Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Lattice QCD

Neutrino oscillation

Weak interaction

NuSTEC News

Nucleon correlation

EMC effect

electron scattering

Dark matter

Subscribe "NuSTEC News"

E-mail to listserv@fnal.gov, Leave the subject line blank, Type "subscribe nustec-news firstname lastname"

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

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

TK, Martini, arXiv:1611.07770 (to be appeared in “JPhysG topical review”)

Highlights from NuSTEC-News 2015-2017

nuclear

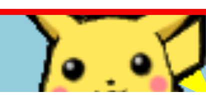
Spin physics

QCD

Neutrino oscillation

Weak interaction

1. Introduction
2. CCQE, CCQE-like, and CC0π data
3. CC data with nucleon final state
4. Electron neutrino CC data
5. A-dependence of neutrino cross section
6. Pion puzzle
7. Conclusion



Nucleon correlation

Teppei Katori
Queen Mary University of London
NuInt 17, The Fields Institute, Toronto, Canada, June 25, 2017

Dark matter

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1. Introduction

2. CCQE, CCQE-like, and CC0π data

3. CC data with nucleon final state

4. Electron neutrino CC data

5. A-dependence of neutrino cross section

6. Pion puzzle

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1. Introduction

The "NuSTEC News" (2012 -) is the community newsletter about neutrino interaction physics. It discusses the latest interesting neutrino cross result, either experimental or theoretical, roughly every other week. This is the place for all of us to learn neutrino interaction physics together.

http://nustec.fnal.gov/nustec-news/
Please subscribe it today!

Our Facebook page is "NuSTEC News" or @nuxsec, please "like" it now!

Use Hashtag #nuxsec for any news about neutrino interaction physics

Today, I covers highlights from NuSTEC-News from Nov. 2015 to June 2017 (=from NuInt15 to today) ordered in topics (not chronological order). We have tremendous amount of new results, indeed!

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2. CCQE-like data, MiniBooNE (2014)

SuSAv2 shows lower normalization due to lack of axial current enhancement.

Where 2p-2h contributions enter in the different approaches

Martini et al. *Nieves et al.* *Amaro et al.* *Lovato et al.* *Bodek et al.*

[Follow the color and the style of the lines:]

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \sigma_0\left[L_{CC}(R^V_{CC}+R^A_{CC}) + L_{CL}(R^V_{CL}+R^A_{CL}) + L_{LL}(R^V_{LL}+R^A_{LL}) + L_T(R^V_T+R^A_T) \pm L_{T'VA}R^{VA}_{T'}\right]$$

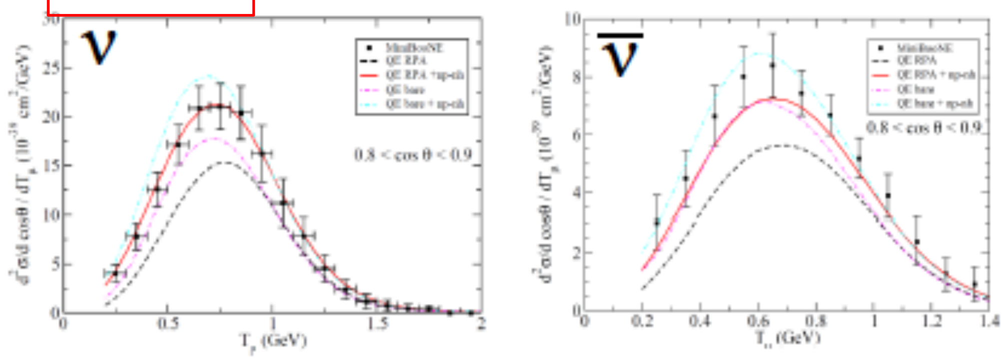
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \sigma_0\left[L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}\right]$$

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\cos^2\theta_c}{2\pi^2}k'\epsilon'\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2 R_\tau + \frac{\omega^2}{q^2}G_A^2 R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\frac{\epsilon+\epsilon'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}\right]$$

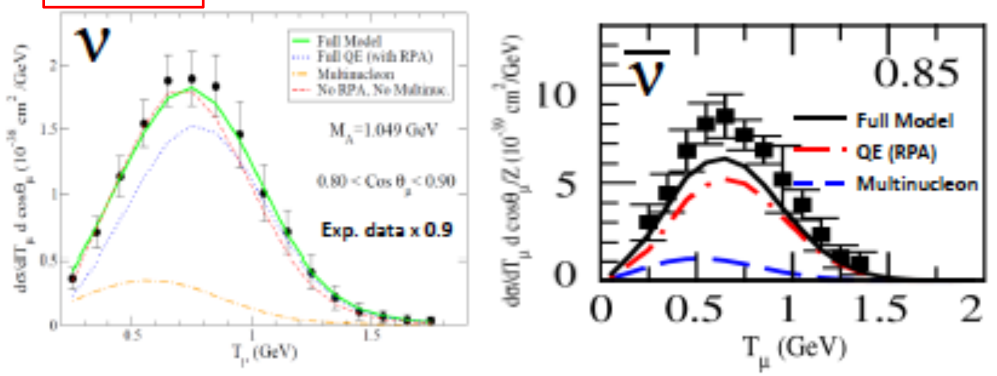
Relative role of 2p-2h for neutrinos and antineutrinos is different due to the **interference term**

21/5/2014 M. Martini, NuInt14 25

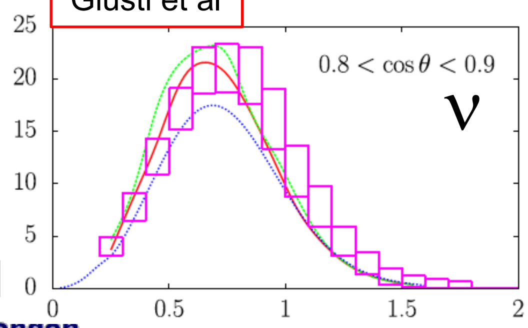
Martini et al



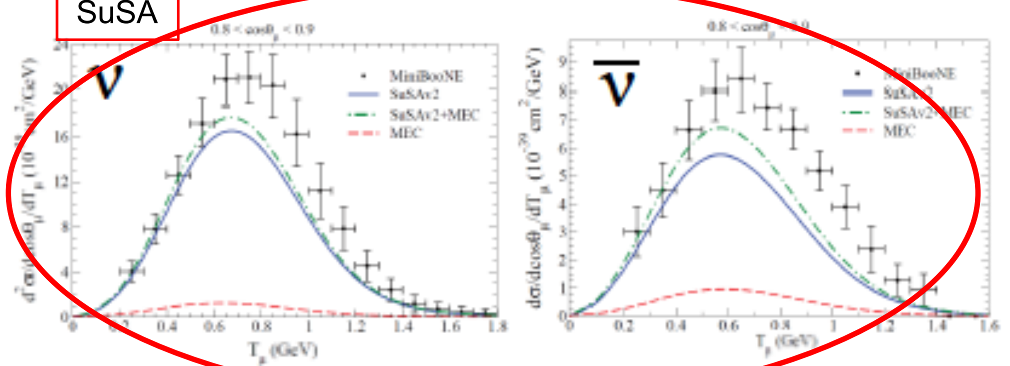
Valencia



Giusti et al



SuSA



Queen Mary University of London

Megias et al.,PRD94(2016)093004

2. CCQE-like data, MiniBooNE (new)

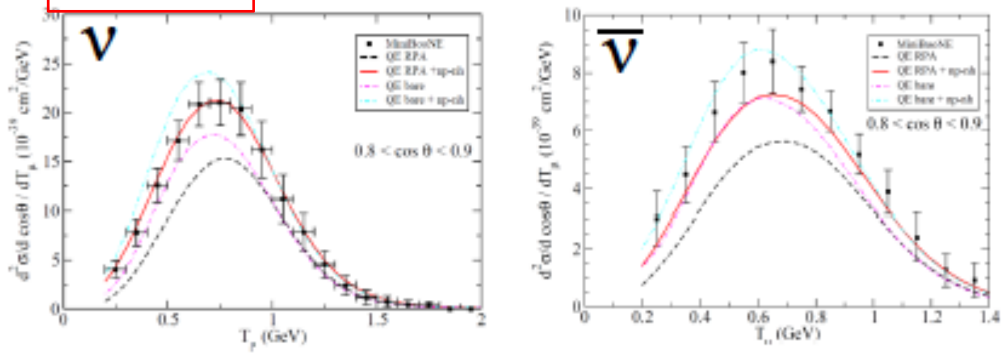
NuSTEC News
3 Aug 2016

SuSAv2 shows lower normalization due to lack of axial current enhancement.

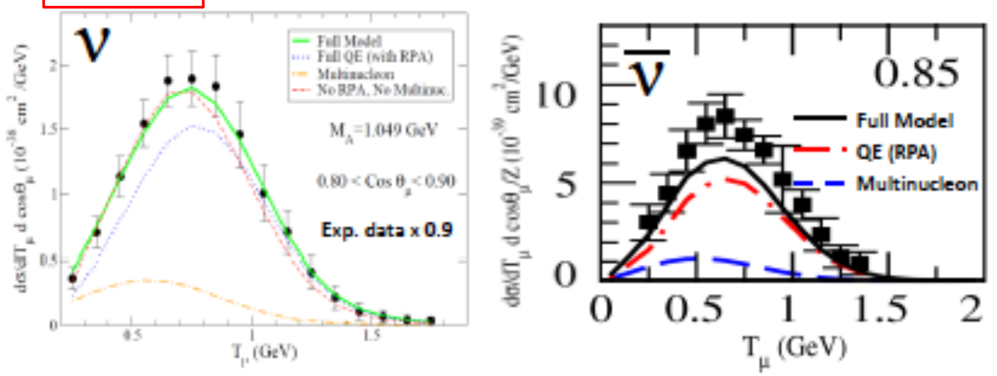
After adding axial MEC contribution, SuSA collaboration (Megias et al.) shows similar enhancement with other groups (Martini et.al., Nieves et al., Meucci et al., Mosel et al., Bodek et al.).

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

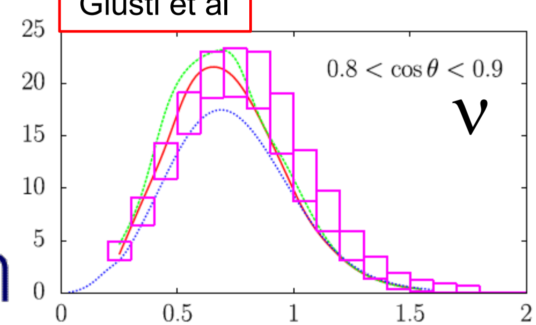
Martini et al



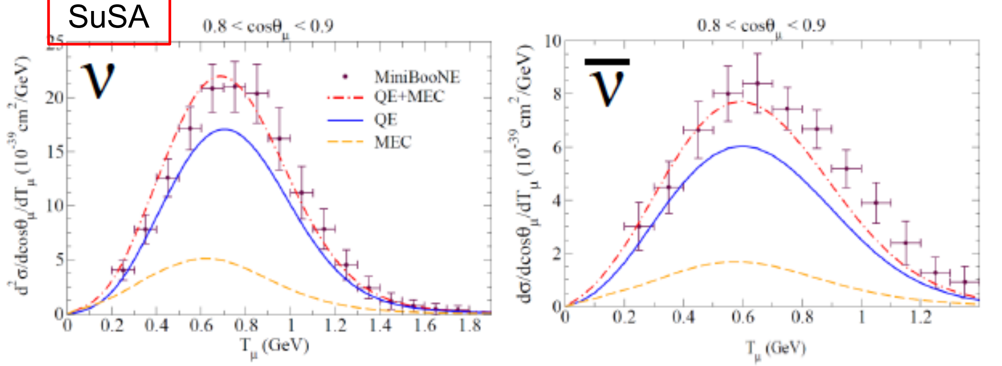
Valencia



Giusti et al



SuSA



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Megias et al.,PRD94(2016)093004, Martini and Ericson,PRC90(2014)025501,Gallmeister et al.,PRC94(2016)035502

2. CC inclusive data, T2K (new)

NuSTEC News
3 Aug 2016

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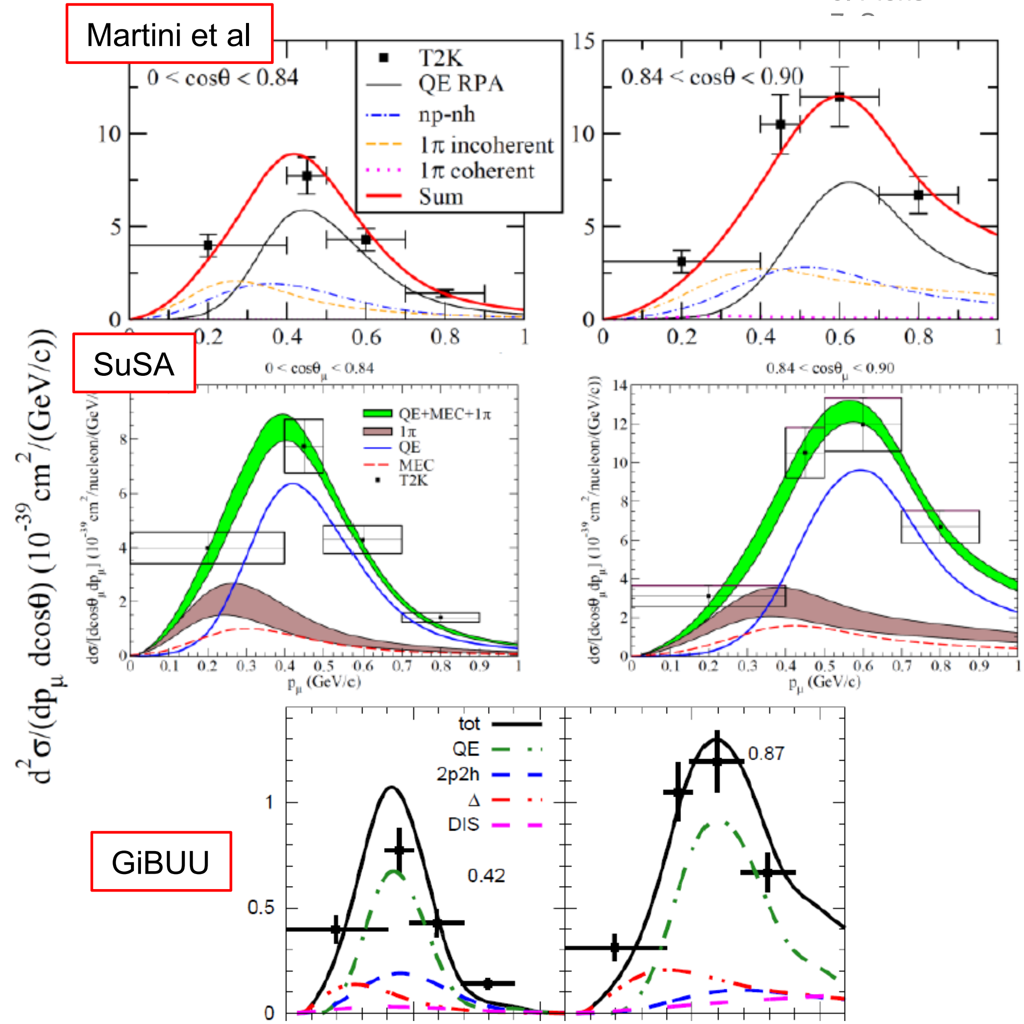
All groups agree qualitatively with MiniBooNE CCQE-like double differential data.

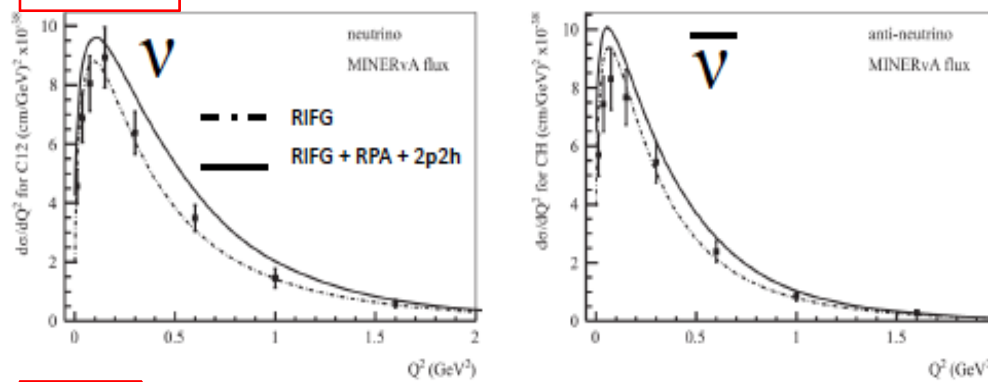
These models are also successful to reproduce T2K CC inclusive data (BNB flux cannot explain MiniBooNE data normalization)



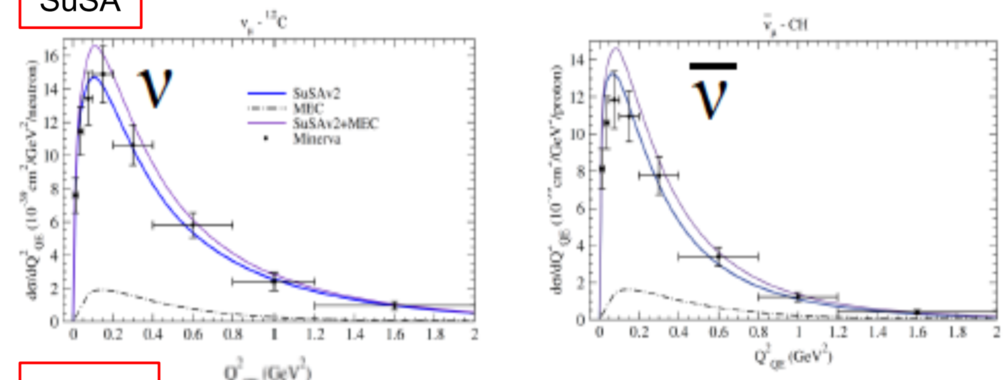
2. CCQE-like data, MINERvA (2014)

On the other hand, models work for MiniBooNE overestimate MINERvA cross sections.

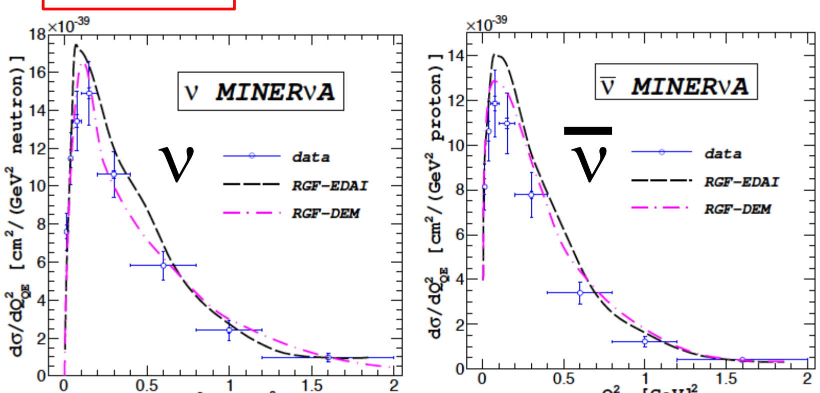
Valencia



SuSA

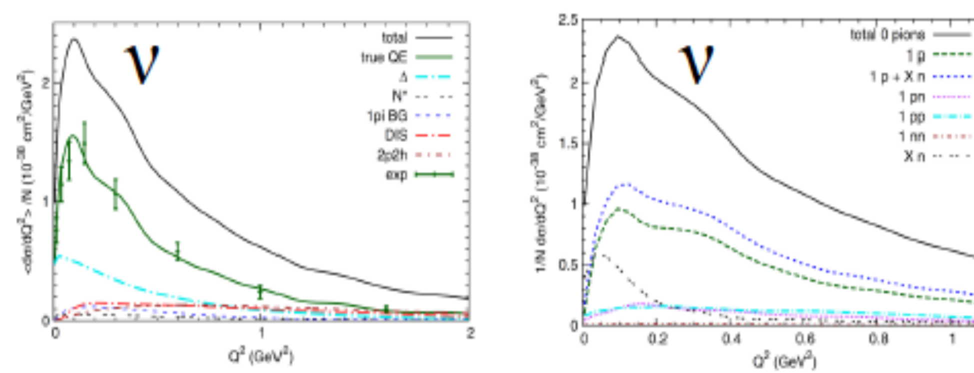


Giusti et al



Que

GiBUU



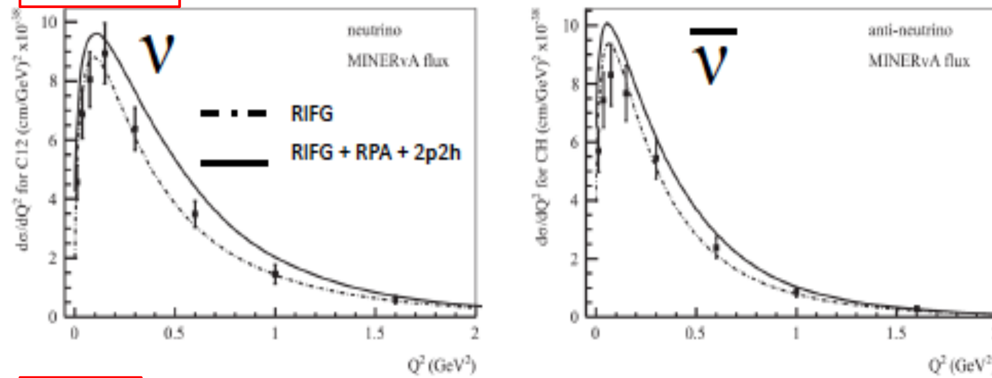
2. CCQE-like data, MINERvA (new)

NuSTEC News
31 Aug 2016

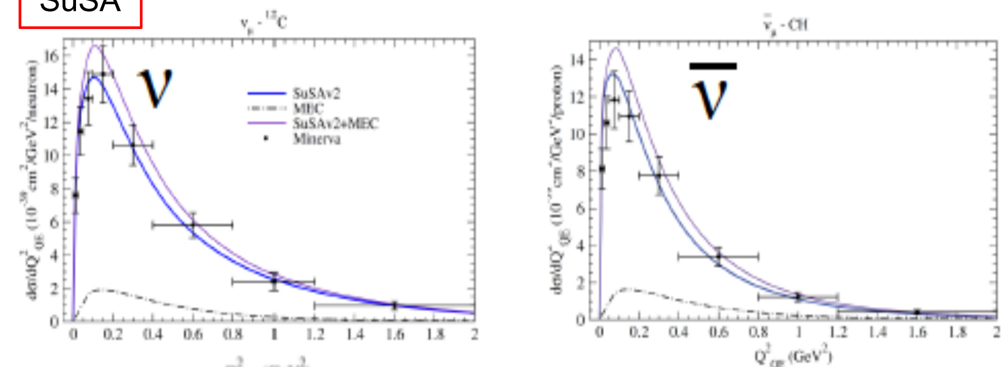
On the other hand, models work for MiniBooNE overestimate MINERvA cross sections.

