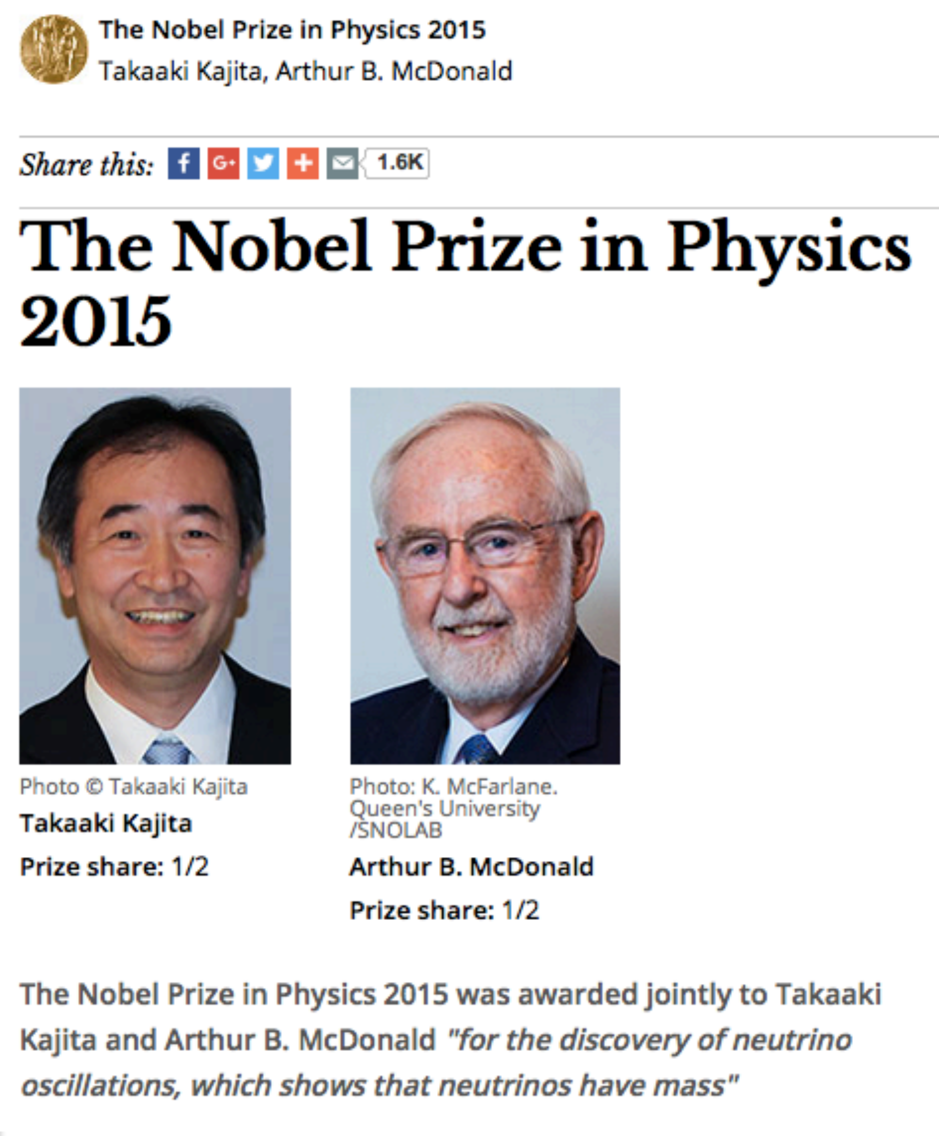
“Year of Neutrinos”

BREAKTHROUGH
PRIZE

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
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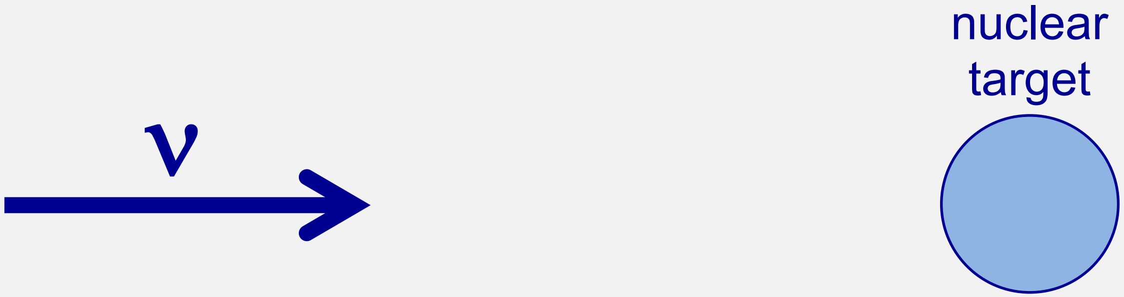
Photo: K. McFarlane. Queen's University /SNOLAB
Arthur B. McDonald
Prize share: 1/2

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"*



ν

nuclear
target

Fun Timely Intellectual Adorable!

TK, Martini, JPhysG45(2017)1

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nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

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Nucleon correlation

EMC effect

electron scattering

Dark matter

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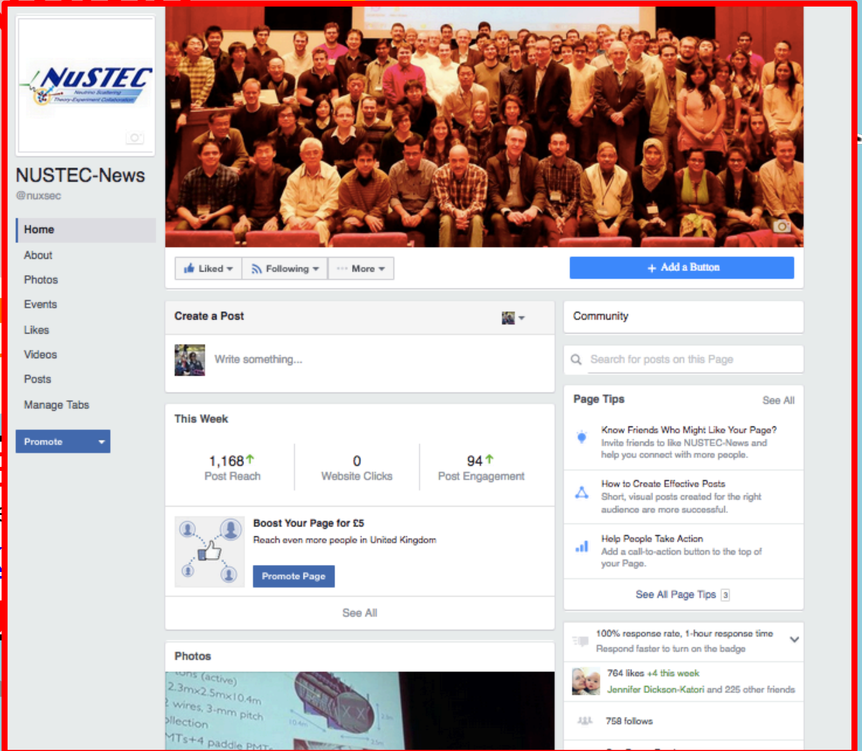

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TK, Martini, JPhysG45(2017)1

Physics of Neutrino Interactions around 1-10 GeV

Teppei Katori
Queen Mary University of London
HEP seminar, Univ. Southampton, Jan. 27, 2018

outline

1. **Neutrino Interaction Physics**
2. **Charged-Current Quasi-Elastic (CCQE) interaction**
3. **Resonance Single Pion Production**
4. **Shallow inelastic scattering, DIS, and Hadronization**
5. **Conclusion**

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1. Neutrino Interaction Physics

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

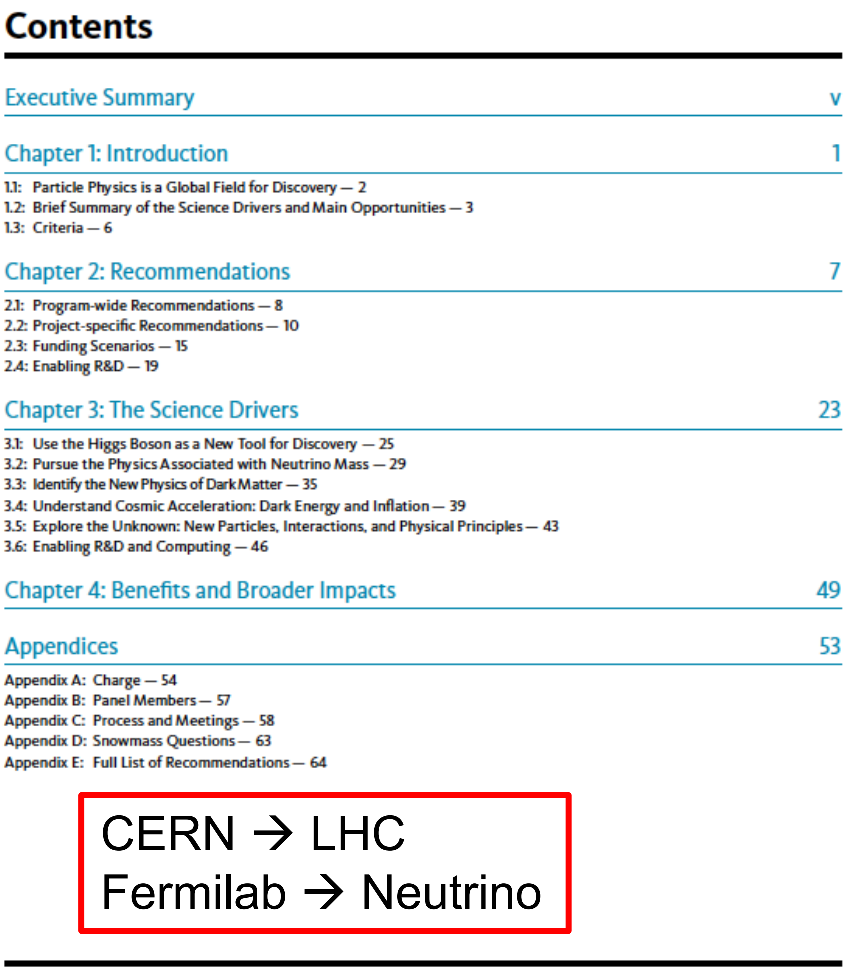
3. Resonance Single Pion Production

4. Shallow inelastic scattering, DIS, and Hadronization

5. Conclusion

1. Neutrino physics is the future of particle physics

P5 (particle physics project prioritization panel) recommend neutrinos to DOE



Contents

CERN → LHC
Fermilab → Neutrino

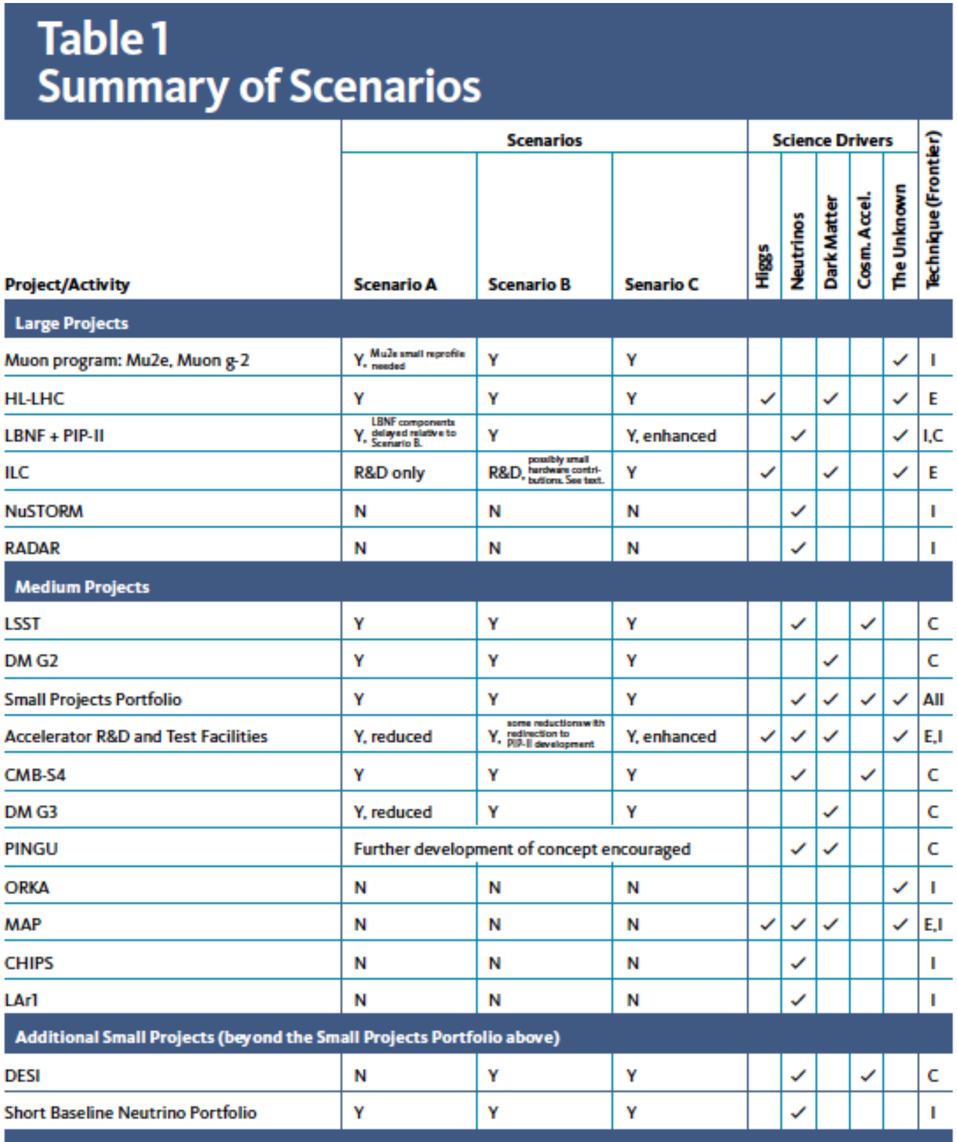


Table 1
Summary of Scenarios

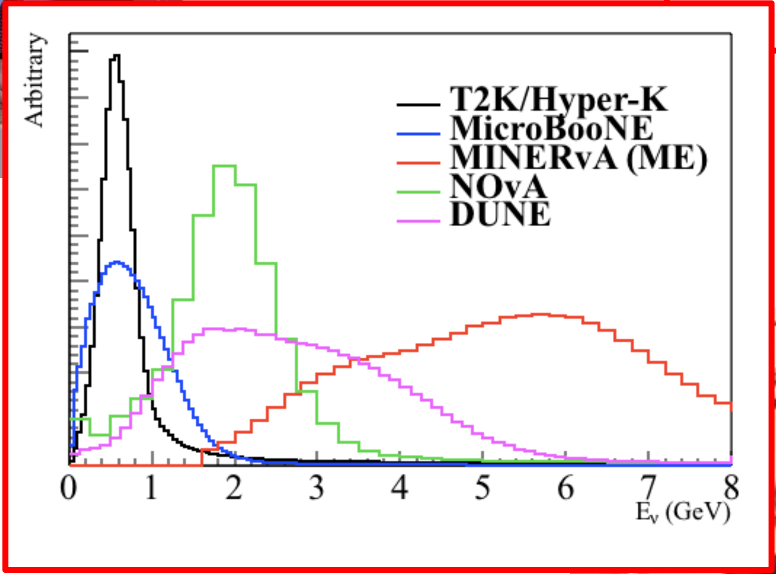
Project/Activity	Scenarios Scenario A	 Scenario B	 Senario C	Science Drivers Higgs	 Neutrinos	 Dark Matter	 Cosm. Accel.	 The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

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

1. Next goal of high energy physics

Establish Neutrino Standard Model (νSM)

- SM + 3 active massive neutrinos

Unknown parameters of νSM

1. Dirac CP phase
2. θ_{23} ($\theta_{23}=40^{o}$ and 50^{o} are same for $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$)
3. normal mass ordering $m_1<m_2<m_3$ or inverted mass ordering $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase
6. absolute neutrino mass

} not relevant to neutrino oscillation experiment(?)

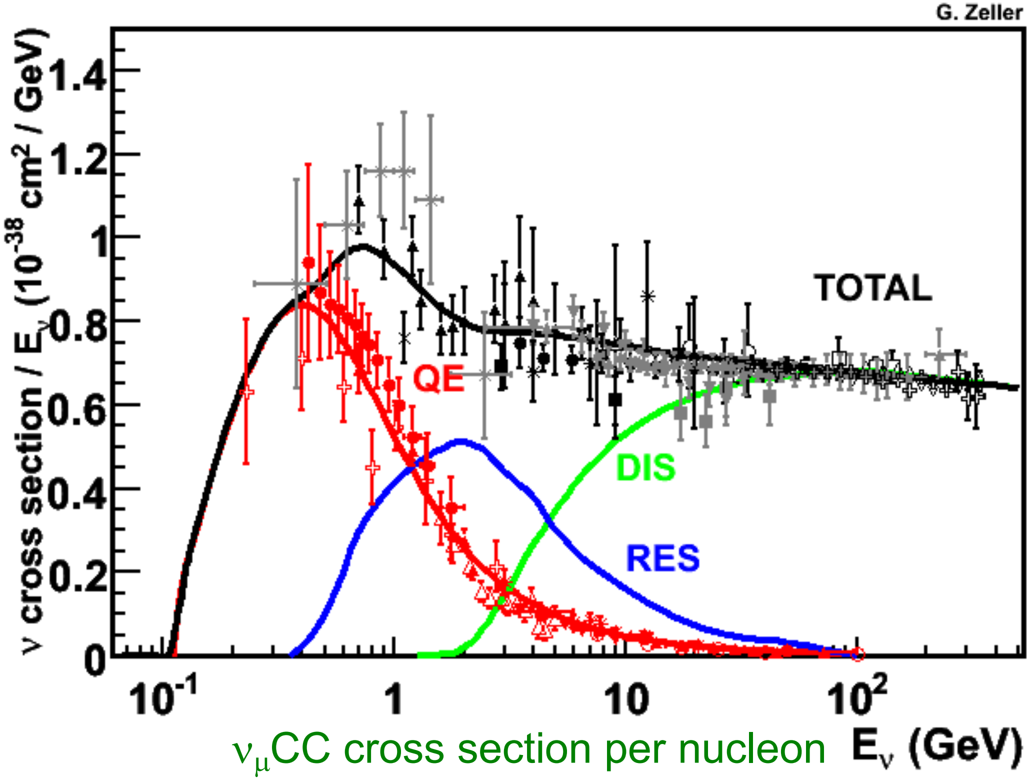
We need higher precision experiments around 1-10 GeV.

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

- Past to Present: K2K, MiniBooNE, MINOS, T2K, DeepCore, Reactors
- Present to Future: T2K, NOvA, PINGU, ORCA, Hyper-Kamiokande, DUNE



ν_μCC cross section per nucleon

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

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

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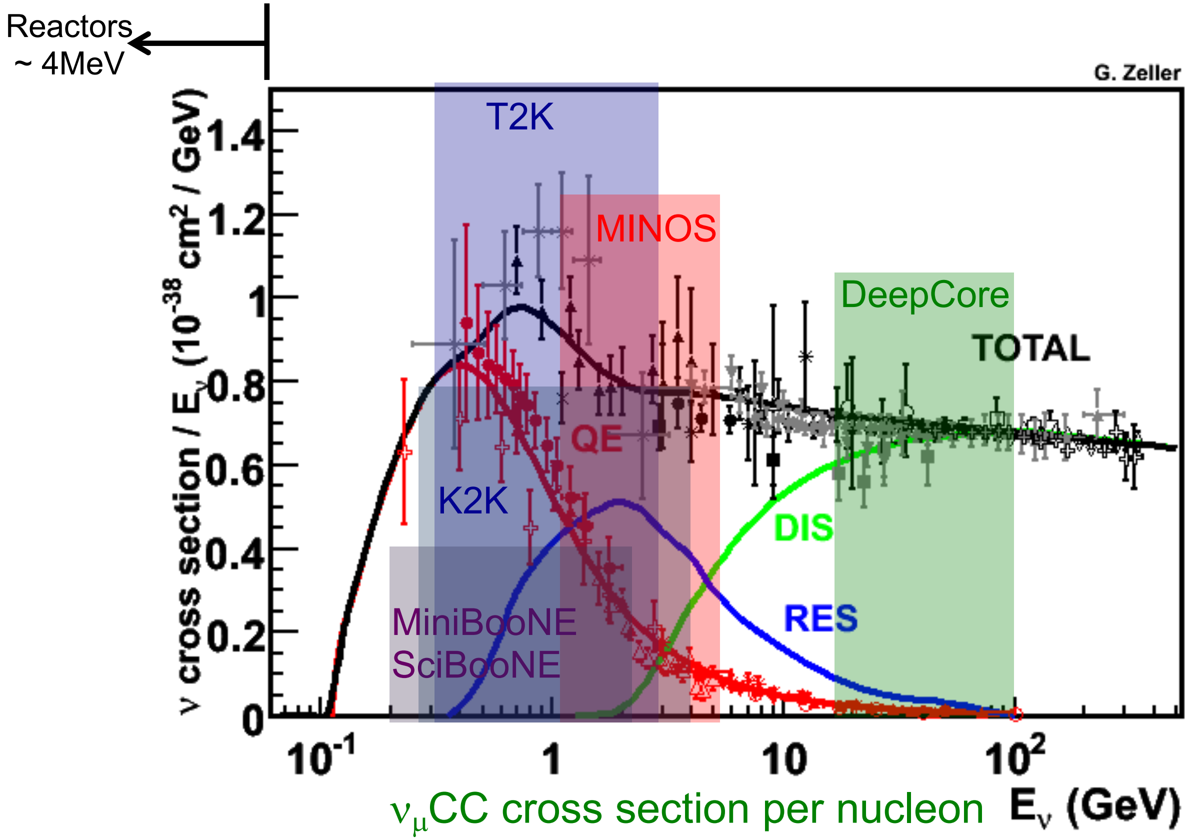

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Teppei Katori

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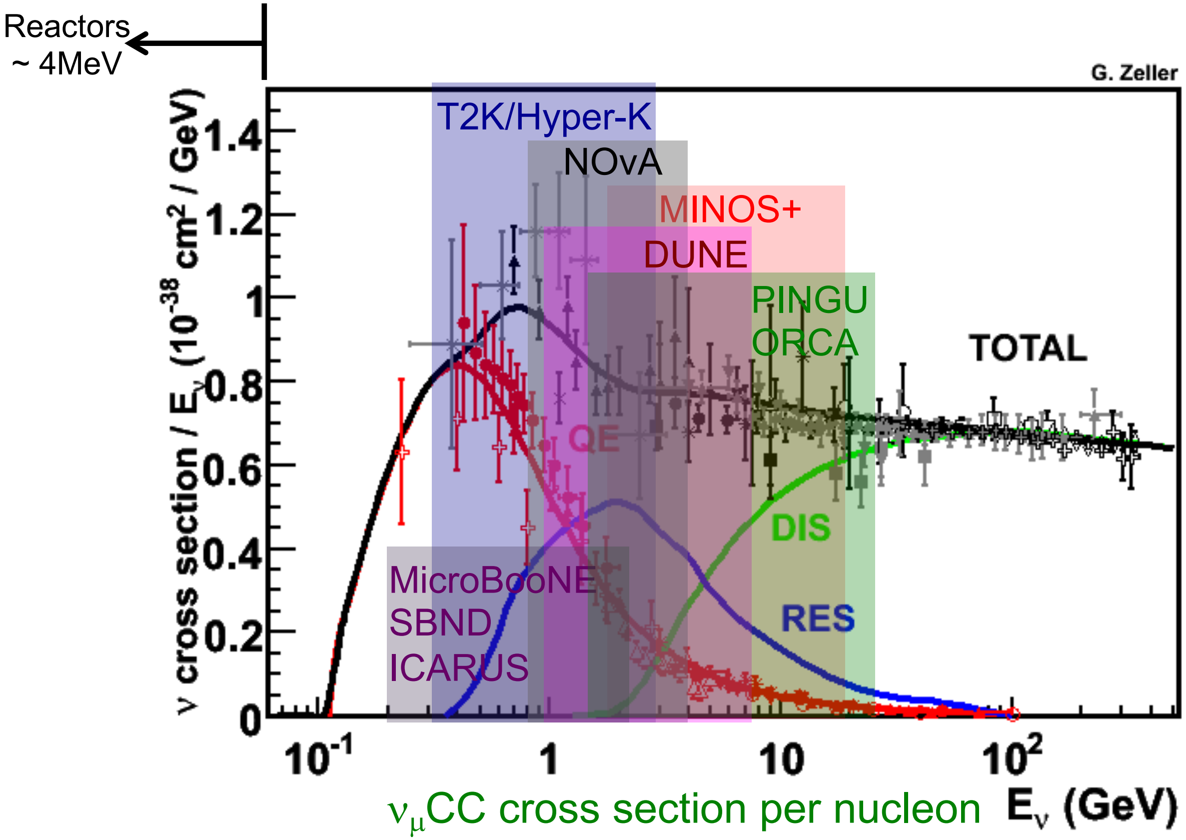

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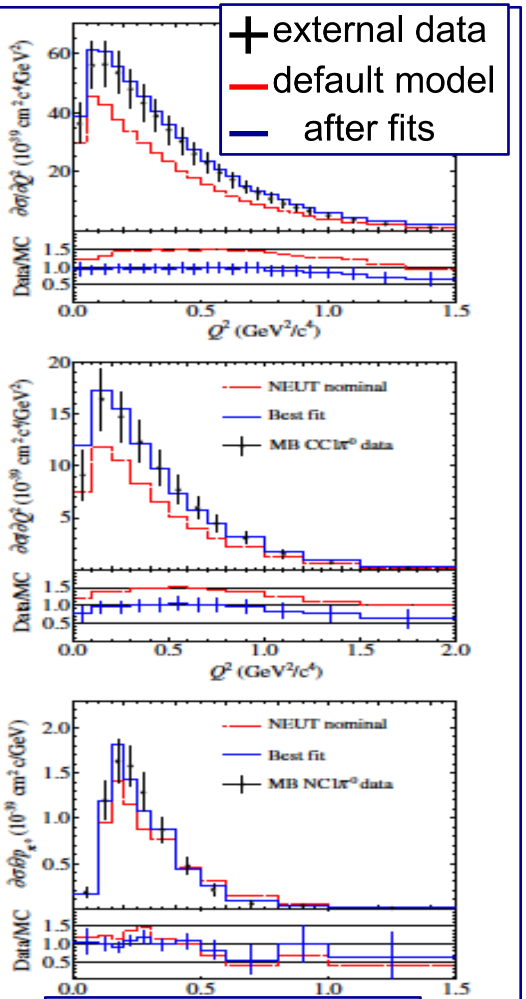
T2K, PRD88(2013)032002; PRL112(2014)061802

1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics

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

1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE
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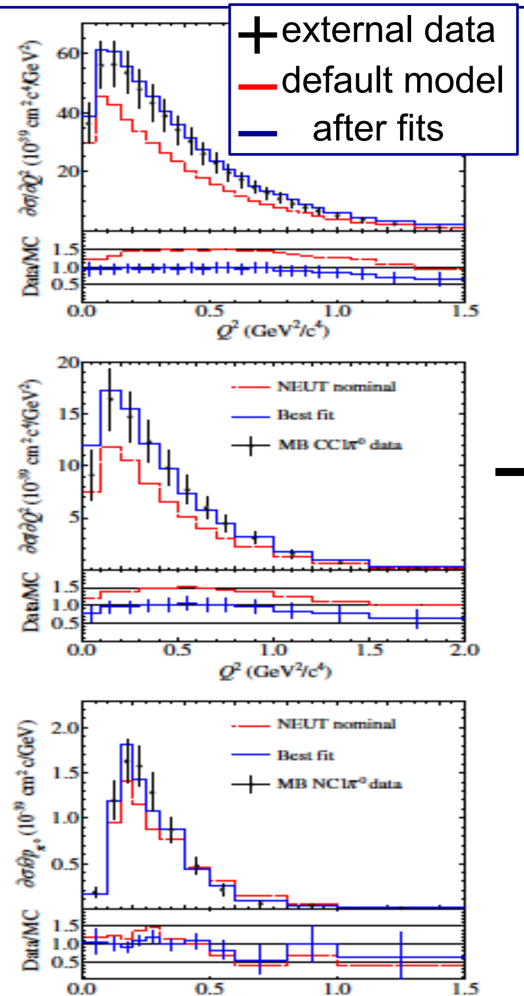
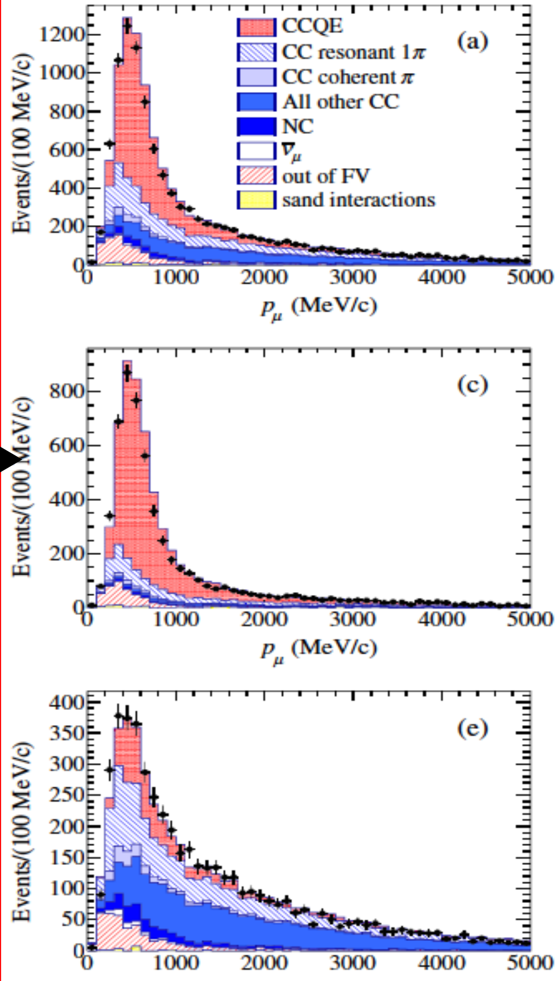
Internal constraint

Near detector
oscillation non-sensitive channels



External data fit

→



T2K ND280 data fit

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

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

1. e.g.) T2K oscillation experiments

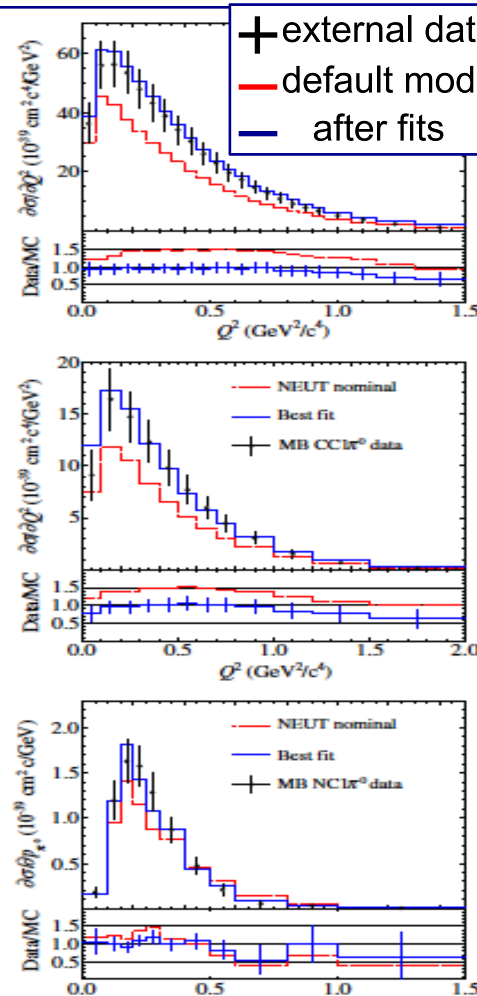
External constraint

MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

Internal constraint

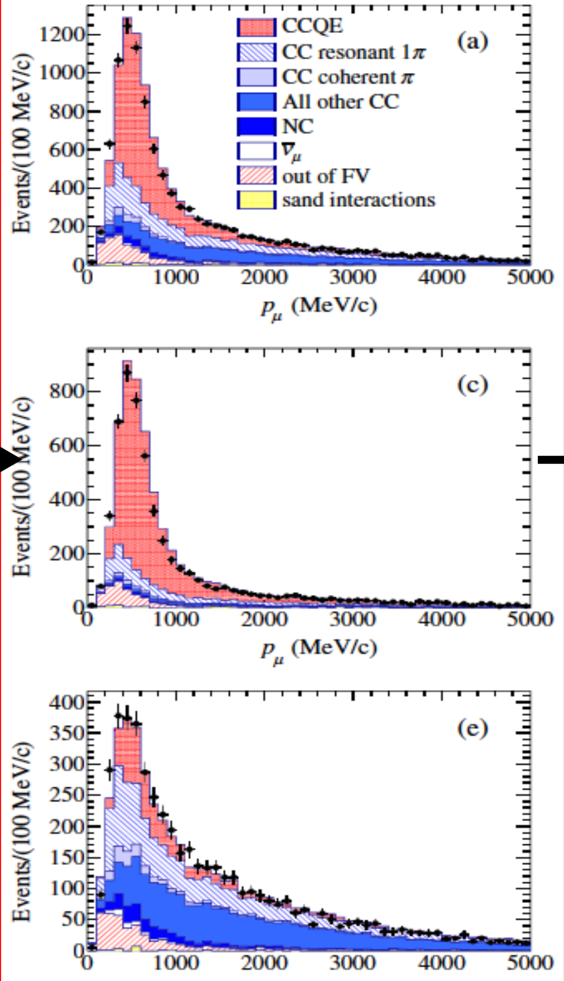
Near detector
oscillation non-sensitive channels

Neutrino interaction model is a large systematics of neutrino oscillation experiment

