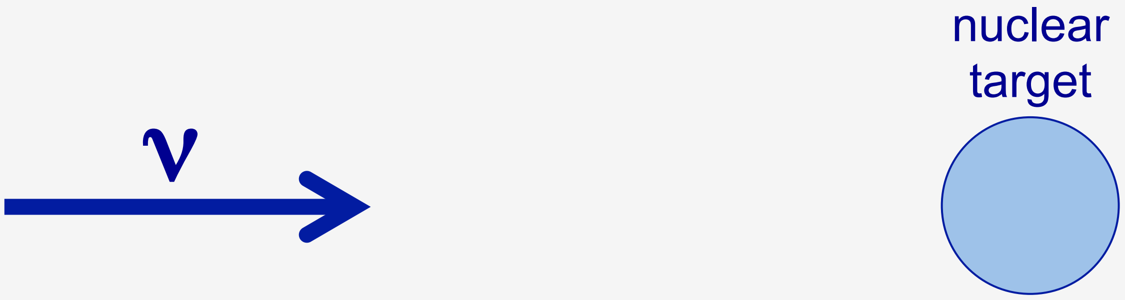

nuclear
target
ν

# Fun Timely Intellectual Adorable!

# Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

## Neutrino Cross-Section Newsletter

Weak interaction

Nucleon correlation

EMC effect

electron scattering

Dark matter

Subscribe "Neutrino Cross-Section Newsletter"
(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please "like" our Facebook page, use hashtag #nuxsec

# Physics of Neutrino Interactions

Teppei Katori
Queen Mary University of London
NP seminar, U. Surrey, Surrey, Nov. 24, 2015

## Neutrino Cross-Section Newsletter

- nuclear many-body problem
- Spin physics
- Leptonic CP violation
- Neutrino oscillation
- Weak interaction
- Nucleon correlation
- EMC effect
- electron scattering
- Dark matter

Subscribe "Neutrino Cross-Section Newsletter"
(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please "like" our Facebook page, use hashtag #nuxsec

# Physics of Neutrino Interactions

Teppei Katori
Queen Mary University of London
NP seminar, U. Surrey, Surrey, Nov. 24, 2015

**outline**

1. Neutrino Interaction Physics
2. Charged-Current Quasi-Elastic (CCQE) interaction
3. Open question of neutrino interaction physics
4. Neutrino induced single pion production
5. Conclusion

Subscribe "Neutrino Cross-Section Newsletter"
(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please "like" our Facebook page, use hashtag #nuxsec

# 1. Neutrino Interaction Physics

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

# 3. Open question of neutrino interaction physics

# 4. Neutrino induced single pion production

# 5. Conclusion

# 1. Neutrino physics, the future of particle physics

2014 May 22, there was a major news
in high energy physics community...

# 1. Neutrino physics, the future of particle physics

2014 May 22, there was a major news in high energy physics community...

NewScientist Physics & Math

Home News In-Depth Articles Opinion CultureLab Galleries Topic Gui

SPACE TECH ENVIRONMENT HEALTH LIFE PHYSICS&MAT

Home | Physics & Math | News

**Neutrinos top list of targets for US particle physics**

15:00 22 May 2014 by Jessica Orwig
For similar stories, visit the US national

NBC NEWS HOME LATEST SEARCH

**Neutrinos Take Center Stage in America's Plan for Future Physics**

BY ALAN BOYLE

yorkdispatch.com
ODDITIES

ment Community Opinion Photos/Media

baby photos Lzzy Hale Prep sports I Art York Top sto

**What's going on???**

ars technica

MAIN MENU MY STORIES: 25 FORUMS SUBSCRIBE JOBS

SCIENTIFIC METHOD / SCIENCE & EXPLORA

**US particle physics roadmap: Build facilities for neutrinos and muons**

But goals face a budget crunch before they leave the starting line.

by John Timmer - May 24 2014, 5:10am JST

PHYSICAL SCIENCES SCIENCE POLICY AND EDUCATION 45

Print Email

**Physics panel to feds: Beam us up some neutrinos**

*Seth Borenstein AP Science Writer*

UPDATED: 05/22/2014 02:16:04 PM EDT

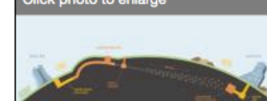
COMMENTS

WASHINGTON (AP) — The U.S. should build a billion-dollar project to beam ghostlike subatomic particles 800 miles underground from Chicago to South Dakota, a committee of experts told the federal government Thursday.

That would help scientists learn about these puzzling particles, called neutrinos, which zip right through us.

The proposed invisible neutrino beam would be the biggest U.S.

Click photo to enlarge

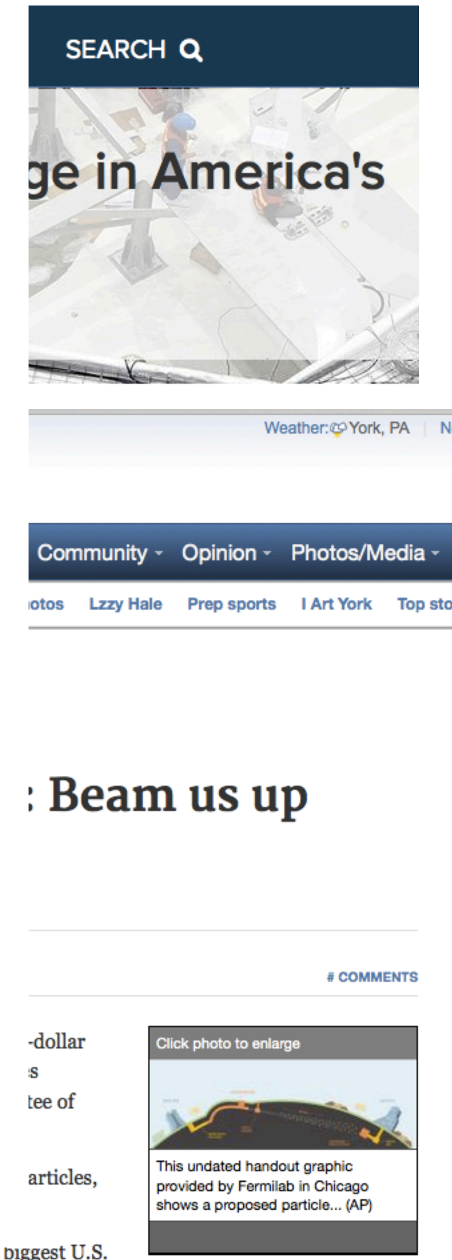


This undated handout graphic provided by Fermilab in Chicago shows a proposed particle... (AP)

# 1. Neutrino

2014 May 22, th
in high energy pl



# 1. P5 report (Particle Physics Project Prioritization Panel)

25 of prominent physicists made a list of recommendations for the future directionality of US particle physics

## Contents



## Table 1
## Summary of Scenarios

| | Scenarios | | | Science Drivers | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Project/Activity | Scenario A | Scenario B | Senario C | 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 contri-butions. 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. P5 report (Particle Physics Project Prioritization Panel)

25 of prominent physicists made a list of recommendations for the future direction of US particle physics

## Contents



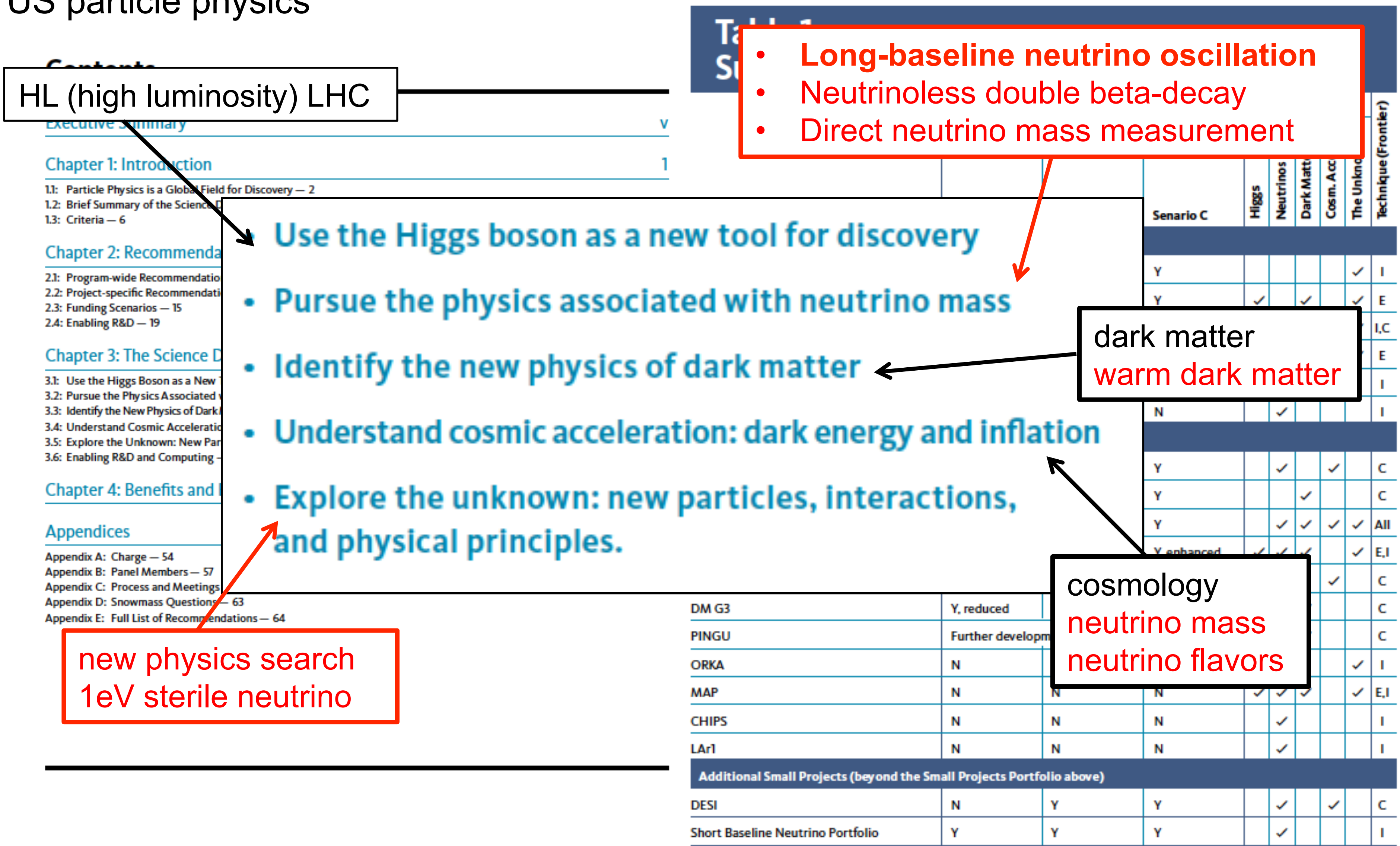
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles.

## Table 1
## Summary of Scenarios

| | Scenarios | | | Science Drivers | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Senario C | Higgs | Neutrinos | Dark Matter | Cosm. Accel. | The Unknown | Technique (Frontier) |
| | | | Y | | | | | ✓ | I |
| | | | Y | ✓ | | ✓ | | ✓ | E |
| | | | Y, enhanced | | ✓ | | | ✓ | I,C |
| | | | Y | ✓ | | ✓ | | ✓ | E |
| | | | N | | ✓ | | | | I |
| | | | N | | ✓ | | | | I |
| | | | Y | | ✓ | | ✓ | | C |
| | | | Y | | | ✓ | | | C |
| | | | Y | | ✓ | ✓ | ✓ | ✓ | All |
| | | | Y, enhanced | ✓ | ✓ | ✓ | | ✓ | E,I |
| | | | 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. P5 report (Particle Physics Project Prioritization Panel)

25 of prominent physicists made a list of recommendations for the future direction of US particle physics



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

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

We need higher precision experiments around 1-10 GeV.

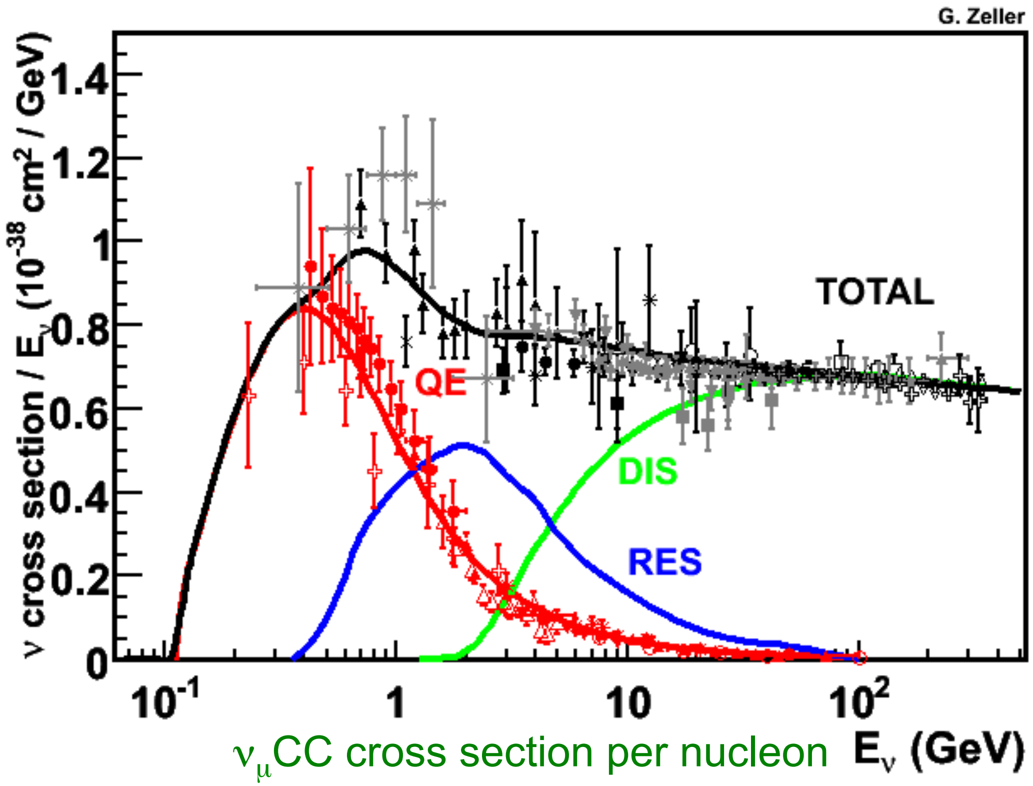
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307



# 1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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




$\nu_\mu$CC cross section per nucleon

Queen Mary University of London

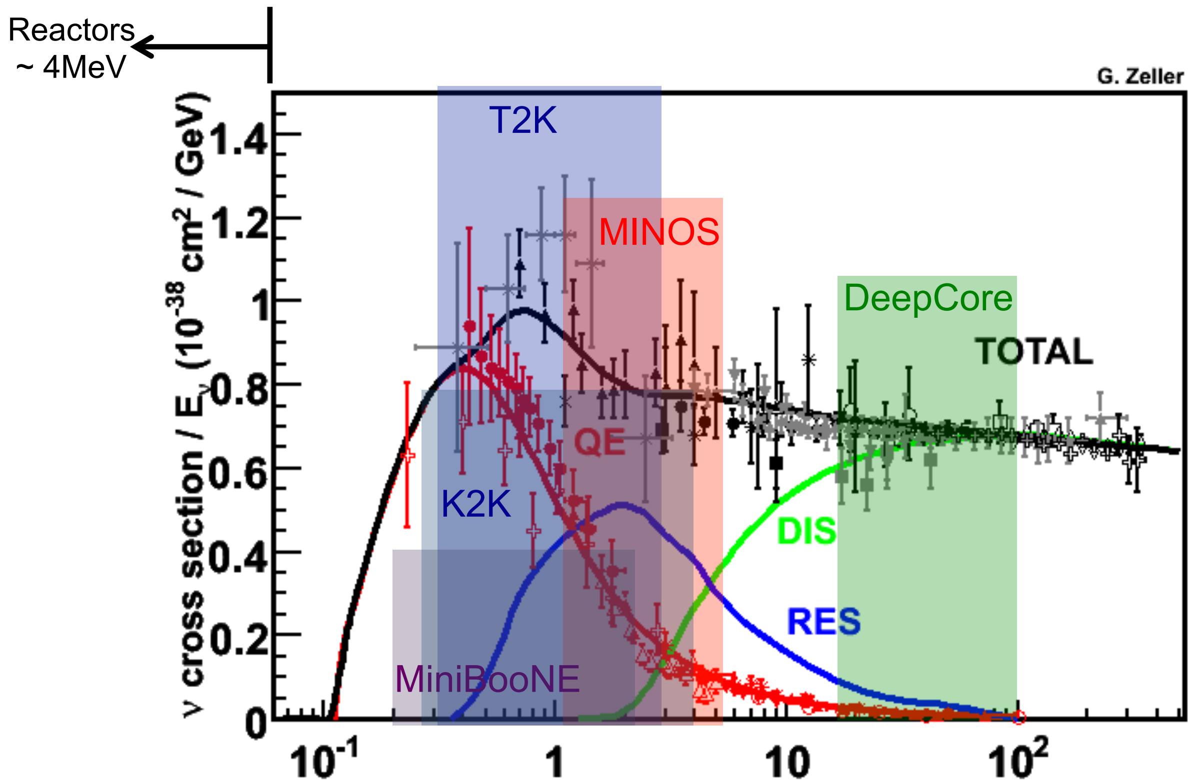
Teppei Katori

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

# 1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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




$\nu_\mu$CC cross section per nucleon

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

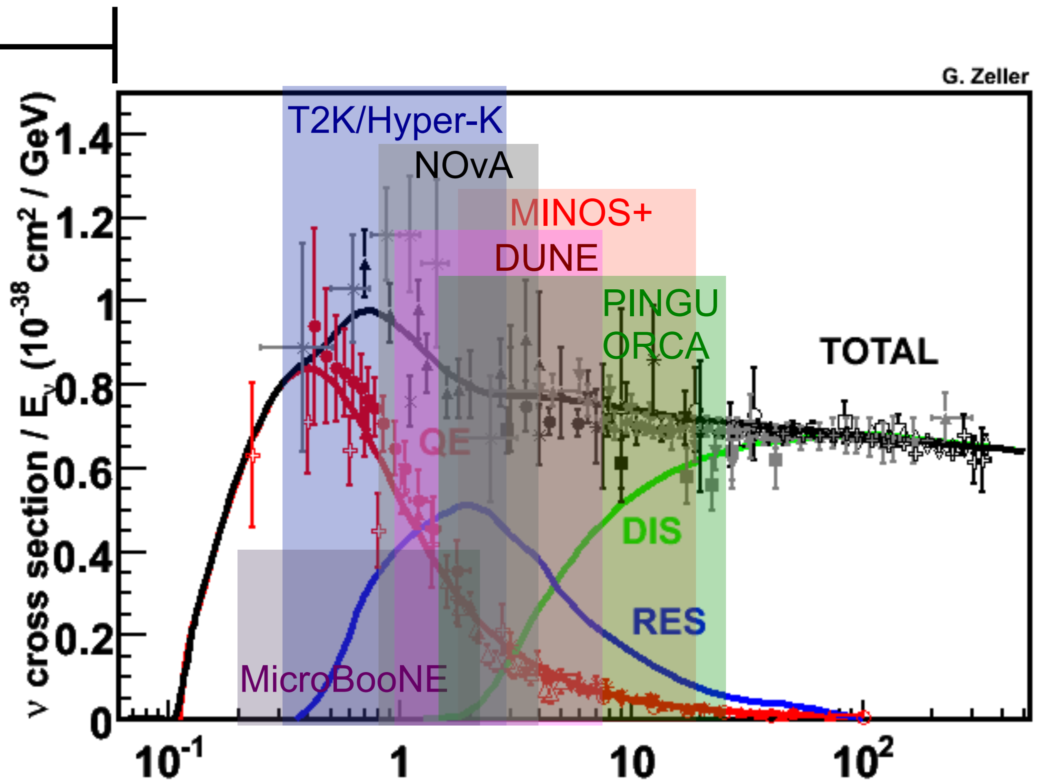
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307



# 1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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




$\nu_\mu$CC cross section per nucleon

including JPARC neutrino beam (no need to say "T2HK")

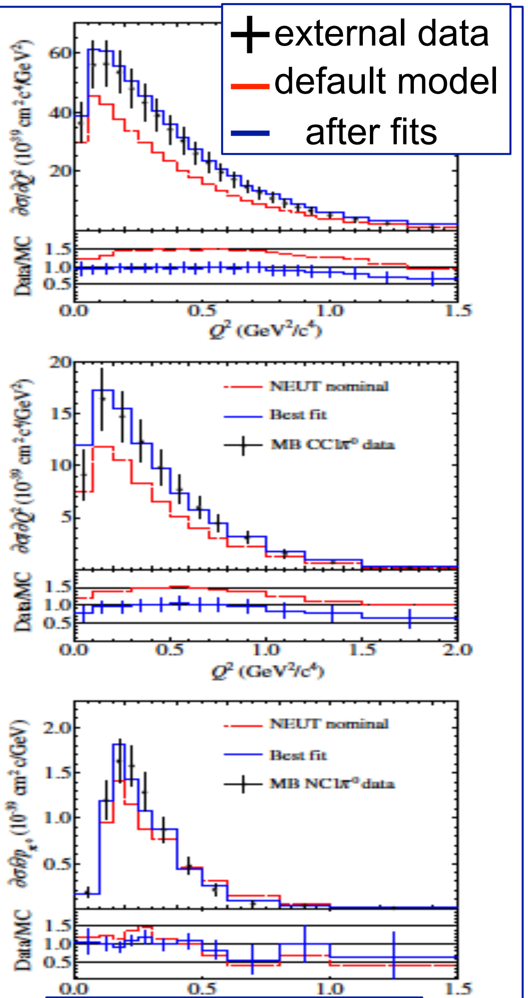
the experiment formerly known as LBNE

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

# 1. T2K oscillation experiments



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



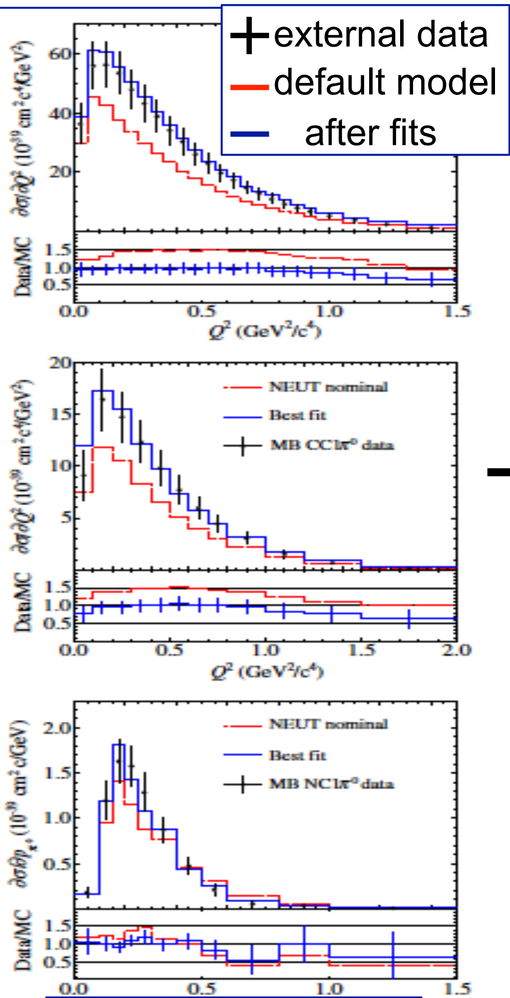

**External data fit**

External data give initial guess of cross-section systematics

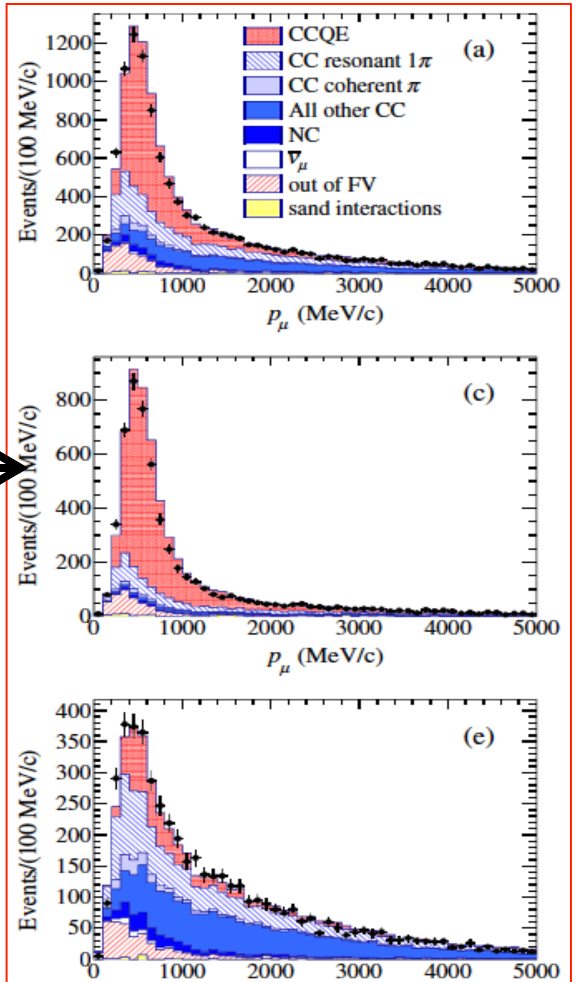
# 1. T2K oscillation experiments

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

**Internal constraint**
Near detector
oscillation non-sensitive channels




External data fit




T2K ND280 data fit

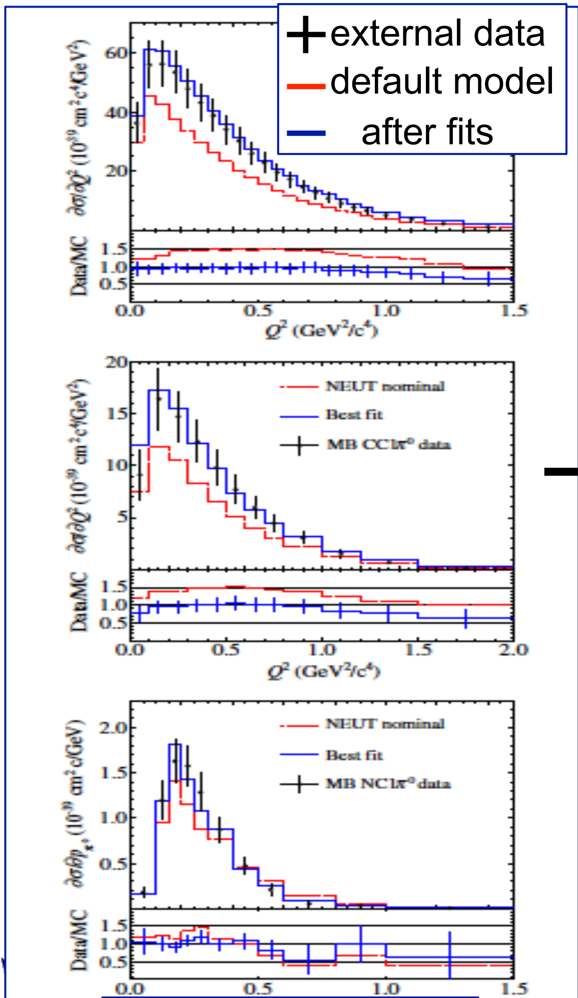
Constraint from internal data find actual size of cross-section errors

# 1. T2K oscillation experiments

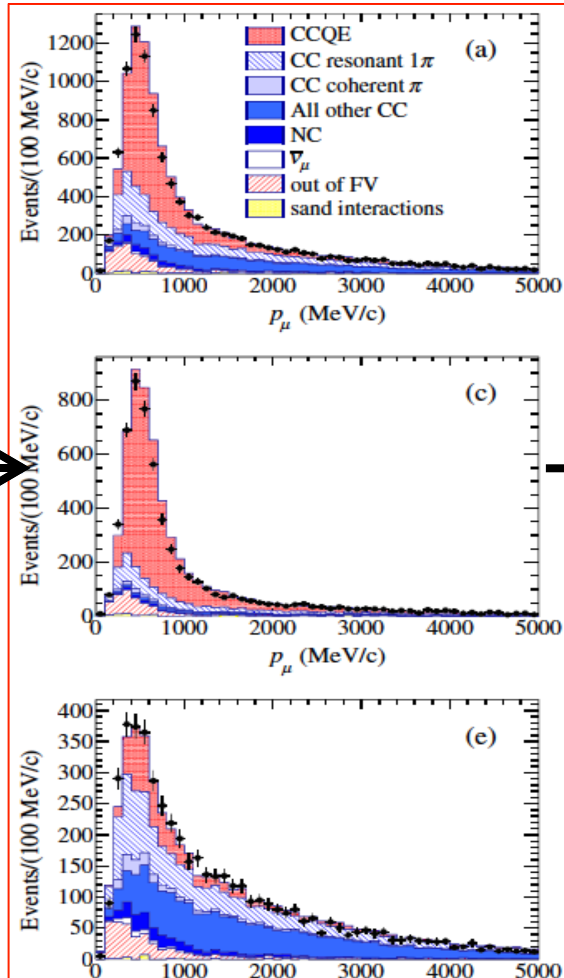
**External constraint**
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

