Nucleon correlations in neutrino oscillation experiments

1. Introduction
2. 2-body current in neutrino interactions
3. Neutrino oscillation experiments
4. Neutrino interaction measurements
5. Conclusion

Teppei Katori
Queen Mary University of London
CLAS data mining group meeting, MIT, MA, USA, Aug. 9, 2014

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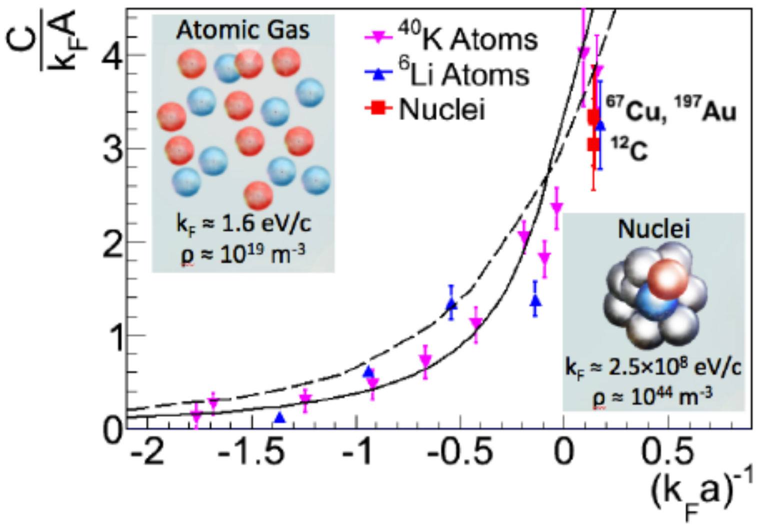
University of London

1. Unexpected connection...

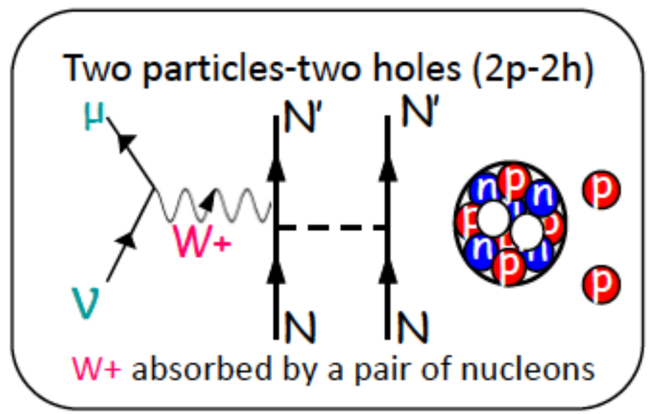
Atomic gas and nuclear gas

- They share same property in terms of "contact".



Short range correlation and neutrino oscillation experiments

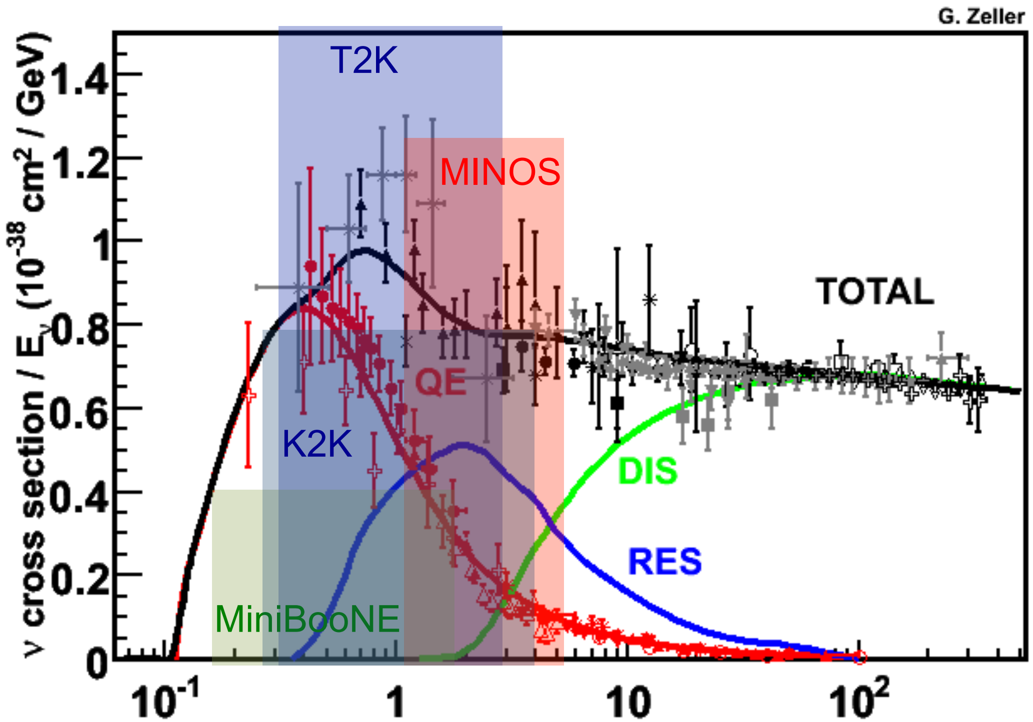
- Significant fraction of interaction(?)
- A correct model must be in our simulation



1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K
- Present to Future: T2K, NOvA, PINGU, JUNO, HyperK, LBNF



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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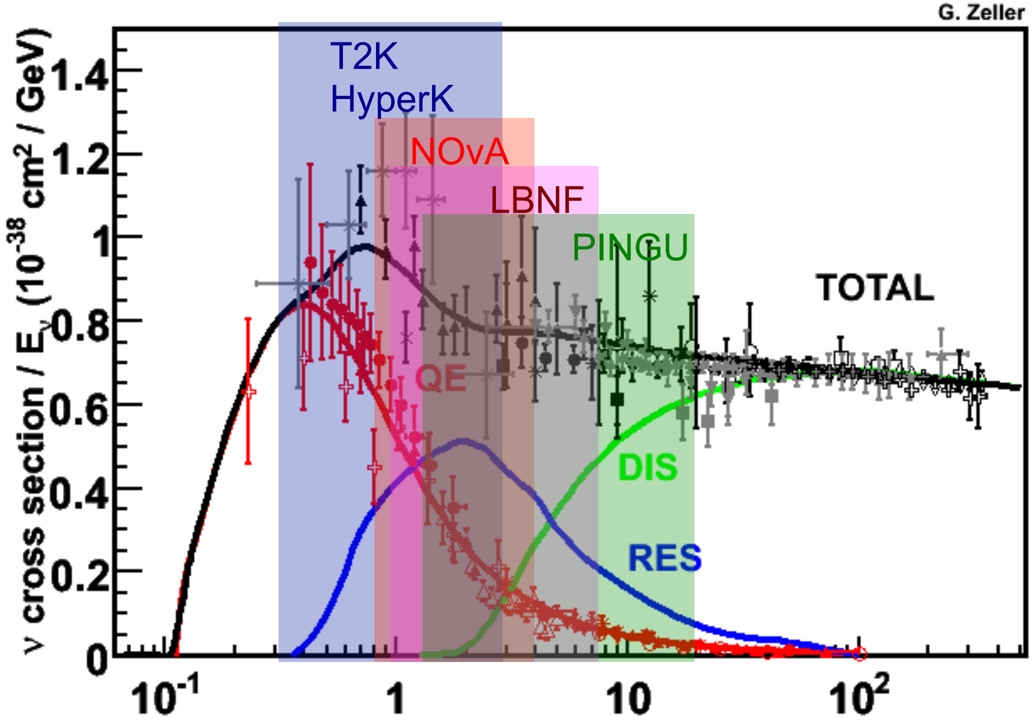
Typical oscillation experiment (L~100-1000km) always choose 1-10 GeV energy region (only exception is reactor neutrino experiment)