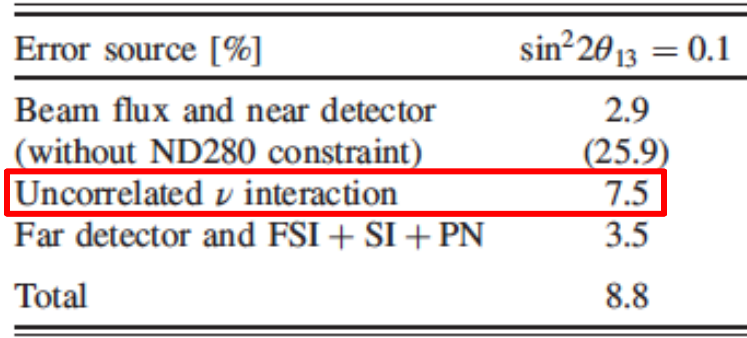


+ external data
— default model
— after fits

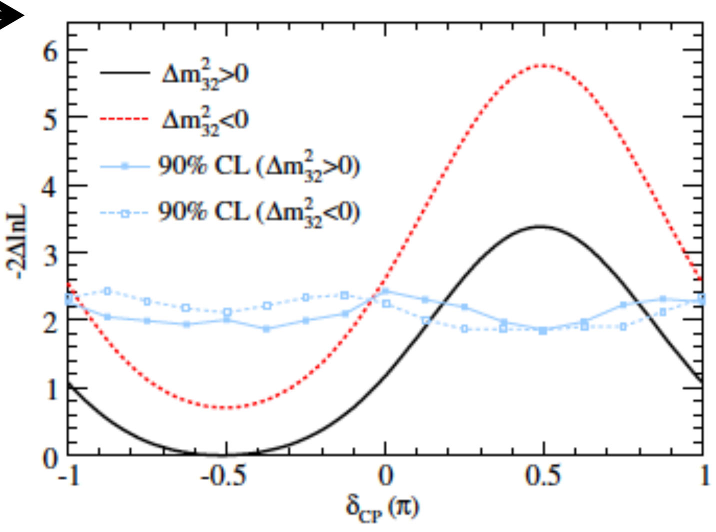
External data fit



T2K ND280 data fit



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



oscillation result

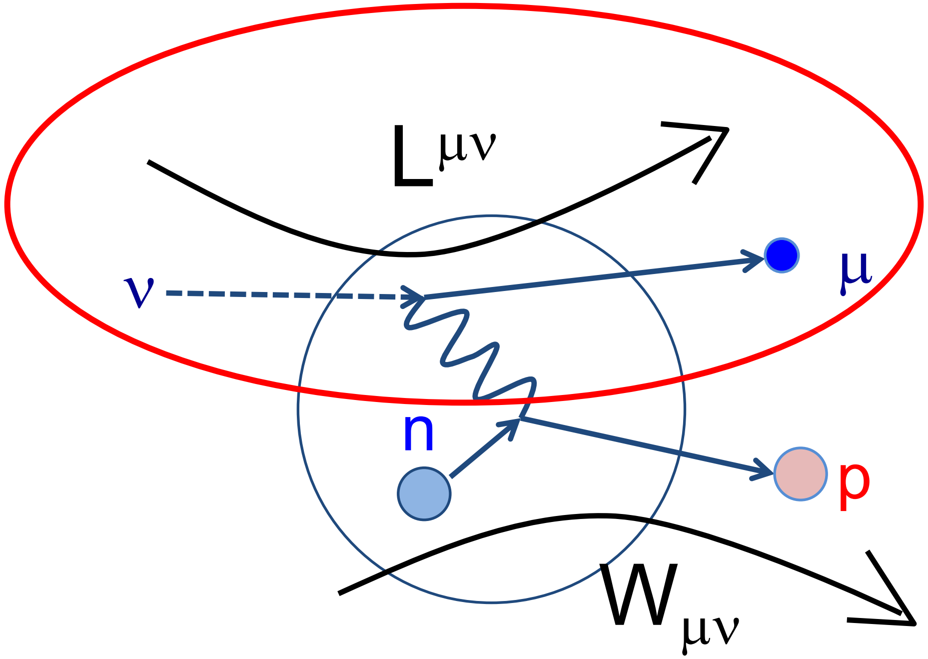
1. Neutrino cross-section formula

Cross-section
- product of Leptonic and Hadronic tensor

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

Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)



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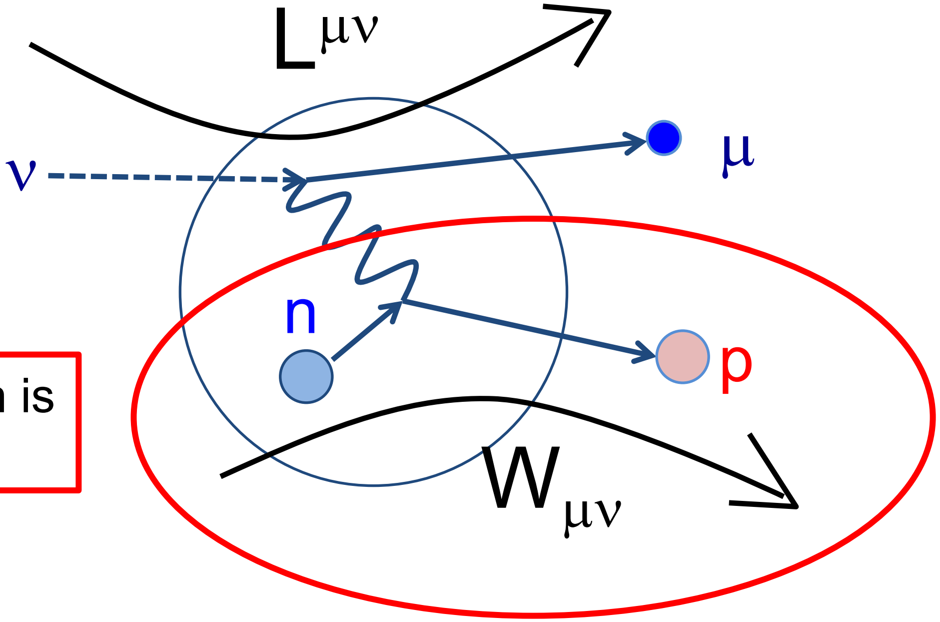


All complication of neutrino cross-section is how to model the hadronic tensor part

1. Neutrino Interaction Physics

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

3. Resonance Single Pion Production

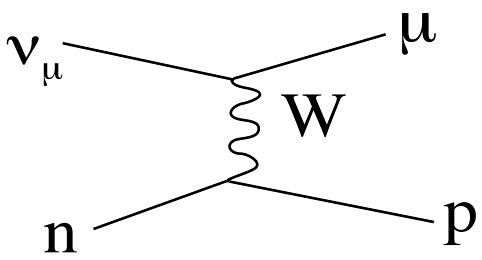
4. Shallow inelastic scattering, DIS, and Hadronization

5. Conclusion

2. Charged Current Quasi-Elastic scattering (CCQE)

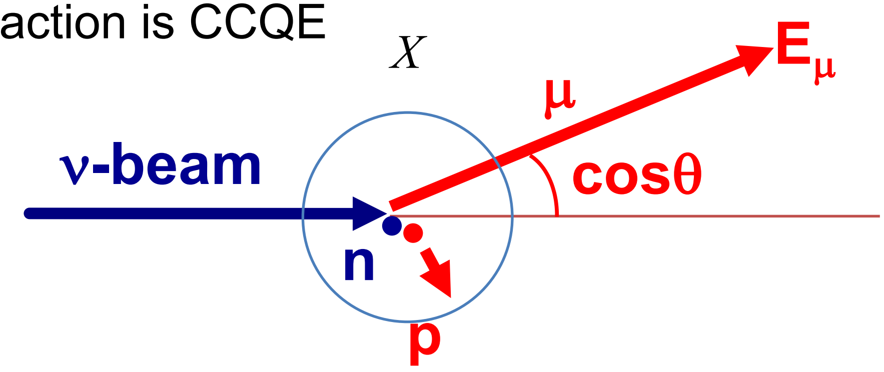
The simplest and the most abundant interaction around ~1 GeV.

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



Neutrino energy is reconstructed from the observed lepton kinematics
"QE assumption"

1. assuming neutron at rest
2. assuming interaction is CCQE



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

CCQE is the single most important channel of neutrino oscillation physics
T2K, NOvA, microBoonE, Hyper-Kamiokande, DUNE (2nd maximum)…etc

MiniBooNE,PRD81(2010)092005

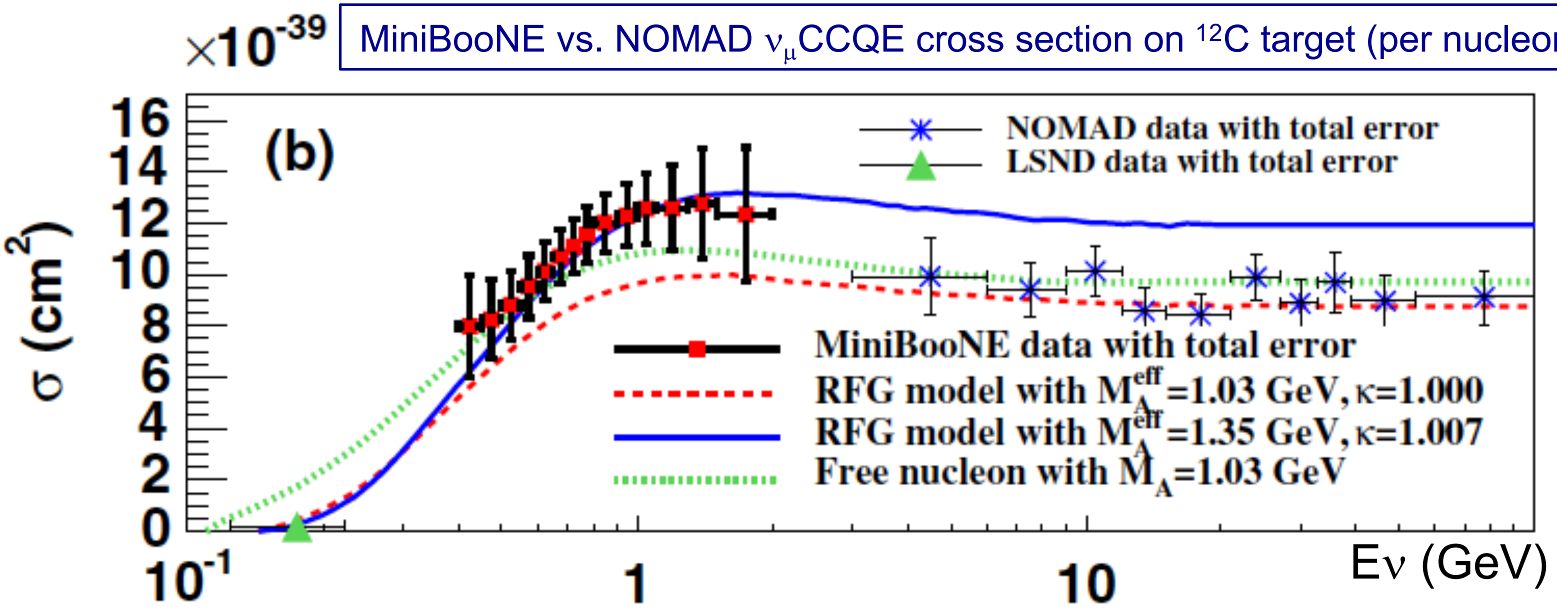
2. Charged Current Quasi-Elastic scattering (CCQE)

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

Simulation disagree with many modern accelerator based neutrino experiment data, neither shape (low Q^2 and high Q^2) nor normalization. By tuning axial mass (M_A) 1.2-1.3 GeV, simulations successfully reproduce data both shape and normalization.

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

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



2. Flux-integrated differential cross-section

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

We want theorists to use our data, but flux-unfolding (model-dependent process) lose details of measurements…

2. Flux-integrated differential cross-section

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

We want theorists to use our data, but flux-unfolding (model-dependent process) lose details of measurements…

Now, all modern experiments publish flux-integrated differential cross-section
→ Detector efficiency corrected event rate
→ Theorists can reproduce the data with neutrino flux tables from experimentalists
→ Minimum model dependent, useful for nuclear theorists

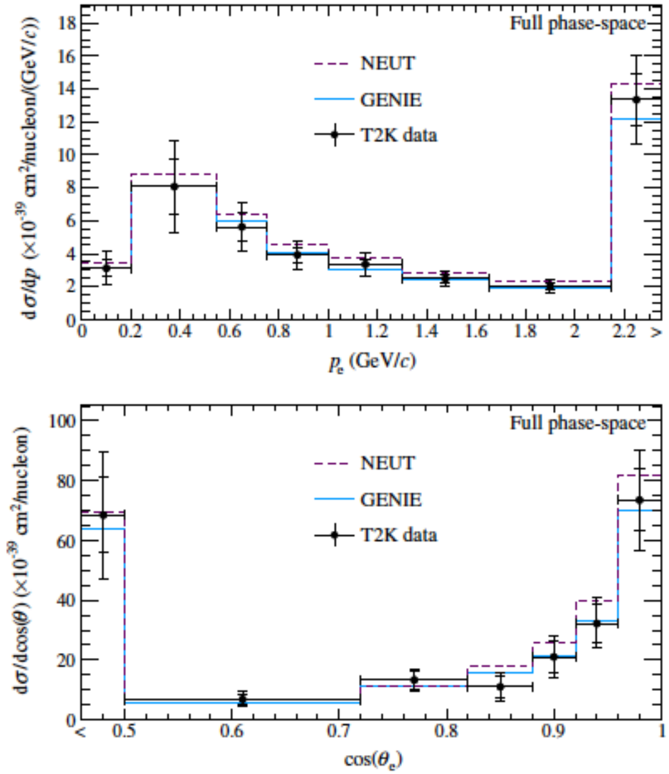
These data play major roles to study/improve neutrino interaction models by theorists

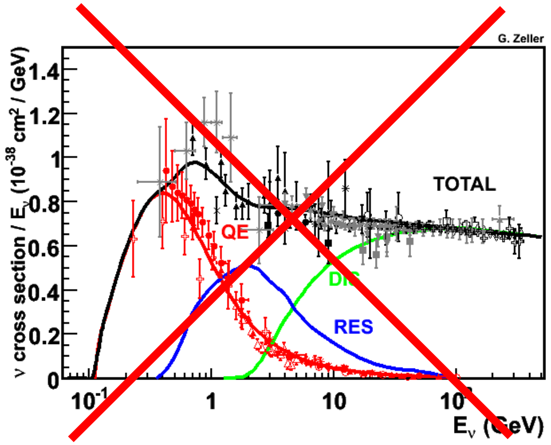
2. Flux-integrated differential cross-section

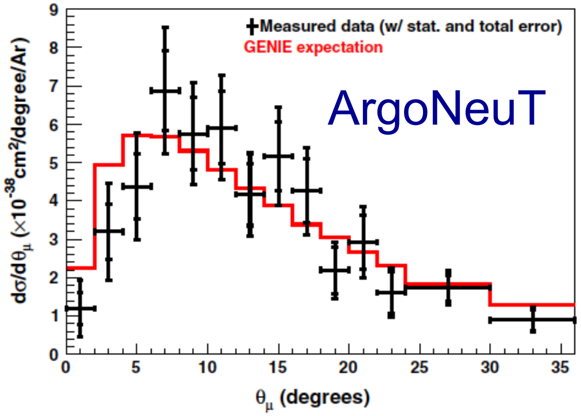
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

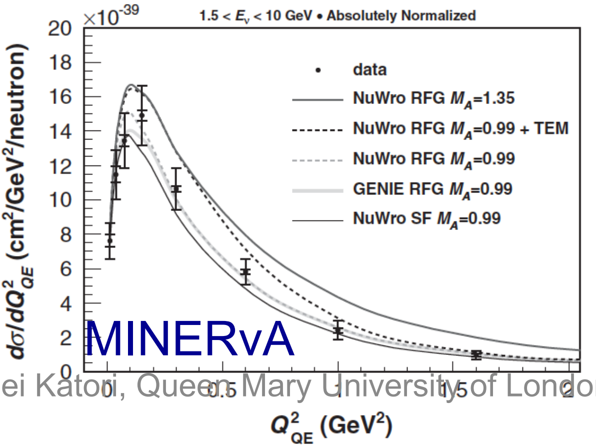
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

T2K

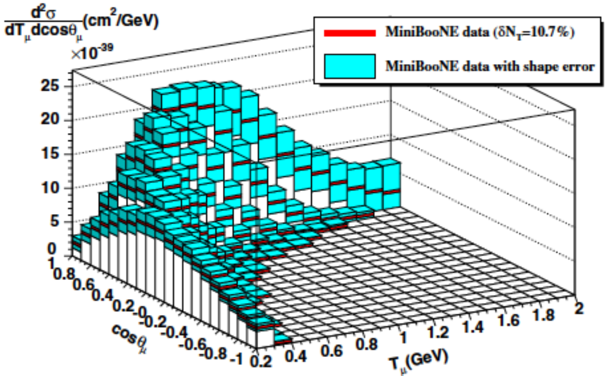








MiniBooNE



PDG2014 Section 49 “Neutrino Cross-Section Measurements”

2. Flux-integrated differential cross-section

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

Theorists

Experimentalists

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

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

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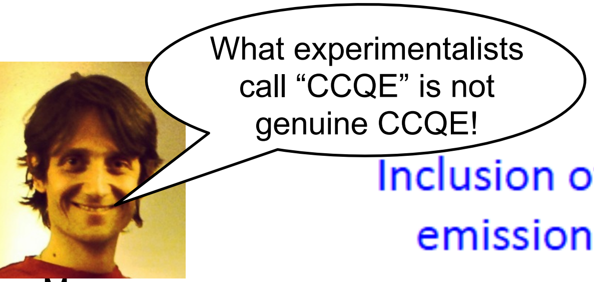
flux-integrated differential cross-section data allow theorists and experimentalists talk first time in neutrino interaction physics history

Martini et al,PRC80(2009)065501

2. The solution of CCQE puzzle

Presence of 2-body current

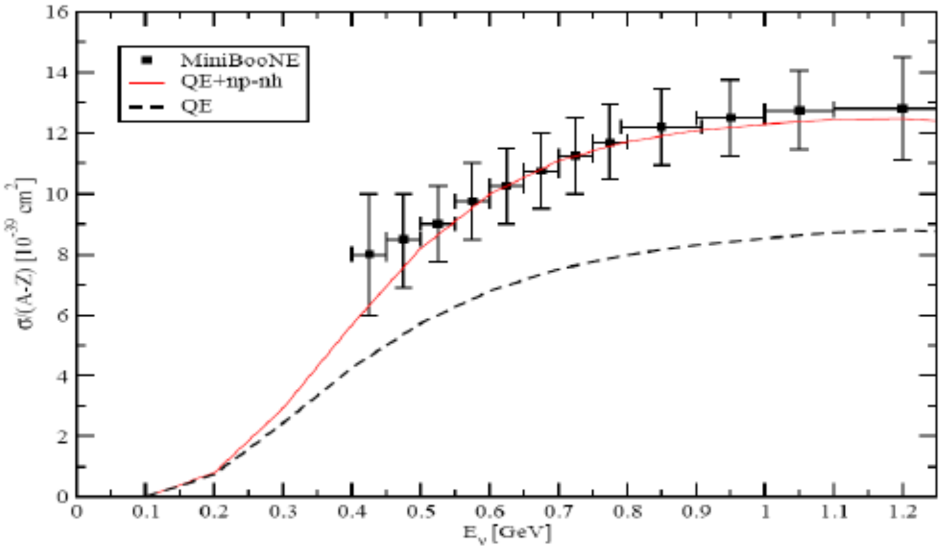
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

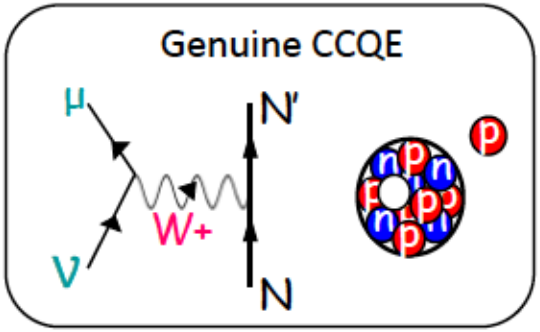


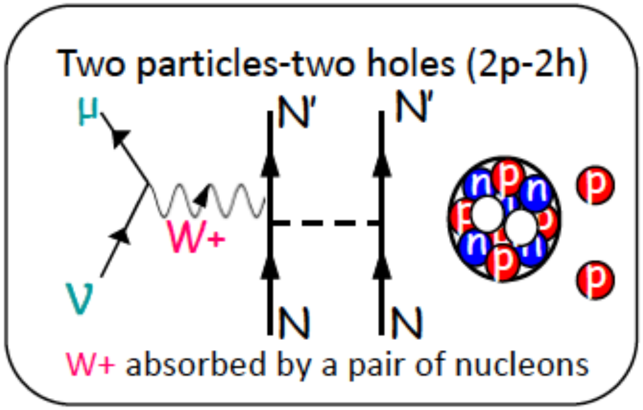
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







W+ absorbed by a pair of nucleons

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

2. The solution of CCQE puzzle

Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al

Marco
Martini
(Saclay)

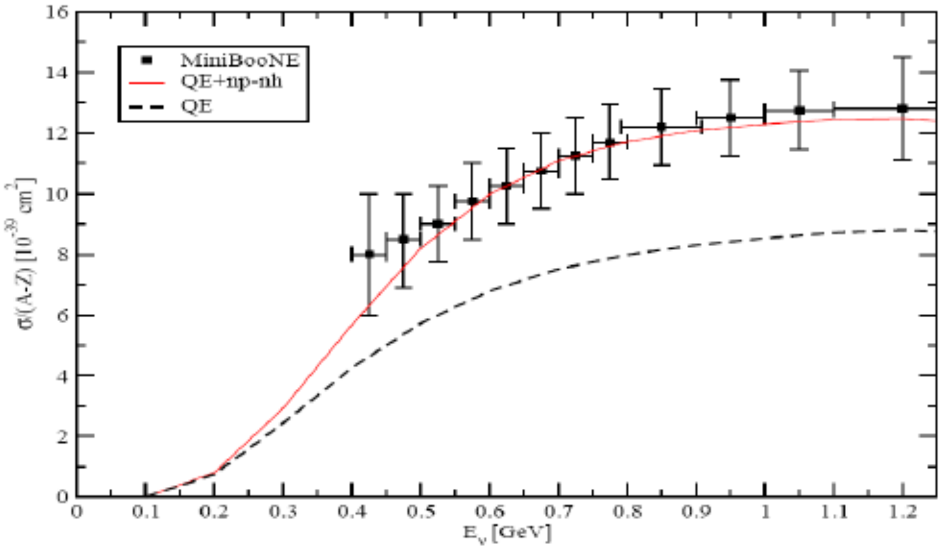
What experimentalists call “CCQE” is not genuine CCQE!

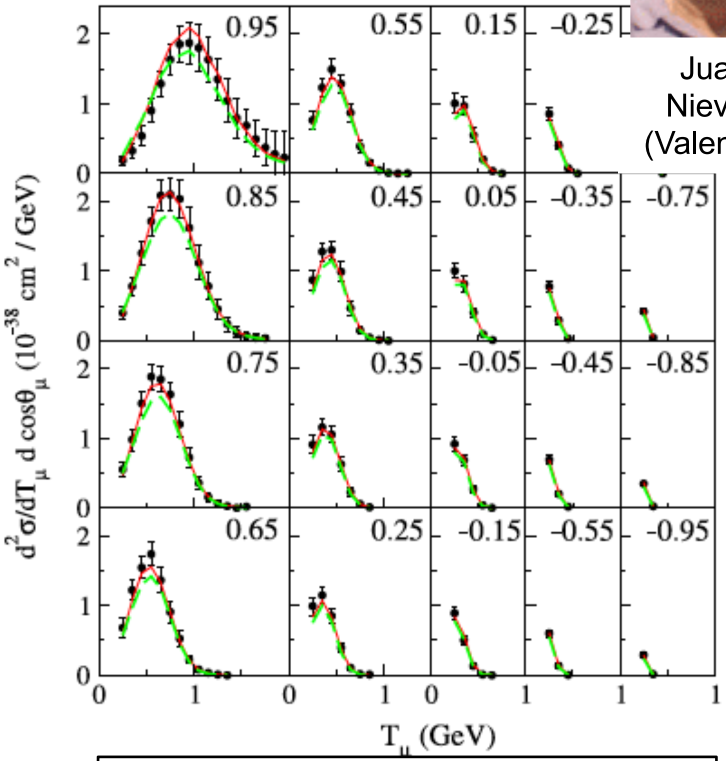
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

Juan
Nieves
(Valencia)

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





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

Queen Mary
University of London

Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72

2. The solution of CCQE puzzle

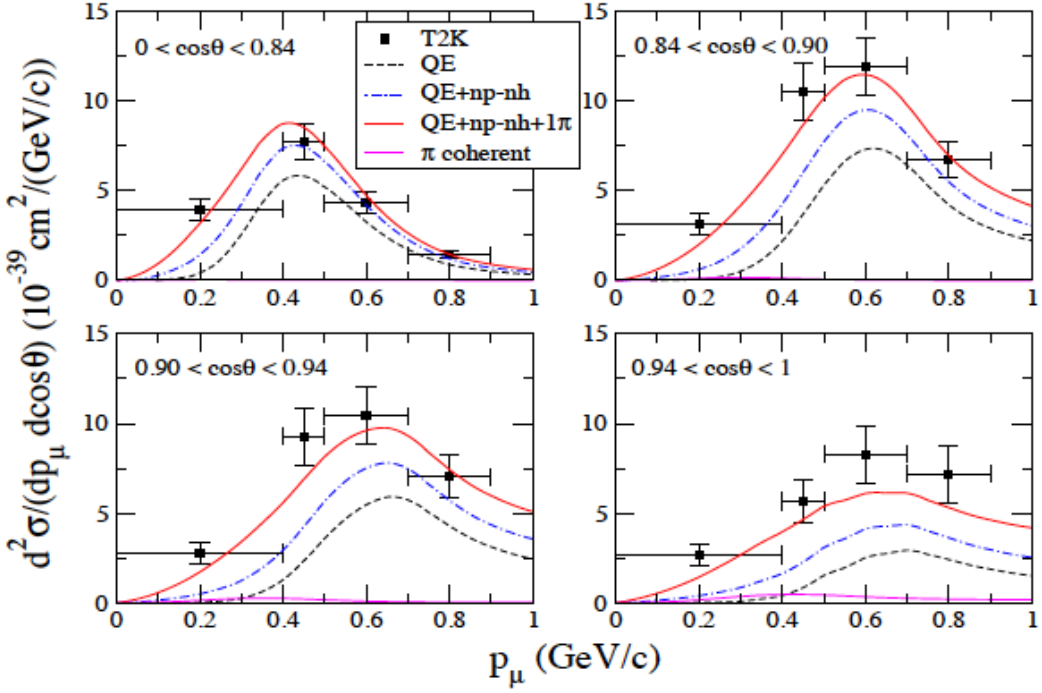
Presence of 2-body current

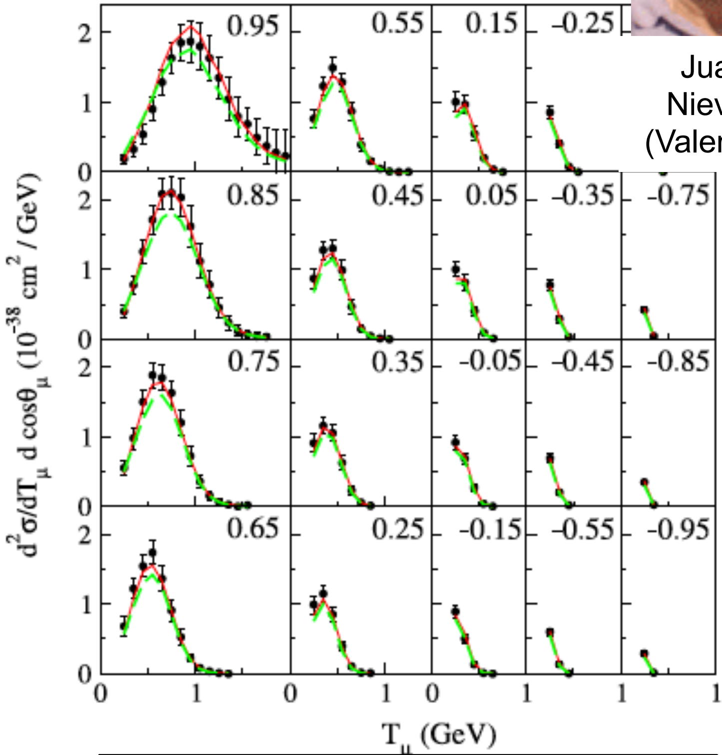
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

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

Juan Nieves (Valencia)

Martini model vs. T2K CC double differential cross-section data





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

Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72

2. The solution of CCQE puzzle

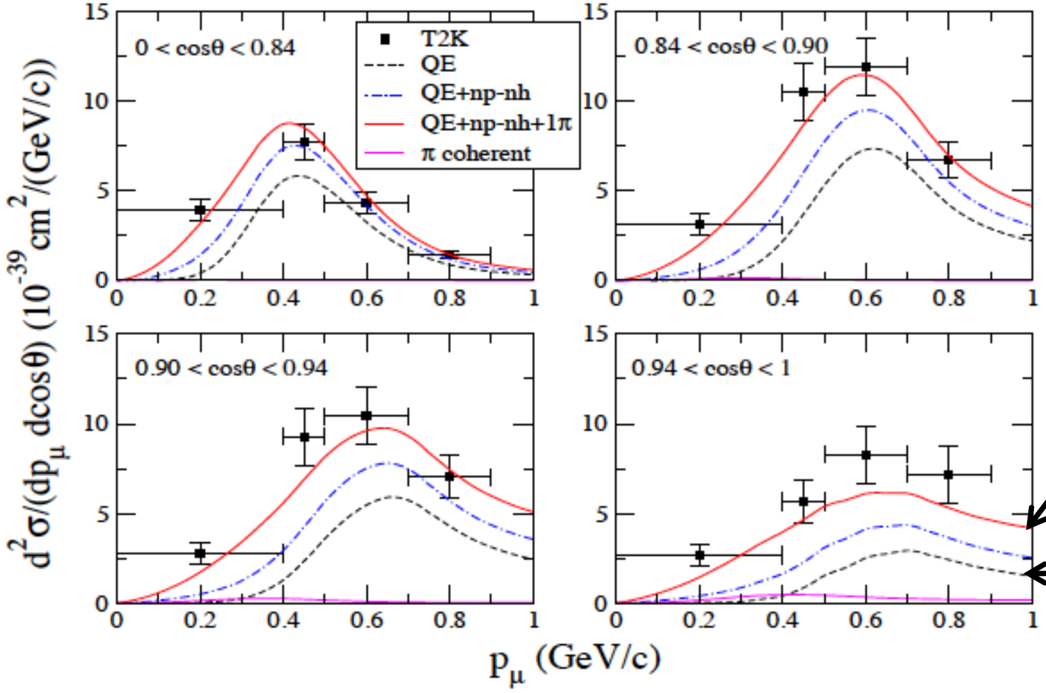
Presence of 2-body current

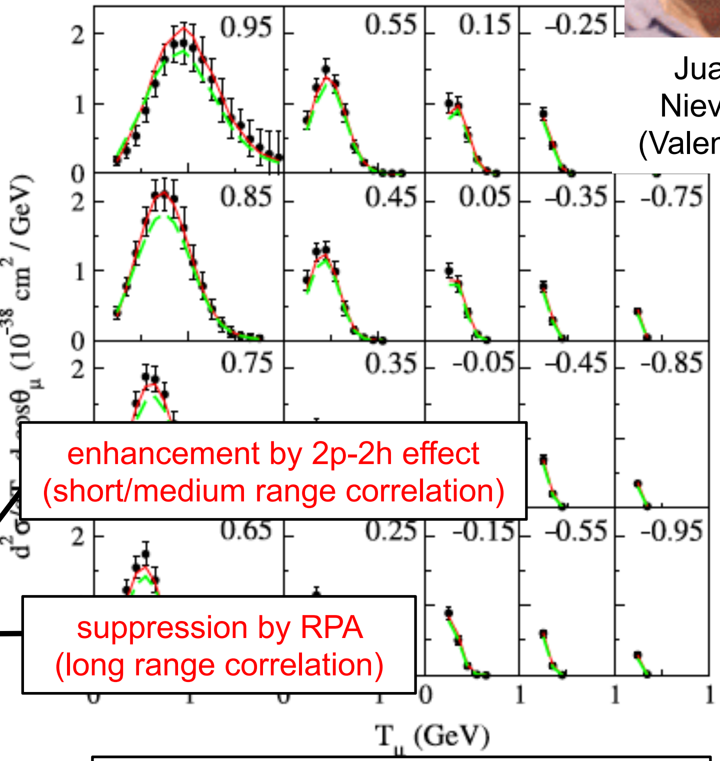
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

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

Juan
Nieves
(Valencia)

Martini model vs. T2K CC double differential cross-section data





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

suppression by RPA (long range correlation)

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

Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRL112(2014)182502, PRC91(2015)062501

2. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato
(Argonne)

Ab-initio calculation

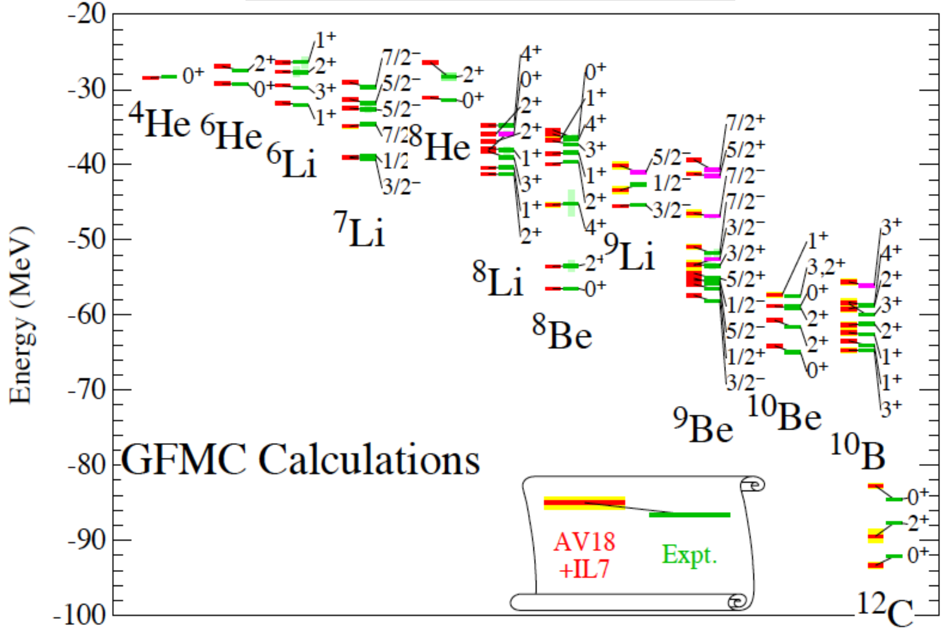
- Green's function Monte Carlo (GFMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

