Neutrino Interaction Physics

Lecture 1: Introduction of neutrino interactions
1. Overview
2. Neutrino lepton scattering
3. Neutrino DIS physics
4. Neutrino nucleus reactions

Lecture 2: Neutrino interactions for long baseline oscillation experiments
1. Overview
2. CCQE interaction
3. Baryonic resonances
4. DIS and hadronization
5. Simulation, systematics

Teppei Katori
Queen Mary University of London
Nov. 14, 2017

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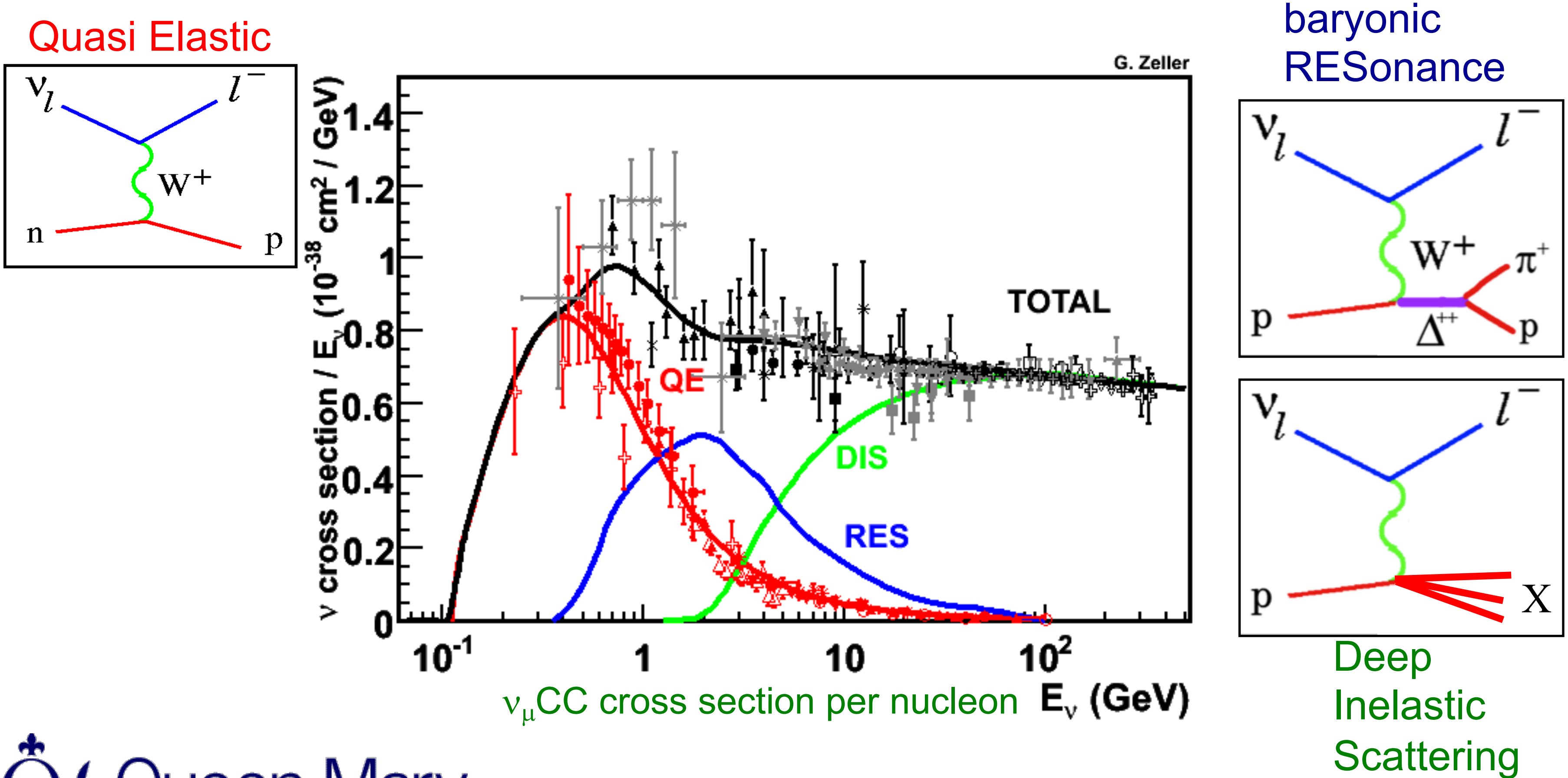
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

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

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

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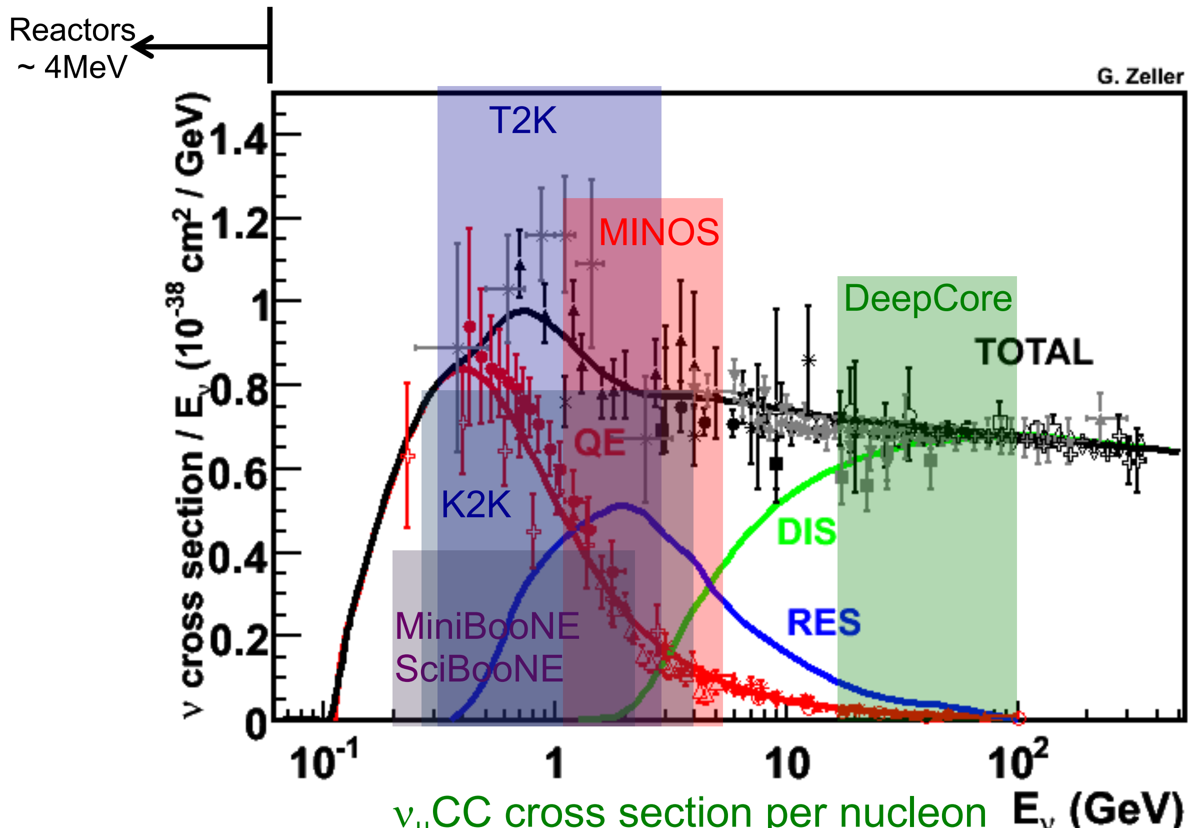

ν_μCC cross section per nucleon

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

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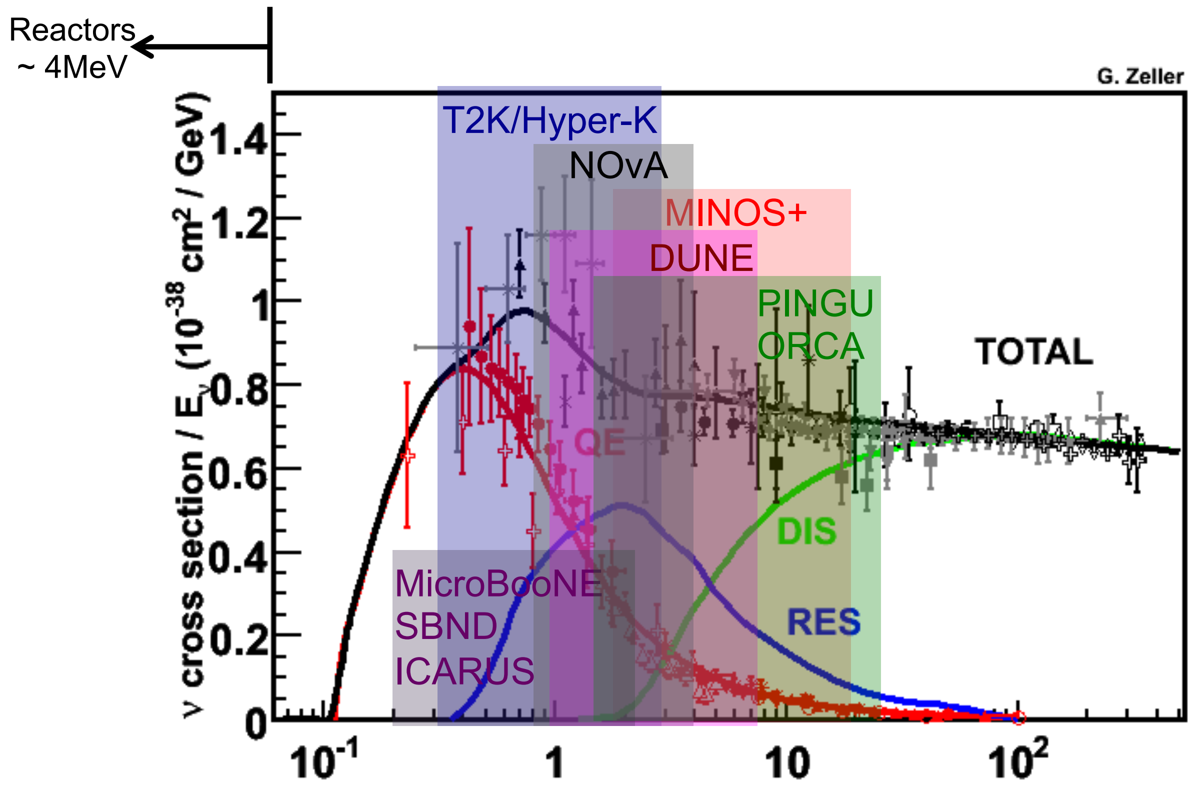

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Most of data are from muon neutrino beam, why?

- create by π-DIF (pion decay-in-flight)
- $\Phi(\nu_\mu) > \Phi(\bar{\nu}_\mu)$: more π^+ than π^- (because they are made by protons)
- d_{CP} study need electro-neutrino cross-section (ν_e appearance) and anti-neutrino cross-section (CP violation)

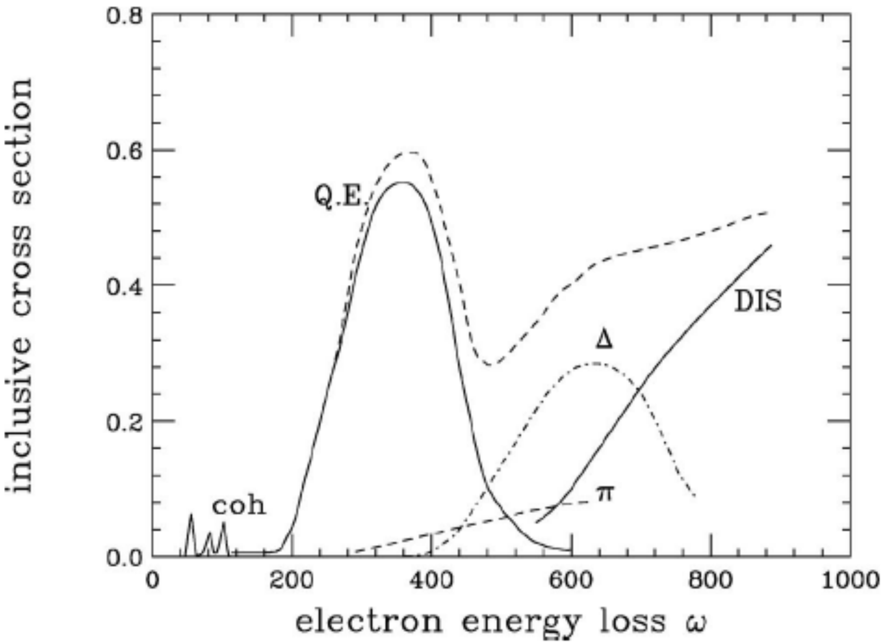
Nuclear physics sucks

- Simple extrapolation may be broken due to nuclear physics
- We are not good at nuclear physics because we are not nuclear physicists
- Nuclear physics = non-perturbative QCD (many models, no theory)
- Particle physics is developed by avoiding nuclear physics…

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

Benhar,Day,Sick,Rev.Mod.Phys.80(2008)189
Nakamura et a;,Rep.Prog.Phys.80(2017)056301