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1. Neutrino interaction model building

Adjust all vector response from available (e,e') data

e.g.) QE scattering (Fermi gas model)

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

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

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

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

1. Neutrino interaction model building

Adjust all vector response from available (e,e') data

known from (e,e') — known from (e,e') — tiny ($\sim m^2/M^2$) — less known from (e,e')

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Often used a free parameter (we do know $M_A\sim1$ from electro-π production data...)

QE: axial form factor is the only unknown part

Resonance: C_5^A form factor is the only unknown part, etc

1. Neutrino interaction model building

Adjust all vector response from available (e,e') data
→ all uncertainties are usually in axial part

1. Quasielastic
   - all vector form factors are from (e,e') data (BBA form factors)
   - axial form factor is the only unknown part
   - assuming dipole form, axial mass is the only one parameter with large error

2. Delta resonance
   - all vector form factors are from (e,e') data (MAID, for example)
   - axial form factors are reduced to one form factor (Adler's theorem)
   - C_5^A form factor is the only unknown part
   - assuming dipole form, axial mass and $C_5^A(Q^2=0)$ are the two parameters with large errors

How to choose these parameters is a part of "open questions of neutrino interaction physics"

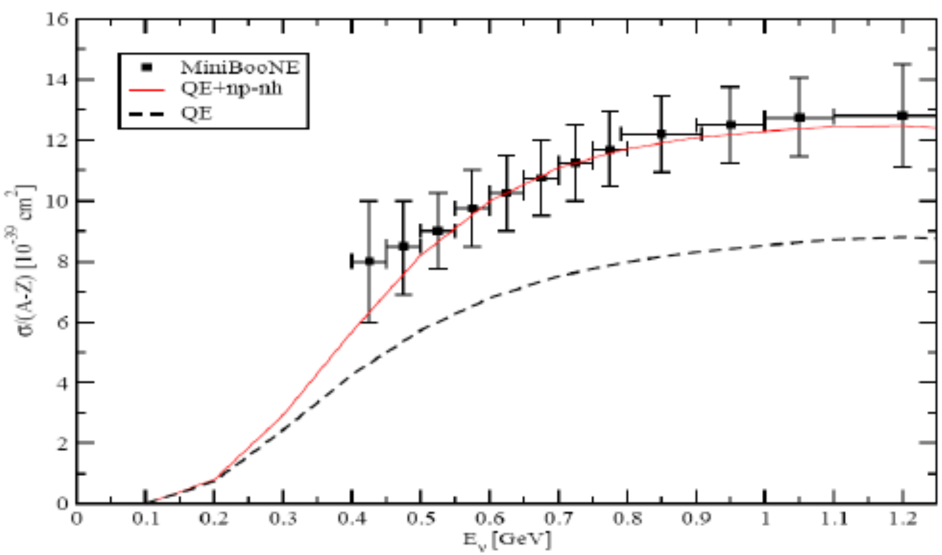
2. Presence of 2p-2h effect in neutrino interactions

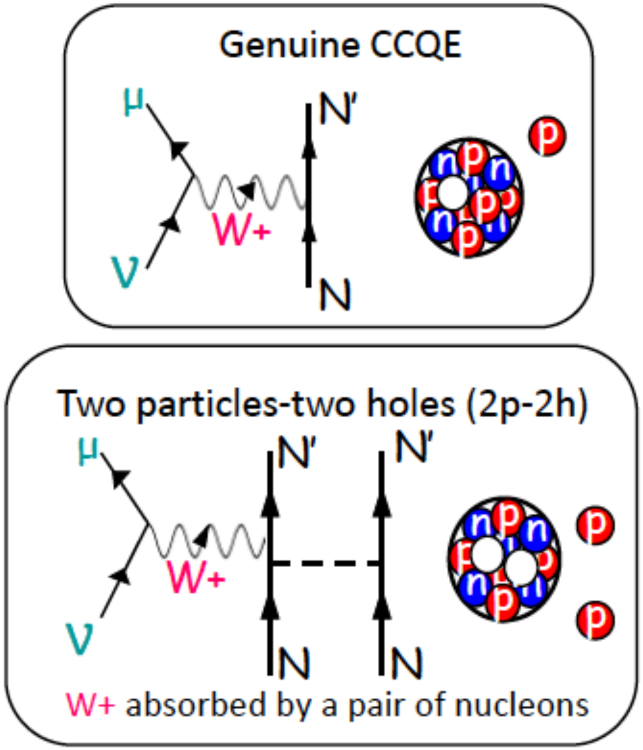
Neutrino oscillation experiments

- Many modern neutrino experiments (K2K, MiniBooNE, etc) show data is higher than prediction.
- Martini et al showed np-nh effect can add up 30-40% more cross section!

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)





M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

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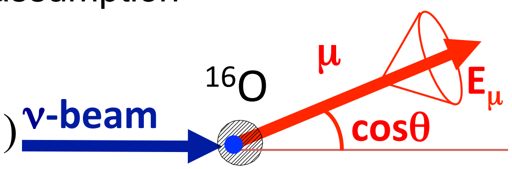
An explar

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

"QE assumption"

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



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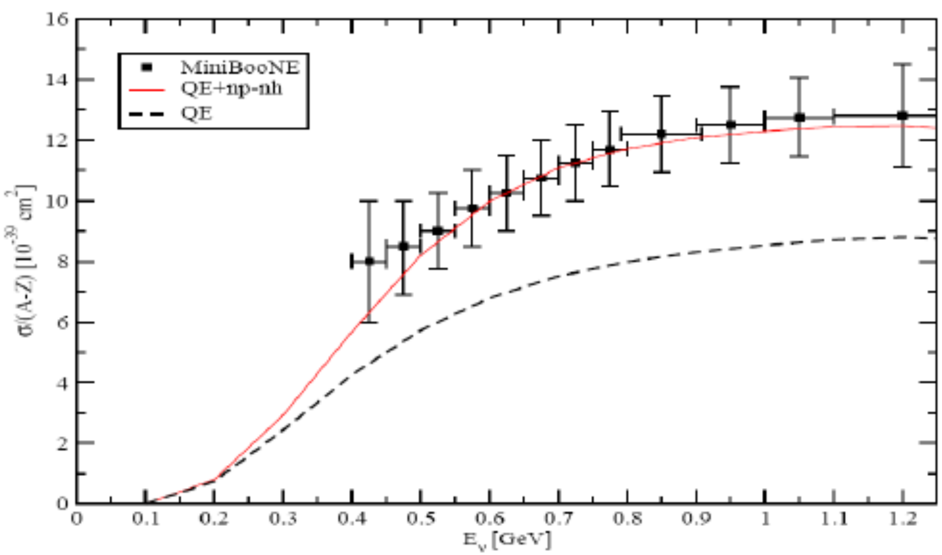