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

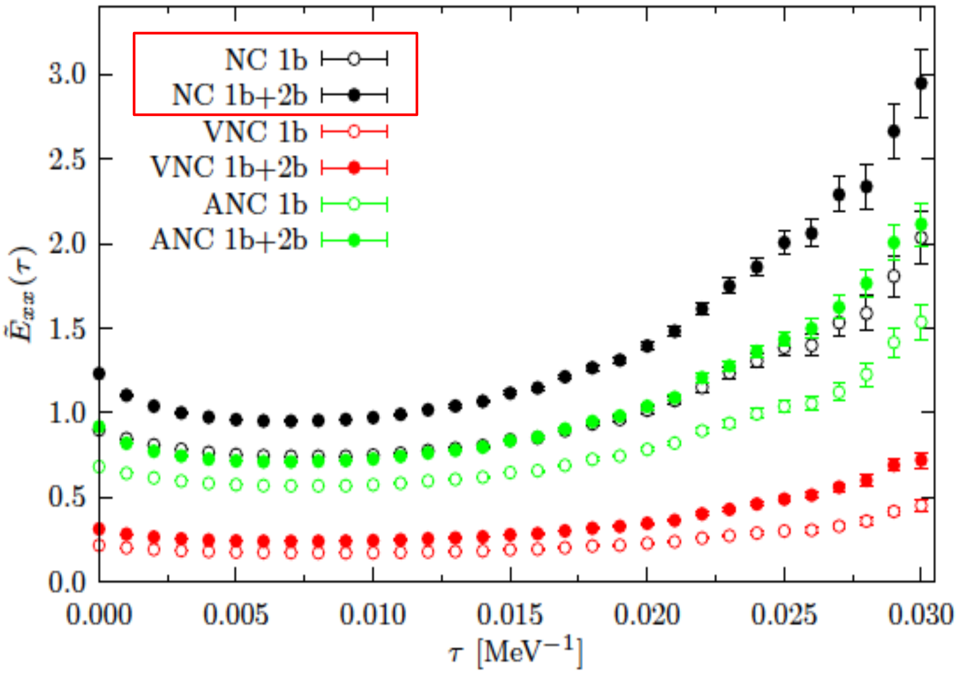
2N potential
(Av18)

3N potential
(IL7)

light nuclear state energies



Neutrino NCQE scattering in ^{12}C response function



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

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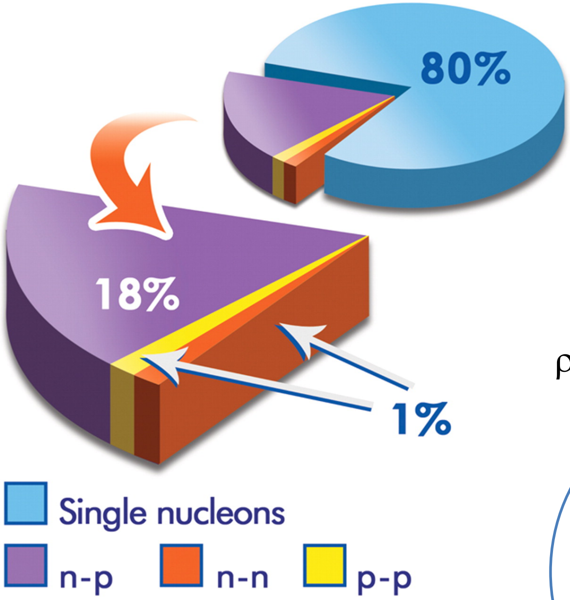
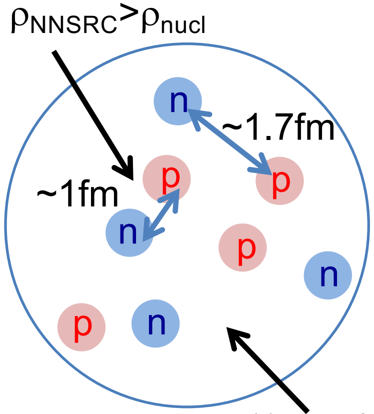
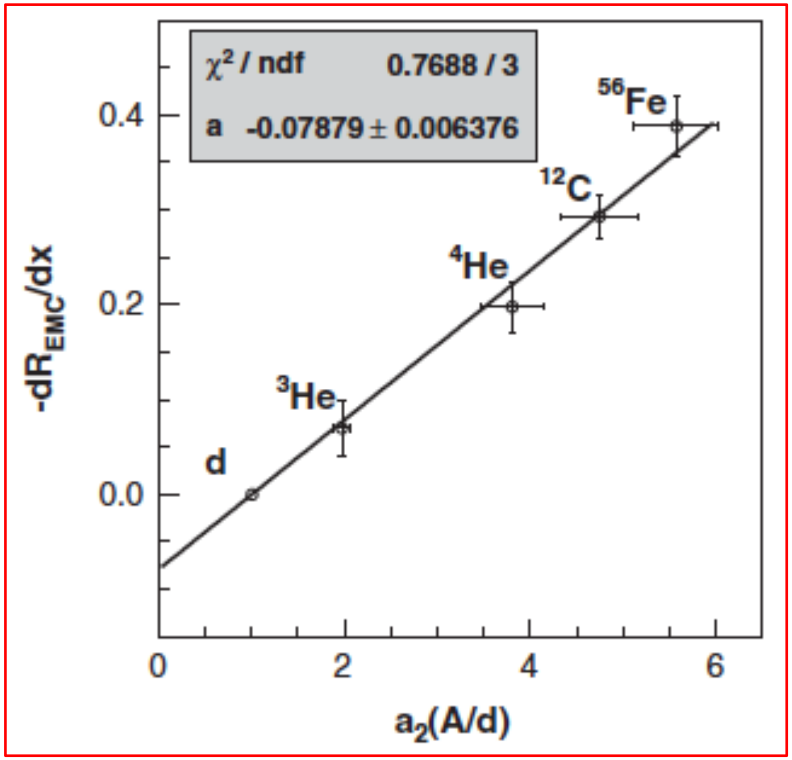


🟦 Single nucleons
🟪 n-p 🟧 n-n 🟨 p-p

Physics of SRC

- neutrino interaction
- 0νββ
- astrophysics
- EMC effect
- etc





Nucleon correlation is a very hot topics!

Queen Mary
University of London

Benhar et al, Rev.Mod. Phys.80(2008)189, PRL105(2010)132301

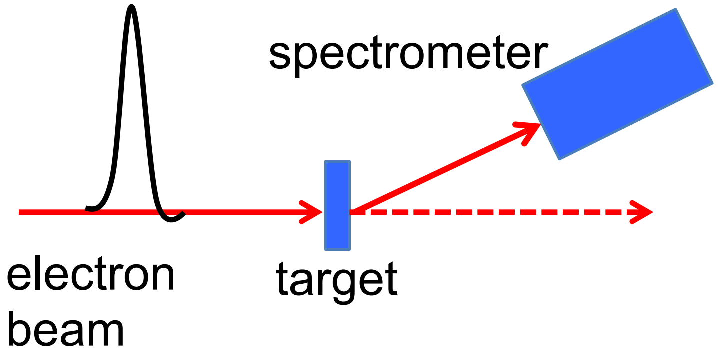
2. Electron scattering vs. Neutrino scattering

Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ kinematics is completely fixed



spectrometer

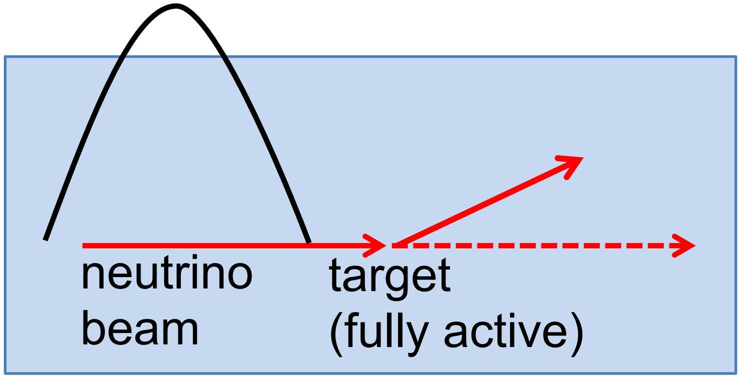
electron beam

target

Neutrino scattering

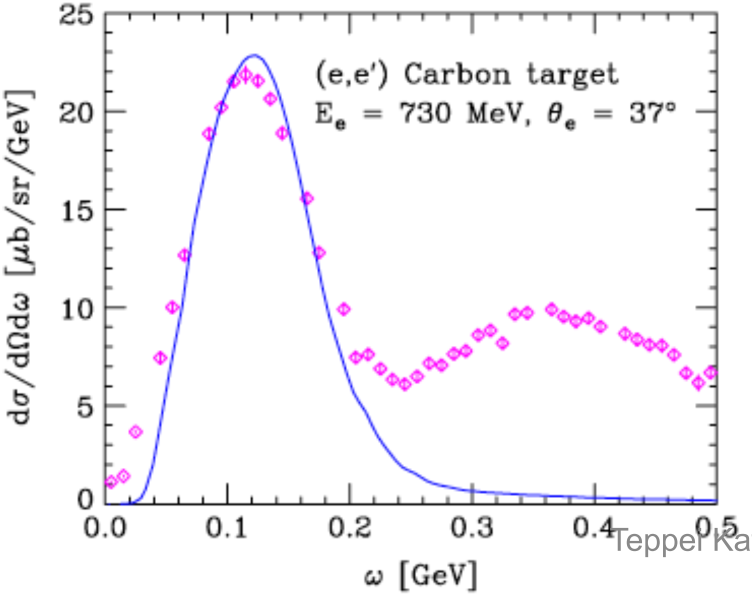
- Wideband beam

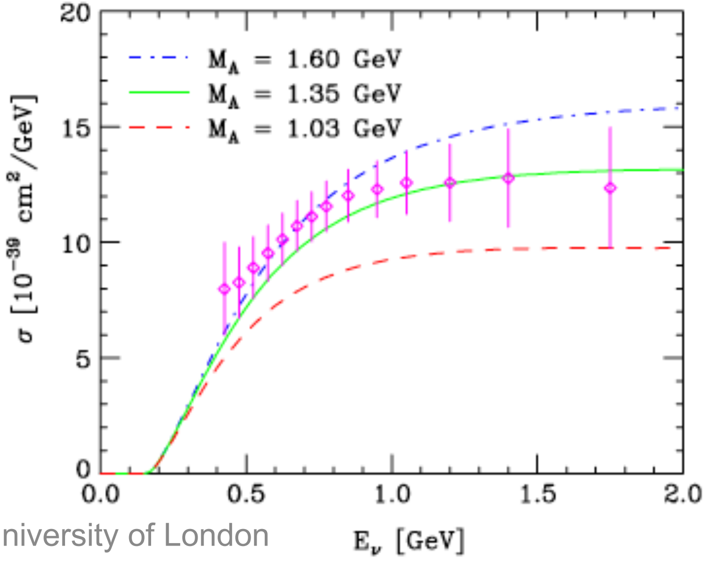
→ observables are inclusive



neutrino beam

target (fully active)





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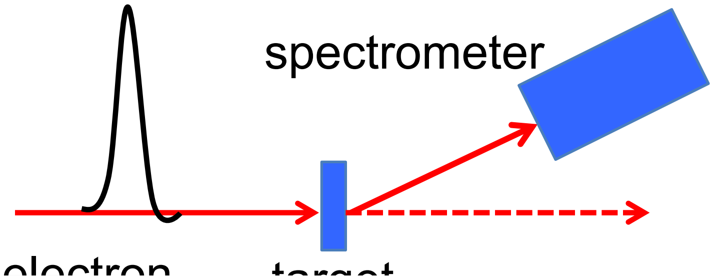

Neutrino scattering

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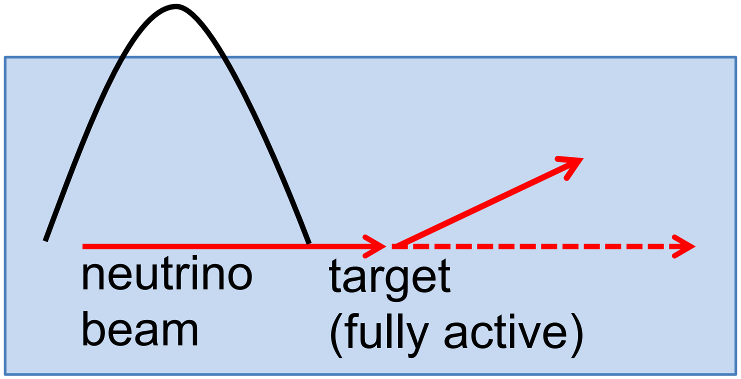
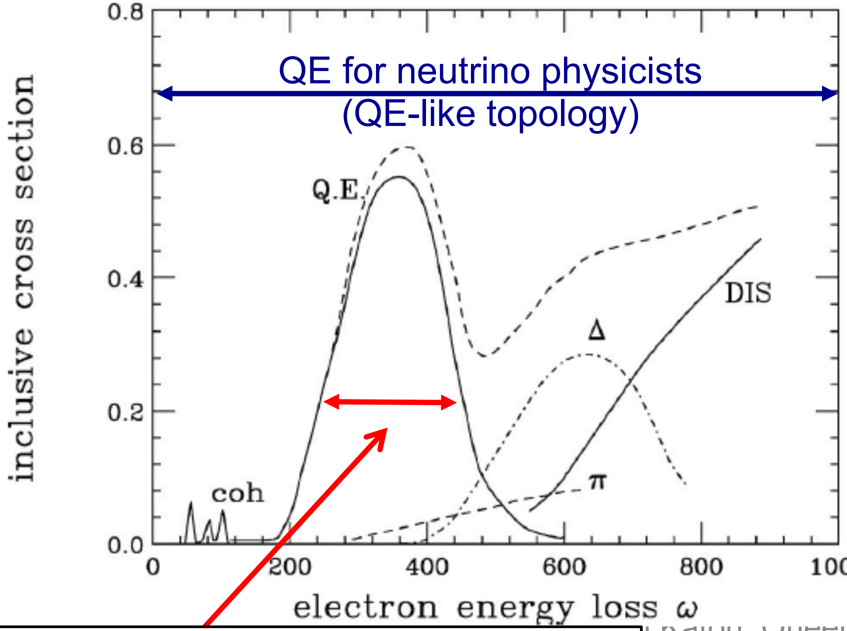
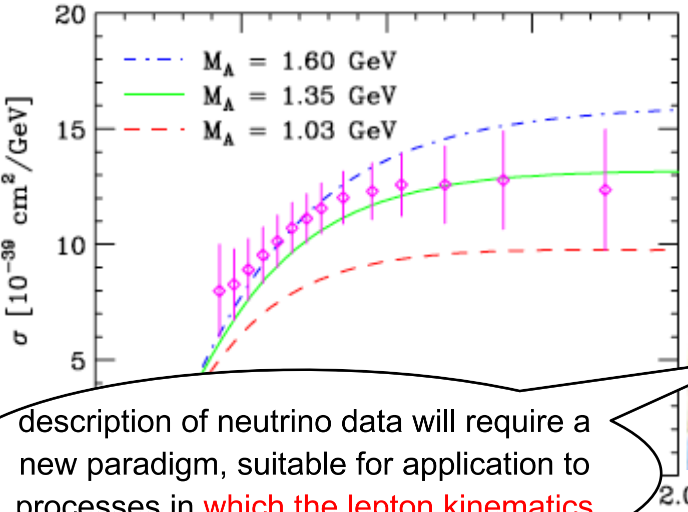




QE for neutrino physicists
(QE-like topology)

QE for nuclear physicists (genuine QE)



Omar
Benhar
(Rome I)

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

Wilkinson et al.,PRD93(2016)072010

2. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation
- Valencia MEC model is available in NEUT
- Implemented in GENIE, officially ready for GENIE v2.12

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

large M_A error → large 2p2h error

It is crucial to have correct CCQE, MEC, pion production models to understand MiniBooNE, MINERvA, T2K data simultaneously. Otherwise M_A error stays around 20-30%.

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

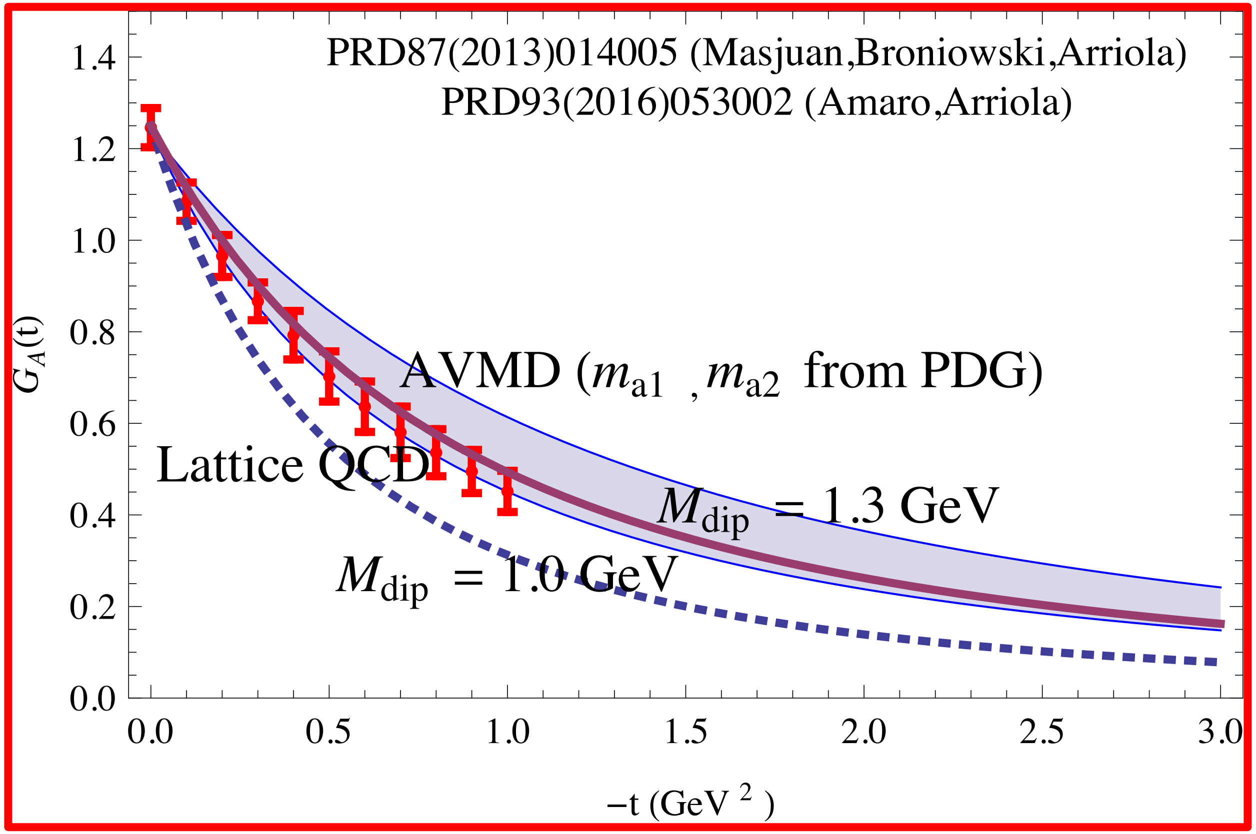
Amaro et al.,PRD93(2016)053002
Alexandrou et al., PRD88(2013)014509

2. Summary of CCQE for oscillation physics

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

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

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

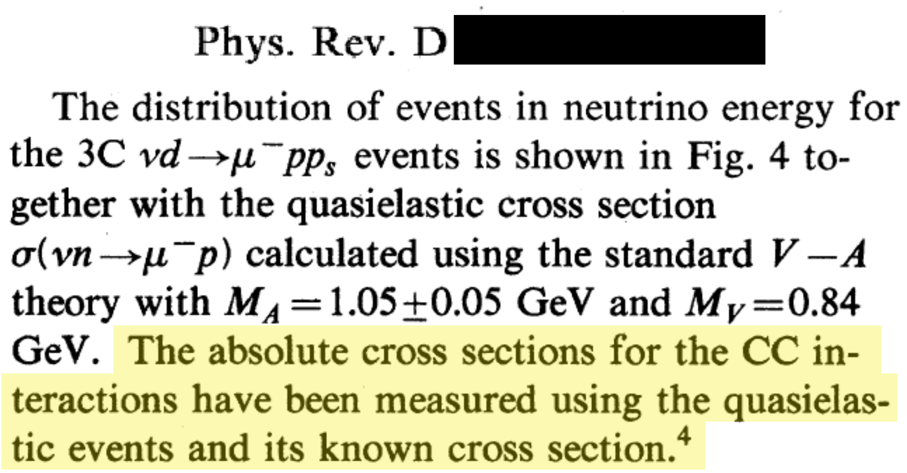


Jon Link, Fermilab Wine & Cheese seminar (2005)

2. Dark age of neutrino interaction physics

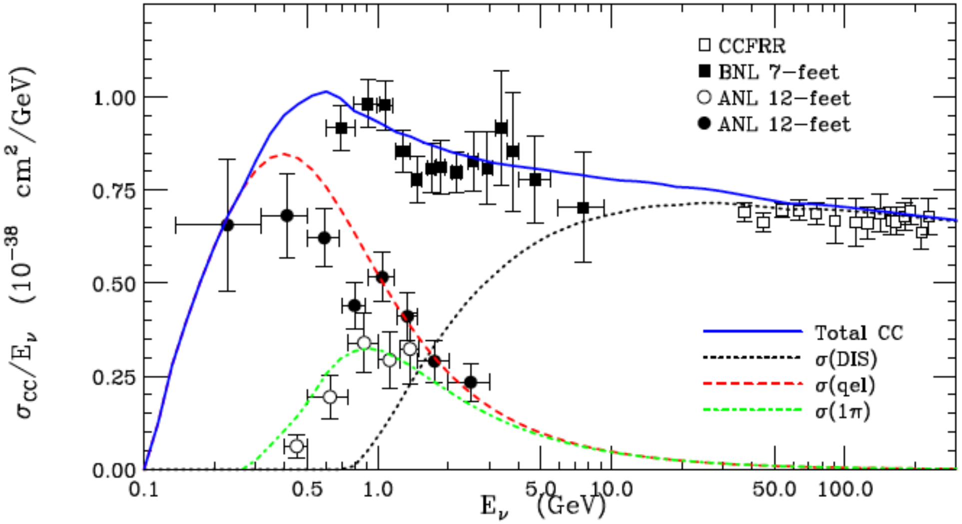
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate

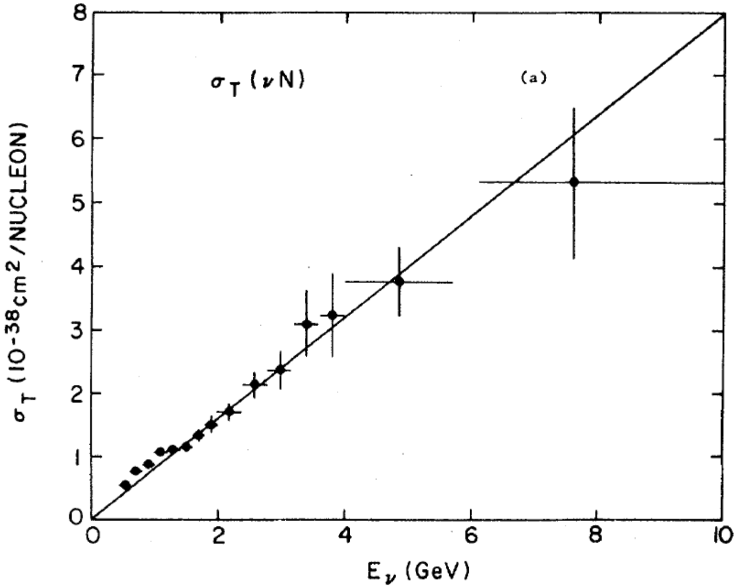
What you get? OF COURSE the cross section you assume!



Phys. Rev. D [redacted]

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





1. Neutrino Interaction Physics

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

3. Resonance Single Pion Production

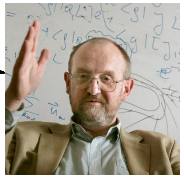
4. Shallow inelastic scattering, DIS, and Hadronization

5. Conclusion

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Garvey et al.,Phys.Rept.580 (2015) 1

3. Open question of neutrino interaction physics

The new data raised doubts in the areas well understood. The list of new puzzles is quite long and seems to be expanding…



Jan
Sobczyk
(Wroclaw)

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

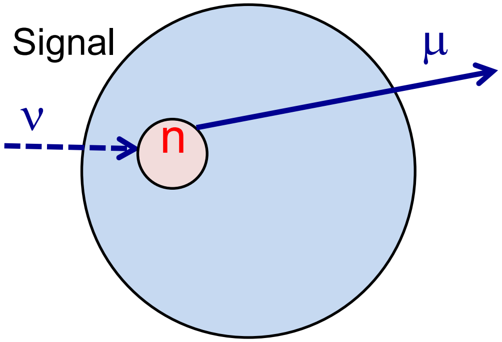
Coherent pion puzzle
- Is there charged current coherent pion production?

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

Baryon resonance, pion production by neutrinos

3. non-QE background

non-QE background → shift spectrum

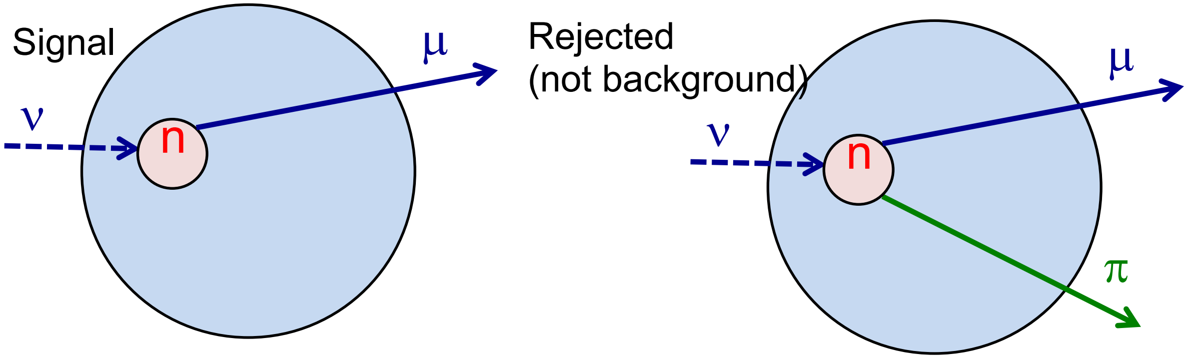


Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

3. non-QE background

non-QE background → shift spectrum



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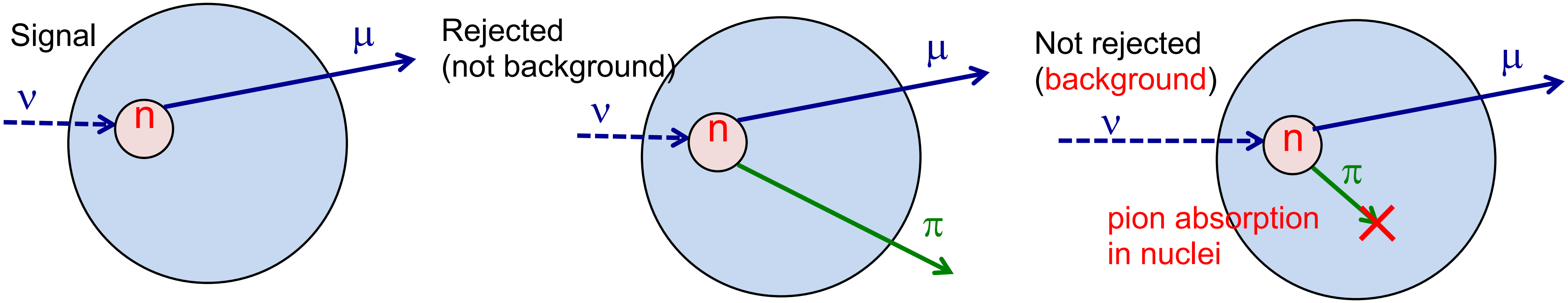
Signal

Rejected
(not background)

Not rejected
(background)

pion absorption
in nuclei

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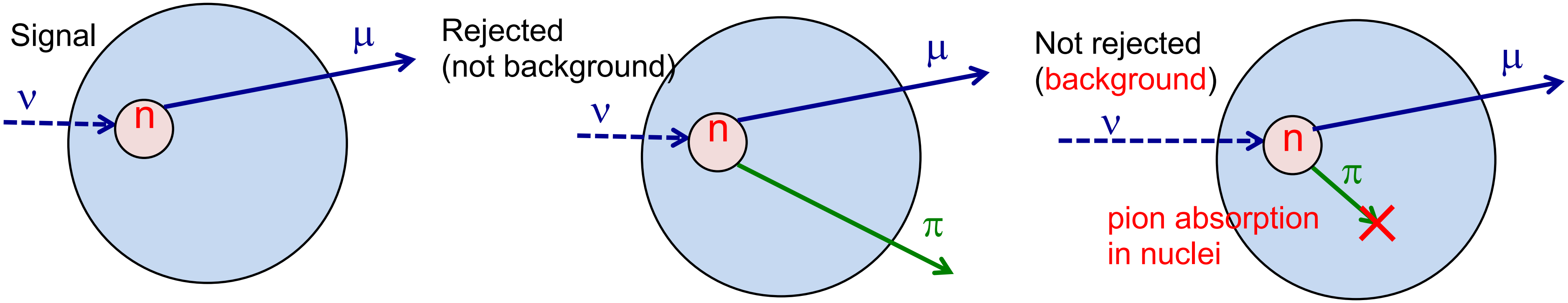
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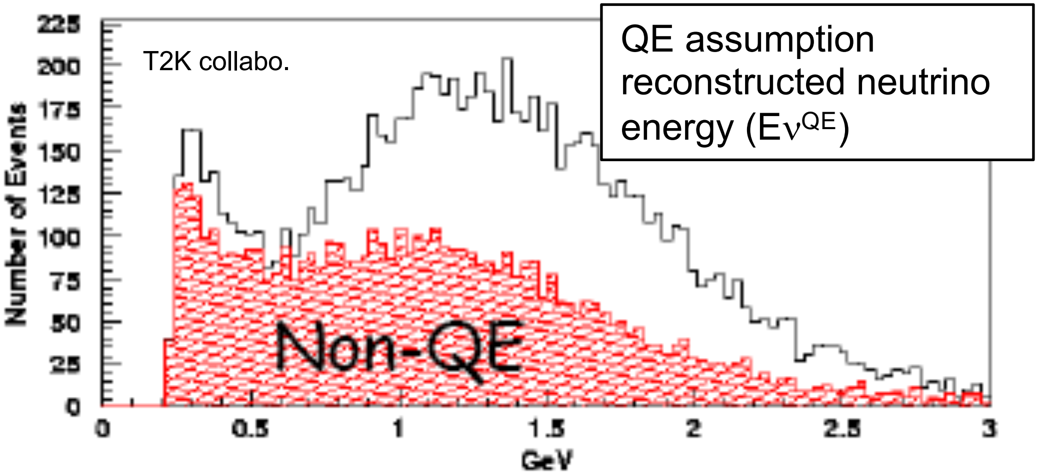
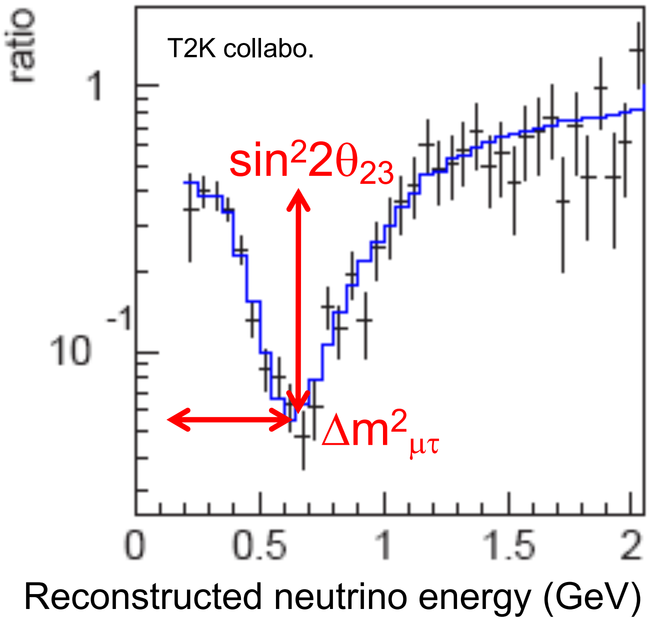


QE assumption
reconstructed neutrino
energy ($E\nu^{QE}$)



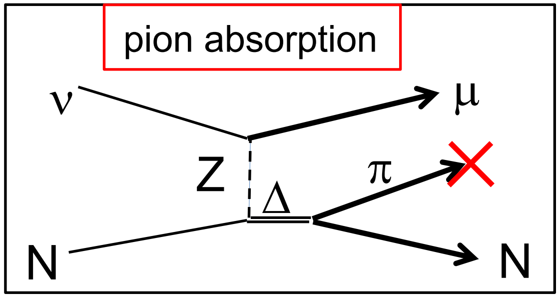
Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

3. non-QE background

Understanding of neutrino pion production is important for oscillation experiments

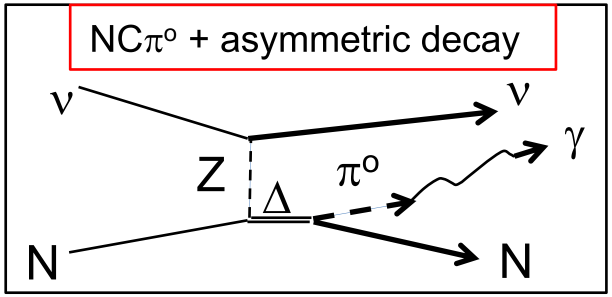
Pion production for ν_μ disappearance search