1. Neutrino cross-section overview

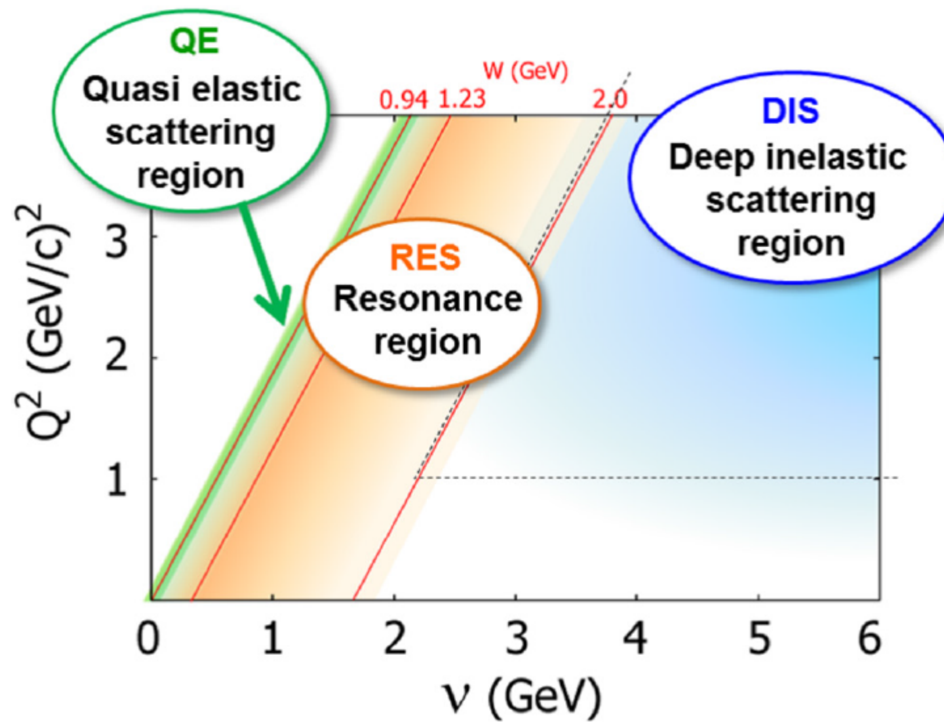


Nuclear physics

Interactions are classified in q (3-momnetum transfer) and ω (energy transfer)

Particle physics (neutrino physics)

Interactions are classified in Q^2 (4-momentum transfer) and ν (energy transfer) or W^2 (invariant mass)



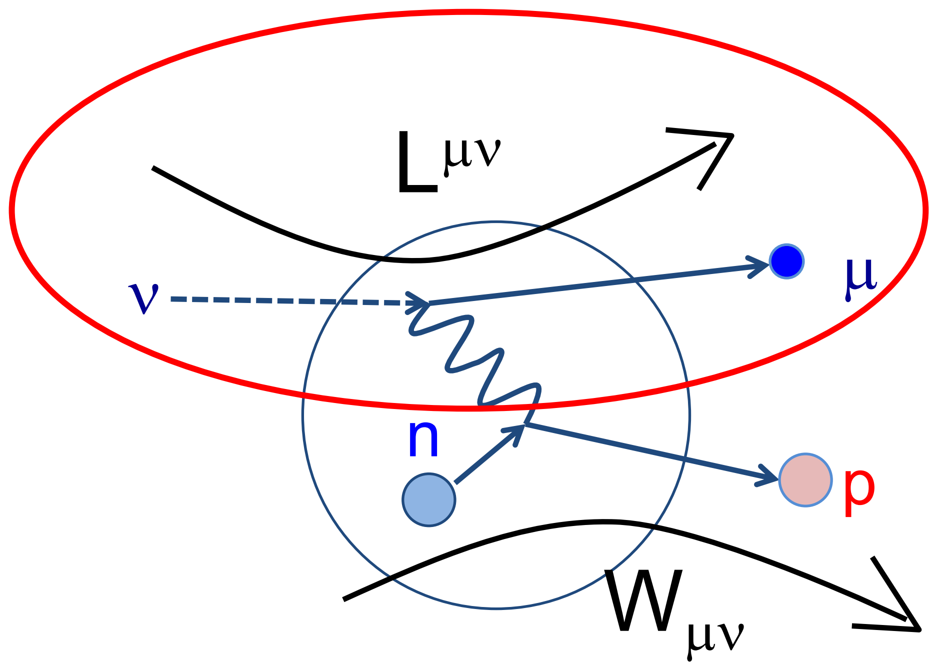
1. Neutrino cross-section formula

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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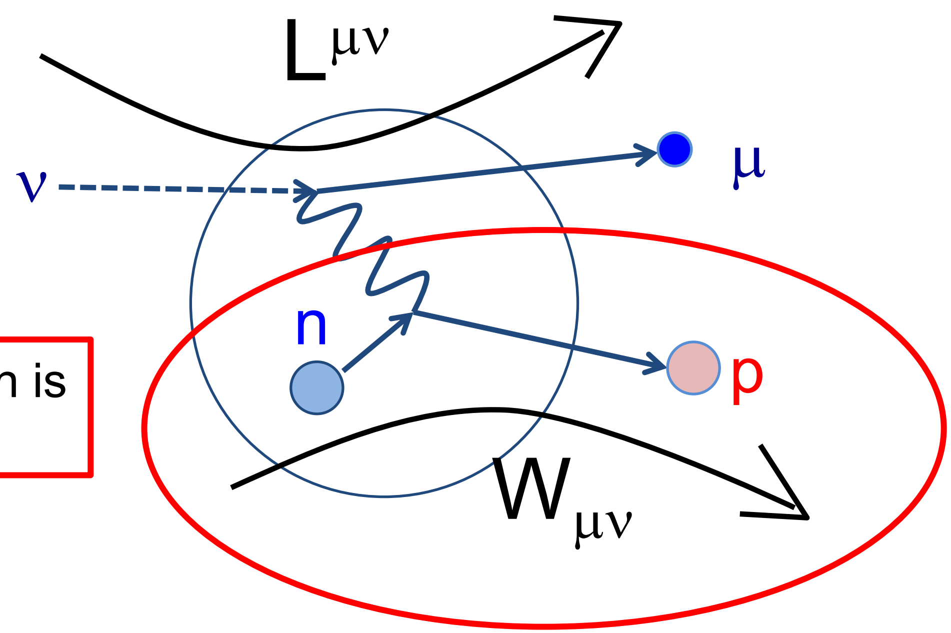
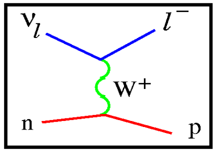


All complication of neutrino cross-section is how to model the hadronic tensor part

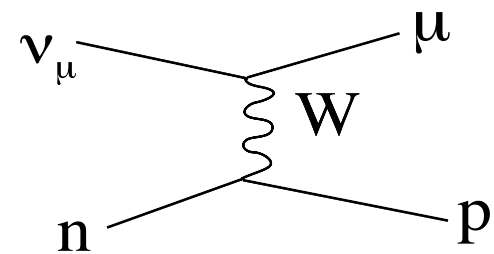
2. Charged Current Quasi-Elastic scattering (CCQE)

Quasi Elastic



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

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



$d\sigma \sim L_{\mu\nu} T^{\mu\nu}$

$L_{\mu\nu} \sim J_\mu J_\nu$: Lepton tensor

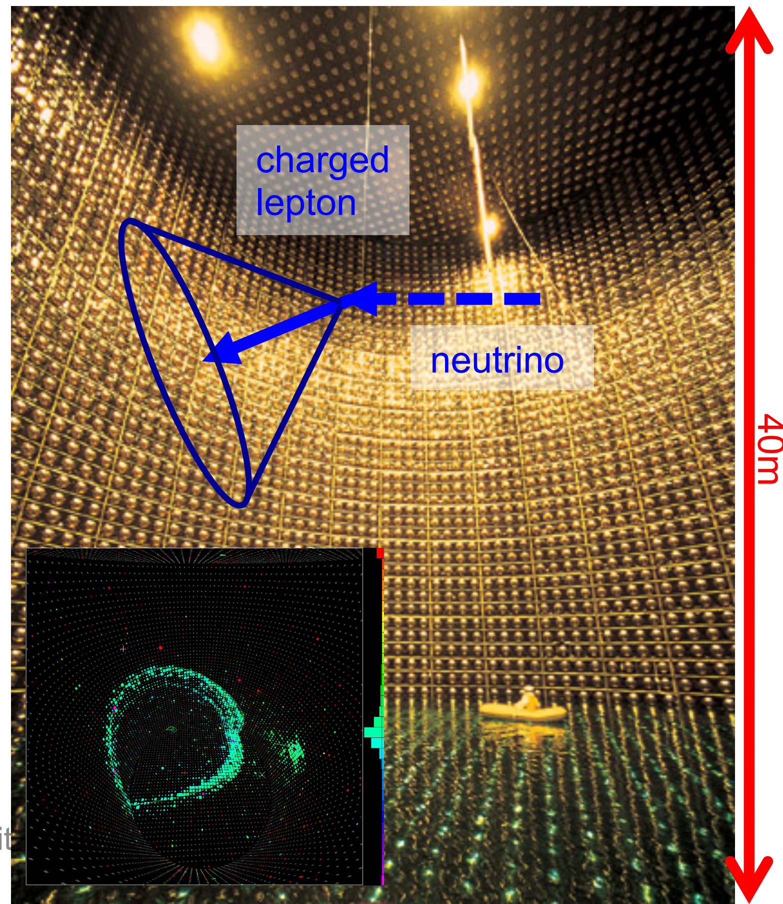
$W_{\mu\nu} = \int f(\vec{k}, \vec{q}, \omega) T_{\mu\nu} dE$: hadronic tensor

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

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

Form factors can be parameterize with dipole form

$$F(Q^2) = \frac{g}{\left(1 + \frac{Q^2}{M^2}\right)^2}$$



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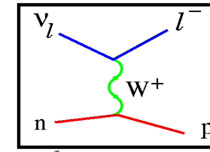
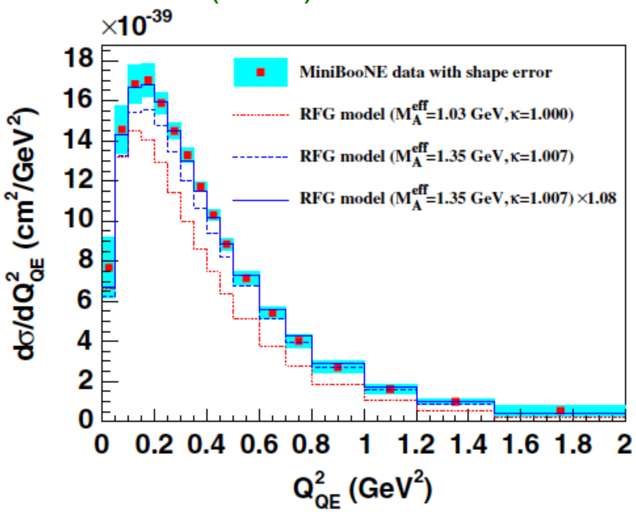


2. Form factors

MiniBooNE CCQE cross section
PRD81(2010)092005



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ρ(r)	$\lvert F(q^2) \rvert$	Example
pointlike	constant	Electron
exponential	dipole	Proton
gauss	gauss	^{6}Li
homogeneous sphere	oscillating	–
sphere with a diffuse surface	oscillating	^{40}Ca

r →　　$\lvert q \rvert$ →

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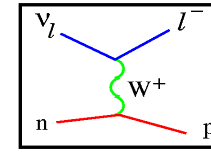
Quasi Elastic



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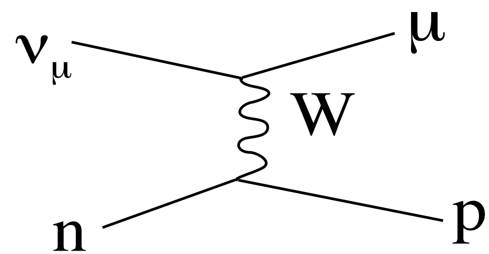
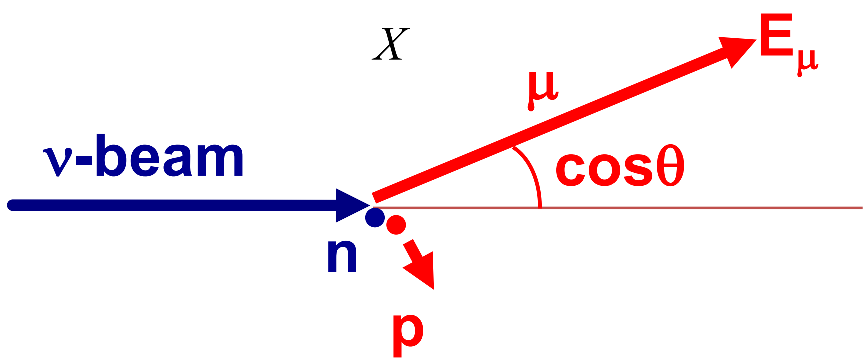
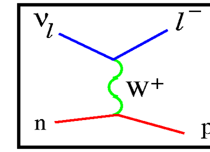


