_nuxsec.pdf

Assessment

Based on 4 homework's, see details in TK_nuxsec.pdf

References – Books

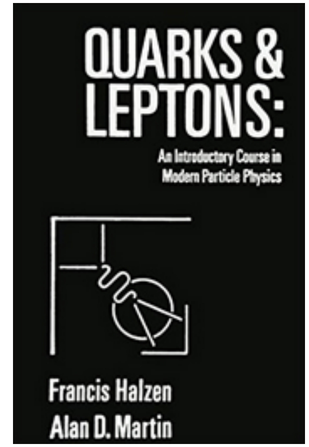
Quarks and Leptons (Q&L, Halzen and Martin)
- classic
- show many calculations
- solutions for all exercises

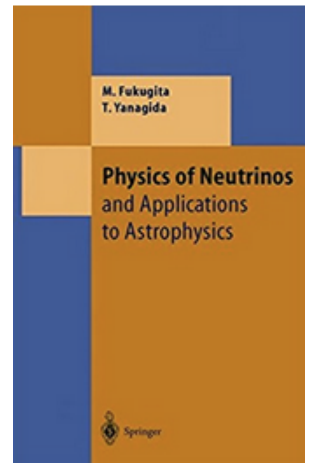
Weak interactions of Leptons and Quarks (Commins and Bucksbaum)
- classic, too many typos
- show details of weak interaction calculations

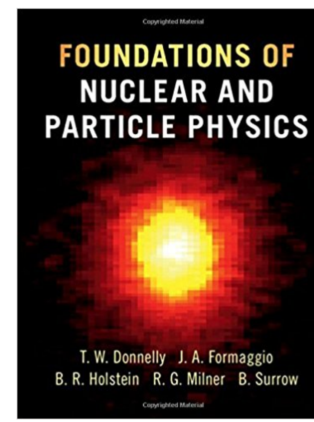
Physics of Neutrinos (Fukugita and Yanagida)
- modern
- very intense, from solar neutrinos to SUSY
- ν-e elastic scattering

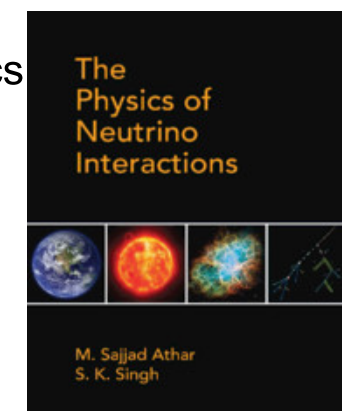
Foundation of Nuclear and Particle Physics (2017)
- modern
- Textbook to fill the gap between nuclear and particle physics

The Physics of Neutrino Interaction (2020)
- modern
- Textbook specialized to the neutrino interaction 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 collaboration
- PPNP100(2018)1, https://arxiv.org/abs/1706.03621
- State-of-the-art list of topics in nuxsec community

Tony Mahn's NOvA technote
- CCQE cross-section calculation

http://nova-docdb.fnal.gov/cgi-bin/ShowDocument?docid=28289

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- Neutrino Scattering Theory-Experiment Collaboration
- http://nustec.fnal.gov/
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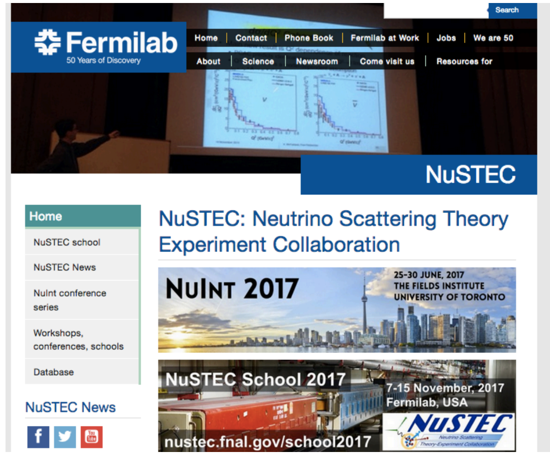

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1. Introduction to cross-sections

1 Neutrino cross section

- Interaction cross-section
- Neutrino cross section measurement
- cross section formula
- Form factor
- Kinematics
- Standard Model
- nu-e elastic scattering
- Leptonic tensor of neutrino
- Leptonic tensor of electron
- Matrix element
- nu-e cross section

1. Neutrino cross-section measurements

Absolute flux-integrated topological differential cross section formula

i :true index
j : reconstructed index

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(d_j - b_j)}{\varepsilon_i(\Phi T)\Delta x_i}$$

U_{ij} :unsmearing matrix

b_j :predicted background

d_j :data vector

Δx_i :bin width

ε_i :efficiency

T :integrated target number

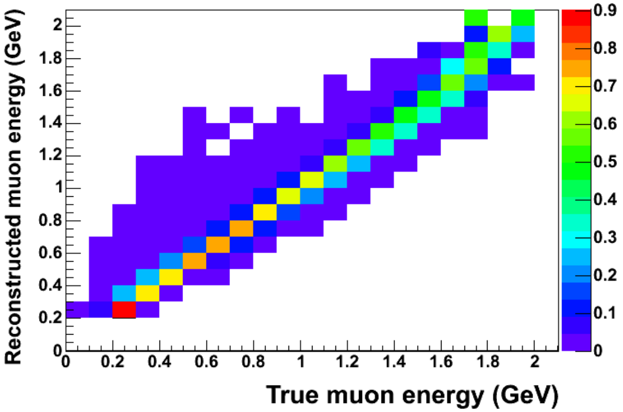
Φ :integrated ν-flux

1. Neutrino cross-section measurements

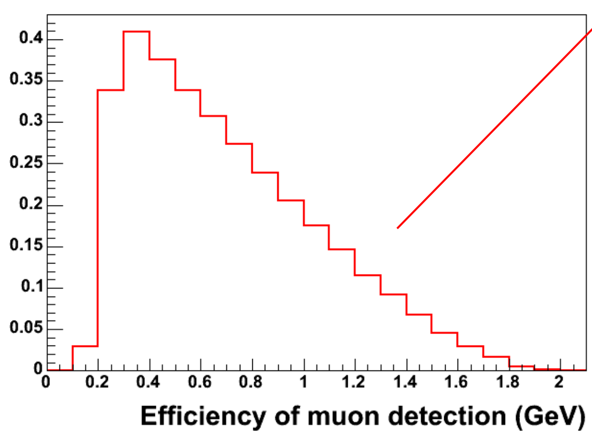
Absolute flux-integrated topological differential cross section formula

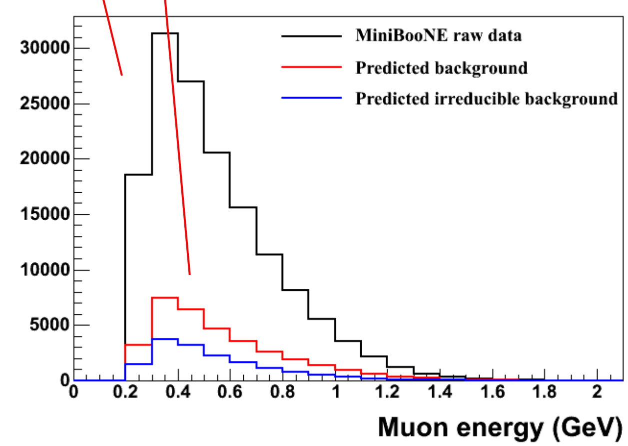
i :true index
j : reconstructed index

Φ~
T~Avogadro's number x detector volume



$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U^{-1}_{ij}(d_j - b_j)}{\varepsilon_i(\Phi T)\Delta x_i}$$





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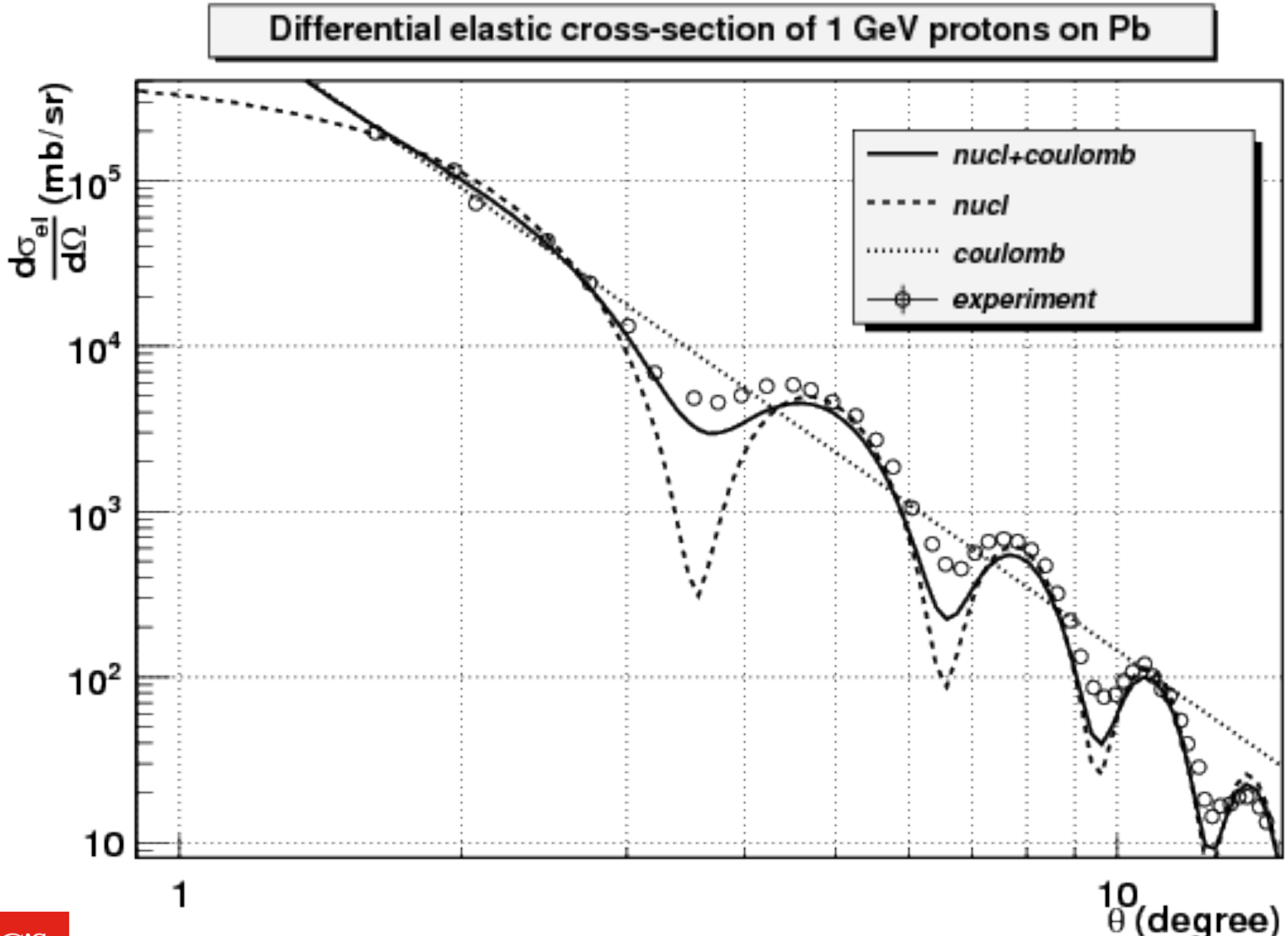
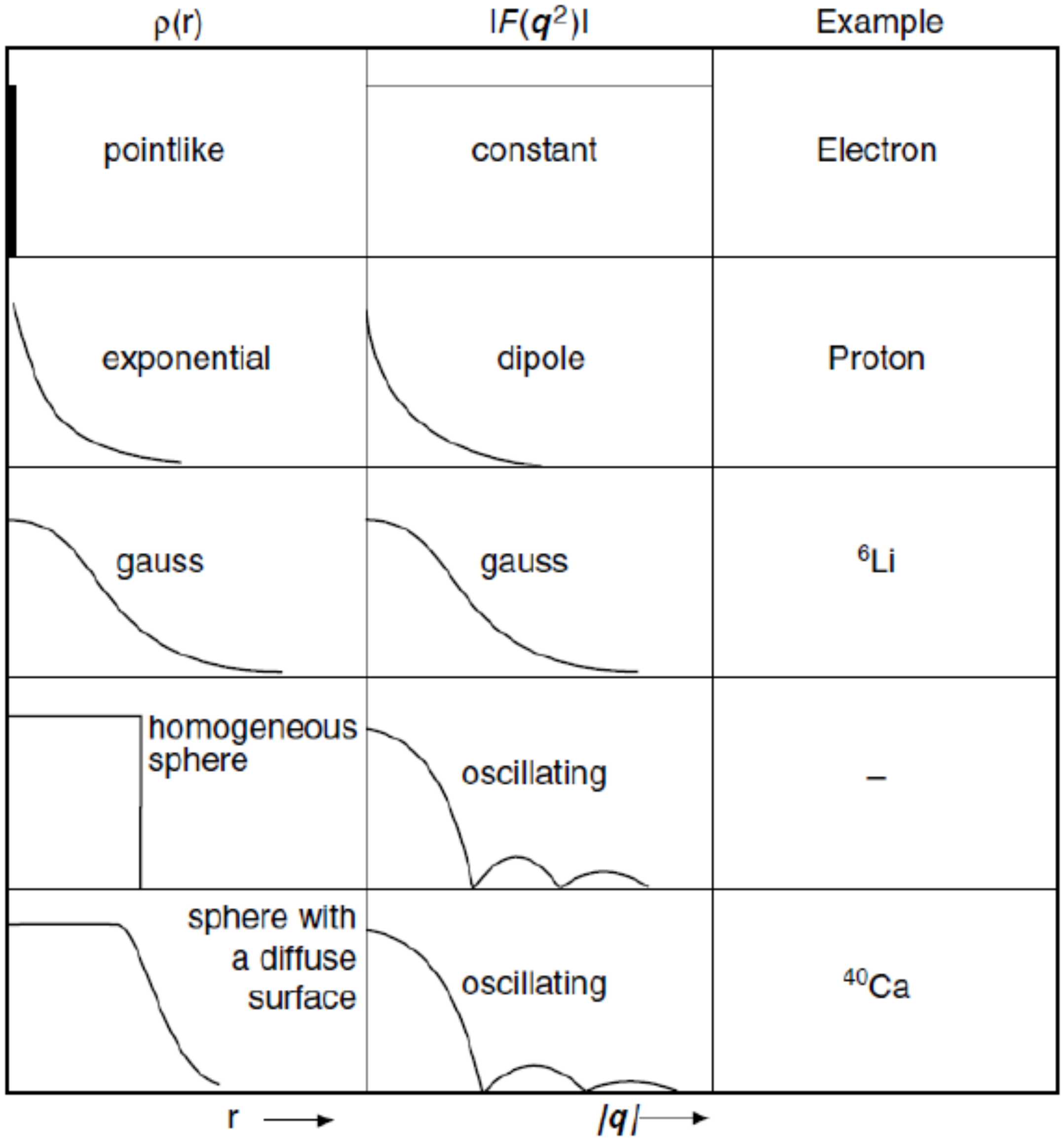
1. e+Pb → e+Pb elastic scattering



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

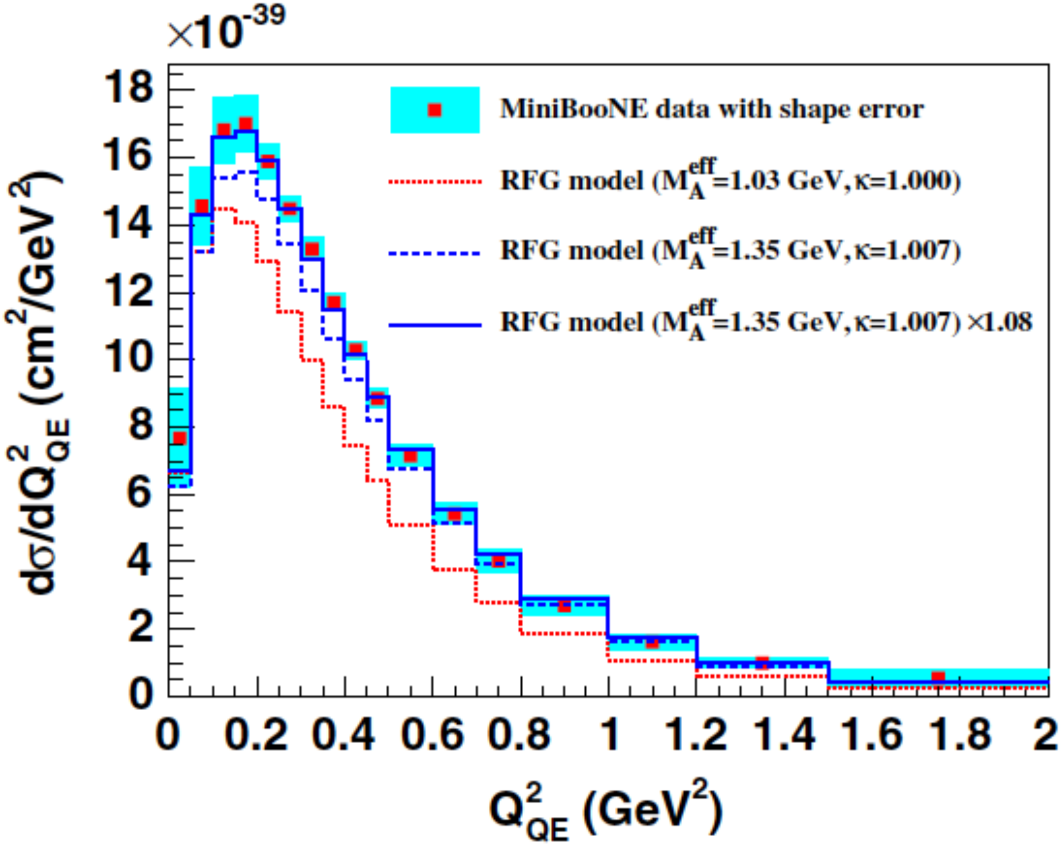


FIG. 14 (color online). Flux-integrated single differential cross section per target neutron for the ν_μ CCQE process. The measured values are shown as points with the shape error as shaded bars. Calculations from the NUANCE RFG model with different assumptions for the model parameters are shown as histograms.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

2. CCQE cross-section

2 CCQE cross section

- Kinematics
- Neutrino energy reconstruction
- CCQE scattering
- Nucleon current
- Conservation of Vector Current
- Sachs form factor
- Leptonic tensor of neutrino
- Hadronic tensor of neutron
- Matrix element
- CCQE cross section
- anti-CCQE cross section
- Summary

2. CCQE cross-section

Llewellyn-Smith formalism
- Dirac f.f. (F1, or F1V)
- Pauli f.f. (F2, or ξF2V)
- Axial vector f.f. (FA)
- Pseudo scalar f.f. (FP)
- Assume all real (assume T-inv)

$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu + n \rightarrow l + p \\ \bar{\nu} + p \rightarrow l^+ + n\end{pmatrix} = \frac{G_F^2 M^2}{8\pi E^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right]$$

$$A = \left[\frac{(m^2+Q^2)}{M^2}\left\{(1+\tau)F_A^2 - (1-\tau)F_1^2 + \tau(1-\tau)F_2^2 + 4\tau F_1 F_2 - \frac{m^2}{4M^2}\left[(F_1+F_2)^2 + (F_A+2F_P)^2 - 4(1+\tau)F_P^2\right]\right\}\right.$$

$$B = -4\tau(F_1+F_2)F_A$$

$$C = \frac{1}{4}(F_1^2 + \tau F_2^2 + F_A^2)$$

$$\frac{d\sigma}{d|q^2|}\begin{pmatrix}\nu n \rightarrow \ell^- p \\ \bar{\nu} p \rightarrow \ell^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4}\right]$$

$$(s-u = 4ME_\nu + q^2 - m^2)\,.$$

$$A = \frac{(m^2-q^2)}{4M^2}\left[\left(4-\frac{q^2}{M^2}\right)|F_A|^2 - \left(4+\frac{q^2}{M^2}\right)|F_V^1|^2 - \frac{q^2}{M^2}|\xi F_V^2|^2\left(1+\frac{q^2}{4M^2}\right) - \frac{4q^2\,\mathrm{Re}\,F_V^{1*}\xi F_V^2}{M^2}\right.$$
$$\left. + \frac{q^2}{M^2}\left(4-\frac{q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1+\xi F_V^2|^2 + |F_A+2F_P|^2 + \left(\frac{q^2}{M^2}-4\right)\left(|F_V^3|^2+|F_P|^2\right)\right)\right] \tag{3.22}$$

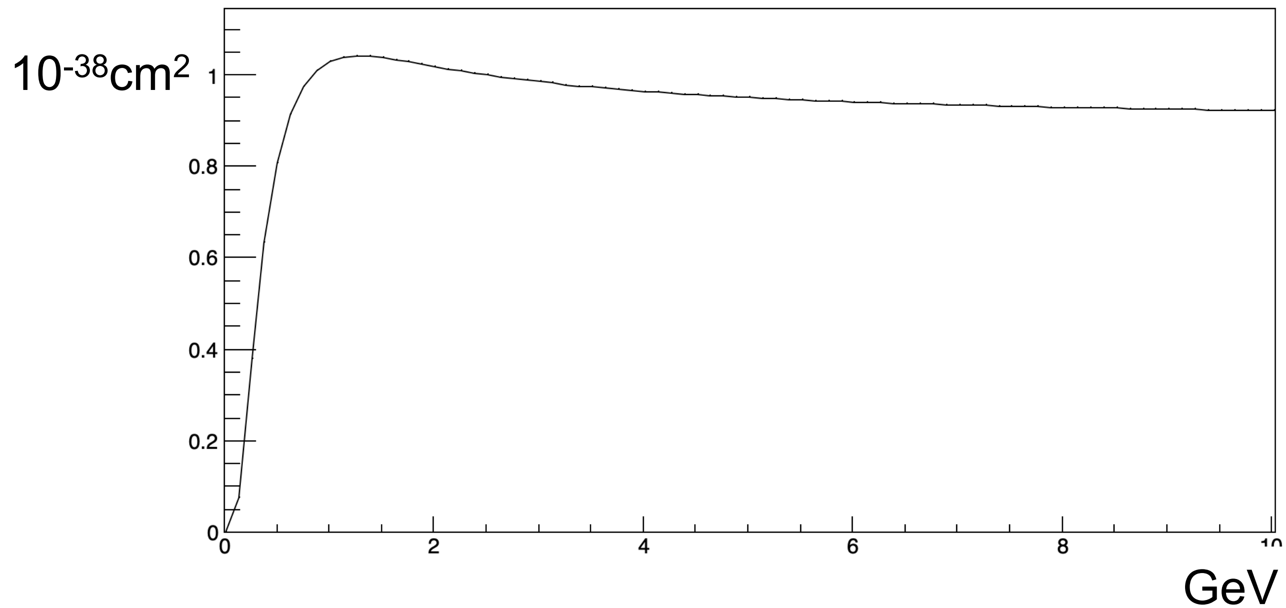
$$B = -\frac{q^2}{M^2}\,\mathrm{Re}\,F_A^*(F_V^1+\xi F_V^2) - \frac{m^2}{M^2}\,\mathrm{Re}\left[\left(F_V^1+\frac{q^2}{4M^2}\xi F_V^2\right)^* F_V^3 - \left(F_A+\frac{q^2 F_P}{2M^2}\right)^* F_A^3\right]$$

$$C = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 - \frac{q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 - \frac{q^2}{M^2}|F_A^3|^2\right)\,.$$

2. CCQE cross-section

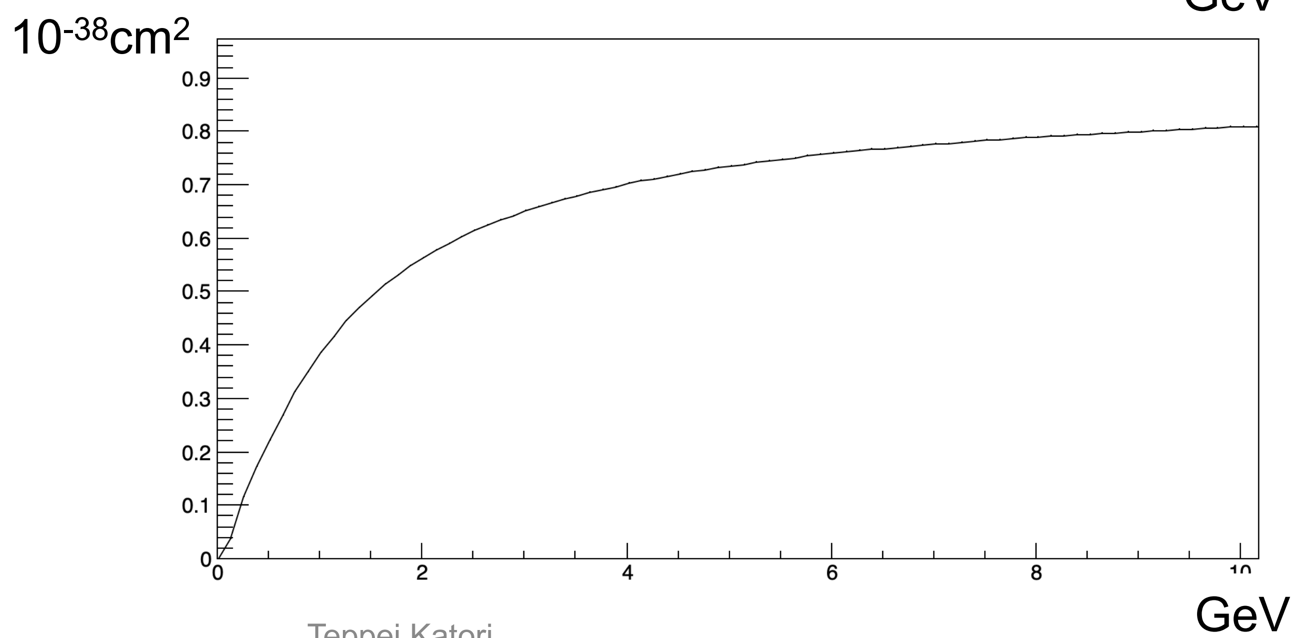
νμCCQE

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



anti-νμCCQE

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

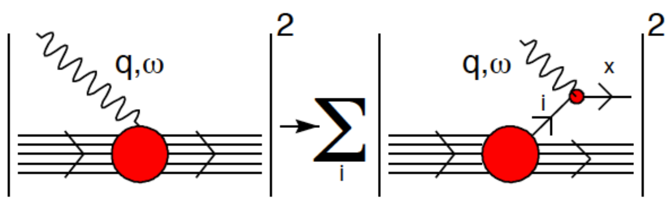


3. Nuclear dynamics

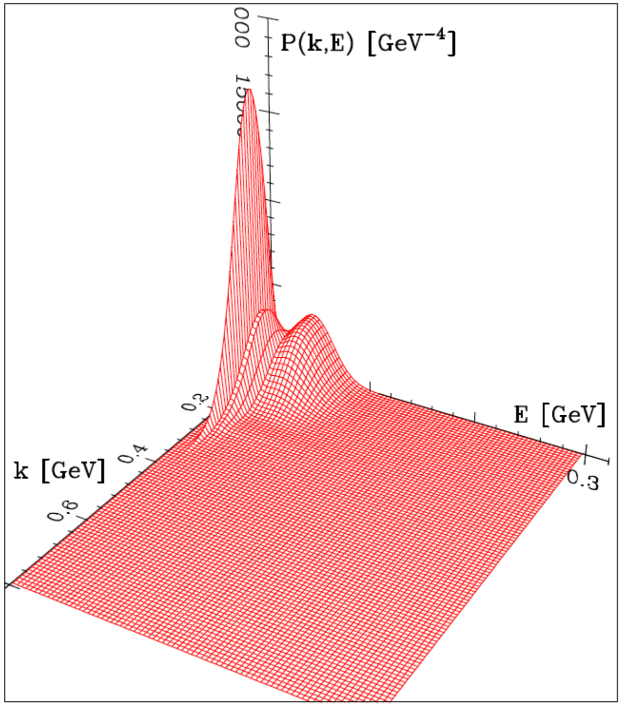
Fermi motion: motion of nucleons, $p = (M, 0,0,0) \rightarrow (E_p, \vec{p})$
Pauli blocking: low momentum transfer is forbidden (Pauli blocking)
Shell structure: nucleons have different momentum, different separation energies
Nucleon correlation: short- and long-range correlation, meson exchange current
Final state interaction: elastic and inelastic scatterings, charge exchange, absorption

Impulse approximation

- Hadronic tensor = (nucleon tensor x correction) x N
- hard scattering with 1 nucleon and spectators



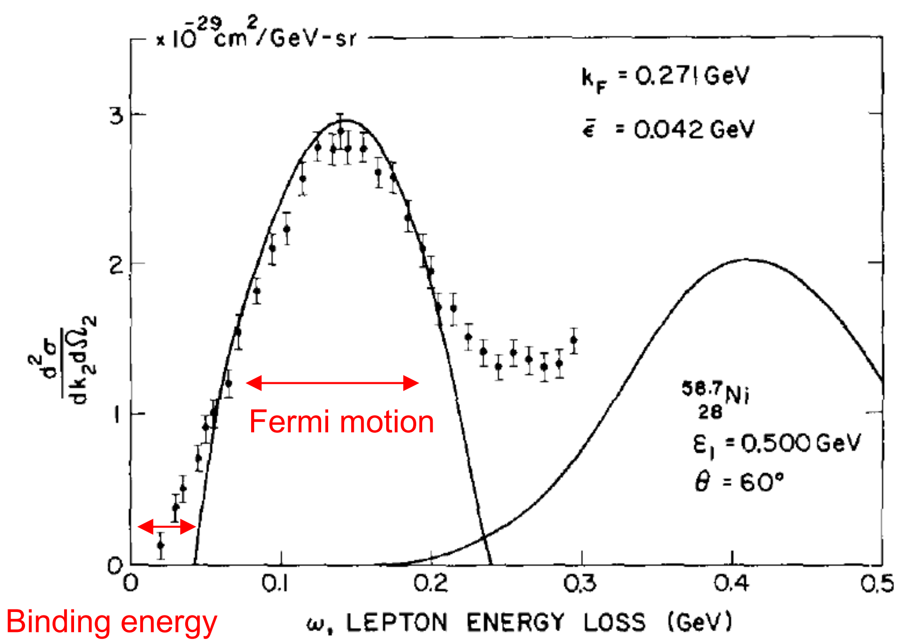
$$W^{\lambda\mu} = N \int d^3k \, dE \, \frac{M}{E_k} P(\mathbf{k}, E) \mathcal{W}_n^{\lambda\mu}$$

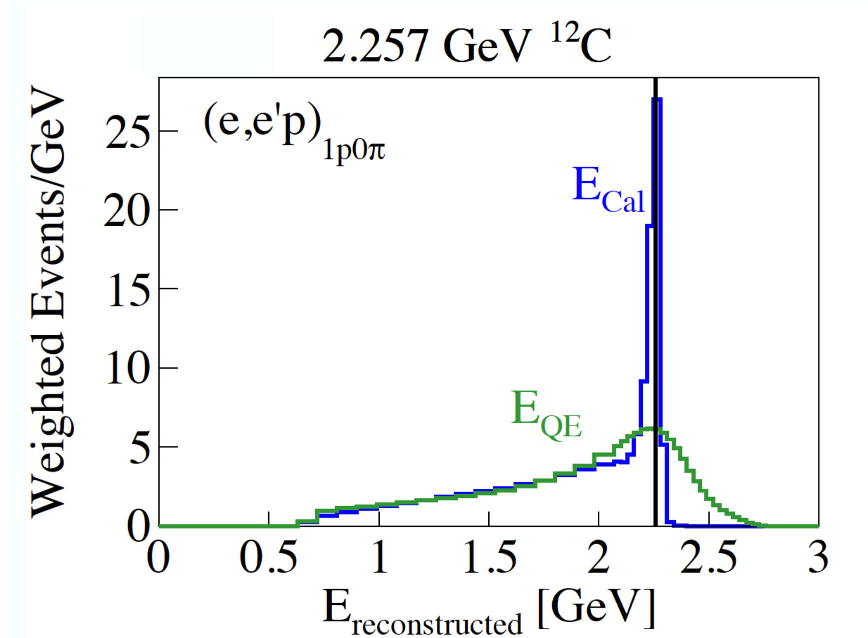


3. Fermi motion

Fermi motion

- Measured energy is smeared from the true energy if you assume nucleon at rest
- High resolution detector can measure all outgoing hadrons
  → initial nucleon momentum can be reconstructed (no Fermi motion smearing)





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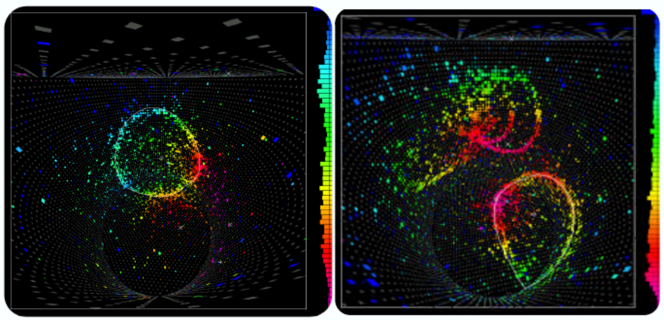
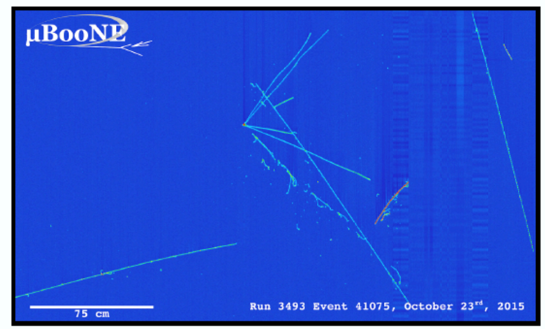


Cherenkov detectors:

Assuming QE interaction

Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$



Tracking detectors:

Calorimetric sum

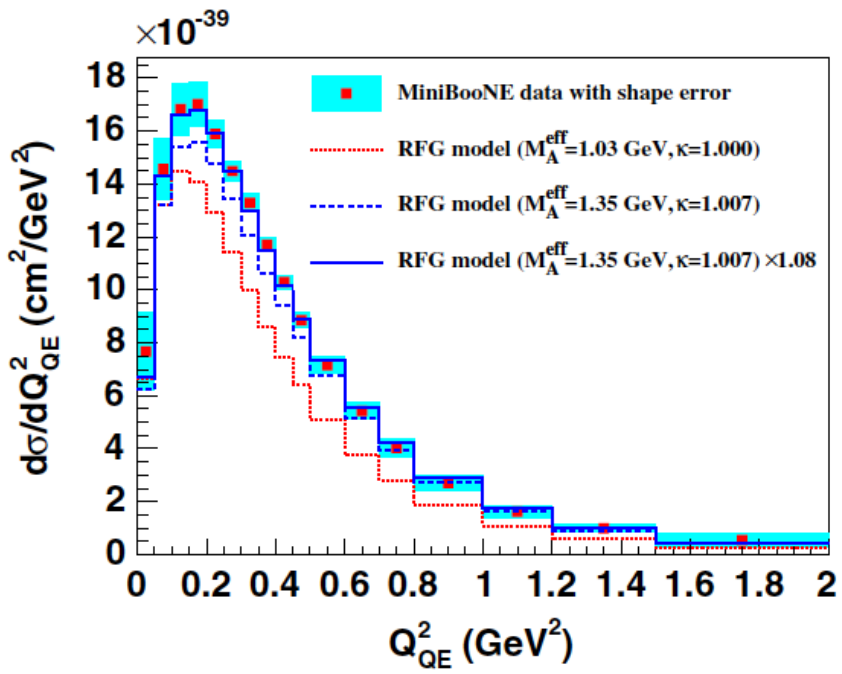
Using All detected particles

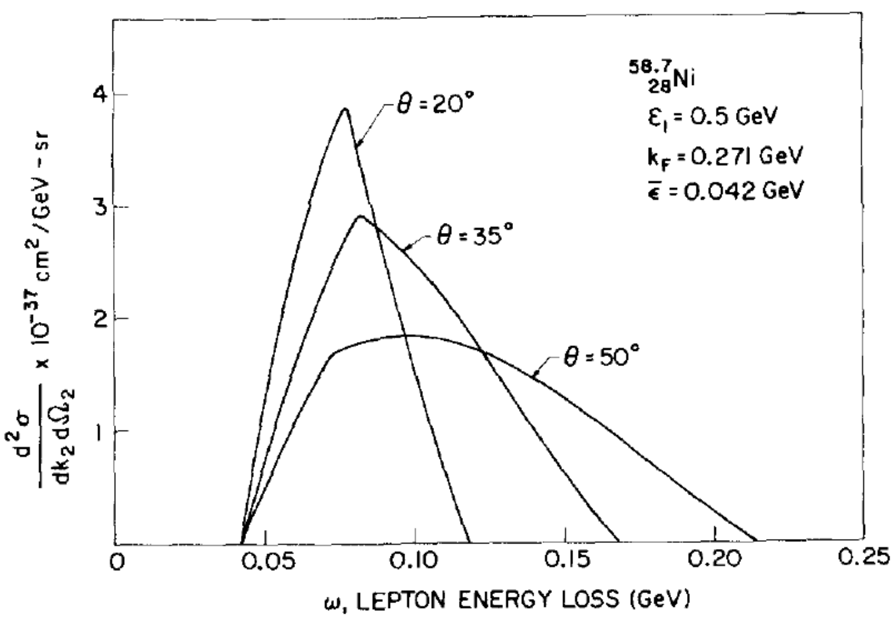
$$E_{\mathrm{cal}} = E_l + E_p^{\mathrm{kin}} + \epsilon$$

