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Spin physics

nuclear many-body problem

Leptonic CP violation

Neutrino oscillation

Weak interaction

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Nucleon correlation

EMC effect

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Dark matter

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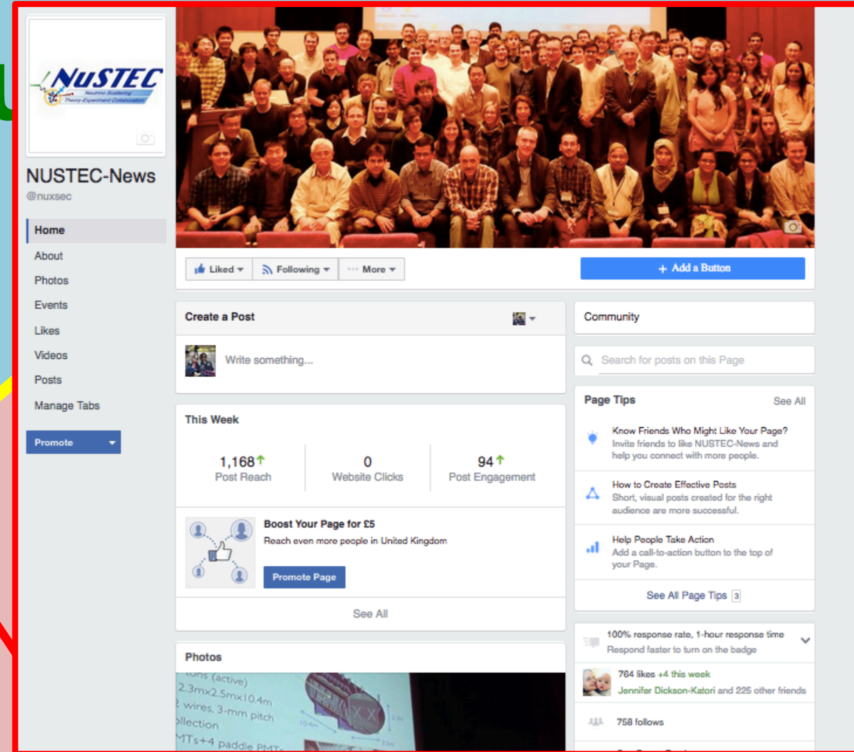

nuclear many-body problem

Neutrino oscillation

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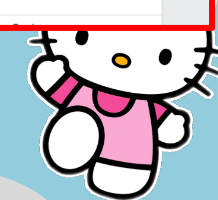

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BREAKTHROUGH PRIZE

"Year of Neutrinos"

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

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

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

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

Arthur B. McDonald

Prize share: 1/2

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

TK, Martini, JPhysG45(2017)1

Physics for Accelerator-based Neutrino Oscillation experiments

Teppei Katori
Queen Mary University of London
ECT* workshop, Trento, April 27, 2018

outline

1. Neutrino Interaction Physics
2. Charged-Current Quasi-Elastic (CCQE) interaction
3. Conclusion

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1. Neutrino Interaction Physics

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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

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

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

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

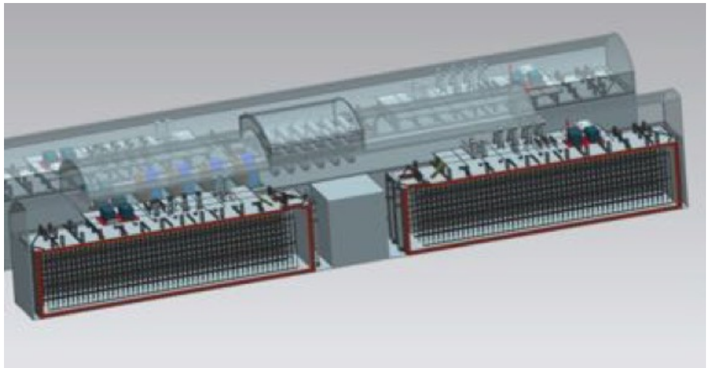
We need higher precision experiments around 1-10 GeV.

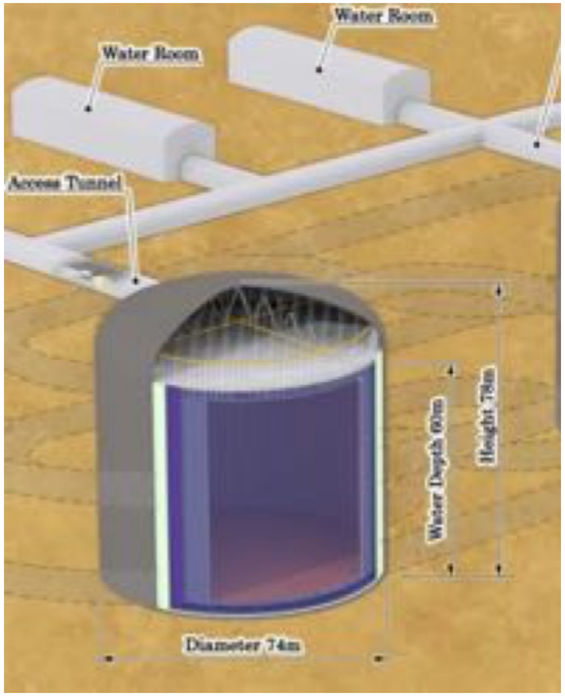
$$P_{\mu\rightarrow e}(L/E)=\sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

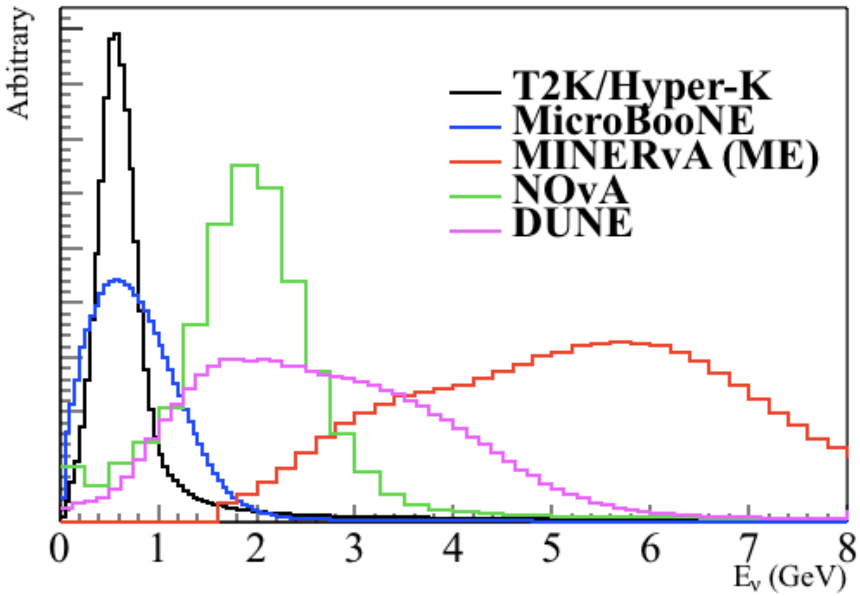
1. Hyper-Kamiokande and DUNE

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

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





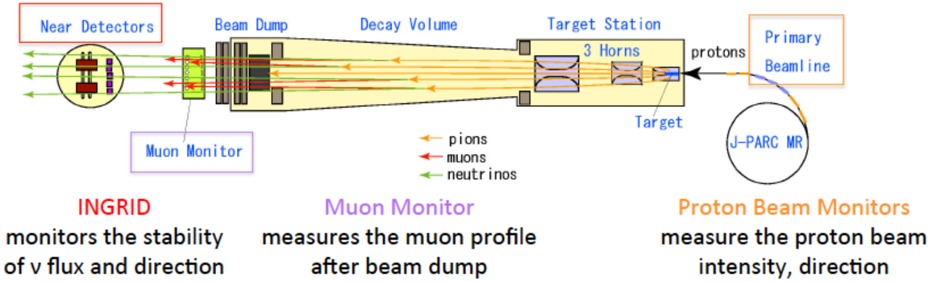


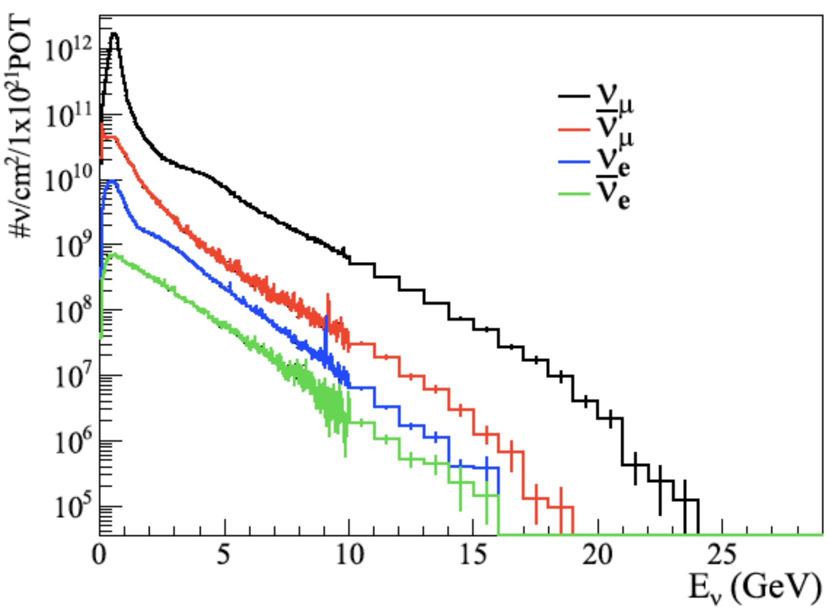
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

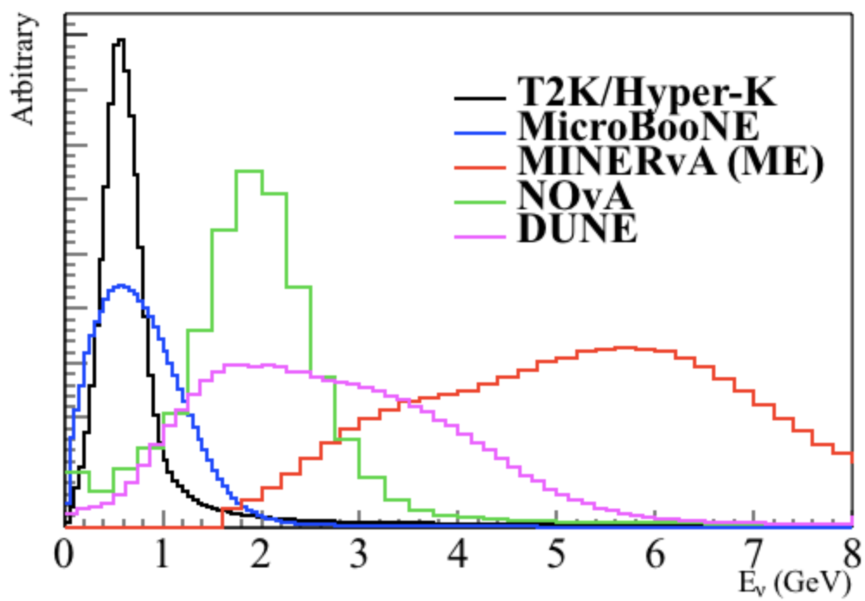
TK, Martini, JPhysG45(2017)1
Kowalik, NuInt18 (Toronto)

1. Typical neutrino beams for oscillation experiments

e.g.) J-PARC neutrino beam (T2K)
- pion decay-in-flight (high flux)
- off-axis beam (narrow band)
- but has components up to ~ 10 GeV
- typical beam 1-10 GeV
- ~4% normalization error (best case)







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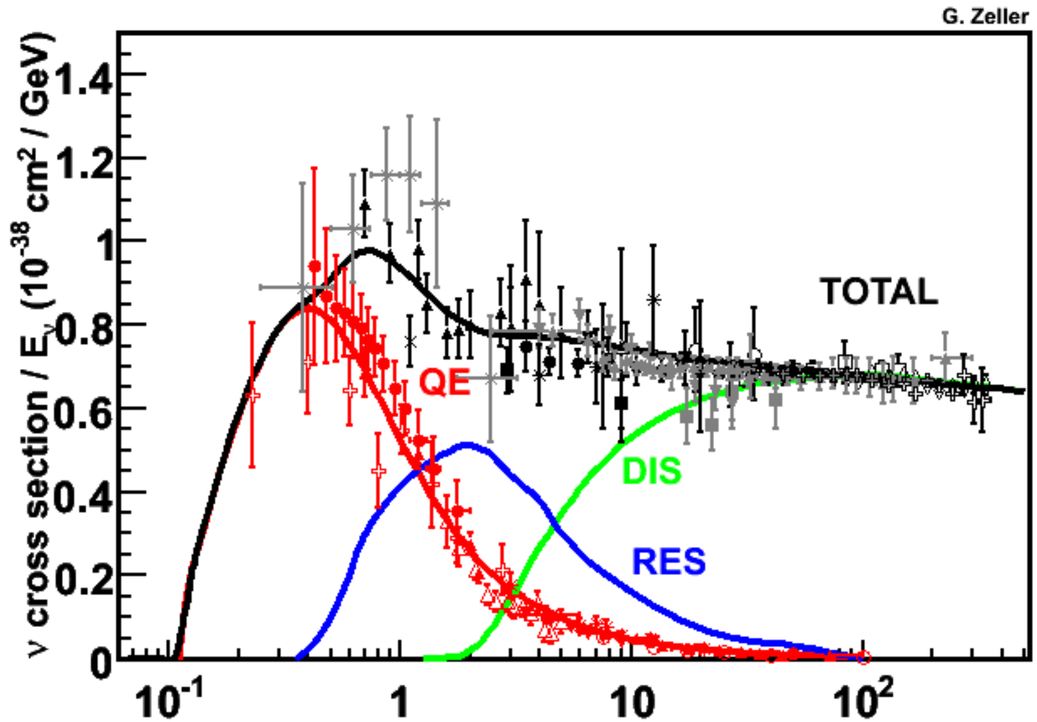
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

1. 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

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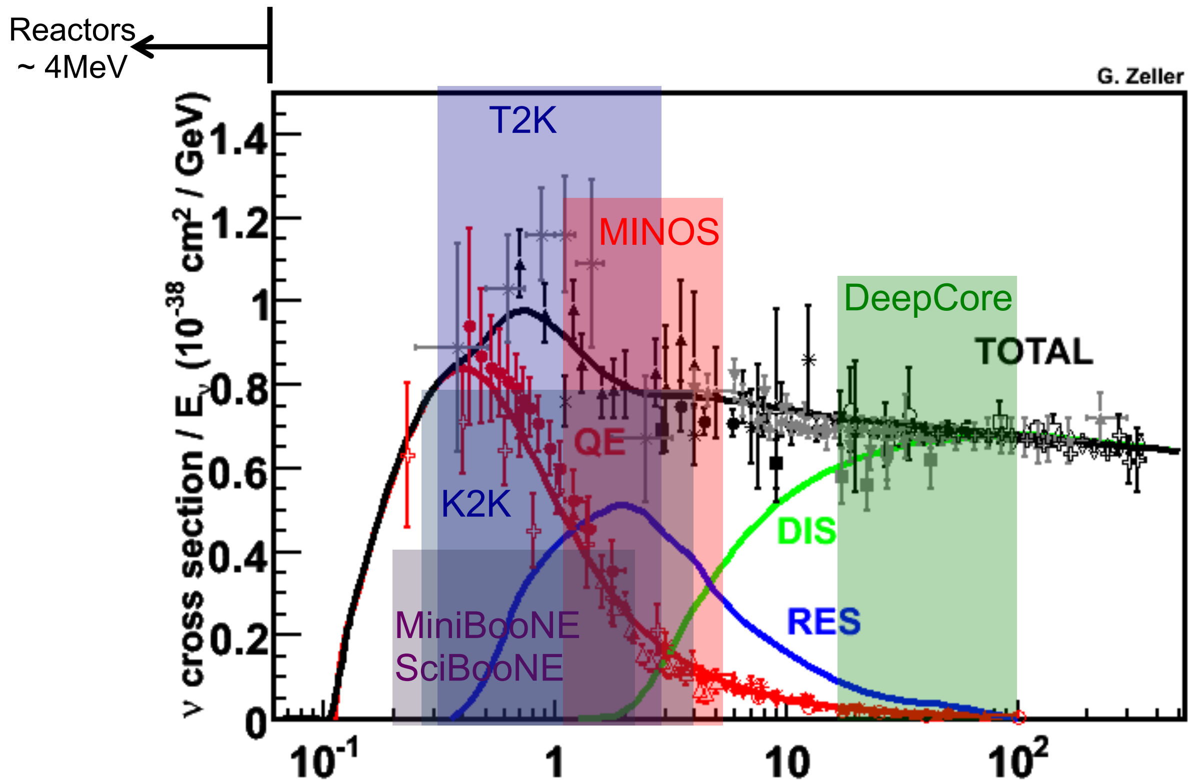

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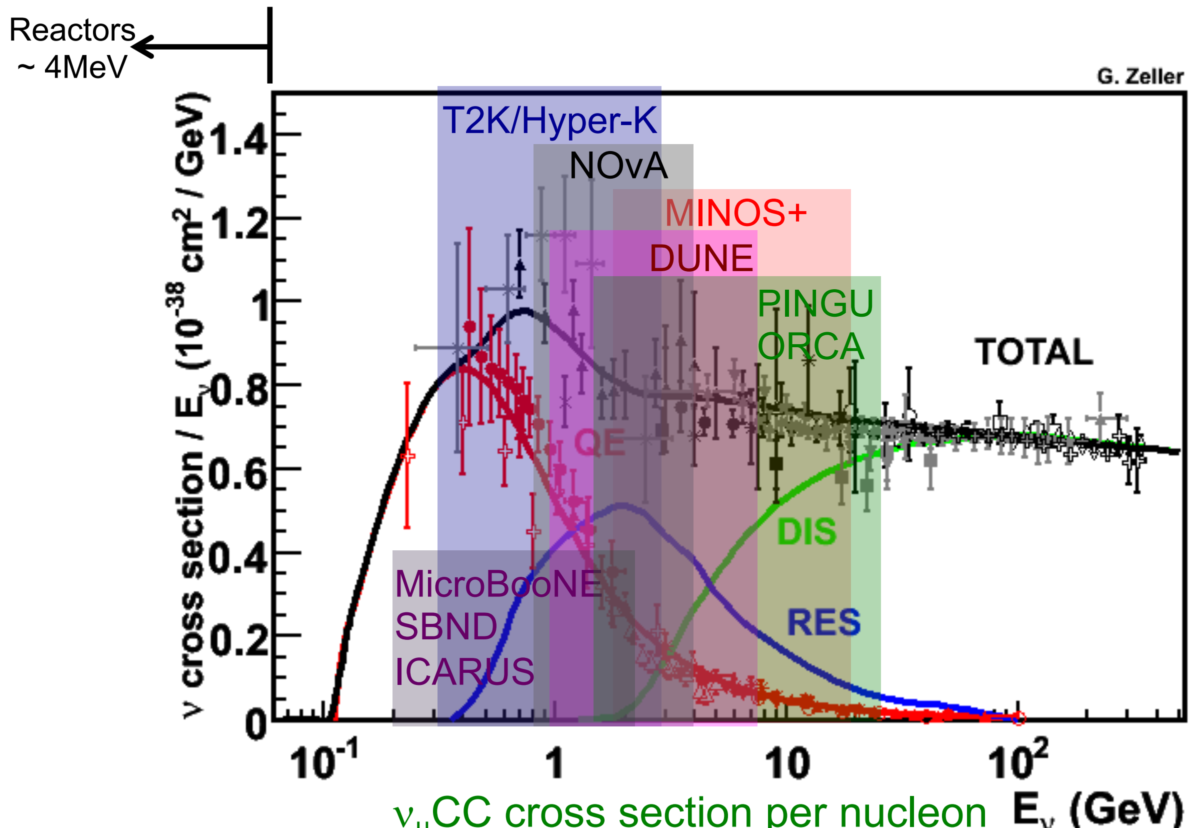

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We don't know the energy of incoming neutrinos…
- We need to simulate all physics from $E\nu$=0 to $E\nu$ ~few GeV
- We need to simulate all physics from $\omega,|\vec{q}|=0$ to $\omega,|\vec{q}|$~few GeV

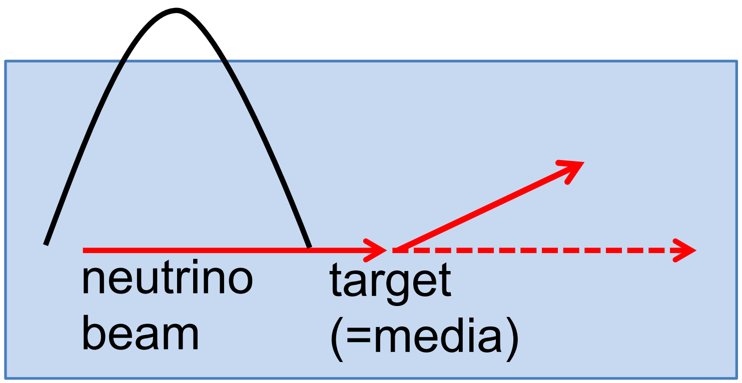
Two rules of neutrino interaction physics
1. Neutrinos cannot choose kinematics
2. Neutrino kinematics are not fully determined

1. Typical neutrino detectors

Neutrino scattering

- Wideband beam

→ observables are inclusive

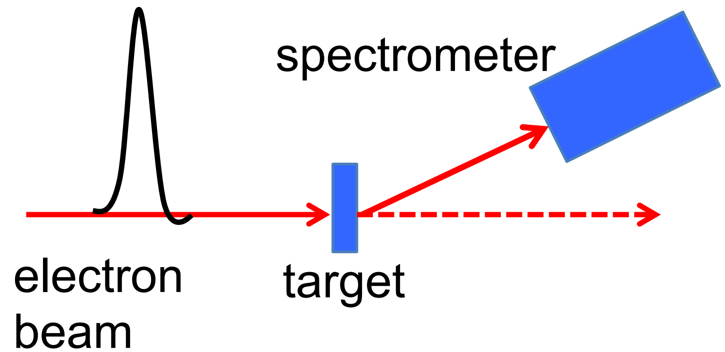


Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ kinematics is completely fixed