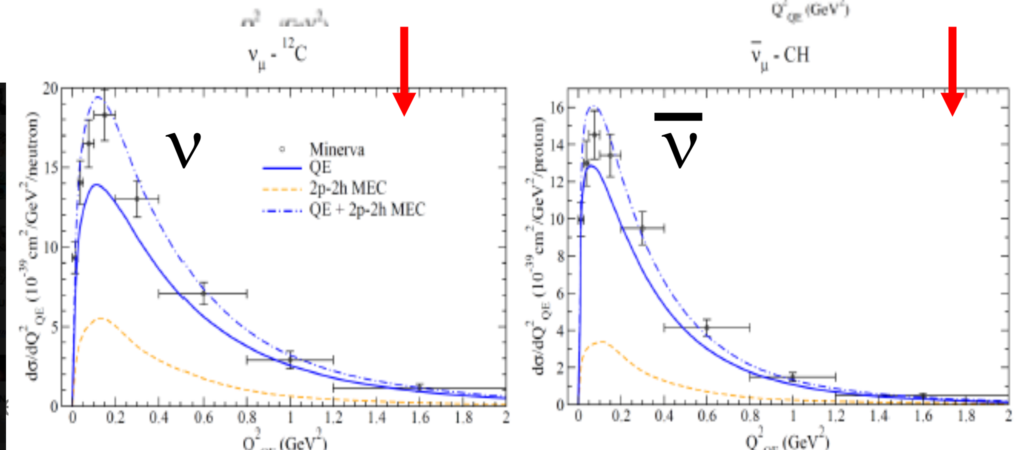
MINERvA found NuMI flux was overestimated. With new flux calculation, normalization tension between MiniBooNE and MINERvA is reduced.

Valencia

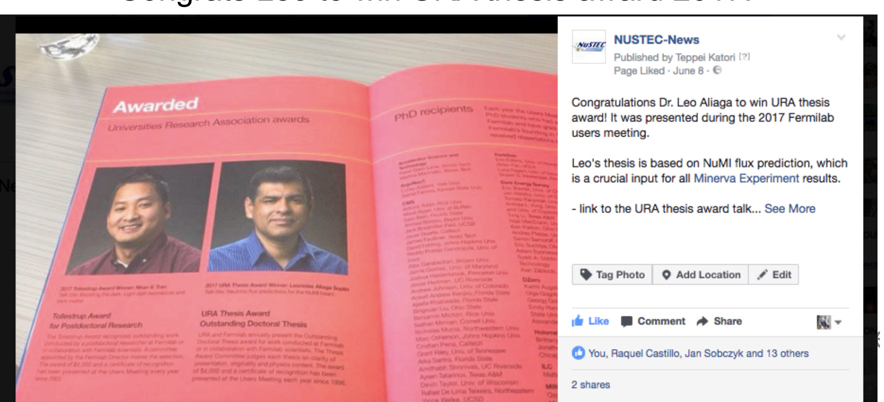


SuSA





Congrats Leo to win URA thesis award 2017!



MINERvA,PRD93(2016)112007;94(2016)092005;94(2016)112007

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NuSTEC News
31 Aug 2016

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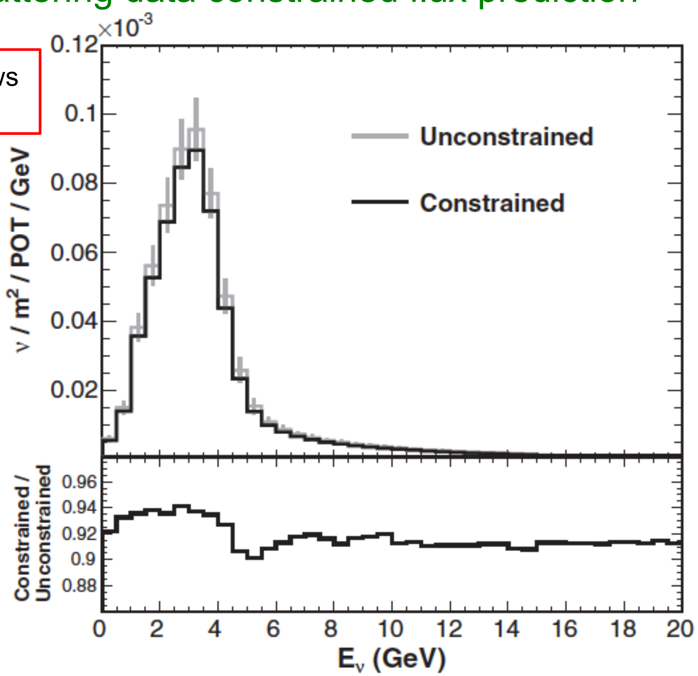
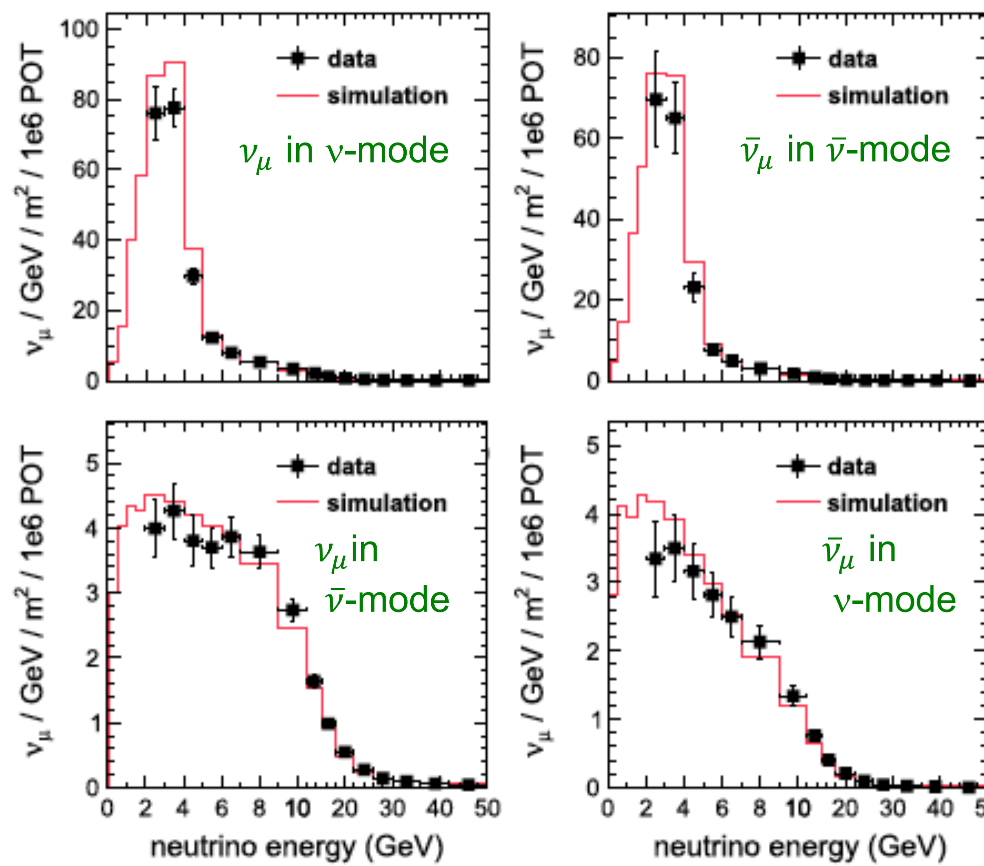
New flux results are independently tested by ν-e scattering data and low-ν method.

ν-e scattering data constrained flux prediction

NuSTEC News
Dec. 30 2015



low-ν method data vs old flux prediction



2. CCQE-like data, global fit tension (new)

NuSTEC News
24 Jan 2016

MiniBooNE and MINERvA data show strong tensions. The origin of tension includes;

1. Lack of full covariance matrix from MiniBooNE data
2. Lack of systematic errors from theoretical models
3. Validity of models at MiniBooNE, T2K, and MINERvA kinematics

New models are qualitatively right idea, but they don't pass a quantitative test

MiniBooNE-MINERvA CCQE-like data simultaneous fit

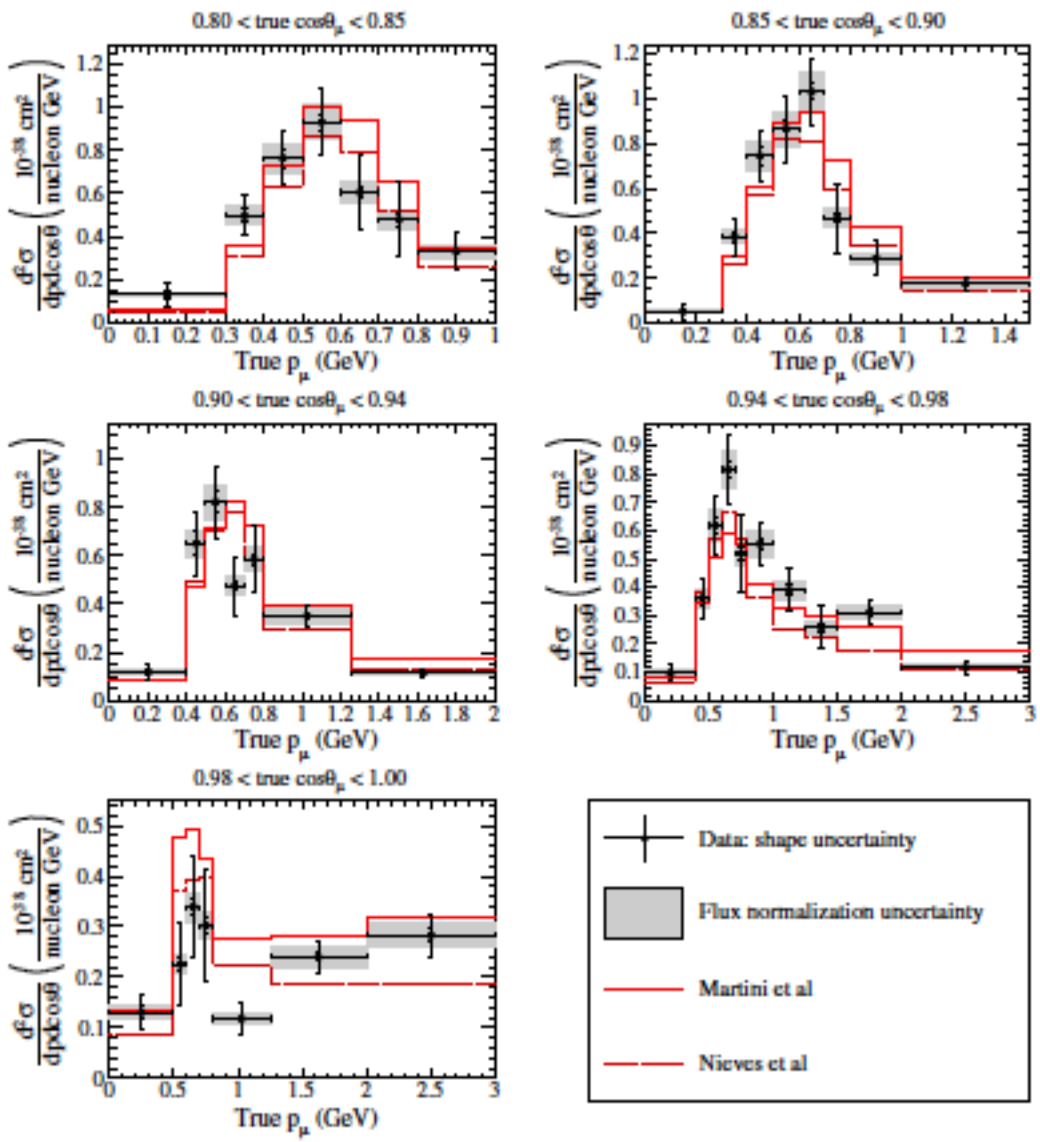
Fit type	χ^2/N_{DOF}	M_A (GeV/c^2)	2p2h norm (%)	p_F (MeV/c)	$\lambda_\nu^{\mathrm{MB}}$	$\lambda_{\bar{\nu}}^{\mathrm{MB}}$
RFG + rel RPA + 2p2h	97.8/228	1.15 ± 0.03	27 ± 12	223 ± 5	0.79 ± 0.03	0.78 ± 0.03
RFG + nonrel RPA + 2p2h	117.9/228	1.07 ± 0.03	34 ± 12	225 ± 5	0.80 ± 0.04	0.75 ± 0.03
SF + 2p2h	97.5/228	1.33 ± 0.02	0 (at limit)	234 ± 4	0.81 ± 0.02	0.86 ± 0.02

2. CC0π double differential data, T2K (new)

NuSTEC News
18 Feb 2016

T2K publish CC0π double differential cross section. This took into account many issues on MiniBooNE data set

1. clearly state what was measured
2. full covariance matrix for precise fit



Study of lepton kinematics
is not completed, yet.

2. Workshops for cross section analysis (new)

The State of Nu-Tion meeting (June 23-24, 2017 https://meetings.triumf.ca/indico/event/12/)

- Try to tackle major cross section analysis problems beyond each collaboration

State of the Nu-tion Workshop

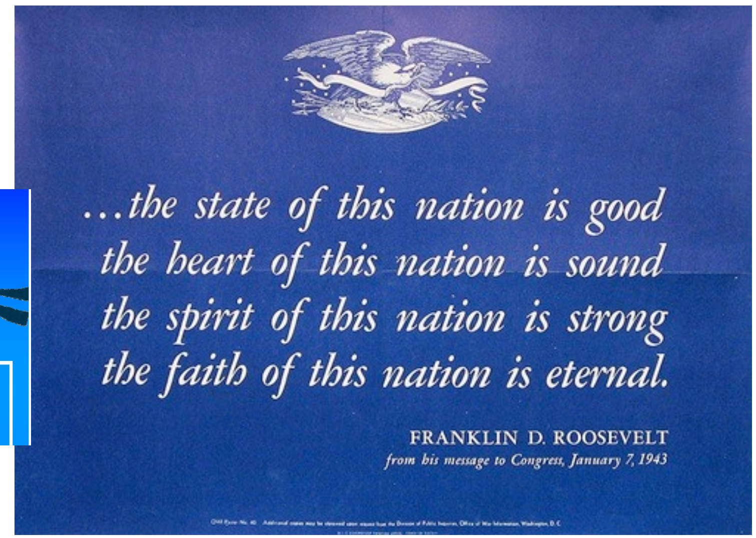
$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}_{ij}^{-1}(N_j - B_j)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

ArgoNeuT

NOvA

μBooNE

T2K



Experimentalist discussion of σ methodology. Next steps:

- Task force to assess minimum bias, practical unfolding approach
- Workshop at FNAL to identify, explore shared systematic uncertainties
  - particle re-interactions in detector, cross section model etc)

2. Workshops for cross section analysis (new)

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- Try to tackle major cross section analysis problems beyond each collaboration

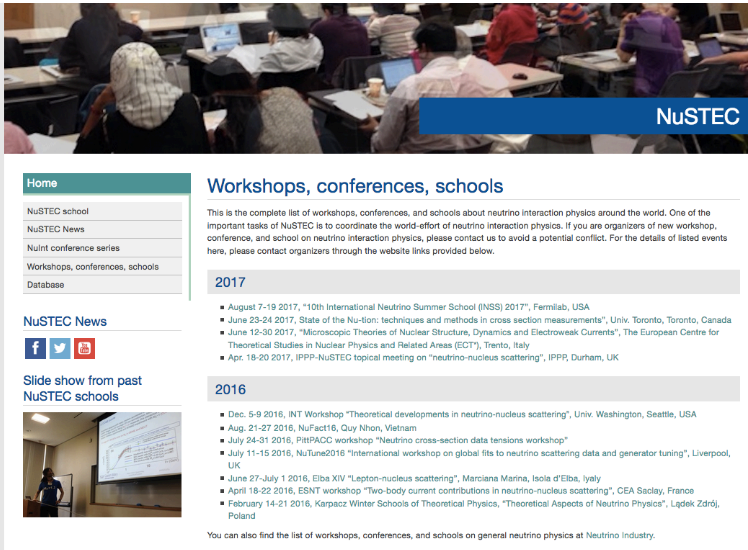
Phystat-nu 2016: Workshop on Statistical Issues in Experimental Neutrino Physics
- IPMU (May 30-June 1, http://indico.ipmu.jp/indico/event/82/)
- Fermilab (Sept. 19-21, https://indico.fnal.gov/conferenceDisplay.py?confId=11906)

The data tension workshop (July 25-31, 2016)
http://nugevxsectensions.pbworks.com/w/page/107587302/Neutrino%20Cross-section%20Data%20Tensions%20Workshop

NuTune 2016: Global fit workshop (July 11-15, 2016)
https://indico.fnal.gov/conferenceDisplay.py?confId=11610

NUISANCE
- public data-MC comparison software
https://nuisance.hepforge.org/

NuSTEC News
Dec 23 2016



Find all nuxsec workshops
http://nustec.fnal.gov/

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University of London

Bhattacharya et al.,PRD92(2015)113011, Mayer et al.,PRD93(2016)113015
Alexandrou et al, arXiv:1705.03399, Amaro and Arriola,PRD93(2016)053002

2. More thoughts on nucleon parameters (new)

NuSTEC News
28 Oct 26 2015
4 Mar 4 2016
27 Feb 2017

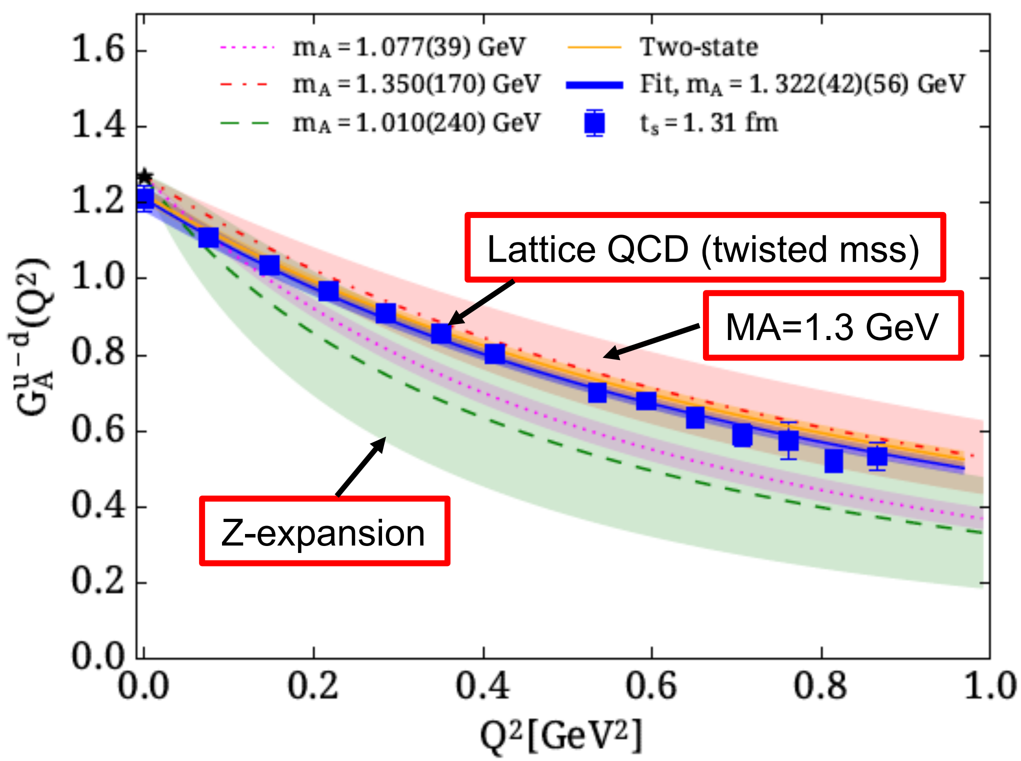
There are number of new thoughts on nucleon parameters

Z-expansion: Precise MA determination, form factor errors are underestimated
Lattice QCD: axial mass could be larger
Large MA: could be motivated from theories

We say "ν-nucleus" scattering is complicated, but we are still confused about "ν-nucleon" scattering…

Jury is still out?!

Axial vector form factor comparison



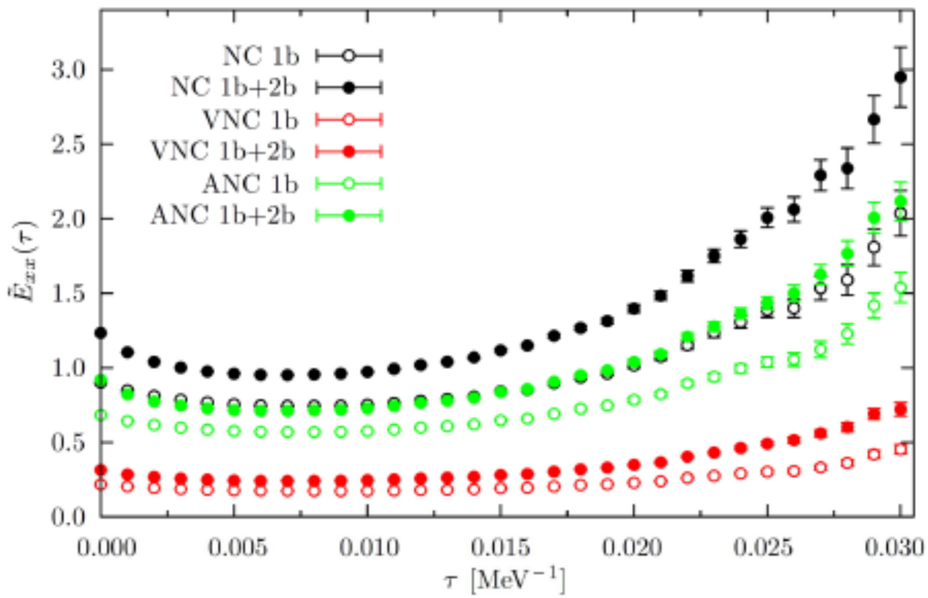
2. Ab initio calculation (2015)

Ab initio calculation support the general idea of transverse response enhancement for neutrino scatterings.