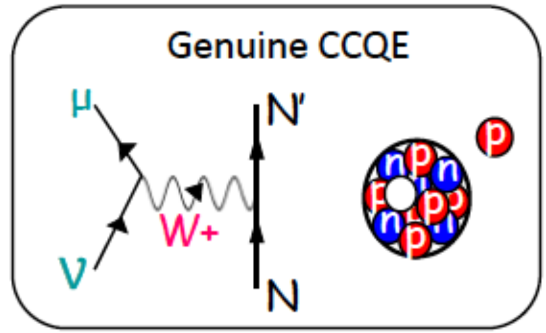

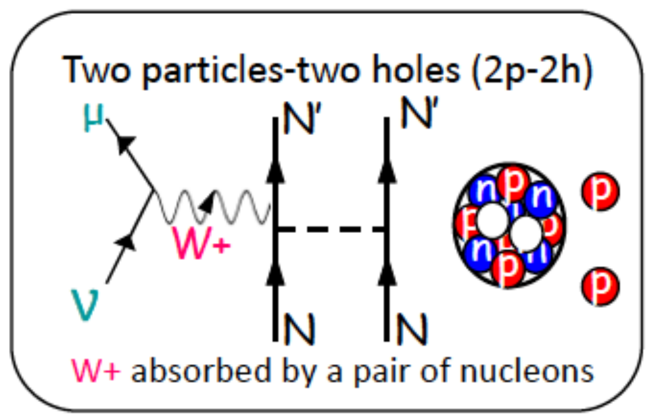

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Alvarez-Ruso,Hayato,Nieves,ArXiv:1403.2673
Nieves et al, PLB707(2012)72

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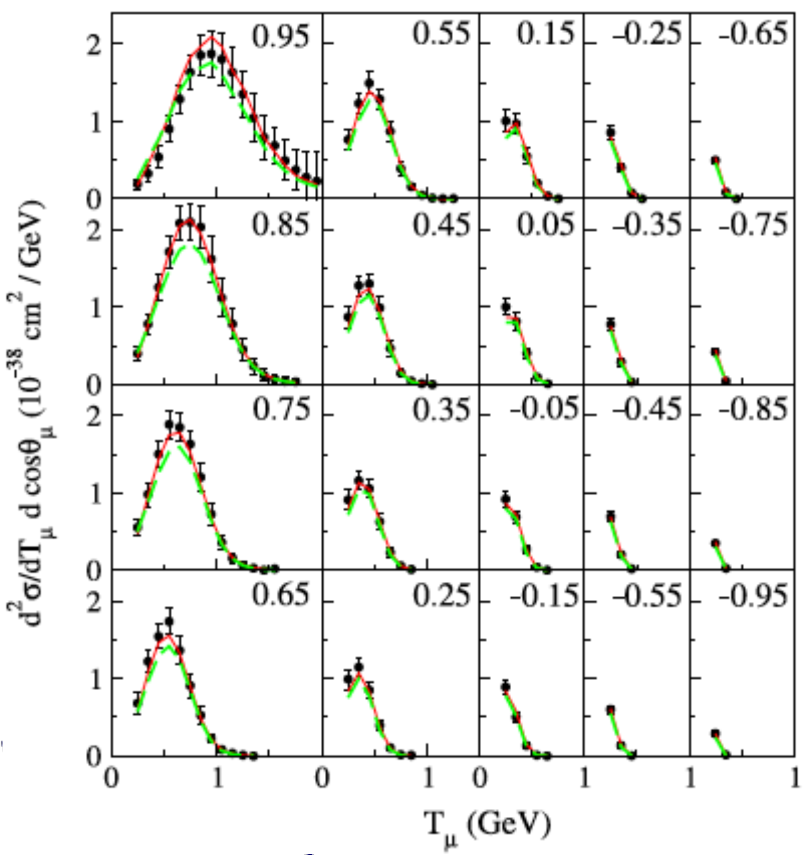
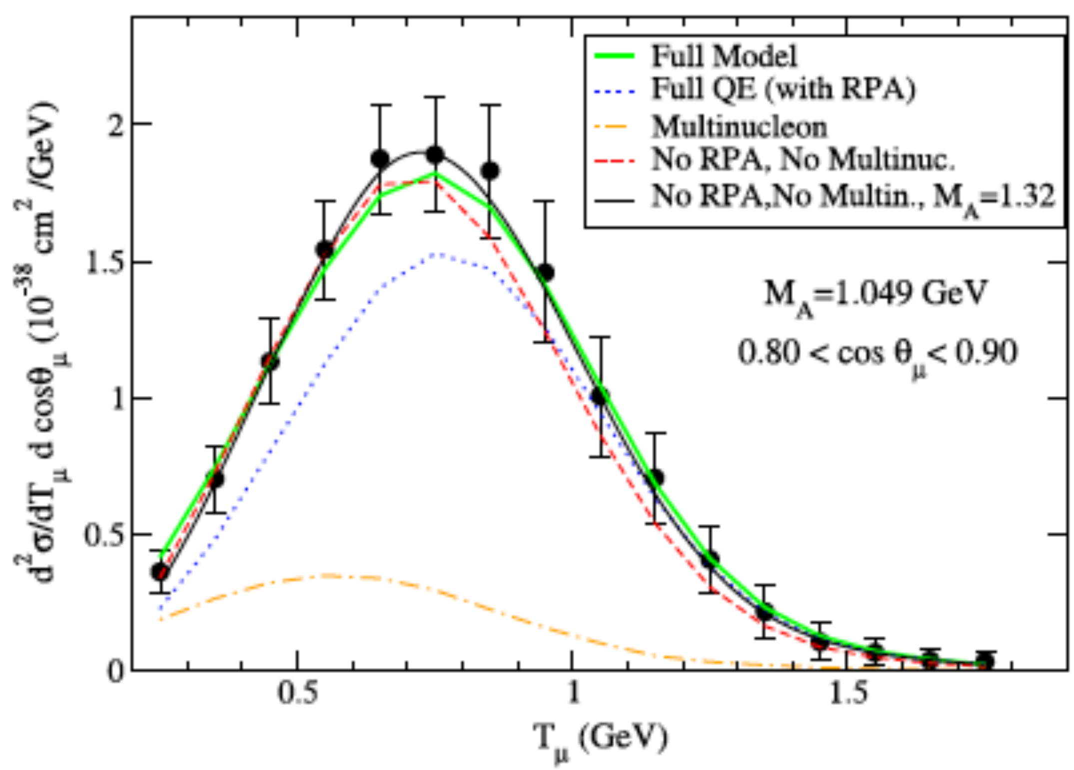
- Especially, MiniBooNE CCQE double differential cross section is explained by np-nh effect (and RPA)!





