BREAKTHROUGH PRIZE

"Year of Neutrinos"

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

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

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The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

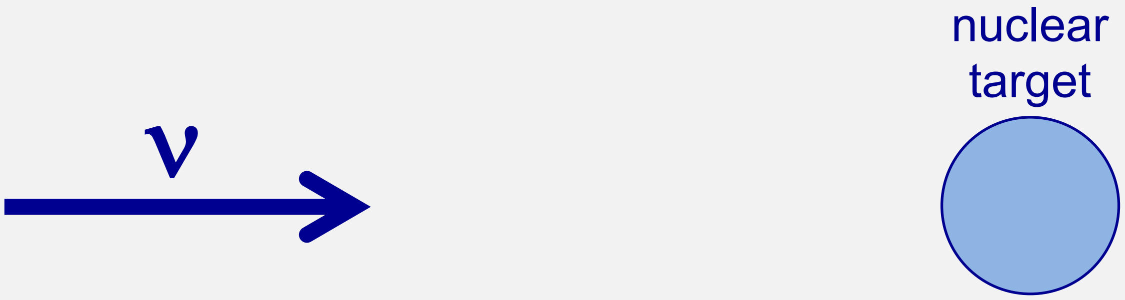
Prize share: 1/2

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

Arthur B. McDonald

Prize share: 1/2

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


nuclear
target
ν

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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TK, Martini, arXiv:1611.07770

Physics of Neutrino Interactions since INT2013

Teppei Katori
Queen Mary University of London
INT workshop, Univ. Washington, Seattle, WA, Dec. 8, 2016

outline

1. **Introduction**
2. **CCQE, CCQE-like, and CC0π data**
3. **CC data with nucleon final state**
4. **Electron neutrino CC data**
5. **Resonant single pion production**
6. **Conclusion**

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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. Resonant single pion production

6. Conclusion

1. Conclusion remarks from INT workshop 2013

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

Toward better neutrino interaction models…

To experimentalists

E.1 Better understanding of neutrino flux prediction
E.2 The data must be reproducible by nuclear theorists
E.3 State what is exactly measured (cf. CCQE → 1muon + 0 pion + N nucleons)

To theorists

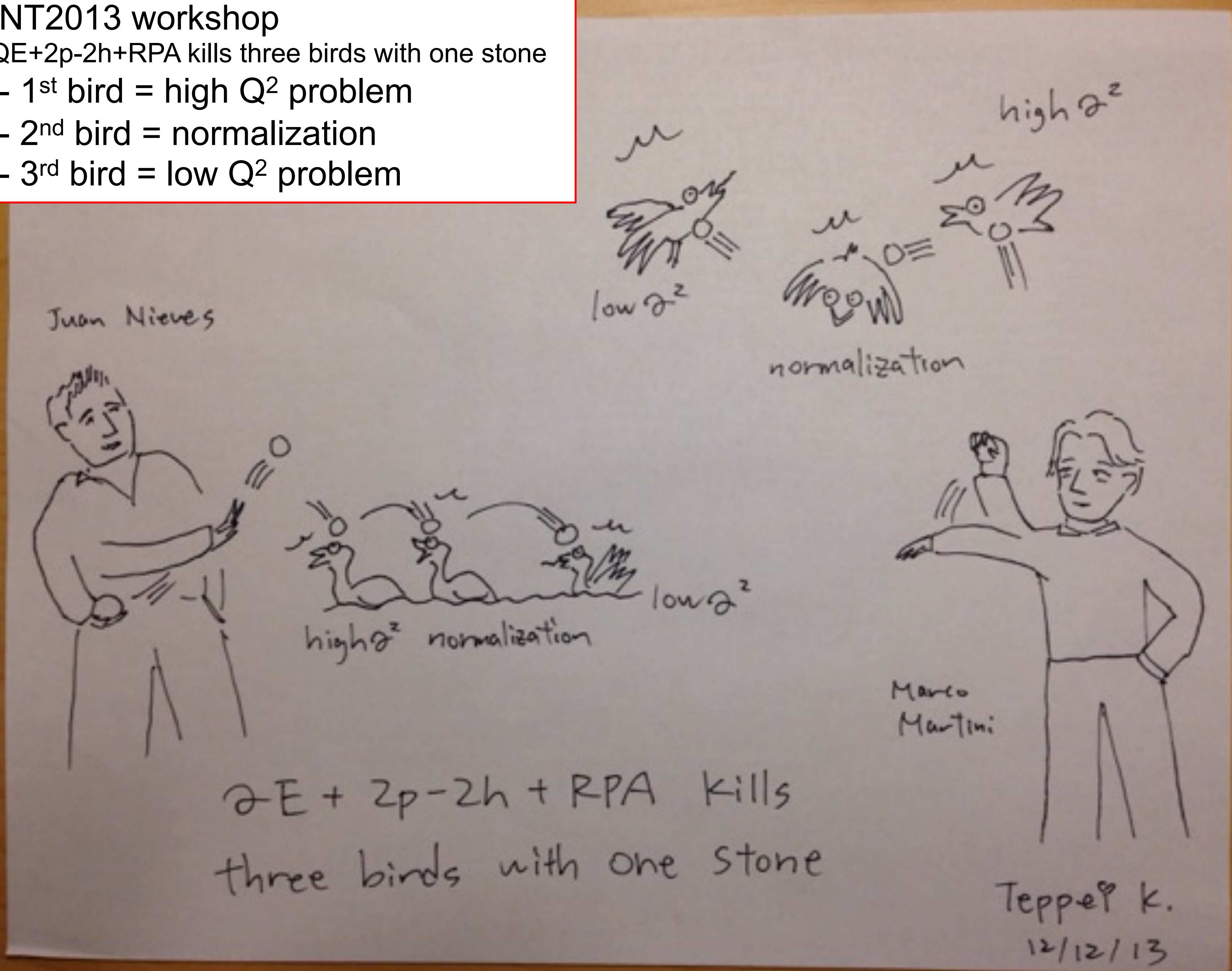
T.1 Understanding the structure of transverse response enhancement
T.2 Relativistic model which can be extended to higher energy neutrinos
T.3 Models should be able to use in neutrino interaction generator
T.4 Theorists should provide theoretical errors
T.5 Precise prediction of exclusive hadronic final state

We do have developments for all of above…

INT2013 workshop

QE+2p-2h+RPA kills three birds with one stone

- 1st bird = high Q^2 problem
- 2nd bird = normalization
- 3rd bird = low Q^2 problem



INT2013 workshop

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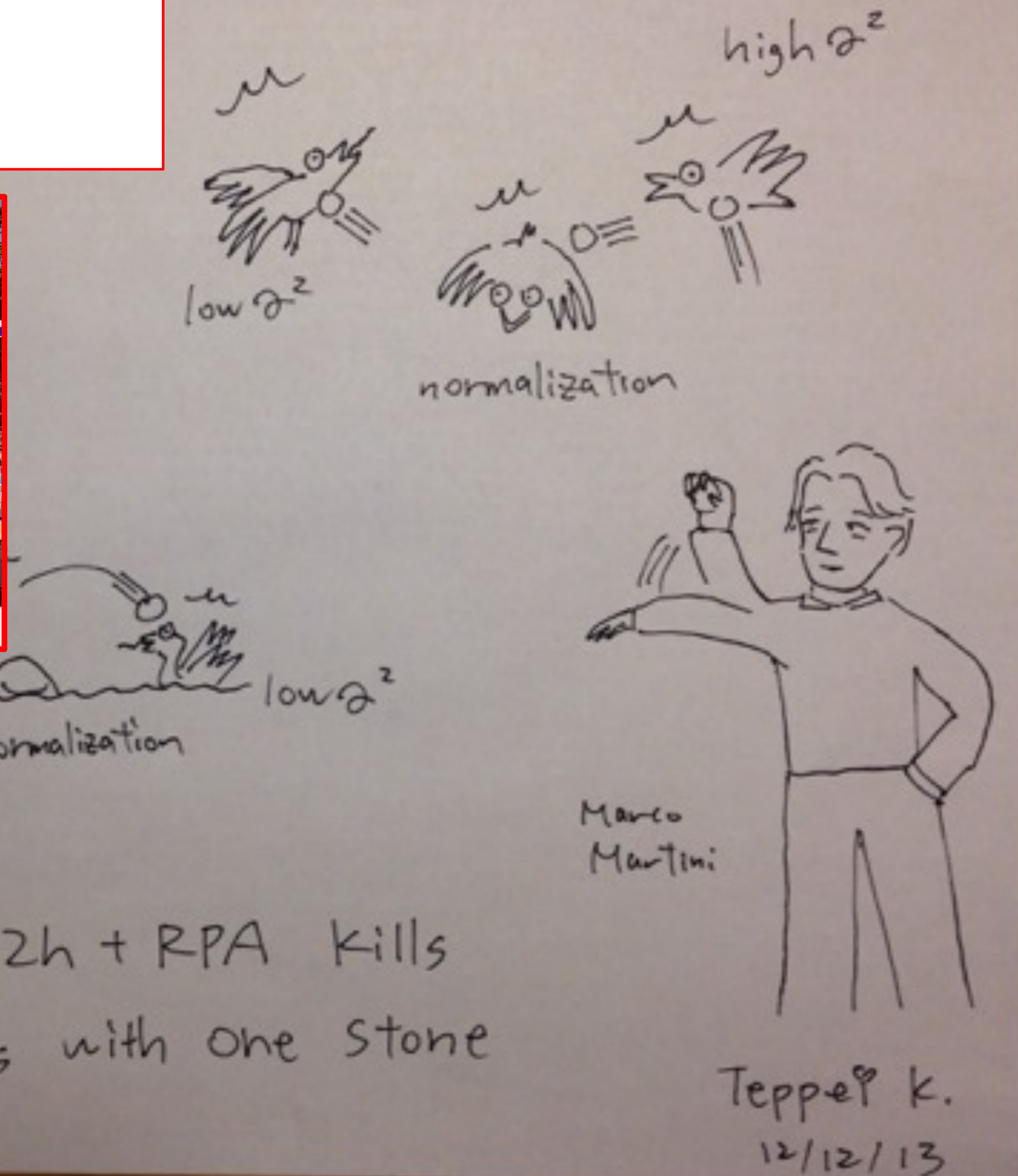
2014



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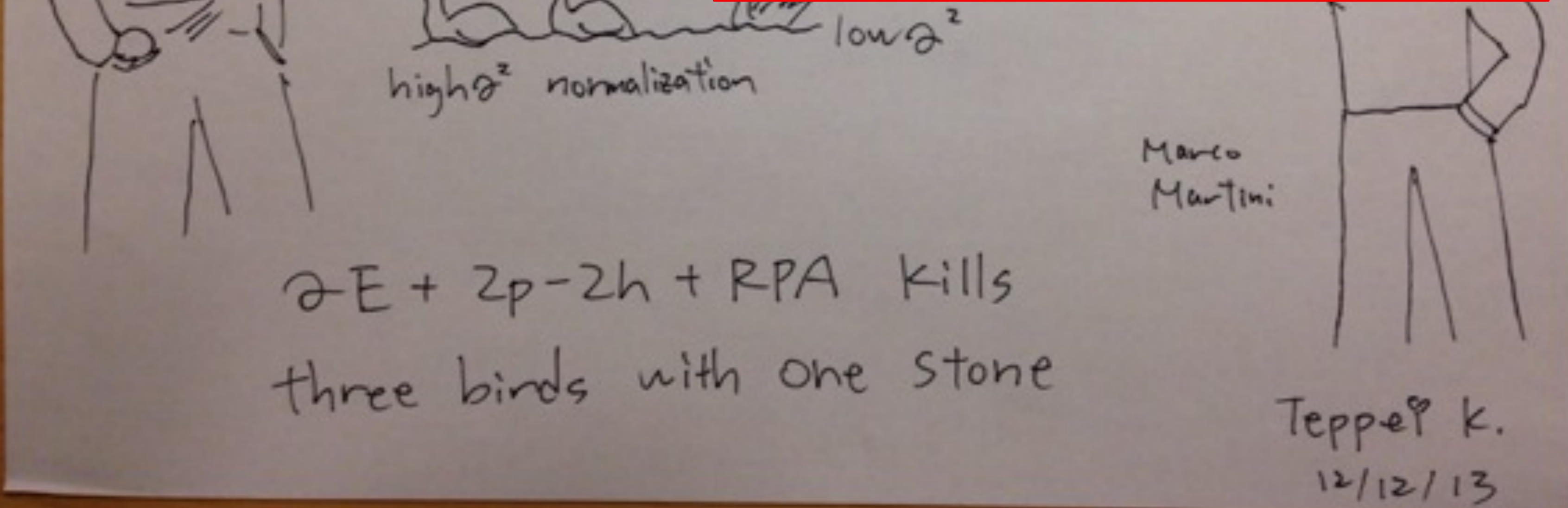

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2014


2015


Sep. 15, 2016


Oct. 4, 2016

∂E

three

stone

Teppei K.

12/12/13

INT2013 workshop

QE+2p-2h+RPA kills three birds with one stone

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2014

2015

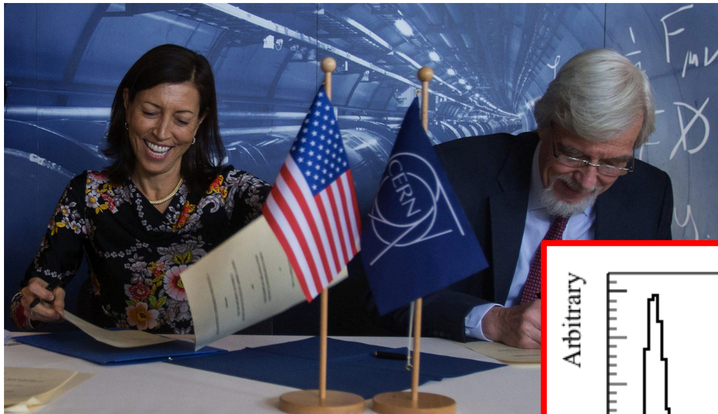
Oct. 4, 2016

Sep. 15, 2016

Feb. 29, 2016

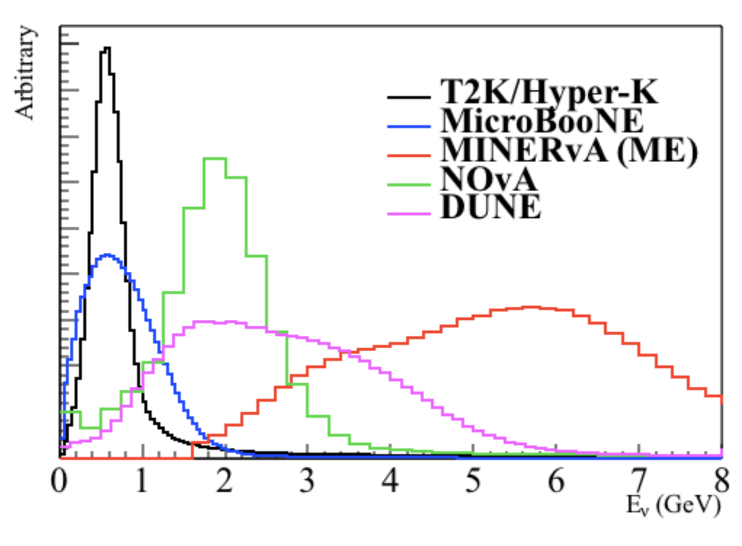
1. CERN-USA, KEK-ICRR…

Political pacts are made to strengthen large collaborations…



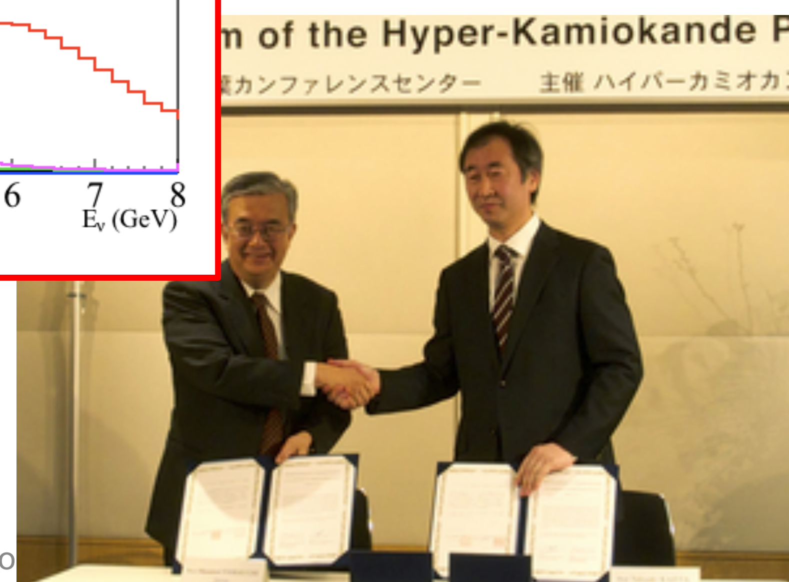
CERN - USA

DUNE (2025?)
LArTPC detector
argon target
wideband 1-4 GeV
(on-axis beam)



Hyper-Kamiokande (2026?)
Water Cherenkov detector
water target
narrowband 0.6 GeV
(off-axis beam)

KEK - ICRR



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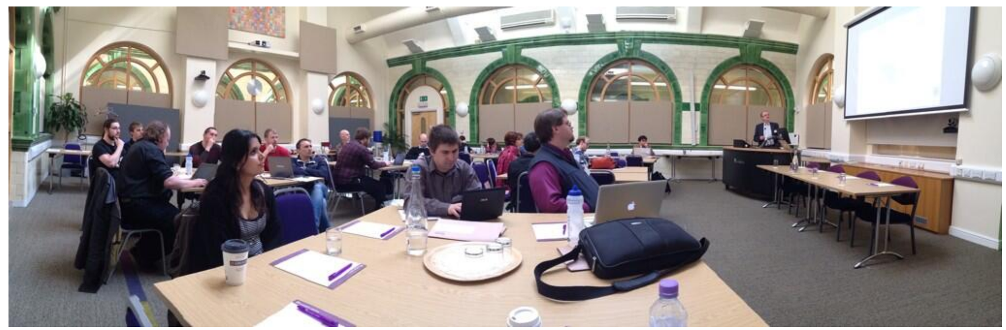
1. NuSTEC

NuSTEC: Neutrino Scattering Theory-Experiment Collaboration

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

NuSTEC school 2014, Fermilab



NuSTEC MC school, Liverpool (2014)

NuSTEC school 2015, Okayama

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1. Future of Particle Physics

CDF run II (2009)
- ~ 500 collaborators
- 59 papers/year

(~1 paper/week)

↓

CMS (2015)
- ~ 2000 collaborators
- 90 papers/year

(>>1 paper/weak)

T2K (2015)
- ~ 500 collaborators
- 11 papers/year

(<1 paper/month)

- 2 oscillation papers
- 6 cross section papers
- 2 phenomenology
- 1 detector/sensitivity

↓

DUNE (2025?)
- ~1000 collaborators
- ? papers/year

Particle physics look different in the future. Neutrino cross sections are one of very few ways to publish papers

