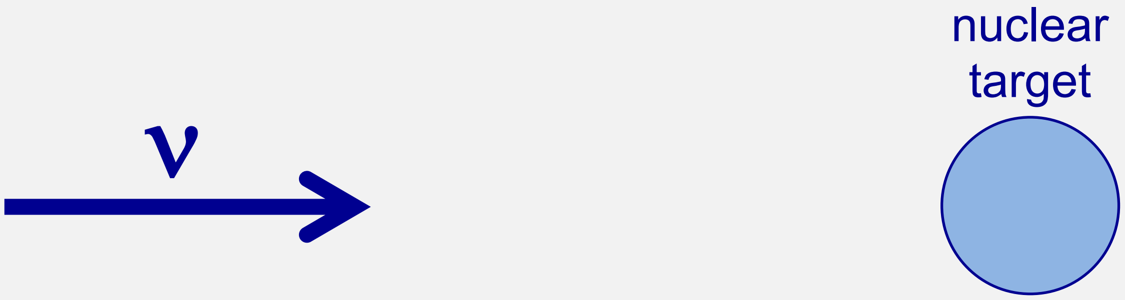
ν
nuclear
target

Fun Timely Intellectual Adorable!

Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

NuSTEC News

Nucleon correlation

EMC effect

electron scattering

Dark matter

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Physics of Neutrino Interactions around 1-10 GeV

Teppei Katori
Queen Mary University of London
NDM 2018, Institute for Basic Science HQ, Daegu, Korea, Jun. 30, 2018

outline

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

Physics of Neutrino Interactions around 1-10 GeV

Further reading

NDM 2018, In . 30, 2018

outline

1. Neutrino Interaction Physics
2. Charged-Current Quasi-Elastic (CCQE) interaction
3. Shallow inelastic scattering (SIS)
4. Conclusions

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

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

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

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

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

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

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

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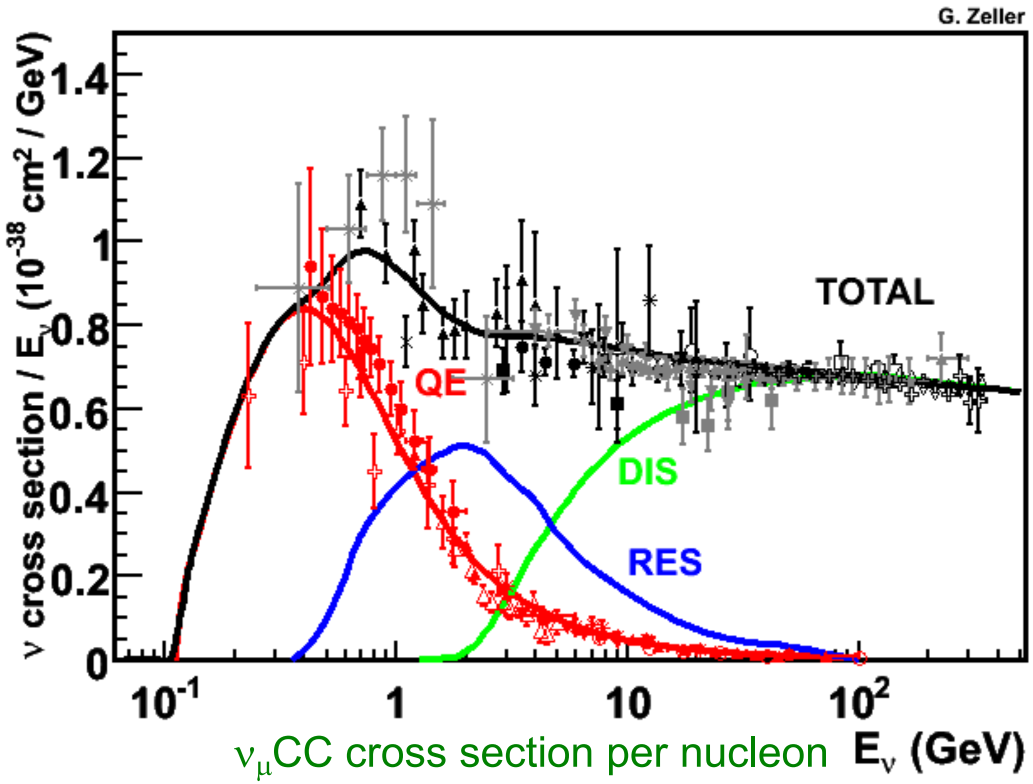
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments mostly around 1-10 GeV!

- 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

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

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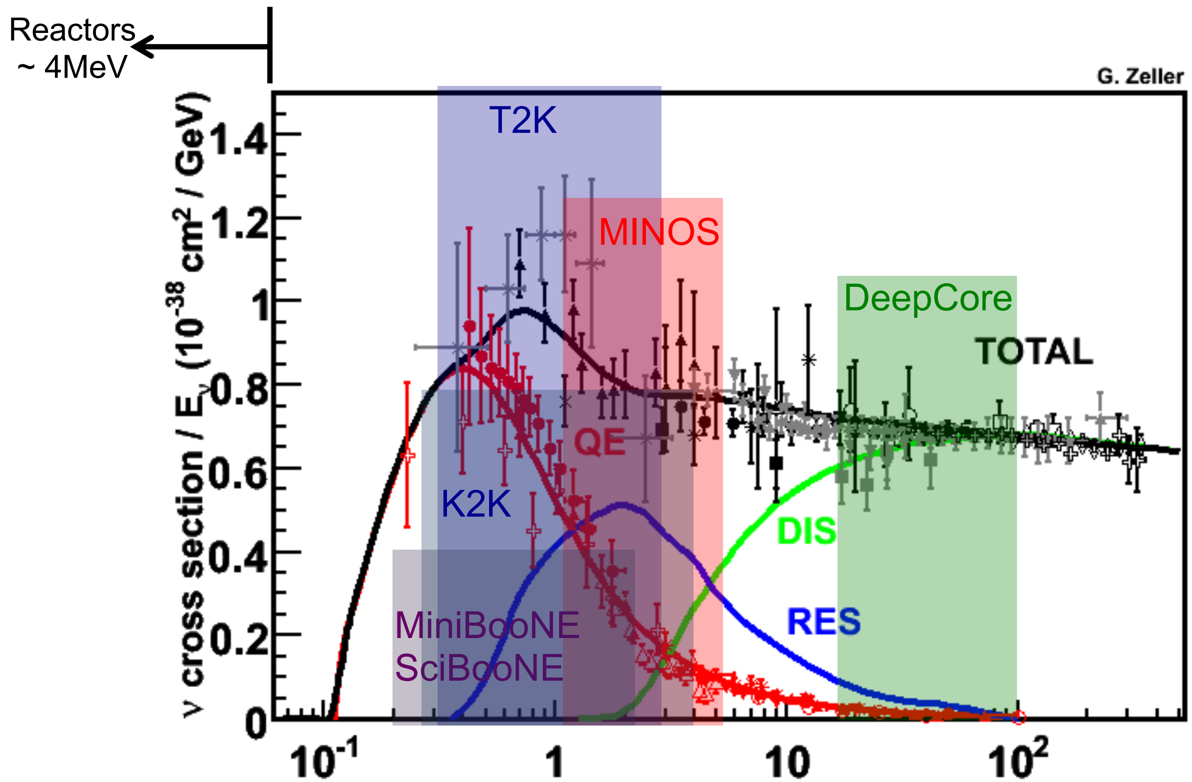

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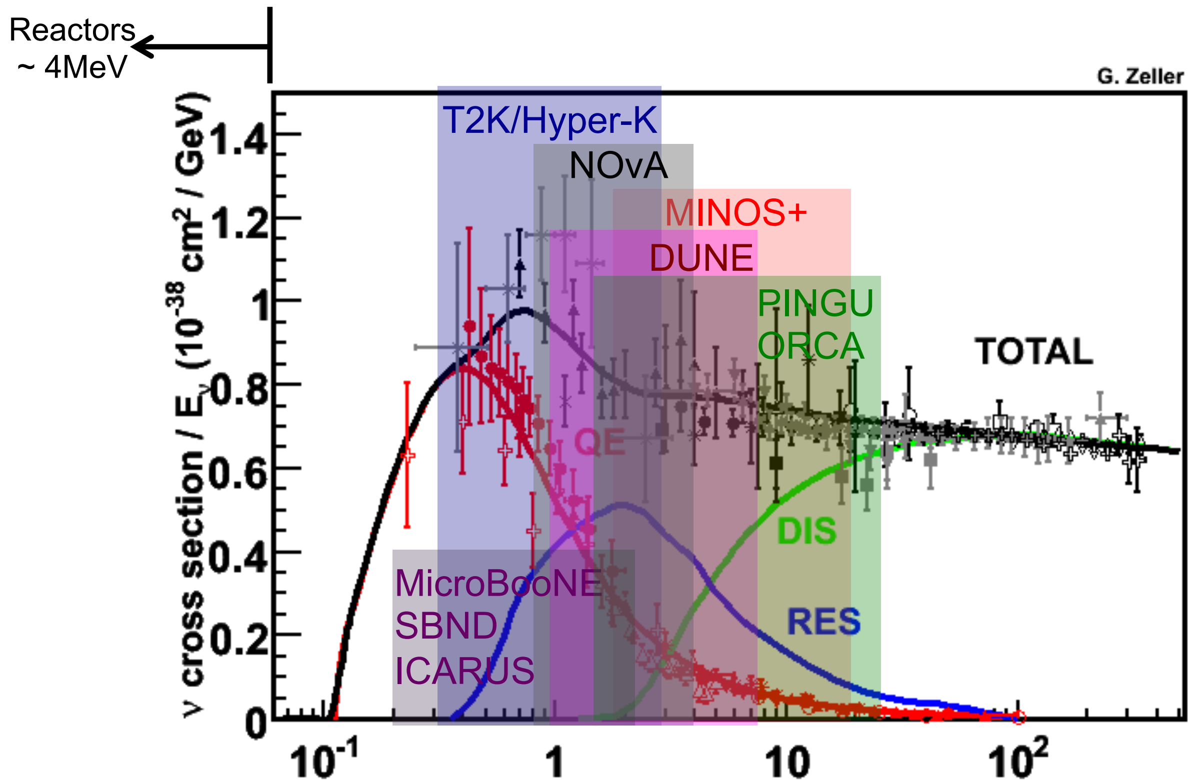

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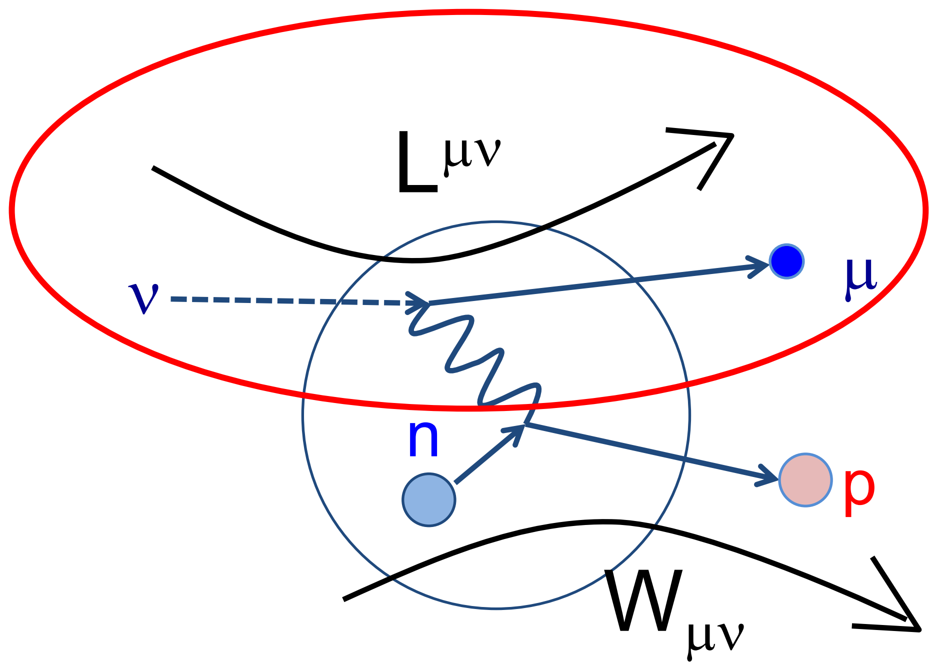
1. Neutrino cross-section formula

Cross-section
- product of Leptonic and Hadronic tensor

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

Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)



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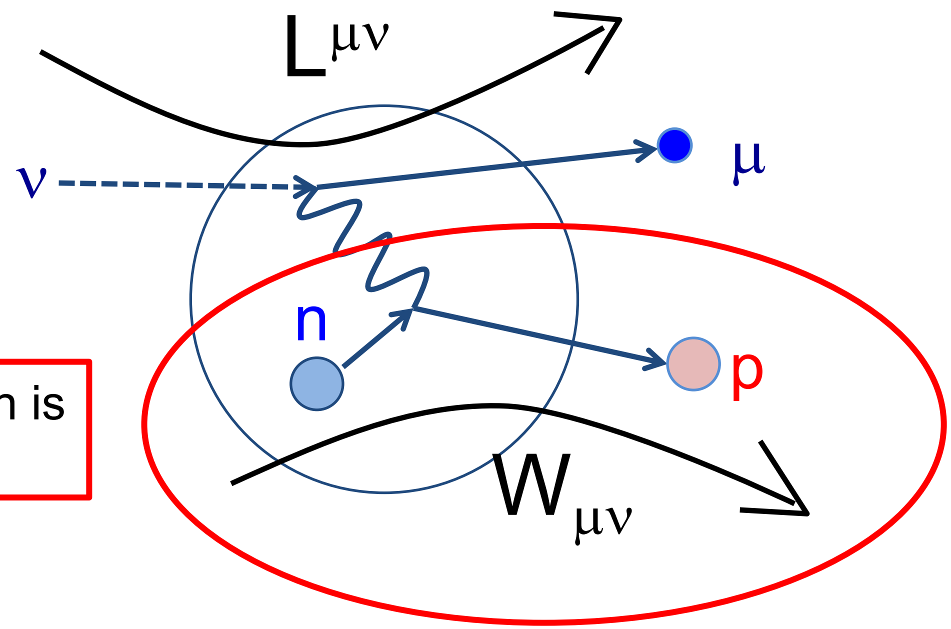

All complication of neutrino cross-section is how to model the hadronic tensor part

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

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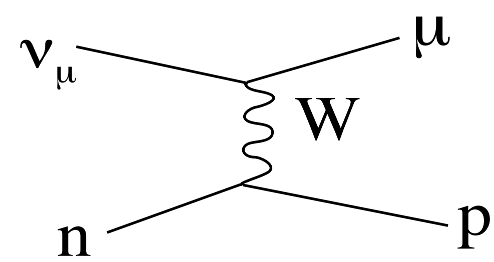
2. Charged Current Quasi-Elastic scattering (CCQE)

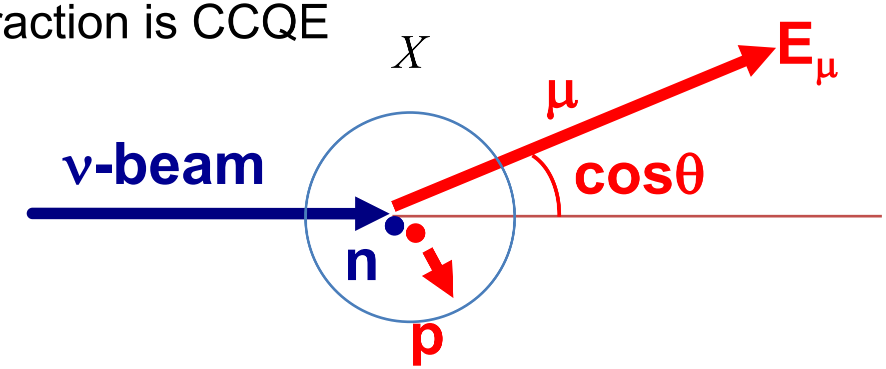
The simplest and the most abundant interaction around ~1 GeV.

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



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 (2nd maximum)…etc

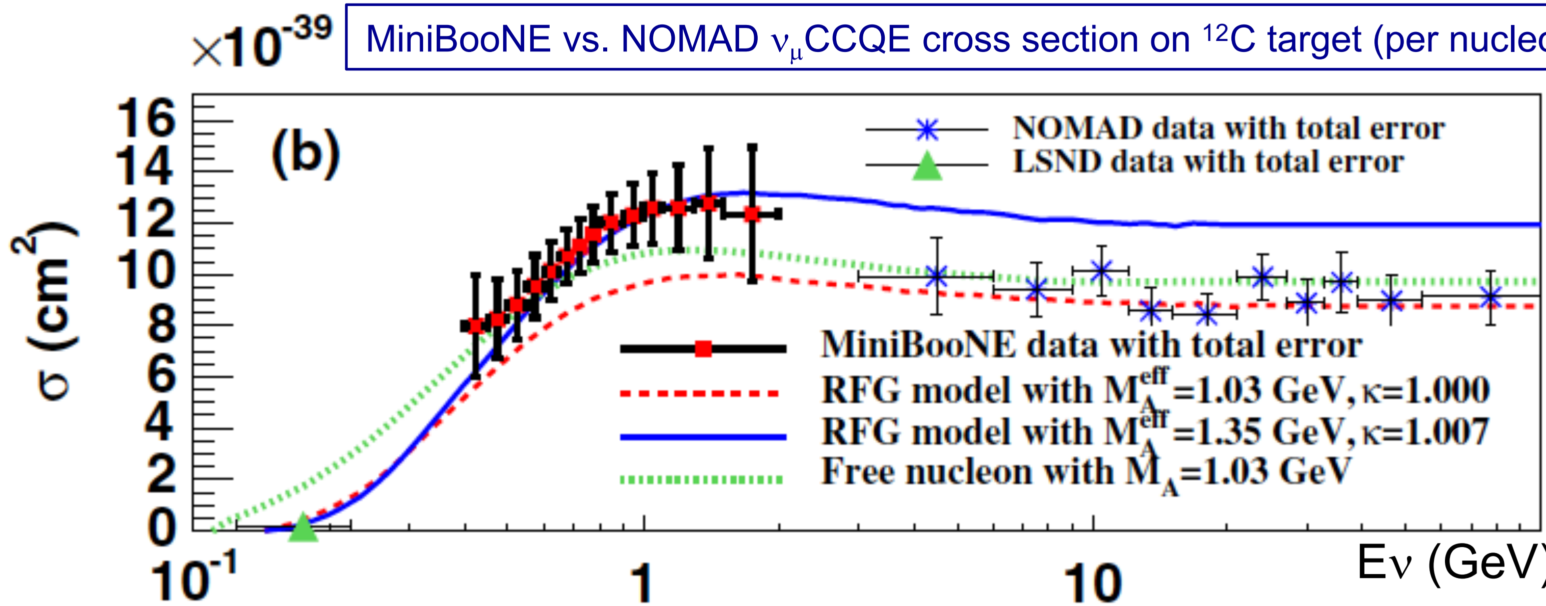
2. Charged Current Quasi-Elastic scattering (CCQE)