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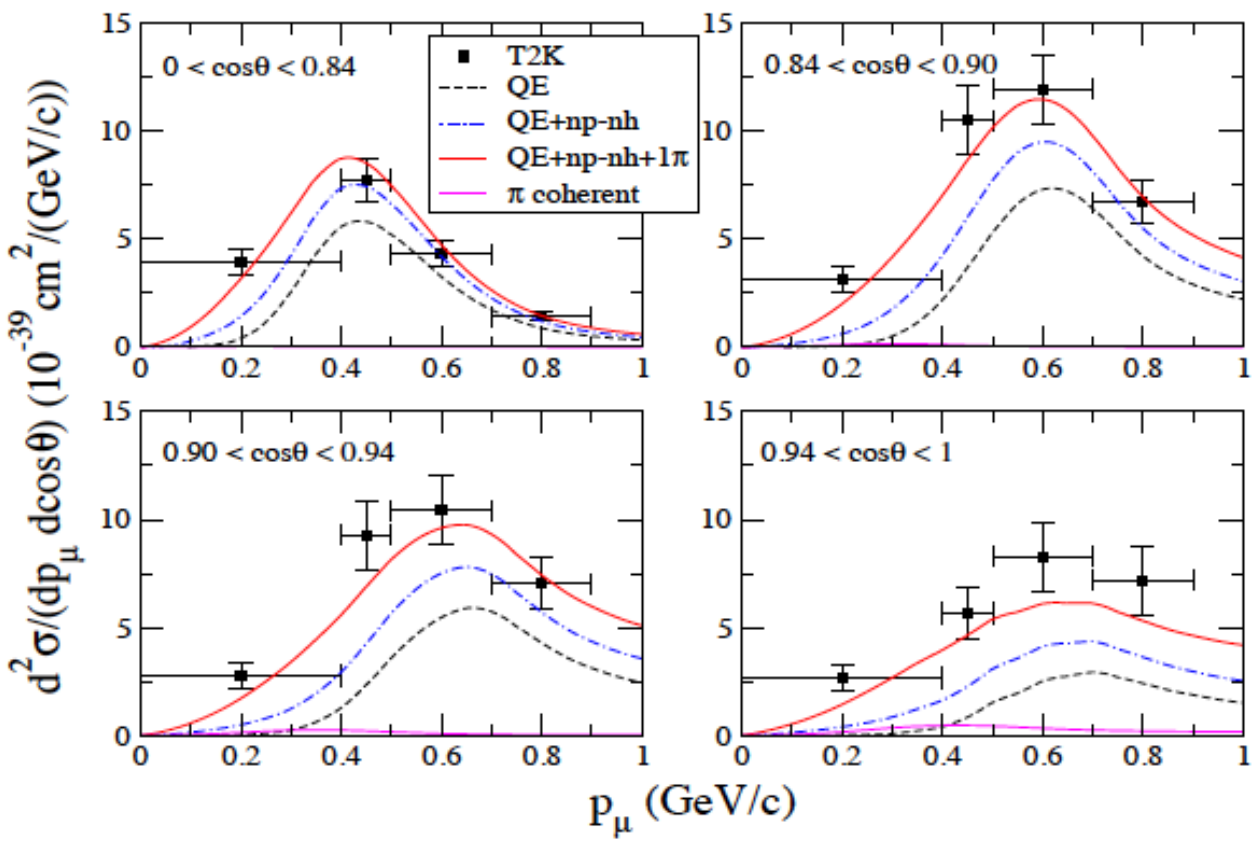

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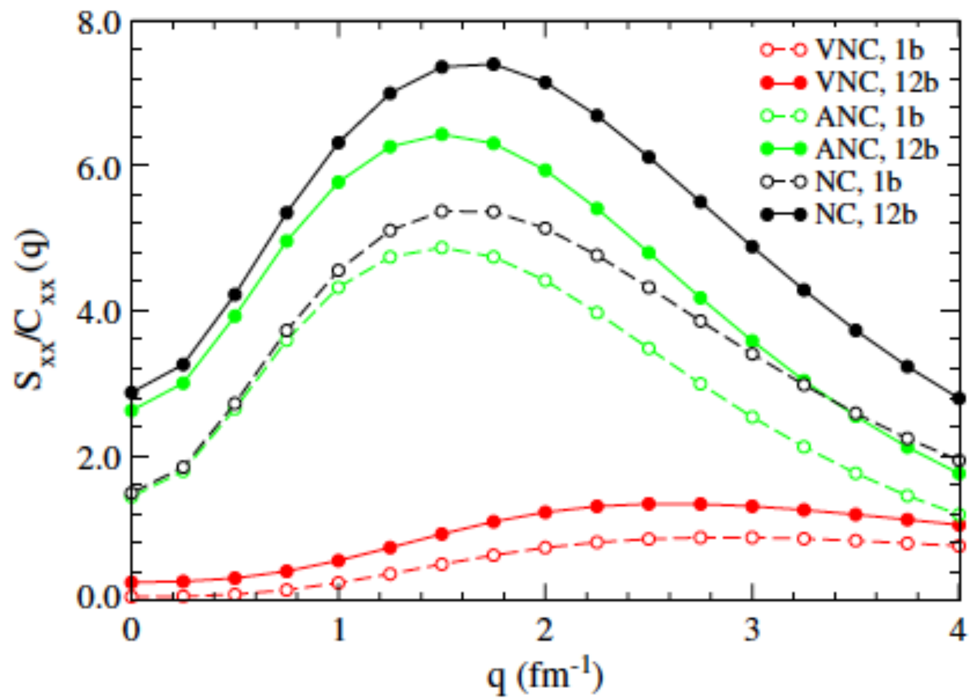
- Especially, MiniBooNE CCQE double differential cross section is explained by np-nh effect (and RPA)!
- Same model also describes T2K CC inclusive data (MiniBooNE flux prediction is right)
- Consistent result is obtained by standard nuclear physics approach (SNPA, ab initio calculation)

It is difficult to translate to experimental observables, but they observed a similar large tensor correlation in axial vector part.

This enhancement is dominated by T=0 n-p pair.

If all these are true, this effect must be included in the simulation for better prediction of neutrino interactions.



Martini et al, PRD85(2012)093012

3. Neutrino oscillation experiment

Super-Kamiokande and Hyper-Kamiokande

- Neutrino energy reconstruction is based on lepton kinematics, assuming CCQE interaction.
- 2p-2h contribution mimics CCQE, and cause mis-calculation of neutrino energy.