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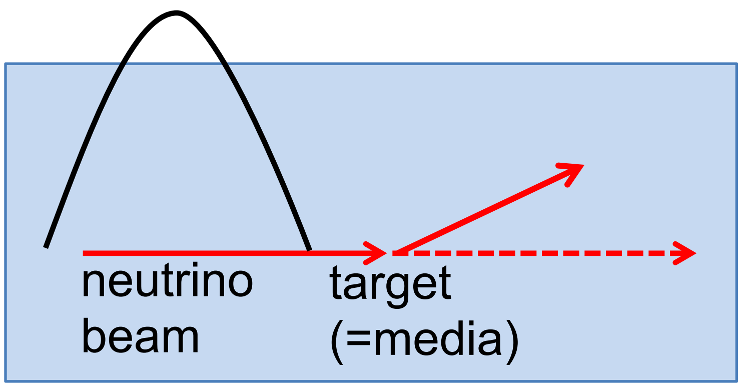

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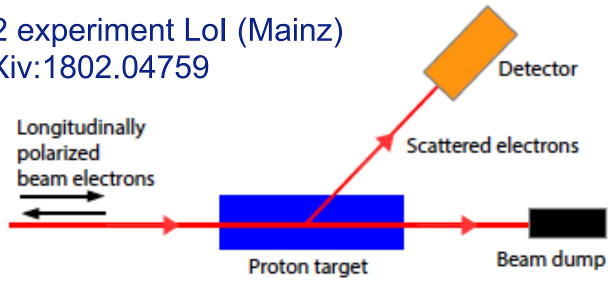
P2 experiment LoI (Mainz)
arXiv:1802.04759



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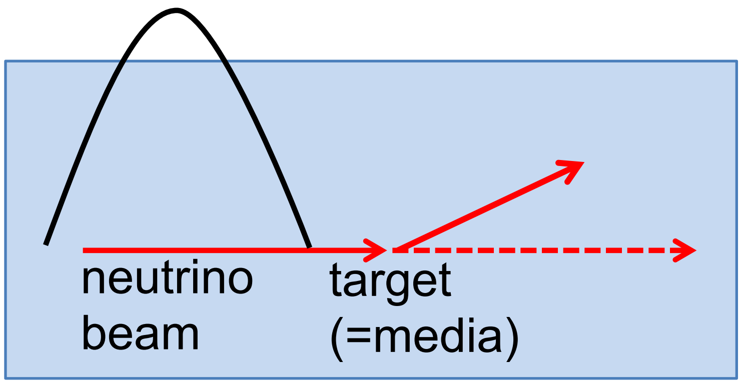

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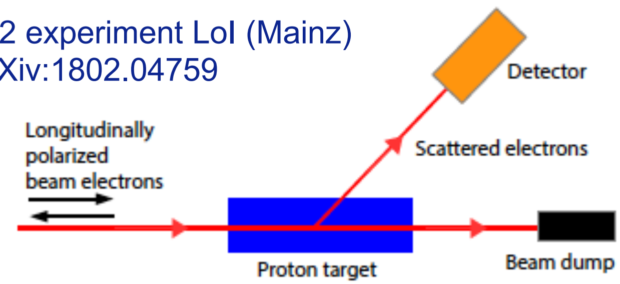

Incomplete kinematics

- Large mass, coarse instrumentation
- No one measures neutrino energy directly
- Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

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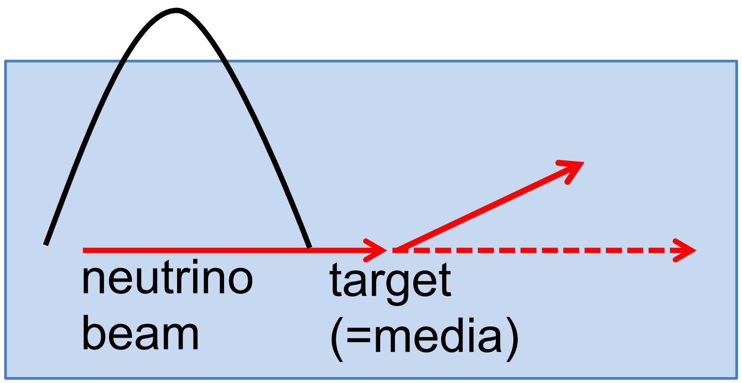
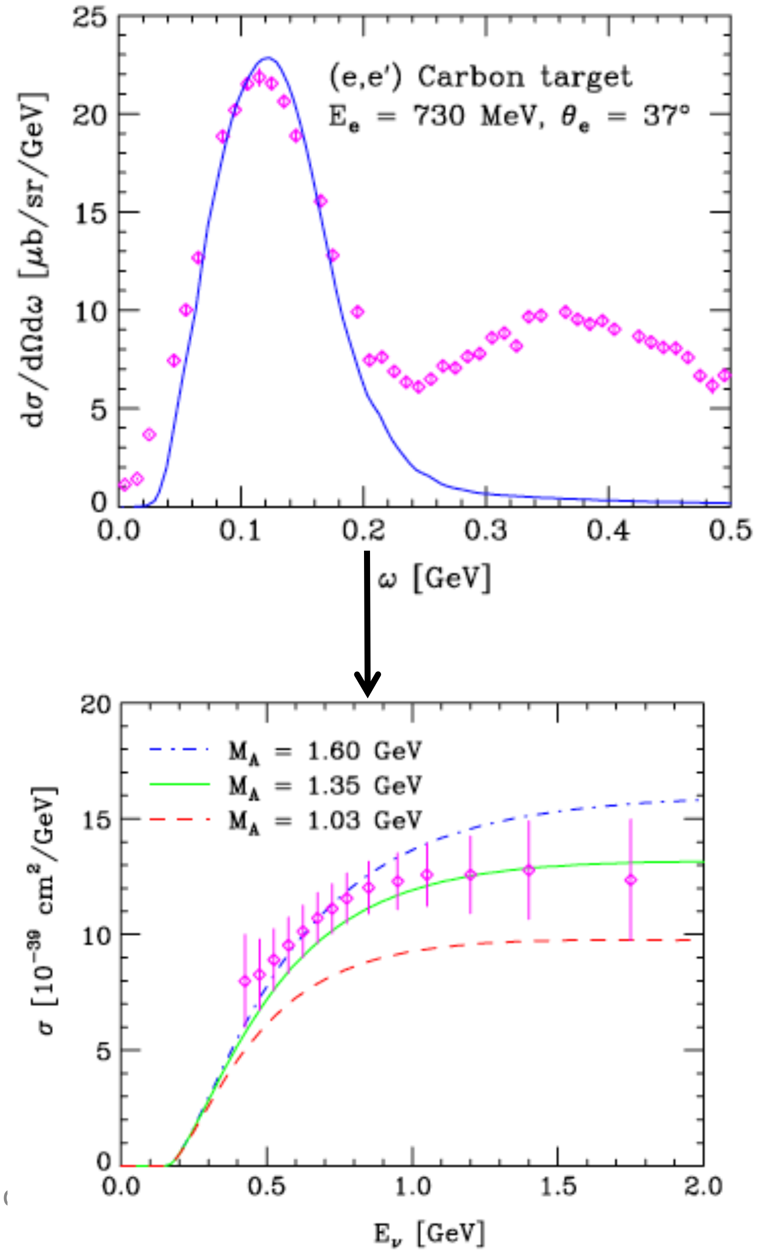
- Wideband beam
→ observables are inclusive





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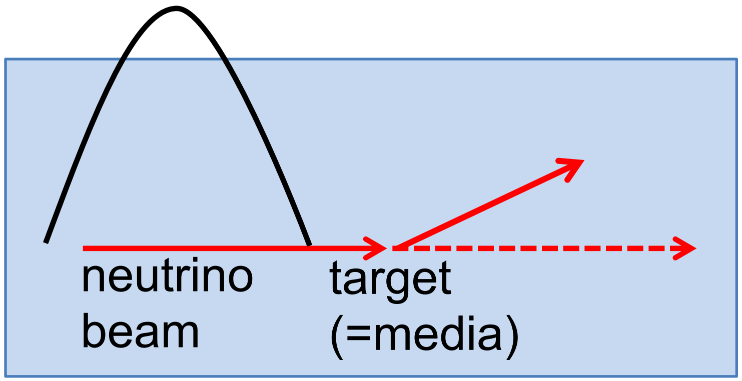
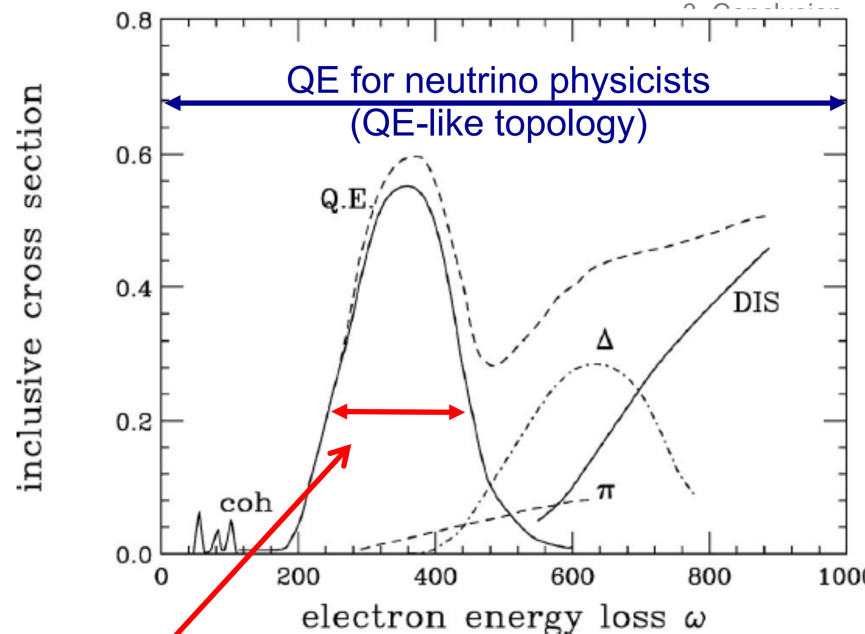
1. Typical neutrino detectors

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

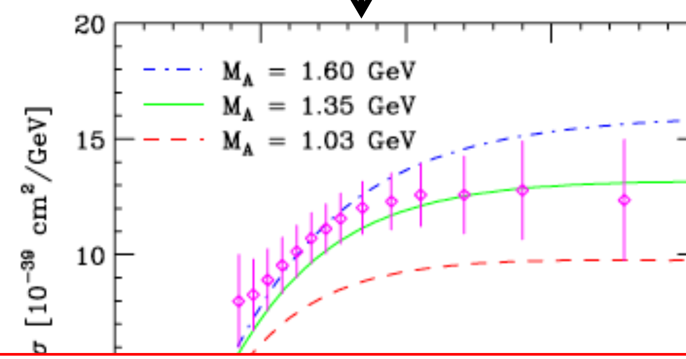
→ observables are inclusive

Omar Benhar (Rome I)





QE for nuclear physicists (genuine QE)



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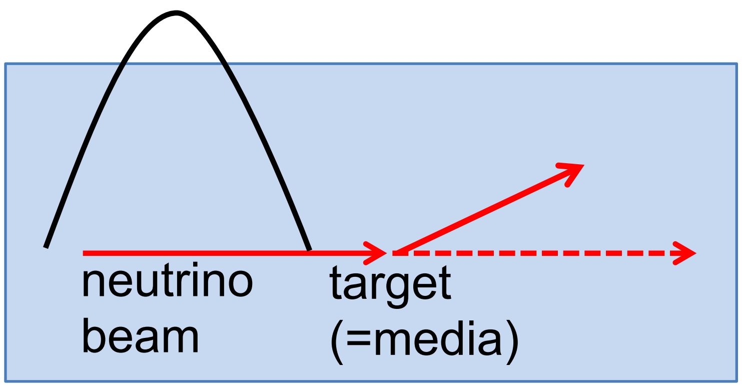
1. Kinematic E reconstruction vs calorimetric E reconstruction

Neutrino scattering
- Wideband beam
→ observables are inclusive



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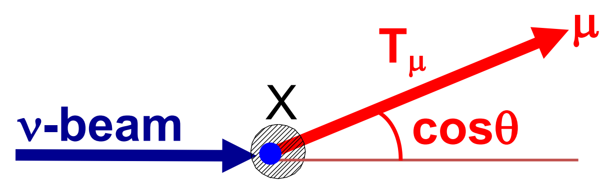
- Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

1. Kinematics energy reconstruction
- problem: you have to assume neutrino interact with single nucleon



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

2. Calorimetric energy reconstruction
- problem: you have to measure energy deposit from all outgoing particles

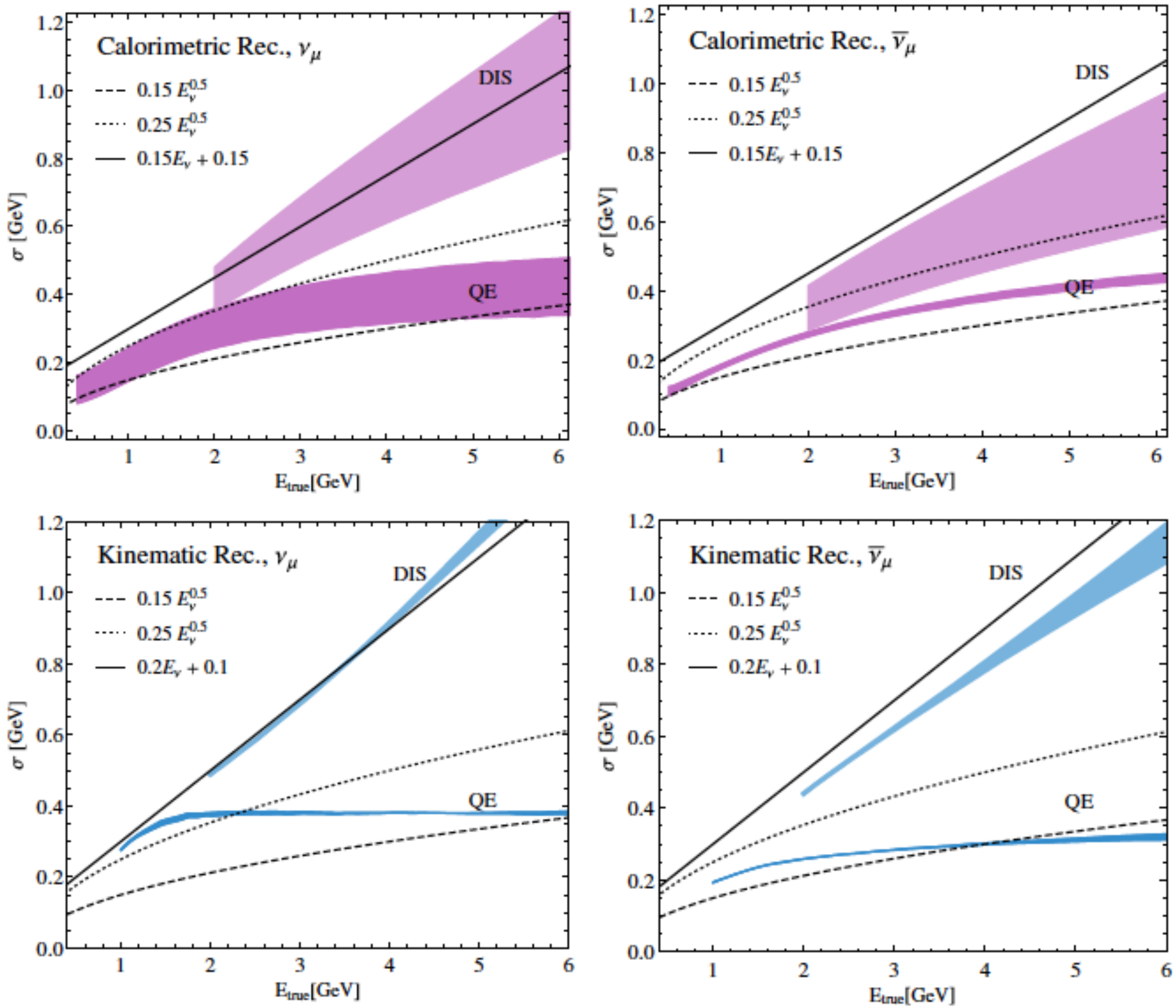
$$E_\nu^{Cal} = E_\mu + \sum_{i=1}^{all} E_{had}^i$$

1. Kinematic E reconstruction vs calorimetric E reconstruction

Calorimetric energy reconstruction suffers invisible hadrons (=neutrons)

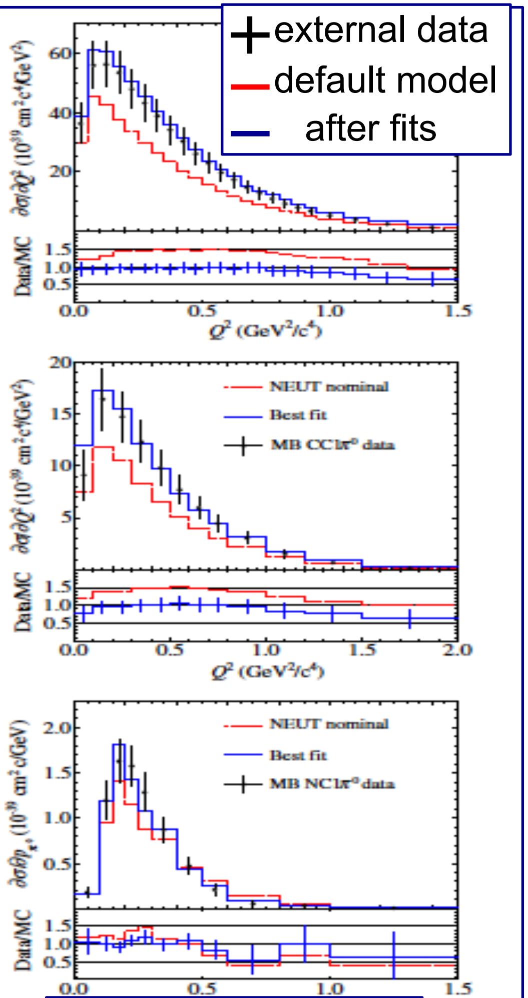
It largely depends on neutrino interaction and hadron simulation
- multiplicity
- kinematics
- nuclear effect
  - re-scattering
  - charge exchange
  - baryonic resonance
  - nucleon correlation

etc



1. e.g.) T2K oscillation experiments

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



External data fit

External data give initial guess of cross-section systematics

T2K collaboration, PRL118(2017)151801

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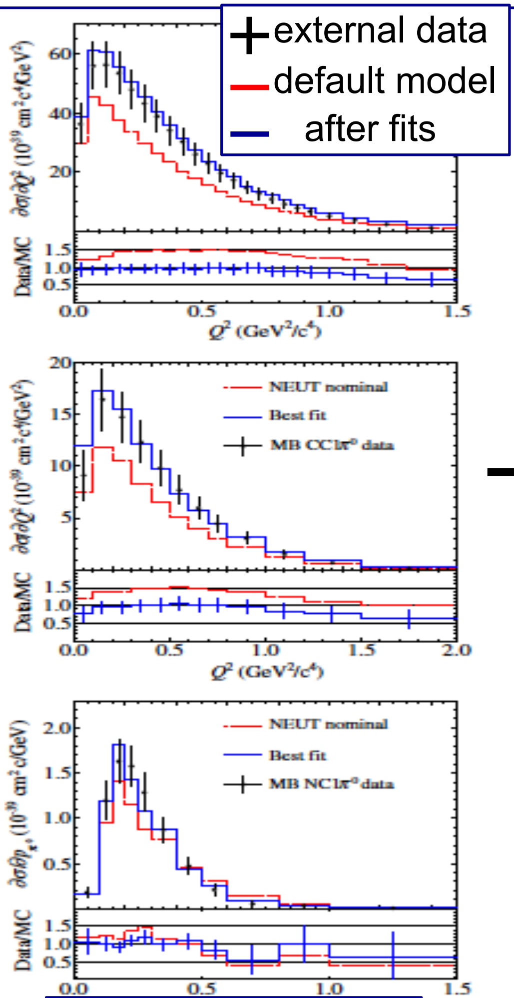
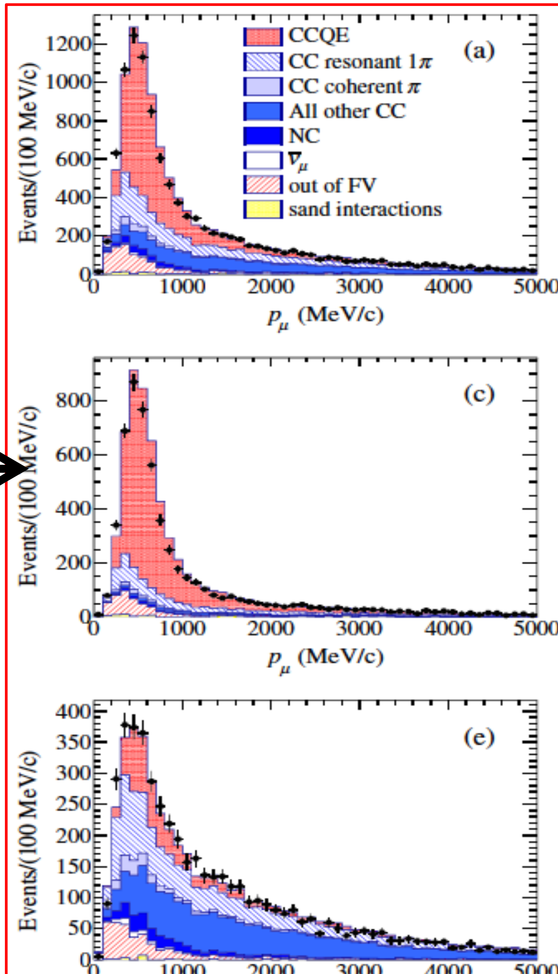
Internal constraint
Near detector
oscillation non-sensitive channels