[1p0π]

3. Pauli blocking

Pauli blocking
- Low momentum transfer reaction is forbidden.
- data show more suppression than what Pauli blocking can) → RPA
- In the global Fermi gas model, it looks unphysical





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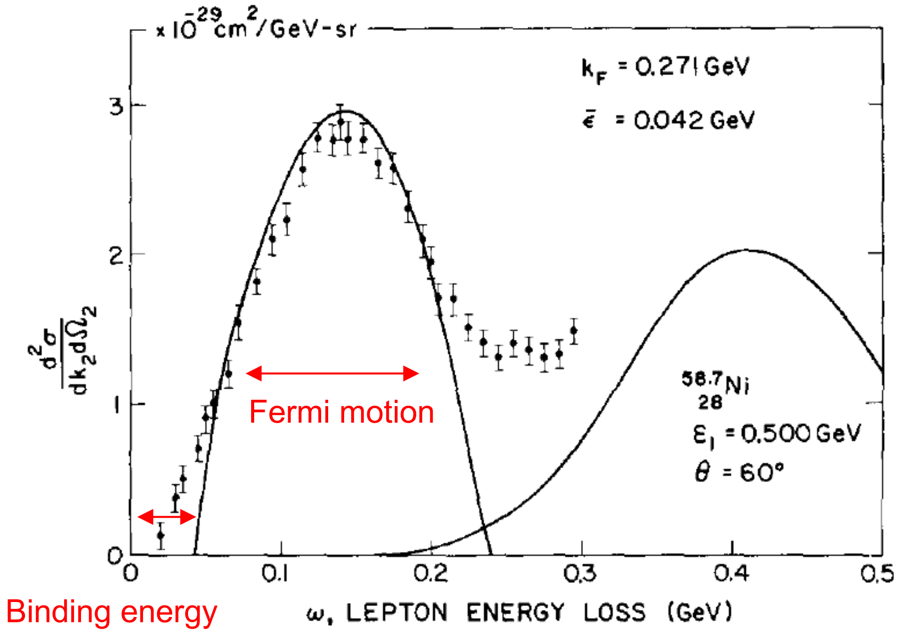
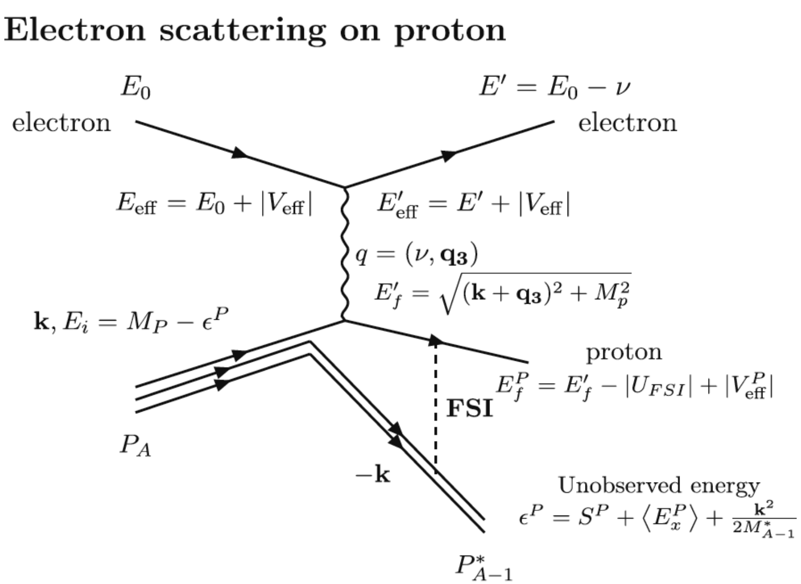
3. Binding energy

Binding energy ~ unobserved energy

- Energy to cost to release 1 nucleon, not constant
- Separation energy + excitation energy + recoil energy
  - Separation energy: energy to release 1 nucleon from the shell (~15 MeV)
  - Excitation energy: energy used to excite leftover target nucleus (~1 MeV)
  - Recoil energy: kinetic energy of recoil target nucleus (~2-3 MeV)





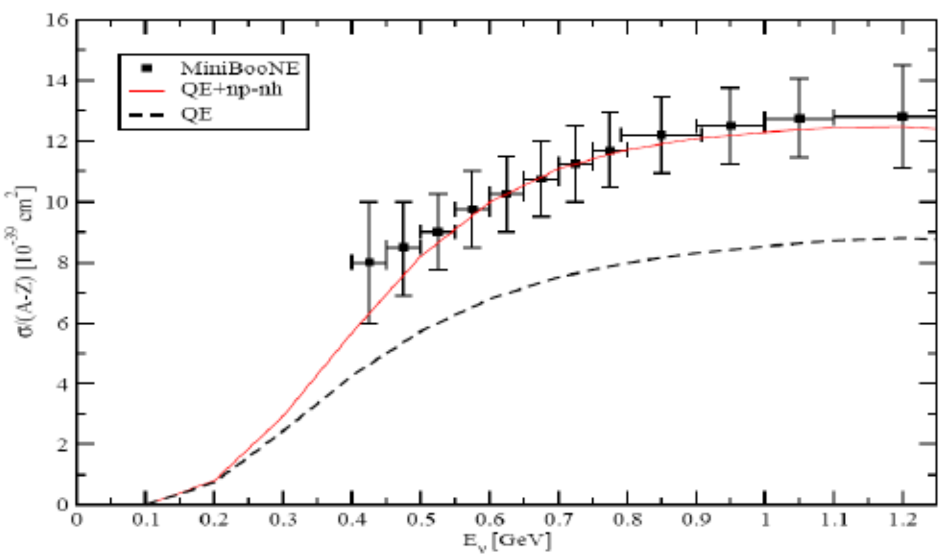
3. Nucleon correlations

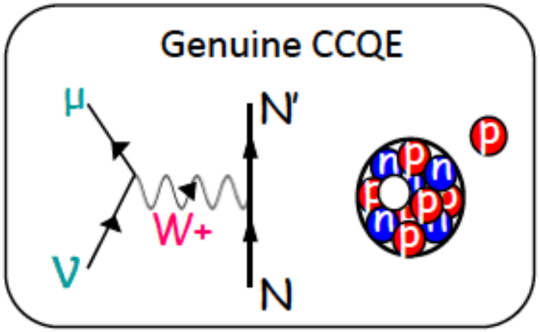
2-particle 2-hole (2p2h) effect

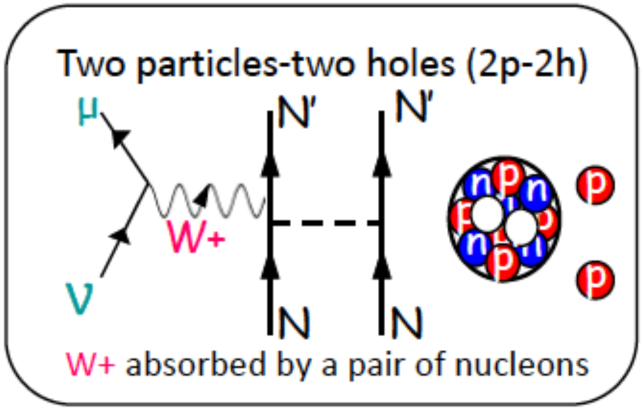
- Mimic CCQE interaction, significant change cross section (both shape and normalization)
- The biggest topic in nuxsec community (T2K, NOvA, MINERvA, MicroBooNE)
- 2p2h models in generators don't describe data well (?)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







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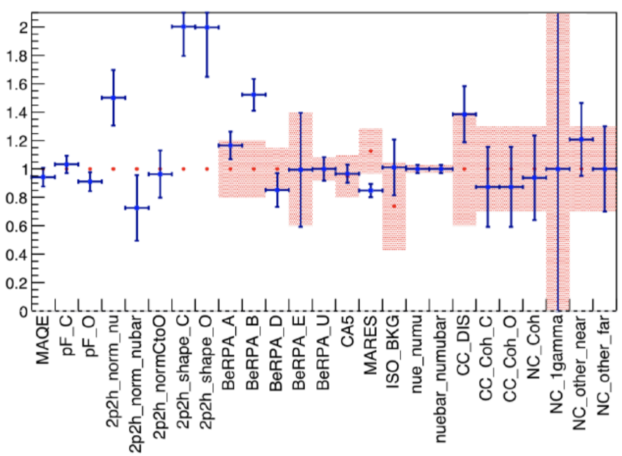
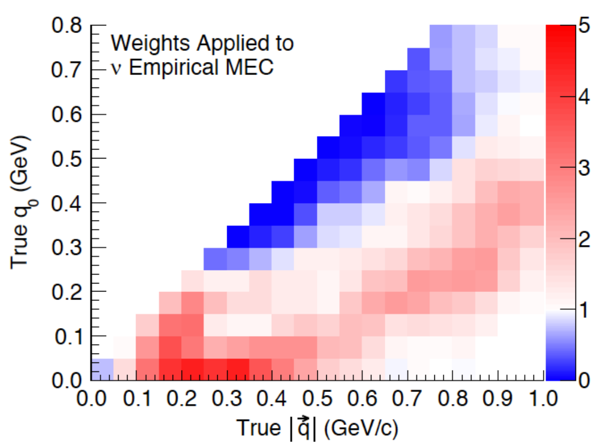
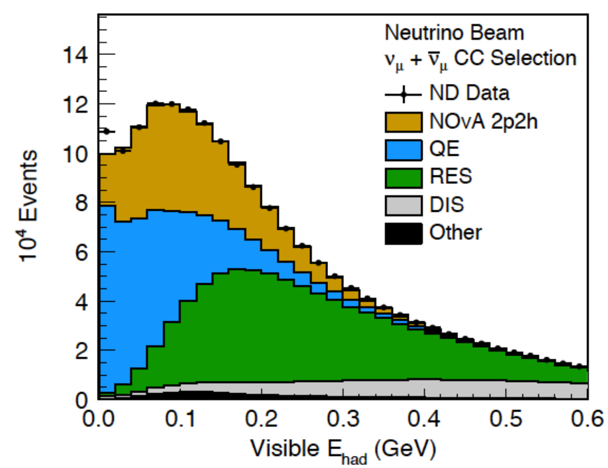
T2K 2p2h model weight



NOvA 2p2h model weight



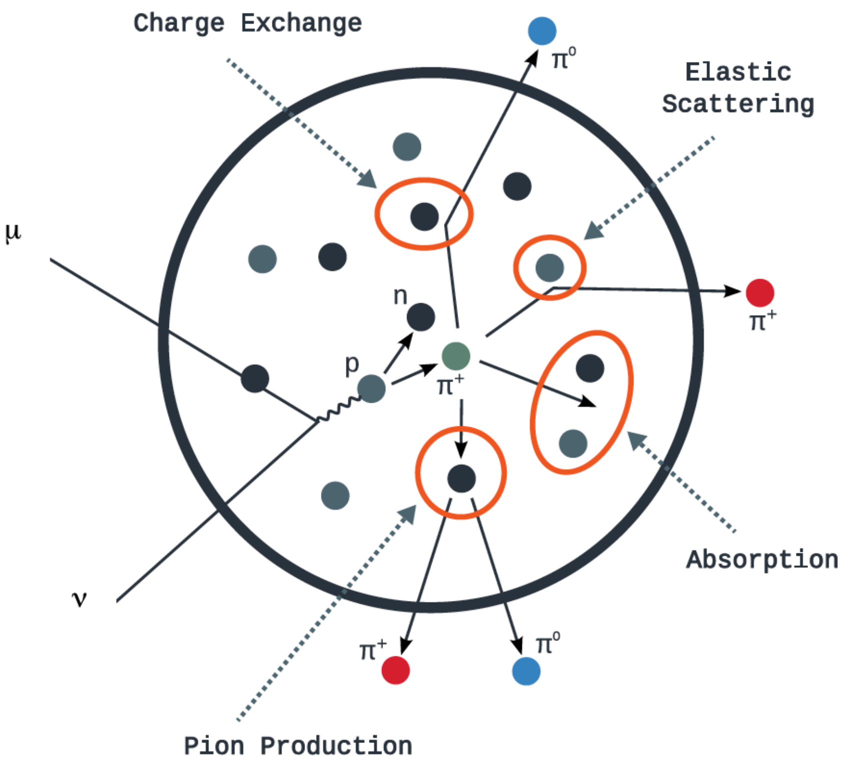
NOvA near detector data-MC comparison after fit

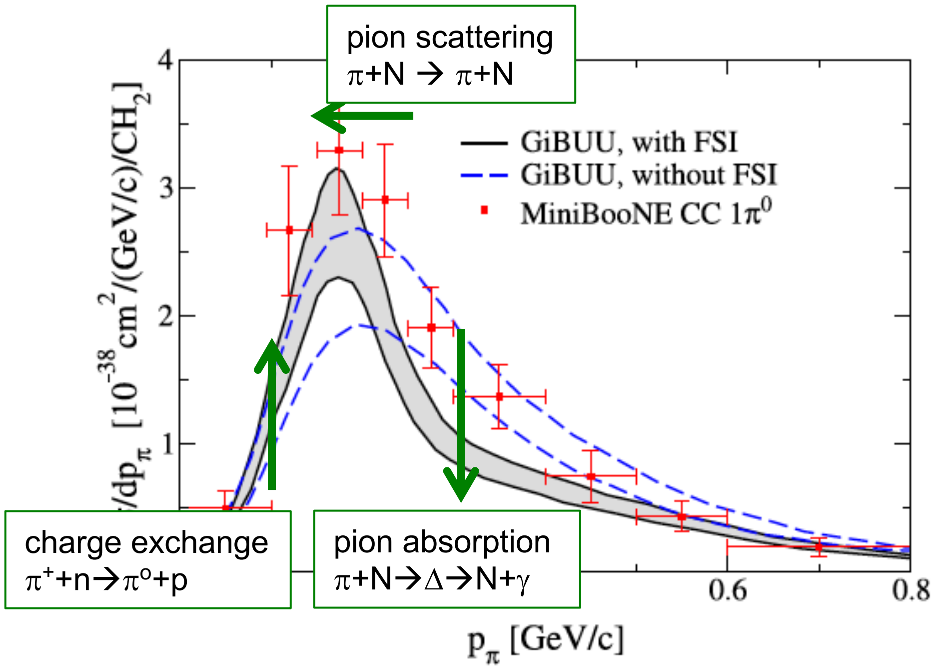


3. Final state interaction

Cascade model

- Elastic scattering: Nucleon elastic scattering, pion elastic scattering
- Inelastic scattering: Nucleon inelastic scattering, pion inelastic scattering
- Charge exchange: Nucleon charge exchange, pion charge exchange
- Absorption: Nucleon absorption, pion absorption





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Teppei Katori
King's College London

Summer lecture series, Nagoya University, Japan, July. 6-10, 2020

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1. Neutrino Interaction Physics

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

3. Higher energy processes

4. Conclusion

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]

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[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

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 neutrino experiments around 1-10 GeV.

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

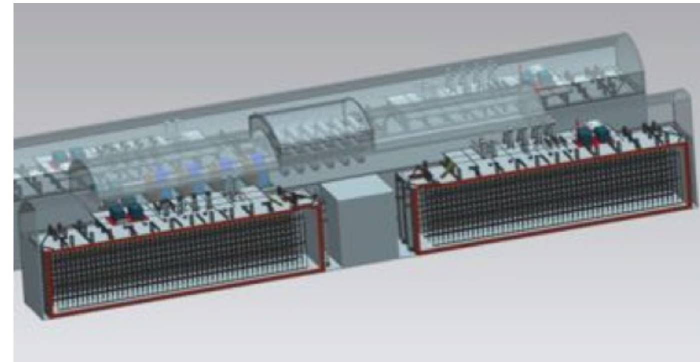
1. Hyper-Kamiokande and DUNE

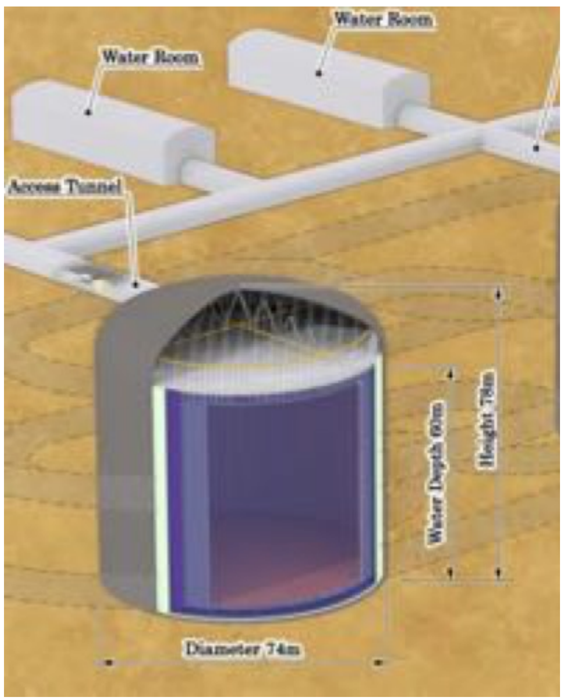
Hyper-Kamiokande

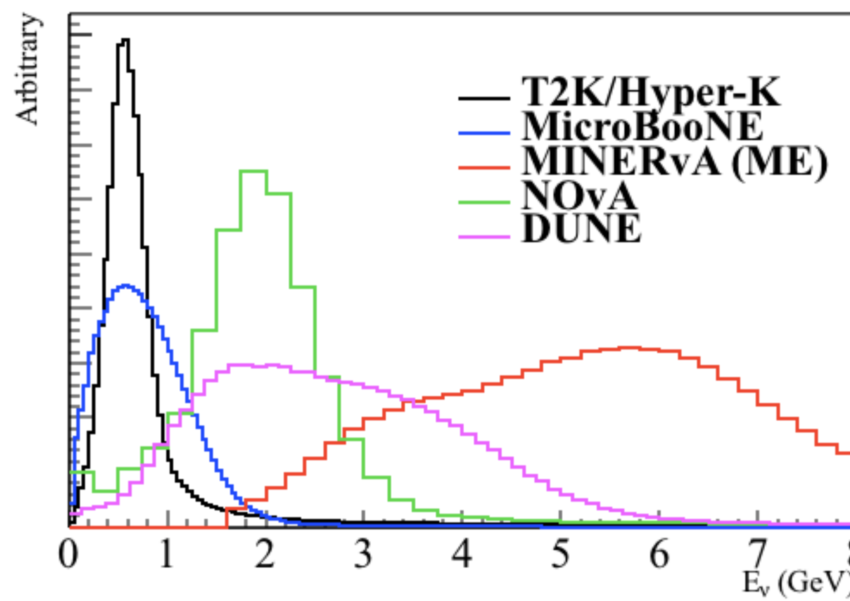
- ~2027+ in Japan
- Water target
- Narrow band 0.6 GeV
- Low spatial resolution
- High time resolution

DUNE

- ~2027+ in USA
- Argon target
- wide band 1-4 GeV
- High spatial resolution
- Low time resolution





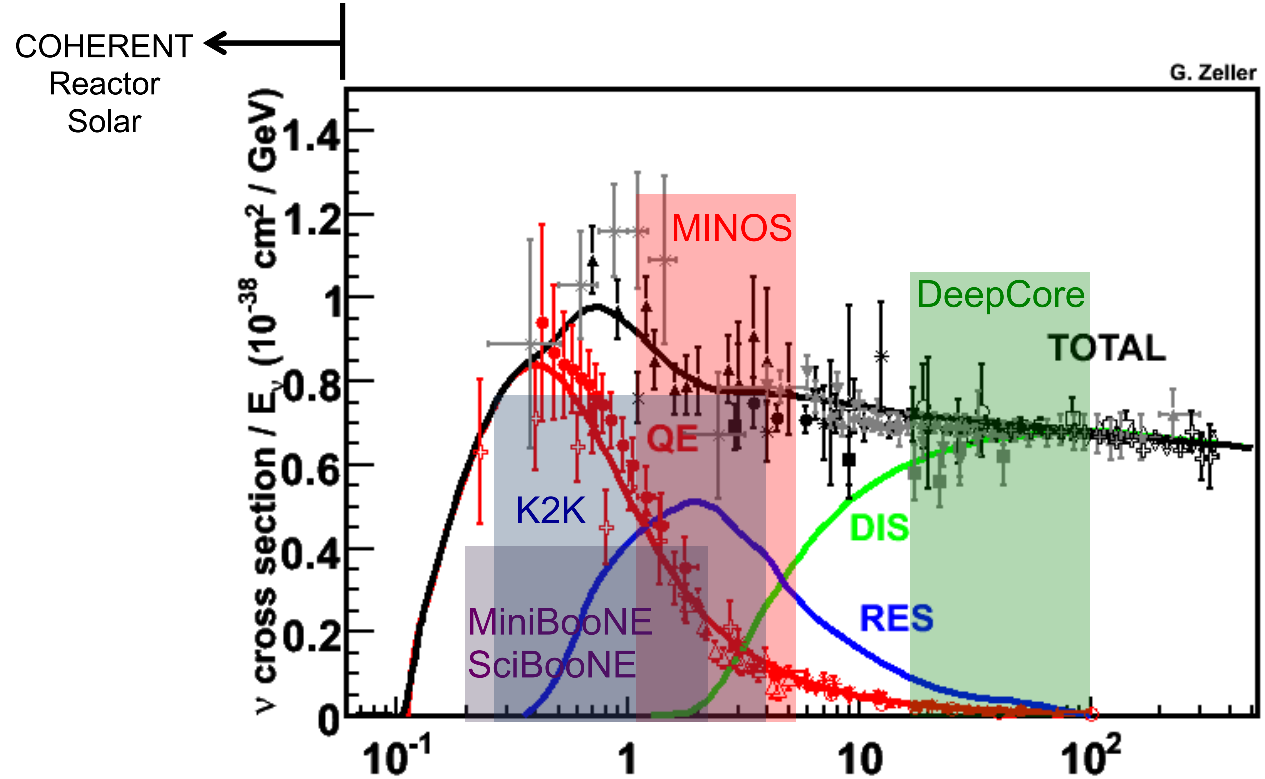


$$P_{\mu \to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 (eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



ν_μCC cross section per nucleon

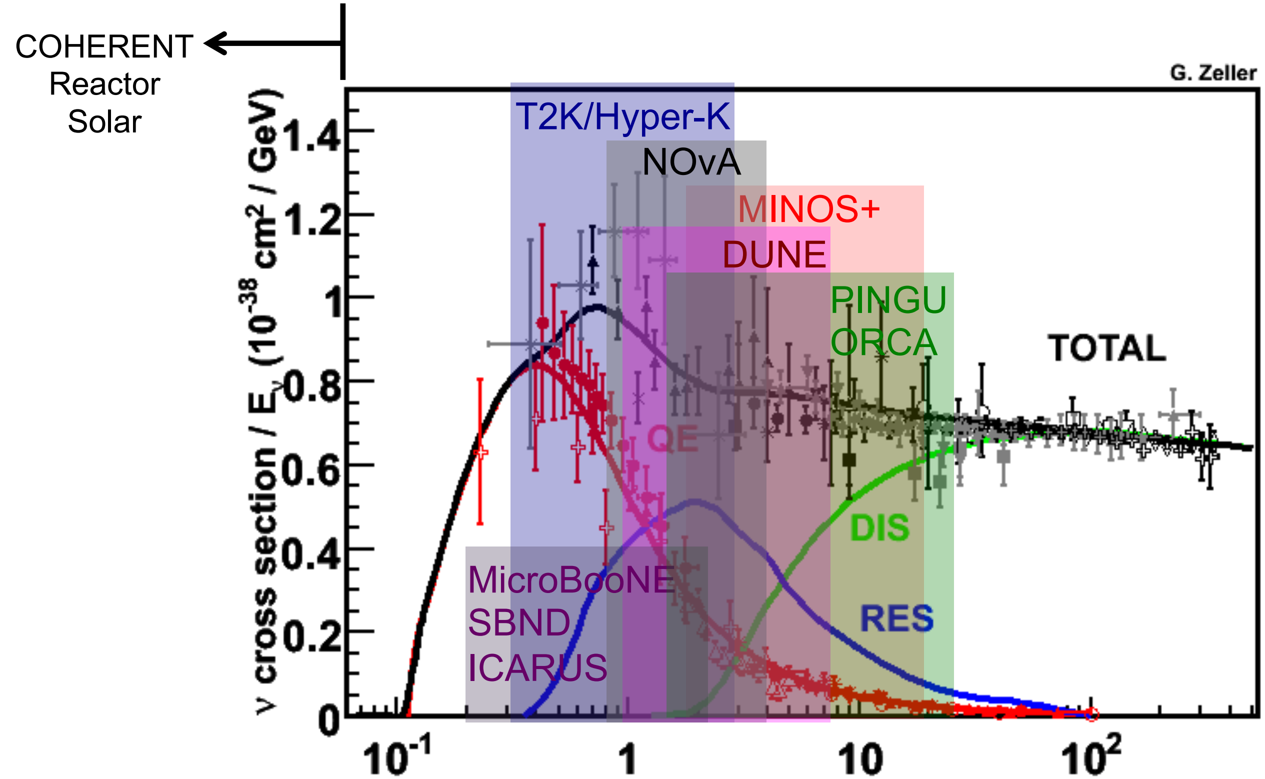
$$P_{\mu\rightarrow e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



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KING'S College LONDON

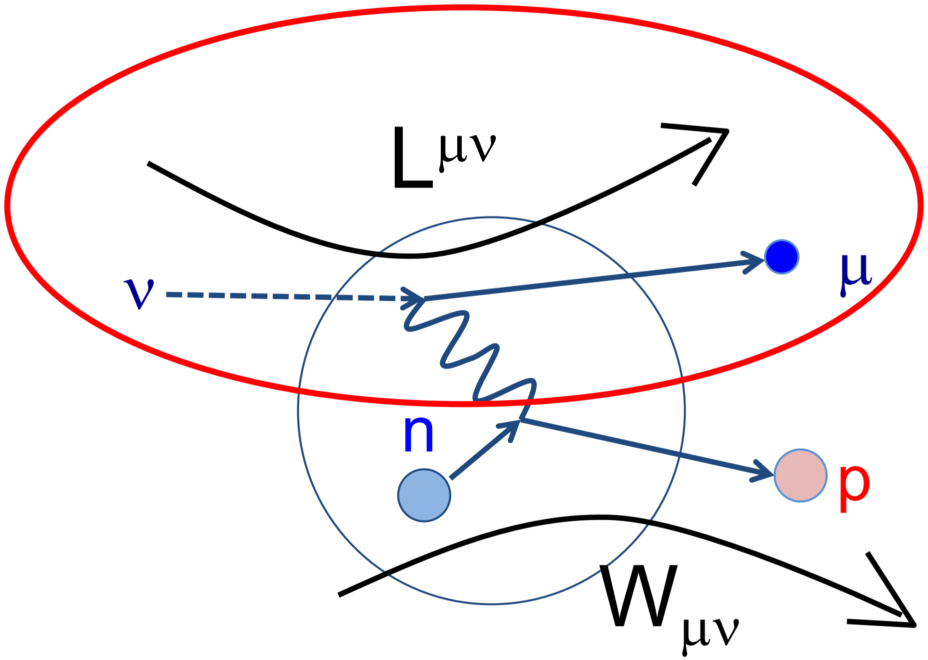
1. Neutrino cross-section formula

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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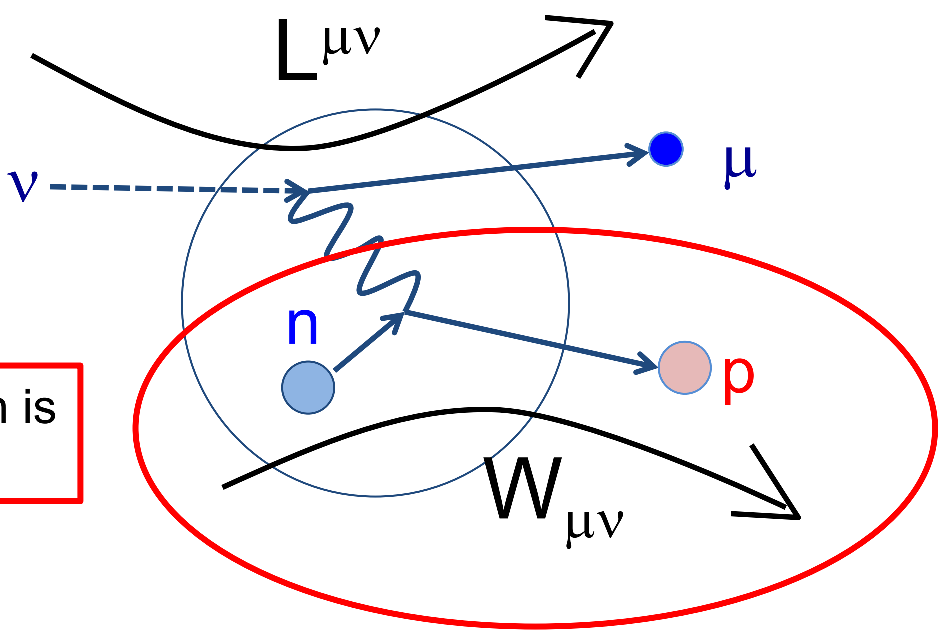


All complication of neutrino cross-section is how to model the hadronic tensor part

TK, Martini, JPhysG45(2017)1

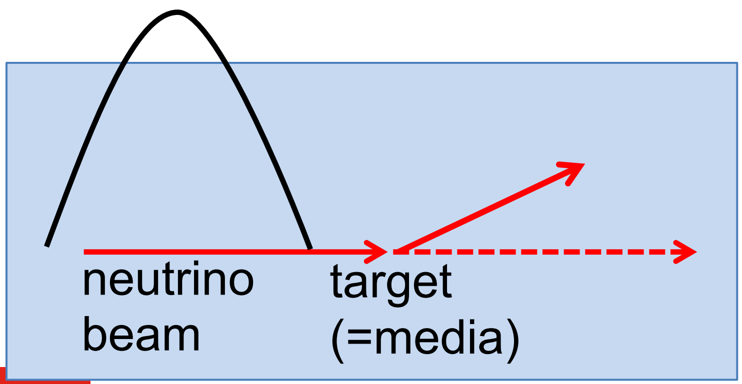
1. Three difficulties of neutrino interaction physics

Three difficulties of neutrino interaction physics

1. Incomplete measurements
2. Incomplete kinematics
3. Nuclear effect

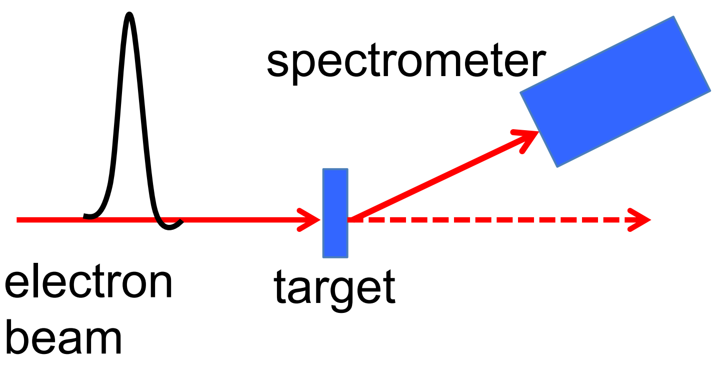
Neutrino scattering

- Coarse instrumentation
- Wide beam or natural flux
- Heavy nuclear target



Electron scattering

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

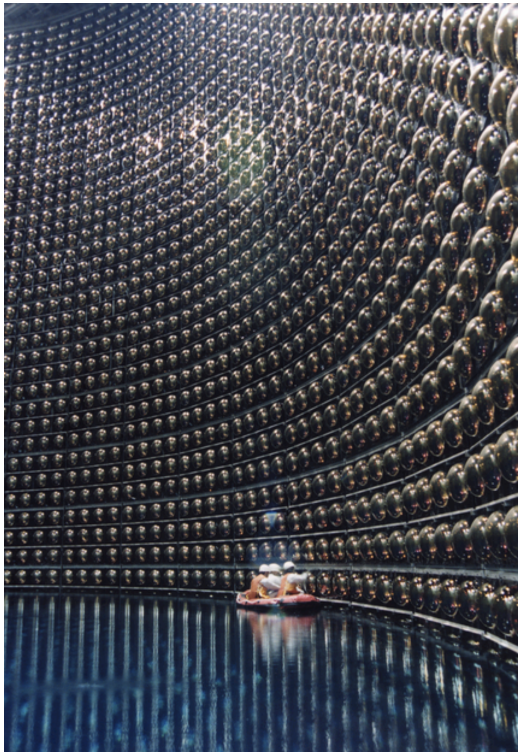


1. Problem 1: Detector performance is poor

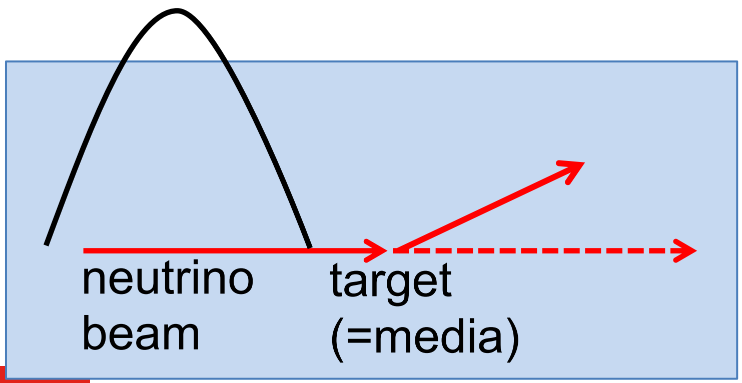
Three difficulties of neutrino interaction physics

1. Incomplete measurements
2. Incomplete kinematics
3. Nuclear effect

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



Neutrino scattering
- Coarse instrumentation
- Wide beam or natural flux
- Heavy nuclear target



TK, Martini, JPhysG45(2017)1

1. Problem 2: Beam energy is unknown

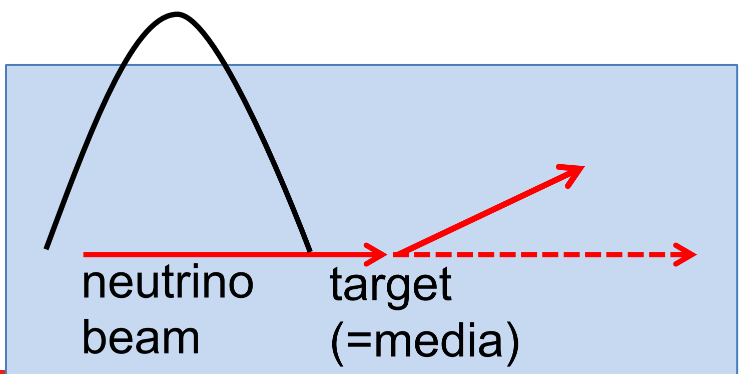
Three difficulties of neutrino interaction physics

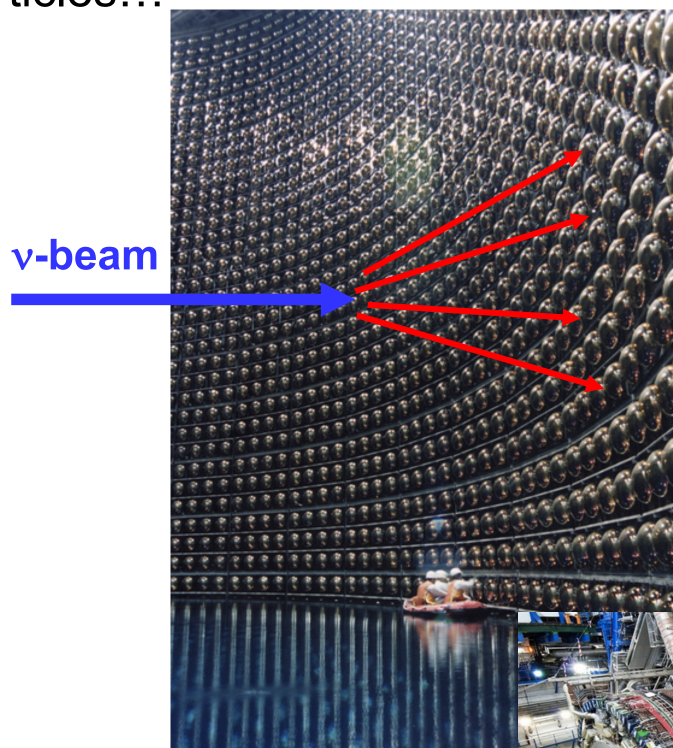
1. Incomplete measurements
2. Incomplete kinematics
3. Nuclear effect

Neutrino energy is reconstructed from measured final state particles, but typical detectors cannot measure all final state particles…

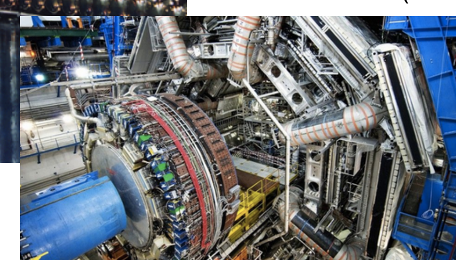
Neutrino scattering

- Coarse instrumentation
- Wide beam or natural flux
- Heavy nuclear target





ATLAS detector (LHC)



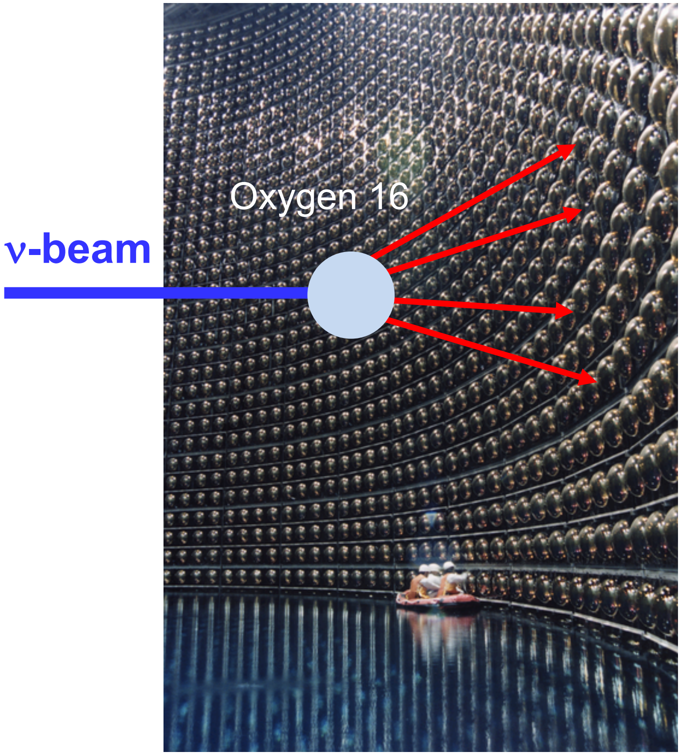
1. Problem 3: Interactions with nuclear targets

Three difficulties of neutrino interaction physics

1. Incomplete measurements
2. Incomplete kinematics
3. Nuclear effect

Neutrino detector materials are heavy nuclei (A>1), and nuclear physics is important.