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

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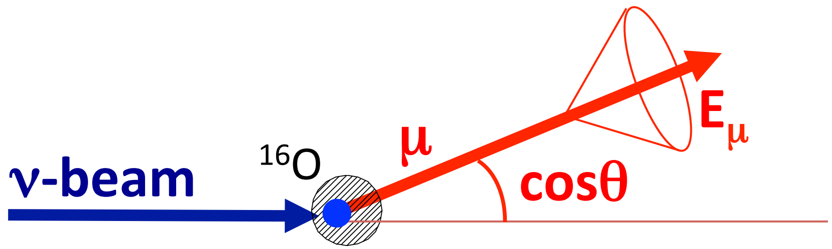
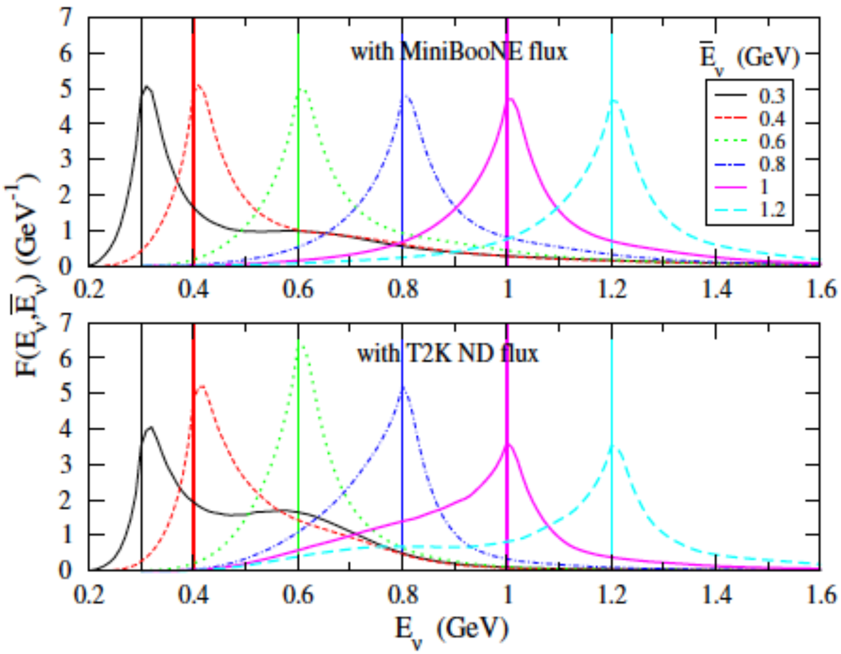
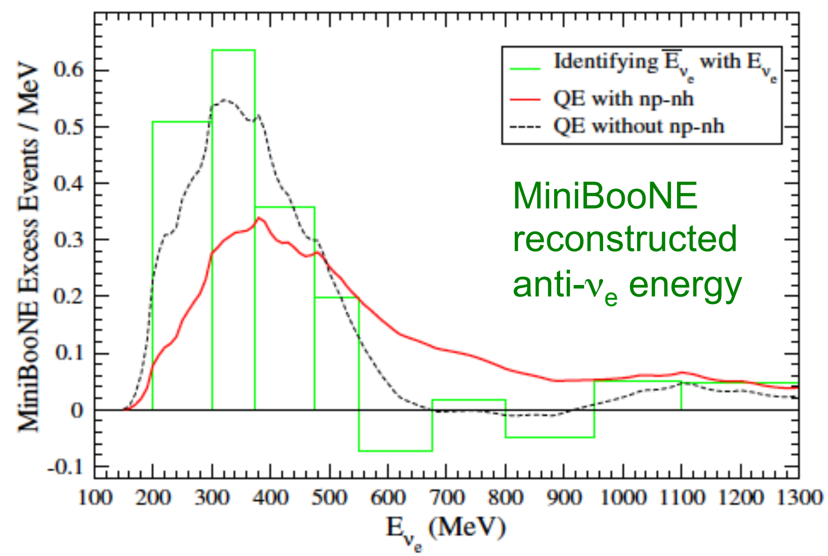






Palamara, NuInt12
ArgoNeuT, PRD90(2014)012008

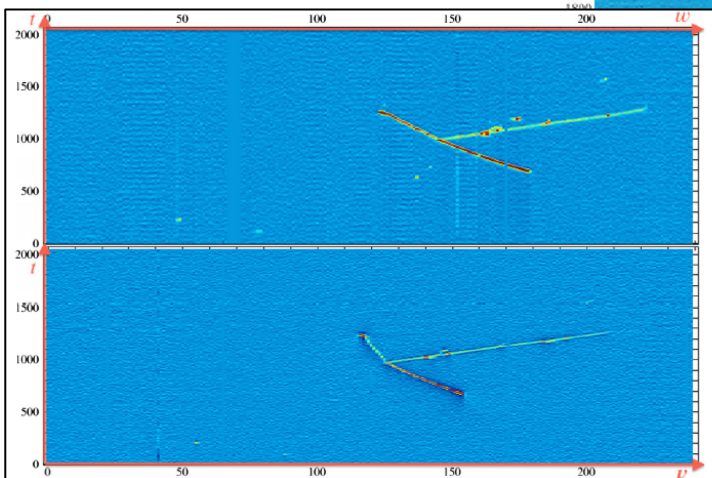
3. Neutrino oscillation experiment

LBNE (Liquid Argon TPC)