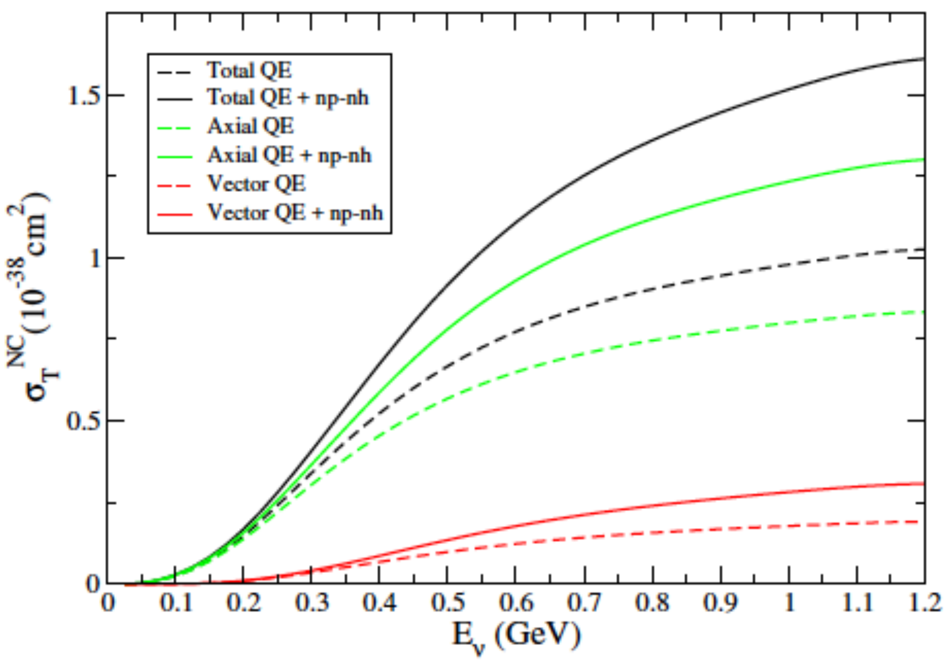
Ab initio calculation for weak interaction response function shows same features with phenomenological models.

Next step: ab initio calculation for oxygen and argon

NC Euclidean transverse response function by ab initio calculation (q=570 MeV)



NCQE-like cross section transverse response contribution by Martini et al.



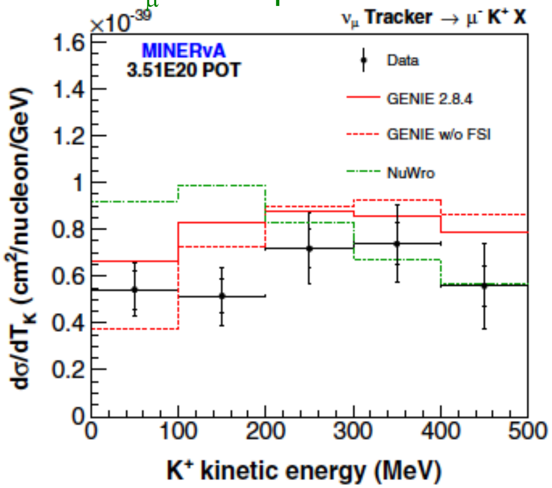
Coffee Break

Honorable mention: Other MINERvA results (new)

Kaon bombs

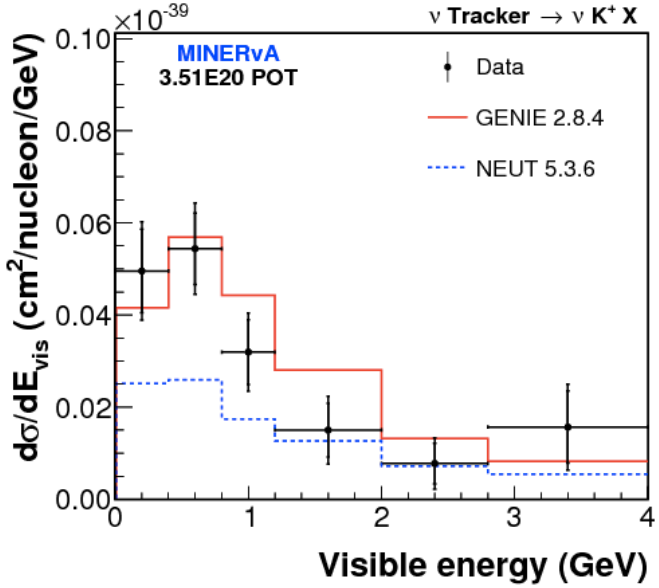
NuSTEC News
11 May 2016

ν_μCC K⁺ production

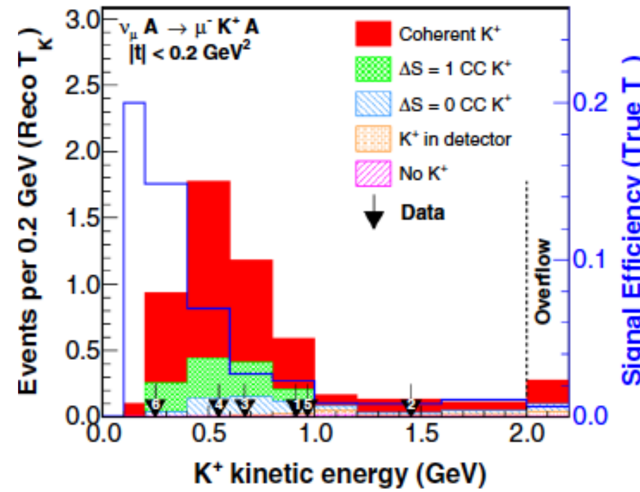


$\nu(\bar{\nu})$NC K⁺ production

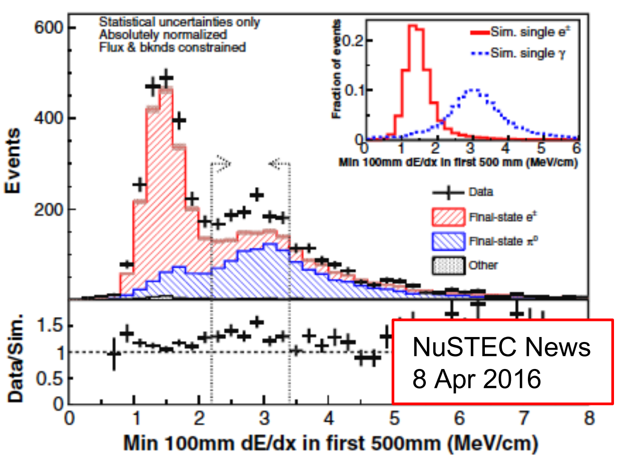
NuSTEC News
16 Nov 2016



ν_μCC coherent K⁺ production



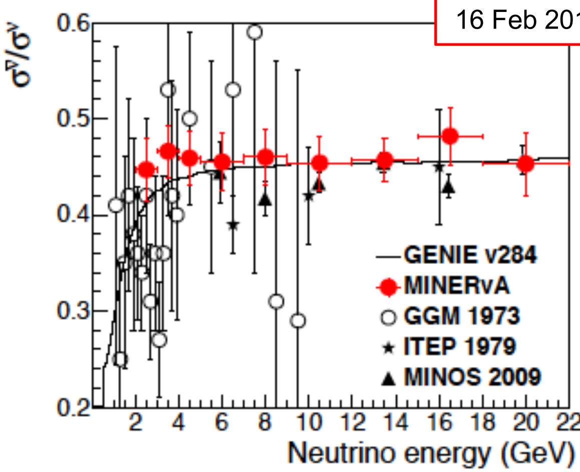
Diffractive pion production



NuSTEC News
8 Apr 2016

DIS $\bar{\nu}/\nu$ ratio

NuSTEC News
16 Feb 2017



Go MINERvA! Go!
- Facebook
@minervaexperiment
- Twitter
@minervaexpt
- Instagram
@minerva.neutrino

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4. Electron neutrino CC data

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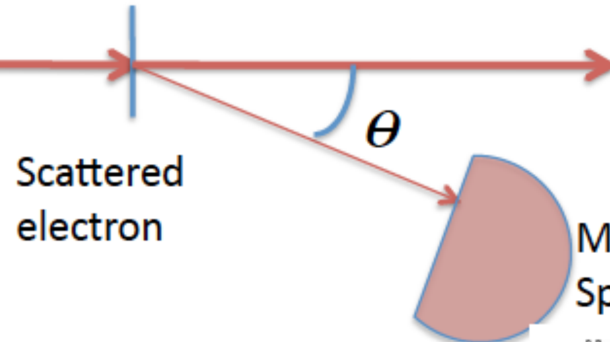
3. Remark from Gerry Garvey (circa 2010)

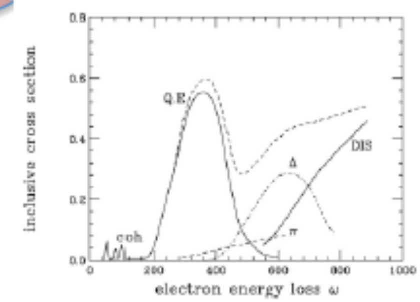
Contrast of e-N with ν-N Experiments

Electron

Electron Beam $\Delta E/E \sim 10^{-3}$

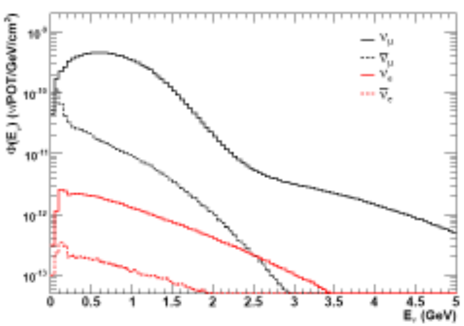
Flux known to 1%





Neutrino

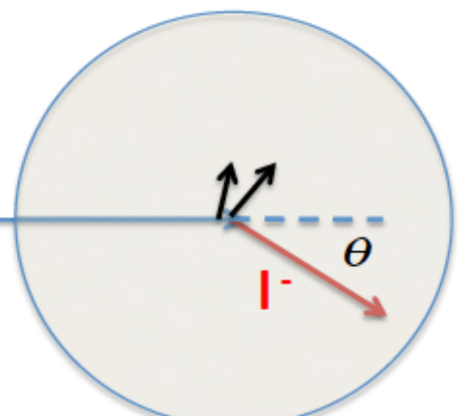
Neutrino-Mode Flux



E_ν

Neutrino Beam $\Delta E/\langle E\rangle \sim 1$

Flux known to 20%



Don't know E_ν !!!

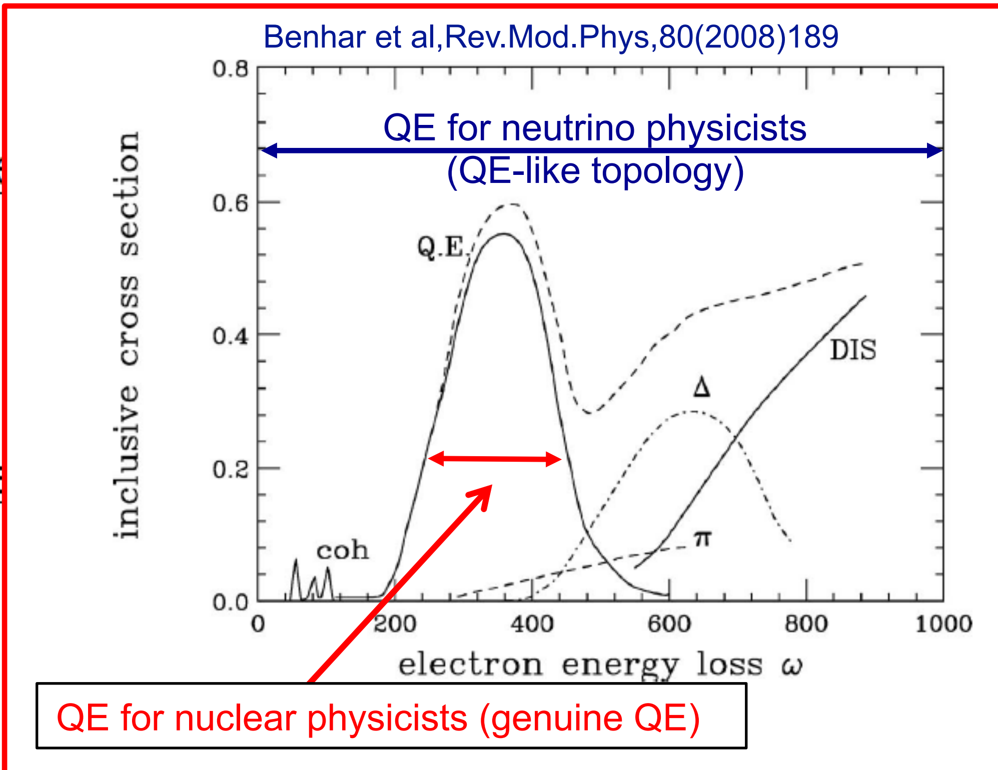
What's ω ???

What's $\vec{q}$????

QE peak???

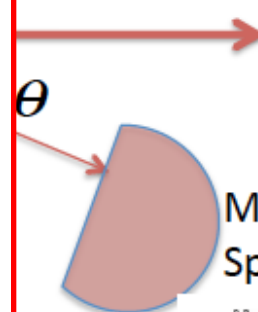
Very Different Situation from inclusive electron scattering!!

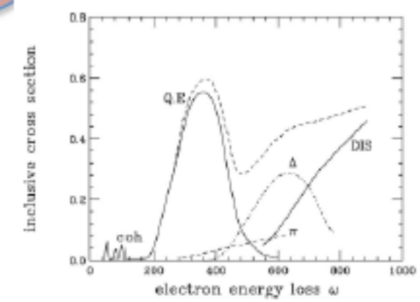
3. Remark from Gerry Garvey (circa 2010)



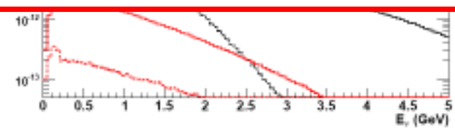
xperiments

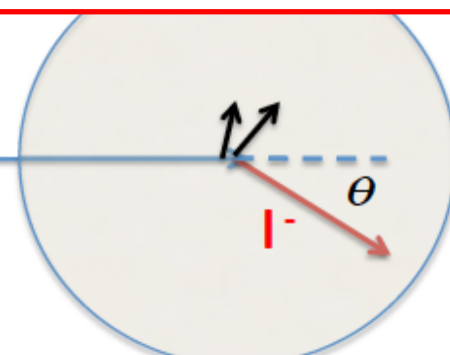
Ele





Ne





Neutrino Beam ΔE/<E>~1

Flux known to 20%

Don't know E_ν !!!

What's ω ???

What's $\vec{q}$????

QE peak???

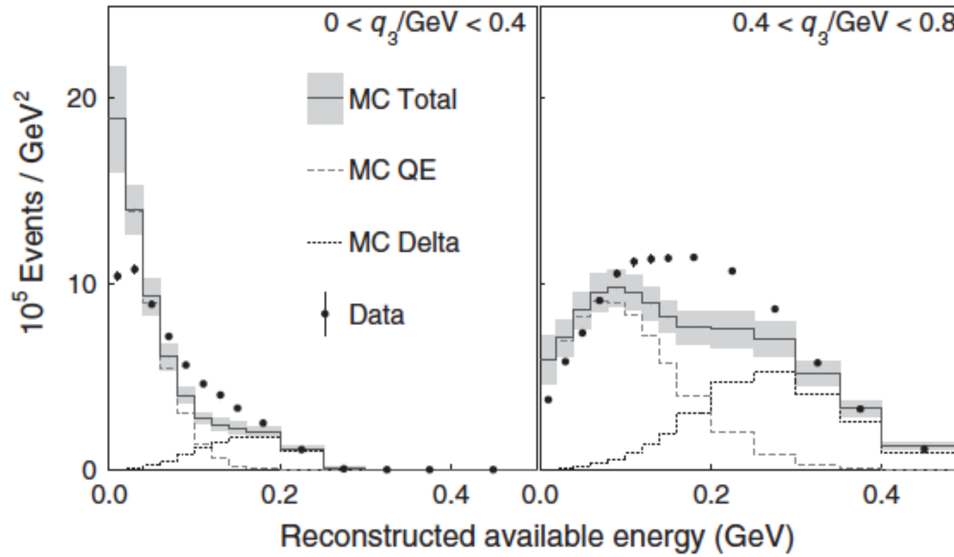
Very Different Situation from inclusive electron scattering!!

3. $d\sigma/dE_{avail}$ data, MINERvA (2015)

NuSTEC News
10 Dec 2015

MINERvA reconstruct full inclusive kinematics (once we thought impossible!)

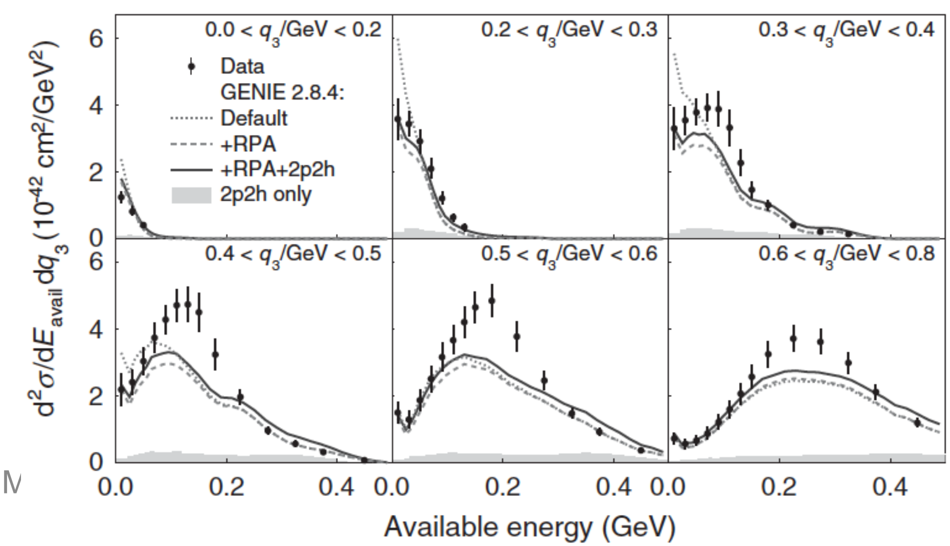
available energy
(visible hadron energy deposit)
↓
energy transfer
↓
3-momentum transfer



Double differential distribution shows "dip" structure in MC, but not in data

Excess of data around the "dip region" is visible.

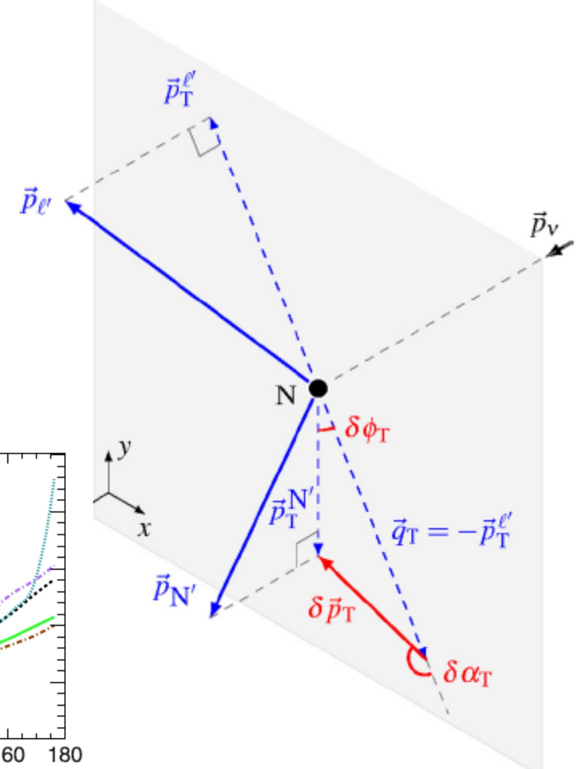
Model(s) fix this distribution also fix CC0π data-MC agreement?



Lu et al.,PRC94(2016)015503,Furmanski and Sobczyk,PRC95(2017)06550

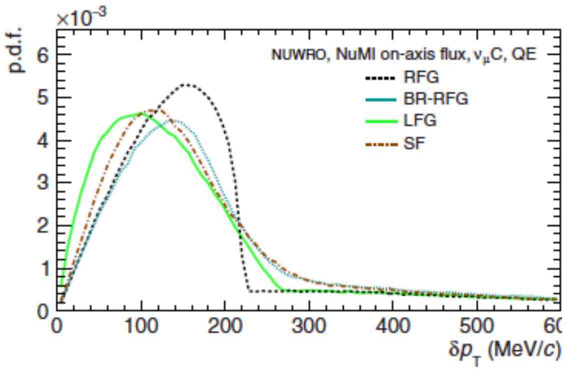
2. 1μ+1p topology kinematics (new)

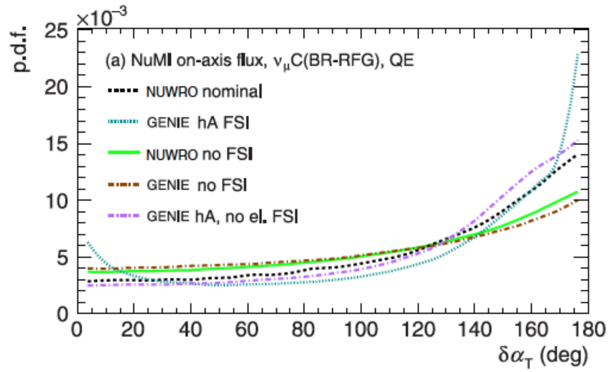
NuSTEC News
23 Sep 2016



Transverse kinematic imbalance

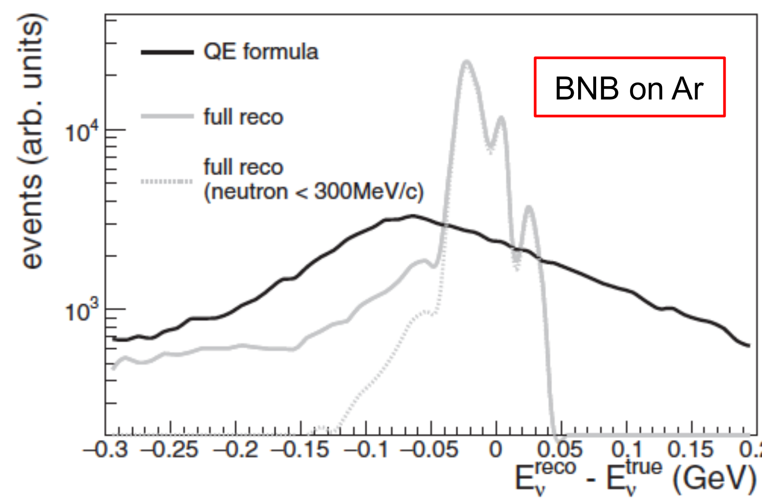
- it may be sensitive to different nuxsec and FSI nuclear models





Improved neutrino energy reconstruction

- Including nuclear structure



To use these techniques, proton reconstruction efficiency must be know well

Fermilab 15ft,PRD18(1978)1367

3. Backward going proton (1978)

Special topology of nucleons from neutrino interactions are studied at Fermilab 15ft bubble chamber, but the subject was forgotten in neutrino physics…

Probing nuclei with antineutrinos

J. P. Berge, D. Bogert, R. Endorf,* R. Hanft, J. A. Malko, G. Moffatt,* F. A. Nezrick, W. G. Scott,† W. Smart, and J. Wolfson
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

V. V. Ammosov, A. G. Denisov, P. F. Ermolov, V. A. Gapienko, V. I. Klyukhin, V. I. Koreshev, A. I. Mukhin, P. V. Pitukhin, Y. G. Rjabov, E. A. Slobodyuk, and V. I. Sirotenko
Institute of High Energy Physics, Serpukhov, USSR