Neutrino interaction happens everywhere, inside and outside of the fiducial volume of the detector, including unknown material.



1. Neutrino Interaction Physics

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

3. Higher energy processes

4. Conclusion

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

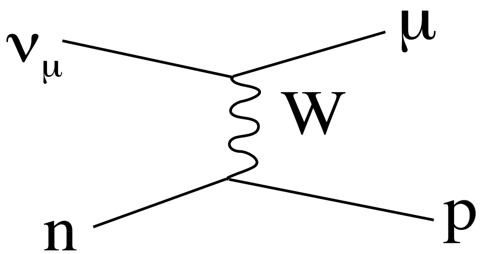
Neutrino–nucleus cross sections for oscillation experiments

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

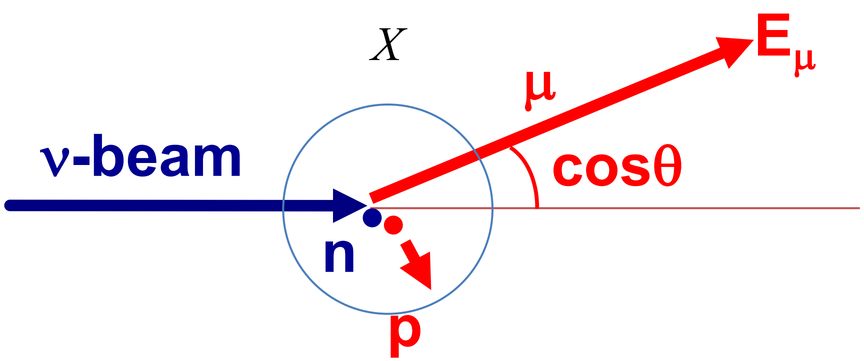
2. Charged Current Quasi-Elastic scattering (CCQE)

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, microBoonE, Hyper-Kamiokande, DUNE…etc

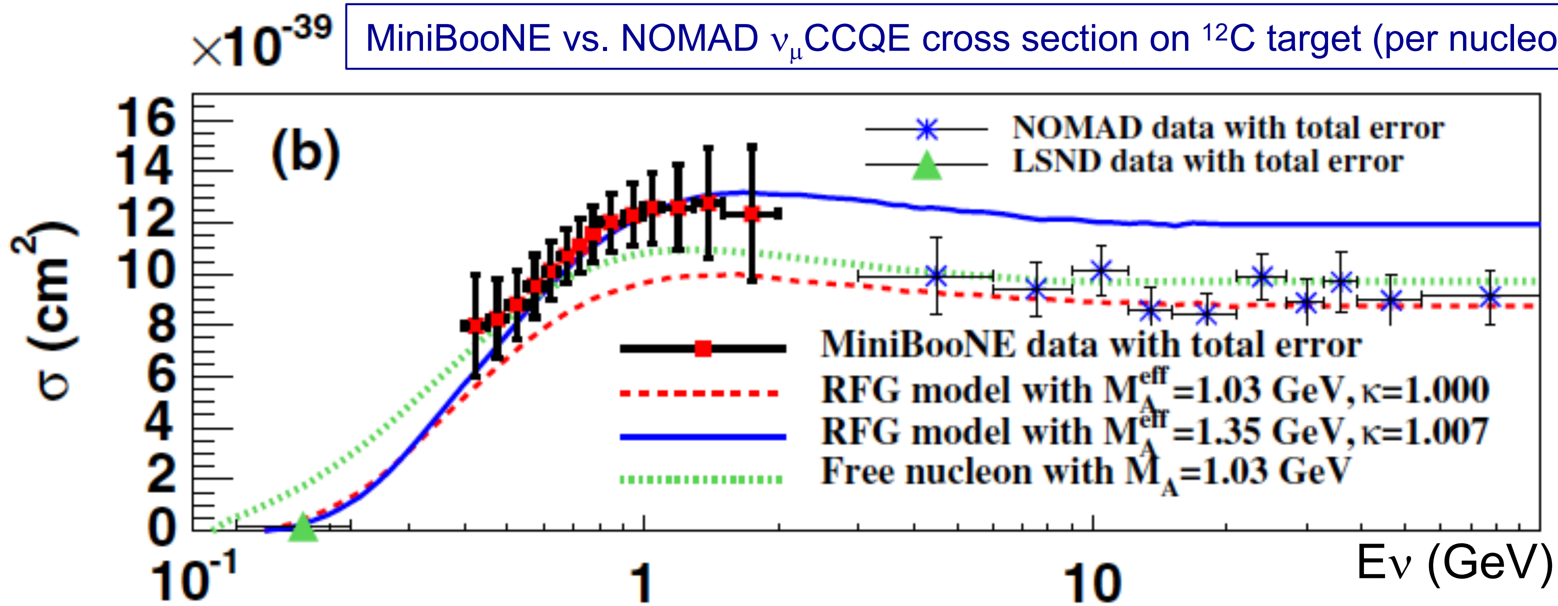
2. Charged Current Quasi-Elastic scattering (CCQE)

CCQE puzzle

1. low Q2 suppression → Low forward efficiency? (detector?)
2. high Q2 enhancement → Axial mass > 1.0 GeV? (physics?)
3. large normalization → Beam simulation is wrong? (flux?)

CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality = precise prediction for neutrino CCQE cross-section...?

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



2. 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…

2. 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

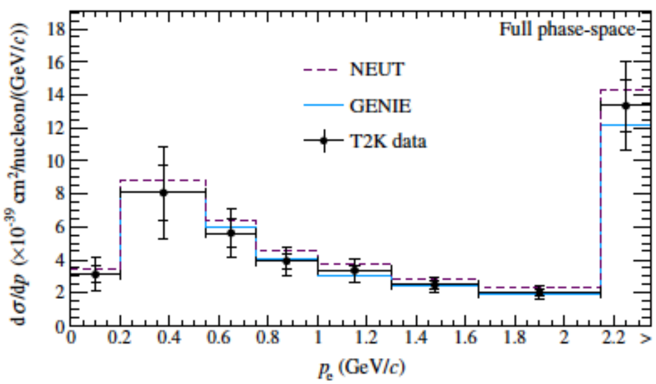
These data play major roles to study/improve neutrino interaction models by theorists

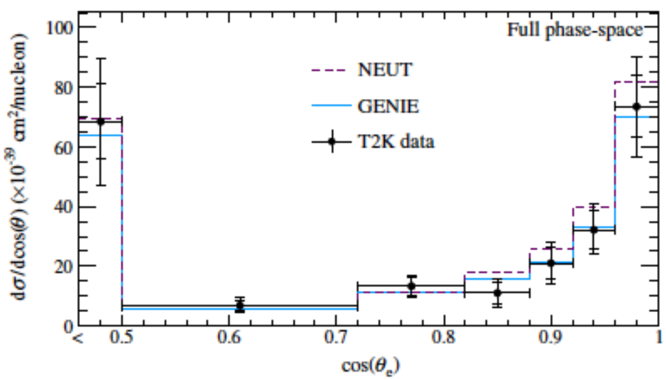
2. Flux-integrated differential cross-section

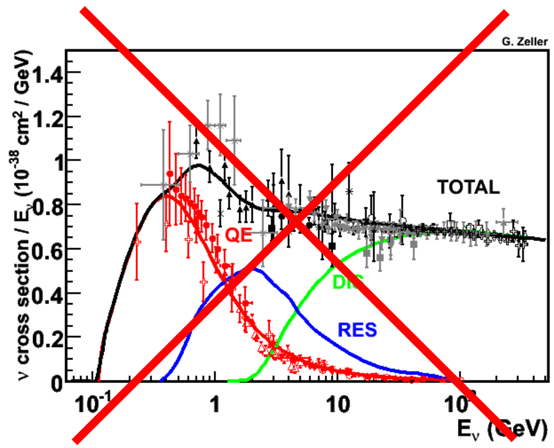
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

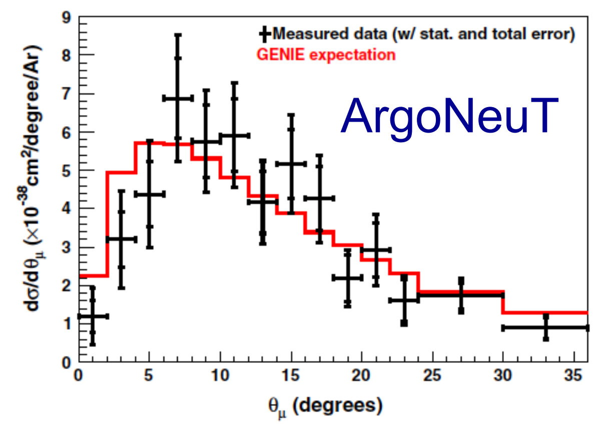
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

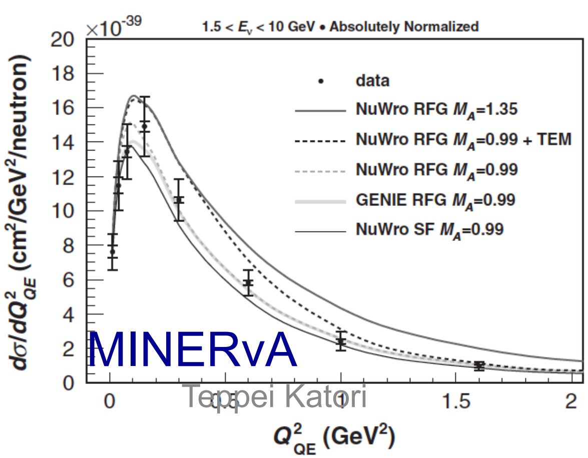
T2K



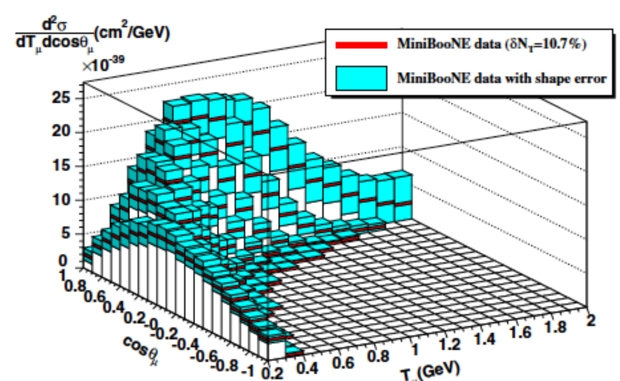








MiniBooNE



2. Flux-integrated differential cross-section

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

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

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

Theorists

Experimentalists

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

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

2. The solution of CCQE puzzle

Presence of 2-body current

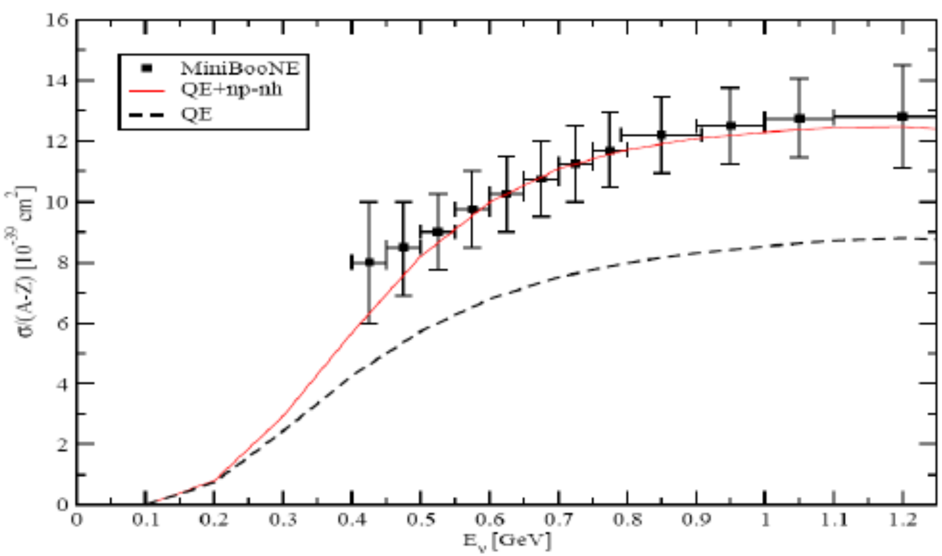
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

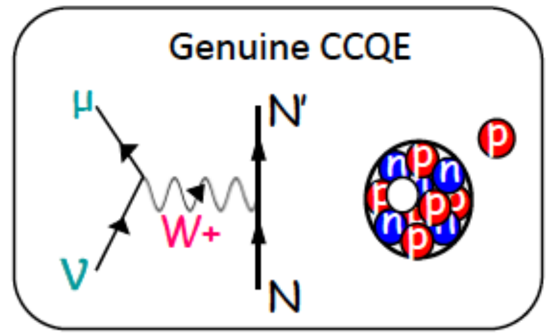
What experimentalists call "CCQE" is not genuine CCQE!

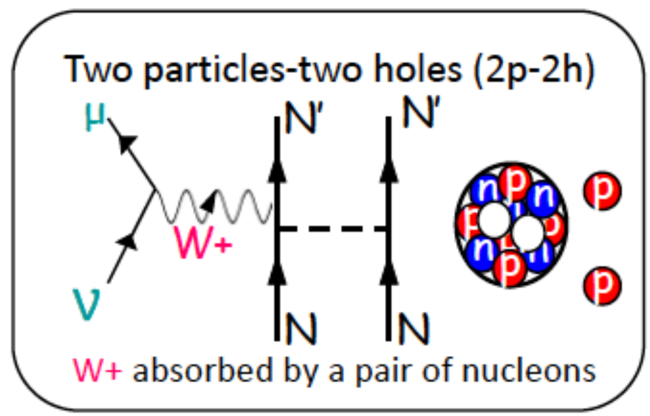
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Martini et al,PRC80(2009)065501
Nieves et al,PLB707(2012)72; NPA627(1997)543

2. The solution of CCQE puzzle

Presence of 2-body current

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Marco Martini (Saclay)

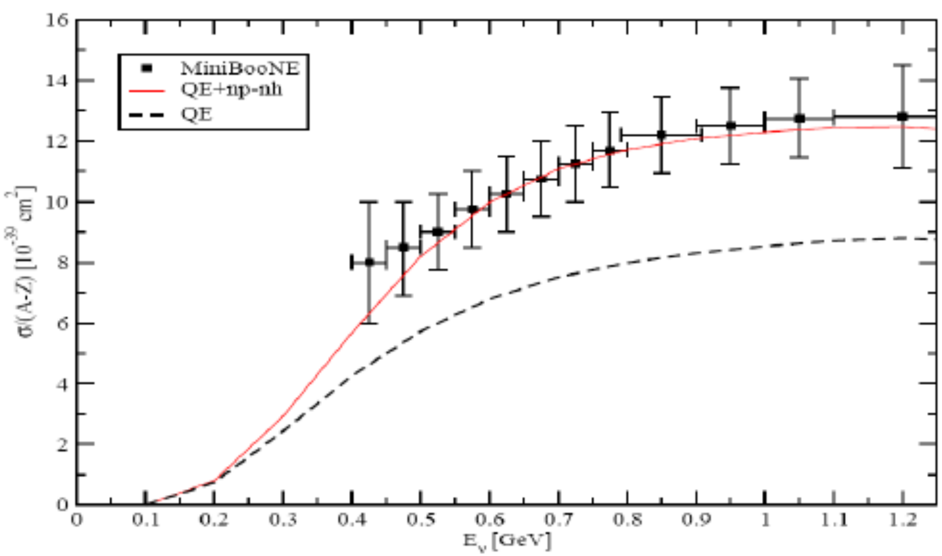
What experimentalists call “CCQE” is not genuine CCQE!

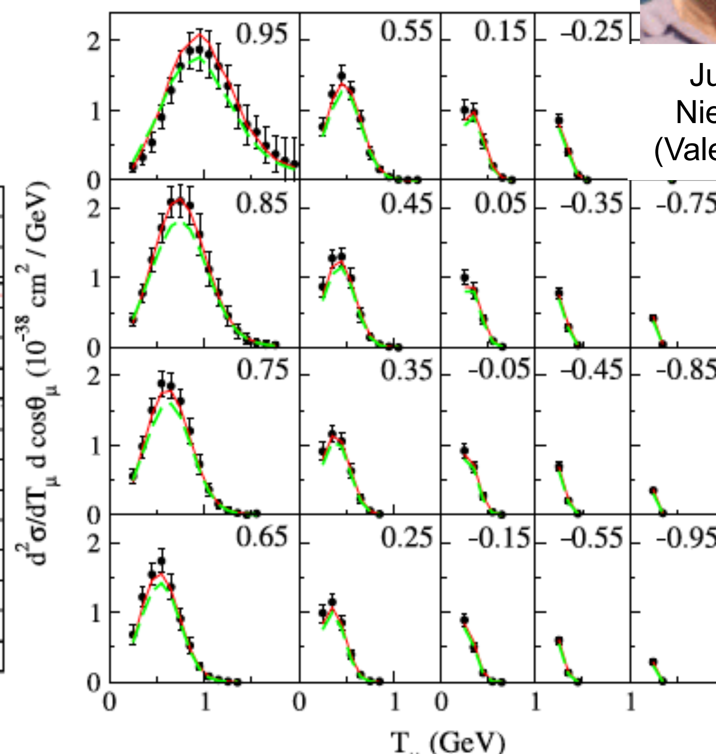
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

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

Juan Nieves (Valencia)





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

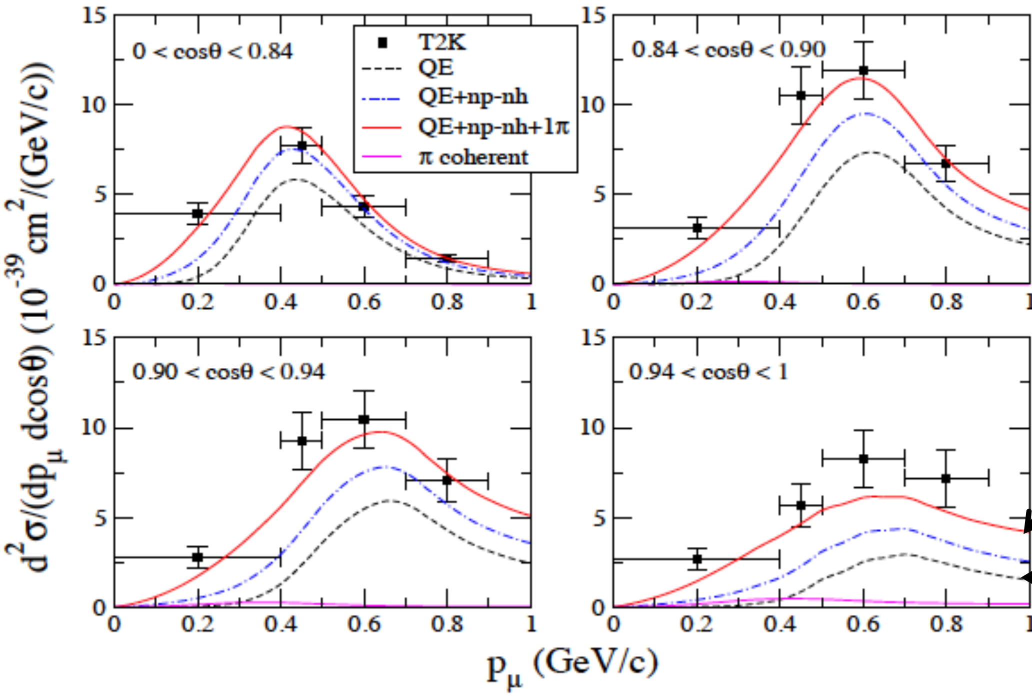
Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72; NPA627(1997)543

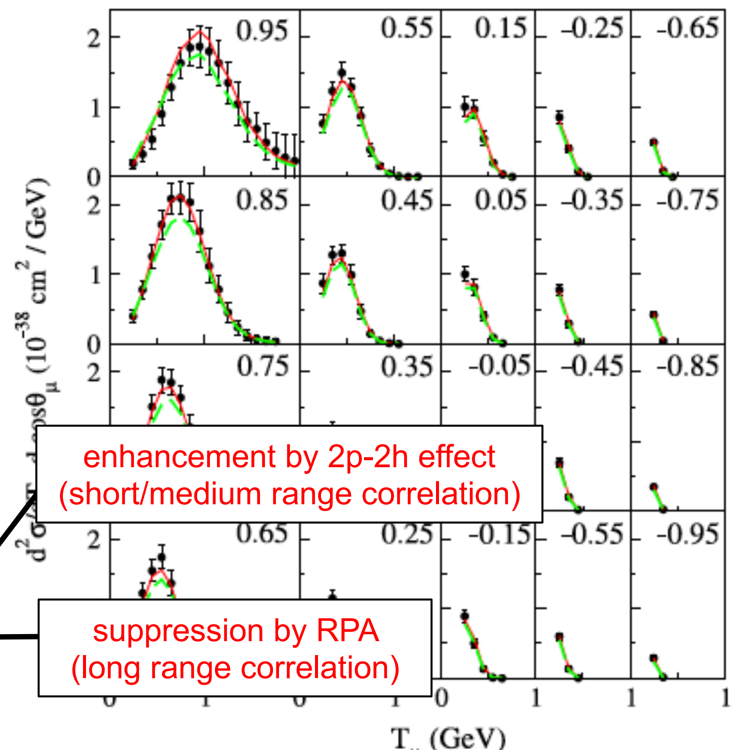
2. The solution of CCQE puzzle

Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

Martini model vs. T2K CC double differential cross-section data





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

suppression by RPA
(long range correlation)

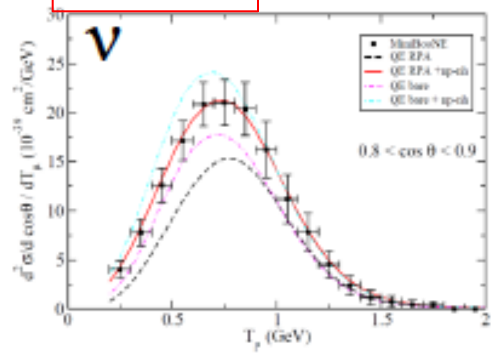
Valencia model vs. MiniBooNE CCQE
double differential cross-section data

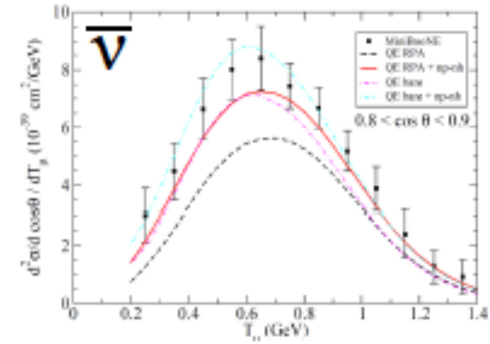
2. CCQE-like data, MiniBooNE (2019)

All groups agree qualitatively with MiniBooNE CCQE-like double differential data.

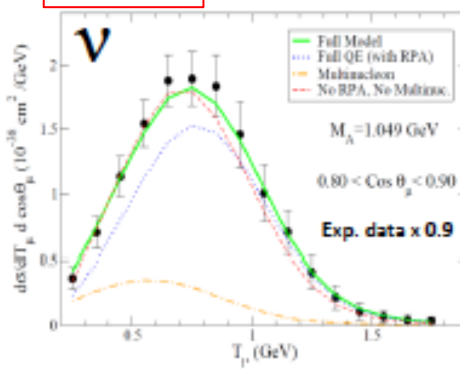
Martini – RPA+2p2h
Nieves – Valencia 2p2h model
SuSA – Superscaling+MEC
Giusti – Relativistic Green's function
Butkevich – RDWIA+MEC

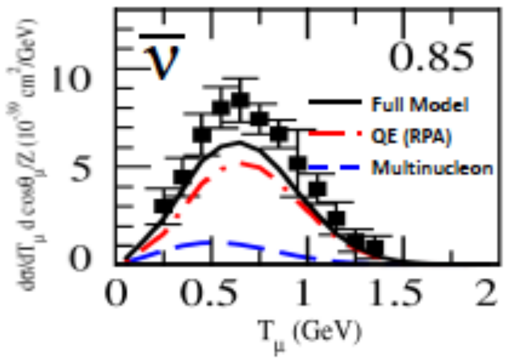
Martini et al



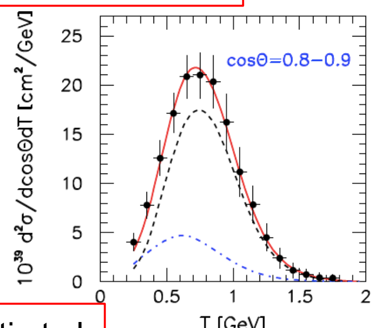


Valencia

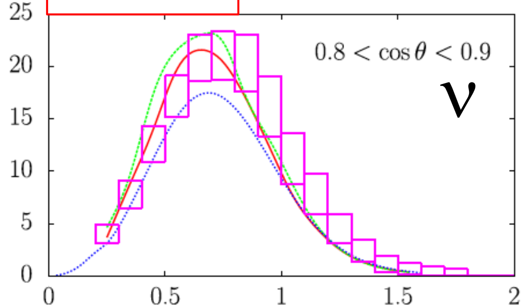




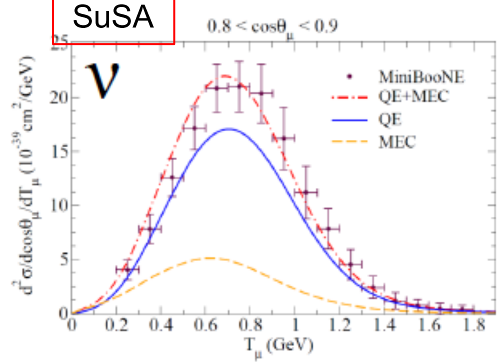
Butkevich et al

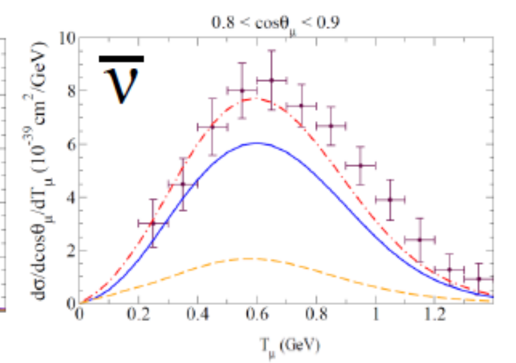


Giusti et al



SuSA





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

2. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato
(Argonne/)

Ab-initio calculation

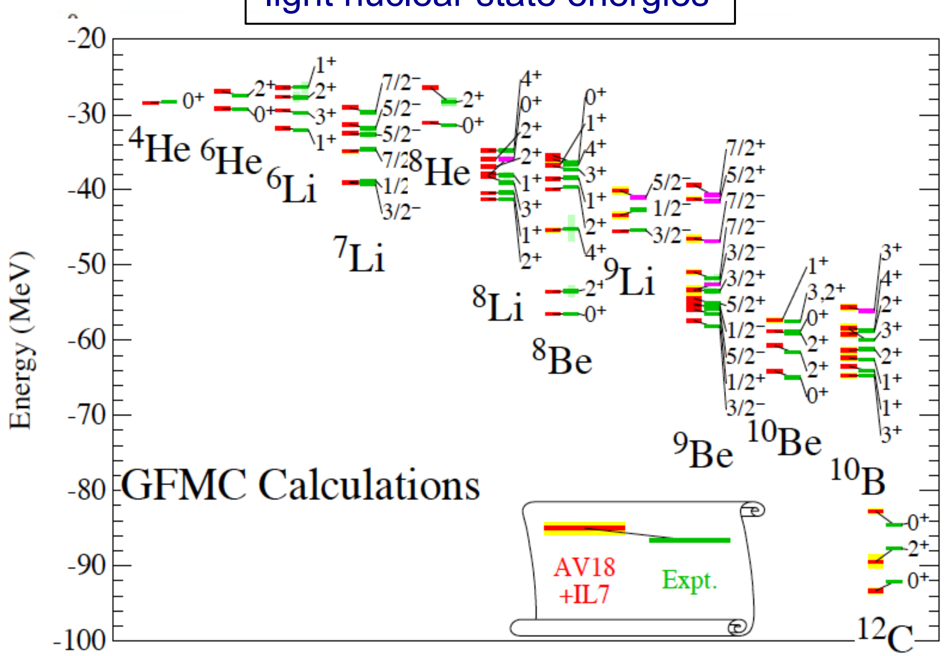
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Correct nucleon correlations are key

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

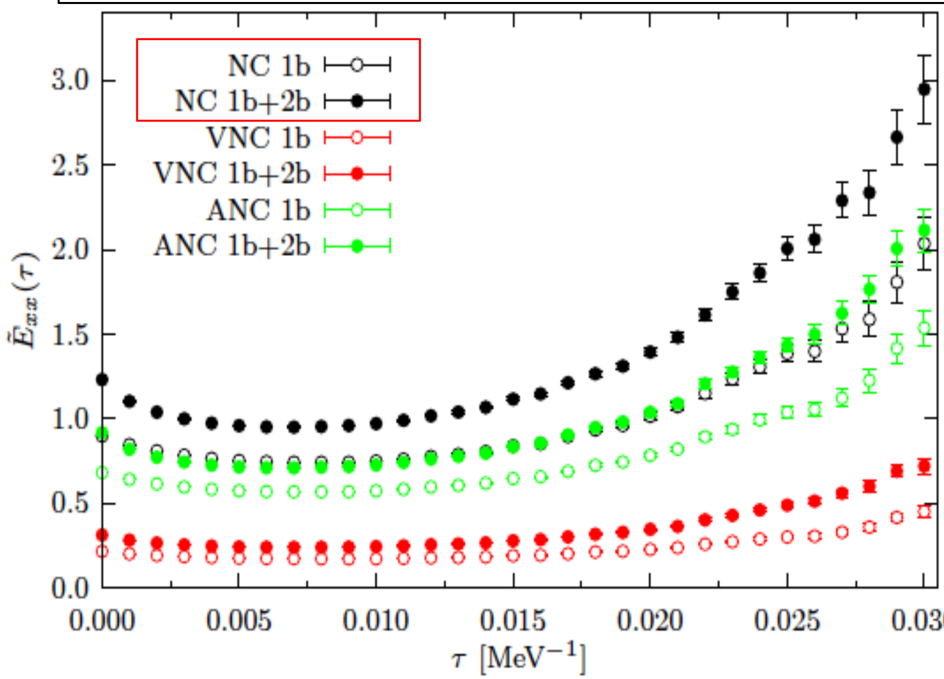
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



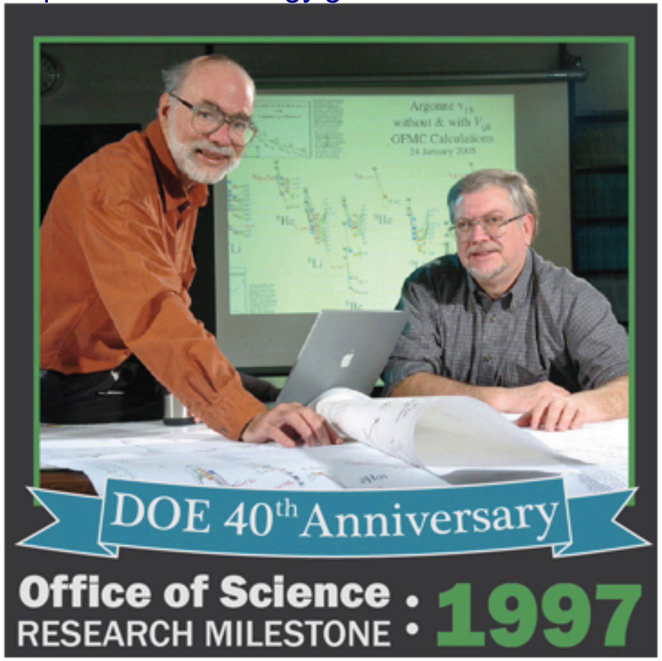
Neutrino NCQE scattering in ^{12}C response function



Pudliner et al., PRC56(1997)1720, Carlson et al, PRC65(2002)024002

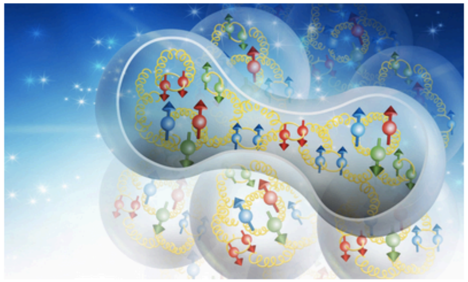
2. Physics of nucleon correlations

https://science.energy.gov/news/doe-science-at-40/



- response function (neutrino oscillation)
- EMC effect (particle physics)
- matrix element (CKM unitarity, $0\nu\beta\beta$)
- form factor (dark matter, COHERENT)
- etc

CORRELATED NUCLEONS MAY SOLVE 35-YEAR-OLD MYSTERY



Short-range correlations among protons ans neutrons in the nucleus may account for the EMC Effect.

Correlated Nucleons May Solve 35-Year-Old Mystery

Guided by data from new high-precision measurements, physicists develop a universal function that suggests that proton-neutron pairs in the nucleus may be responsible for the EMC Effect.

NEWPORT NEWS, VA – A careful re-analysis of data taken at the Department of Energy's Thomas Jefferson National Accelerator Facility has revealed a possible link

supports an explanation for the effect. The study has been

EMC effect and nucleon correlations (CLAS, JLab)

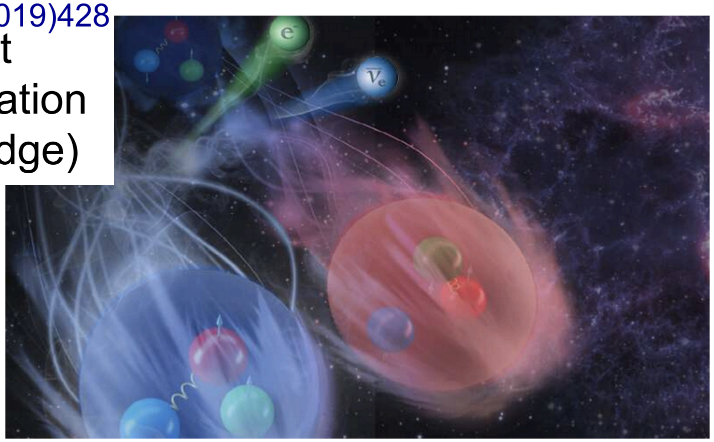
Nature566(2019)354

Physicists solve a beta-decay puzzle with advanced nuclear models

by Oak Ridge National Laboratory

NaturePhysics15(2019)428

Matrix element media modification (Titan, Oak Ridge)

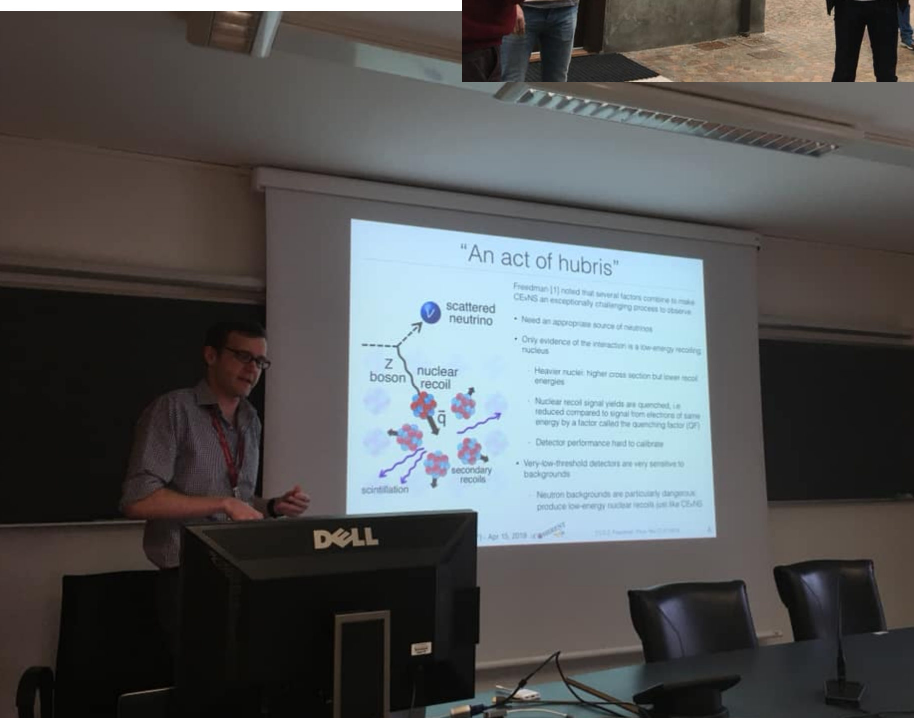


Nuclear structure is a very hot topic in particle physics!

