# BREAKTHROUGH PRIZE

# "Year of Neutrinos"

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

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

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## The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

**Takaaki Kajita**

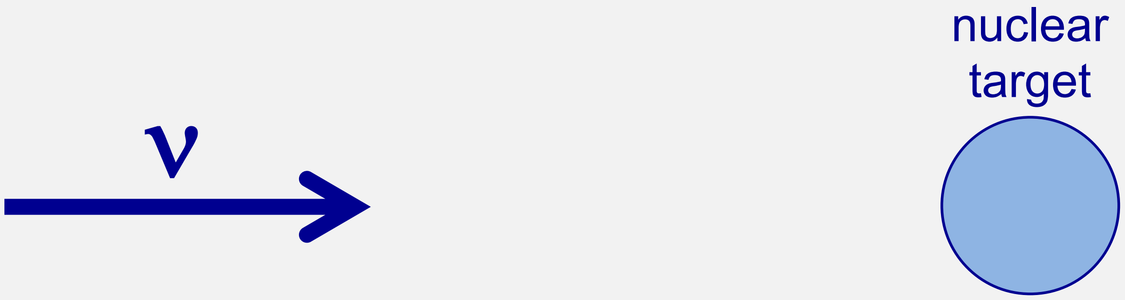
**Prize share:** 1/2

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

**Arthur B. McDonald**

**Prize share:** 1/2

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


nuclear
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# Fun Timely Intellectual Adorable!

# Fun Timely Intellectual Adorable!

nuclear many-body problem

Spin physics

Leptonic CP violation

Neutrino oscillation

Weak interaction

NuSTEC News

Nucleon correlation

EMC effect

electron scattering

Dark matter

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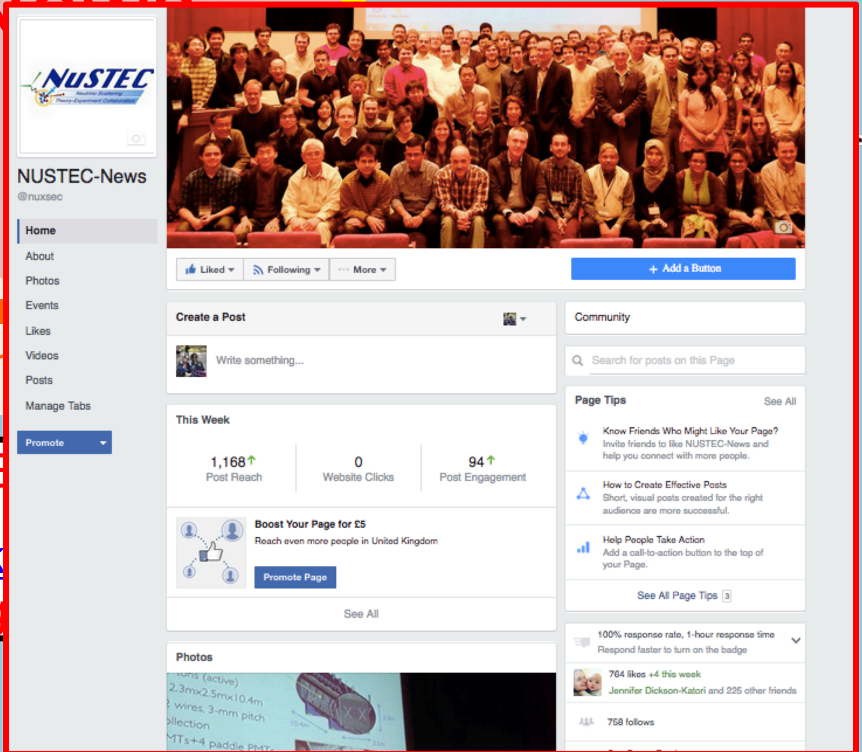


Teppei Katori

# Challenges of modelling neutrino induced shallow-inelastic scattering (SIS) interactions for neutrino oscillation experiments around 1-10 GeV

## outline

1. Neutrino Interaction Physics
2. Shallow inelastic scattering (SIS)
3. Nuclear dependent DIS physics
4. Neutrino hadronization process
5. Conclusion

Teppei Katori
Queen Mary University of London
HEP seminar, Michigan State University, USA, June 19, 2018

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Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1



# 1. Neutrino interaction physics

# 2. Shallow-Inelastic scattering (SIS)

# 3. Nuclear-dependent DIS physics

# 4. Neutrino hadronization process

# 5. Conclusion

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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journal homepage: www.elsevier.com/locate/ppnp

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Review

NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

L. Alvarez-Ruso [a], M. Sajjad Athar [b], M.B. Barbaro [c], D. Cherdack [d], M.E. Christy [e], P. Coloma [f], T.W. Donnelly [g], S. Dytman [h], A. de Gouvêa [i], R.J. Hill [j,f], P. Huber [k], N. Jachowicz [l], T. Katori [m], A.S. Kronfeld [f], K. Mahn [n], M. Martini [o], J.G. Morfín [f,*], J. Nieves [a], G.N. Perdue [f], R. Petti [p], D.G. Richards [q], F. Sánchez [r], T. Sato [s,t], J.T. Sobczyk [u], G.P. Zeller [f]

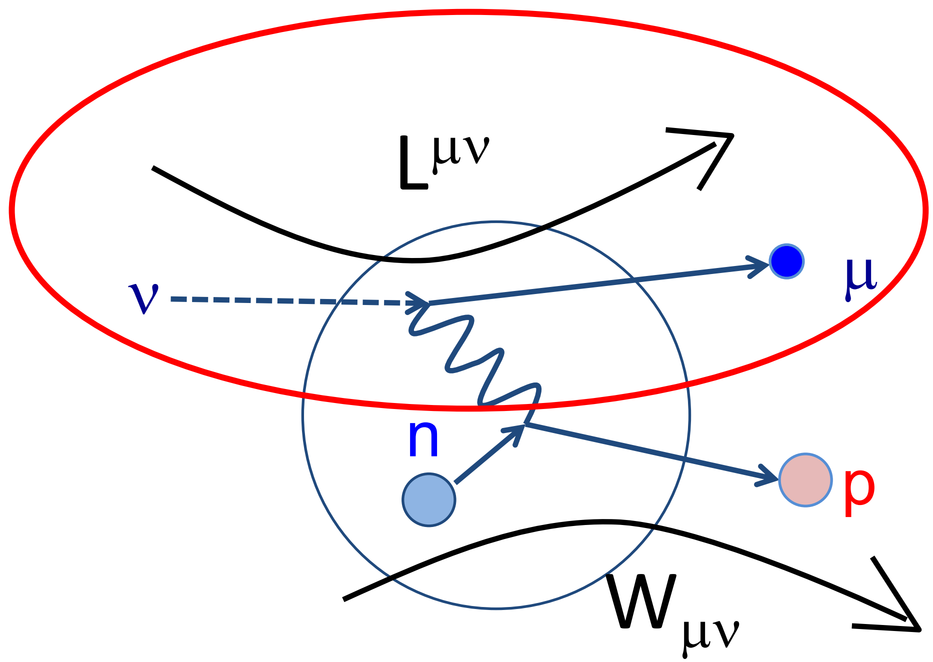
# 1. Neutrino cross-section formula

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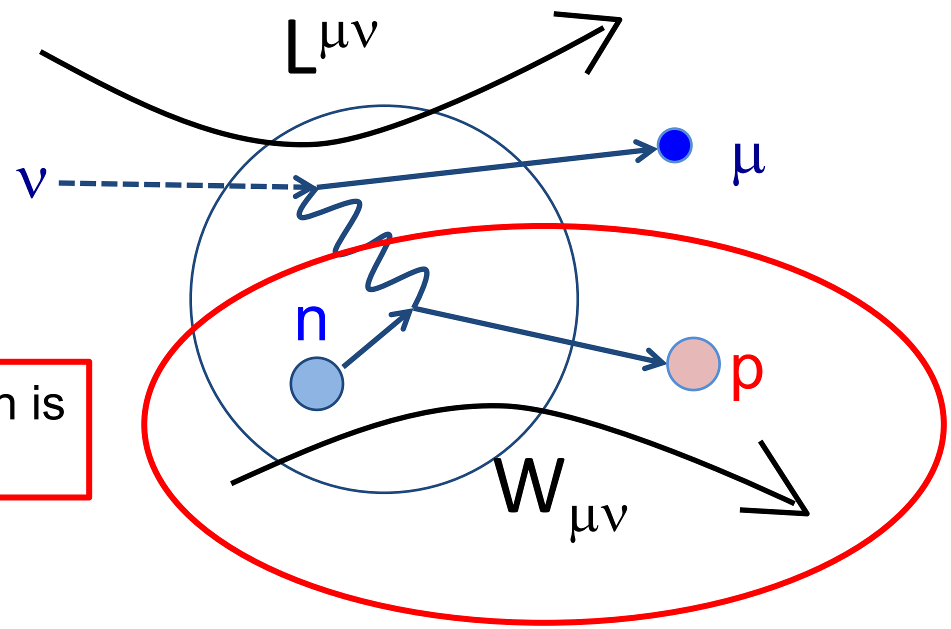
All complication of neutrino cross-section is how to model the hadronic part



# 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$^o$ and 50$^o$ are same for sin2$\theta_{23}$, 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.

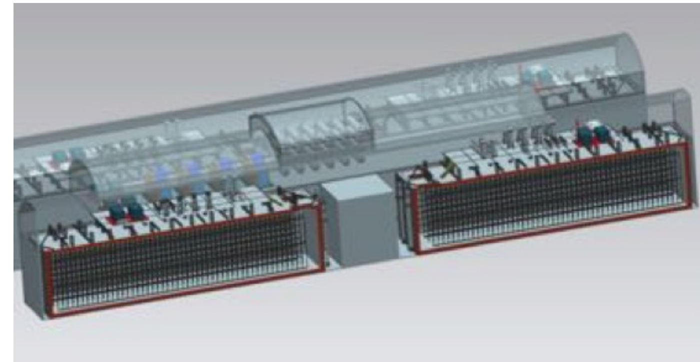


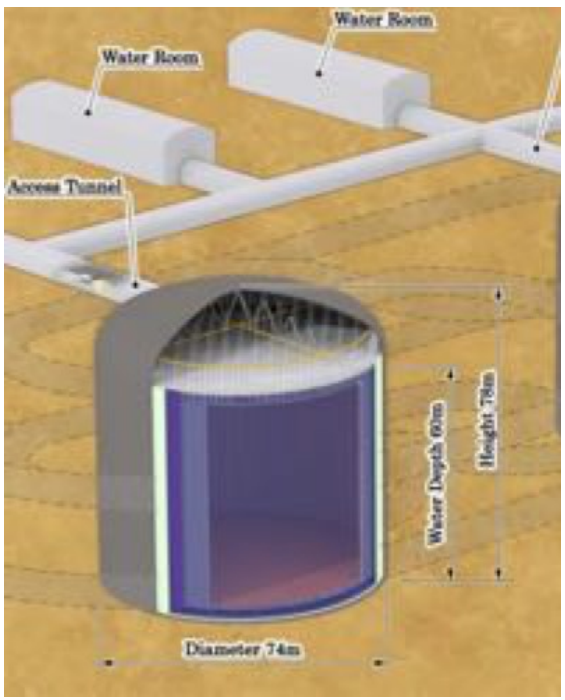
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

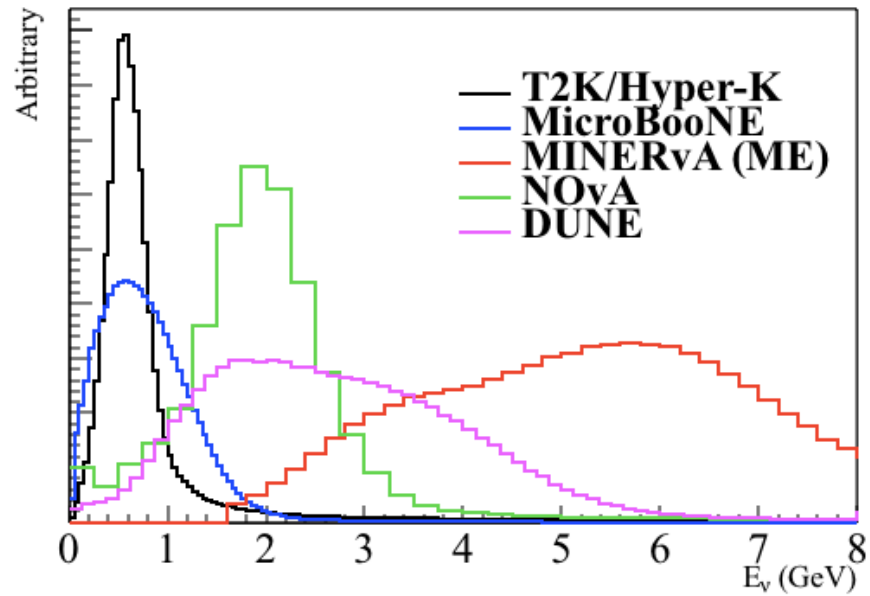
# 1. Hyper-Kamiokande and DUNE

## HyperK
- ~2026? in Japan
- Water target
- Narrow band 0.6 GeV
- Low resolution

## DUNE
- ~2025? in USA
- Argon target
- wide band 1-4 GeV
- High resolution






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

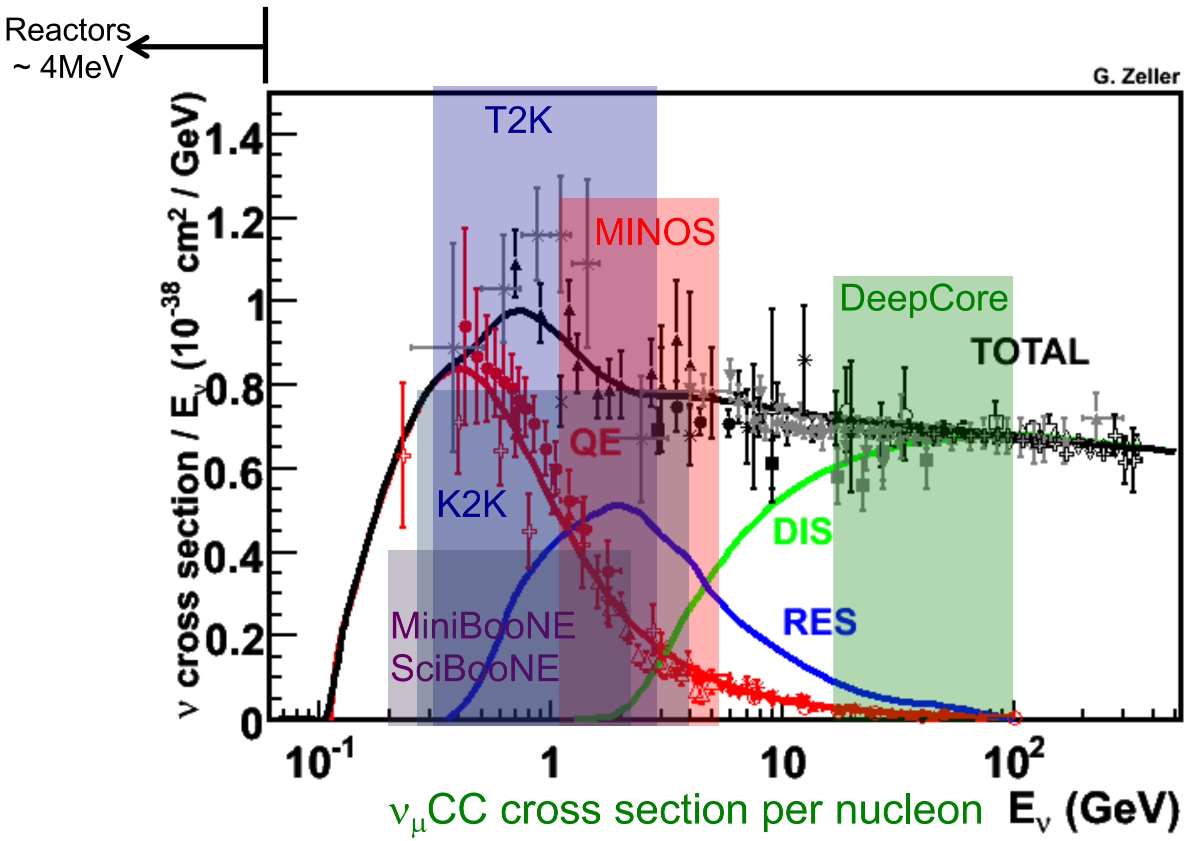
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307



# 1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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

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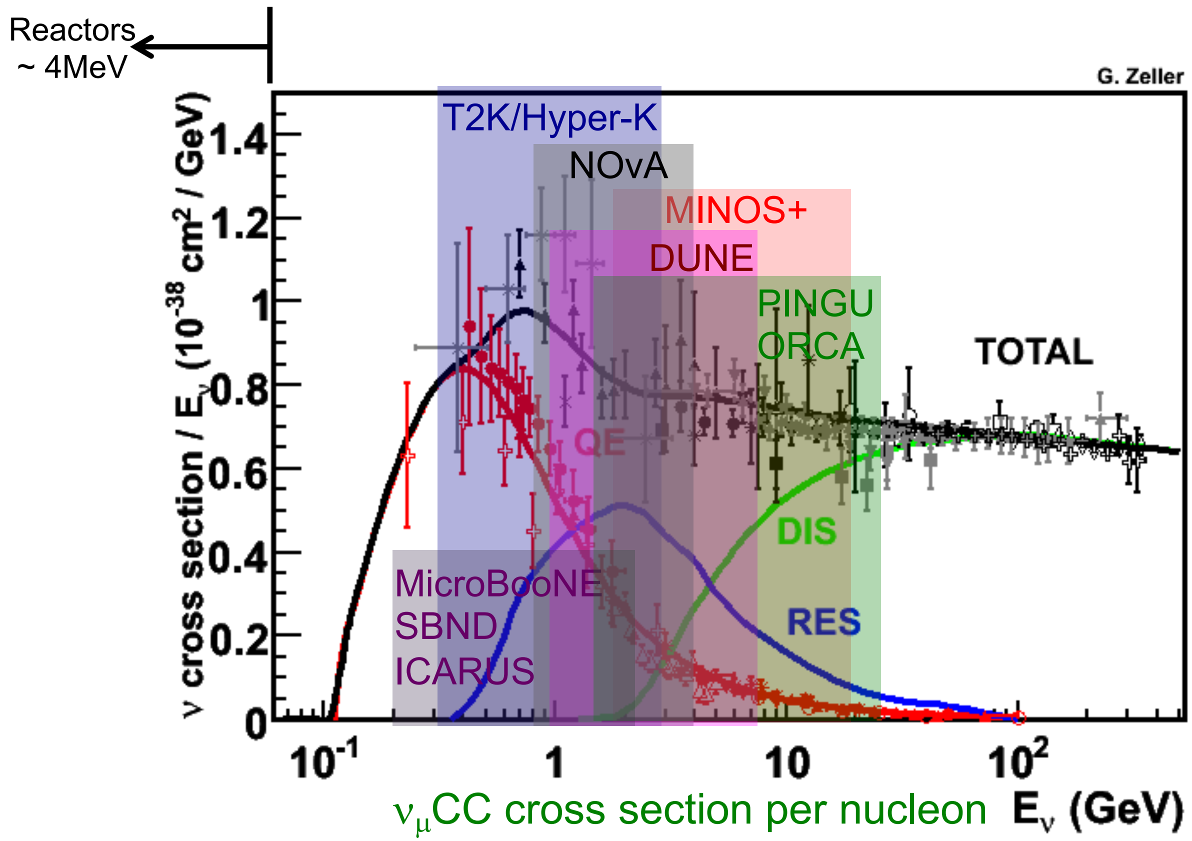


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Neutrino oscillation experiments

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

We don't know the energy of incoming neutrinos…

- We need to simulate all physics from Ev=0 to Ev ~few GeV
- We need to simulate all physics from $\omega,|\vec{q}|$=0 to $\omega,|\vec{q}|$~few GeV (x,y=0 to ~1)

Two rules of neutrino interaction physics

1. Neutrinos cannot choose kinematics
2. Neutrino kinematics are not fully determined

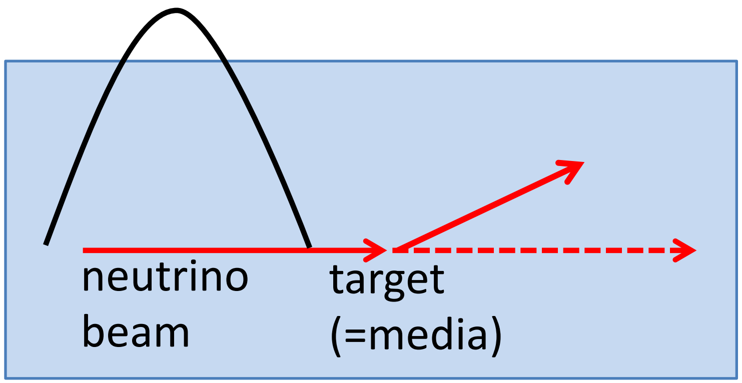
$$P_{\mu\to e}(L/E)=\sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

# 1. Typical neutrino detectors

## Neutrino scattering

- Wideband beam

→ Measure all reactions

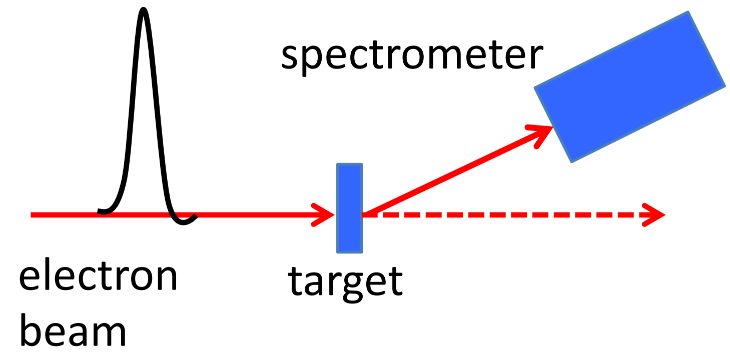



## Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ kinematics is completely fixed