V. I. Efremenko, P. A. Gorichev, V. S. Kaftanov, V. D. Khovansky, G. K. Kliger, V. Z. Kolganov, S. P. Krutchinin, M. A. Kubantsev, A. N. Rosanov, M. M. Savitsky, and V. G. Shevchenko
Institute of Theoretical and Experimental Physics, Moscow, USSR

J. Bell, C. T. Coffin, H. T. French,‡ W. C. Louis, B. P. Roe, R. T. Ross, A. A. Seidl, and D. Sinclair
University of Michigan, Ann Arbor, Michigan 48109

(Received 24 April 1978)

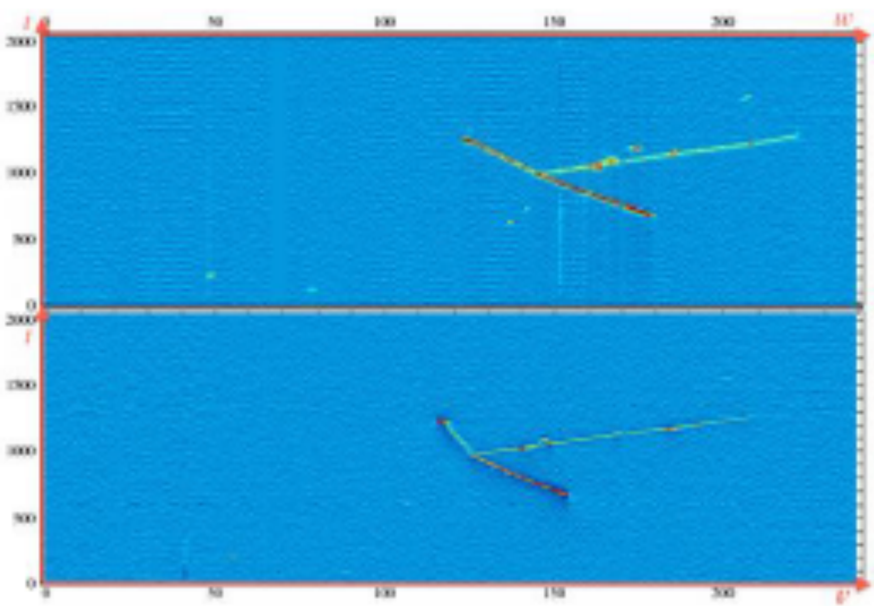
Variable[a]	Backward-proton events	Charged-current events
Number of events	36	837
$\langle E_{\bar\nu}\rangle$ (GeV)	25.48 ± 2.82	28.78 ± 0.71
$\langle P_\mu\rangle$ (GeV/c)	18.10 ± 2.36	19.02 ± 0.53
$(1-\cos\theta_\mu)$	$(2.87 \pm 0.60) \times 10^{-3}$	$(5.96 \pm 0.31) \times 10^{-3}$
$\langle \nu\rangle$ (GeV)	7.38 ± 1.47	9.71 ± 0.44
$\langle Q^2\rangle$ [(GeV/c)^2]	1.43 ± 0.25	3.58 ± 0.15
$\langle x\rangle$	0.17 ± 0.02	0.23 ± 0.01
$\langle y\rangle$	0.26 ± 0.03	0.33 ± 0.01
$\langle n\rangle$	7.42 ± 0.64	6.20 ± 0.11
$\langle C\rangle$	2.14 ± 0.17	1.25 ± 0.04
$\langle C_1\rangle$	0.81 ± 0.28	0.98 ± 0.04

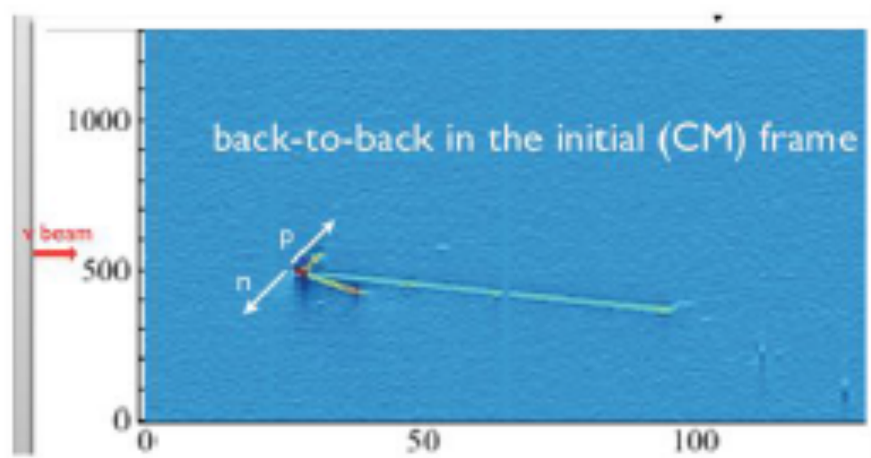
Queen Mar
University of London

ArgoNeuT,PRD90(2014)012008

3. Hammer events, ArgoNeuT (2014)

ArgoNeuT published so called “hammer” events.
→ candidate topology of NNSRC from ν_μ+(np)→μ+p+p



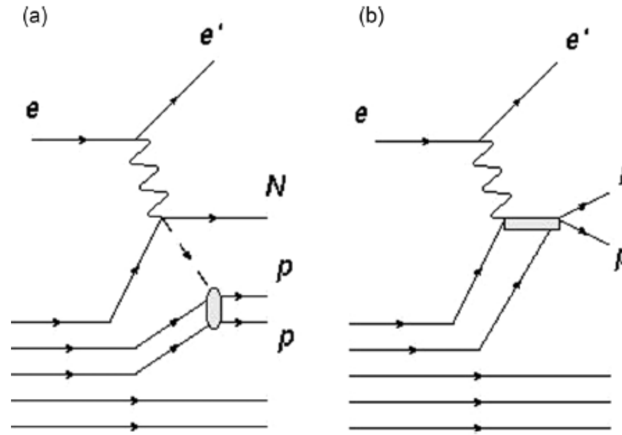


ArgoNeuT,PRD90(2014)012008
Niewczas and Sobczyk,PRC93(2016)035503,Weinstein et al.,PRC94(2016)045501

3. Interpretation of hammer events (new)

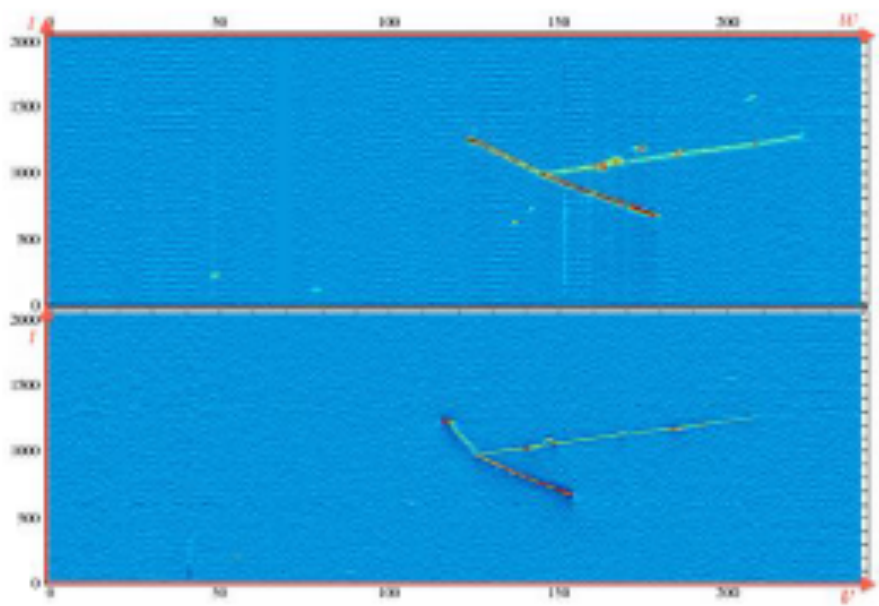
NuSTEC News
Jan. 7 2016

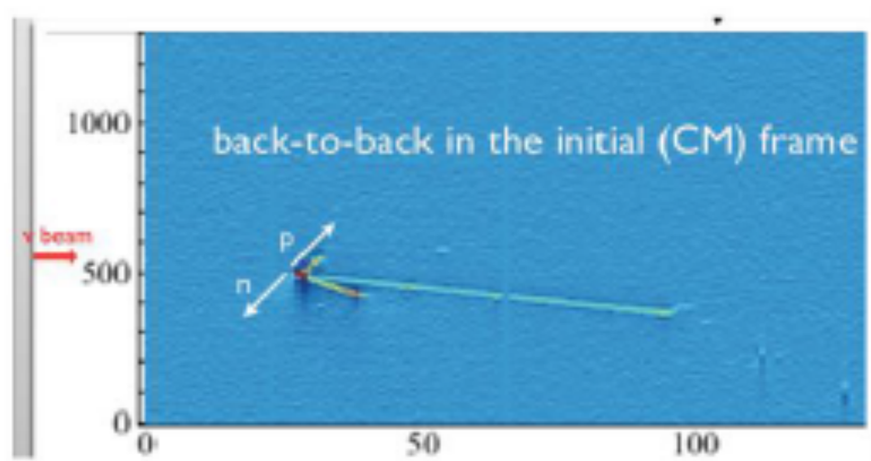
ArgoNeuT published so called "hammer" events.
→ candidate topology of NNSRC from ν_μ+(np)→μ+p+p



Other reactions contribute comparable amount on this topology…

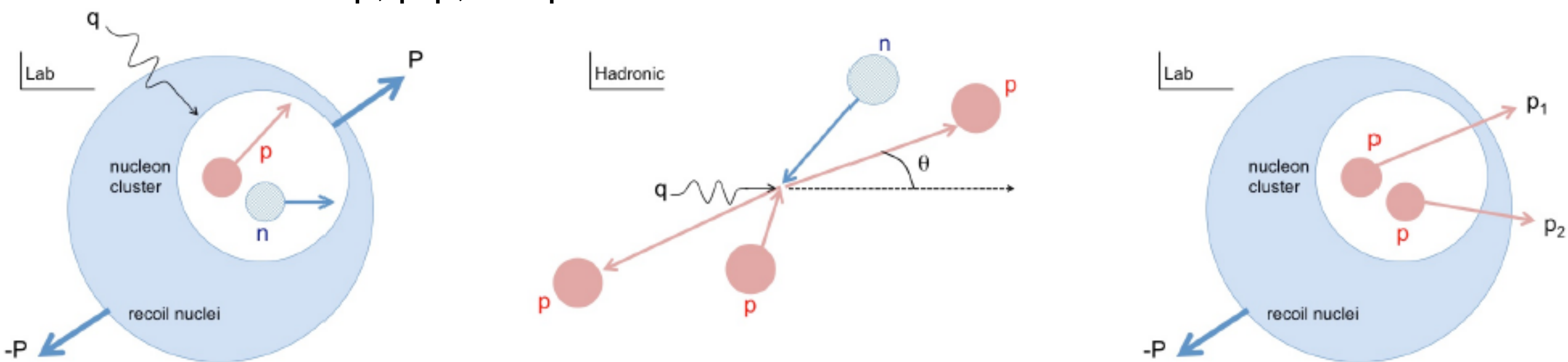
To study more detail, detection efficiency need to be understood.





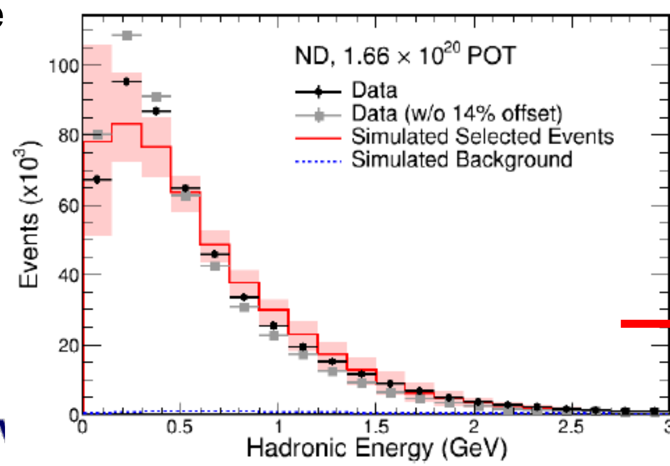
3. Nucleon kinematics predictions (2015)

So far, all generators are based on "nucleon cluster model"
- isotropic decay in hadronic frame
- fixed ratio for n-p, p-p, n-n pairs

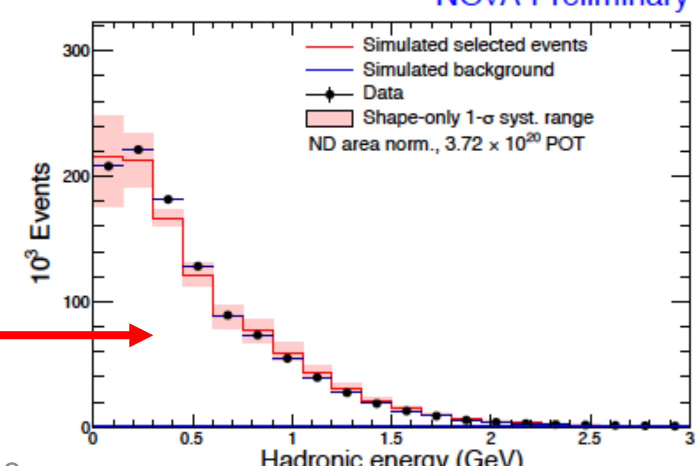


Although it is too naïve model, but it may not be too wrong

NOvA reduce energy scale mismatch from 5 to 2% by 2p2h+MEC (Nieves et al.)+nucleon cluster model



NOvA Preliminary



Queen Mary
University of London

Van Chuyk et al.,PRC94(2016)024611
Ruiz Simo et al.,PLB762(2016)124, arXiv:1706.06377v1

3. Nucleon kinematics predictions (new)

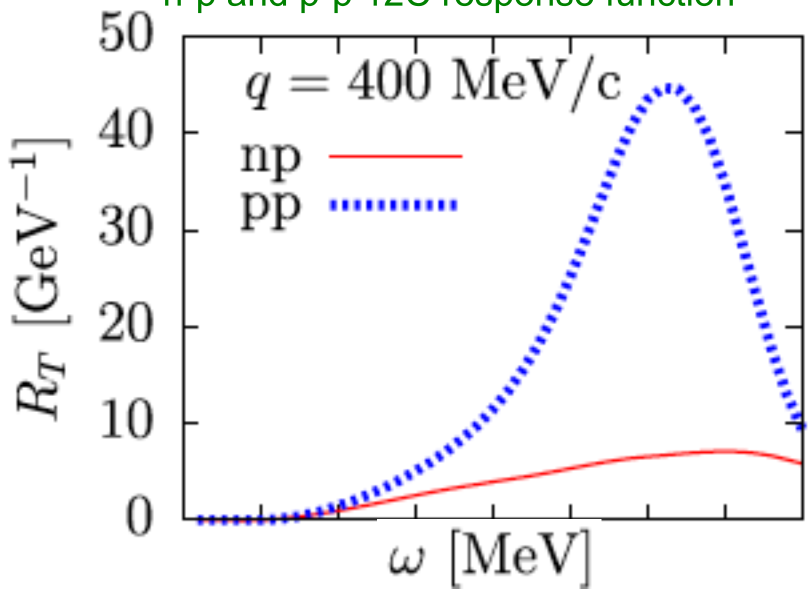
So far, all generators are based on "nucleon cluster model"
- isotropic decay in hadronic frame
- fixed ratio for n-p, p-p, n-n pairs

Number of groups made detailed predictions of hadron final states

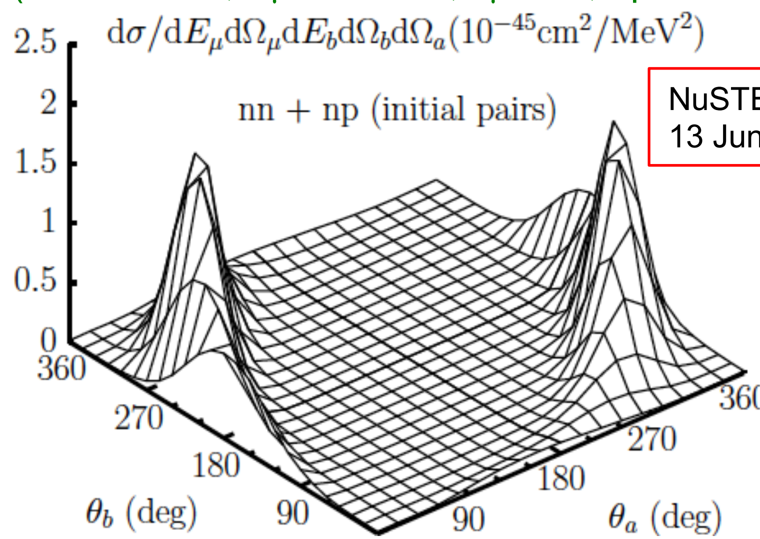
→ Question, how to use them in experiments?

NuSTEC News
3 Aug 2016

n-p and p-p 12C response function



proton in-plane kinematics from 2p2h
(Eν=750MeV, Eμ=550MeV, θμ=15°, Tp=50MeV)



NuSTEC News
13 Jun 2016

4. ν_eCC data (1978)

- ν_e appearance oscillation is measured by ν_eCC interaction.
- No ν_eCC data in low energy region. This was one of motivations for neutrino factory (including nuSTORM).
- ν_e to ν_μ cross section ratio is an important systematics, but it is often optimistic.

TOTAL CROSS SECTIONS FOR ν_e AND $\bar{\nu}_e$ INTERACTIONS AND SEARCH FOR NEUTRINO OSCILLATIONS AND DECAY

Gargamelle Collaboration

J. BLIETSCHAU, H. DEDEN, F.J. HASERT, W. KRENZ, D. LANSKE, J. MORFIN, M. POHL, K. SCHULTZE, H. SCHUMACHER, H. WEERTS and L.C. WELCH
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E. BELLOTTI, S. BONETTI, D. CAVALLI, E. FIORINI, A. PULLIA and M. ROLLIER
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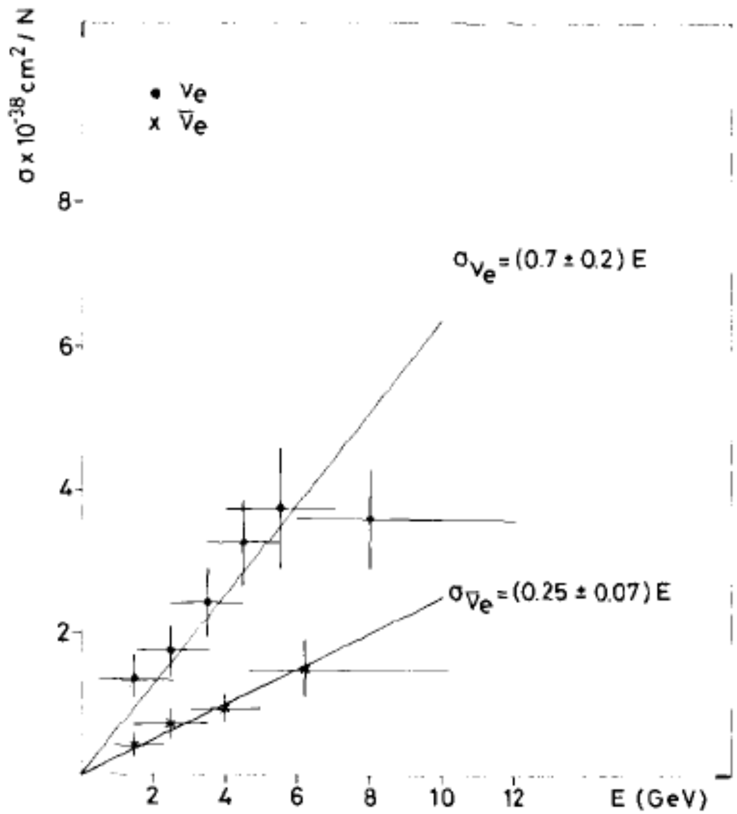
Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK and A.G. MICHETTE +++
University College London, London, UK



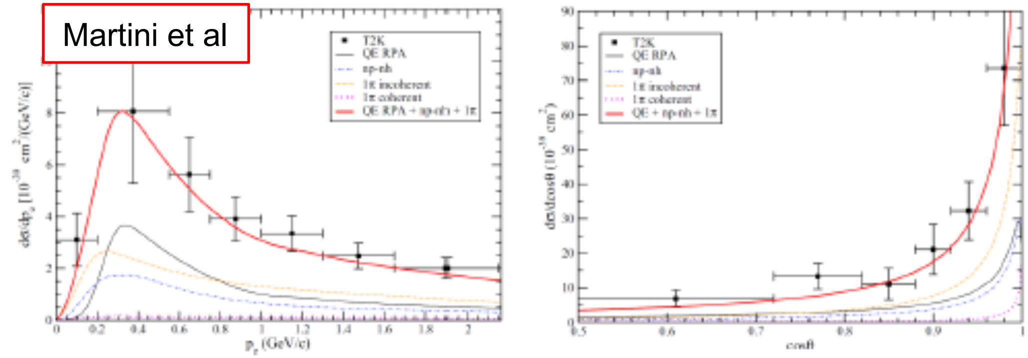
Martini et al.,PRC94(2016)015501,Gallmeister et al.,PRC94(2016)035502,Megias et al.,PRD94(2016)093004
T2K,PRL113(2014)241803;PRD91(2015)112010

4. ν_eCC inclusive data, T2K (new)

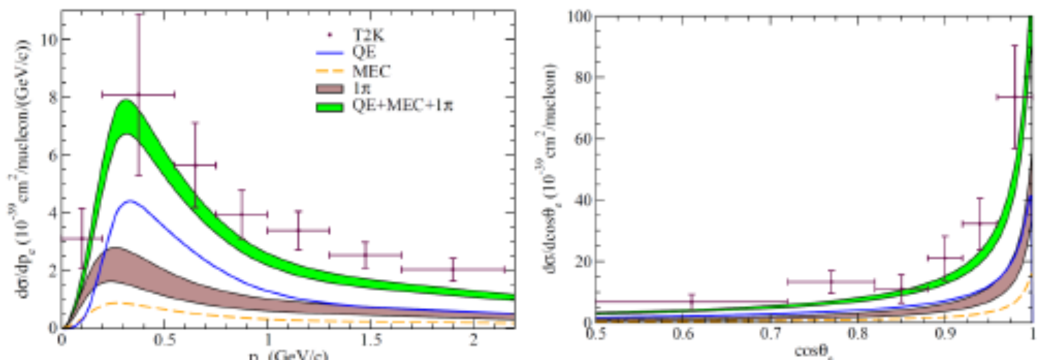
NuSTEC News
3 Aug 2016

T2K measured ν_eCC inclusive cross section, and models already reproduced them!