Neutrino energy is reconstructed from the observed lepton kinematics



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

Quasi Elastic



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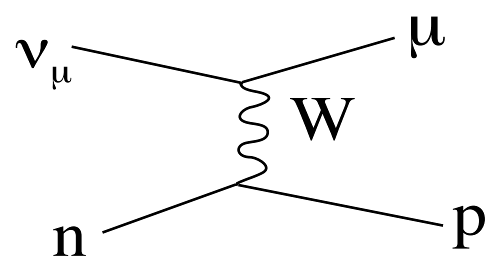

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"QE assumption"

1. assuming neutron at rest
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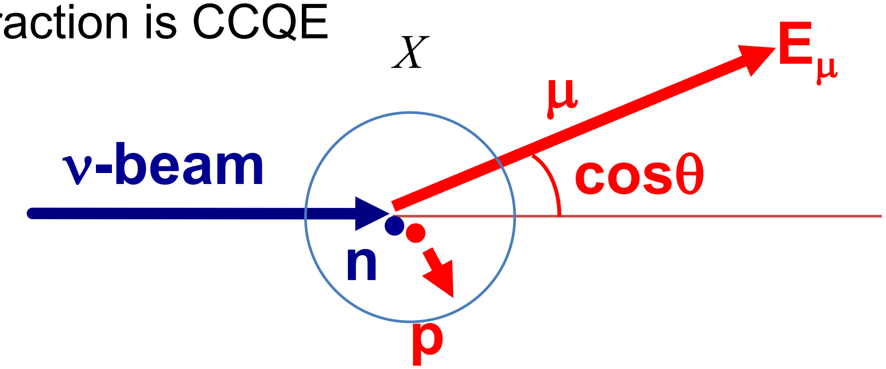

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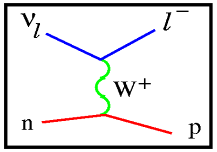
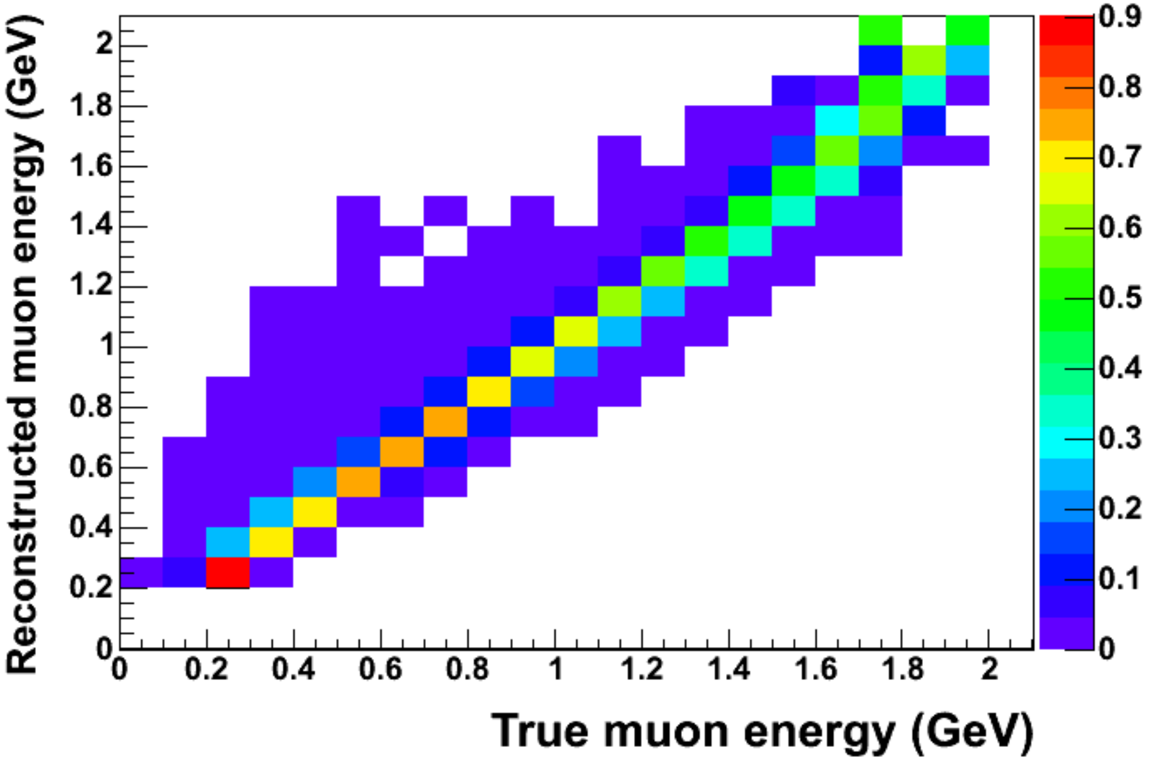
Neutrinos hit nucleons inside of nucleus, and the energy reconstruction is possible only with QE assumption



2. Basic nuclear physics in nucleus

Fermi motion
- Nucleons move with ~200 MeV/c momentum in the nucleus.
  → This smear neutrino energy reconstruction.



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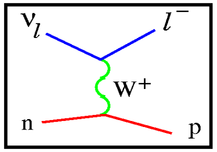

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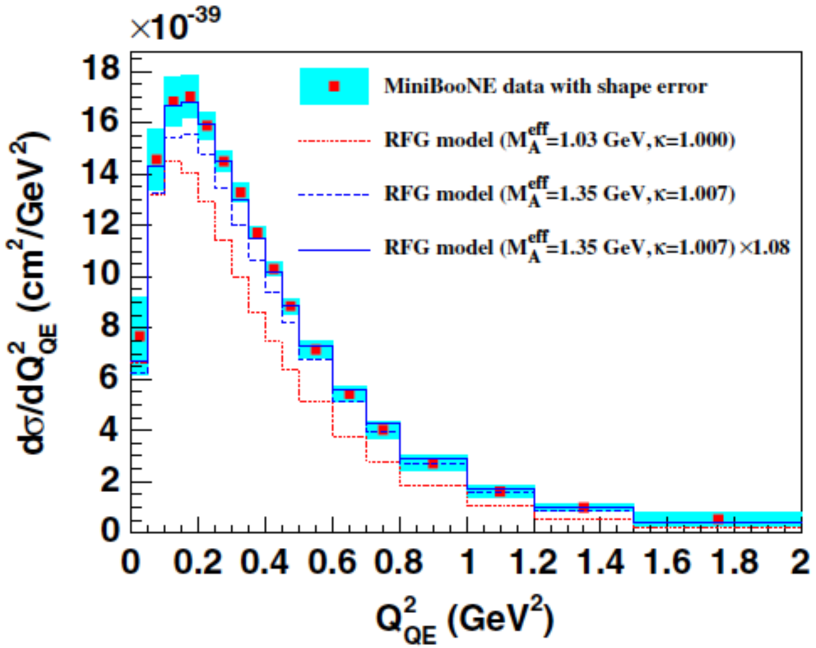
Pauli blocking

- Nucleon Fermi sea is occupied.
  → Low momentum transfer transition (<200 MeV/c) is forbidden.



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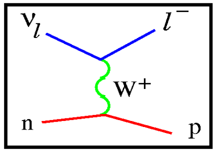

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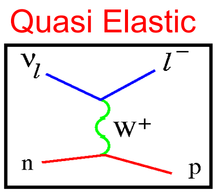
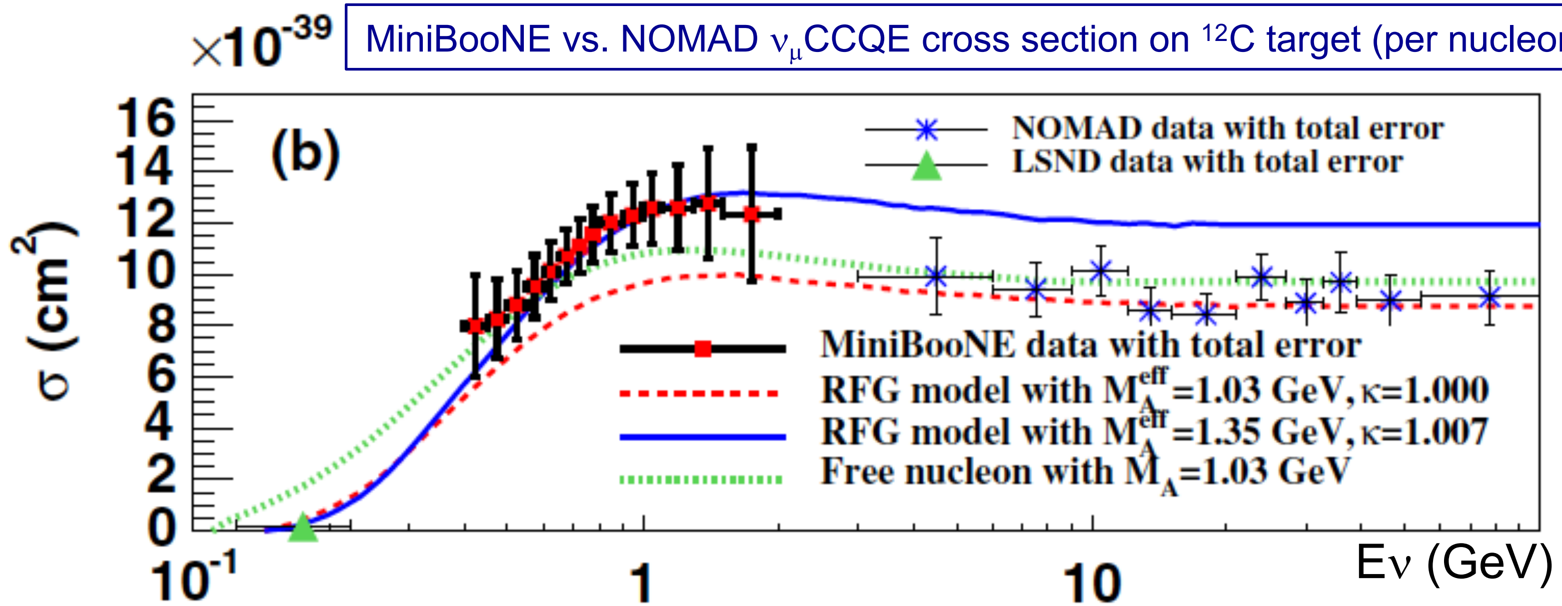
Even if you have a perfect measurement of CCQE, measured neutrino energy doesn't represent the true neutrino energy due to Fermi motion.

2. CCQE puzzle



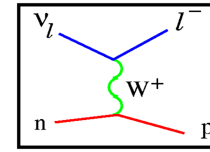
CCQE interaction on nuclear targets are precisely measured by electron scattering
- Lepton universality → precise prediction for neutrino CCQE cross-section

Simulation disagree with many modern accelerator based neutrino experiment data (K2K, MiniBooNE, MINOS, T2K, etc), neither shape (low Q^2 and high Q^2) nor normalization (CCQE puzzle).



Martini et al,PRC80(2009)065501

Quasi Elastic



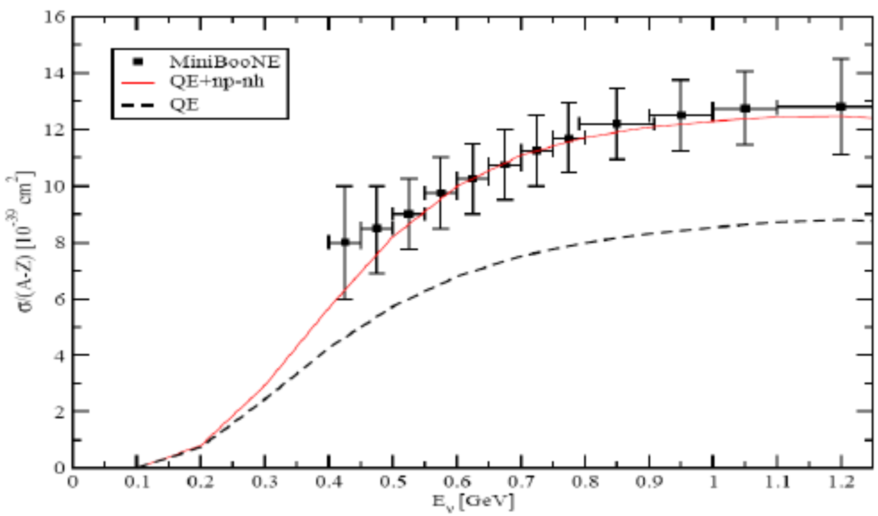
2. CCQE puzzle

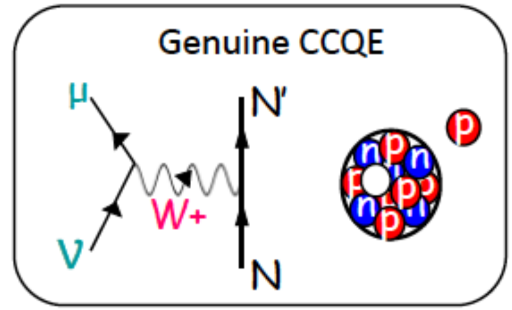
Nuclear correlation

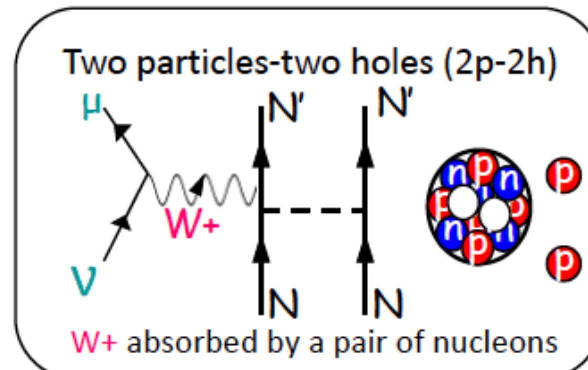
- two particle – two hole (2p-2h) effect to enhance cross section
- long range correlation to distort shape (suppress low Q^2)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