1. Introduction

2. CCQE, CCQE-like, and CC0π data

3. CC data with nucleon final state

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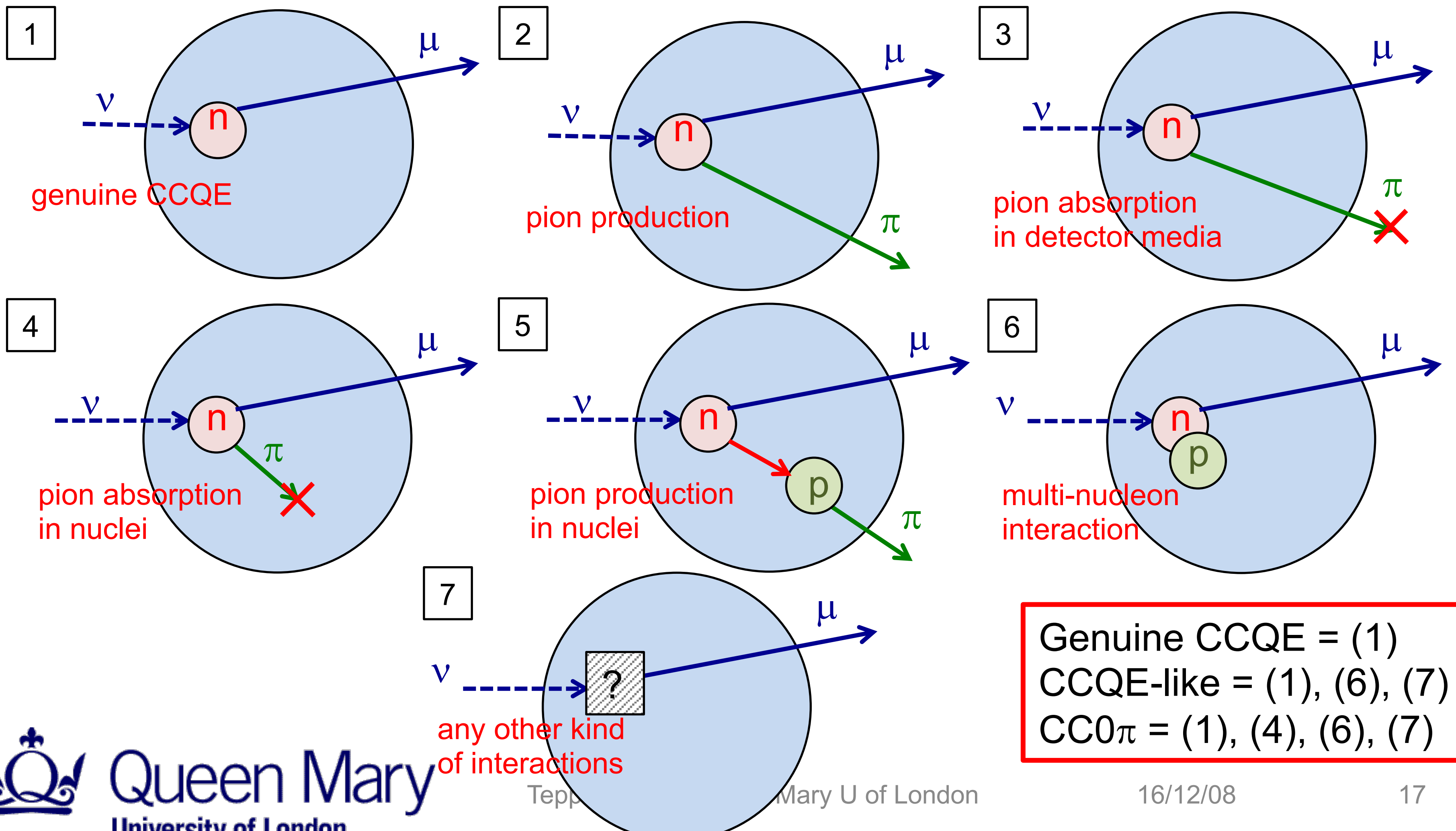
2. CC0π data

Final state particle topology dependent definition is widely used.

CC0π data → 1 muon + 0 pion + N nucleon



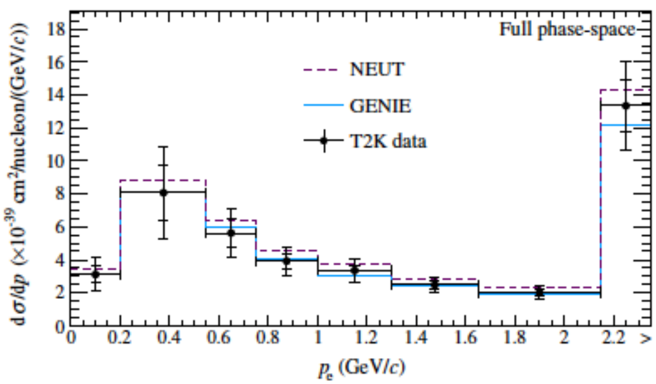
Genuine CCQE = (1)
CCQE-like = (1), (6), (7)
CC0π = (1), (4), (6), (7)

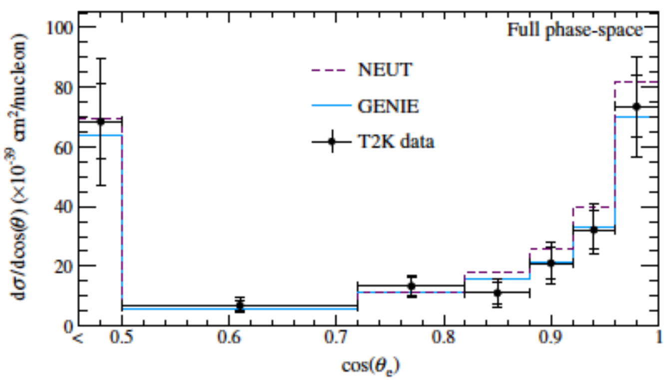
2. Flux-integrated differential cross-section

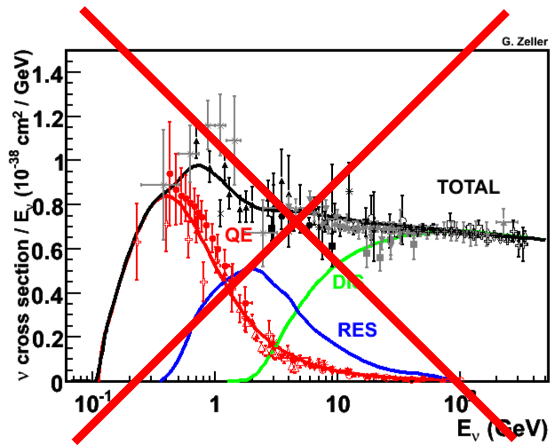
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

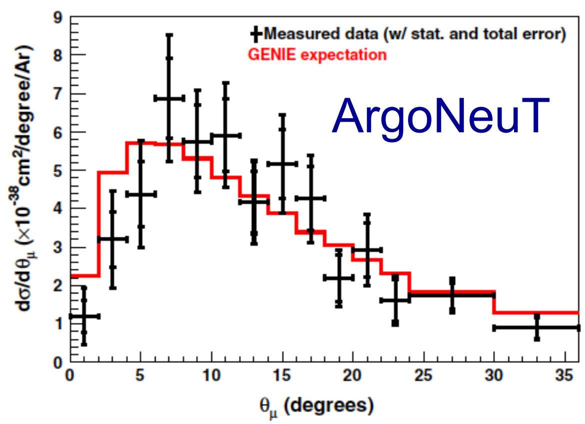
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

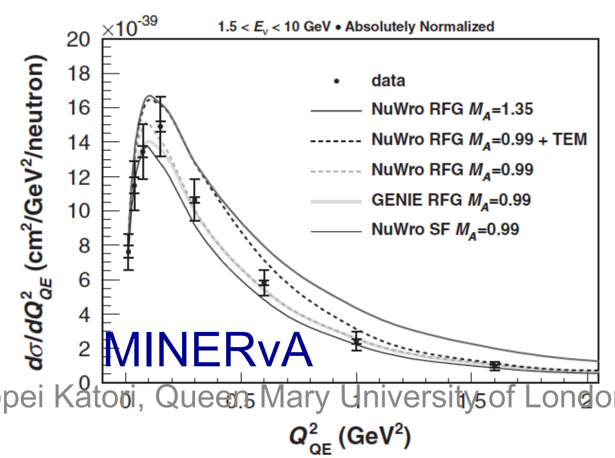
T2K



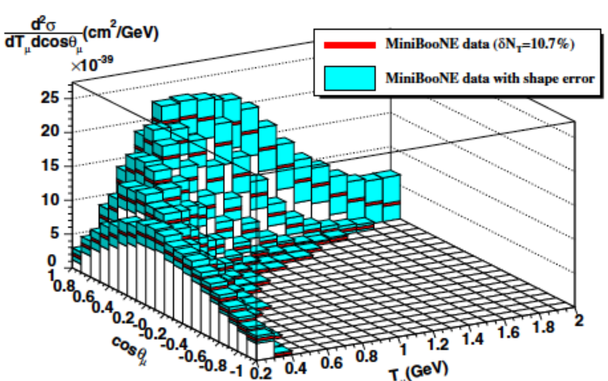








MiniBooNE



2. Flux-integrated differential cross-section

Function of observables

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

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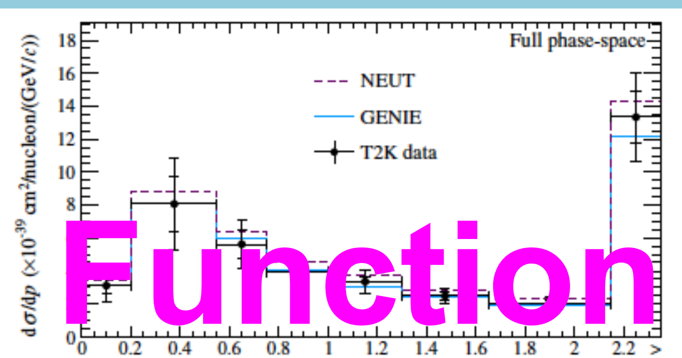
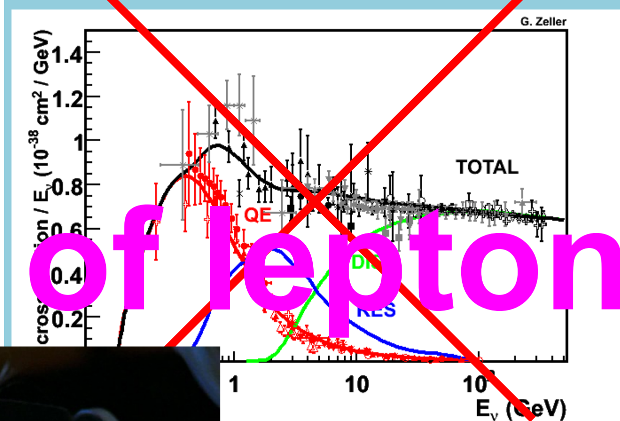
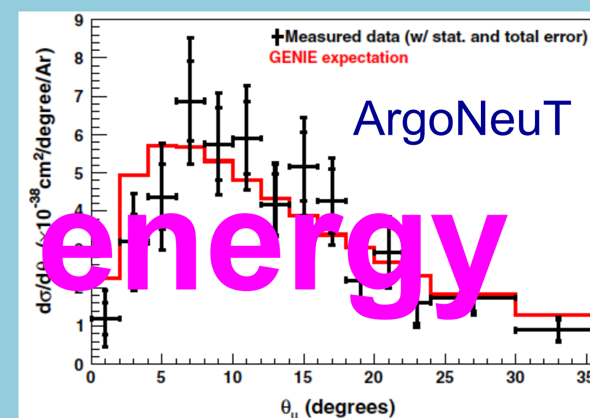
Function of angle

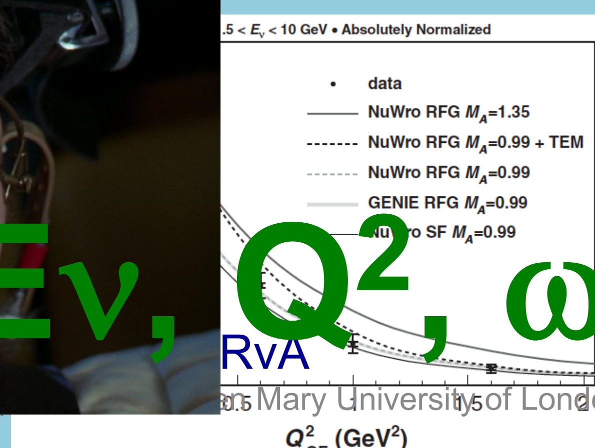
Function of lepton energy

T2K



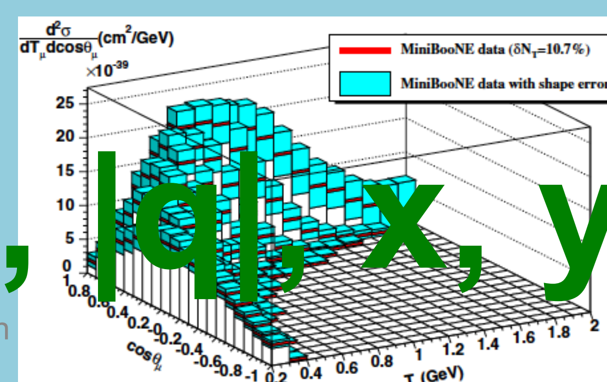






MINERvA

MiniBooNE



Fuck Eν, Q², ω, |q|, x, y

2. Flux-integrated differential cross-section

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

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

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

Theorists

Experimentalists

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

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

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Experimentalists

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Theorists

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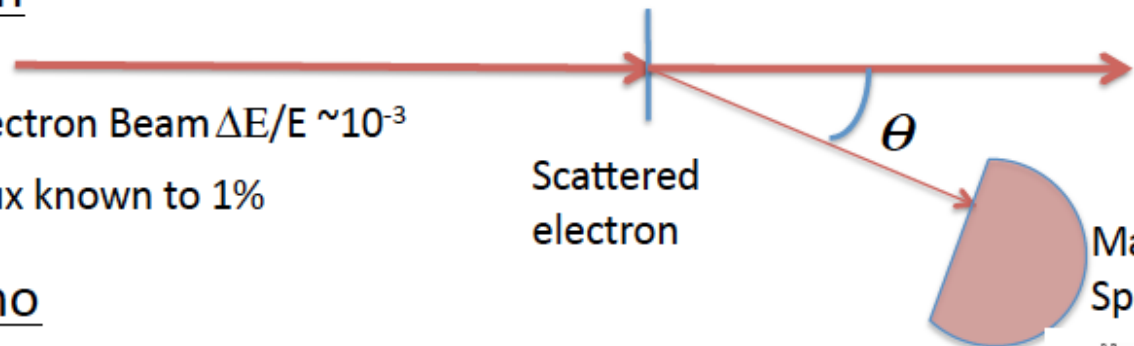
Flux-integrated differential cross-section data allow theorists and experimentalists to talk

2. Remark from Gerry (circa 2010)

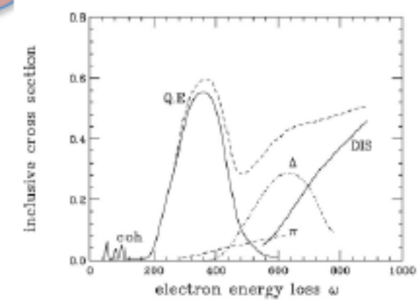
Contrast of e-N with ν-N Experiments

Electron



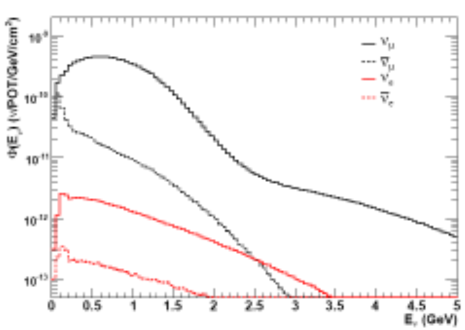
Electron Beam $\Delta E/E \sim 10^{-3}$

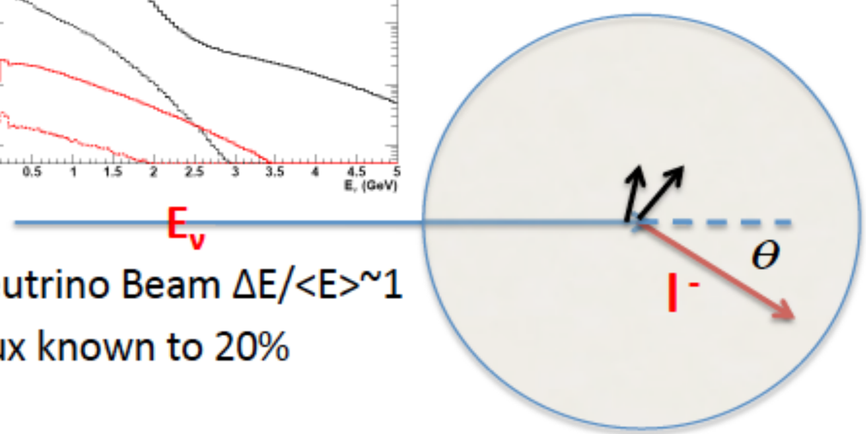
Flux known to 1%



Neutrino

Neutrino-Mode Flux





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!!