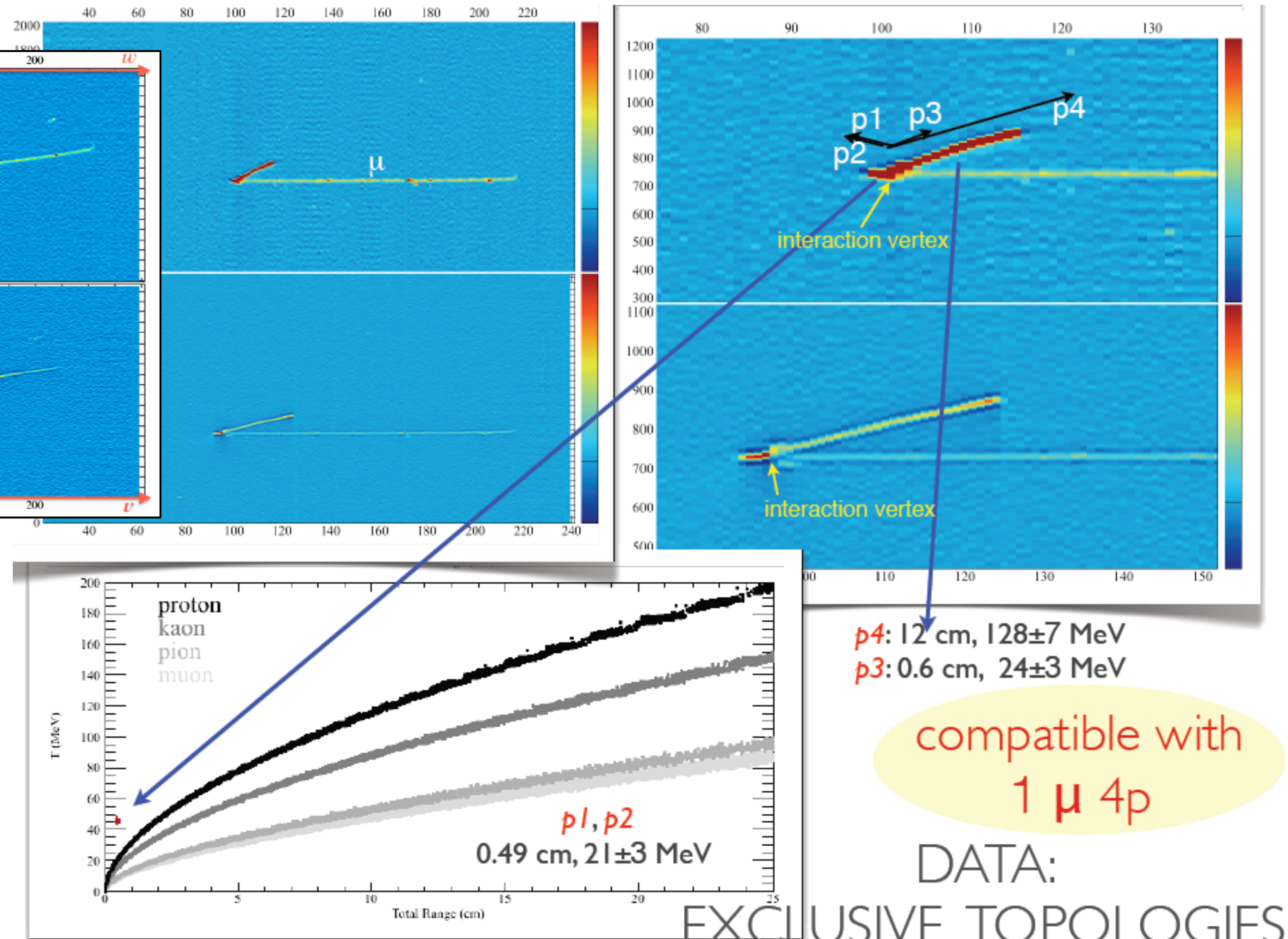
- They try to measure all outgoing hadrons, on top of the leading lepton

$$E_\nu = E_{lepton} + \sum E_{hadron}$$

- Neutrons are worry (we are 4 GeV, energy carried away by neutrons are significant)
- Study is on-going to understand outgoing nucleons (exclusive topological cross section)



$$\nu_\mu + (n-p) \to \mu^- + p + p?$$



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4. Neutrino-induced 2 nucleon emission

Charged-current NNSRC

$$\nu_\mu + (n - p) \to \mu^- + p + p$$

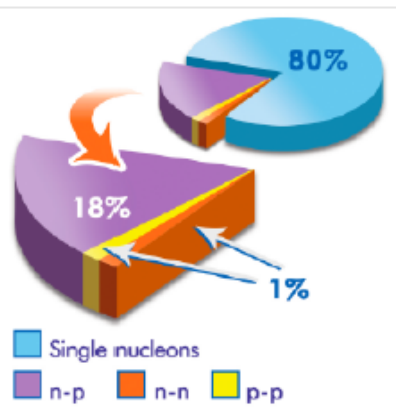
- Naively we expect 2 outgoing protons (easier than (e,e') experiment?!)
- General structure is known from (e,e') experiments

Theory overview on neutrino-nucleon (-nucleus) scattering
└Theoretical models
 └Correlations

Nucleon correlations

^{12}C From (e,e'), (e,e'p), and (e,e'pN) Results

- 80 +/- 5% single particles moving in an average potential
  - 60 – 70% independent single particle in a shell model potential
  - 10 – 20% shell model long range correlations
- 20 +/- 5% two-nucleon short-range correlations
  - 18% np pairs (quasi-deuteron)
  - 1% pp pairs
  - 1% nn pairs (from isospin symmetry)
- Less than 1% multi-nucleon correlations



INT Workshop 4 December 2013

Jefferson Lab

from Higinbotham

26 / 42

Sobczyk, PRC86(2012)015504
Katori, arXiv:1304.6014

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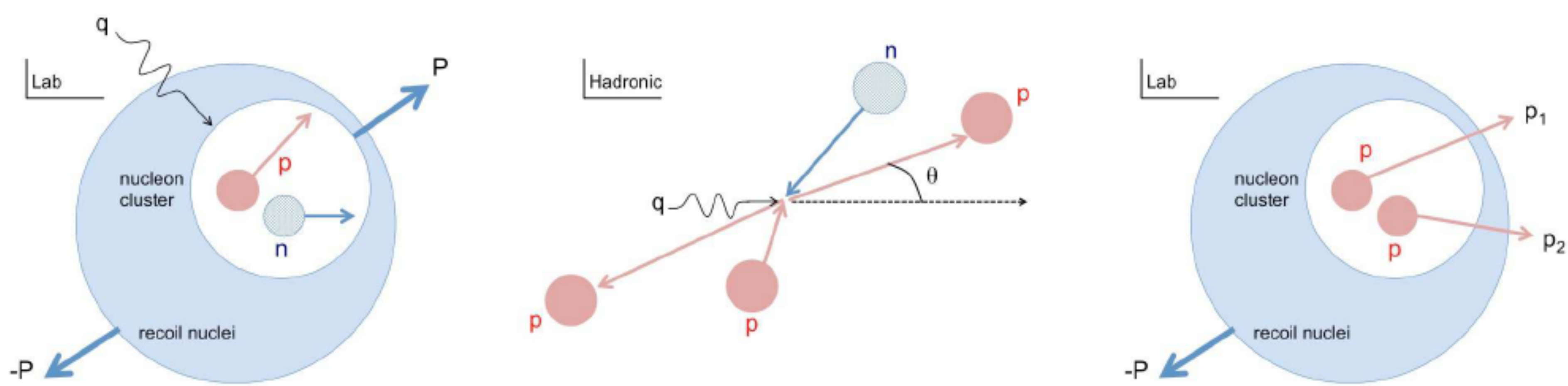
Nucleon cluster model

- Based on these information, we simulate 2-nucleon emission in our MC
- energy-momentum vector and 2 nucleons make center mass system (hadronic system)
- isotropic decay is boosted back, to simulate 2 outgoing nucleons
- here, (n-p) pair is maybe 80% or so, but higher than (n-n) or (p-p) pairs.