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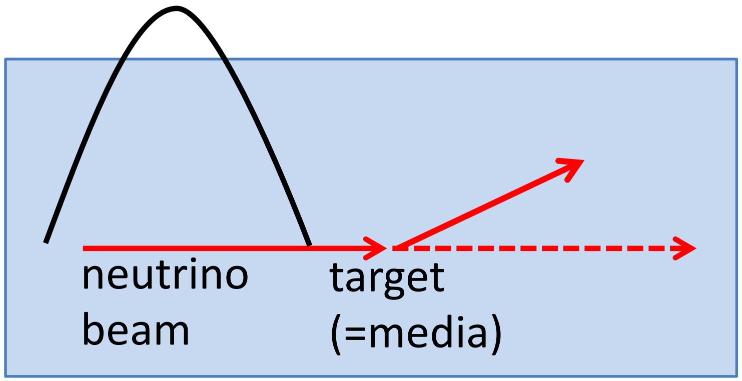


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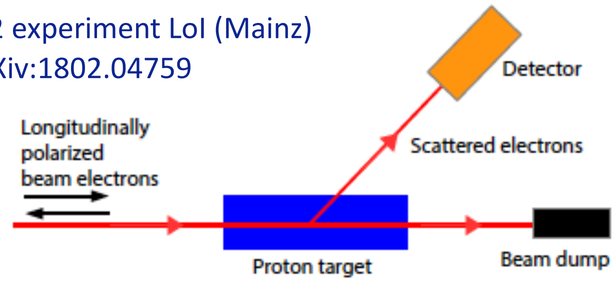
P2 experiment LoI (Mainz)
arXiv:1802.04759



TK, Martini, JPhysG45(2017)1



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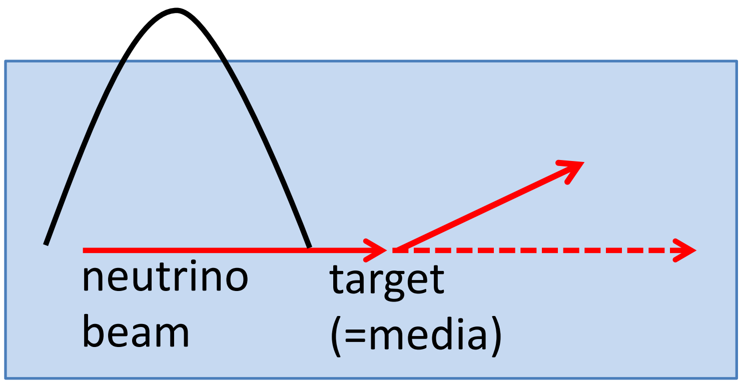


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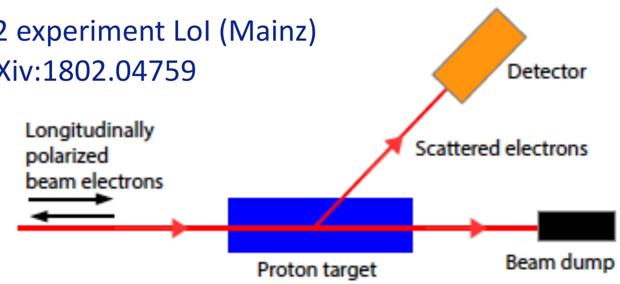


## Incomplete kinematics
- Large mass, coarse instrumentation
- No one measures neutrino energy directly
- Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

# 1. Typical neutrino detectors

## Neutrino scattering

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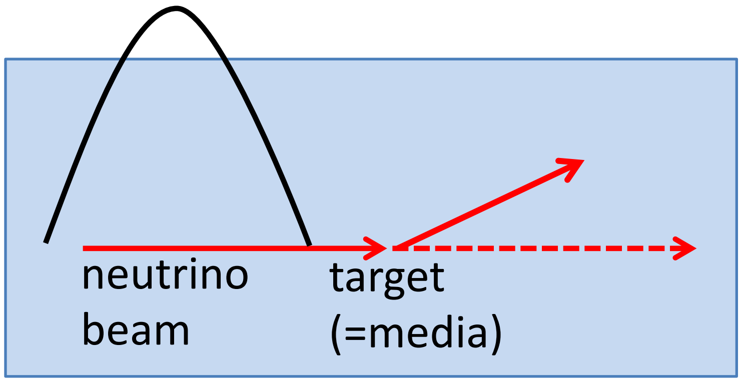


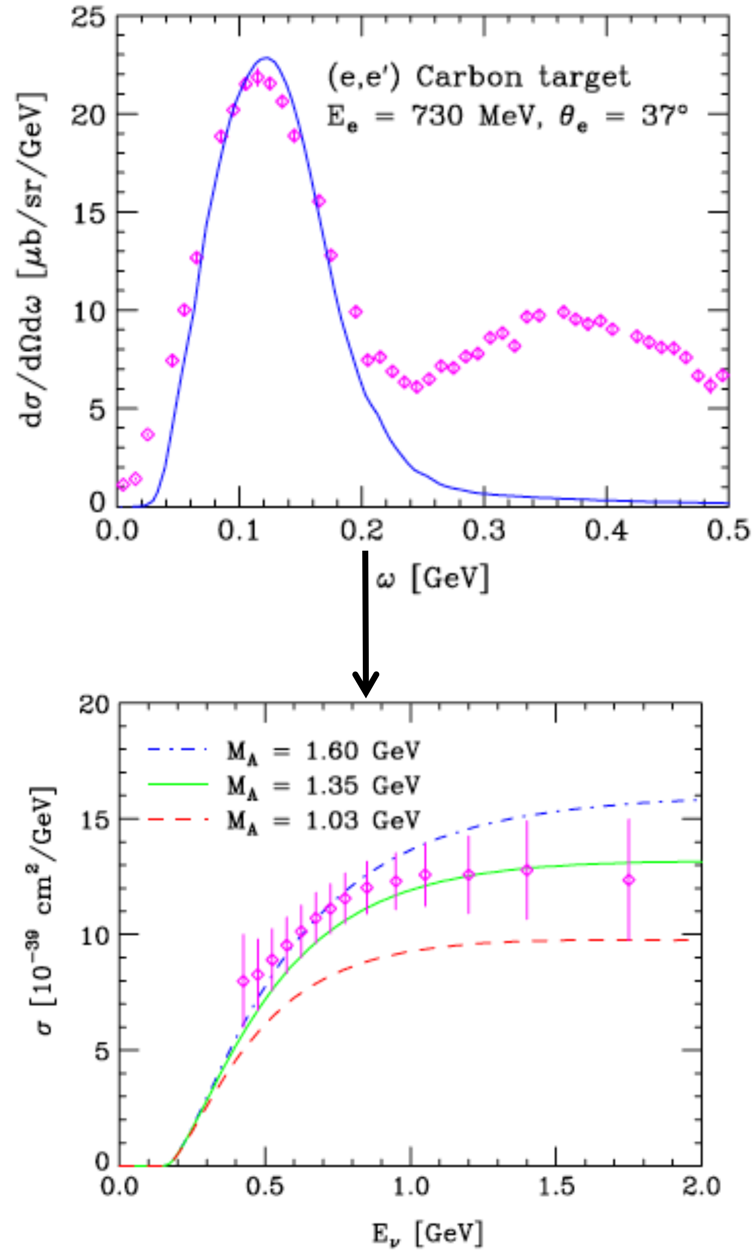


## Incomplete kinematics

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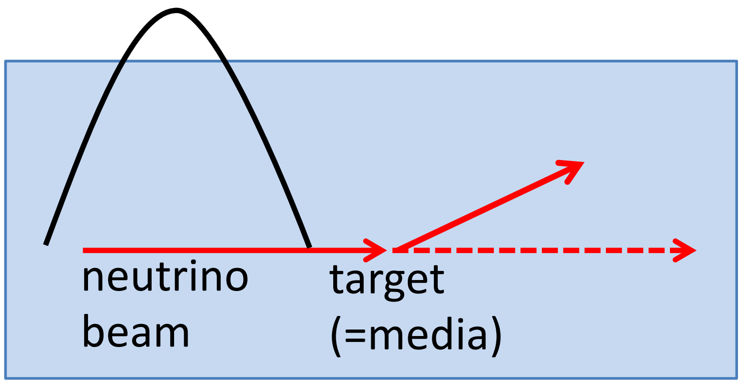
  - No one measures neutrino energy directly
  - Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

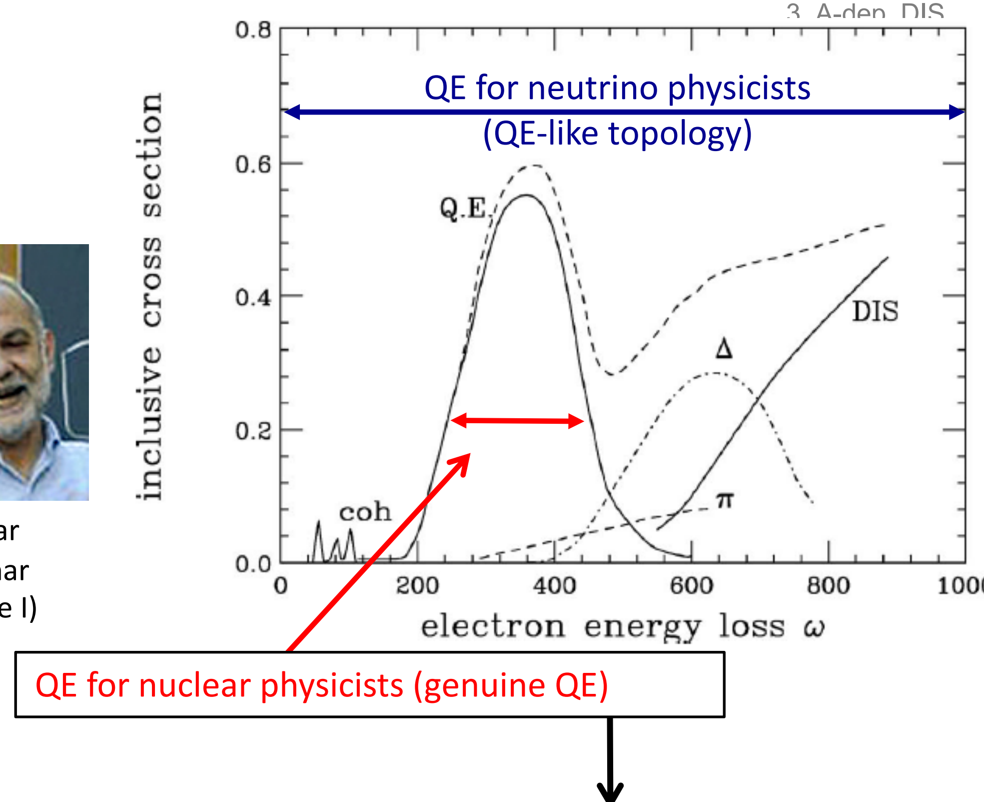
# 1. Typical neutrino detectors

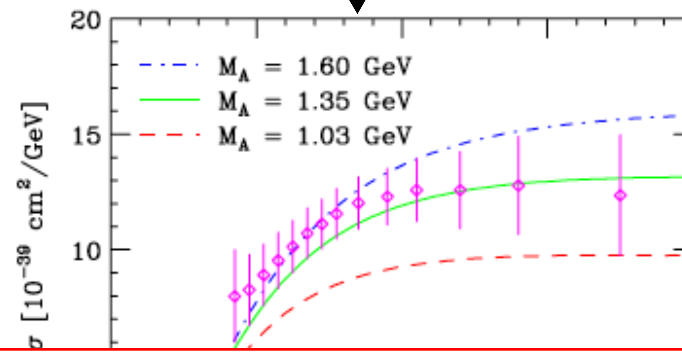
description of neutrino data will require a new paradigm, suitable for application to processes in which the lepton kinematics is not fully determined

→ Measure all reactions




Omar
Benhar
(Rome I)




## Incomplete kinematics

- Large mass, coarse instrumentation
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Two rules of neutrino interaction physics
1. Neutrinos cannot choose kinematic
2. Neutrino kinematics are not fully determined

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University of London

MiniBooNE: PRD81(2010)092005
Martini et al,PRC80(2009)065501

# 1. Discovery of nucleon correlation in neutrino scattering

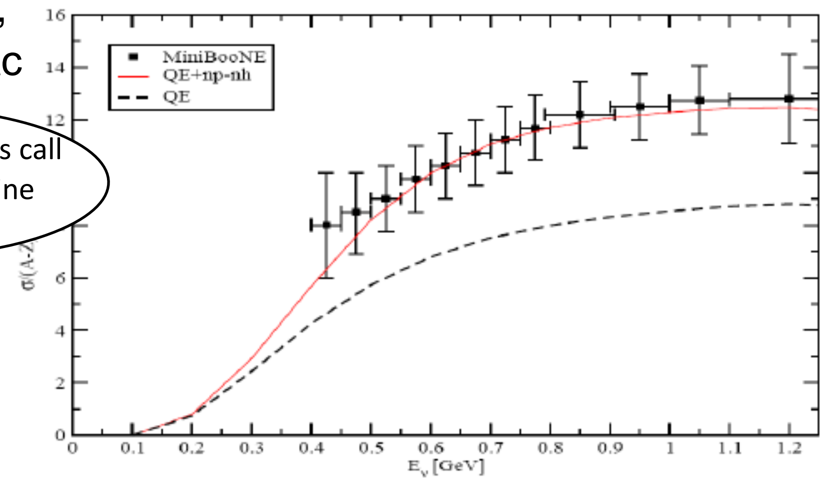
- Significant enhancement of cross section (10-30%) around 1 GeV
- Modify lepton kinematics and final state hadrons
- The hottest topic for T2K, MINERvA, MicroBooNE, etc

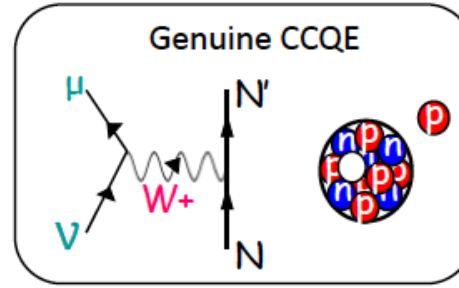
What experimentalists call "CCQE" is not genuine CCQE!

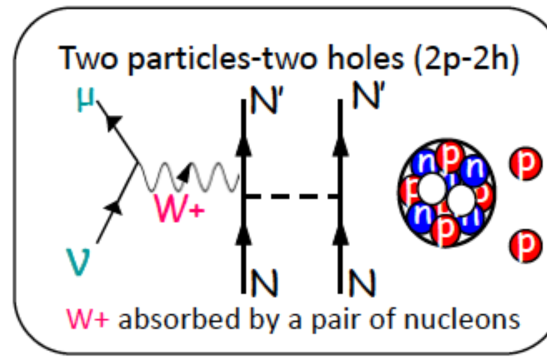
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)




Particle Data Group
- Section 42, "Monte Carlo Neutrino Generators" (Hugh Gallagher, Yoshinari Hayato)
- Section 50, "Neutrino Cross-Section Measurements" (Sam Zeller)

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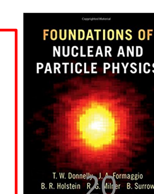
The first textbook of neutrino interaction physics!
"Foundation of Nuclear and Particle Physics"
- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow



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



# 1. Discovery of nucleon correlation in neutrino scattering

## 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)

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

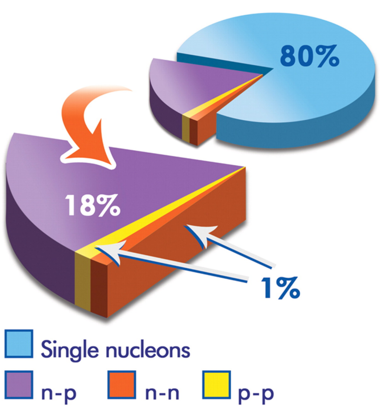
2N potential (Av18) — 3N potential (IL7)

Ab initio calculation reproduce same feature

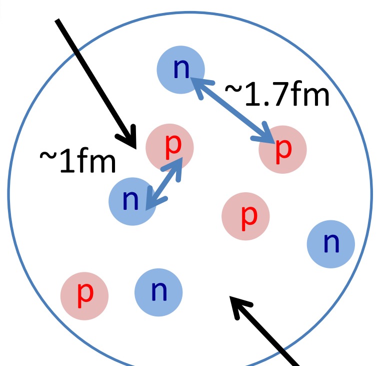
Alessandro Lovato (Trento)

## Physics of SRC

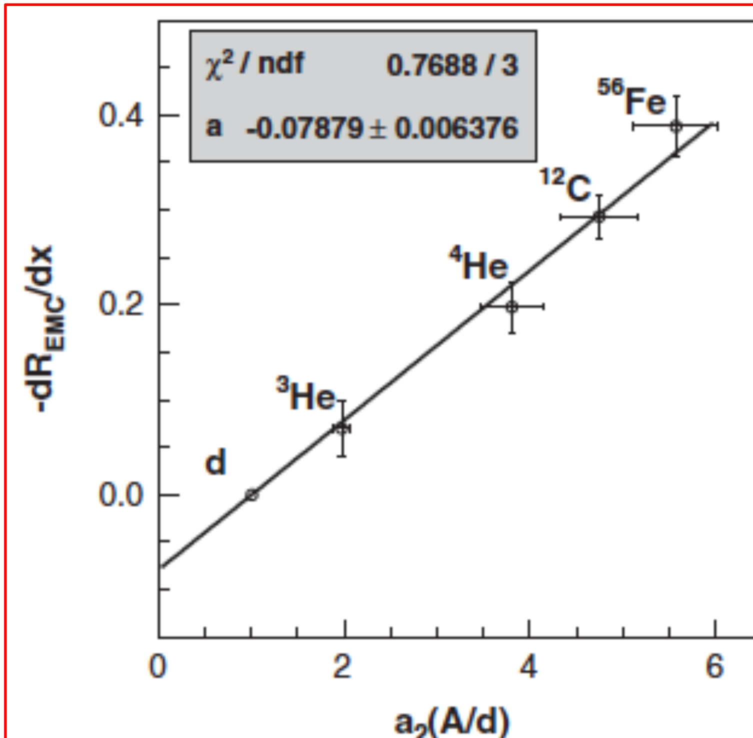
- neutrino interaction
- $0\nu\beta\beta$
- astrophysics
- EMC effect
- etc




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




$\rho_{nucl} = 2.4\times10^{14}\,g/cm^3$




**Nucleon correlation is a very hot topics!**

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

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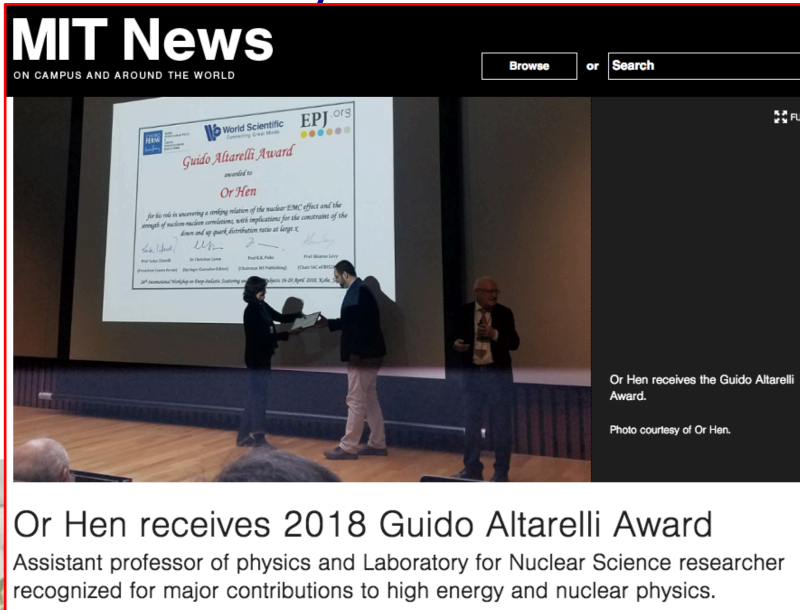



l models

SRC)

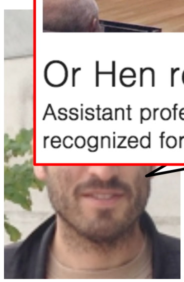
$$|\Psi_V\rangle = \mathcal{S}\prod_{i<j}^{A}\left[1+U_{ij}+\sum_{k\neq i,j}^{A}\tilde{U}^{TNI}_{ijk}\right]|\Psi_J\rangle$$

2N potential (Av18)

3N potential (IL7)