External data fit

T2K ND280 data fit

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

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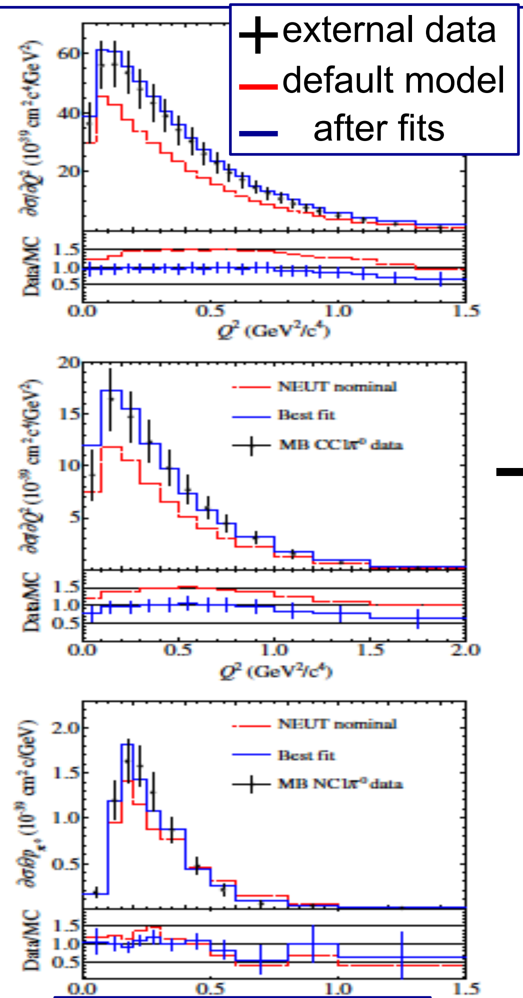
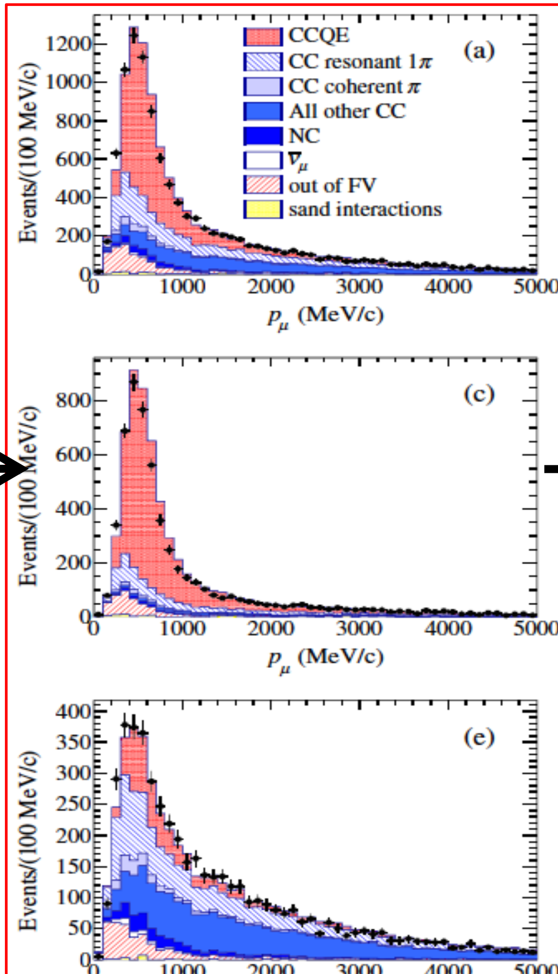
Neutrino interaction model is a large systematics of neutrino oscillation experiment



External data fit

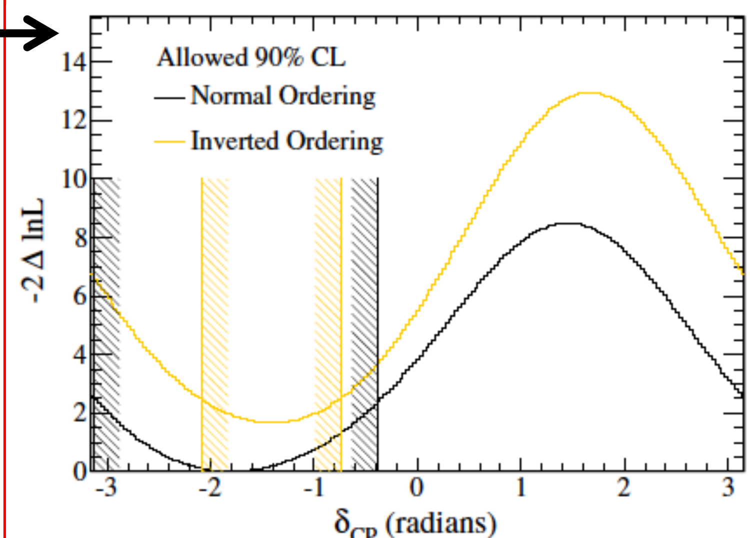
→



T2K ND280 data fit

→

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



oscillation result

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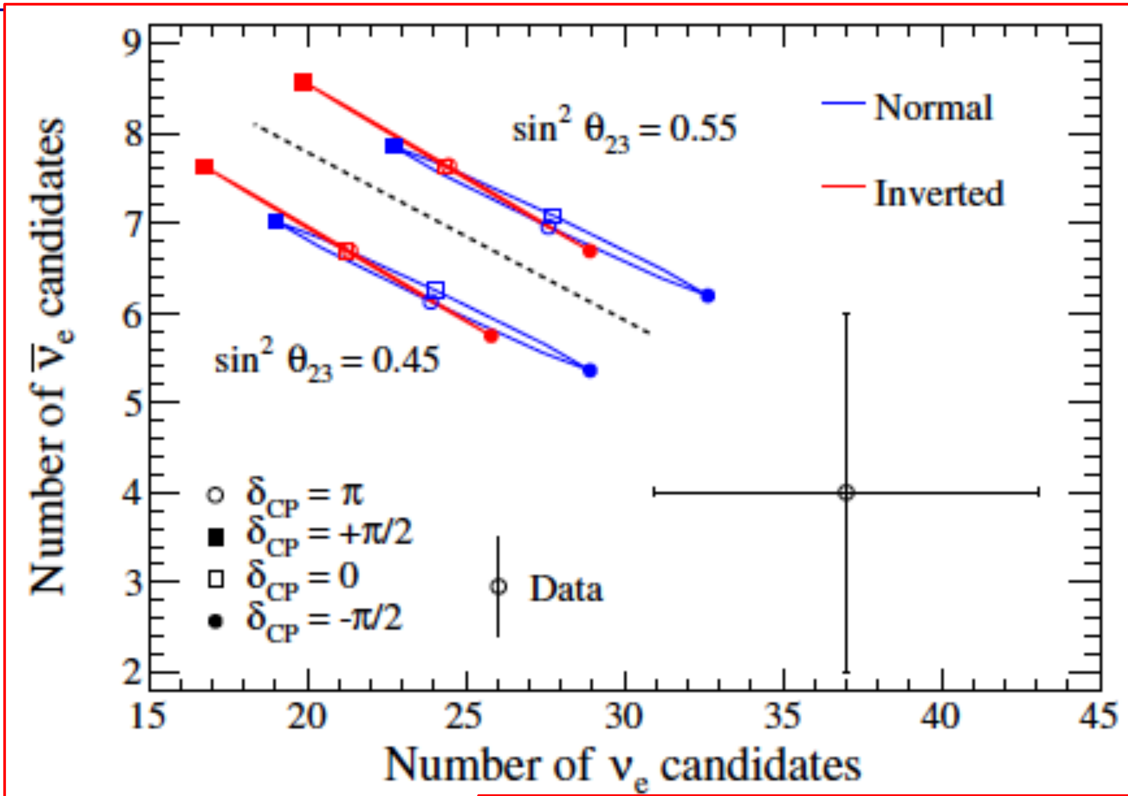

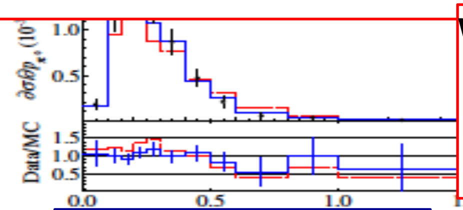

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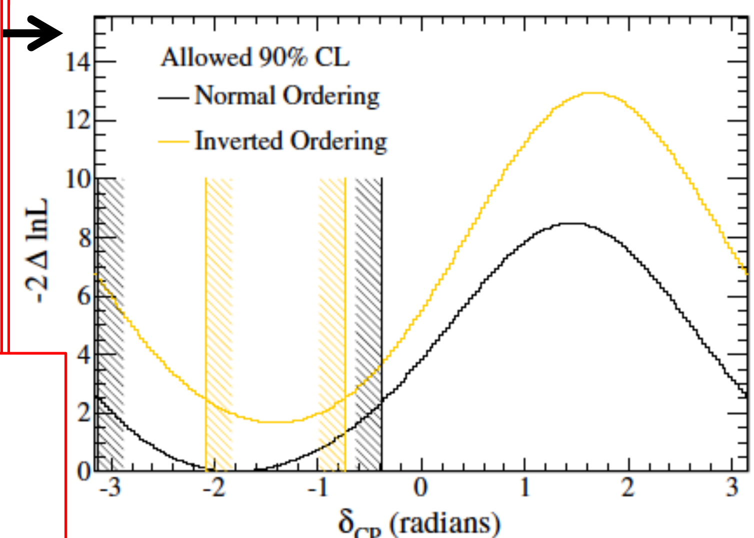


We observe way more ν_e
- statistical fluctuation?
- is ν_e cross section right?

External data fit

T2K ND280 data fit

oscillation result

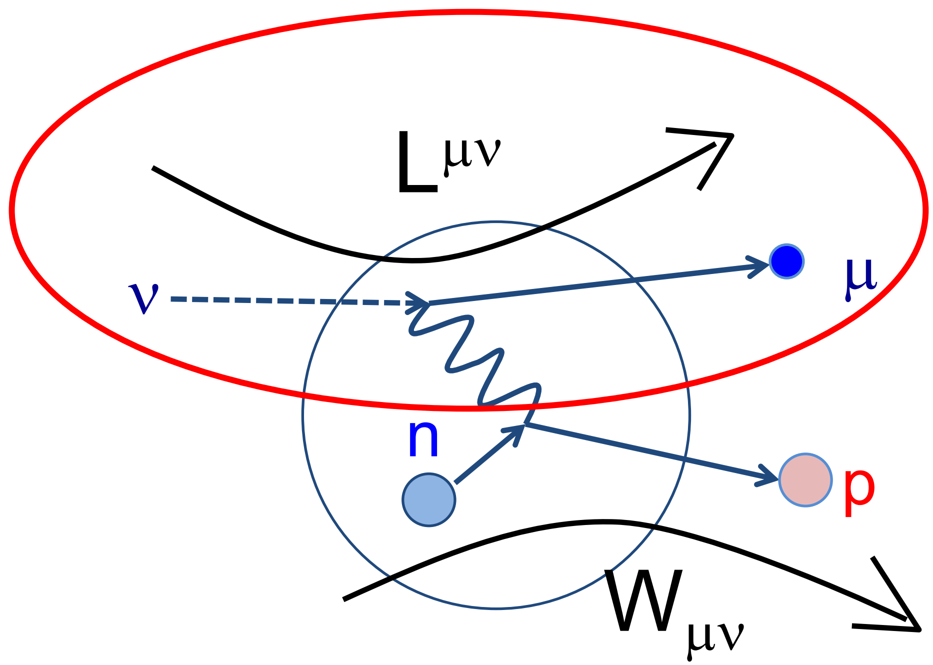
1. Neutrino cross-section formula

Cross-section
- product of Leptonic and Hadronic tensor

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

Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)



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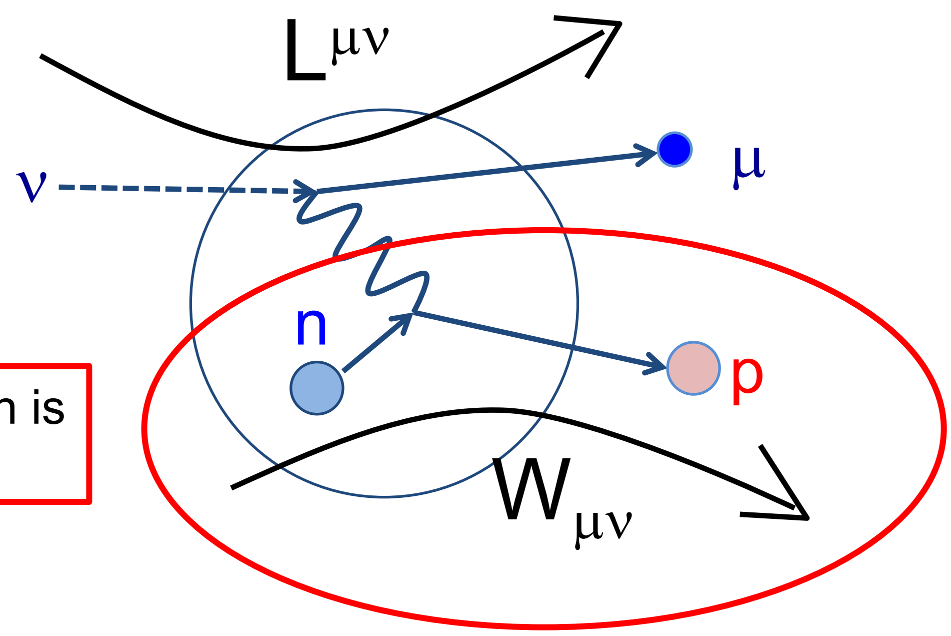

All complication of neutrino cross-section is how to model the hadronic tensor part

Chris Marshall, Physics slam (2015)

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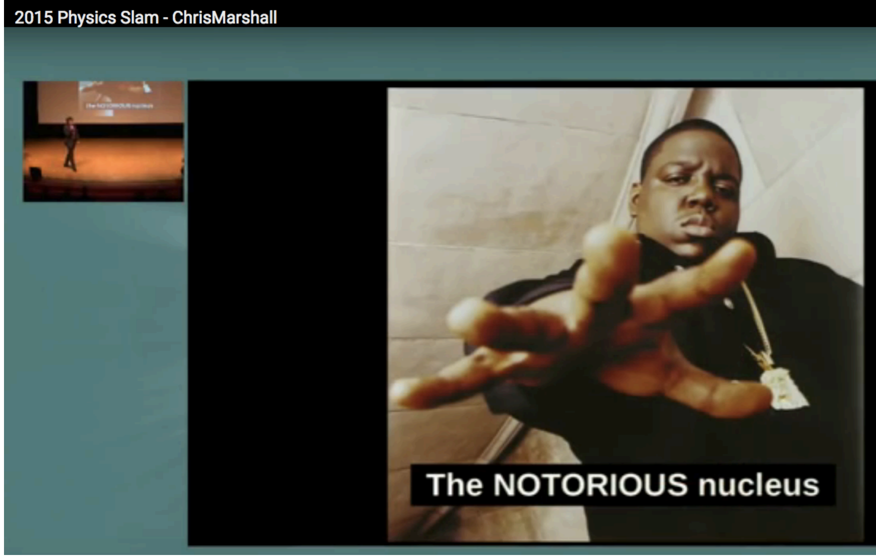

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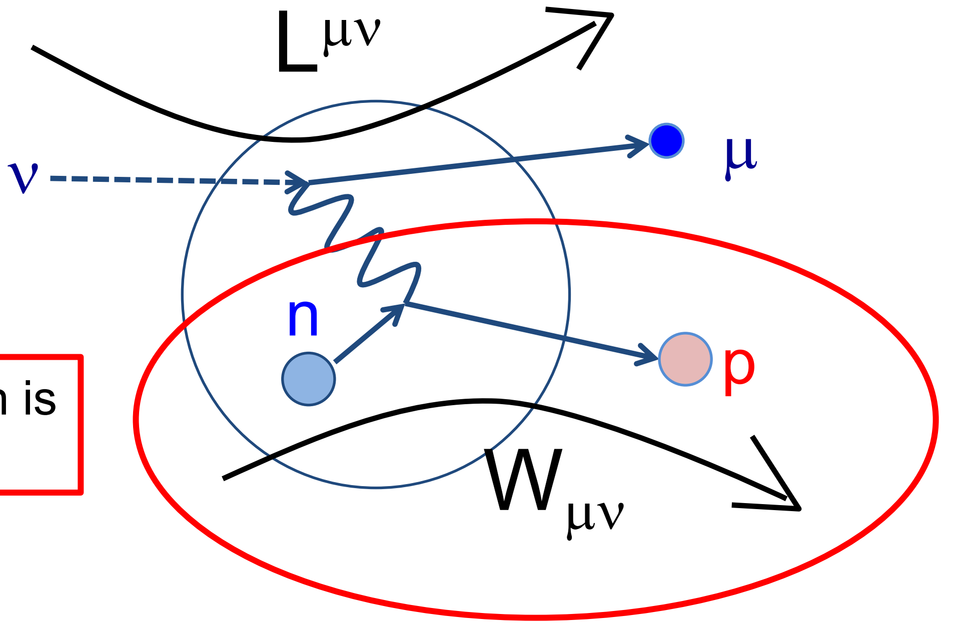

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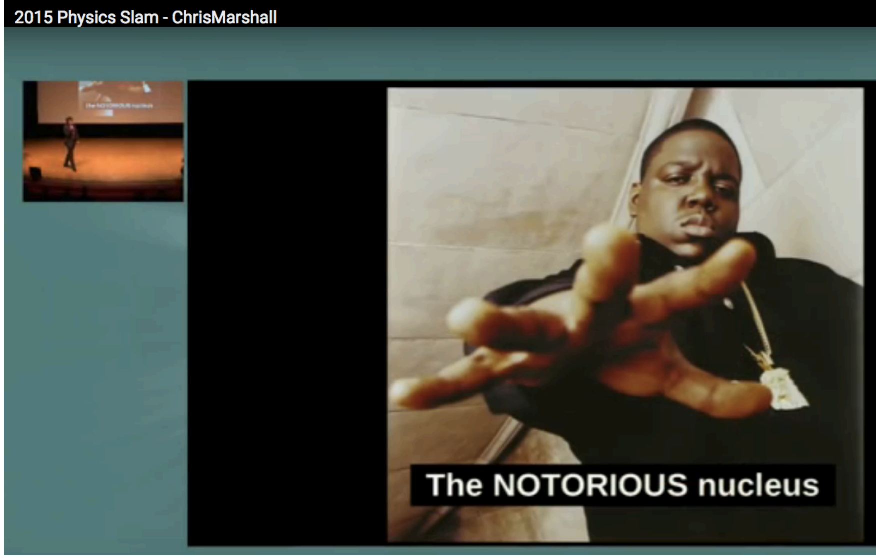

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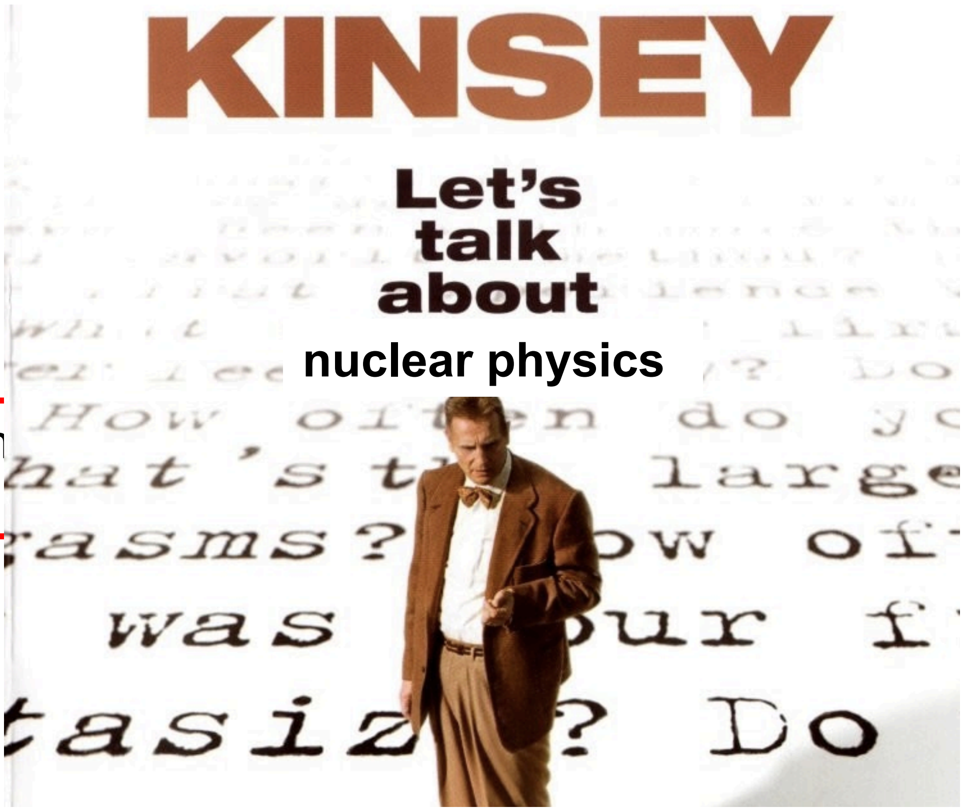

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3. Conclusion

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

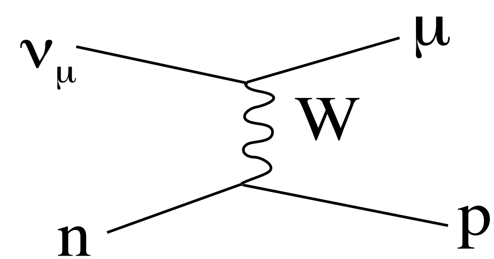
[2] ESNT, CEA, IRFU, Service de Physique Nucléaire, Université de Paris-Saclay, F-91191 Gif-sur-Yvette, France

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

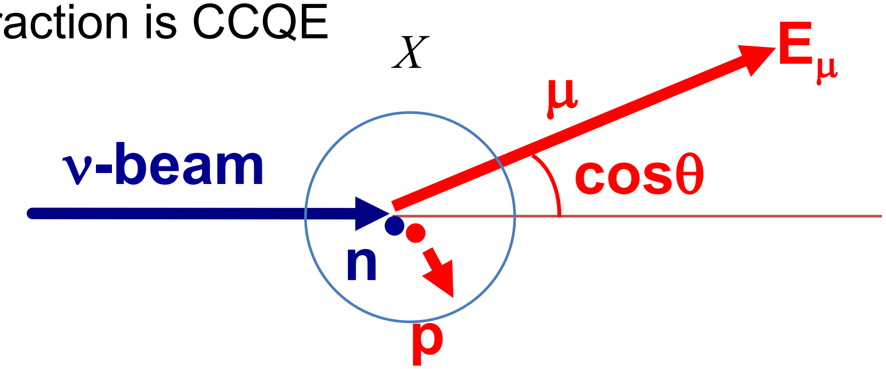
2. Charged Current Quasi-Elastic scattering (CCQE)

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

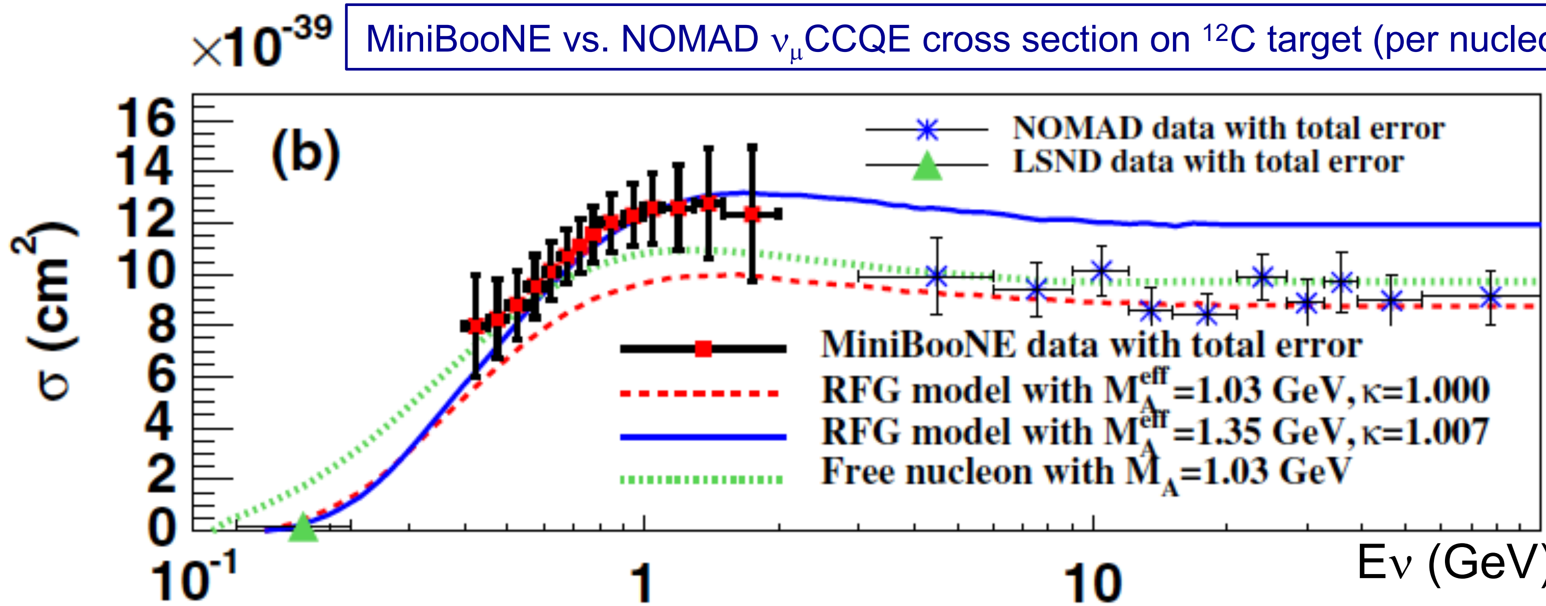
2. Charged Current Quasi-Elastic scattering (CCQE)

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

Simulation disagree with many modern accelerator based neutrino experiment data, neither shape (low Q^2 and high Q^2) nor normalization. By tuning axial mass (M_A)~1.3 GeV, simulations successfully reproduce data both shape and normalization.