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) 1.2-1.3 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…

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

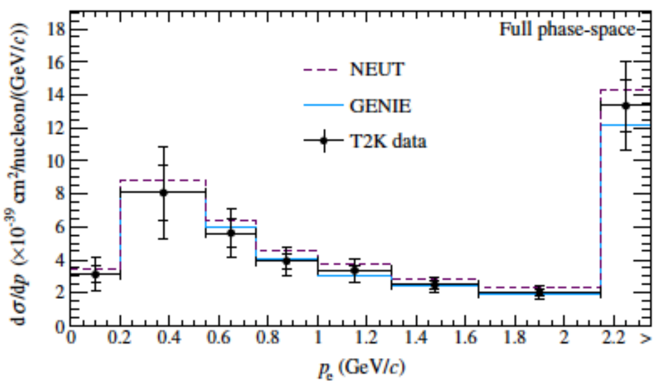
These data play major roles to study/improve neutrino interaction models by theorists

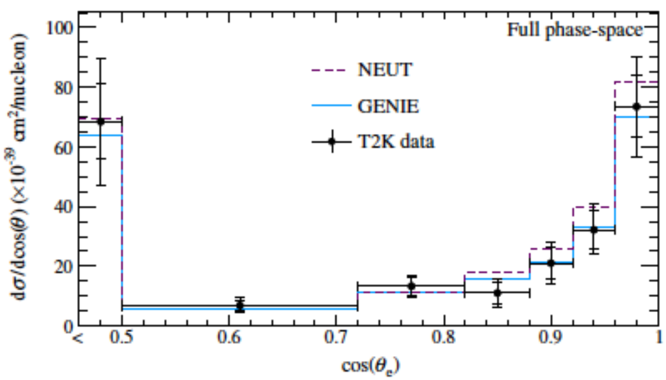
2. Flux-integrated differential cross-section

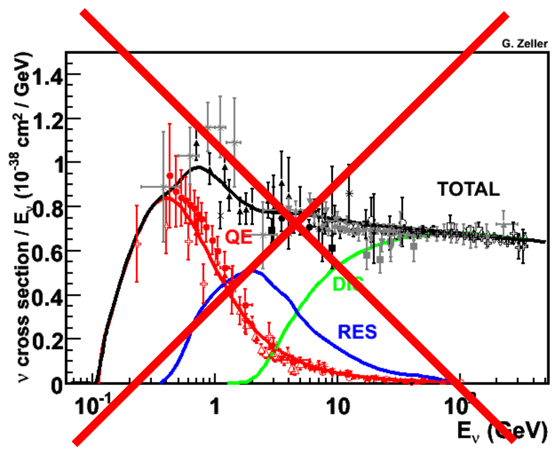
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

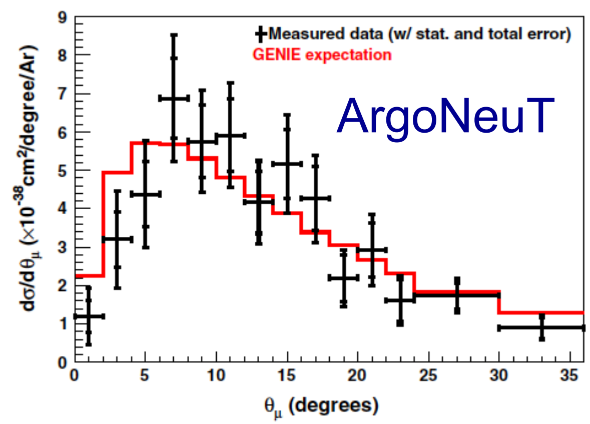
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

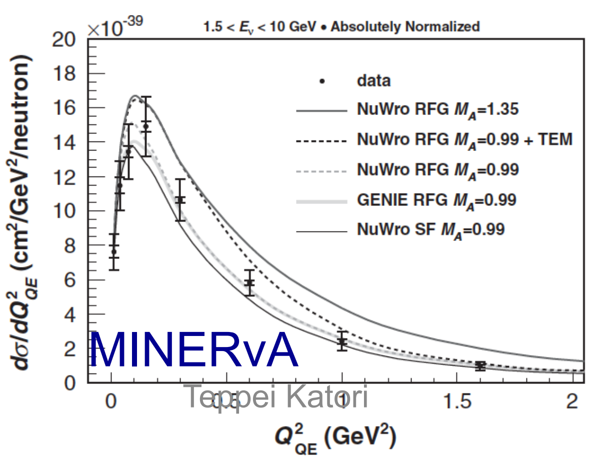
T2K



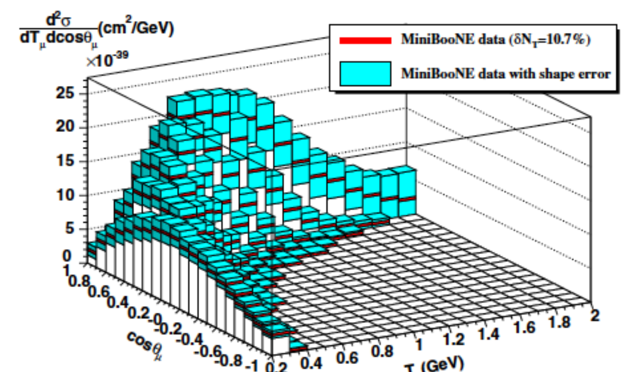








MiniBooNE



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

Theorists

Experimentalists

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

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

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2. The solution of CCQE puzzle

Presence of 2-body current

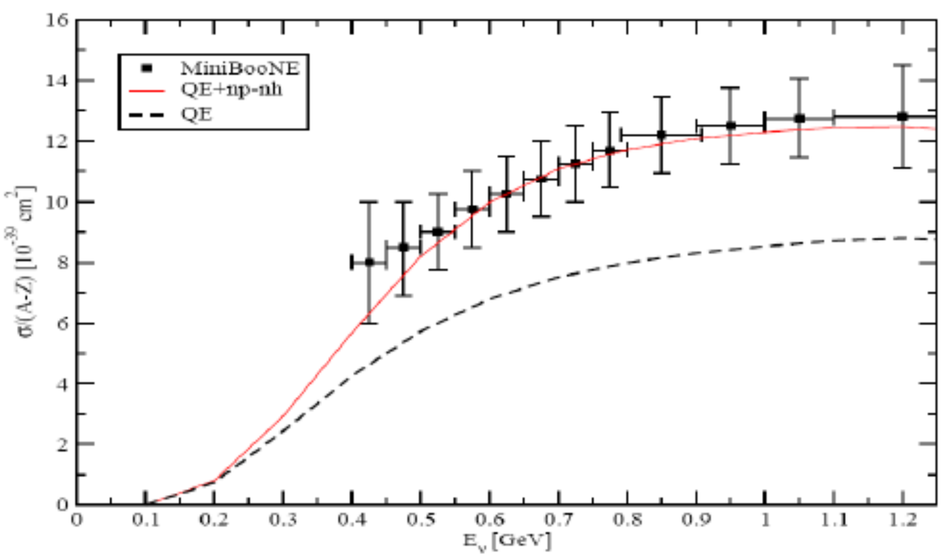
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

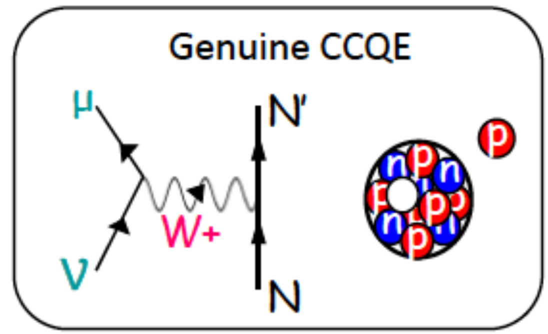
What experimentalists call "CCQE" is not genuine CCQE!

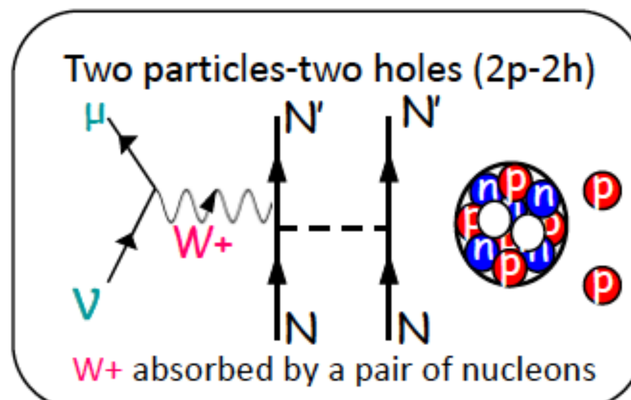
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Martini et al,PRC80(2009)065501;87(2013)065501
Nieves et al,NPA627(1997)543; PLB707(2012)72;721(2013)90

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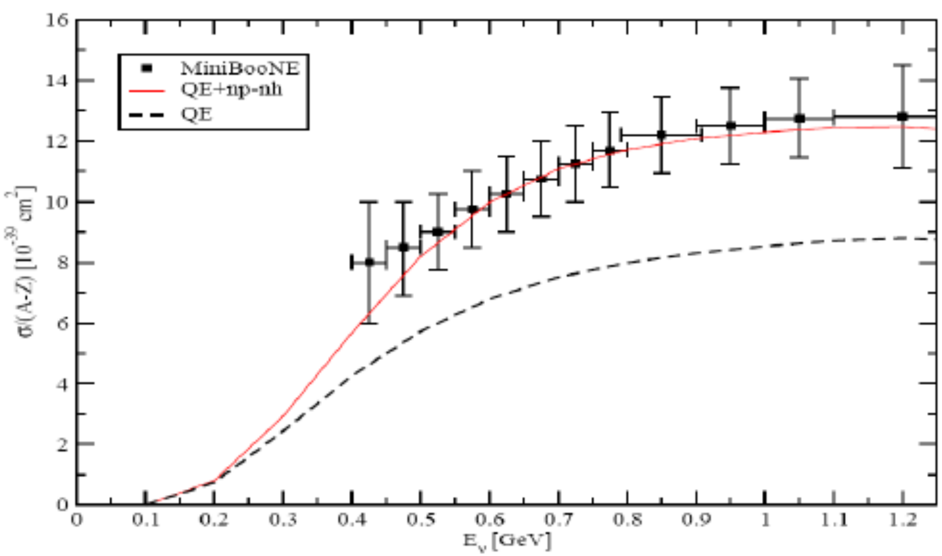
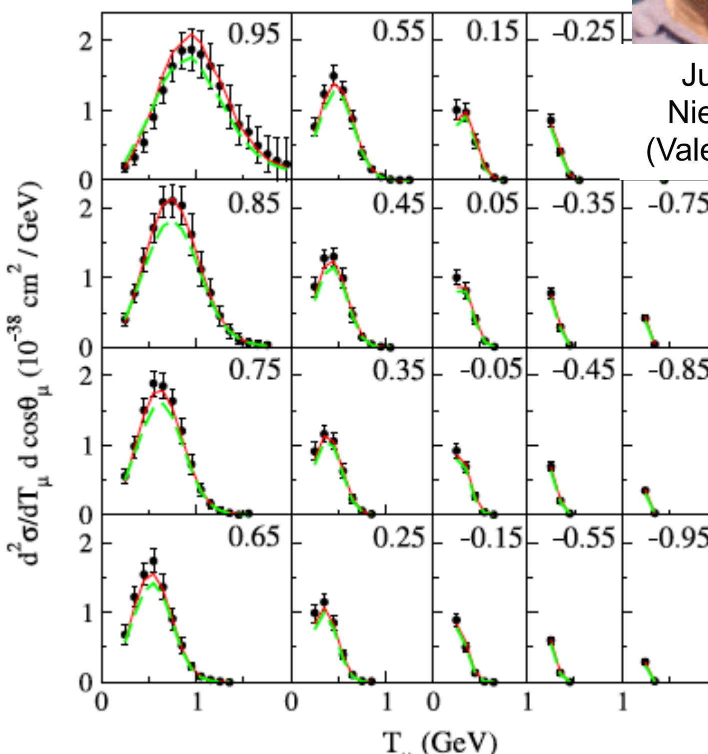
The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)





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

Meucci et al.,PRL107(2011)172501;PRD85(2012)093002;PRD91(2015)093004;Sobczyk,PRC86(2012)015504
Megias et al.,PRD94(2016)093004, Martini and Ericson,PRC90(2014)025501,Gallmeister et al.,PRC94(2016)035502

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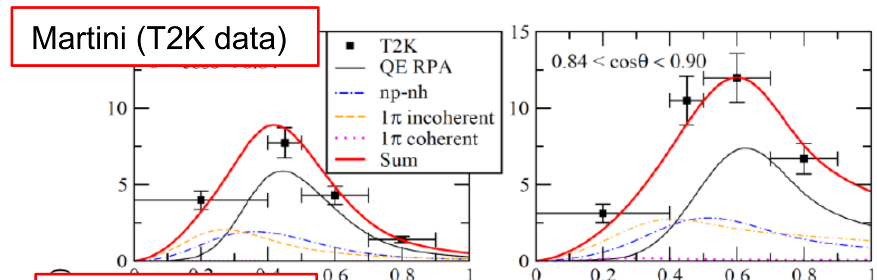
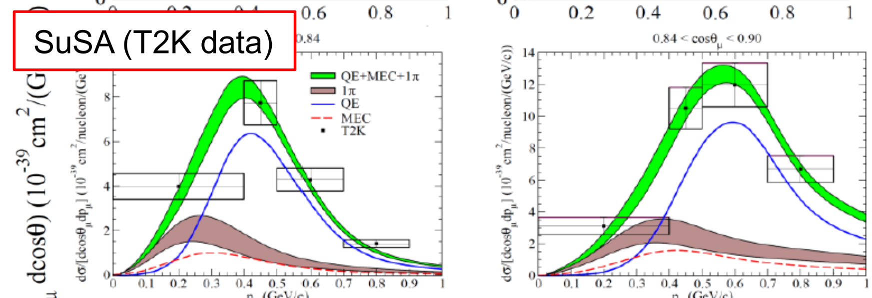
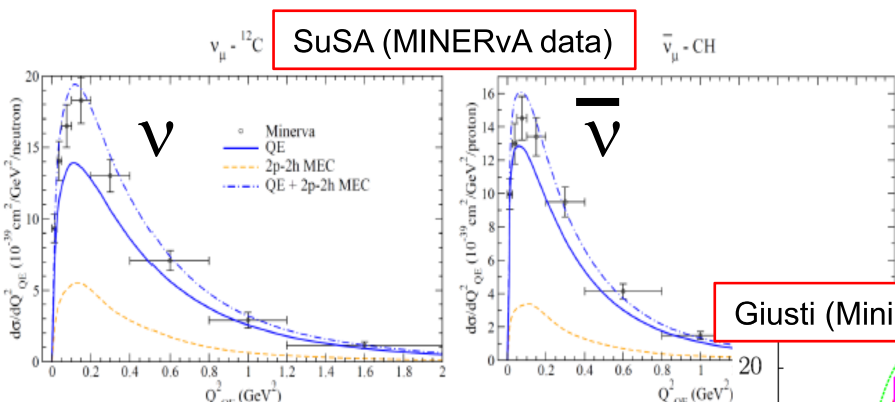
Presence of 2-body current

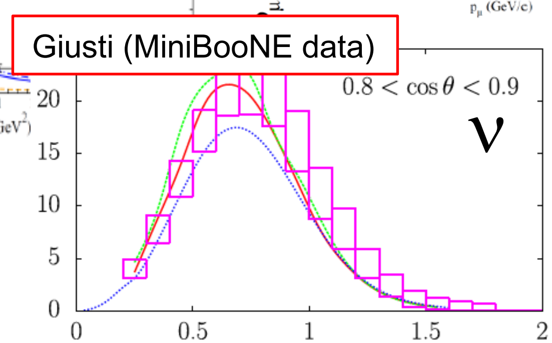
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- phenomenological models can reproduce MiniBooNE, T2K, MINERvA data simultaneously

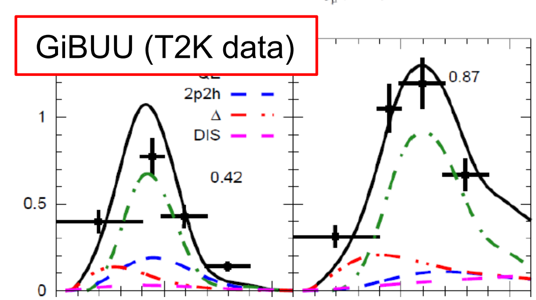
MiniBooNE neutrino beam is not the source of CCQE puzzle
Models reasonably describe lepton kinematics in wide energy region











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

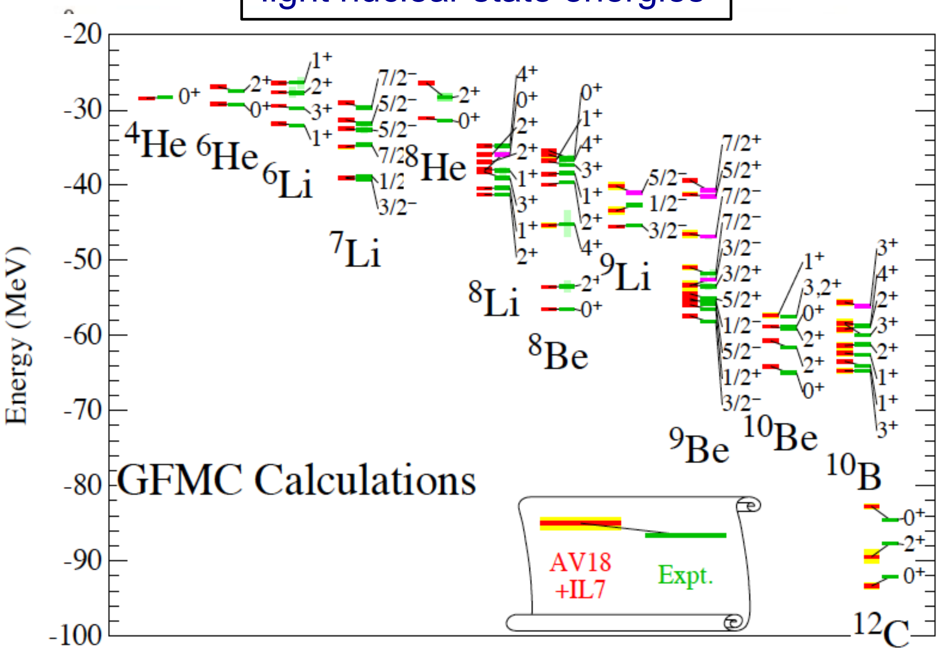
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