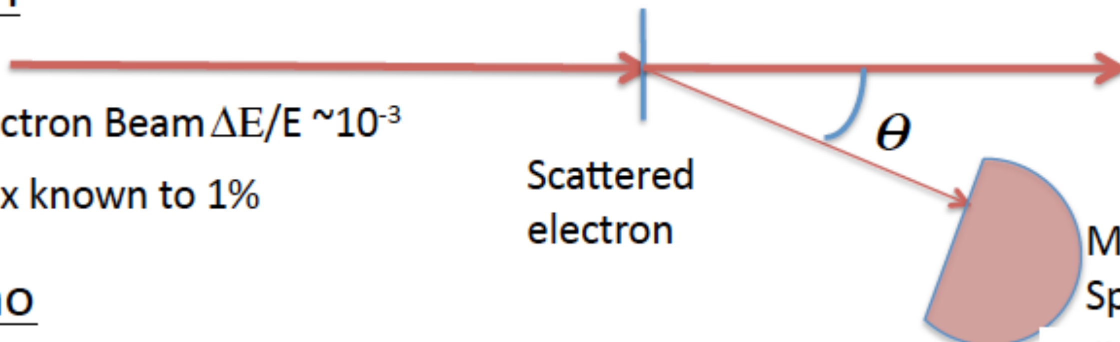
2. Remark from Gerry (circa 2010)

Contrast of e-N with ν-N Experiments

Electron

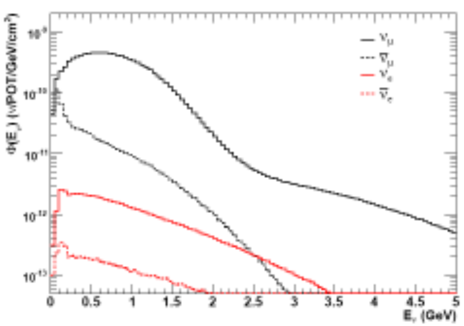
Electron Beam $\Delta E/E \sim 10^{-3}$

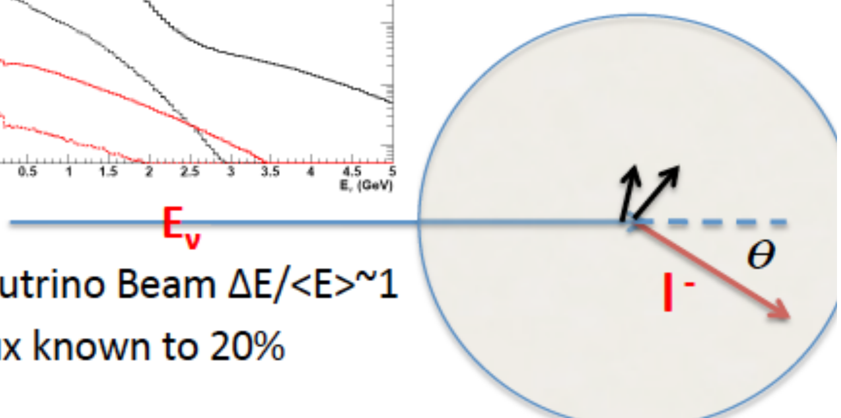
Flux known to 1%



Neutrino

Neutrino-Mode Flux





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

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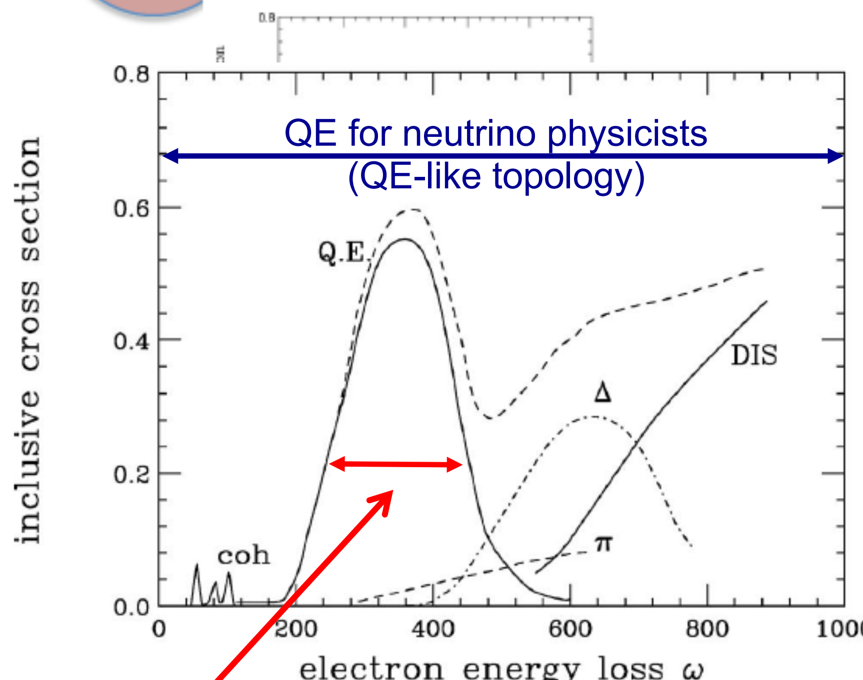
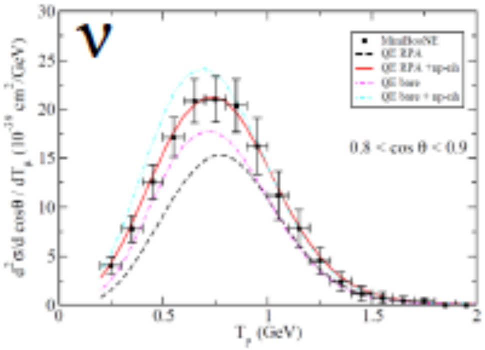


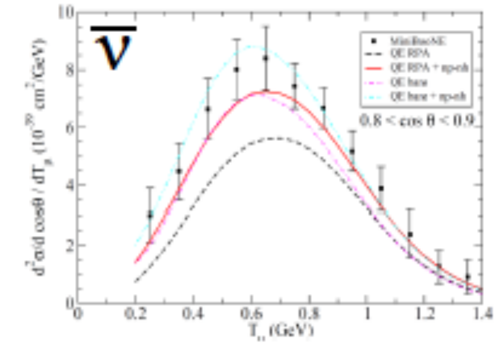
QE for nuclear physicists (genuine QE)

Very Different Situation from inclus

2. CCQE-like data, MiniBooNE (2013)

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





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

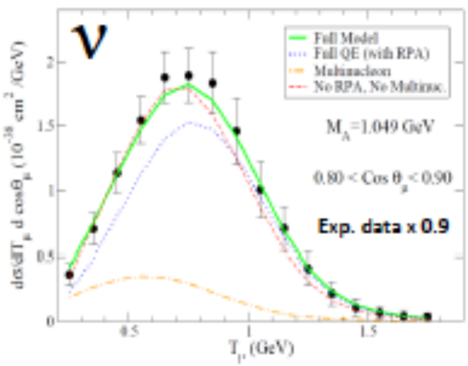
Martini et al. *Nieves et al.* *Amaro et al.* *Lovato et al.* *Bodek et al.*

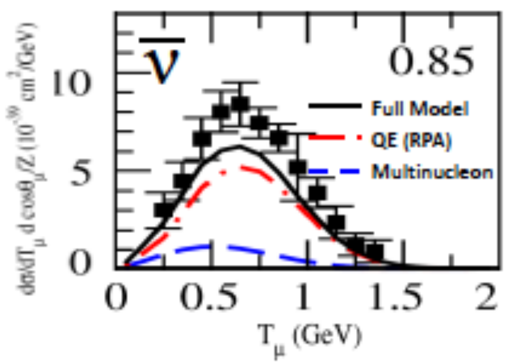
[Follow the color and the style of the lines:]

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

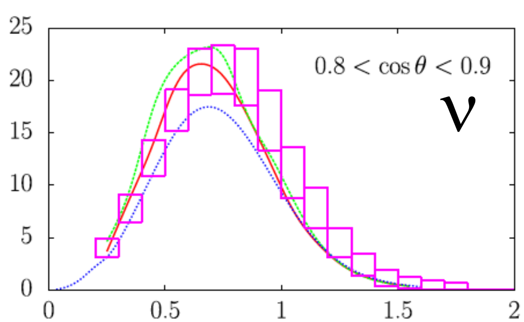
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \sigma_0\left[L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}\right]$$

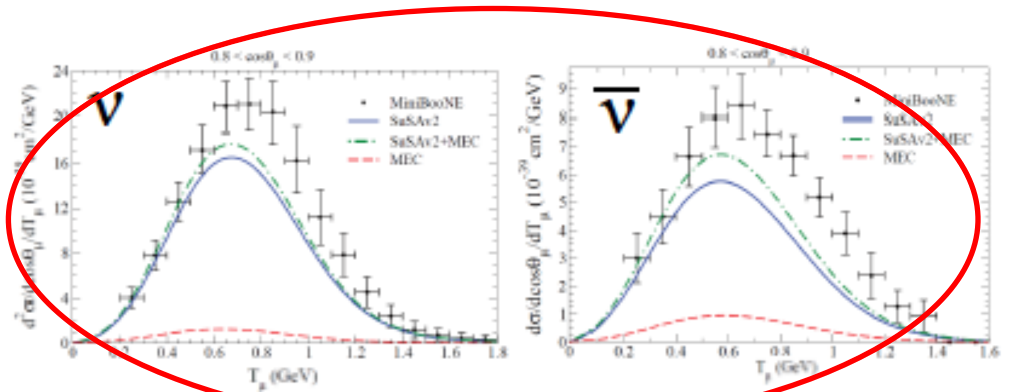
$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\cos^2\theta_c}{2\,\pi^2}k'\epsilon'\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2\,R_\tau + \frac{\omega^2}{q^2}G_A^2\,R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)}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





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





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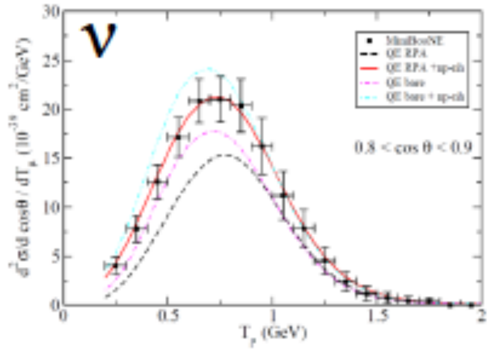
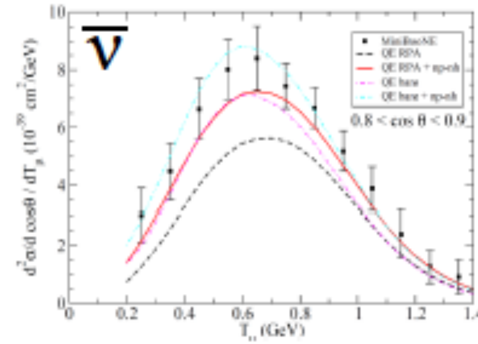
2. CCQE-like data, MiniBooNE (now)

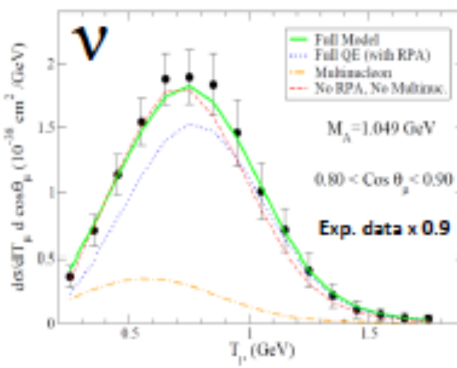
SuSAv2 shows lower normalization due to lack of axial current enhancement.

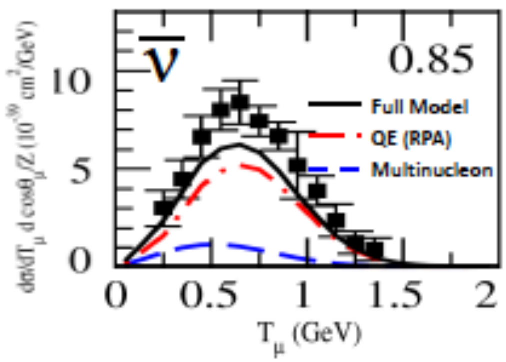
After adding axial MEC contribution, SuSA collaboration (Megias et al.) shows similar enhancement with other groups (Martini et.al., Nieves et al., Meucci et al., Mosel et al., Bodek et al.).

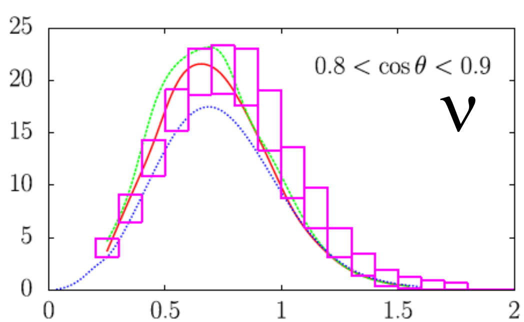
All groups agree qualitatively with MiniBooNE CCQE-like double differential data.

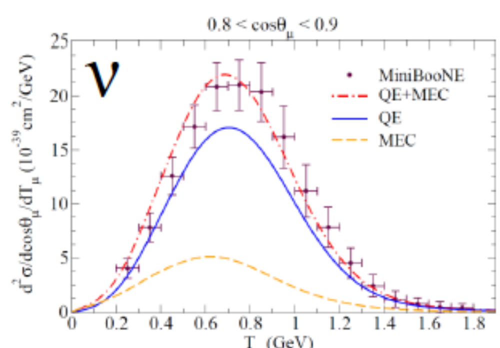


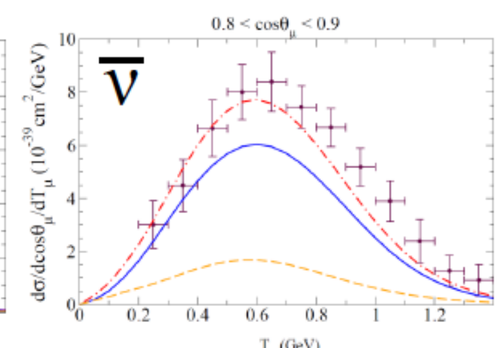












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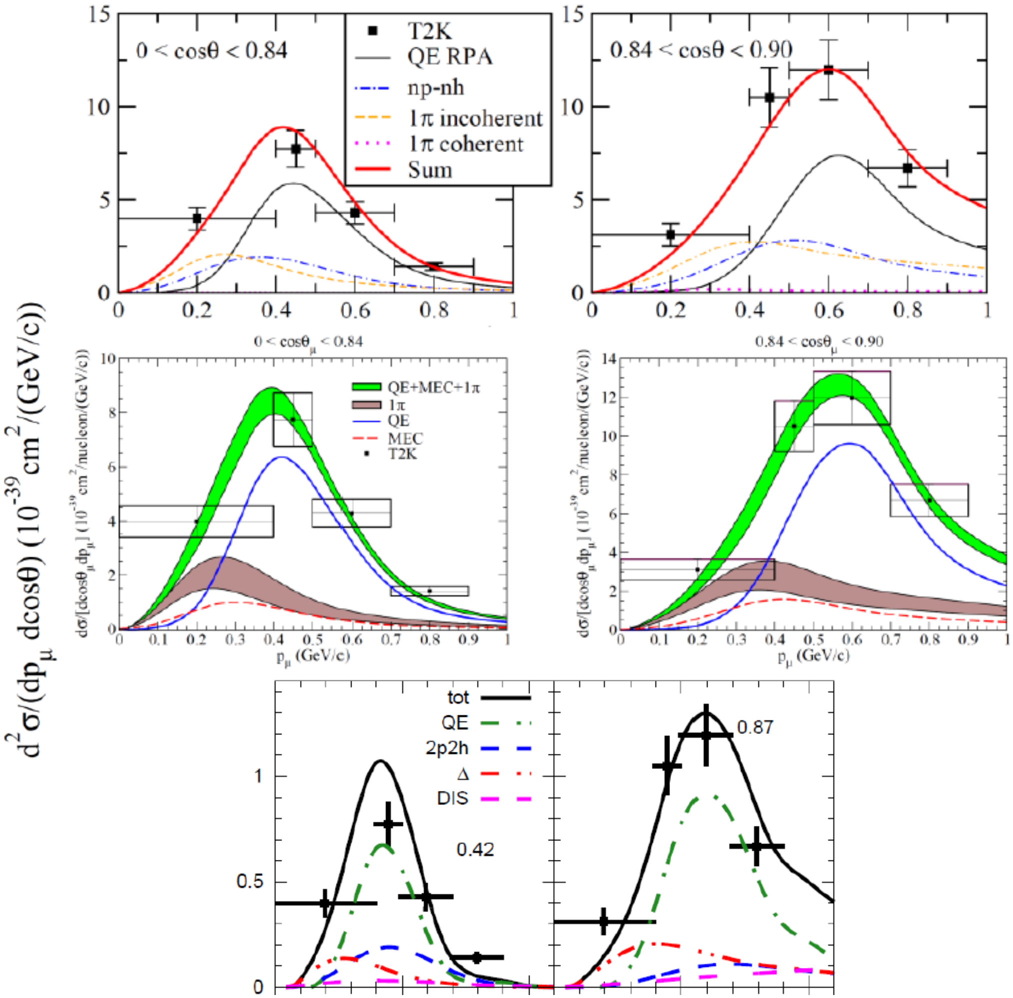
2. CC inclusive data, T2K (now)

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.).

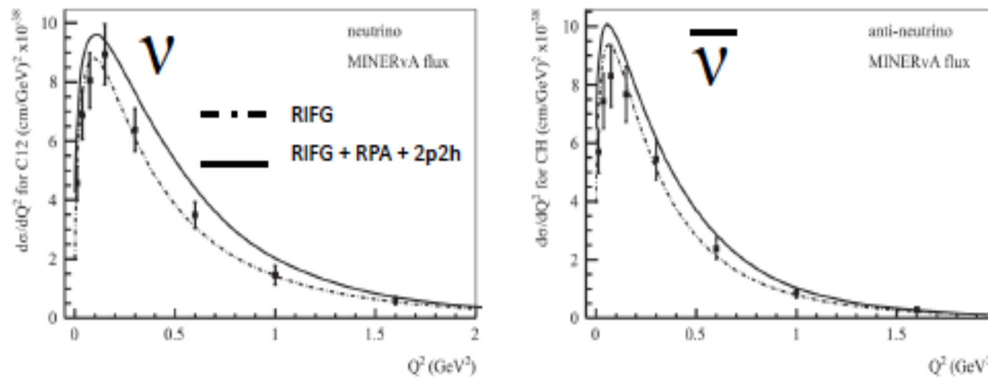
All groups agree qualitatively with MiniBooNE CCQE-like double differential data.