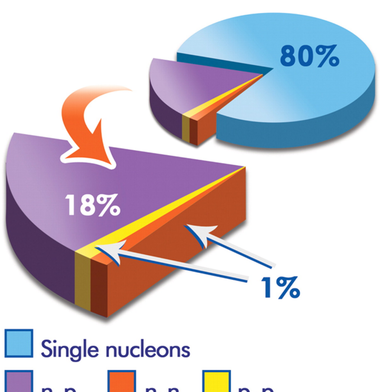
SRC

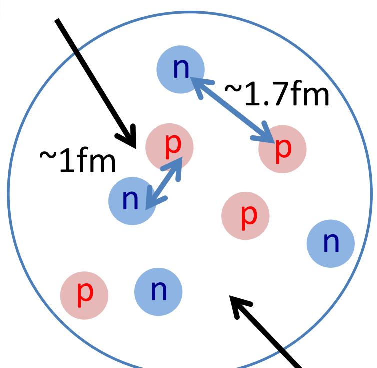
interaction

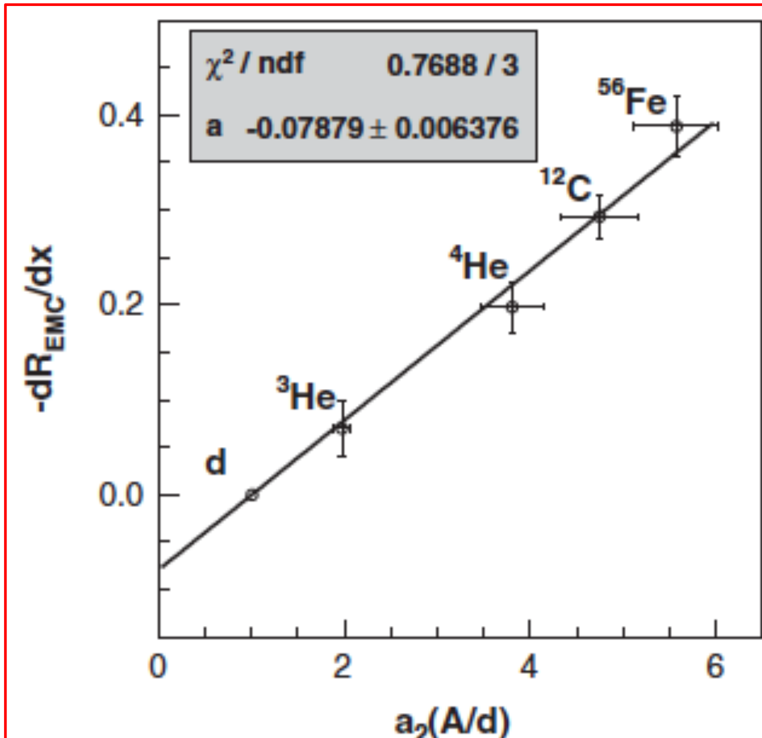


Alessandro Lovato (Trento)

- astrophysics
- EMC effect
- etc



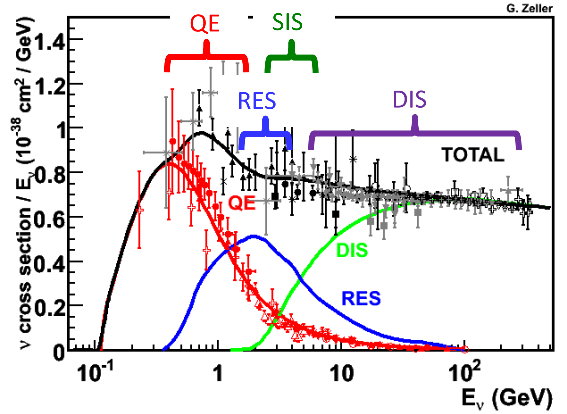



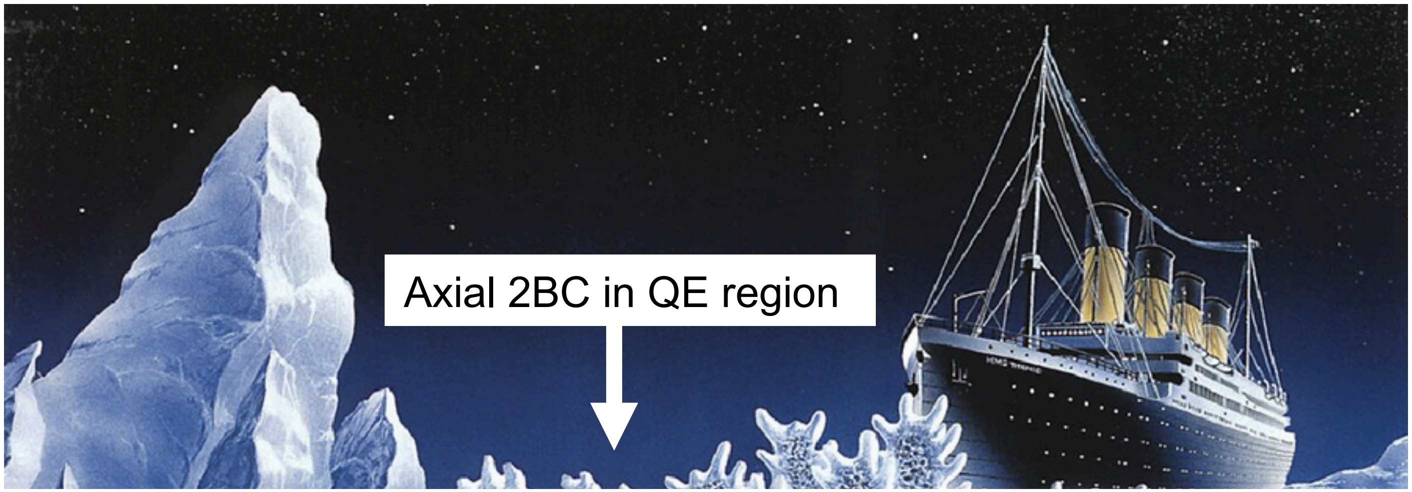



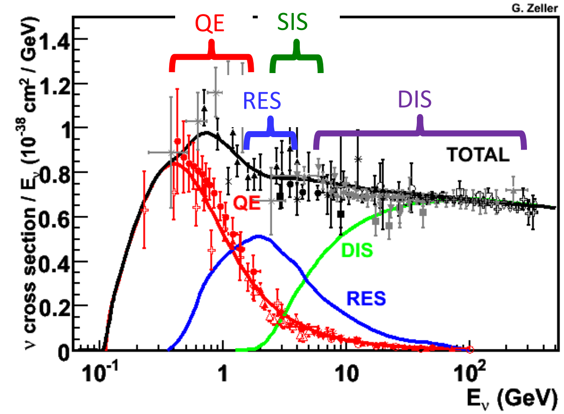

Nucleon correlation is a very hot topics!

# 1. Beyond QE peak

Axial 2-body current in QE region may be a tip of the iceberg…

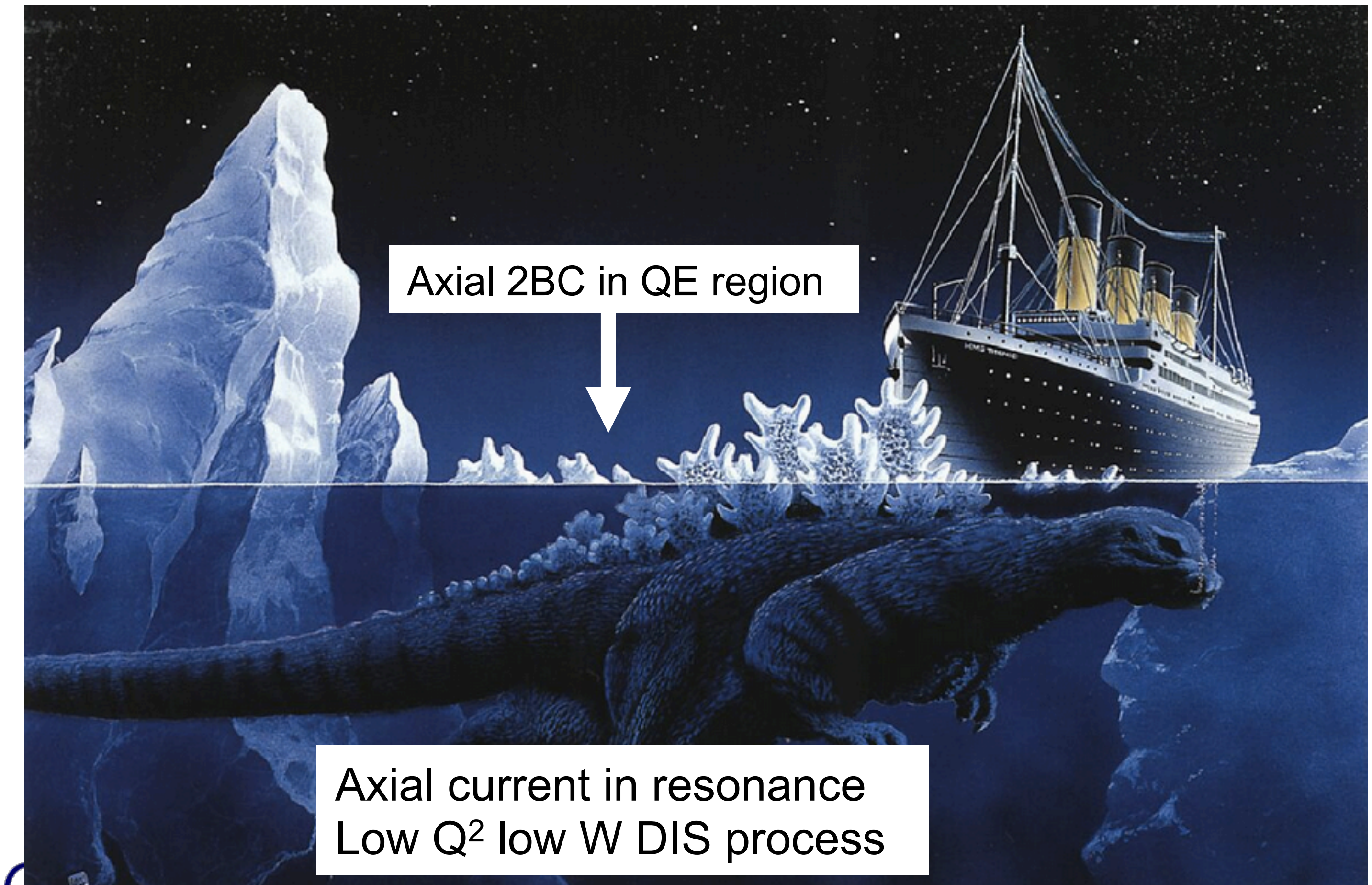




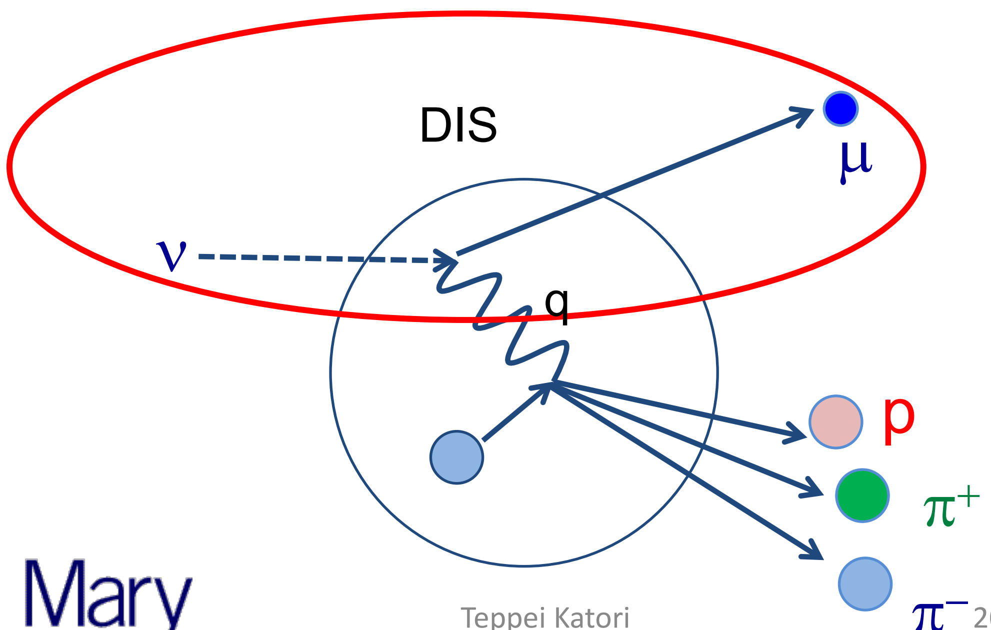

# 1. Beyond QE peak

Axial 2-body current in QE region may be a tip of the iceberg…, or maybe tip of gozilla



# 1. Neutrino DIS cross section overview

Neutrino Deep Inelastic Scattering (DIS)
- a process to scatter a charged lepton by an incident lepton with given energy
- DIS differential cross section is function of x and y
- DIS total cross section is function of Eν, integrated in x and y



# 1. Neutrino DIS cross section overview

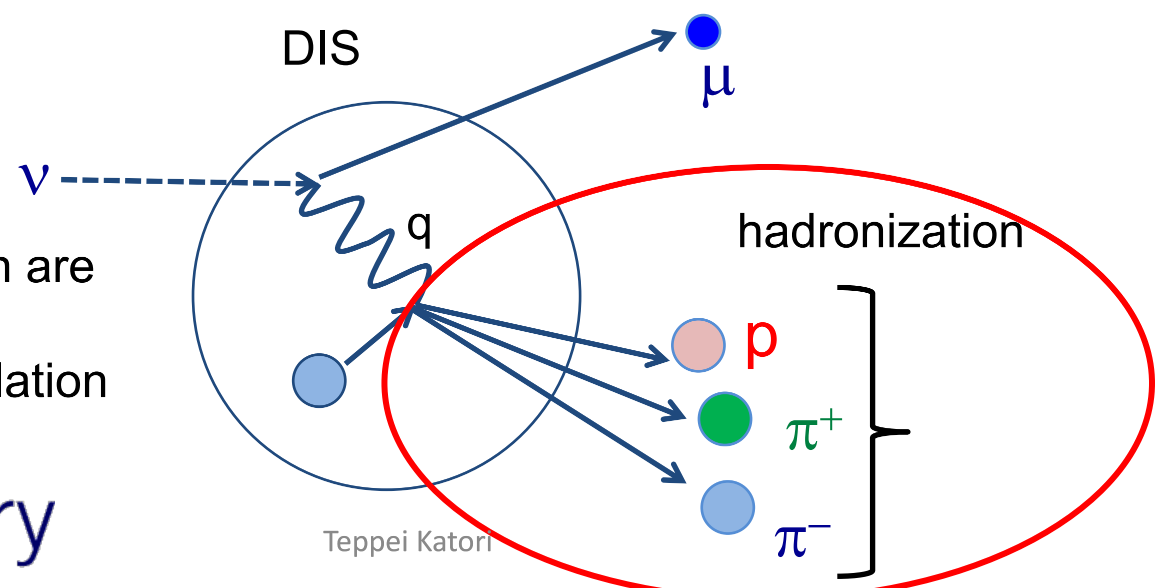
## Neutrino Deep Inelastic Scattering (DIS)

- a process to scatter a charged lepton by an incident lepton with given energy
- DIS differential cross section is function of x and y
- DIS total cross section is function of $E\nu$, integrated in x and y

## Neutrino hadronization

- a process to generate hadrons from given $Q^2$ and W
- number of hadrons (multiplicity) and hadrons kinematics are computed.

DIS and Hadronization are usually modelled independently in simulation

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Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307
MINOS, PRD81(2010)072002

# 1. Neutrino DIS cross section overview



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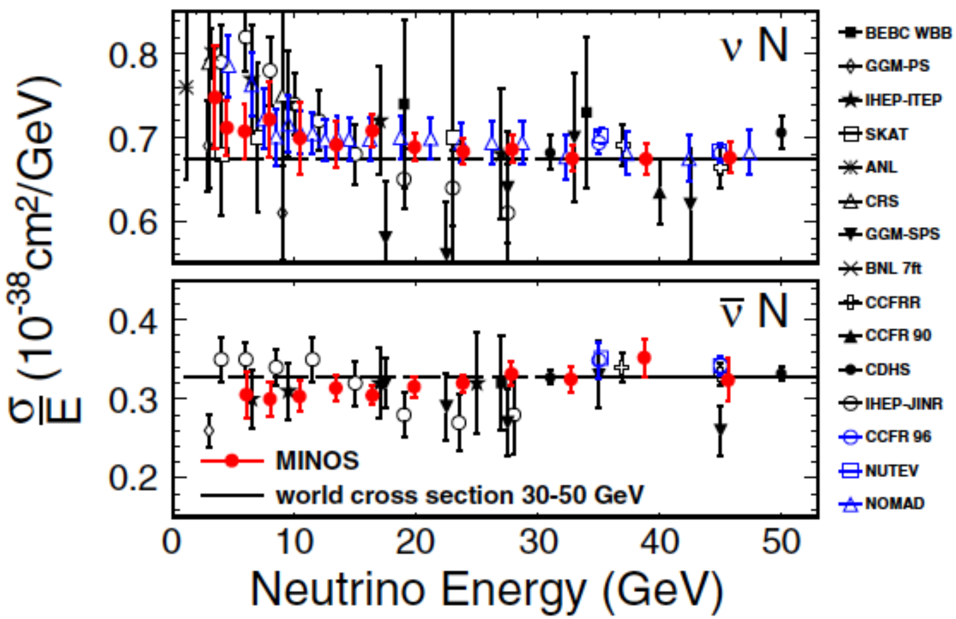
## Neutrino hadronization

- a process to generate hadrons from given $Q^2$ and W
- number of hadrons (multiplicity) and hadrons kinematics are computed.

## DIS total cross section error ~ few %?

- This is the error of CCDIS total cross section on iron target around ~10 GeV
- Most of neutrino oscillation experiments are neither iron target or this energy range

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Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1



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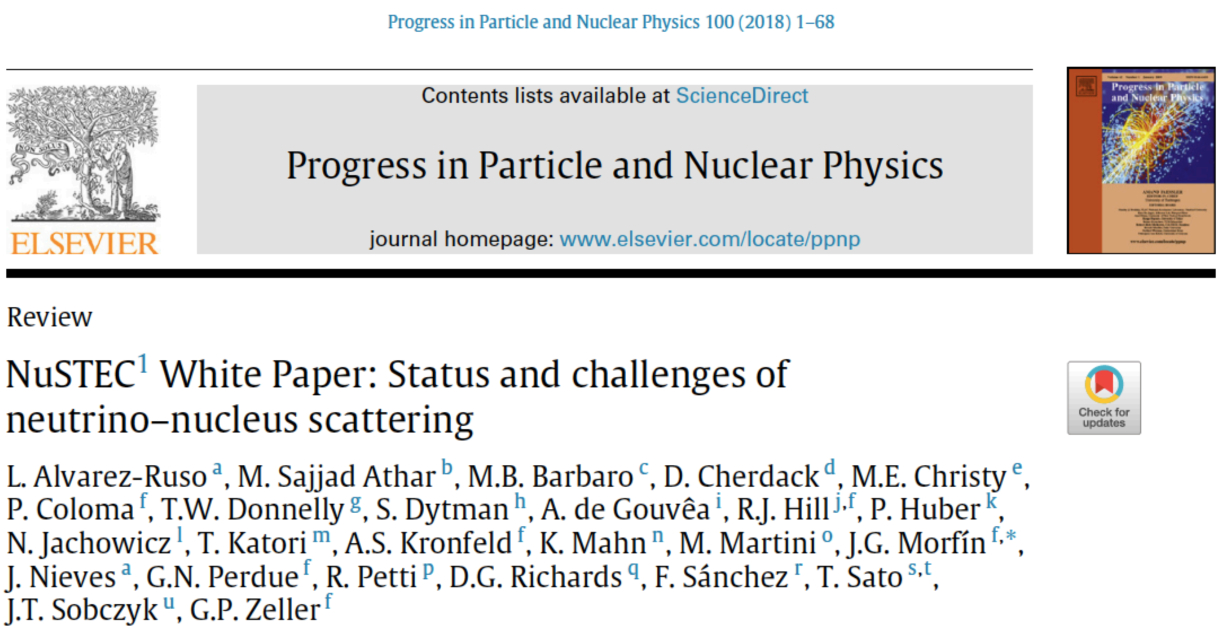
# 3. Nuclear-dependent DIS physics

# 4. Neutrino hadronization process

# 5. Conclusion

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

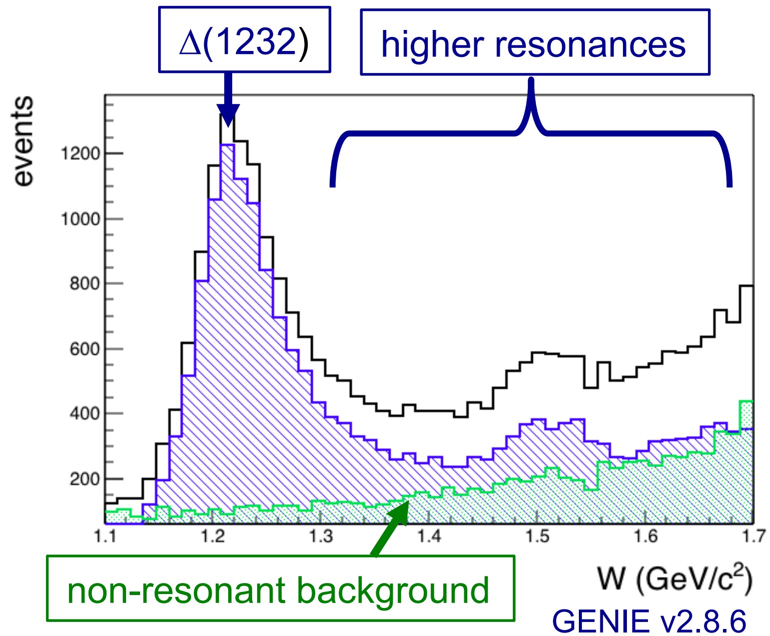
Traditionally called "transition" region