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

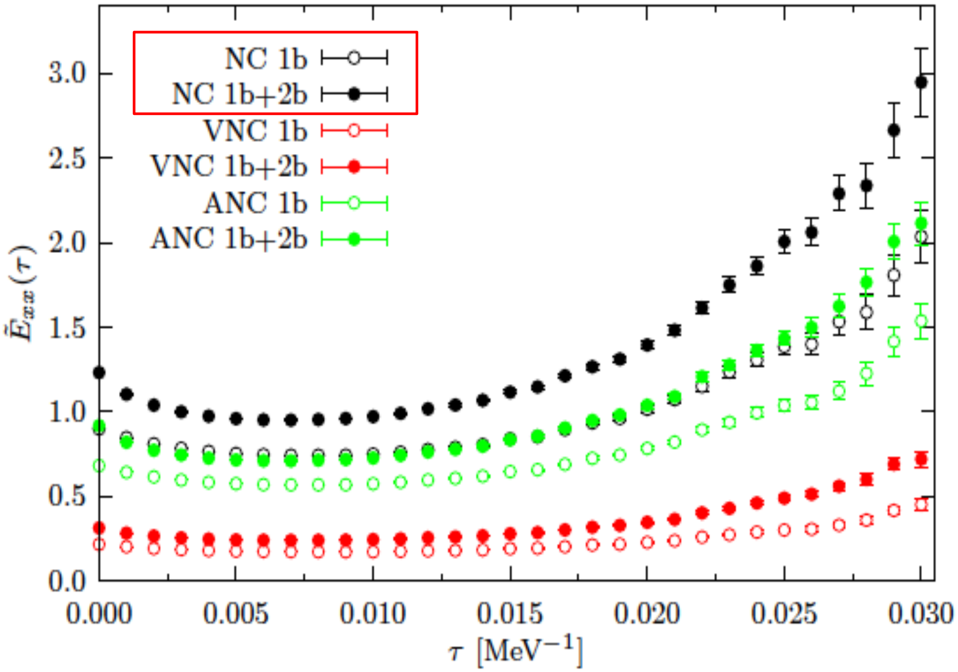
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



Neutrino NCQE scattering in ^{12}C response function



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

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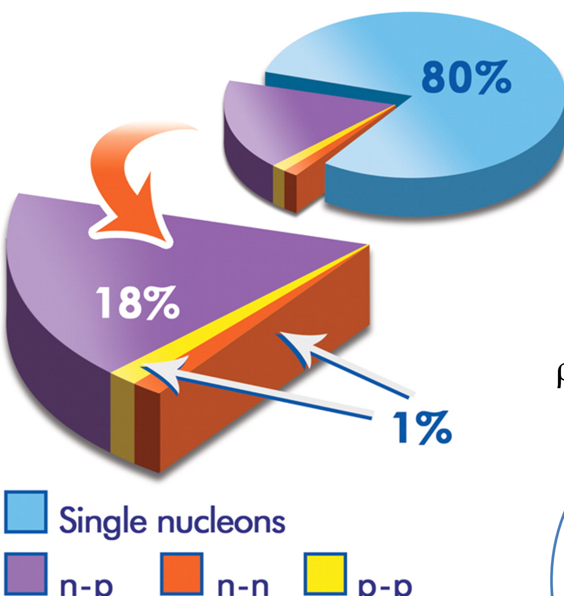
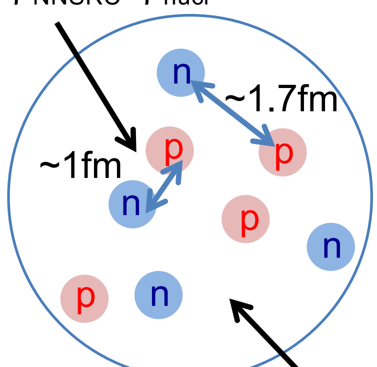
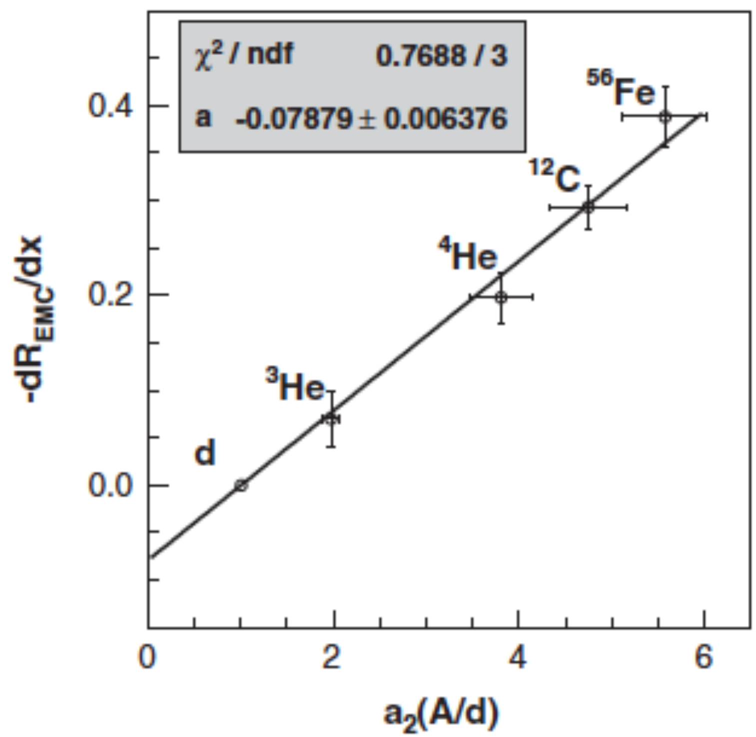


Physics of SRC

- neutrino interaction
- $0\nu\beta\beta$
- astrophysics
- EMC effect
- etc

$\rho_{NNSRC} > \rho_{nucl}$





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Nucleon correlation is a very hot topic in Particle Physics!

Frankfurt et al,IJMPA23(2008)2991, JLab HallA, Science320(2008)14
Sobczyk, Neutrino2014, Piasetzky et al, PRL106(2011)052301

2. The solution of CCQE puzzle

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Or Hen (MIT)

Or Hen receives the Guido Altarelli Award.

Photo courtesy of Or Hen.

Or Hen receives 2018 Guido Altarelli Award

Assistant professor of physics and Laboratory for Nuclear Science researcher recognized for major contributions to high energy and nuclear physics.

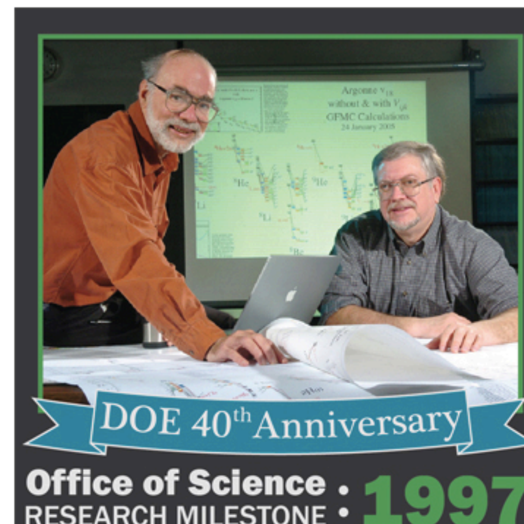
Stefano Gandolfi (LANL)

Los Alamos National Laboratory
Delivering science and technology to protect our nation and promote world s

SCIENCE & INNOVATION | COLLABORATION | CAREERS

Top young Los Alamos researchers honored with DOE Early Career Awards

This is the ninth year DOE has provided the awards, designed to bolster the nation's scientific workforce with support to exceptional researchers during their early careers.



2017 Herman Feshbach Prize in Theoretical Nuclear Physics Recipient

Joseph Carlson
Los Alamos National Laboratory

Citation:

Joe Carlson (LANL)

APS physics

"For pioneering the development of quantum Monte Carlo techniques to solve key problems in nuclear structure physics, cold atom physics, and dense matter theory of relevance to neutron stars."

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Nucleon correlation is a very hot topic in Particle Physics!

Wilkinson et al.,PRD93(2016)072010
Lu et al,PRC94(2016)015503, T2K,arXiv:1802.05078, MINERvA,arXiv:1805.05486

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
- Implemented in GENIE, officially ready for GENIE v2.12

This moment…
- Valencia MEC model does not fit MiniBooNE, MINERvA, T2K, Super-K, data very well
- lepton-hadron correlations (STVs) from T2K and MINERVA reveal new information

large M_A error → large nucleon correlation 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%.

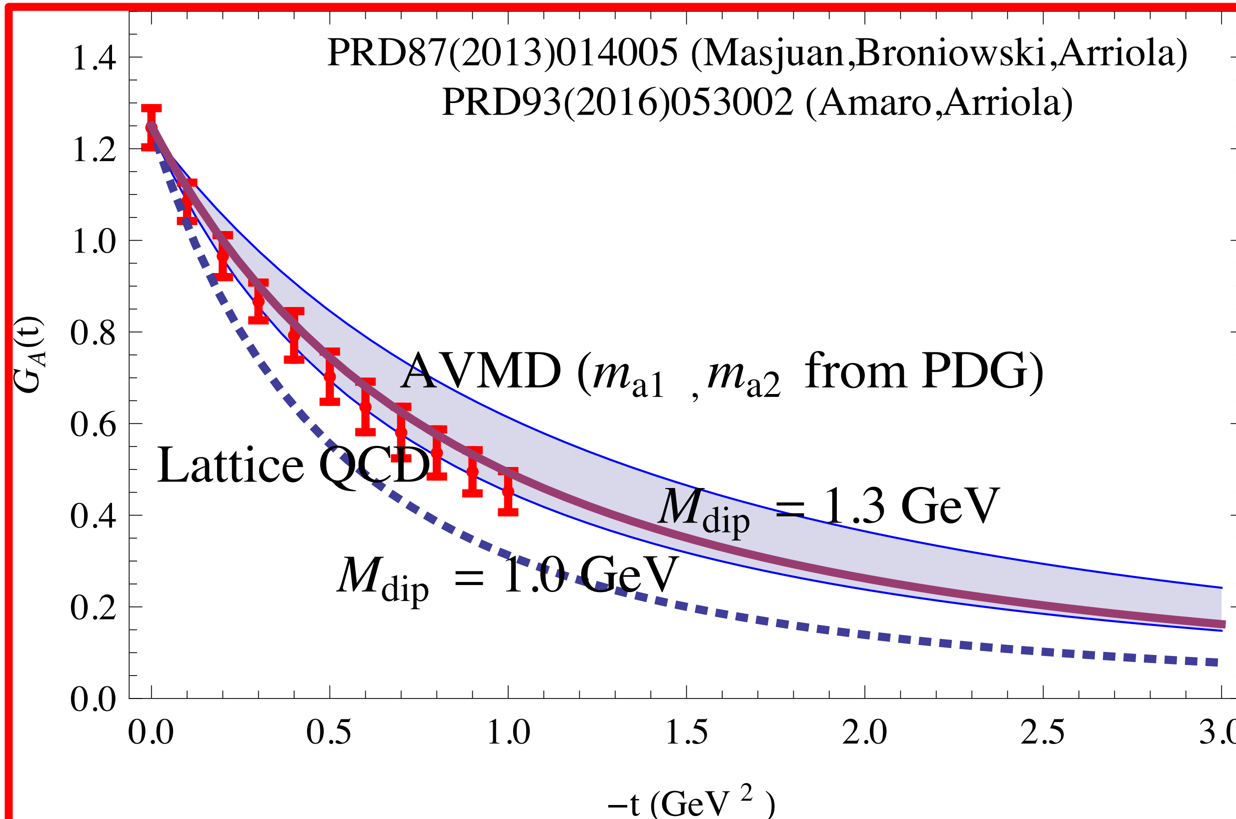
We have good theorists who make models, and good experimentalists who measure data, but we are still lacking people between them.

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. It looks we are bit far from building a correct neutrino-nucleus scattering model.



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

1. Neutrino Interaction Physics

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

3. Shallow inelastic scattering (SIS)

4. Conclusions

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

Topical Review

Neutrino–nucleus cross sections for oscillation experiments

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

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

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

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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

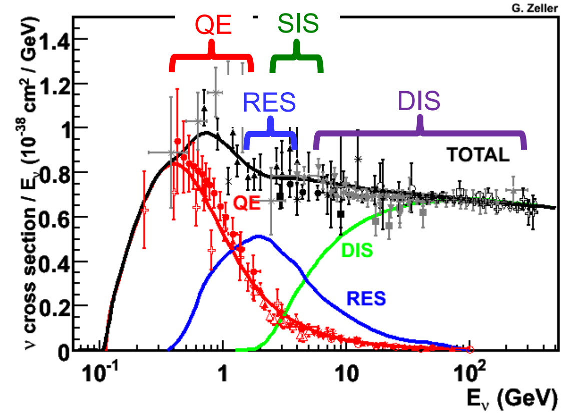
Review

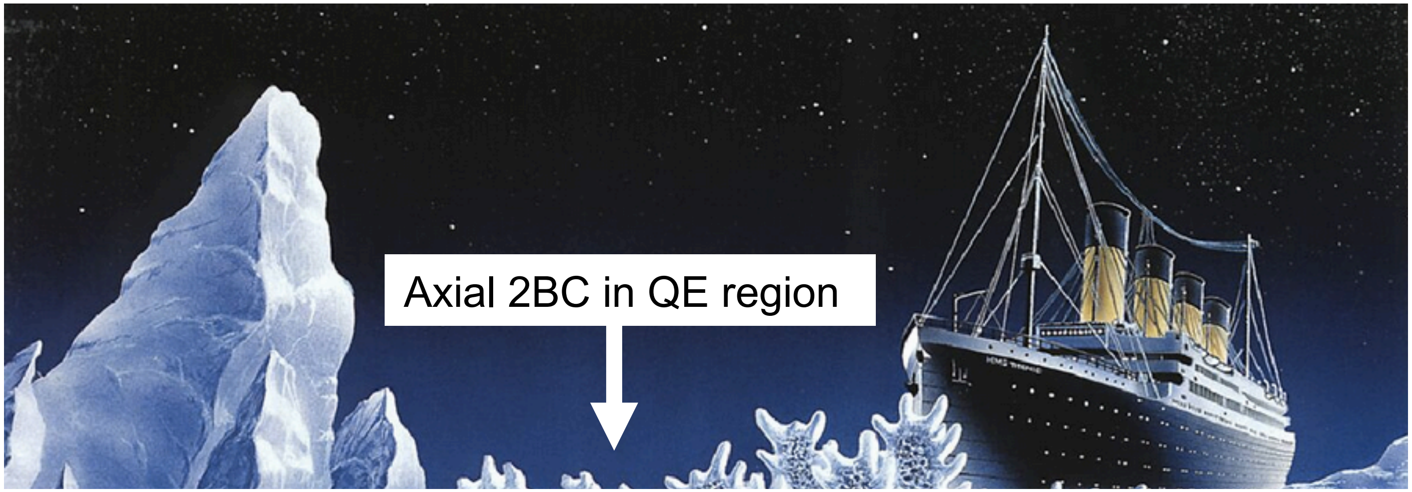
NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

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

3. Beyond QE peak

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





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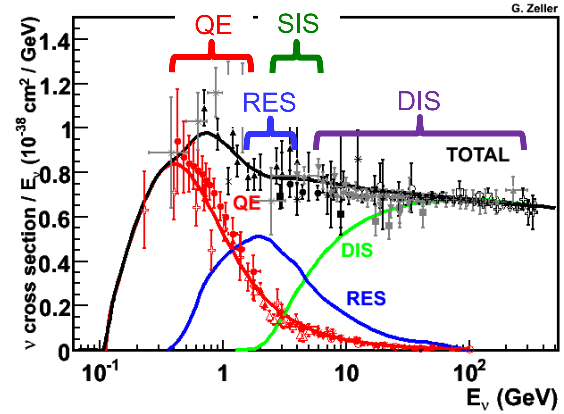
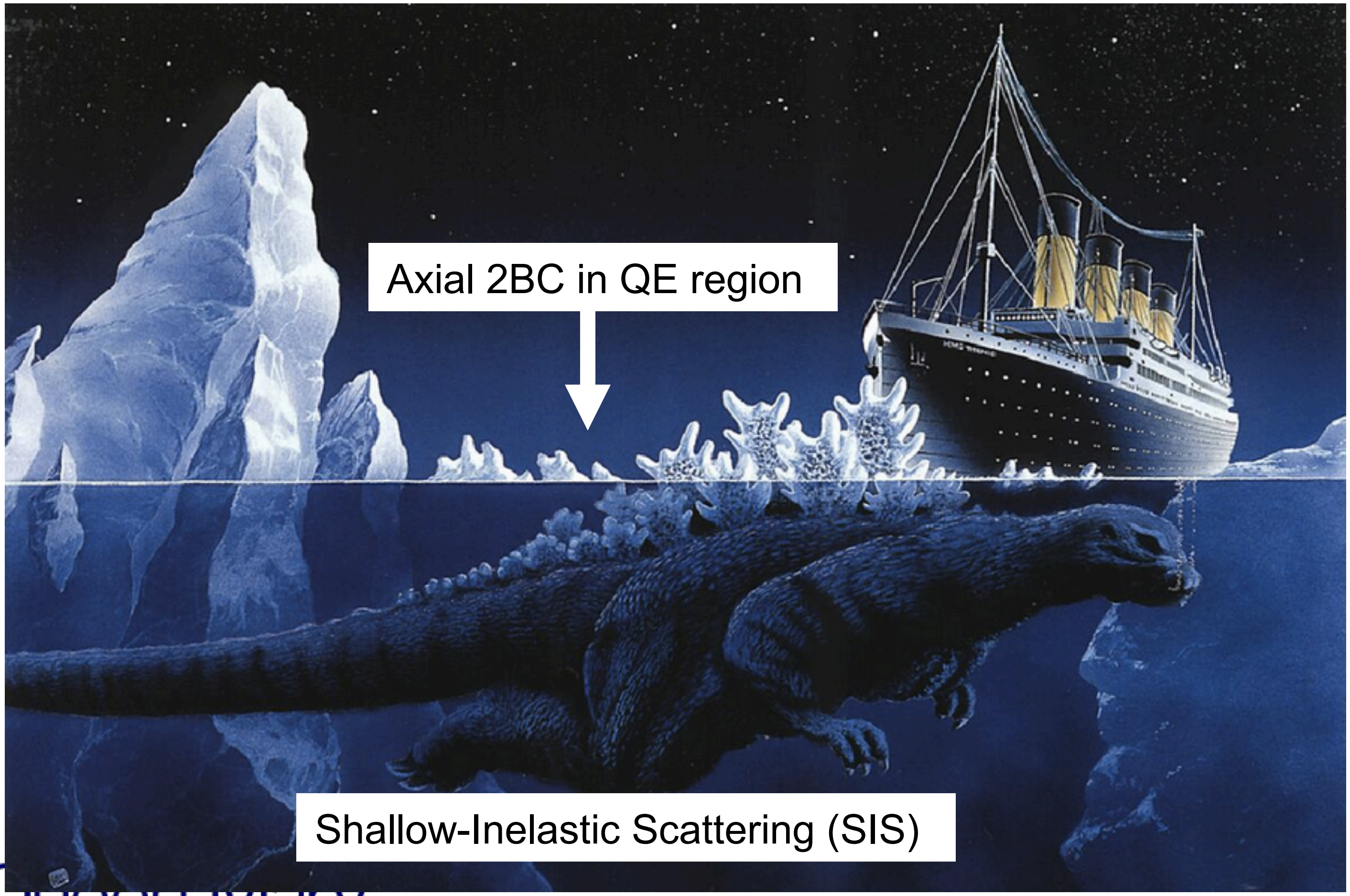
3. Beyond QE peak