2. Atomic nuclei as laboratories for BSM physics

ECT* workshop, 15 Apr. 15-19 2019, Trento, Italy
http://www.ectstar.eu/node/4436

Topics include;
- Neutrino physics
- EDM
- $0\nu\beta\beta$
- dark matter
- etc



Alfredo's wild B-day party!

Wilkinson et al.,PRD93(2016)072010, T2K, PRD98(2018)032003
MINERvA,PRD99(2019)012004

2. Summary of CCQE for oscillation physics

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

This moment…
New nuclear models available in simulations do not quantitatively describe T2K and MINERvA CCQE μ+p data

large M_A error → large 2p2h error

It is crucial to have correct CCQE, 2p2h, pion production models to understand data simultaneously. Otherwise M_A error stays around 20-30%.

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

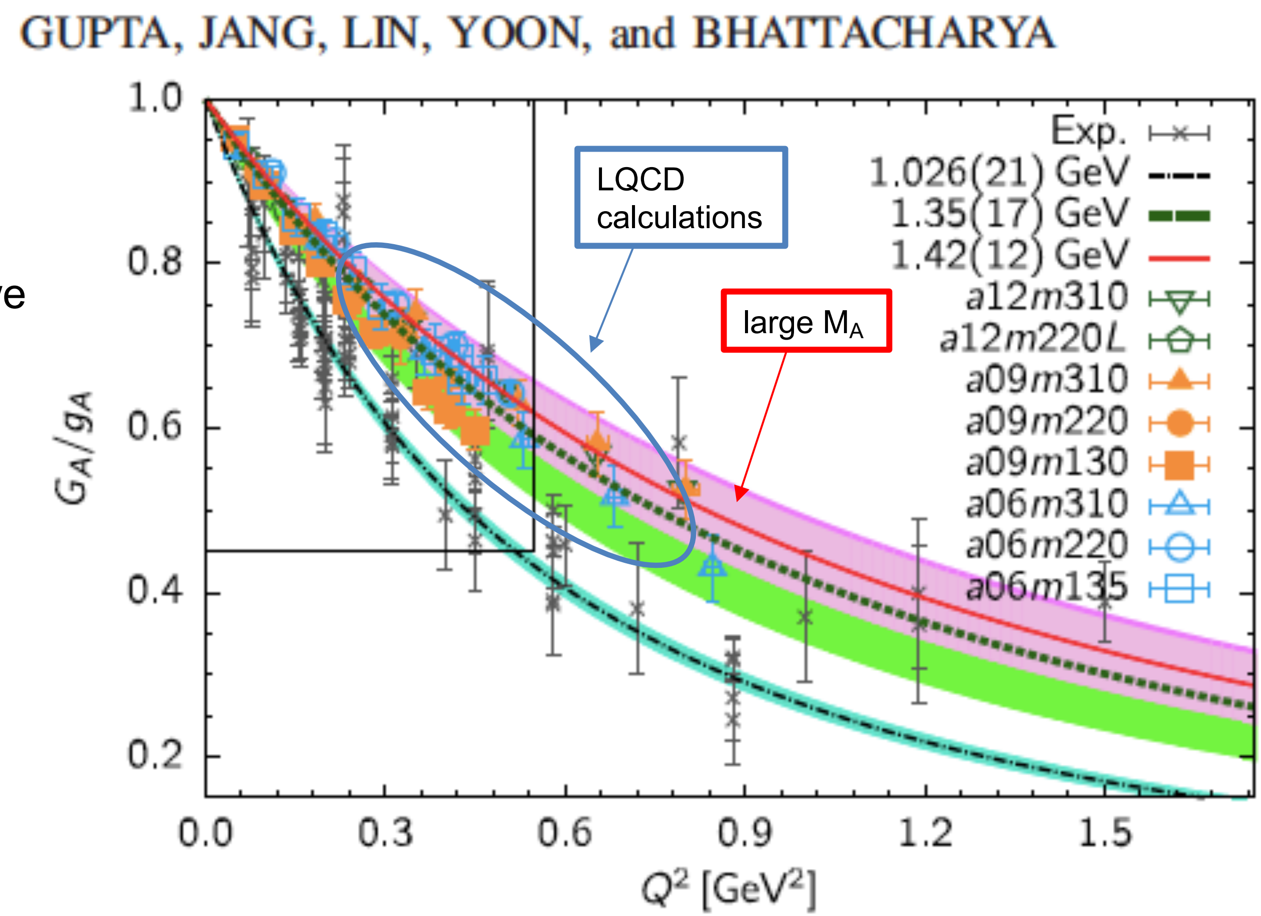
PNDME, PRD96(2017)114503
UCQCD, EPJA55 (2019) 196

2. Summary of CCQE for oscillation physics

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

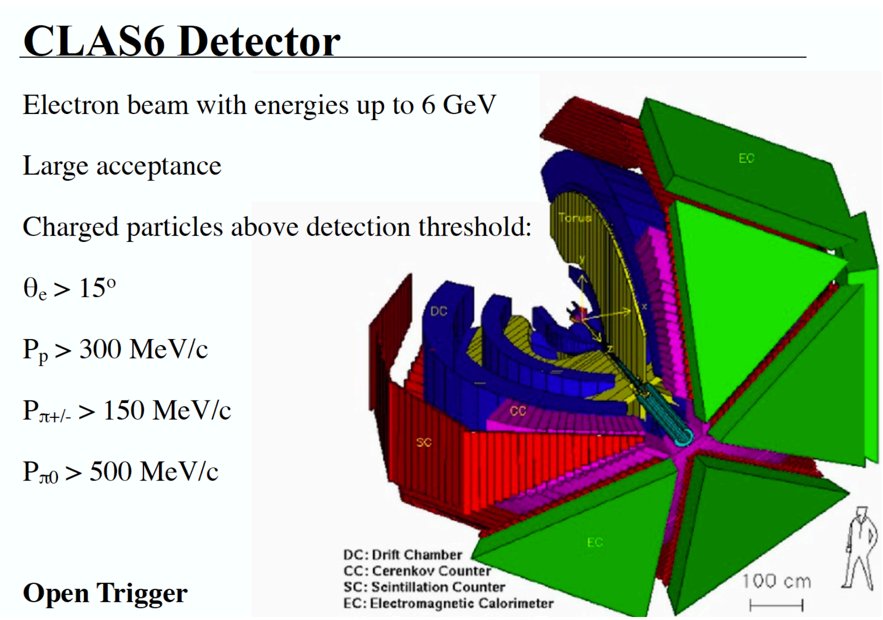
- Lattice QCD prefers large M_A
- If this is true, we don't need nucleon correlations

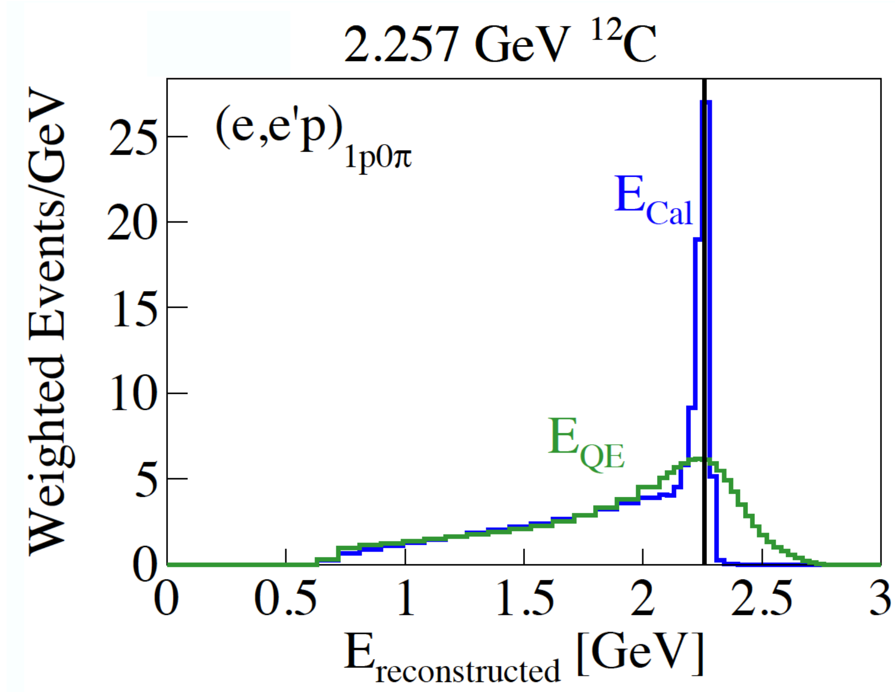
Before we study neutrino-nucleus scattering model, we should fix neutrino-nucleon scattering model!



2. Summary of CCQE for oscillation physics

Electron scattering CLAS)
- Jefferson Lab (USA)
- Complete kinematics
- Energy reconstruction is tested with 2 formula
- QE kinematics: $E\nu^{QE}=(ME\mu-0.5m^2)/(M-E\mu+p\mu\cos\theta\mu)$
- Calorimetric: $E\nu^{cal}=E\mu+Ehad$



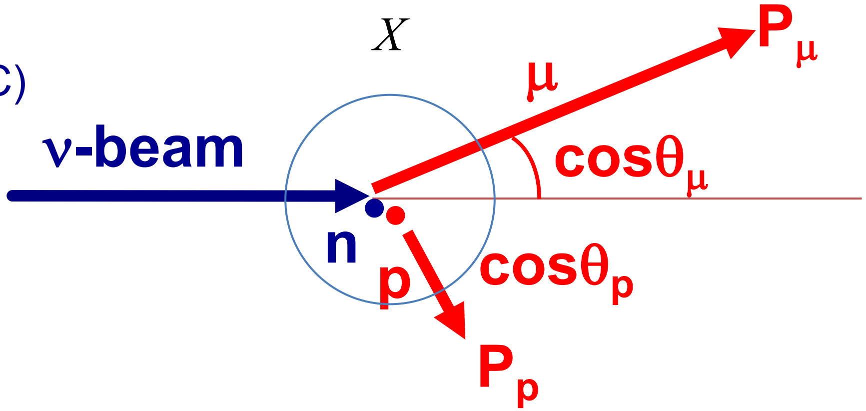


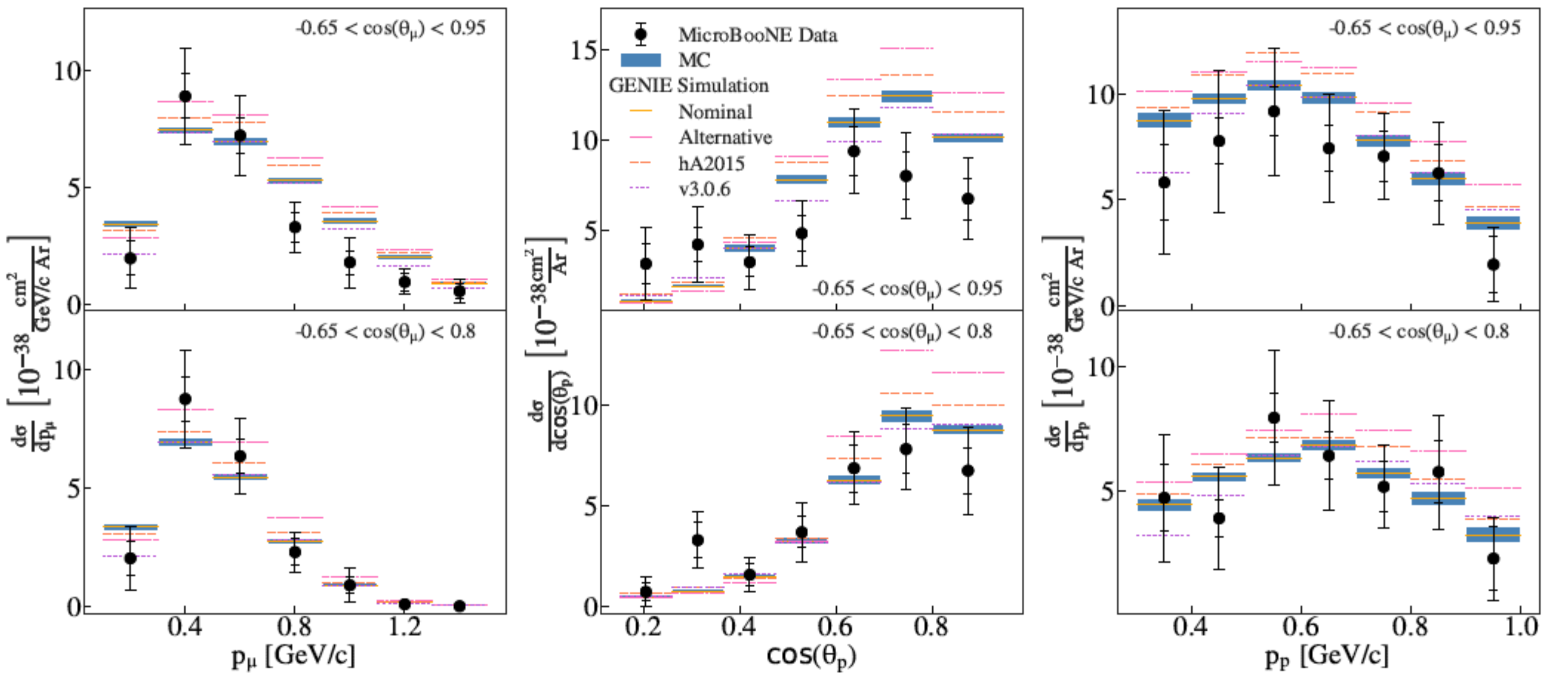
Duffy (MicroBooNE), Neutrino 2020
MicroBooNE, arXiv:2006.00108

2. Summary of CCQE for oscillation physics

Liquid Argon Time Projection Chamber (LArTPC)

- Fermilab (USA)
- Semi-complete kinematics
- Statistics really matter





1. Neutrino Interaction Physics

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

3. Higher energy processes

4. Conclusion

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

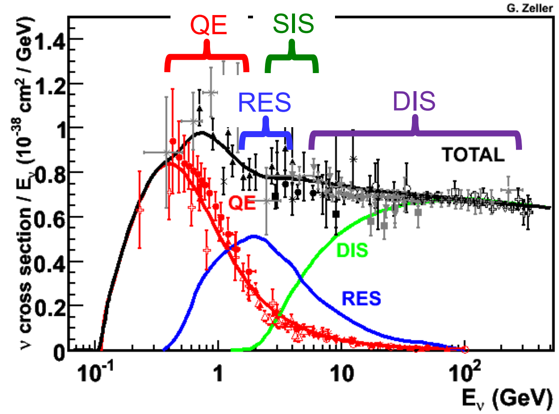
Neutrino–nucleus cross sections for oscillation experiments

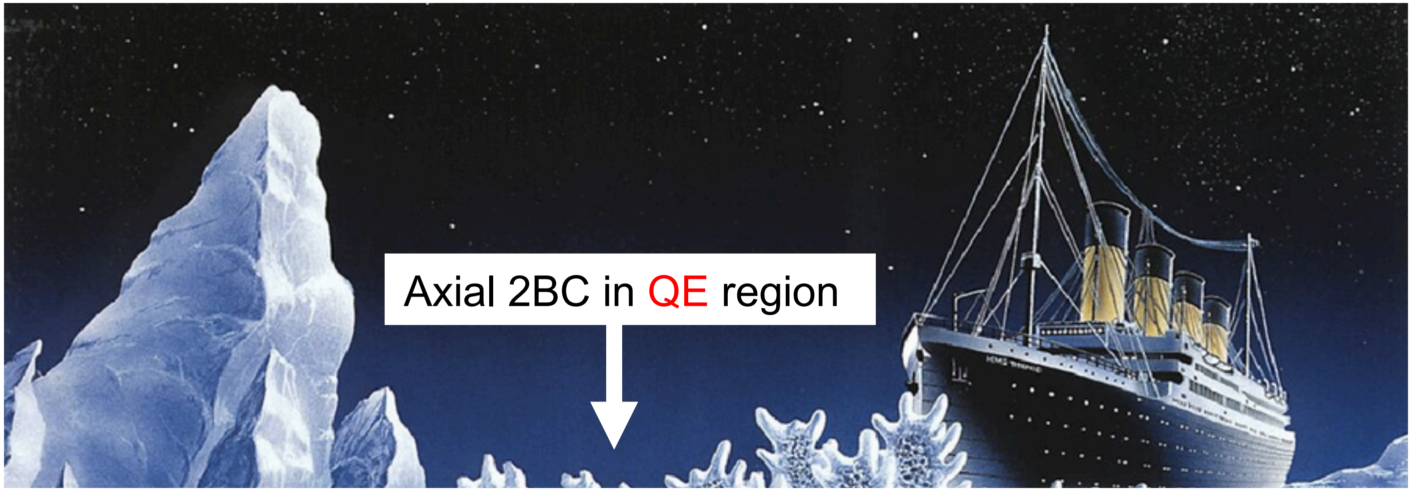
Teppei Katori[1,4,5] and Marco Martini[2,3,4,5]

[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

3. Beyond QE peak

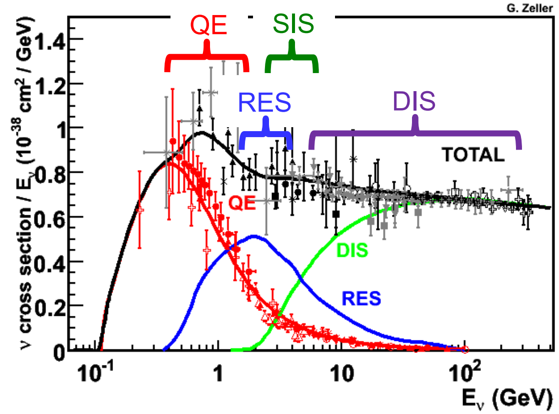
Axial 2-body current in QE region may be a tip of the iceberg…

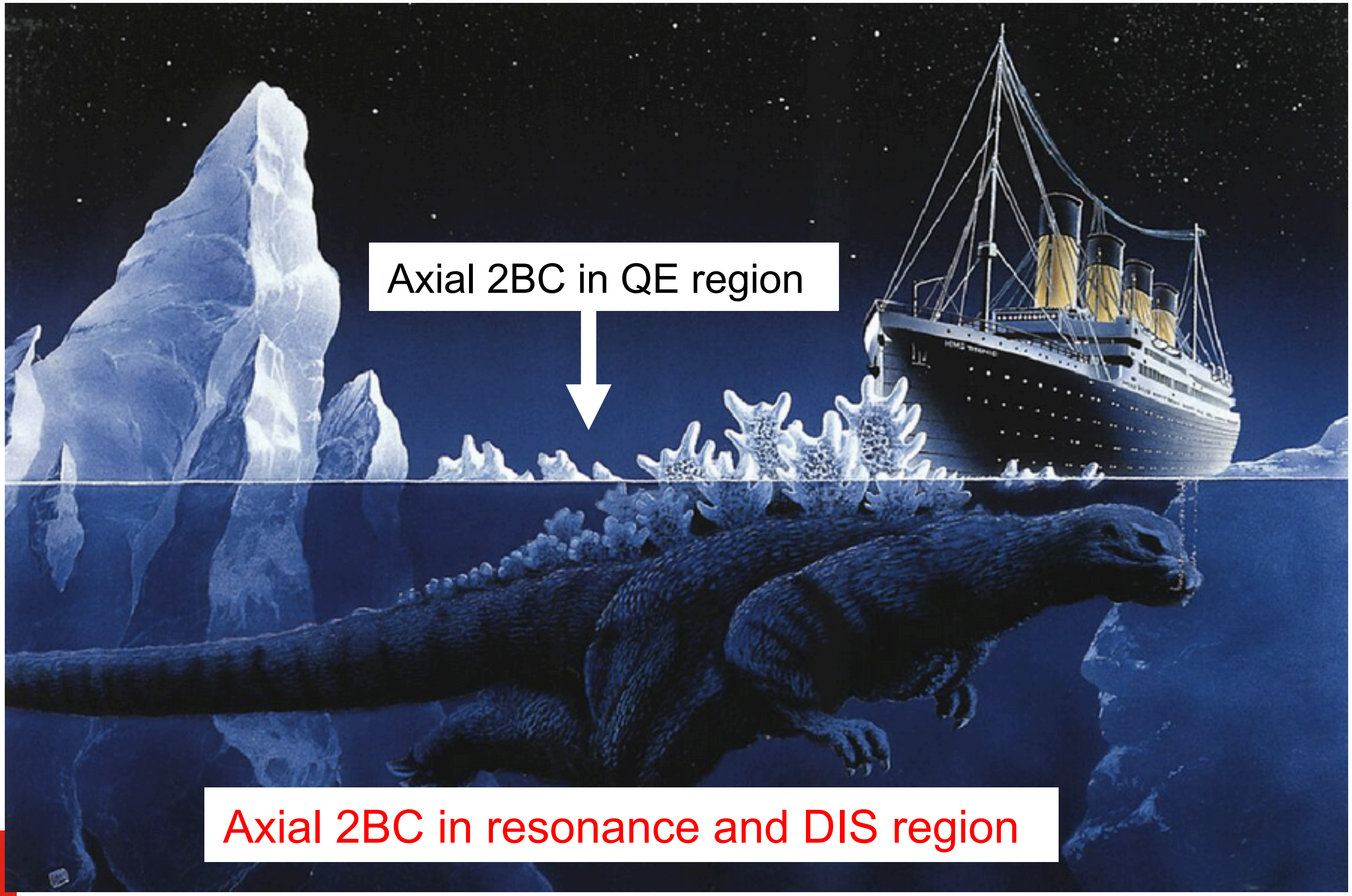




3. Beyond QE peak

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

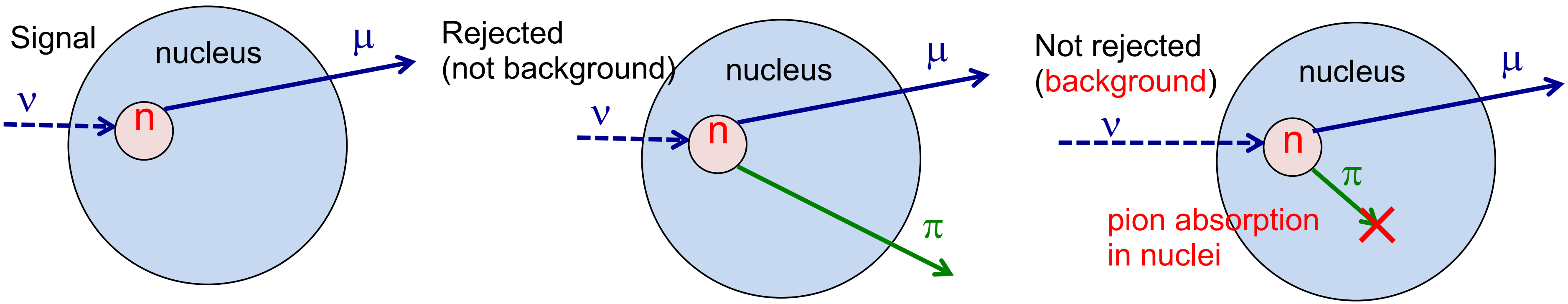




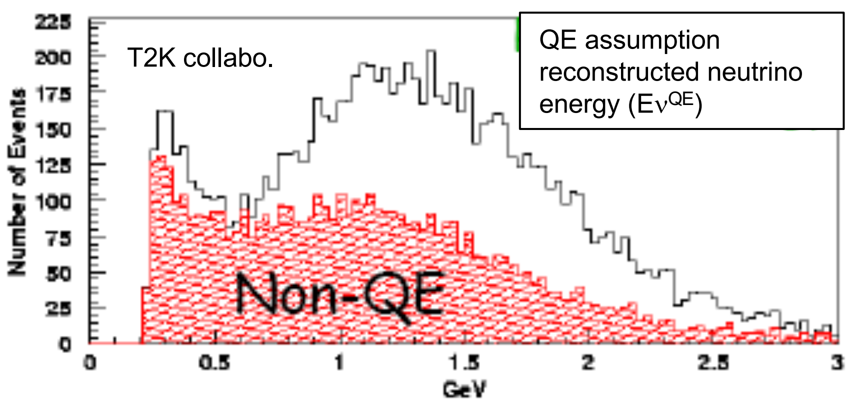
3. Neutrino-induced single pion production

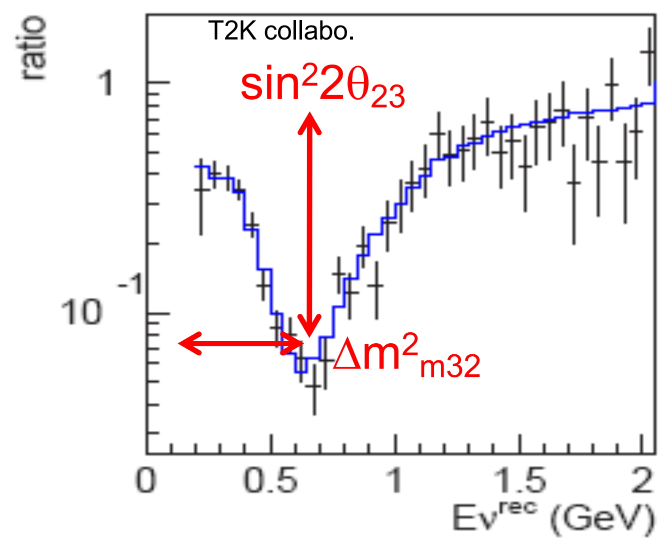
Baryon resonant pion production + final state interaction (FSI)

- Neutrino induced pion productions have large errors
- Final state interaction of hadrons have large errors



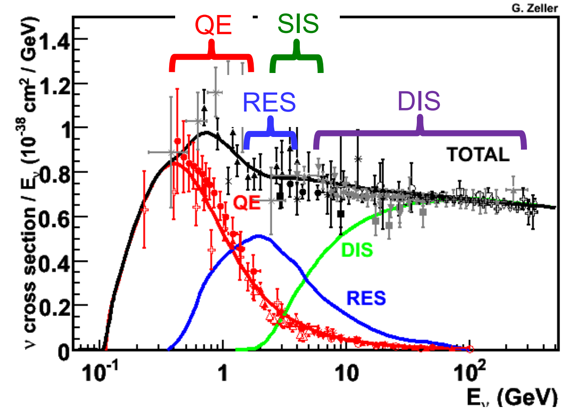
muon neutrino disappearance simulation





MINERvA, PRD100(2019)072005

3. Pion puzzle (2019)



MINERvA try to fit 4 different data set to tune MC…, and it is very hard

Strong tensions between data set
- Both cross section models and FSI models are important
- MC doesn't have enough freedom to fit all (or models may be wrong)

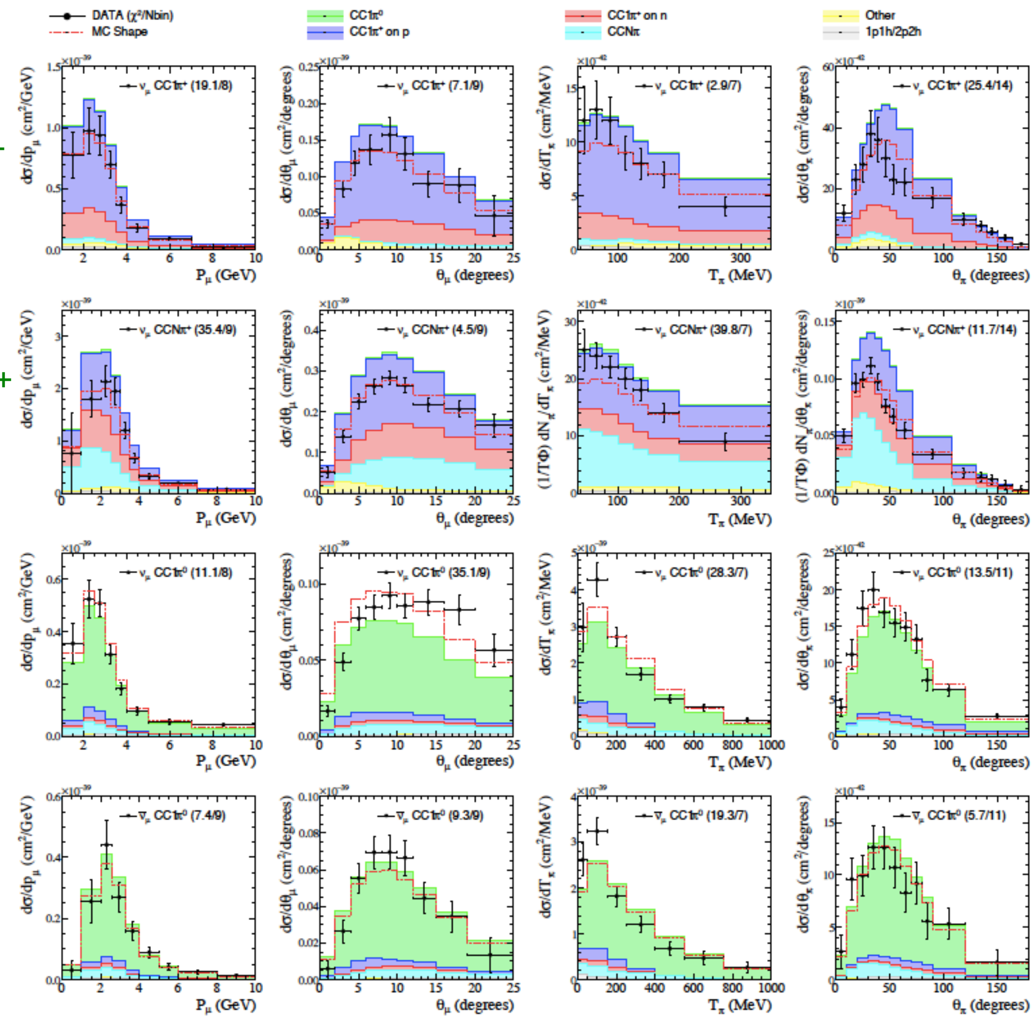
Few GeV neutrino experiments don't have good hadron final state predictions (cf. CCQE).

$\nu_\mu CC1\pi^+$

$\nu_\mu CCN\pi^+$

$\nu CC1\pi^o$

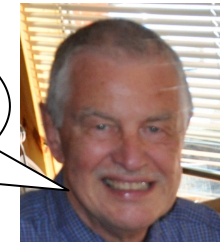
$\bar{\nu} CC1\pi^o$



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

3. Pion puzzle (2019)

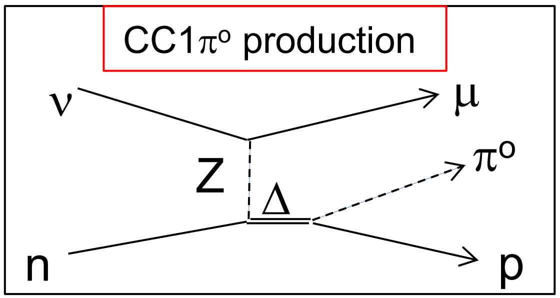
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

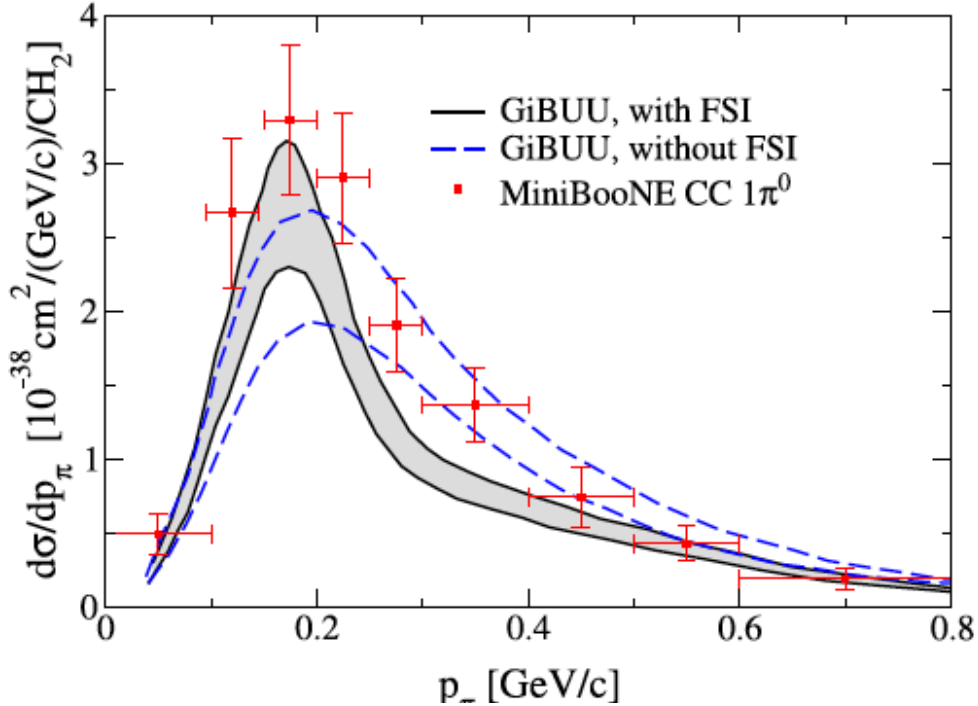


Ulrich Mosel (Giessen)

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

MiniBooNE,PRD83(2011)052009
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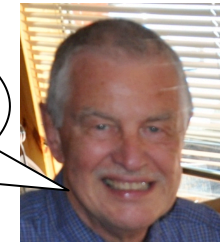

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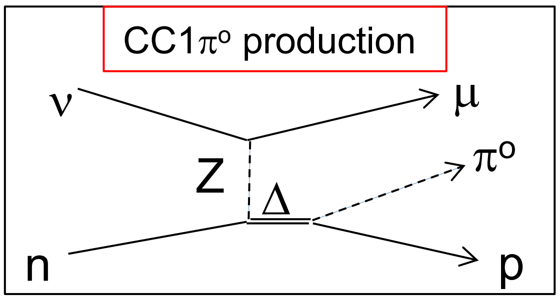

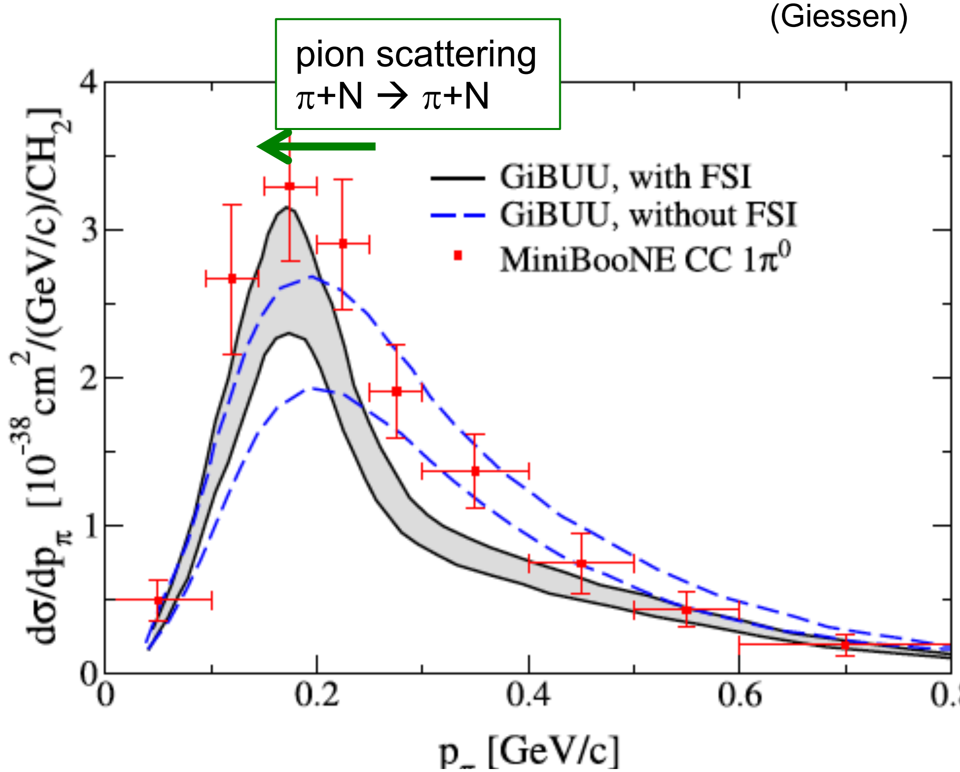

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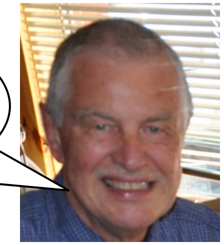

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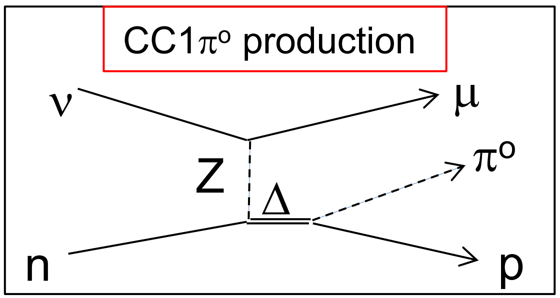