# 2. Sallow Inelastic Scattering (SIS) physics

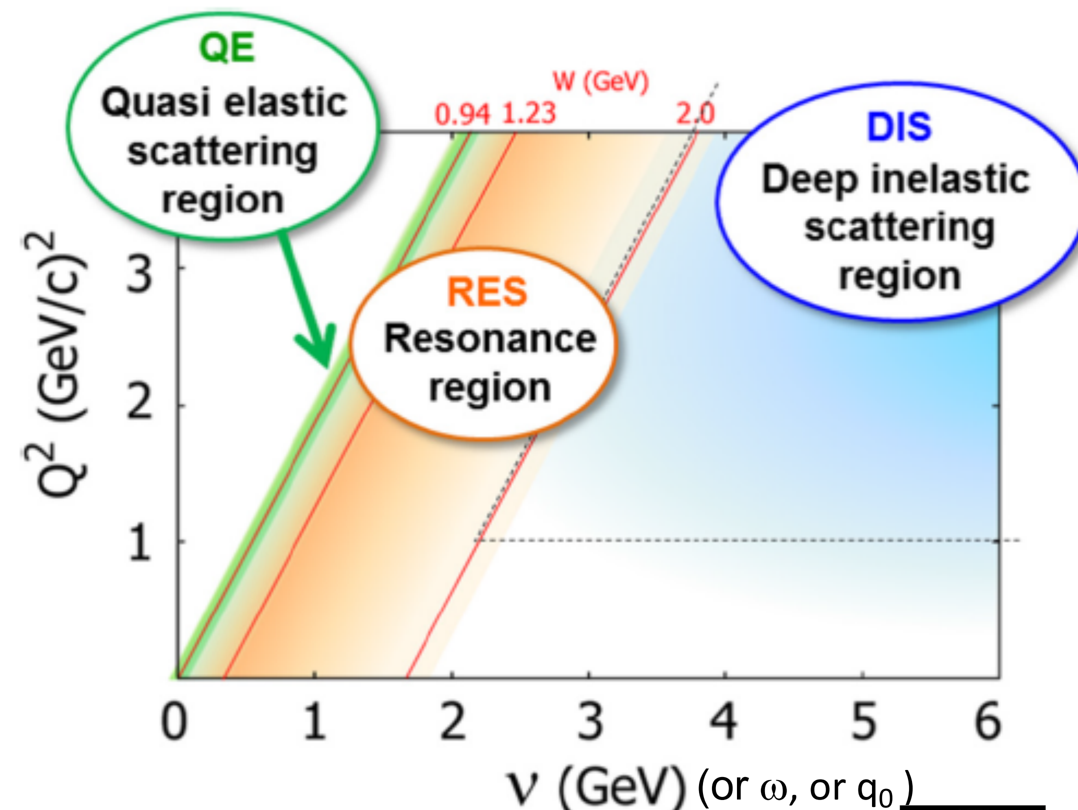


Basic ingredients

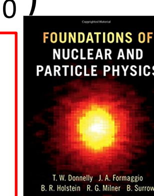
1. $\Delta(1232)$-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$ , low W DIS
5. Nuclear dependent DIS




Rep. Prog. Phys. 80 (2017) 056301




The first textbook of neutrino interaction physics!
"Foundation of Nuclear and Particle Physics"
- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow

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# 2. Physics of Δ resonance

Giessen BUU transport model (GiBUU) describes final states of hadrons in nuclear media

Ulrich Mosel (Giessen)

Basic ingredients

1. Δ(1232)-resonance
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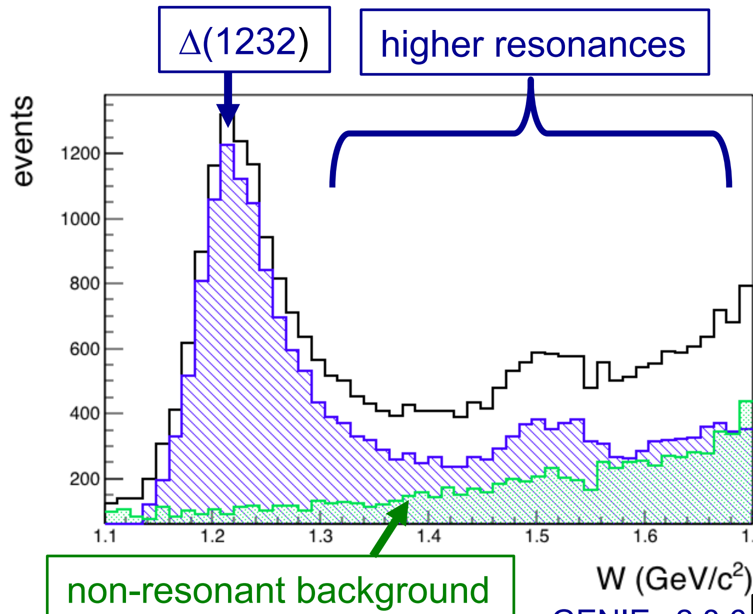
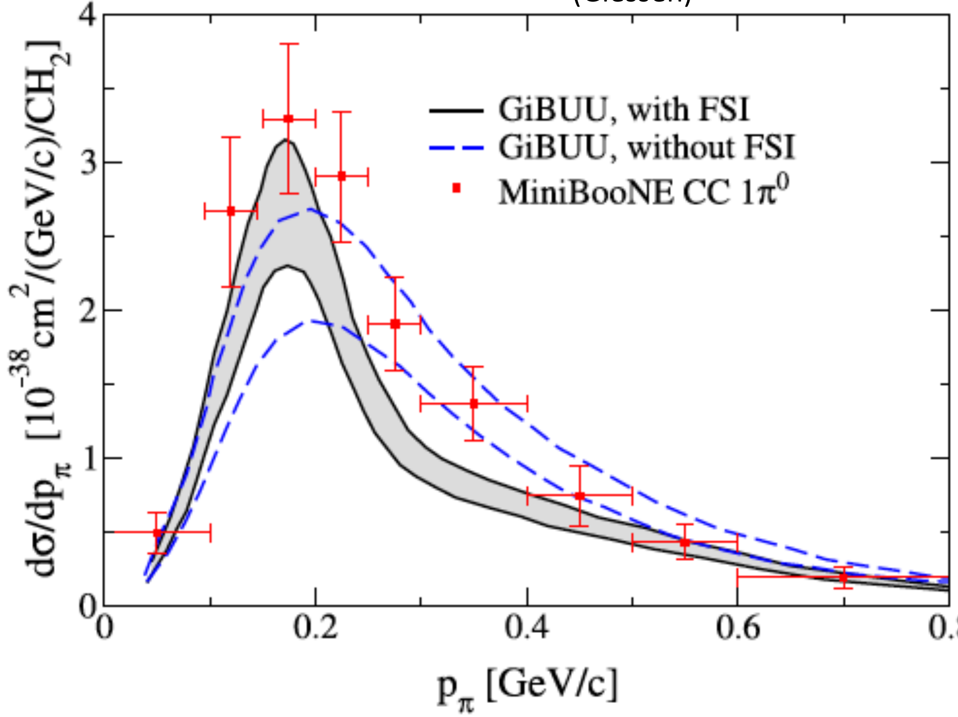
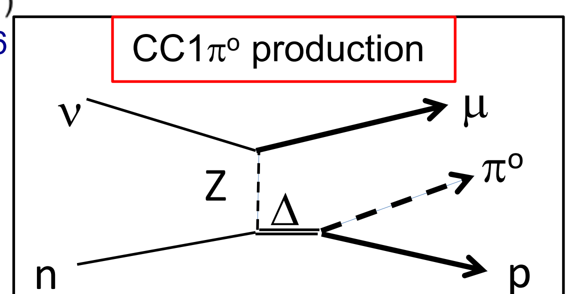



GENIE v2.8.6

MiniBooNE CC1π° data



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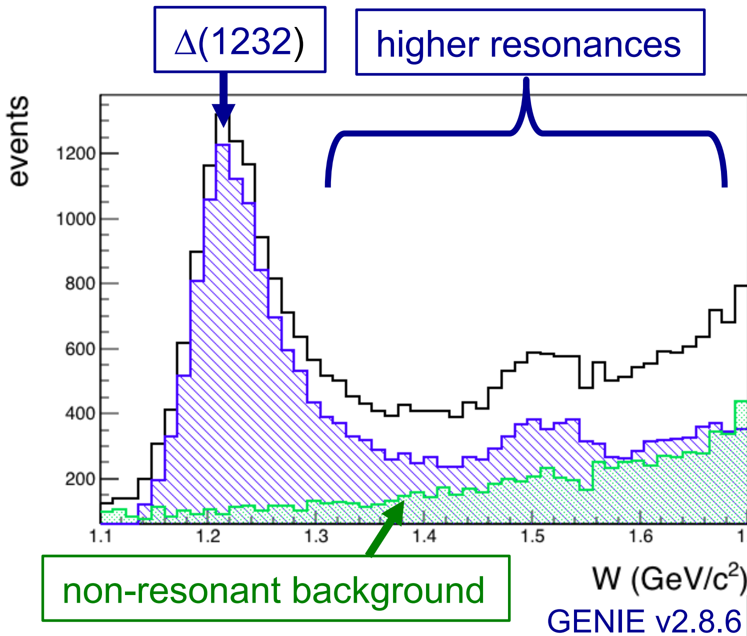


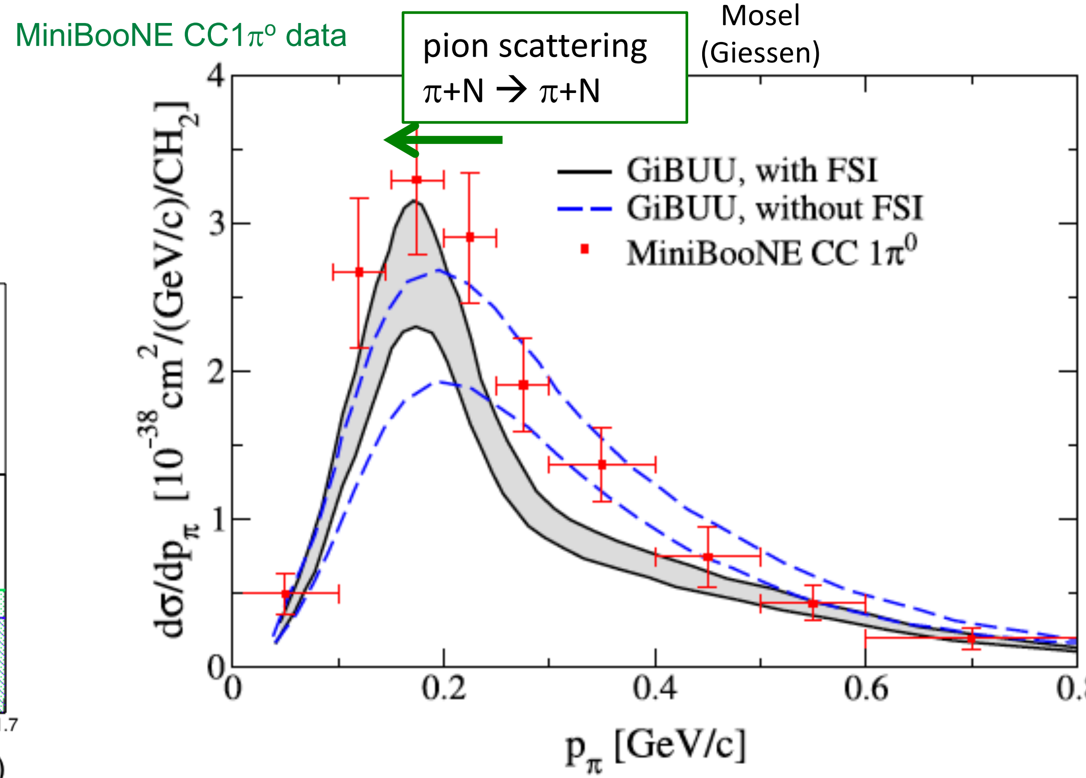


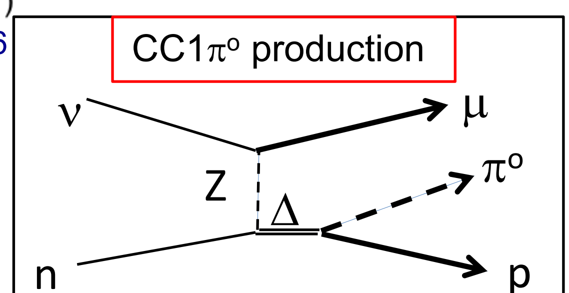

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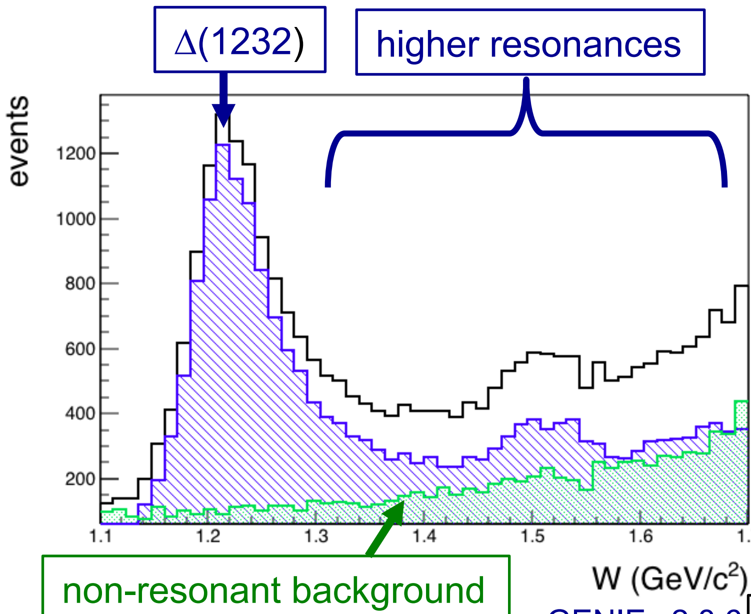


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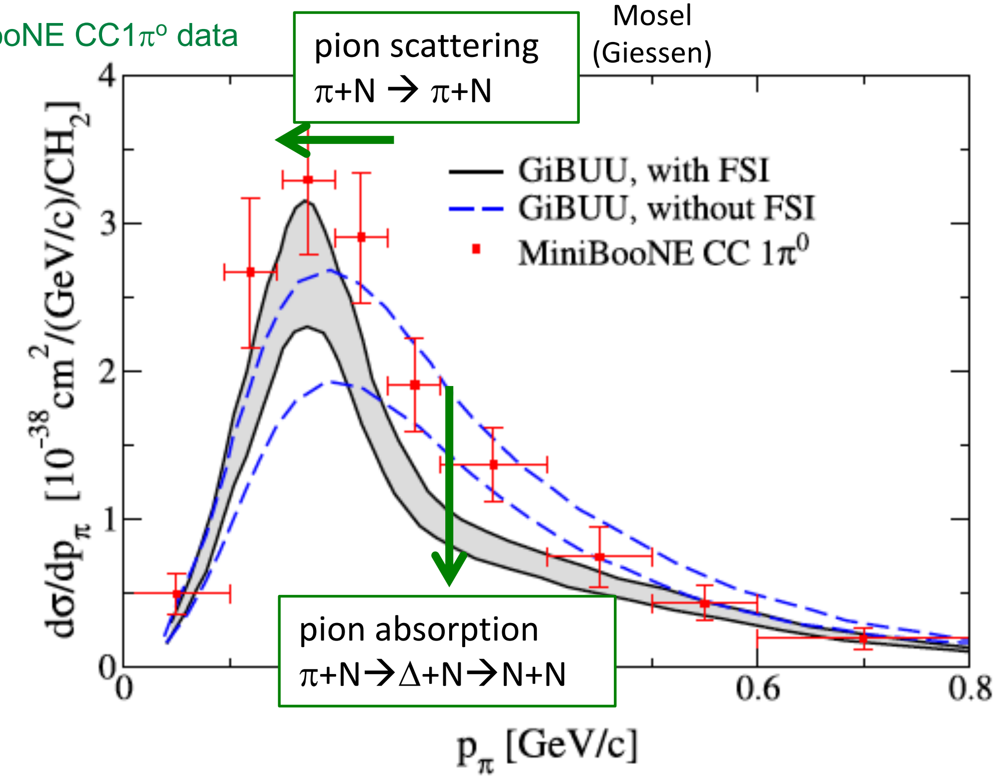


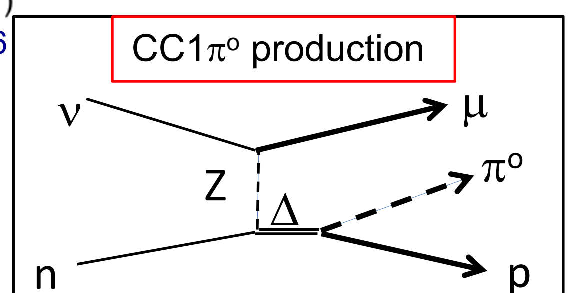


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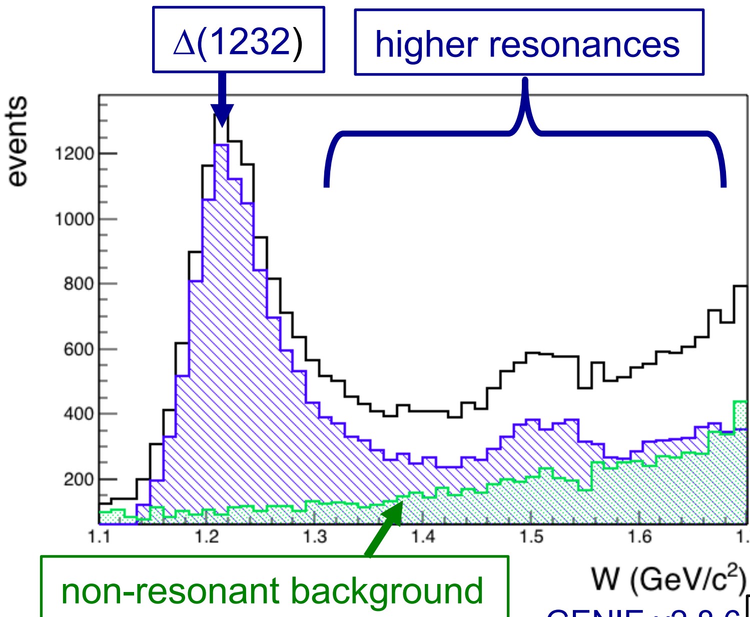
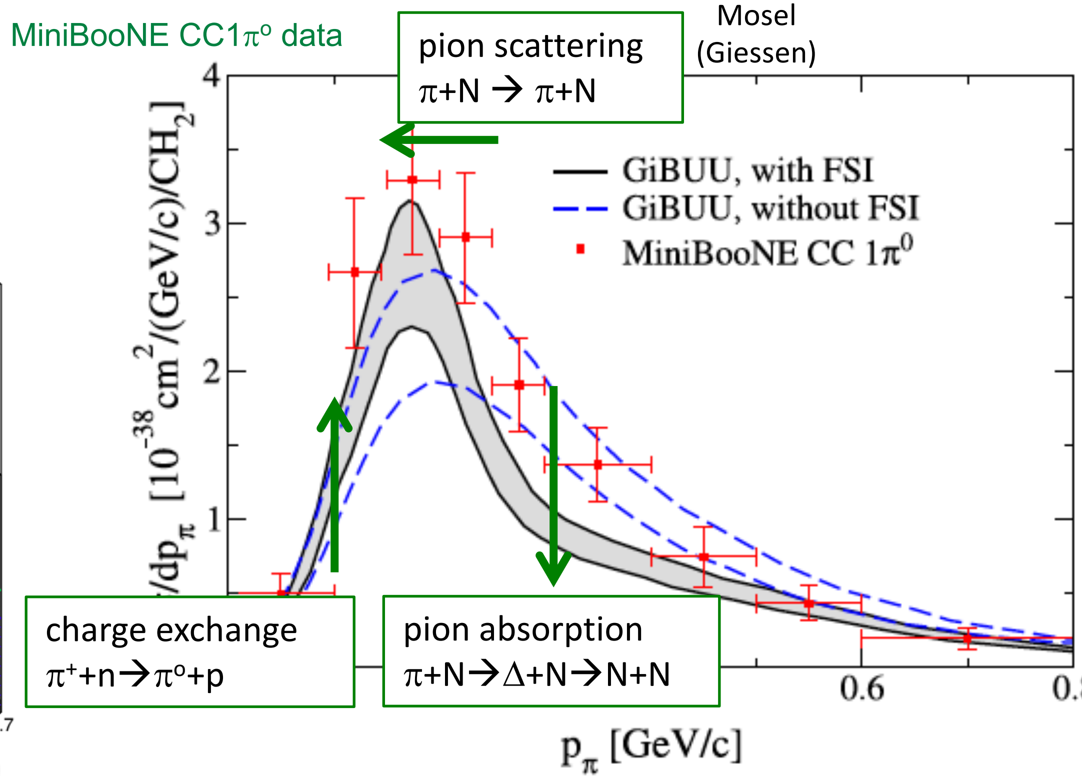
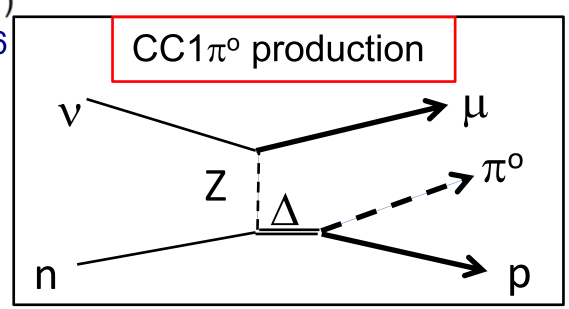
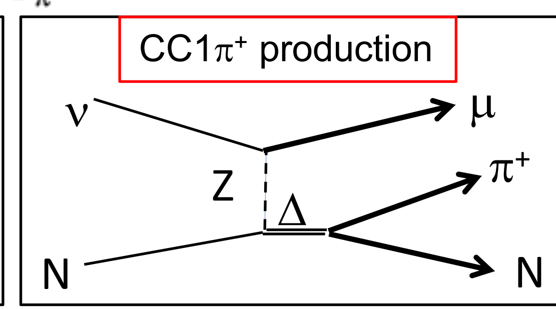