All neutrino baryonic resonance processes have ~30% errors
CCQE process also have ~30% error

Martini et al,PRC80(2009)065501;PRC90(2014)025501
T2K, PRD87(2013)092003

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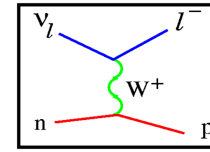

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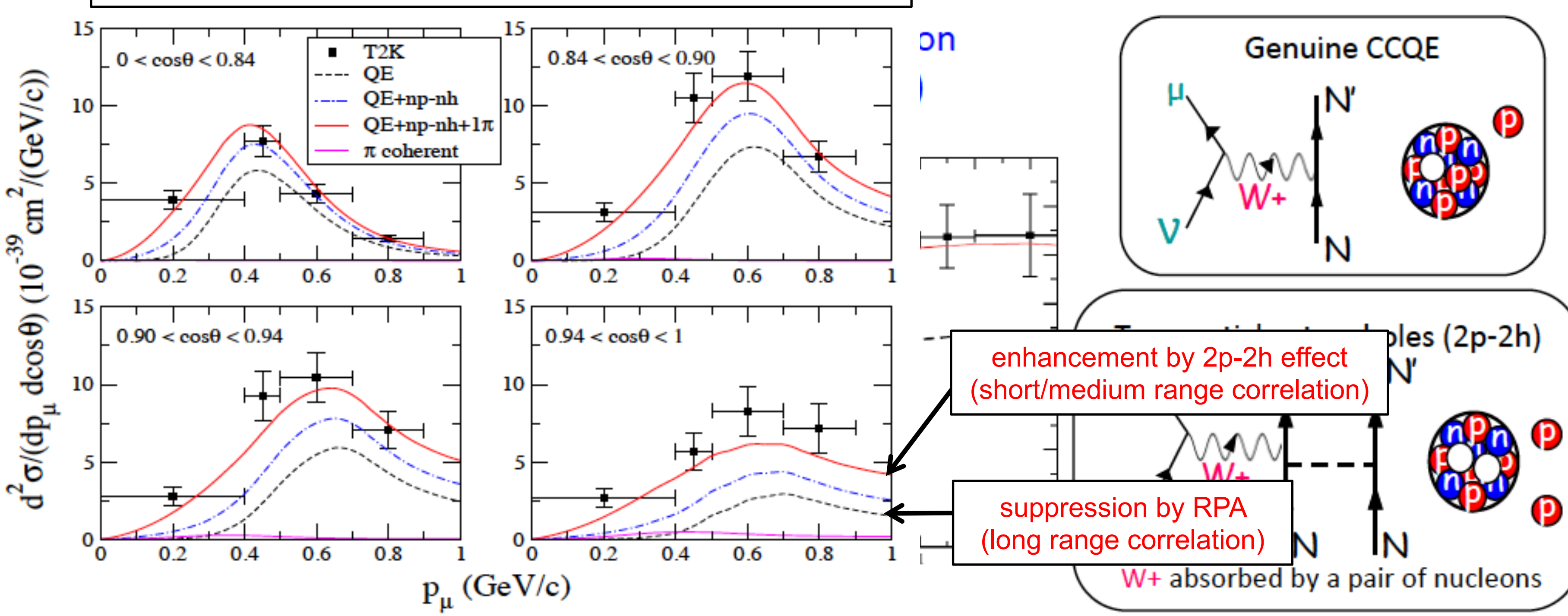
Martini model vs. T2K CC double differential cross-section data



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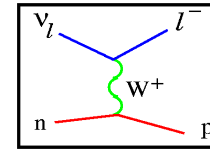

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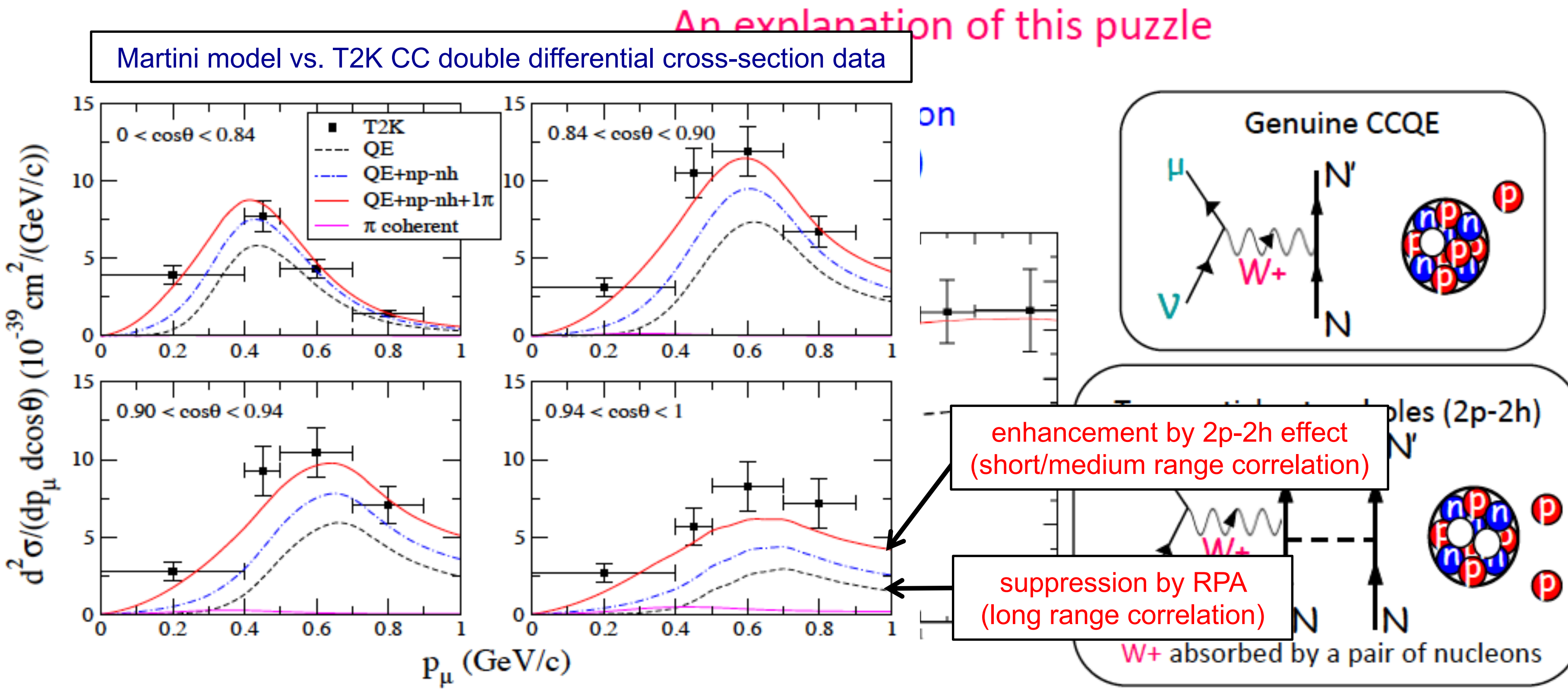

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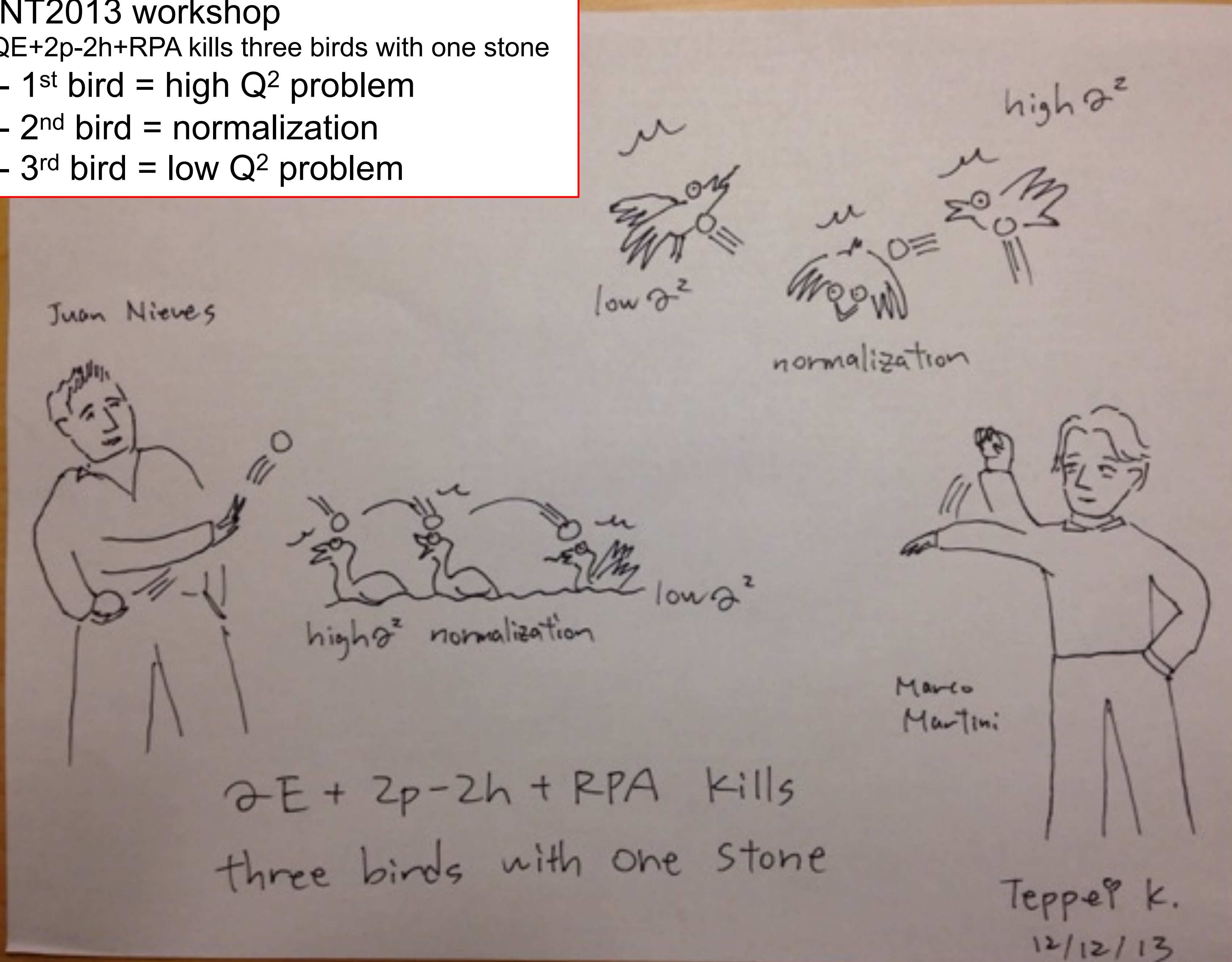
INT2013 workshop

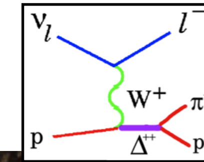
QE+2p-2h+RPA kills three birds with one stone

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

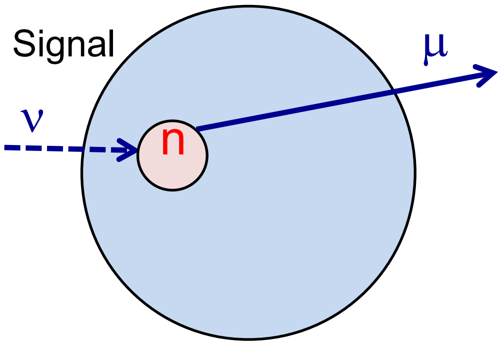


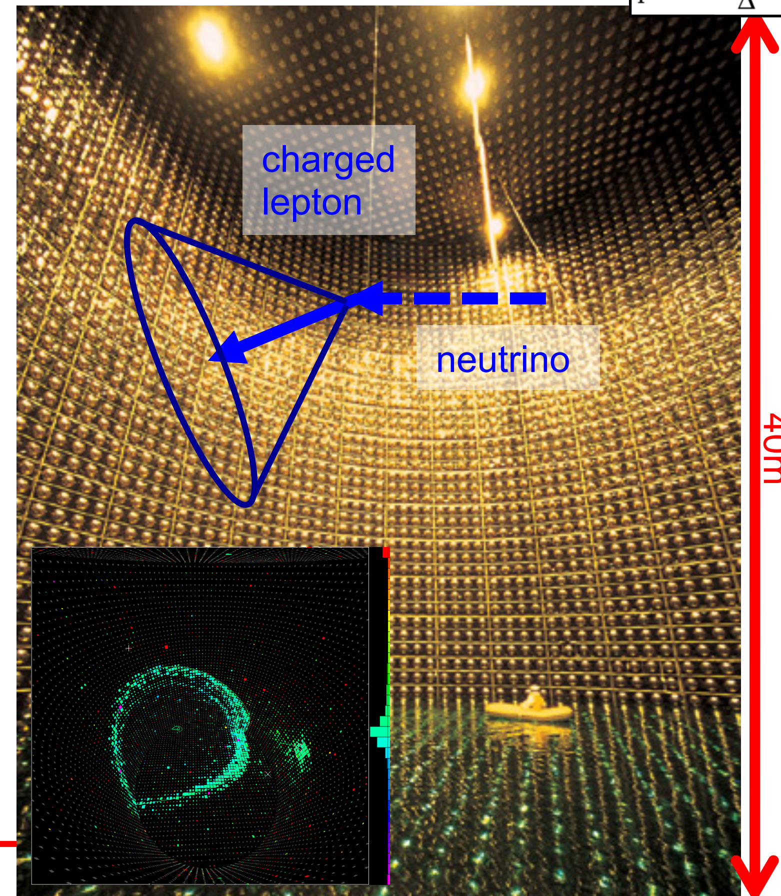
3. non-QE background (resonance pion production)