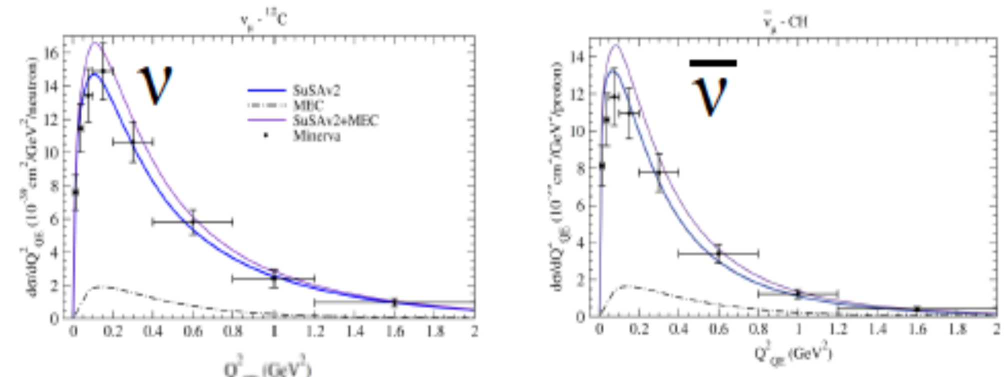
These models are also successful to reproduce T2K CC inclusive data (BNB flux cannot explain MiniBooNE data normalization)

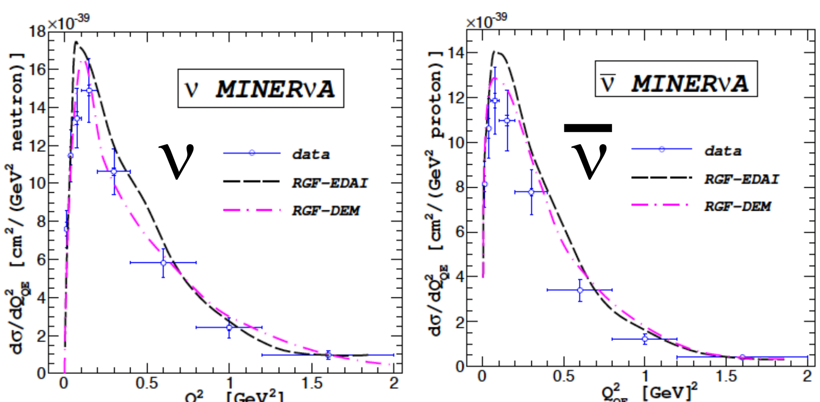


2. CCQE-like data, MINERvA (2013)

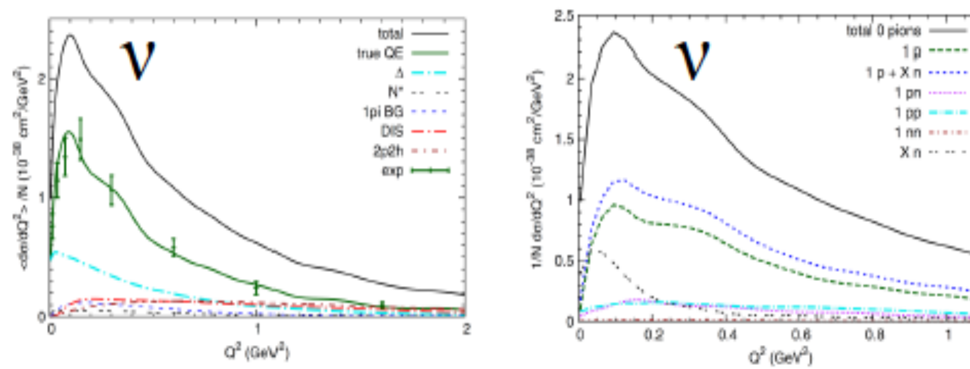
On the other hand, models work for MiniBooNE overestimate MINERvA cross sections.







tori,

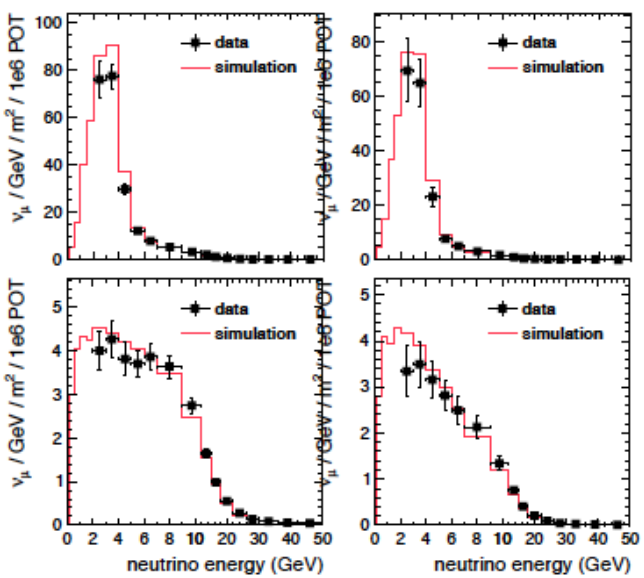


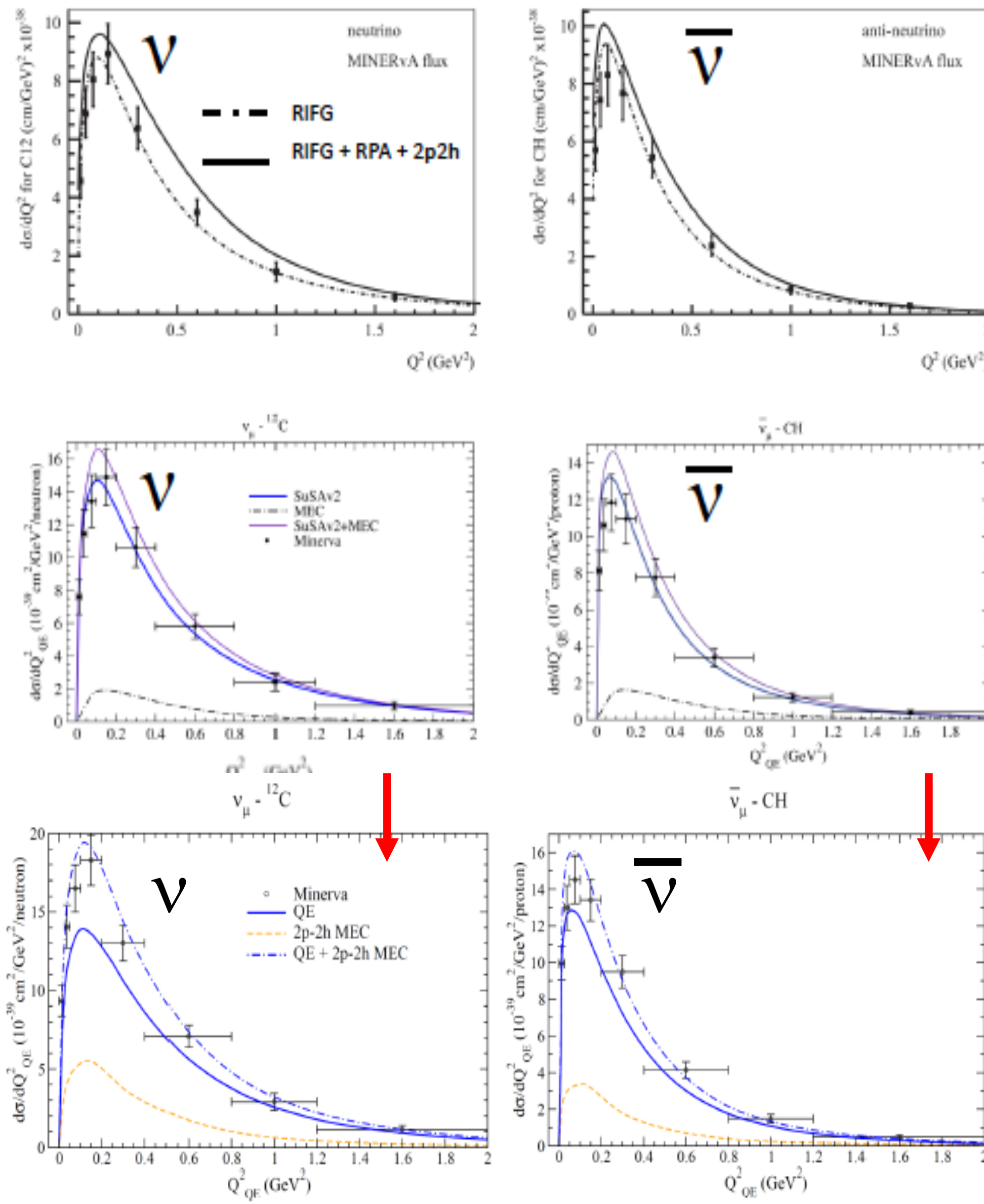
2. CCQE-like data, MINERvA (now)

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

new flux calculation is checked by ν-e scattering data and low-ν method



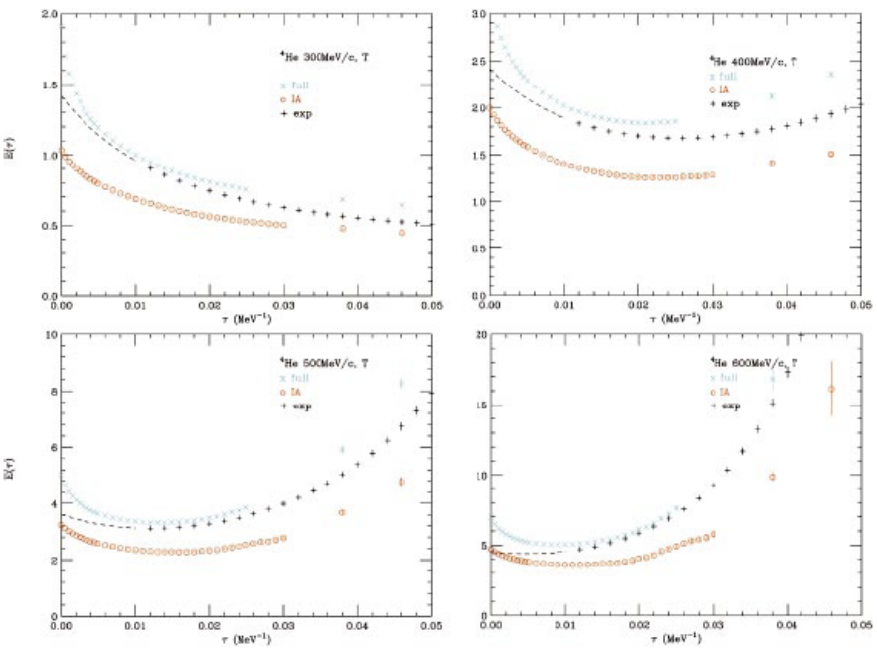


Carlson et al., PRC65(2002)024002
Lovato et al.,PRL112(2014)182502

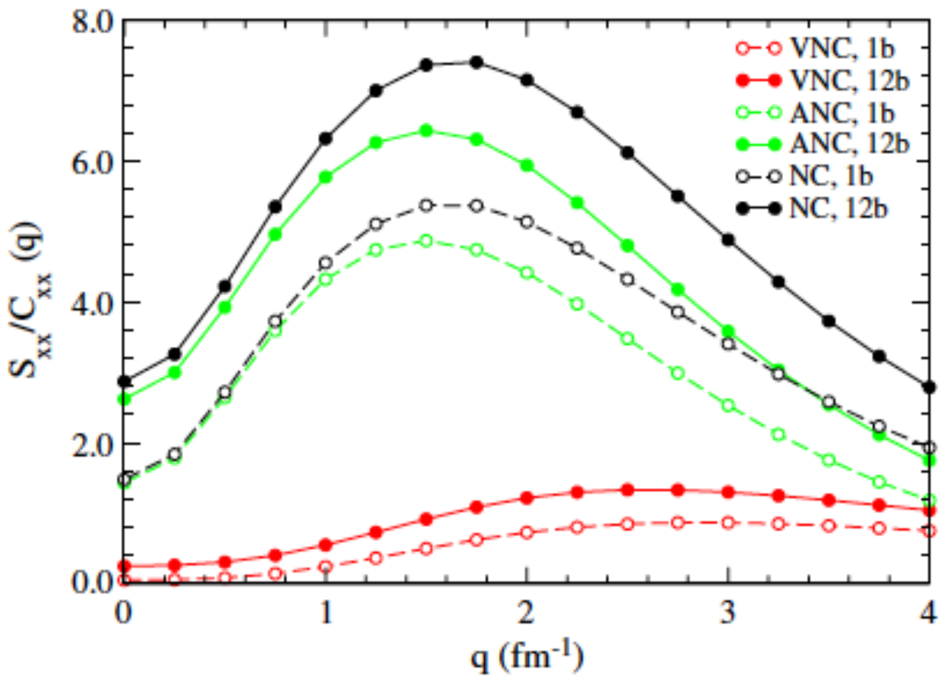
2. Ab initio calculation (2013)

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



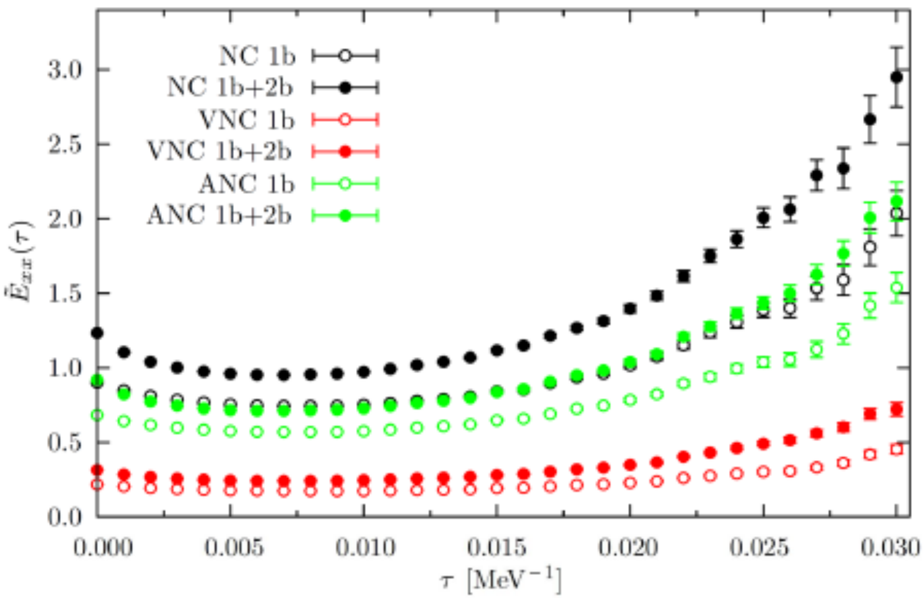
Lovato et al.,PRL112(2014)182502;PRC91(2015)062501

2. Ab initio calculation (now)

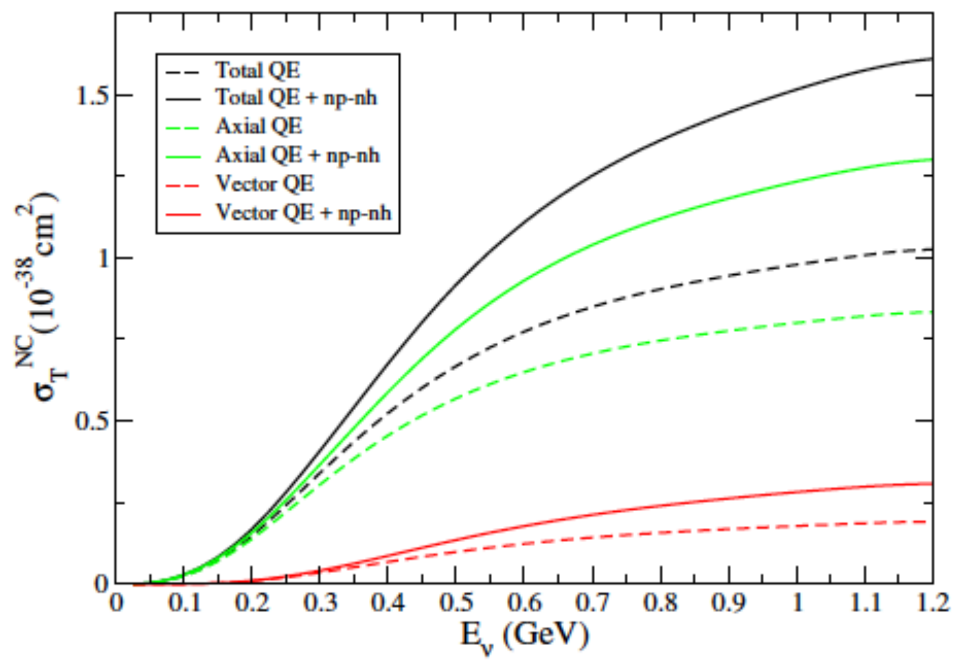
Ab initio calculation support the general idea of transverse response enhancement for neutrino scatterings.

Ab initio calculation for weak interaction response function shows same features with phenomenological models.
(can we perform 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.



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

Main topic at Pittsburgh (PITTPACC) workshop 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 didn't pass a quantitative test

MiniBooNE-MINERvA CCQE-like data simultaneous fit

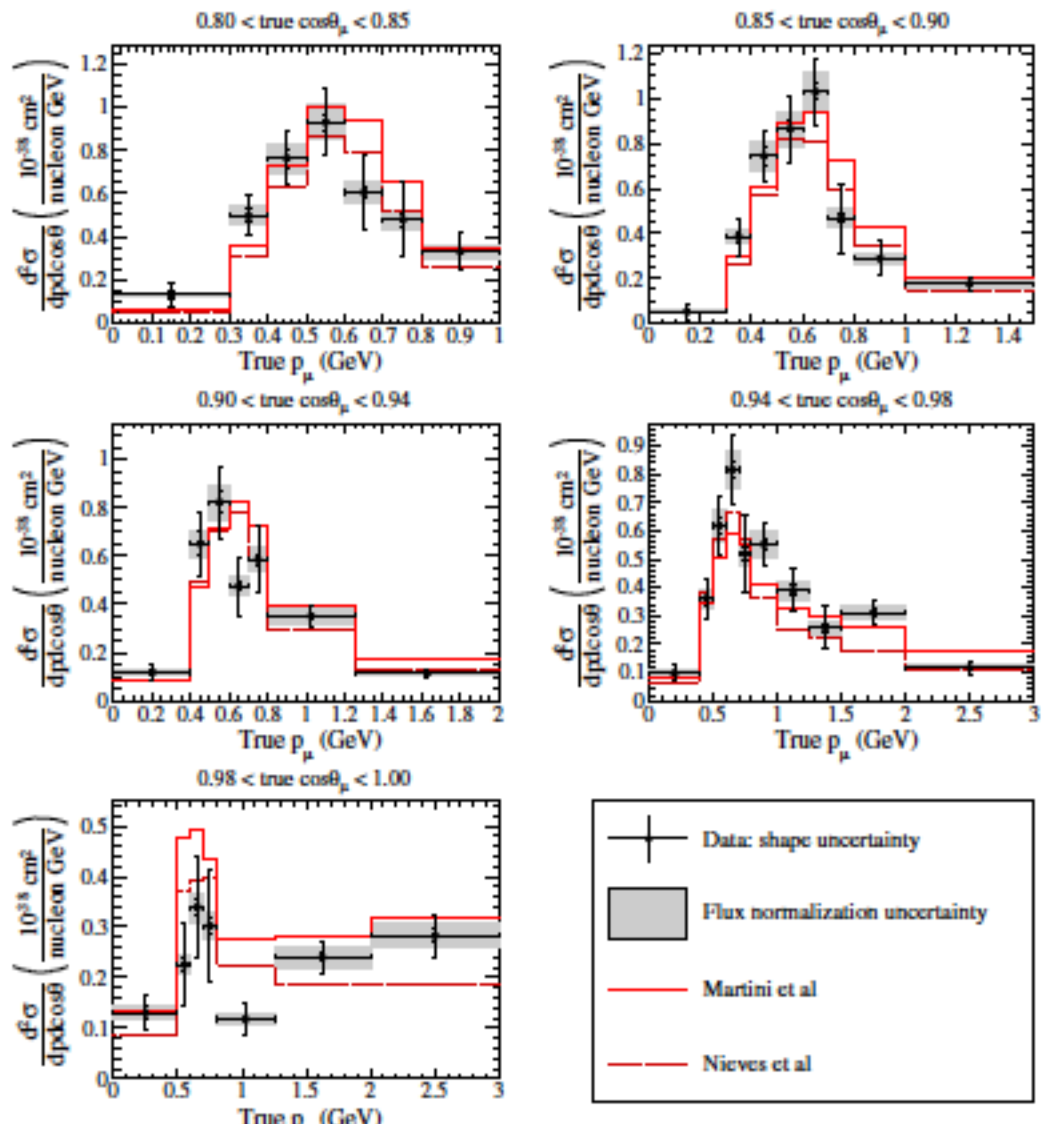
Fit type	χ^2/N_{DOF}	M_A (GeV/c^2)	2p2h norm (%)	p_F (MeV/c)	λ_ν^{MB}	$\lambda_{\bar{\nu}}^{MB}$
RFG + rel RPA + 2p2h	97.8/228	1.15 ± 0.03	27 ± 12	223 ± 5	0.79 ± 0.03	0.78 ± 0.03
RFG + nonrel RPA + 2p2h	117.9/228	1.07 ± 0.03	34 ± 12	225 ± 5	0.80 ± 0.04	0.75 ± 0.03
SF + 2p2h	97.5/228	1.33 ± 0.02	0 (at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

T2K,PRD93(2016)112012

2. CC0π double differential data, T2K (now)

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.