There is no great understanding even for the simplest baryonic resonance

# 2. Physics of higher resonances

DCC model vs. electro-pionproduction data

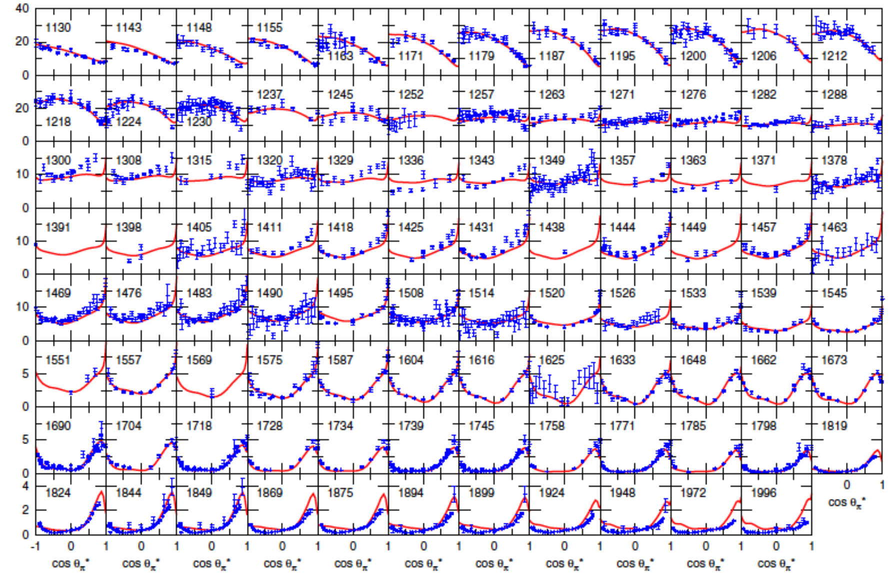


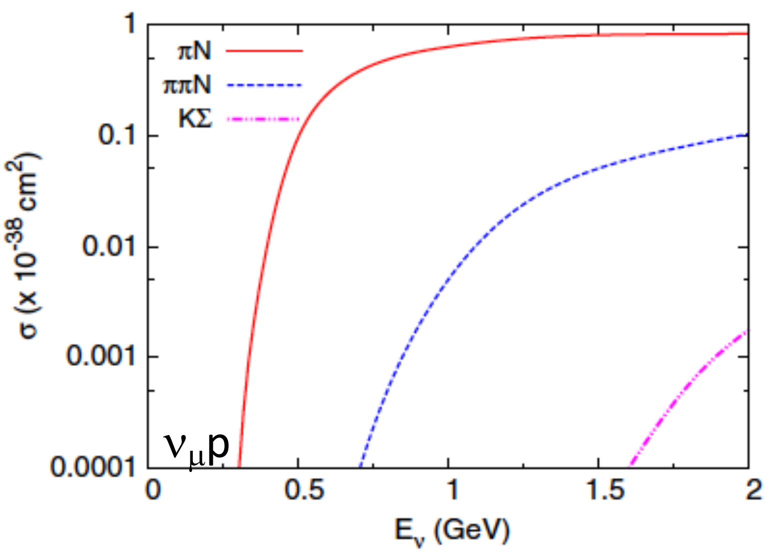

FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ ($\mu$b/sr), for $\gamma n \rightarrow \pi^- p$. The data are from Refs. [55–78].

Basic ingredients

1. $\Delta$(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$ , low W DIS
5. Nuclear dependent DIS

DCC model

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



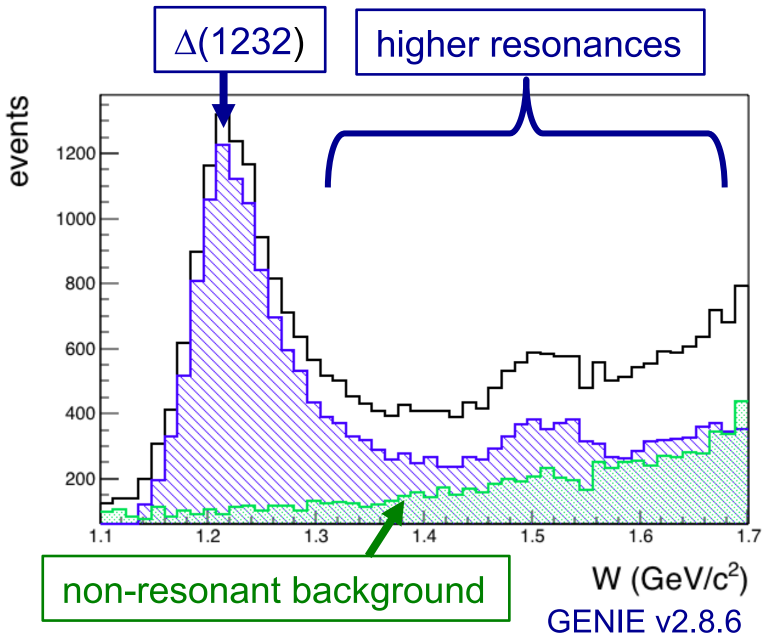

Role of high W resonances in neutrino experiments is not understood (and probably modeled incorrectly), and I don’t discuss today

# 2. Physics of non-resonant background



Basic ingredients

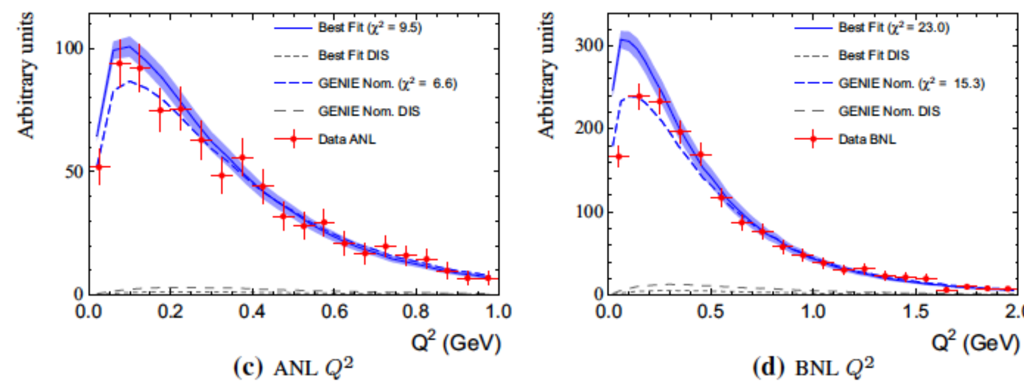
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$ , low W DIS
5. Nuclear dependent DIS




Non-resonant component and resonances are incoherently added (=wrong, but easy to simulate).

Non-resonant background is identified to be DIS at higher W.

Non-resonant background in GENIE needs to be reduced more than 50%.



Bloom and Gilman, PRL25(1970)1140
Graczyk et al,NPA781(2007)227, Lalakulich et al, PRC75(2007)015202

# 2. Quark-Hadron Duality

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



## Basic ingredients

1. $\Delta$(1232)-resonance
2. higher resonances
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4. low $Q^2$ , low W DIS
5. Nuclear dependent DIS

## GRV98 LO PDF + Bodek-Yang correction

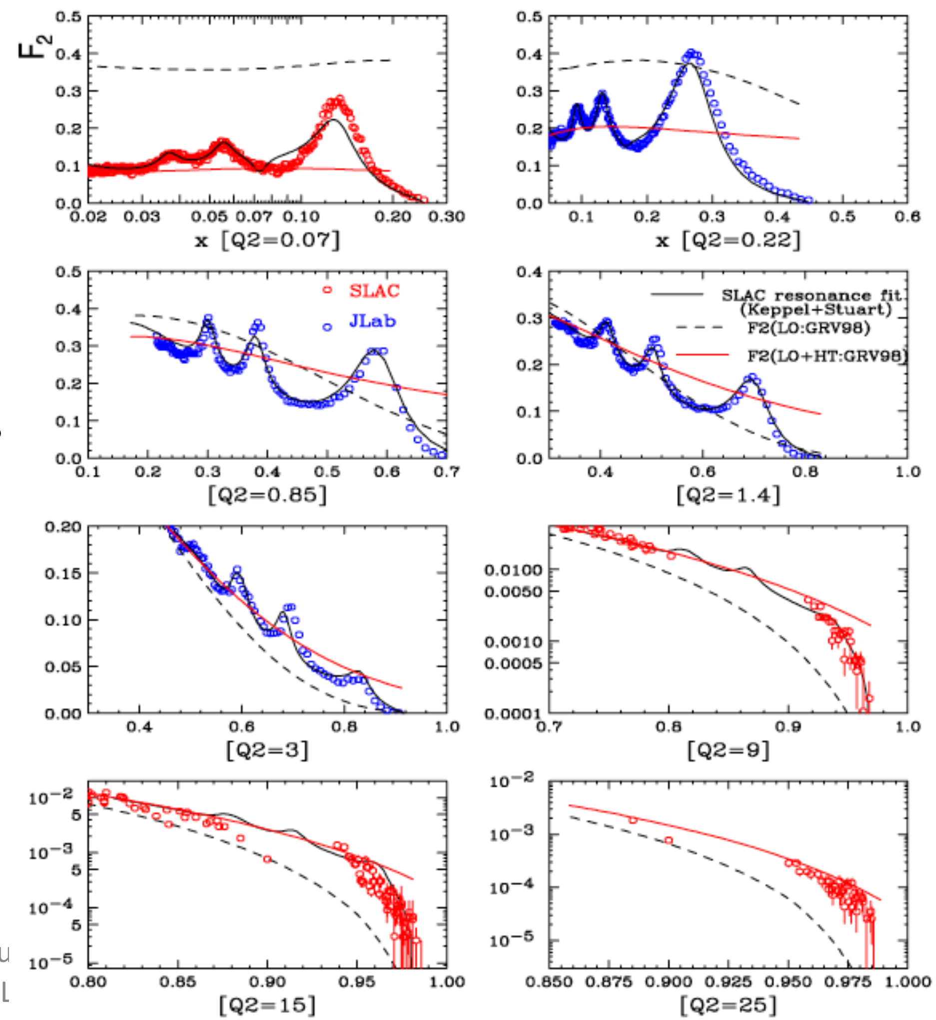
- GRV98 for low $Q^2$ DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data



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

# 2. GENIE SIS model

GENIE is the most widely used neutrino interaction generator



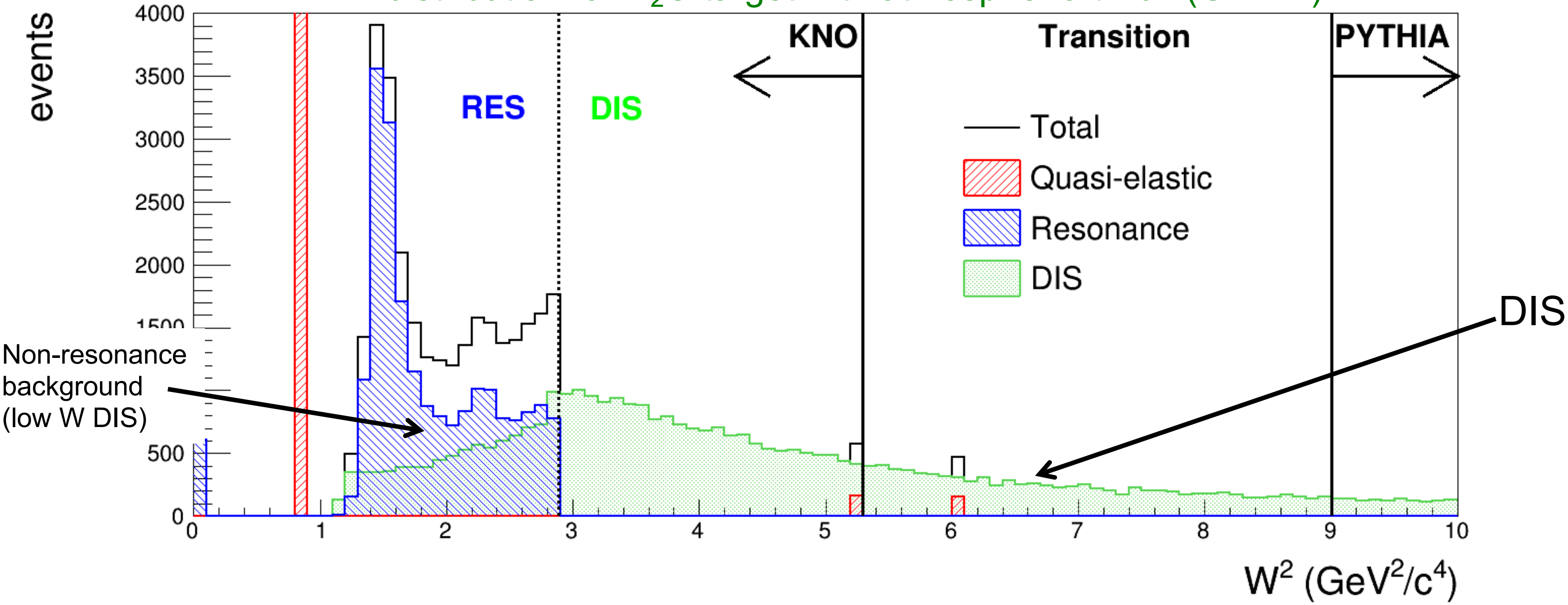
**Cross section**
$W^2$<2.9 $GeV^2$ : RES
$W^2$>2.9 $GeV^2$ : DIS

**Hadronization**
$W^2$<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

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

GENIE v2.8.0



# 2. NEUT SIS model

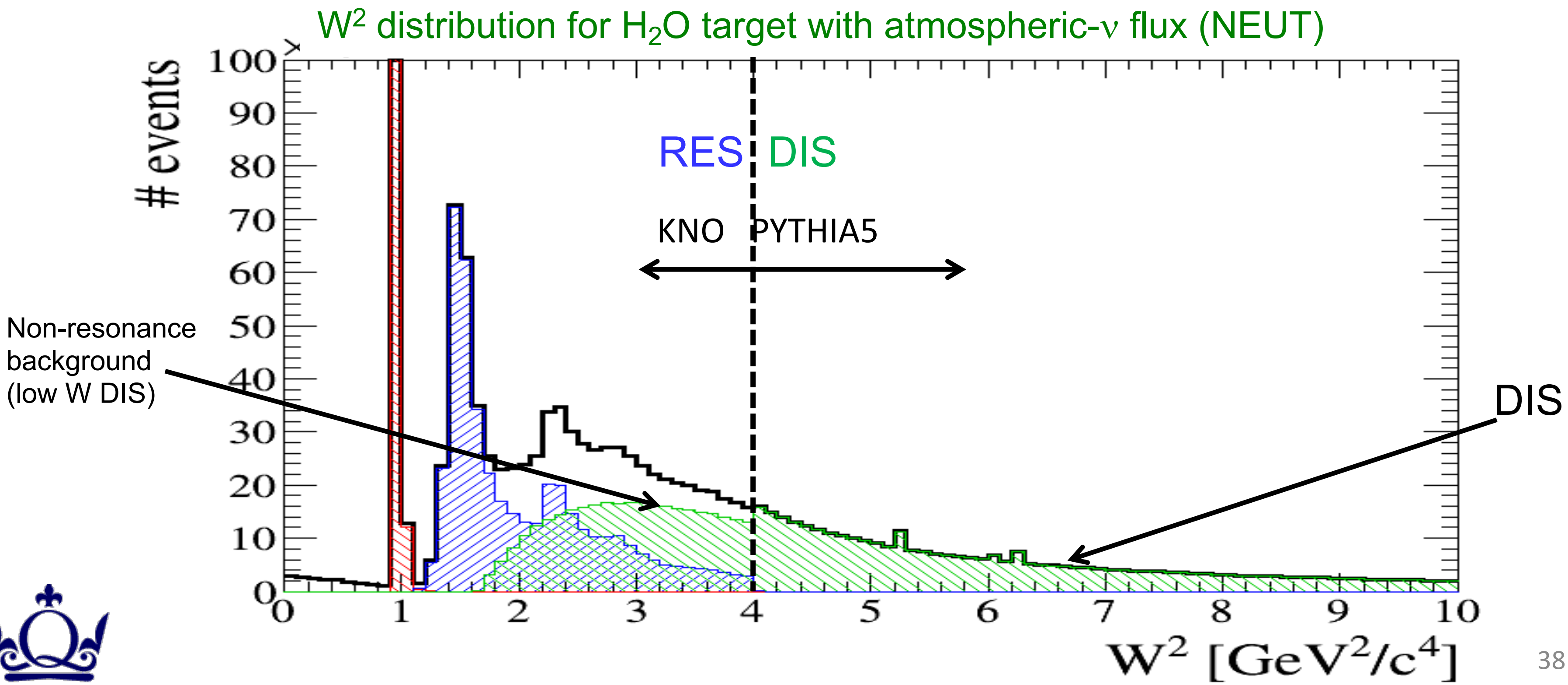
NEUT is the generator used by all Japanese neutrino programs (T2K, SuperK, etc)

**Cross section**
$W^2<4$ $GeV^2$ : RES
$W^2>4$ $GeV^2$ : DIS

**Hadronization**
$W^2<4GeV^2$ : KNO scaling based model
$4GeV^2<W^2$ : PYTHIA5

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

plot made by Christophe Bronner (IPMU)



# 2. NuWro SIS model

NuWro is often used for some studies because of user-friendly structure

Cross section

$W^2<2.5$ GeV$^2$ : RES

$W^2>2.5$ GeV$^2$ : DIS

Hadronization

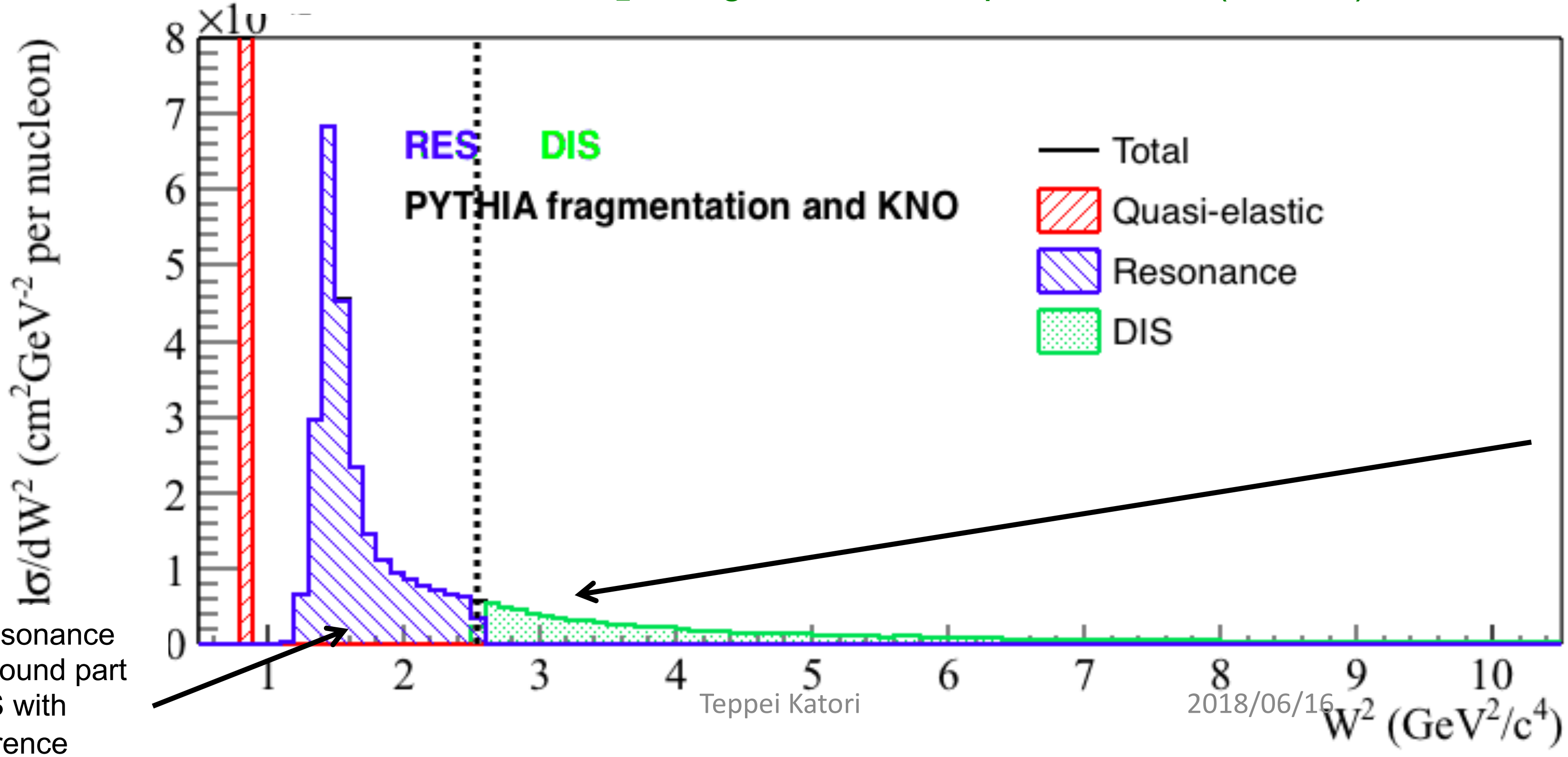
- PYTHIA fragmentation
- KNO scaling

There are 2 kind of "transitions" in SIS region

- cross-section
- hadronization

File made by Luke Pickering (MSU)