**Internal constraint**
Near detector
oscillation non-sensitive channels

Neutrino interaction model is a large systematics of neutrino oscillation experiment

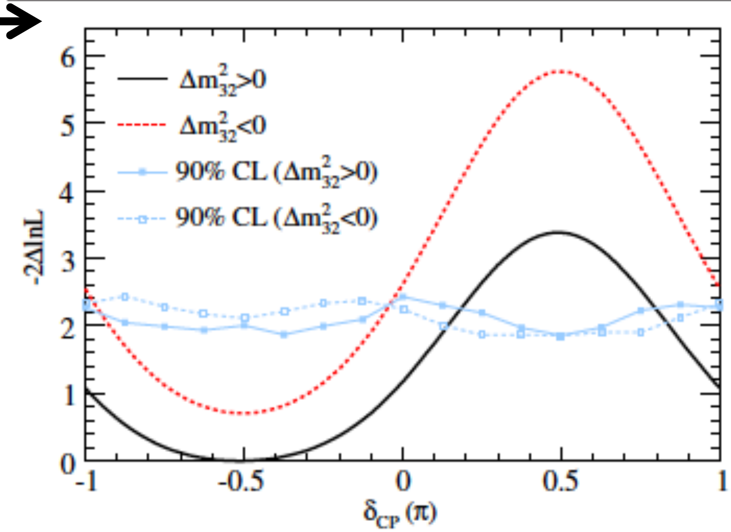



External data fit




T2K ND280 data fit

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




oscillation result

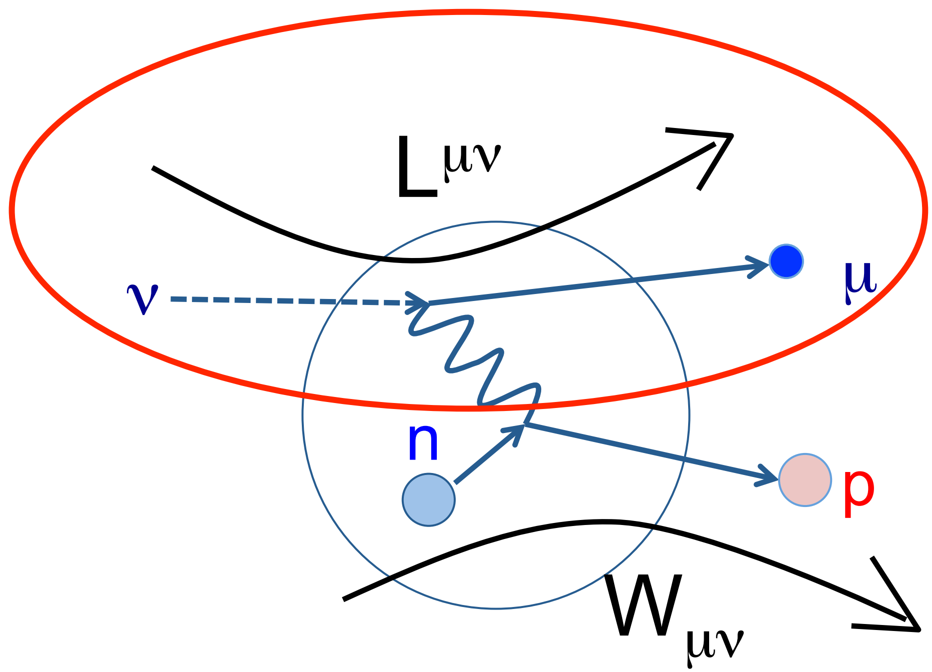
# 1. Neutrino cross-section formula

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)



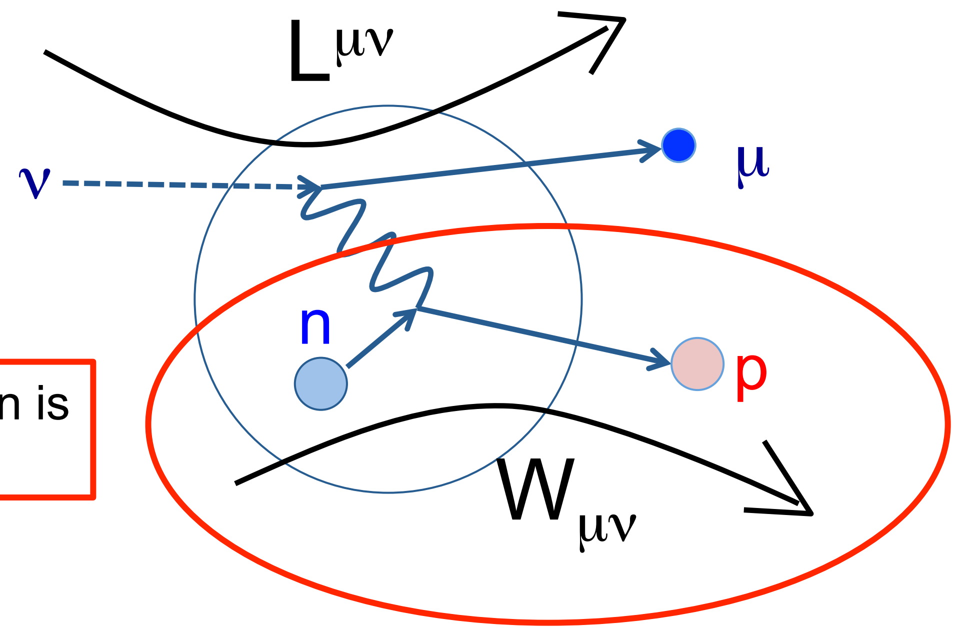
# 1. Neutrino cross-section formula

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)




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. Open question of neutrino interaction physics

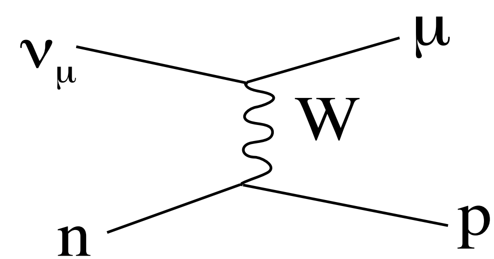
4. Neutrino induced single pion production

5. Conclusion

# 2. Charged Current Quasi-Elastic scattering (CCQE)

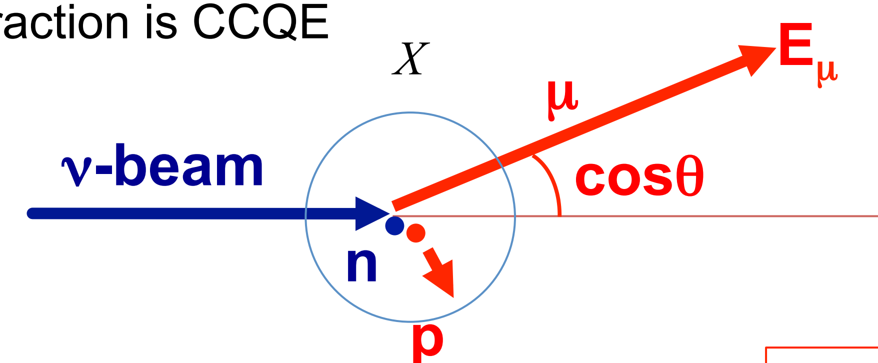
The simplest and the most abundant interaction around ~1 GeV.

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




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

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




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

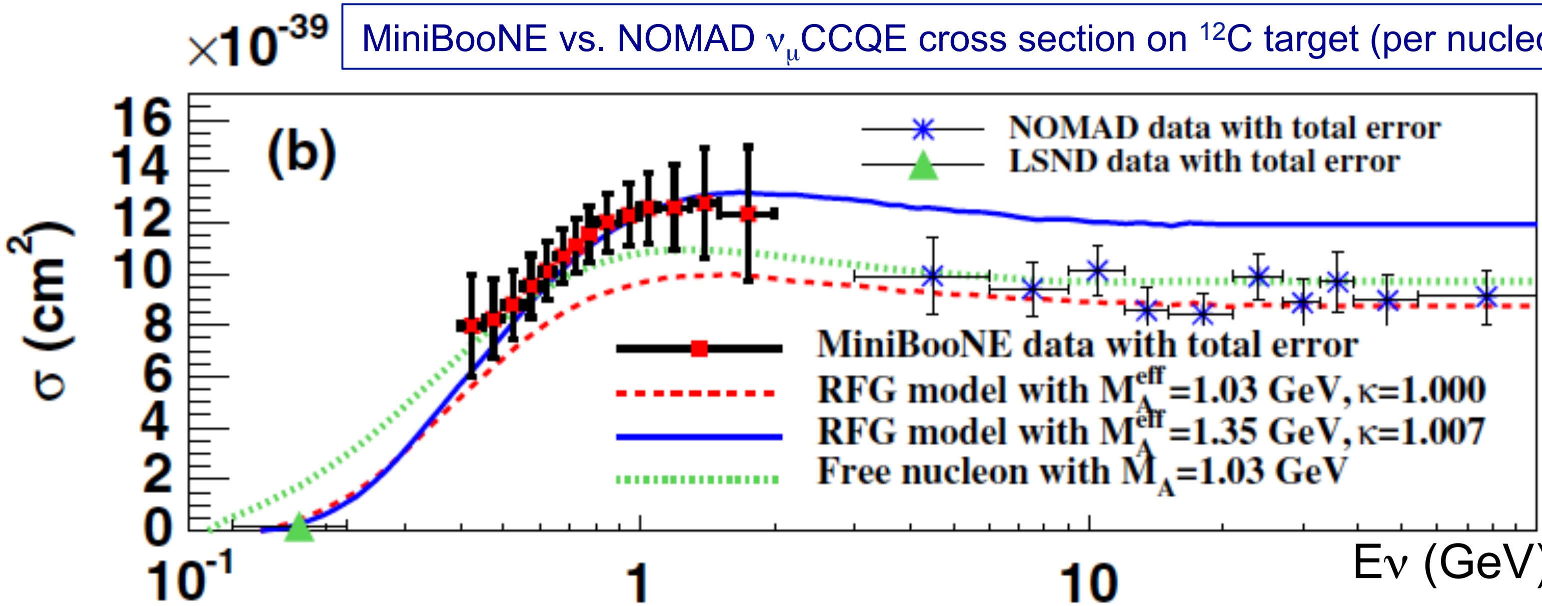
# 2. Charged Current Quasi-Elastic scattering (CCQE)



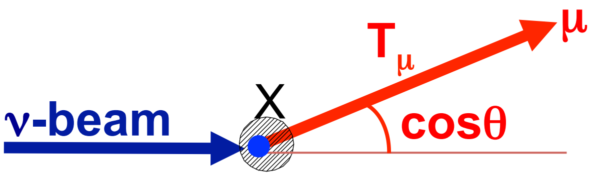
CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality → precise prediction for neutrino CCQE cross-section

Simulation disagree with many modern accelerator based neutrino experiment data, neither shape (low $Q^2$ and high $Q^2$) nor normalization. However, this interaction was successfully measured by bubble chamber experiments and NOMAD experiment (CCQE puzzle).

MiniBooNE vs. NOMAD $\nu_\mu$CCQE cross section on $^{12}$C target (per nucleon)



# 2. Neutrino experiment



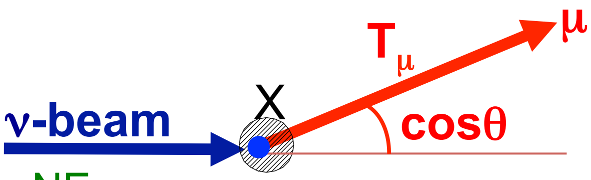

Experiment measure the interaction rate R,

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

- $\Phi$ : neutrino flux
- $\sigma$ : cross section
- $\varepsilon$ : efficiency

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

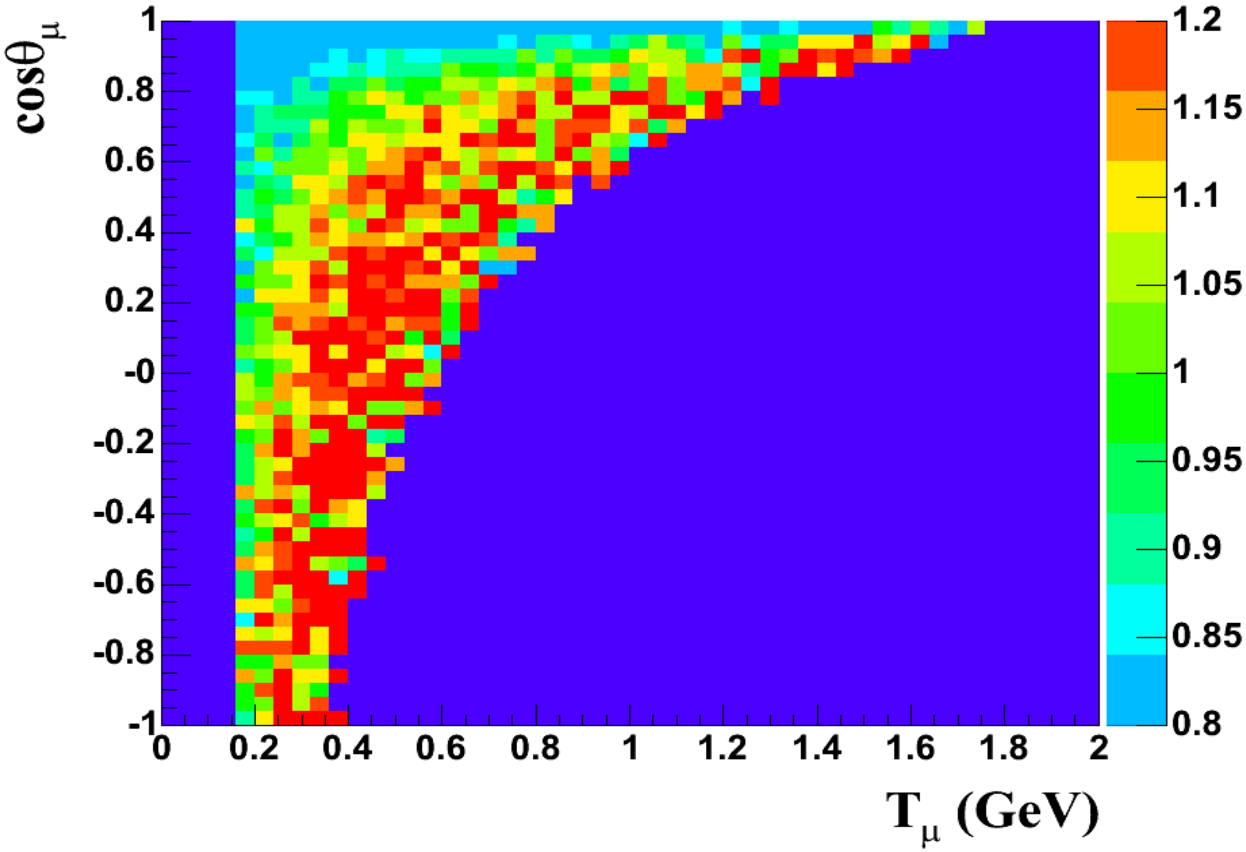
# 2. MiniBooNE phase space




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

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

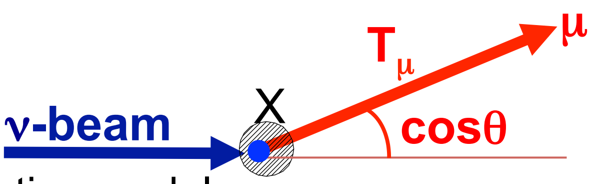
$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$




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

We would like to improve our simulation, but how?

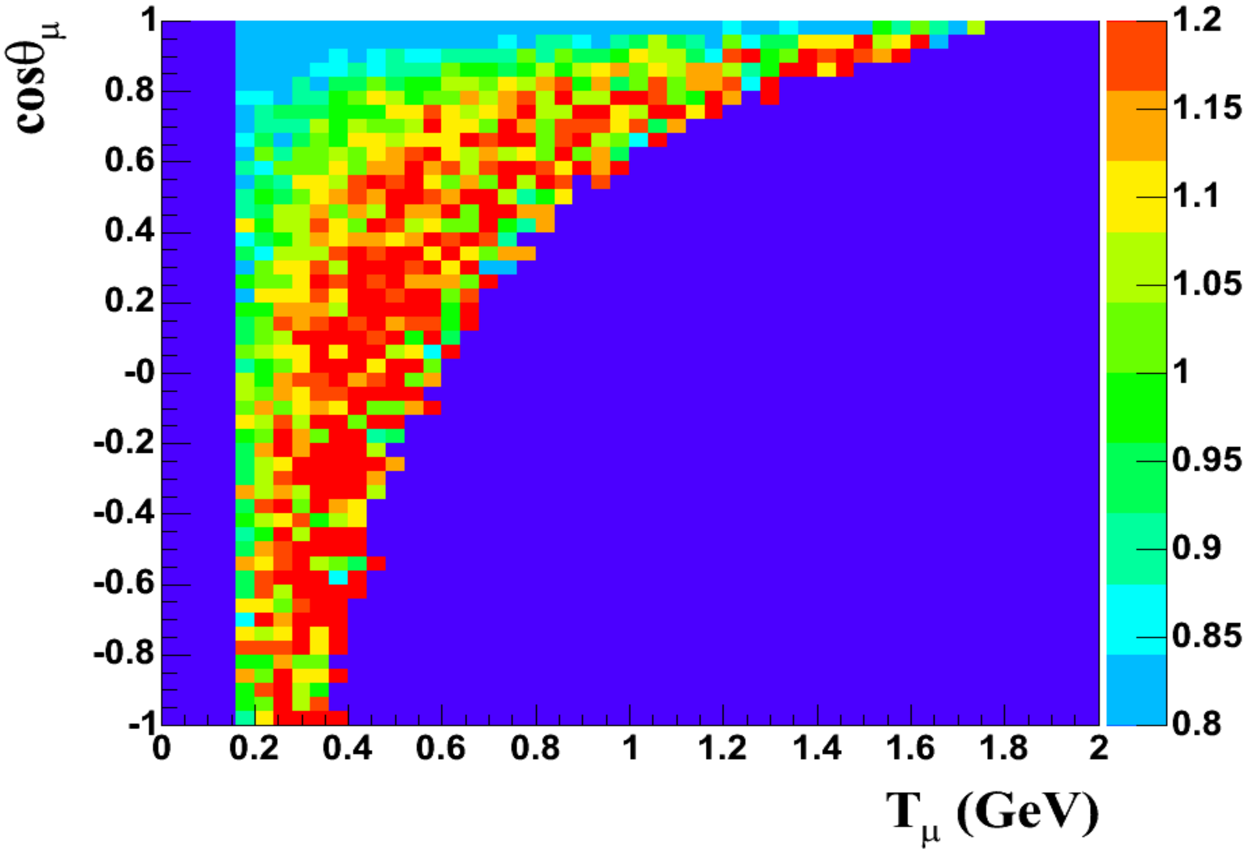
# 2. MiniBooNE phase space



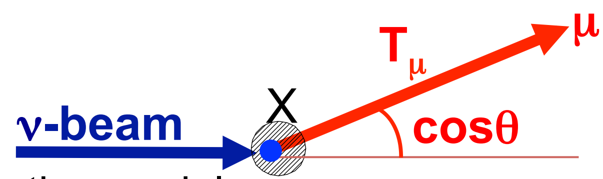

Without knowing flux, you cannot modify cross section model

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

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



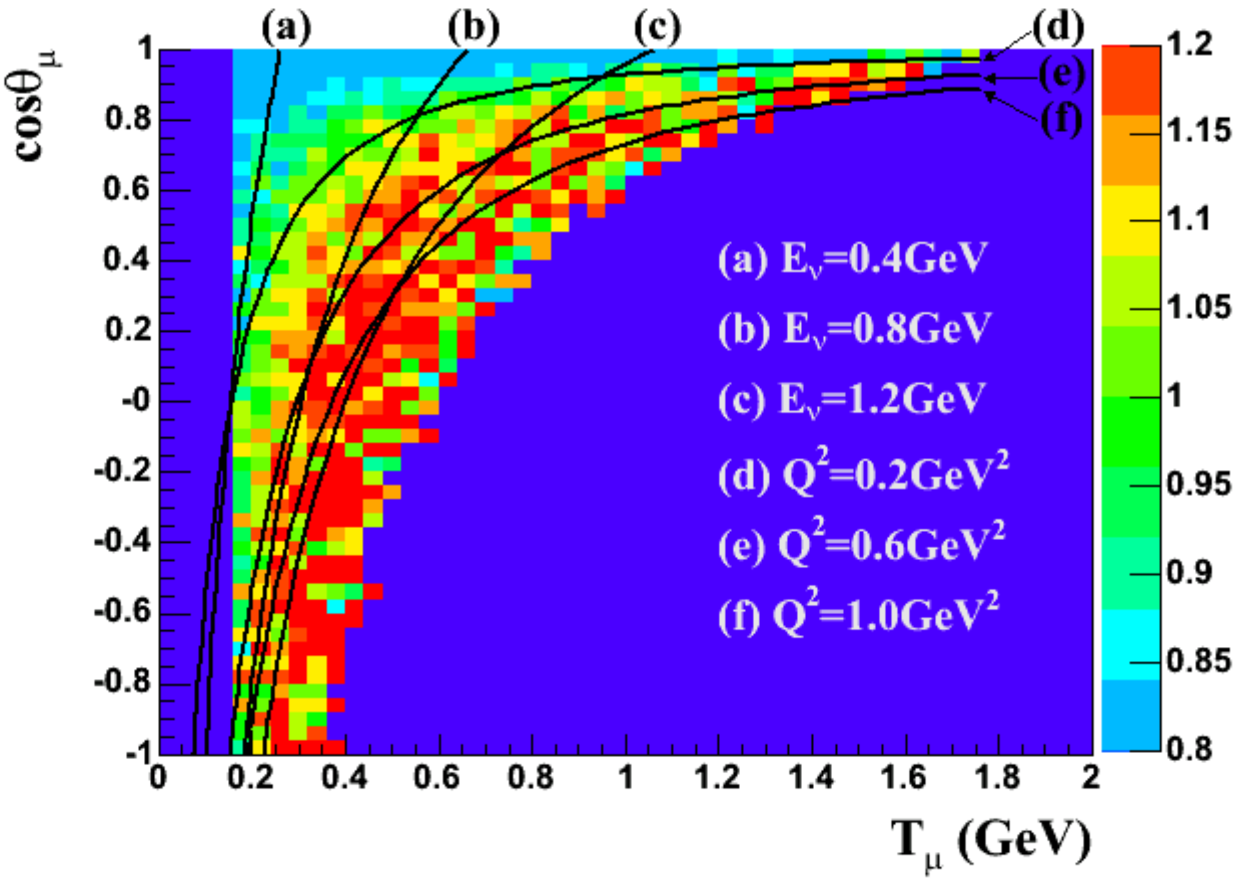
# 2. MiniBooNE phase space




Without knowing flux, you cannot modify cross section model

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

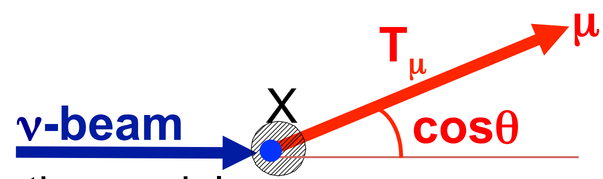
$$\frac{d\sigma^2}{dEd\Omega} \sim \frac{d\sigma^2}{dEd(\cos\vartheta)}$$




The data-MC disagreement follows equal $Q^2$- lines, not equal $E_\nu$-lines.

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

# 2. MiniBooNE phase space

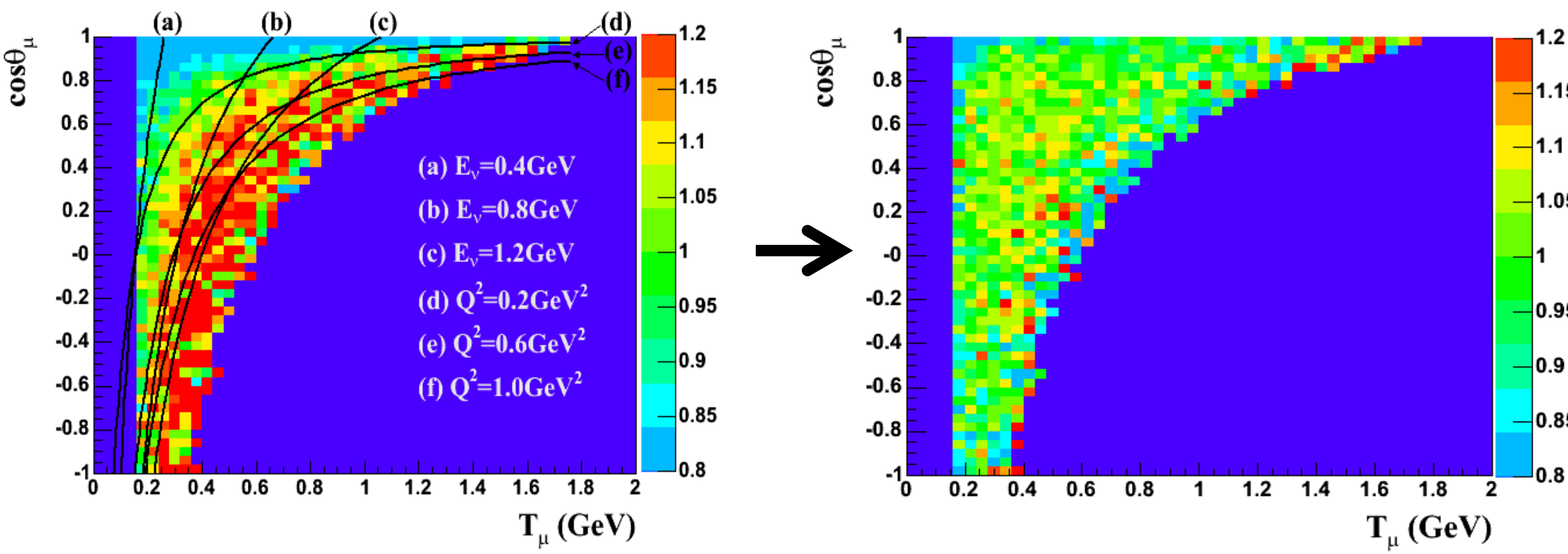



Without knowing flux, you cannot modify cross section model

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

After tuning cross section parameters, data and MC agree.