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What neutrino interaction community want to know

→ Any knowledge to improve this picture

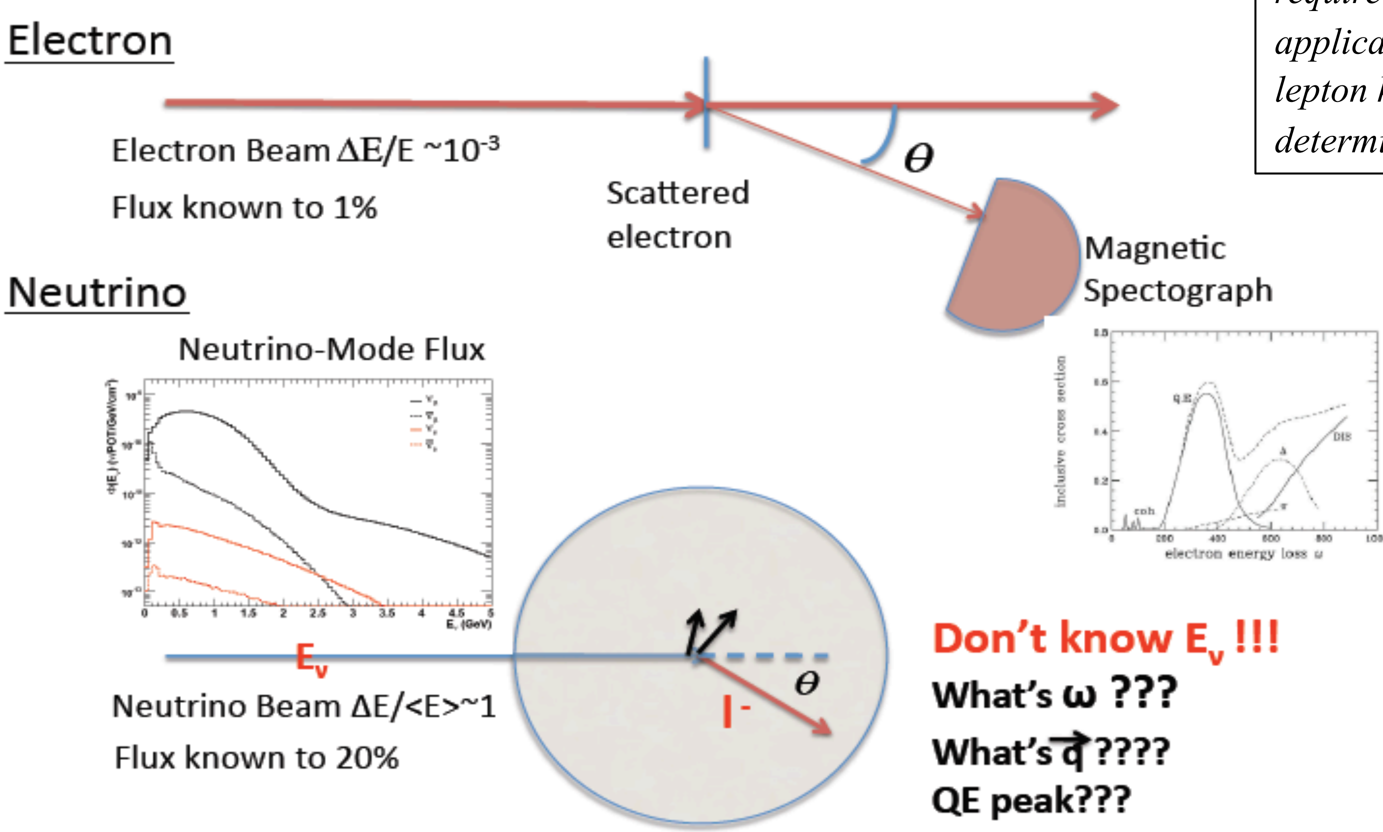
4. Neutrino interaction measurement

In neutrino physics, we don't know the energy of incoming neutrino

- We don't have ω and |q| (and initial nucleon momentum, light-cone fraction, etc)
- We need a model works fine in all kinematic space

"description of neutrino data will require a new paradigm, suitable for application to processes in which the lepton kinematics is not fully determined" - Benhar

Contrast of e-N with ν-N Experiments



Very Different Situation from inclusive electron scattering!!

4. Neutrino interaction measurement

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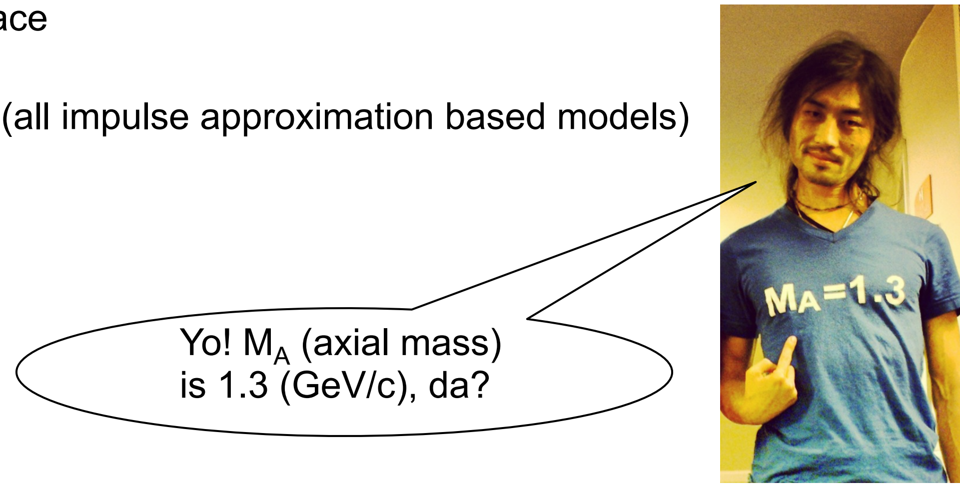
This fact tricked many successful nuclear models (all impulse approximation based models)



Spectral function

- It cannot describe low q region and dip region.

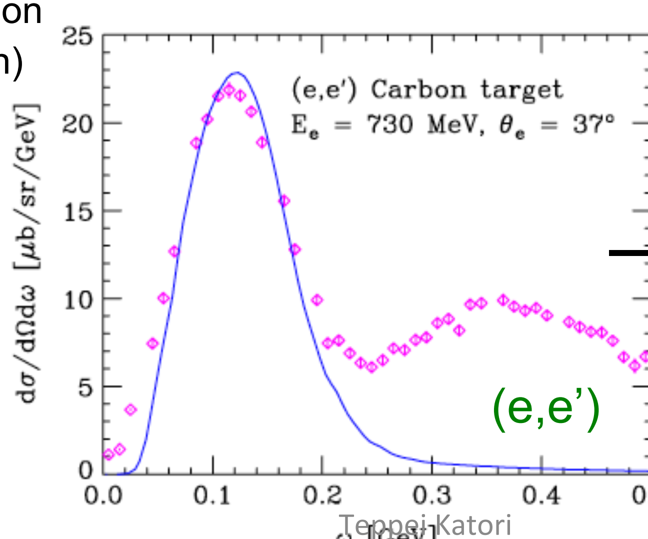
(new model takes into account low q region)