- Source of mis-reconstruction of neutrino energy

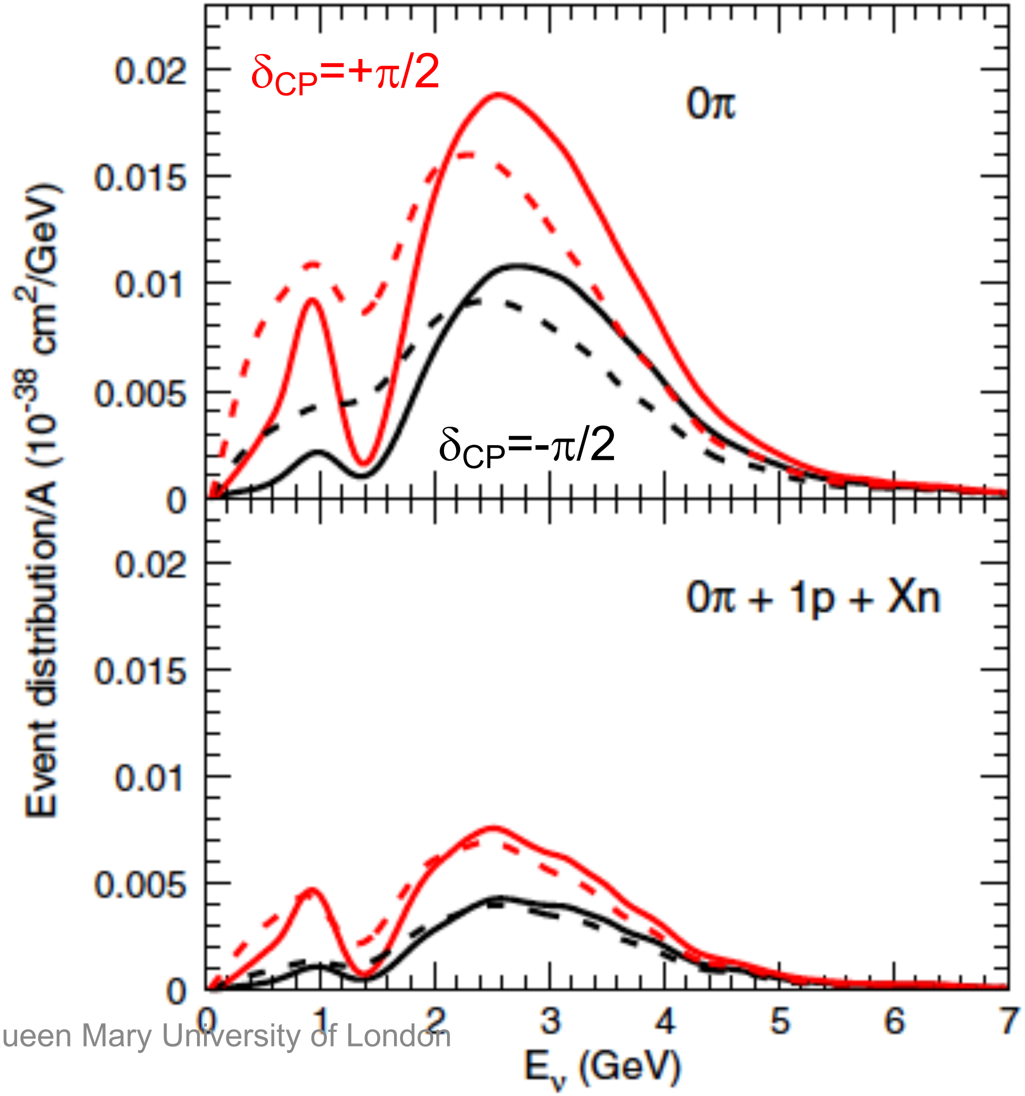


Neutral pion production in ν_e appearance search

- Source of misID of electron



DUNE true vs. reconstructed Eν spectrum



Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
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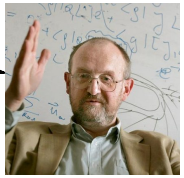
3. Open question of neutrino interaction physics

The new data raised doubts in the areas well understood. The list of new puzzles is quite long and seems to be expanding…



Jan Sobczyk (Wroclaw)

CCQE puzzle

- Low Q2 suppression, high Q2 enhancement, high normalization

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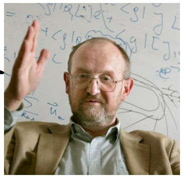
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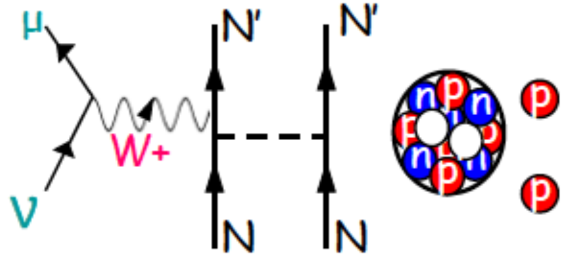
Two particles-two holes (2p-2h)



W+ absorbed by a pair of nucleons

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
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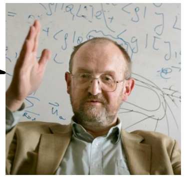

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Hernandez et al,PRD87(2013)113009
Alvarez-Ruso et al,PRC89(2014)015503

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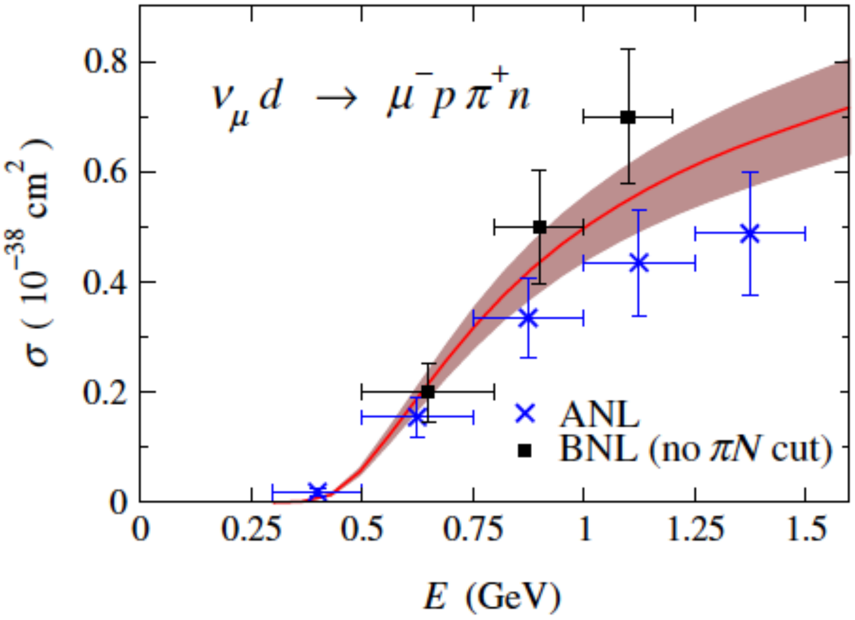
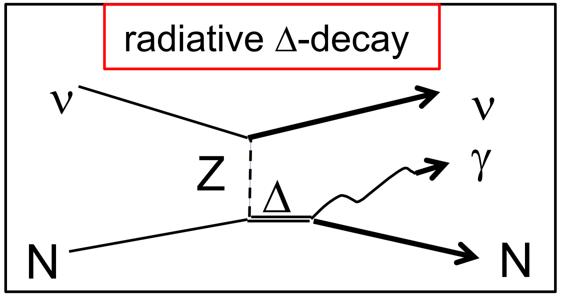
Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25%.

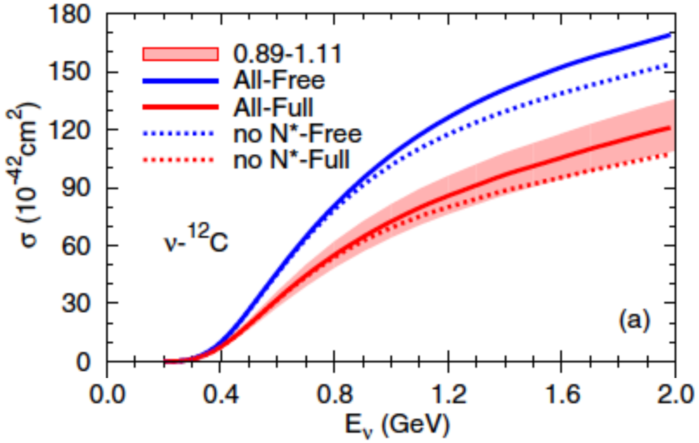
→ this propagates to every interactions with baryon resonance

ANL vs. BNL



e.g.) NCγ production model





Wilkinson et al,PRD90(2014)112017,Graczyk et al,PRD80(2009)093001
Wu et al,PRC91(2015)035203

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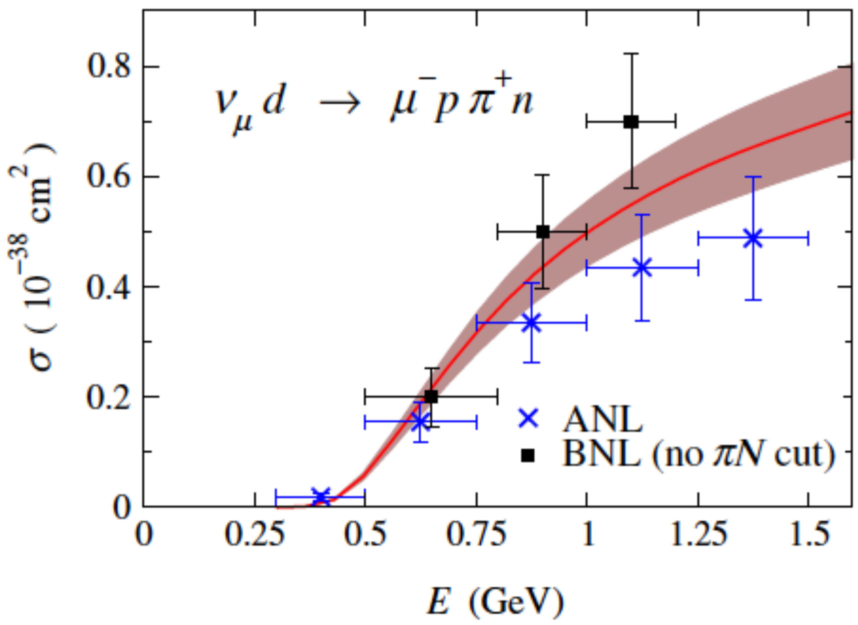
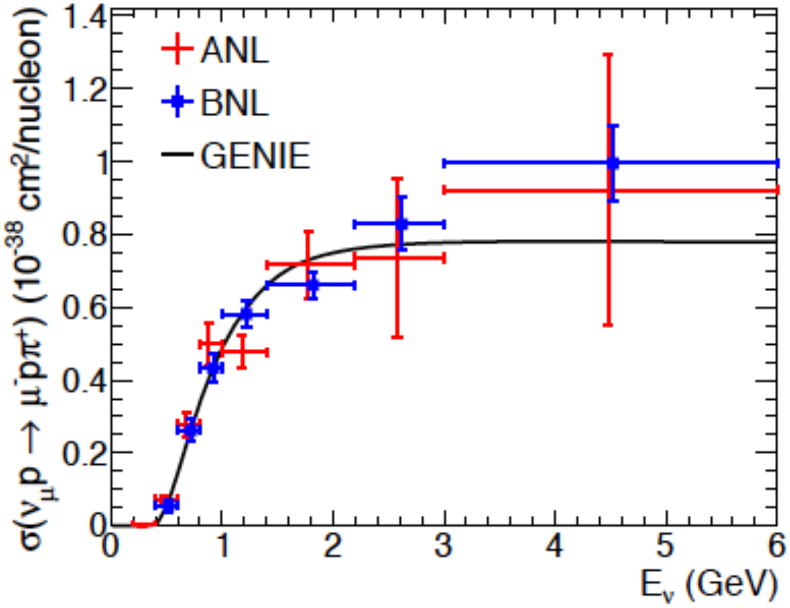
Reanalysis by Sheffield-Rochester group found a normalization problem on BNL

ANL vs. BNL





Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
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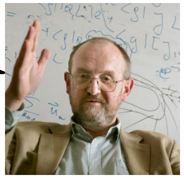

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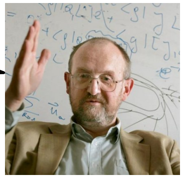

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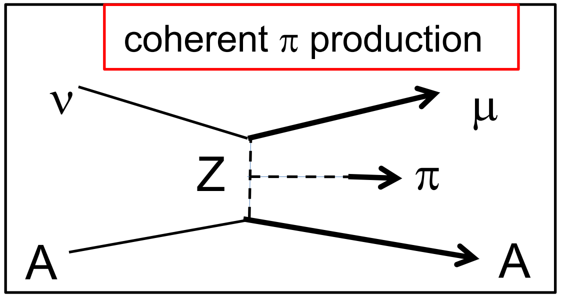
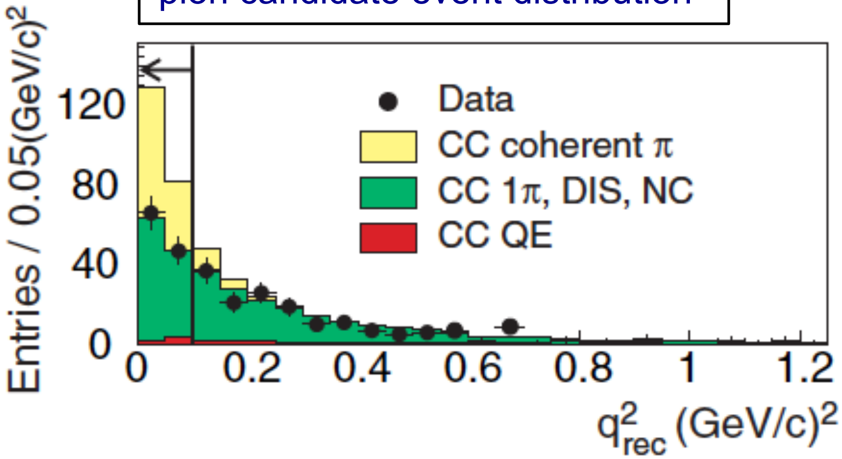
3. Coherent pion puzzle

K2K and SciBooNE data show CC coherent pion production is consistent with zero.



K2K muon neutrino CC coherent pion candidate event distribution



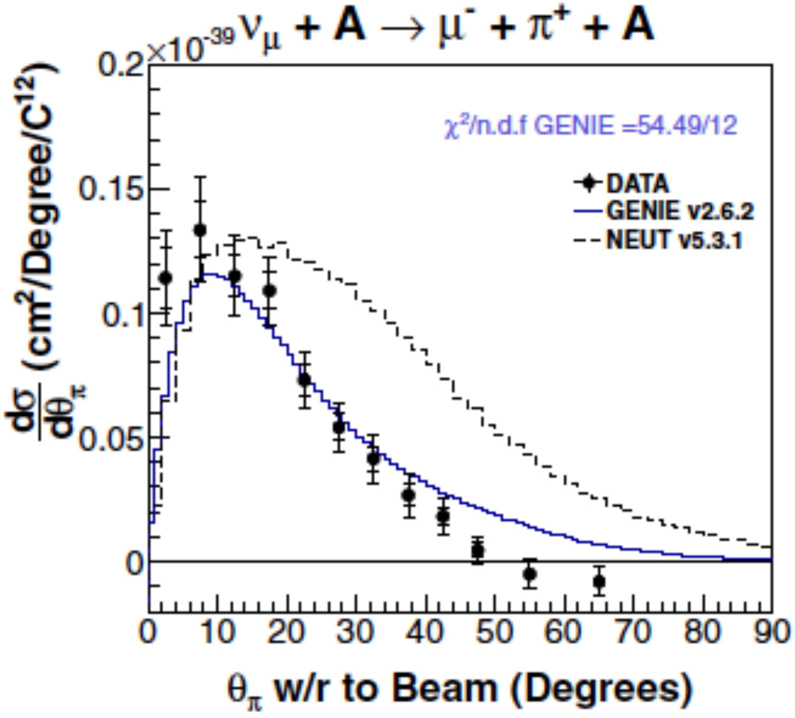
K2K,PRL95(2005)252301, SciBooNE, PRD78(2008)112004
Suzuki, NuFact2014, ArgoNeuT, PRL114(2015)039901, MINERvA, PRL113(2014)261802, T2K, PRL117(2016)192501

3. Coherent pion puzzle

K2K and SciBooNE data show CC coherent pion production is consistent with zero.

ArgoNeuT, T2K, and MINERvA discovered nonzero CC coherent pion production, but details of kinematics are not understood.

MINERvA muon neutrino CC coherent pion production differential cross-section



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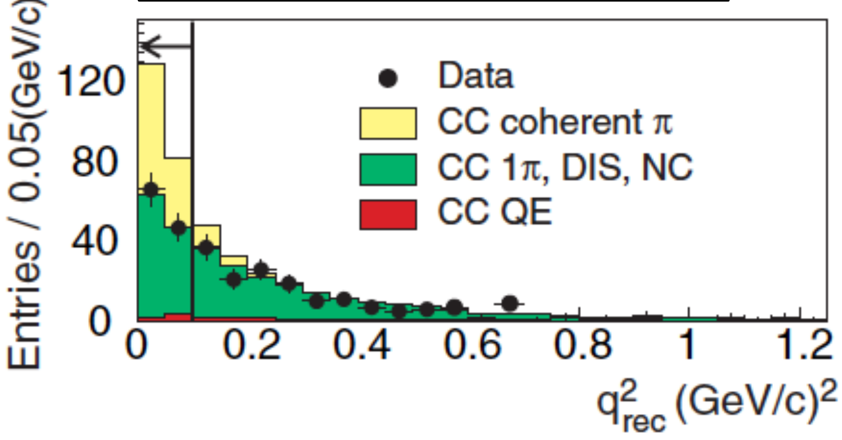
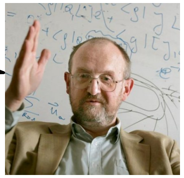


T2K (on-axis): Suzuki, NuFact2014
MINERvA: PRL113(2014)261802
ArgoNeuT: PRL114(2015)039901
T2K (off-axis): PRL117(2016)192501

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Garvey et al.,Phys.Rept.580 (2015) 1

3. Open question of neutrino interaction physics

The new data raised doubts in the areas well understood. The list of new puzzles is quite long and seems to be expanding…



Jan Sobczyk (Wroclaw)

CCQE puzzle

- Low Q2 suppression, high Q2 enhancement, high normalization

→ presence of short and long range nucleon correlations

ANL-BNL puzzle

- Normalization difference between ANL and BNL bubble chamber pion data

→ After correcting BNL normalization, ANL and BNL data agree

Coherent pion puzzle

- Is there charged current coherent pion production?

→ yes it is, but details of kinematic need to be studied more

Pion puzzle

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

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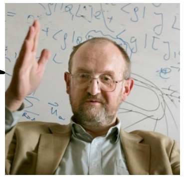

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MiniBooNE,PRD83(2011)052007
MINERvA,PRD92(2015)092008

3. Pion puzzle

Data from MiniBooNE and MINERvA and simulation are all incompatible

Flux-integrated differential cross-section are not comparable (unless 2 experiments use same neutrino beam)

Two data set are related by a model (=GENIE neutrino interaction generator).

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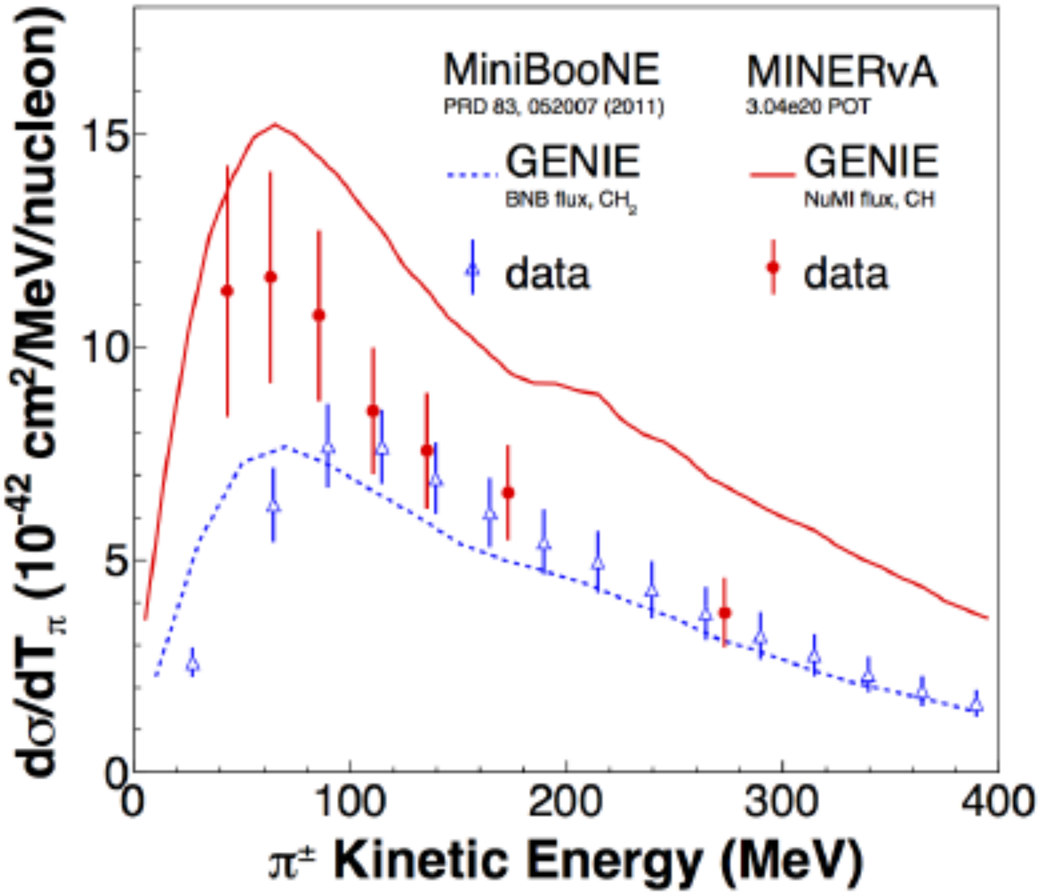

MiniBooNE,PRD83(2011)052007
MINERvA,PRD92(2015)092008, Sobczyk and Zmuda,PRC91(2015)045501

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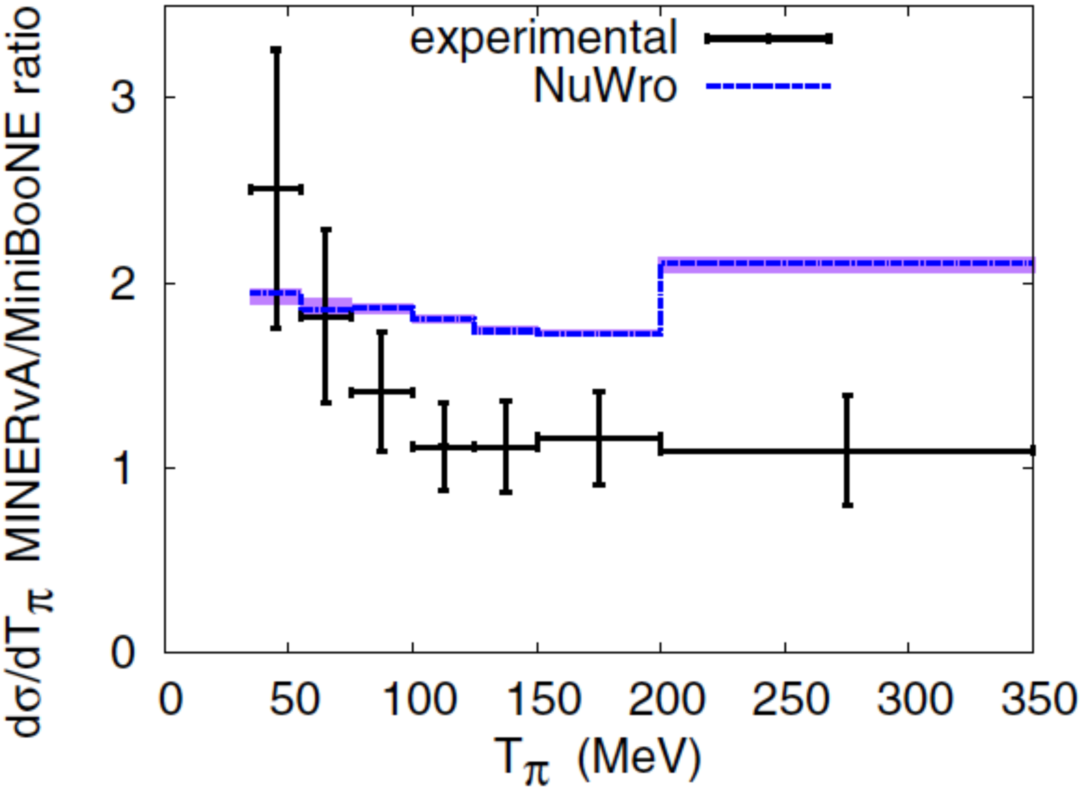


MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

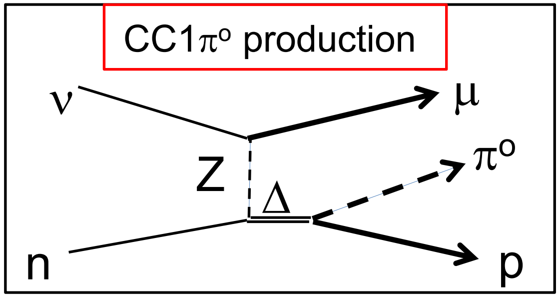
3. Pion puzzle

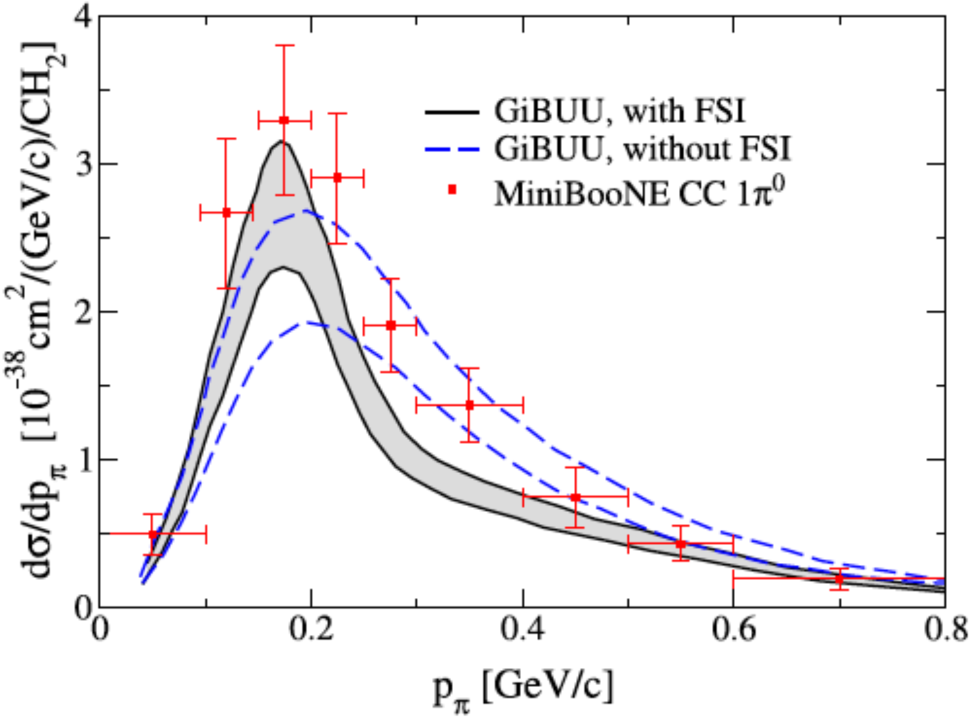
Final state interaction

- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation

For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich
Mosel
(Giessen)





ex) Giessen BUU transport model

- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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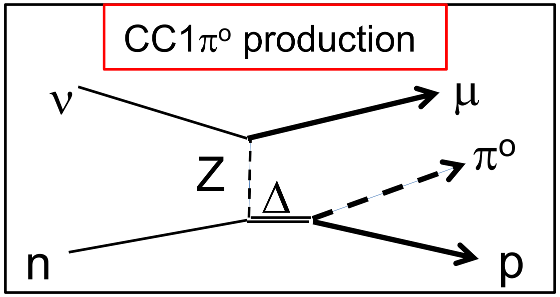

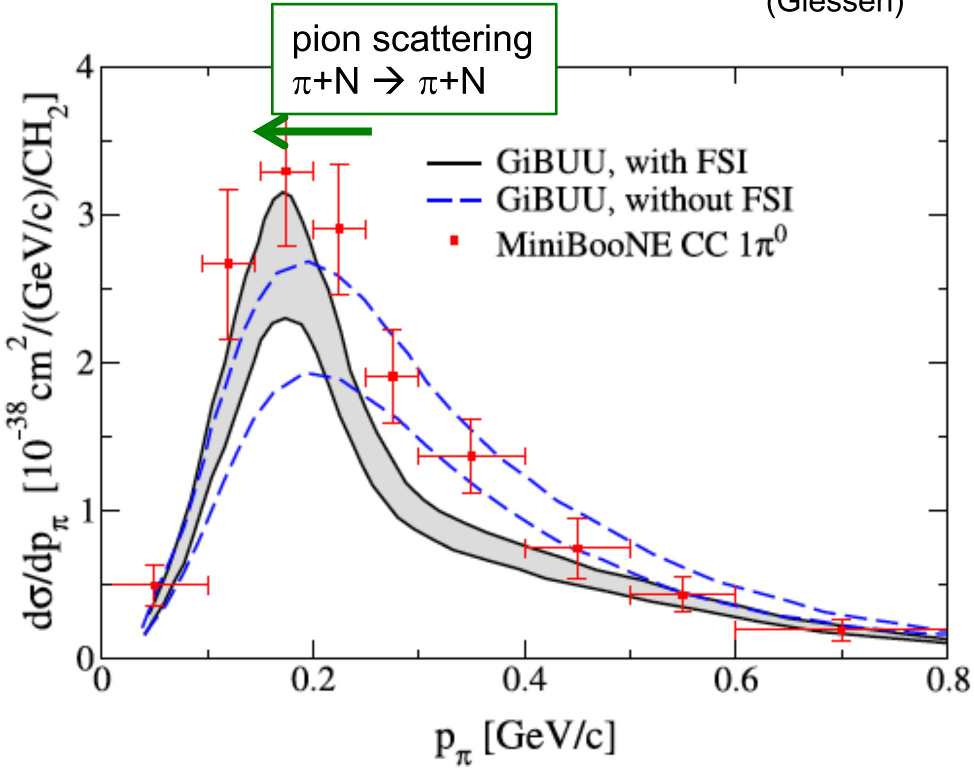

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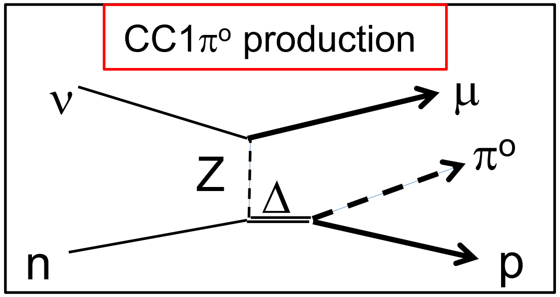
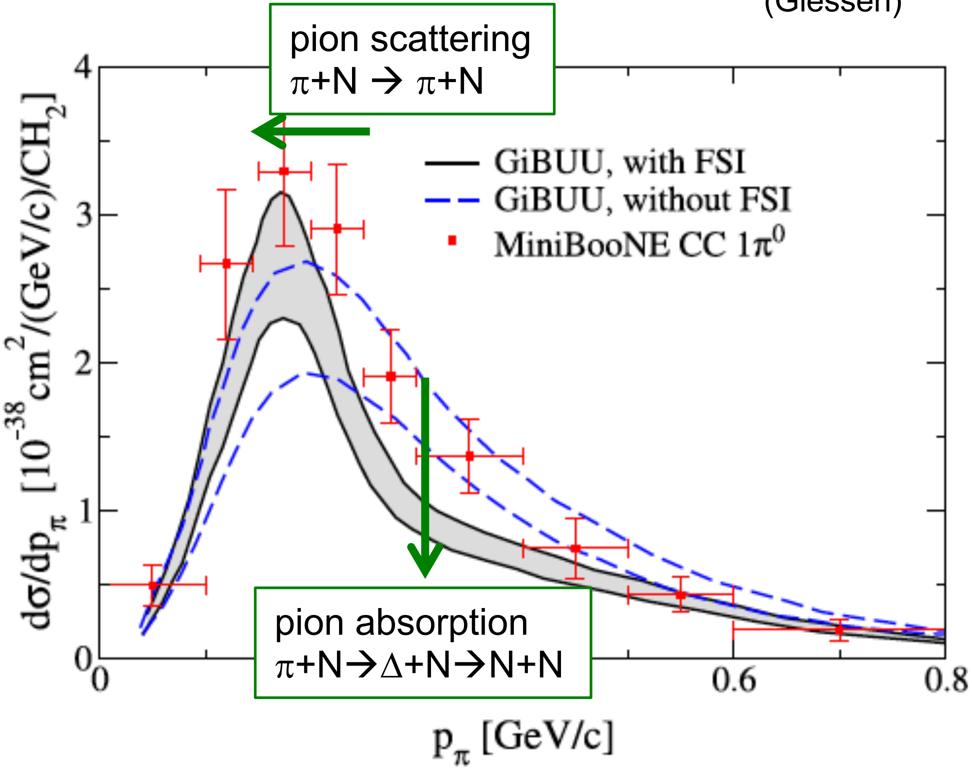


CC1π° production



pion scattering
$\pi+N \rightarrow \pi+N$

pion absorption
$\pi+N \rightarrow \Delta+N \rightarrow N+N$

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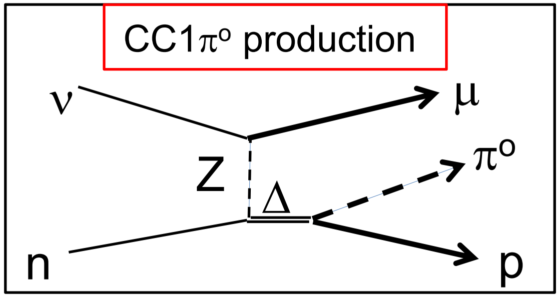
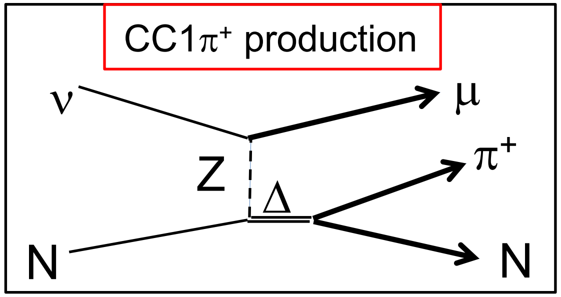
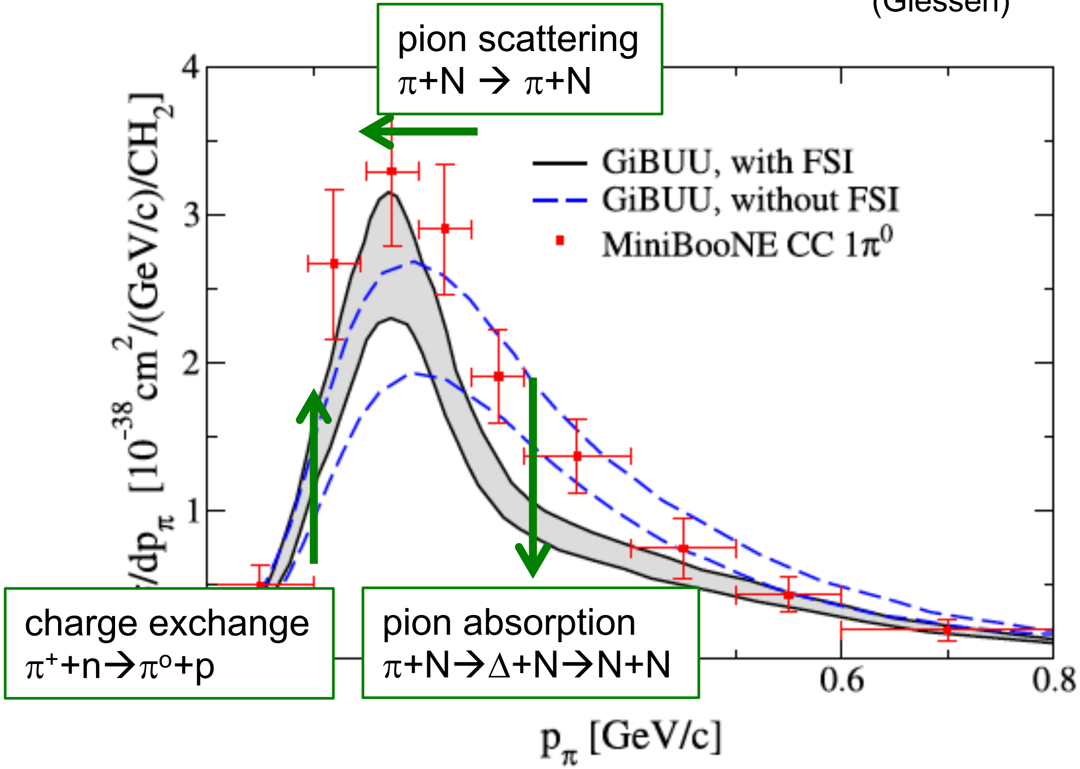


CC1π^o production



CC1π^+ production



pion scattering
$\pi+N \rightarrow \pi+N$

charge exchange
$\pi^++n \rightarrow \pi^o+p$

pion absorption
$\pi+N \rightarrow \Delta+N \rightarrow N+N$

You need to be right for all
1. neutrino flux prediction
2. pion production model
3. final state interaction

ex) Giessen BUU transport model

- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
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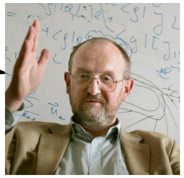
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Pion puzzle

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

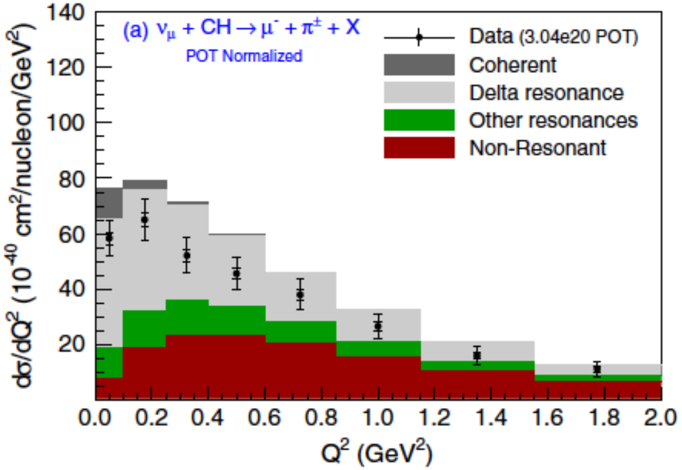
→ ???