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



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

# 2. Smith-Moniz formalism



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

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

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

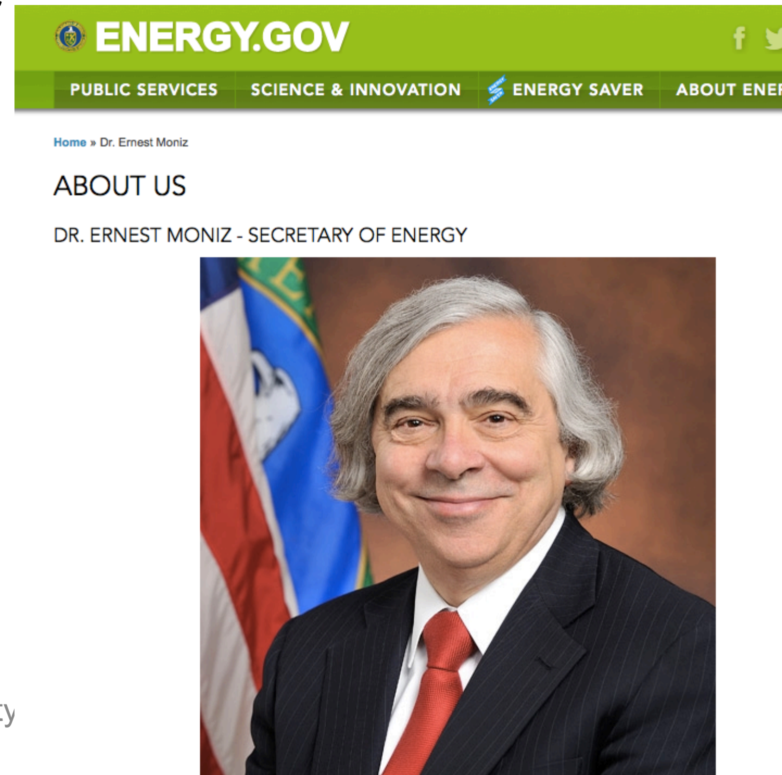
$T_{\mu\nu}=T_{\mu\nu}(F_1, F_2, F_A, F_P)$ : nucleon form factors

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

Ehi : the highest energy state of nucleon

Elo : the lowest energy state of nucleon

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



# 2. Relativistic Fermi Gas (RFG) model



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 $=\sqrt{(p_F^2+M^2)}$

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



# 2. Relativistic Fermi Gas (RFG) model

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 $=\sqrt{(p_F^2+M^2)}$

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

MiniBooNE tuned following 2 parameters using $Q^2$ distribution by least $\chi^2$ fit;
$M_A$ = effective axial mass
$\kappa$ = effective Pauli blocking parameter

MiniBooNE tuned their axial mass to 1.3 GeV!

but axial mass is not 1.3 GeV!

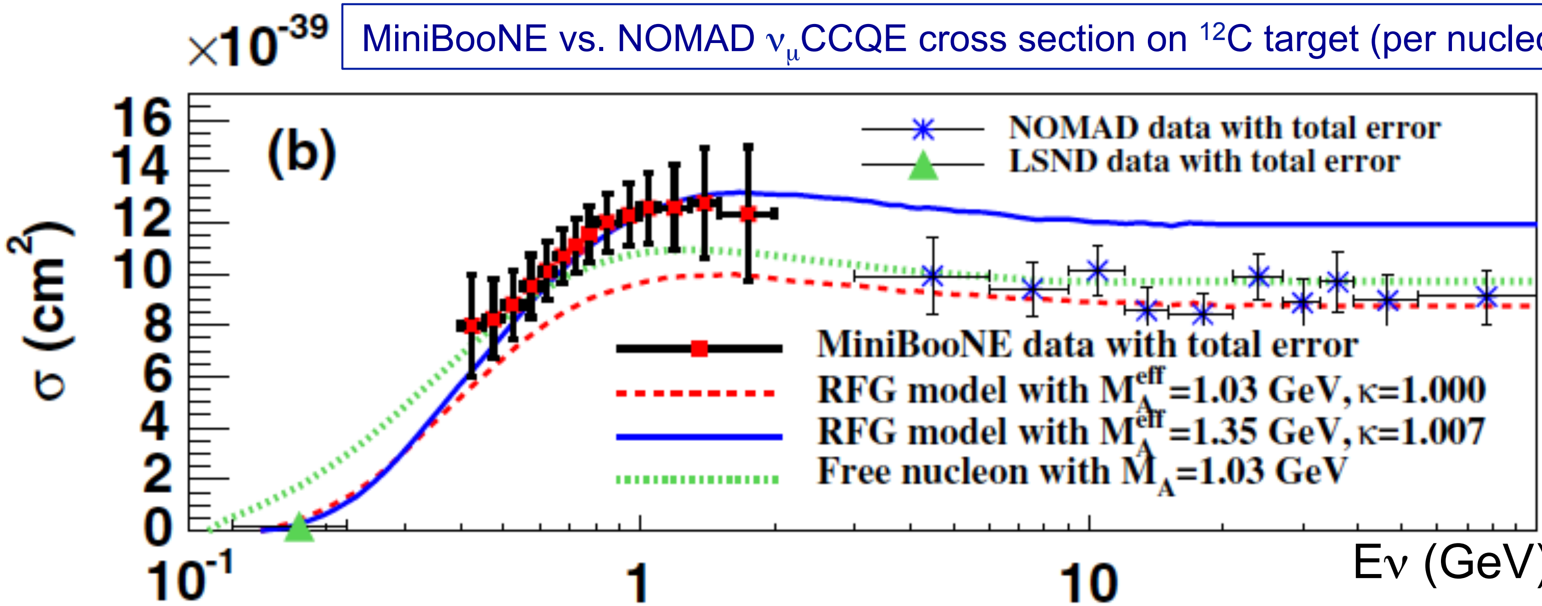
# 2. Charged Current Quasi-Elastic scattering (CCQE)



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. However, this interaction was successfully measured by bubble chamber experiments and NOMAD experiment (CCQE puzzle).

MiniBooNE vs. NOMAD $\nu_\mu$CCQE 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
→ Can anybody propose a better name for this quantity?
(Flussintegrierterdifferentiellerwirkungsquerschnitt®?)
→ 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

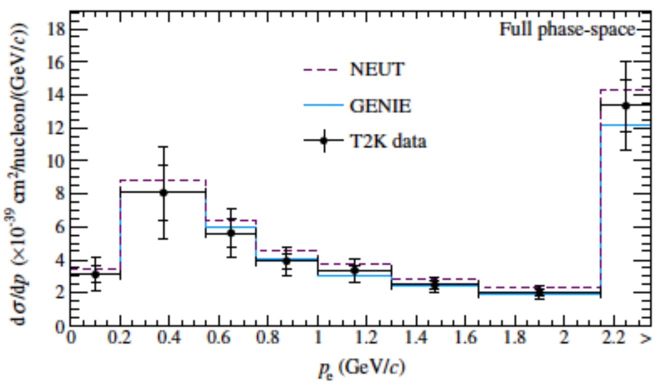
Fluss-integrierter Differentieller Wirkungsquerschnitt® is a copyrighted trademark of theT2K experiment

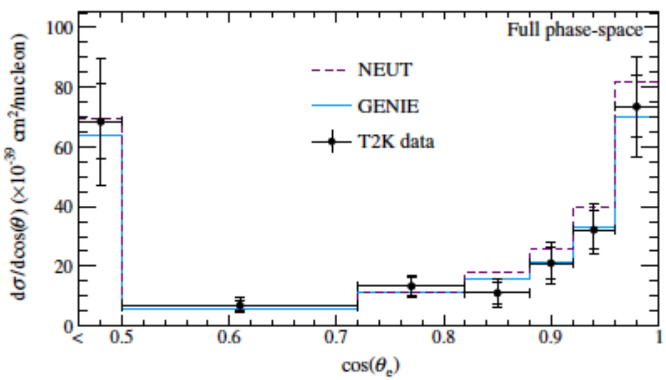
# 2. Flux-integrated differential cross-section

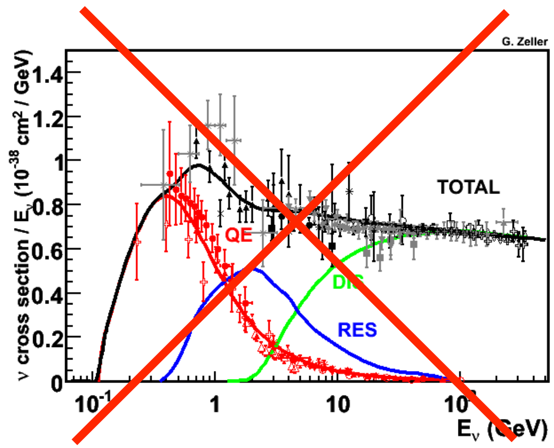
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.

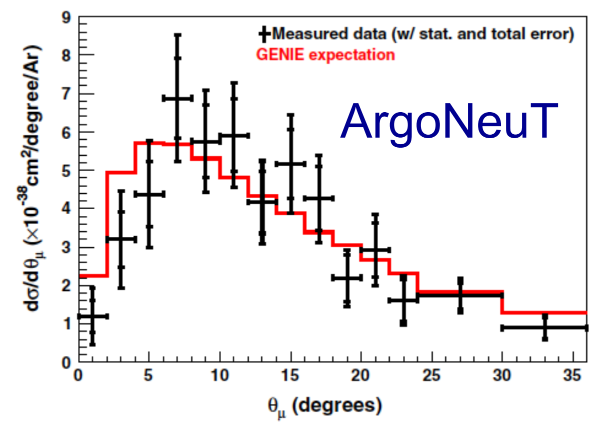
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

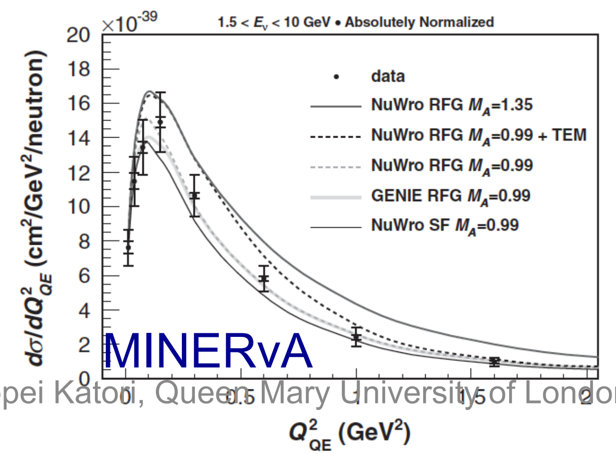
T2K



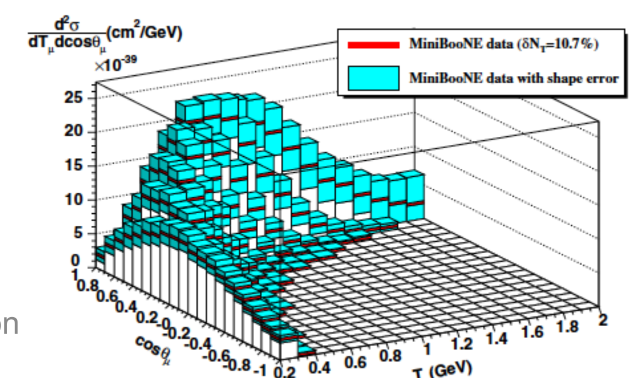




MiniBooNE



# 2. Flux-integrated differential cross-section

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 talk first time in neutrino interaction physics history

# 2. The solution of CCQE puzzle

## Presence of 2-body current

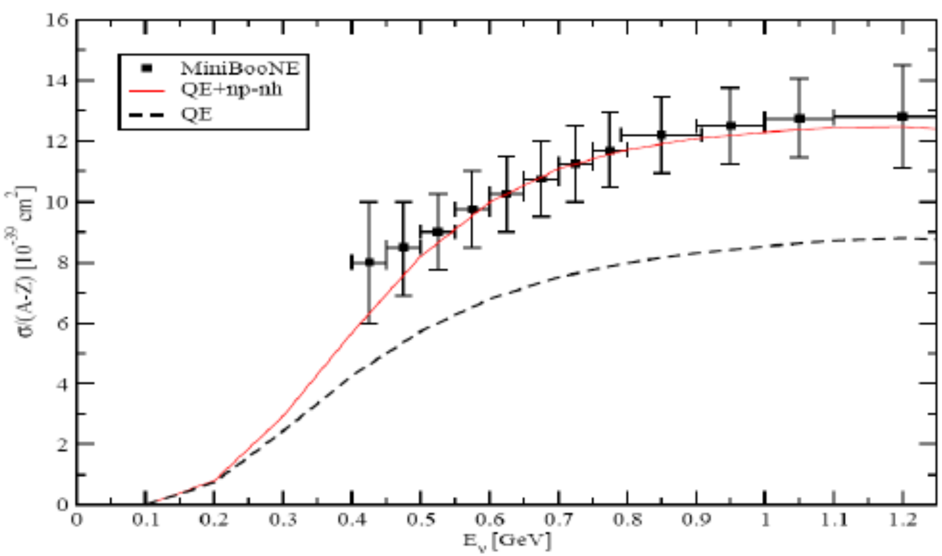
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

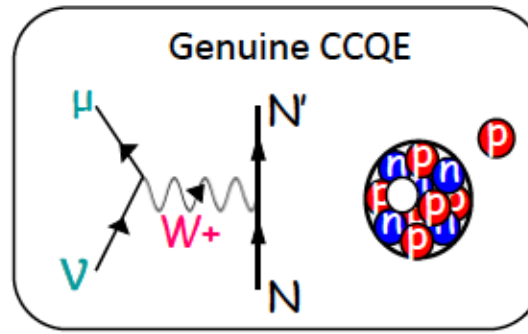
What experimentalists call "CCQE" is not genuine CCQE!

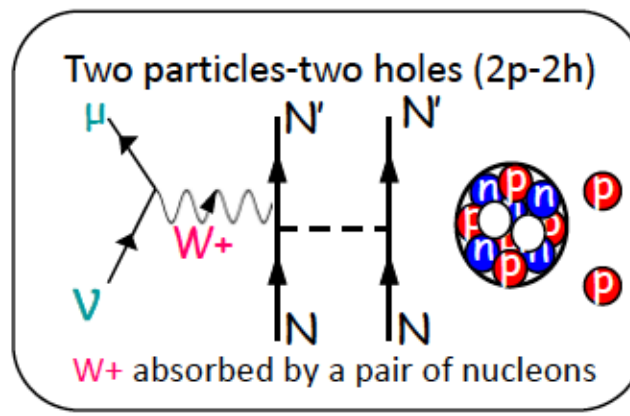
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



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

# 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

What experimentalists call “CCQE” is not genuine CCQE!

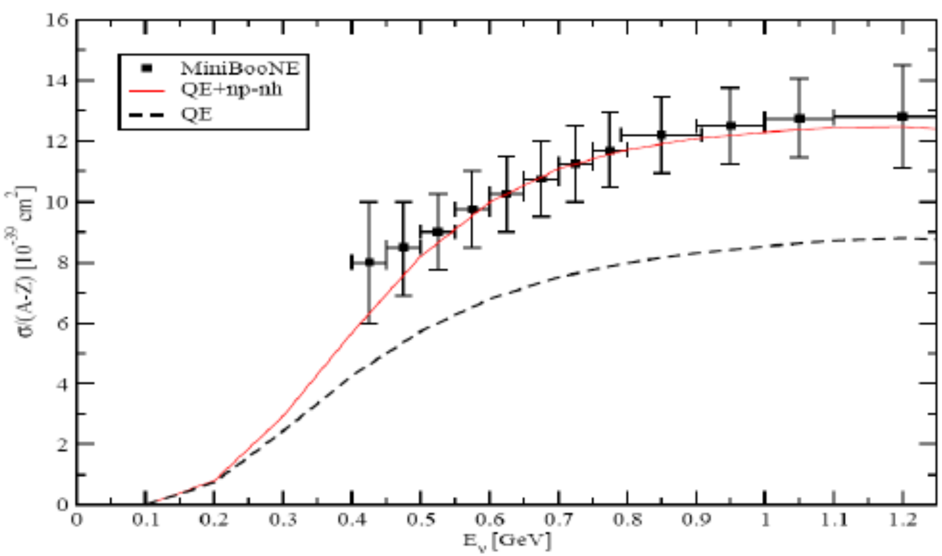
Marco Martini (Saclay)

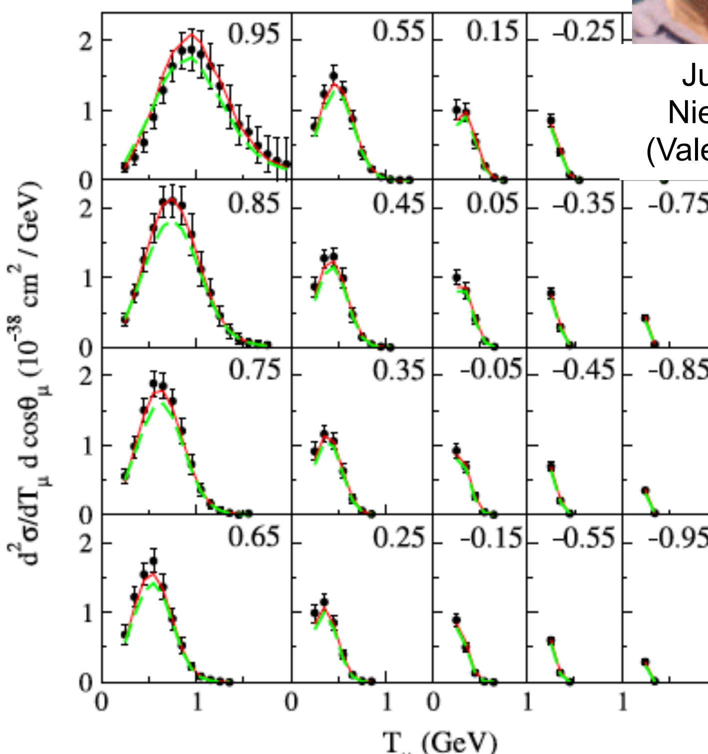
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

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

Juan Nieves (Valencia)




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



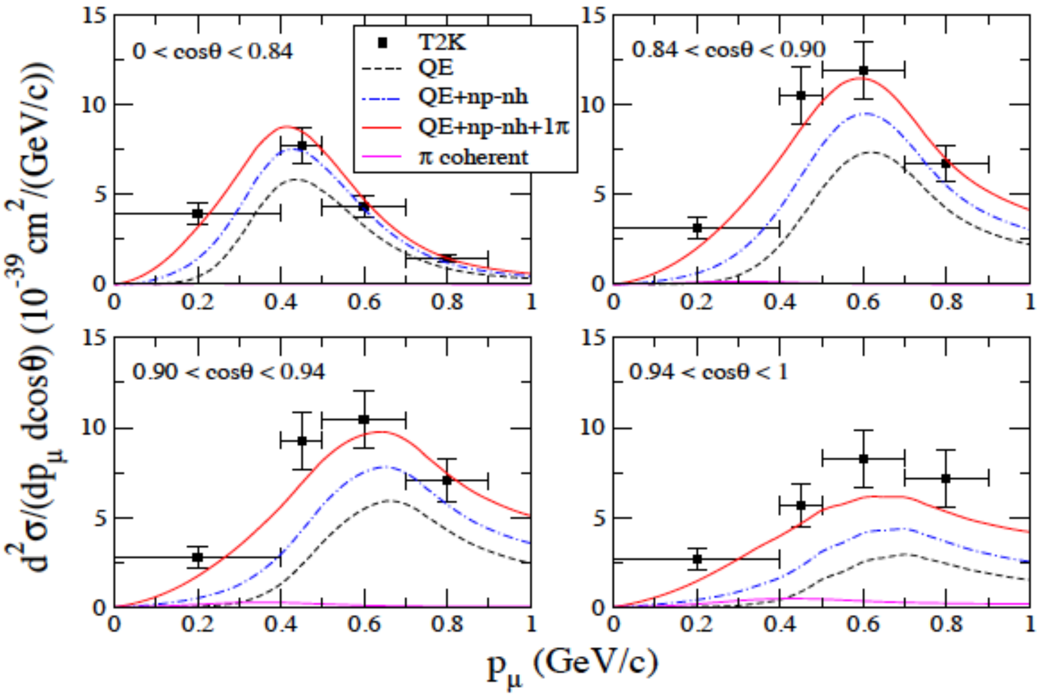
## Presence of 2-body current

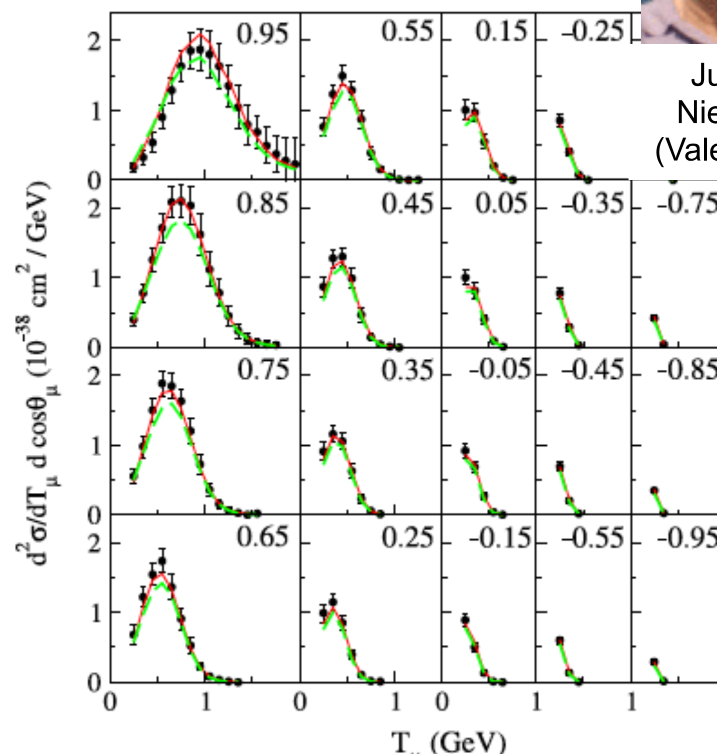
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

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

Juan Nieves (Valencia)

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




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



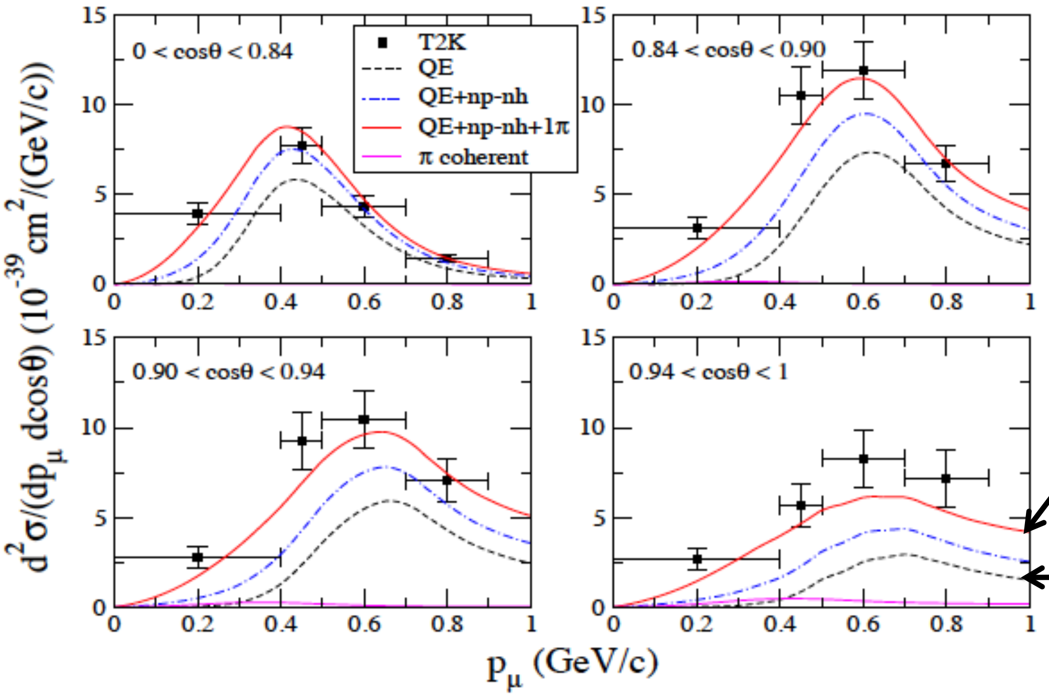
## Presence of 2-body current

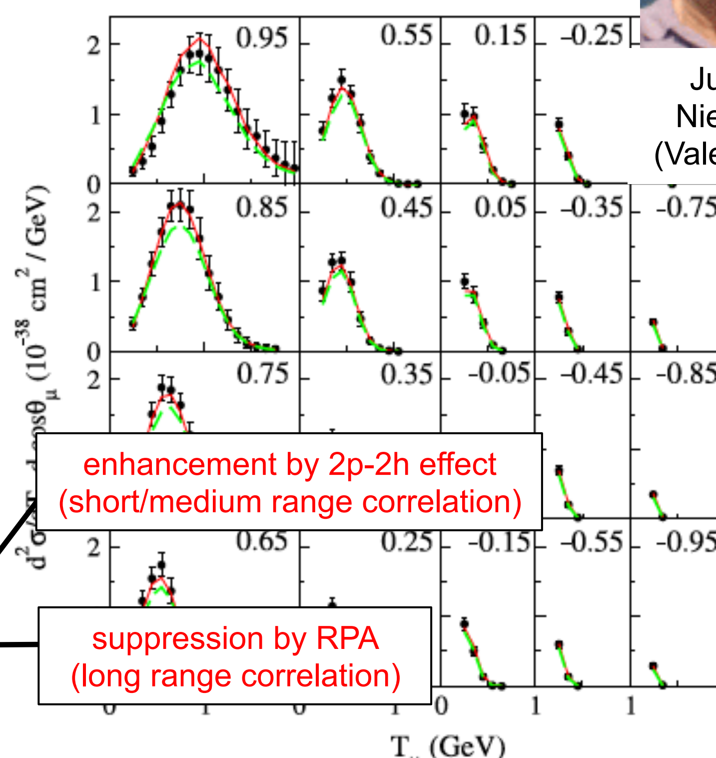
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

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

Juan Nieves (Valencia)

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



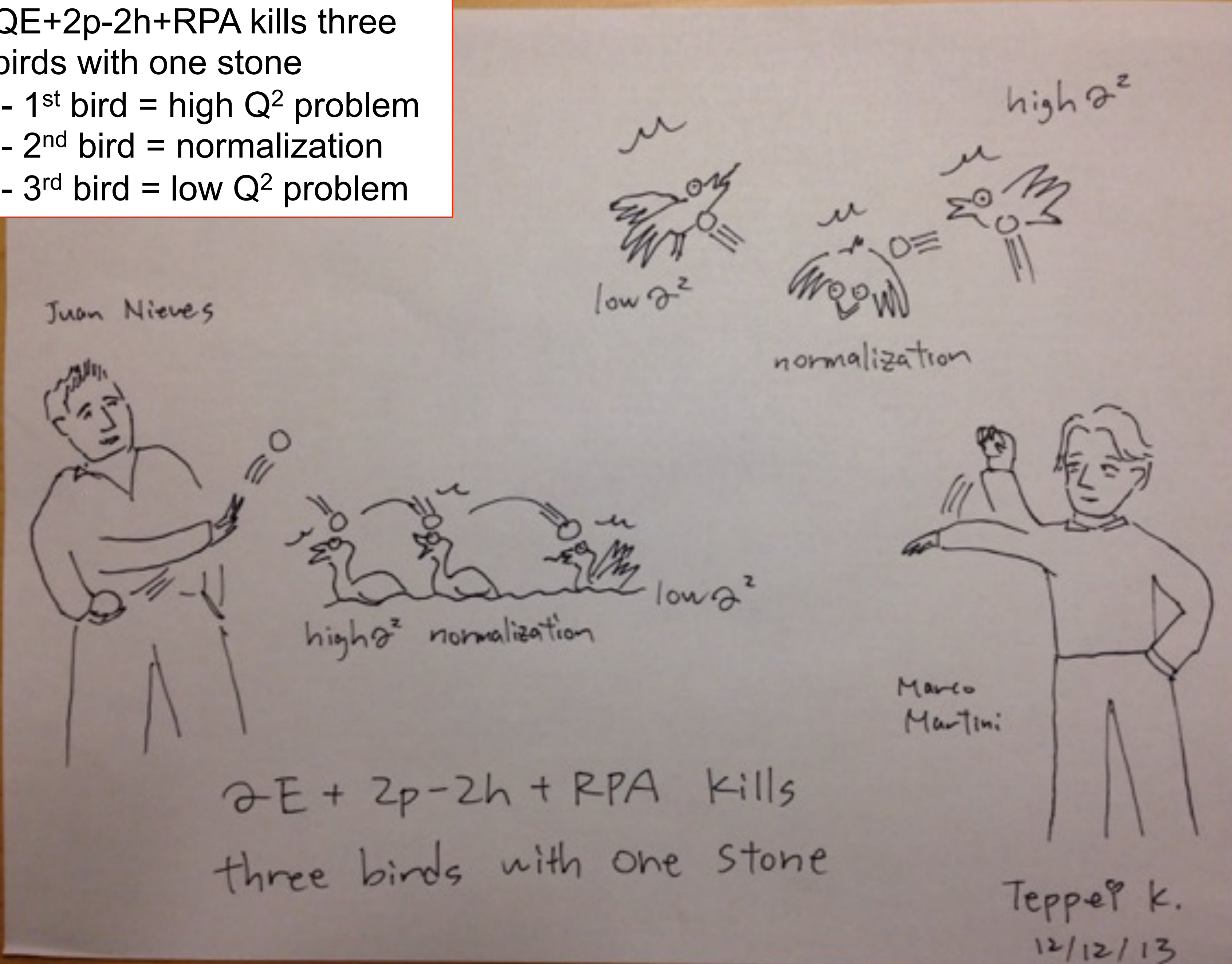

enhancement by 2p-2h effect (short/medium range correlation)

suppression by RPA (long range correlation)