Problem: we know M_A=1 GeV from electron scattering experiments (CCQE puzzle).

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…

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

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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

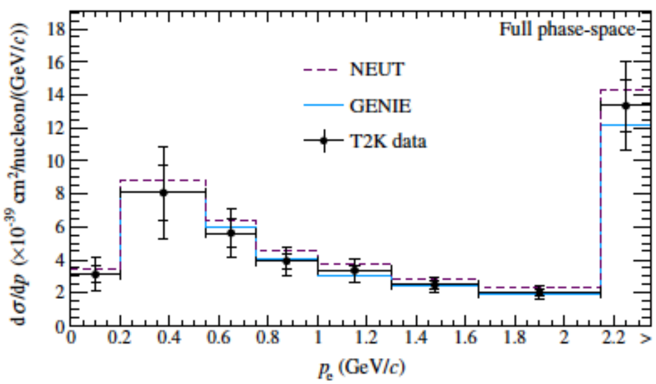
These data play major roles to study/improve neutrino interaction models by theorists

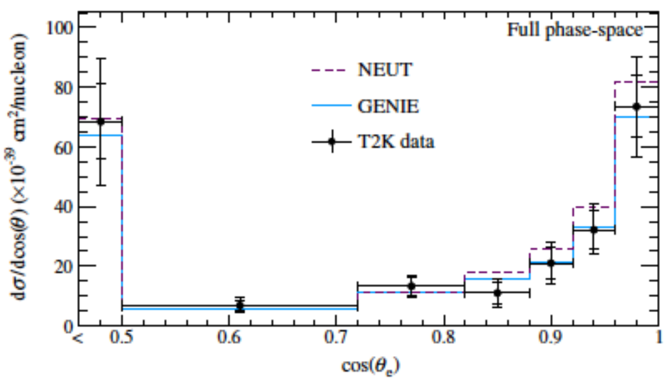
2. Flux-integrated differential cross-section

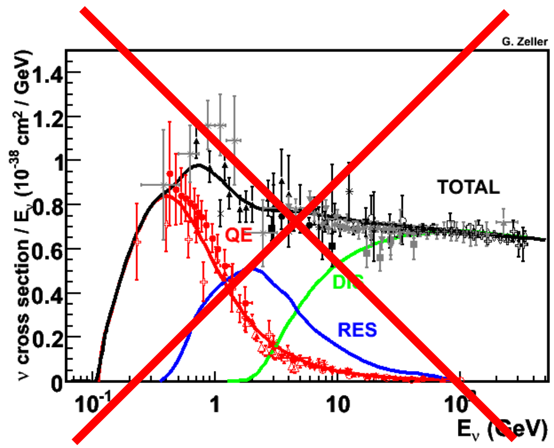
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

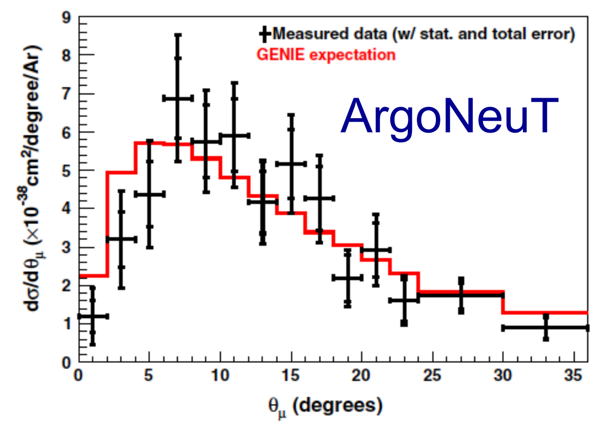
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

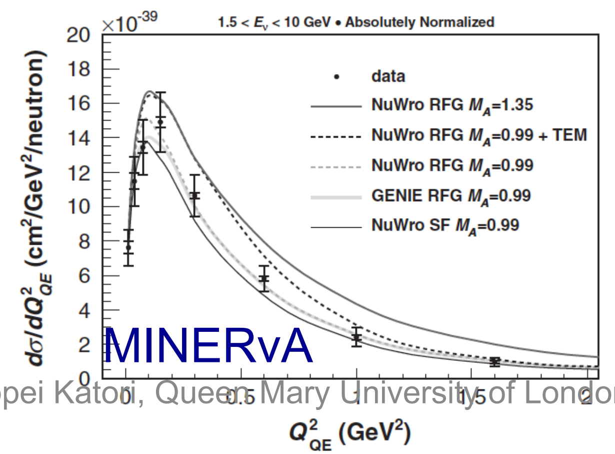
T2K



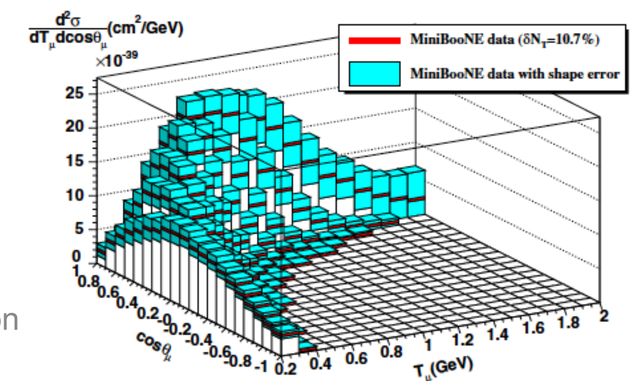








MiniBooNE



Queen Mary
University of London

2. Flux-integrated differential cross-section

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→ 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

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2. The solution of CCQE puzzle

Presence of 2-body current

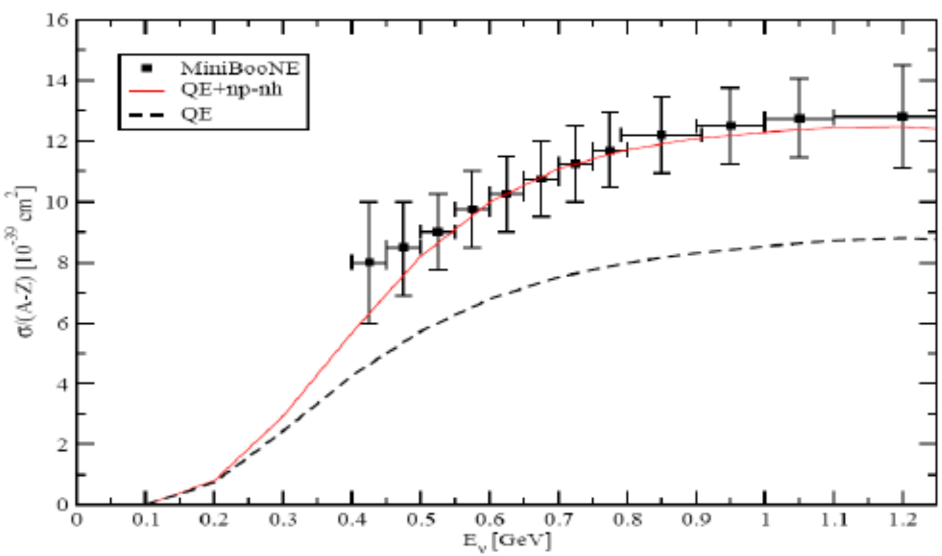
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

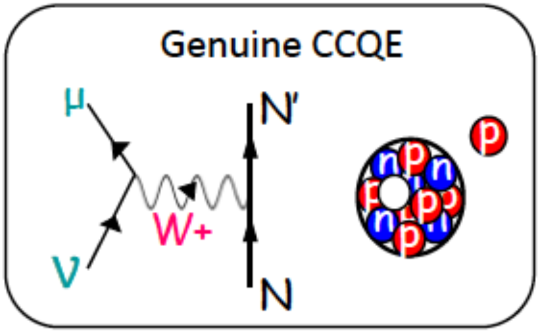
What experimentalists call "CCQE" is not genuine CCQE!

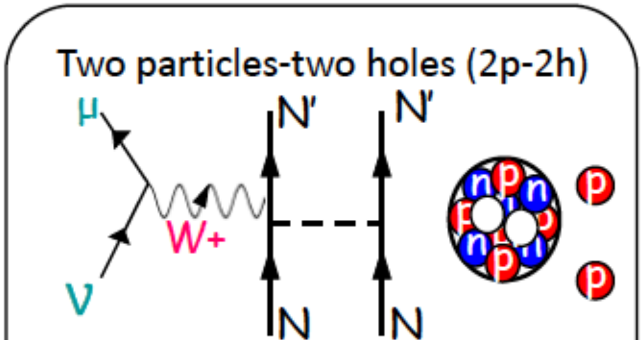
Marco Martini (Saclay)

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

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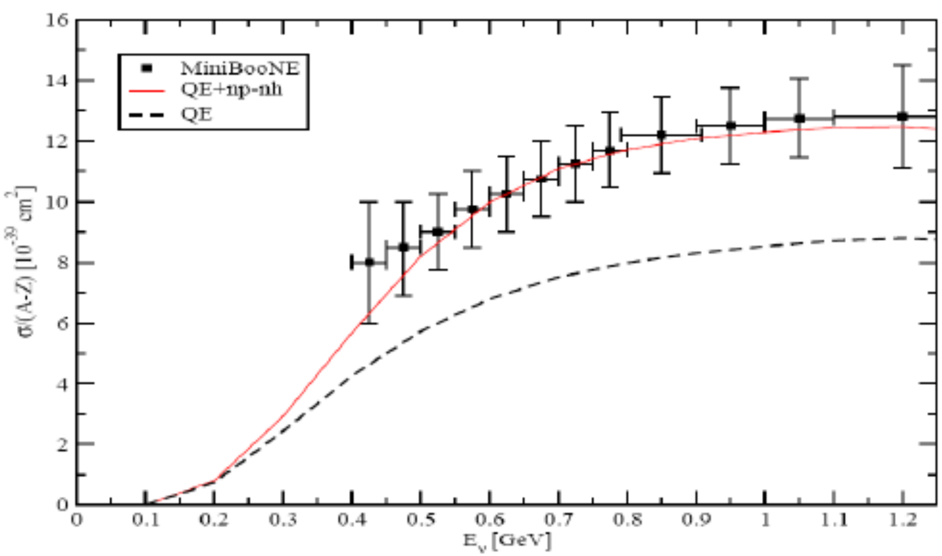
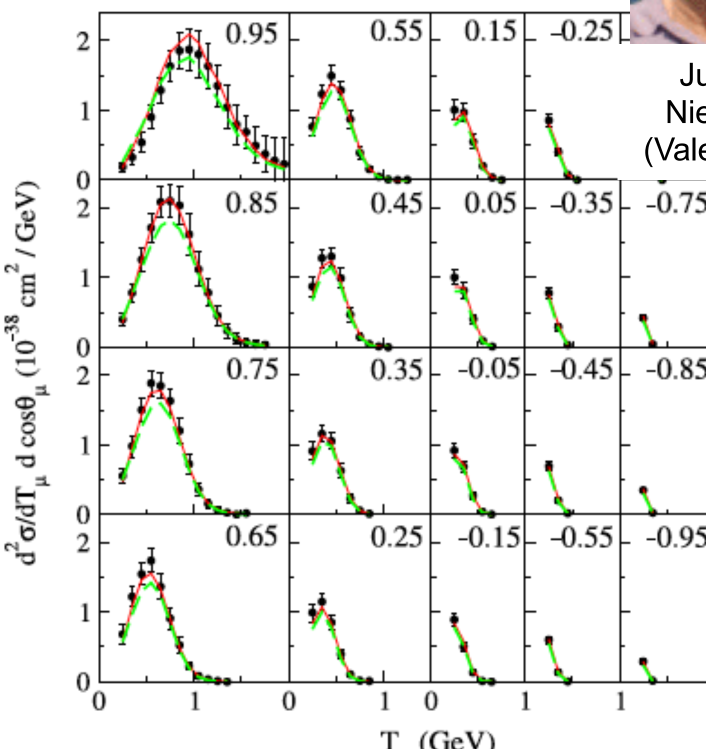
The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)





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

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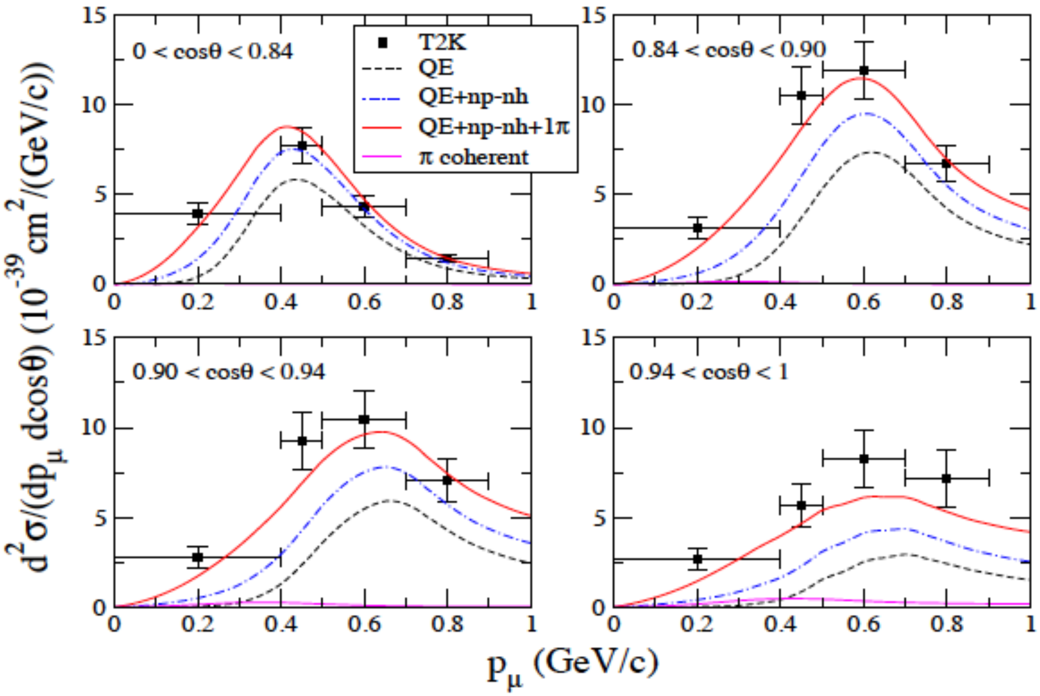

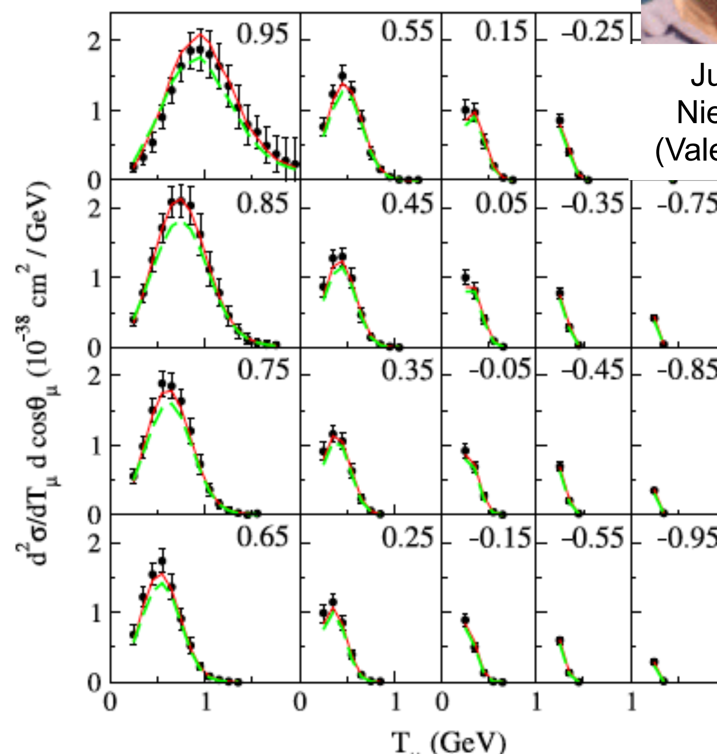

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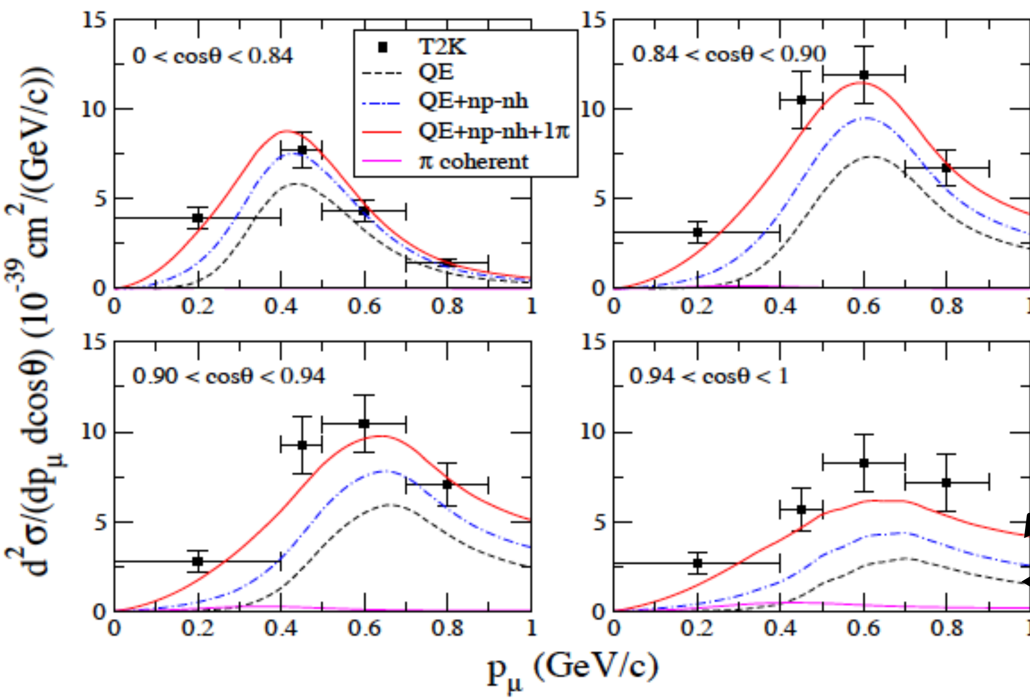
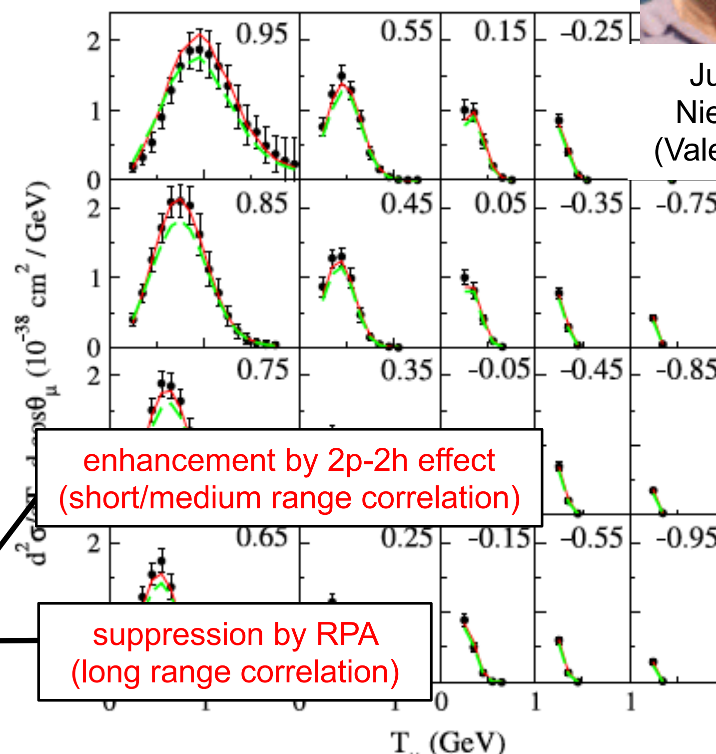




enhancement by 2p-2h effect
(short/medium range correlation)

suppression by RPA
(long range correlation)

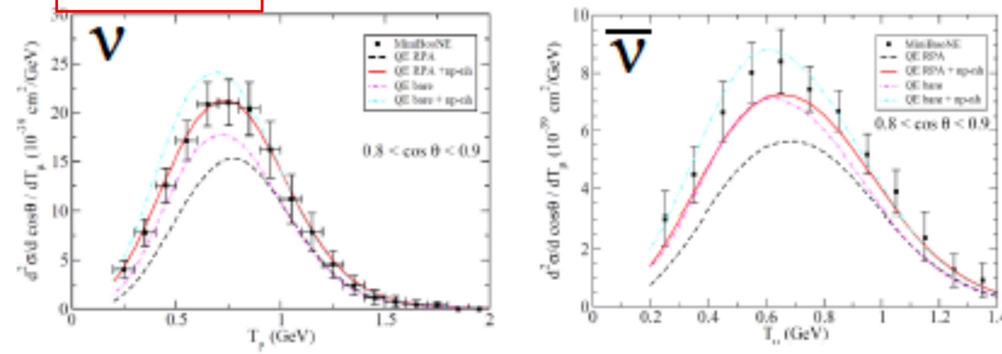
Valencia model vs. MiniBooNE CCQE double differential cross-section data

2. CCQE-like data, MiniBooNE (2016)

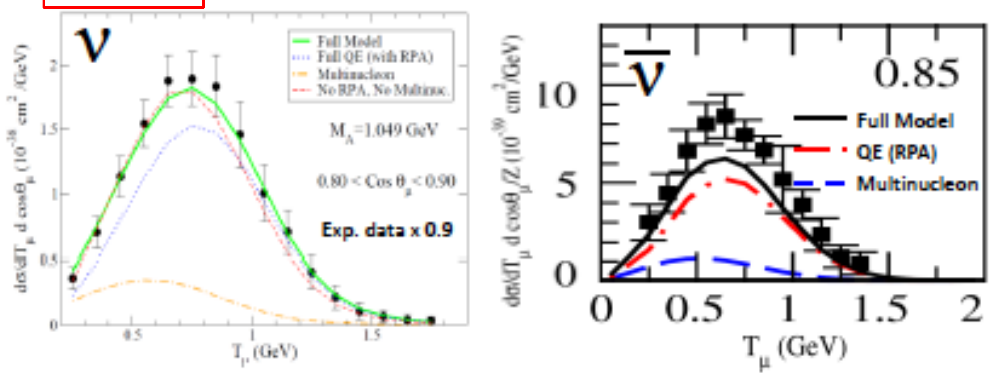
All groups agree qualitatively with MiniBooNE CCQE-like double differential data.