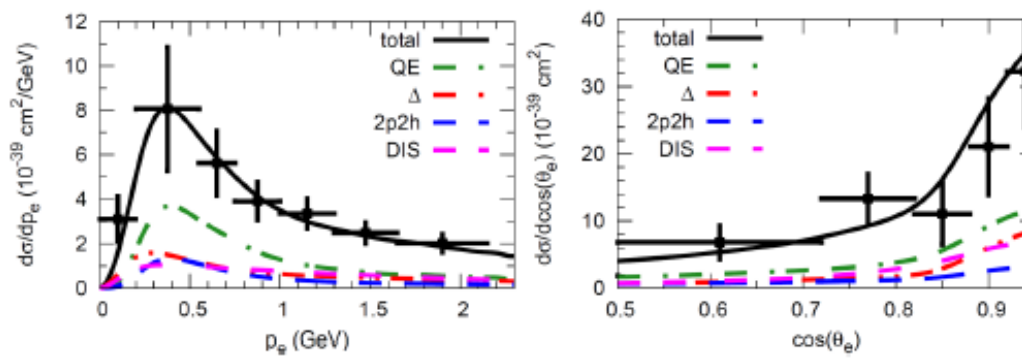
Martini et al



SuSA



GiBUU

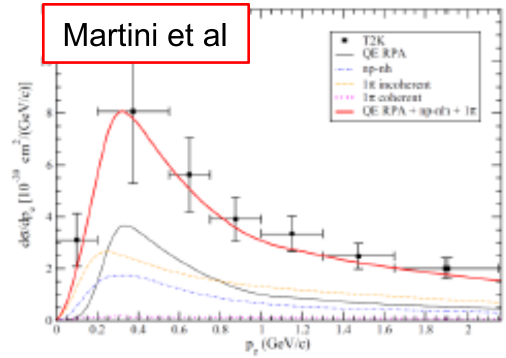


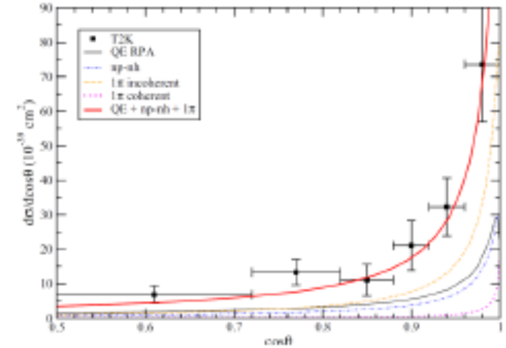
MINERvA,PRL116(2016)081802

4. ν_eCCQE-like data, MINERvA (2015)

NuSTEC News
23 Sep 2015

Martini et al

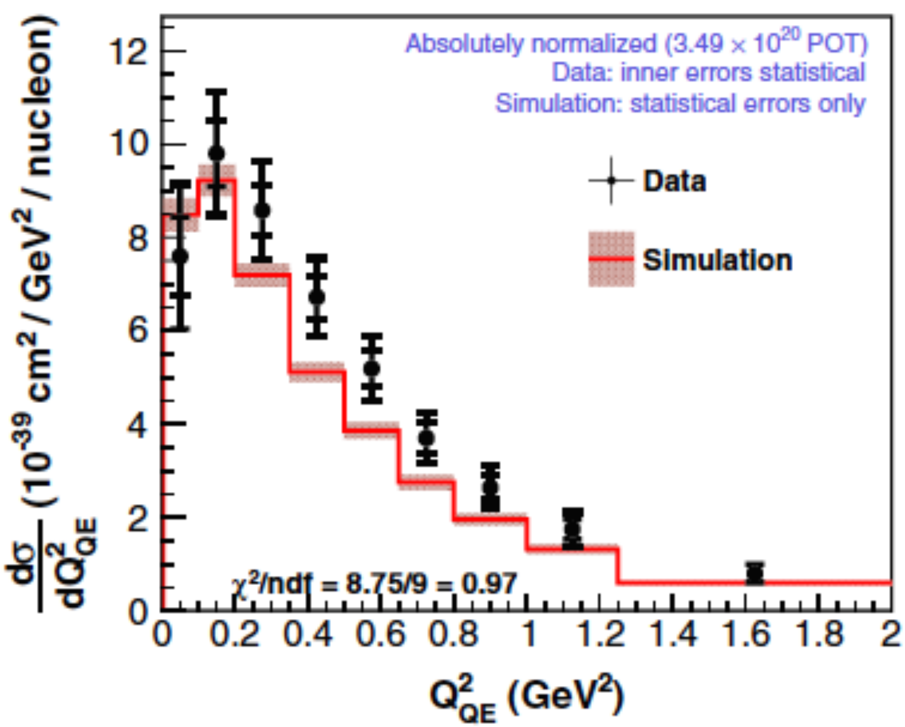


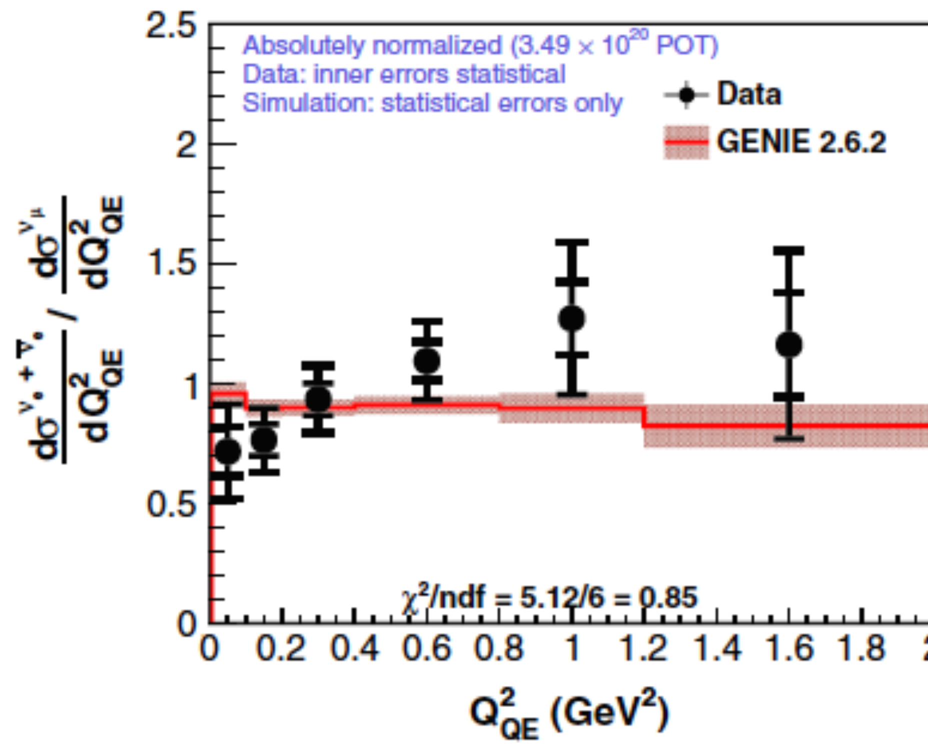


T2K measured ν_eCC inclusive cross section, and models already reproduced them!

MINERvA measured ν_eCCQE-like

Summary: we have many ν_eCC data from zero, but precision (=statistics) is much worse than ν_μCC data.





1. Introduction

2. CCQE, CCQE-like, and CC0π data

3. CC data with nucleon final state

4. Electron neutrino CC data

5. A-dependence of neutrino cross section

6. Pion puzzle

7. Conclusion

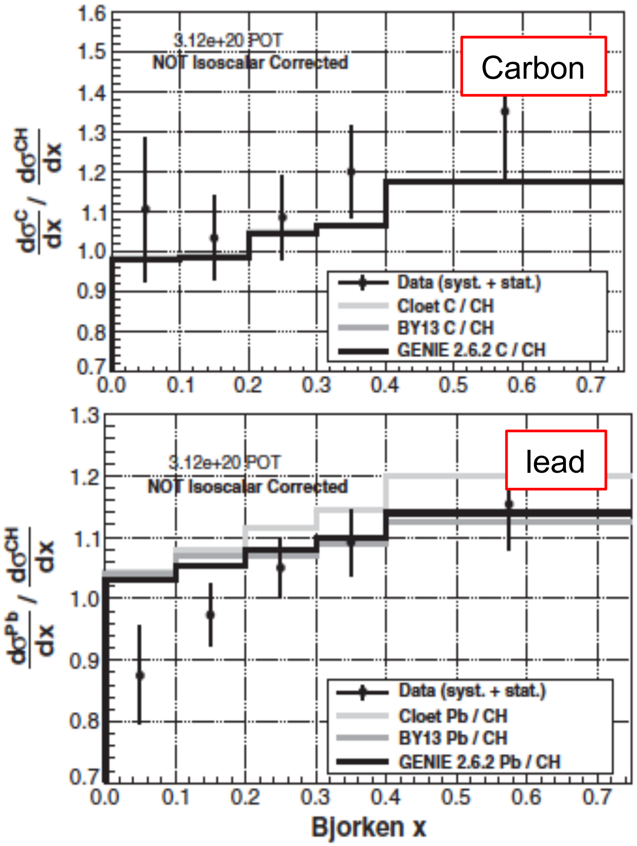
HKN,PRC76(2007)065207,Kulagin and Petti,Nucl.Phys.A765(2006)126,nCTEQ,PRD80(2009)094004
MINERvA,PRD93(2016)071101

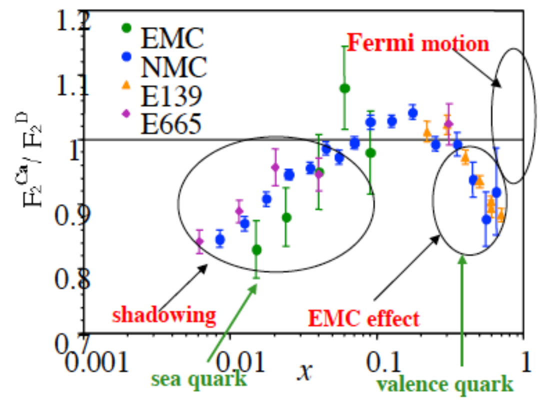
5. Target dependent results (new)

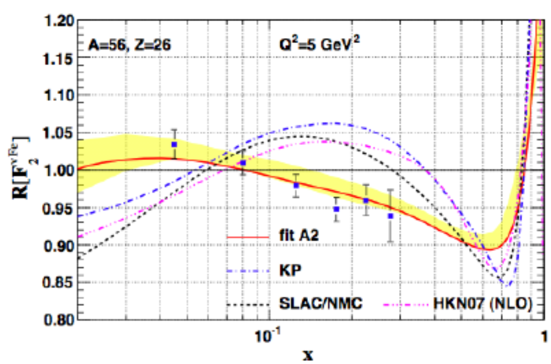
NuSTEC News
14 Mar 2016

DIS target ratio cross section

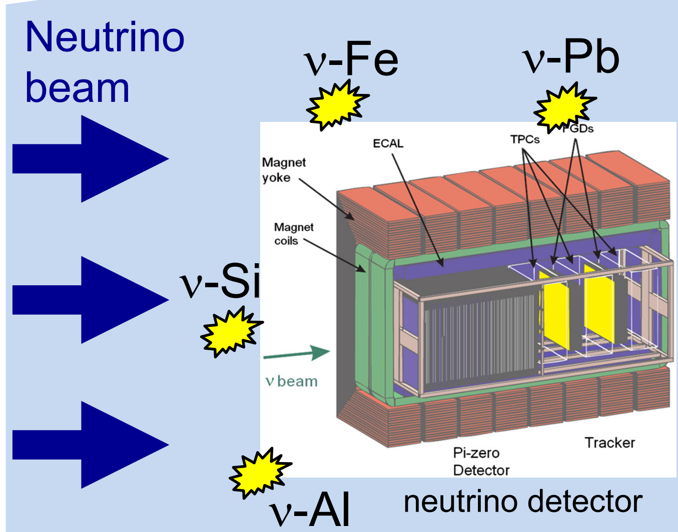
- nuclear shadowing may be stronger than simulation







Modern neutrino experiments need characterizations of all elements with all energy



MINERvA,PRD93(2016)071101,arXiv:1705.03791

5. Target dependent results (new)

NuSTEC News
12 May 2017

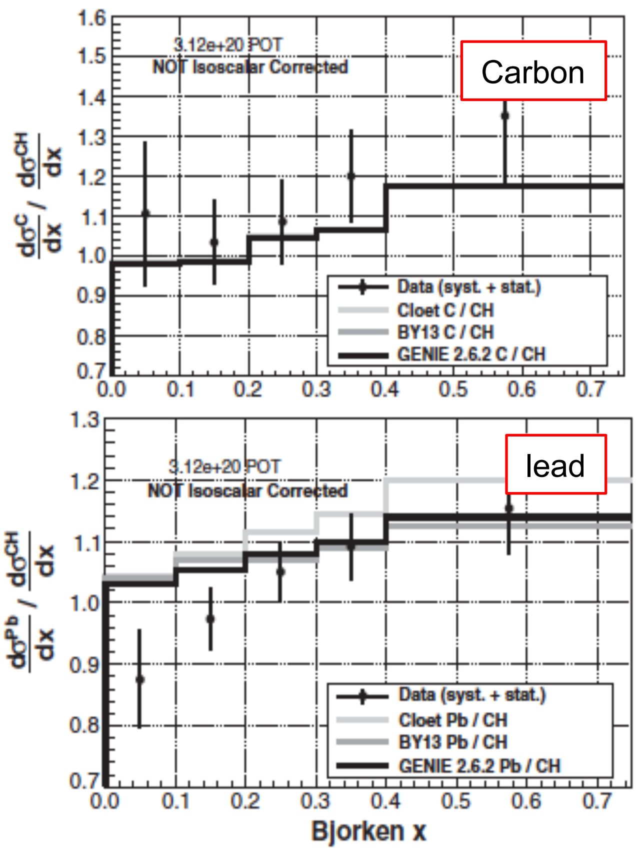
DIS target ratio cross section

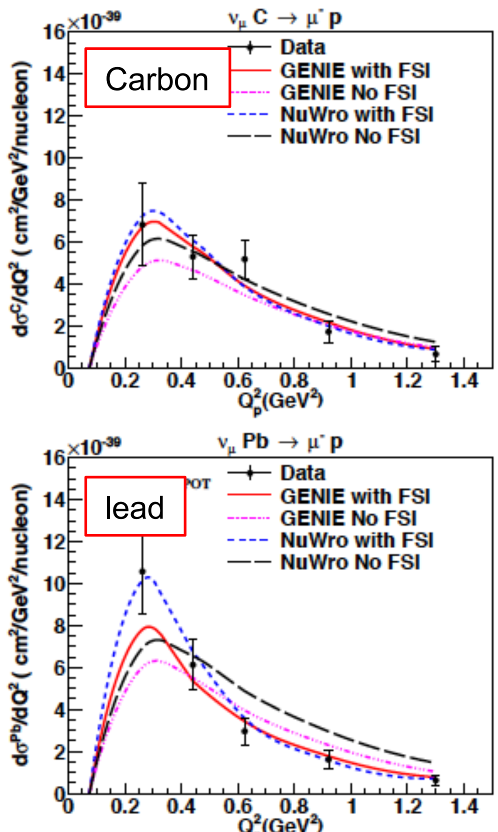
- nuclear shadowing may be stronger than simulation

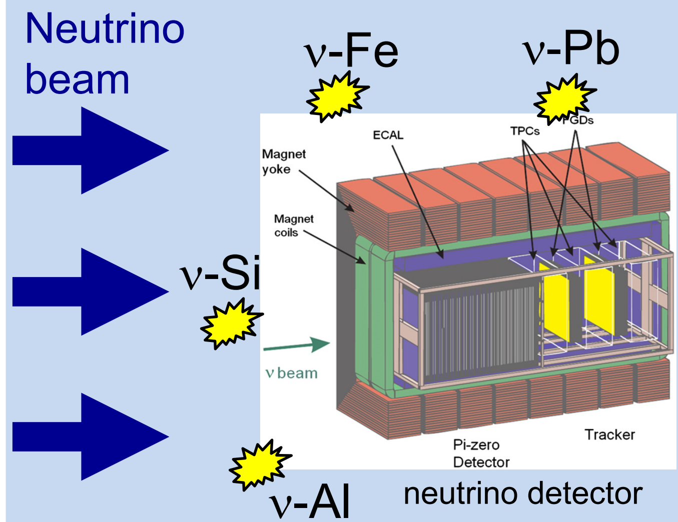
CC0πNp A-dependent cross section

- proton feels more FSI in larger A

Modern neutrino experiments need characterizations of all elements with all energy





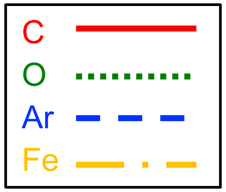


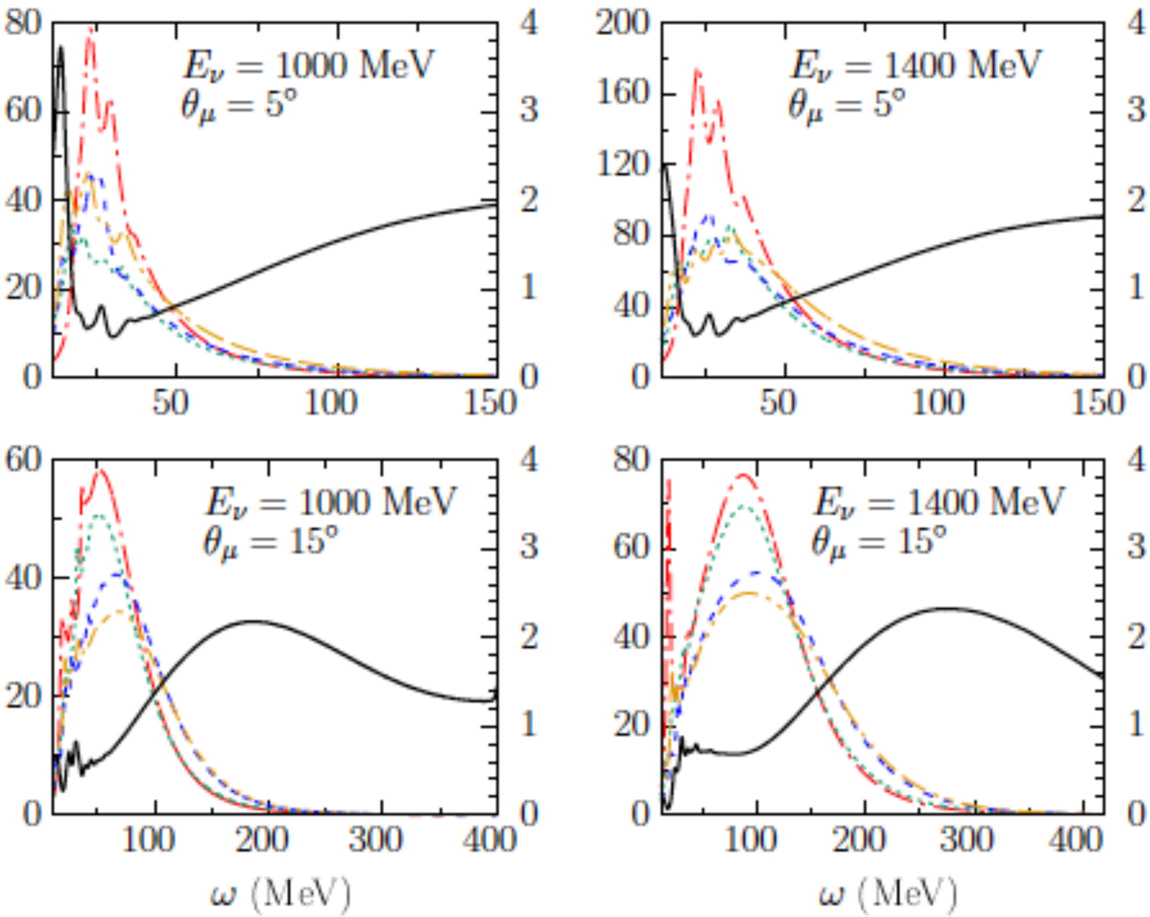
5. Target dependent results (new)

NuSTEC News
1 May 2017

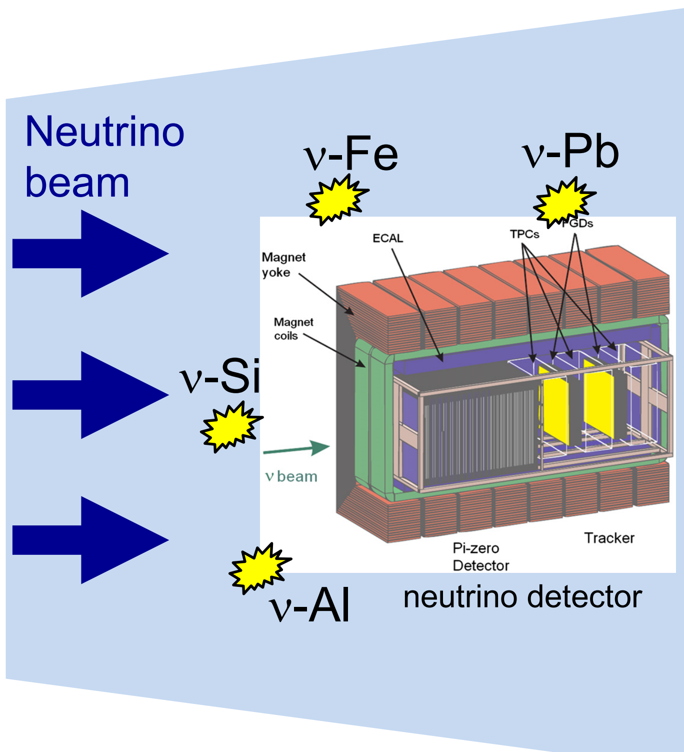
Target dependent RPA

- Argon=Heavy element (C≠Ar~Fe)
- O≠C in certain kinematics





Modern neutrino experiments need characterizations of all elements with all energy

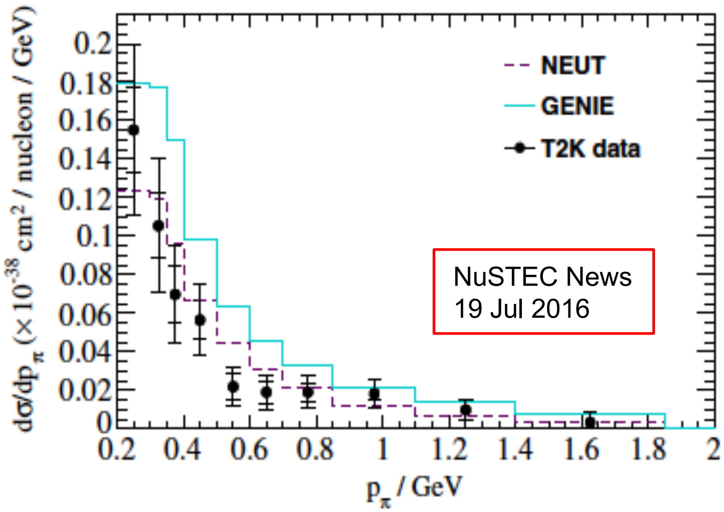


Coffee Break

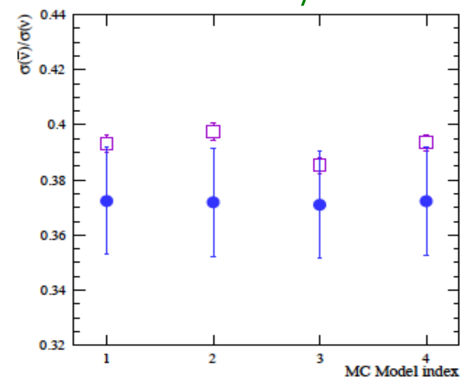
T2K,PRD91(2015)112010;95(2017)012010,arXiv:1704.07467,1706.04257