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



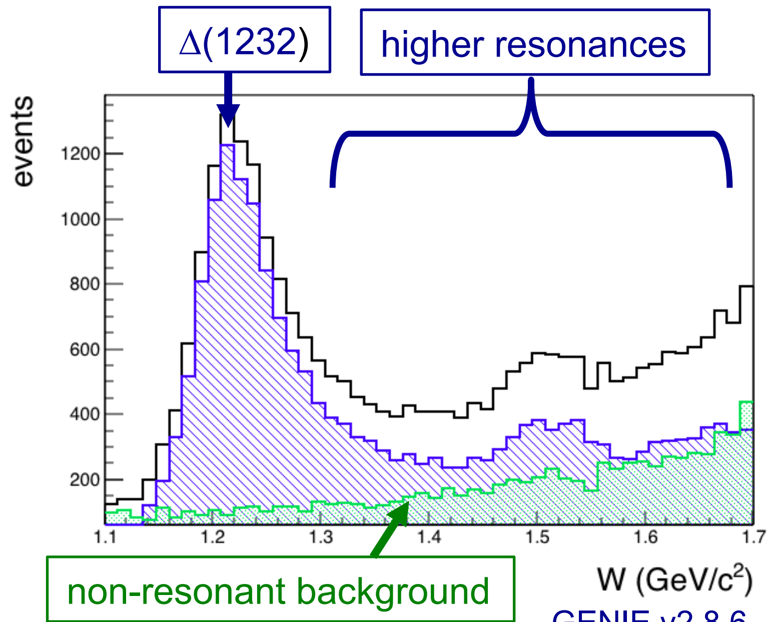


Traditionally called “transition” region

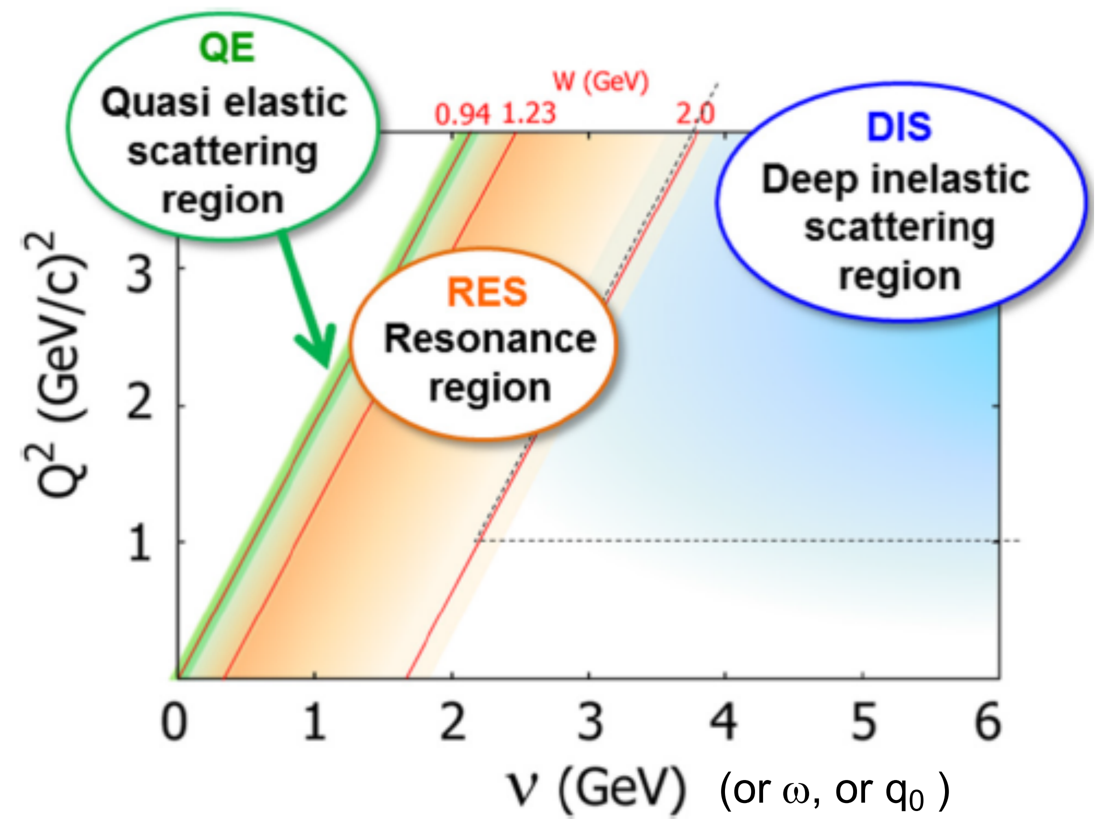
3. Sallow Inelastic Scattering (SIS) physics

Basic ingredients

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



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



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

3. Physics of Δ resonance

Giessen BUU transport model (GiBUU) describes final states of hadrons in nuclear media

Ulrich Mosel (Giessen)

Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
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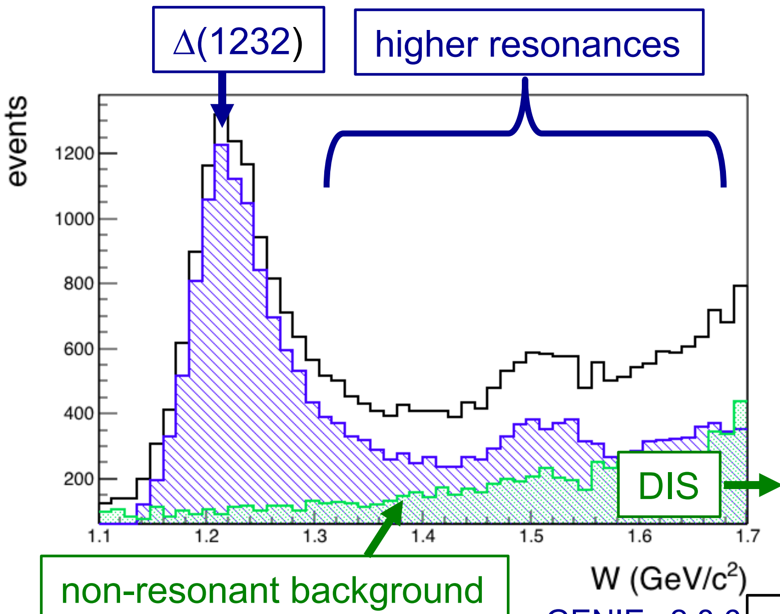
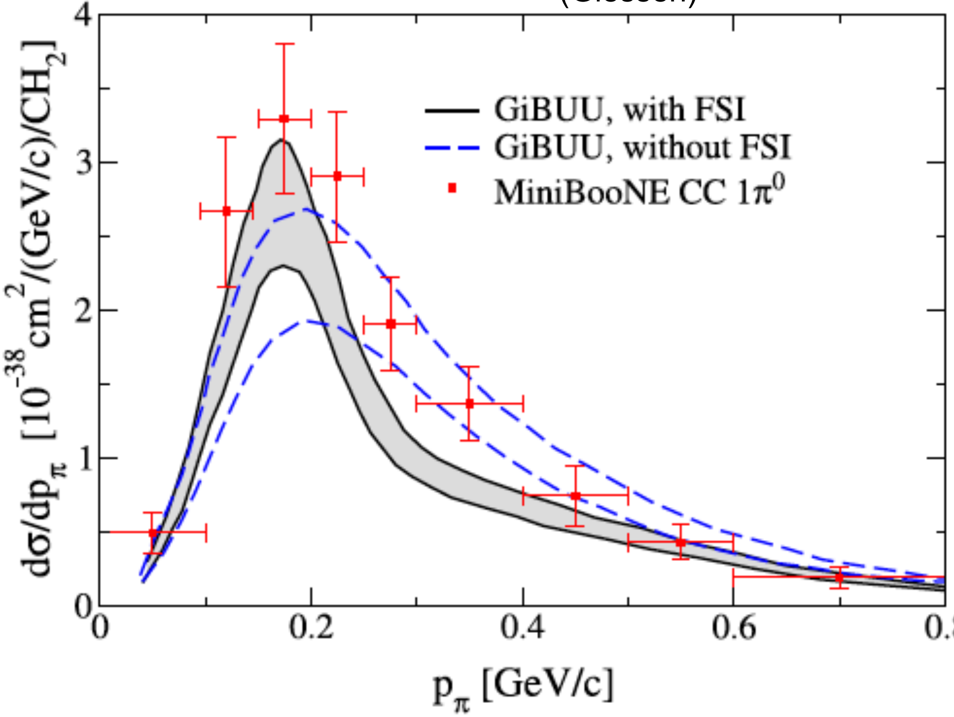
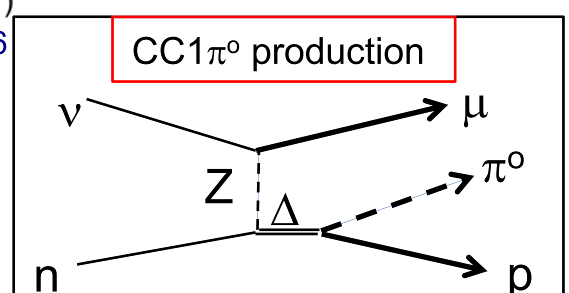


GENIE v2.8.6

MiniBooNE CC1π^o data





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

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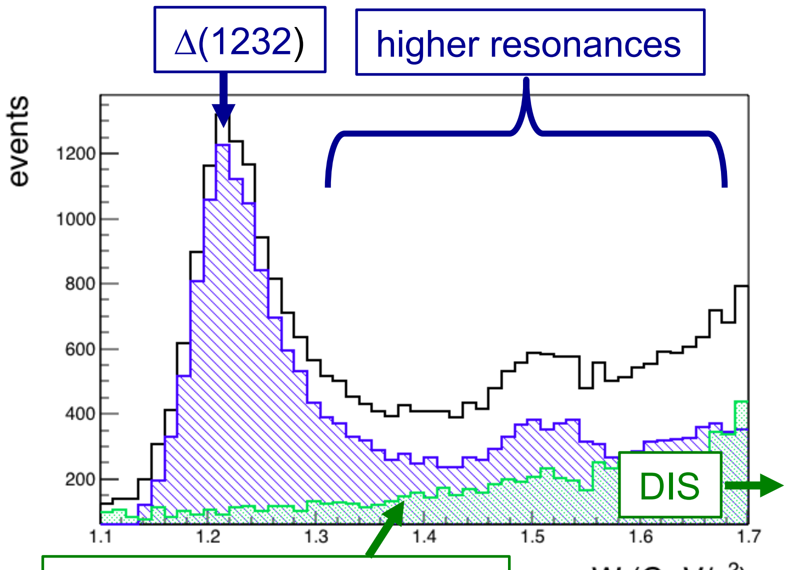

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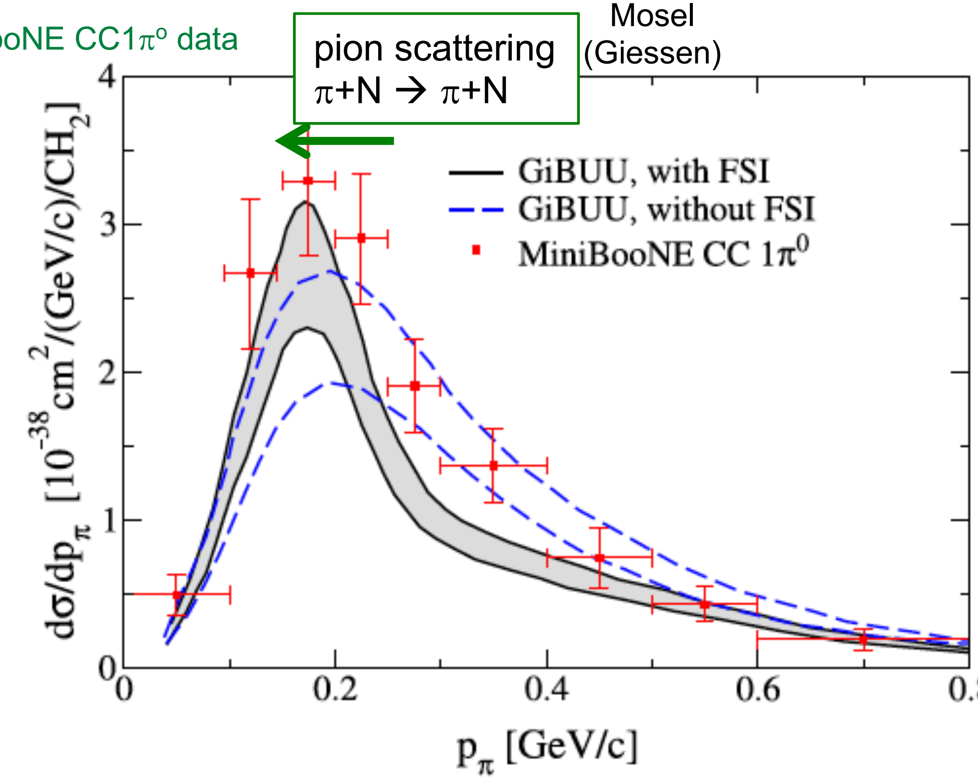

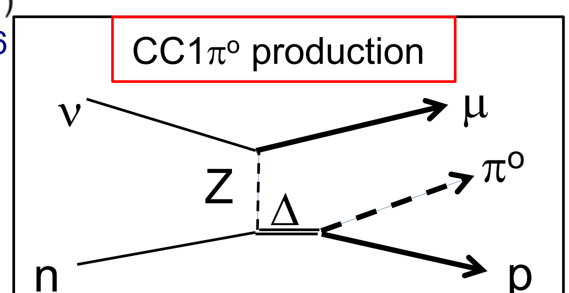

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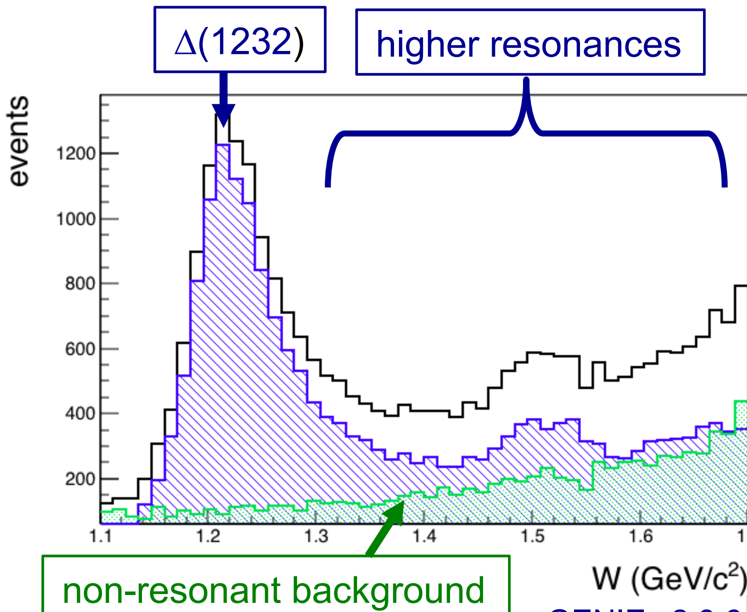
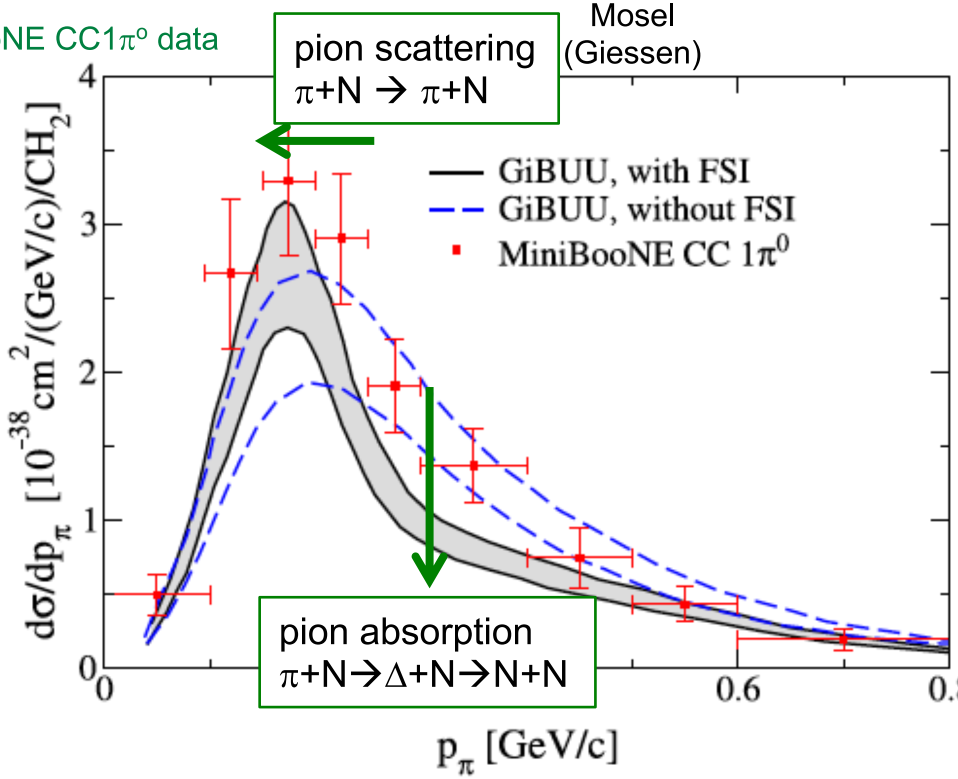
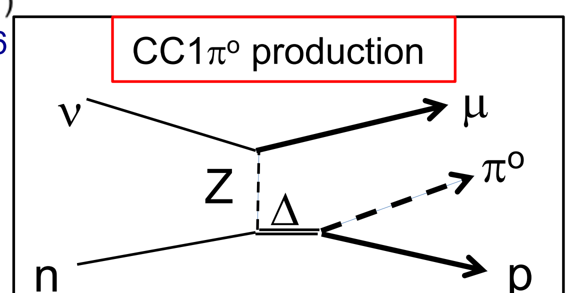


GENIE v2.8.6

MiniBooNE CC1π^o data





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

3. Physics of Δ resonance

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Ulrich Mosel (Giessen)