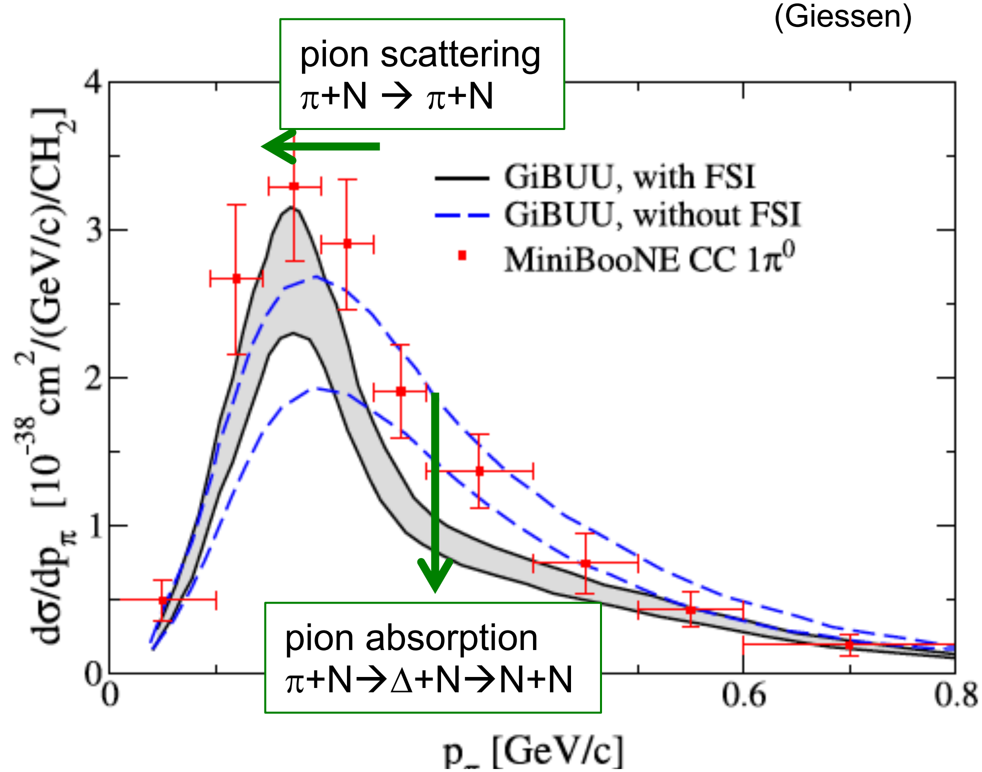

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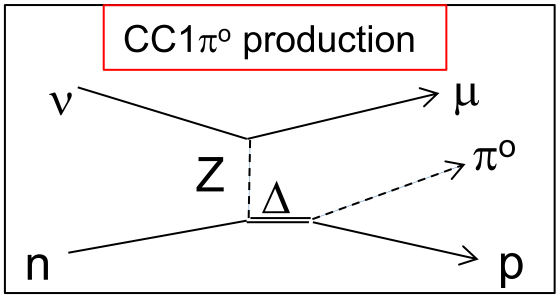
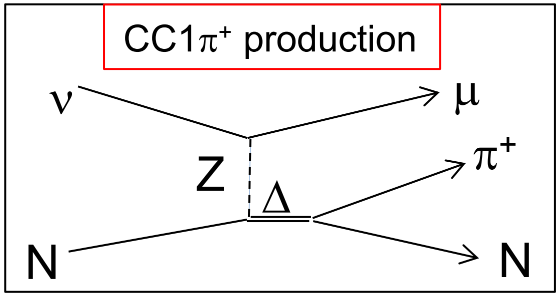
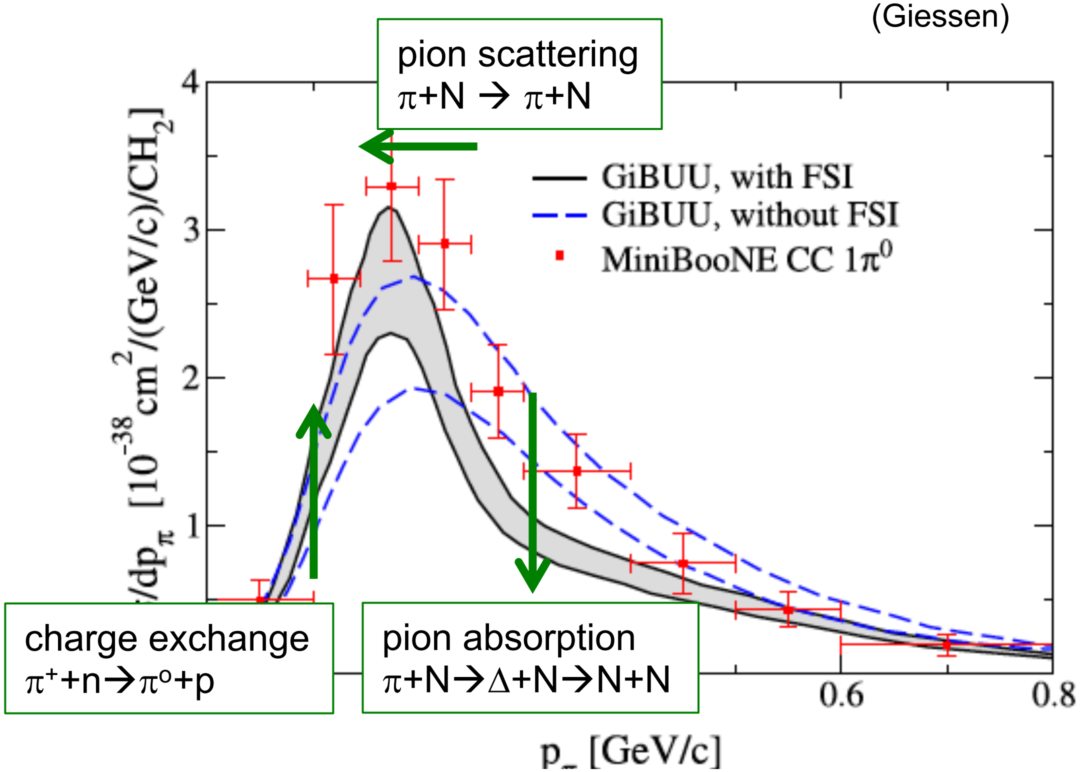






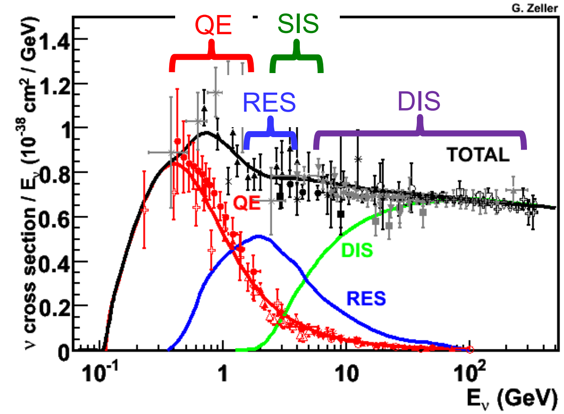
ex) Giessen BUU transport model

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

You need to predict both
1. pion production model
2. final state interaction

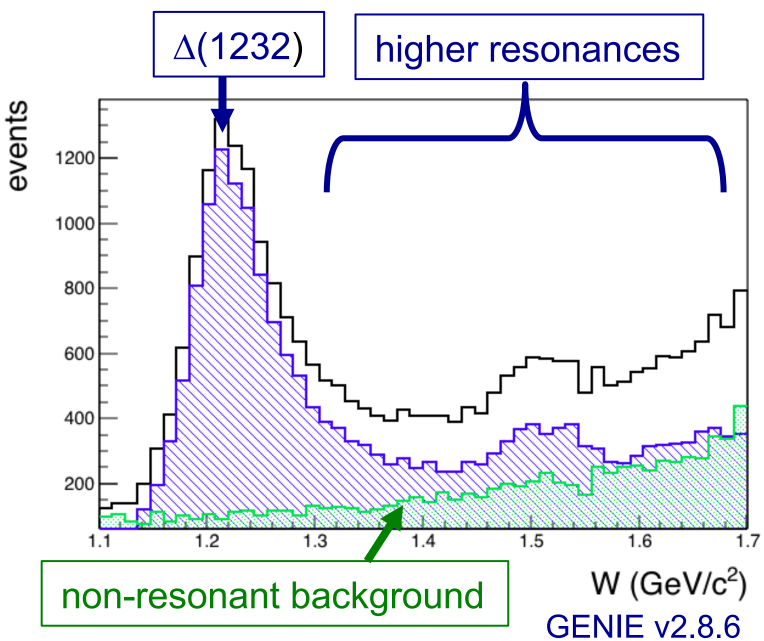
Nakamura et al.,Rep.Prog.Phys.80(2017)056301

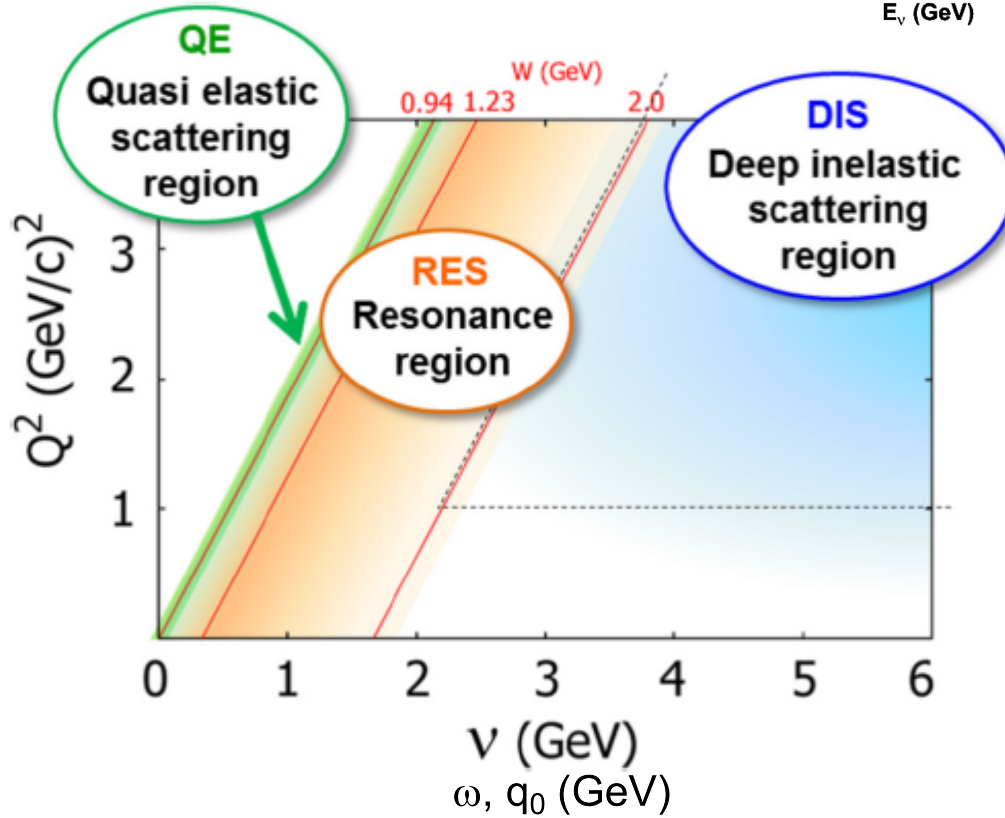
3. Shallow inelastic scattering (SIS)



Ingredients of SIS physics

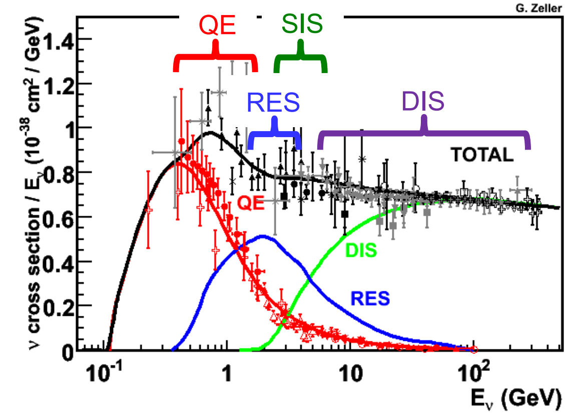
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS





Bronner (NuSTEC workshop 2018)

3. Shallow inelastic scattering (SIS)

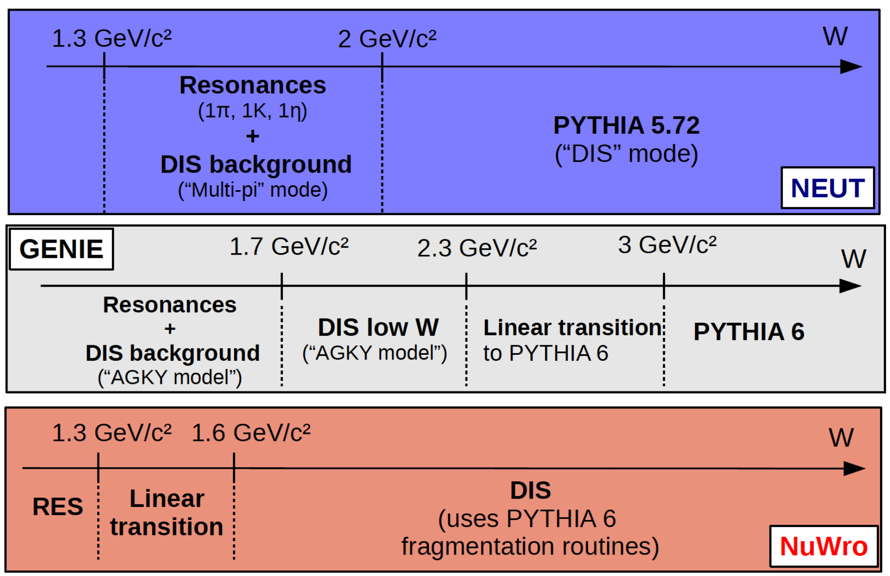


Ingredients of SIS physics

- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS
- Neutrino hadronization

SIS/DIS region in the generators

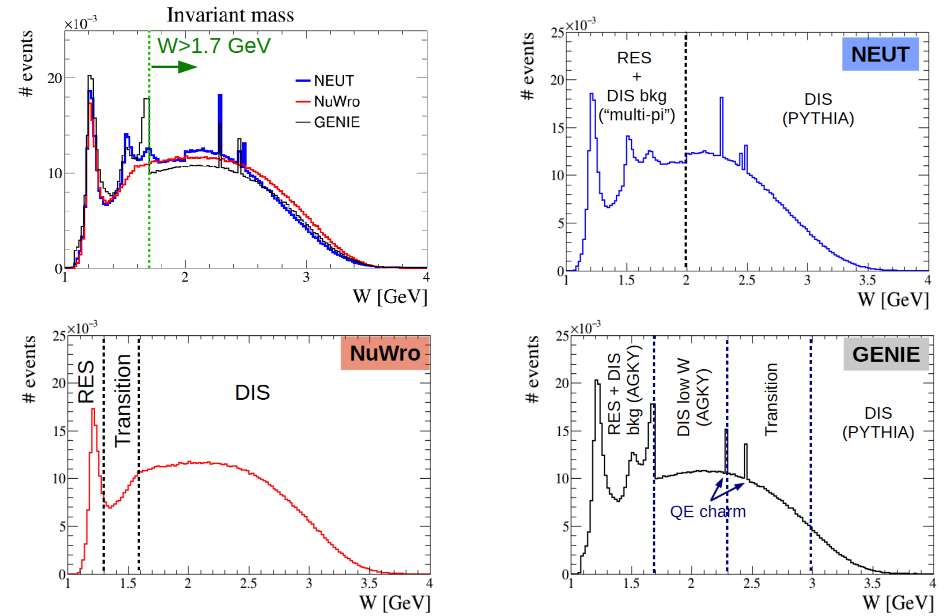
4



Invariant mass distribution

ν_μ on Fe, E_ν=6.0 GeV

5



DIS is model-dependent

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

3. SIS model

Ingredients of SIS physics
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS
- Neutrino hadronization

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

DCC model vs. electro-pionproduction data

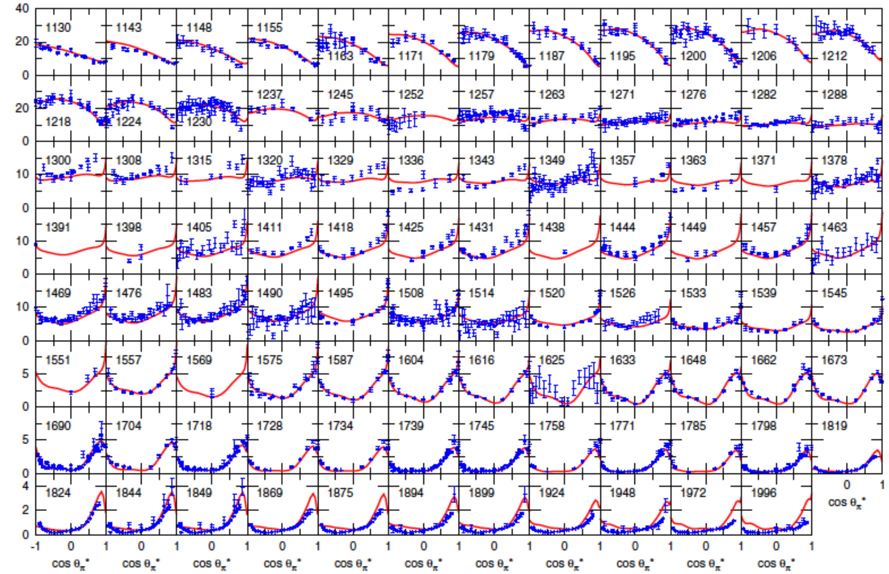
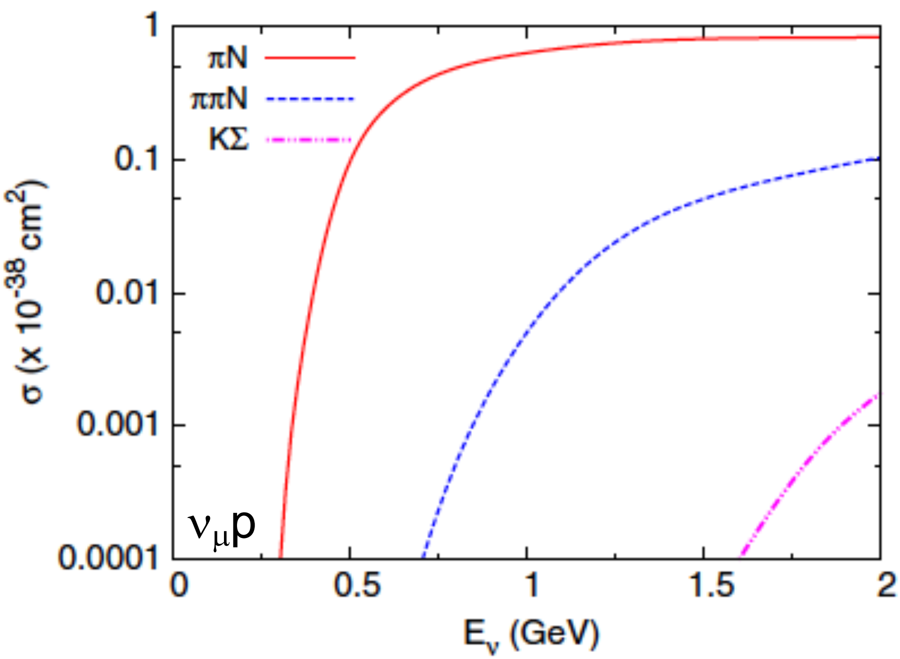
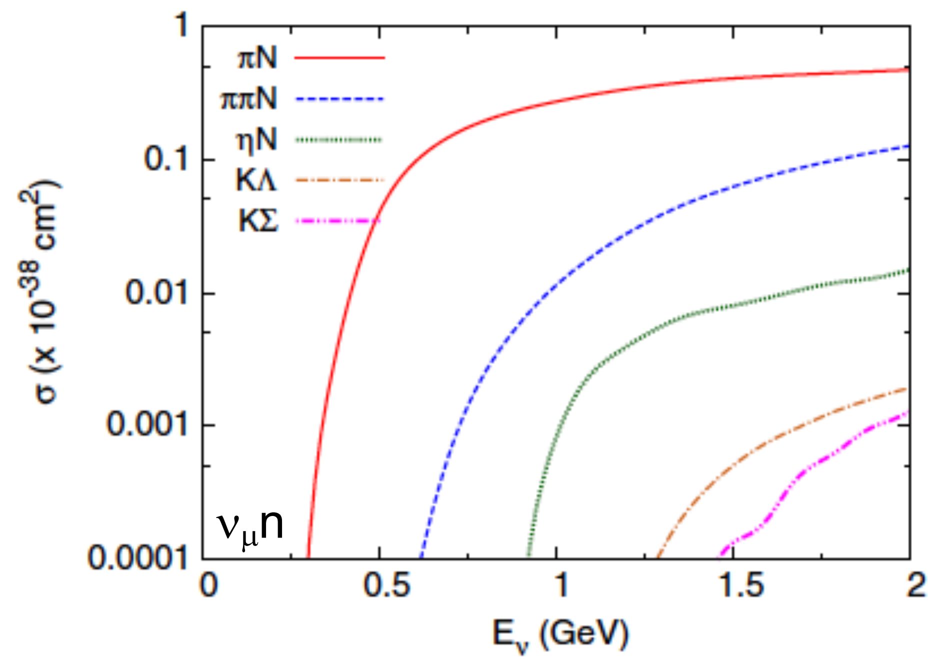


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega^*_\pi$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].





3. SIS model

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

Ingredients of SIS physics
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS
- Neutrino hadronization

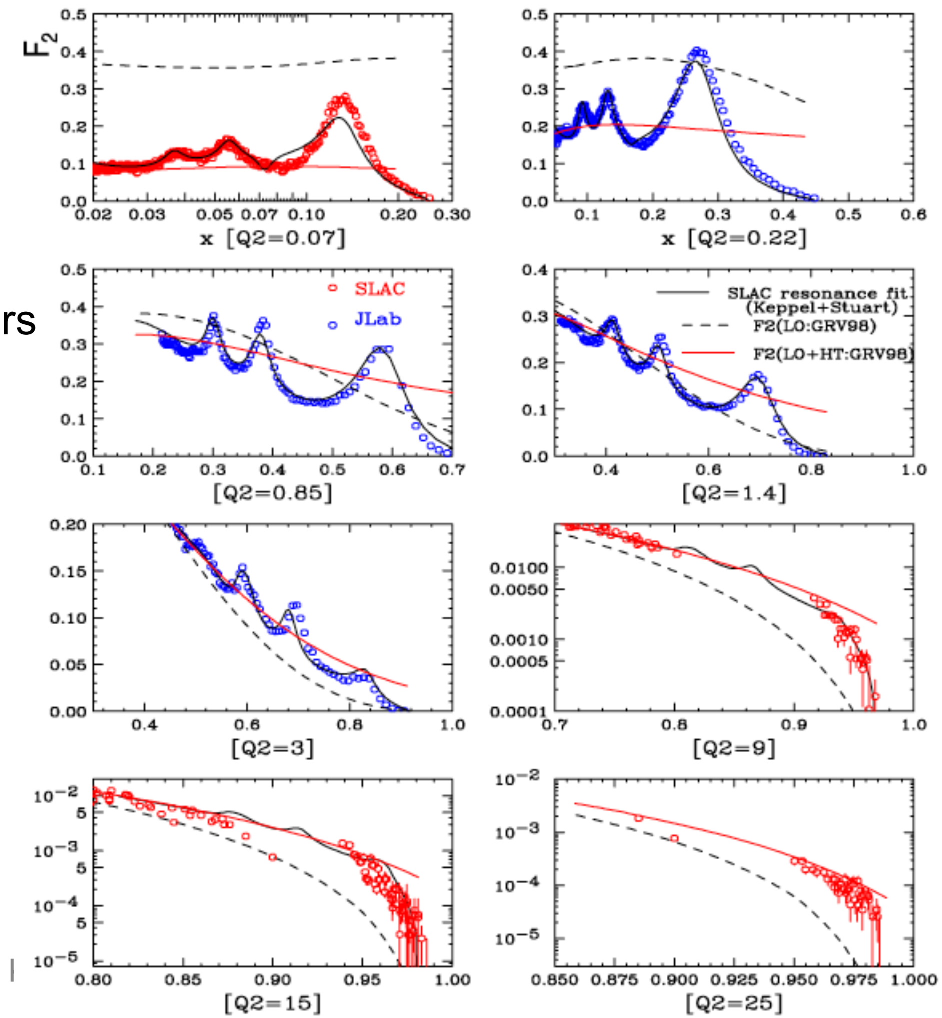
GRV98 LO PDF + Bodek-Yang correction
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data



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

3. SIS model

Ingredients of SIS physics
- Higher resonances and hadron dynamics
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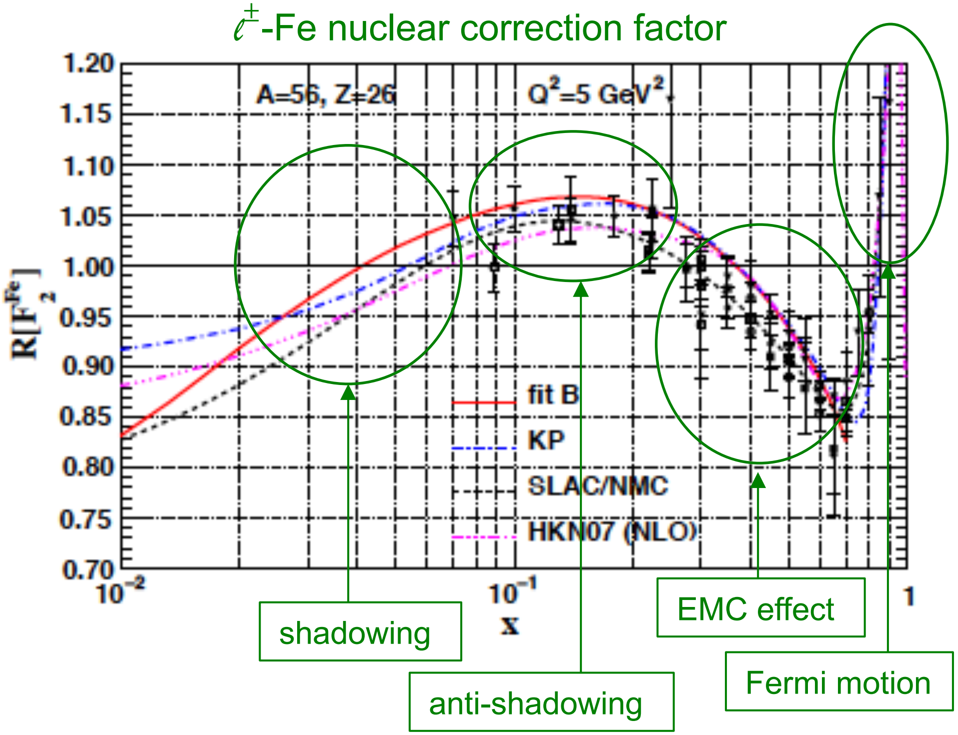
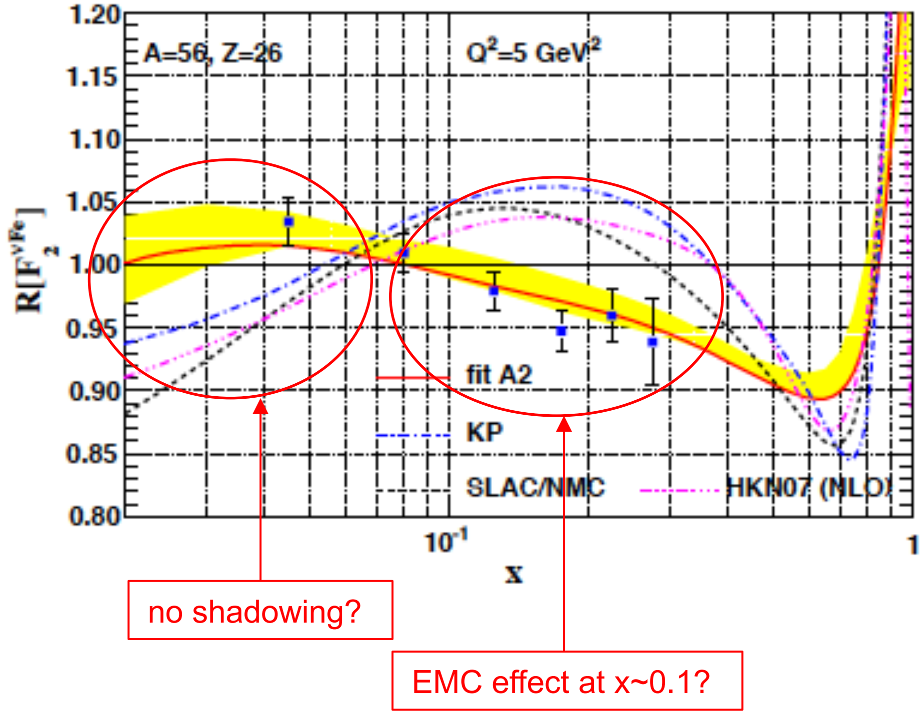
Nuclear PDF
- Shadowing, EMC effect, Fermi motion
- Theoretical origin is under debate
- Various models describe charged lepton data
- Neutrino data look very different

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



ν-Fe nuclear correction factor



TK and Mandalia, JPhysG42(2015)115004
Zieminska et al (Fermilab 15'), PRD27(1993)47

3. SIS model

Ingredients of SIS physics

- Higher resonances and hadron dynamics
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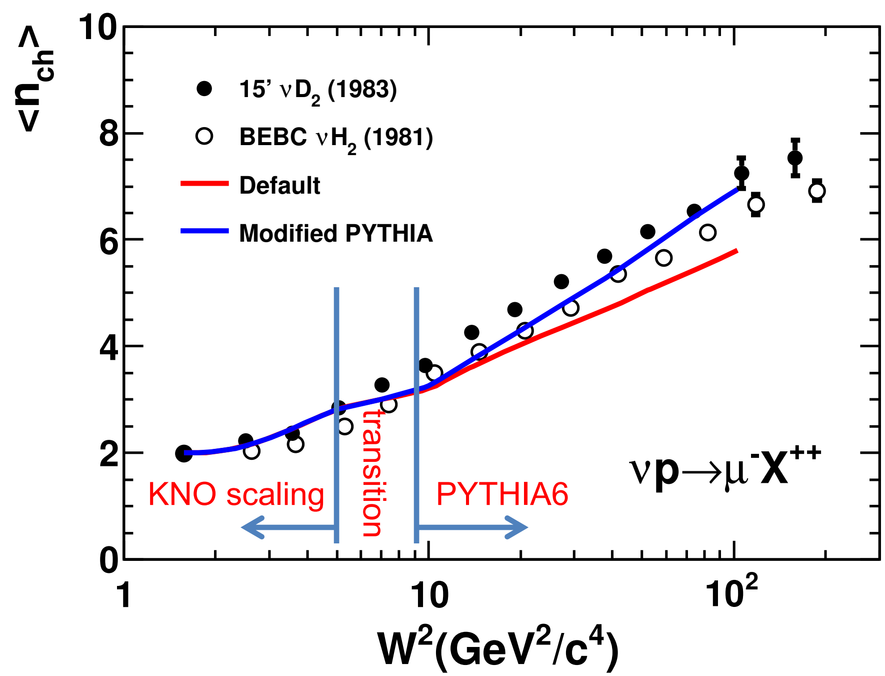
- Neutrino hadronization

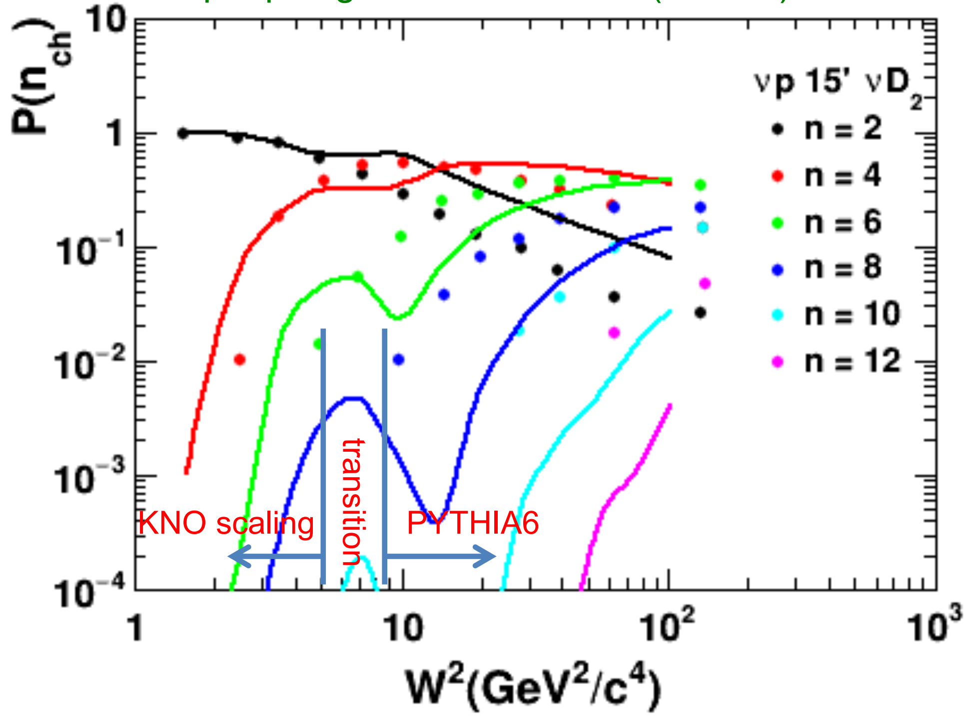
Custom hadronization + PYTHIA

- KNO scaling model at low W, high multiplicity and large dispersion (=data)
- PYTHIA at high W, low multiplicity and small dispersion (=preferred by collider data?)
- For event-by-event simulation of outgoing hadrons, dispersion is important.

Neutrino average charged hadron multiplicity



ν-p topological cross section (GENIE)



TK, Martini, JPhysG45(2017)1

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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

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[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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4. NuSTEC (nustec.fnal.gov)

NuSTEC pion workshop (Oct. 2-5 2019)
the University of Pittsburgh, USA
https://nustec.fnal.gov/pion19/

NuSTEC SIS workshop (Oct. 11-13 2018)
L'Aquila, Italy
https://nustec.fnal.gov/nuSDIS18/
Summary paper (https://arxiv.org/abs/1907.13252)

NuSTEC promotes physics of neutrino interaction
- Check the latest news in the community, Facebook: @nuxsec or Twitter: #nuxsec
- Subscribe our mailing list (online seminars, new papers, workshops school information)
- Find more info: https://nustec.fnal.gov

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

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Conclusion

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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. The role of ab initio calculation is important (but what can we do for argon?!).

Resonance region: Many confusions, poor understanding of cross-section and final state interaction models, low statistics data

SIS, DIS, hadronization: So far nobody really care but extremely important for DUNE

Nuclear physics is important because hadron final state is important. We need nuclear models working in all kinematic region. Neutrino experiment is always “inclusive” comparing with electron scattering (nuclear physics) and collider physics (particle physics) where they can select kinematics.