Martini – RPA
Nieves – Valencia 2p2h model
SuSA – Superscaling
Giusti – Relativistic Green’s function

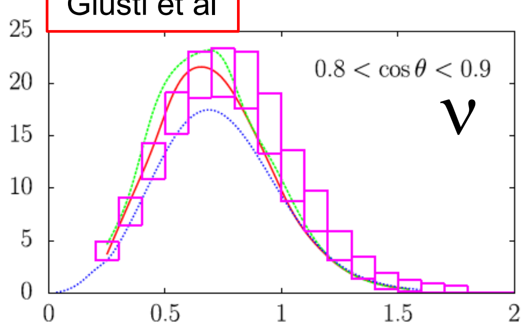
Martini et al



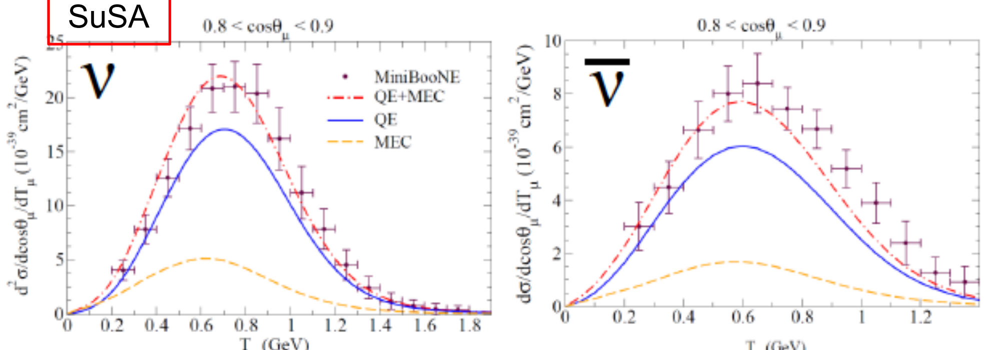
Valencia



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

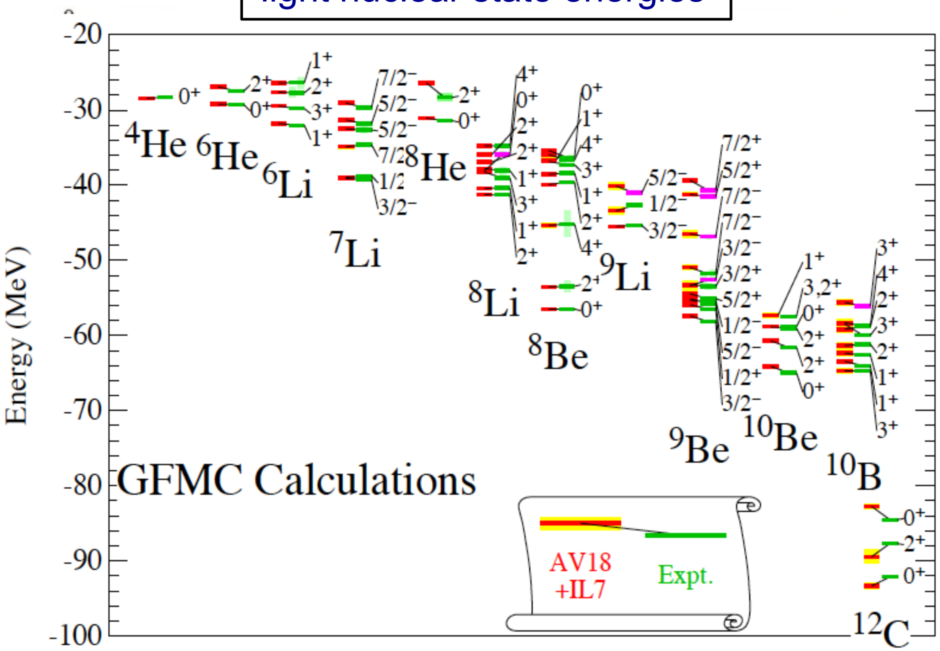
- Green's function Monte Carlo (GFMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

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

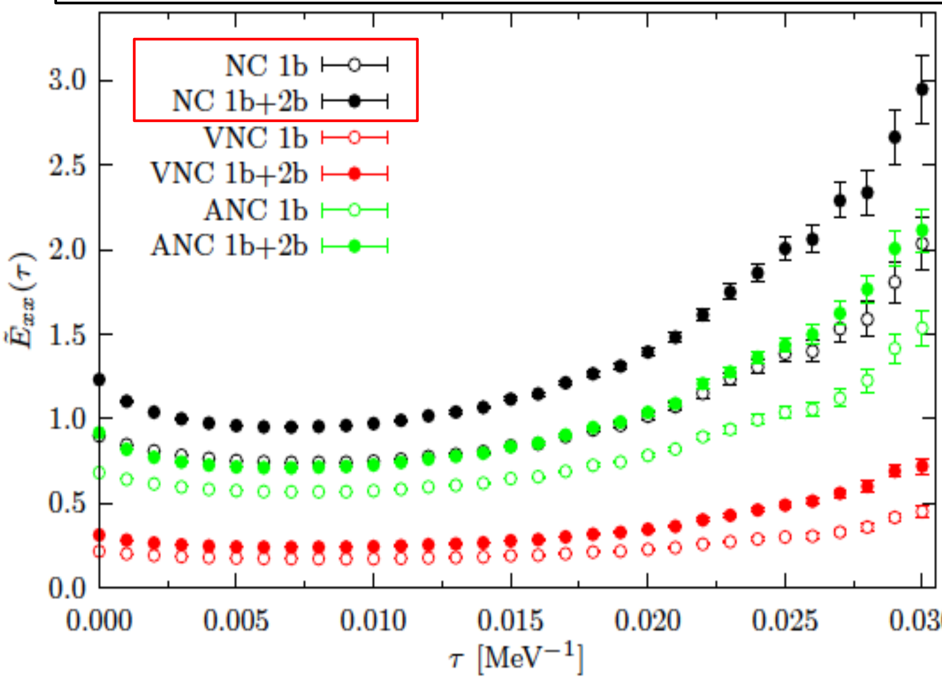
2N potential (Av18)

3N potential (IL7)

light nuclear state energies

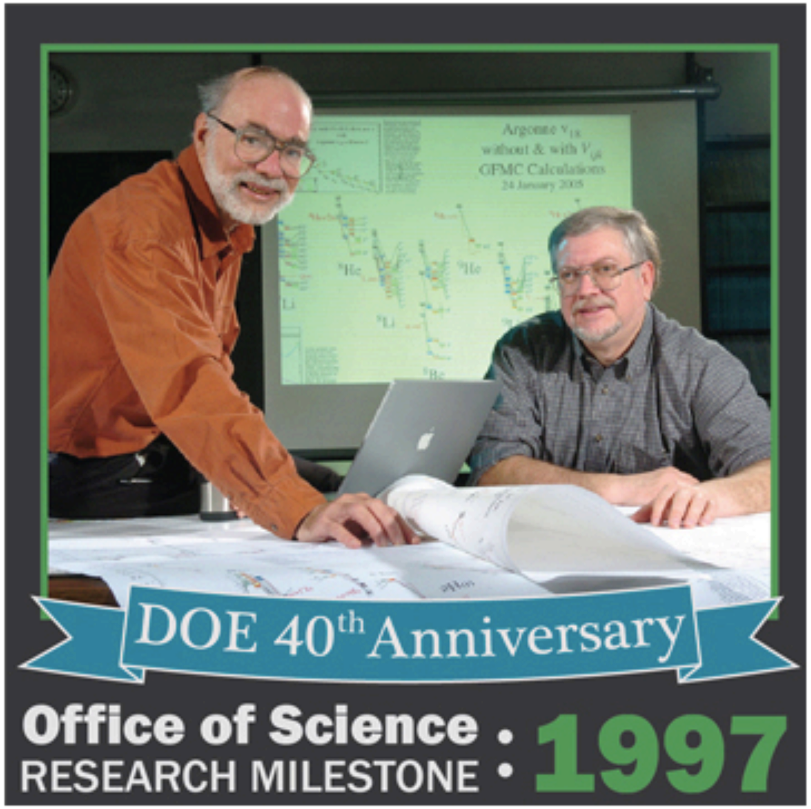


Neutrino NCQE scattering in ^{12}C response function



Pudliner et al., PRC56(1997)1720, Carlson et al, PRC65(2002)024

2. The solution of CCQE puzzle



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

PHYSICAL REVIEW C, VOLUME 65, 024002

Longitudinal and transverse quasielastic response functions of light nuclei

J. Carlson,[1] J. Jourdan,[2] R. Schiavilla,[3,4] and I. Sick[2]

[1]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

[2]*Departement für Physik und Astronomie, Universität Basel, Basel, Switzerland*

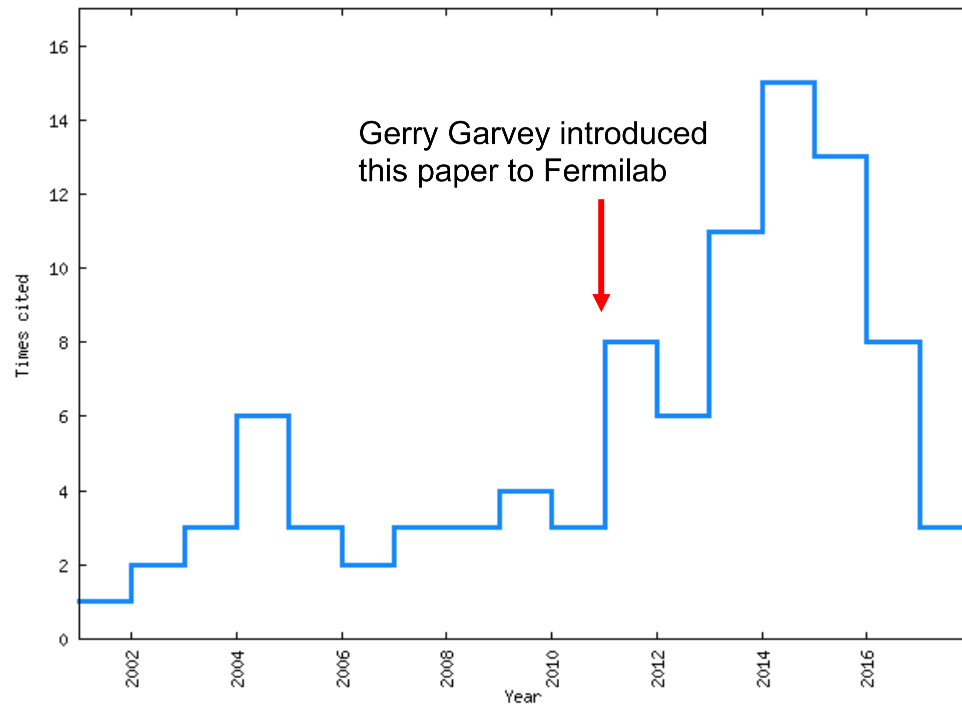
[3]*Jefferson Lab, Newport News, Virginia 23606*

[4]*Physics Department, Old Dominion University, Norfolk, Virginia 23529*

(Received 21 June 2001; published 25 January 2002)

The ^{3}He and ^{4}He longitudinal and transverse response functions are determined from an analysis of the world data on quasielastic inclusive electron scattering. The corresponding Euclidean response functions are derived and compared to those calculated with Green's function Monte Carlo methods, using realistic interactions and currents. Large contributions associated with two-body currents are found, particularly in the ^{4}He transverse response, in agreement with data. The contributions of the two-body charge and current operators in the ^{3}He, ^{4}He, and ^{6}Li response functions are also studied via sum-rule techniques. A semiquantitative explanation for the observed systematics in the excess of transverse quasielastic strength, as function of mass number and momentum transfer, is provided. Finally, a number of model studies with simplified interactions, currents, and wave functions are carried out to elucidate the role played, in the full calculation, by tensor interactions and correlations.

DOI: 10.1103/PhysRevC.65.024002 PACS number(s): 25.30.Fj, 25.10.+s, 21.45.+v



Gerry Garvey beats me by arm-wrestling (2016)

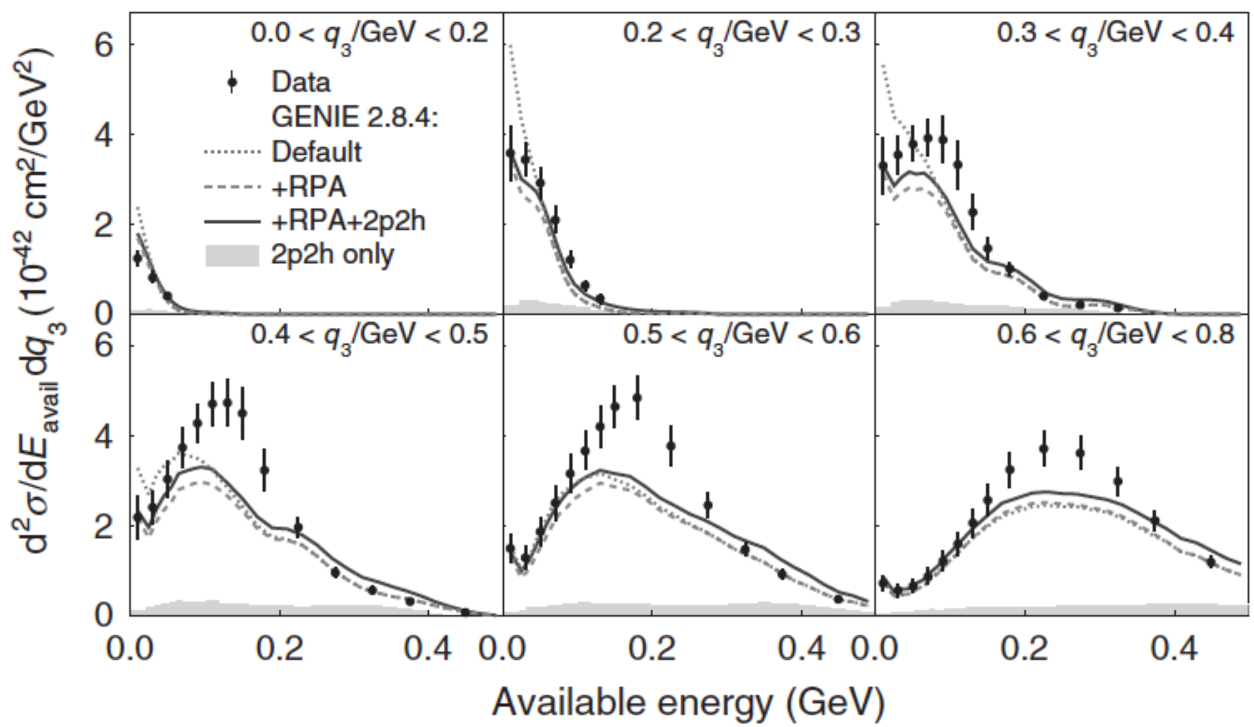
Queen Mary
University of London

Wilkinson et al.,PRD93(2016)072010
MINERvA,PRL116(2016)071802

2. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation
- Valencia MEC model is available in NEUT and GENIE

This moment…
Valencia MEC model does not fit T2K (and Super-K) data very well, people are working very hard to understand what is going on



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large M_A error → large 2p2h error

It is crucial to have correct CCQE, MEC, pion production models to understand MiniBooNE, MINERvA, T2K 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.

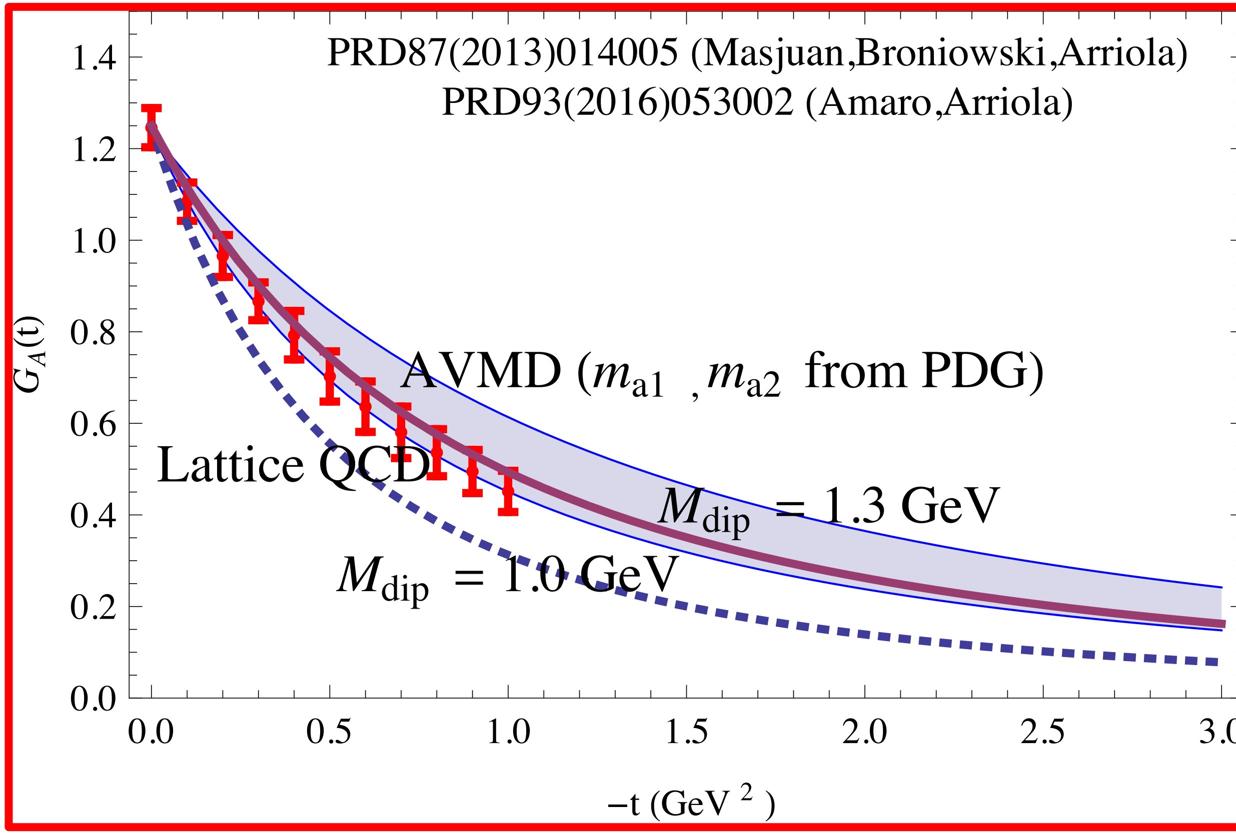
Amaro et al.,PRD93(2016)053002
Alexandrou et al., PRD88(2013)014509

2. Summary of CCQE for oscillation physics

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

- Lattice QCD prefers large MA
- Some top down axial form factor model prefers harder spectrum (~large MA)