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TK, Martini, arXiv:1611.07770

1. Introduction

2. CCQE, CCQE-like, and CC0π data

3. CC data with nucleon final state

4. Electron neutrino CC data

5. Resonant single pion production

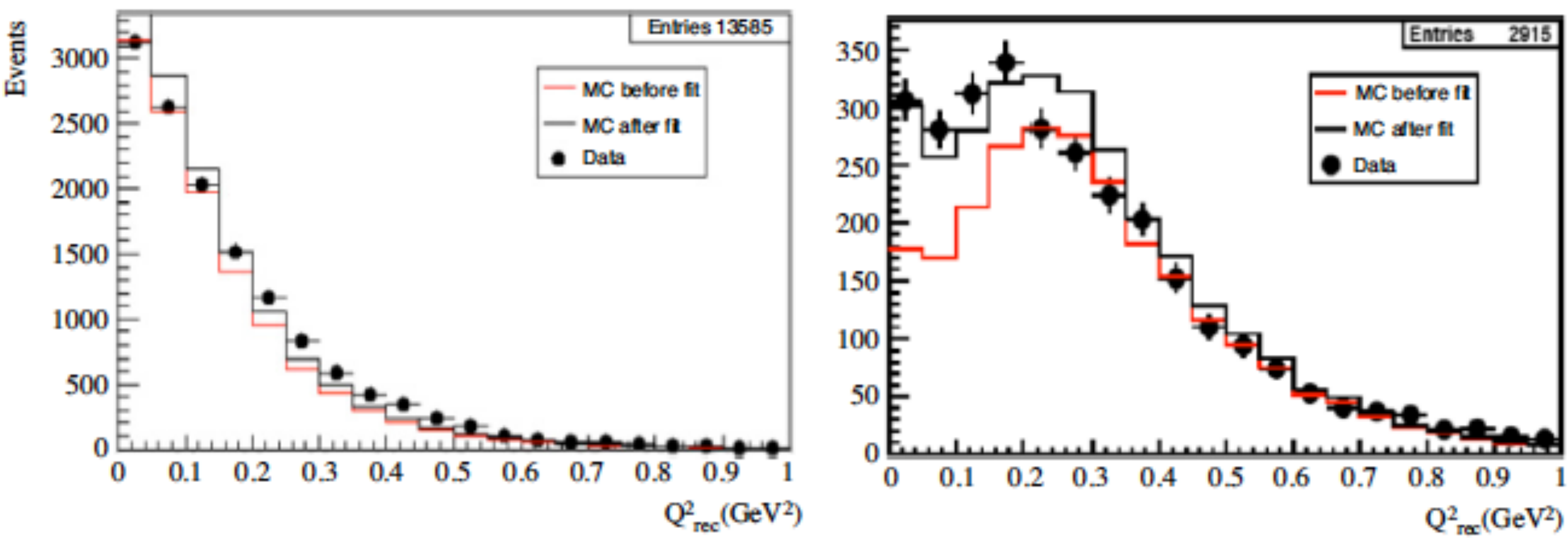
6. Conclusion

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

3. CC data with nucleon final state (2013)

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



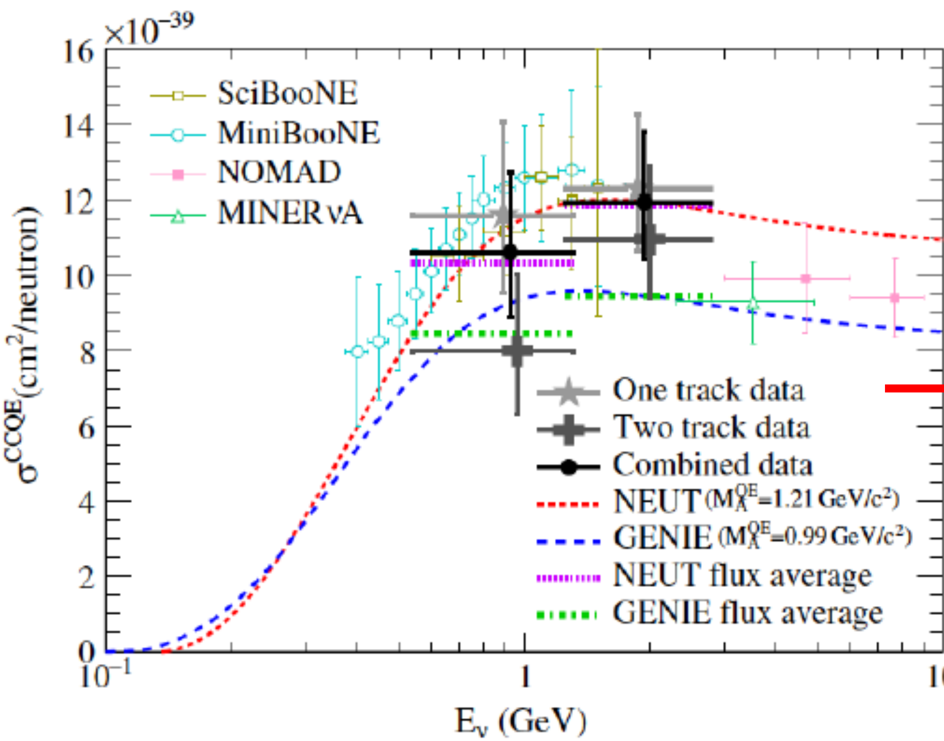
T2K,PRD91(2015)112002

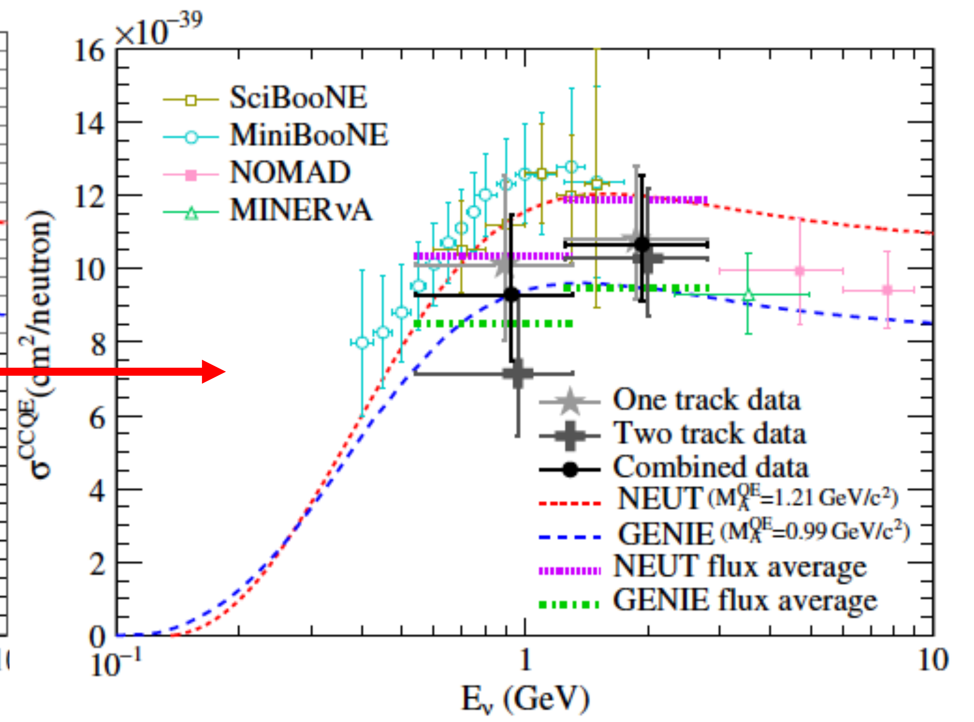
3. 1&2 track genuine CCQE total cross section, T2K (now)

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.



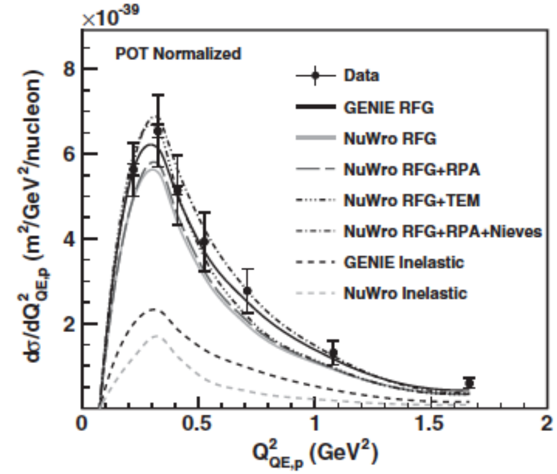


MINERvA,PRD91(2015)071301

3. CC0p0>p data, MINERvA (now)

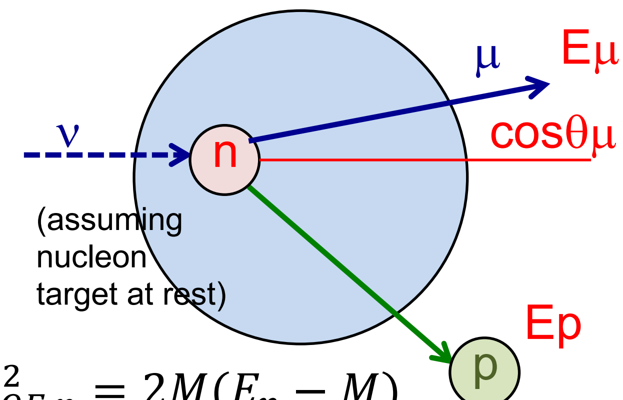
MINERvA measured μ+p sample differential cross section, more precisely "final state include a muon, at least one proton, and no pions". Q^2 is reconstructed from muon kinematics and proton kinematics, and they agree.

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

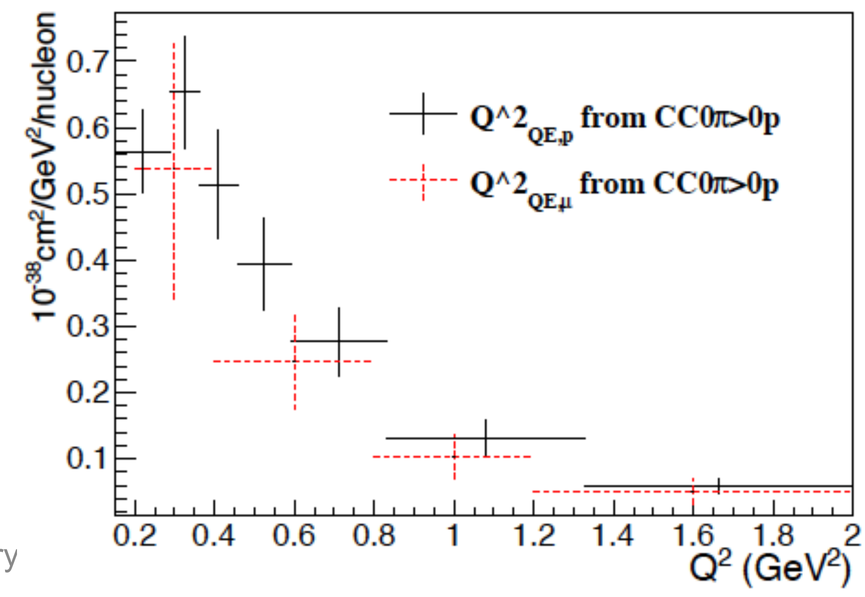


$$E^{\nu}_{QE,\mu} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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



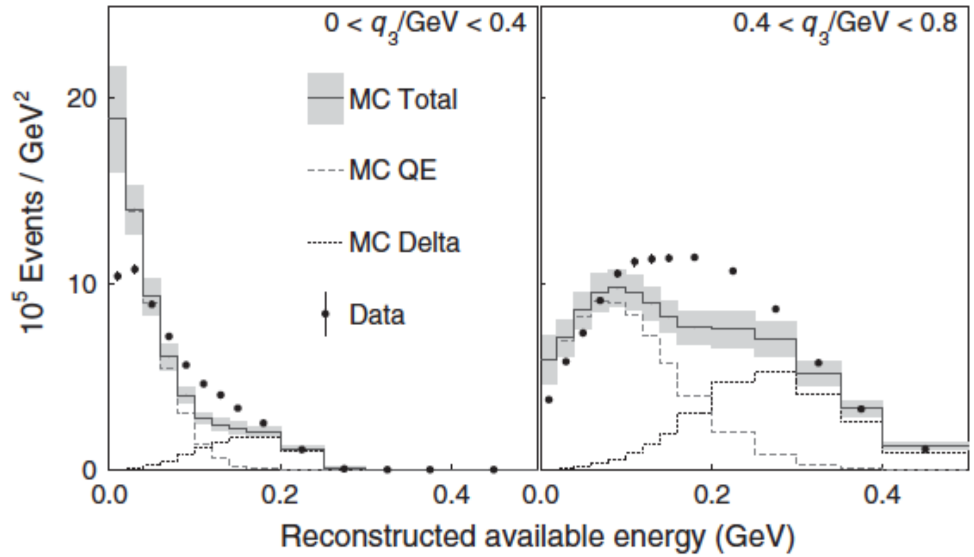
$$Q^2_{QE,p} = 2M(E_p - M)$$



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

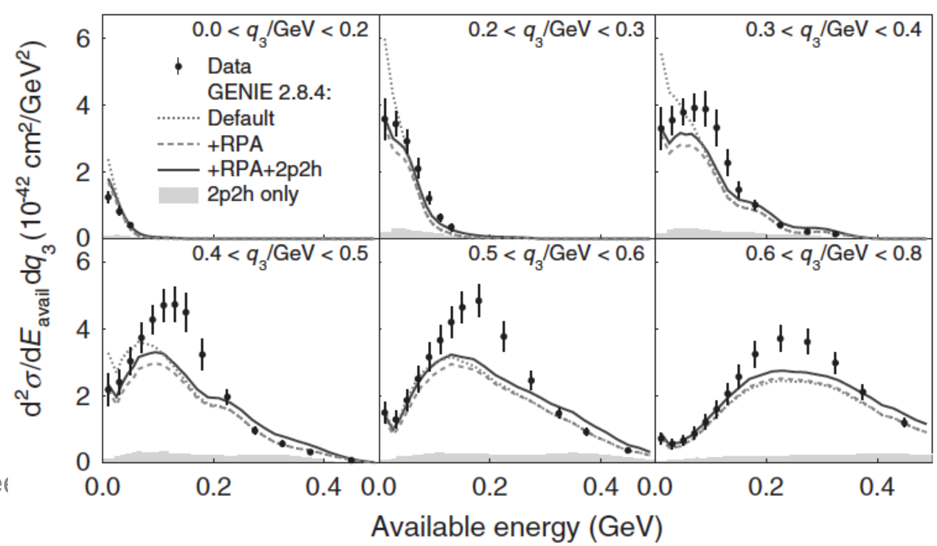
MINERvA reconstruct full inclusive kinematics (which once we thought impossible!)

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 very large.



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

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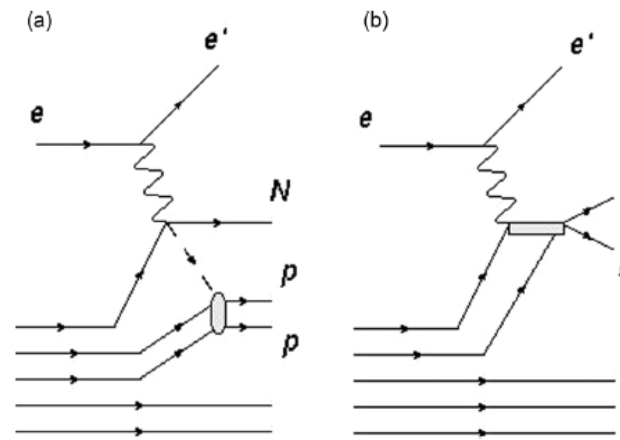
ArgoNeuT,PRD90(2014)012008
Niewczas and Sobczyk,PRC93(2016)035503,Weinstein et al.,PRC94(2016)045501

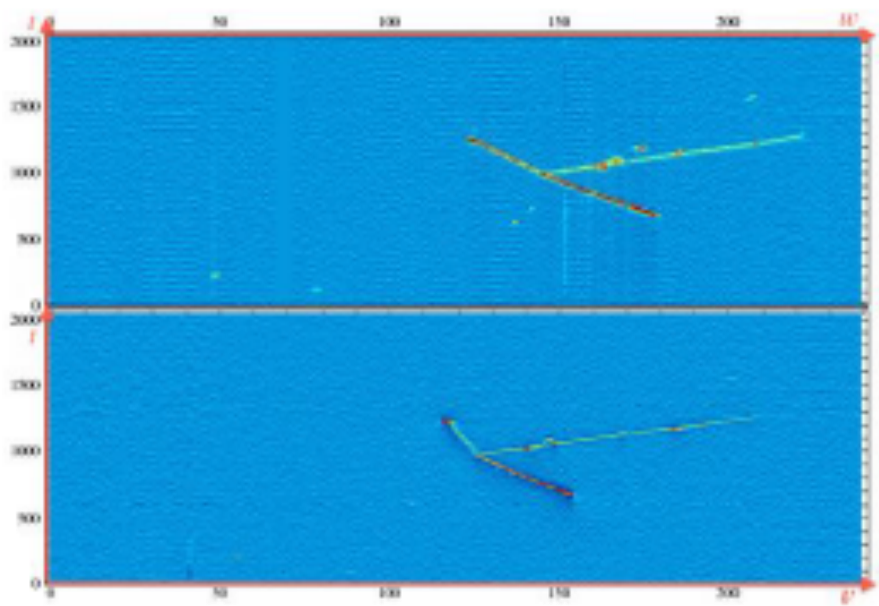
3. Hammer events, ArgoNeuT (now)

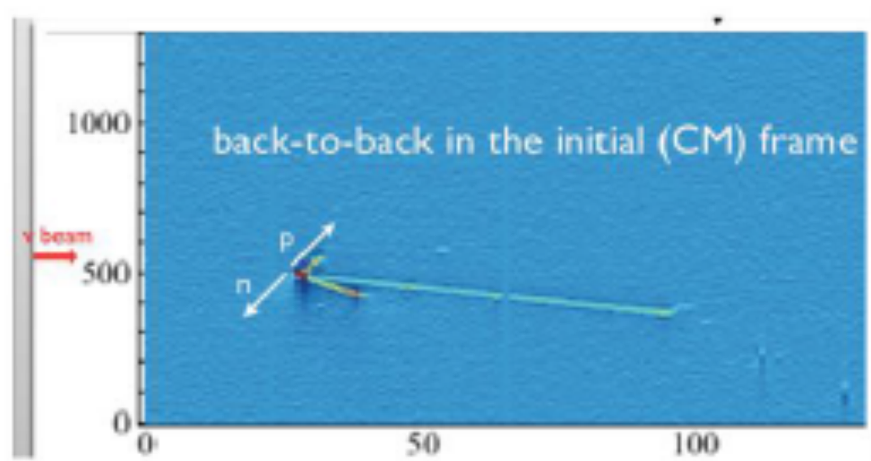
ArgoNeuT published so called “hammer” events.
→ candidate topology of NNSRC from ν_μ+(np)→μ+p+p



Other reactions contribute comparable amount on this topology…

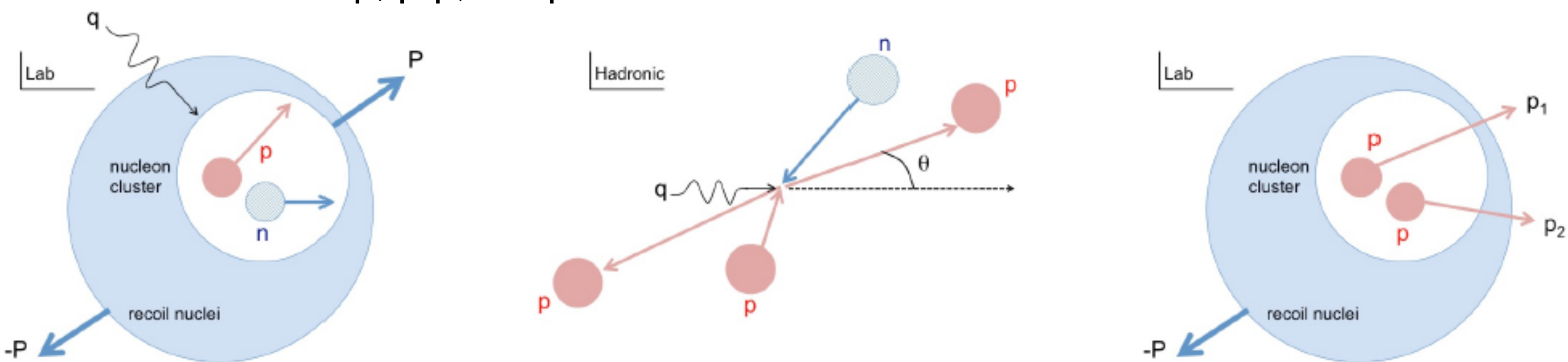
To study more detail, detection efficiency need to be understood.