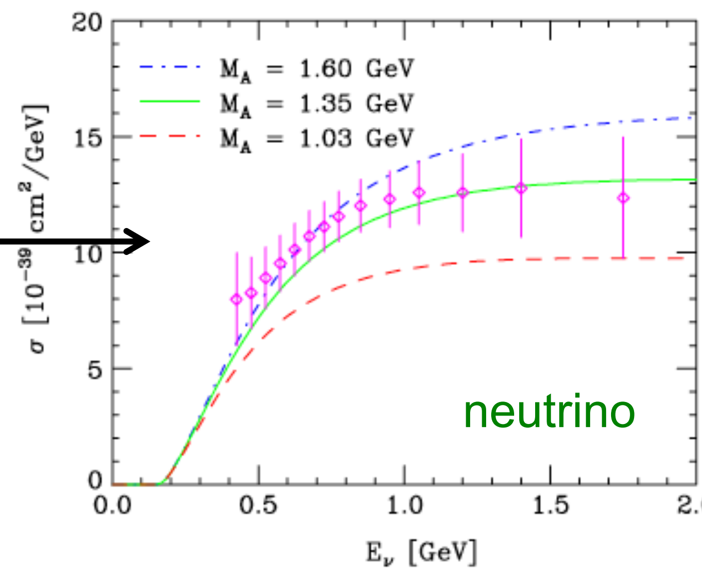
Superscaling

- It cannot describe low q region.
- $f_L = f_T$ is a bad assumption

(new model include 2p2h)

DWIA, etc





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5. Conclusion, what we want to know...

Isospin

- Is 20% (n-p) pair reasonable? Is there any energy dependence?

(ω-|q| dependence is not measureable, but we can put in simulation, if we know that is right)

Momentum sharing

- Is it isotropic? can sometimes one nucleon takes more energy-momentum? if so, what kind of distribution is that?
- Are initial momentums back-to-back? can sometimes deviate? if so, what kind of distribution is that?
- Is there any energy dependence in this picture?

Separation energy

- Is there any "cost" to liberate (n-p) pair? are both nucleons on-shell?

Nuclear explosion

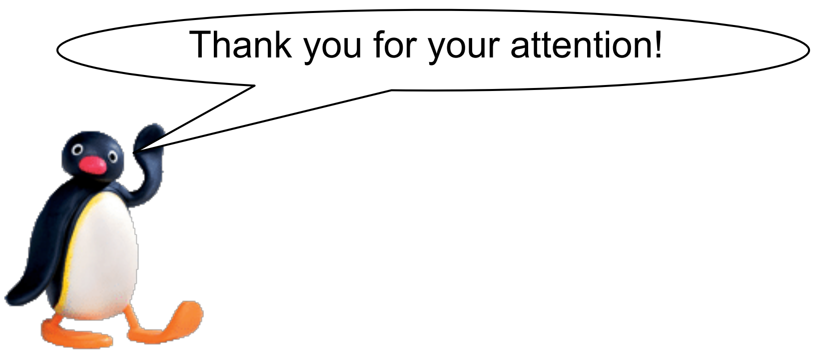
- In fact, LArTPC can measure de-excitation gamma rays (<1 MeV) from the nuclear remnant. This is a great advantage of vertex detector (=neutrino experiment) than arm spectrometer (electron experiment). Any there any predictions for that? 2 nucleon emissions should leave nuclei more unstable...

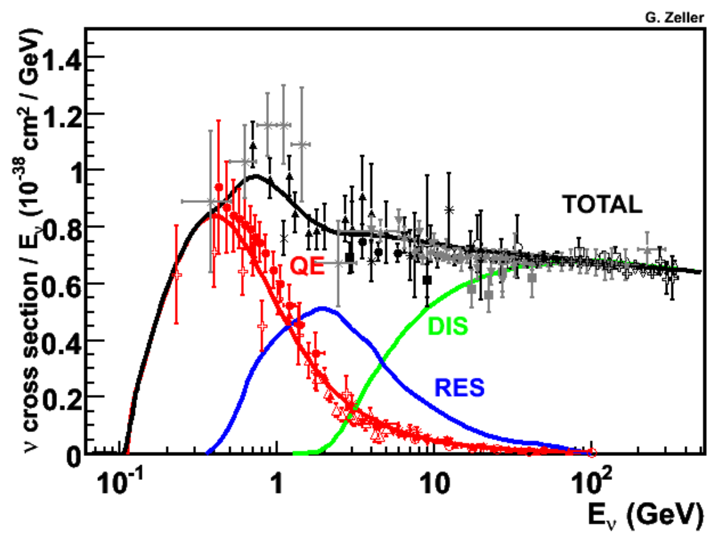
5. Conclusion, nuclear model we want

Interaction type
- It should work on all interactions, QE, resonance, transition, to DIS
- T2K, MicroBooNE=QE dominant, NOvA, LBNE=resonance dominant, PINGU=DIS dominant

Kinematic region
- It should work in all kinematic space, low ω-|q| to high ω-|q|.
- Too low ω (most of models break down) and too high |q| (many RPA approaches fails) can be ignored?

Target material
- It should work on heavy element, Fiducial volume is made by carbon, water, argon, etc, but the surrounding material is made of heavier elements (and they produce more interactions)



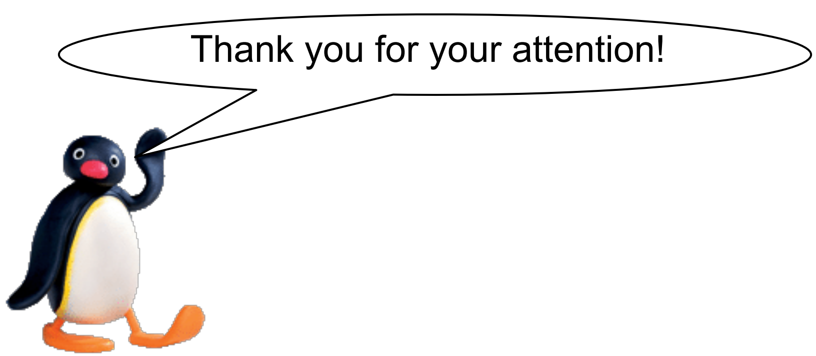


5. NuSTEC collaboration

NuSTEC School at Fermilab, Oct. 20-30, 2014
- NuSTEC is CTEQ-like collaboration to improve neutrino interaction models
- School is designed for an introduction to both nuclear and particle physics of neutrino-nucleus scattering
- Ideal for experimental and theoretical advanced graduate students and young postdocs

http://nustec2014.phys.vt.edu/

Lecturers
Luis Arvarez-Ruso (IFIC), Rocco Schiavilla (ODU), Bill Donnelly (MIT), Juan Nieves (IFIC), Omar Benhar (Roma), Toru Sato (Osaka), Pawel Danielewicz (MSU), Jeff Owens (FSU), Pilar Coloma (FErmilab), Tom Dealty (Oxford), Mitch Soderberg (Syracuse), Chris Mauger (Los Alamos)



Neutrino Cross-Section Newsletter
- Teppei Katori's one-person journal club
- Discuss the latest papers (both theory and experiment)
- news around the neutrino cross-section community
- 1 or 2 per month, depending on how many new papers

https://pprc.qmul.ac.uk/~katori/nu-xsec.html