Honorable mention: T2K water target results (new)

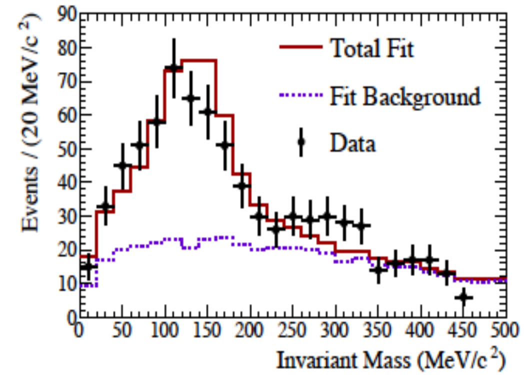
CC1π^+ production differential cross section



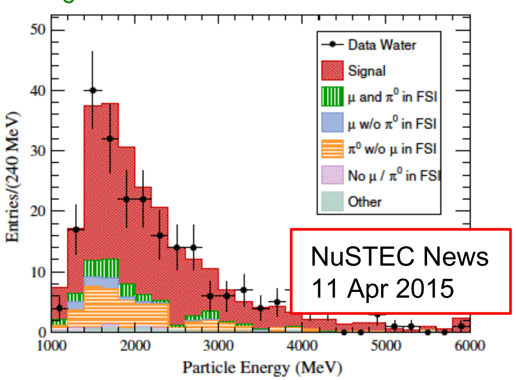
CC inclusive $\bar{\nu}/\nu$ ratio



NCπ^o production rate

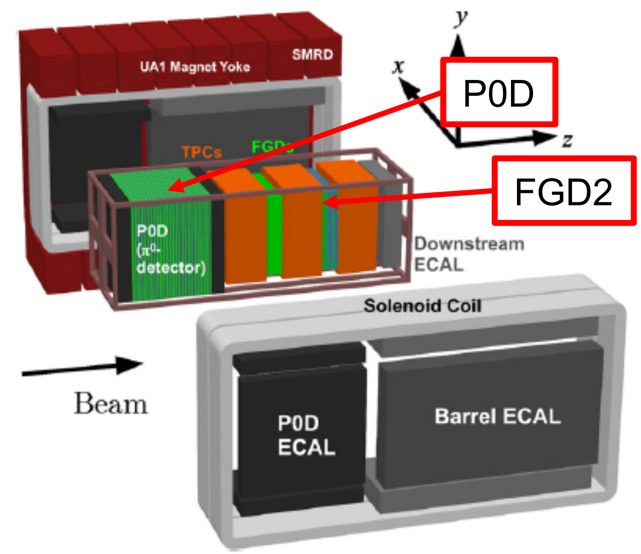


ν_eCC rate measurement



Problem: If the target material is inactive (=water layer), systematic errors are inflated during active material subtraction process

$$N_{\text{On-Water}} = N_{\text{WI}} - \frac{\epsilon_{\text{NW}}\text{POT}_{\text{WI}}}{\epsilon_{\text{WO}}\text{POT}_{\text{WO}}} N_{\text{WO}}$$



Watch “Higgs-tan” on T2K
https://www.youtube.com/watch?v=kQkS5jnr63g

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7. Conclusion

6. Open question of neutrino interaction physics (2012)

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

NCgamma
- Can NCgamma explain MiniBooNE ν_e-candidate excess?

Coherent pion
- Is there charged current coherent pion production?

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

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

Baryon resonance, pion production by neutrinos

6. Open question of neutrino interaction physics (new)

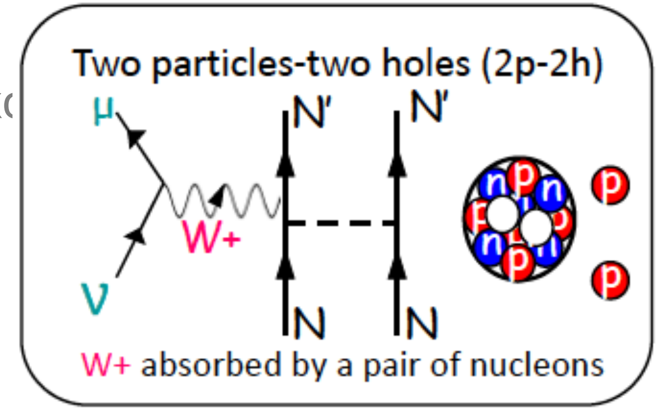
CCQE puzzle

- Low Q2 suppression, high Q2 enhancement, high normalization

→ presence of short and long range nucleon correlations

NCgamma

- Can NCgamma explain MiniBooNE ν_e-candidate exc



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- Normalization difference between ANL and BNL bubble chamber pion data

Pion puzzle

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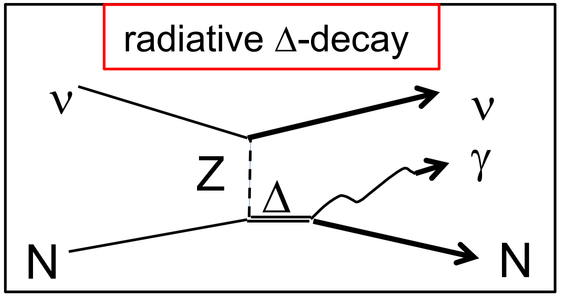
6. Open question of neutrino interaction physics (new)

CCQE puzzle
- Low Q2 suppression, high Q2 enhancement, high normalization
→ presence of short and long range nucleon correlations

NCgamma
- Can NCgamma explain MiniBooNE ν_e-candidate excess?
→ probably not, but no measurement, yet



Coherent pion
- Is there charged current coherent pion production?

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

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

K2K,PRL95(2005)252301, SciBooNE, PRD78(2008)112004

6. Open question of neutrino interaction physics (2008)

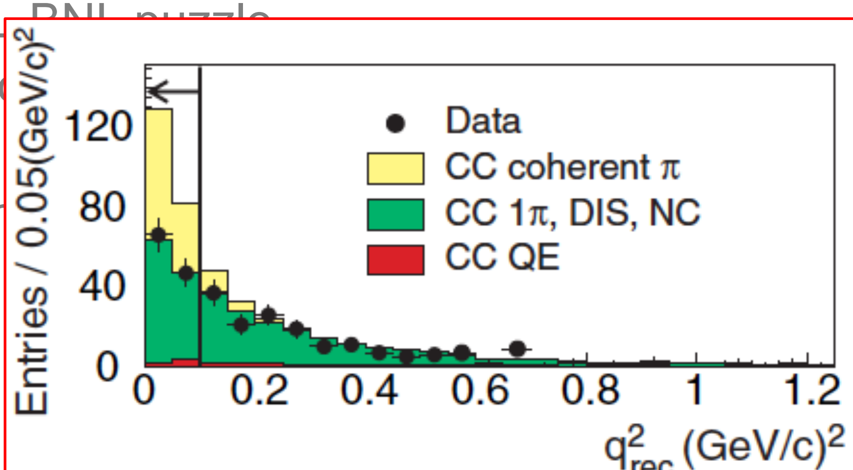
CCQE puzzle
- Low Q2 suppression, high Q2 enhancement, high normalization
→ presence of short and long range nucleon correlations

NCgamma
- Can NCgamma explain MiniBooNE ν_e-candidate excess?
→ probably not, but no measurement, yet

Coherent pion
- Is there charged current coherent pion production?

ANL ... puzzle
- N... BNL bubble chamber pion data

Pion...
- M... data are incompatible under any models



K2K,PRL95(2005)252301, SciBooNE, PRD78(2008)112004
ArgoNeuT,PRL114(2015)039901,MINERvA,PRL113(2014)261802,T2K,PRL117(2016)192501,MINOS,PRD94(2016)072006

6. Open question of neutrino interaction physics (new)

CCQE puzzle
- Low Q2 suppression, high Q2 enhancement, high normalization
→ presence of short and long range nucleon correlations

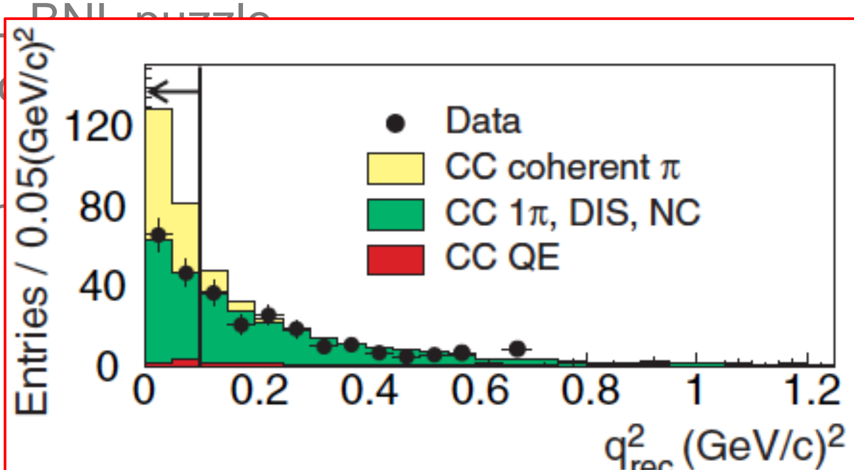
NCgamma
- Can NCgamma explain MiniBooNE ν_e-candidate excess?
→ probably not, but no measurement, yet

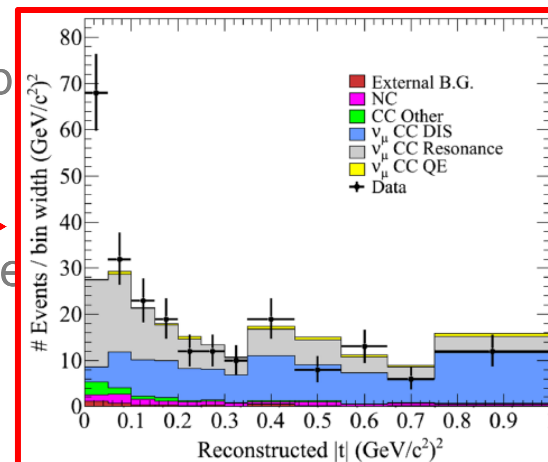
Coherent pion
- Is there charged current coherent pion production?
→ yes, data from T2K, MINERvA, ArgoNeuT, MINOS

NuSTEC News
24 May 2016

ANL-BNL puzzle
- N... BNL b...

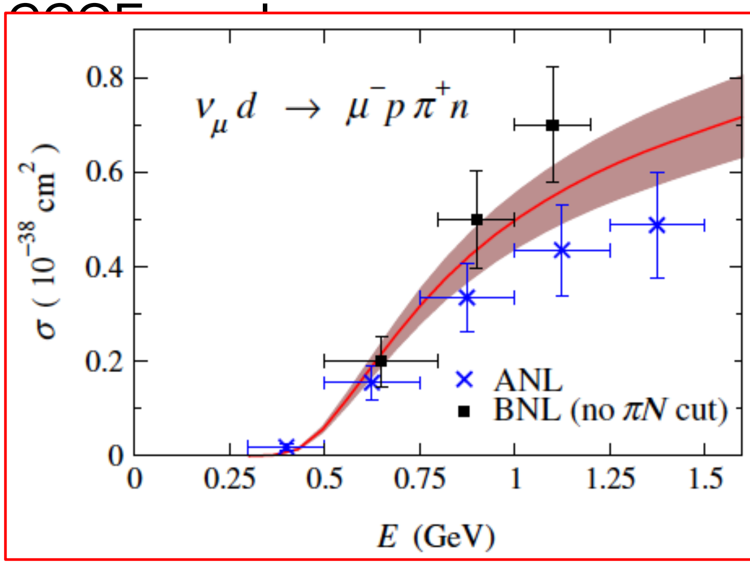
Pion...
- M... data are ... models





Hernandez et al.,PRD87(2013)113009

6. Open question of neutrino interaction physics (2013)



…hancement, high normalization

…e nucleon correlations

…E ν_e-candidate excess?

…ent, yet

… pion production?

…ArgoNeuT, MINOS

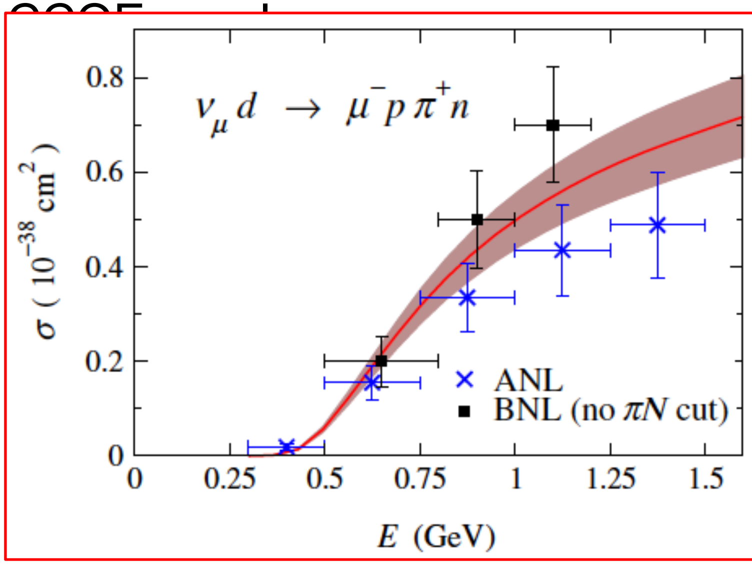
ANL-BNL puzzle

- Normalization difference between ANL and BNL bubble chamber pion data

Pion puzzle

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

6. Open question of neutrino interaction physics (new)



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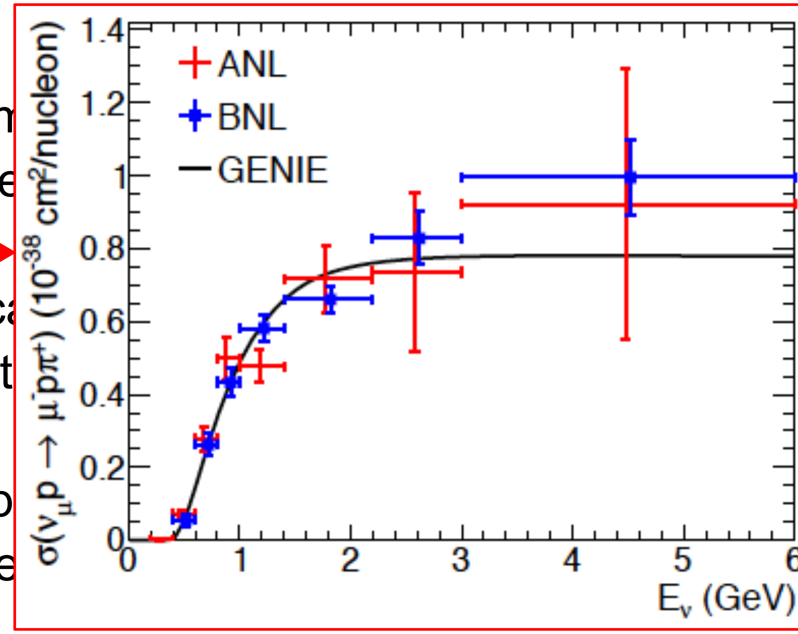

ANL-BNL puzzle

- Normalization difference between ANL and BNL bubble chamber pion data

→ BNL data was wrong, but both might have wrong deuteron correction

Pion puzzle

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

6. Open question of neutrino interaction physics (2014)

CCQE puzzle

- Low Q2 suppression, high Q2 enhancement

→ presence of short and long range nucleon

NCgamma

- Can NCgamma explain MiniBooNE ν_e-candi

→ probably not, but no measurement, yet

Coherent pion

- Is there charged current coherent pion produ

→ yes, data from T2K, MINERvA, ArgoNeuT,

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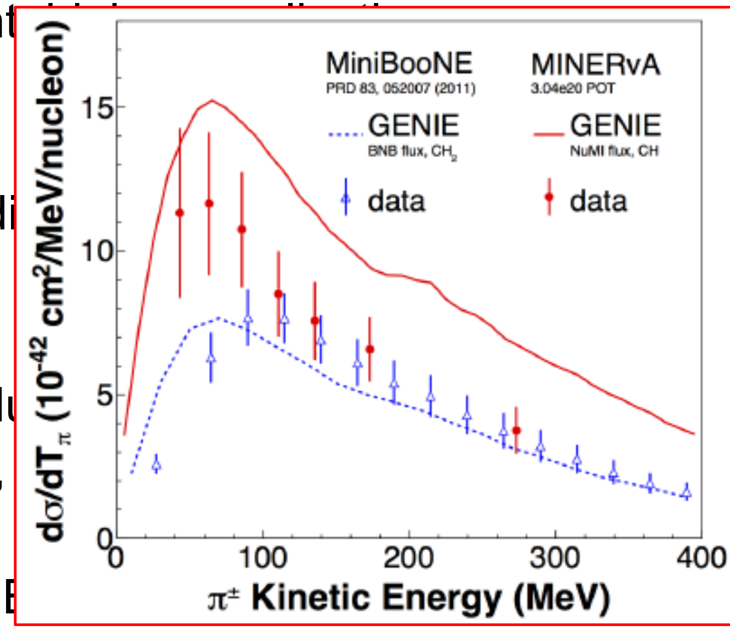

6. Open question of neutrino interaction physics (new)

CCQE puzzle
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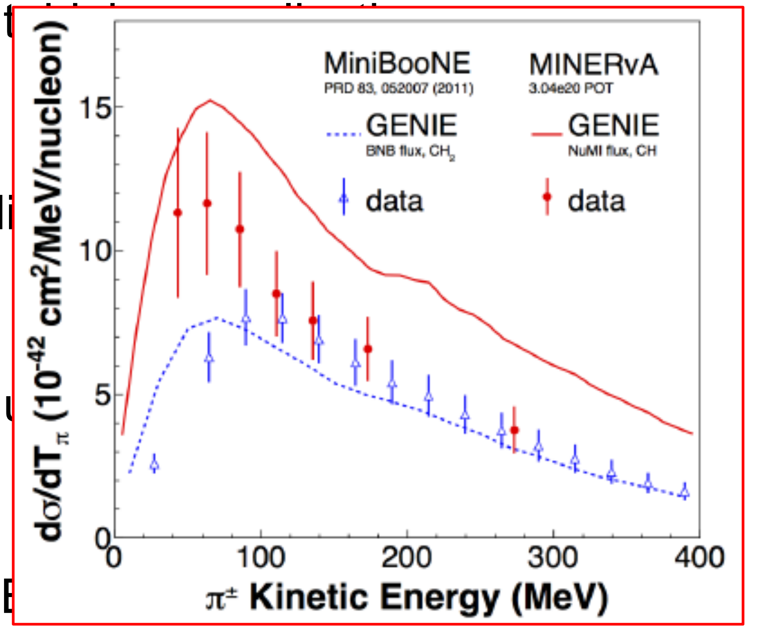


Pion puzzle
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models
→ ???

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

6. Pion puzzle (new)

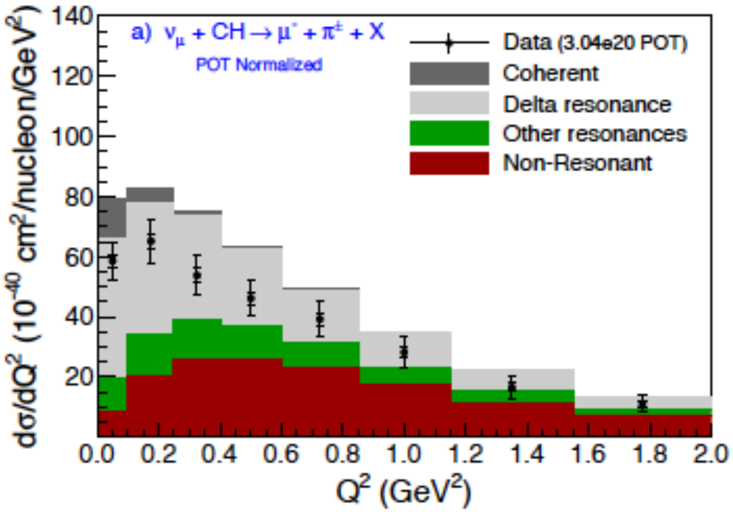
The problem is a combination of SPP, SIS, DIS, FSI, pion scattering in the detector, data analysis, etc

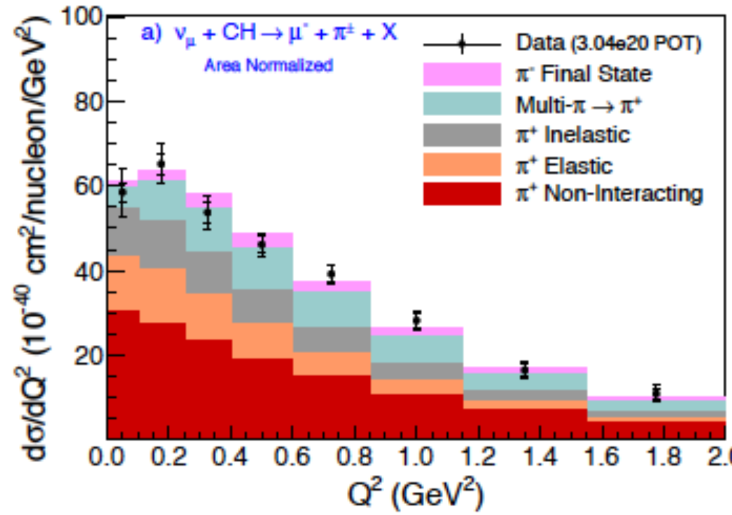
MINERvA $\nu_\mu CC1\pi^+$ vs. $\overline{\nu_\mu} CC1\pi^o$

- this moment, there is no clear way to tune MC… (tune non-resonant background?)