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

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



Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRL112(2014)182502, arXiv:1501.01981

# 2. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato (Argonne)



## Ab initio calculation

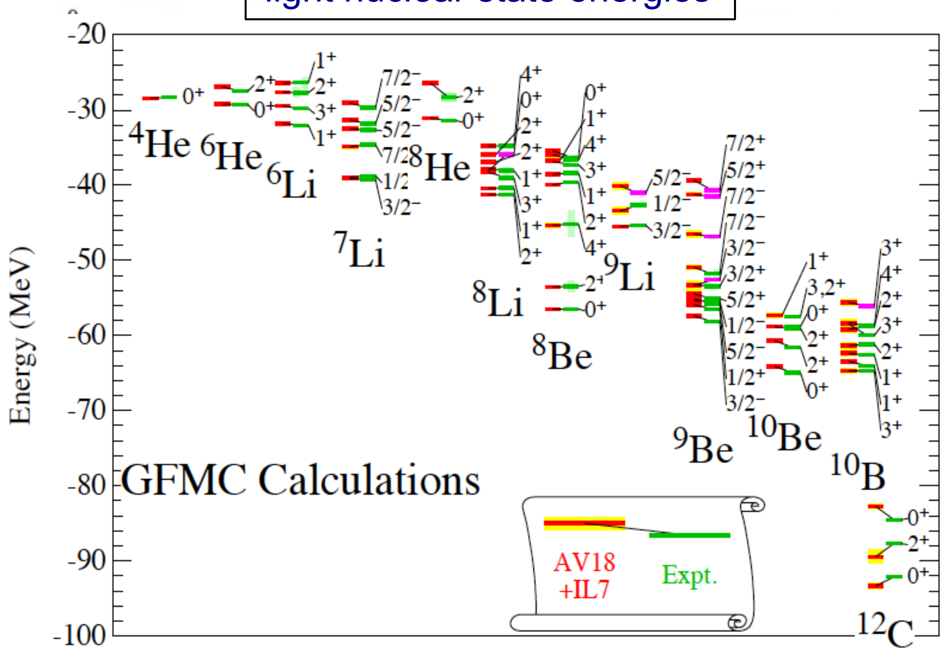
- Green's function Monte Carlo (GFMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- neutron-proton short range correlation (SRC)

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

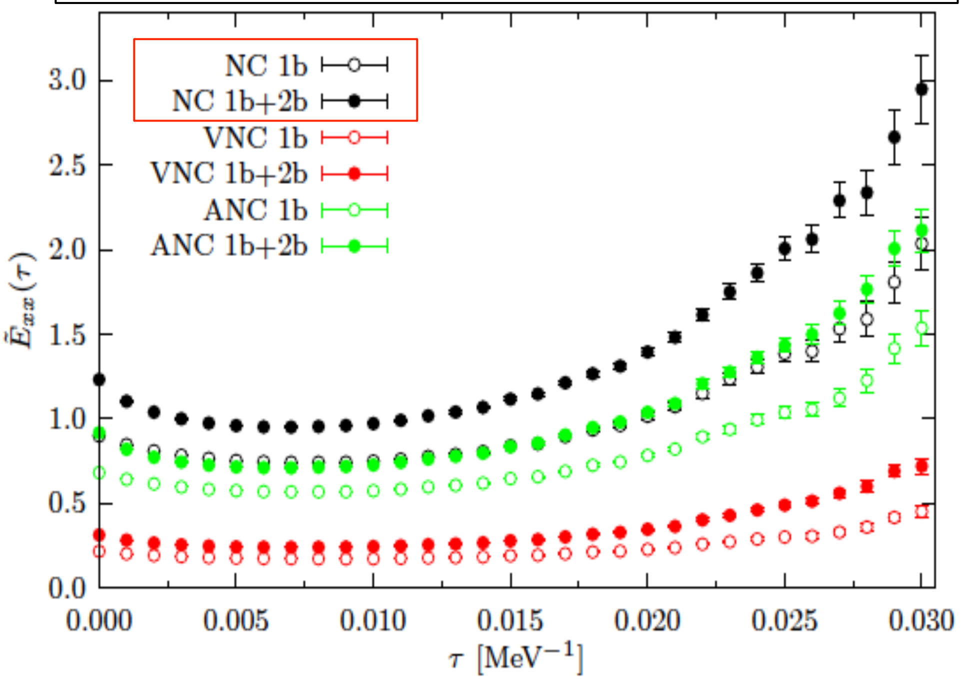
2N potential (Av18)

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

# 2. The solution of CCQE puzzle



Ab initio calculation reproduce same feature

Alessandro Lovato (Argonne)

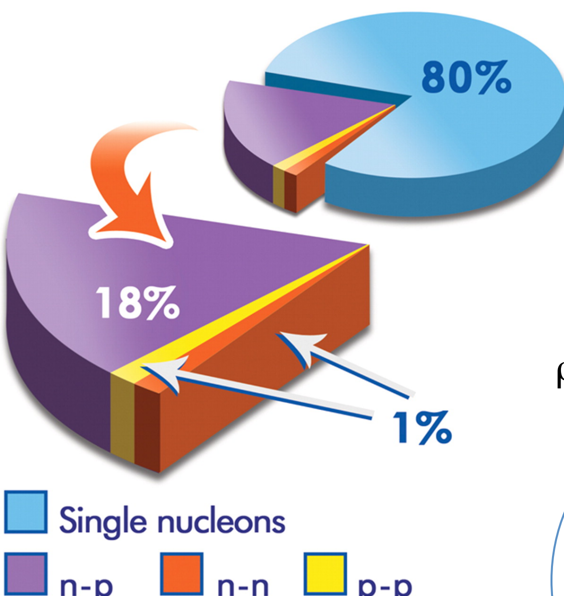
## Ab initio calculation

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

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

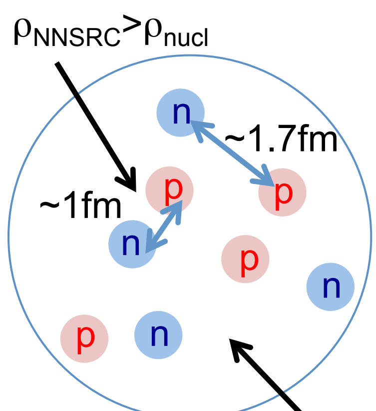
2N potential (Av18)

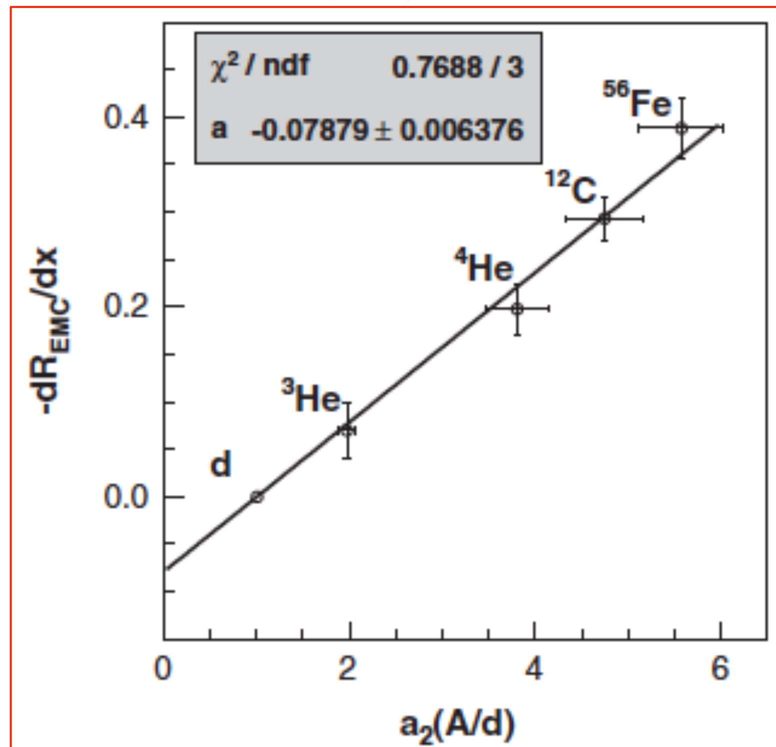
3N potential (IL7)




## Physics of SRC

- neutrino interaction
- $0\nu\beta\beta$
- 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



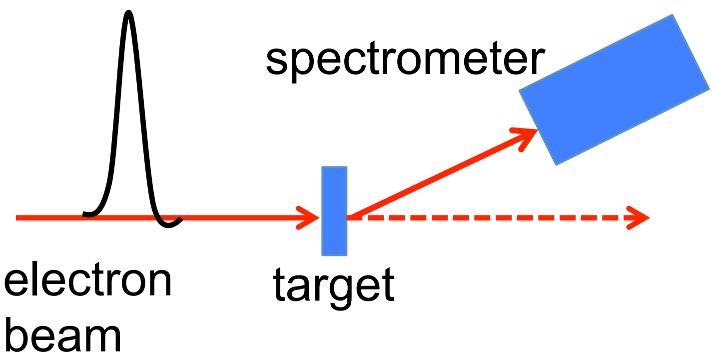
# 2. Electron scattering vs. Neutrino scattering

## Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

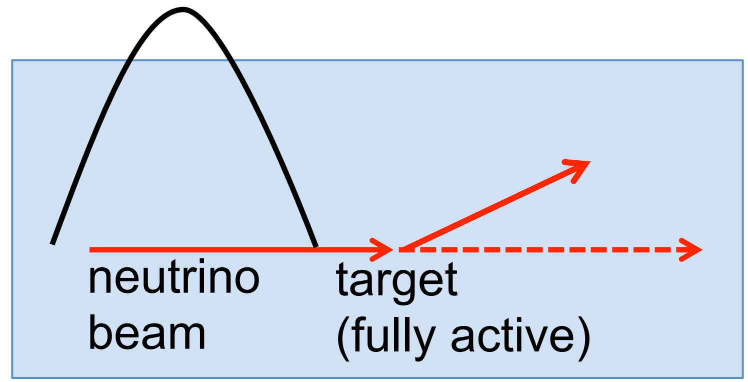
→ kinematics is completely fixed

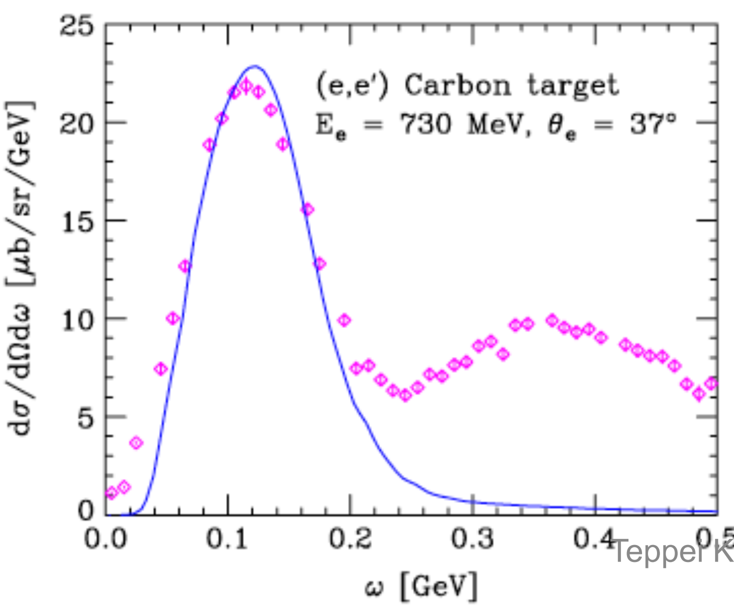


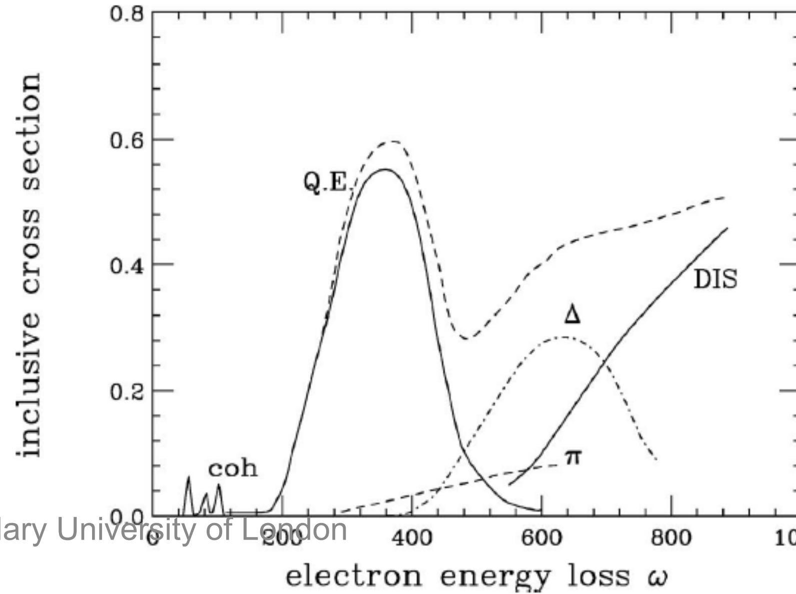

## Neutrino scattering

- Wideband beam

→ observables are inclusive



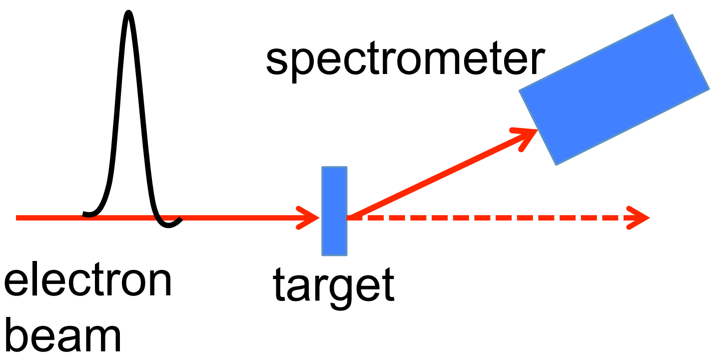



Benhar et al, Rev.Mod. Phys.80(2008)189, PRL105(2010)132301

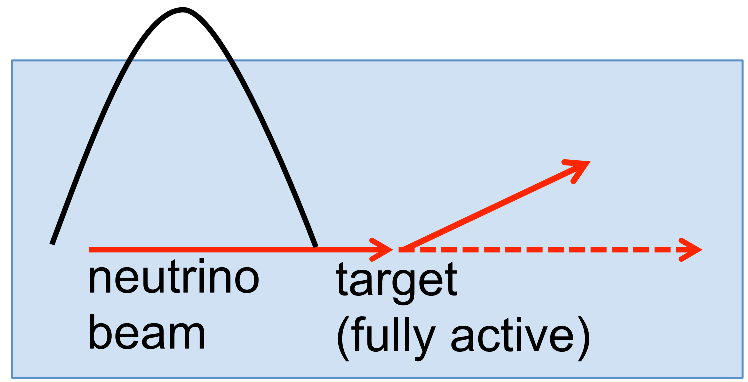


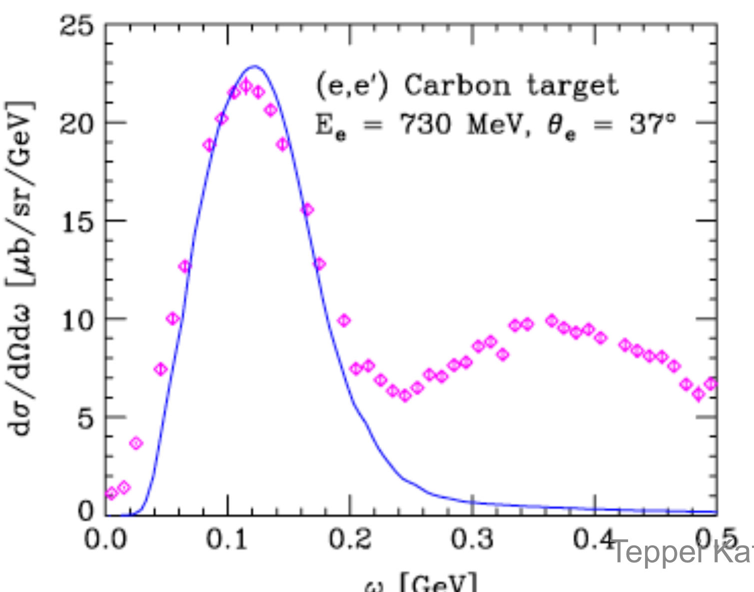
# 2. Electron scattering vs. Neutrino scattering

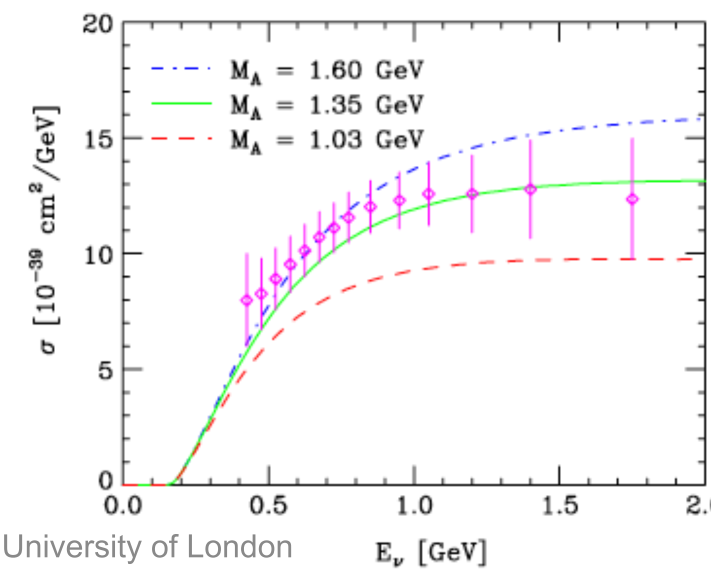
**Electron scattering**
- well defined energy, well known flux
→ reconstruct energy-momentum transfer
→ kinematics is completely fixed




**Neutrino scattering**
- Wideband beam
→ observables are inclusive



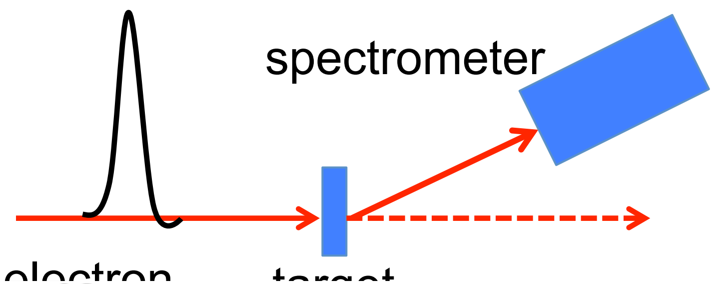



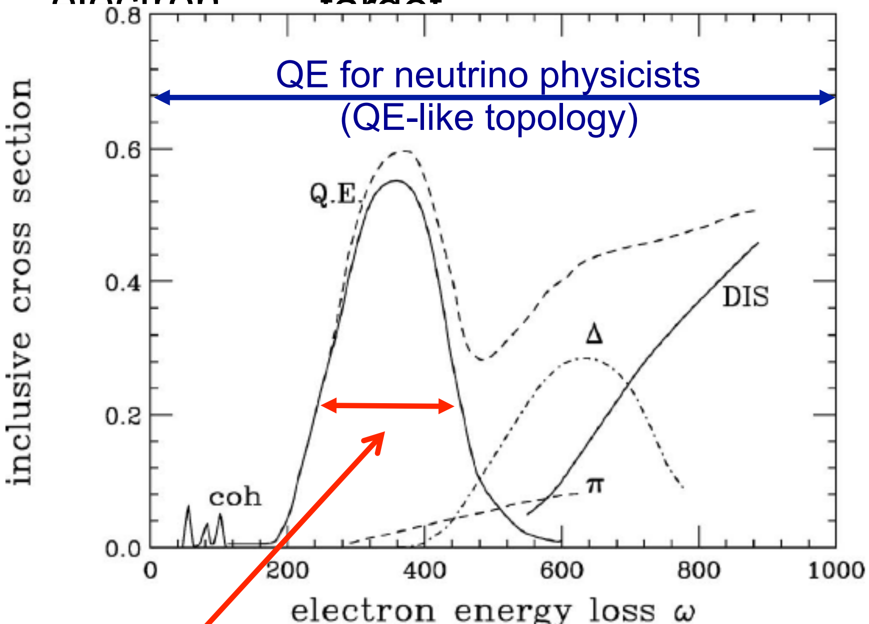



# 2. Electron scattering vs. Neutrino scattering

## Electron scattering

- well defined energy, well known flux
→ reconstruct energy-momentum transfer
→ kinematics is completely fixed

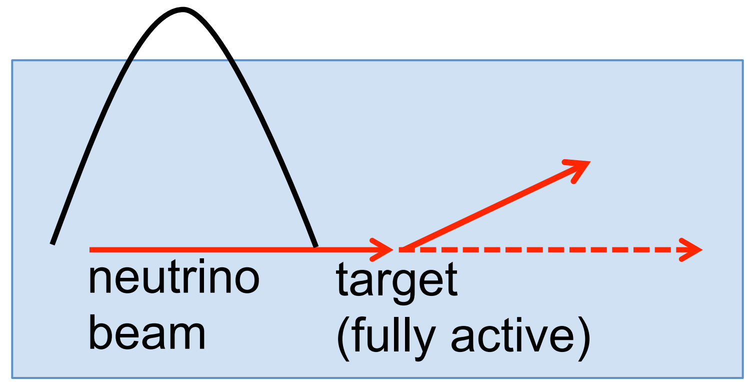


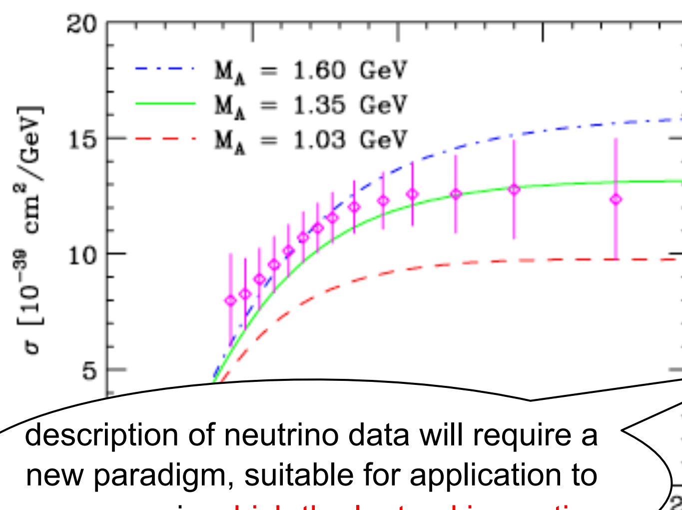




QE for nuclear physicists (genuine QE)

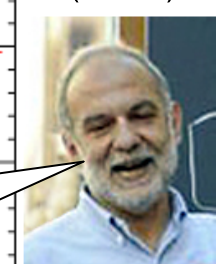
## Neutrino scattering

- Wideband beam
→ observables are inclusive




Omar Benhar (Rome)



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

# 2. Summary for oscillation physics

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

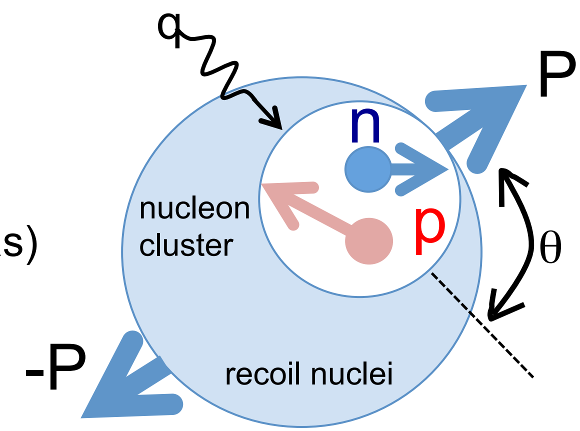
It is crucial to have correct CCQE, MEC, pion production models to understand MiniBooNE, MINERvA, T2K data simultaneously. Otherwise $M_A$ error stays around 20-30%.

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

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

# 2. How to emit 2 nucleons from correlated pair?

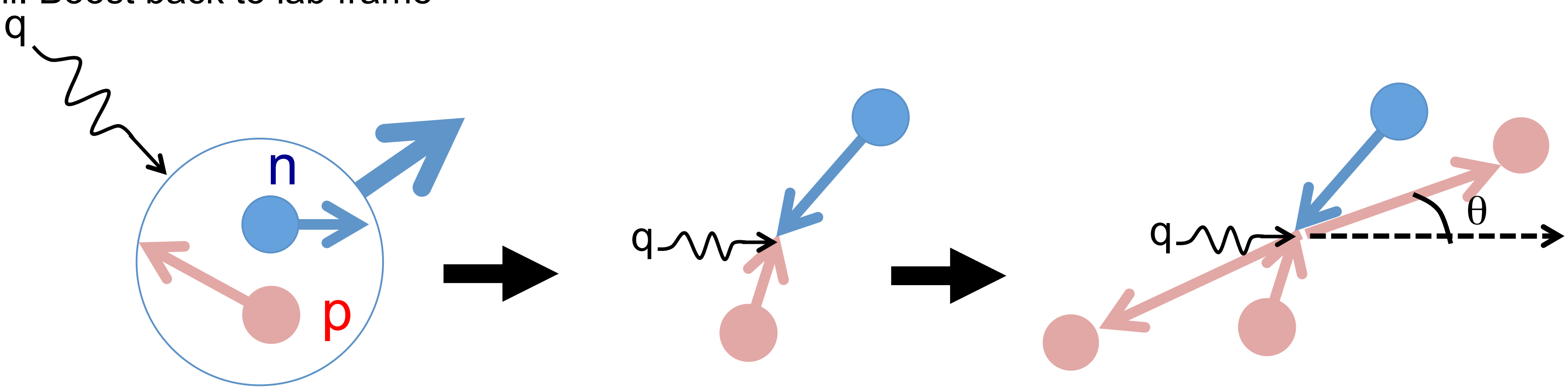





Default model for GENIE, NEUT, NuWro…

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?

1. Neutrino Interaction Physics

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

**3. Open question of neutrino interaction physics**

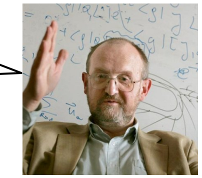
4. Neutrino induced single pion production

5. Conclusion

# 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

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

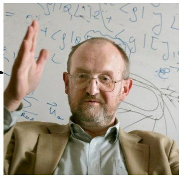
Coherent pion puzzle
- Is there charged current coherent pion production?

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

# 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

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

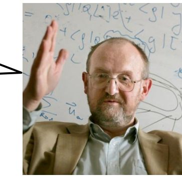
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Neutrino Cross-Section Newsletter,2014/04/14



# 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)

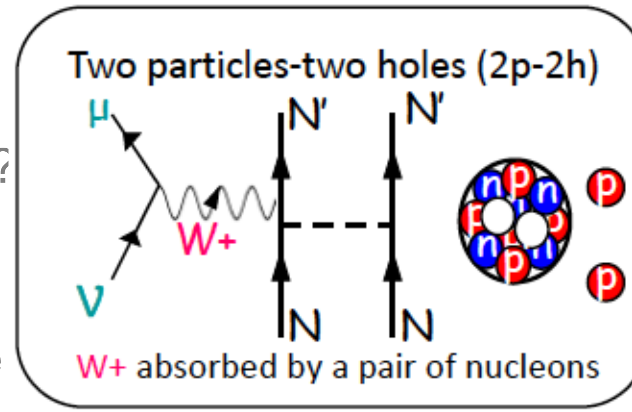
CCQE puzzle

- 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




Coherent pion puzzle

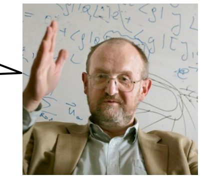
- Is there charged current coherent pion production?

Pion puzzle

- MiniBooNE and MINERvA pion kinematic data are

# 3. Open question of neutrino interaction physics






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

Coherent pion puzzle

- Is there charged current coherent pion production?