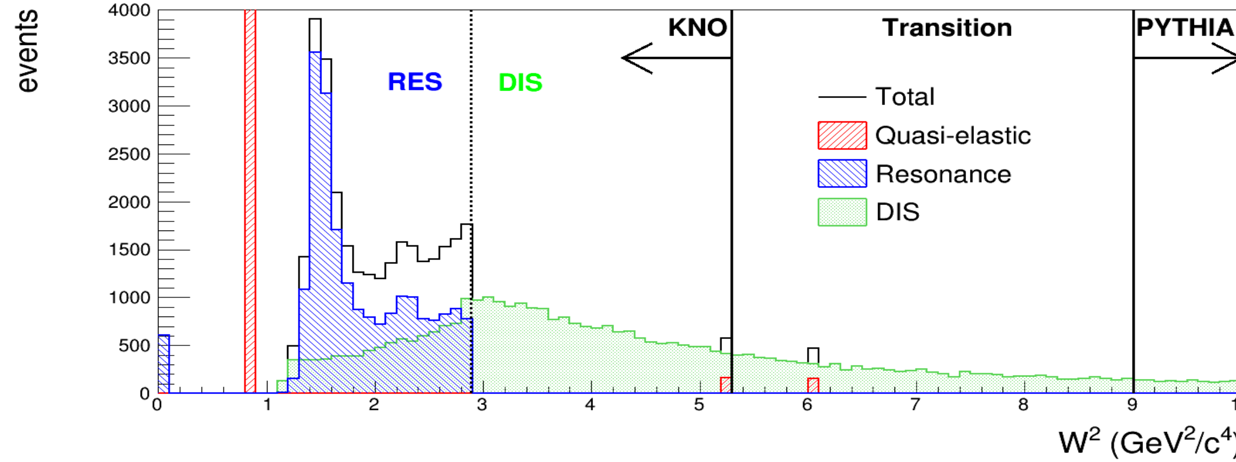
$W^2$ distribution for $H_2O$ target with atmospheric-ν flux (NuWro)




DIS

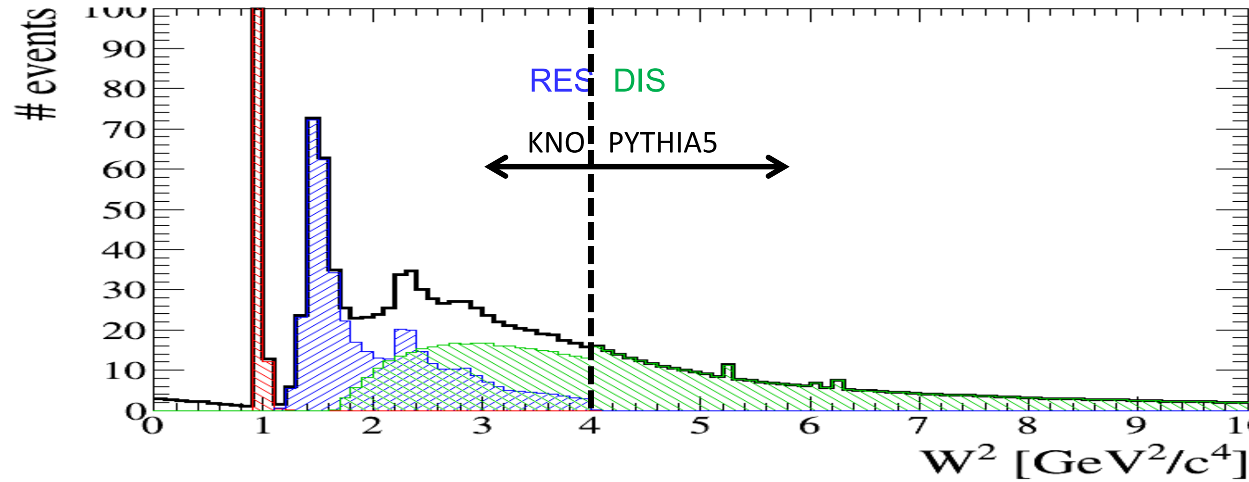
Non-resonance background part of RES with interference

GENIE



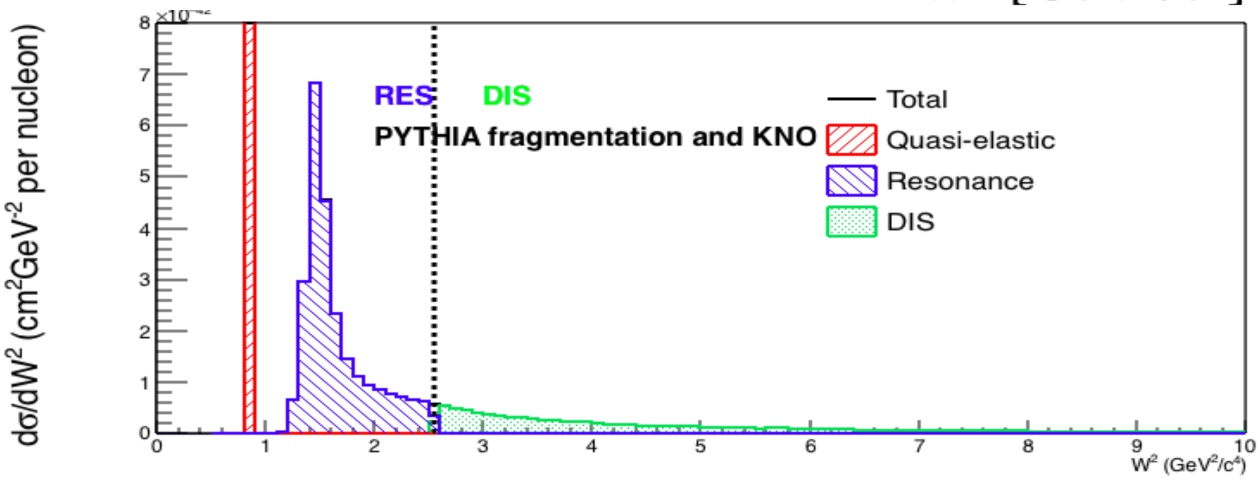

vs

NEUT




vs

NuWro

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# 2. SIS cross section summary 1

Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$ , low W DIS
5. Nuclear dependent DIS

Each sub-field has been developed in a limited kinematics. But it is not easy to combine them together.

The challenge we (=neutrino physics) have is a new kind.



Two rules of neutrino interaction physics

1. Neutrinos cannot choose kinematic
2. Neutrino kinematics are not fully determined

# 1. Neutrino interaction physics

# 2. Shallow-Inelastic scattering (SIS)

# 3. Nuclear-dependent DIS physics

# 4. Neutrino hadronization process

# 5. Conclusion

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

## NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

Check for updates

L. Alvarez-Ruso [a], M. Sajjad Athar [b], M.B. Barbaro [c], D. Cherdack [d], M.E. Christy [e], P. Coloma [f], T.W. Donnelly [g], S. Dytman [h], A. de Gouvêa [i], R.J. Hill [j,f], P. Huber [k], N. Jachowicz [l], T. Katori [m], A.S. Kronfeld [f], K. Mahn [n], M. Martini [o], J.G. Morfín [f,*], J. Nieves [a], G.N. Perdue [f], R. Petti [p], D.G. Richards [q], F. Sánchez [r], T. Sato [s,t], J.T. Sobczyk [u], G.P. Zeller [f]

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

# 3. Nuclear dependent DIS process

1. $\Delta$(1232)-resonance
2. higher resonances
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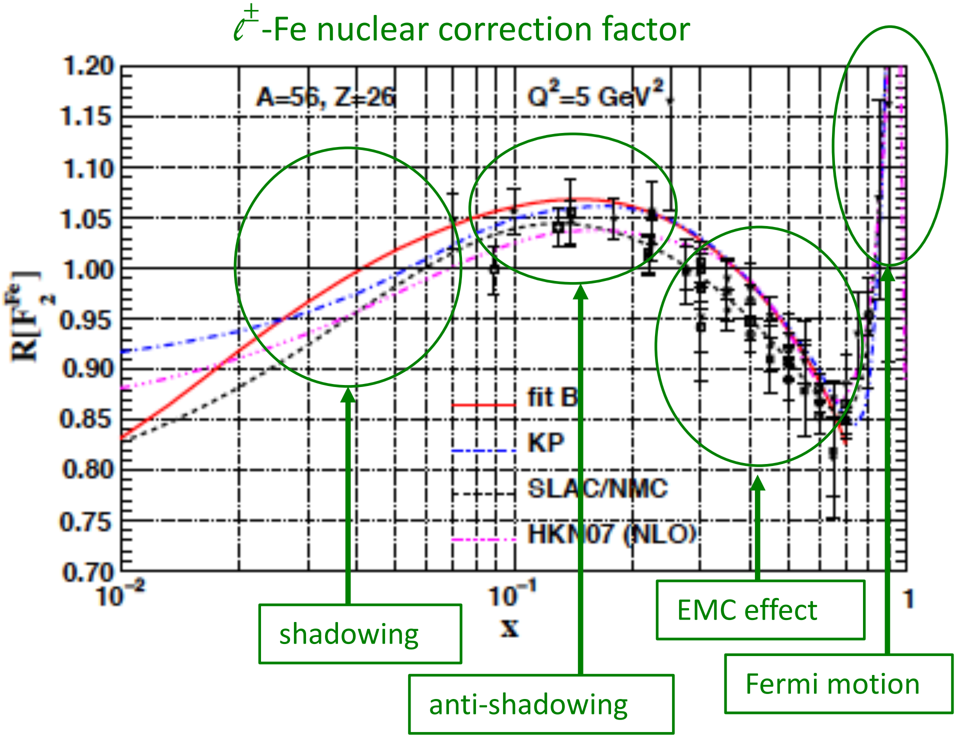
Nuclear PDF
- Shadowing, EMC effect, Fermi motion
- Theoretical origin is under debate
- Various models describe charged lepton data

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



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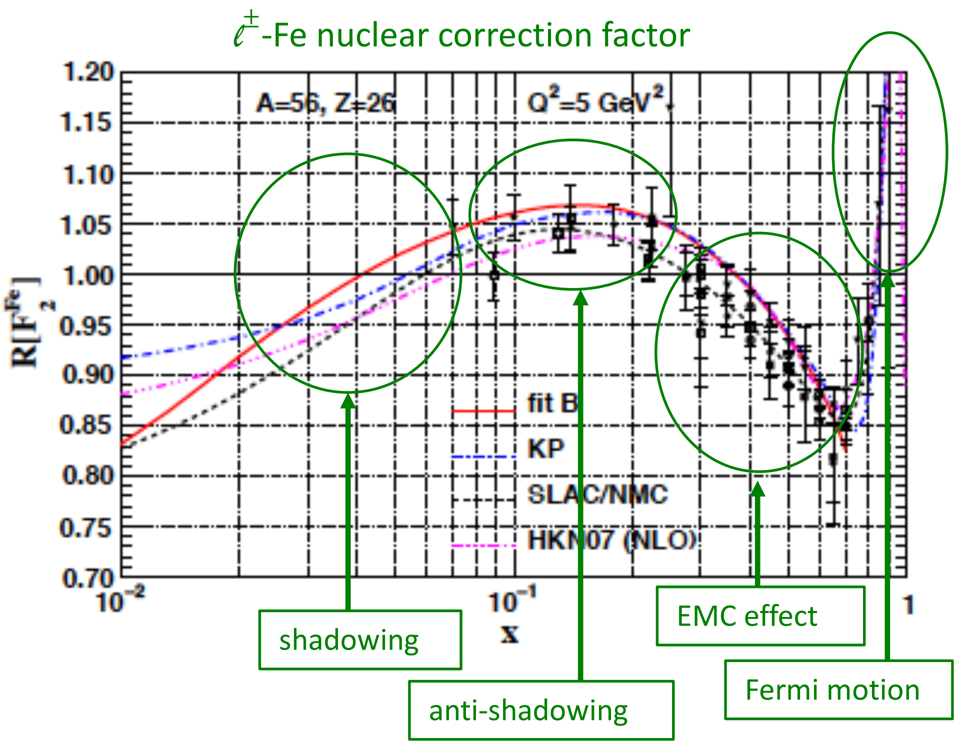
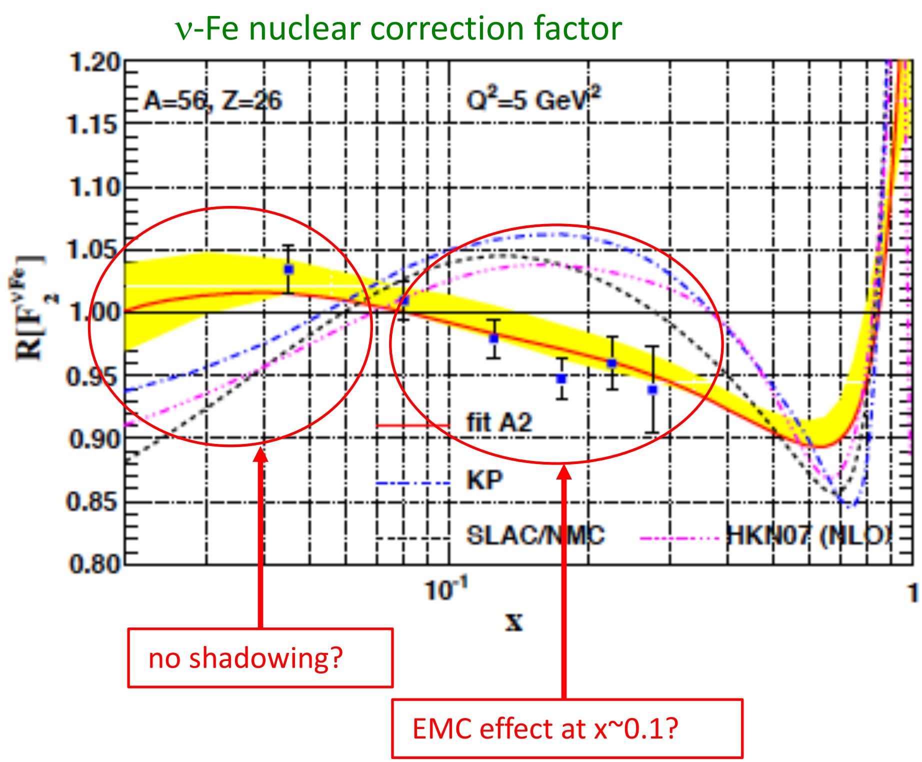
Nuclear PDF
- Shadowing, EMC effect, Fermi motion
- Theoretical origin is under debate
- Various models describe charged lepton data
- Neutrino data look very different



MINERvA,PRD93(2016)071101



# 3. Nuclear dependent DIS process

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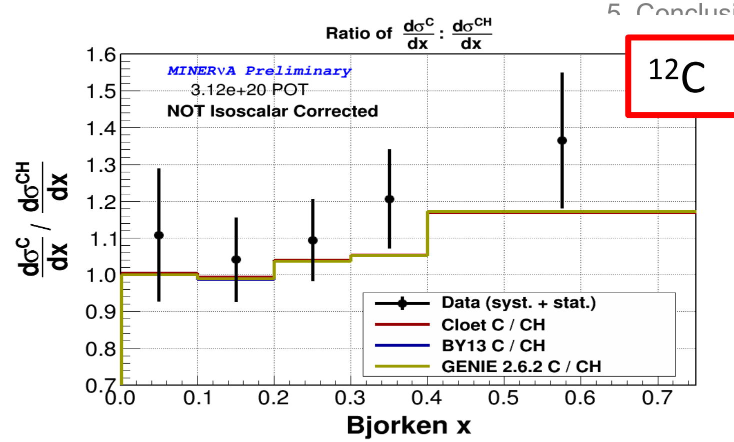
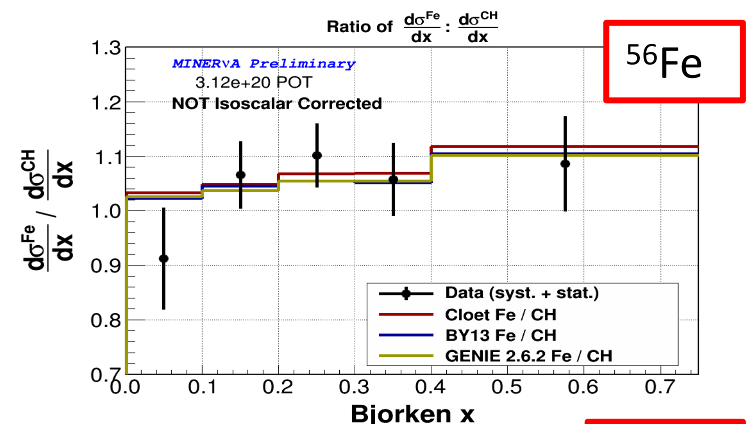
MINERvA DIS target ratio data (C, Fe, Pb)

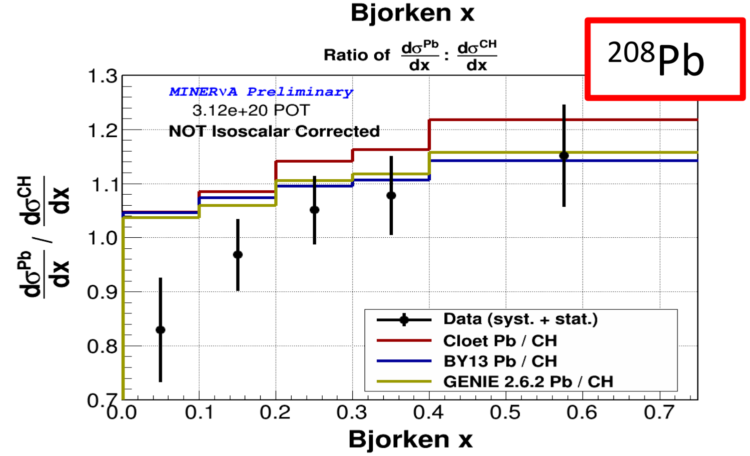
- MINERvA data reveal shadowing effect on neutrino may be larger than expected

We care all nuclear targets

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

MINERvA,PRD93(2016)071101



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# 2. SIS cross section summary 2

Basic ingredients

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5. Nuclear dependent DIS

All precise modern neutrino DIS data from iron target, and many validation data of other nucleus, in particular argon (=DUNE), are missing.

We don't have any neutrino beam for DIS before DUNE starts

Three rules of neutrino interaction physics

1. Neutrinos cannot choose kinematic
2. Neutrino kinematics are not fully determined
3. Neutrinos interact with every material

**Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1**



# 1. Neutrino interaction physics

# 2. Shallow-Inelastic scattering (SIS)

# 3. Nuclear-dependent DIS physics

# **4. Neutrino hadronization process**

# 5. Conclusion

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

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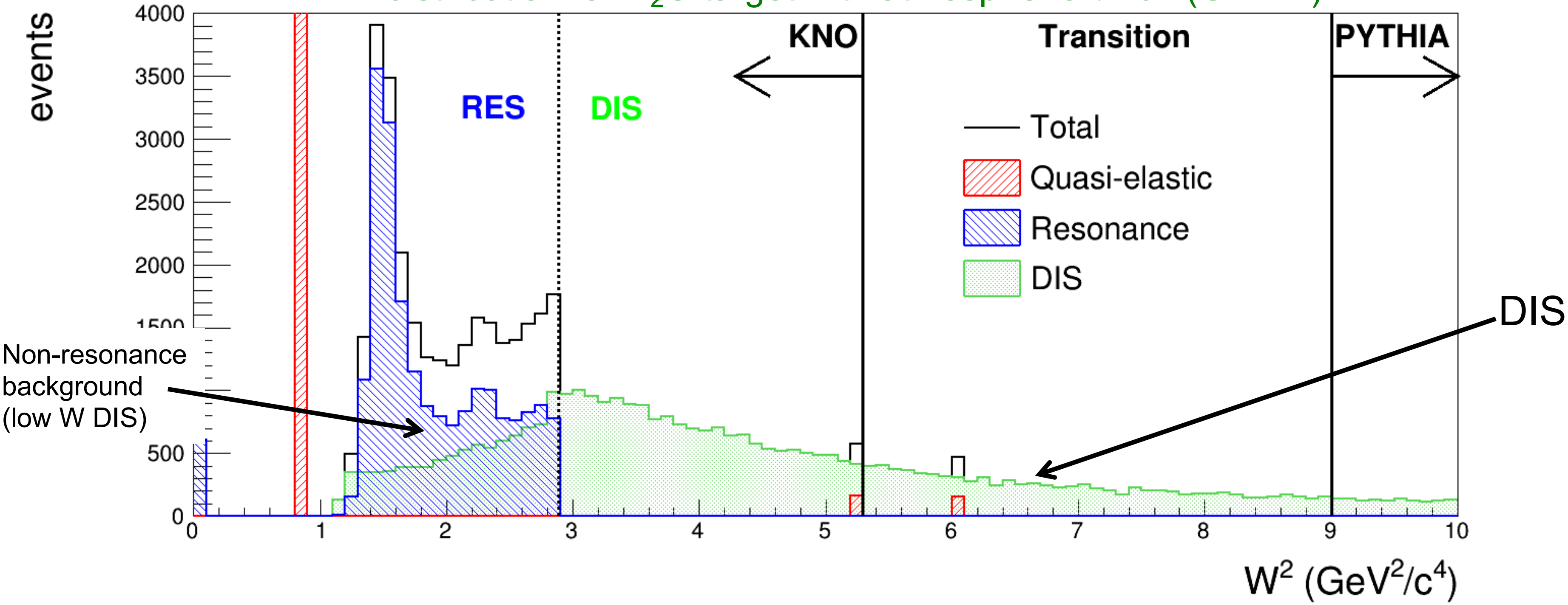


AGKY model, EPJC63(2009)1
TK and Mandalia, JPhysG42(2015)115004, arXiv:1602.00083

# 4. Low-W hadronization model



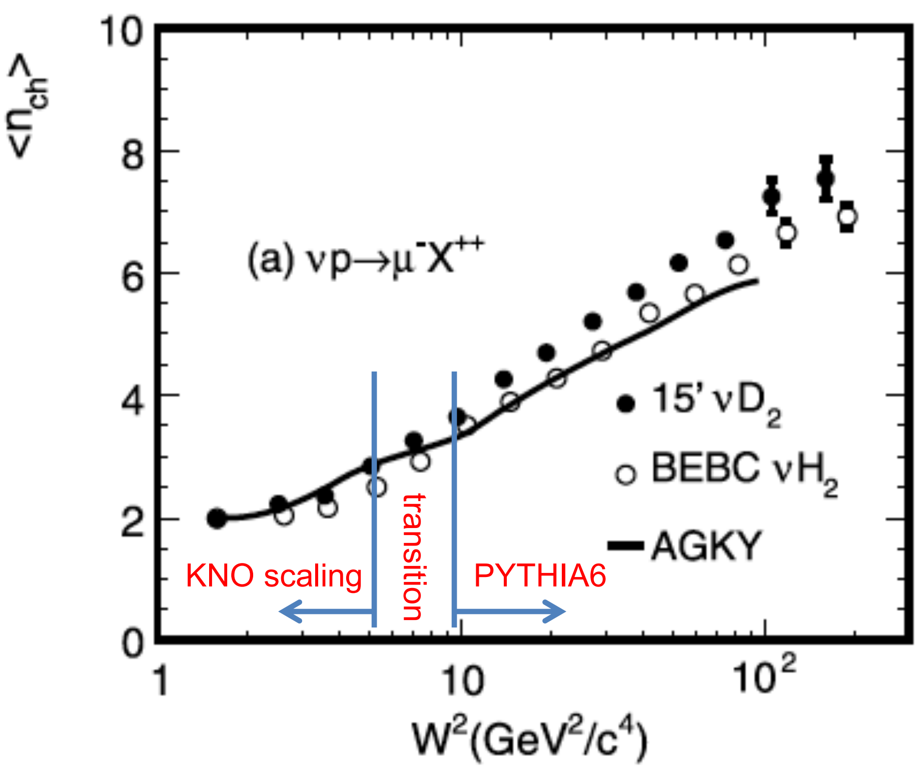
In AGKY model, hadronization model is a combination of 2 models.