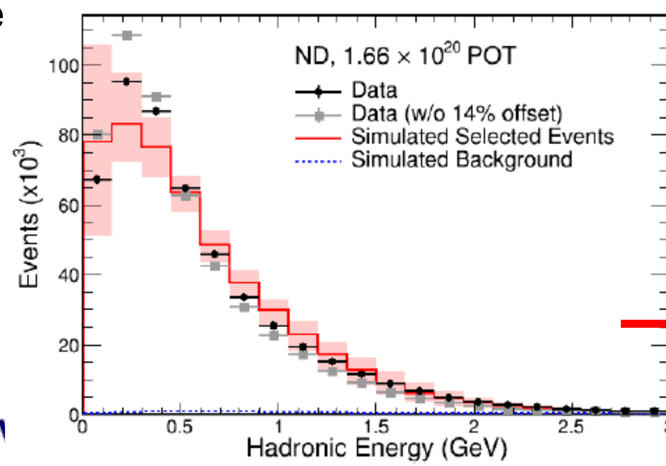
3. Nucleon kinematics predictions (2013)

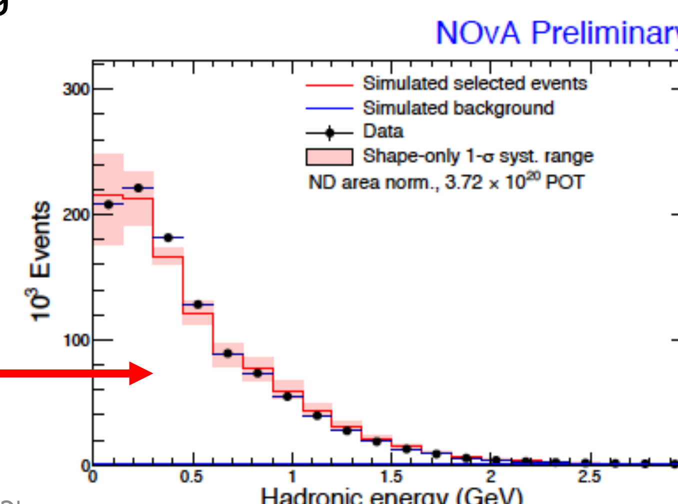
So far, all generators are based on "nucleon cluster model"
- isotropic decay in hadronic frame
- fixed ratio for n-p, p-p, n-n pairs



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

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





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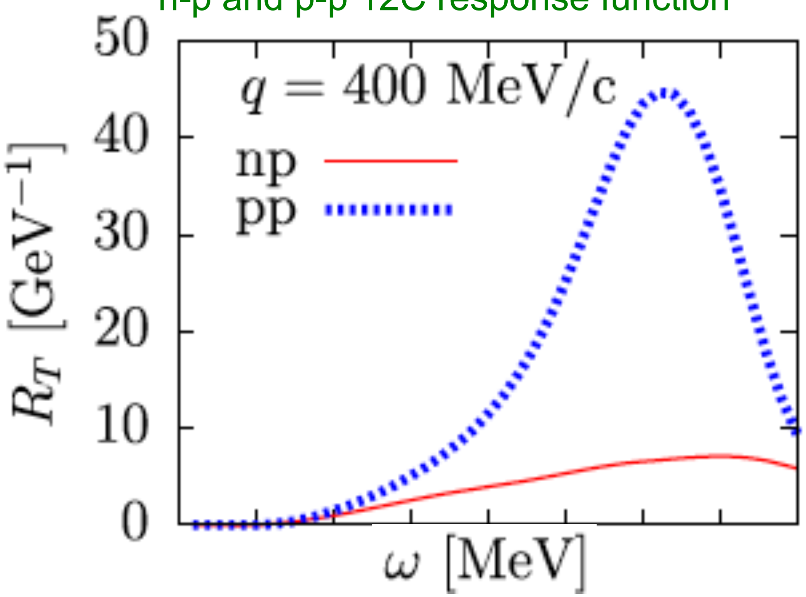
3. Nucleon kinematics predictions (now)

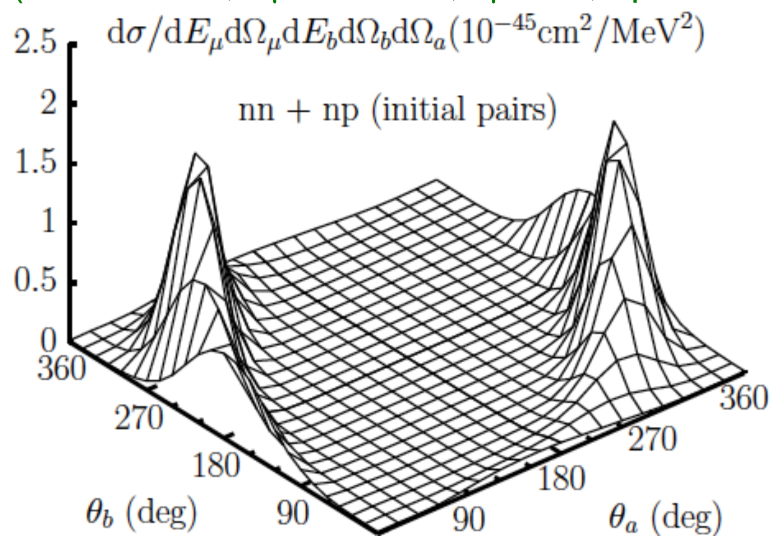
So far, all generators are based on "nucleon cluster model"
- isotropic decay in hadronic frame
- fixed ratio for n-p, p-p, n-n pairs

Number of groups made detailed predictions of hadron final states
→ Question, how to use them in experiments?

n-p and p-p 12C response function



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



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4. ν_eCC data (1978)

No ν_eCC data in low energy region. This was a main argument 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
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G. BERTRAND-COREMANS, M. DEWIT *, H. MULKENS **, J. SACTON and W. VAN DONINCK ***
Interuniversity Institute for High Energies, ULB, VUB Brussels, Belgium

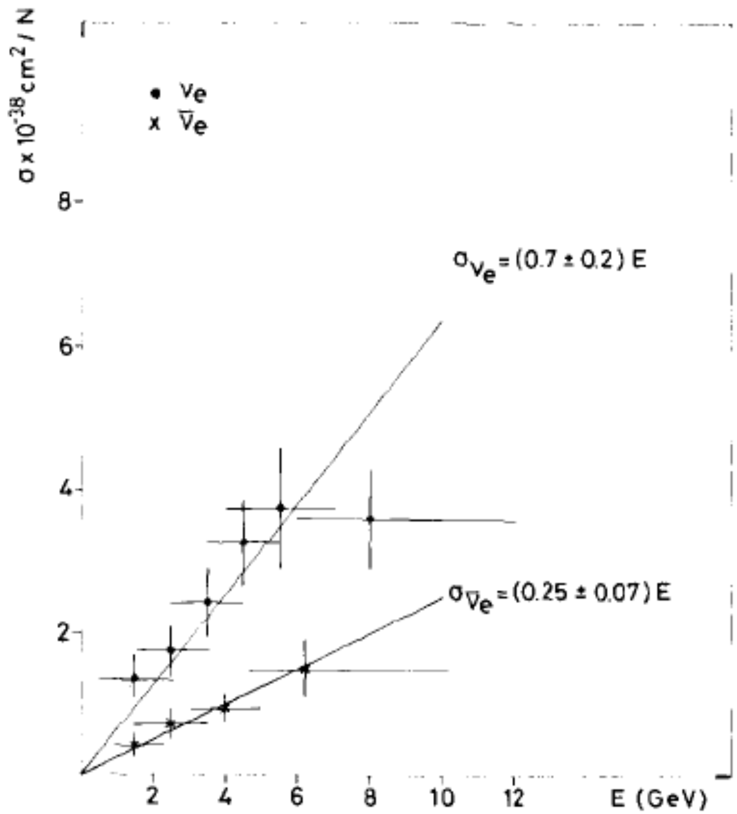
D. HAIDT, C. MATTEUZZI, P. MUSSET, B. PATTISON, F. ROMANO +, J.P. VIALLE ++ and A. WACHSMUTH
CERN, European Organization for Nuclear Research, Geneva, Switzerland

A. BLONDEL, V. BRISSON, B. DEGRANGE, T. FRANÇOIS, M. HAGUENAUER, U. NGUYEN-KHAC and P. PETIAU
Laboratoire de Phys. Nucl. des Hautes Energies, Ecole Polytechnique, Paris, France

E. BELLOTTI, S. BONETTI, D. CAVALLI, E. FIORINI, A. PULLIA and M. ROLLIER
Istituto di Fisica dell'Università and INFN, Milano, Italy

B. AUBERT, D. BLUM, A.M. LUTZ and C. PASCAUD
Laboratoire de l'Accélérateur Linéaire, Orsay, France

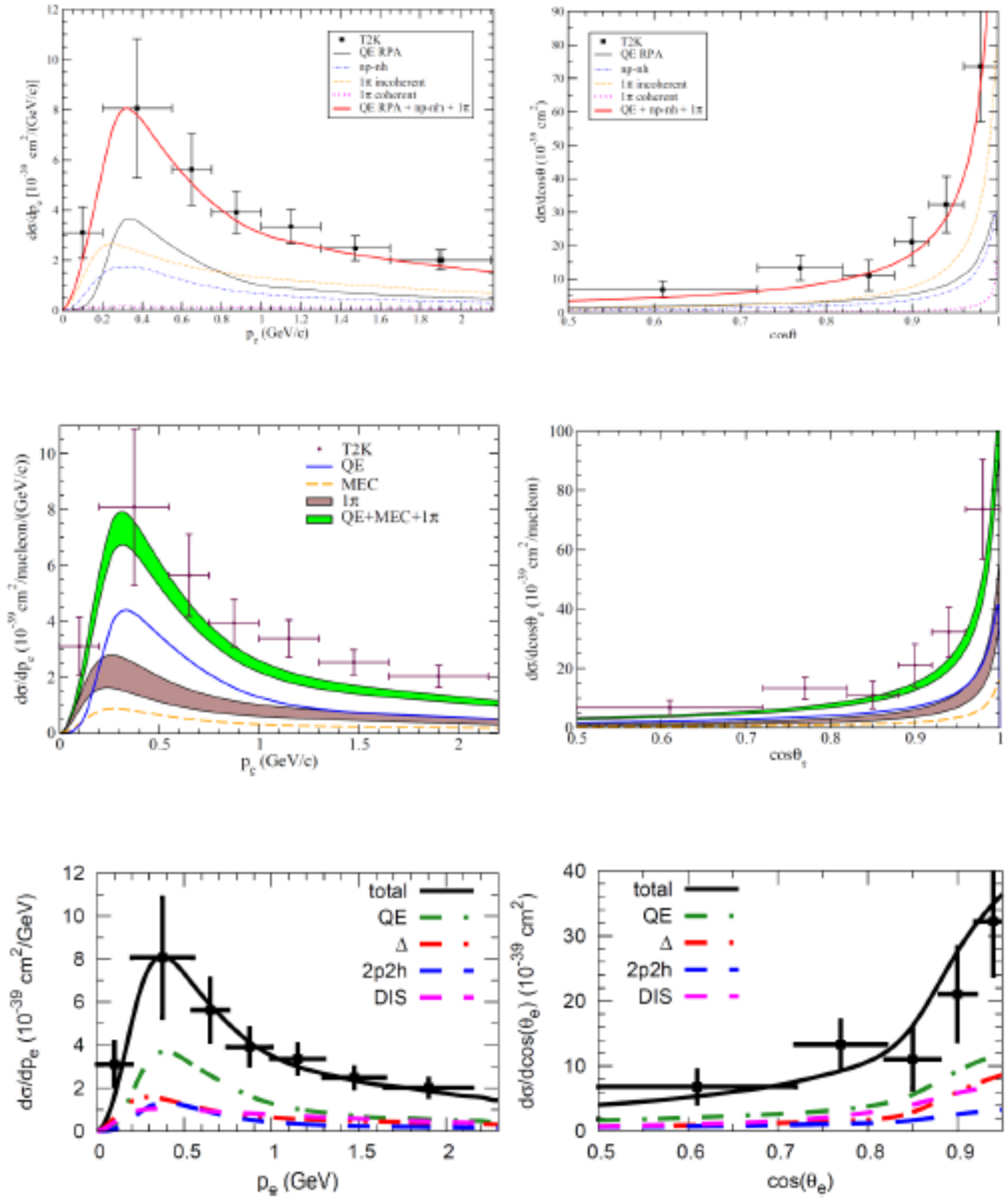
F.W. BULLOCK and A.G. MICHETTE +++
University College London, London, UK



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

4. ν_eCC inclusive data, T2K (now)

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



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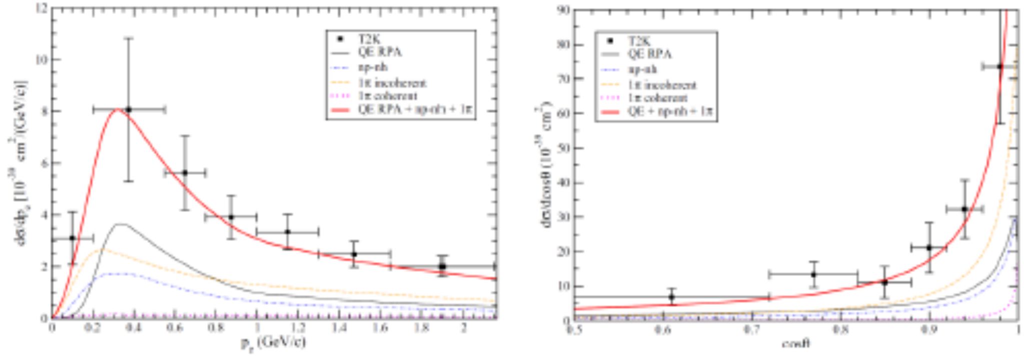
MINERvA,PRL116(2016)081802

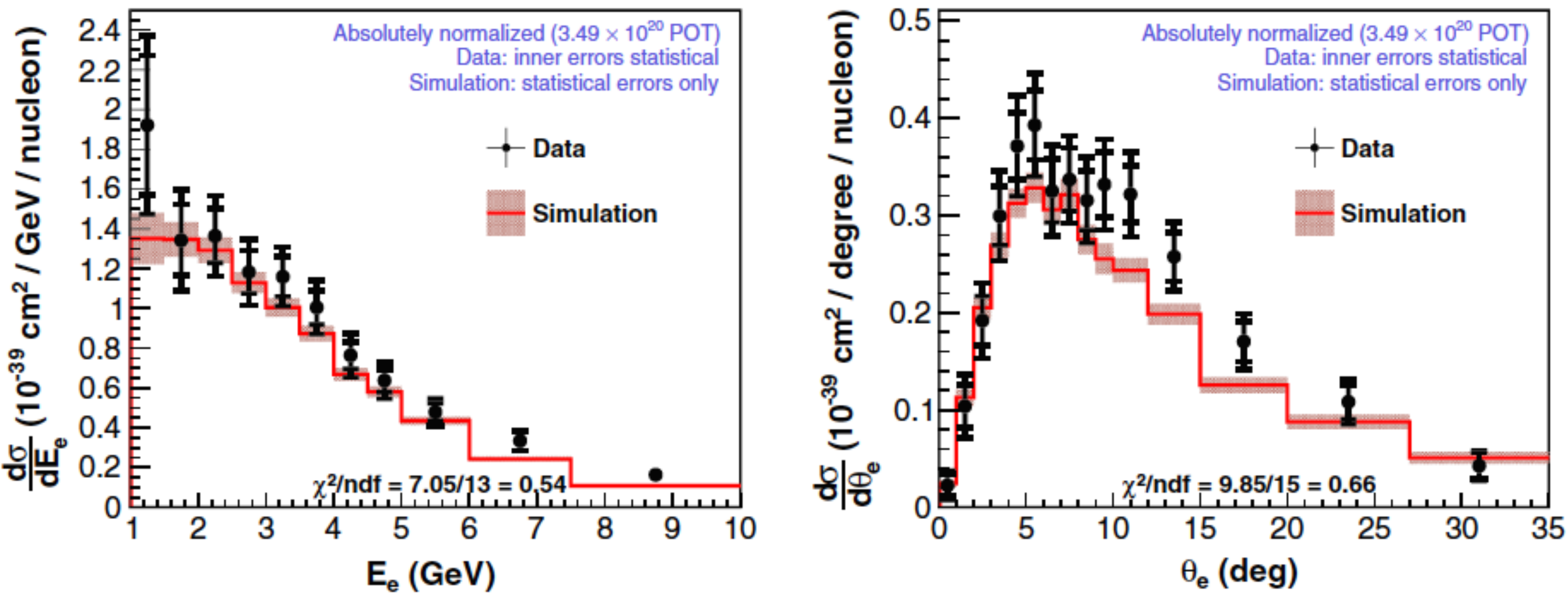
4. ν_eCCQE-like data, MINERvA (now)

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.