Pion puzzle

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

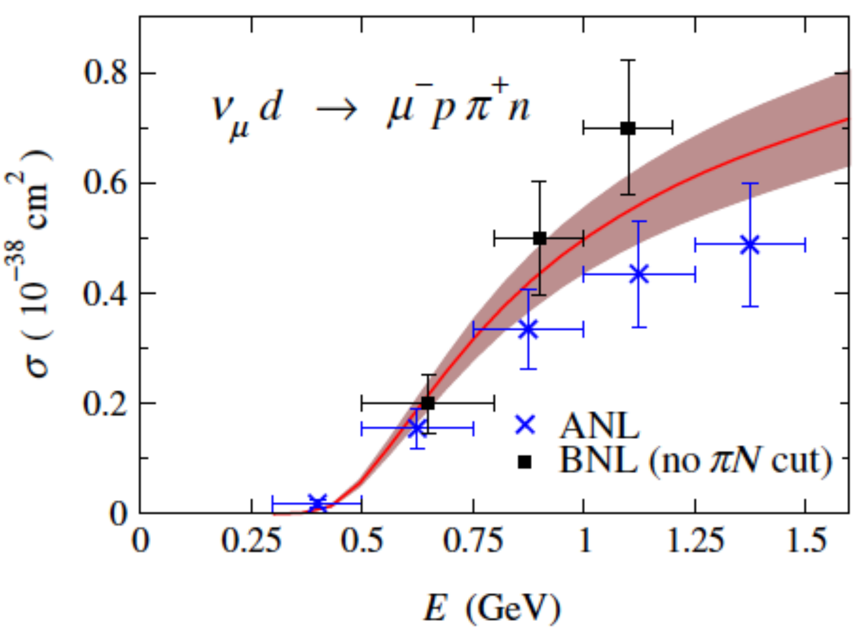
Hernandez et al,PRD87(2013)113009
Alvarez-Ruso et al,PRC89(2014)015503

# 3. ANL-BNL puzzle

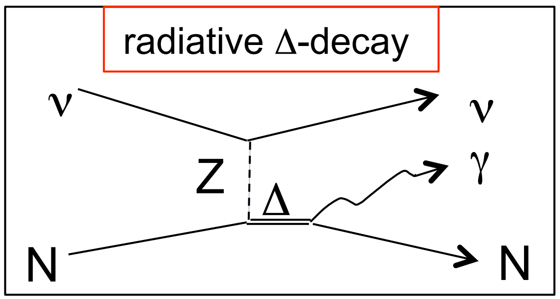
Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25%.

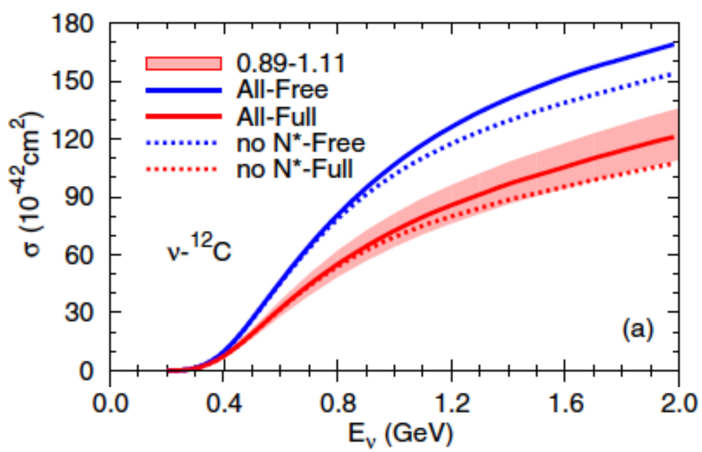
→ this propagates to every interactions with baryon resonance

ANL vs. BNL




ex) NCγ production model



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

# 3. ANL-BNL puzzle

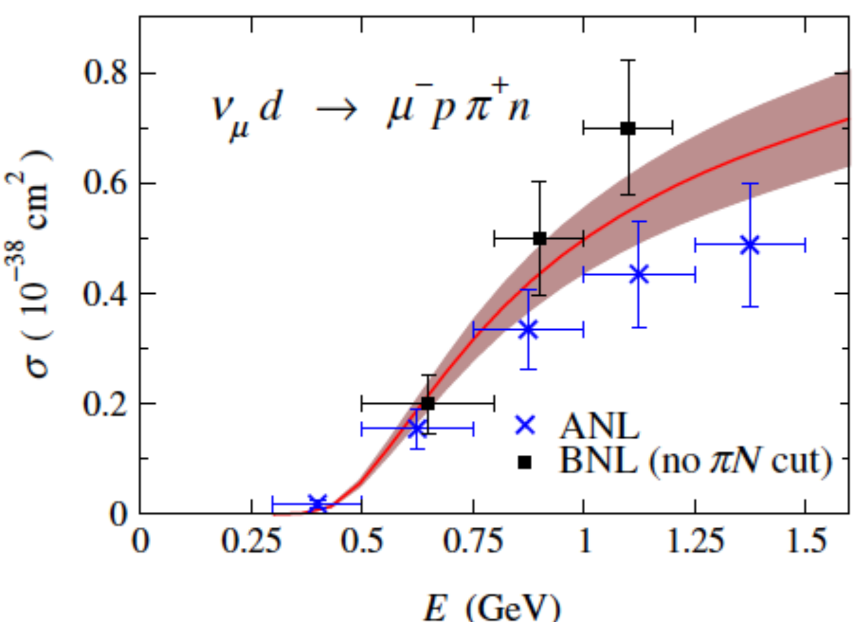


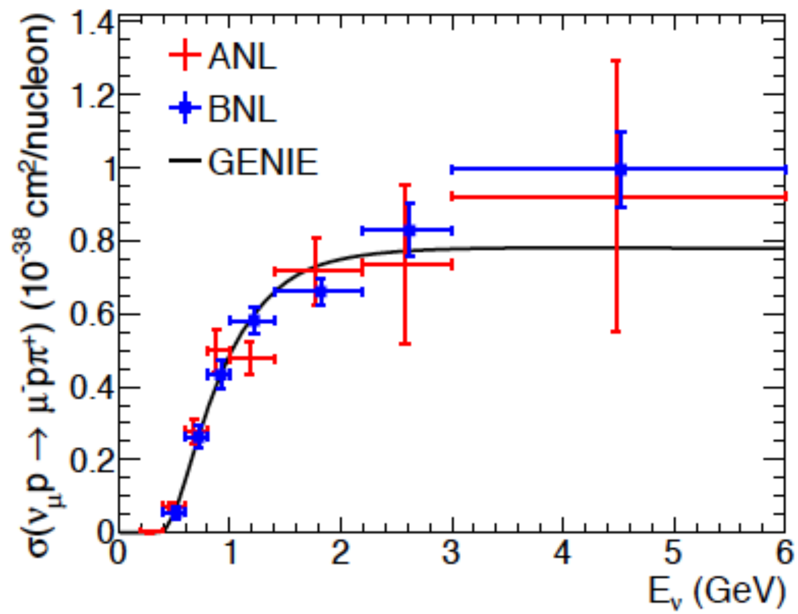
Deuteron target bubble chamber data are used to tune resonance models for nuclear target. However, 2 data set from Argonne (ANL) and Brookhaven (BNL) disagree their normalization ~25%.

→ this propagates to every interactions with baryon resonance

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

ANL vs. BNL



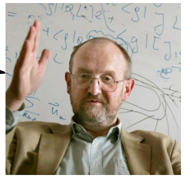




Remained task, was nuclear effect correctly taken into account to extract these data? (Wu. et al)

# 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?

Pion puzzle

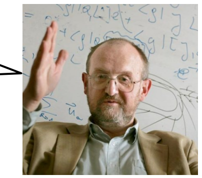
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Neutrino Cross-Section Newsletter,2014/04/14



# 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?

Pion puzzle

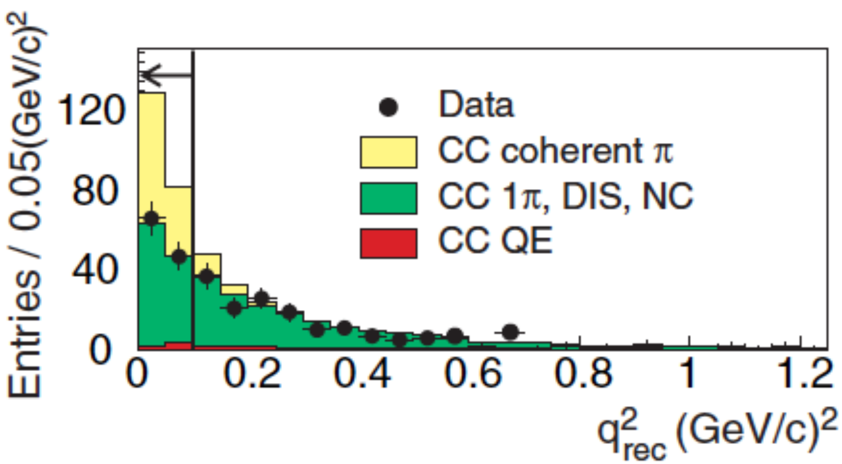
- MiniBooNE and MINERvA pion kinematic data are incompatible under any models

# 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



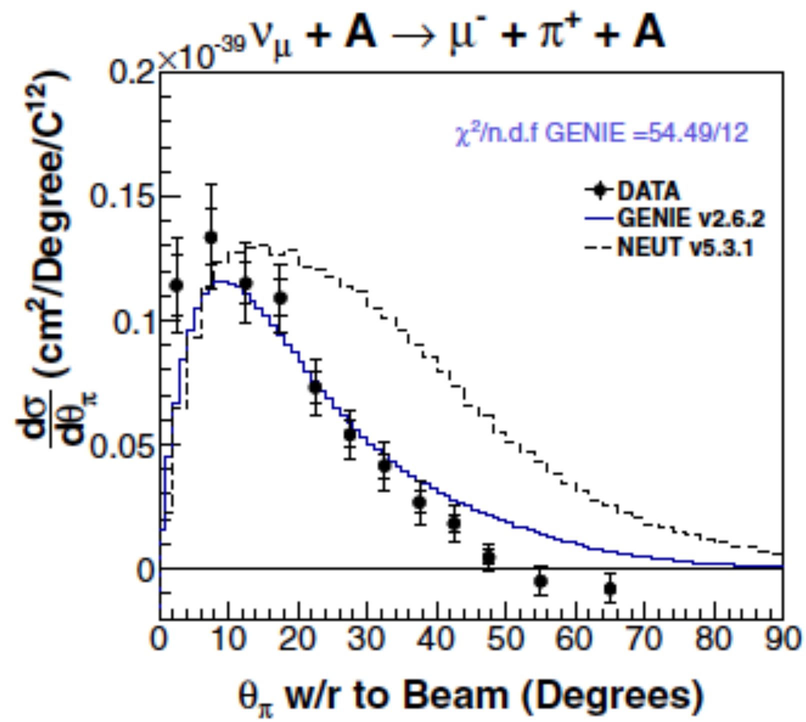
# 3. Coherent pion puzzle



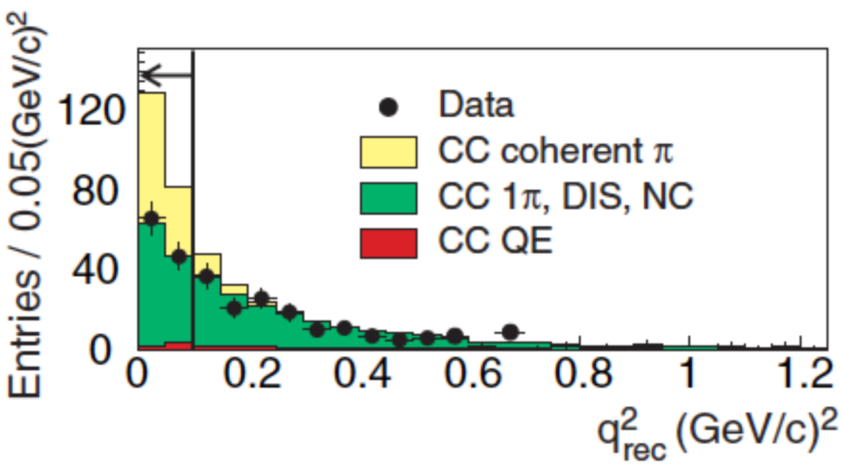
K2K and SciBooNE data show CC coherent pion production is consistent with zero.

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




K2K muon neutrino CC coherent pion candidate event distribution

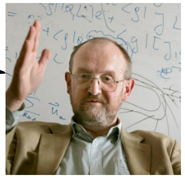



T2K off-axis: Scully, PhD thesis (Warwick, 2013)
T2K on-axis: Suzuki, NuFact2014
ArgoNeuT: PRL114(2015)039901
MINERvA: PRL113(2014)261802

# 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

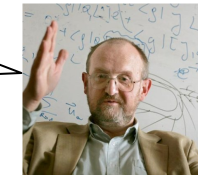
Pion puzzle

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

Alvarez-Ruso et al,NewJ.Phys.16(2014)075015, Morfin et al, AHEP(2012)934597
Neutrino Cross-Section Newsletter,2014/04/14

# 3. Open question of neutrino interaction physics






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

1. Neutrino Interaction Physics

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

3. Open question of neutrino interaction physics

**4. Neutrino induced single pion production**

5. Conclusion

# 4. Pion puzzle

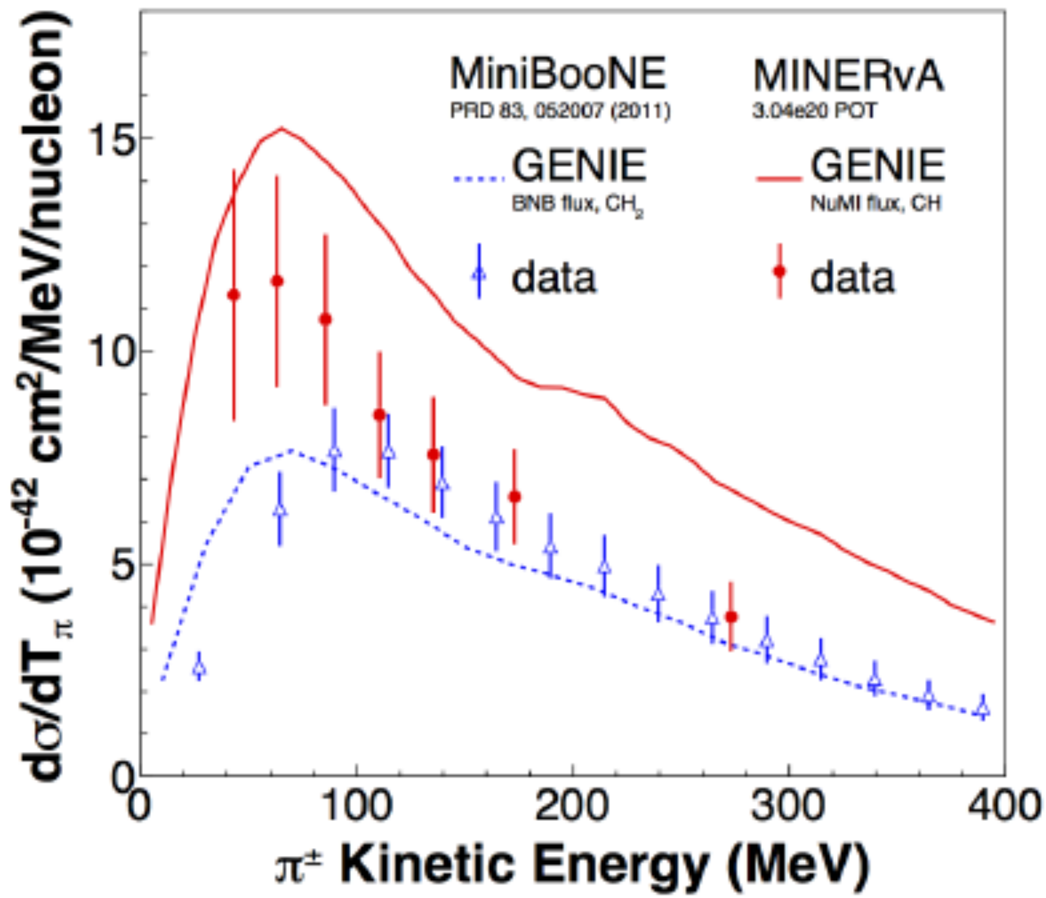


Data from MiniBooNE and MINERvA and simulation are all incompatible

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).

MINERvA data describe the shape well, but MiniBooNE data have better normalization agreement…



# 4. Pion puzzle

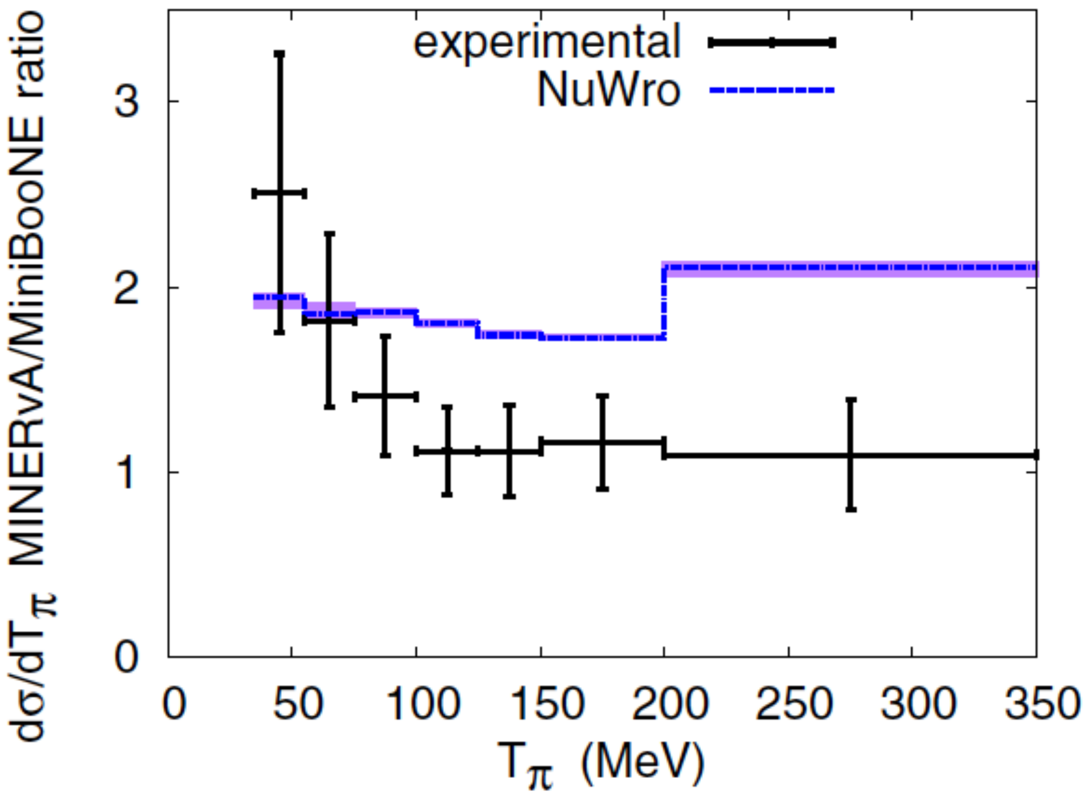


Data from MiniBooNE and MINERvA and simulation are all incompatible

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).

MINERvA data describe the shape well, but MiniBooNE data have better normalization agreement…

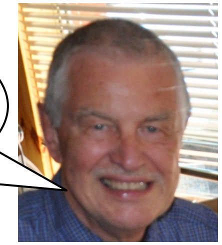


MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

# 4. Pion puzzle



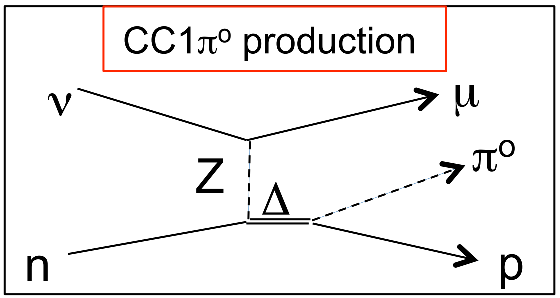
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

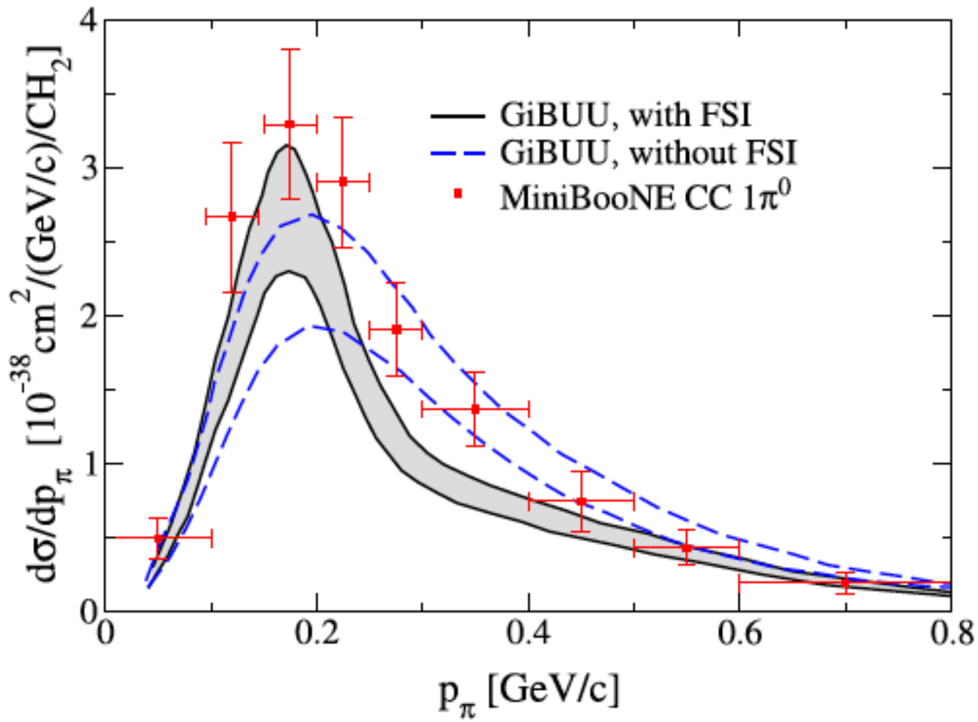


Ulrich Mosel (Giessen)

## Final state interaction

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




ex) Giessen BUU transport model

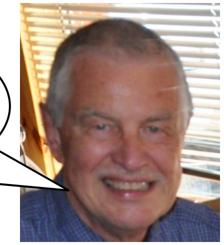
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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

# 4. Pion puzzle



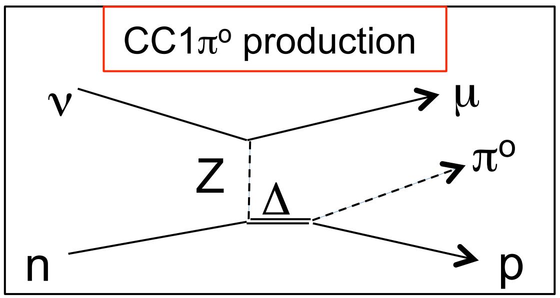
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

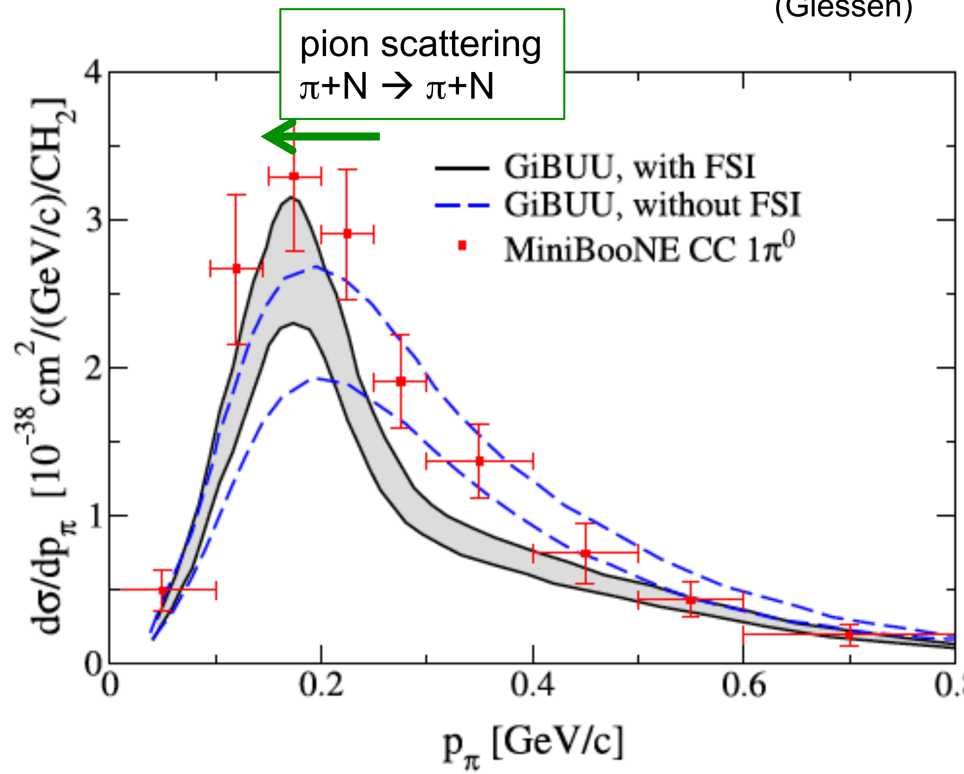


Ulrich Mosel (Giessen)

## Final state interaction

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




ex) Giessen BUU transport model

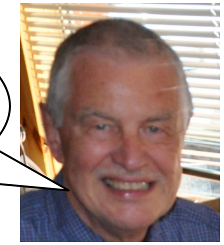
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

Queen Mary University of London

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

# 4. Pion puzzle

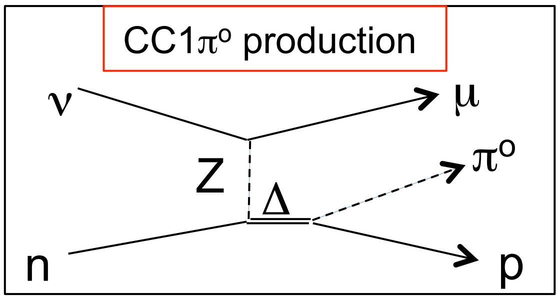
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

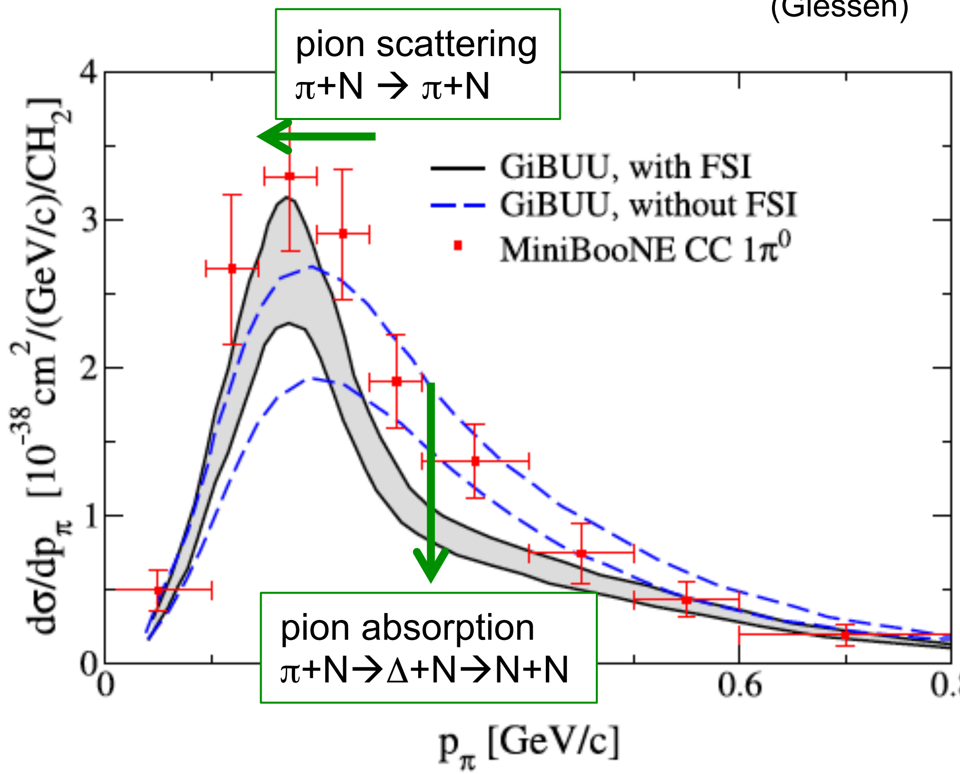


Ulrich Mosel (Giessen)