Neutrino Interaction Physics

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

Lecture 2: Charged-current quasi-elastic (CCQE) interaction
4. Introduction to CCQE interaction
5. CCQE scattering cross section

Lecture 3: Overview of neutrino cross sections
6. Neutrino-nucleus interactions
7. Neutrino interaction physics around 1-10 GeV
8. Neutrino cross section experiments

Teppei Katori
King's College London
Summer lecture series, Nagoya University, Japan, July. 6-10, 2020

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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

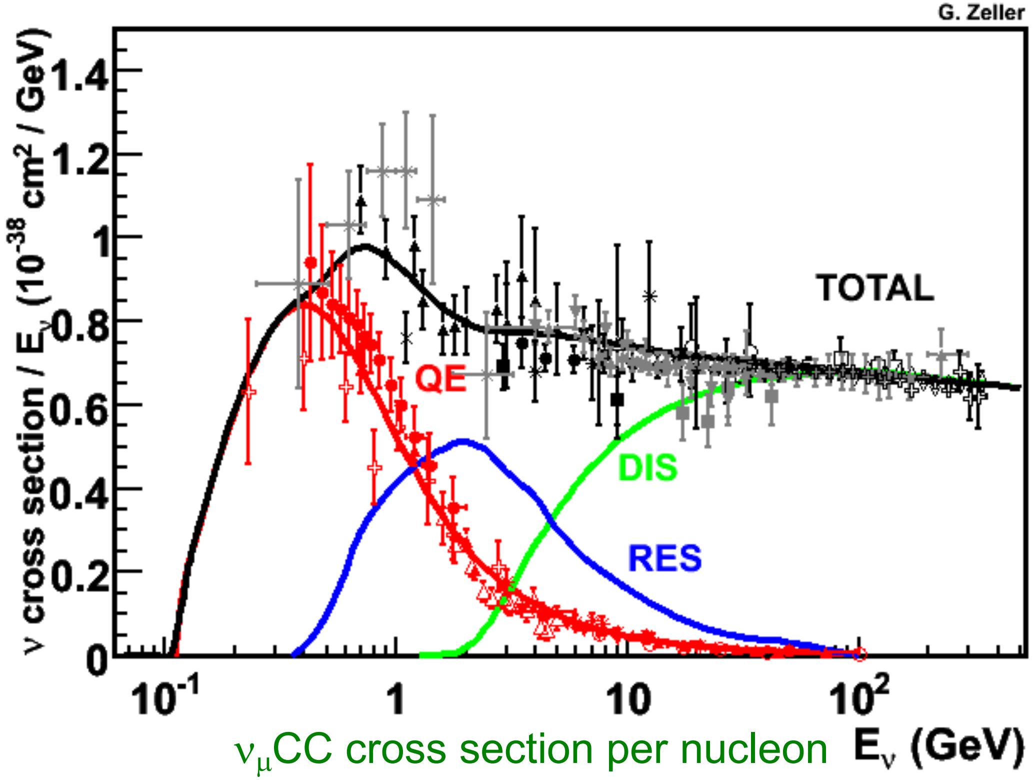
6. Conclusion

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

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

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

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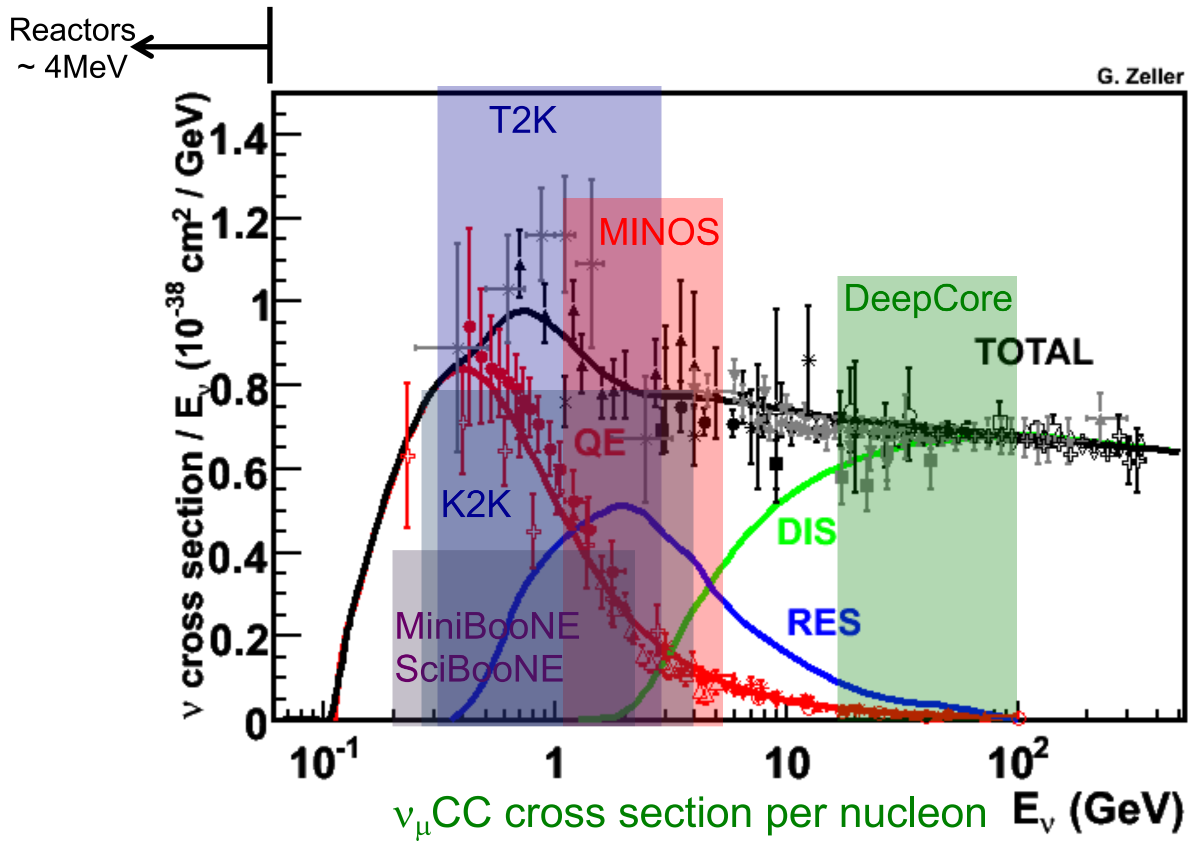

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Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

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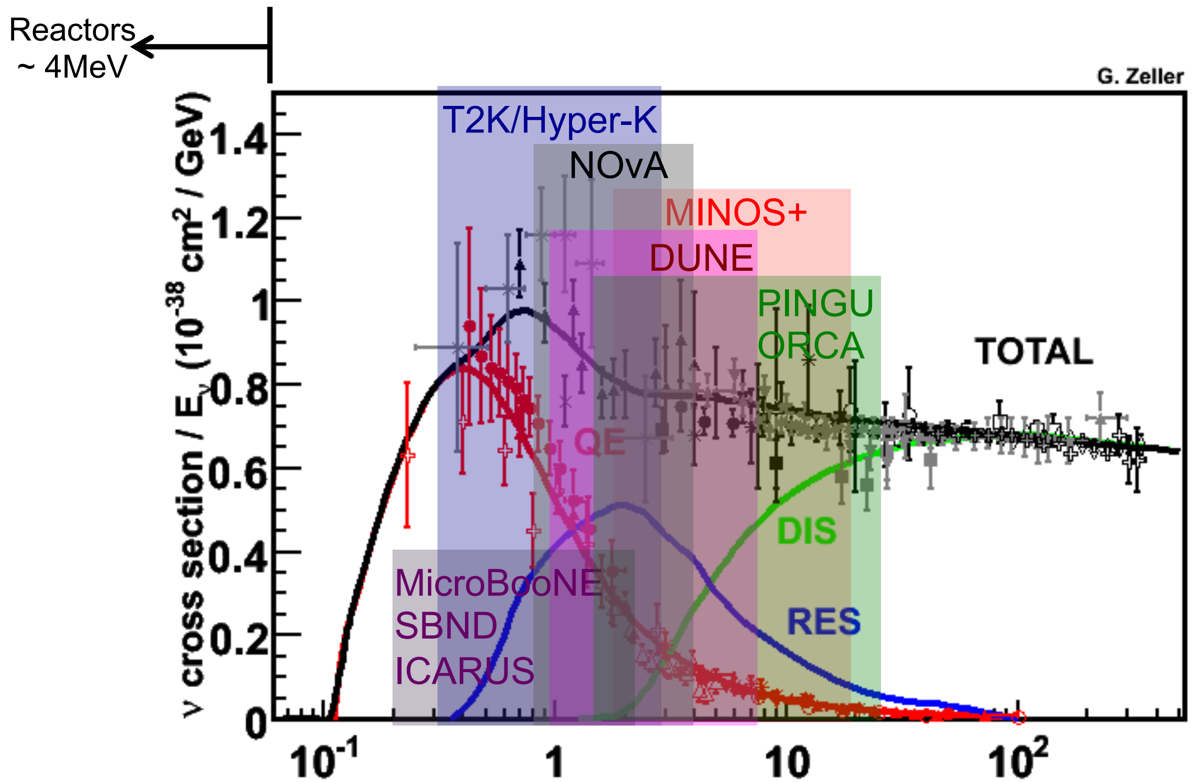

ν_μCC cross section per nucleon

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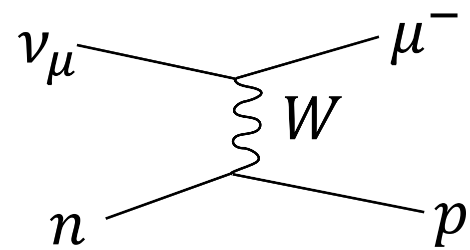
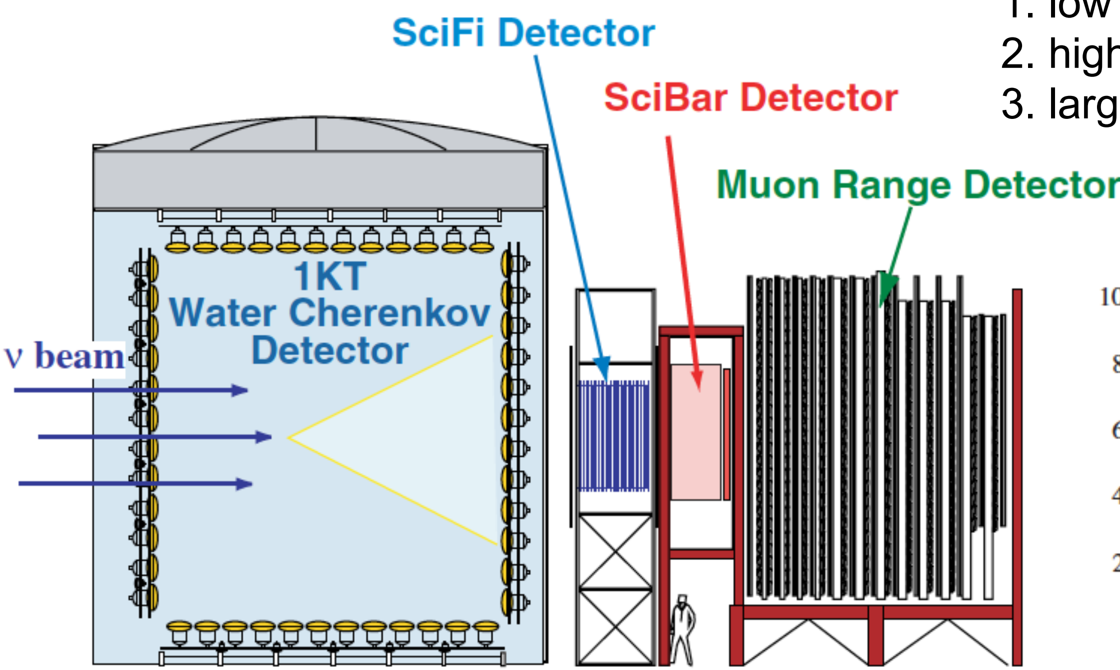
1. K2K



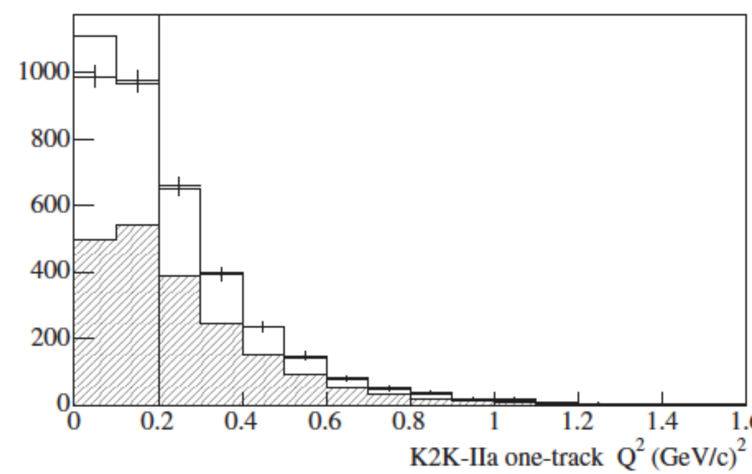
Scintillation tracker

- 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 shows large disagreement!
→ we need more experiments to improve models

1. Neutrino Interaction Physics

2. MiniBooNE

3. T2K near detector

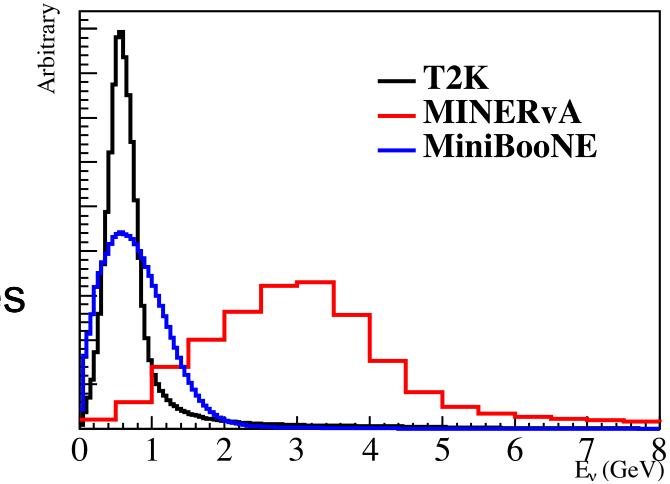
4. MINERvA

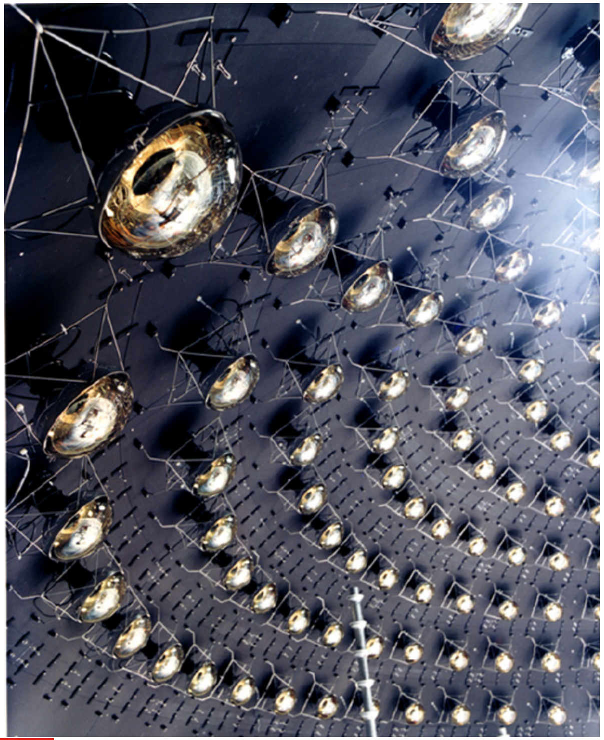
5. LArTPC

6. Conclusion

2. MiniBooNE

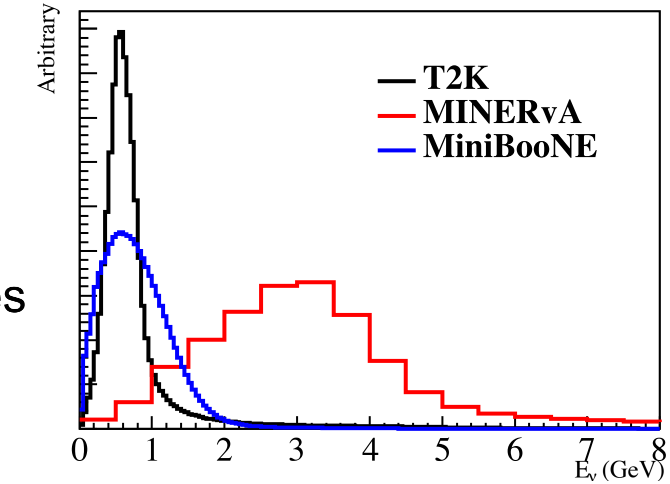
Mineral oil (CH_2) Cherenkov detector
- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Measure Cherenkov radiations from charged particles
- Some calorimetric (scintillation)





MiniBooNE, PRL100(2008)032301,PRD81(2010)092005:88(2013)032001

2. MiniBooNE



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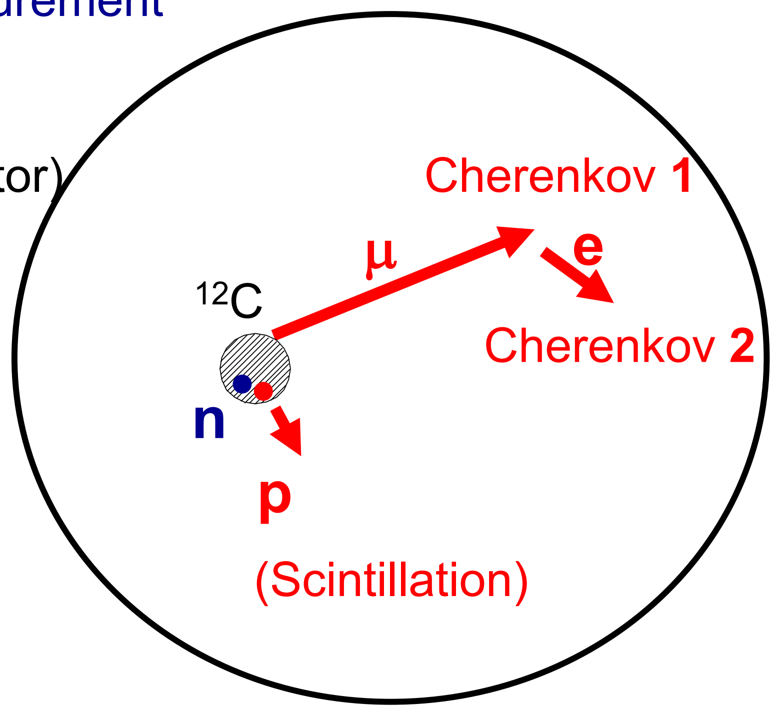
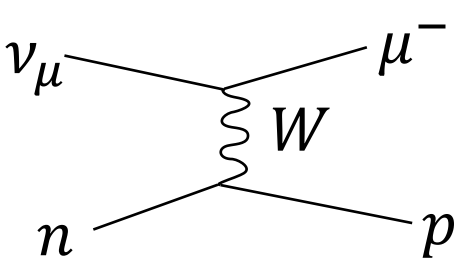
MiniBooNE CCQE measurement

MiniBooNE detector
(spherical Cherenkov detector)

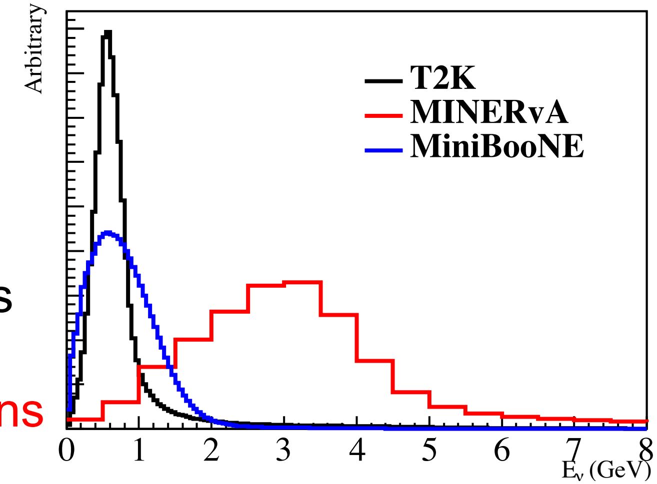
ν-beam



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



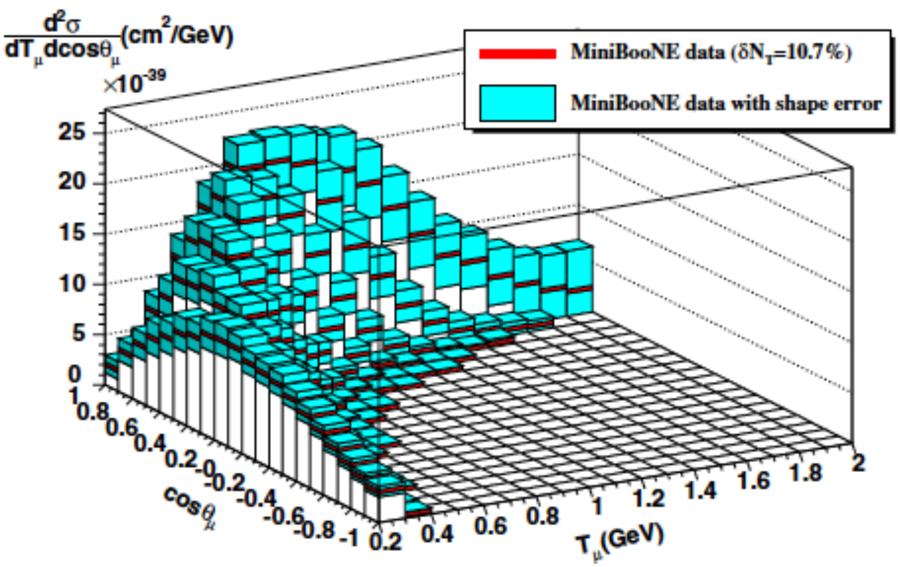
2. MiniBooNE

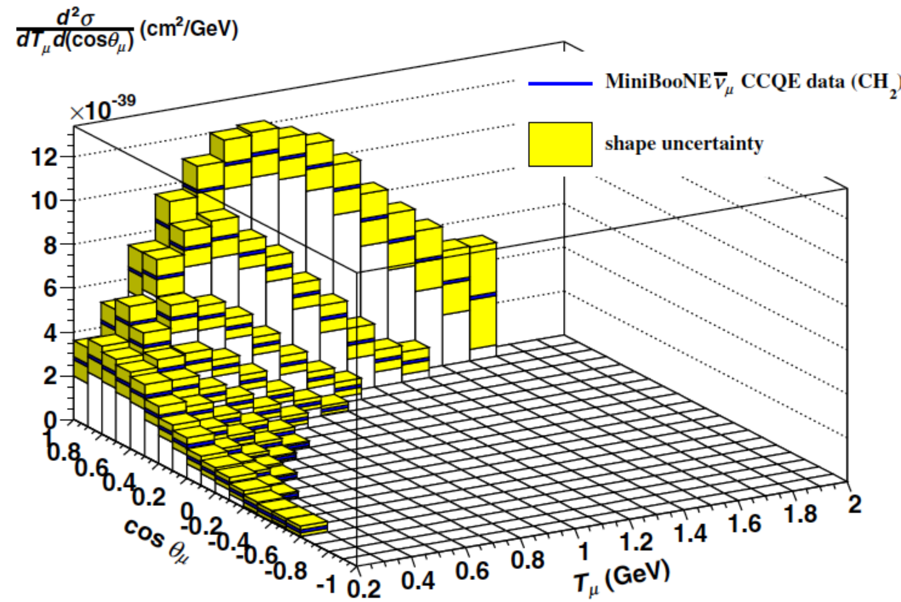


Mineral oil (CH_2) Cherenkov detector

- 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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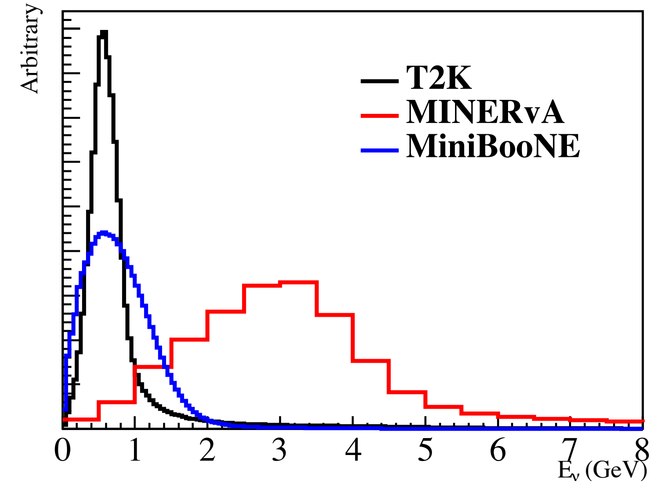
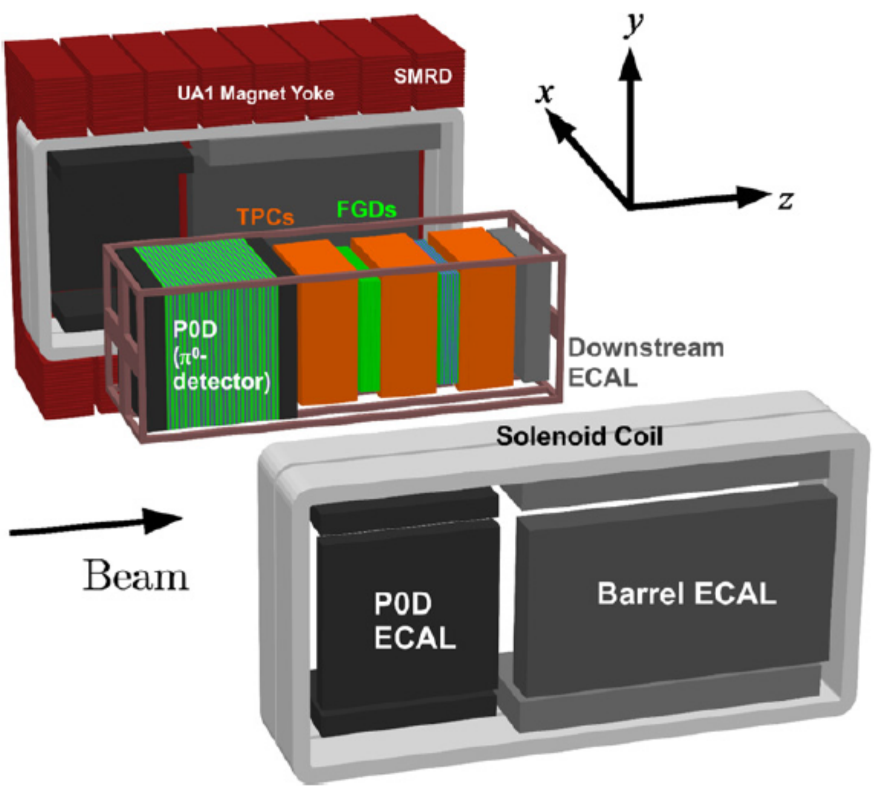
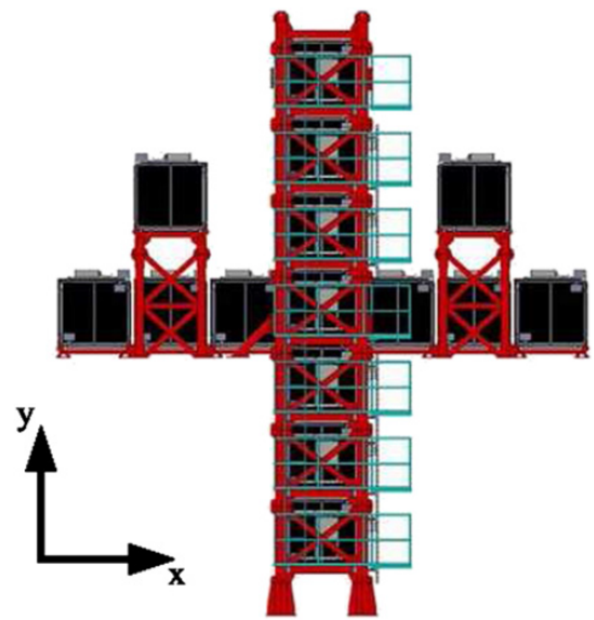


INGRID, FGD, P0D, ECal, TPC, SMRD

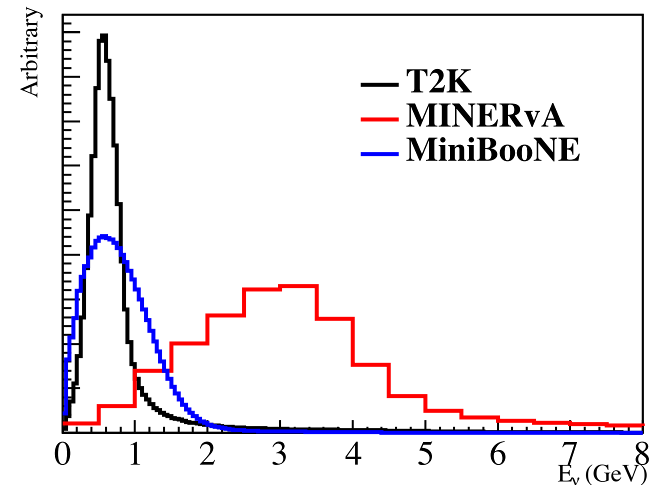
- Plastic scintillation trackers (except gas TPC)
- 0.2T magnet for momentum measurement
- <E>~600 MeV off-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)





T2K, NIMA659(2011)106, T2K,PRD93(2016)112012

3. T2K near detector



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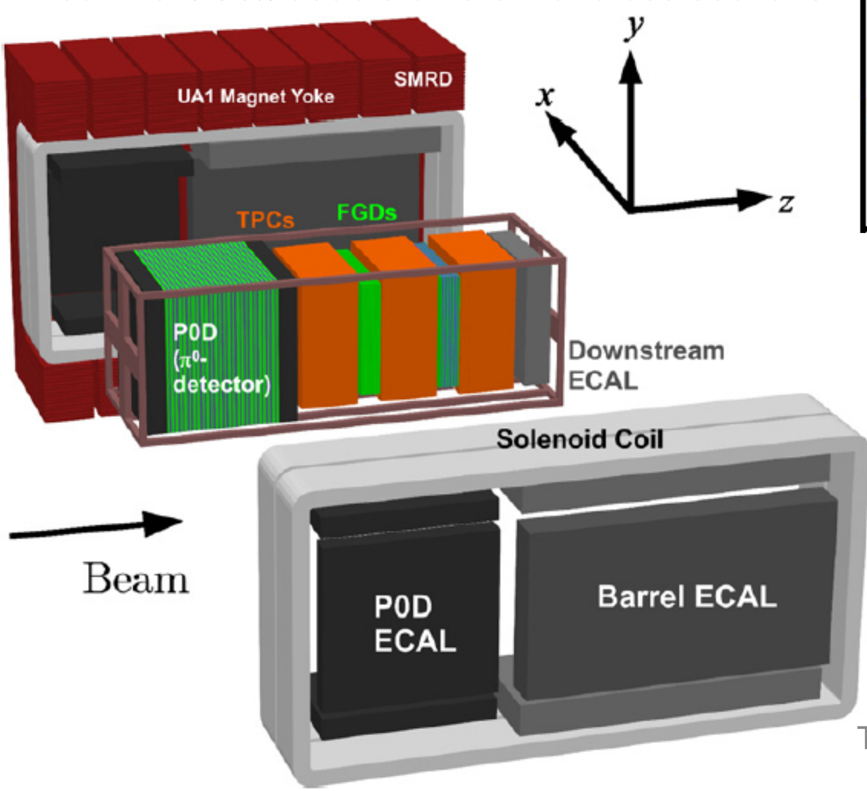
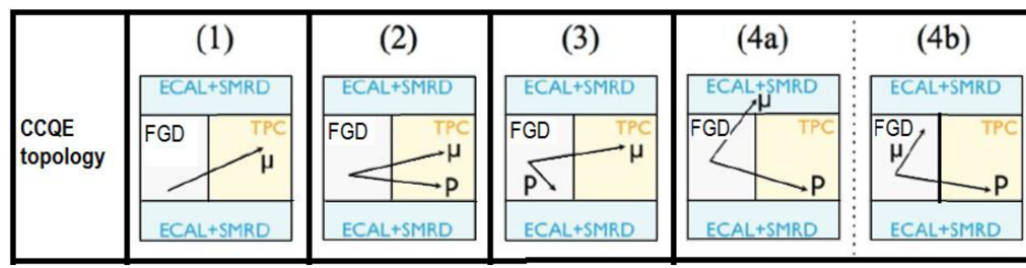
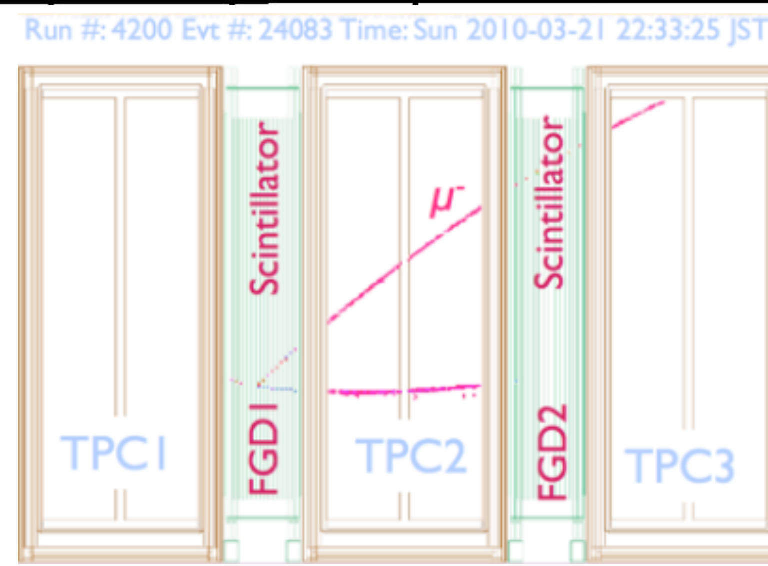
neutrino CC0π double differential cross sections







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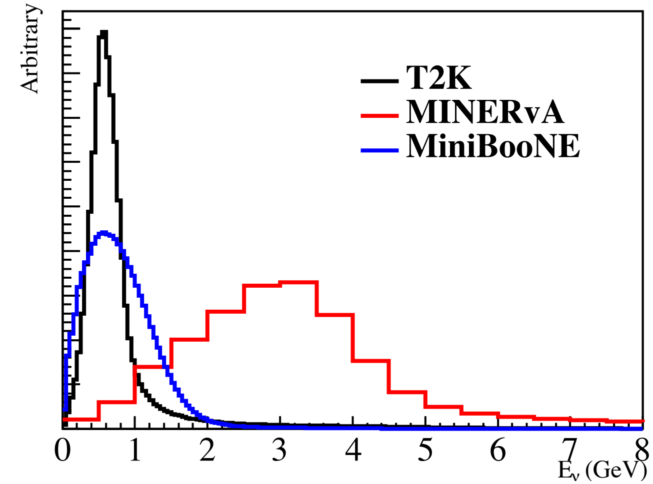

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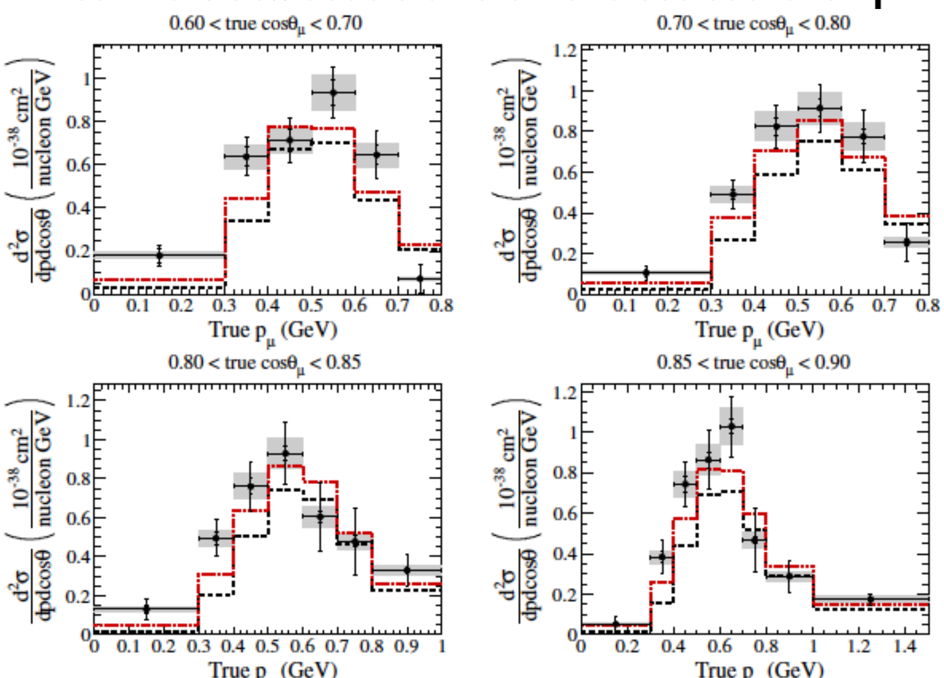