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5. Open question of neutrino interaction physics (2013)

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

5. Open question of neutrino interaction physics (now)

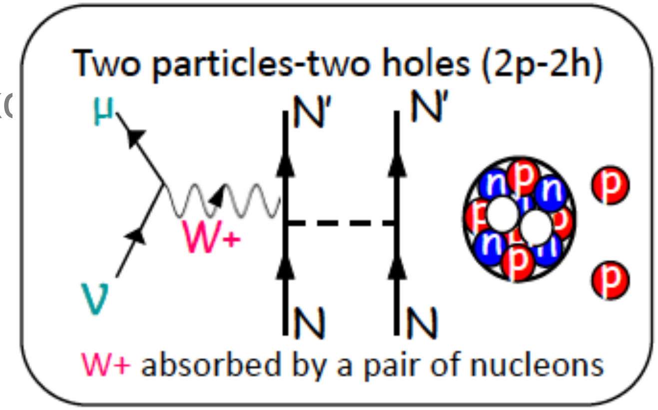
CCQE puzzle

- 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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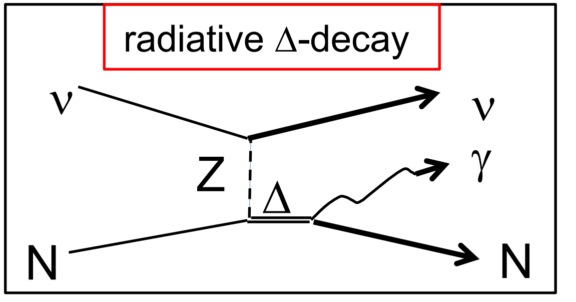
→ probably not, but no measurement, yet



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ANL
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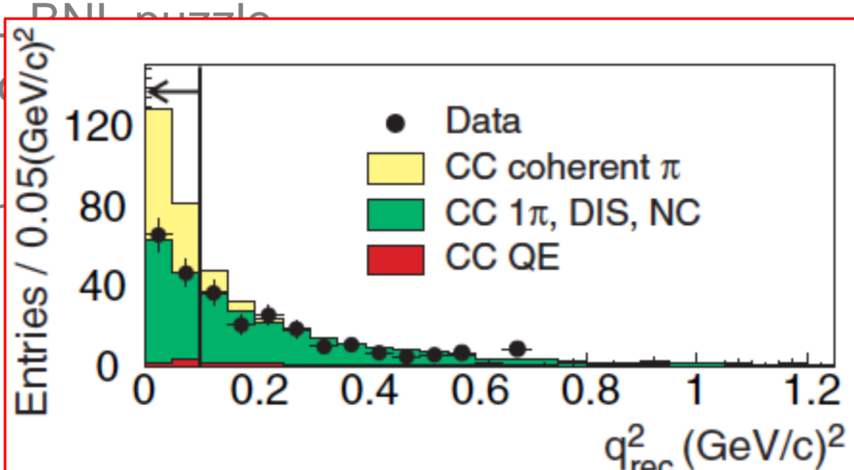
Pio
- M data are incompatible under any models



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

5. Open question of neutrino interaction physics (now)

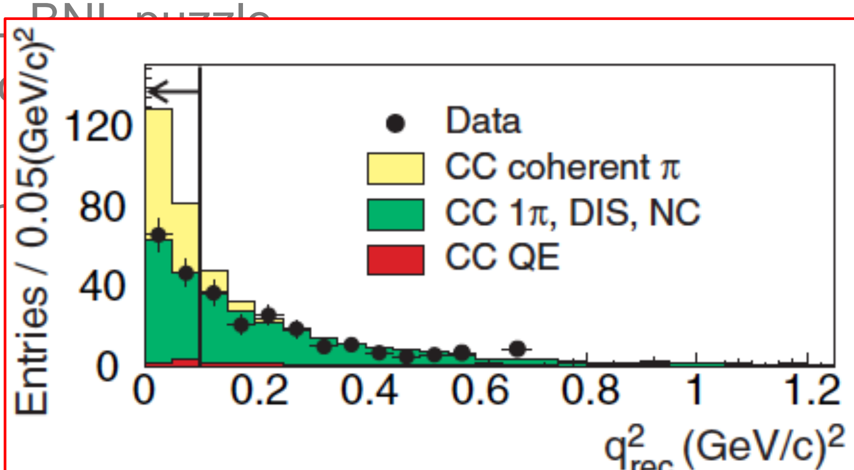
CCQE puzzle
 - Low Q2 suppression, high Q2 enhancement, high normalization
 → presence of short and long range nucleon correlations

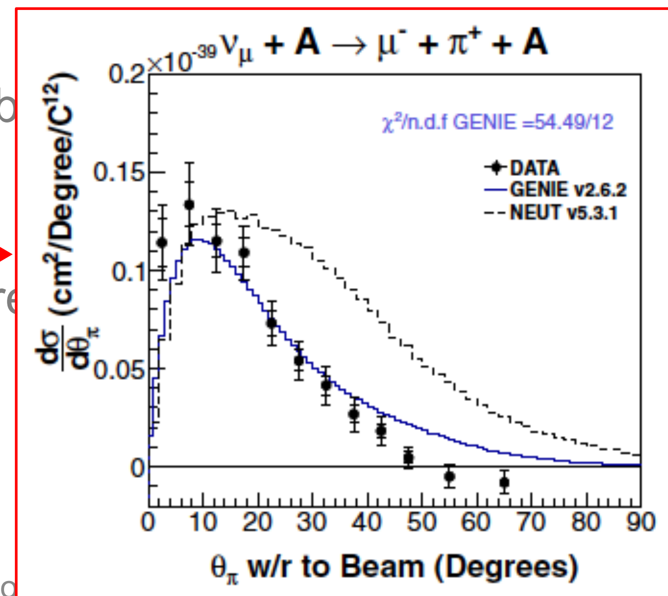
NCgamma
 - Can NCgamma explain MiniBooNE ν_e-candidate excess?
 → probably not, but no measurement, yet

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

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

Pion...
 - M... data are ... s





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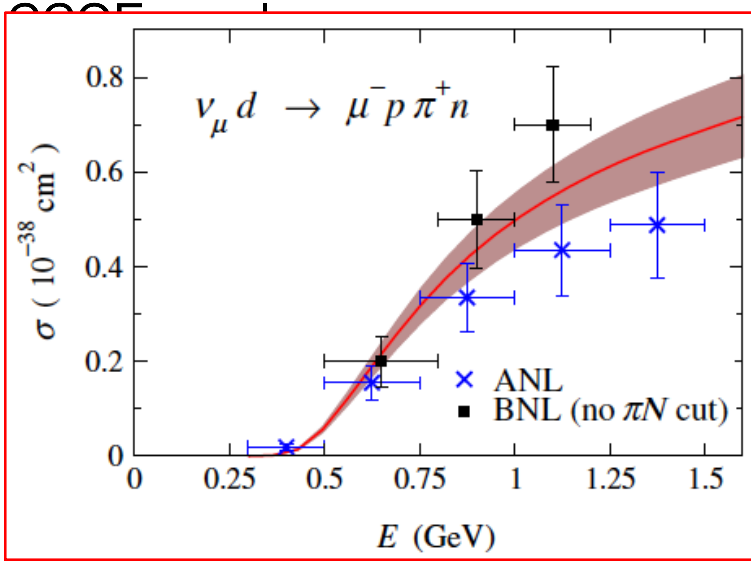

hancement, high normalization

e nucleon correlations

IE ν_e-candidate excess?

ent, yet

pion production?

ArgoNeuT, MINOS

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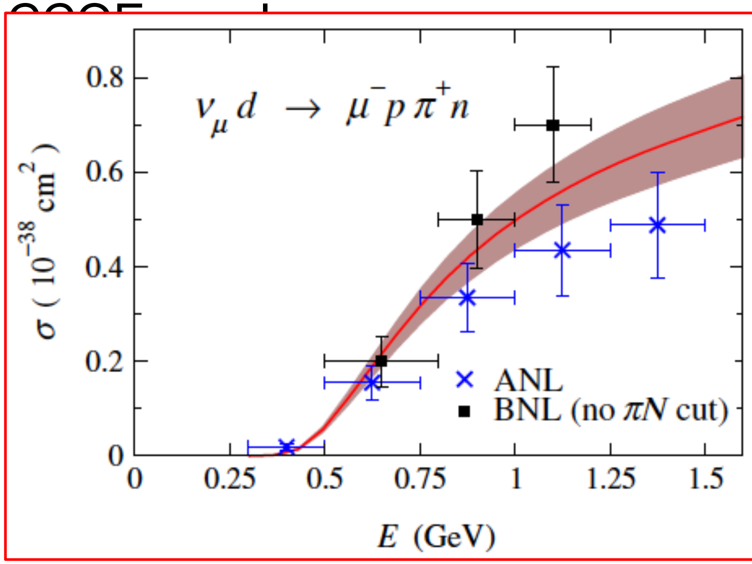
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models

5. Open question of neutrino interaction physics (now)



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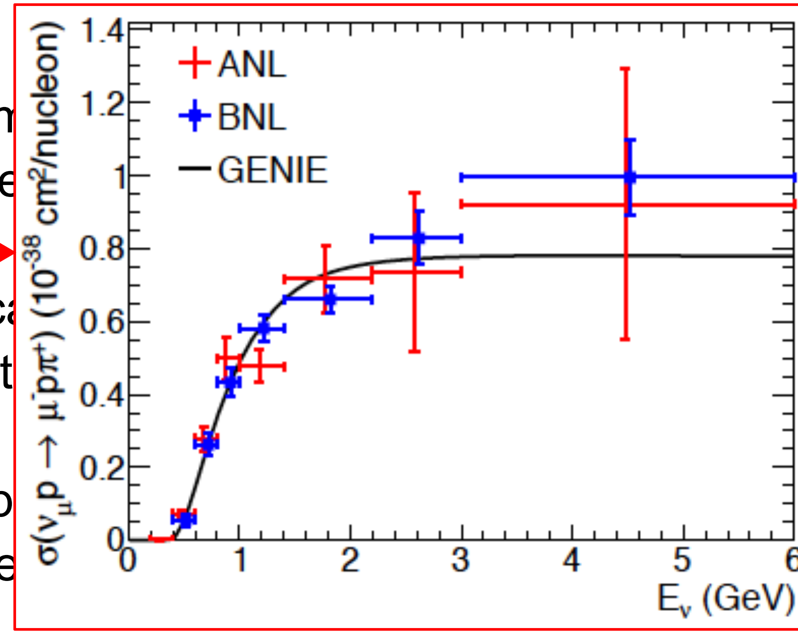


ANL-BNL puzzle

- 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

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al,AHEP(2012)934597, Garvey et al.,Phys.Rept.580 (2015)1
Wilkinson et al,PRD90(2014)112017,Graczyk et al,PRD80(2009)093001,Wu et al,PRC91(2015)035203

5. Open question of neutrino interaction physics (2013)

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

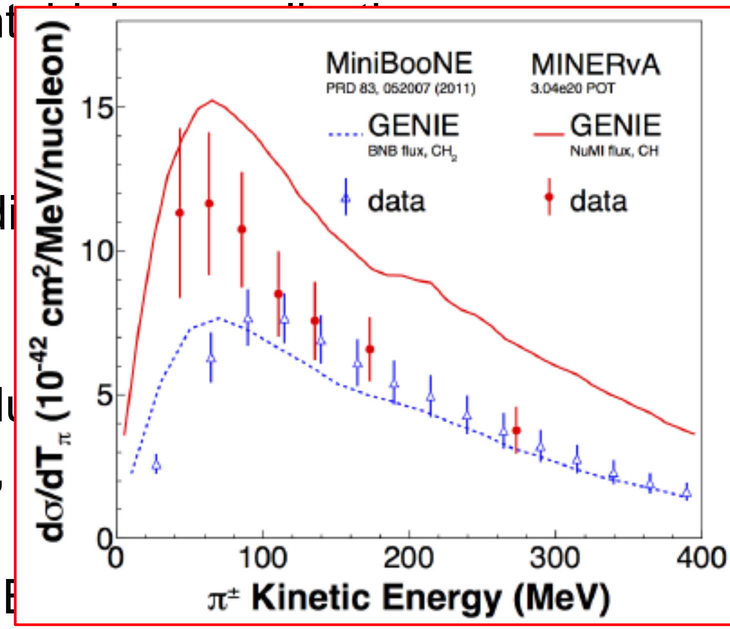
- Is there charged current coherent pion produ

→ yes, data from T2K, MINERvA, ArgoNeuT,

ANL-BNL puzzle

- Normalization difference between ANL and B

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



Pion puzzle

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

5. Open question of neutrino interaction physics (now)

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

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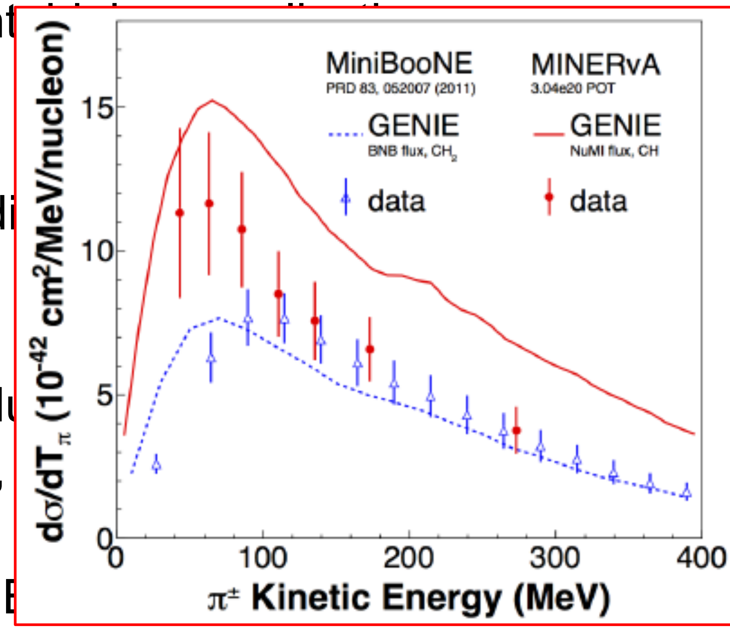


Pion puzzle
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models
→ ???

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

5. Pion puzzle (now)

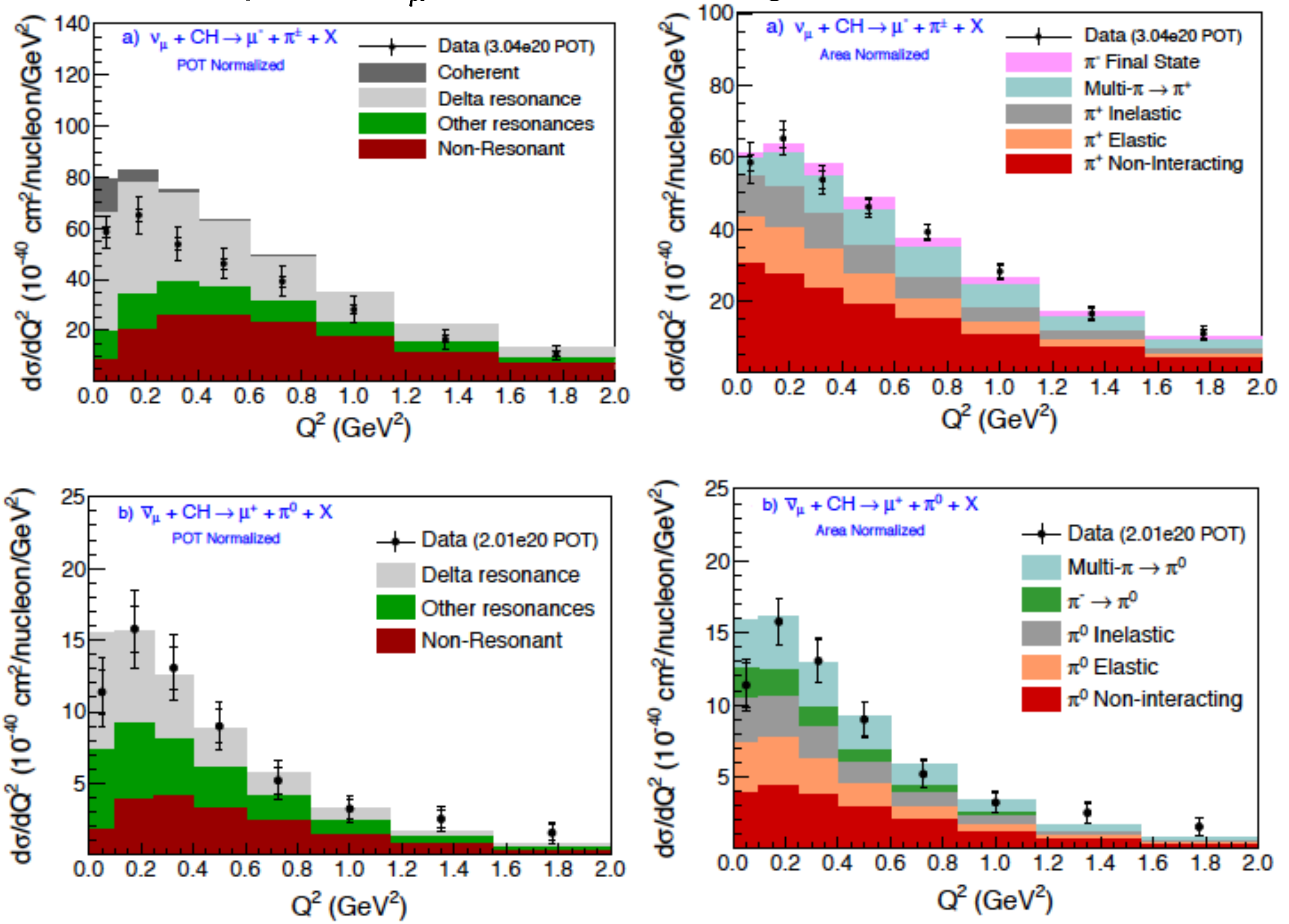
MINERvA $\nu_\mu CC1\pi^+$ vs. $\overline{\nu_\mu} CC1\pi^o$

- In general, $\nu_\mu CC1\pi^+$ has shape, and $\overline{\nu_\mu} CC1\pi^o$ has norm agreement with simulation

It's hard to improve data-MC by tuning FSIs within GENIE.

Reduce non-resonant background.

Add RPA correction to fix low Q²?