The community is still confused with neutrino-nucleon scattering theory…

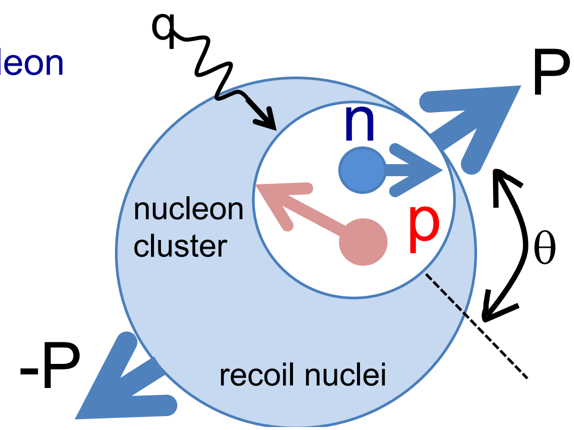


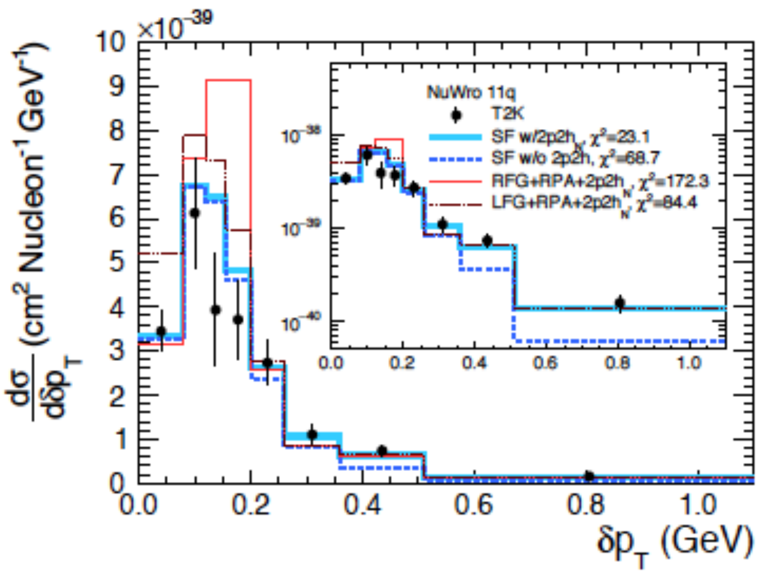
2. Hadron measurement for nuclear correlation

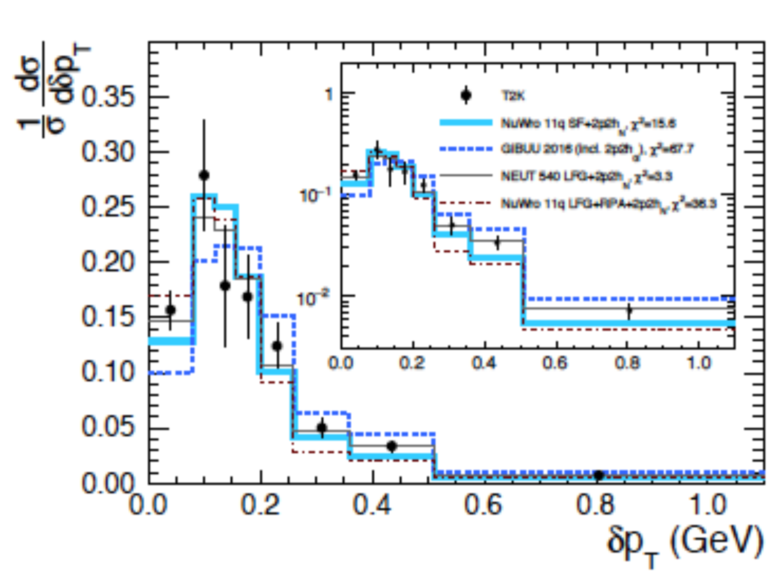
There is a strong belief in experimental community that hadron final states tell everything about 2p2h…

We need prediction of hadronic final states from theorists

home-made nucleon emission model







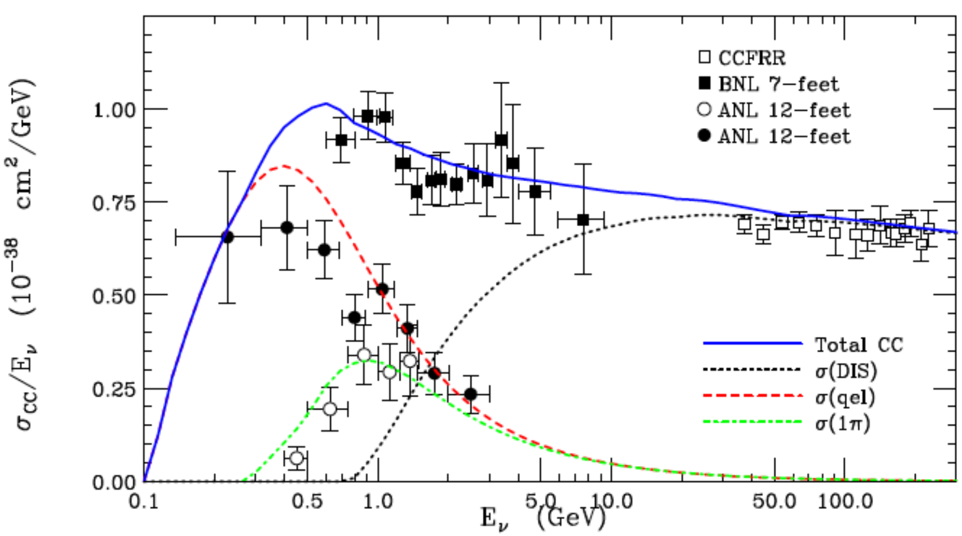
2. Dark age of neutrino interaction physics

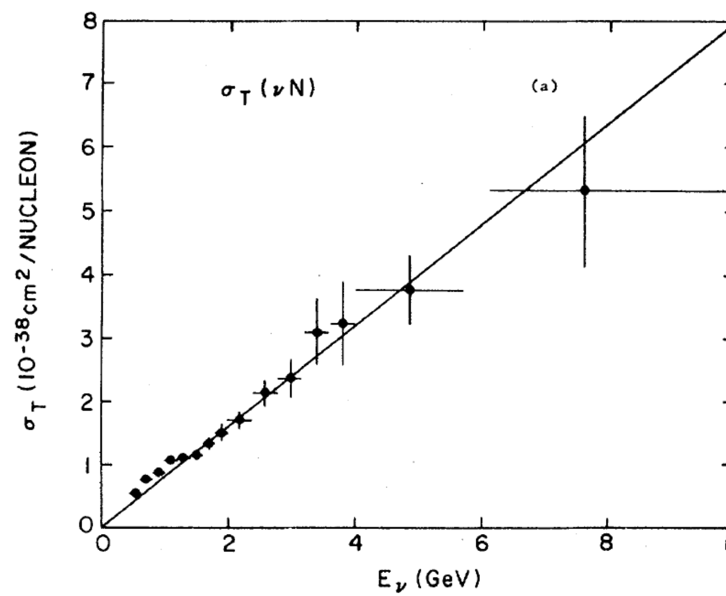
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate

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

Phys. Rev. D [redacted]

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





TK, Martini, JPhysG45(2017)1

1. Neutrino Interaction Physics

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

3. 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

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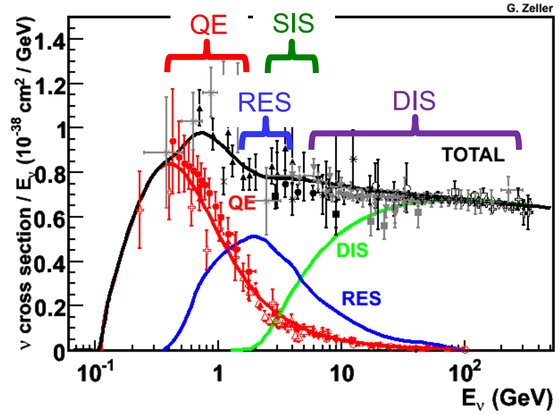
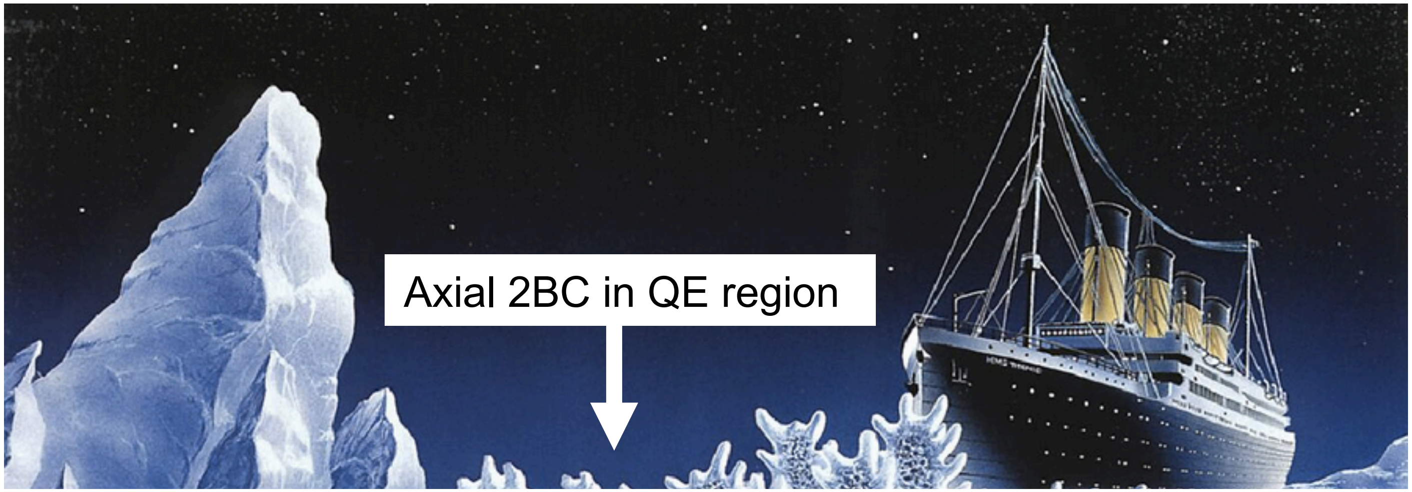
[3] Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium

3. Beyond QE peak

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

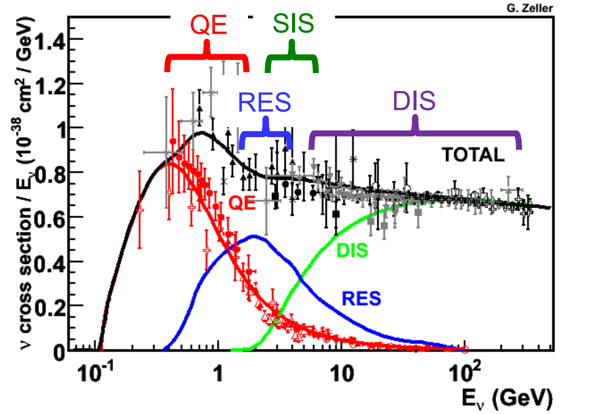


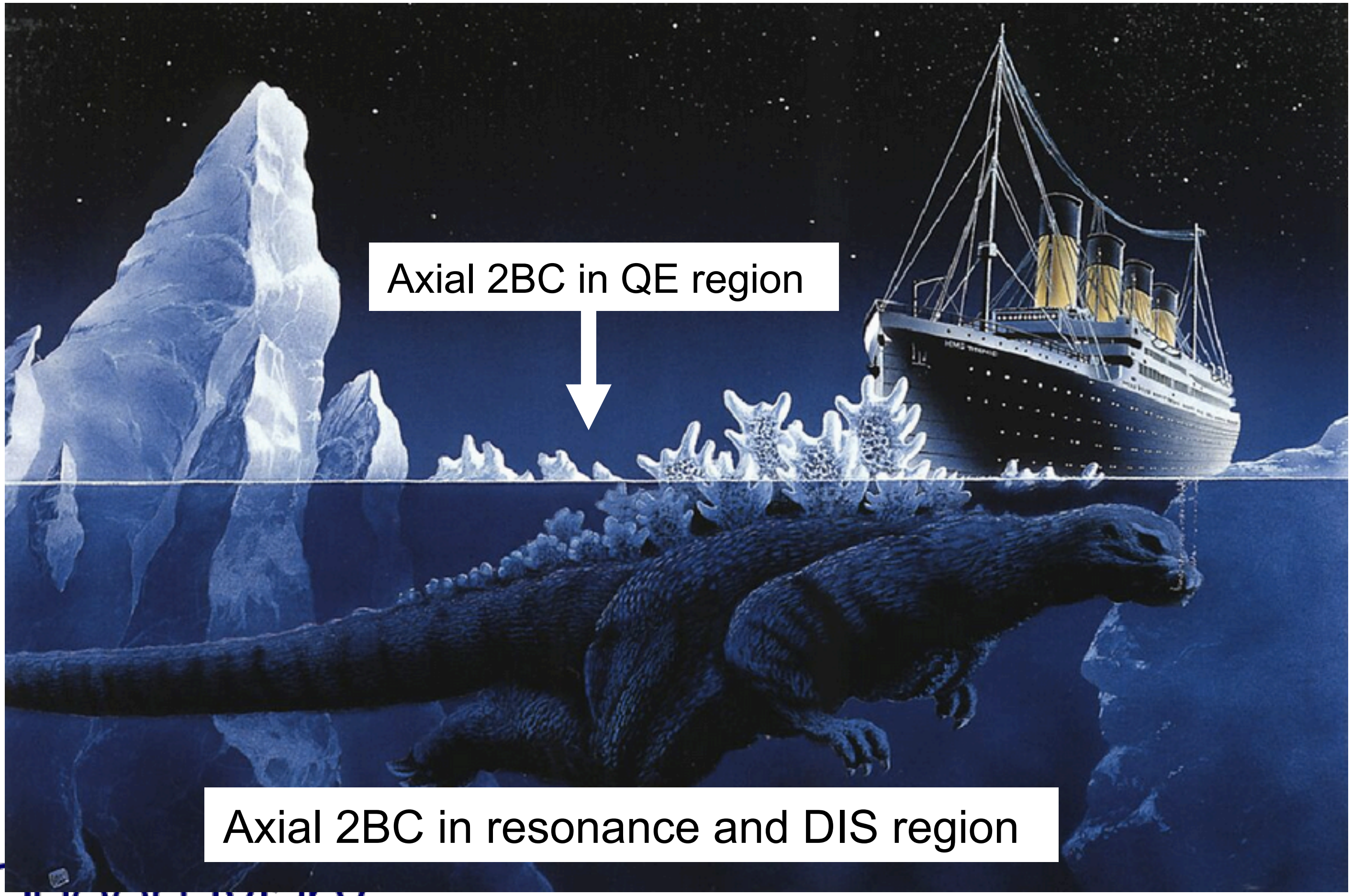


MINERvA,PRD94(2016)052005

3. Beyond QE peak

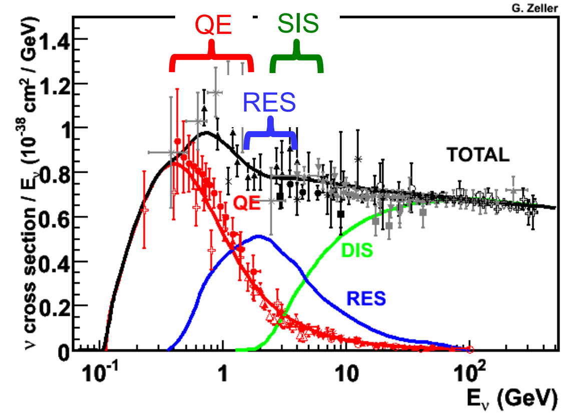
Axial 2-body current in QE region may be a tip of the iceberg…, or maybe tip of gozilla





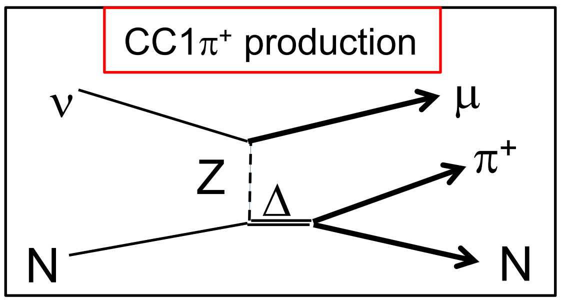
MINERvA,PRD94(2016)052005

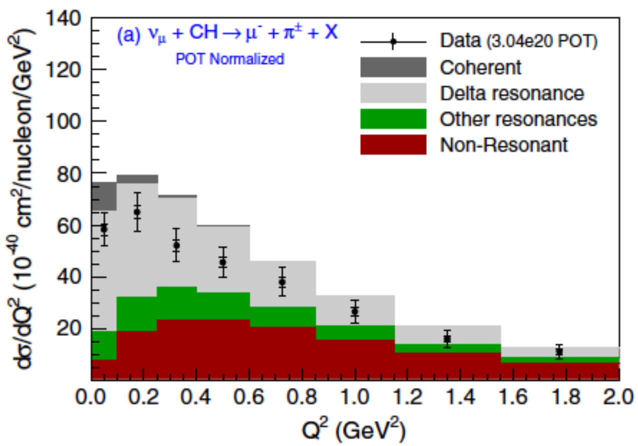
3. Baryonic resonance

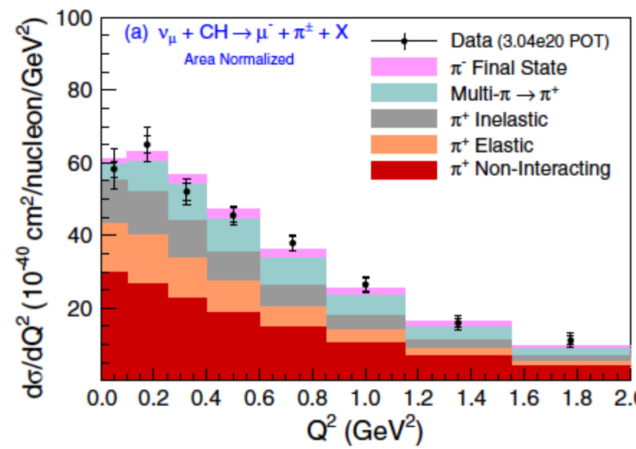


Data from MiniBooNE and MINERvA and simulation are all incompatible.

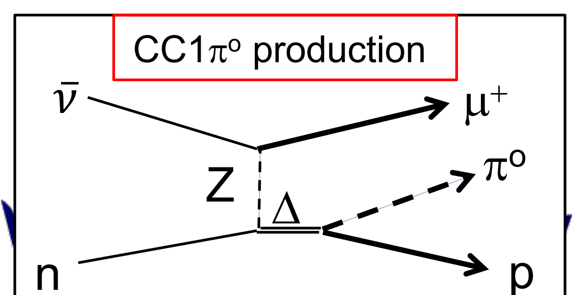
$\nu_\mu CC1\pi^+$ data has better shape agreement with GENIE

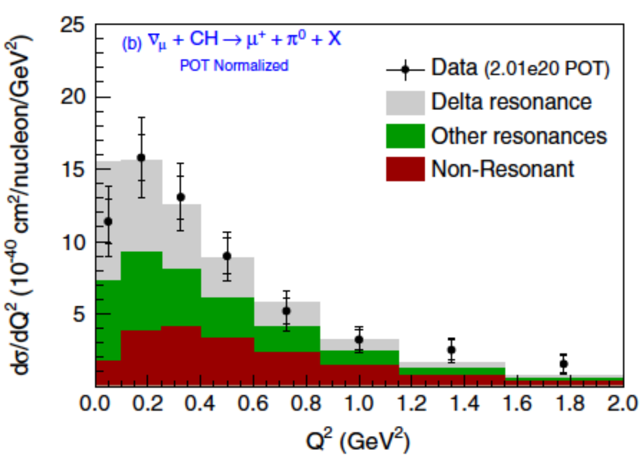


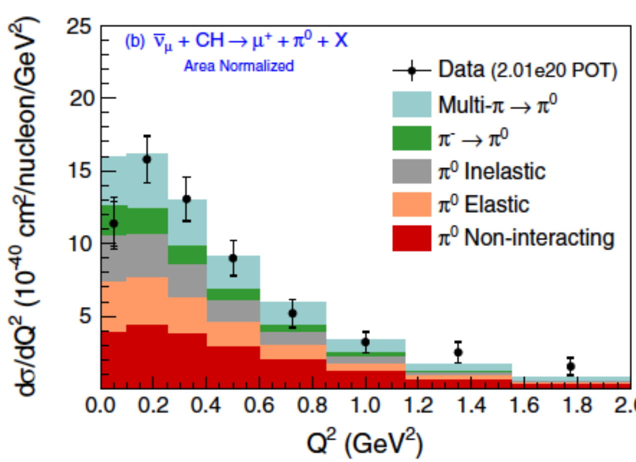




$\bar{\nu}CC1\pi^o$ data has better normalization agreement with GENIE

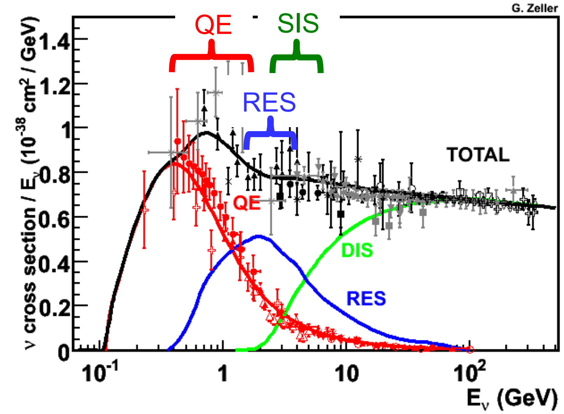






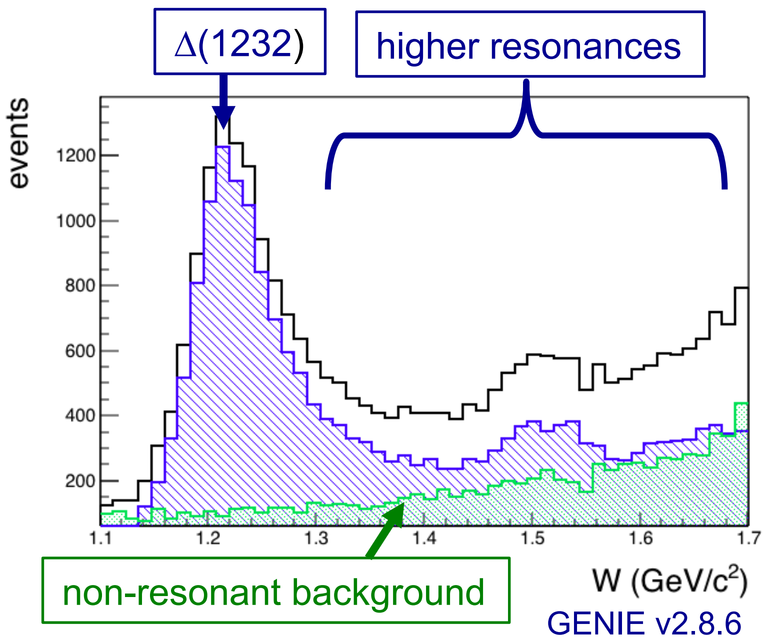
Nakamura et al.,Rep.Prog.Phys.80(2017)056301