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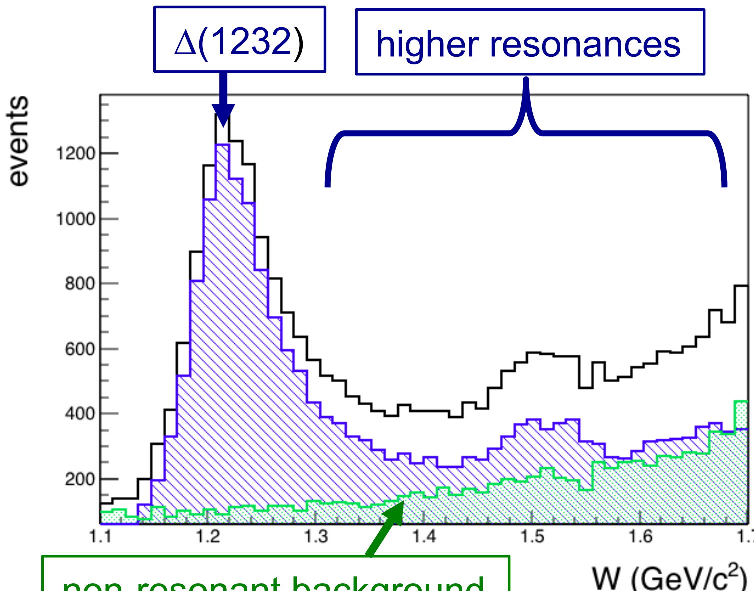
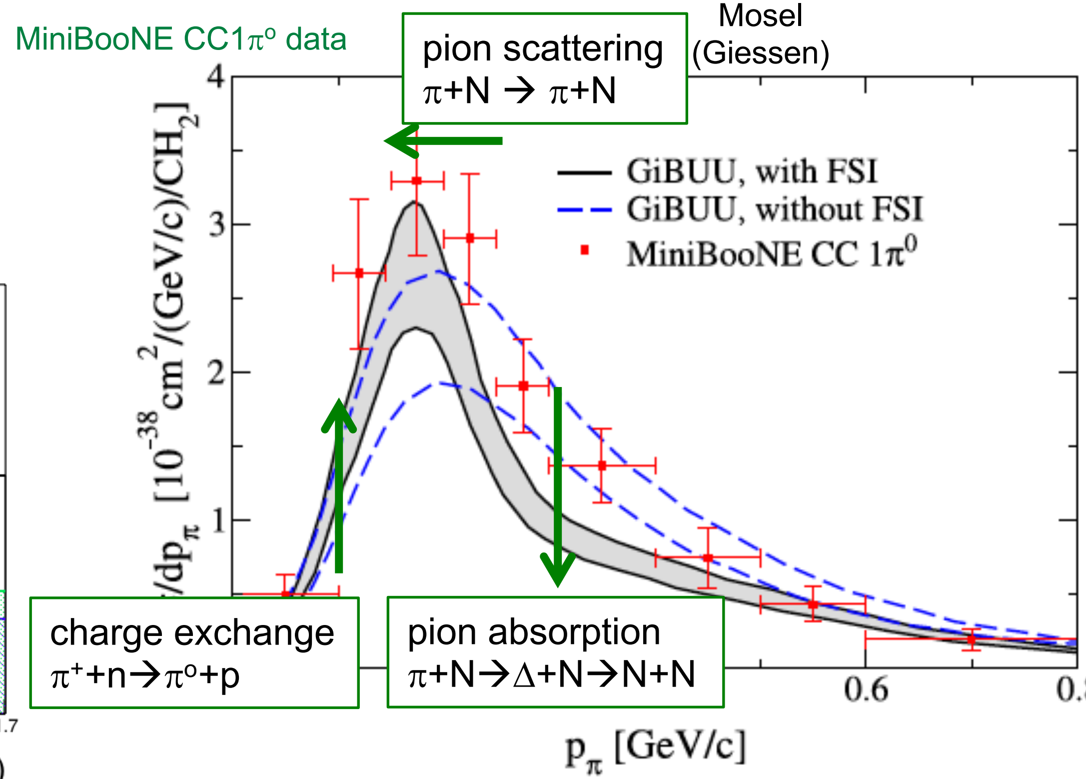
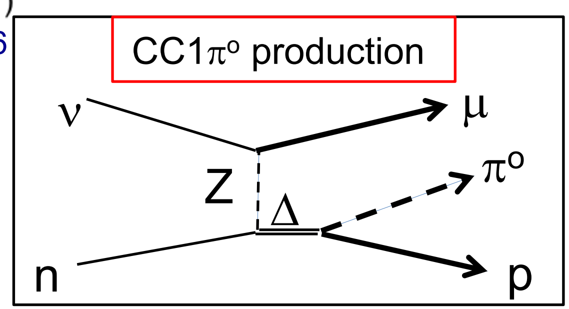
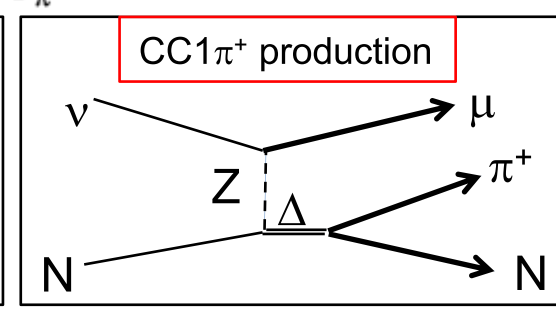


GENIE v2.8.6



There is no great understanding even for the simplest baryonic resonance





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

3. Physics of higher resonances

DCC model vs. electro-pionproduction data

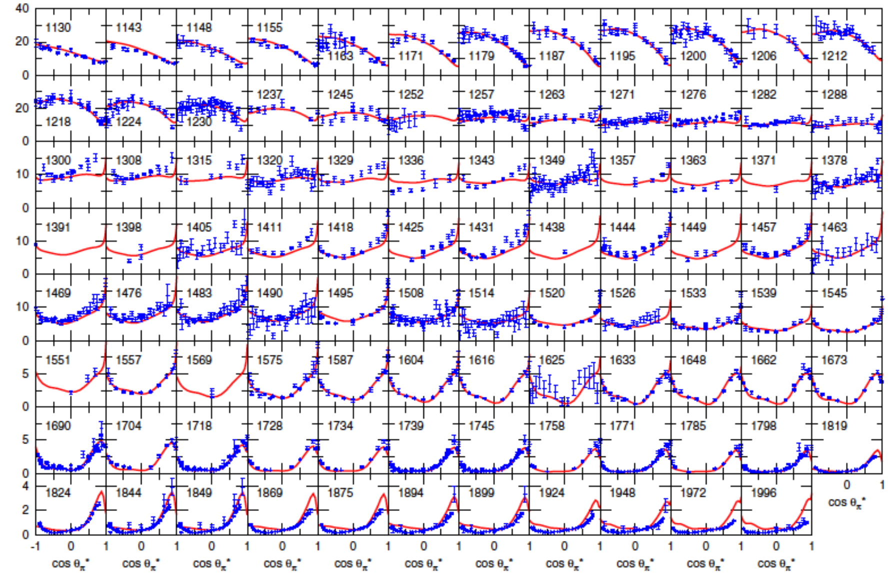


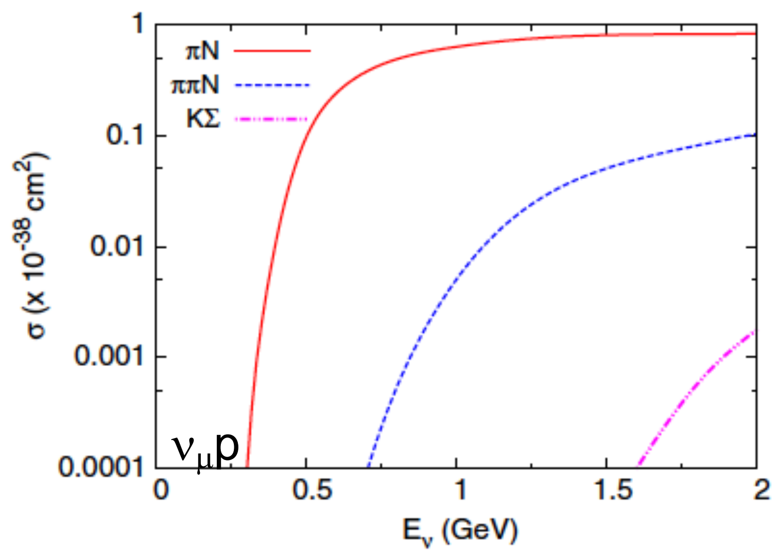
FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega^*_\pi$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

Basic ingredients

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

DCC model

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



Role of high W resonances in neutrino experiments is not understood (and probably modeled incorrectly), and I don't discuss today

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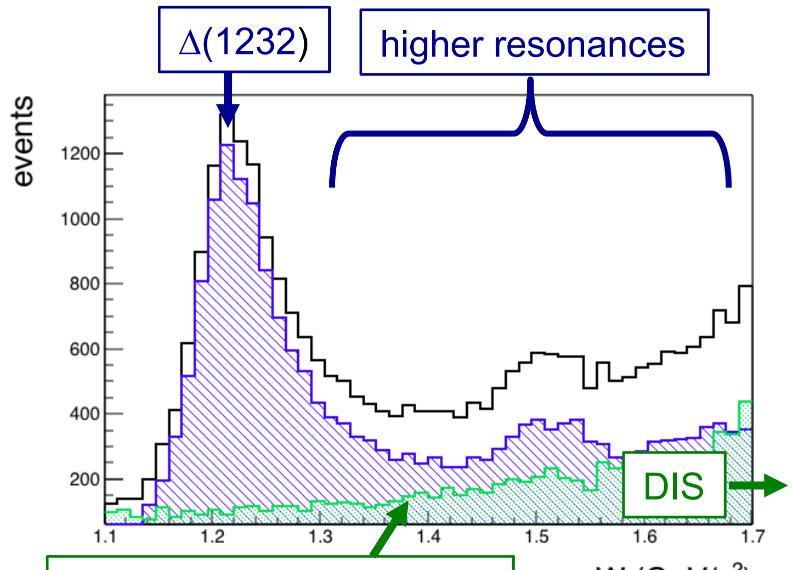
University of London

3. Physics of non-resonant background

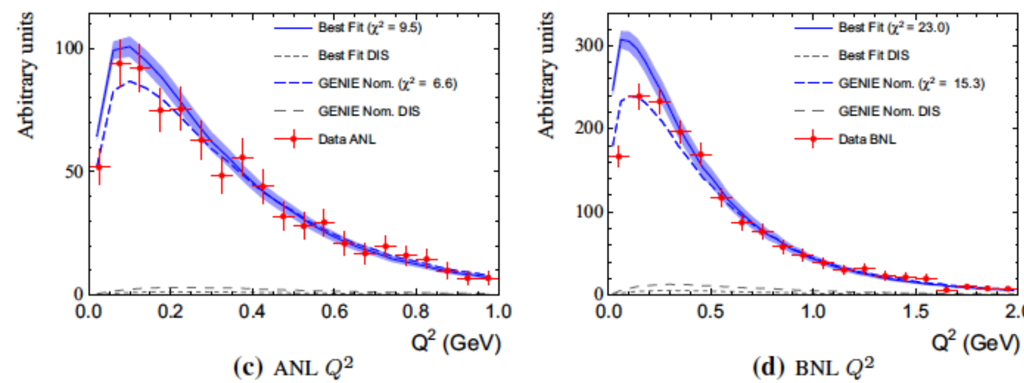
Basic ingredients
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS



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

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

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



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

3. Quark-Hadron Duality

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

Basic ingredients

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

GRV98 LO PDF + Bodek-Yang correction

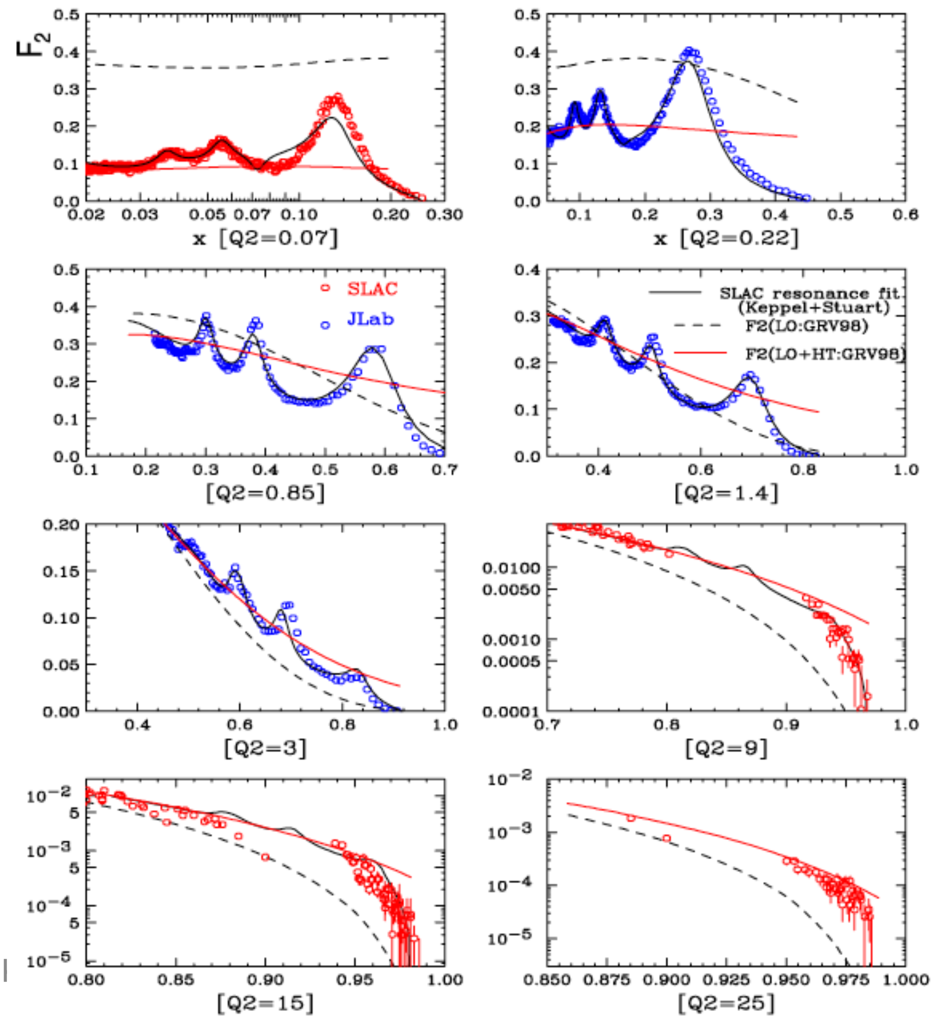
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data



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

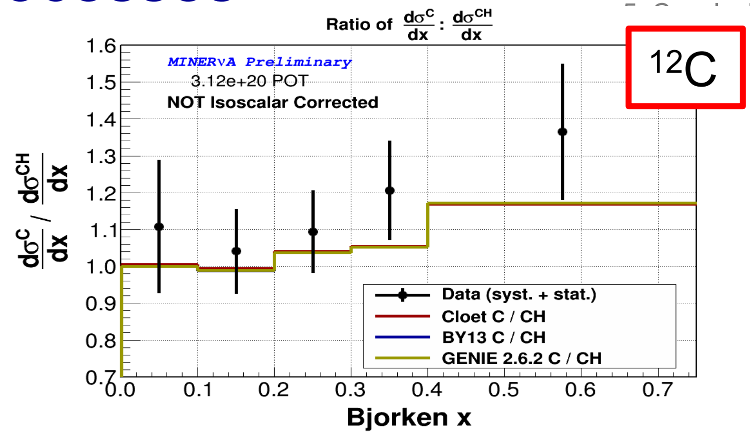
3. Neutrino nuclear-dependent DIS processes

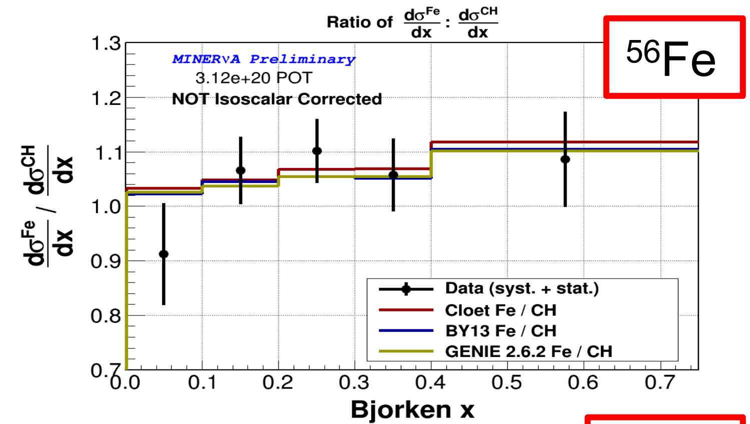
Basic ingredients

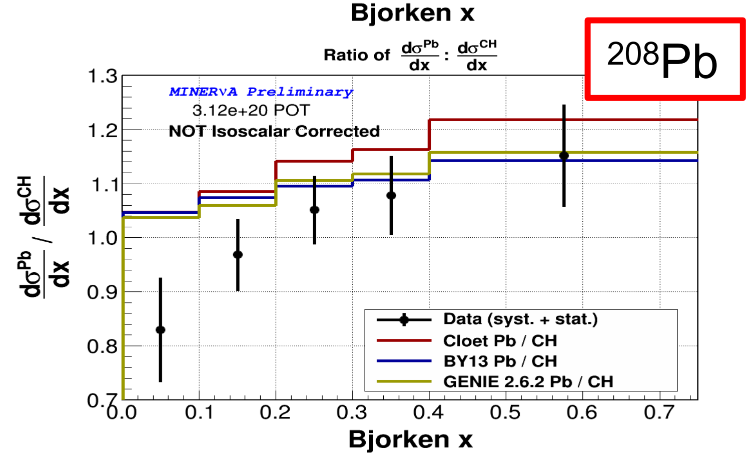
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

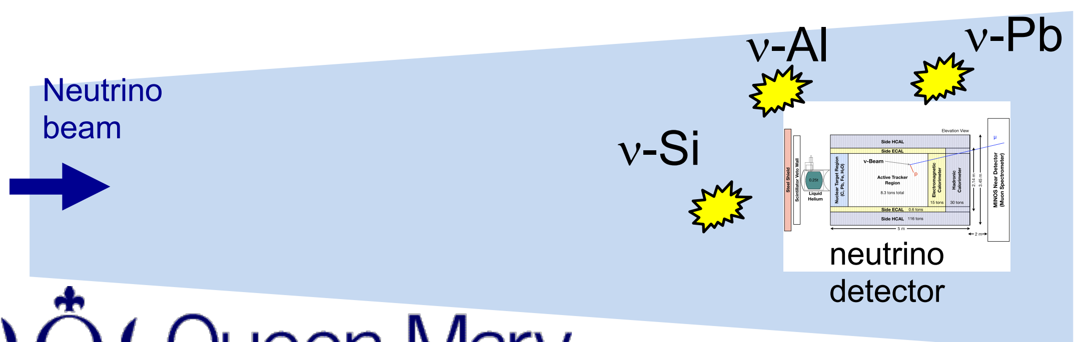
MINERvA DIS target ratio data (C, Fe, Pb)

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









3. SIS summary

Basic ingredients

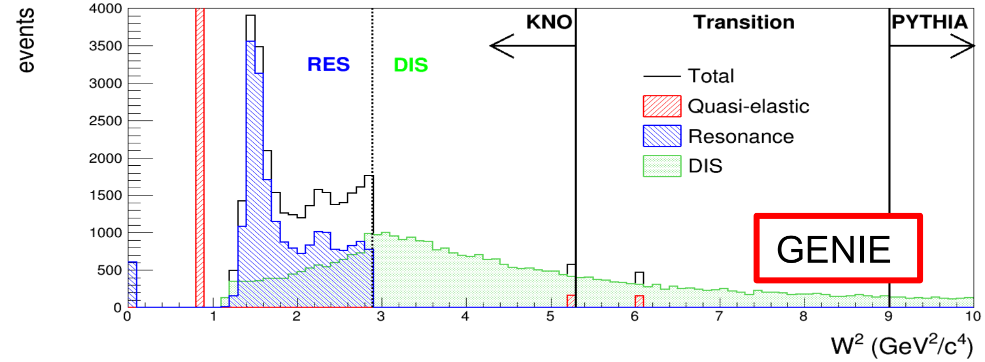
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS

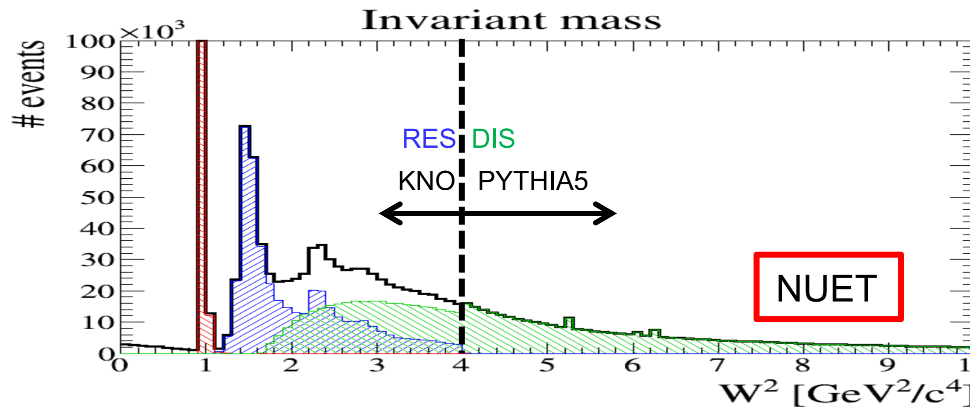
Current models accepted in generators are not physical and don't make any sense

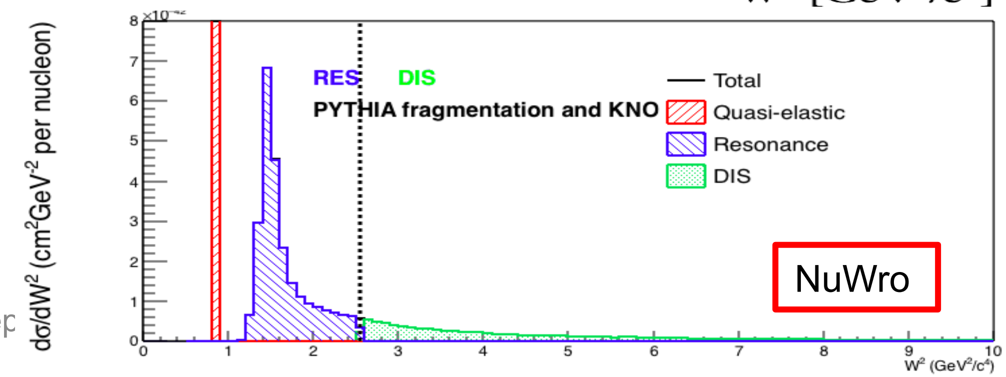
Each sub-field has been developed in a limited kinematics. But it is not easy to combine them together. The challenge we (=neutrino physics) have is a new kind.

Remember, this is the signal models for DUNE oscillation measurement!

Neutrino interaction generator comparison







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

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

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

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

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

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

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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
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Review

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

Check for updates

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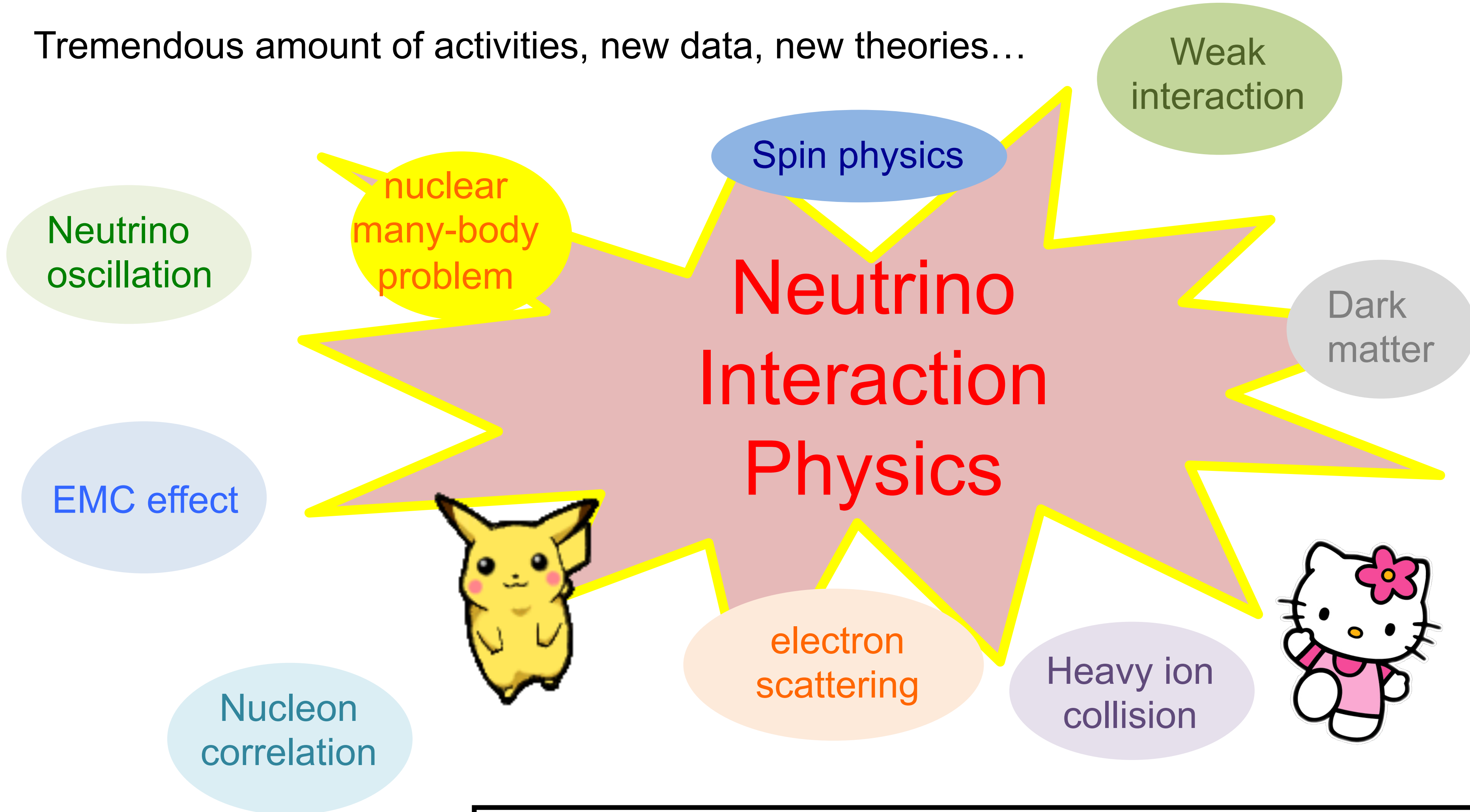
Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…



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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 (University of Texas Houston, 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)

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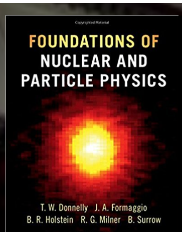
NuSTEC school

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

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

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

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



Foundation of Nuclear and Particle Physics

- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- First textbook to fill the gap of nuclear&particle physics!

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NuInt18, Gran Sasso Science Institute, Italy (Oct. 15-19, 2018)

https://indico.cern.ch/event/703880/
- The main conference in this community
- Topics include;
  - latest results from T2K, MINERvA, NOvA, MicroBooNE (next talk!)
  - latest calculations from nuclear models to describe neutrino data
  - latest study to constrain neutrino interaction systematics for future oscillation experiments

Thank you for your attention!

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Backup

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 $\sin2\theta_{23}$, 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(?)

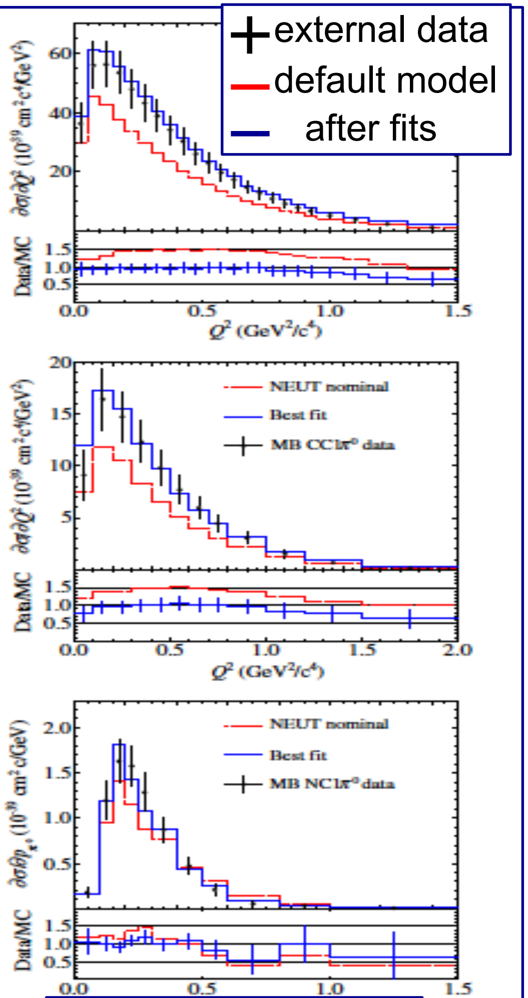
We need higher precision experiments around 1-10 GeV.

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

1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



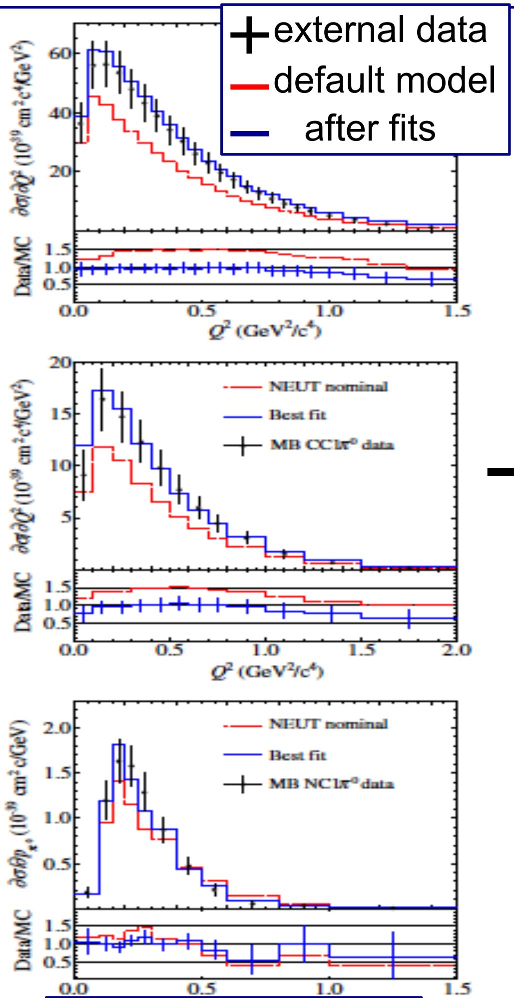
External data fit

External data give initial guess of cross-section systematics

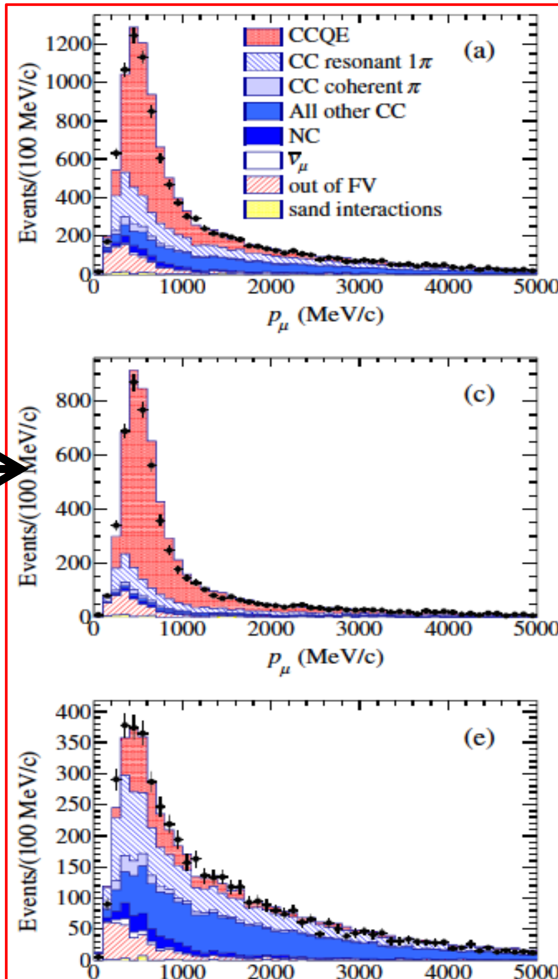
1. e.g.) T2K oscillation experiments

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

Internal constraint
Near detector
oscillation non-sensitive channels



External data fit



T2K ND280 data fit

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

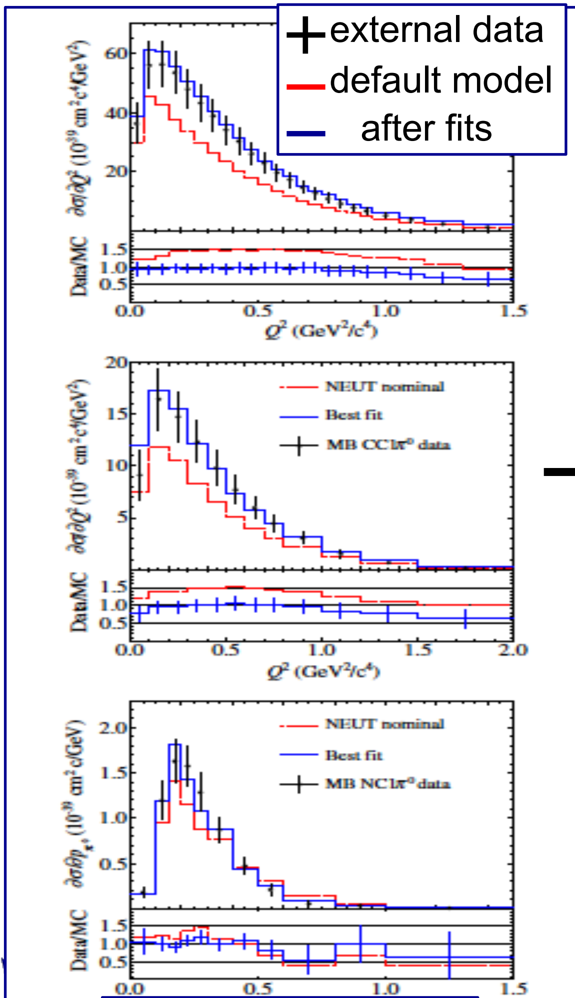
T2K, PRD88(2013)032002; PRL112(2014)061802

1. e.g.) T2K oscillation experiments

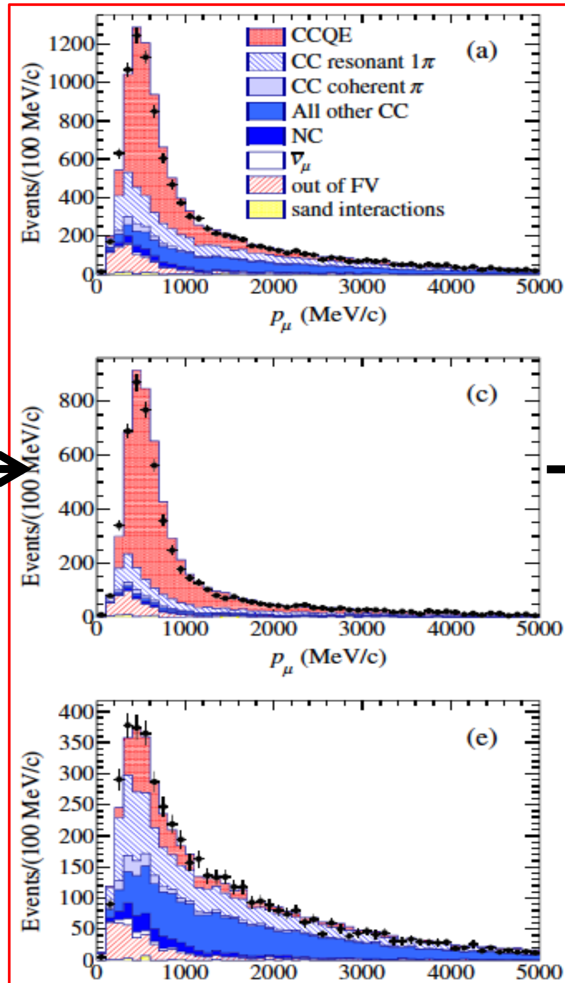
External constraint
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint
Near detector
oscillation non-sensitive channels

Neutrino interaction model is a large systematics of neutrino oscillation experiment

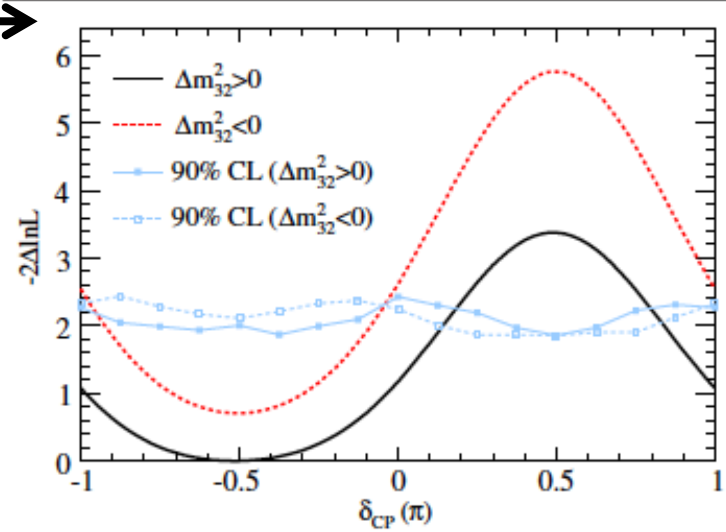


External data fit



T2K ND280 data fit

Error source [%]	$\sin^2 2\theta_{13} = 0.1$
Beam flux and near detector	2.9
(without ND280 constraint)	(25.9)
Uncorrelated ν interaction	7.5
Far detector and FSI + SI + PN	3.5
Total	8.8



oscillation result

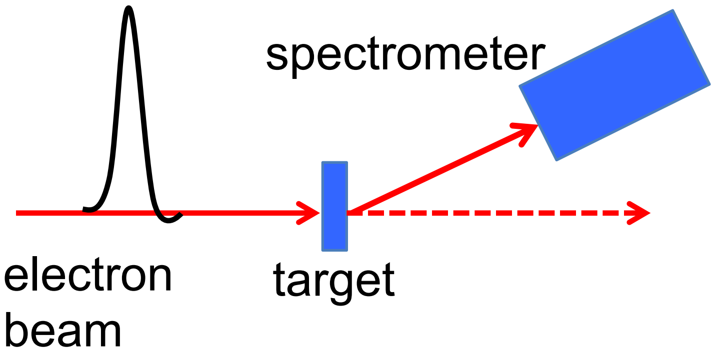
2. Electron scattering vs. Neutrino scattering

Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

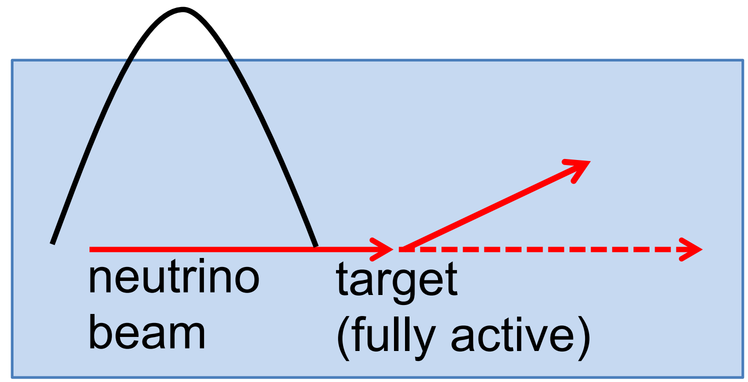
→ kinematics is completely fixed

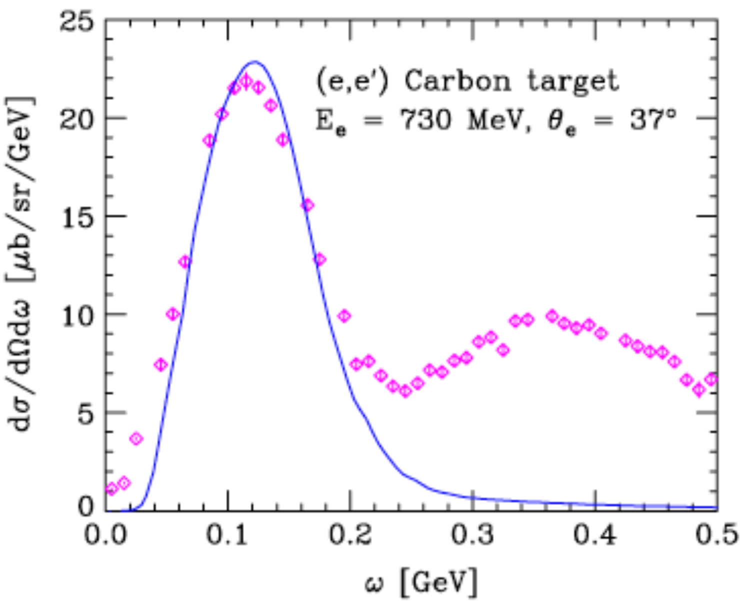


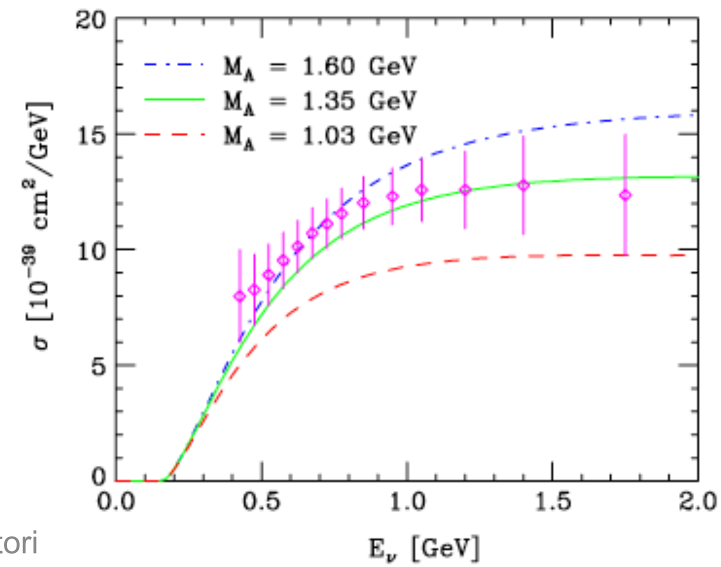
Neutrino scattering

- Wideband beam

→ observables are inclusive







2. Electron scattering vs. Neutrino scattering

Electron scattering

- well defined energy, well known flux
→ reconstruct energy-momentum transfer
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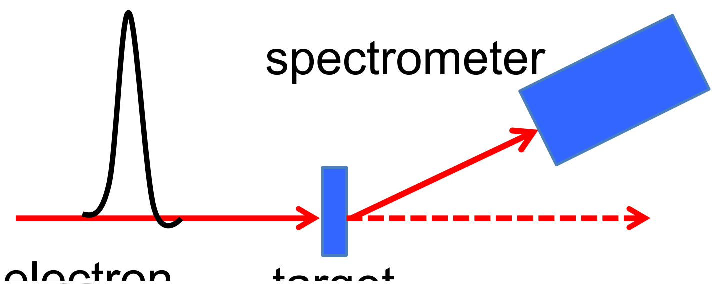
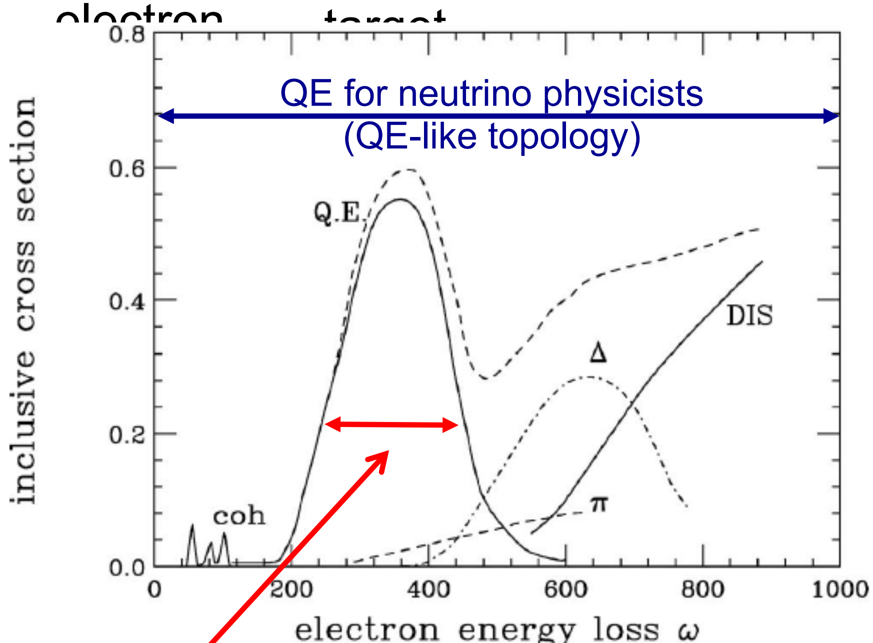
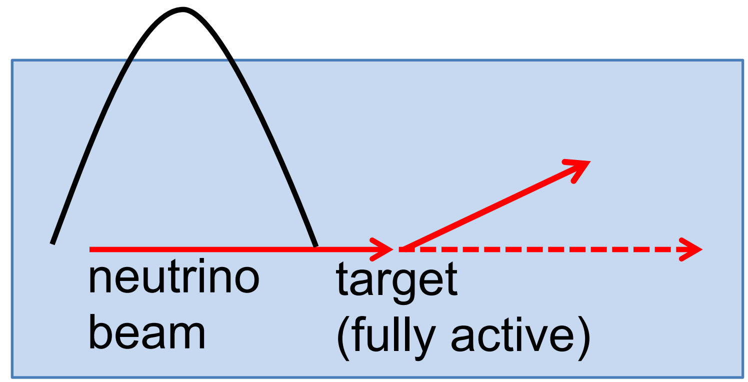


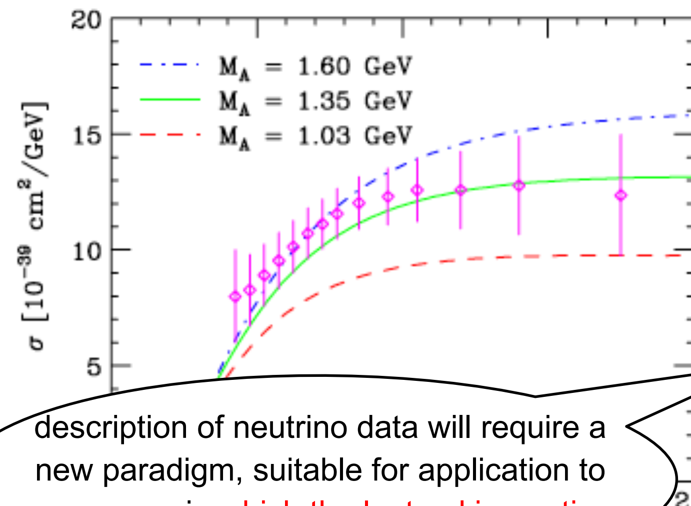


QE for nuclear physicists (genuine QE)

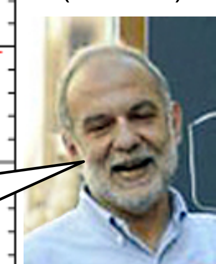
Neutrino scattering

- Wideband beam
→ observables are inclusive





Omar Benhar (Rome I)



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

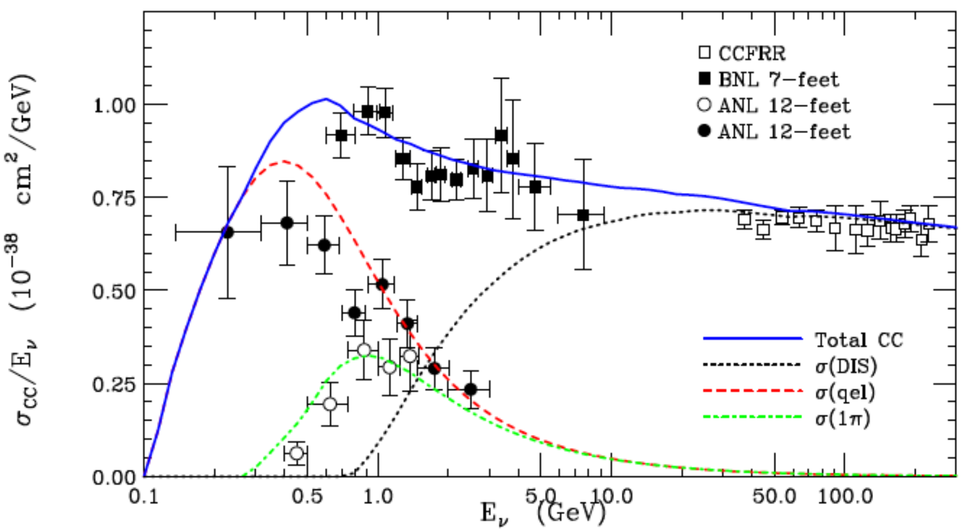
2. Dark age of neutrino interaction physics

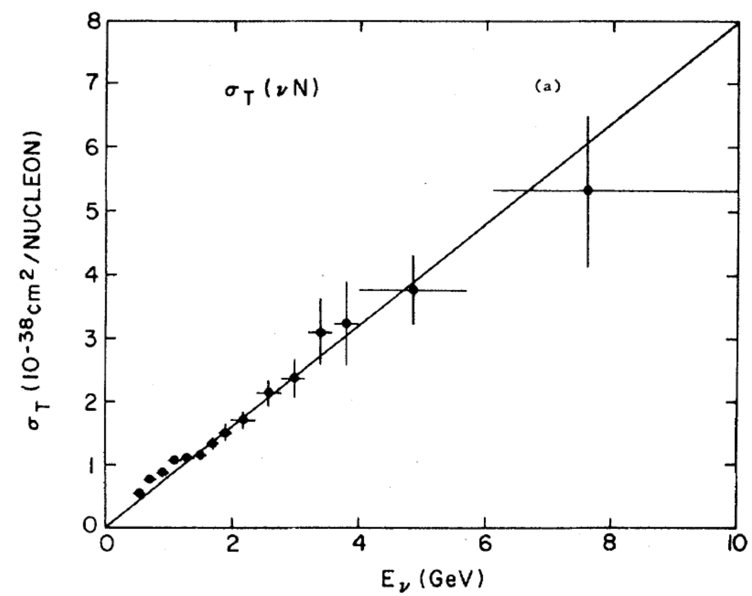
(1) Measure interaction rate
(2) Divide by known cross section to obtain flu
(3) use this flux, measure cross-section from measured rate

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]

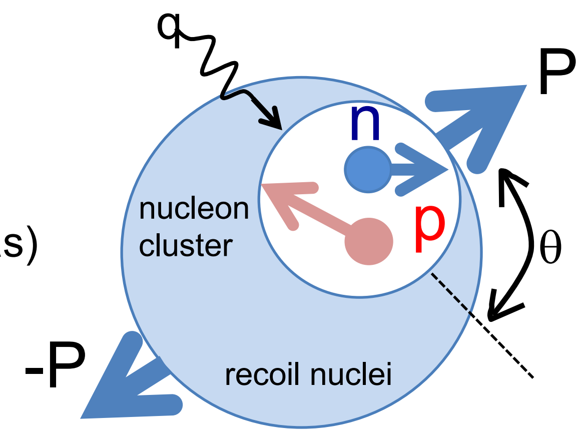




Queen Mary
University of London

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

2. How to emit 2 nucleons from correlated pair?



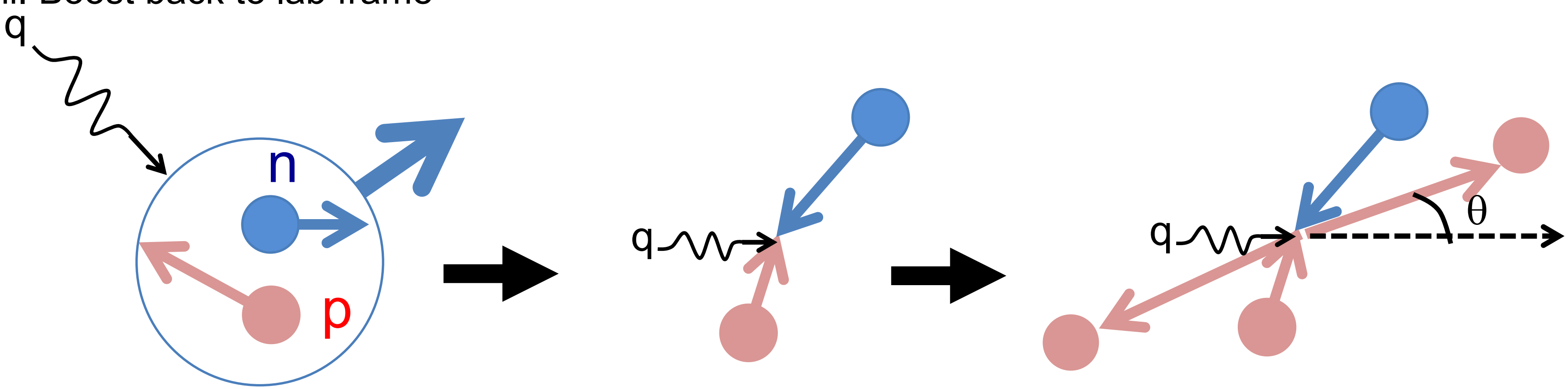
Default model for GENIE, NEUT, NuWro…

For a given Energy-Momentum transfer...

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

Once 2 nucleons from on-shell are choosed

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



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

3. Neutrino oscillation experiment

Reconstruction of neutrino energy with QE assumption

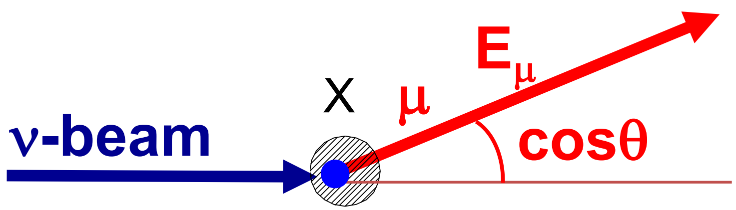
- We can reconstruct neutrino energy if we know it is CCQE interaction

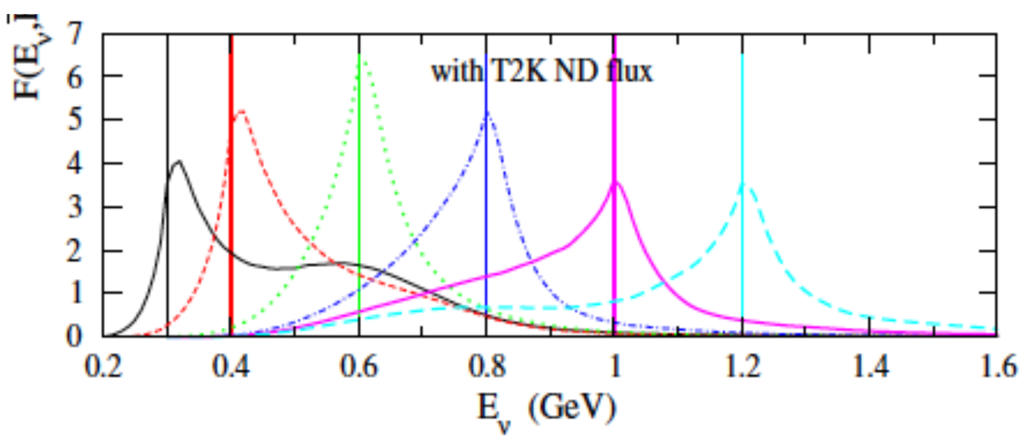
→ There is bias because of all “CCQE-like” interactions.