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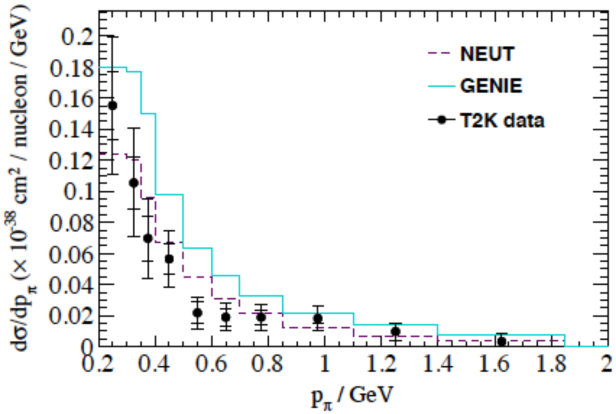
T2K,arXiv:1605.07964,ArgoNeuT,arXiv:1511.00941, MINOS,PRD94(2016)072006
DUET,PRC92(2015)035205,arXiv:1611.05612

5. Pion puzzle (now)

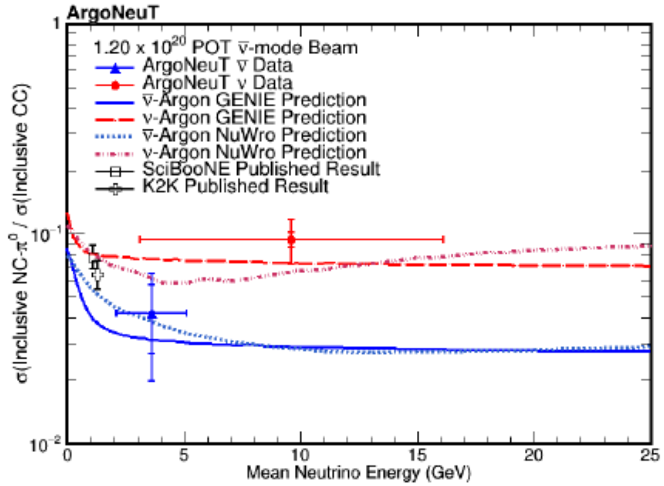
T2K $\nu_\mu CC1\pi^+$ on water

- Large error for inactive target



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

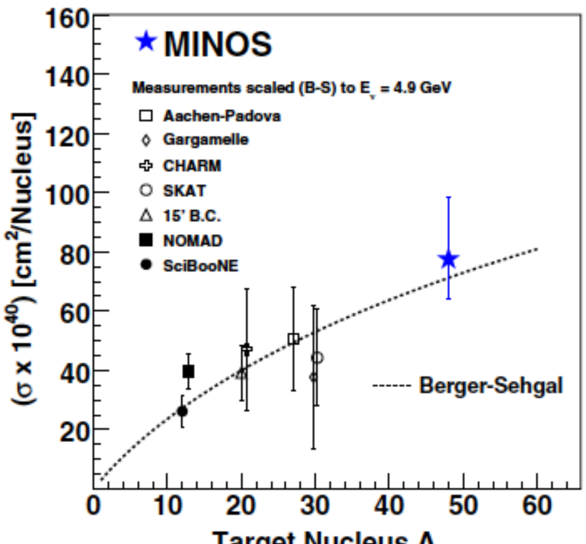
- π^o reconstruction from γ opening angle



Water and argon are the most important targets to study

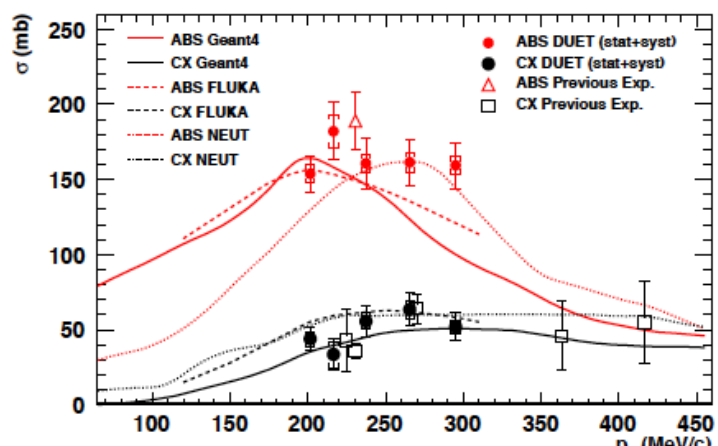
MINOS $\nu_\mu NC\pi^o$ on iron

- A-scaling of coherent pion production



DUET FSI study for π^+ in carbon

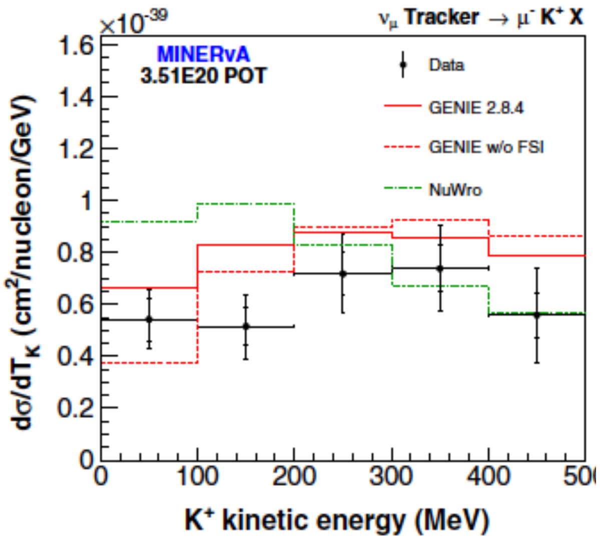
- σ_{ABS} and σ_{CEX} are measured



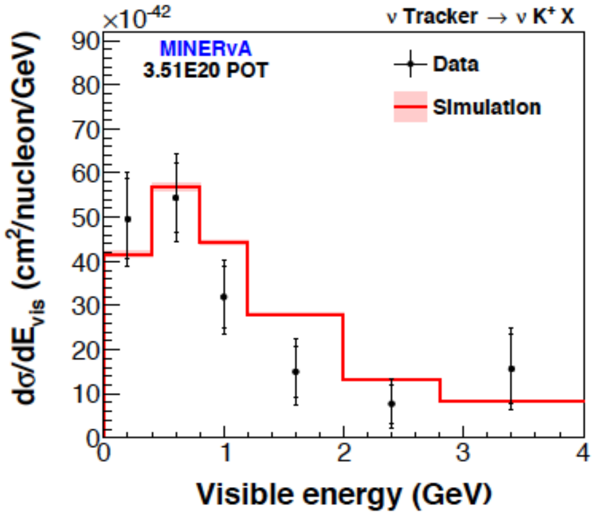
5. Other new MINERvA data (now)

Kaon bombs

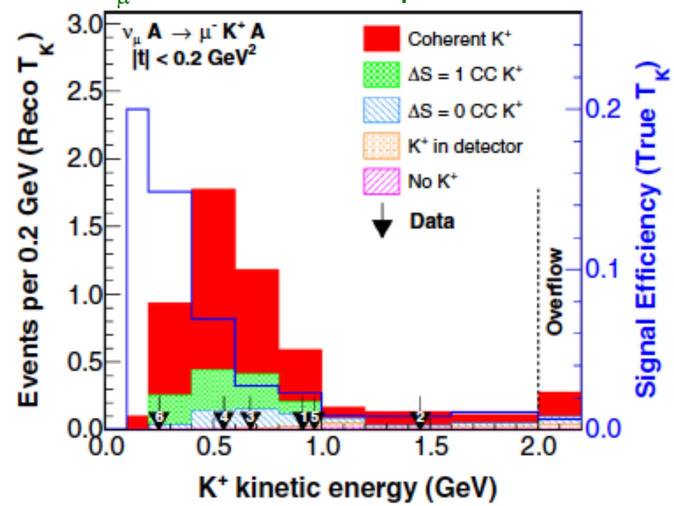
ν_μCC K^+ production



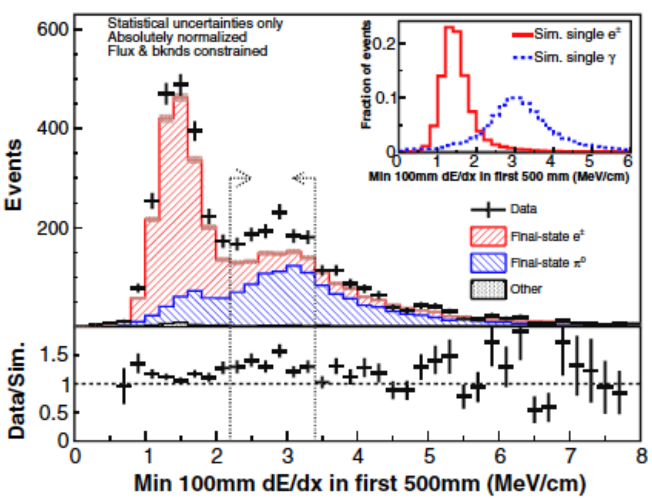
$\nu(\bar{\nu})$NC K^+ production



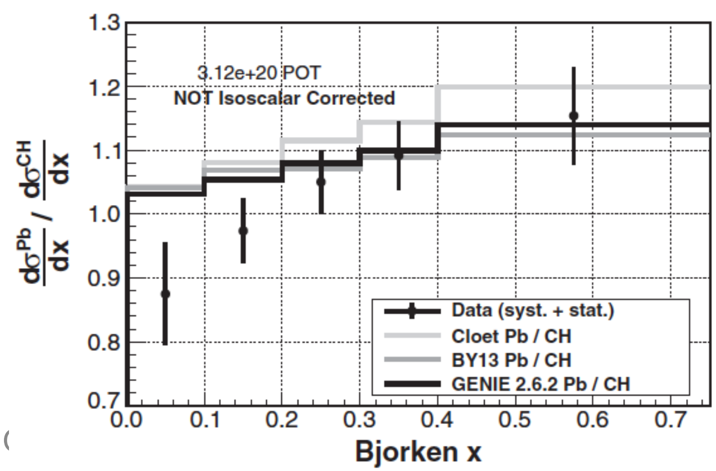
ν_μCC coherent K^+ production



Diffractive pion production



DIS target ratio

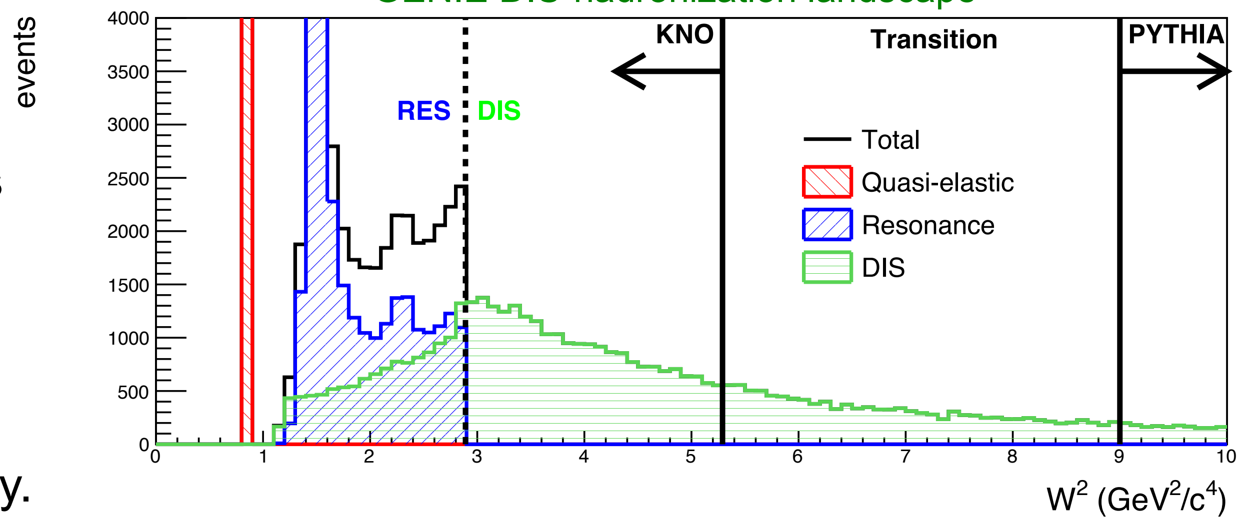


5. Multi-pion production and beyond (now)

Shallow Inelastic Scattering

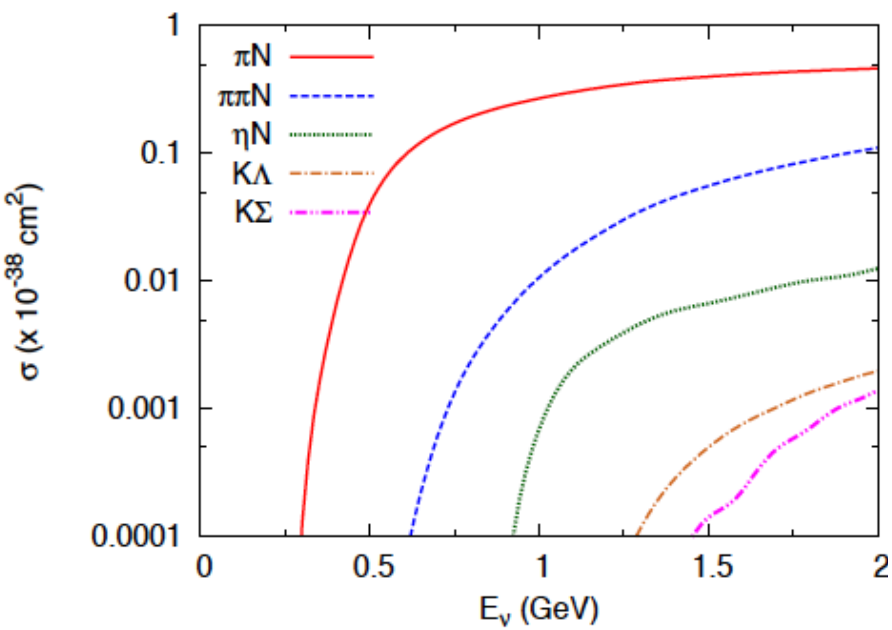
- Very small activities to use DIS and hadronization models in generators

GENIE DIS-hadronization landscape

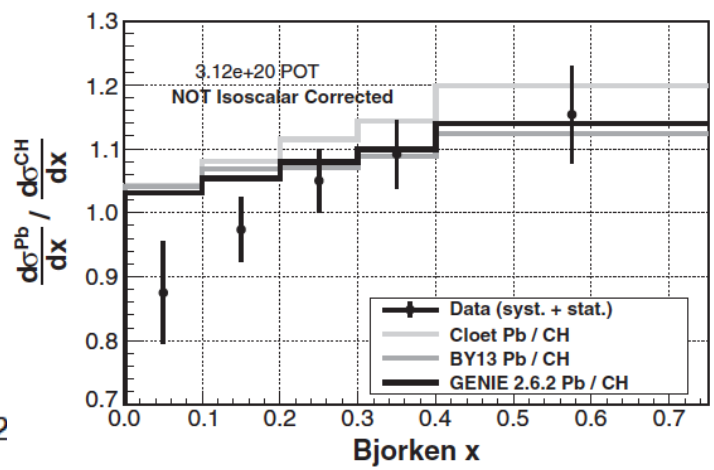


DCC model

- model exists to predict all resonance channels coherently.



DIS target ratio



5. 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.

5. Round table

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1. What are some of the biggest issues we face in calculating ν-A scattering reactions and kinematics?

2. Where are we lacking in experimental measurements? Is there some area where neutrino experiments should focus next? Is there any meaningful re-analysis of existing data that can/should be done?

3. What can we learn from e-scattering? Do we need new e- scattering experiments?

4. Are our theoretical efforts and generators work connecting in the way that they should?

5. How do we connect the relativistic and non-relativistic worlds?

6. Do we know enough about the ν-N interaction? Do we need neutrino hydrogen/deuterium data?

7. What is the relation between 2p2h and initial nucleon (deuterium) pairs inside the nucleus? Are we double counting? How to model both?

8. What are some of the most important points that you think came out of this workshop?

5. Conclusion

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Neutrino Interaction Physics

electron scattering

many-body problem

Weak interaction

Neutrino oscillation

EMC effect

Nucleon correlation

Spin physics

Dark matter

Heavy ion collision

Thank you for your attention!

Backup

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

5. Shallow Inelastic Scattering (SIS)

Cross section

$W^2 < 2.9$ GeV^2 : RES

$W^2 > 2.9$ GeV^2 : DIS

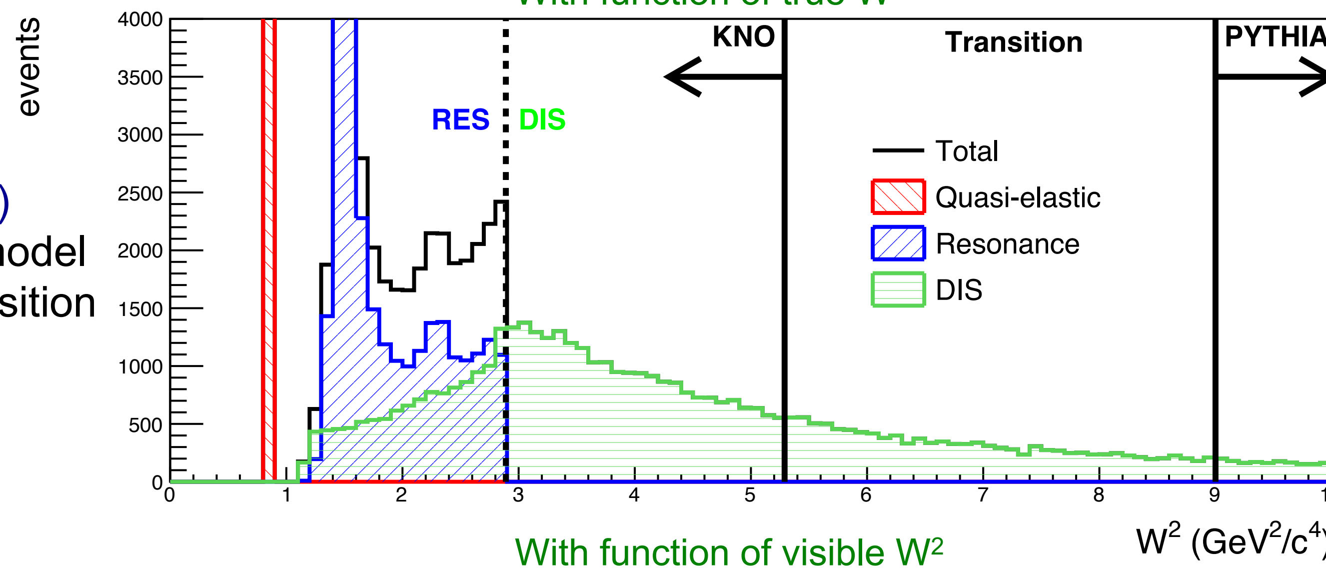
Hadronization (AGKY model)

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

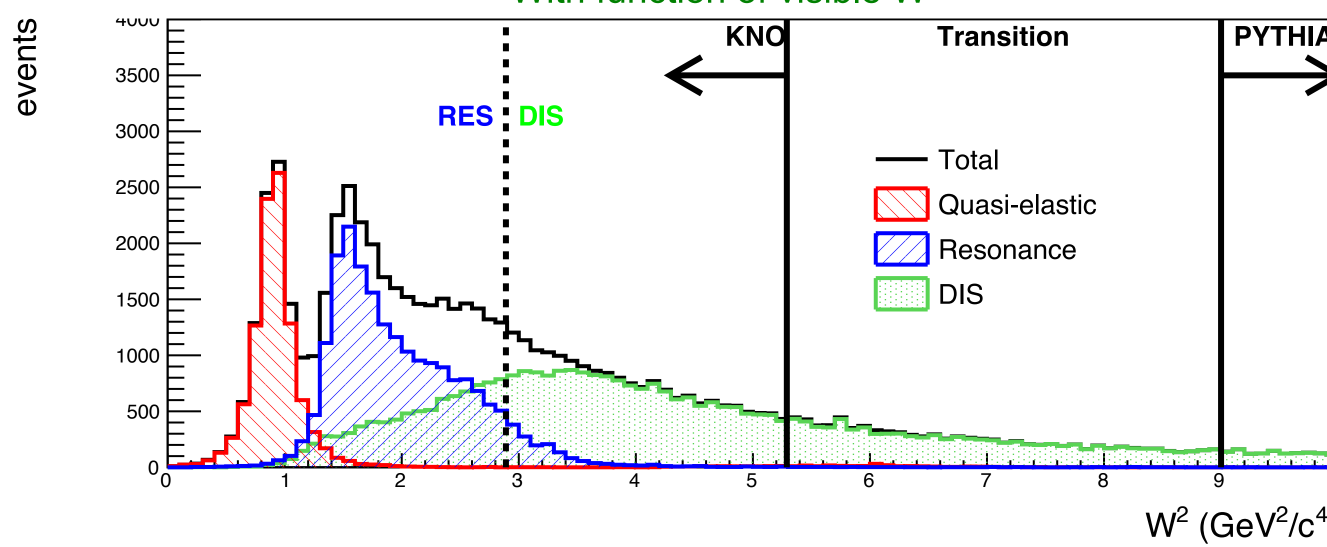
2.3GeV^2 $< W^2 <$ 9.0GeV^2 : transition

9.0GeV^2 $< W^2$: PYTHIA6

With function of true W²



With function of visible W²



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