## Final state interaction

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




## ex) Giessen BUU transport model

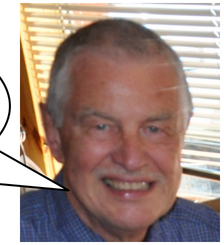
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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



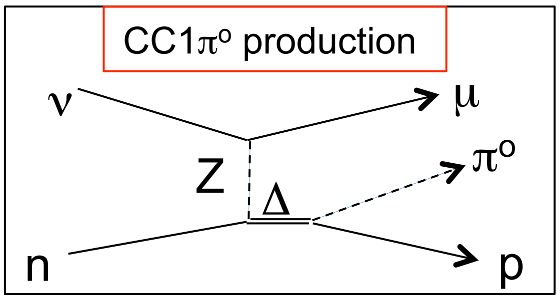
# 4. Pion puzzle

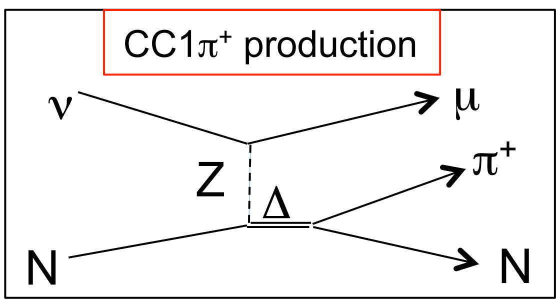
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

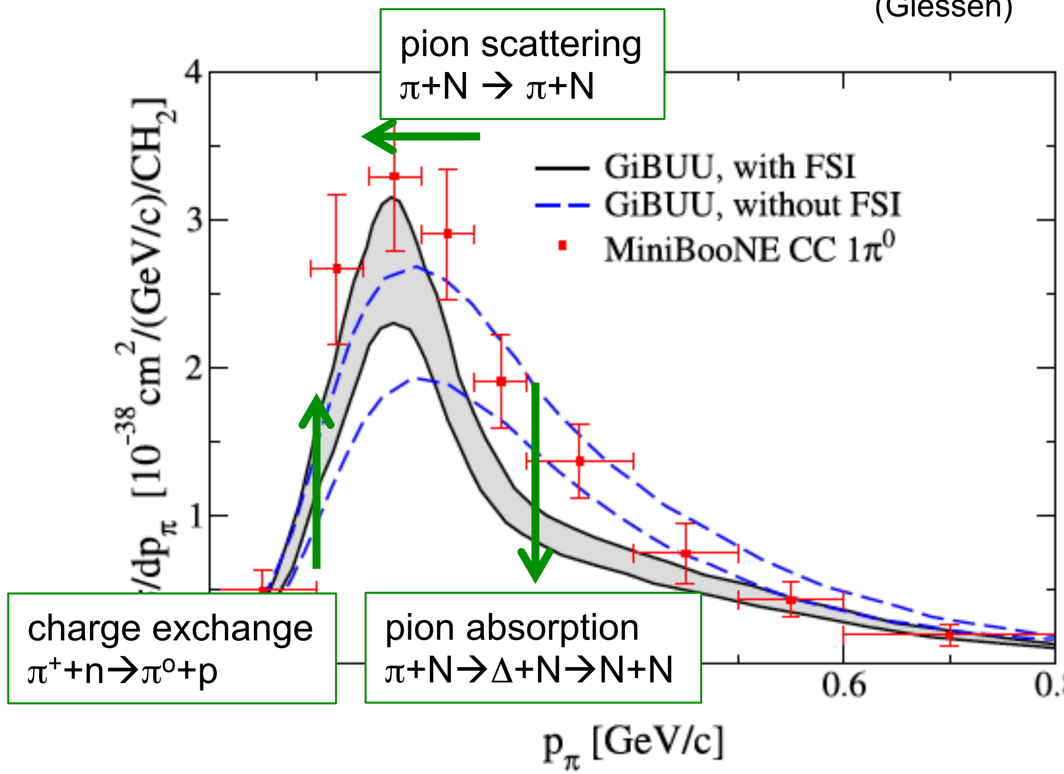

Ulrich Mosel (Giessen)

## Final state interaction

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



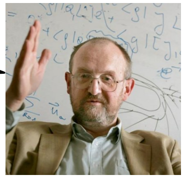

You need to be right for all
1. neutrino flux prediction
2. pion production model
3. final state interaction

ex) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

# 4. 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

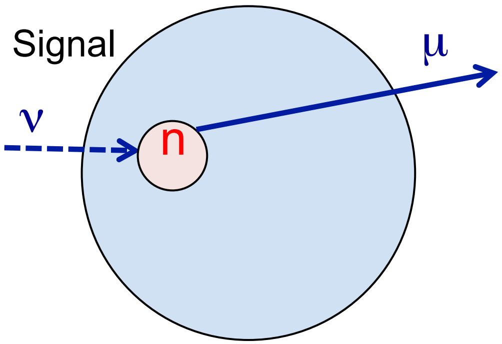
Pion puzzle

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

→ ???

# 4. non-QE background

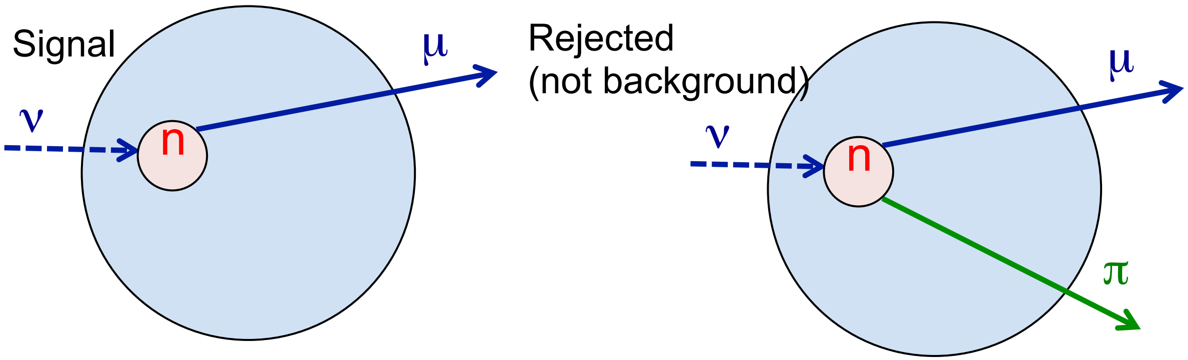
non-QE background → shift spectrum




Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost
(not great detector to measure hadrons)

# 4. non-QE background

non-QE background → shift spectrum

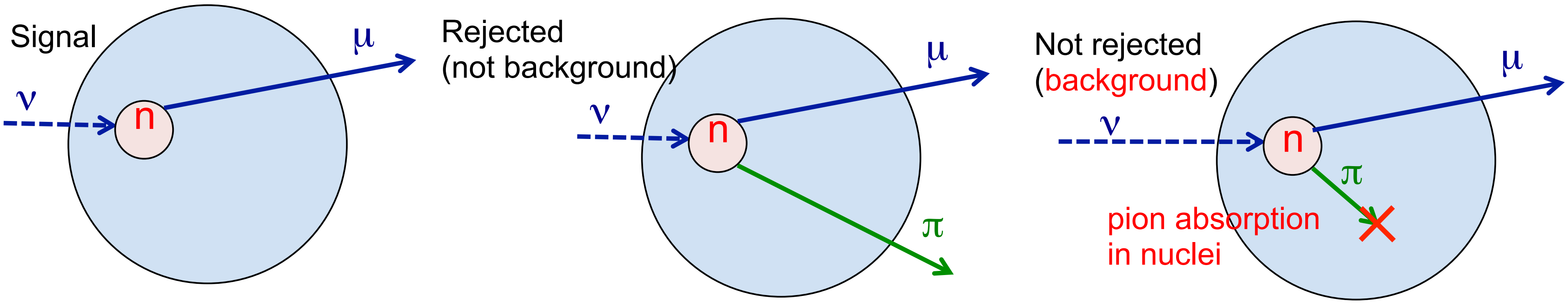



Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

# 4. non-QE background

non-QE background → shift spectrum

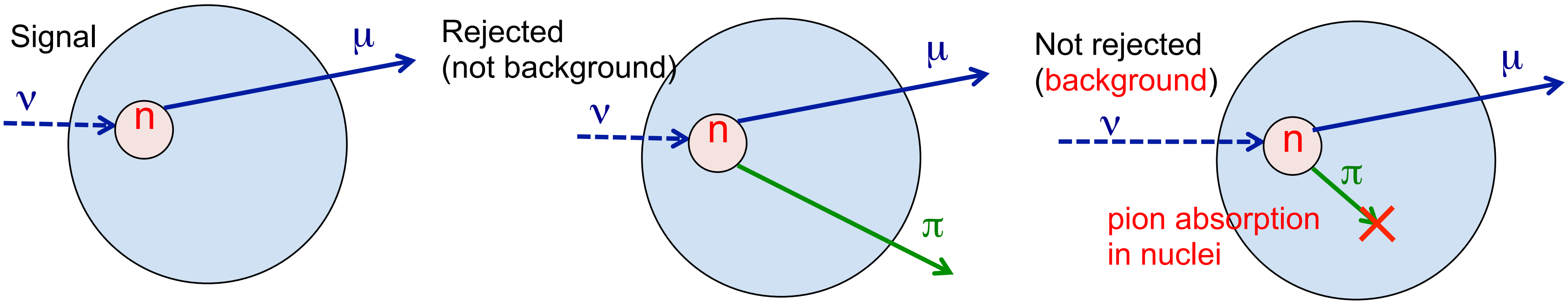


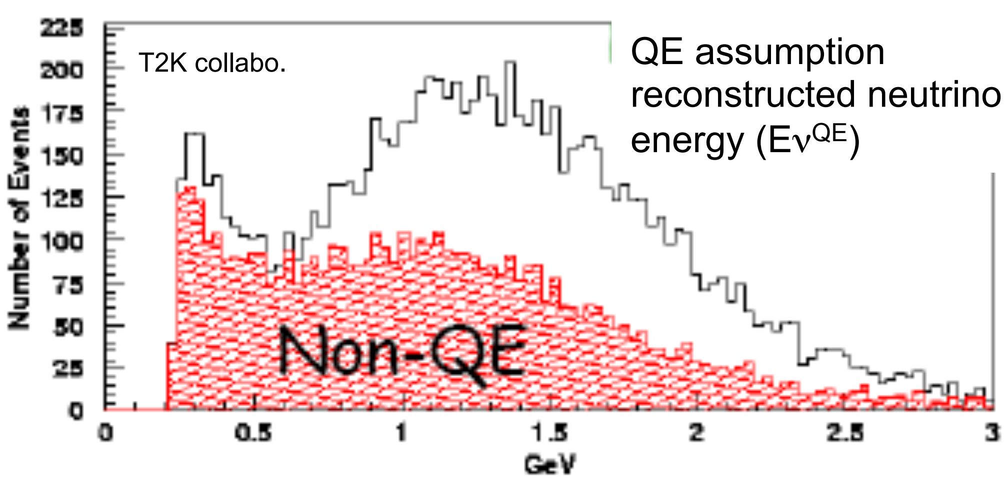

Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

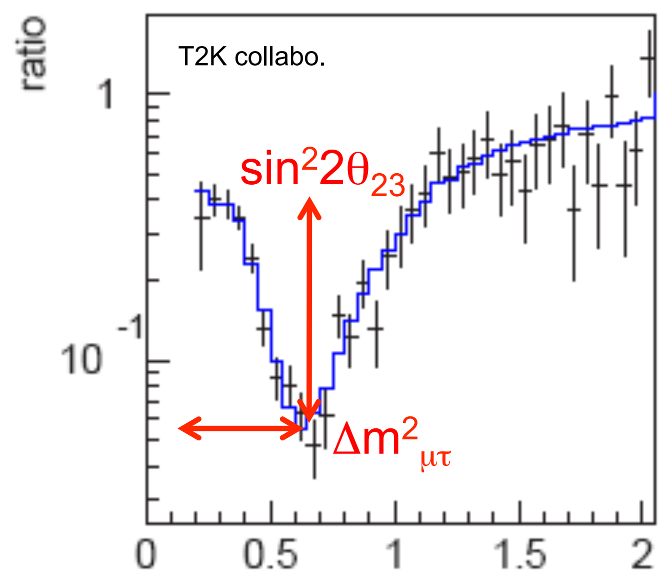
(not great detector to measure hadrons)

# 4. non-QE background

non-QE background → shift spectrum



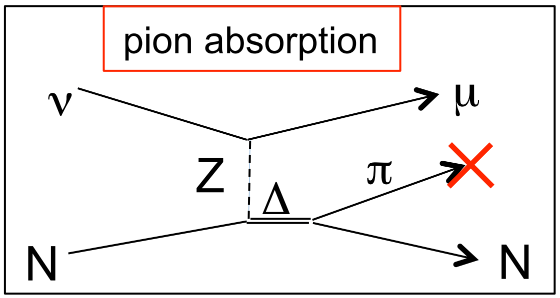



# 4. non-QE background

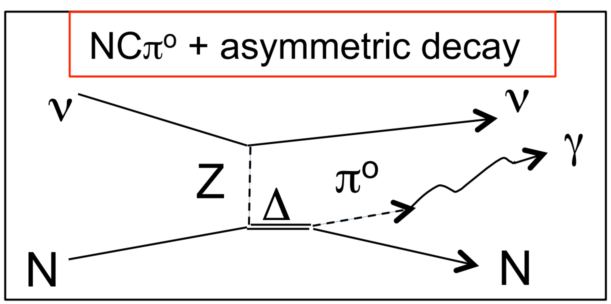
**Understanding of neutrino pion production is important for oscillation experiments**



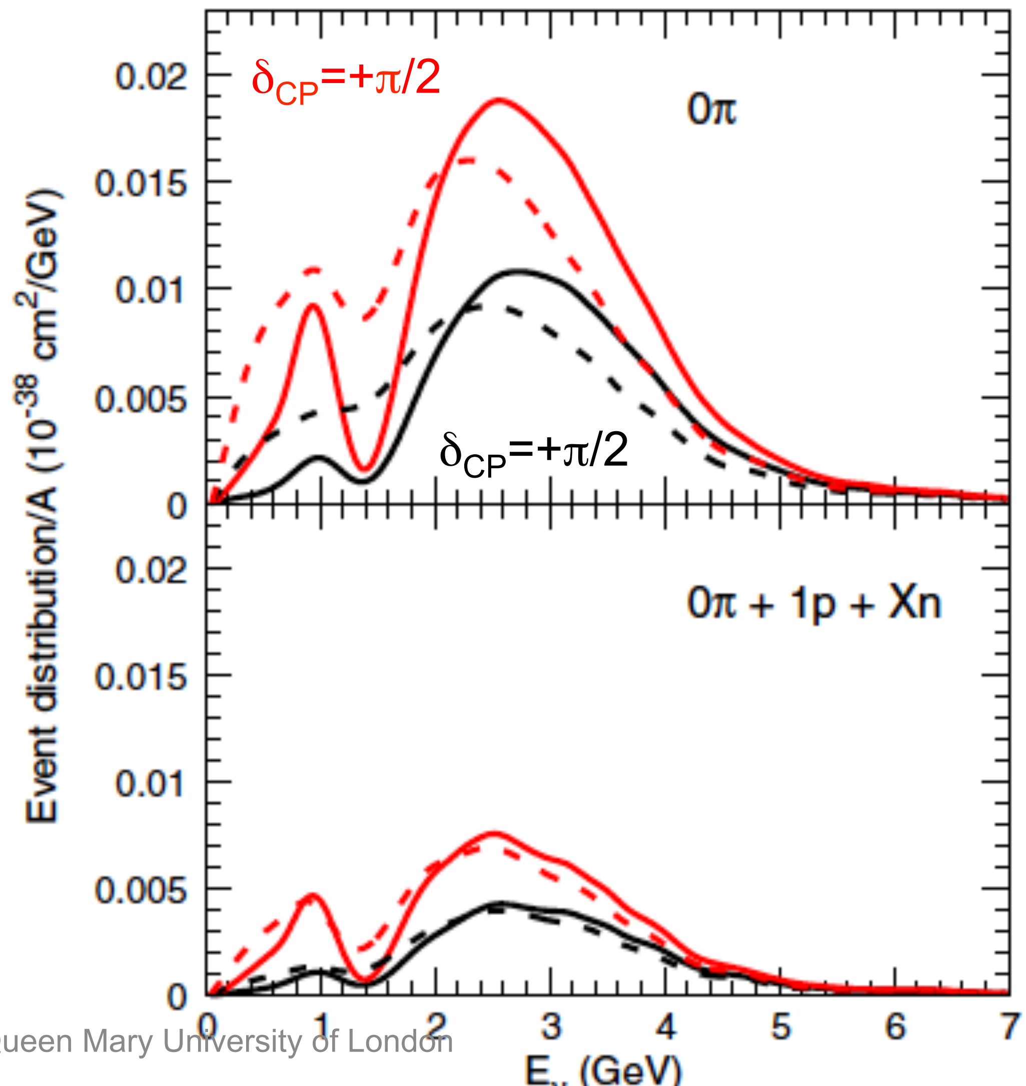
Pion production in $\nu_\mu$ disappearance search
- Source of mis-reconstruction of neutrino energy




Neutral pion production in $\nu_e$ appearance search
- Source of misID of electron




DUNE true vs. reconstructed Eν spectrum



# 4. 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, recently 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%.

# 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

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

# 4. Shallow Inelastic Scattering (SIS) region



**Cross section**

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

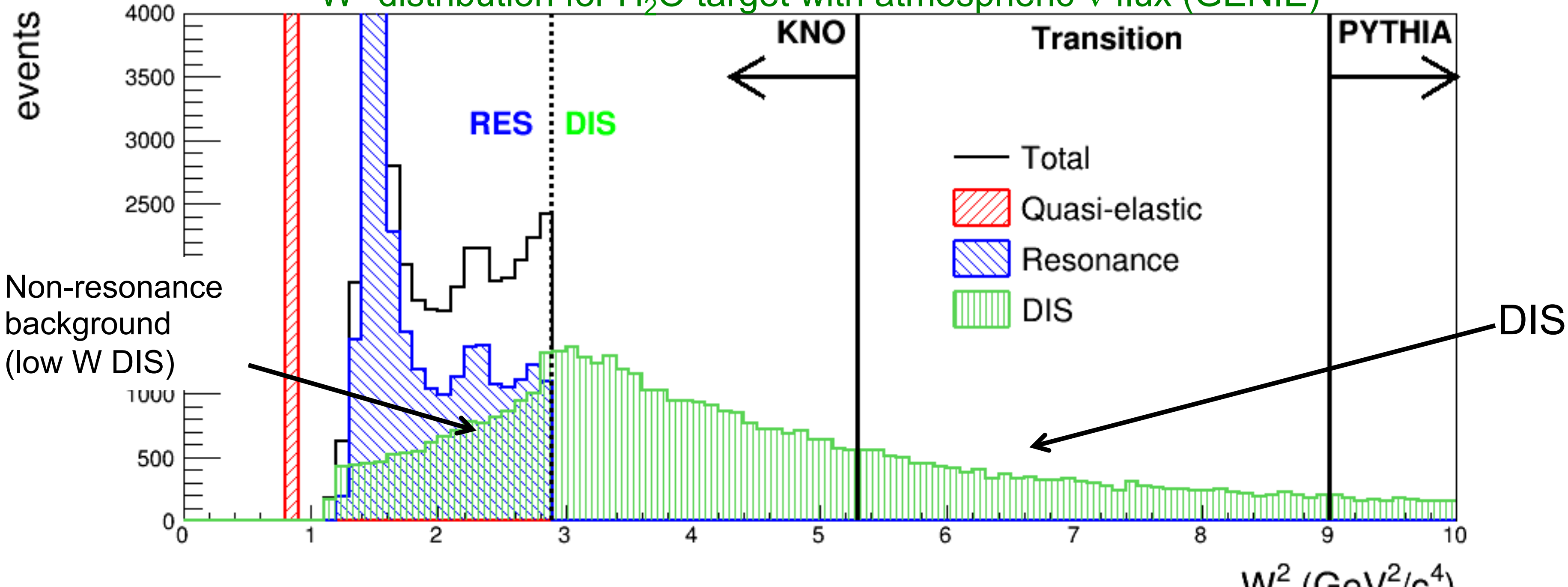
**Hadronization (GENIE-AGKY model)**

$W^2 < 5.3$GeV$^2$ : KNO scaling based model
2.3GeV$^2 < W^2 < 9.0$GeV$^2$ : 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)




Typical "Frankenstein" style model!

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

# 4. Shallow Inelastic Scattering (SIS) region

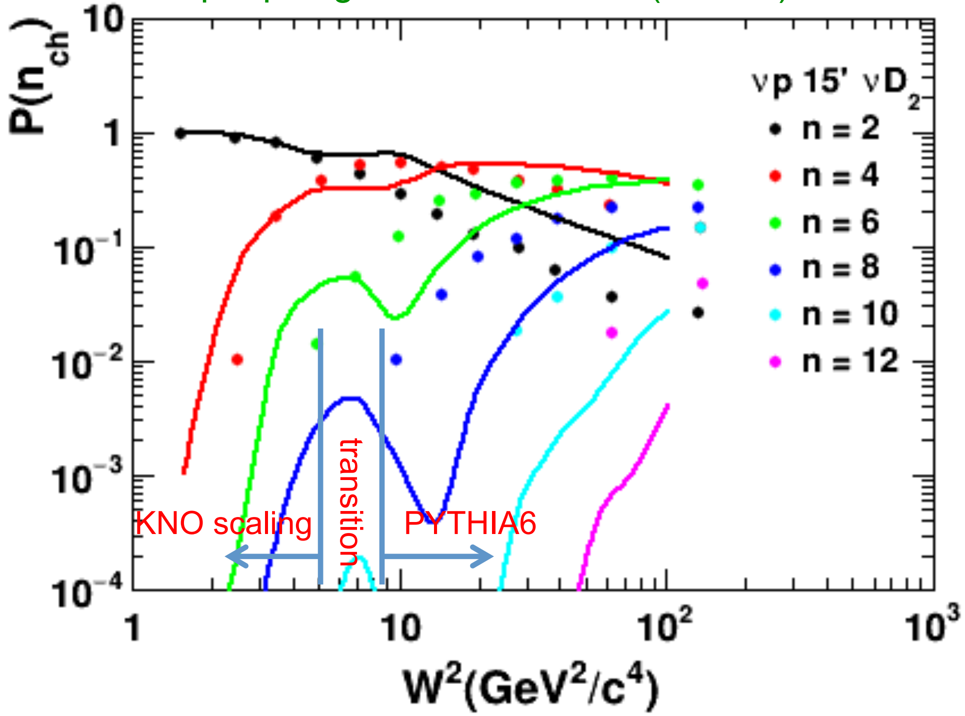


**Cross section**
$W^2 < 2.9\ GeV^2$ : RES
$W^2 > 2.9\ GeV^2$ : DIS
**Hadronization (GENIE-AGKY model)**
$W^2 < 5.3 GeV^2$ : KNO scaling based model
$2.3 GeV^2 < W^2 < 9.0 GeV^2$ : transition
$9.0 GeV^2 < W^2$ : PYTHIA6

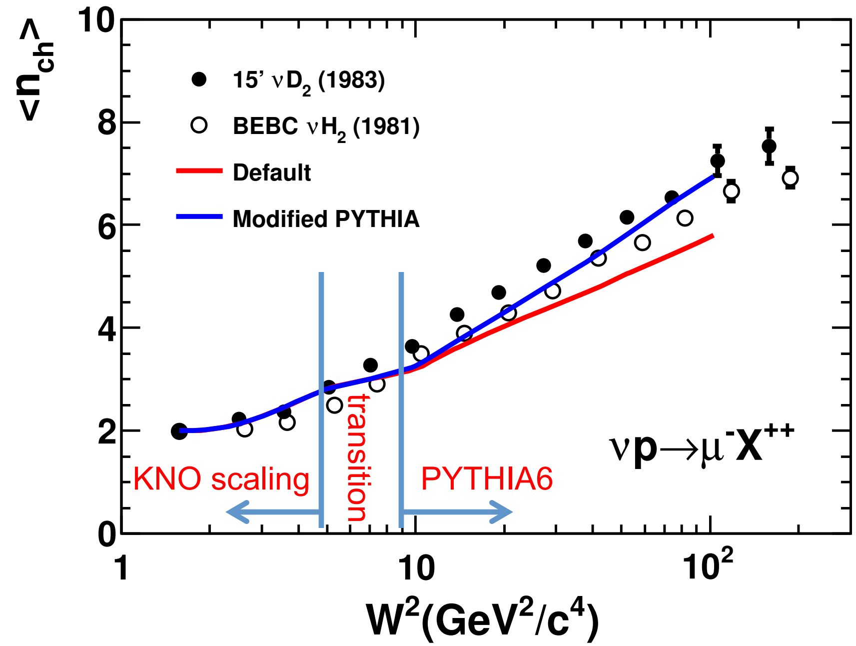
There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

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

ν-p topological cross section (GENIE)




ν-p averaged charged hadron multiplicity (GENIE)




Typical "Frankenstein" style model!