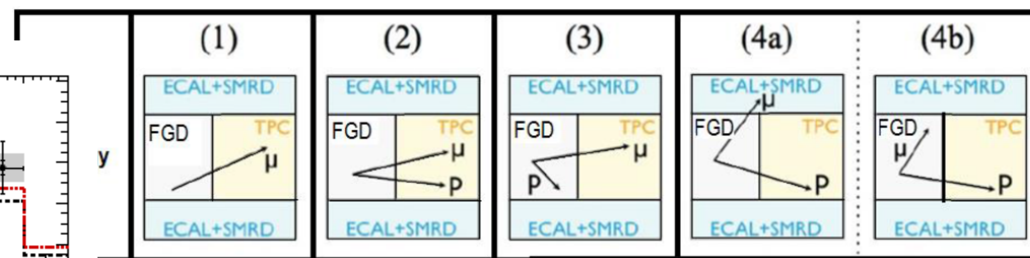

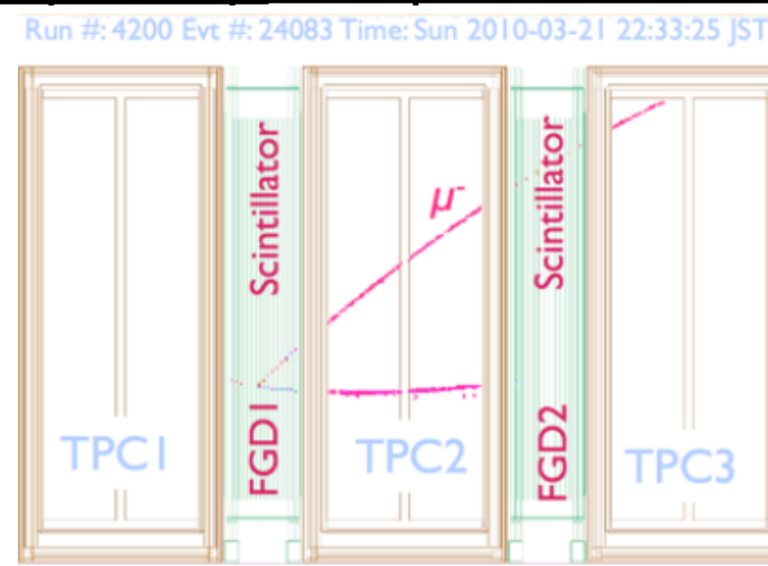

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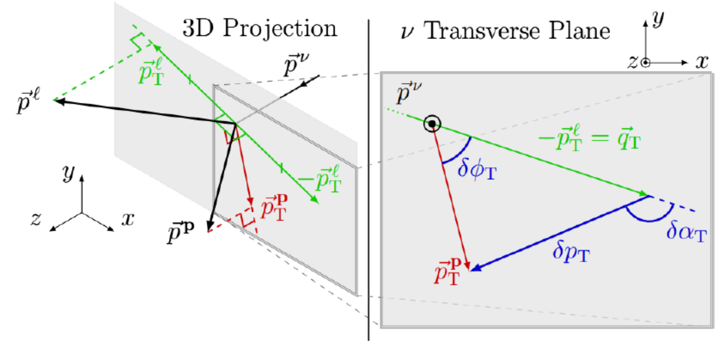
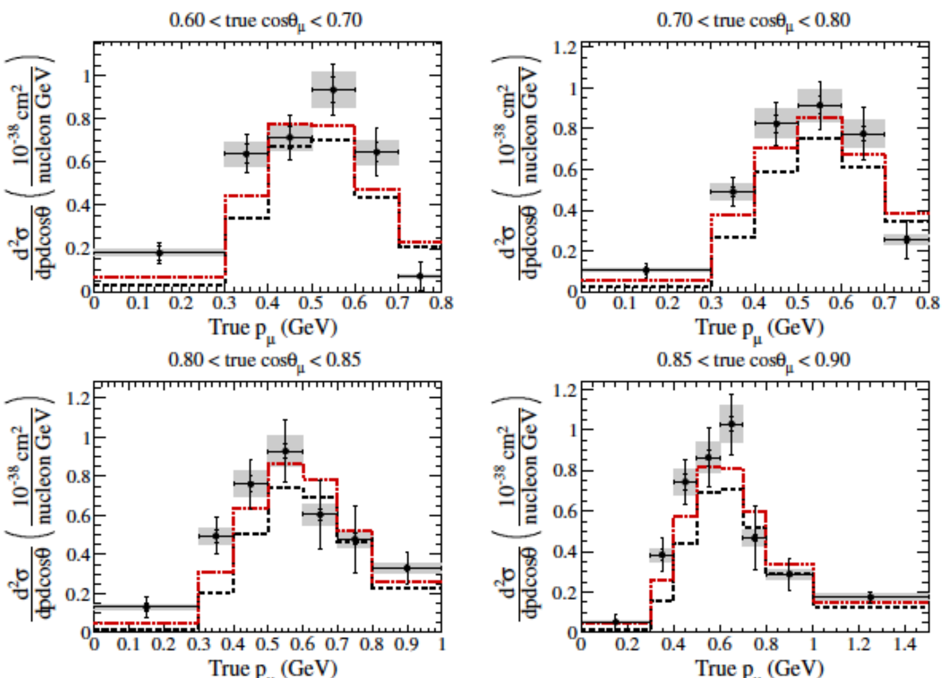
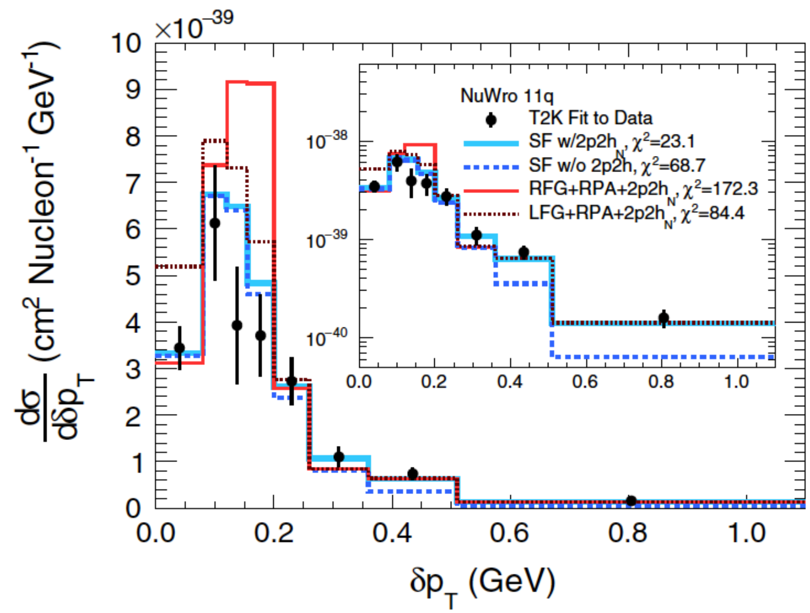


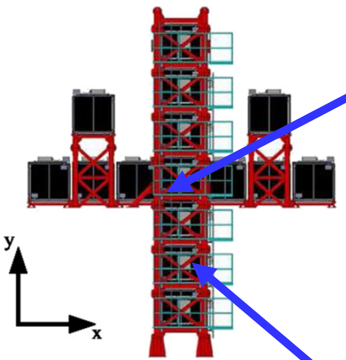
neutrino CC0π double differential cross sections



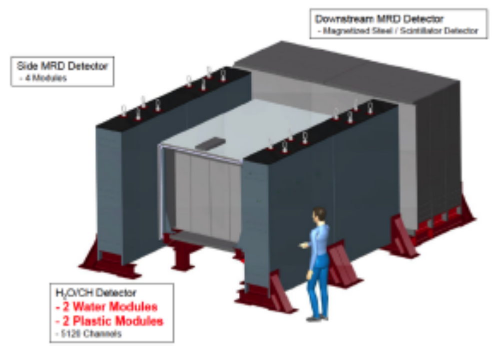
neutrino CC0π1p differential cross sections

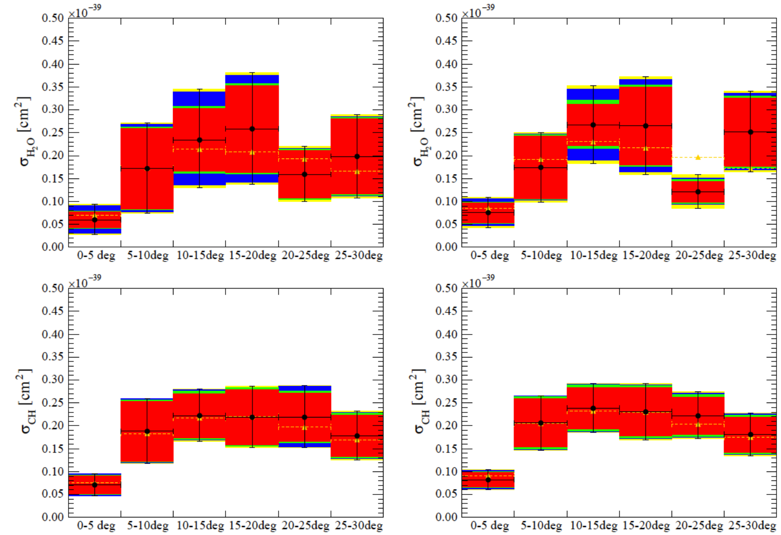


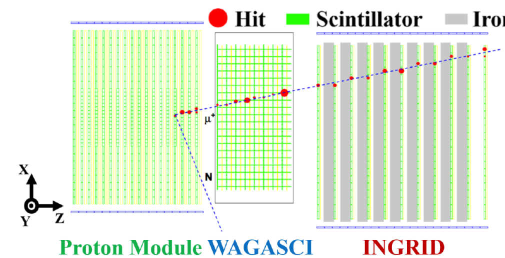
3. T2K near detectors



WAGASCI
- water target

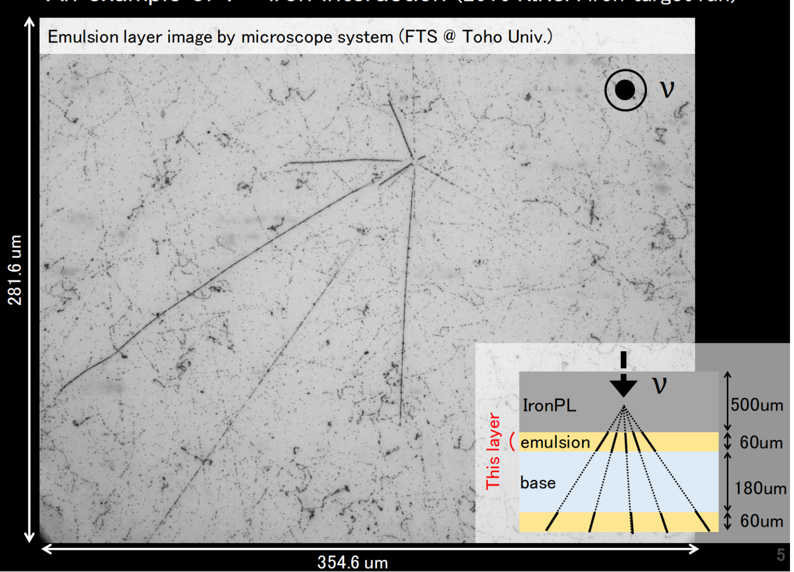






NINJA
- emulsion detector
- Multiple hadron tracks

An example of ν − iron interaction (2016 NINJA iron target run)



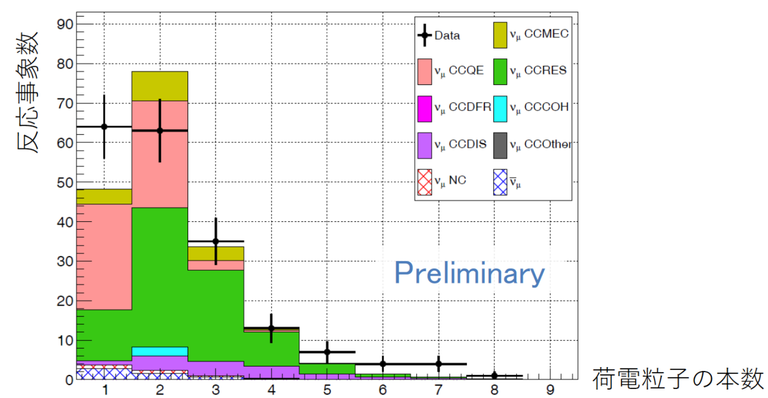
結果(1)：終状態の荷電粒子の本数分布

検出条件

|tan θ x|≦1.7,　|tan θ y|≦1.7,　Nseg(Number of emulsion layers) ≧ 2

シミュレーション

ν 反応：NEUT5.4.0,　検出器応答：Geant4,　規格化：POT & 標的質量



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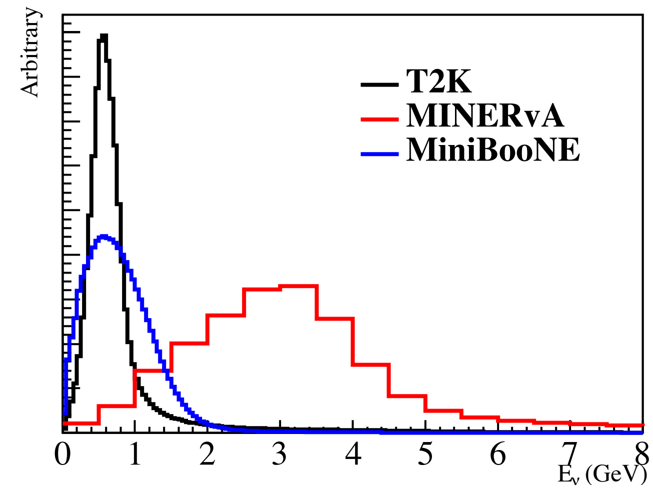
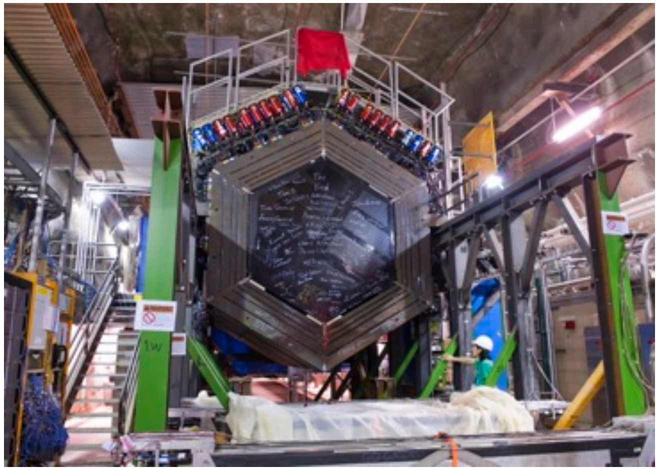
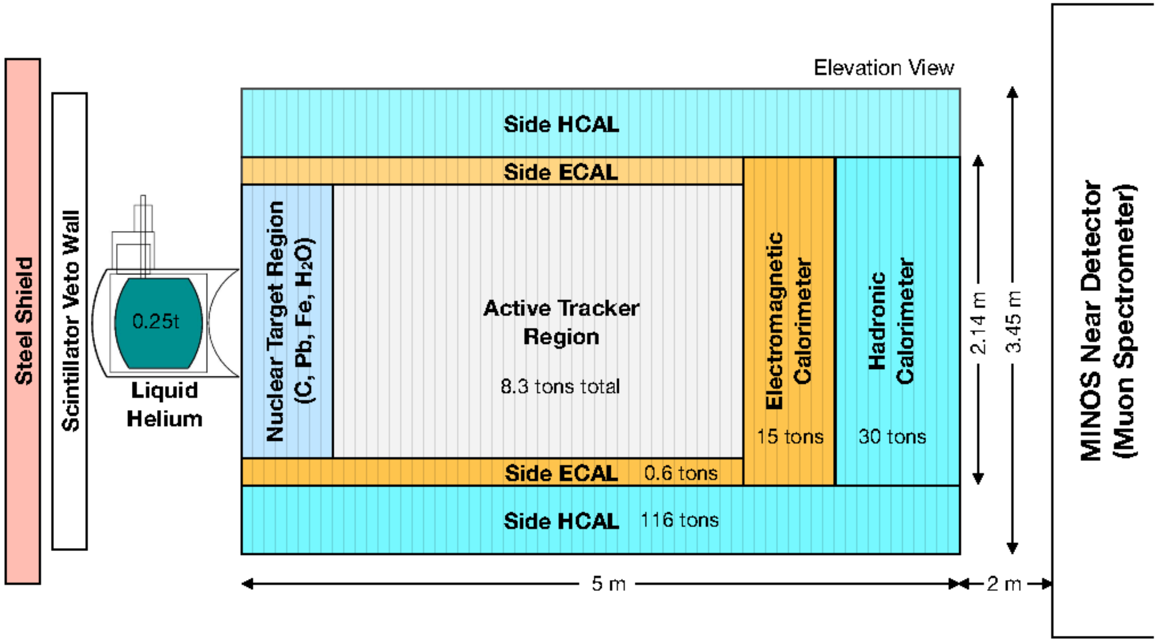
Scintillation tracker
- <E>~3.5 GeV on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)







4. MINERvA

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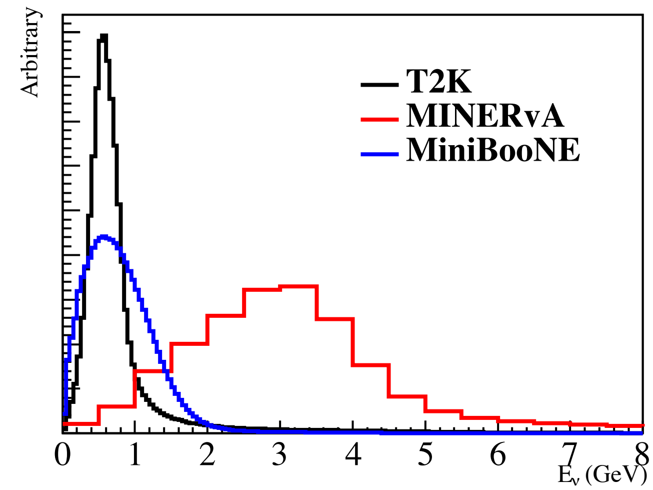

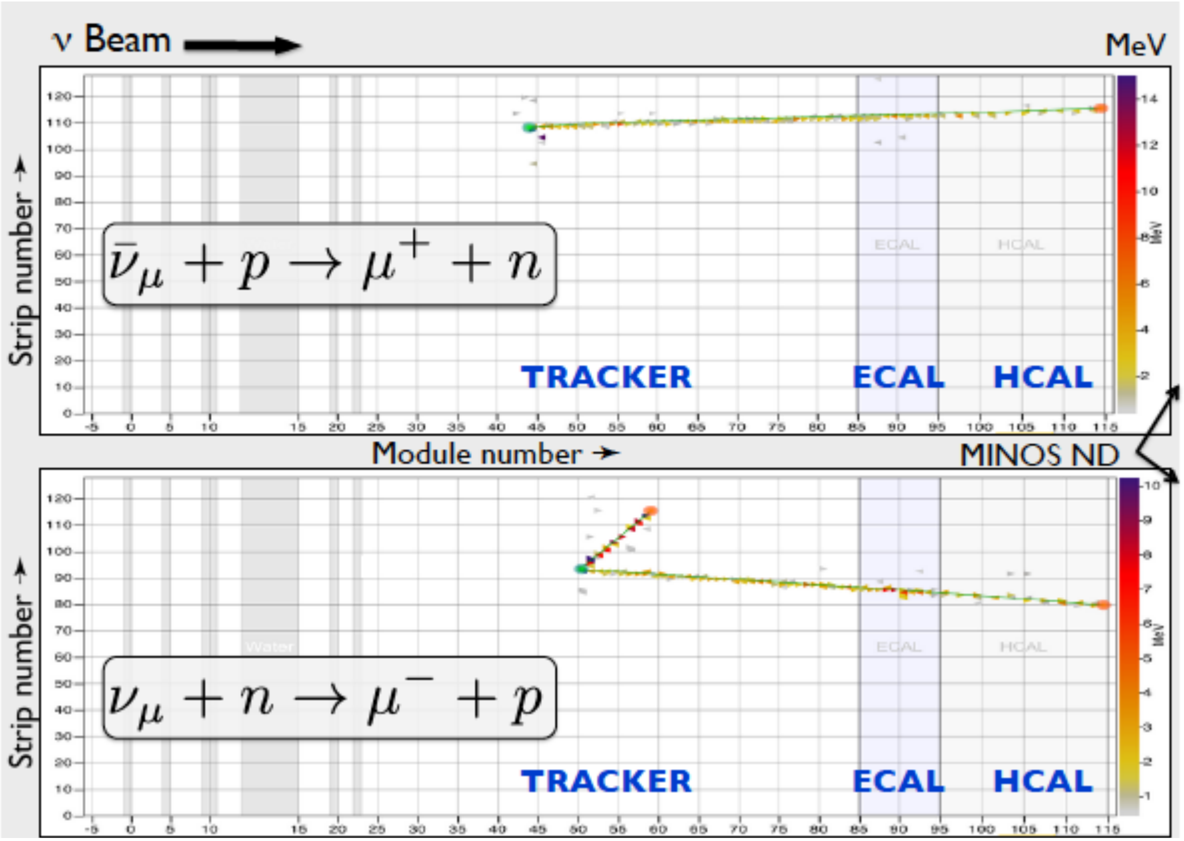

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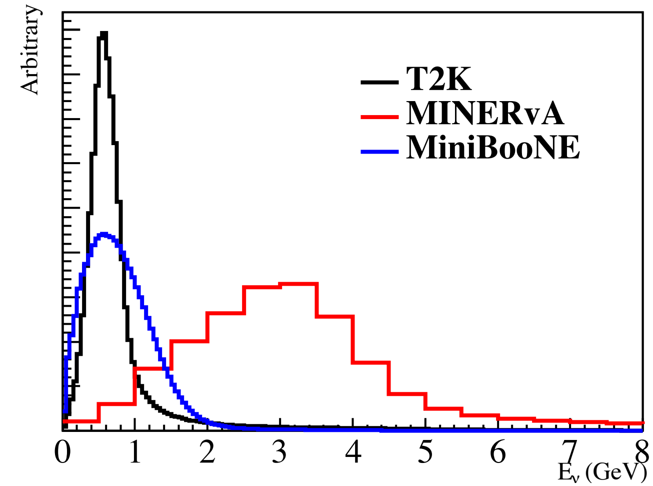

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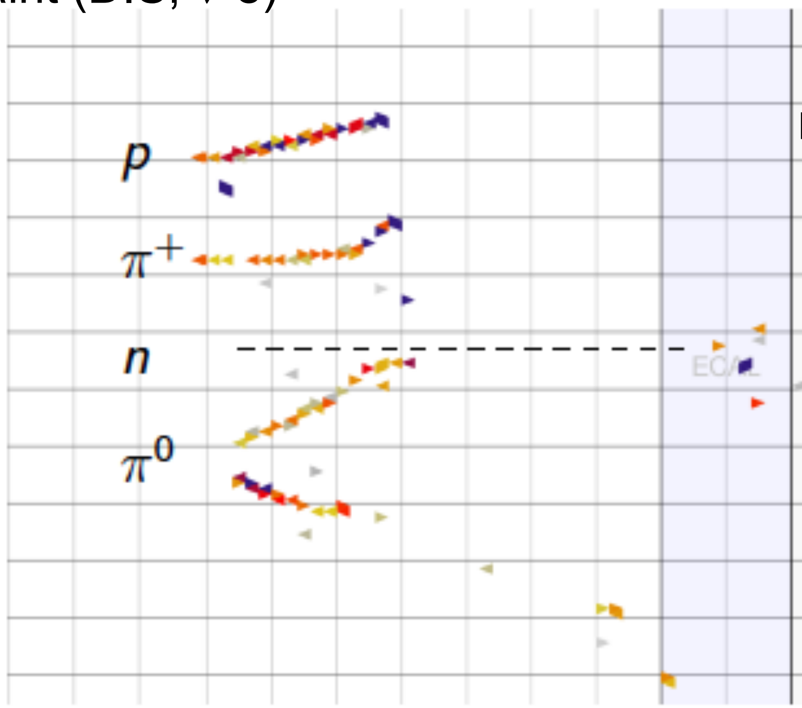
Kinetic energy

Kinetic energy

0

Total energy



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

model-dependent

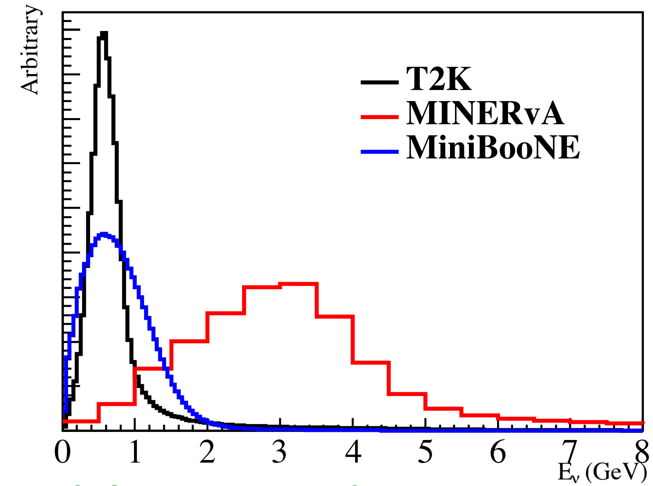
visible hadron energy
↓
total hadron energy
↓
Eν
↓
Q2

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

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

MINERvA, PRL116(2016)071802

4. MINERvA



Scintillation tracker

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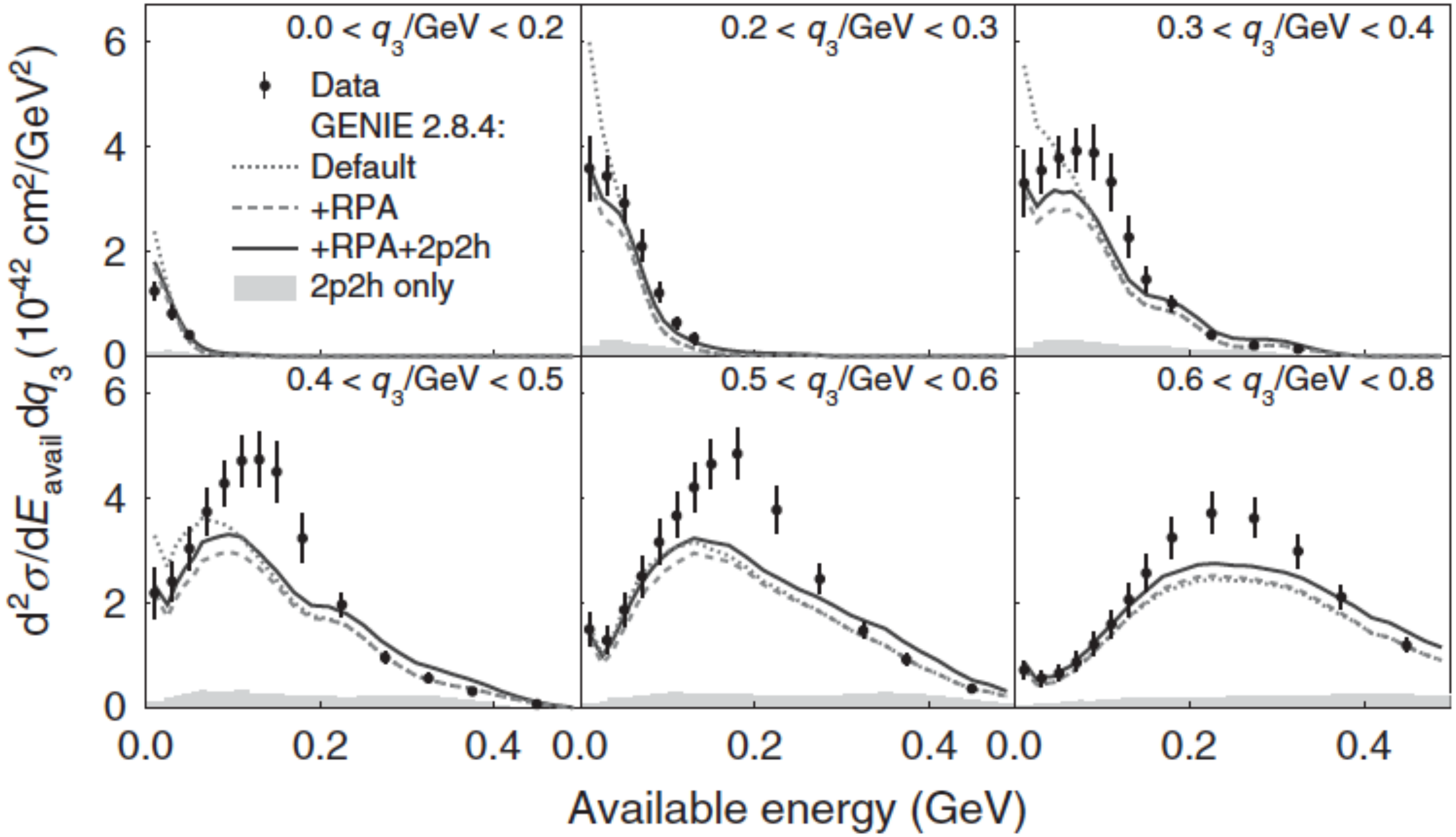
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)

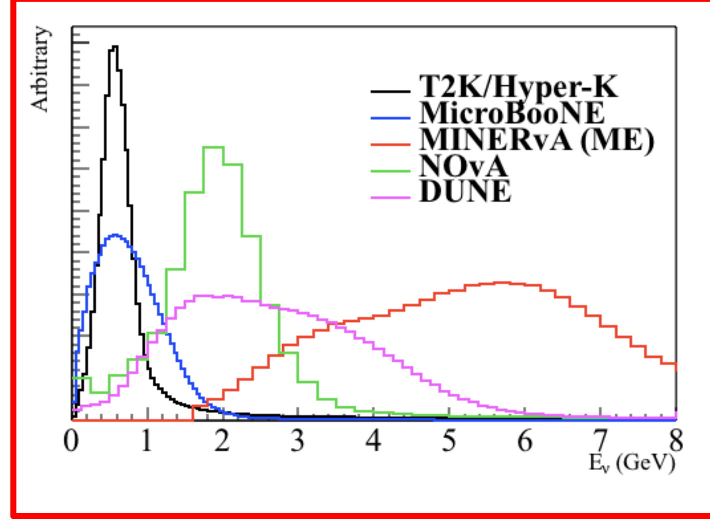
Flux-unfolded double differential cross section

Directly comparable with nuclear theories



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

4. Pion puzzle

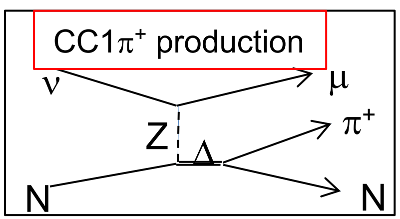


After CCQE puzzle, pion puzzle is the next biggest problem…

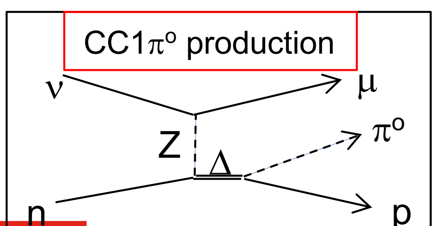
MINERvA $\nu_\mu CC1\pi^+$ vs. $\overline{\nu_\mu} CC1\pi^o$

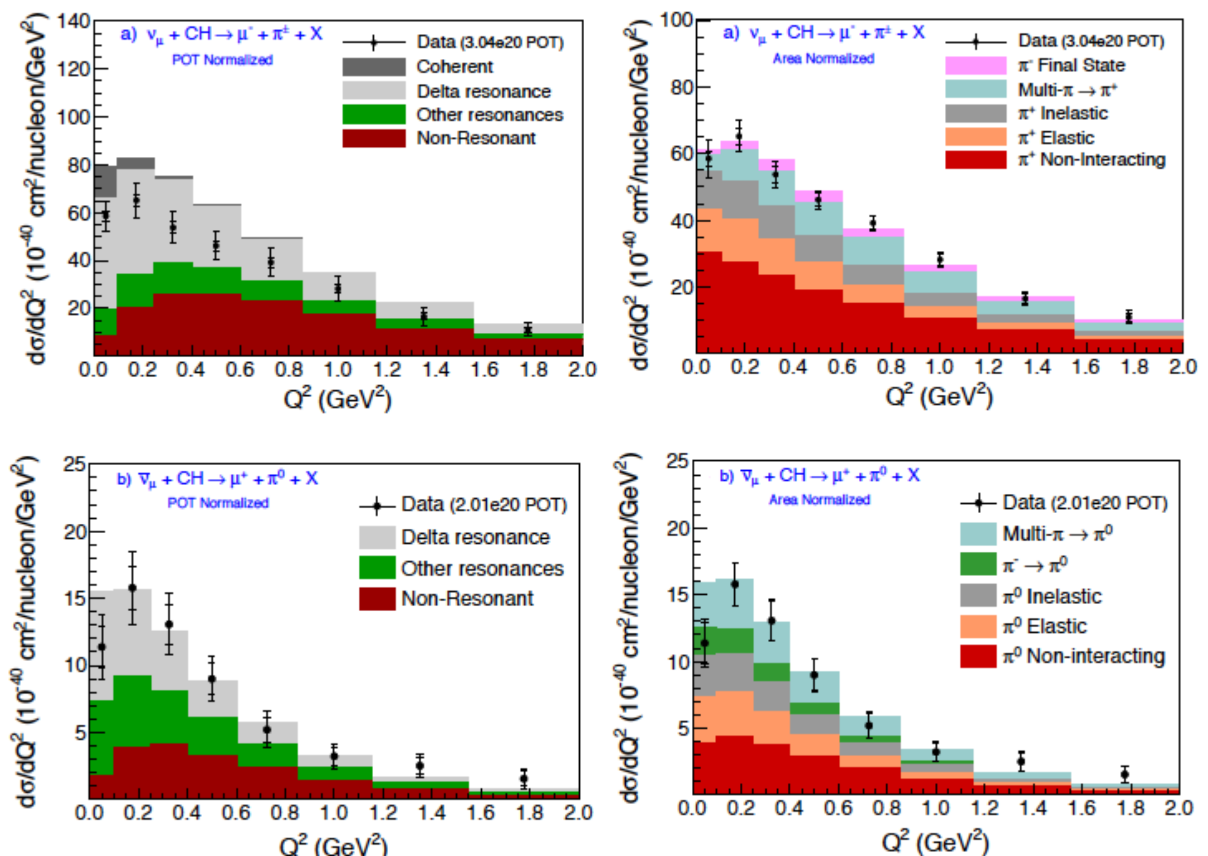
- simultaneous fit of 2 samples to understand structures of neutrino scatterings and pion propagations.

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



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





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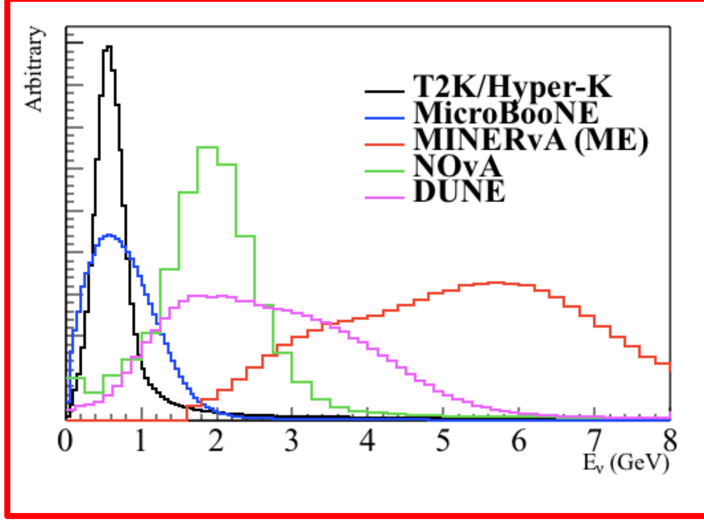
4. Pion puzzle, 2019



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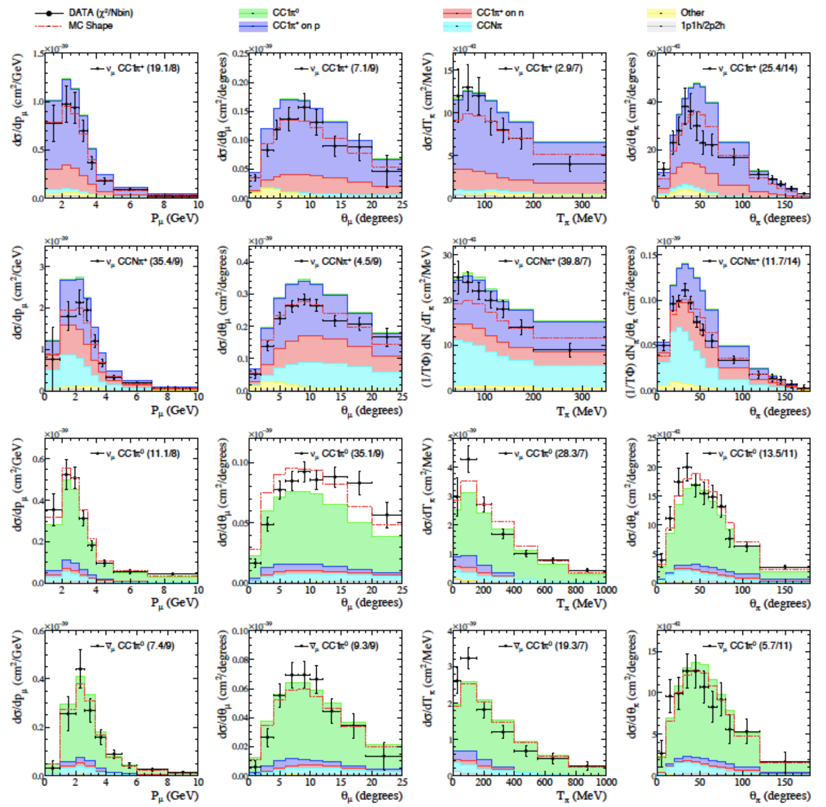
MINERvA $\nu_\mu CC1\pi^+$ vs. $\overline{\nu_\mu}CC1\pi^o$ vs. $\nu_\mu CCN\pi^+$ vs. $\nu_\mu CC1\pi^o$

- simultaneous fit of 4 samples to understand structures of neutrino scatterings and pion propagations.