RESonance



non-QE background → shift spectrum





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Typical neutrino detector
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- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

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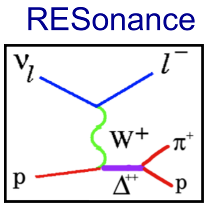

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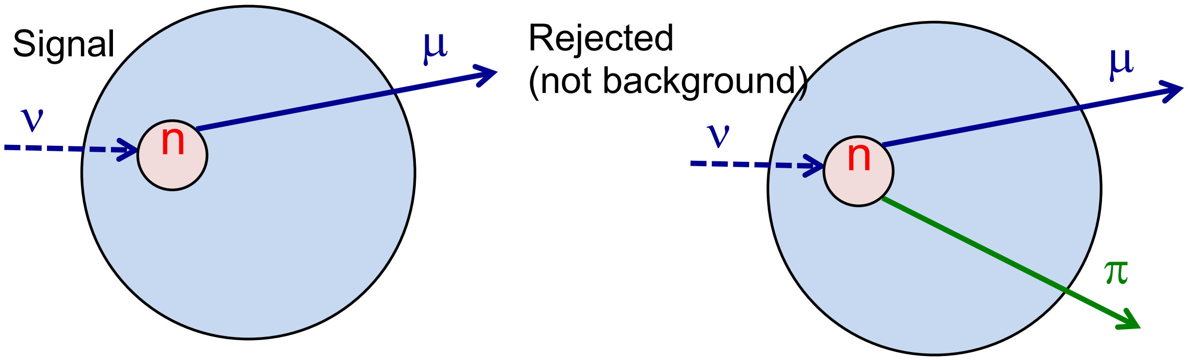

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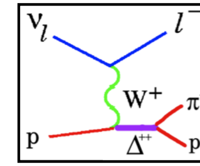

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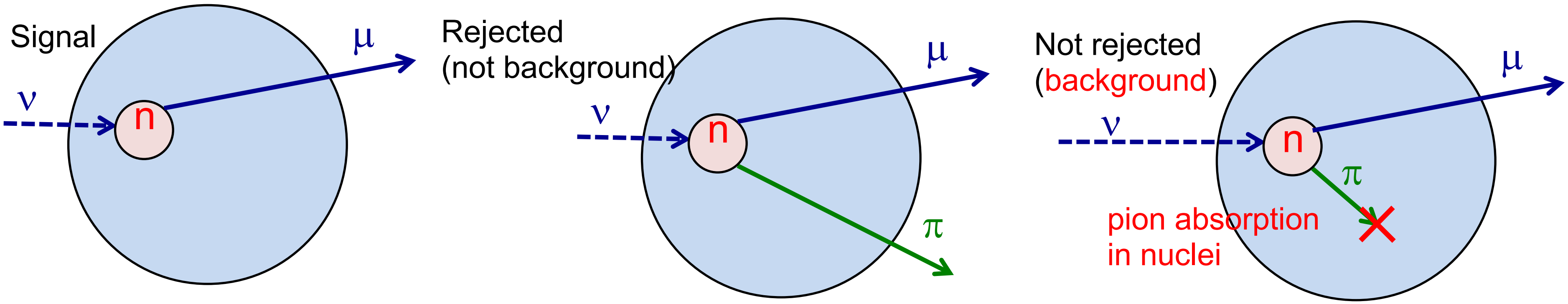

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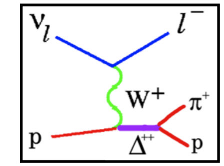

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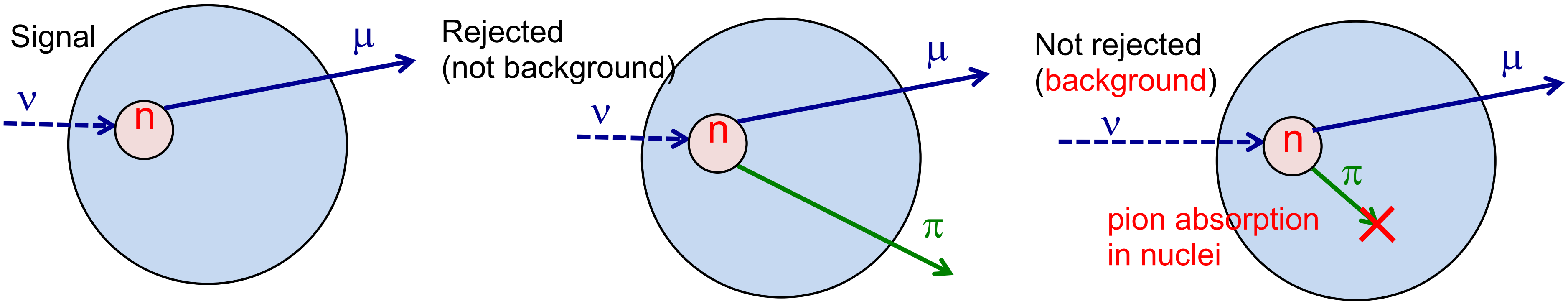
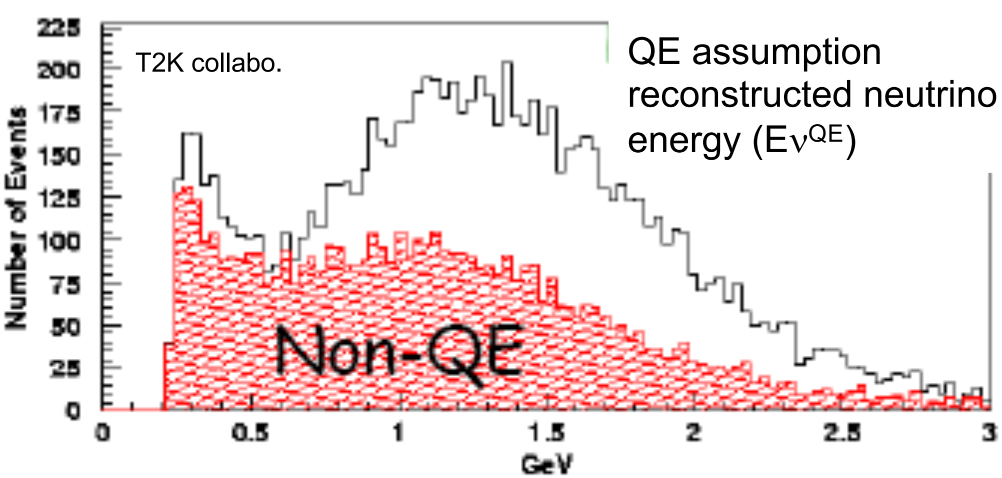
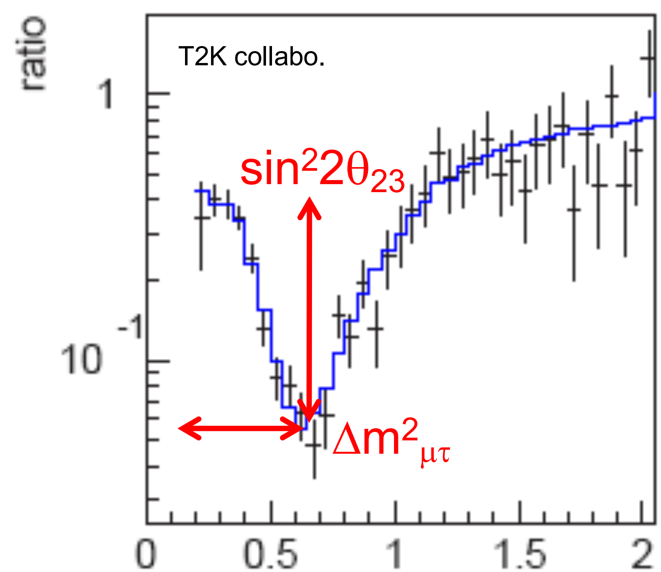
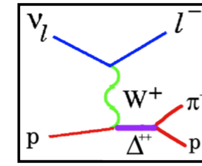






Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

RESonance



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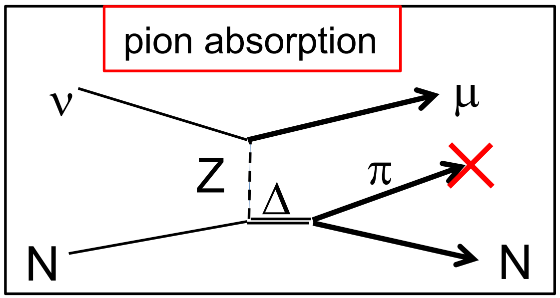
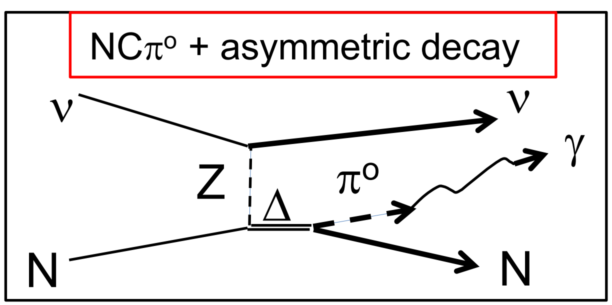
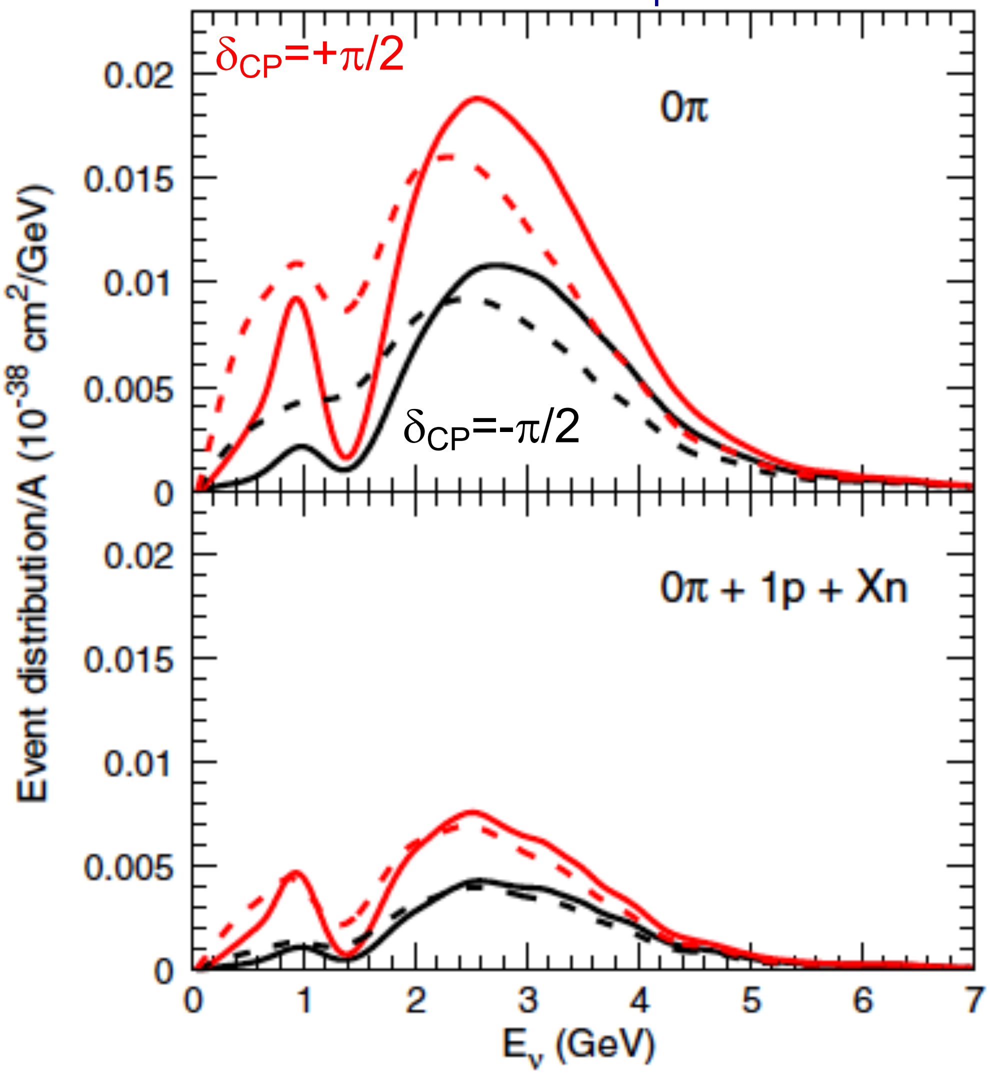
Pion production for ν_μ disappearance search
- Source of mis-reconstruction of neutrino energy