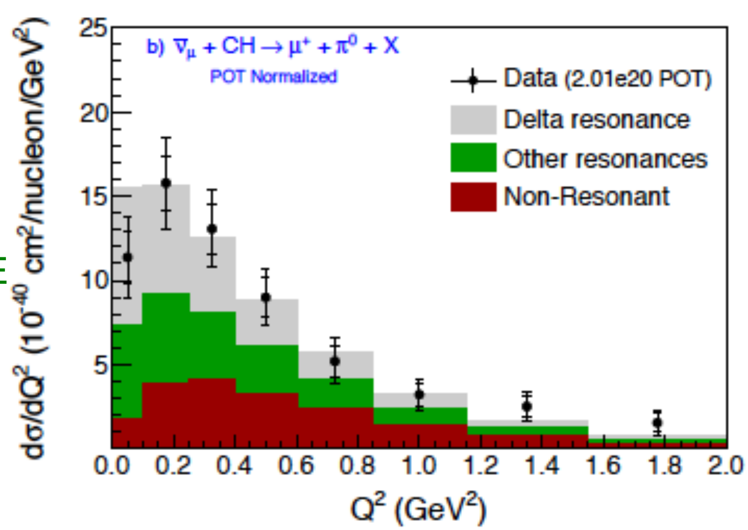
NuSTEC News
16 Aug 2016

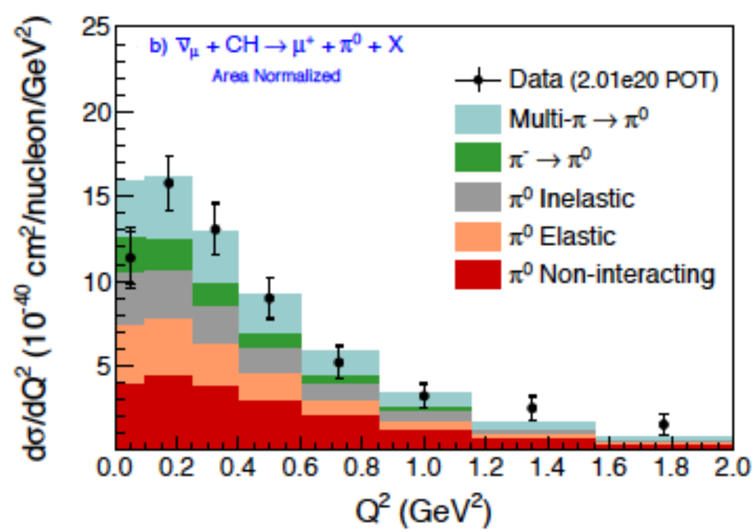
$\nu_\mu CC1\pi^+$ data has better shape agreement with GENIE





anti-$\nu_\mu CC1\pi^o$ data has better normalization agreement with GENIE





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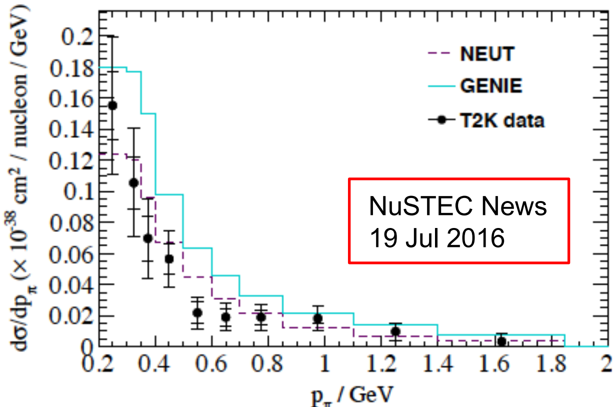
T2K, PRD95(2017)012010,arXiv:1704.07467,ArgoNeuT,arXiv:1511.00941,MINOS,PRD94(2016)072006
DUET,PRC92(2015)035205;95(2017)045203

6. Pion puzzle (new)

T2K pion data from water target

- Large error for inactive target



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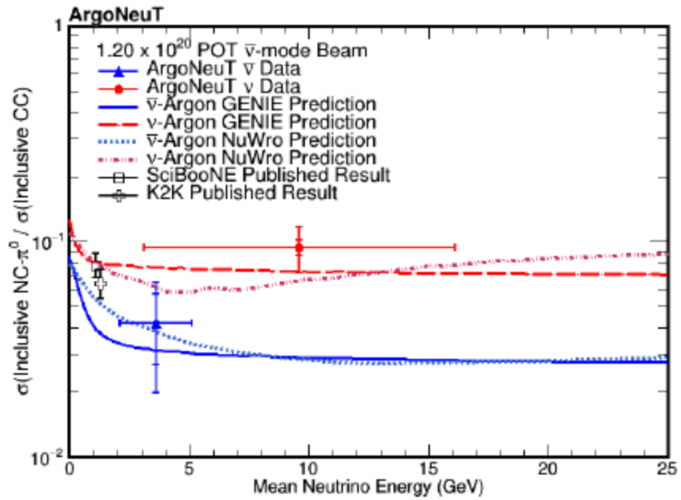
19 Jul 2016

ArgoNeuT $\nu_\mu(\overline{\nu_\mu})NC\pi^o$ on argon

NuSTEC News
Nov. 13 2015

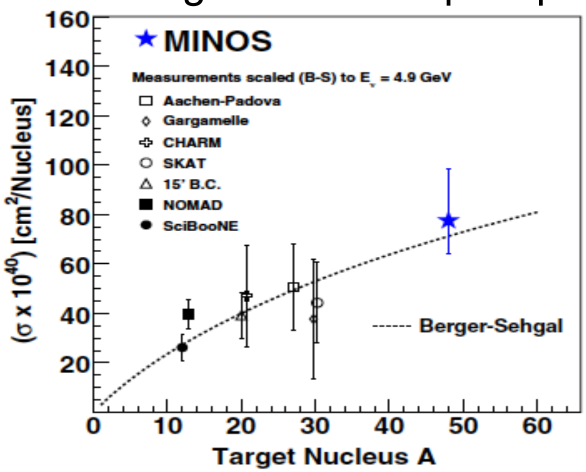
- π^o reconstruction from γ opening angle



MINOS ν_μNCπ^o on iron

NuSTEC News
14 Oct 2016

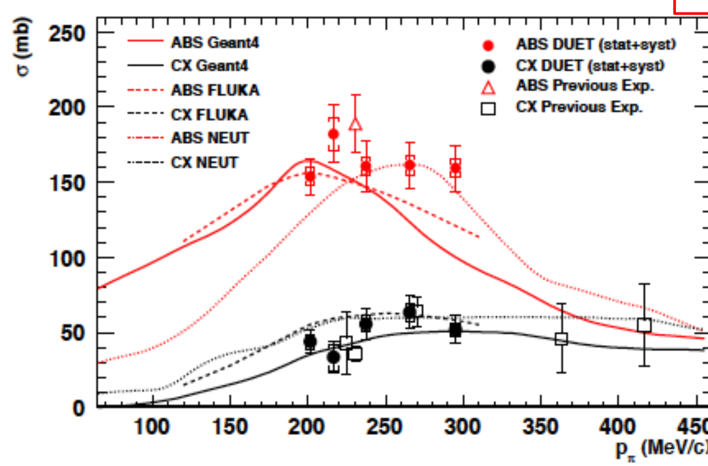
- A-scaling of coherent pion production



DUET FSI study for π^+ in carbon

- σ_{ABS} and σ_{CEX} are measured

NuSTEC News
26 Aug 2015



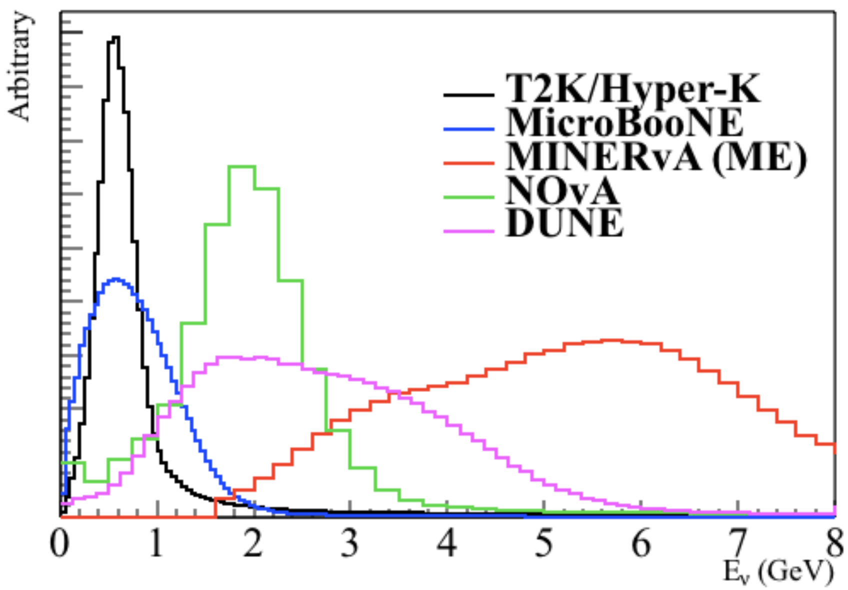
6. SIS, Multi-pion production and beyond (2015)

Shallow Inelastic Scattering

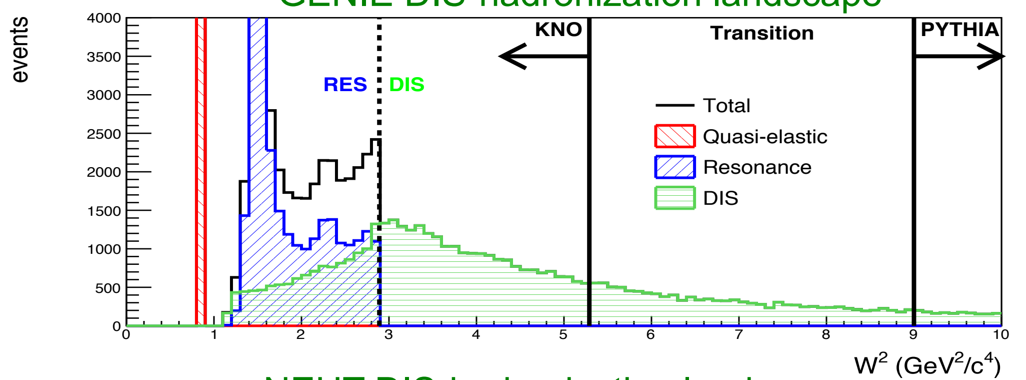
- Extremely difficult to connect both cross section and hadron multiplicity smoothly

Current and future beams

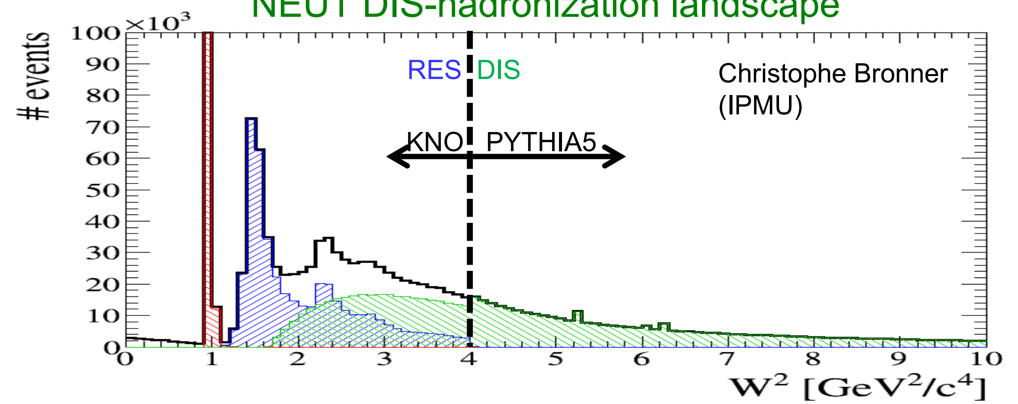
- DUNE, QE:RES:DIS~1:1:1



GENIE DIS-hadronization landscape



NEUT DIS-hadronization landscape



6. SIS, Multi-pion production and beyond (new)

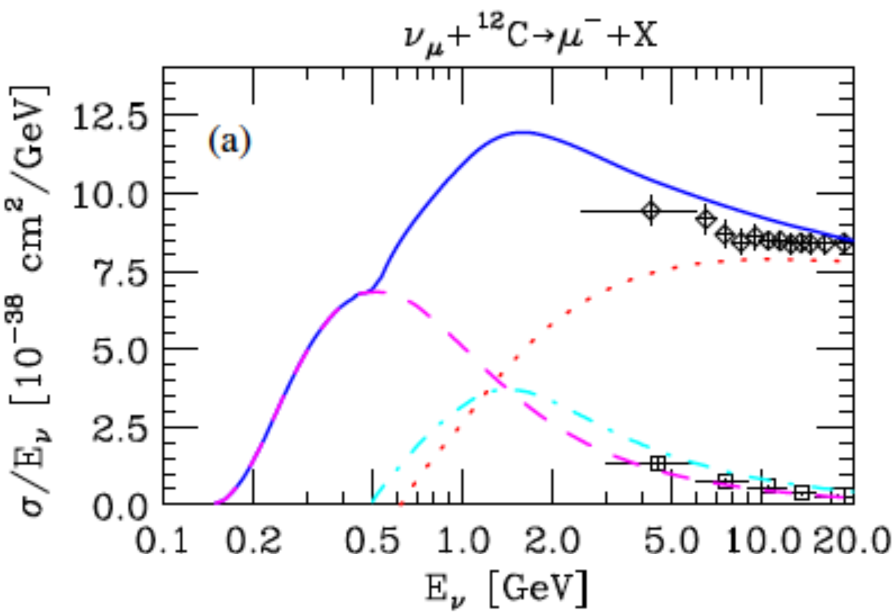
Shallow Inelastic Scattering

- Extremely difficult to connect both cross section and hadron multiplicity smoothly

Spectral function for DIS

NuSTEC News
20 Jan 2017

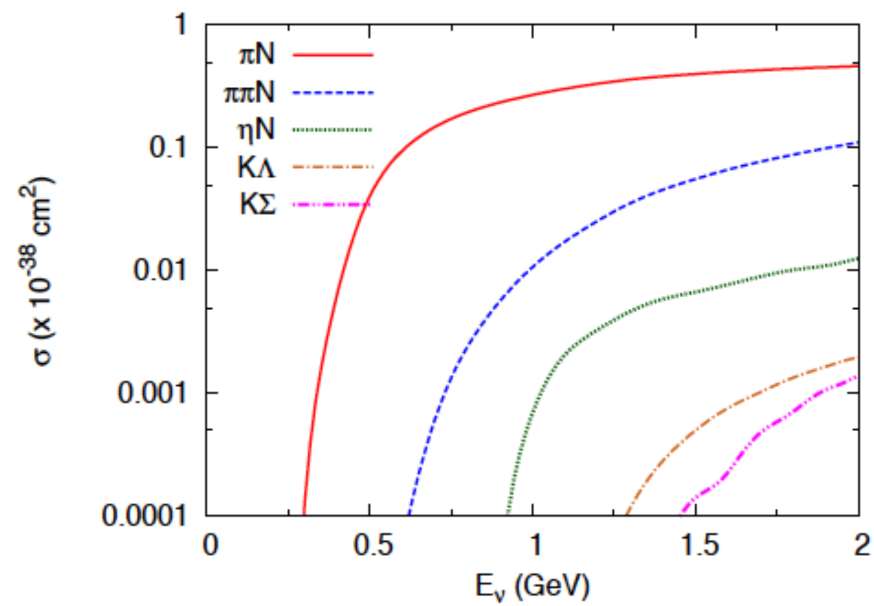
- Consistent model for wide energy range
- Impulse approximation based



DCC model

NuSTEC News
31 Jul 2015

- all channels are coupled
- 2 pion production



→ Can we use these models in experiments?

1. Introduction

2. CCQE, CCQE-like, and CC0π data

3. CC data with nucleon final state

4. Electron neutrino CC data

5. A-dependence of neutrino cross section

6. Pion puzzle

7. Conclusion

7. Conclusion

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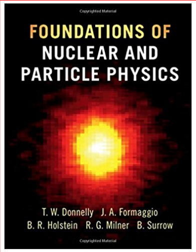
There are many major developments

Lepton kinematics study is not completed. We need a precise quantitative data-theory comparison. For this we need; covariance matrix for all data set, validity of covariance matrices, theoretical systematic errors, better global fit machinery, etc.

Many new data are targeting to identify 2p2h signature from nucleon kinematics. For this, we need; understand nucleon detection efficiencies, simulation of nucleon propagation within detector (GEANT), predictions of initial nucleon distribution and nucleon propagation within nuclear media, and how to use these theories in event generators.

It looks "pion puzzle" is still an outstanding open question. On top of the better understanding of detector efficiency, we need to improve resonance, DIS, SIS, hadronization, FSI, and hadron propagation models.

Do you think you don't know much about neutrino-nucleus scattering physics? Read this.



"Foundation of Nuclear and Particle Physics" (Cambridge university press, 2017)
- Bill Donnelly (MIT)
- Joe Formaggio (MIT)
- Barry Holstein (U. Mass)
- Richard Milner (MIT)
- Bernd Surrow (Temple)

Thank you Kevin McFarland for careful comments to prepare this talk

7. Conclusion

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Lattice QCD

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

NuSTEC-News

Nucleon correlation

EMC effect

electron scattering

Dark matter

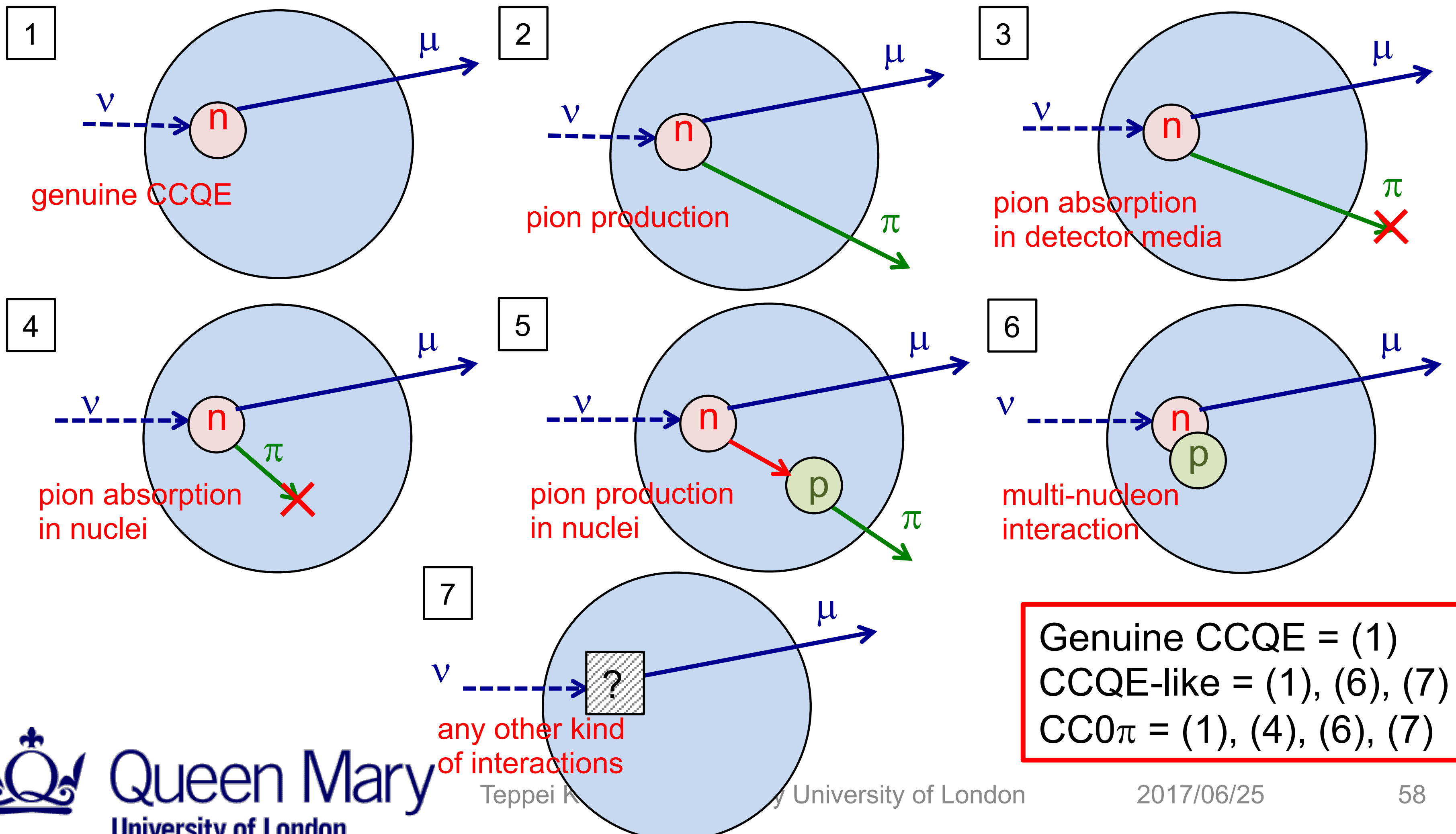
Thank you for your attention!

Backup

2. CC0π data

Final state particle topology dependent definition is widely used.