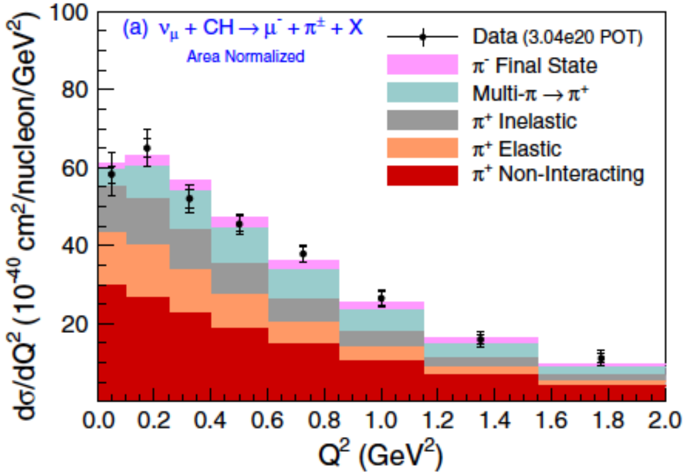
3. MINERvA FSI and cross section model tuning (2016)

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

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

ν_μCC1π^+ data has better shape agreement with GENIE





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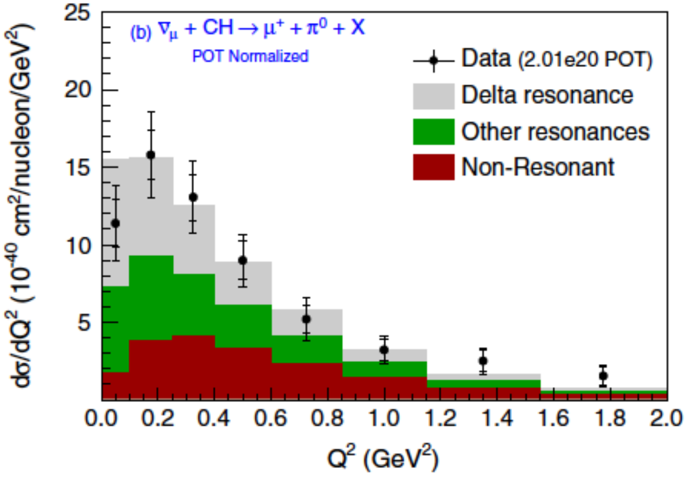
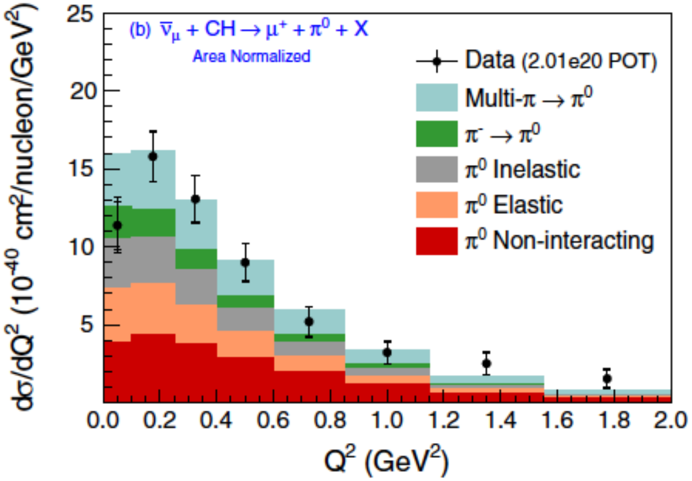




Wilkinson et al,PRD90(2014)112017,Graczyk et al,PRD80(2009)093001
Wu et al,PRC91(2015)035203, Alvarez-Ruso, arXiv:1510.06266

3. Summary of resonance region for oscillation

Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25% (ANL-BNL puzzle).

→ origin of 20-30% error on M_A^{RES}

Recent re-analysis found a normalization problem on BNL

Recent fit on re-analyzed ANL-BNL data shows on $C^A_5(0)$ error is 6%. This would give ~6-10% error on M_A^{RES} for experimentalist.

…However, Wu et al pointed out there might be significant contribution of nuclear effect in bubble chamber data. This mean, perhaps, cross section extracted by re-analyzed ANL-BNL would be underestimated?!

M_A^{RES} imitates all normalization errors associated with SPP data ($C^A_5(0)$, M_A^{RES}, nuclear effect, etc). Unless all mysteries are solved (including MiniBooNE-MINERvA tension, pion puzzle), M_A^{RES} error stays ~20-30%.

TK, Martini, JPhysG45(2017)1

1. Neutrino Interaction Physics

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

3. Resonance Single Pion Production

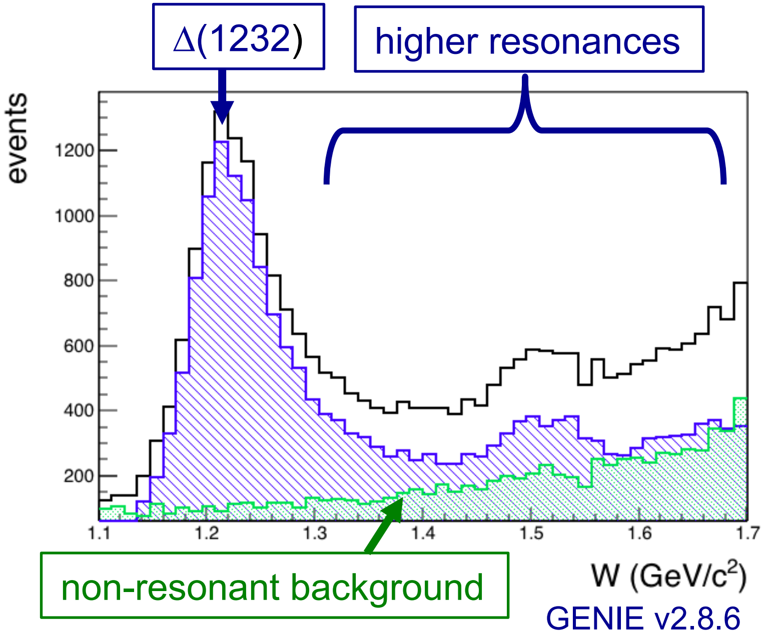
4. Shallow inelastic scattering, DIS, and Hadronization

5. Conclusion

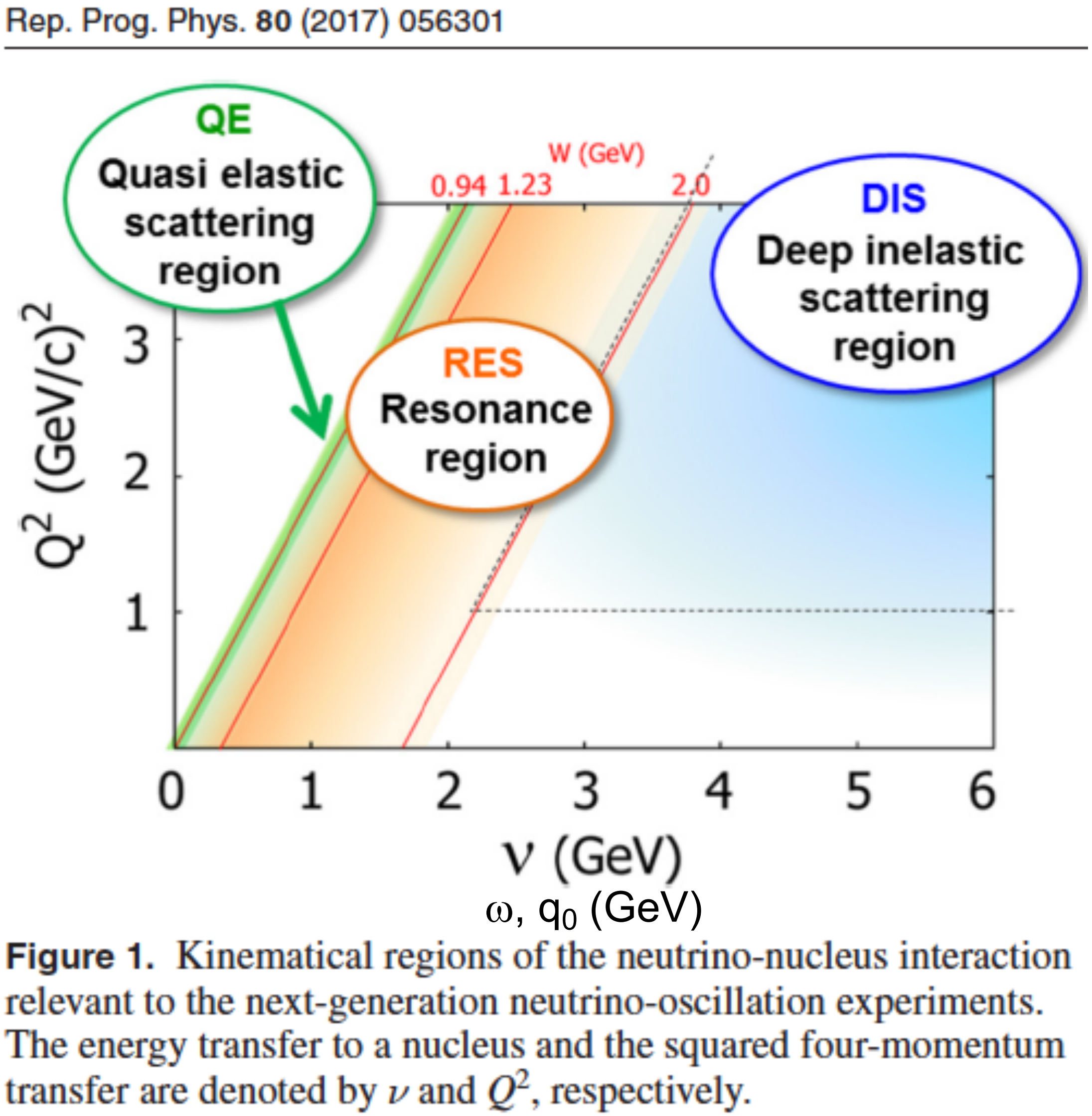
Nakamura et al.,Rep.Prog.Phys.80(2017)056301

4. Shallow Inelastic Scattering (SIS) region physics

Basic ingredients
- Δ(1232)-resonance
- higher resonances
- non-resonant background



GENIE v2.8.6



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

ω, q_0 (GeV)

Figure 1. Kinematical regions of the neutrino-nucleus interaction relevant to the next-generation neutrino-oscillation experiments. The energy transfer to a nucleus and the squared four-momentum transfer are denoted by ν and Q^2, respectively.

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

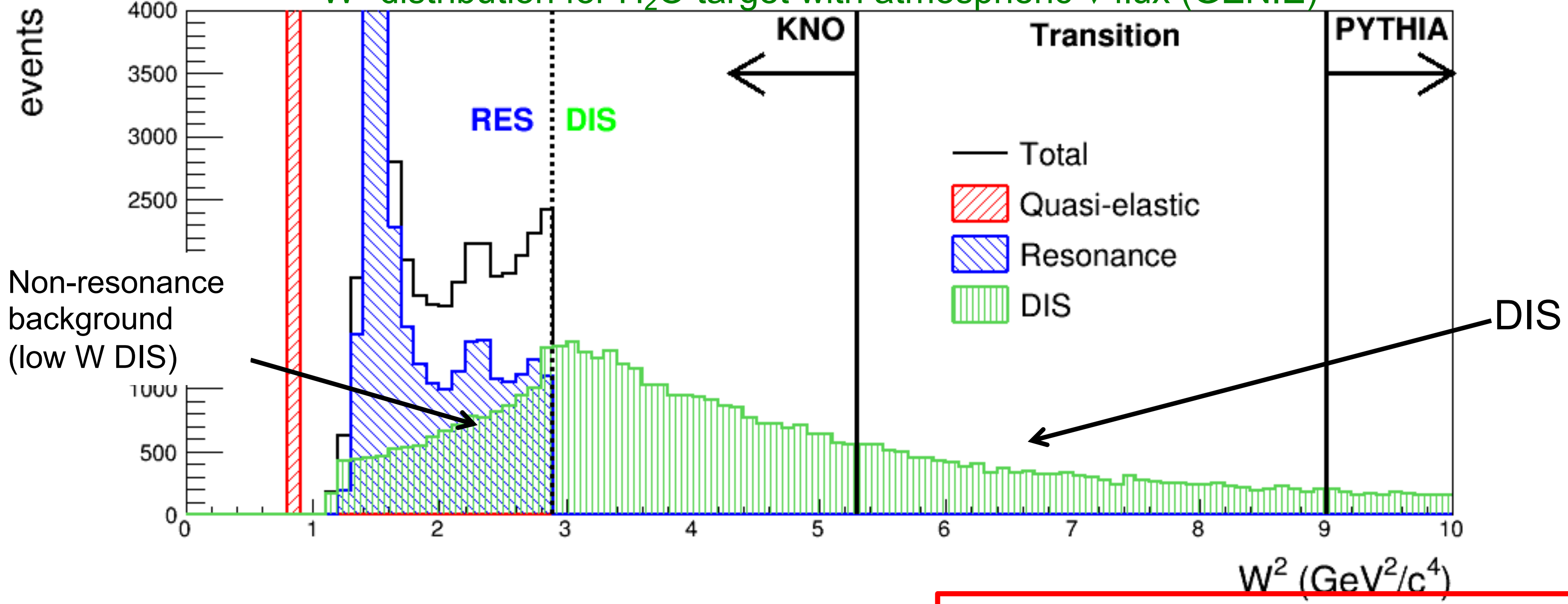
4. SIS-DIS model

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

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

Very important energy region for NOvA, PINGU, ORCA, Hyper-K, DUNE

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



Non-resonance background (low W DIS)

DIS

Typical "Frankenstein" style model!

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

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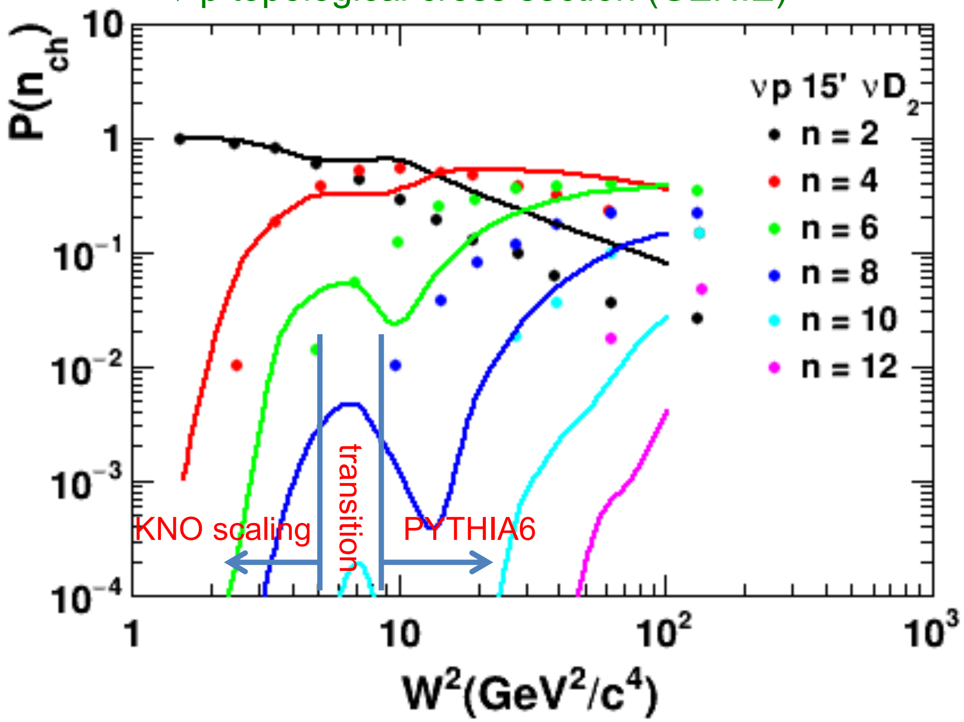
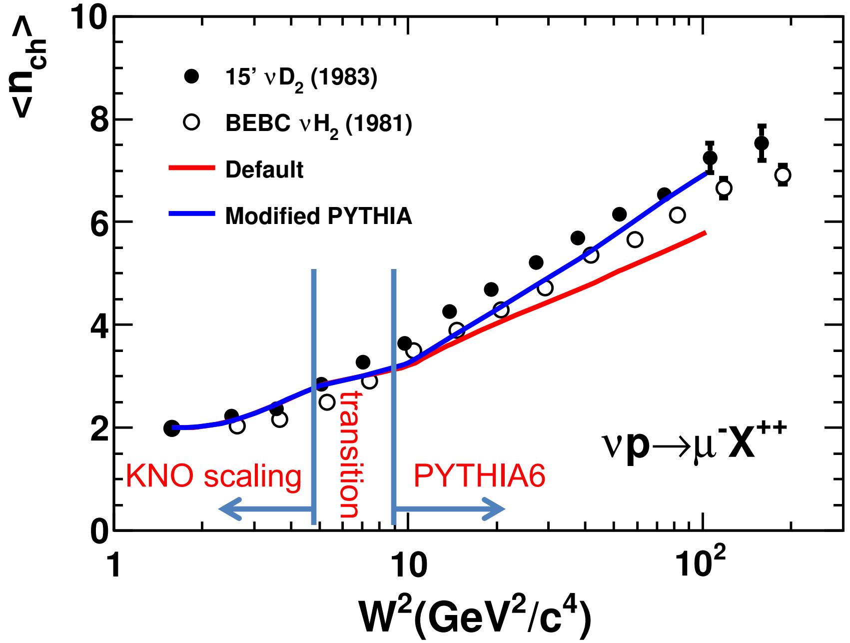
ν-p topological cross section (GENIE)



ν-p averaged charged hadron multiplicity (GENIE)



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

4. SIS-DIS model

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

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

DCC model vs. electro-pionproduction data

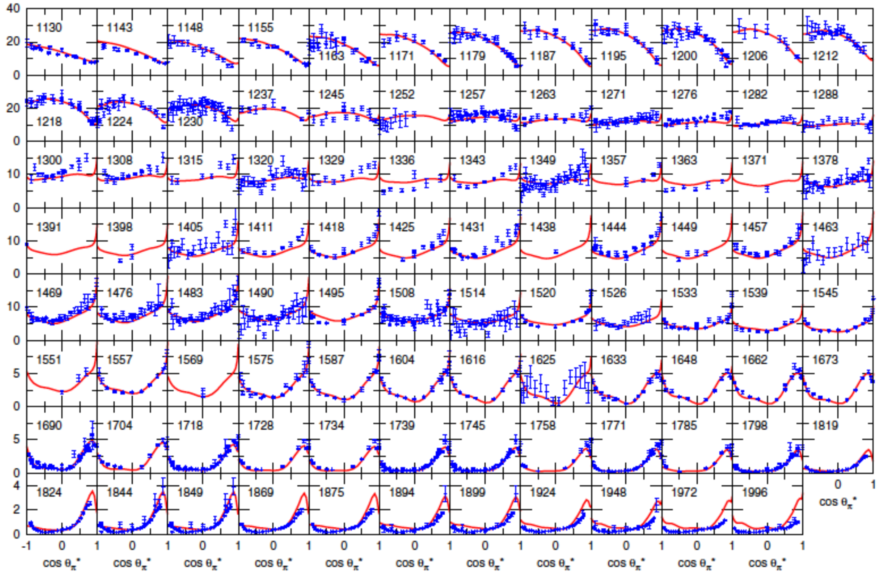
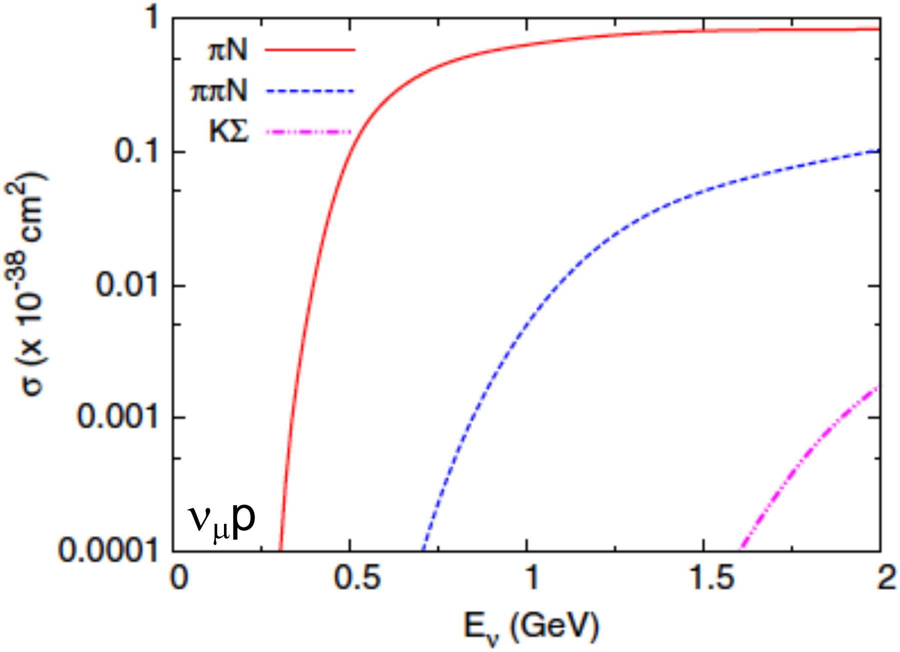
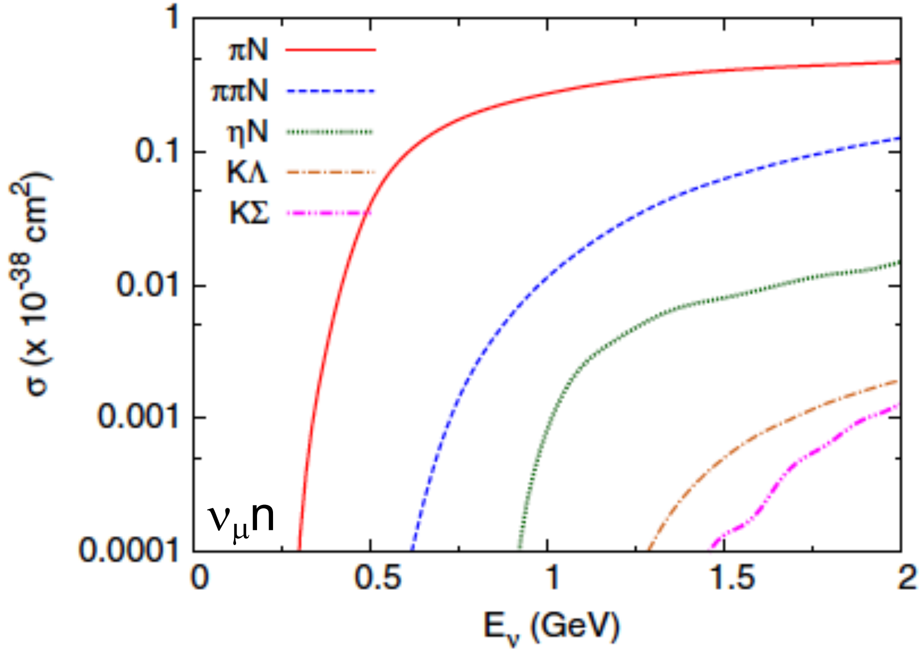


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].





Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11

4. SIS-DIS model

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

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

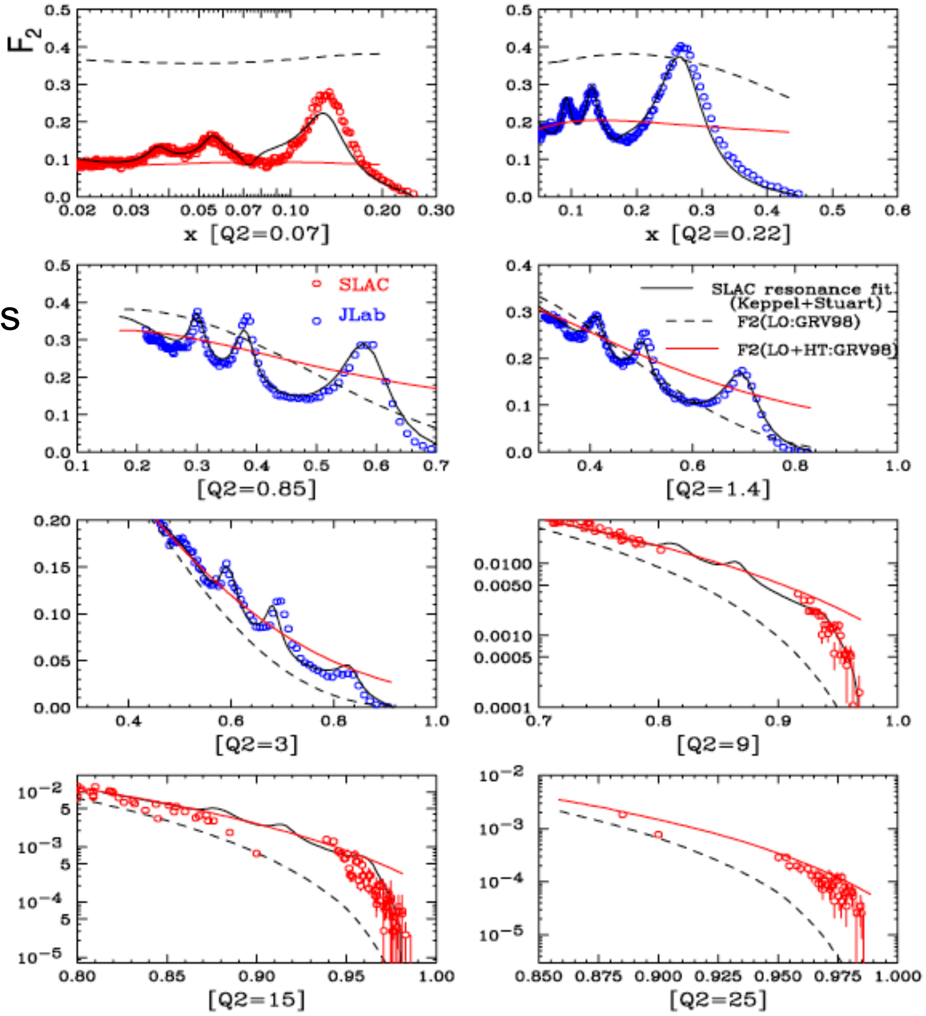
GRV98 LO PDF + Bodek-Yang correction
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data



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

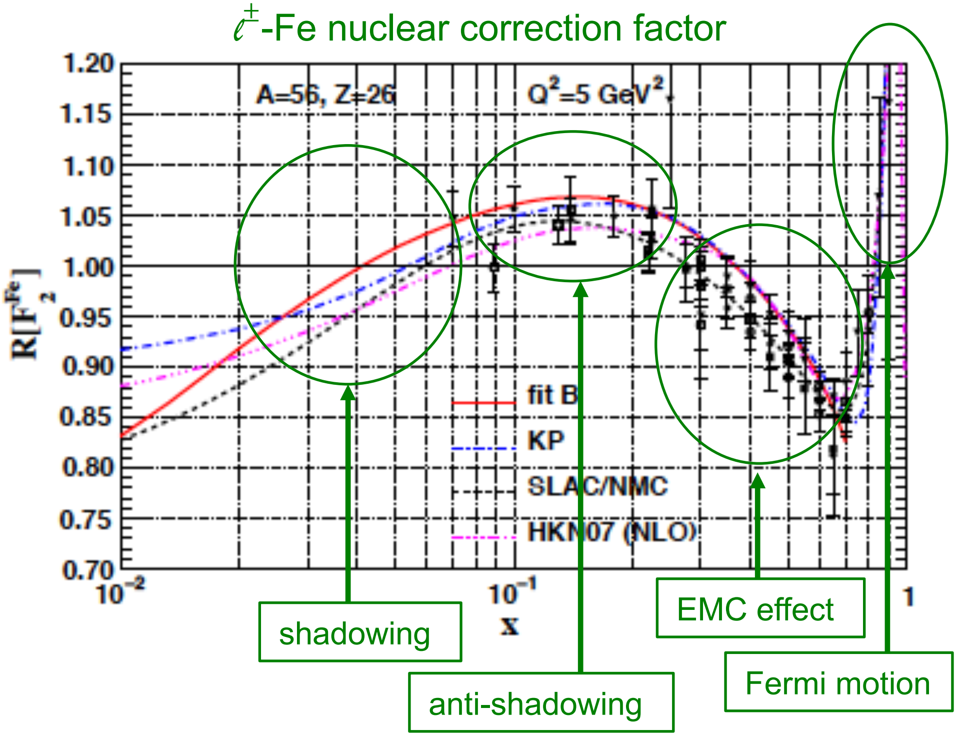
4. SIS-DIS model

Cross section

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

Nuclear PDF

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



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

shadowing

anti-shadowing

EMC effect

Fermi motion

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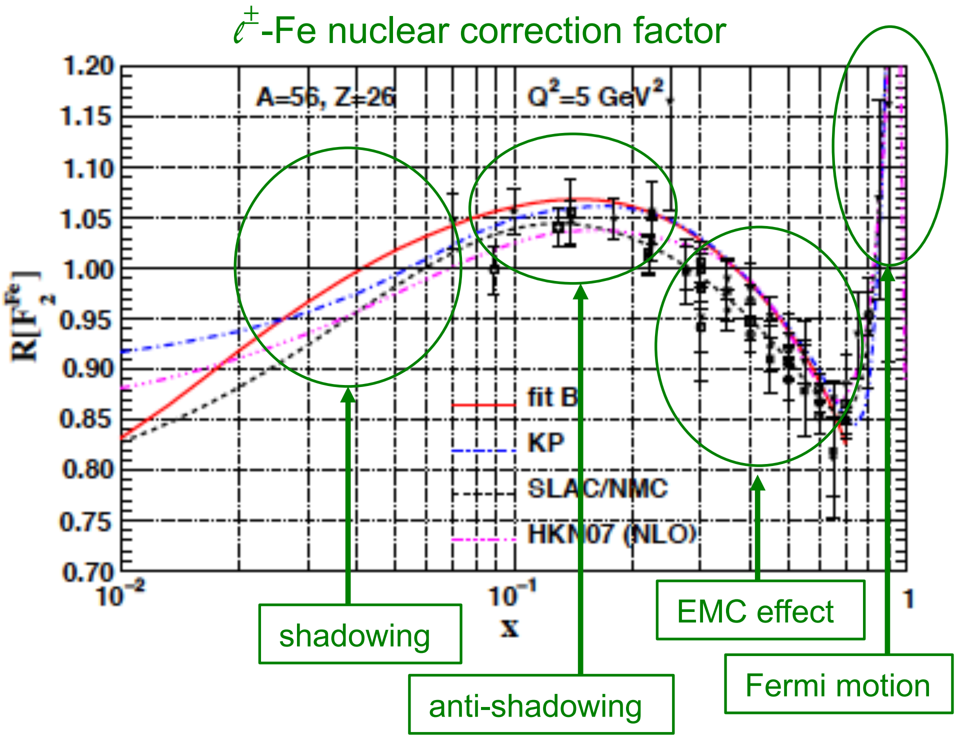
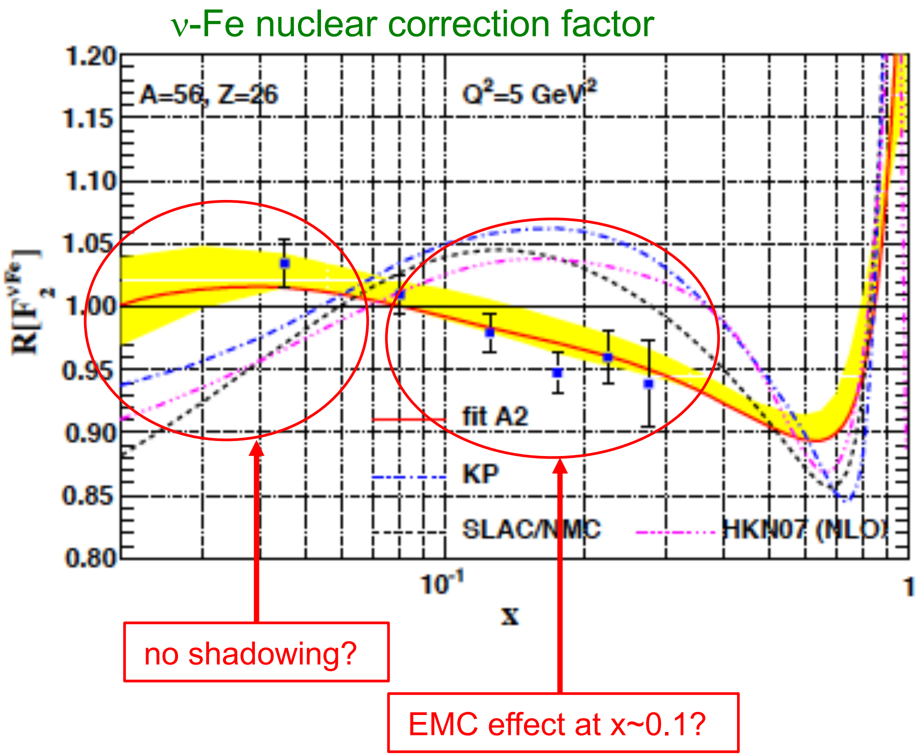

$\ell^{\pm}$-Fe nuclear correction factor

shadowing

anti-shadowing

EMC effect

Fermi motion


ν-Fe nuclear correction factor

no shadowing?