Neutral pion production in ν_e appearance search
- Source of misID of electron



DUNE true vs. reconstructed Eν spectrum



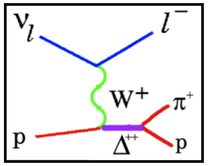
Queen Mary University of London

Understanding of neutrino baryonic resonance meson production is important for oscillation experiments

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

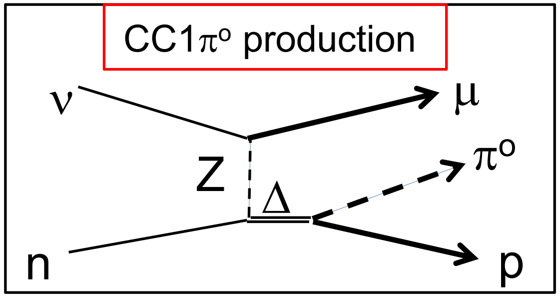
3. Neutrino Baryonic resonance data

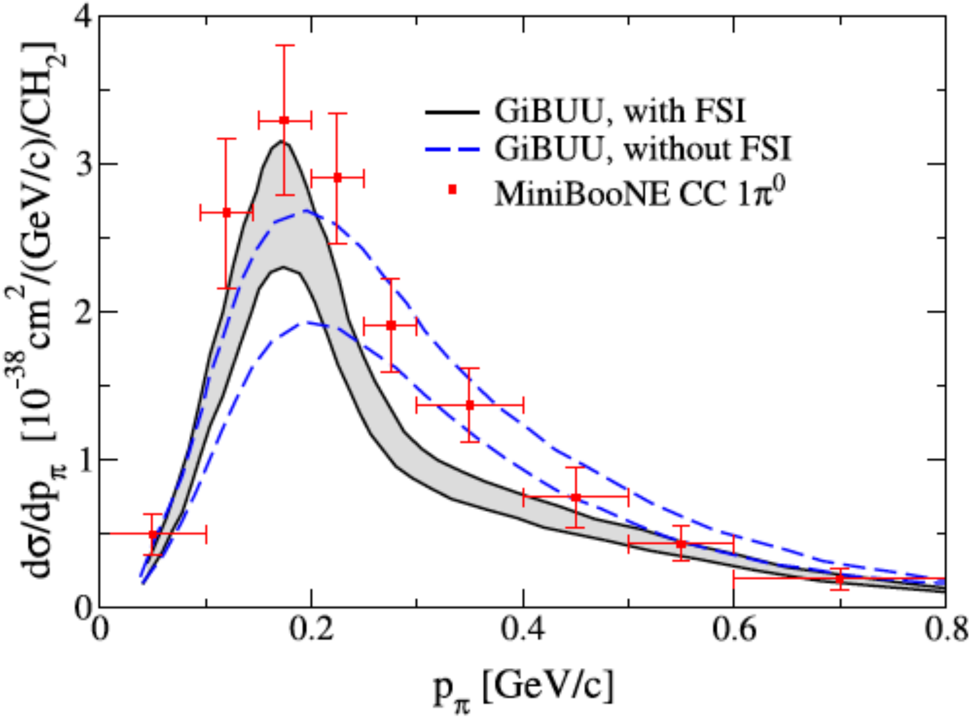
RESonance



Final state interaction

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



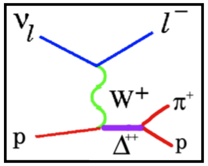


MiniBooNE π^o momentum vs simulation

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

3. Neutrino Baryonic resonance data

RESonance



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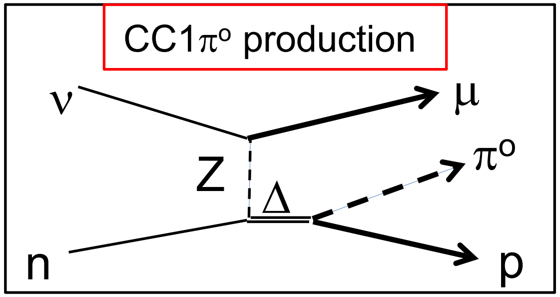
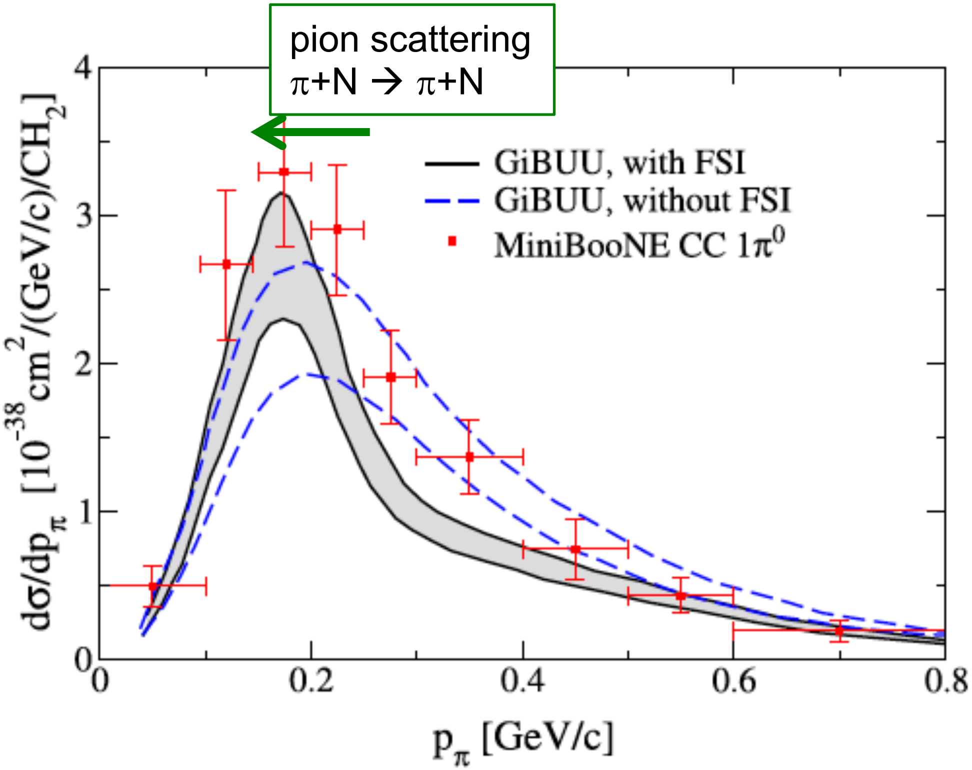
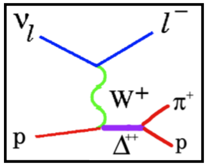




MiniBooNE πº momentum vs simulation

3. Neutrino Baryonic resonance data



Final state interaction

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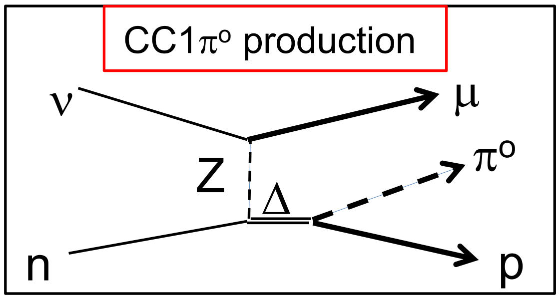
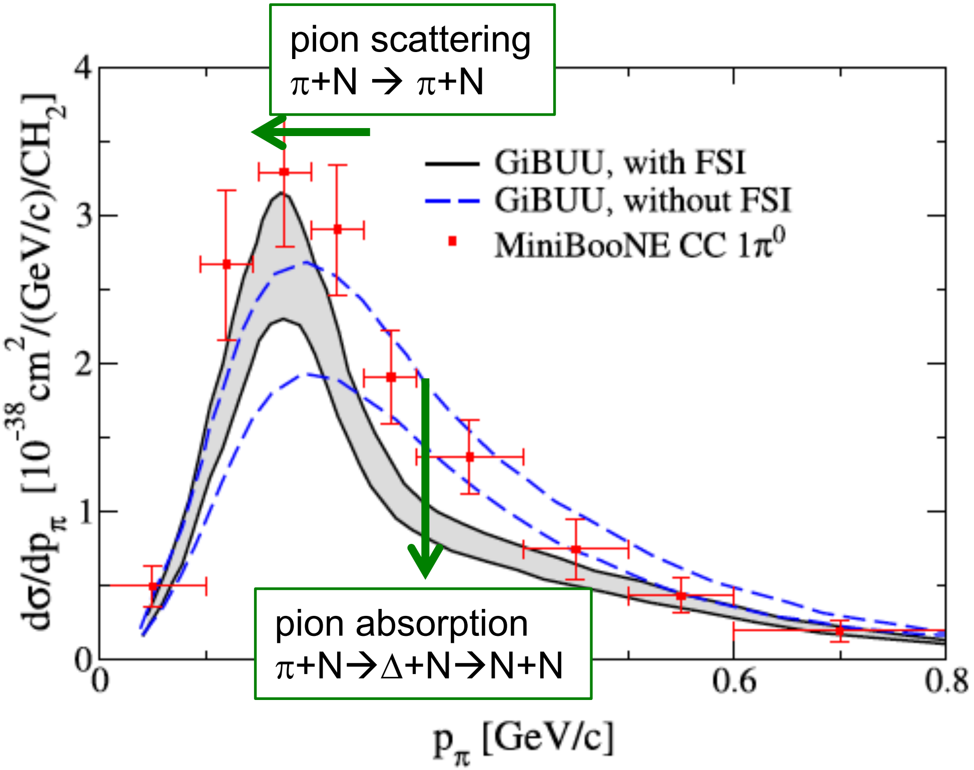
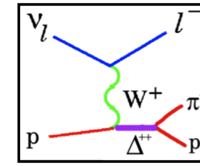




MiniBooNE πº momentum vs simulation

3. Neutrino Baryonic resonance data

RESonance



Final state interaction

- Cascade model as a standard of the community
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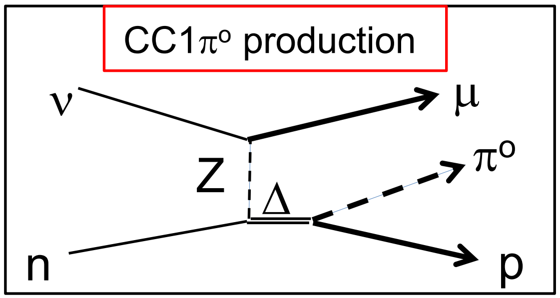
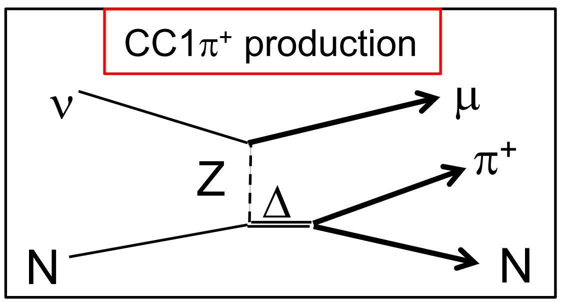
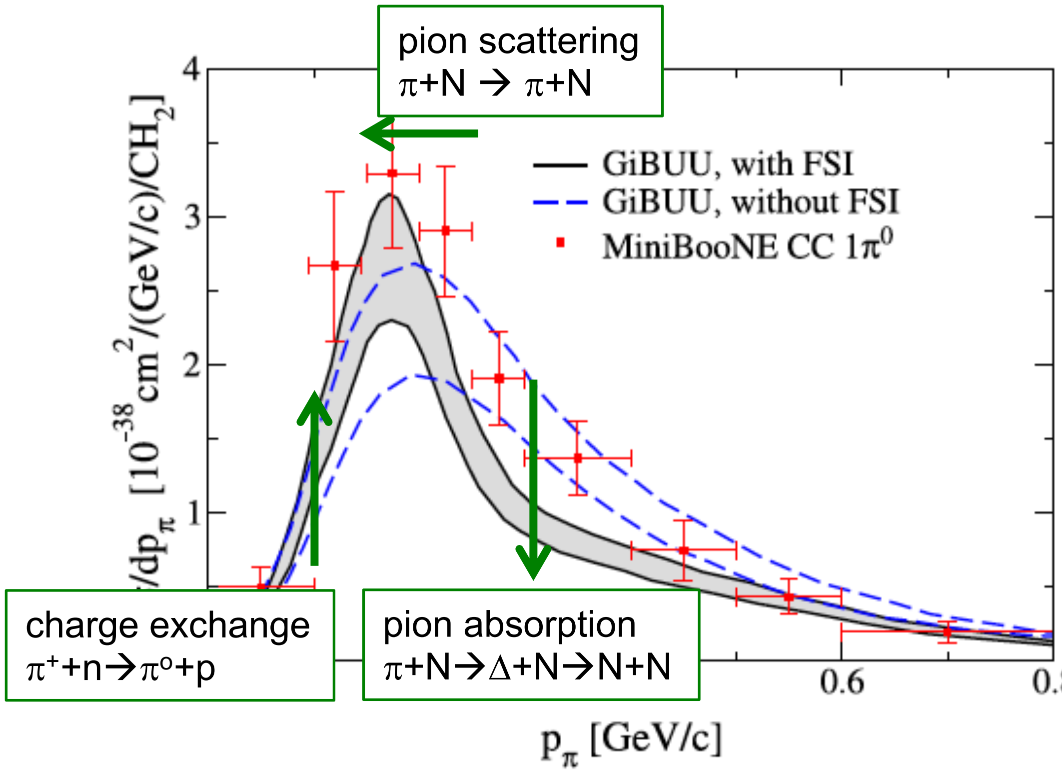