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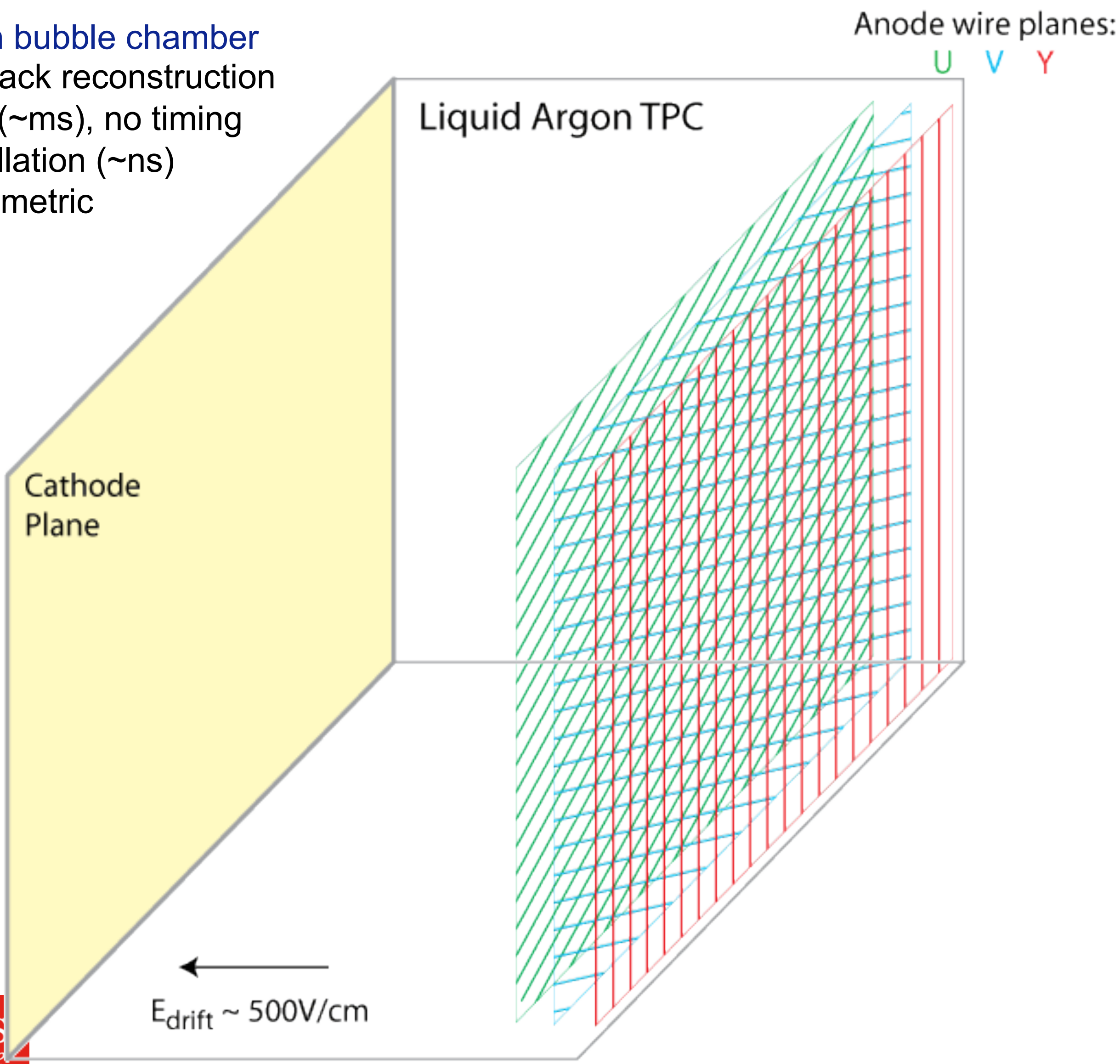
5. LArTPC

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



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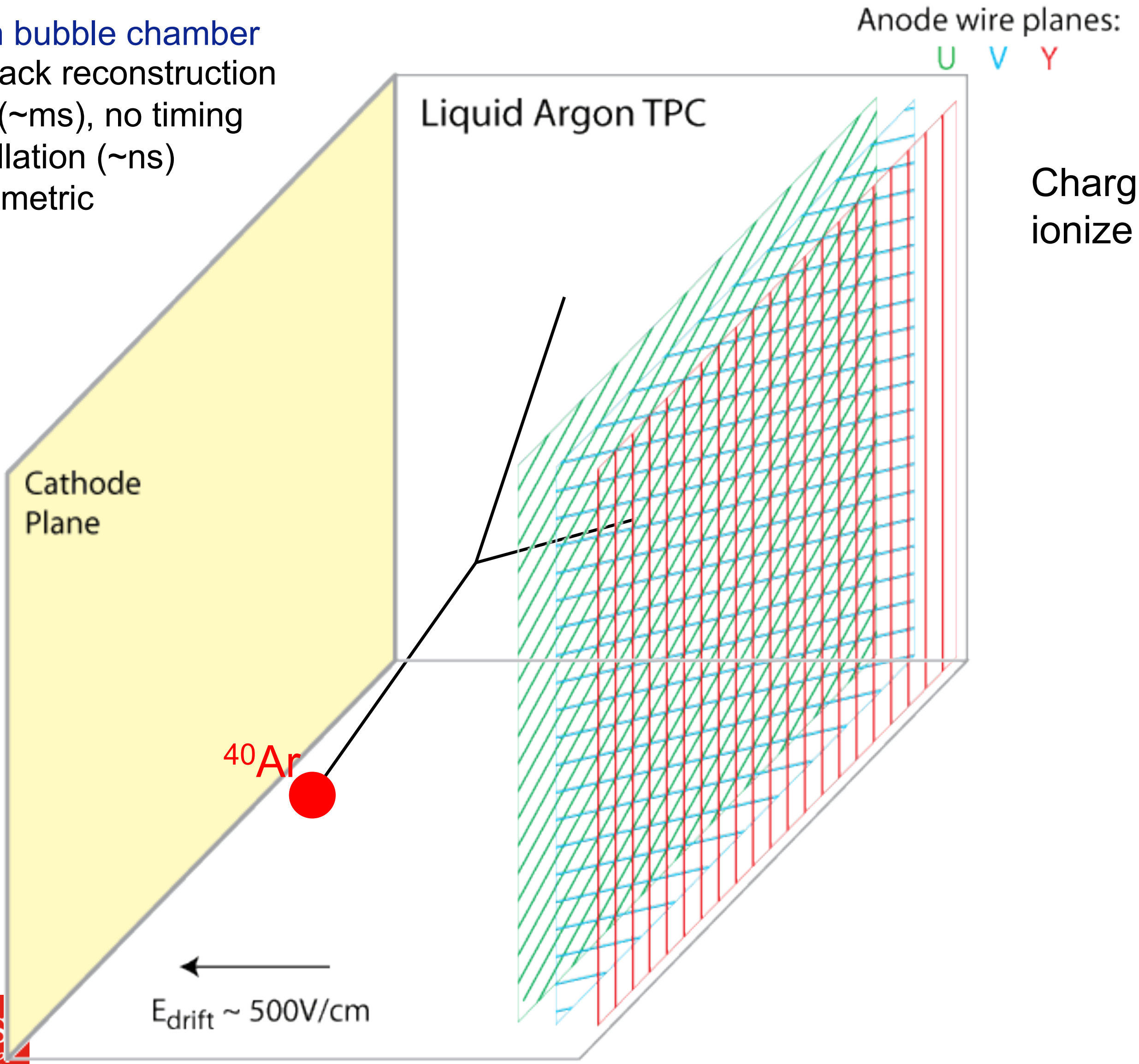

Charged particle tracks ionize Argon atoms

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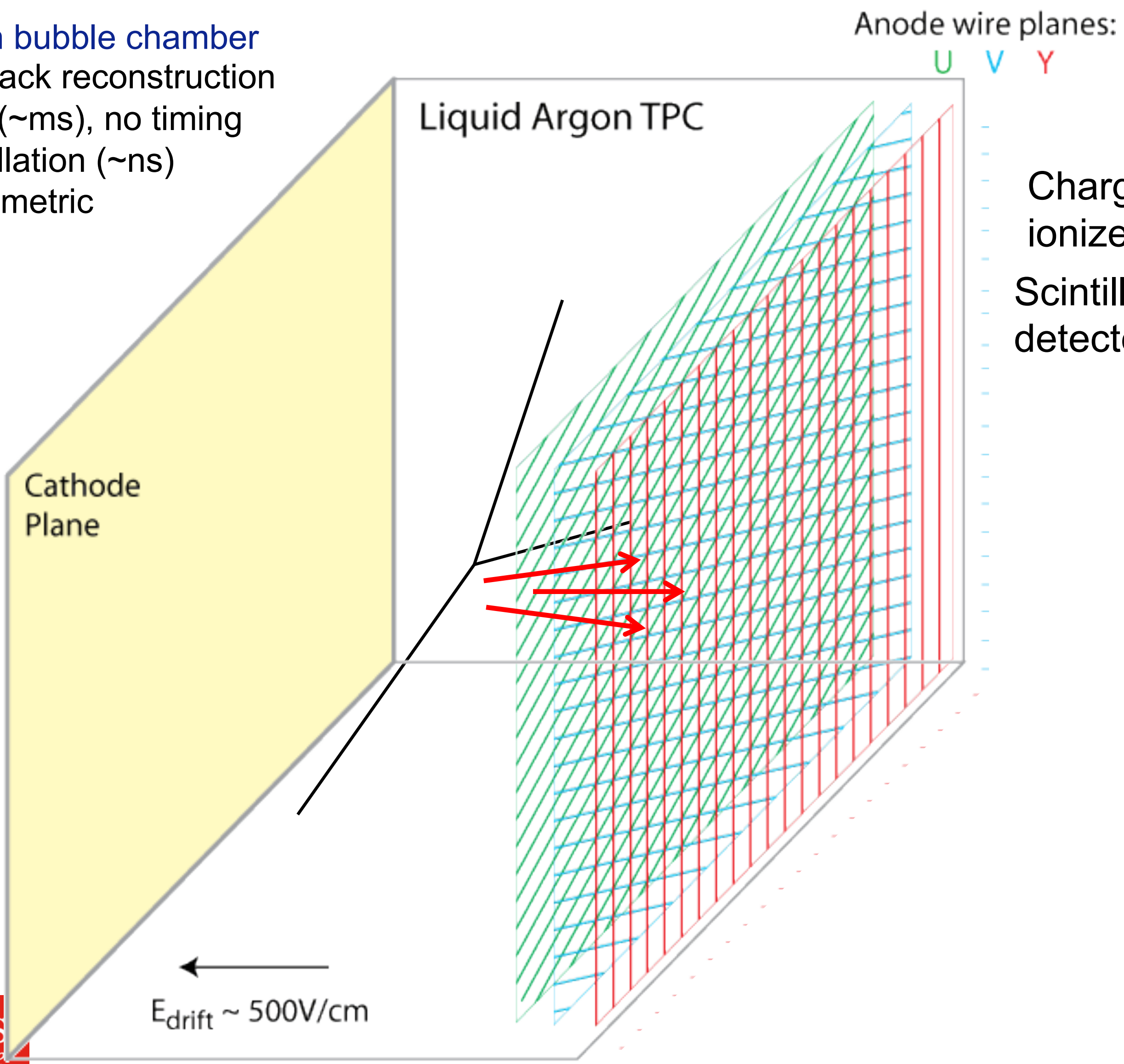
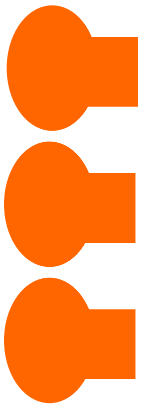


Charged particle tracks ionize Argon atoms

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



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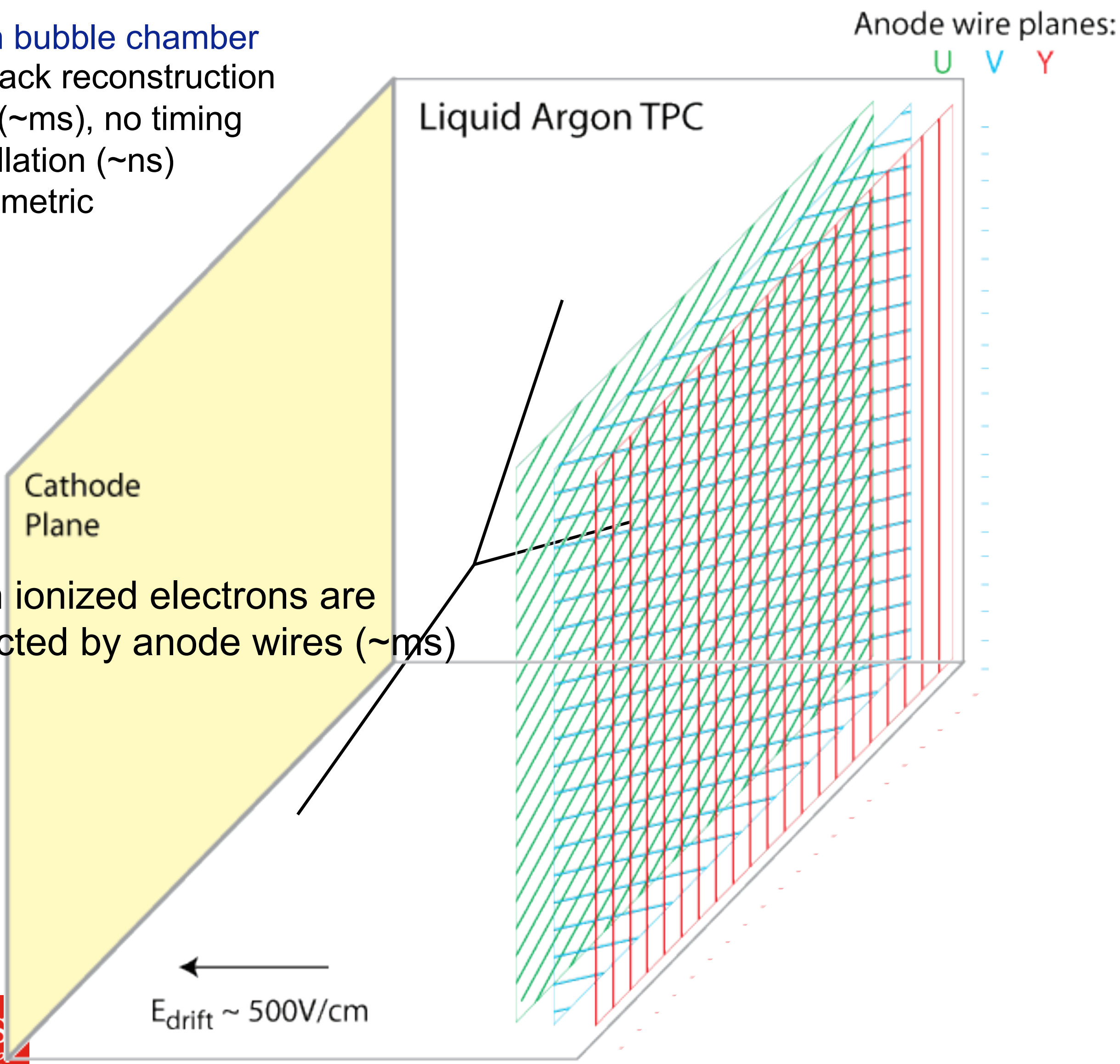

Then ionized electrons are collected by anode wires (~ms)

5. LArTPC

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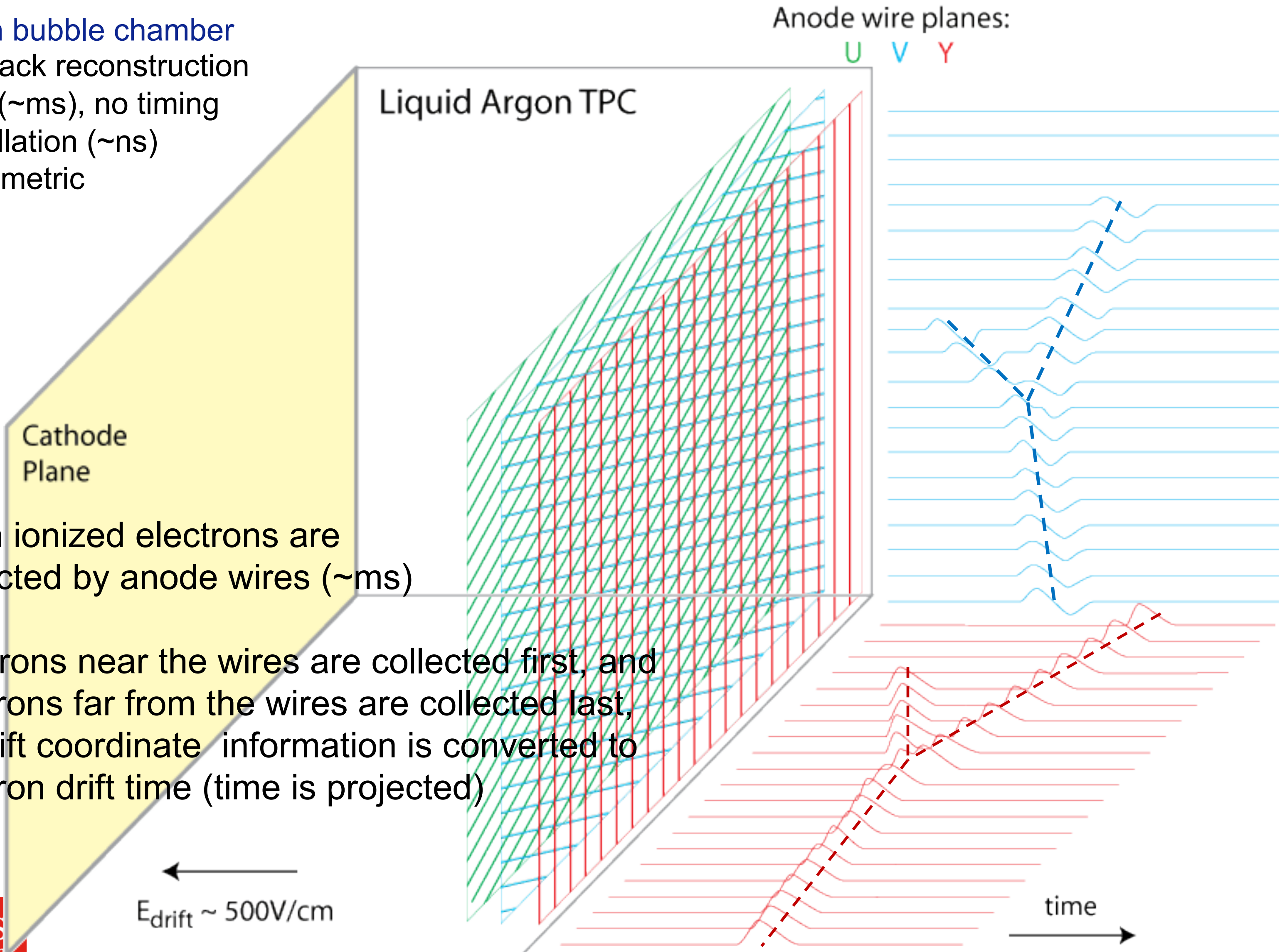
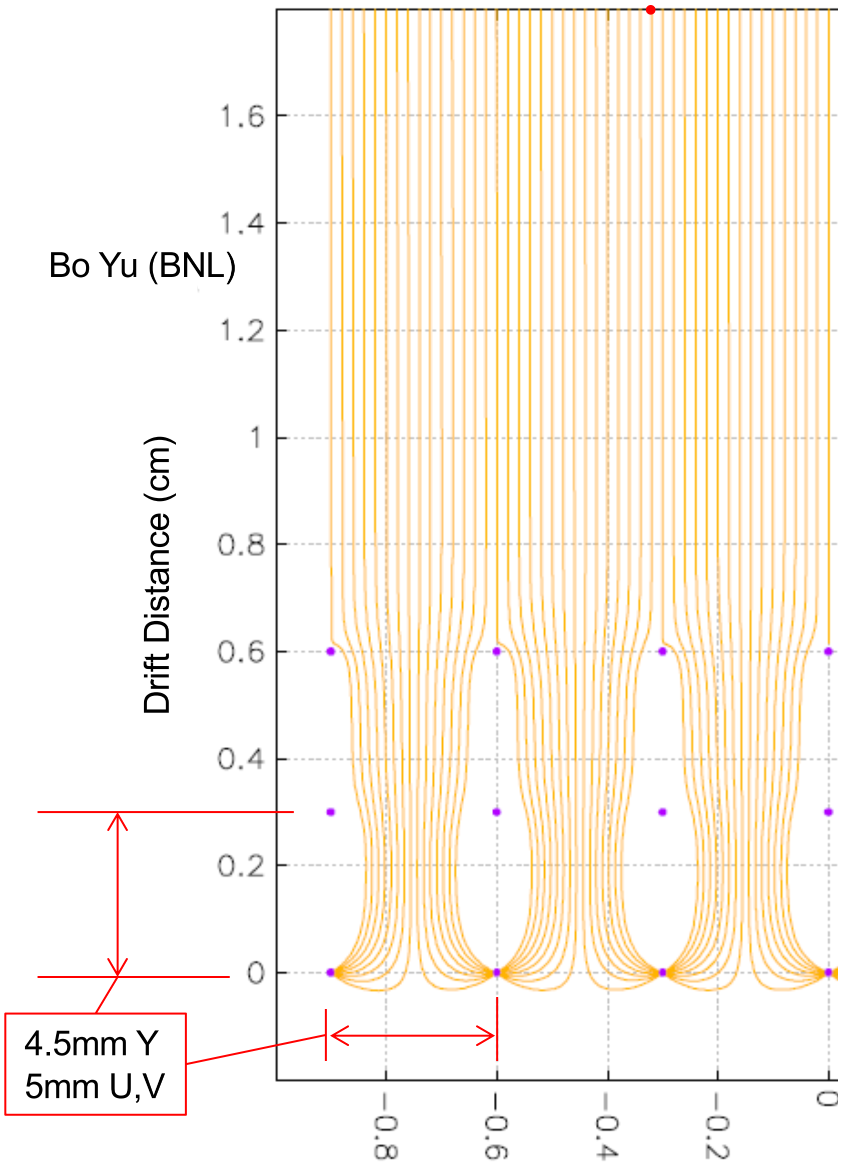
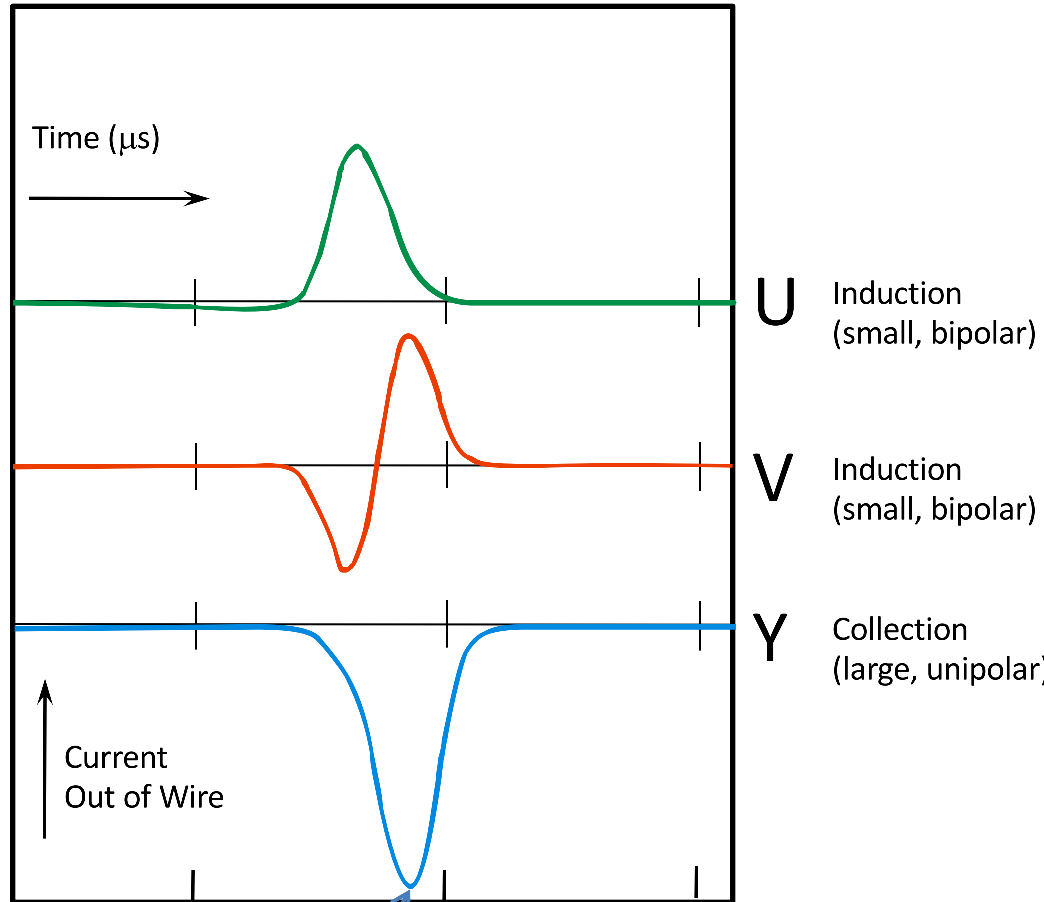


Then ionized electrons are collected by anode wires (~ms)

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)

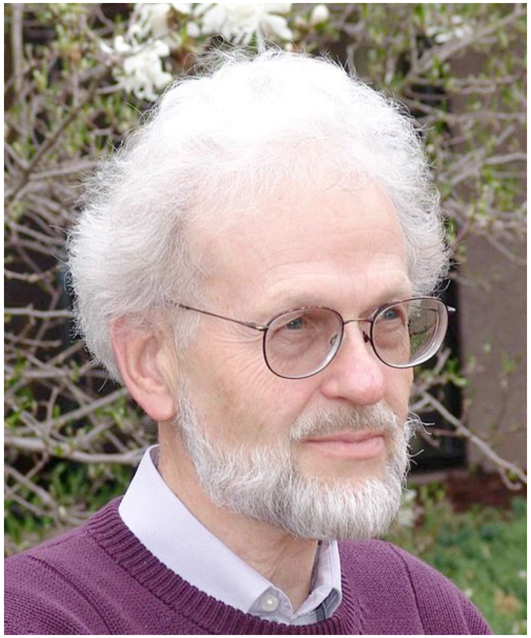
Charge Signal Formation





<u>ArgoNeuT</u>
1 MIP peak ~ 26 ADC counts
Noise rms ~ 1 ADC count

Living legends



Time Projection Chamber
David Nygren
(Berkeley lab → U. Texas, Arlington)

Liquid Ionization Detector
Veljko Radeka
(Brookhaven national lab)

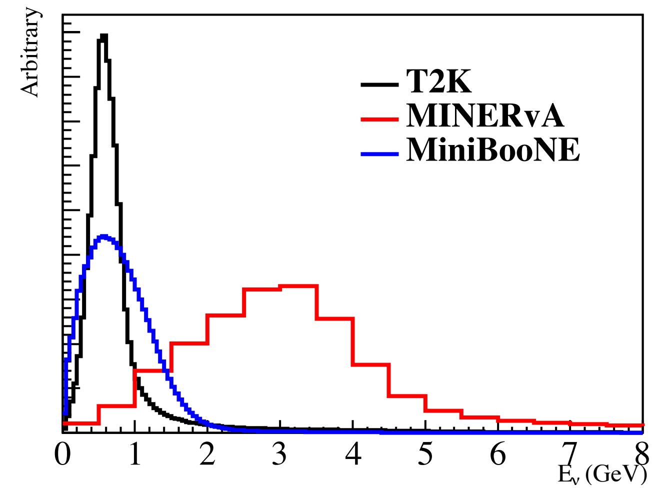
Liquid Argon Time Projection Chamber
Carlo Rubbia
(CERN → Senator of Italy)
Nobel Prize, 1984

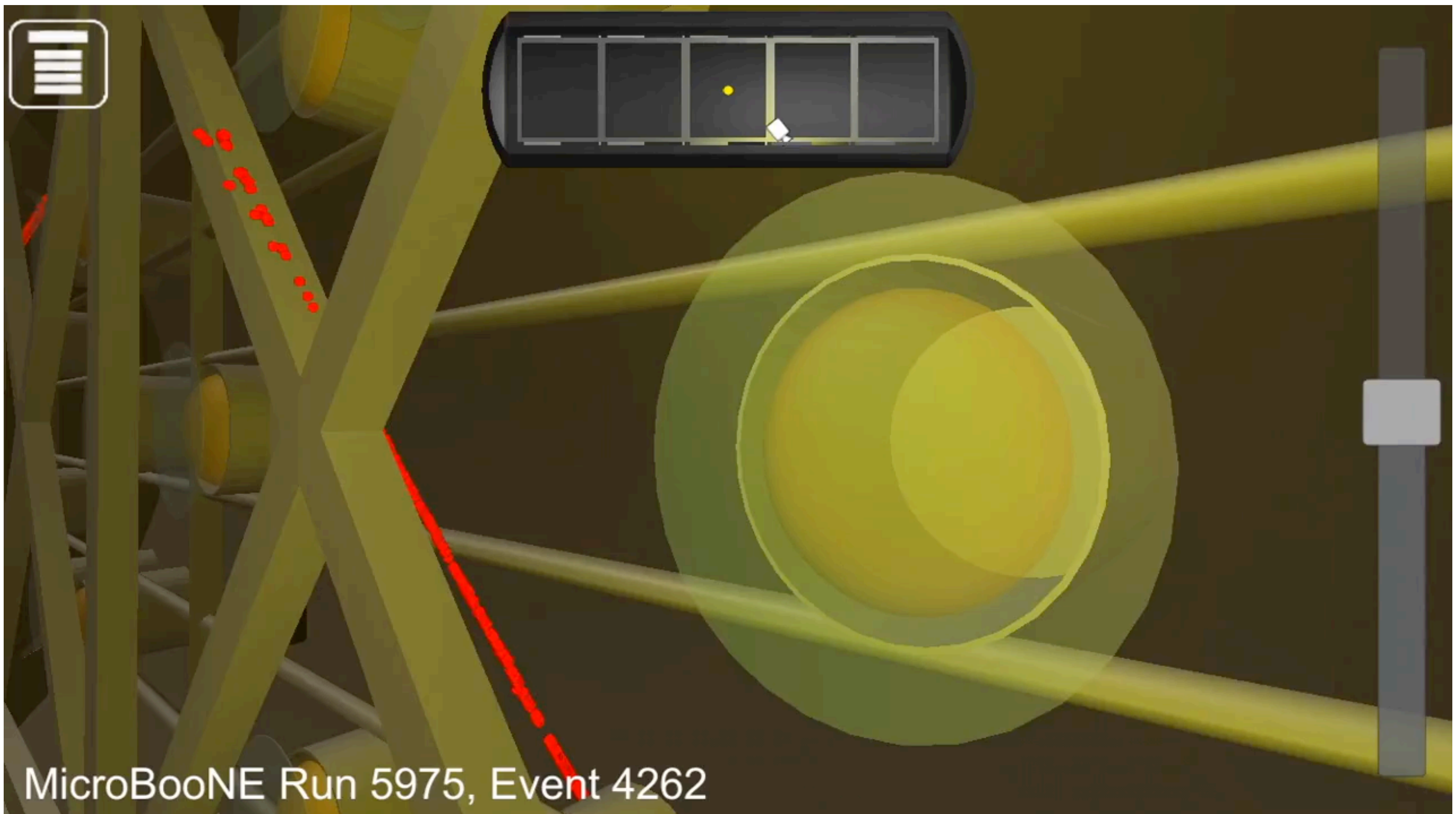
MicroBooNE, JINST12(2018)PO2017
VENu, http://venu.physics.ox.ac.uk/

5. MicroBooNE

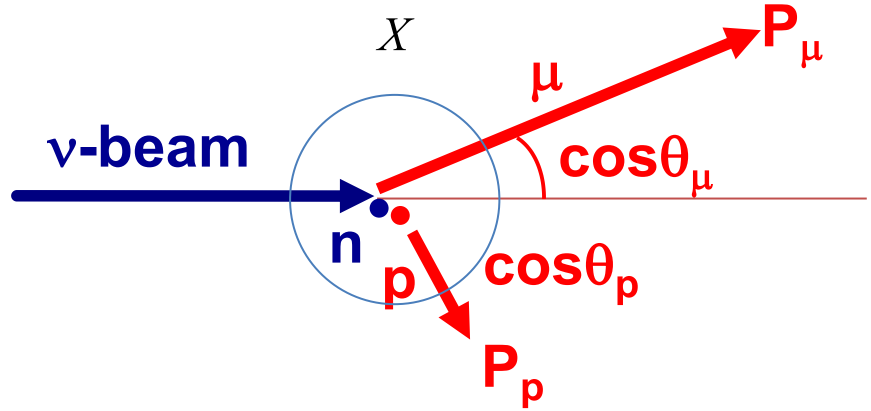
VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- smart phone app for MicroBooNE data

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…





5. MicroBooNE



86ton LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
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- photon detection system
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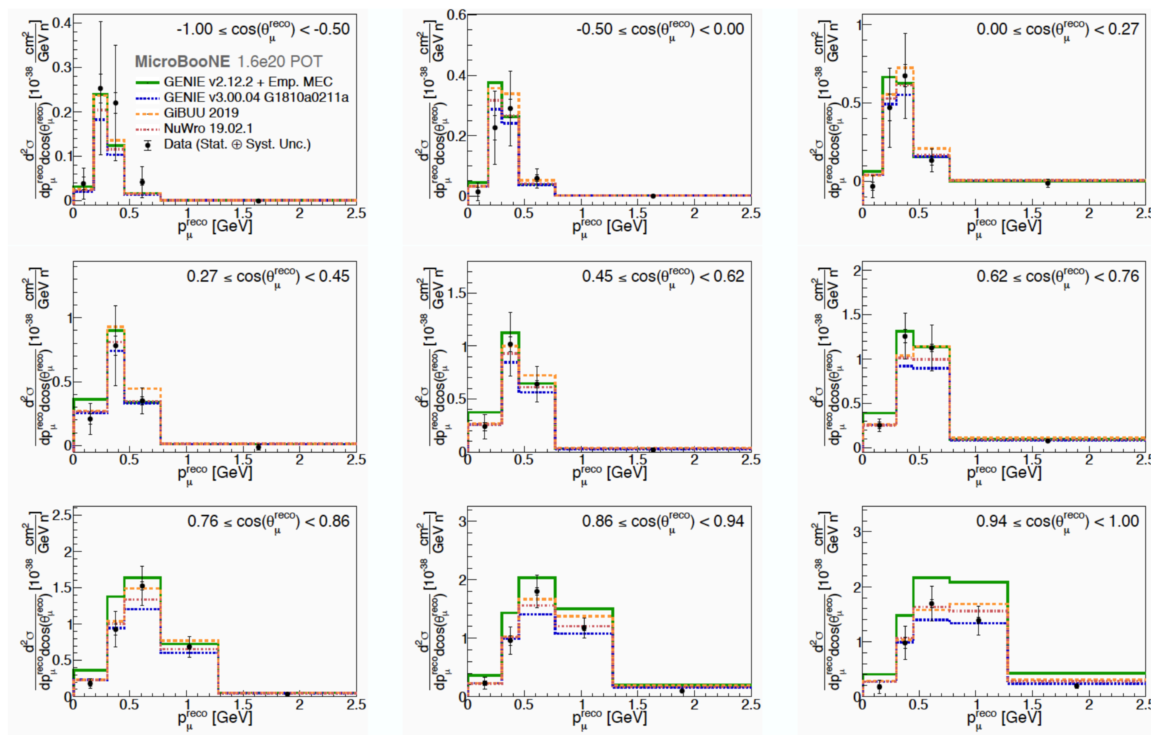
MicroBooNE CC inclusive differential cross section

Outgoing proton kinematics are measured to reconstruct Fermi motion

Multiple Coulomb scattering to estimate escaping muon energy

Large cosmic ray background, but mostly understood

Low statistics for hadron measurements...?



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

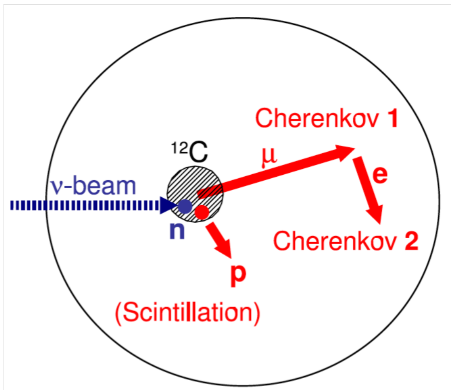
5. LArTPC

6. Conclusion

MiniBooNE,PRD81(2010)092005
Redij (T2K), NuInt15

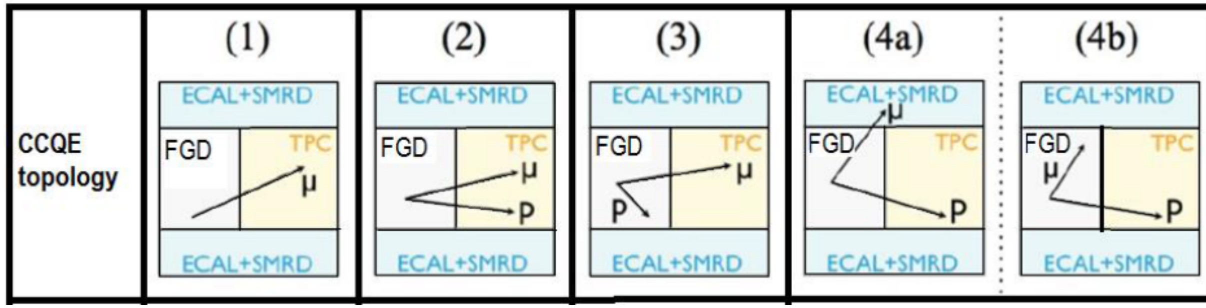
Type of neutrino detectors

Cherenkov neutrino detector
- MiniBooNE
- Super-Kamiokande



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

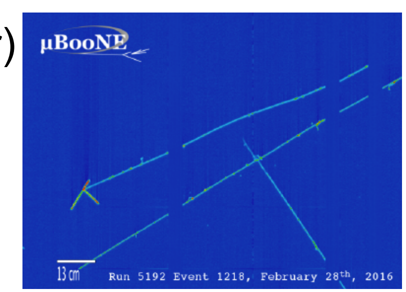
Tracker neutrino detector
- K2K, T2K near detectors
- MINERvA



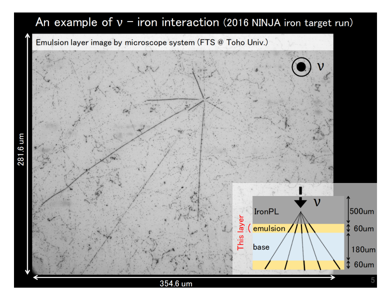
- multi-track measurements
- vertex activity measurement (high resolution)
- efficiency depends on topology

Scintillator detector
- KamLAND, SNO
- calorimetric

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



Emulsion detector
- NINJA (J-PARC), FASERnu (LHC)
- Similar ability with LArTPC
- no timing (off-line)
- Easy installation (tunnel, pyramid, etc)



KING'S College LONDON

最後までご静聴ありがとうございました。

質問その他 (日本語、英語): katori@fnal.gov
- この授業の内容について
- ニュートリノ反応一般
- ローレンツ不変性の破れについて
- アメリカ、イギリスの大学院、ポスドク、教職について
- その他何でも(恋愛、音楽、趣味)

Neutrino Scattering Theory-Experiment Collaboration
https://nustec.fnal.gov/
https://www.facebook.com/nuxsec
#nustec

Institute of Physics Astroparticle Physics group
https://www.facebook.com/IOPAPP/

Photo: Reider Hahn (Fermilab)