EMC effect at x~0.1?

MINERvA,PRD93(2016)071101

4. SIS-DIS model

Cross section

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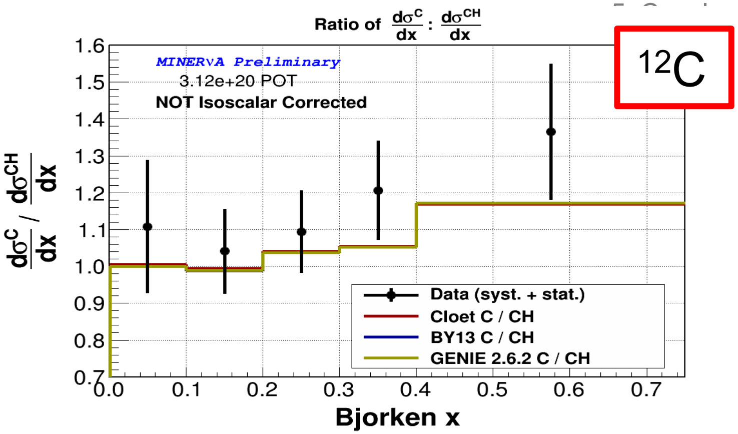
- low Q^2, low W DIS
- Nuclear dependent DIS

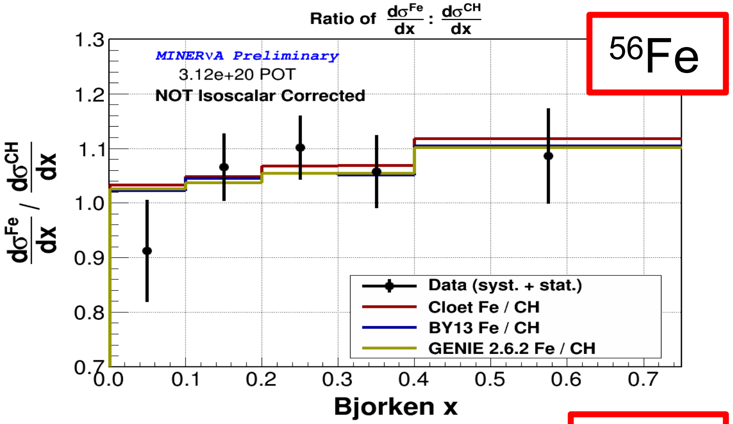
MINERvA DIS target ratio data (C, Fe, Pb)

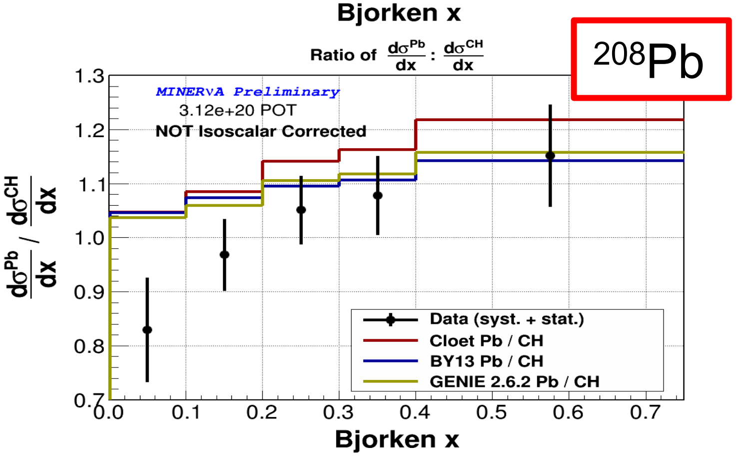
- MINERvA data reveal shadowing effect on neutrino may be larger than expected

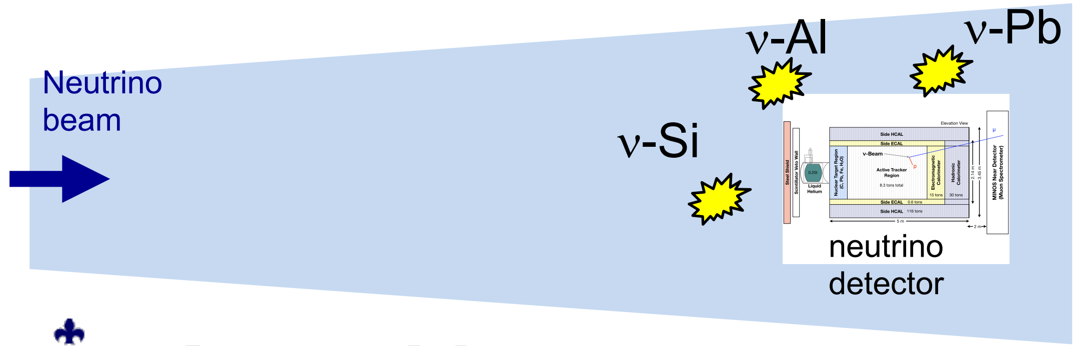
We care all nuclear targets

- Neutrino beam is like a “shower”, and it interacts with all materials surrounding the vertex detector. MC needs to simulate neutrino interactions (and particle propagations) for all inactive materials.









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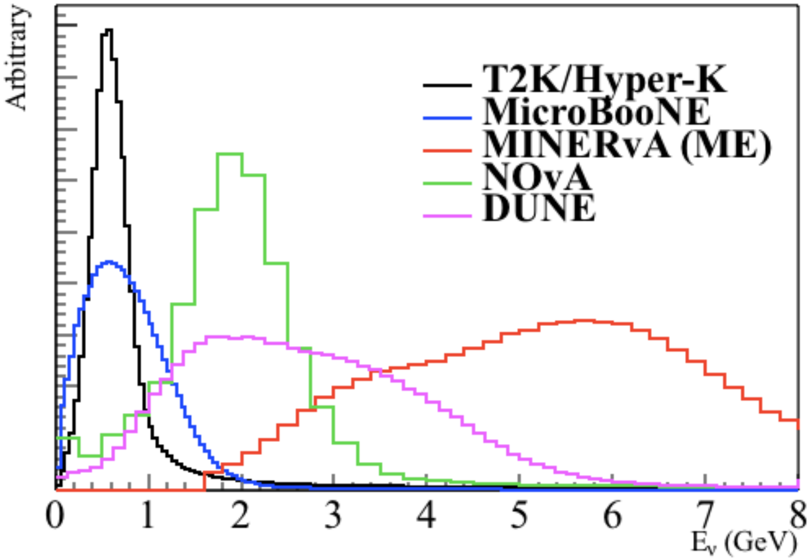
University of London

4. Summary of SIS, DIS, and hadronization

DIS and hadronization processes have been ignored for oscillation experiments

DIS errors and hadronization errors are not considered seriously
→ Problem for future PINGU, ORCA, DUNE



SIS model is wrong in many ways…
- no good higher resonances model
- no good low Q^2 DIS model
- no good A-dependent DIS model
- no good neutrino hadronization model
- no good resonance→DIS transition model

1. Neutrino Interaction Physics

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

3. Resonance Single Pion Production

4. Shallow inelastic scattering, DIS, and Hadronization

5. Conclusion

Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…

Neutrino oscillation

nuclear many-body problem

Spin physics

Weak interaction

Dark matter

EMC effect

Neutrino Interaction Physics

Nucleon correlation

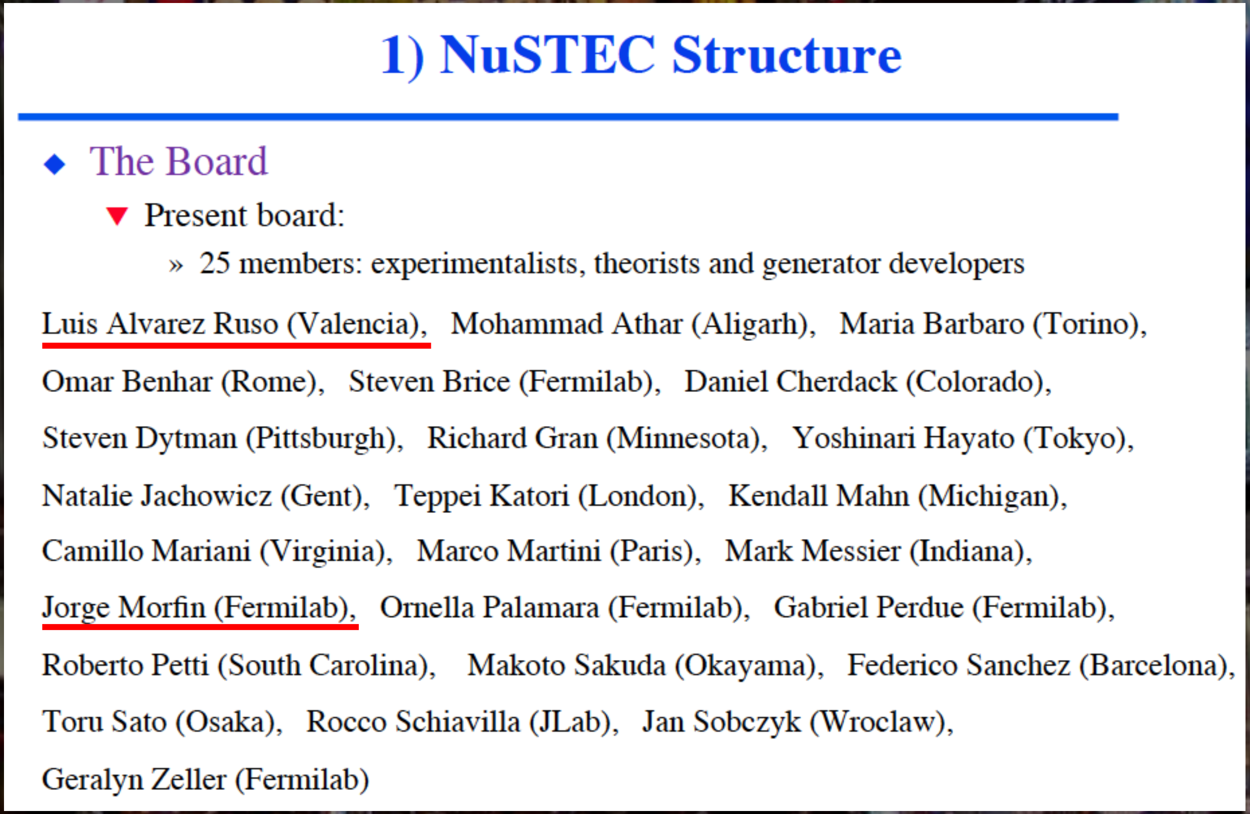
electron scattering

Heavy ion collision

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

The main goal is to improve our understanding of neutrino interactions with nucleons and nuclei



1) NuSTEC Structure

◆ The Board

- Present board:
  - » 25 members: experimentalists, theorists and generator developers

Luis Alvarez Ruso (Valencia), Mohammad Athar (Aligarh), Maria Barbaro (Torino), Omar Benhar (Rome), Steven Brice (Fermilab), Daniel Cherdack (Colorado), Steven Dytman (Pittsburgh), Richard Gran (Minnesota), Yoshinari Hayato (Tokyo), Natalie Jachowicz (Gent), Teppei Katori (London), Kendall Mahn (Michigan), Camillo Mariani (Virginia), Marco Martini (Paris), Mark Messier (Indiana), Jorge Morfin (Fermilab), Ornella Palamara (Fermilab), Gabriel Perdue (Fermilab), Roberto Petti (South Carolina), Makoto Sakuda (Okayama), Federico Sanchez (Barcelona), Toru Sato (Osaka), Rocco Schiavilla (JLab), Jan Sobczyk (Wroclaw), Geralyn Zeller (Fermilab)

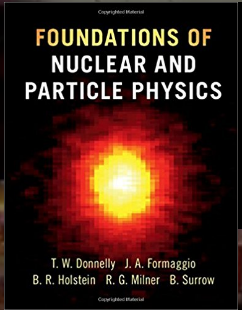
NuSTEC school

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

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

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

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



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FOUNDATIONS OF NUCLEAR AND PARTICLE PHYSICS
T. W. Donnelly J. A. Formaggio
B. R. Holstein R. G. Milner B. Surrow
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Foundation of Nuclear and Particle Physics

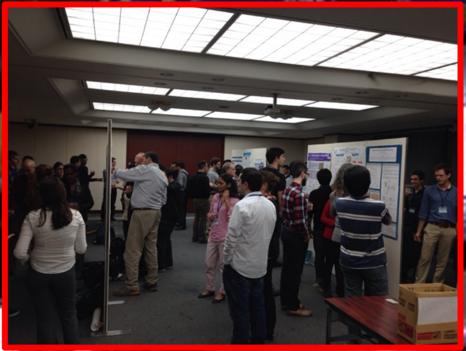
- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- The first textbook on this subject!

NuInt15, Osaka, Japan (Nov. 16-21, 2015)

Tremendous amount of activities, new data, new theories…
http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46

New data, new ideas
- MINERvA CC ω-q measurement
- ν_eCC cross-section measurement from NOvA near detector
- T2K CC0π double differential cross-sections
- MINERvA QE-like double differential cross-sections
- ArgoNeuT CC cross-sections with proton counting
- Charge exchange and pion absorption cross section
- CLAS pion production
- DIS cross-section target ratio by MINERvA

and more…



10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt15)

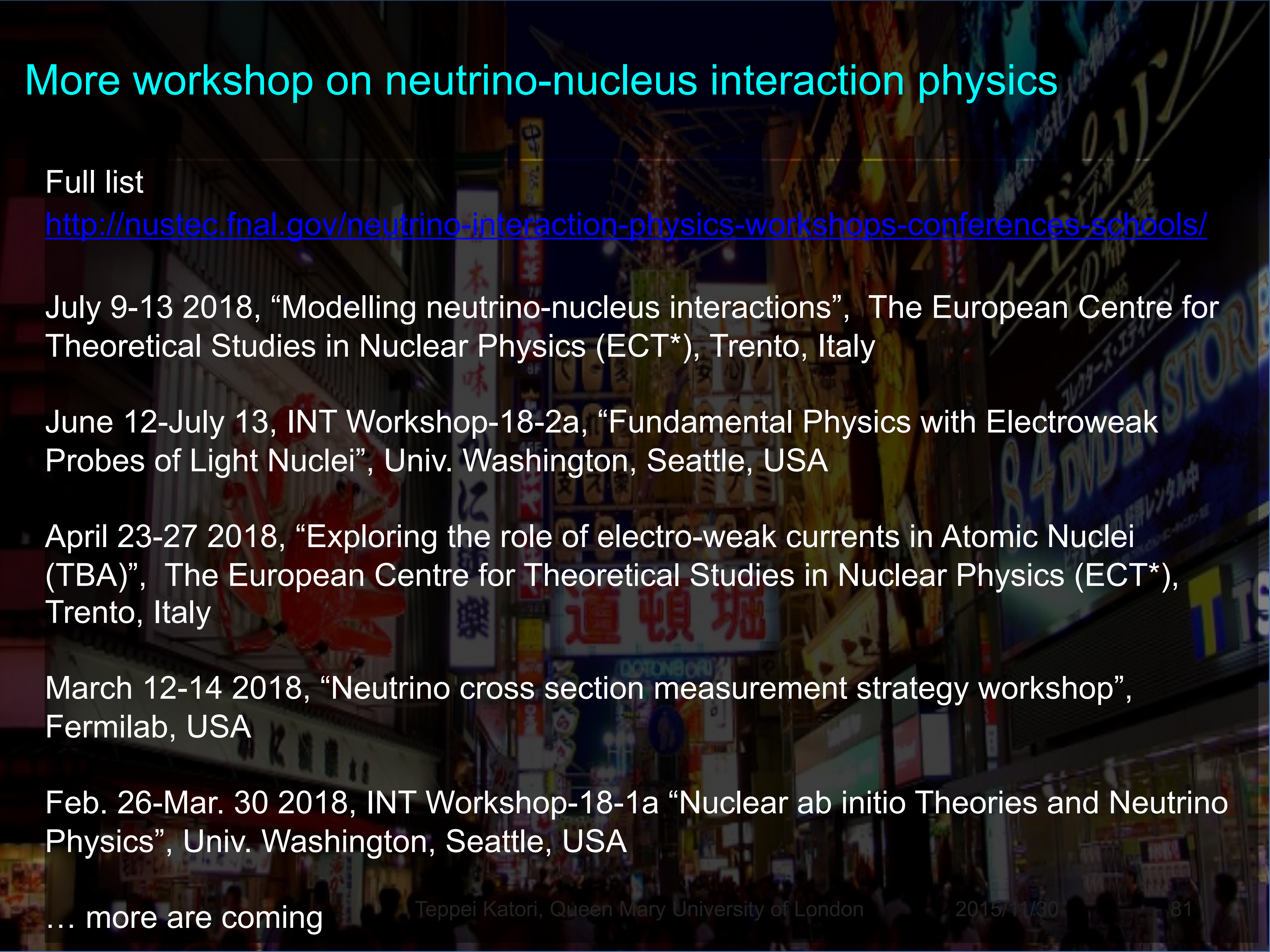
16-21 November 2015 *Icho-Kaikan, Osaka University Suita Campus*

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

The last NuInt17 was in Toronto
https://nuint2017.physics.utoronto.ca/

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

NuInt18, Gran Sasso, Italy (Oct. 15-19, 2018), stay tuned!



More workshop on neutrino-nucleus interaction physics

Full list
http://nustec.fnal.gov/neutrino-interaction-physics-workshops-conferences-schools/

July 9-13 2018, “Modelling neutrino-nucleus interactions”, The European Centre for Theoretical Studies in Nuclear Physics (ECT*), Trento, Italy

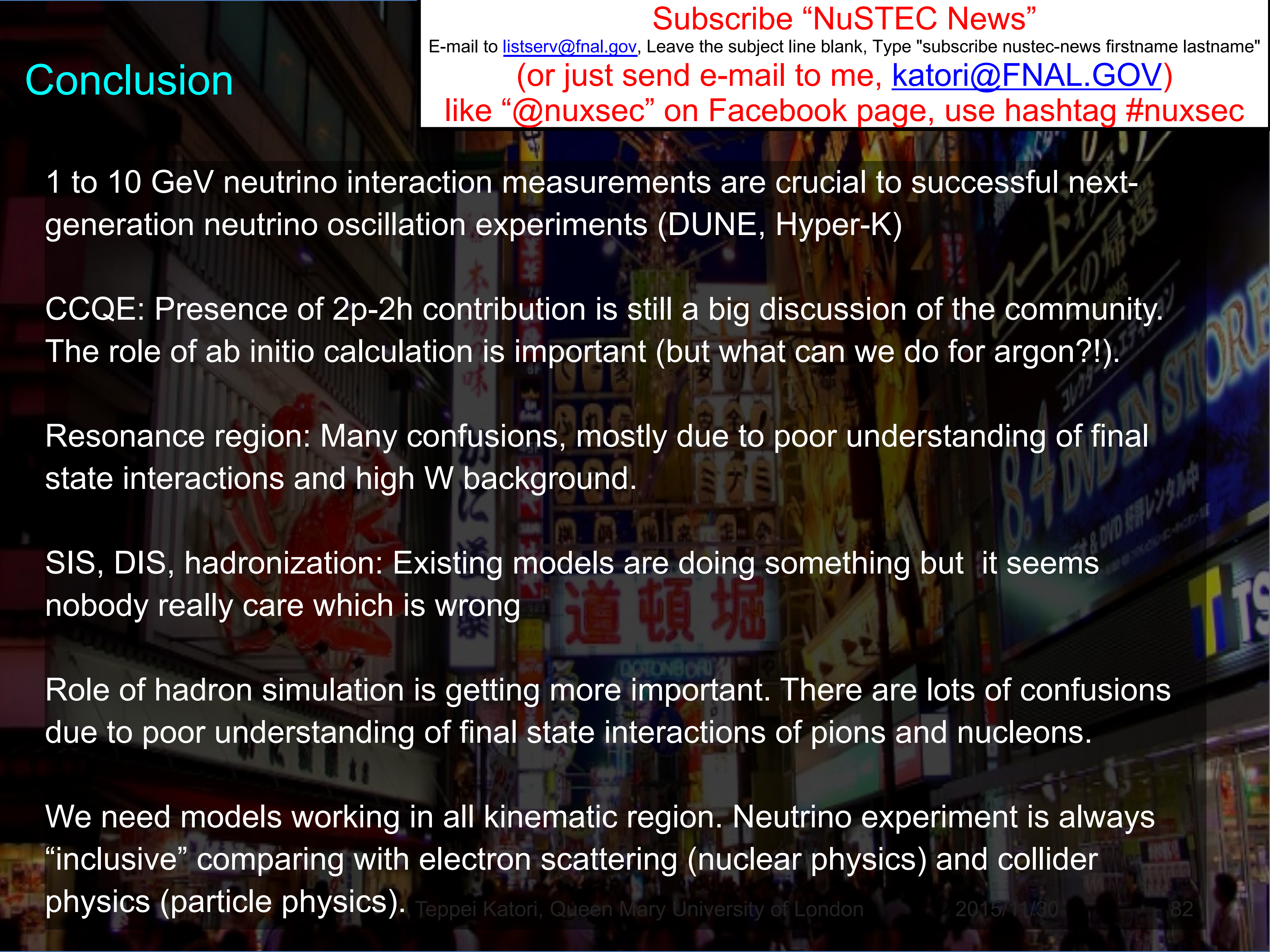
June 12-July 13, INT Workshop-18-2a, “Fundamental Physics with Electroweak Probes of Light Nuclei”, Univ. Washington, Seattle, USA

April 23-27 2018, “Exploring the role of electro-weak currents in Atomic Nuclei (TBA)”, The European Centre for Theoretical Studies in Nuclear Physics (ECT*), Trento, Italy

March 12-14 2018, “Neutrino cross section measurement strategy workshop”, Fermilab, USA

Feb. 26-Mar. 30 2018, INT Workshop-18-1a “Nuclear ab initio Theories and Neutrino Physics”, Univ. Washington, Seattle, USA

… more are coming



Conclusion

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

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

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

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

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

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

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

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

Conclusion

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Neutrino oscillation

electron scattering

nuclear many-body problem

Weak interaction

Neutrino Interaction Physics

EMC effect

Nucleon correlation

Spin physics

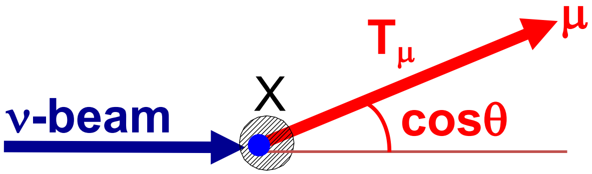
Dark matter

Heavy ion collision

Thank you for your attention!

Backup

2. Neutrino experiment



Experiment measure the interaction rate R,

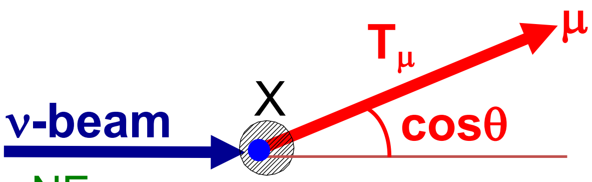
$$R \sim \int \Phi \times \sigma \times \varepsilon$$

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

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

MiniBooNE collaboration,PRL.100(2008)032301

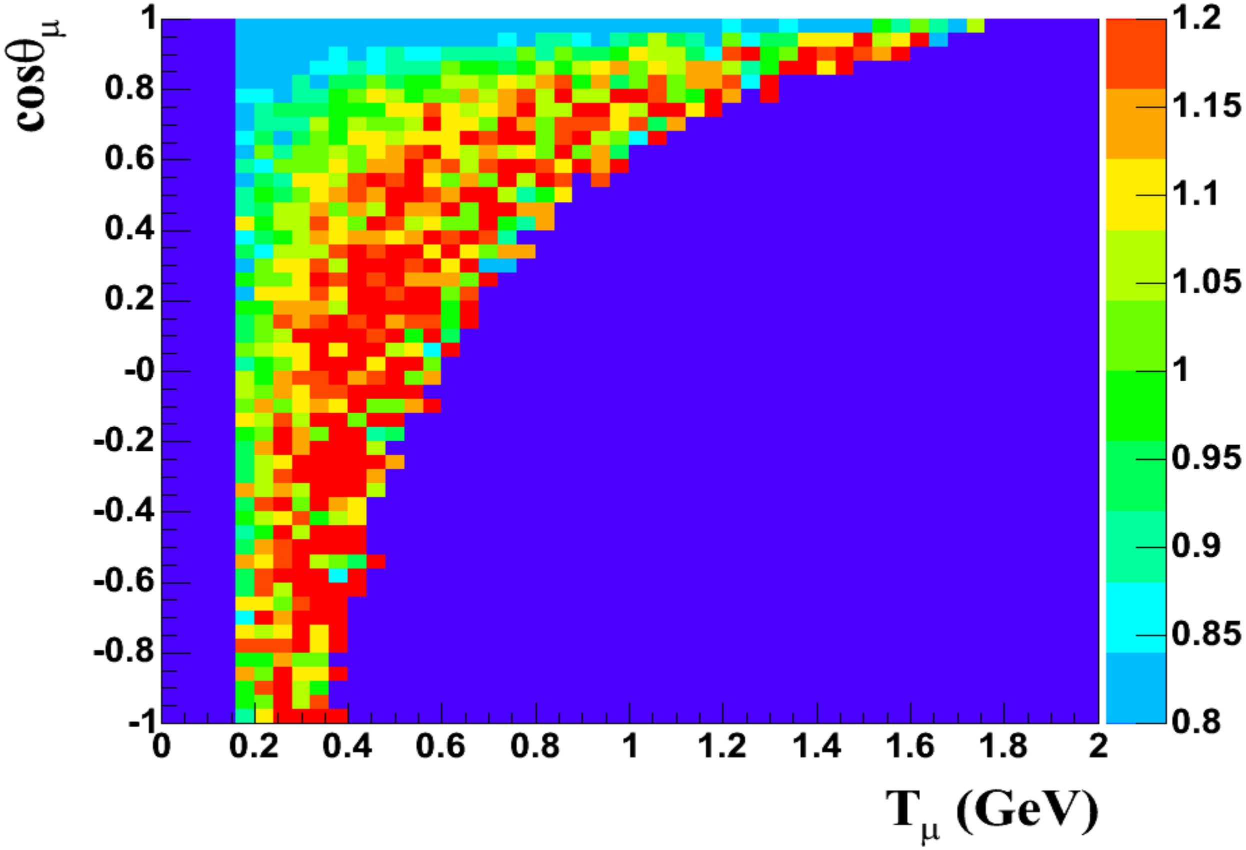
2. MiniBooNE phase space



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

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

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

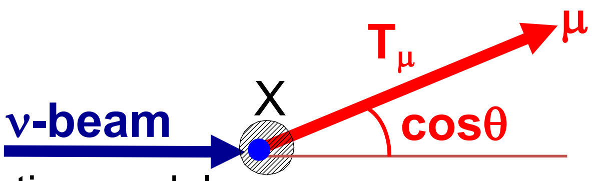


Data-MC ratio for T_μ-$\cos\theta_\mu$ plane (arbitrary normalization). MiniBooNE MC doesn't describe data very well.

We would like to improve our simulation, but how?