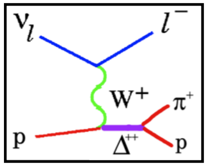


MiniBooNE π° momentum vs simulation

All neutrino baryonic resonance processes have ~30% errors

MicroBooNE,JINST12(2017)P02017

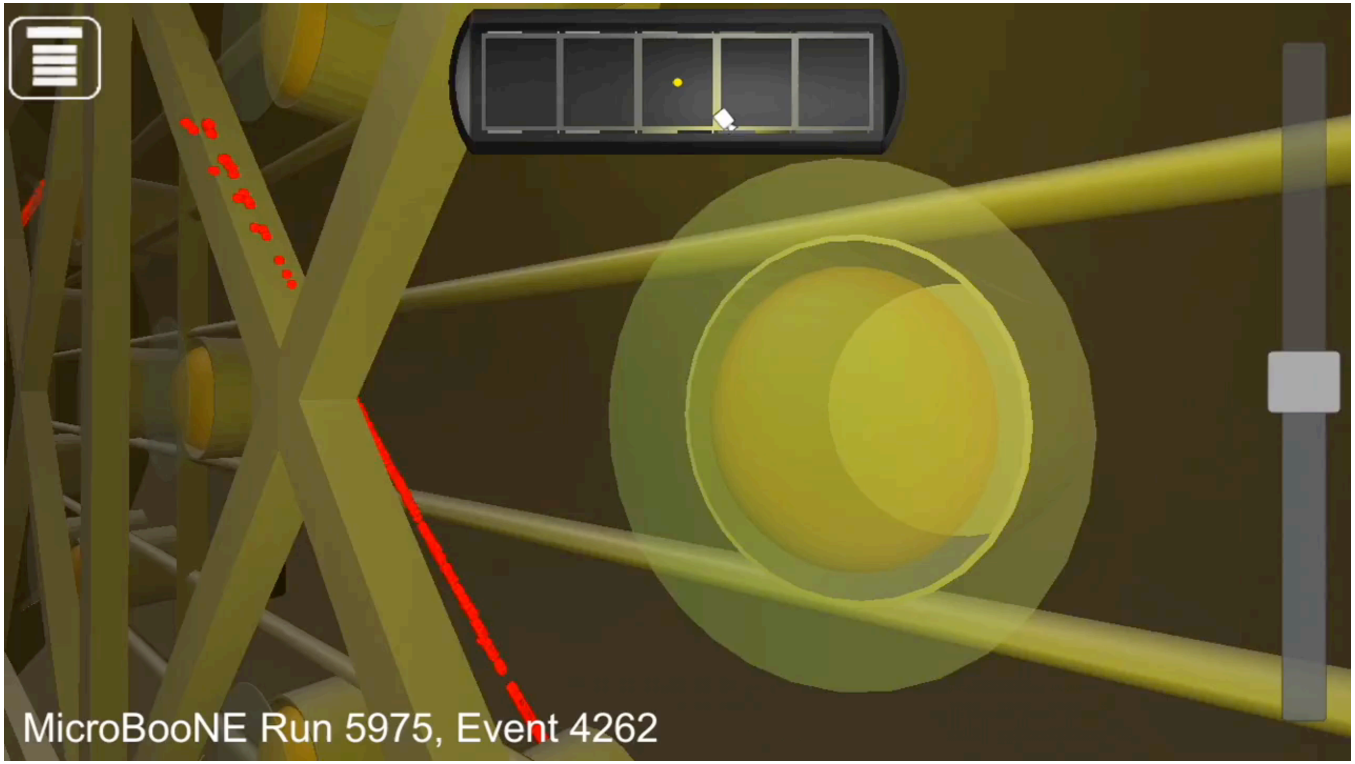
RESonance



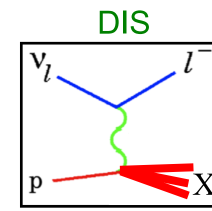
3. LArTPC

Exclusive neutrino interaction measurements?

- Neutrino energy can be reconstructed using total hadron energies
- Inefficiencies of hadron measurements (neutrons) cause energy mis-reconstruction
- Fermilab SBN programs will provide a lot of new information

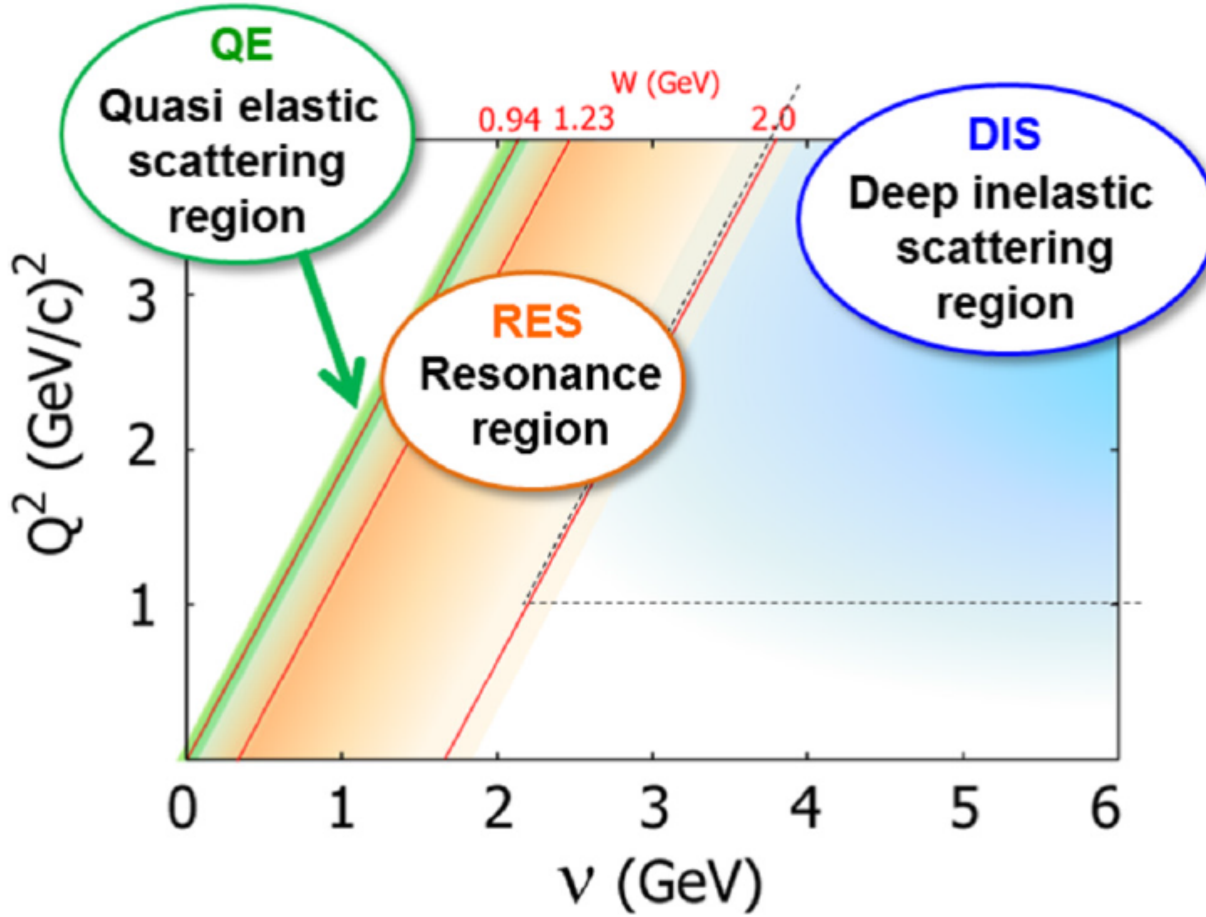


VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- smart phone app to take a look MicroBooNE data



4. Shallow Inelastic Scattering (SIS)

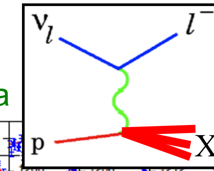
Cross section
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS



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

4. Shallow Inelastic Scattering (SIS)

DIS



DCC model vs. electro-pionproduction data

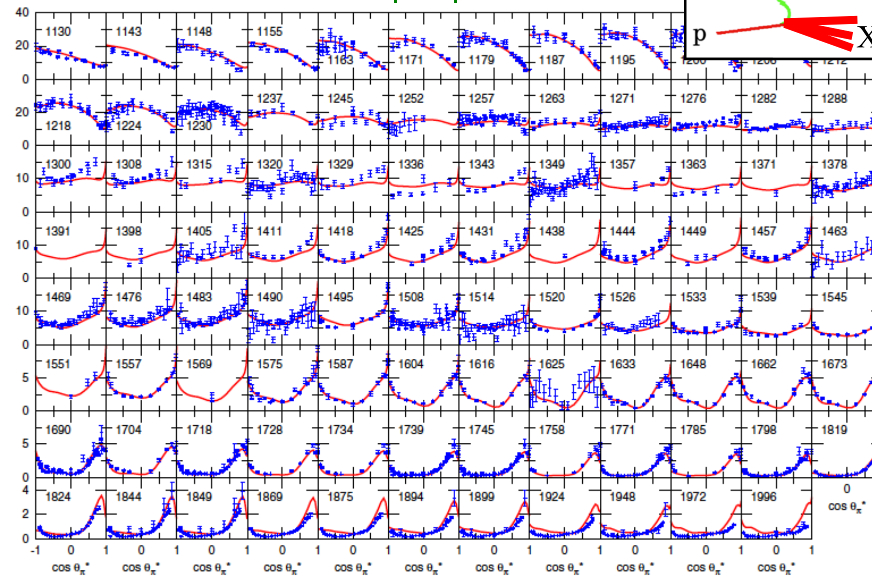
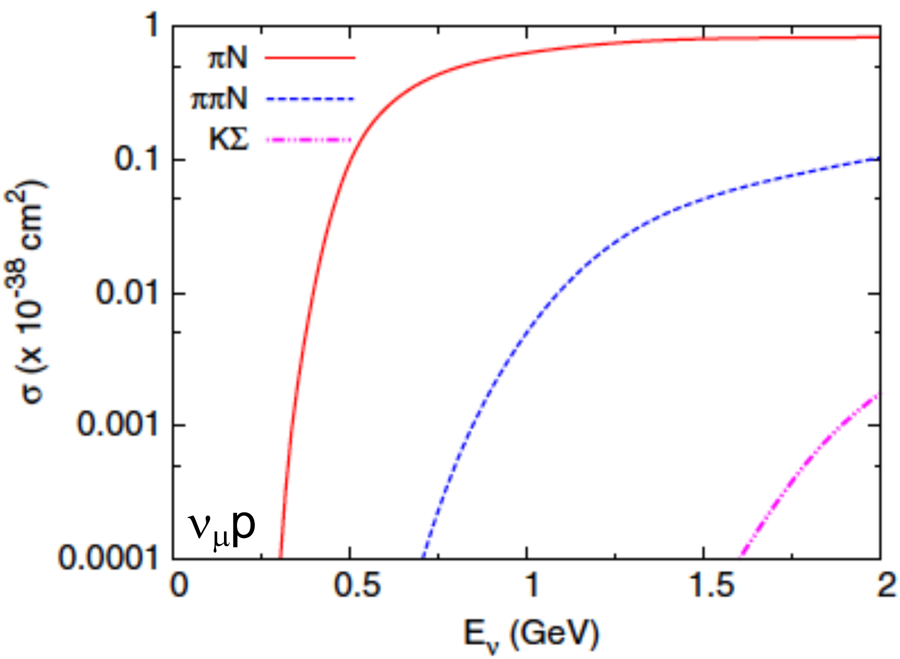
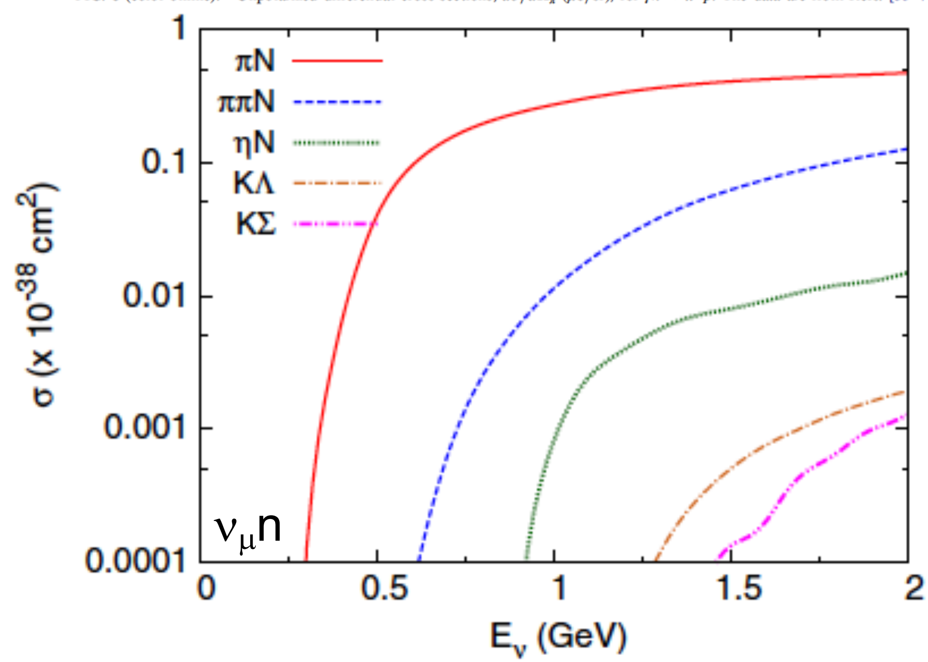