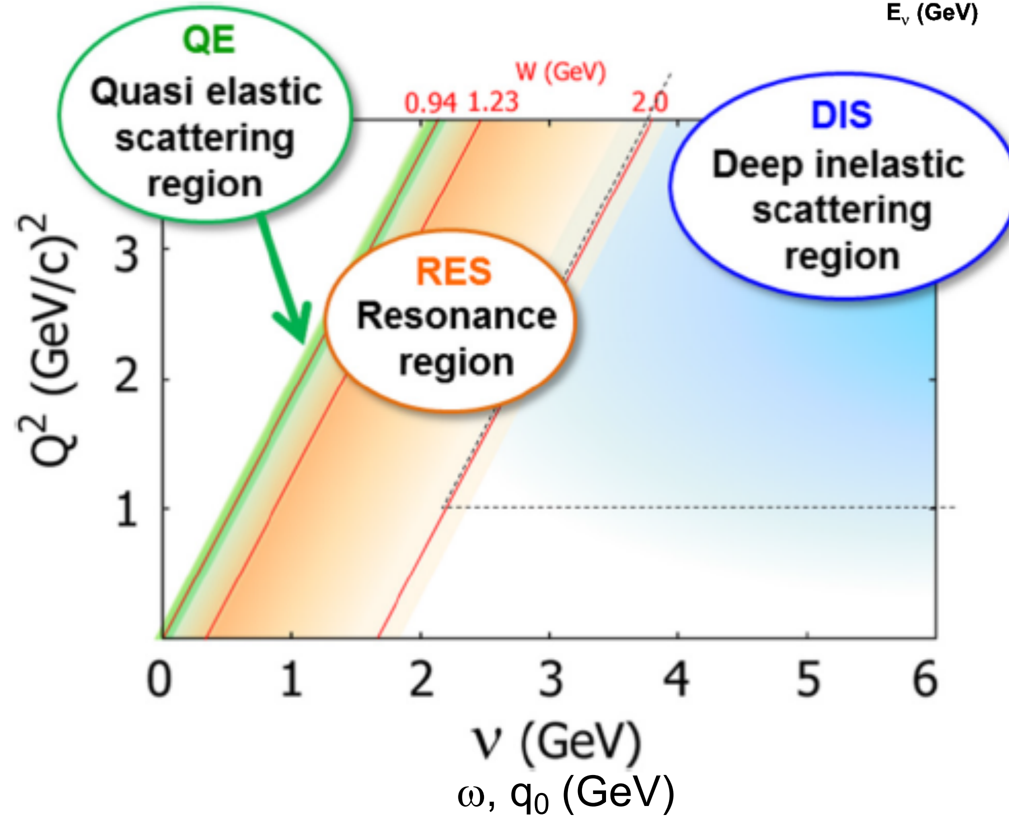
3. Shallow inelastic scattering (SIS)



SIS physics includes;

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





Queen Mary University of London

Teppei Katori, Q

Two rules of neutrino interaction physics

1. Neutrinos cannot choose kinematic phase space
2. Neutrino kinematics are not fully determined

NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

http://nustec.fnal.gov/

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

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

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

NuSTEC white paper

https://arxiv.org/abs/1706.03621

Cover all topics of neutrino interaction physics around 1-10 GeV

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

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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

ELSEVIER

Review

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

Check for updates

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

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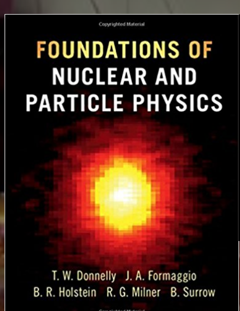
NuSTEC school

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

3rd NuSTEC school, Fermilab, USA (Nov. 7-15, 2017)

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

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



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

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

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

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

NuInt18, GSSI, Italy (Oct. 15-19, 2018)

https://indico.cern.ch/event/703880/

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

Conclusion

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

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

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

CCQE: Presence of 2p-2h contribution is still a big discussion of the community. The role of ab initio calculation is important (but what can we do for argon?!).

Resonance region: Many confusions, mostly due to poor understanding of final state interactions and high W background.

SIS, DIS, hadronization: Existing models are doing something but it seems nobody really care which is wrong

Role of hadron simulation is getting more important. There are lots of confusions due to poor understanding of final state interactions of pions and nucleons.

We need models working in all kinematic region. Neutrino experiment is always "inclusive" comparing with electron scattering (nuclear physics) and collider physics (particle physics).

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Conclusion

Neutrino oscillation

electron scattering

nuclear many-body problem

Weak interaction

Neutrino Interaction Physics

EMC effect

Nucleon correlation

Spin physics

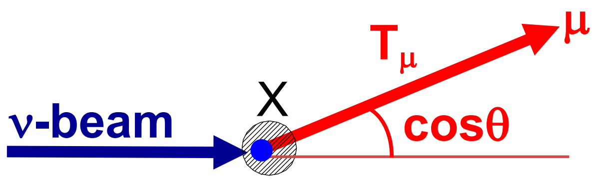
Dark matter

Heavy ion collision

Thank you for your attention!

Backup

2. Neutrino experiment



Experiment measure the interaction rate R,

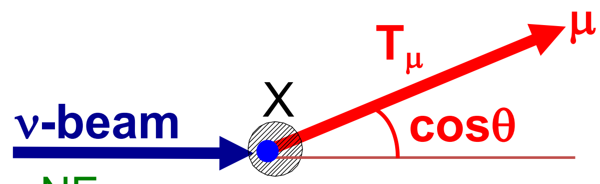
$$R \sim \int \Phi \times \sigma \times \varepsilon$$

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

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

1. ν-interaction
2. CCQE
3. Conclusion

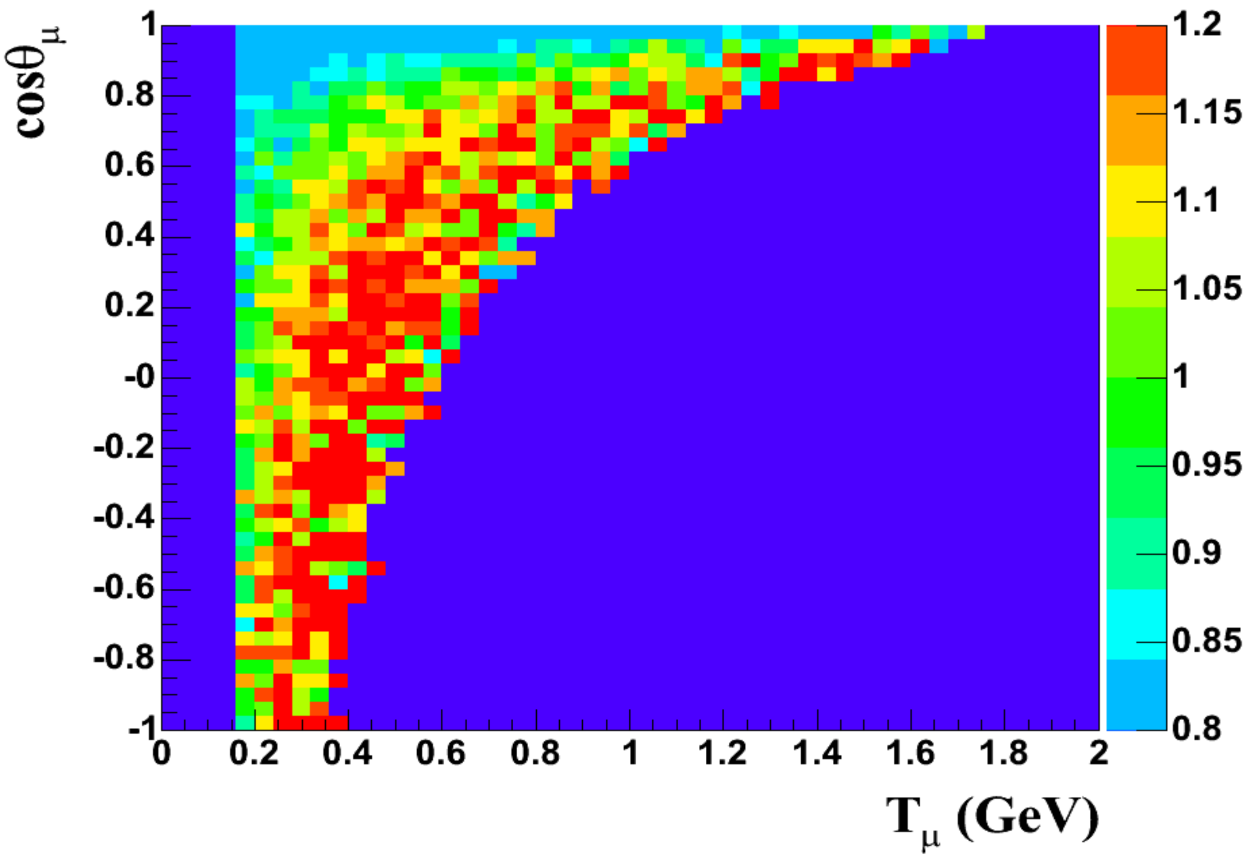
2. MiniBooNE phase space



CCQE kinematic space (T_μ-$\cos\theta_\mu$ plane) in MiniBooNE

Since observables are muon energy (T_μ) and angle ($\cos\theta_\mu$), these 2 variables completely specify the kinematic space.

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

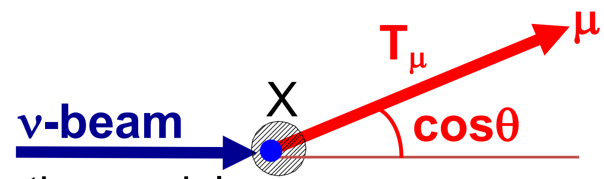


Data-MC ratio for T_μ-$\cos\theta_\mu$ plane (arbitrary normalization).
MiniBooNE MC doesn't describe data very well.

We would like to improve our simulation, but how?

MiniBooNE collaboration,PRL.100(2008)032301

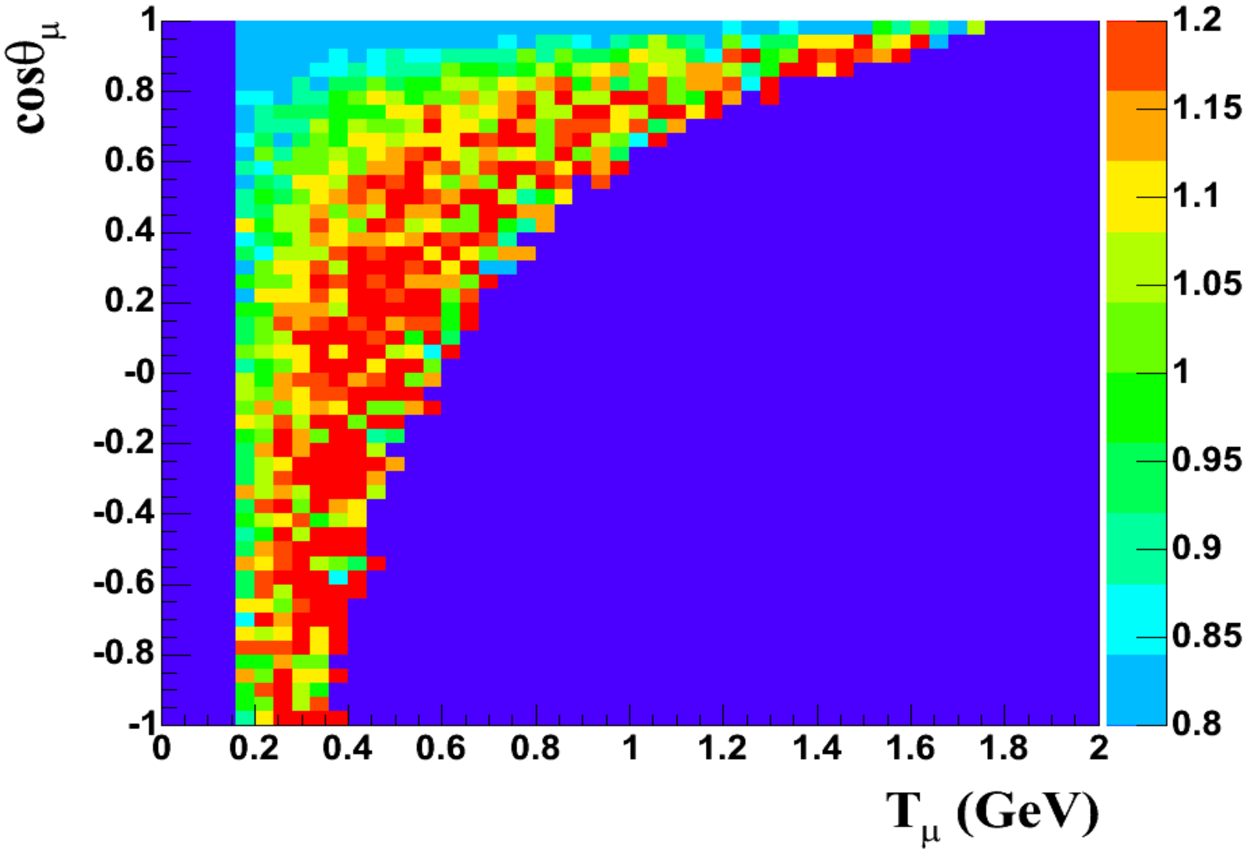
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

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

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



MiniBooNE collaboration,PRL.100(2008)032301

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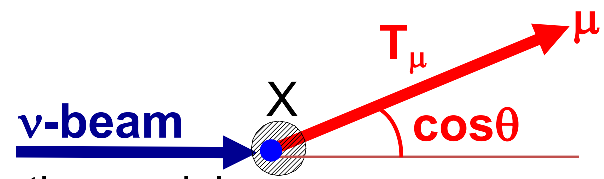
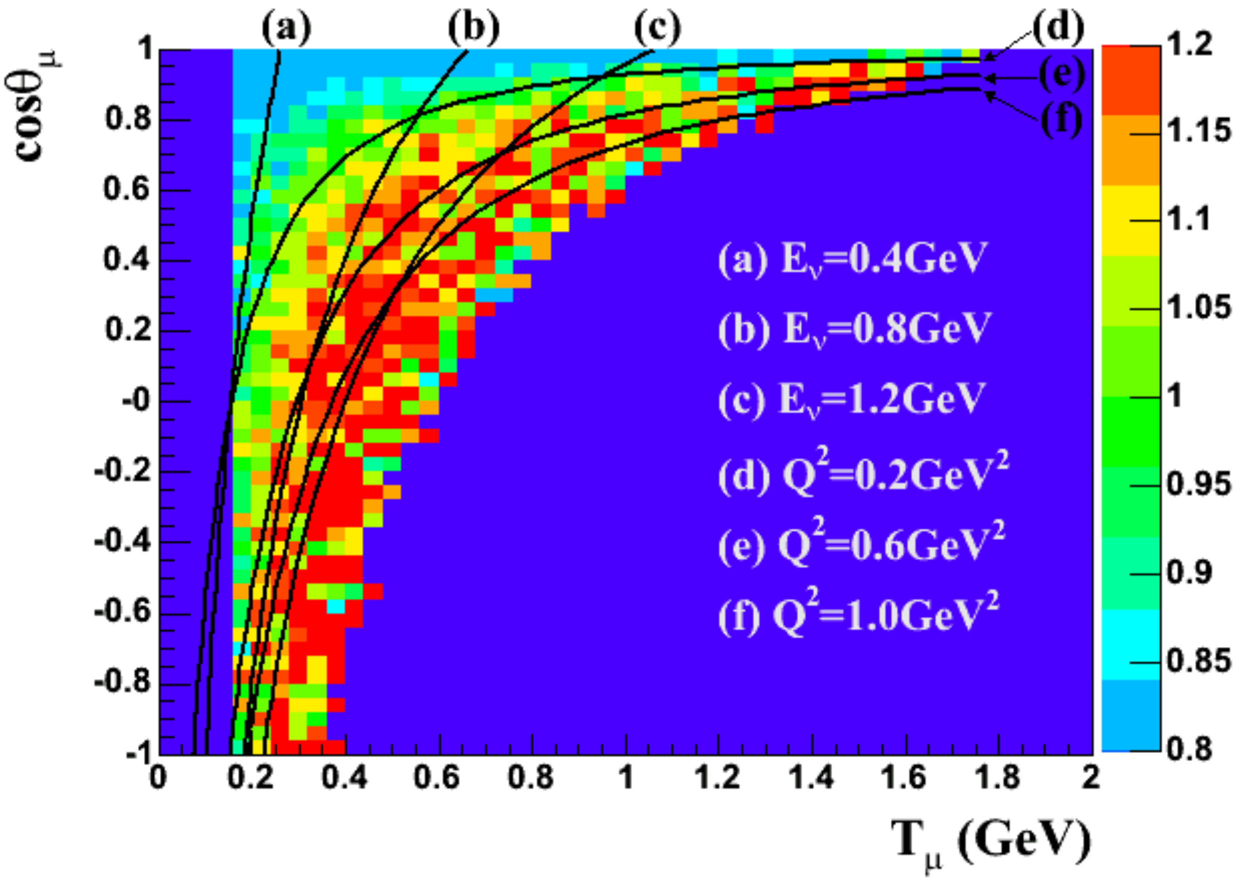


Without knowing flux, you cannot modify cross section model

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

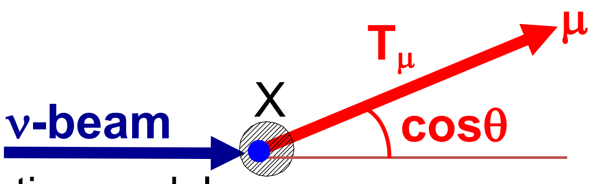
$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$



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

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

2. MiniBooNE phase space

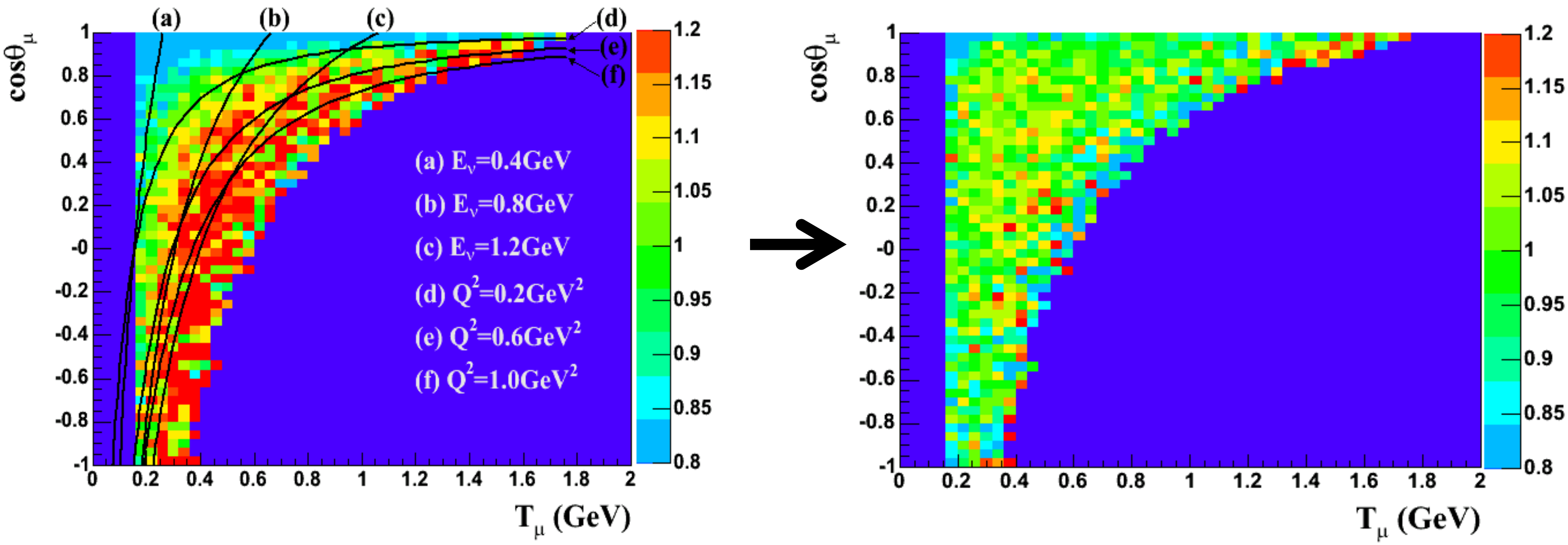


Without knowing flux, you cannot modify cross section model

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

After tuning cross section parameters, data and MC agree.

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



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

2. Smith-Moniz formalism

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

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

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

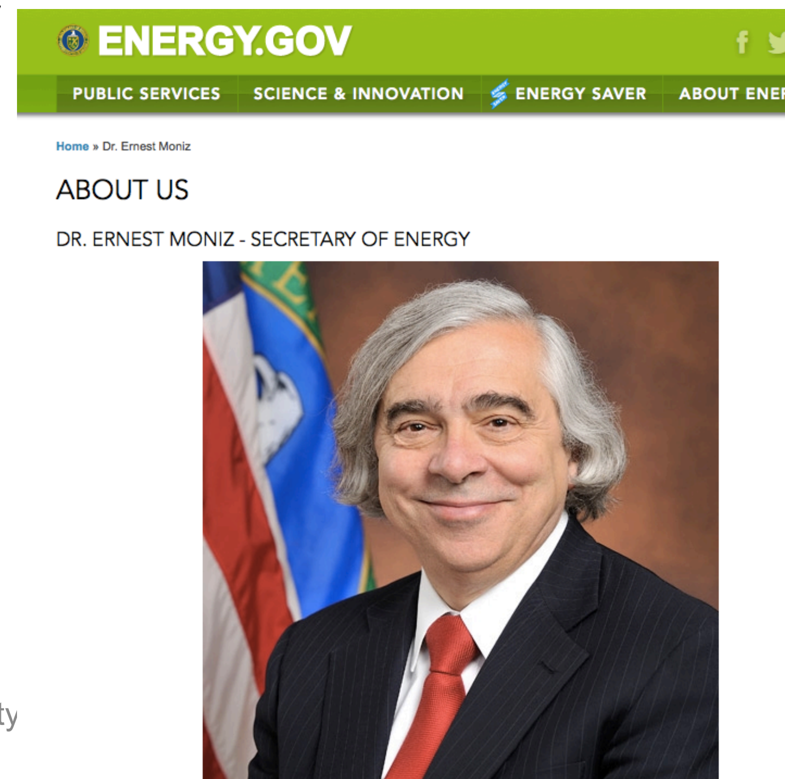
$T_{\mu\nu}=T_{\mu\nu}(F_1, F_2, F_A, F_P)$: nucleon form factors

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

Ehi : the highest energy state of nucleon

Elo : the lowest energy state of nucleon

Although Smith-Moniz formalism offers variety of choice, one can solve this equation analytically if the nucleon space is simple.