# 1. Neutrino Interaction Physics

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

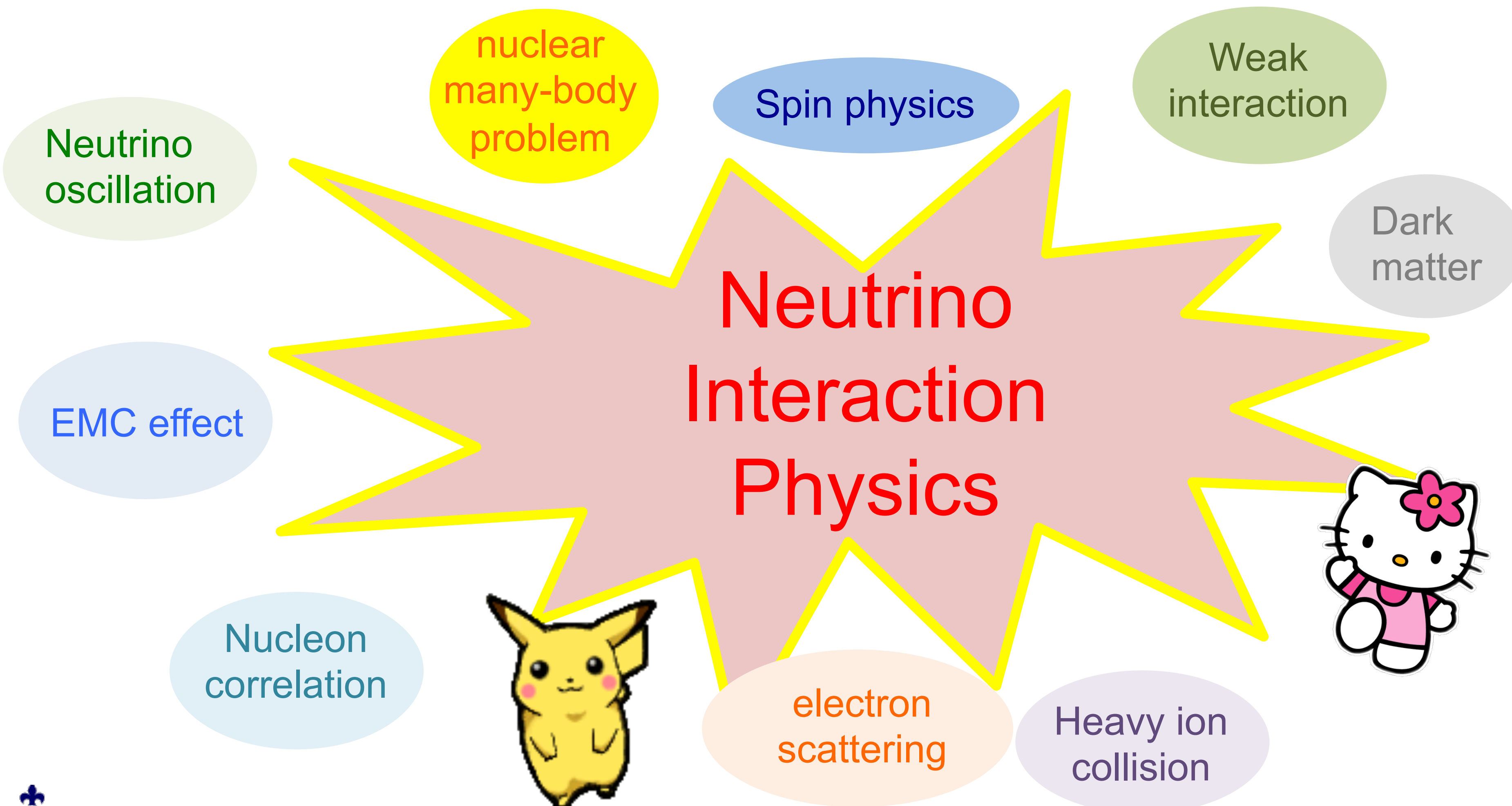
# 3. Open question of neutrino interaction physics

# 4. Neutrino induced single pion production

# 5. Conclusion

# 5. Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…



# 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, Okayama, Japan (Nov. 8-14, 2015)

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

Lecture 1 Introduction to NuSTEC School, Importance of Neutrino Interactions from MeV to GeV energy region
(Electro-magnetic Structure of the nucleus, Electron/Neutrino Nucleus Elastic Scattering)
(M. Sakuda, Okayama U., Japan)

Lecture 2,4,7 (Sakuda) Neutrino Physics and Neutrino Interactions (L. Alvarez-Ruso, IFIC, Spain)

Lecture 3, 5 Basics of Nuclear theory (potential ,current, symmetry etc) (A. Lovato, ANL, USA)

Lecture 8 Nuclear effects in quasi-elastic scattering (S. K. Singh, AMU, India)

Lecture 6, 9 Water Cherenkov Detector and Neutrino Physics (Y. Koshio, Okayama U., Japan)

Lecture 11 Neutrino Oscillation Experiments (TBA)

Lecture 10 ,12 Pion production from nucleons and nuclei & Other Inelastic processes like strange particle production, eta production and associated particle production (M. Sajjad Athar, AMU, India)

Lecture 15 Deep Inelastic Scattering (M Sajjad Athar, AMU, India)

Lecture 13, 16 Liquid Argon Detector and Neutrino Interactions (F. Cavanna, Yale U., USA),

Lecture 14, 17 Generator (TBA)

Lecture 18 Liquid Scintillator Detector and KamLAND [Latest Result] (TBA)

Lecture 19 Reactor Experiment RENO and RENO-50 (S.B.Kim, Seoul Natl. U., South Korea)

Lecture 20 MiNERVA and Neutrino Interactions (J. Morfin,Fermi Lab, USA)

# 5. 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


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

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

# 5. 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
1. MINERvA CC $\omega$-q measurement
2. $\nu_e$CC cross-section measurement from NOvA near detector
3. T2K CC0$\pi$ double differential cross-sections
4. MINERvA QE-like double differential cross-sections
5. ArgoNeuT CC cross-sections with proton counting
6. Charge exchange and pion absorption cross section on carbon
7. CLAS pion production
8. DIS cross-section target ratio by MINERvA

and more…

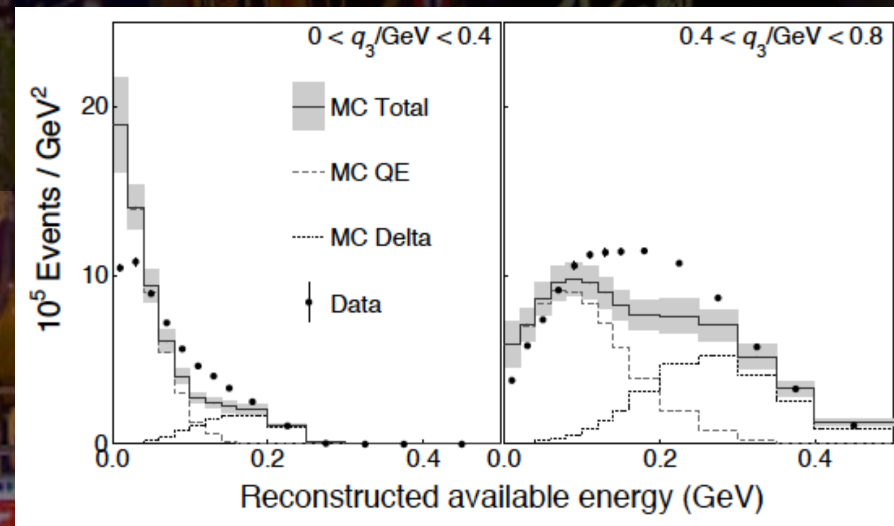
10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt15)

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

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

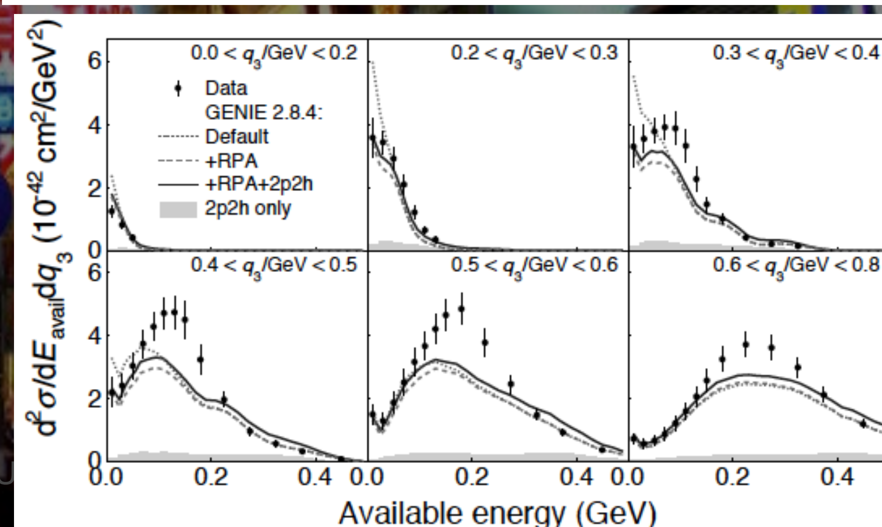
Tremendous amount of activities, new data, new theories…
http://indico.ipmu.jp/indico/conferenceDisplay.py?ovw=True&confId=46

New data
1. MINERvA CC ω-q measurement




Data clearly requires RPA-like suppression.

Valencia 2p-2h model does not quite fill the neutrino "dip" region




- Is w-q reconstruction right?
- Is model implemented correctly?
- Are there any effect overlooked?

# 5. Conclusion



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

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 oxygen and argon?!).

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

SIS: Premature.

DIS: Nuclear dependent PDF is necessary.

# 5. Conclusion

Subscribe “Neutrino Cross-Section Newsletter”
(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please “like” our Facebook page, use hashtag #nuxsec

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

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 work in all phase space. This moment, RPA based calculation shows successful. Neutrino experiment is always “inclusive” in terms of electron scattering.

Subscribe “Neutrino Cross-Section Newsletter”
(search by Google, or send e-mail to t.katori@qmul.ac.uk)
Please “like” our Facebook page, use hashtag #nuxsec

# 5. Conclusion

**Neutrino Interaction Physics**

- electron scattering
- nuclear many-body problem
- Weak interaction
- Neutrino oscillation
- EMC effect
- Nucleon correlation
- Spin physics
- Dark matter
- Heavy ion collision

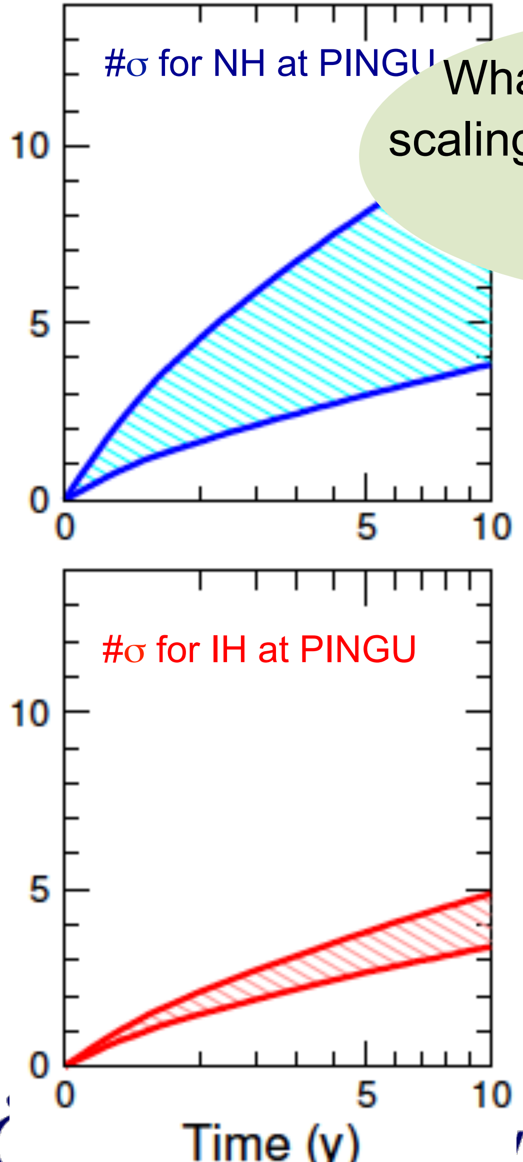
**Thank you for your attention!**

# Backup

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)

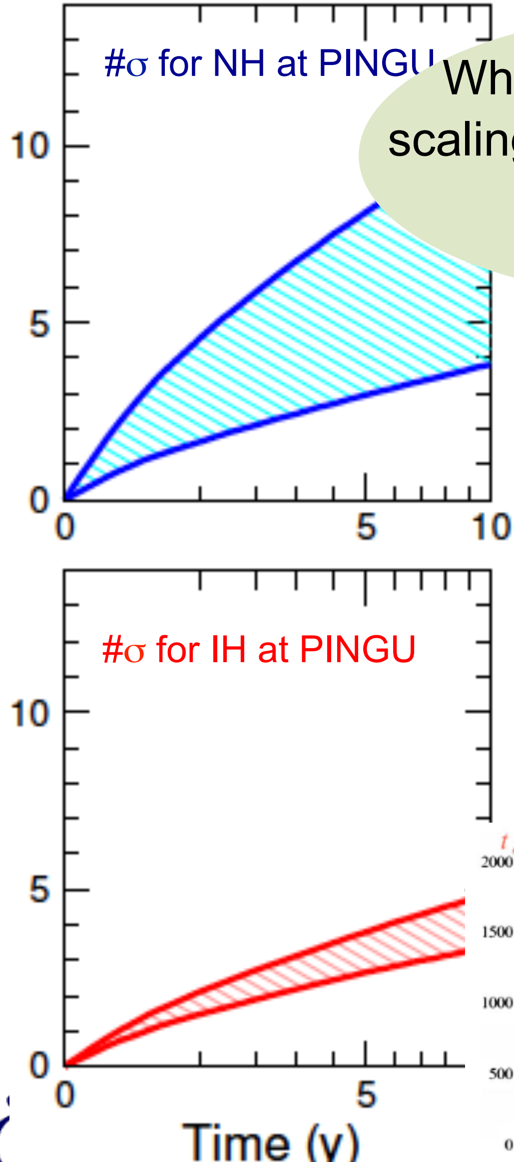
Neutrino interaction model is a large systematics of neutrino oscillation experiment

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



# 1. NOvA, PINGU, Hyper-K, DUNE

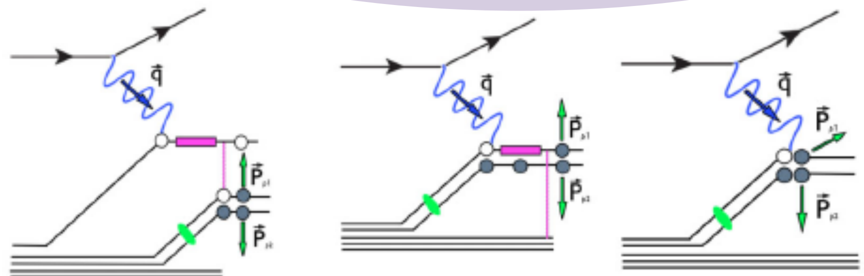
See talk by Georgia Karagiorgi (PP+APP session)

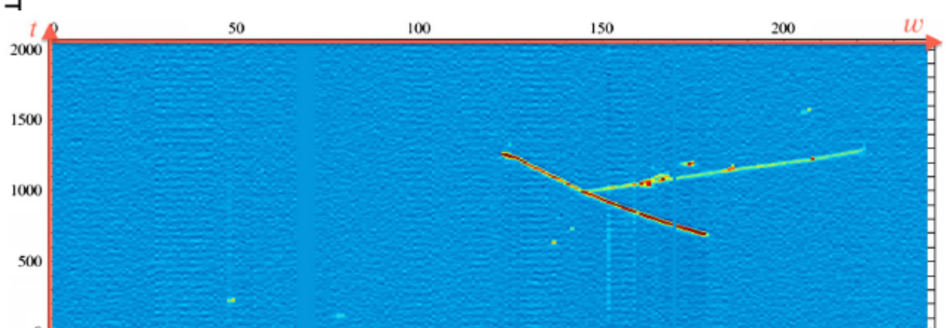



What is the real energy scaling error on atmospheric neutrinos???
(Hyper-K, PINGU)

Neutrino interaction model is a large systematics of neutrino oscillation experiment

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

# 1. NOvA, PINGU, Hyper-K, DUNE

See talk by Georgia Karagiorgi (PP+APP session)

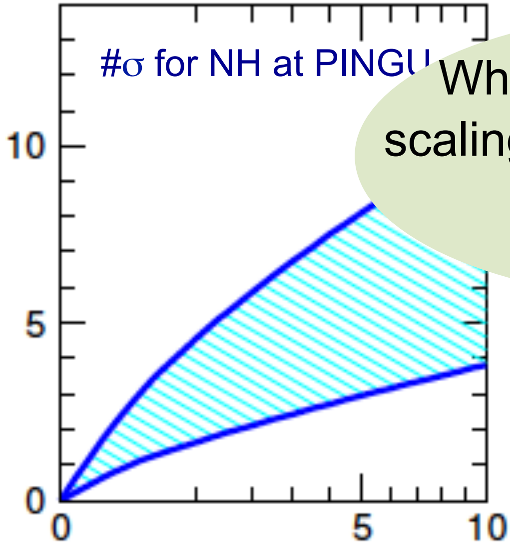


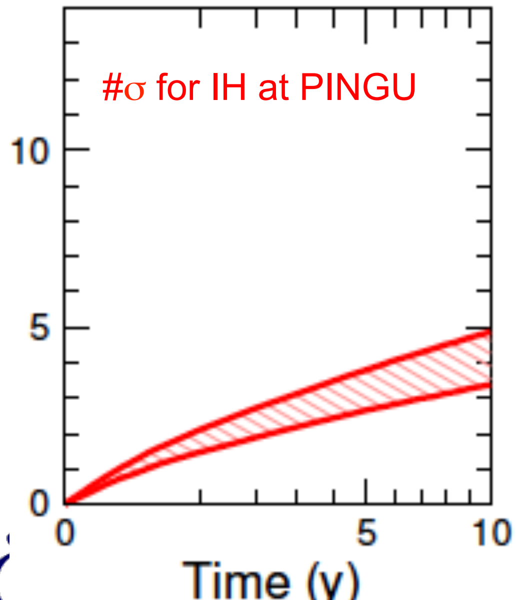
Neutrino interaction model is a large systematics of neutrino oscillation experiment

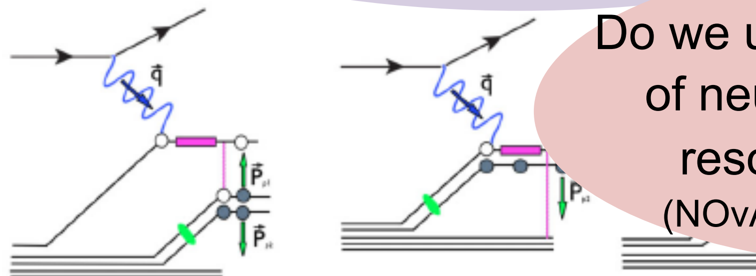
What is the real energy scaling error on atmospheric neutrinos???
(Hyper-K, PINGU)

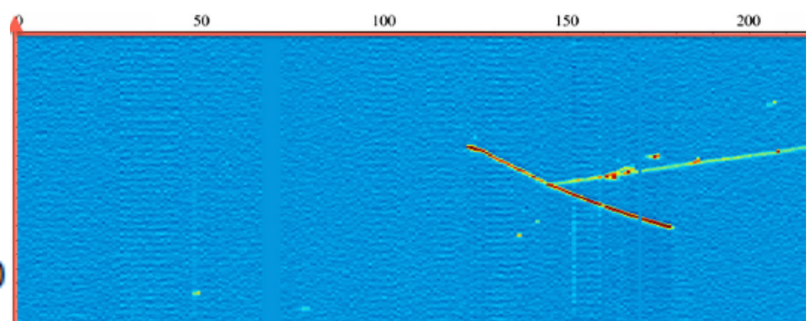
Are there any phenomenological models predicting final hadronic state correctly with argon target???
(DUNE)

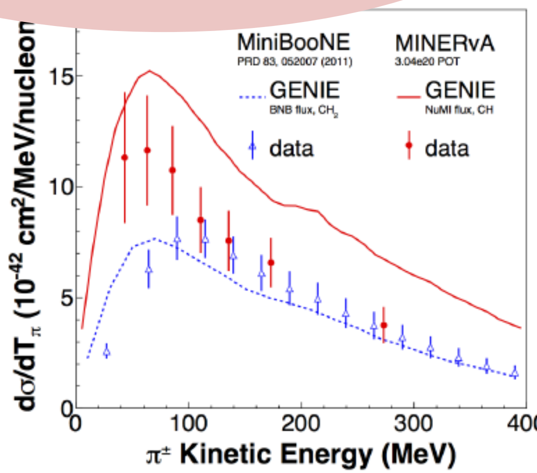
Do we understand the structure of neutrino induced baryon resonance someday???
(NOvA, PINGU, Hyper-K, DUNE)








University of London

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

# 2. Relativistic Fermi Gas (RFG) model

Butkevich and Mikheyev, PRC72(2005)025501

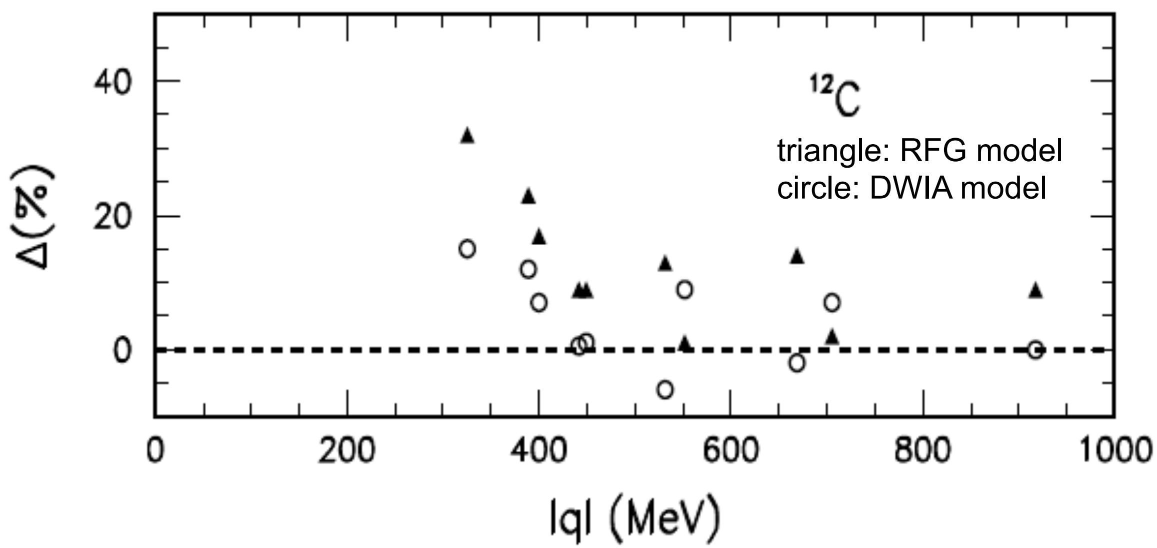


Relativistic Fermi Gas (RFG) Model

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

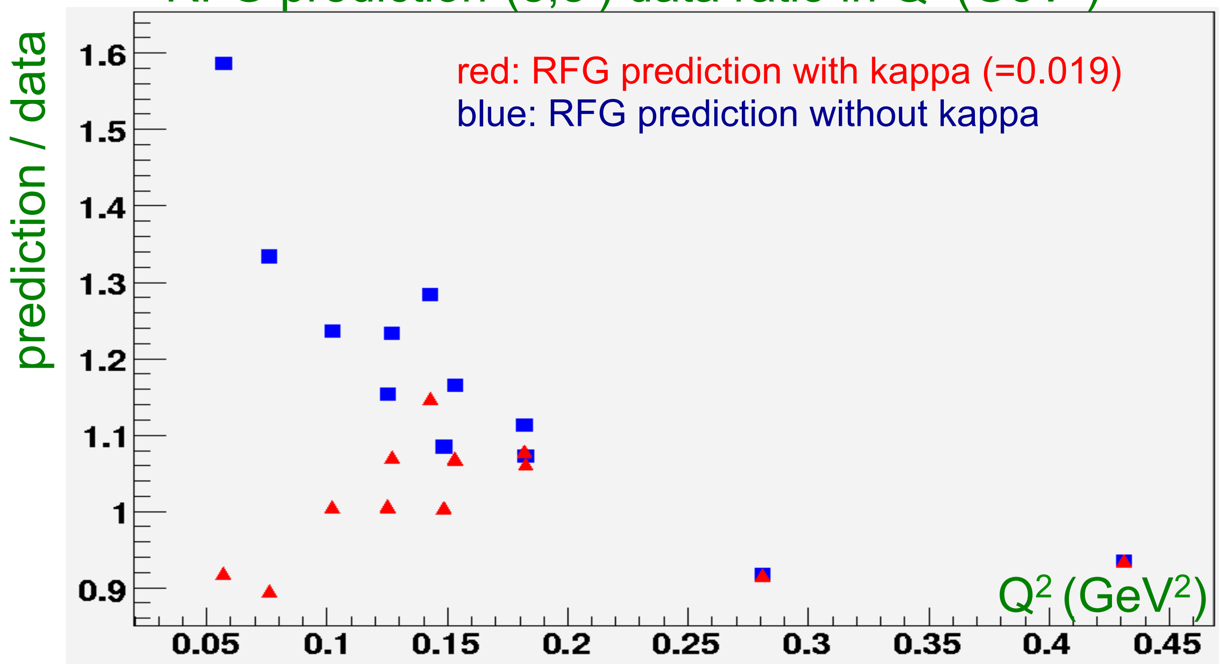
# 2. Relativistic Fermi Gas (RFG) model



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

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

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

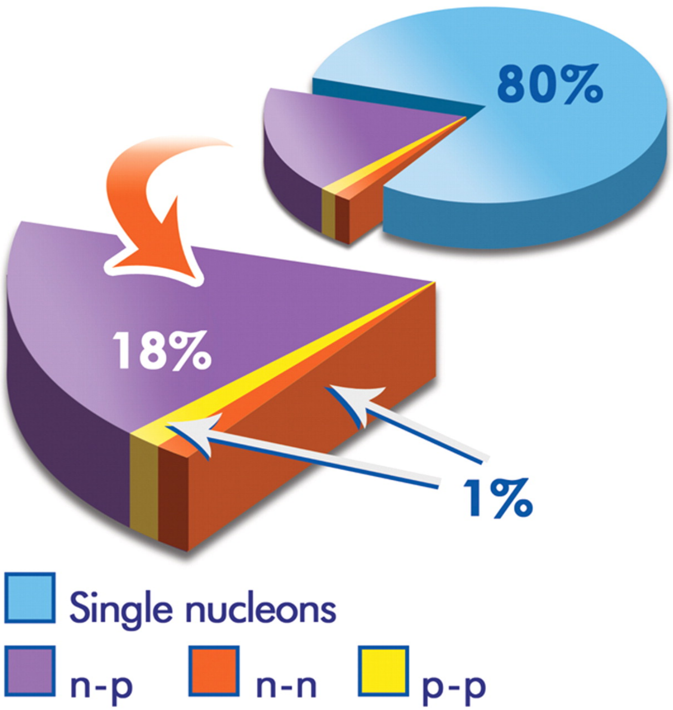


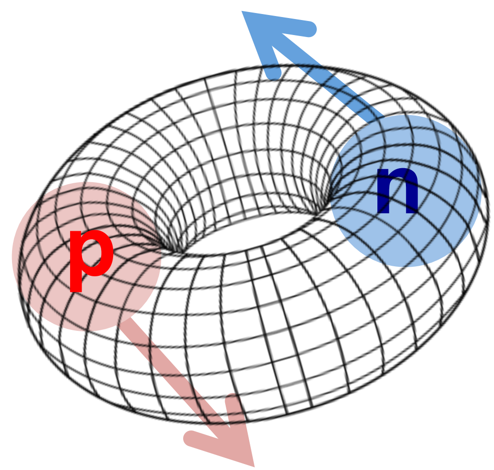
CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504
JLab HallA, PRL99(2007)072501, Science320(2008)1476

# 2. Nucleon correlations

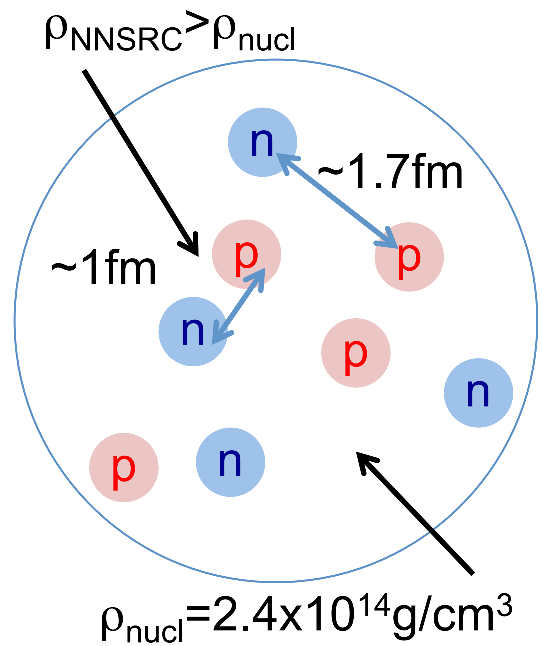
## Short Range Correlation (SRC)

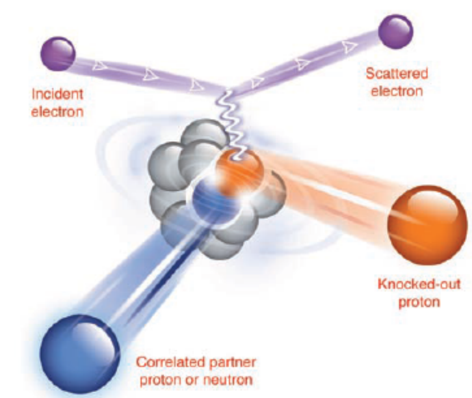
- ~20% of all nucleons in heavy elements (A>4)
- ~90% are neutron-proton (n-p) pair
- ~nucleon pair have back-to-back momentum
- ~ momentum can be beyond Fermi sea




NNSRC~quasi deuteron



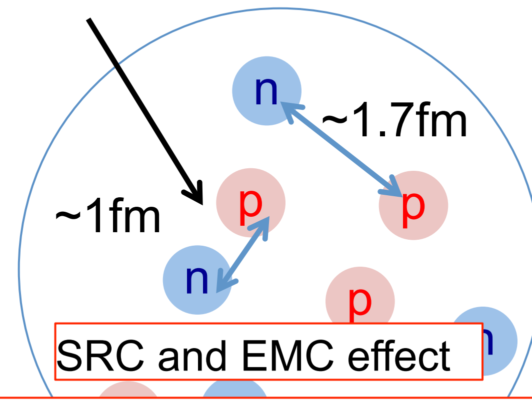
CLAS, PRL96(2006)082501, Piasetzky et al, PRL97(2006)162504;106(2011)052301
JLab HallA, PRL99(2007)072501, Science320(2008)1476