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

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, $\pi\pi$N, etc)
- 2 pion productions ~10% at 2 GeV



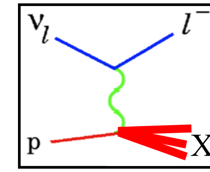


Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11

4. Shallow Inelastic Scattering (SIS)

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

DIS



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

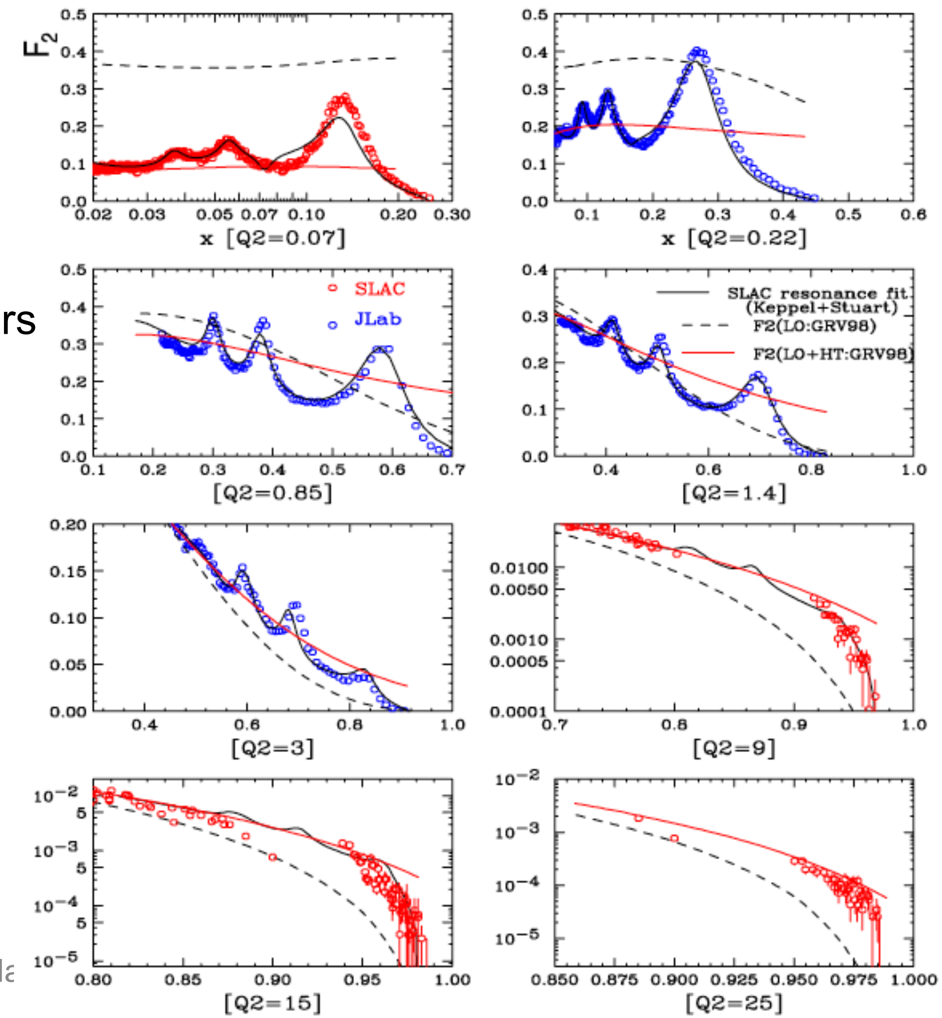
GRV98 LO PDF + Bodek-Yang correction
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

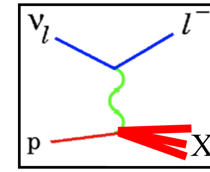
Proton F2 function GRV98-BY correction vs. data



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

4. Shallow Inelastic Scattering (SIS)

DIS



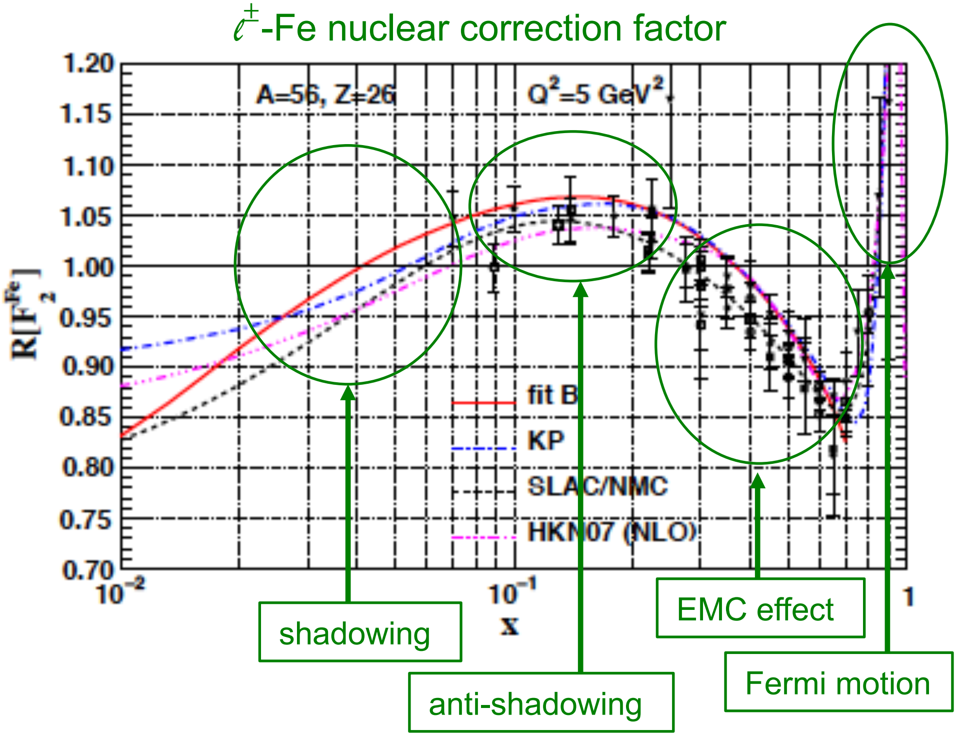
Cross section

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

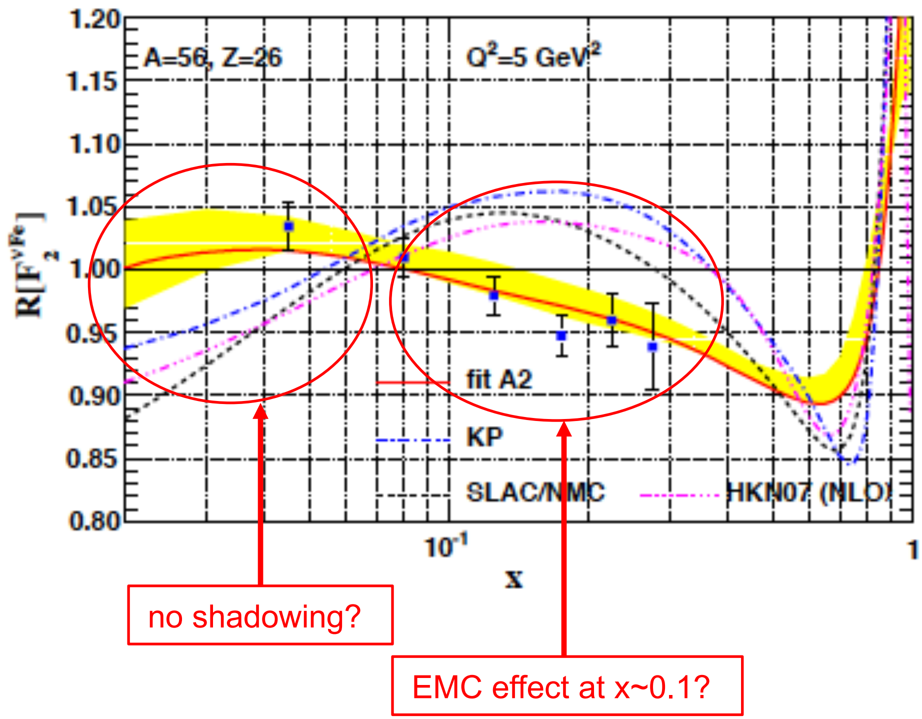
Nuclear PDF

- 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



ν-Fe nuclear correction factor



Conclusion

Neutrinos interact by weak force

ν-l scattering : test of weak theory

- Neutrino-electron scattering
- Muon decay

ν-q scattering : test of weak theory, test of quark model

- DIS cross sections
- Di-muon production
- Paschos-Wolfenstein ratio

ν-A scattering :

- Neutrino nuclear capture by Cl and Ga, important for solar neutrinos
- Neutrino coherent scattering, important for supernova
(first observation, Aug. 2017)

Conclusion

Neutrinos interact by weak force

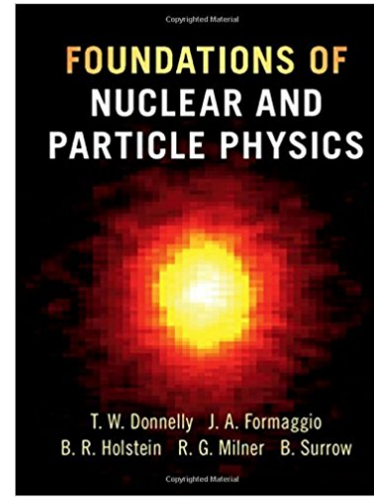
ν-N scattering : important reactions for long baseline neutrino oscillation experiment
(T2K, NOvA, DUNE, Hyper-Kamiokande)

CCQE: charged-current quasi-elastic, around 1 GeV
RES: baryonic resonance, around 2 GeV
DIS: deep inelastic scattering, 3 GeV to higher

Nuclear physics sucks
- Fermi motion: nucleon motion smears kinematic reconstruction
- Pauli blocking: It limits low momentum transfer reaction
- Baryonic resonance: if you fail to tag outgoing mesons, get incorrect neutrino energy
- Nucleon correlation: Physics between ν-N and ν-A interaction
- Quark-Hadron duality: Physics between ν-q and ν-N interaction
- Nuclear dependent PDF: quarks inside of nucleons depend on nucleus

Currently, ~30% error is acceptable for many processes… (future experiments will be systematically limited)

References

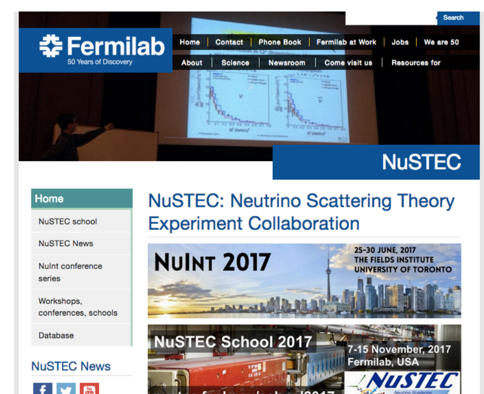


Foundation of Nuclear and Particle Physics (2017)
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- one and only one textbook on this subject
- buy if your PhD thesis topic is about neutrino cross section

“From eV to EeV: Neutrino cross sections across energy scales”
- Authors: Formaggio and Zeller (MicroBooNE spokesperson)
- Rev.Mod.Phys.84(2012)1307, arXiv:1305.7513
- very good summary of neutrino cross sections

“Neutrino-Nucleus Cross Sections for Oscillation Experiments”
- Authors: Katori (me) and Martini (Martini model)
- my paper, a review both theoretical and experimental views
- cite and give me citation number!

“NuSTEC News”
- http://nustec.fnal.gov/
- subscribe mailing list, “like” facebook page, use#nuxsec



1. 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]