MiniBooNE collaboration,PRL.100(2008)032301

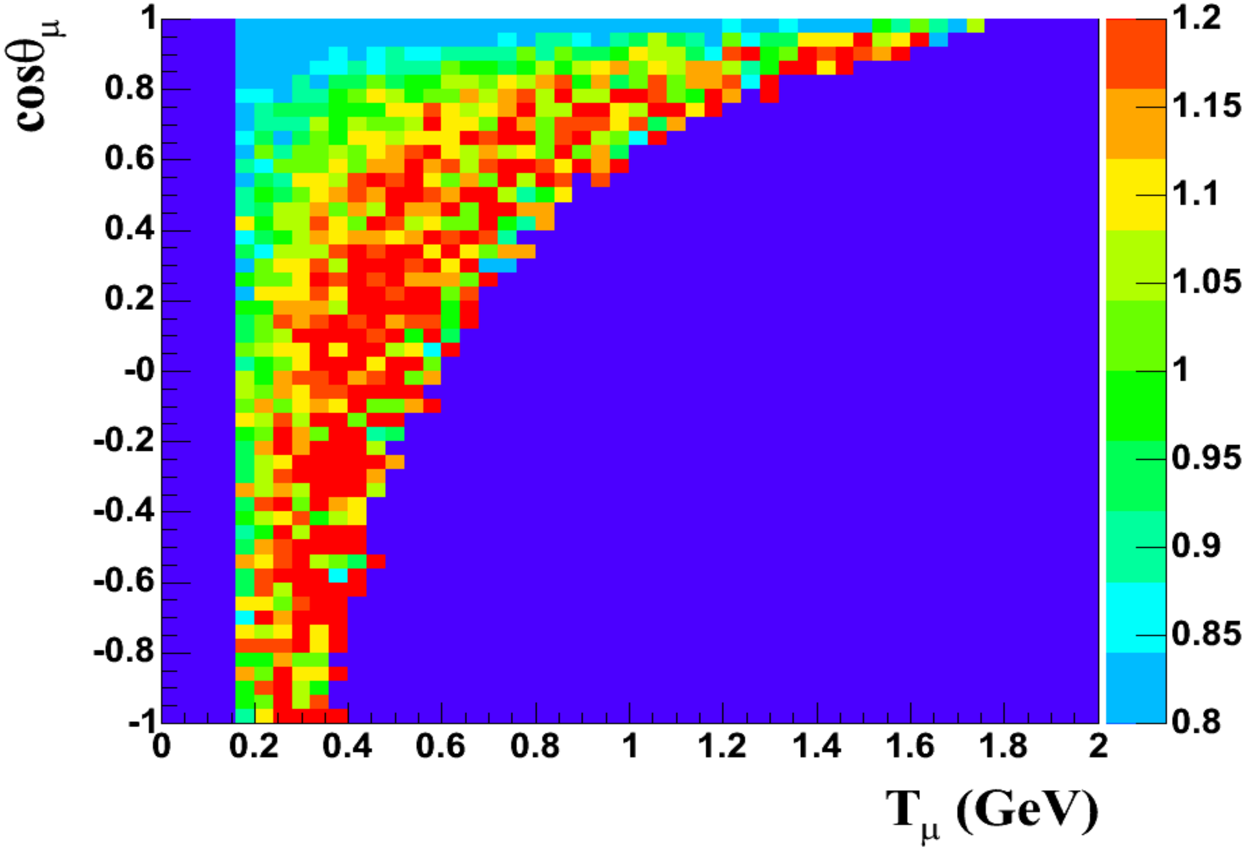
2. MiniBooNE phase space



Without knowing flux, you cannot modify cross section model

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

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



MiniBooNE collaboration,PRL.100(2008)032301

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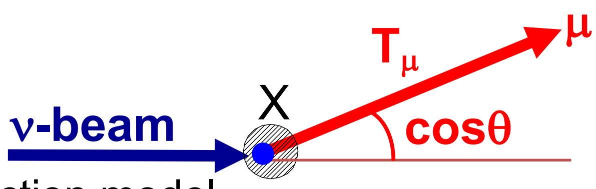
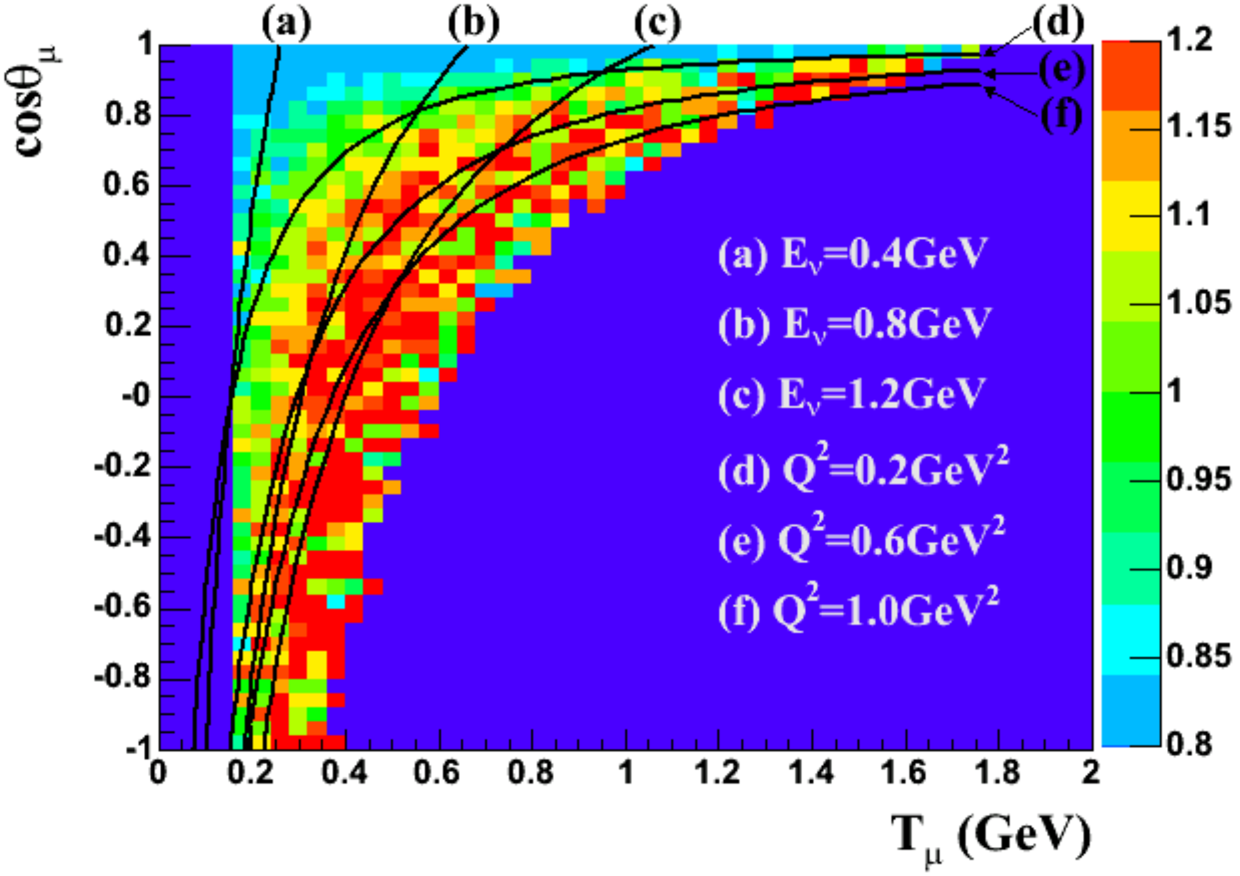


Without knowing flux, you cannot modify cross section model

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

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

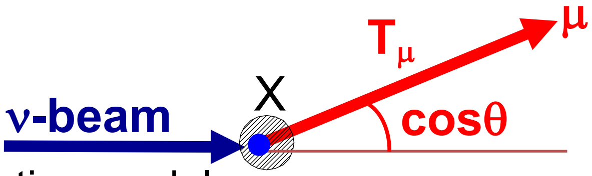


The data-MC disagreement follows equal Q^2- lines, not equal E_ν-lines.

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

MiniBooNE collaboration,PRL.100(2008)032301

2. MiniBooNE phase space

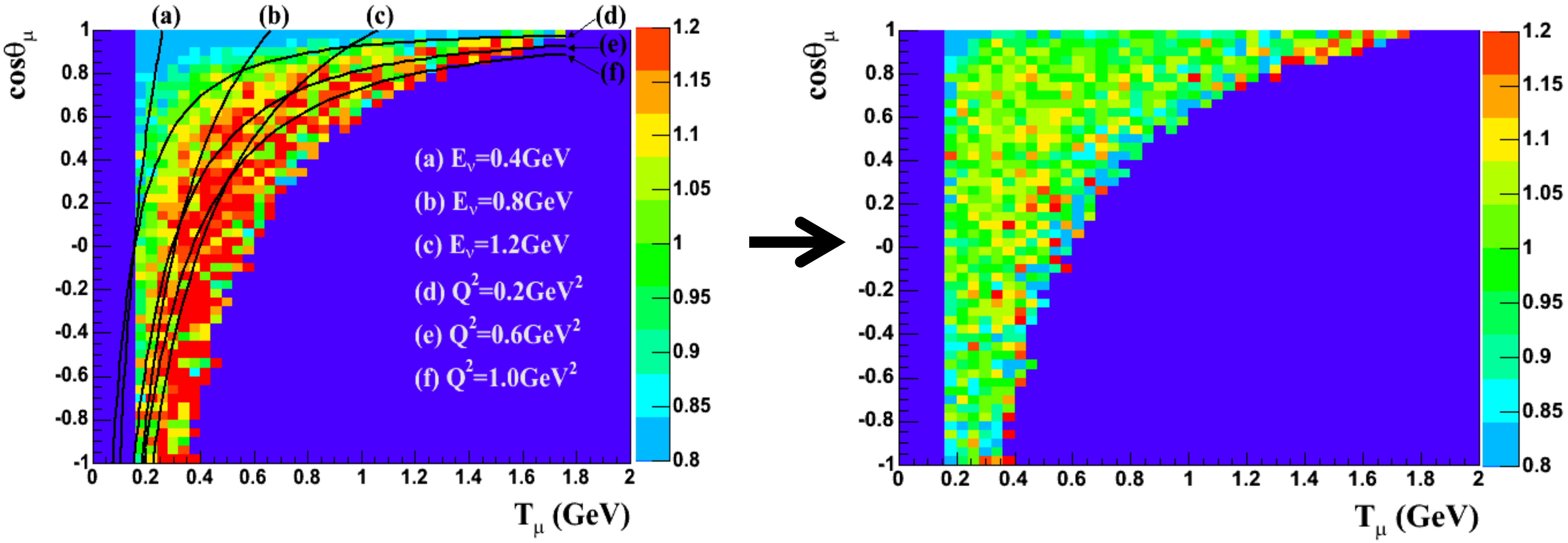


Without knowing flux, you cannot modify cross section model

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

After tuning cross section parameters, data and MC agree.

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



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

2. Smith-Moniz formalism

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

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

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

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

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

Ehi : the highest energy state of nucleon

Elo : the lowest energy state of nucleon

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

Home » Dr. Ernest Moniz

ABOUT US

DR. ERNEST MONIZ - SECRETARY OF ENERGY

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

2. Relativistic Fermi Gas (RFG) model

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

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

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

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

MiniBooNE tuned following 2 parameters using Q^2 distribution by least χ^2 fit;

M_A = effective axial mass

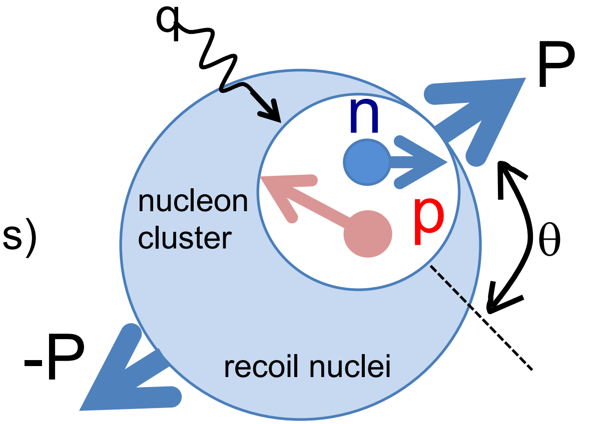
κ = effective Pauli blocking parameter

MiniBooNE tuned their axial mass to 1.3 GeV!

but axial mass is not 1.3 GeV!

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

2. How to emit 2 nucleons from correlated pair?



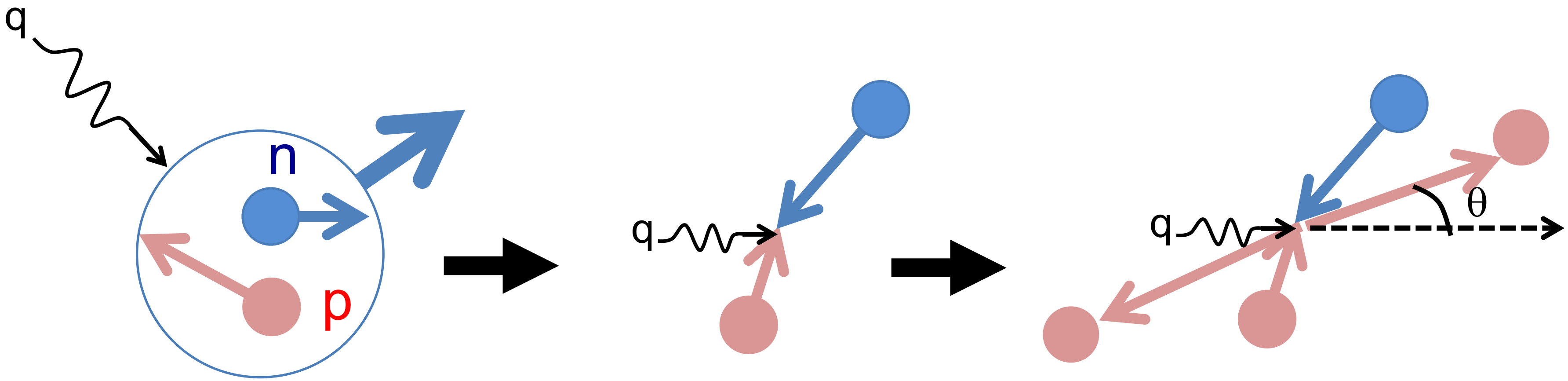
Default model for GENIE, NEUT, NuWro…

For a given Energy-Momentum transfer...

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

Once 2 nucleons from on-shell are choosed

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

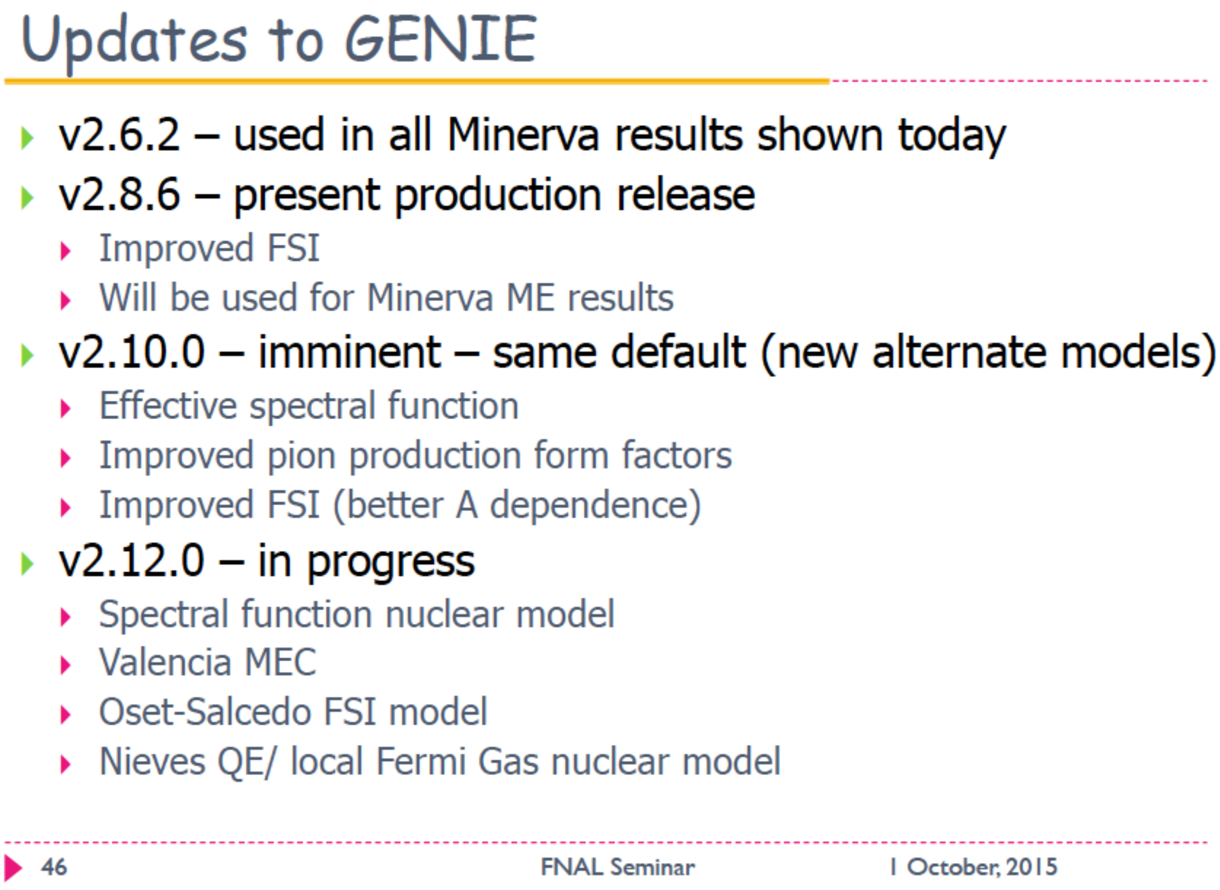


Is there correct way to model 2 nucleon emissions from a correlated nucleon pair?

Dytman, Fermilab neutrino seminar (2015)

4. GENIE update

Many new neutrino pion production data are available from T2K and MINERvA, but theories are not successful to reproduce them. For GENIE, having correct pion production model and FSI (final state interaction) is an urgent issue (for DUNE, NOvA, T2K, etc)



Updates to GENIE

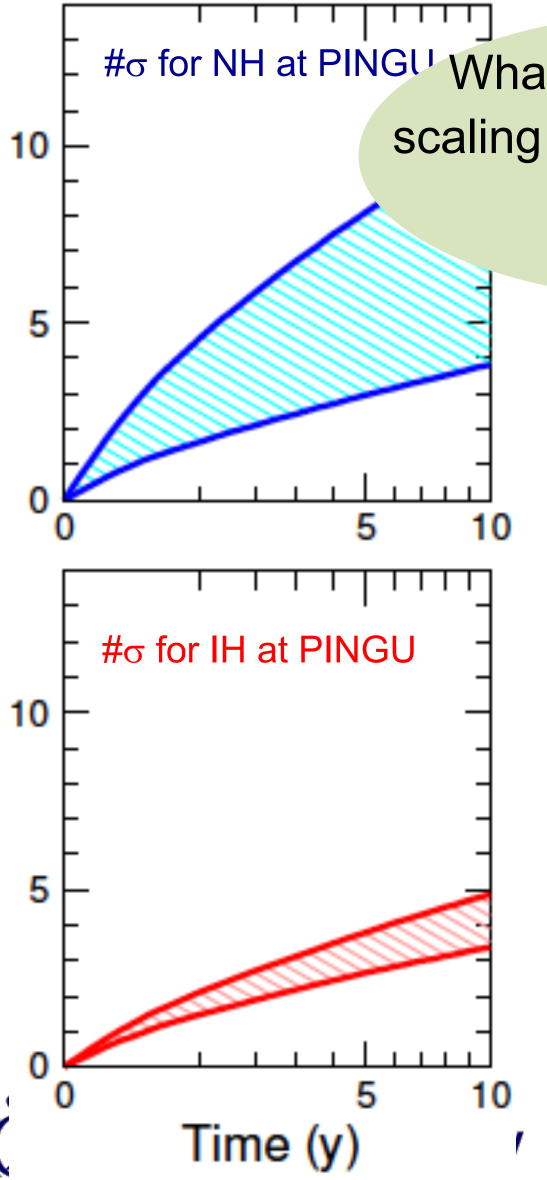
- v2.6.2 – used in all Minerva results shown today
- v2.8.6 – present production release
  - Improved FSI
  - Will be used for Minerva ME results
- v2.10.0 – imminent – same default (new alternate models)
  - Effective spectral function
  - Improved pion production form factors
  - Improved FSI (better A dependence)
- v2.12.0 – in progress
  - Spectral function nuclear model
  - Valencia MEC
  - Oset-Salcedo FSI model
  - Nieves QE/ local Fermi Gas nuclear model

46 FNAL Seminar | October, 2015

Capozzi et al,arXiv:1503.01999

1. NOvA, PINGU, Hyper-K, DUNE

See talk by Georgia Karagiorgi (PP+APP session)



What is the real energy scaling error on atmospheric neutrinos???
(Hyper-K, PINGU)

Neutrino interaction model is a large systematics of neutrino oscillation experiment

Capozzi et al,arXiv:1503.01999, ArgoNeuT,90PRD(2014)012008

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What is the real energy scaling error on atmospheric neutrinos???
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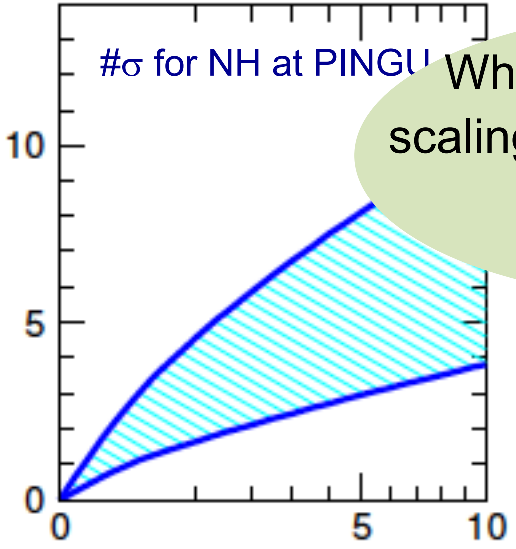
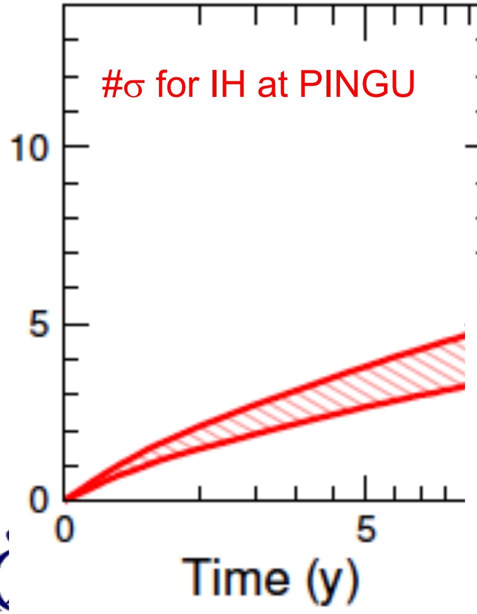
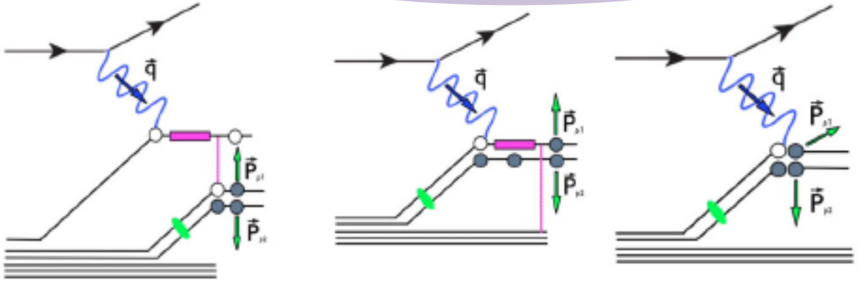
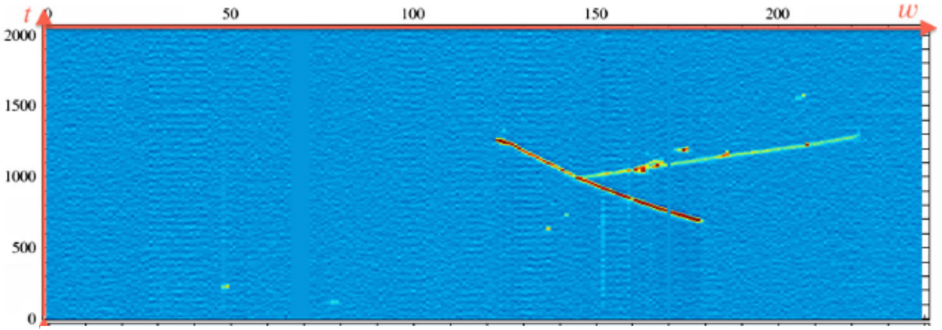
Are there any phenomenological models predicting final hadronic state correctly with argon target???
(DUNE)









Capozzi et al,arXiv:1503.01999, ArgoNeuT,90PRD(2014)012008
MiniBooNE,PRD83(2011)052007, MINERvA,arXiv:1406.6415

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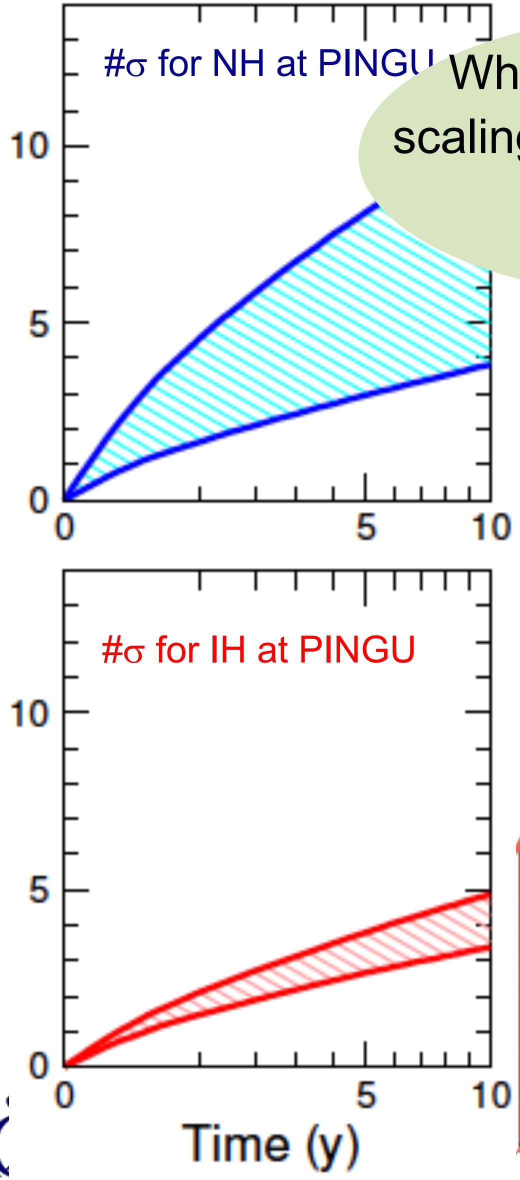
See talk by Georgia Karagiorgi (PP+APP session)

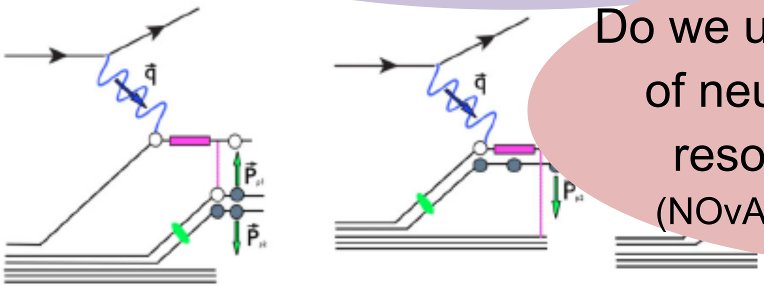
Neutrino interaction model is a large systematics of neutrino oscillation experiment

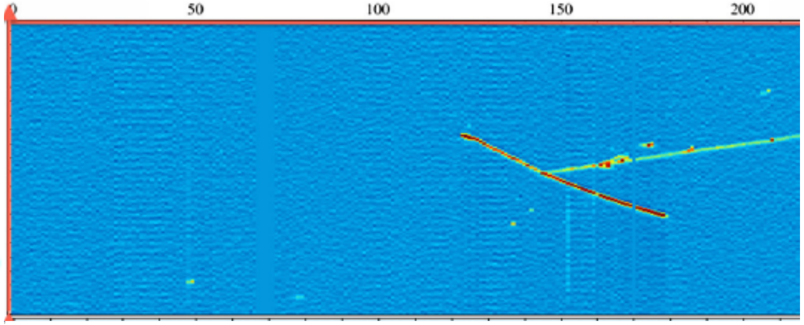


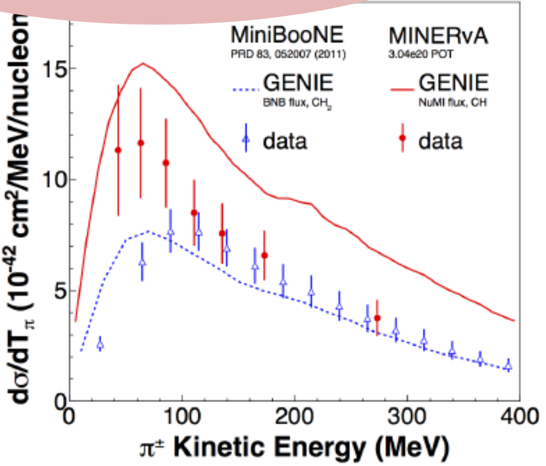
What is the real energy scaling error on atmospheric neutrinos???
(Hyper-K, PINGU)

Are there any phenomenological models predicting final hadronic state correctly with argon target???
(DUNE)

Do we understand the structure of neutrino induced baryon resonance someday???
(NOvA, PINGU, Hyper-K, DUNE)







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

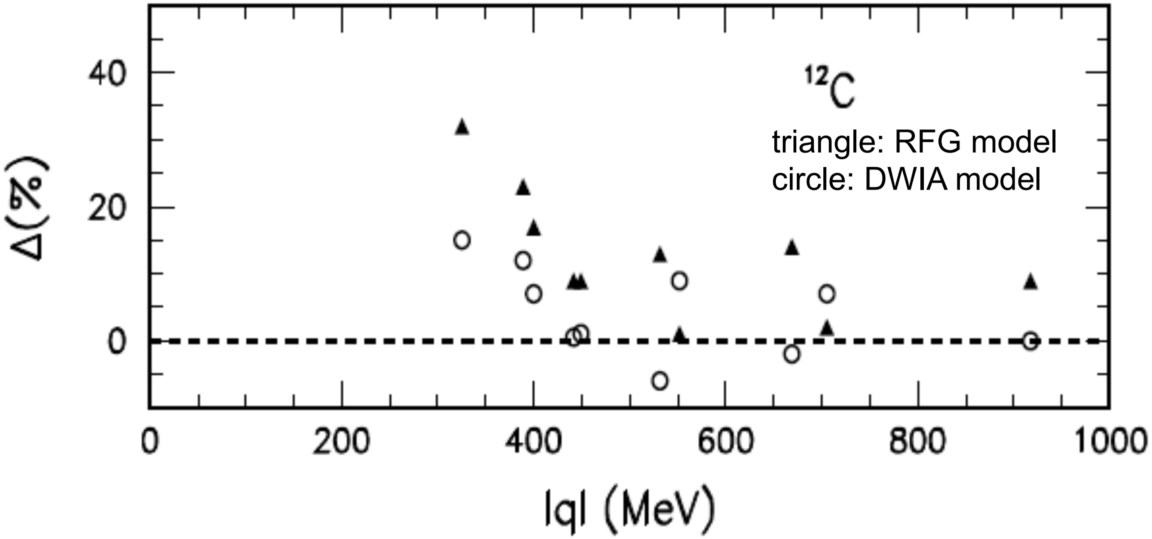
2. Relativistic Fermi Gas (RFG) model

Butkevich and Mikheyev, PRC72(2005)025501

Relativistic Fermi Gas (RFG) Model
Nucleus is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

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

Data and predicted xs difference for ^{12}C



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

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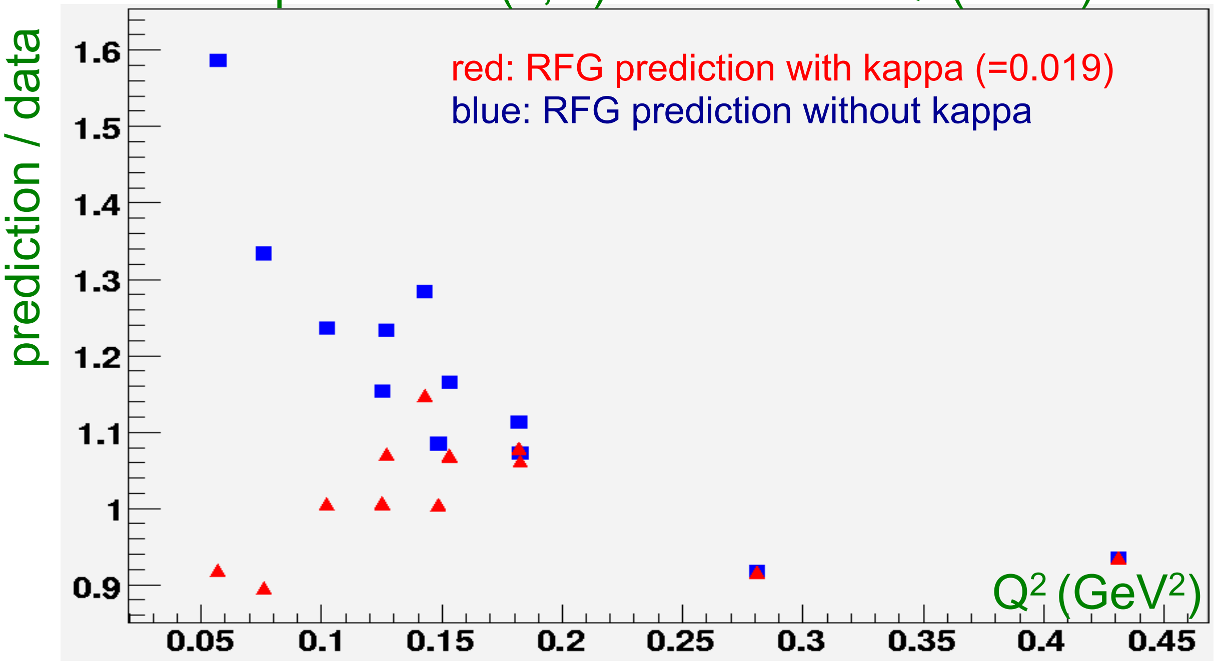
RFG prediction-(e,e') data ratio in Q^2 (GeV^2)

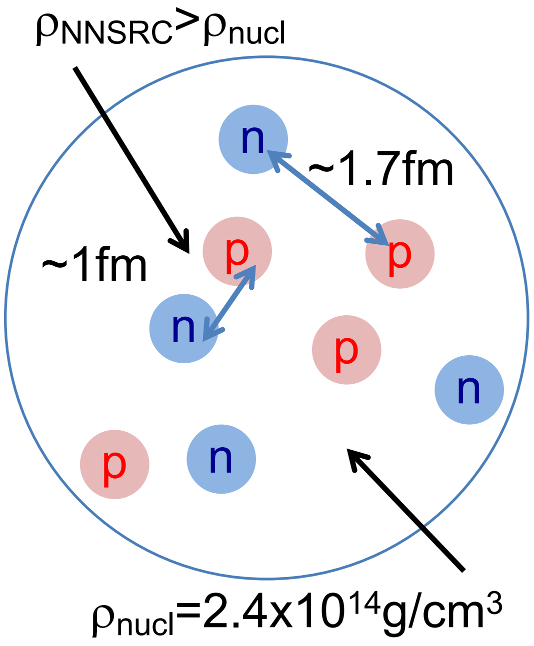


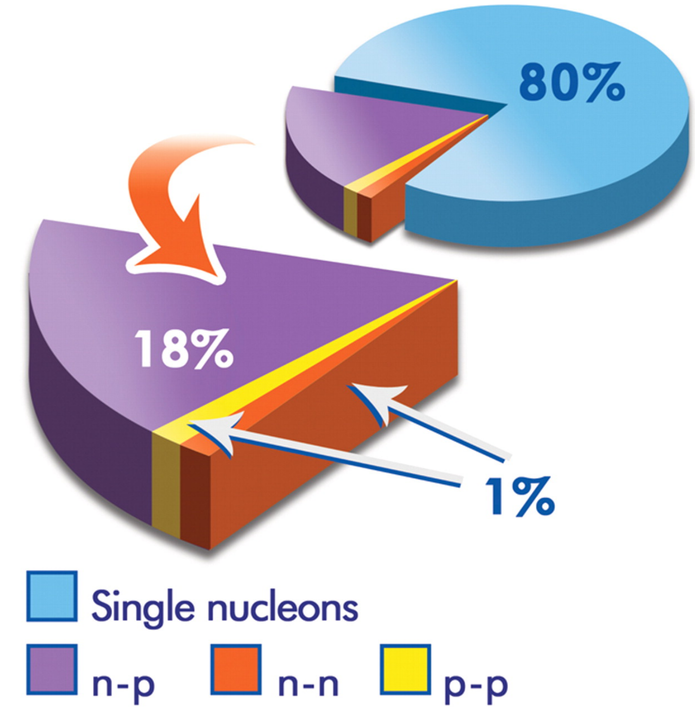
CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504
JLab HallA, PRL99(2007)072501, Science320(2008)1476