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

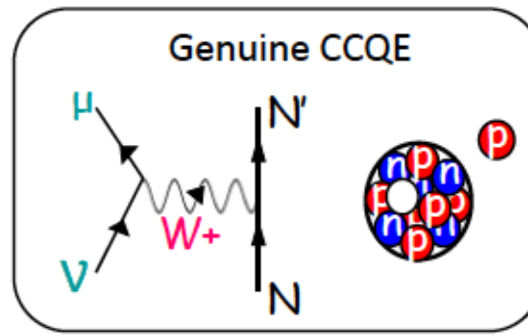
$$\nu_\mu + n \to p + \mu^- \quad (\nu_\mu + X \to X' + \mu^-)$$

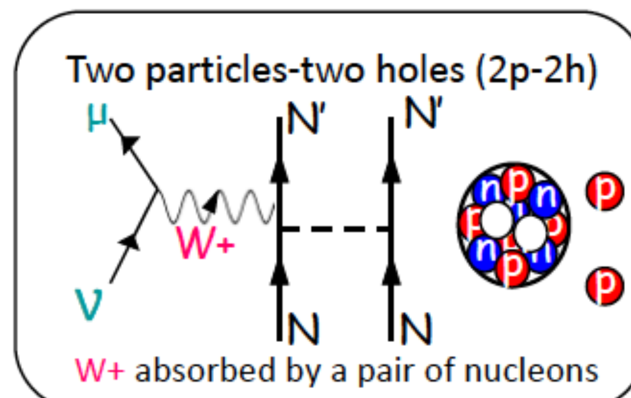
$$E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$





estimated reconstruction due to 2-body current



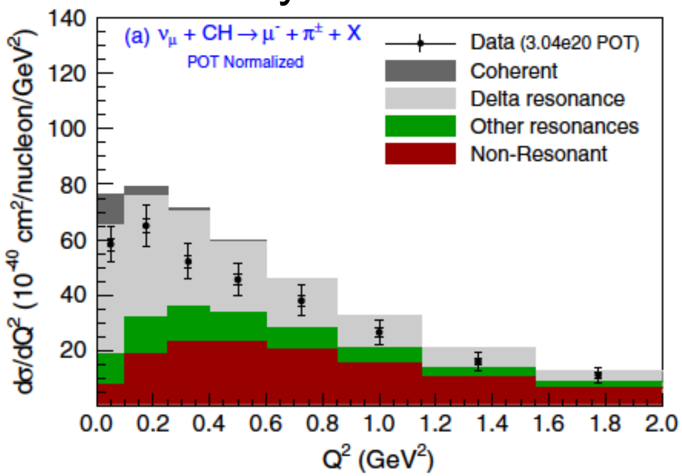


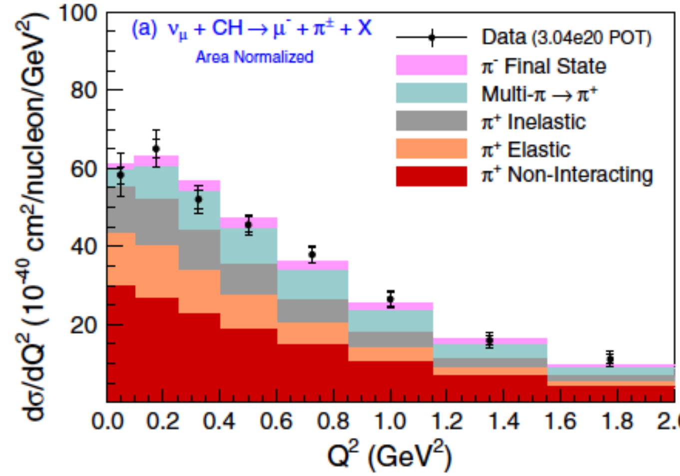
3. MINERvA FSI and cross section model tuning (2016)

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

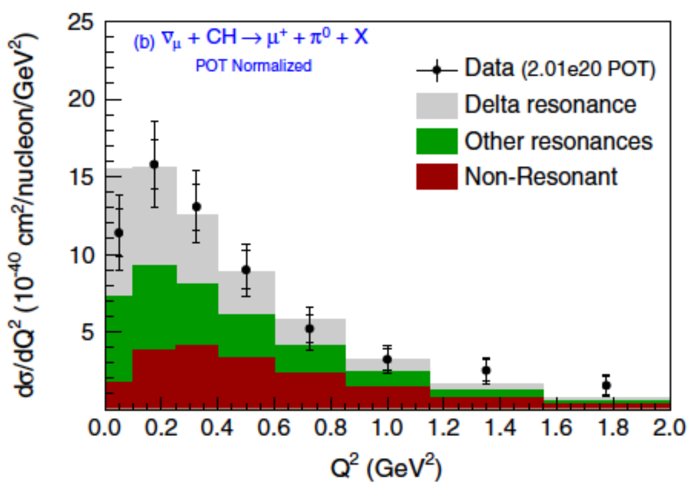
- this moment, there is no clear way to tune MC from data…

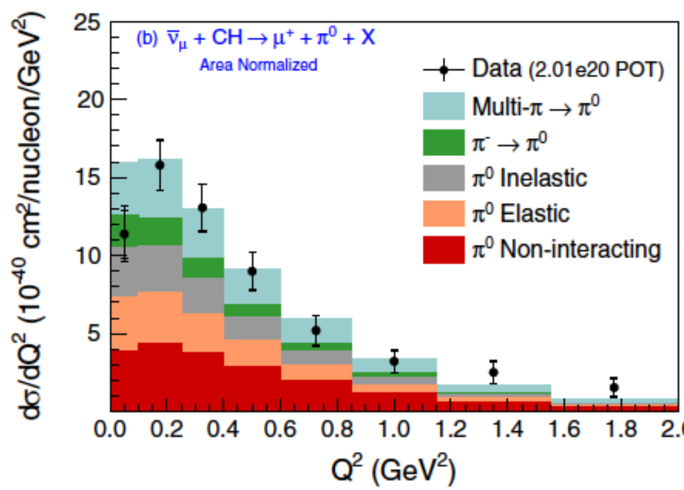
ν_μCC1π^+ data has better shape agreement with GENIE





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





AGKY, EPJC63(2009)1
TK and Mandalia,JPhysG42(2015)115004

3. GENIE SIS model

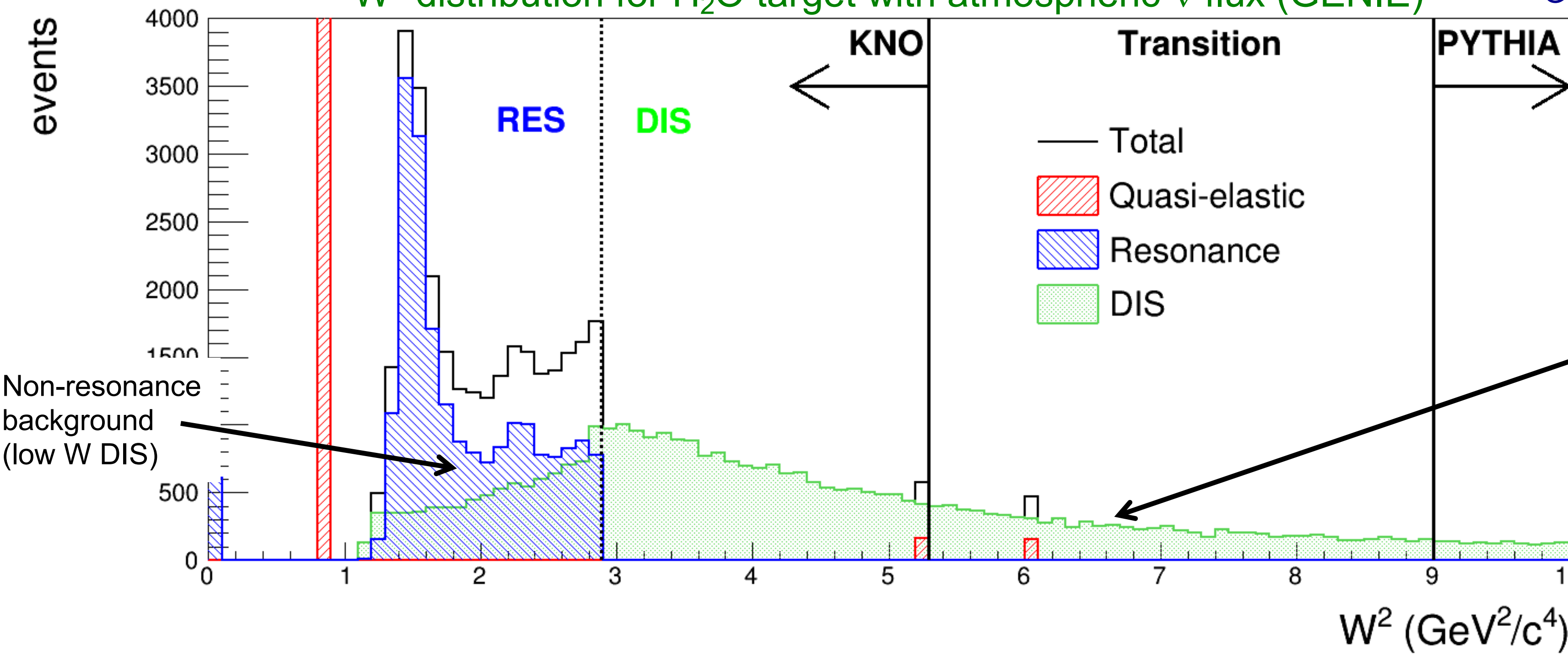
GENIE is the most widely used neutrino interaction generator

Cross section
W^2<2.9 GeV^2 : RES
W^2>2.9 GeV^2 : DIS
Hadronization
W^2<5.3GeV^2 : KNO scaling based model
2.3GeV^2<W^2<9.0GeV^2 : transition
9.0GeV^2<W^2 : PYTHIA6

There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

W^2 distribution for H_2O target with atmospheric-ν flux (GENIE)

GENIE v2.8.0



Non-resonance background (low W DIS)

DIS

3. NEUT SIS model

NEUT is the generator used by all Japanese neutrino programs (T2K, SuperK, etc)

Cross section

$W^2<4$ GeV^2 : RES
$W^2>4$ GeV^2 : DIS

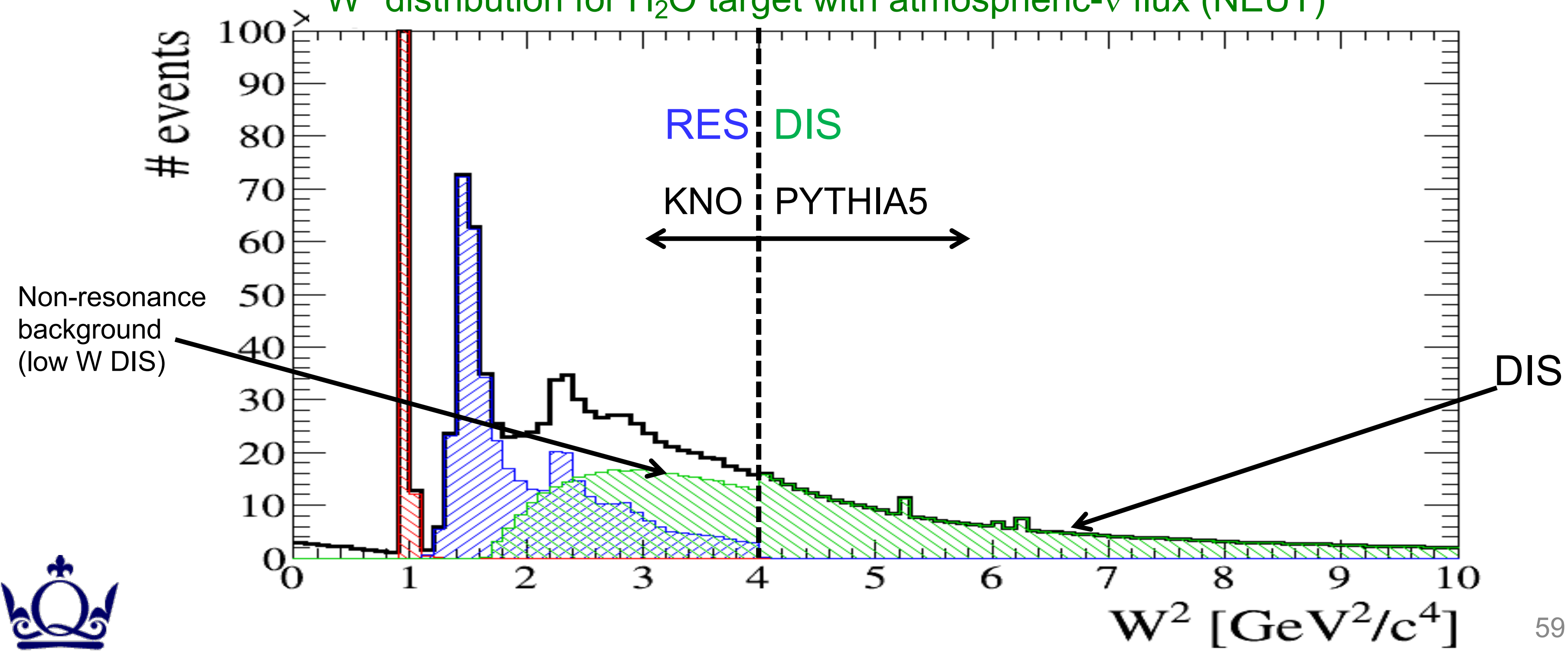
Hadronization

$W^2<4GeV^2$: KNO scaling based model
$4GeV^2<W^2$: PYTHIA5

There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

plot made by Christophe Bronner (IPMU)

W^2 distribution for H_2O target with atmospheric-ν flux (NEUT)



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3. NuWro SIS model

NuWro is often used for some studies because of user-friendly structure

Cross section

W^2<2.5 GeV^2 : RES

W^2>2.5 GeV^2 : DIS

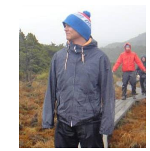
Hadronization

- PYTHIA fragmentation
- KNO scaling

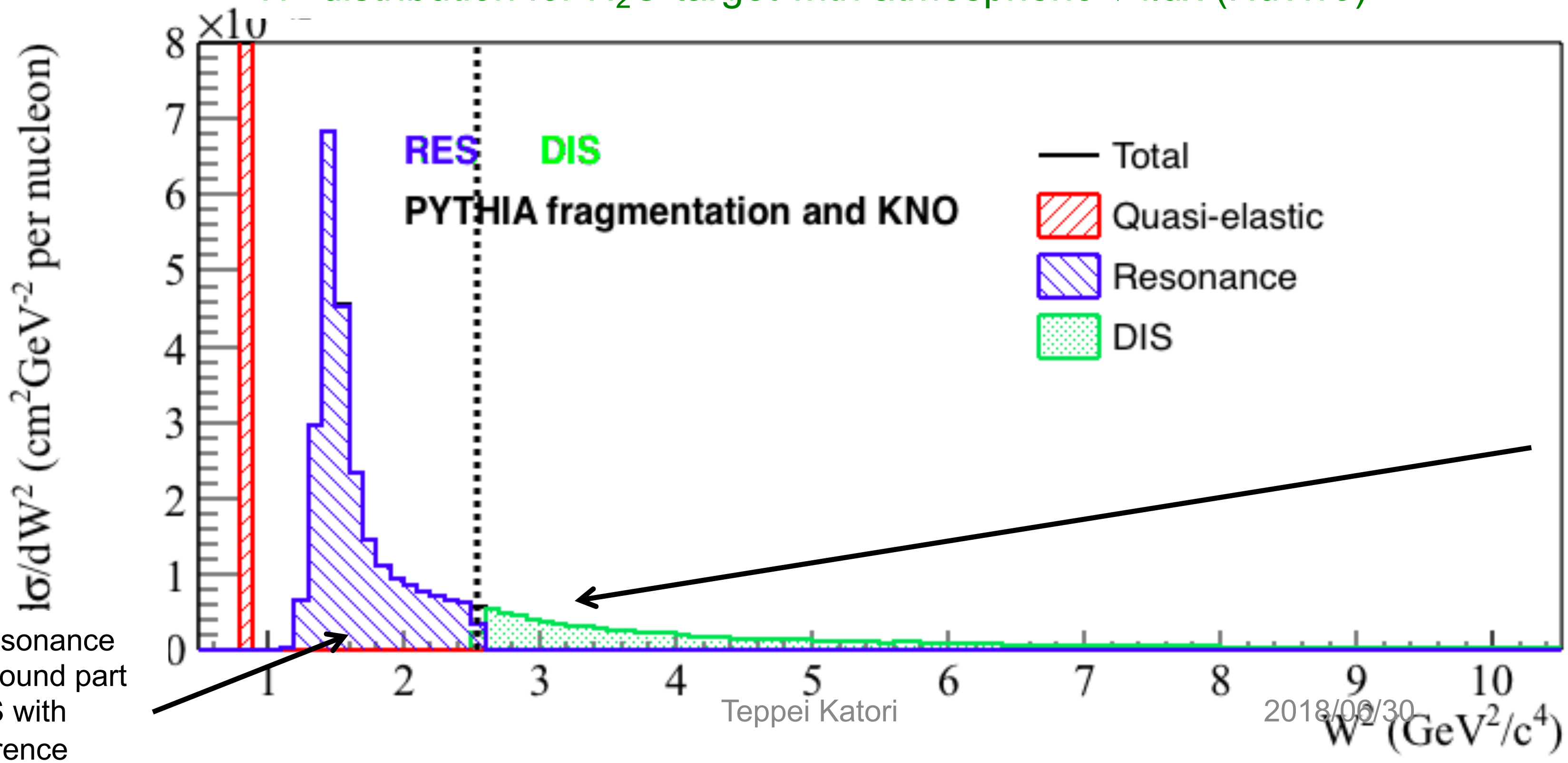
There are 2 kind of “transitions” in SIS region

- cross-section
- hadronization

File made by Luke Pickering (MSU)



W^2 distribution for H_2O target with atmospheric-ν flux (NuWro)



DIS

Non-resonance background part of RES with interference

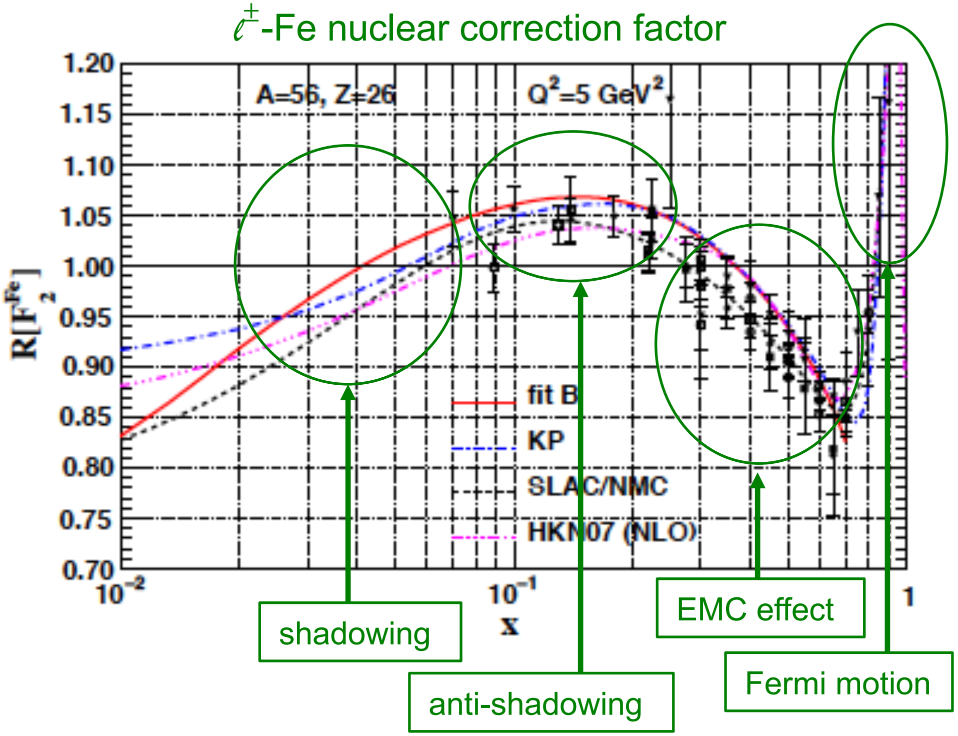
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028
nCTEQ, PRD80(2009)094004

3. Nuclear dependent DIS process

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

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

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



ν-Fe nuclear correction factor