CC0π data → 1 muon + 0 pion + N nucleon



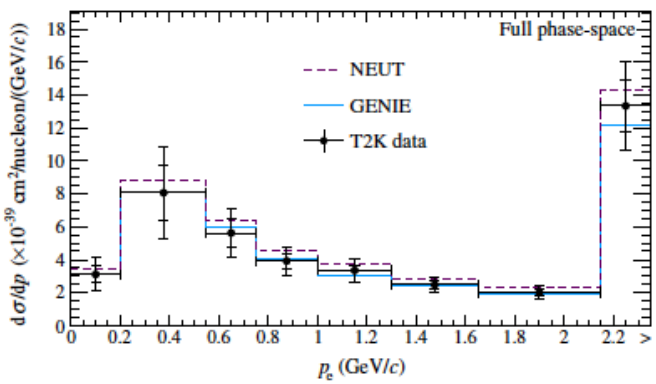
Genuine CCQE = (1)
CCQE-like = (1), (6), (7)
CC0π = (1), (4), (6), (7)

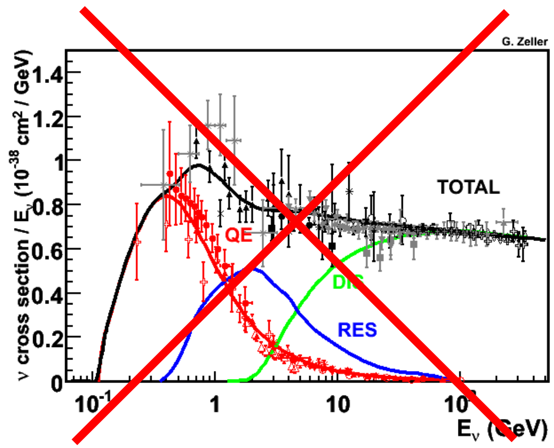
2. Flux-integrated differential cross-section

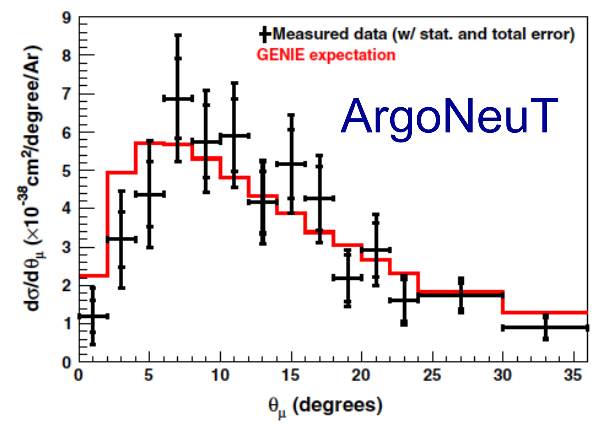
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

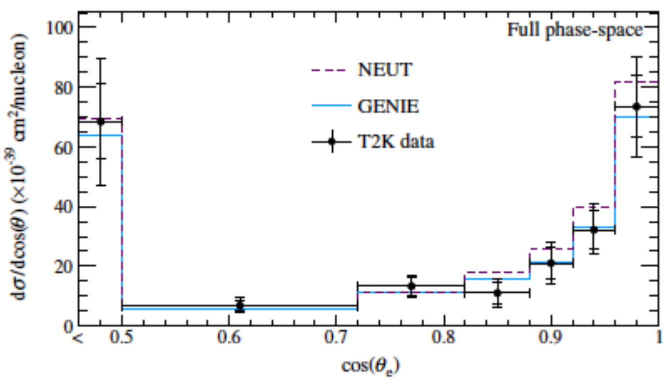
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

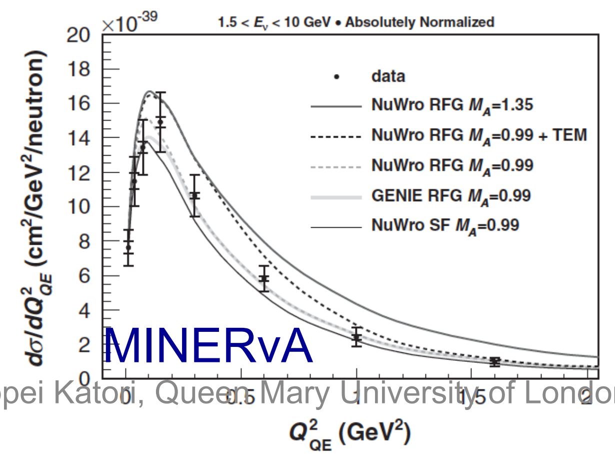
T2K



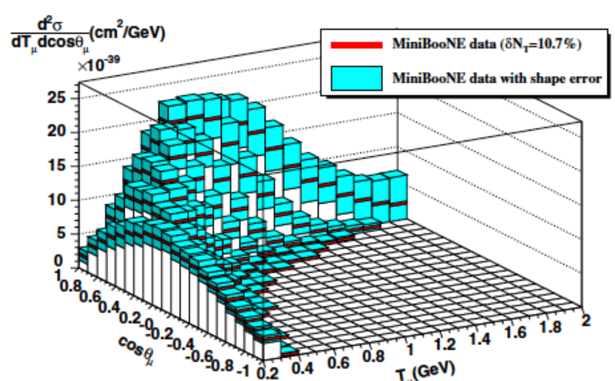








MiniBooNE



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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 to talk

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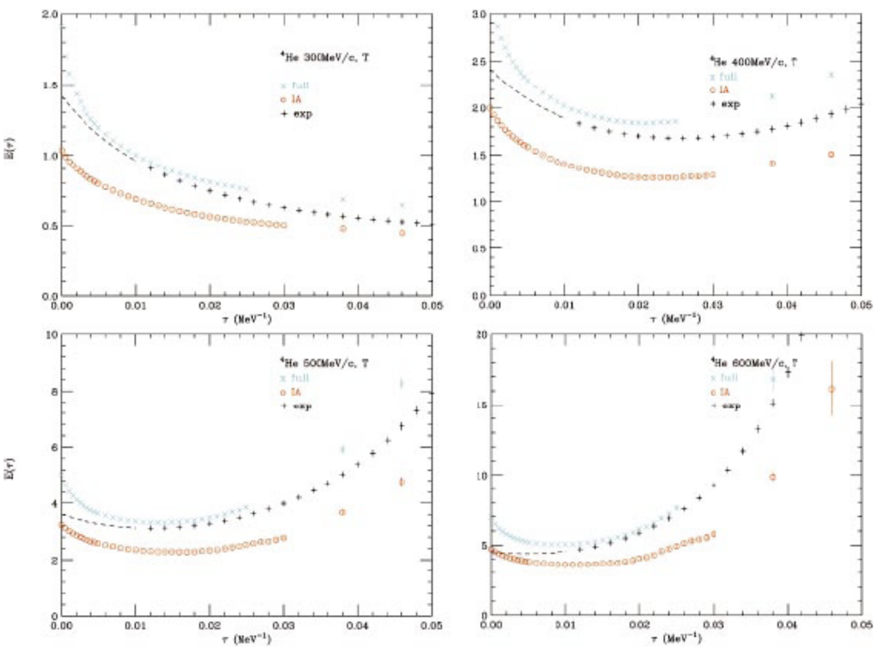
Flux-integrated differential cross-section data allow theorists and experimentalists to talk

Carlson et al., PRC65(2002)024002
Lovato et al.,PRL112(2014)182502

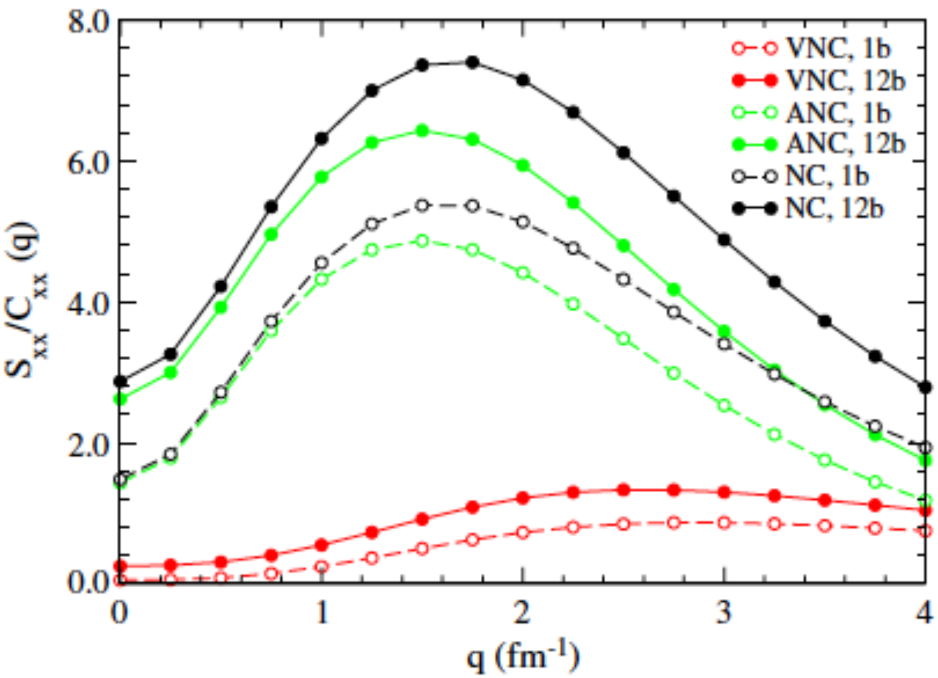
2. Ab initio calculation (2014)

Ab initio calculation support the general idea of transverse response enhancement for neutrino scatterings.

^{4}He Euclidian transverse response



Transverse sum rule for NC interaction

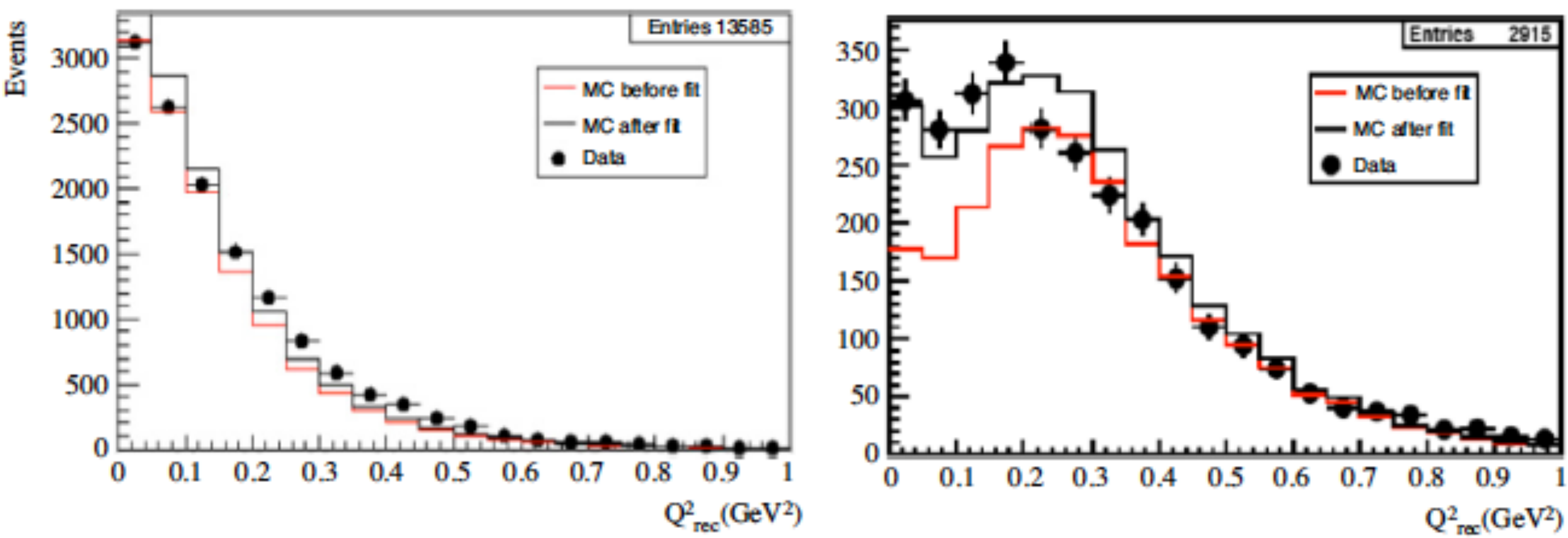


K2K,PRD74(2006)052002 (2006), NOMAD,EPJC63(2009)355
SciBooNE,arXiv:0909.5647

3. CC data with nucleon final state (2009)

Tensions between 1 track (μ) and 2 track (μ+p) are known, but experimentalists tried to understand that within their simulations.

SciBooNE 1 and 2 track Q^2 distribution

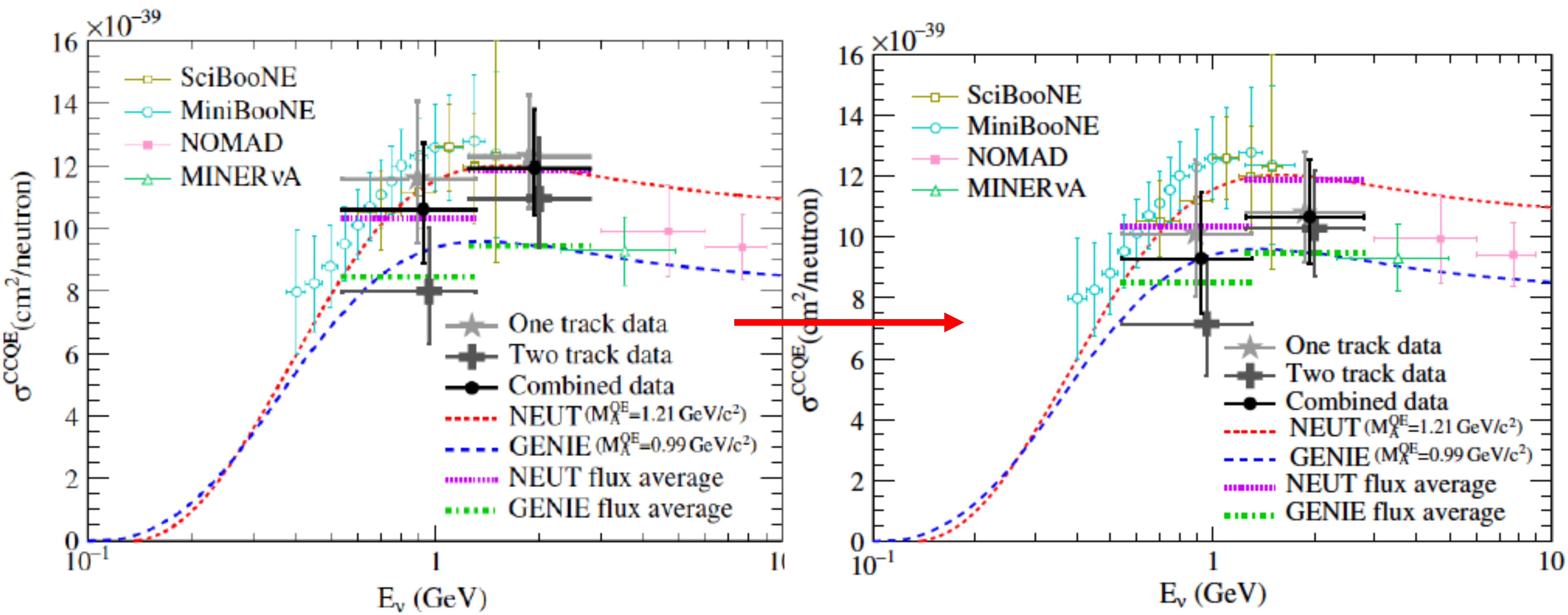


3. 1&2 track genuine CCQE total cross section, T2K (2015)

T2K measured CCQE total cross section from 1 track (μ) and 2 track (μ+p) sample separately (model-dependent). 1 track cross sections are consistently higher than 2 track cross section.

→ 2p2h contribution is contaminated in 1 track.

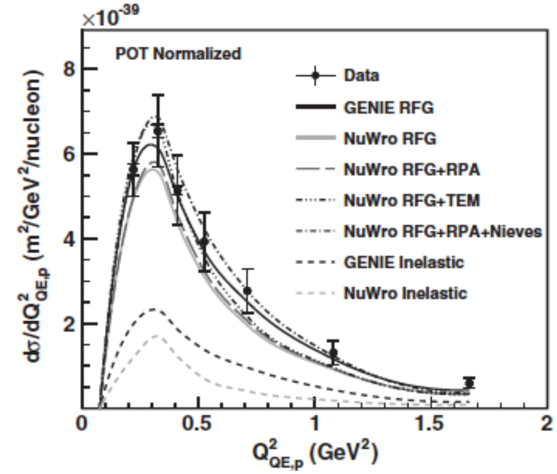
Unfortunately, after including 2p2h in analysis (=2p2h contribution becomes background and removed) 1 trach cross section is still higher than 2 track cross section.



3. CC0πNp data, MINERvA (2015)

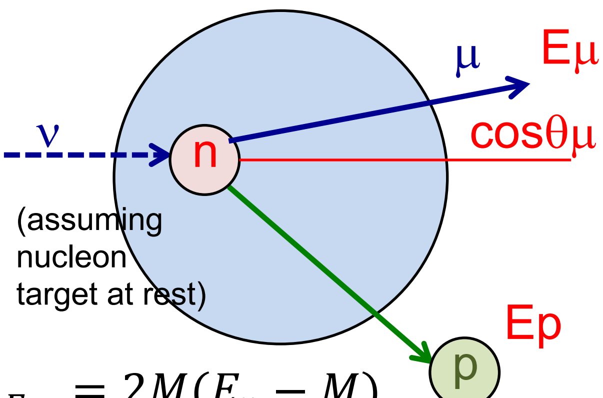
MINERvA measured μ+p sample differential cross section, more precisely "final state include a muon, at least one proton, and no pions". Q^2 is reconstructed from muon kinematics and proton kinematics, and they agree.

1. normalization agrees with old flux.
2. background subtraction is complicated.

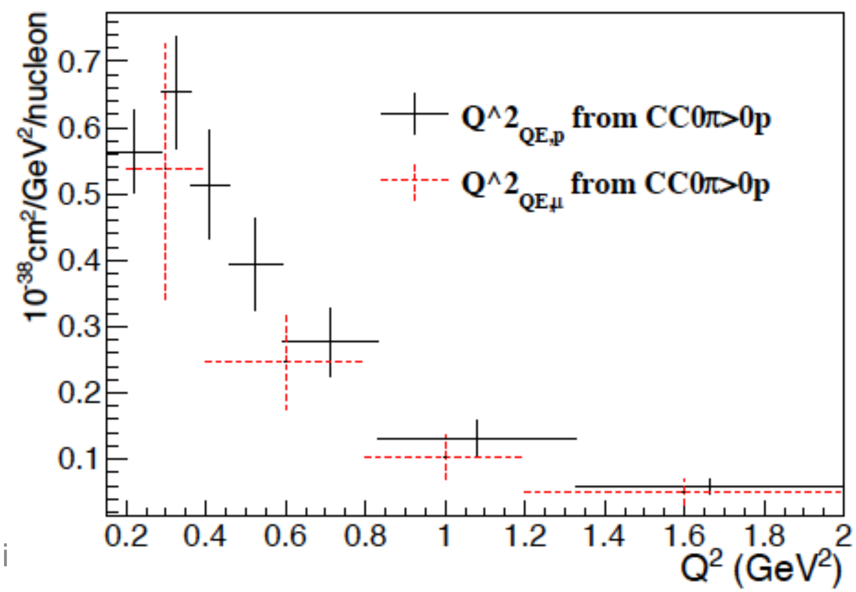


$$E^{\nu}_{QE,\mu} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

$$Q^2_{QE,\mu} = -m_\mu^2 + 2E^{\nu}_{QE,\mu}(E_\mu - \sqrt{E_\mu^2 - m_\mu^2} cos\theta_\mu)$$



$$Q^2_{QE,p} = 2M(E_p - M)$$



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AGKY, EPJC63(2009)1,TK and Mandalia,JPhysG42(2015)115004,arXiv:1602.00083

6. Shallow Inelastic Scattering (SIS)

Cross section

W^2<2.9 GeV^2 : RES

W^2>2.9 GeV^2 : DIS

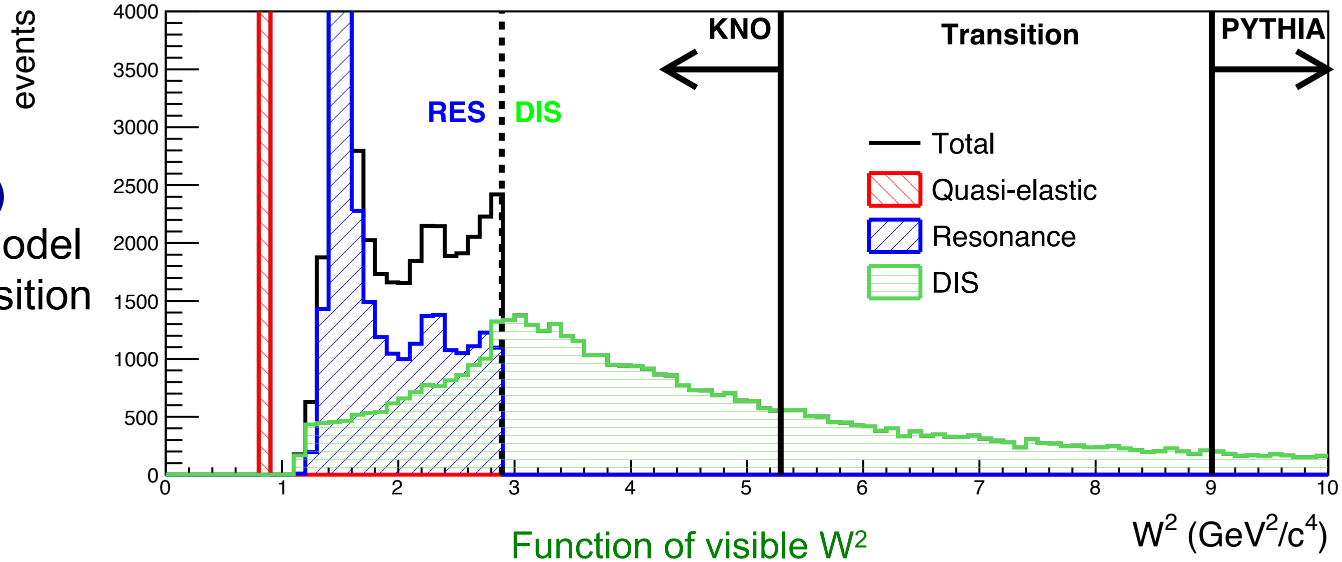
Hadronization (AGKY model)

W^2<5.3GeV^2 : KNO based model

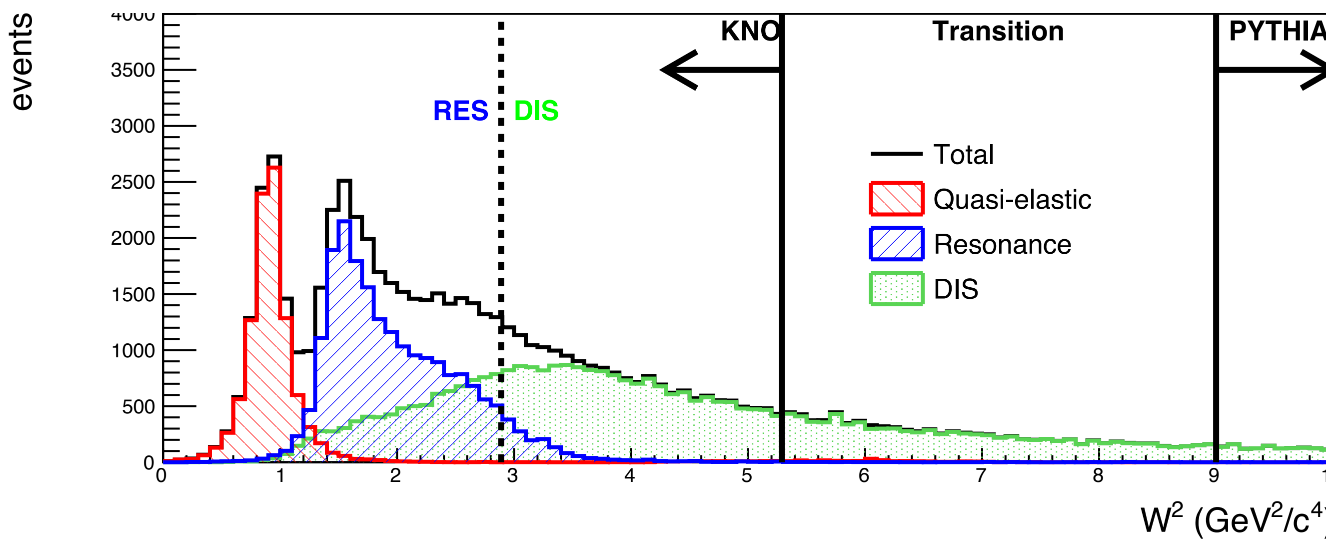
2.3GeV^2<W^2<9.0GeV^2 : transition

9.0GeV^2<W^2 : PYTHIA6

Function of true W^2



Function of visible W^2



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