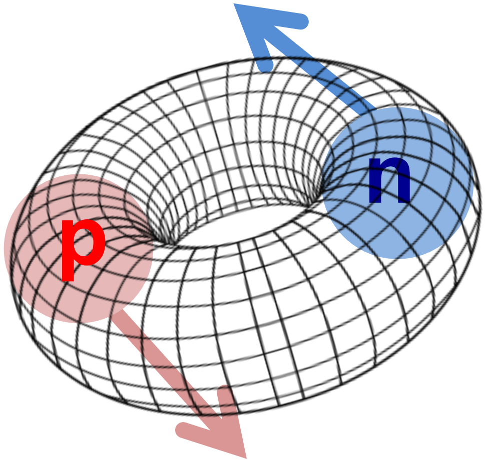
2. Nucleon correlations

Short Range Correlation (SRC)

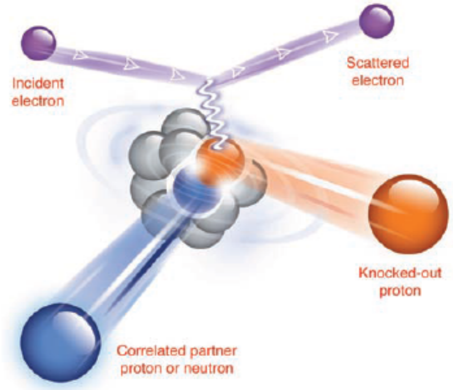
~20% of all nucleons in heavy elements (A>4)
~90% are neutron-proton (n-p) pair
~nucleon pair have back-to-back momentum
~ momentum can be beyond Fermi sea







NNSRC~quasi deuteron

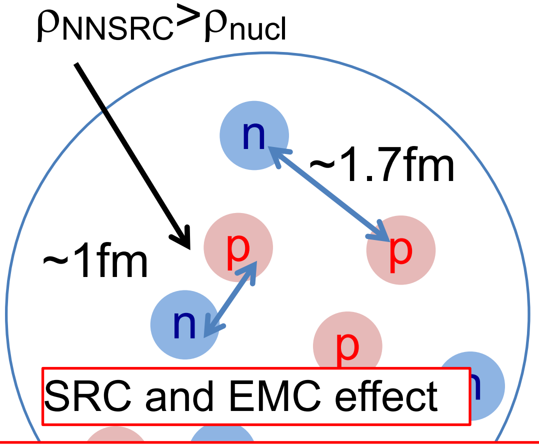


CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504;106(2011)052301
JLab HallA, PRL99(2007)072501, Science320(2008)1476

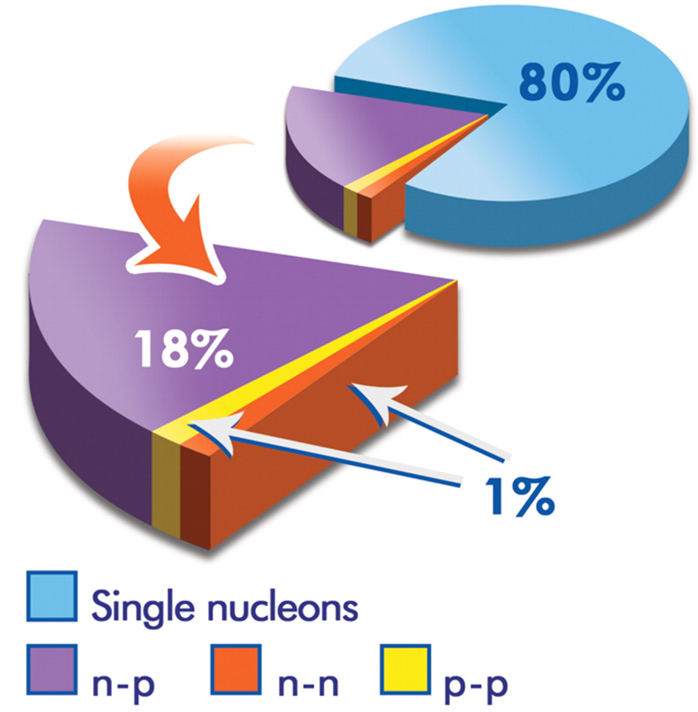
2. Nucleon correlations

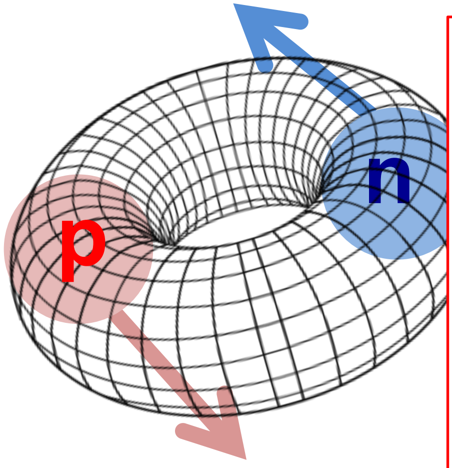
Short Range Correlation (SRC)

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

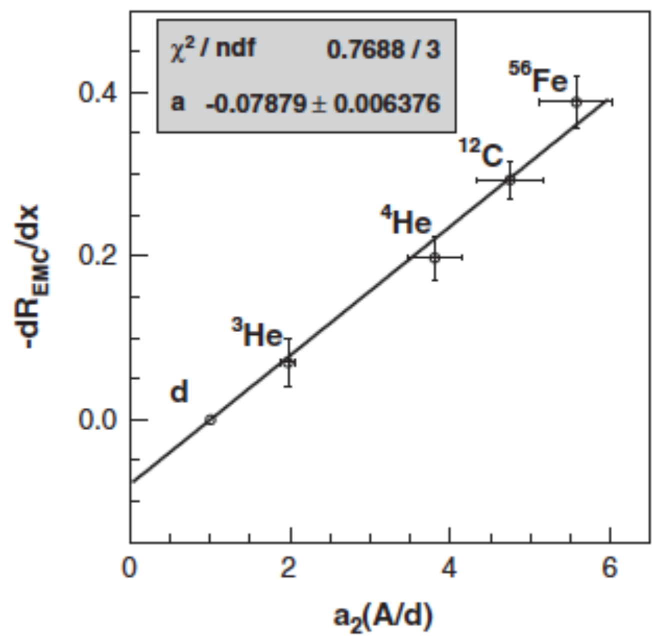


SRC and EMC effect





NNSRC~quasi deuter



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

3. Neutrino oscillation experiment

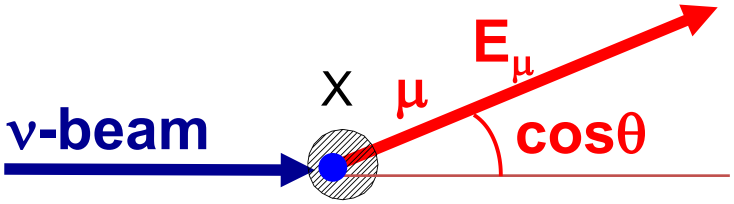
Reconstruction of neutrino energy with QE assumption

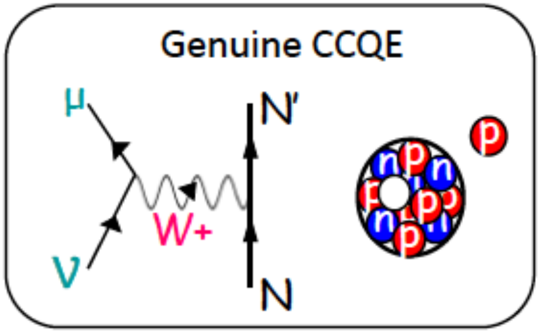
- We can reconstruct neutrino energy if we know it is CCQE interaction

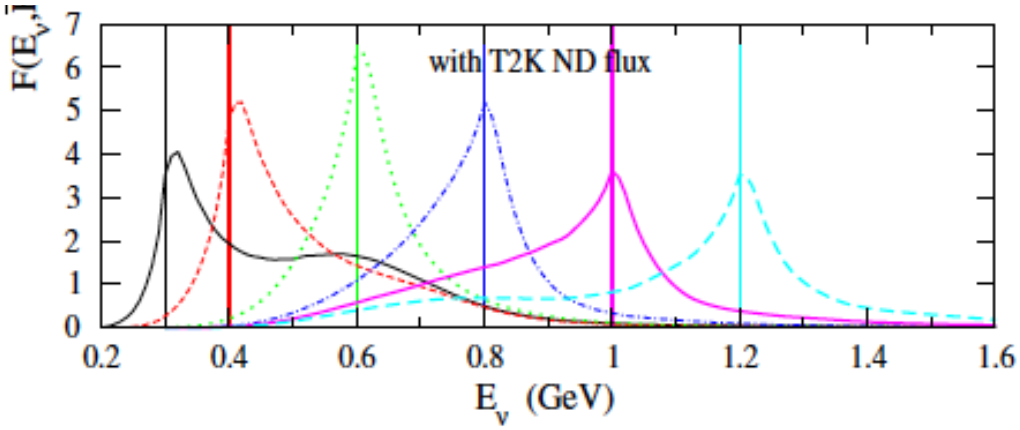
→ There is bias because of all “CCQE-like” interactions.

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

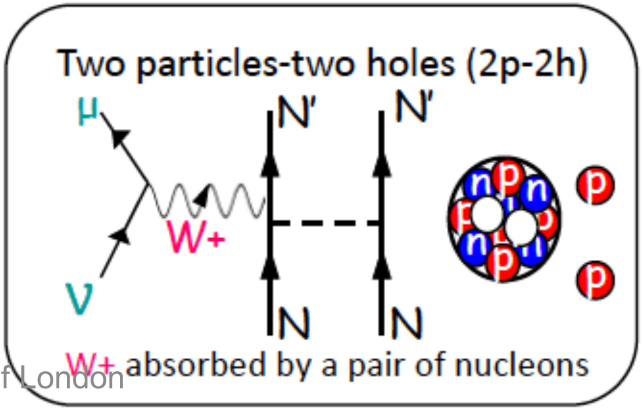
$$\nu_\mu + n \to p + \mu^- \quad (\nu_\mu + X \to X' + \mu^-) \qquad E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$







estimated reconstruction due to 2-body current



5. Conclusion remarks from INT workshop 2013

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

Toward better neutrino interaction models…

To experimentalists

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

To theorists

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

4. Differential cross-section measurements for New physics

Differential cross-section measurement itself is often new physics search
→ model-independent rate measurements

Two tantalizing examples

1. Neutral Current gamma production (NCγ) and MiniBooNE low energy excess
2. Neutral Current Quasi-Elastic (NCQE) scattering and dark matter particle search

MiniBooNE,PRL110(2013)161801
TK, arXiv:1107.5112

4. MiniBooNE low energy excess

MiniBooNE observed oscillation candidate event excess
→ but MiniBooNE cannot distinguish e and γ

signal

$$\nu_\mu \xrightarrow{oscillation} \nu_e + n \rightarrow p + \boxed{e^-}$$

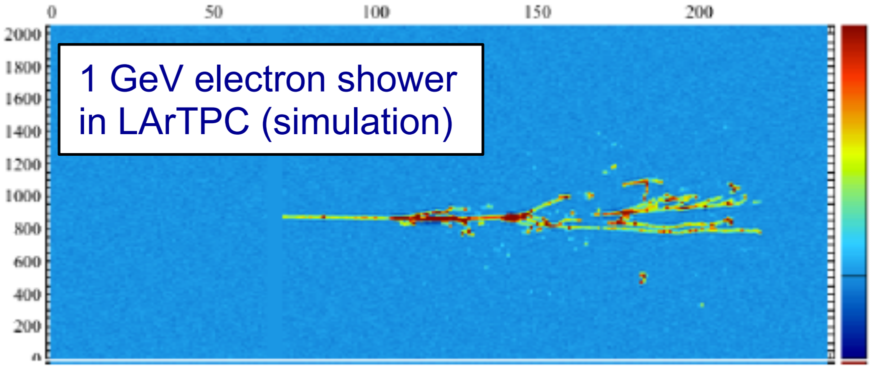
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow n + \boxed{e^+}$$

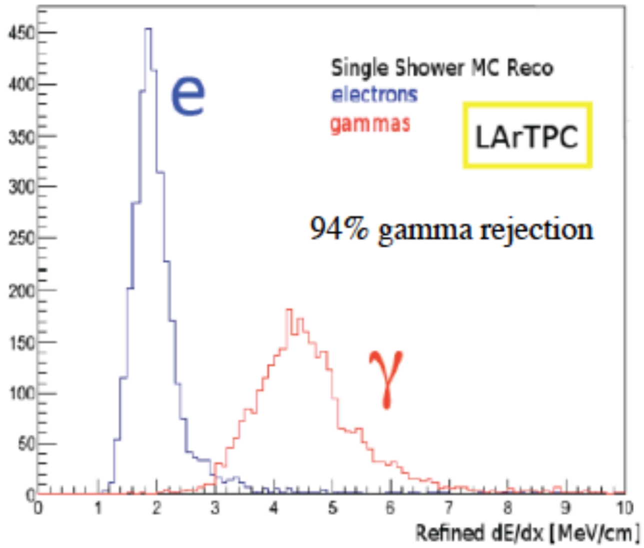
background

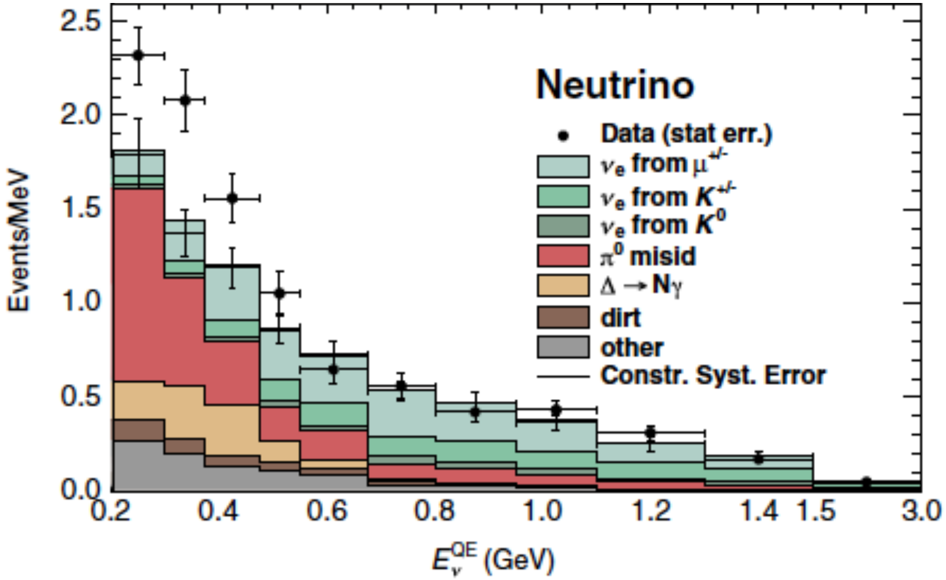
$$\nu_\mu + X \rightarrow \nu_\mu + X' + \pi^o \rightarrow \cancel{\gamma} + \boxed{\gamma}$$

$$\nu_\mu + X \rightarrow \nu_\mu + X' + \boxed{\gamma}$$

Can new NCγ model explain this excess?


1 GeV electron shower in LArTPC (simulation)





Alvarez-Ruso,Nieves,Wang, arXiv:1311.2151, Zhang,Serot, PLB719(2013)409
Hill, PRD81(2010)013008, Gninenko, PRL103(2009)241802

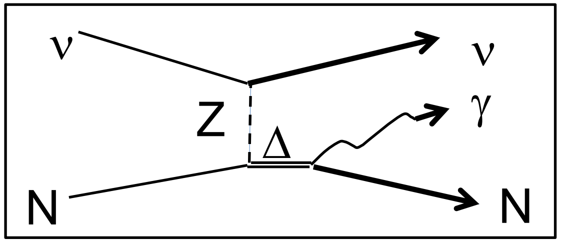
4. MiniBooNE low energy excess

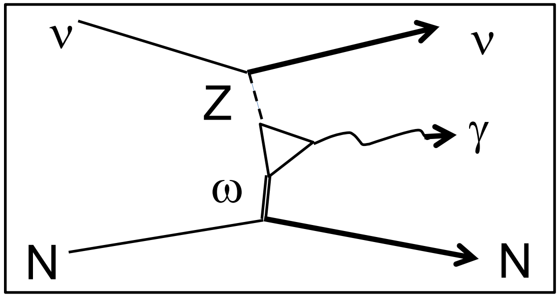
MiniBooNE observed oscillation candidate event excess
→ but MiniBooNE cannot distinguish e and γ

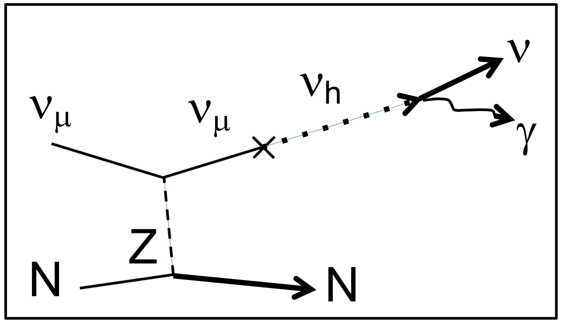
Can new NCγ model explain this excess?

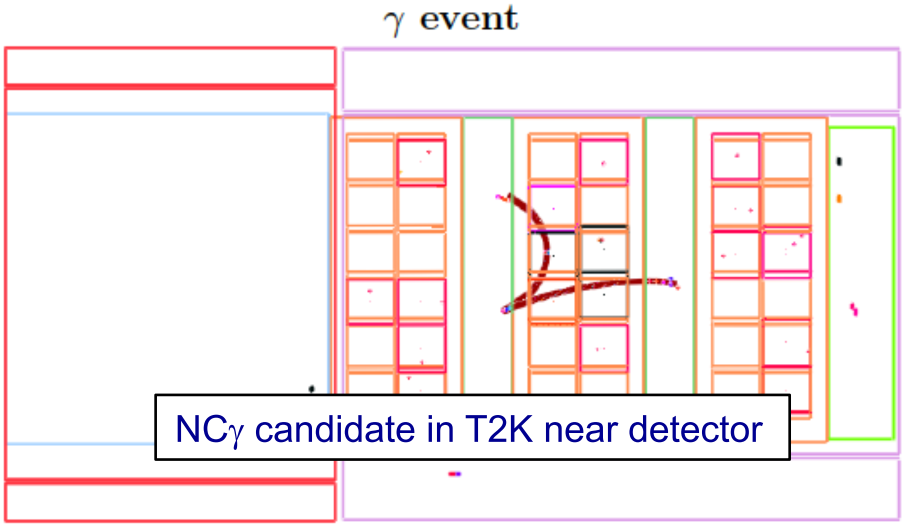
1. New nuclear models
2. New mechanism but within the SM
3. Beyond the SM but not sterile neutrino oscillation

NOMAD measured at <E>~25GeV
T2K can measure this at lower energy









NCγ candidate in T2K near detector

Differential cross-section measurement can test, nuclear physics, new diagram, and BSM physics simultaneously!

MiniBooNE,PRD82(2010)092005;91(2015)012004
T2K,PRD90(2014)072012

4. Neutral Current Quasi-Elastic (NCQE) scattering

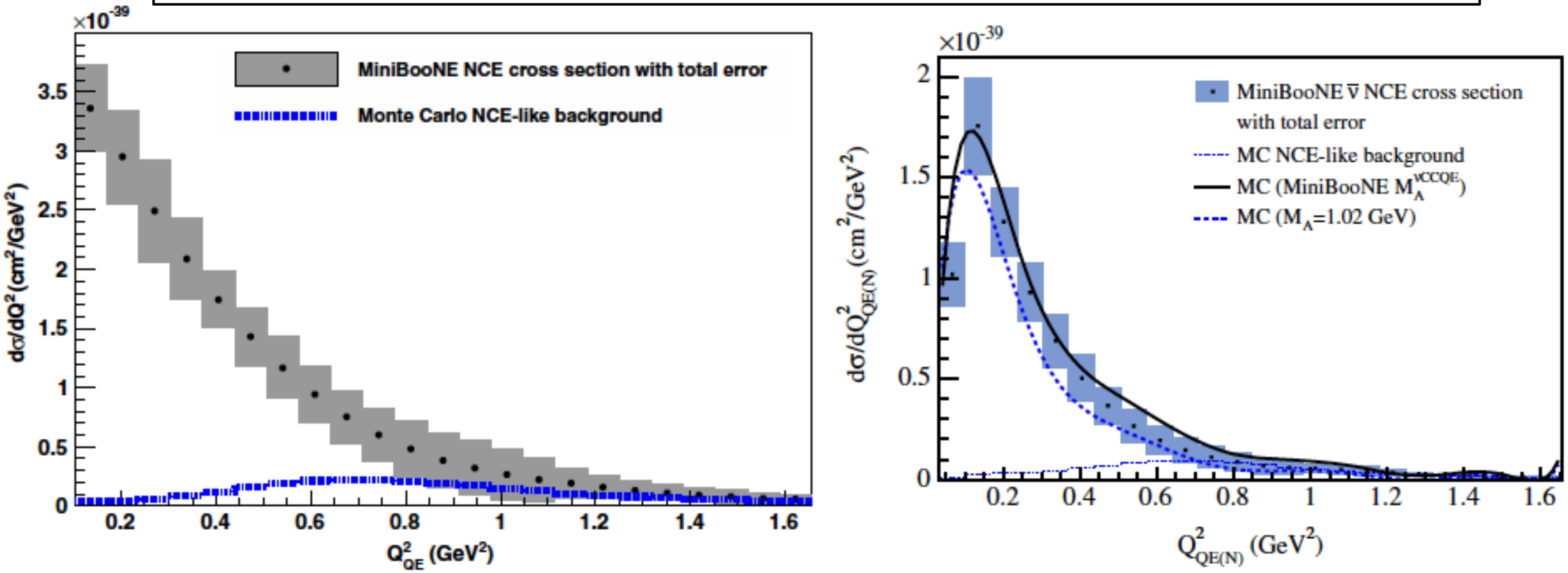
This channel has so many topics

1. Spin physics
2. Sterile neutrino oscillation
3. Light dark matter particle

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

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

Neutrino and anti-neutrino flux-integrated NCQE differential cross-section on CH_2



Garvey et al,PRC48(1993)761, Pate et al,PRC78(2008)015207
HERMES,PLB666(2008)446,

4. Neutral Current Quasi-Elastic (NCQE) scattering

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2. Sterile neutrino oscillation
3. Light dark matter particle

"proton spin crisis"

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

quark longitudinal polarization
ΔΣ=Δu+Δd+**Δs** ~ 0.25

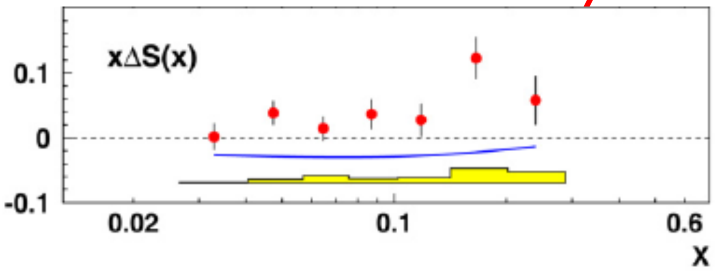
gluon longitudinal
polarization ~ 0.2

quark and gluon orbital
angular momentum ~?

NC is a unique source of axial-vector isoscalar form factor → strange quark spin components (Δs)

$$\boxed{\int_0^1 dx\Delta s(x) \equiv \Delta s \equiv G_A^s(Q^2=0)}$$

HERMES SIDIS
~0 (0.02<x<0.6)



ν_μNCQE+
PV e-scattering
~ -0.1

Garvey et al,PRC48(1993)761, Pate et al,PRC78(2008)015207
HERMES,PLB666(2008)446, Butkevich et al,PRC84(2011)015501

4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

1. Spin physics
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"proton spin crisis"

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

quark longitudinal polarization
$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.25$

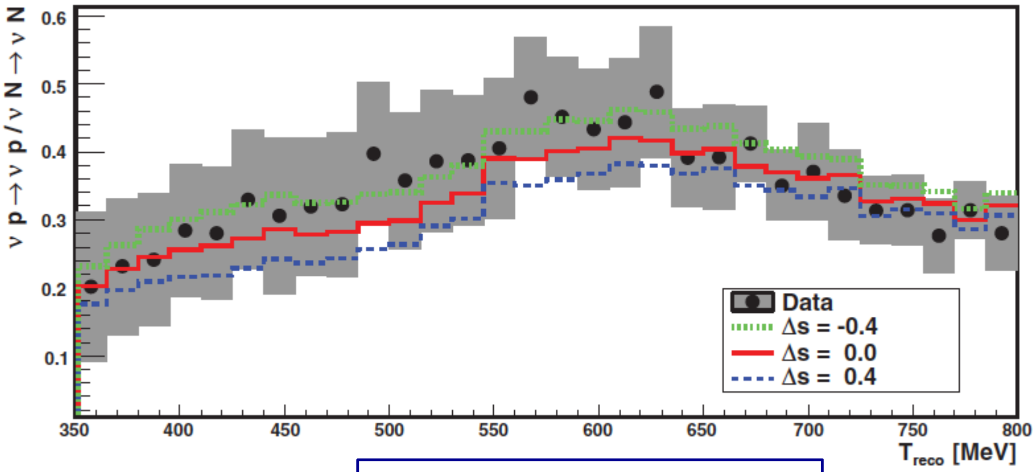
gluon longitudinal polarization ~ 0.2

quark and gluon orbital angular momentum ~?

NC is a unique source of axial-vector isoscalar form factor → strange quark spin components (Δs)

The latest fit is consistent with Δs~0

Problem: separation of νp→νp and νn→νn scattering is very hard



Δs fit on νp→νp/νN→νN data

Wilkinson et al,JHEP01(2014)064

4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

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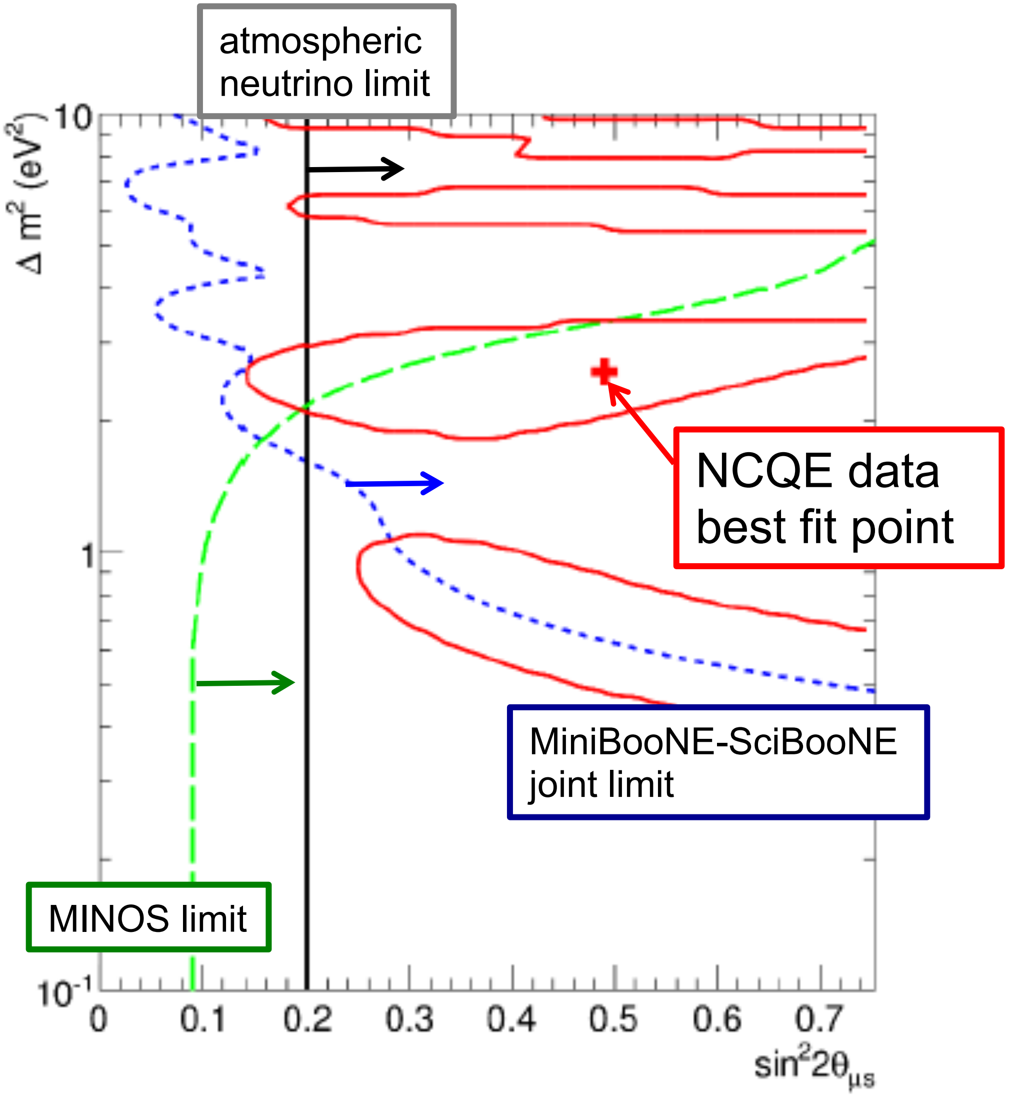
2. Sterile neutrino oscillation
3. Light dark matter particle

NC data can test sterile neutrino hypothesis independently
 - different event topology

Problem: large cross-section error
 → simultaneous fit of sterile neutrino parameters and neutrino interaction parameters.



atmospheric neutrino limit

NCQE data best fit point

MiniBooNE-SciBooNE joint limit

MINOS limit

TK et al, AHEP(2015)362971
deNiverville et al,PRD84(2011)075020, Batell et al,PRD90(2014)115014

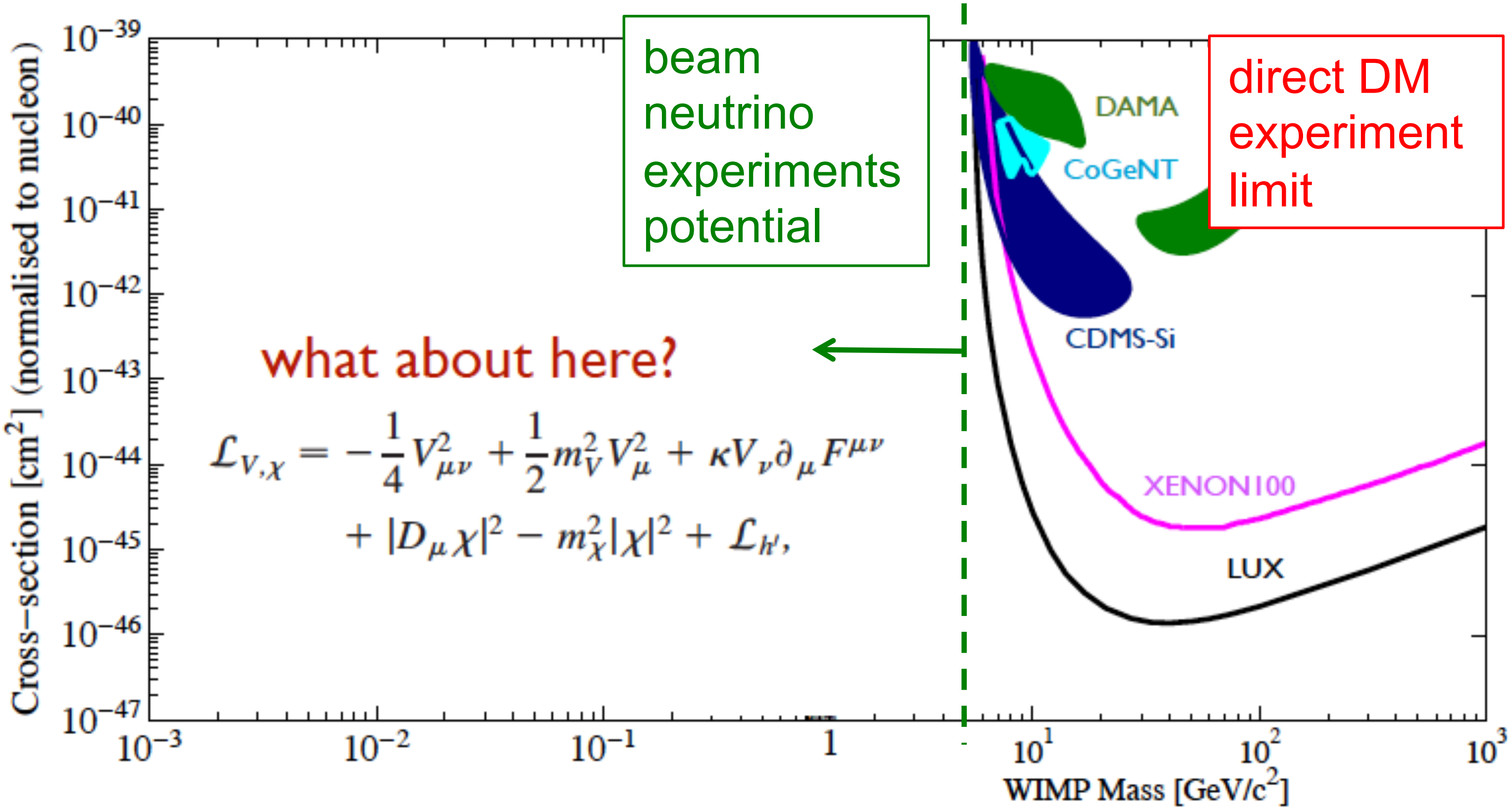
4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

1. Spin physics
2. Sterile neutrino oscillation
3. Light dark matter particle

Experiment sensitive to NCQE are sensitive to all invisible-type particles (cf dark matter particles)

→ NCQE is a large background. Understanding of NCQE is important.



$$\mathcal{L}_{V,\chi} = -\frac{1}{4}V_{\mu\nu}^2 + \frac{1}{2}m_V^2 V_\mu^2 + \kappa V_\nu \partial_\mu F^{\mu\nu} + |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 + \mathcal{L}_{h'},$$

beam neutrino experiments potential

direct DM experiment limit

4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

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2. Sterile neutrino oscillation
3. Light dark matter particle

Both measurements and predictions of hadron final states need to be improved

- nucleon correlation
- baryon resonance
- final state interactions
- hadronization

There is a huge potential of discovery physics!