# 2. Nucleon correlations

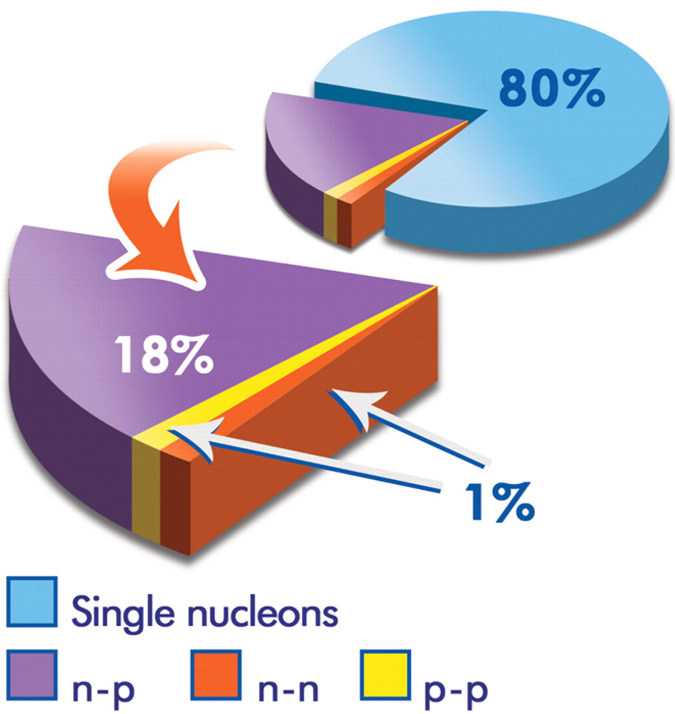
## Short Range Correlation (SRC)

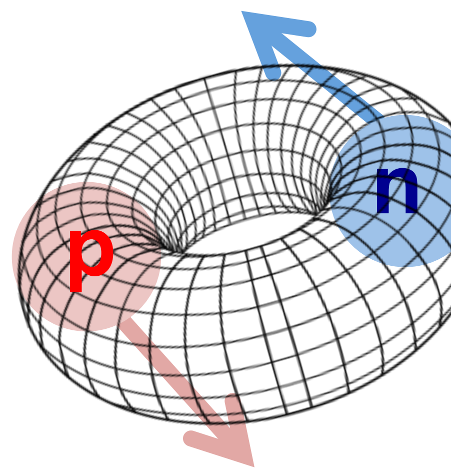
~20% of all nucleons in heavy elements (A>4)
~90% are neutron-proton (n-p) pair
~nucleon pair have back-to-back momentum
~ momentum can be beyond Fermi sea

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

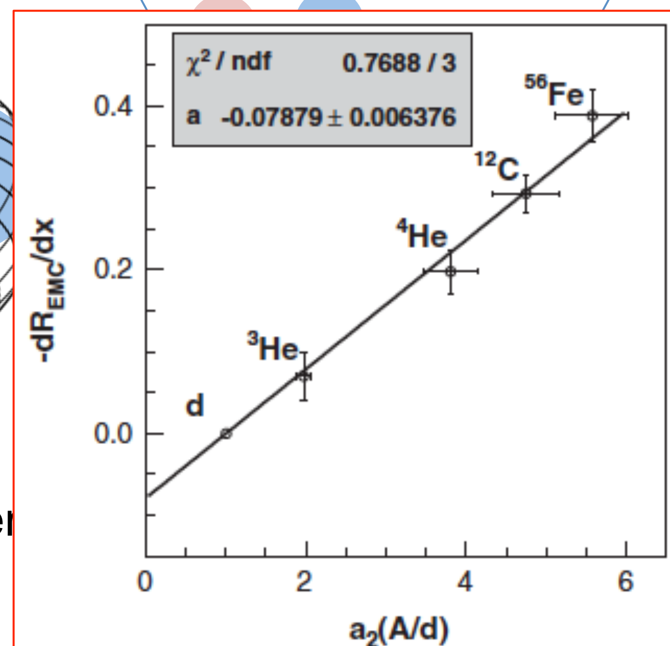



SRC and EMC effect




NNSRC~quasi deuteron




Queen Mary University of London

# 3. Neutrino oscillation experiment

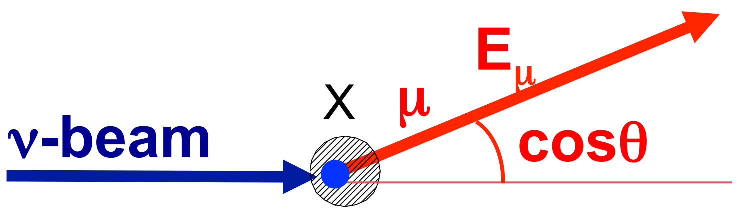


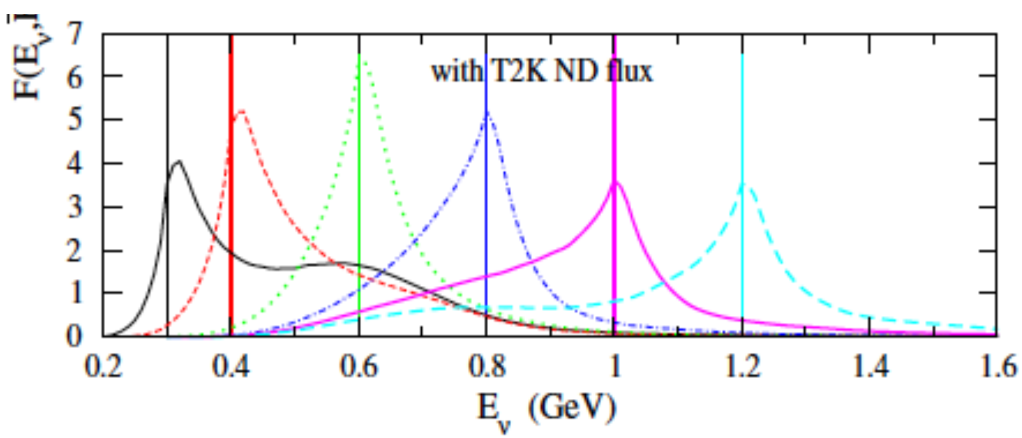
## Reconstruction of neutrino energy with QE assumption

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

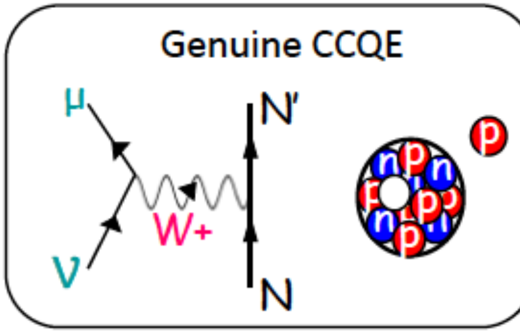
(interaction with 2-nucleons, pion production with pion nuclear absorption)

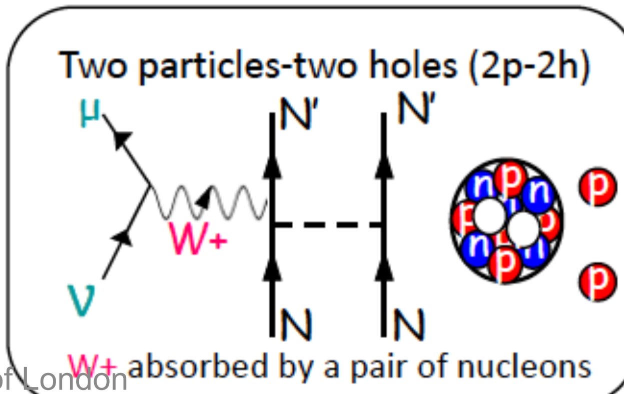
$$\nu_\mu + n \rightarrow p + \mu^- \quad (\nu_\mu + X \rightarrow X' + \mu^-) \qquad E_\nu^{QE} = \frac{ME_\mu - 0.5m_\mu^2}{M - E_\mu + p_\mu \cos\theta_\mu}$$




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

# 4. MiniBooNE low energy excess



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

signal

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

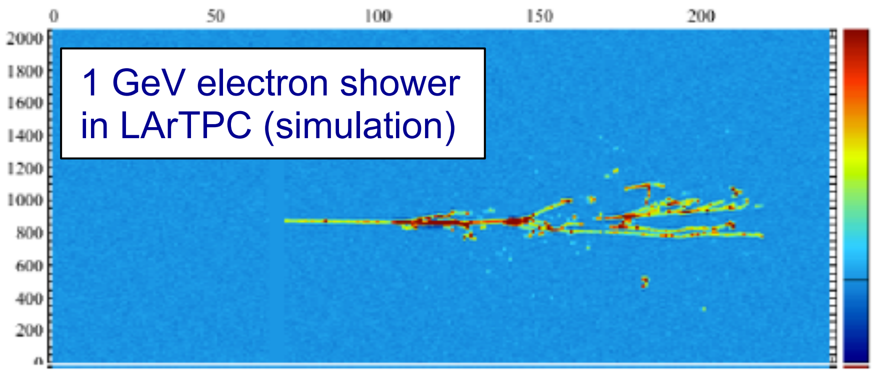
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow n + e^+$$

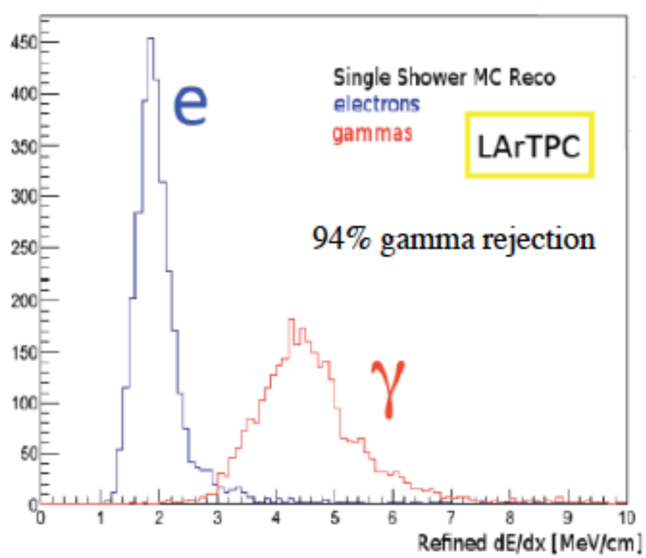
background

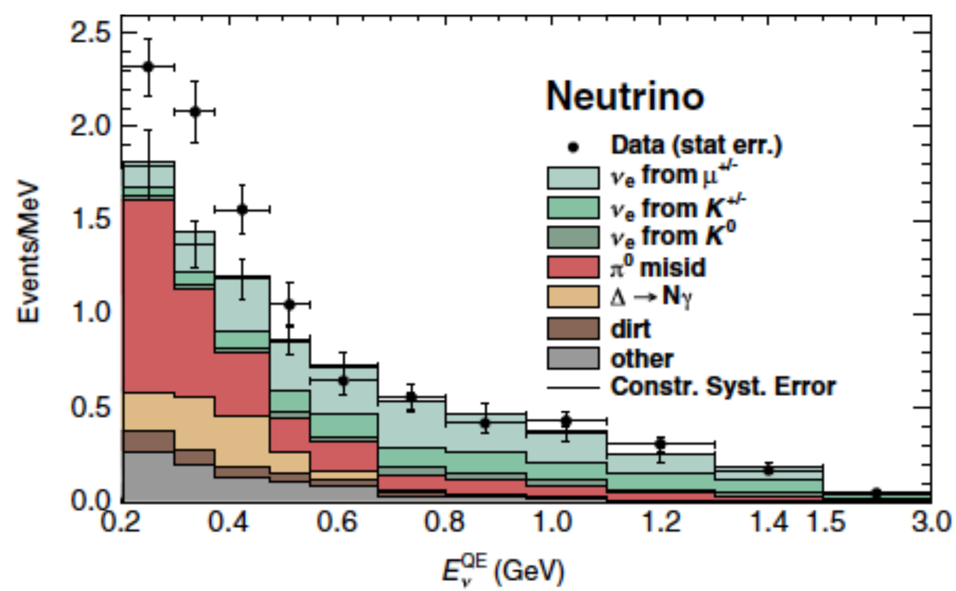
$$\nu_\mu + X \rightarrow \nu_\mu + X' + \pi^o \rightarrow \gamma + \gamma$$

$$\nu_\mu + X \rightarrow \nu_\mu + X' + \gamma$$

Can new NCγ model explain this excess?



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



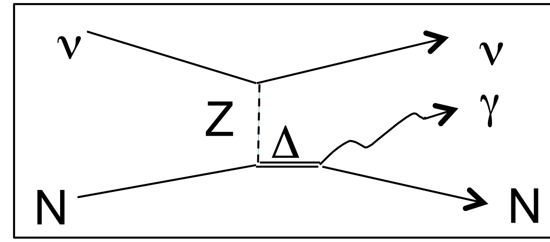
# 4. MiniBooNE low energy excess

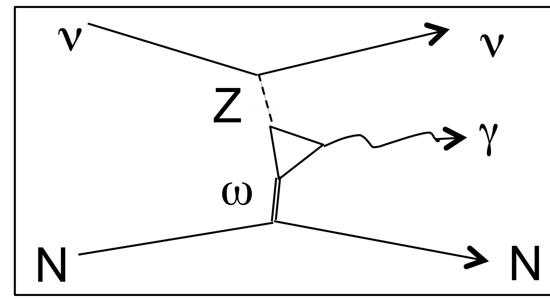
MiniBooNE observed oscillation candidate event excess
→ but MiniBooNE cannot distinguish e and γ

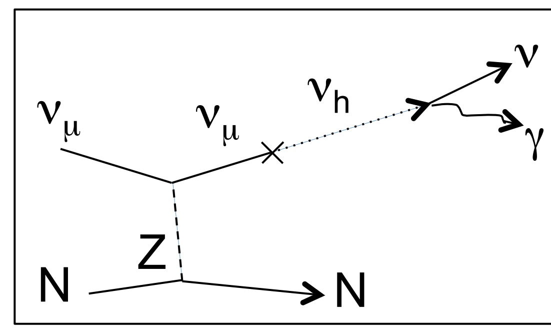
Can new NCγ model explain this excess?

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

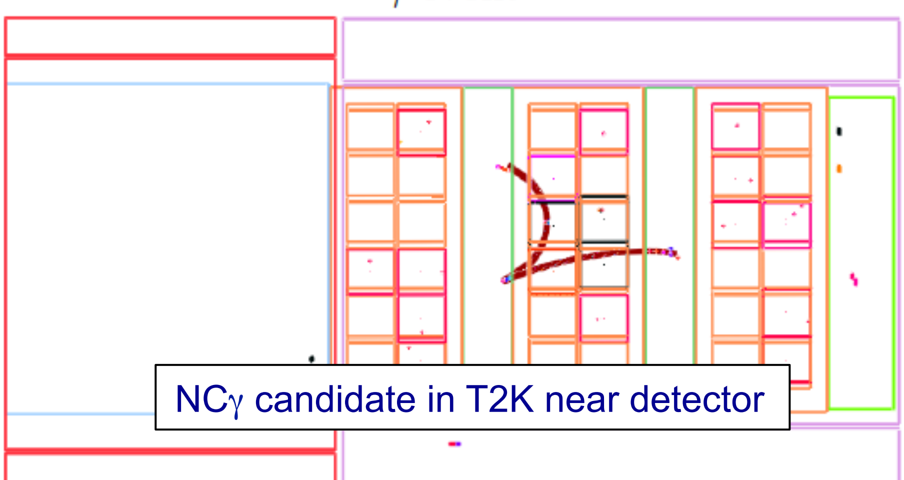
NOMAD measured at <E>~25GeV
T2K can measure this at lower energy




γ event



NCγ candidate in T2K near detector

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

# 4. Neutral Current Quasi-Elastic (NCQE) scattering



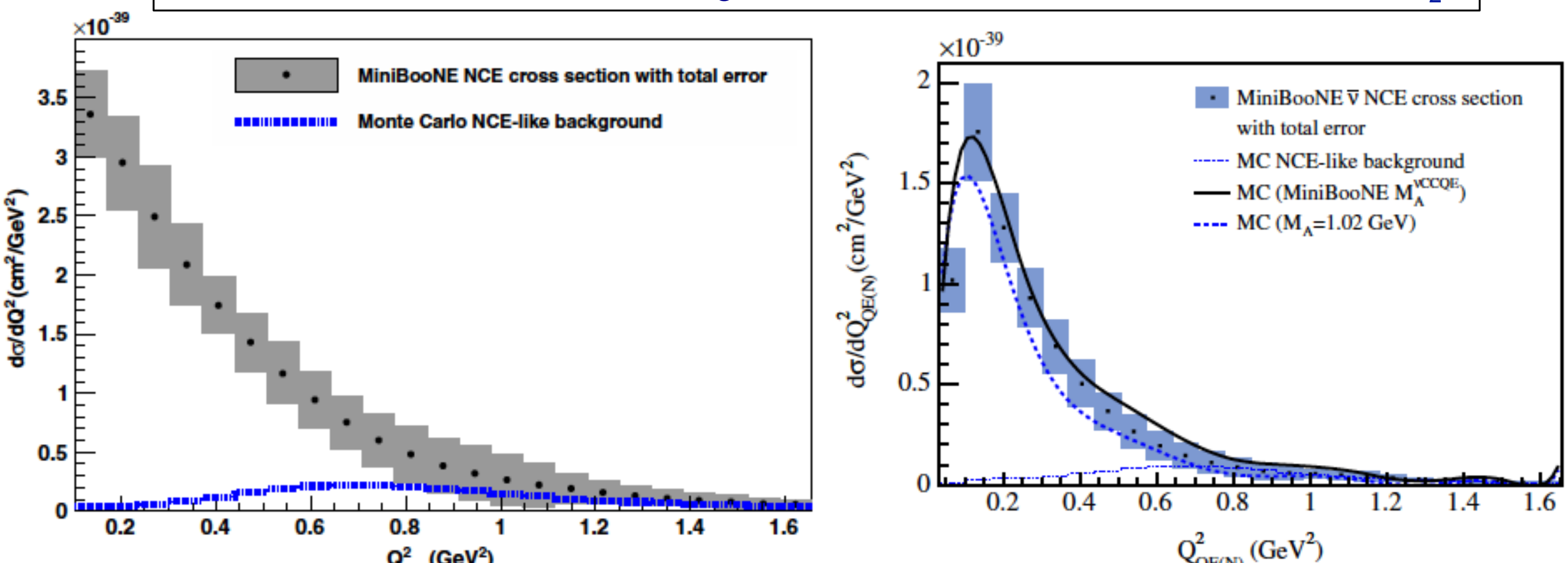
This channel has so many topics

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 $CH_2$



# 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

"proton spin crisis"

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

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

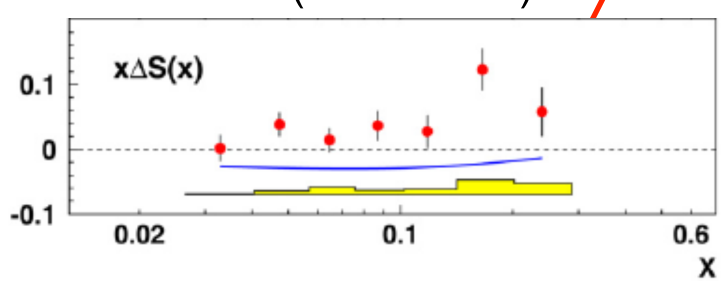
gluon longitudinal polarization ~ 0.2

quark and gluon orbital angular momentum ~?

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

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

HERMES SIDIS
~0 (0.02<x<0.6)




$\nu_\mu$NCQE+
PV e-scattering
~ -0.1

# 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

"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

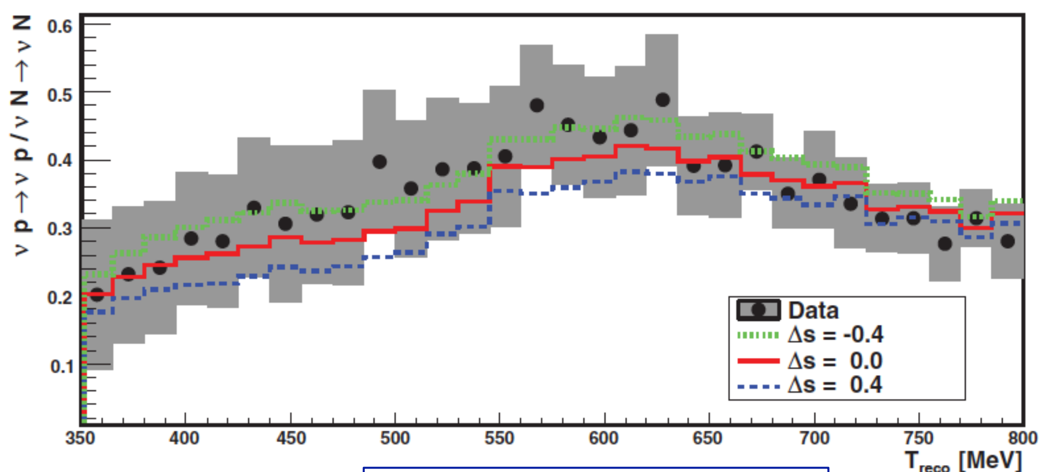
gluon longitudinal polarization ~ 0.2

quark and gluon orbital angular momentum ~?

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

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

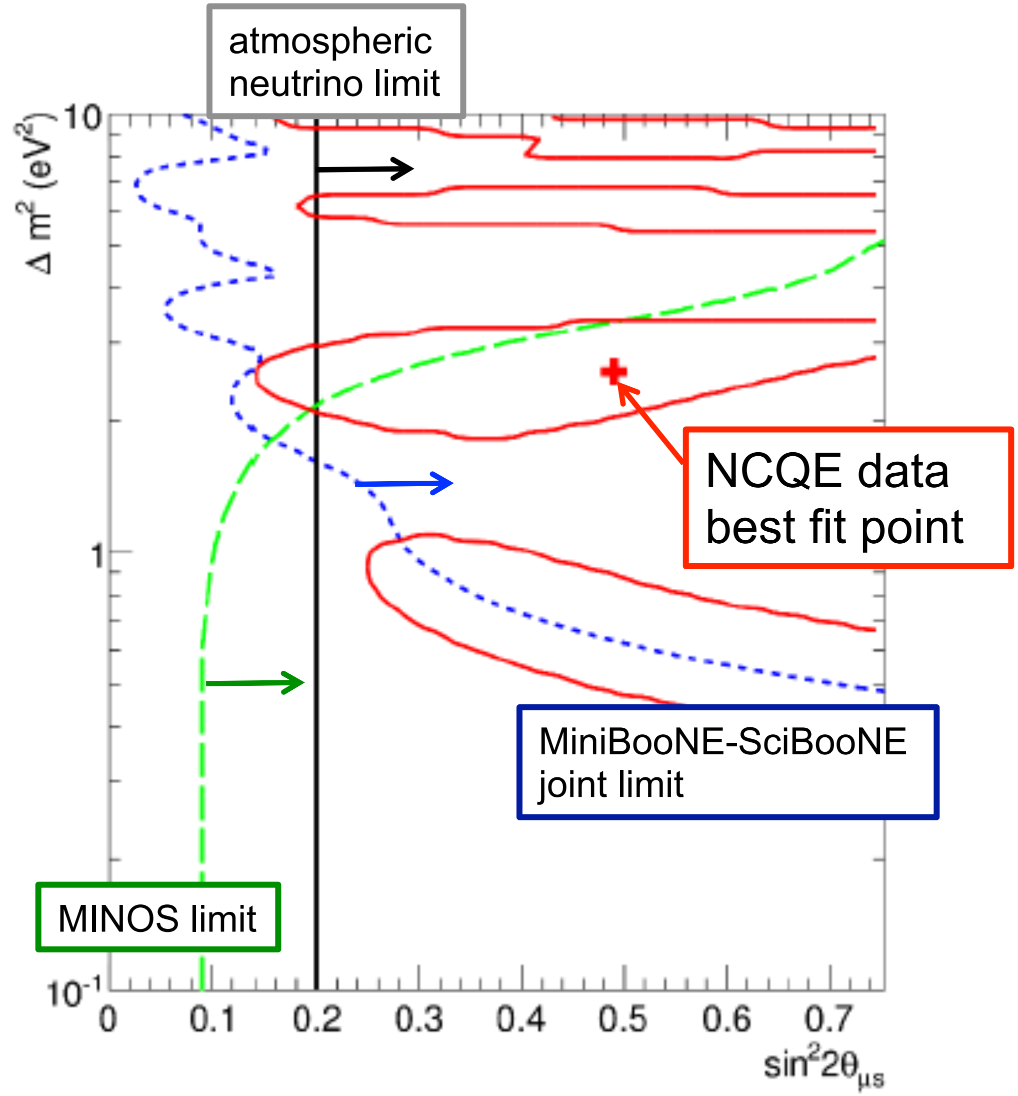
# 4. Neutral Current Quasi-Elastic (NCQE) scattering

This channel has so many topics

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

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.



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



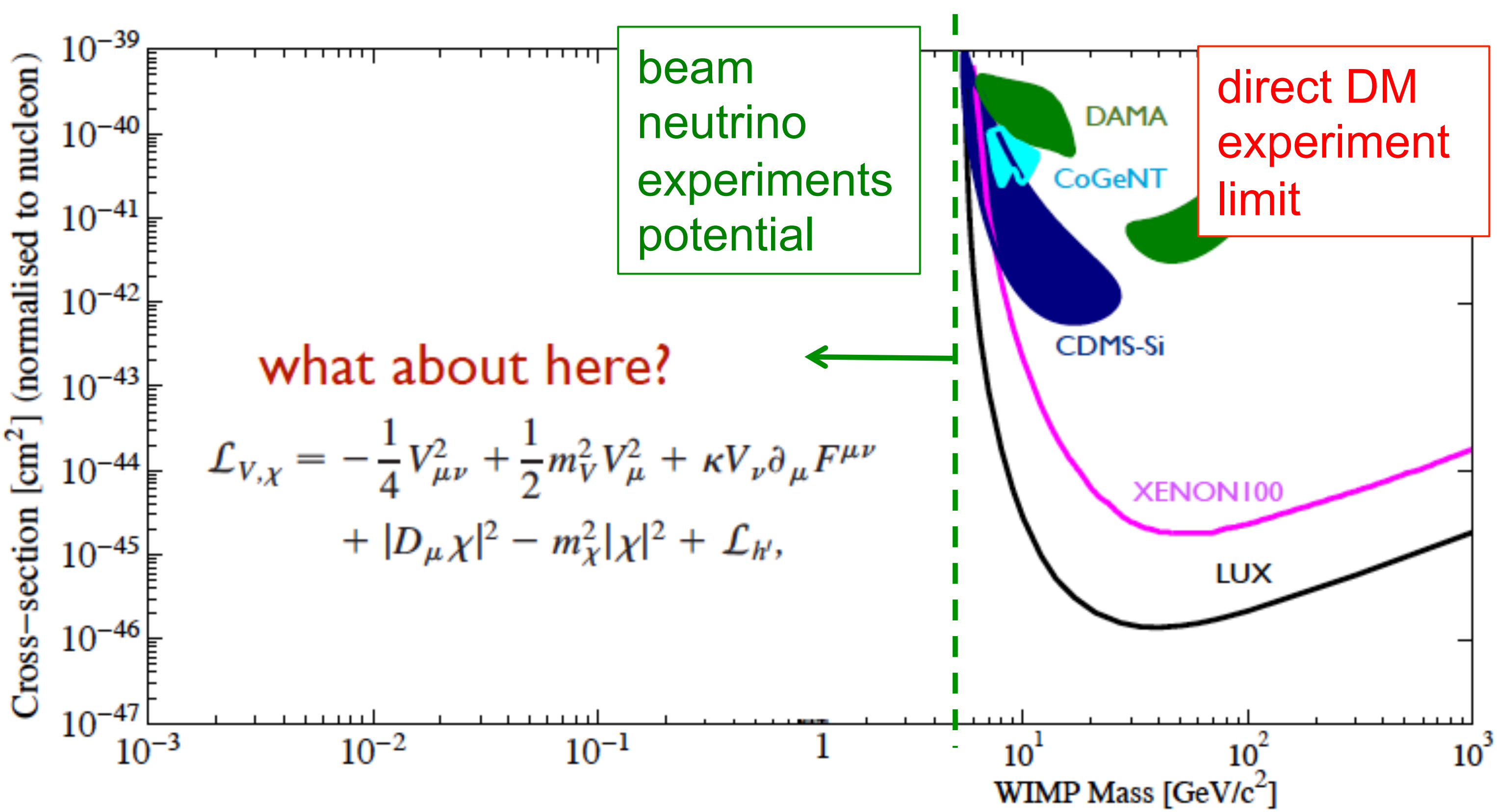
# 4. Neutral Current Quasi-Elastic (NCQE) scattering

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.



# 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

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!