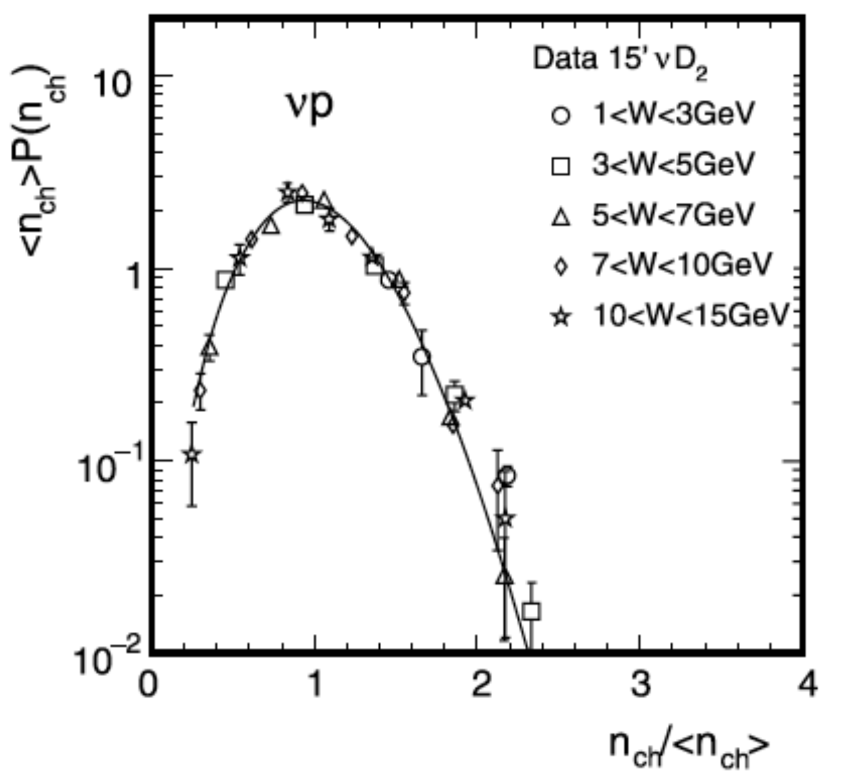
KNO-scaling based model (low W hadronization)

- Data-driven model (agree with bubble chamber data, by construction)
- Averaged charged hadron multiplicity $\langle n_{ch} \rangle$ is chosen from data, with empirical function
- Averaged neutral hadron multiplicity is chosen from isospin.
- Then variance of multiplicity is chosen from KNO-scaling law.

$$\langle n_{ch} \rangle = a_{ch} + b_{ch} \cdot \ln(W^2)$$

$$\langle n \rangle \cdot P(n) = \frac{2e^{-c} c^{cn/\langle n \rangle + 1}}{\Gamma(cn/\langle n \rangle + 1)}$$



Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
http://particlezoo.net/



# 4. High-W hadronization model

## Lund string fragmentation model (PYTHIA)

Lund fragmentation function, f(z), describes distribution of hadrons with z=E/ν, fraction of energy transfer taken by hadron

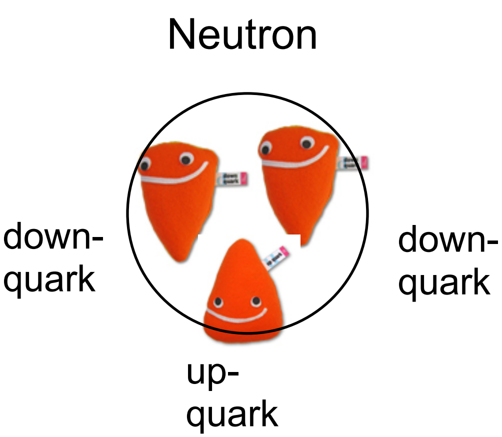
hadron energy distribution from iterative process

$$f(z) \propto z^{-1}(1-z)^{a} \cdot exp(-bm_{\perp}^{2}/z)$$

"transverse mass"

$$m_{\perp}^{2} = m^{2} + p_{x}^{2} + p_{y}^{2}$$

tunnelling probability




time

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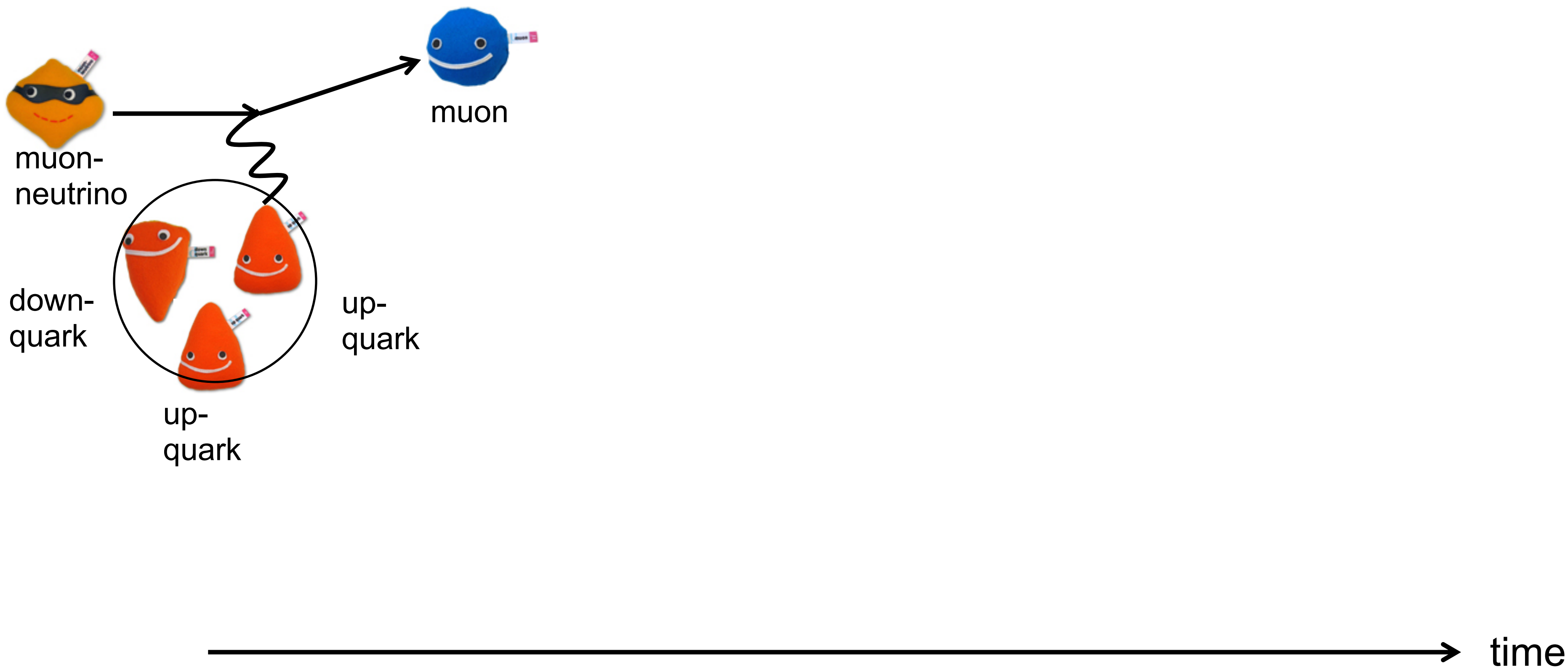
"transverse mass"

$$m_{\perp}^{2} = m^{2} + p_{x}^{2} + p_{y}^{2}$$

tunnelling probability



Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
http://particlezoo.net/

# 4. High-W hadronization model

## Lund string fragmentation model (PYTHIA)

Lund fragmentation function, f(z), describes distribution of hadrons with z=E/ν, fraction of energy transfer taken by hadron

hadron energy distribution from iterative process

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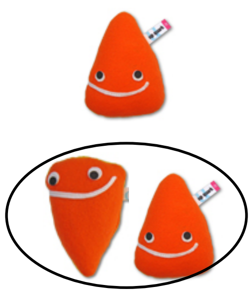
tunnelling probability

quark

di-quark



time

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
http://particlezoo.net/



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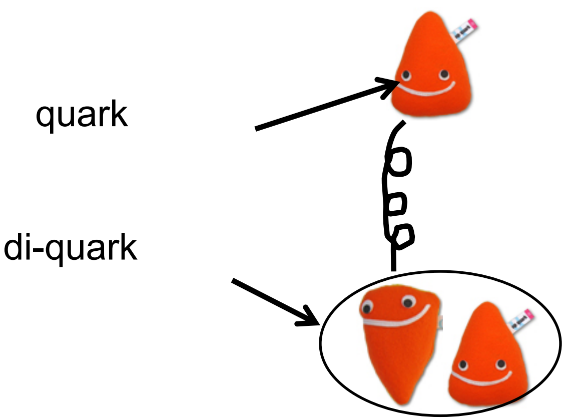
~1GeV/fm




## Linear confinement

- colour flux to minimize surface area

→ string

time

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
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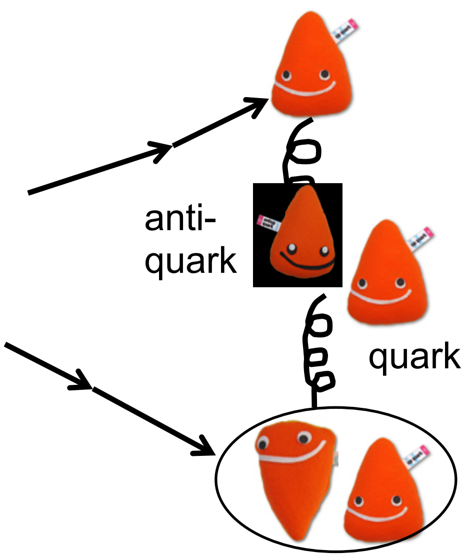


### Linear confinement

- colour flux to minimize surface area

→ string

### String breaking

- quantum tunnelling
- enough energy to produce a $q\bar{q}$ pair

$$u\bar{u}: d\bar{d}: s\bar{s}: c\bar{c} = 1:1:0.3:10^{-11}$$

time

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
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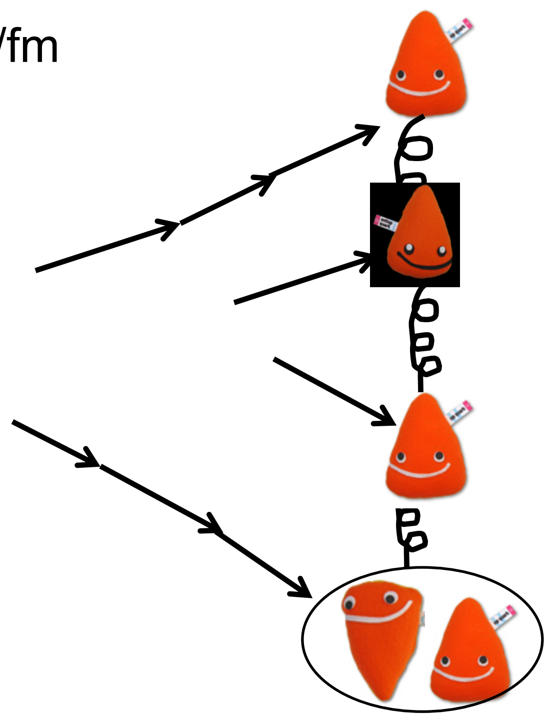

time

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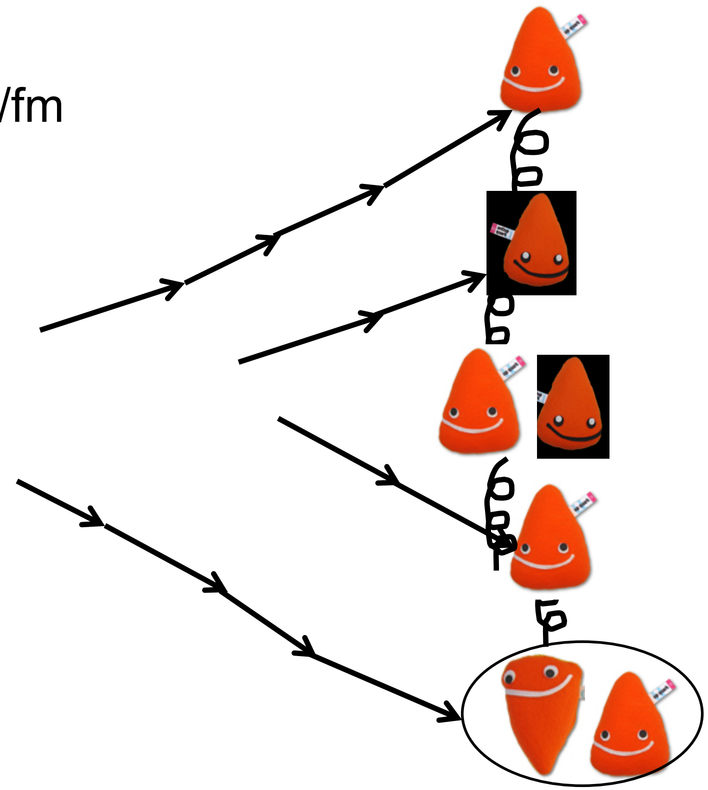

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Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
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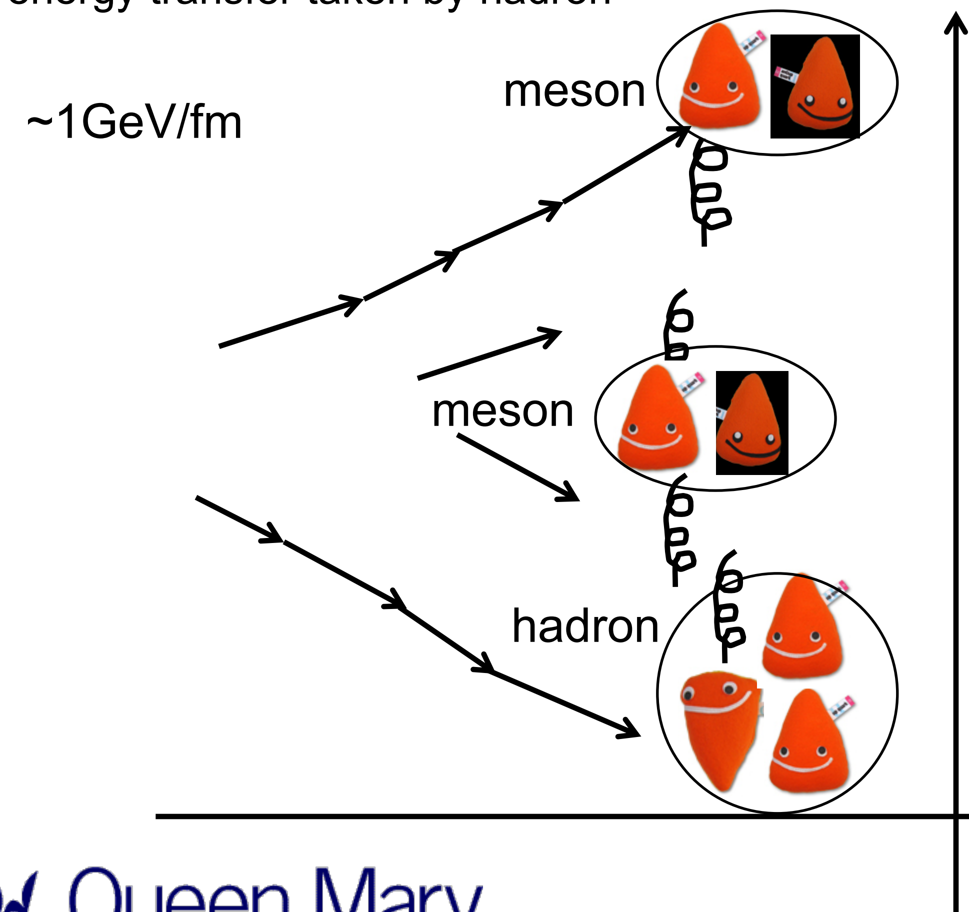


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### Quark confinement

- 4 vectors of hadrons are produced

time

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
http://particlezoo.net/



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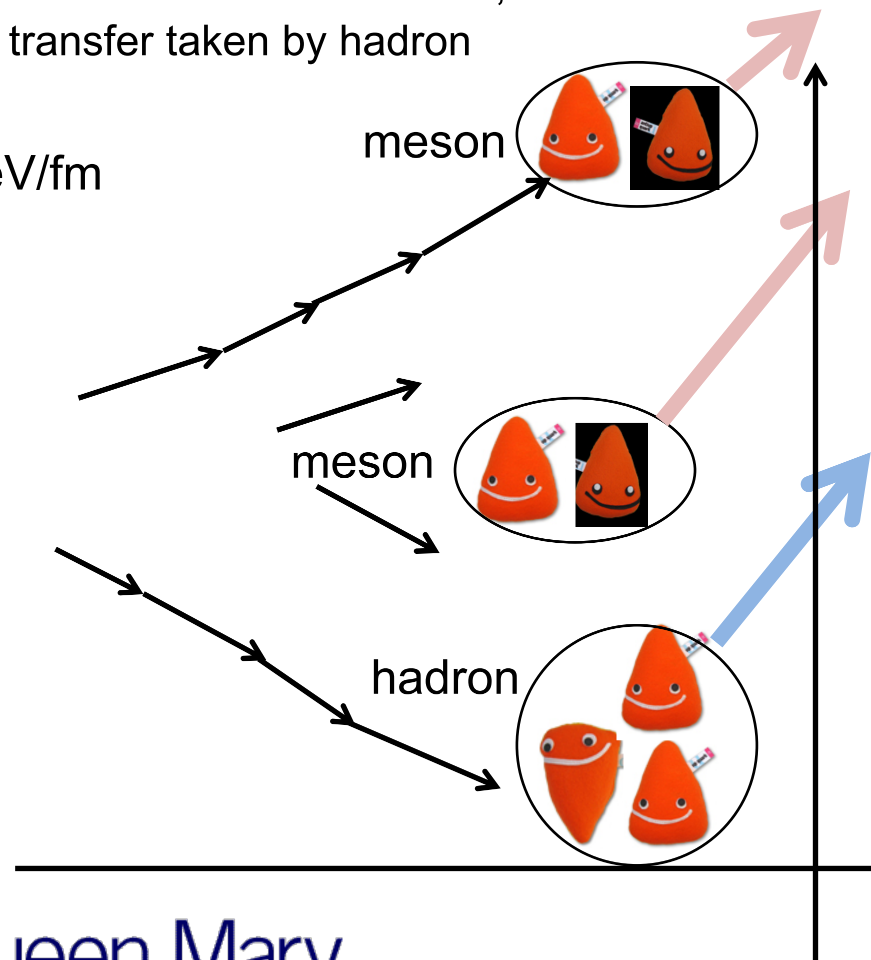
~1GeV/fm




time

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→ string

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### Quark confinement

- 4 vectors of hadrons are produced

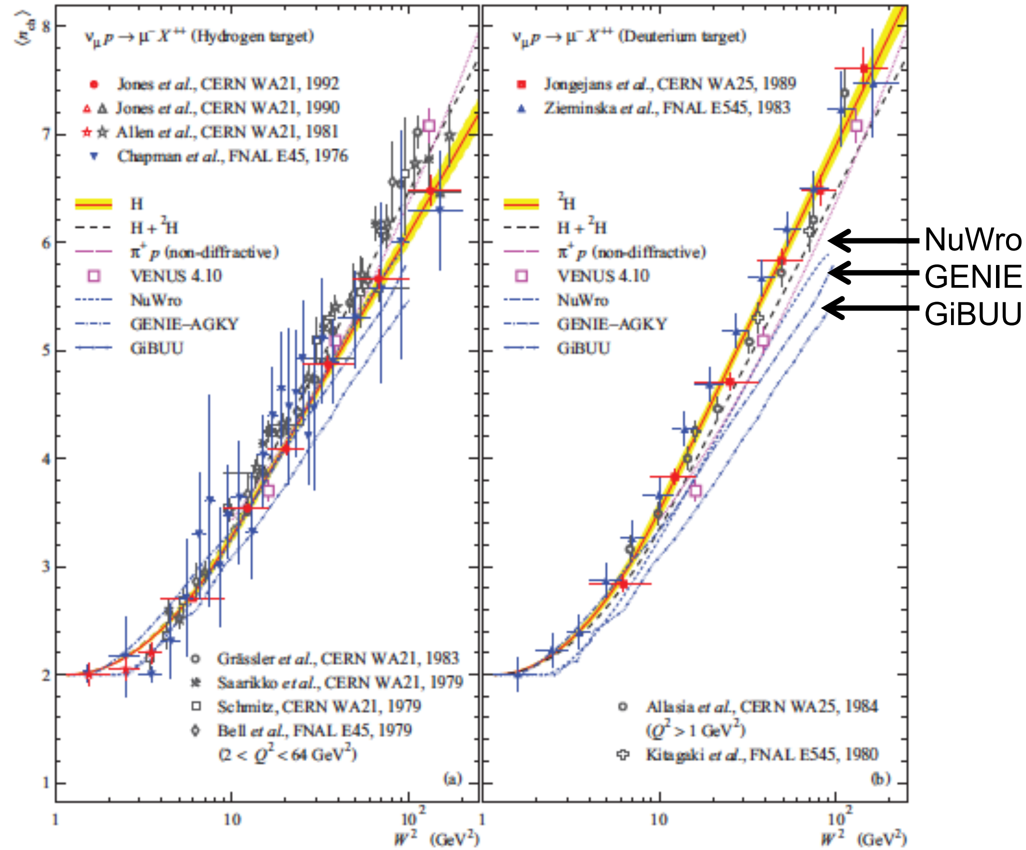
# 4. High-W hadronization model



## Kuzmin-Naumov fit

- They systematically analysed all bubble chamber data
  - Difference of hydrogen and deuterium data
  - Presence of kinematic cuts
  - Better parameterization