2. Relativistic Fermi Gas (RFG) model

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Ehi : the highest energy state of nucleon $=\sqrt{(p_F^2+M^2)}$

Elo : the lowest energy state of nucleon $= \kappa\left(\sqrt{(p_F^2+M^2)} - \omega + E_B\right)$

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

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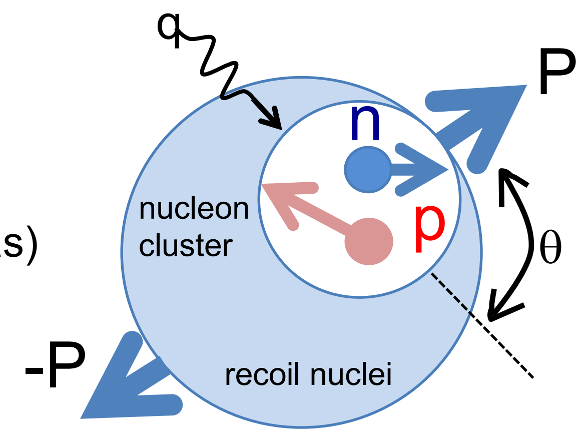
MiniBooNE tuned following 2 parameters using Q^2 distribution by least χ^2 fit;
M_A = effective axial mass
κ = effective Pauli blocking parameter

MiniBooNE tuned their axial mass to 1.3 GeV!

but axial mass is not 1.3 GeV!

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

2. How to emit 2 nucleons from correlated pair?



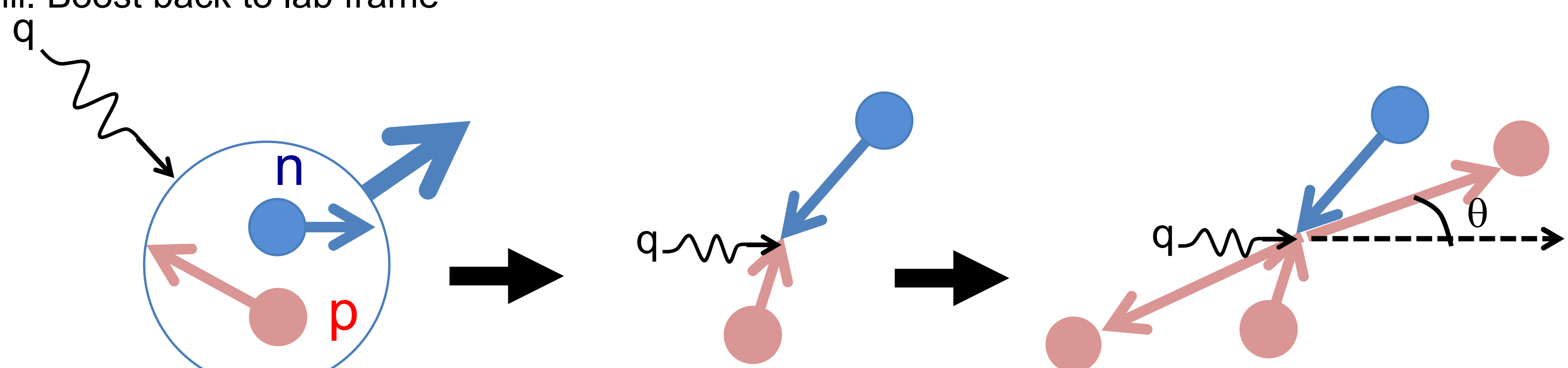
Default model for GENIE, NEUT, NuWro…

For a given Energy-Momentum transfer...

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

Once 2 nucleons from on-shell are choosed

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



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

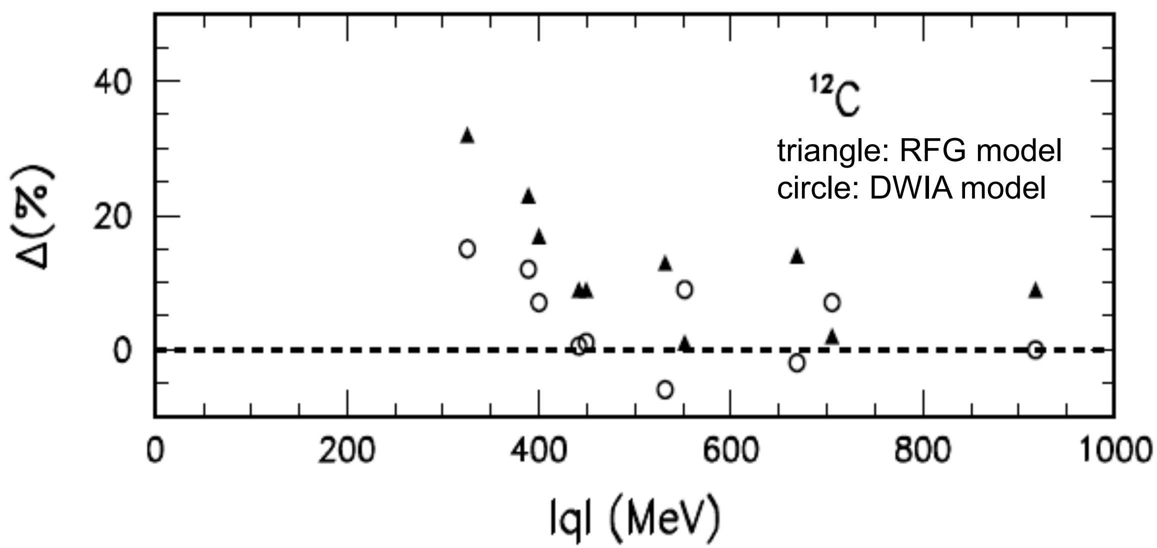
2. Relativistic Fermi Gas (RFG) model

Relativistic Fermi Gas (RFG) Model

Nucleus is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

In low |q|, The RFG model systematically over predicts cross section for electron scattering experiments at low |q| (~low Q^2)

Data and predicted xs difference for ^{12}C



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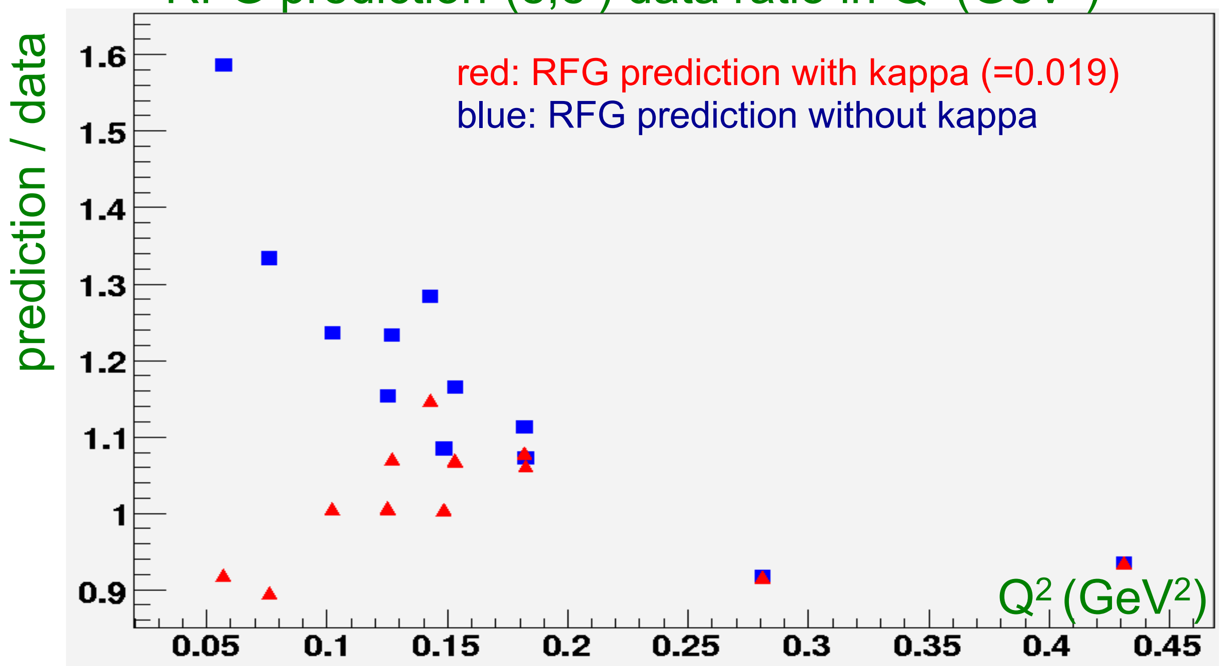
RFG prediction-(e,e') data ratio in Q^2 (GeV^2)

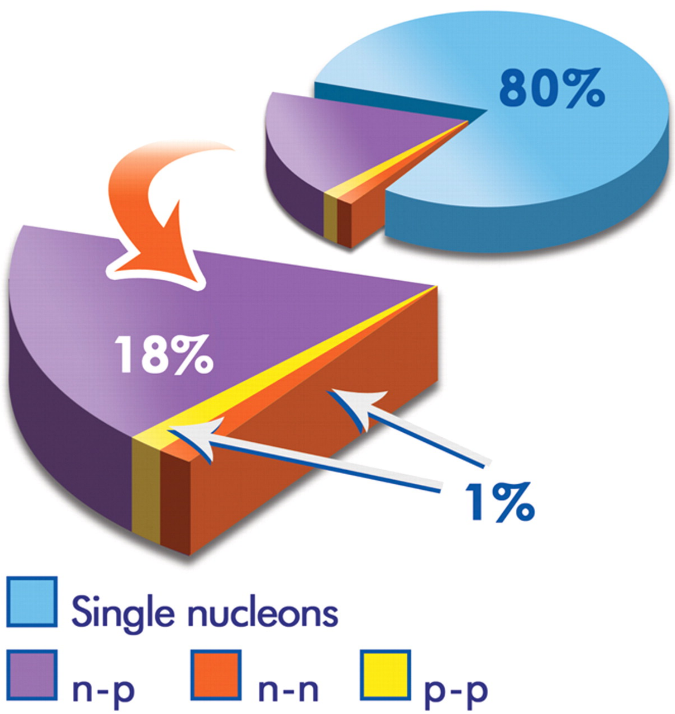


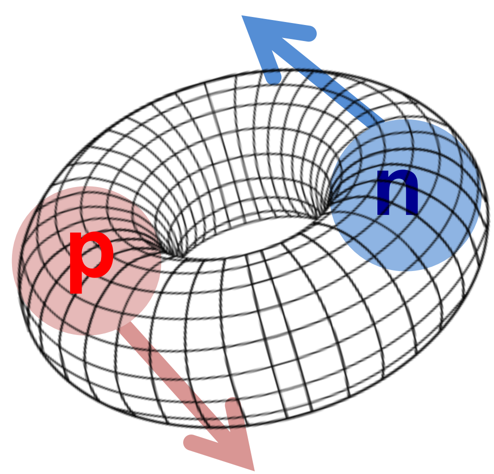
CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504
JLab HallA, PRL99(2007)072501, Science320(2008)1476

2. Nucleon correlations

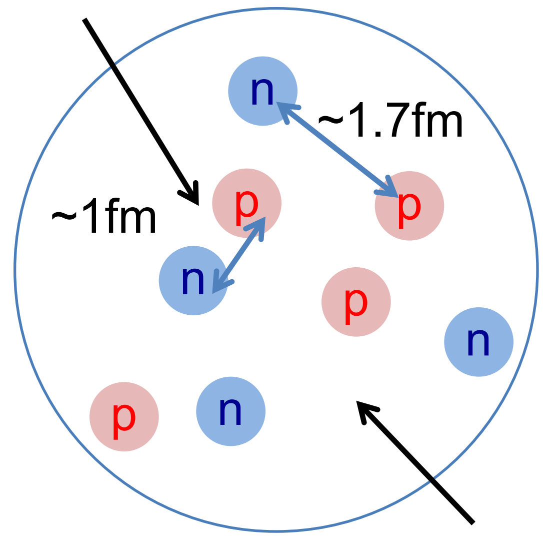
Short Range Correlation (SRC)

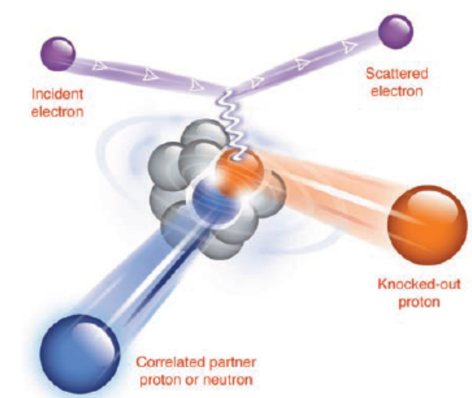
~20% of all nucleons in heavy elements (A>4)
~90% are neutron-proton (n-p) pair
~nucleon pair have back-to-back momentum
~ momentum can be beyond Fermi sea





NNSRC~quasi deuteron





CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504;106(2011)052301
JLab HallA, PRL99(2007)072501, Science320(2008)1476

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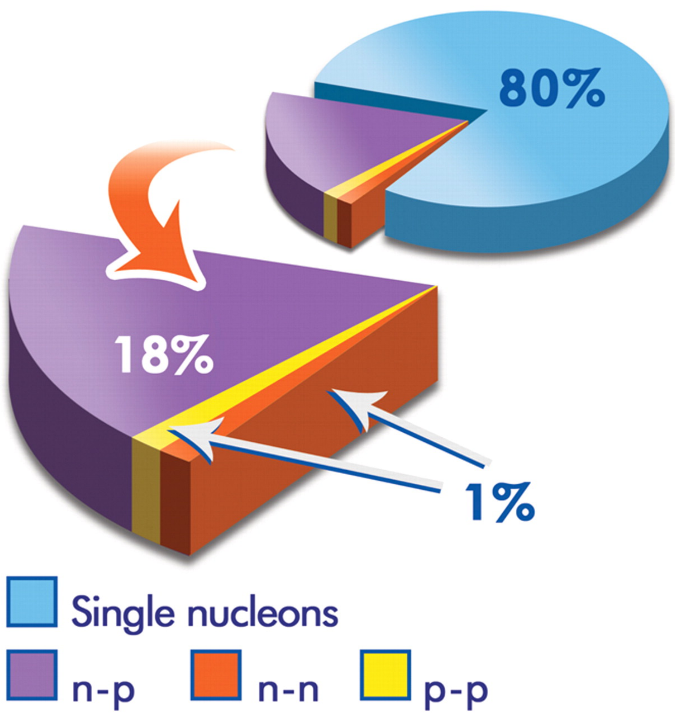
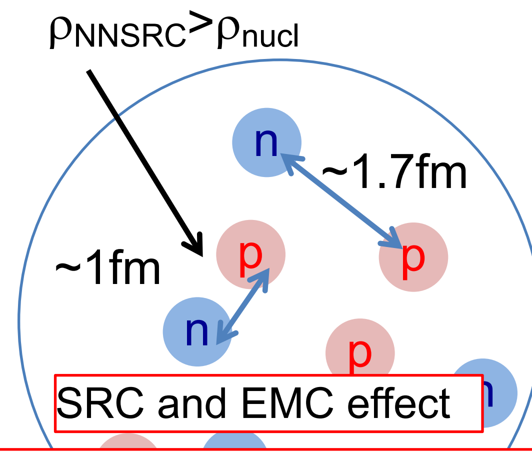
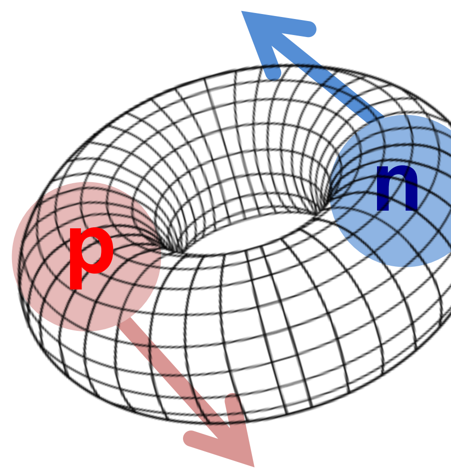
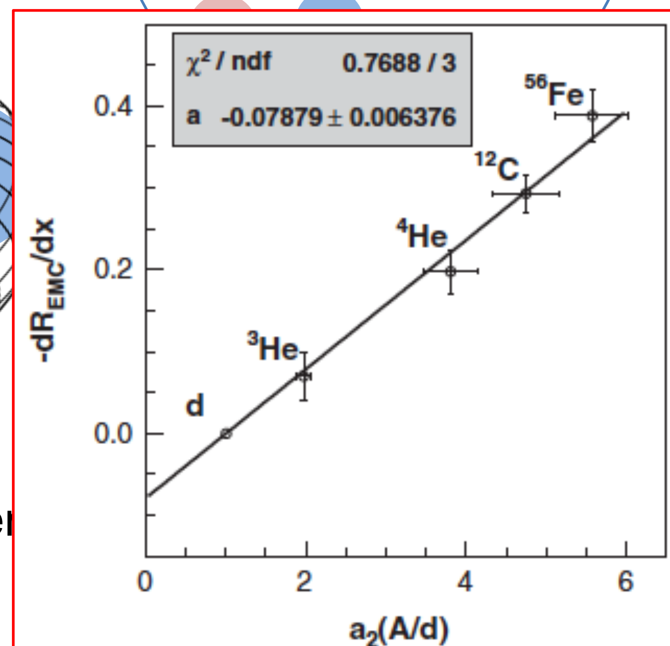






NNSRC~quasi deuter

SRC and EMC effect



Martini et al,PRD85(2012)093012
Nieves et al,PRD85(2012)113008

3. Neutrino oscillation experiment

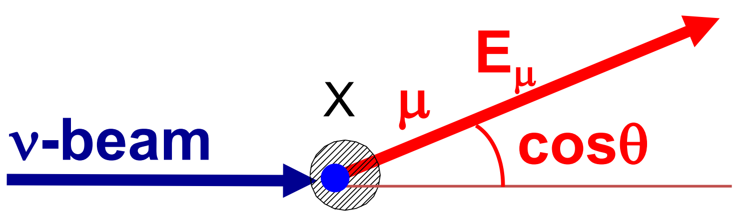
Reconstruction of neutrino energy with QE assumption

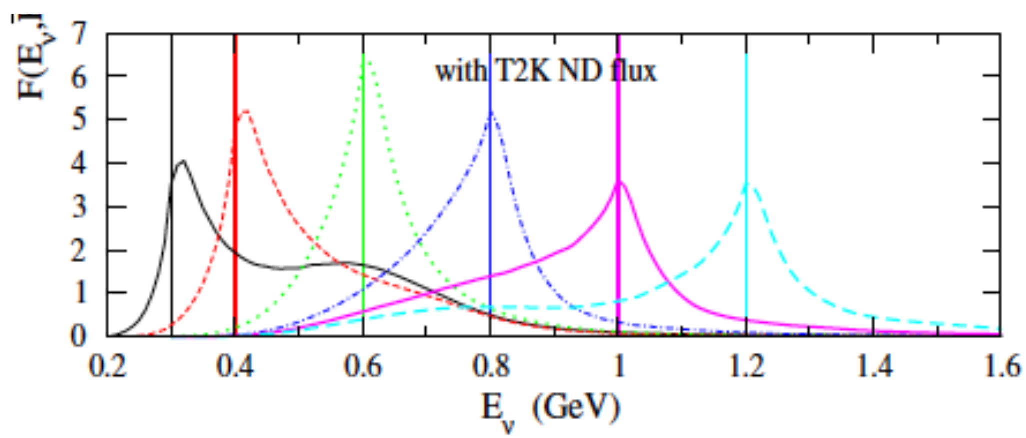
- We can reconstruct neutrino energy if we know it is CCQE interaction
  → There is bias because of all "CCQE-like" interactions.

(interaction with 2-nucleons, pion production with pion nuclear absorption)

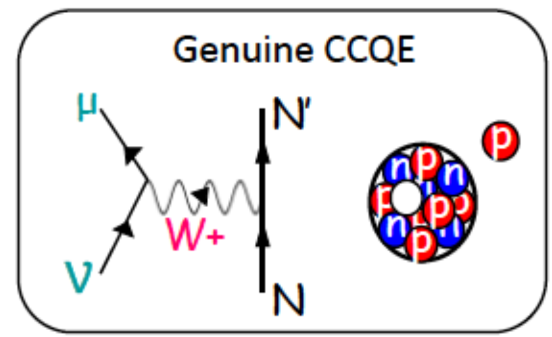
$$\nu_\mu + n \rightarrow p + \mu^- \quad (\nu_\mu + X \rightarrow X' + \mu^-)$$

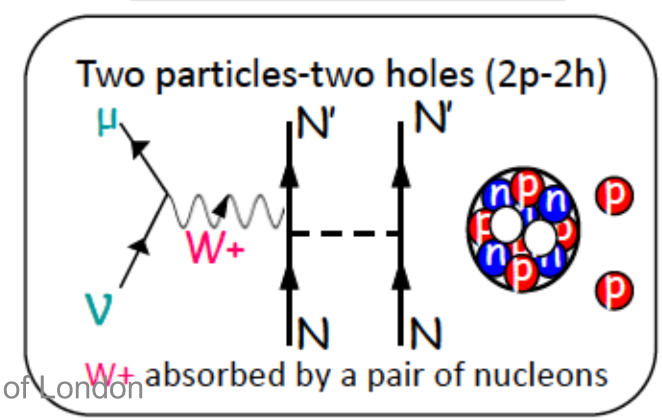
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$





estimated reconstruction due to 2-body current





5. Conclusion remarks from INT workshop 2013

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

Toward better neutrino interaction models…

To experimentalists

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

To theorists

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