All PYTHIA-based models underestimate averaged charged hadron multiplicity data (GiBUU, GENIE, NuWro, NEUT)




Average charged hadron multiplicity with function of $W^2$

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
Gallmeister and Falter, PLB630(2005)40, TK and Mandalia,JPhysG42(2015)115004

# 4. High-W hadronization model



Averaged charged hadron multiplicity <$n_{ch}$>

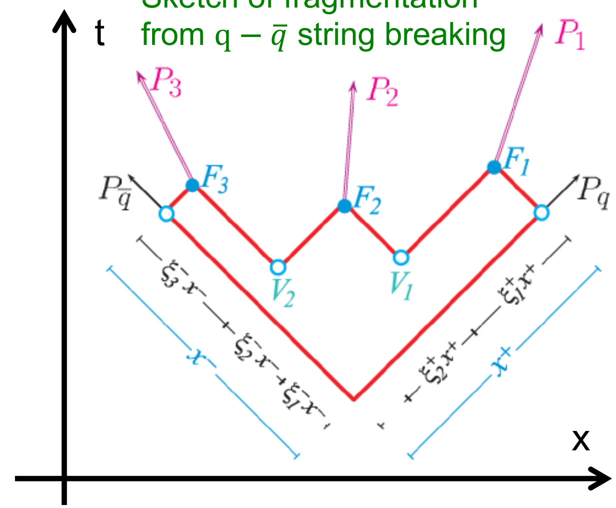
- PYTHIA6 with tuned Lund string function can reproduce <$n_{ch}$> data both neutrino and antineutrino.

Lund string function

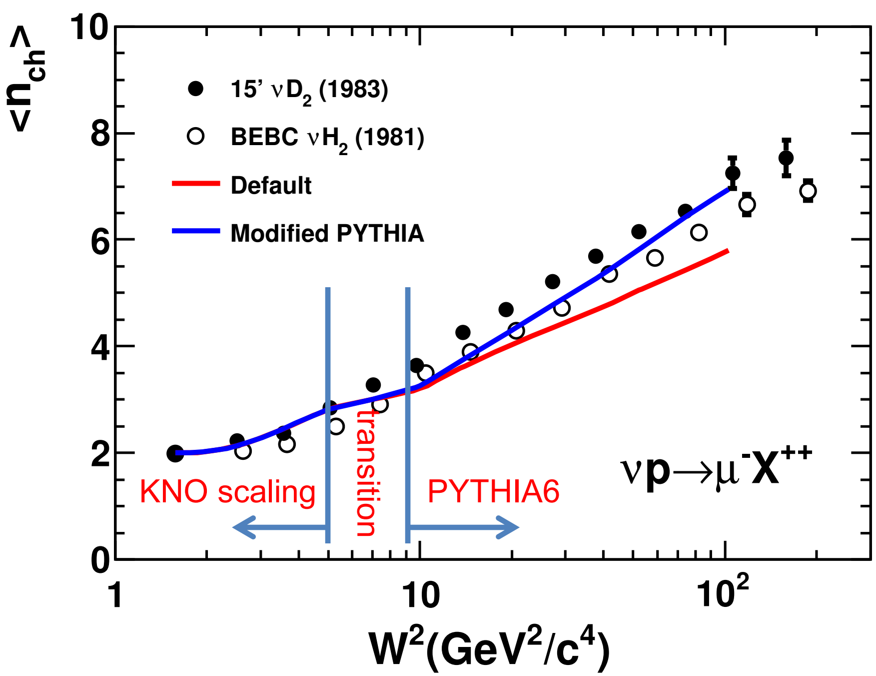
hadron energy distribution from iterative process

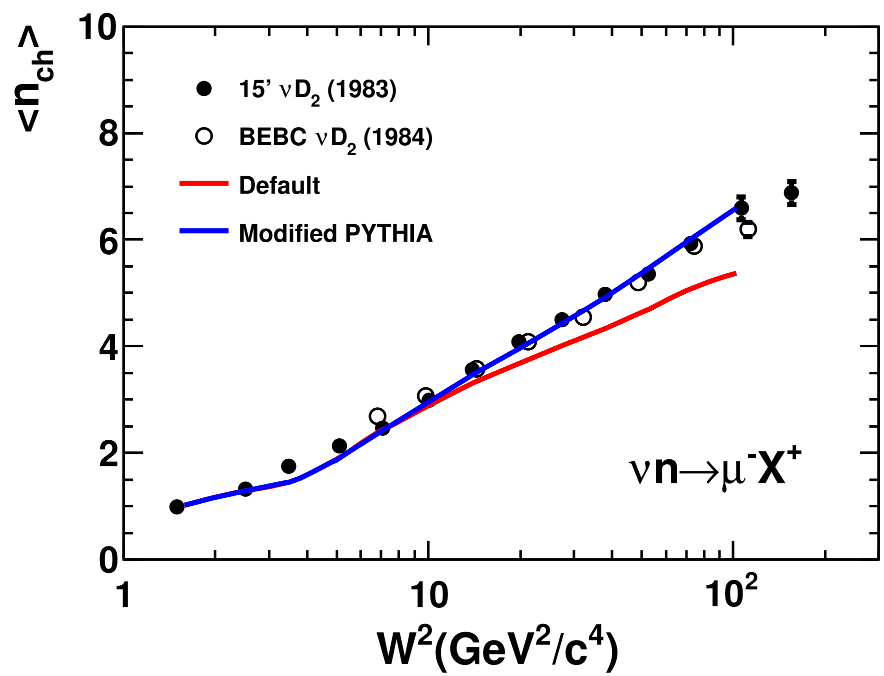
tunnelling probability

$$f(z) \propto z^{-1}(1-z)^a \cdot exp(-bm_\perp^2/z)$$




Neutrino average charged hadron multiplicity



TK and Mandalia,JPhysG42(2015)115004
Zieminska et al (Fermilab 15'),PRD27(1993)47

# 4. High-W hadronization dispersion error?

Shivesh Mandalia
(Queen Mary)

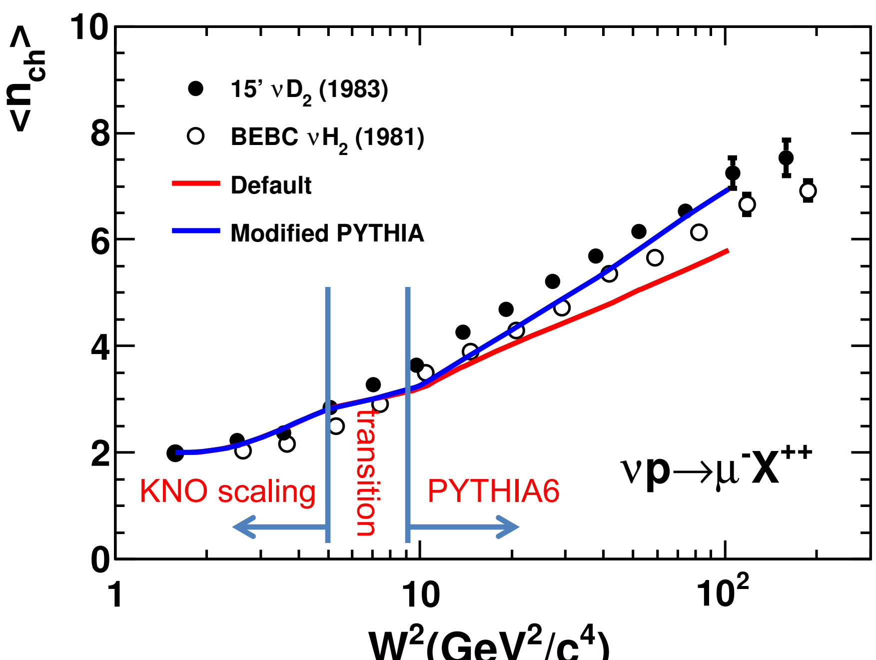


## Bubble chamber topological cross section data

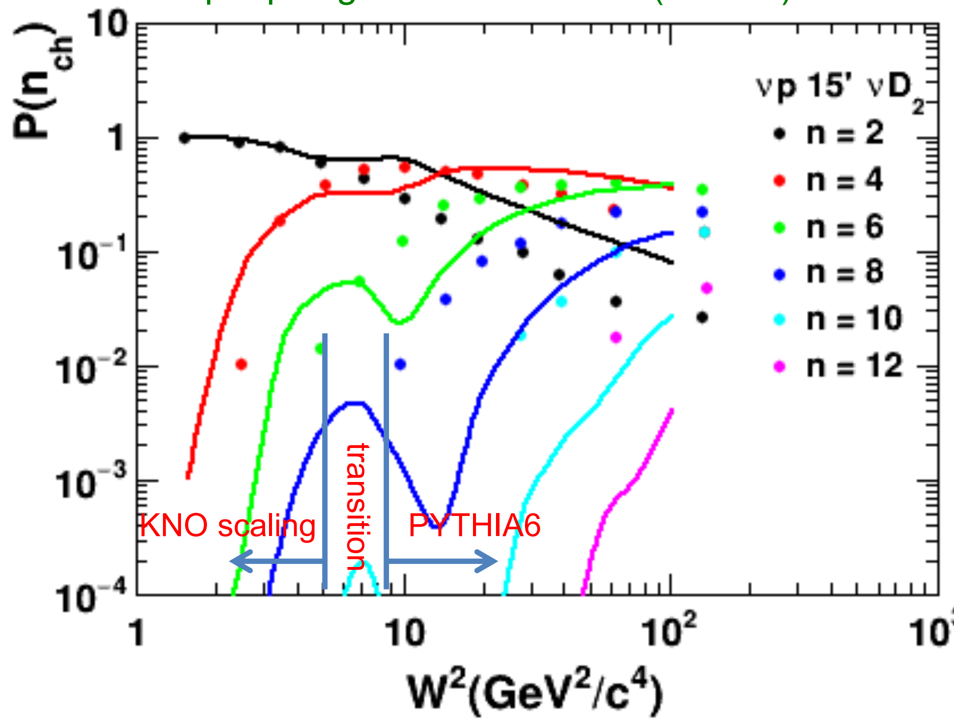
Although averaged charged hadron multiplicity makes continuous curve, topological cross sections are discontinuous, because multiplicity dispersion by PYTHIA6 is much narrower than bubble chamber data.

If the experiment is sensitive to hadron counting, you need to re-think how to propagate hadronization error…

Neutrino average charged hadron multiplicity




$\nu$-p topological cross section (GENIE)



Guenette (MicroBooNE), Neutrino 2018

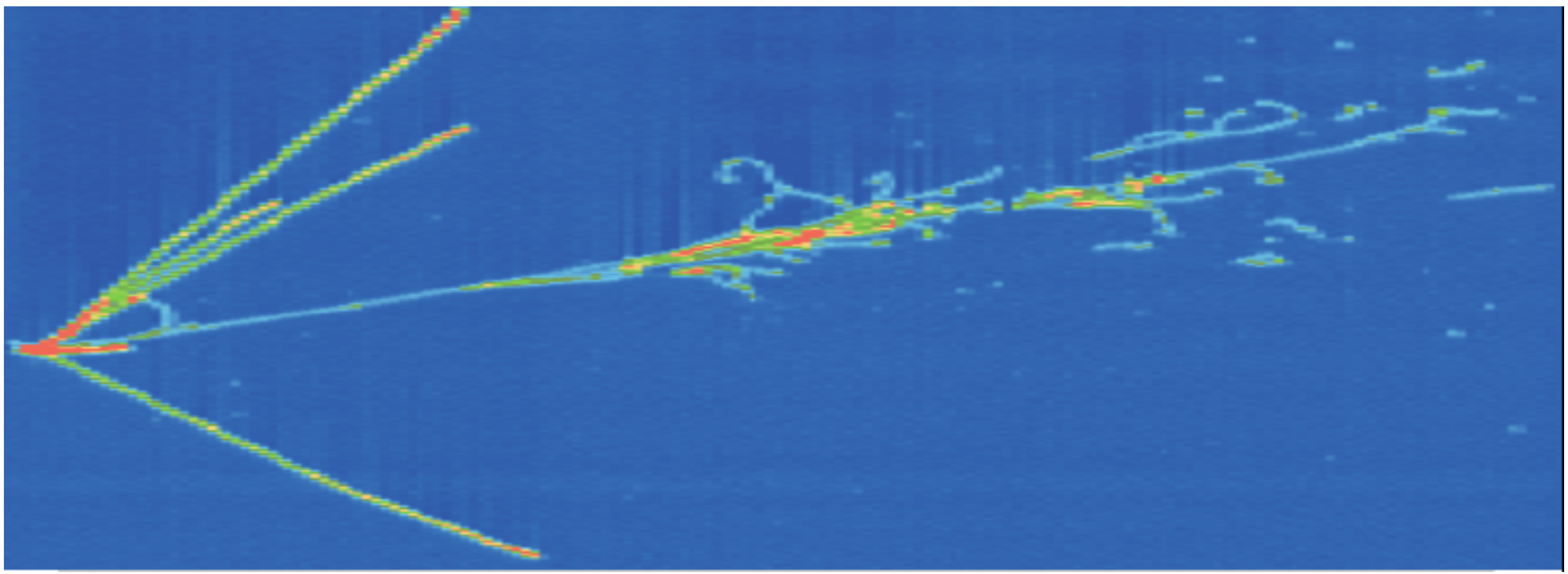
# 4. Hadronization summary



LArTPC is a high resolution detector to measure exclusive final states of hadrons

Due to lack of manpower (or motivation?), neutrino hadronization is a forgotten subject

Validation data are lacking (again, argon!)



**Alvarez-Ruso et al, Prog.Part.Nucl.Phys.100(2018)1**



## 1. Neutrino interaction physics

## 2. Shallow-Inelastic scattering (SIS)

## 3. Nuclear-dependent DIS physics

## 4. Neutrino hadronization process

## 5. Conclusion

Progress in Particle and Nuclear Physics 100 (2018) 1–68

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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Queen Mary
University of London

# Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…

- nuclear many-body problem
- Spin physics
- Weak interaction
- Neutrino oscillation
- Dark matter
- EMC effect

**Neutrino Interaction Physics**

- Nucleon correlation
- electron scattering
- Heavy ion collision

# NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

http://nustec.fnal.gov/

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

Theorists
Luis Alvarez Ruso (co-spokesperson, IFIC, Spain)
Mohammad Sajjad Athar (Aligarh Muslim University, India)
Maria Barbaro (University of Turin, Italy)
Omar Benhar (Sapienza University of Rome, Rome, Italy)
Richard Hill (University of Kentucky and Fermilab, USA)
Patrick Huber (Center for neutrino physics, Virginia Tech, USA)
Natalie Jachowicz (Ghent University, Belgium)
Andreas Kronfeld (Fermilab, USA)
Marco Martini (IRFU Saclay, France)
Toru Sato (Osaka, University, Japan)
Rocco Schiavilla (Old Dominion Univ. and Jefferson Lab, USA)
Jan Sobczyk (nuWro representative, University of Wroclaw, Poland)

Experimentalists
Sara Bolognesi (CEA-IRFU, France)
Steve Brice (Fermilab, USA)
Raquel Castillo Fernández (Fermilab, USA)
Dan Cherdack (Colorado State University, USA)
Steve Dytman (University of Pittsburgh, USA)
Andy Furmanski (University of Manchester, UK)
Yoshinari Hayato (NEUT representative, ICRR, Japan)
Teppei Katori (Queen Mary University of London, UK)
Kendall Mahn (Michigan State University, USA)
Camillo Mariani (Center for neutrino physics, VirginiaTech, USA)
Jorge G. Morfin (co-spokesperson, Fermilab, USA)
Ornella Palamara (Fermilab, USA)
Jon Paley (Fermilab, USA)
Roberto Petti (University of South Carolina, USA)
Gabe Perdue (GENIE representative, Fermilab, USA)
Federico Sanchez (IFAE, University of Barcelona, Spain)
Sam Zeller (Fermilab, USA)

# NuSTEC white paper

https://arxiv.org/abs/1706.03621

- It addresses all topics of neutrino-nucleus scattering around 1-10 GeV.

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

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# NuSTEC school

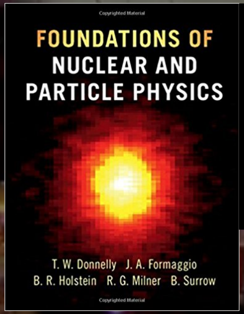
NuSTEC Training in Neutrino-Nucleus Scattering Physics

Nov.8-14, 2015, Okayama, Japan

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

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

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




Foundation of Nuclear and Particle Physics

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

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

https://nuint2017.physics.utoronto.ca/

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


NuInt18, Gran Sasso Science Institute (GSSI), Italy, October 15-19, 2018
https://indico.cern.ch/event/703880/

# Neutrino Shallow and Deep-Inelastic scattering, GSSI, Oct 11-13

http://nustec.fnal.gov/nuSDIS18/

A dedicated workshop for physics related to DUNE, NOvA, etc
- generator developments, impact on oscillation analyses
- higher resonance and non-resonance contributions
- low Q2 low W DIS
- nuclear modifications and nuclear-dependent PDFs
- neutrino hadronization problem

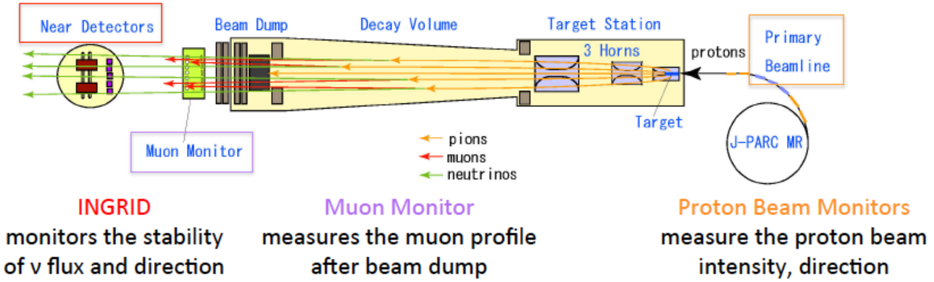

**Thank you for your attention!**
**(register now!)**

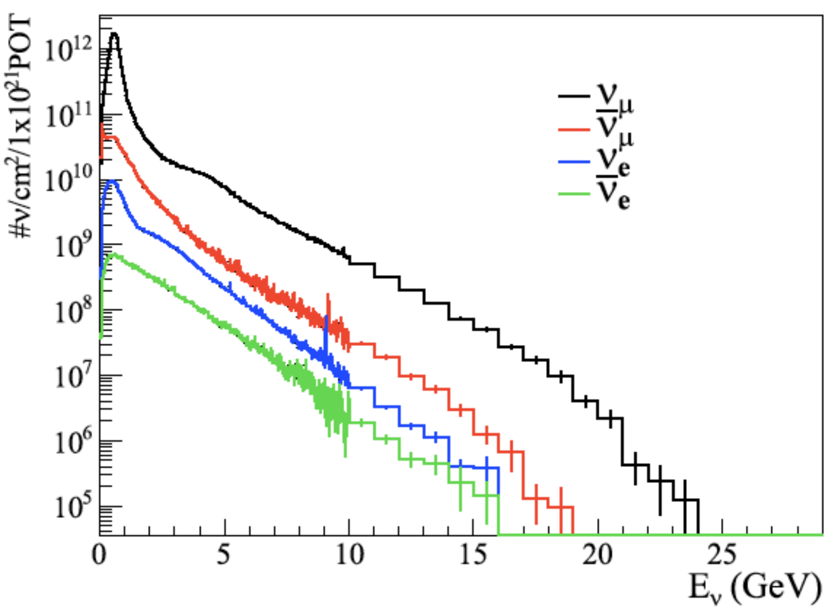
# Back up

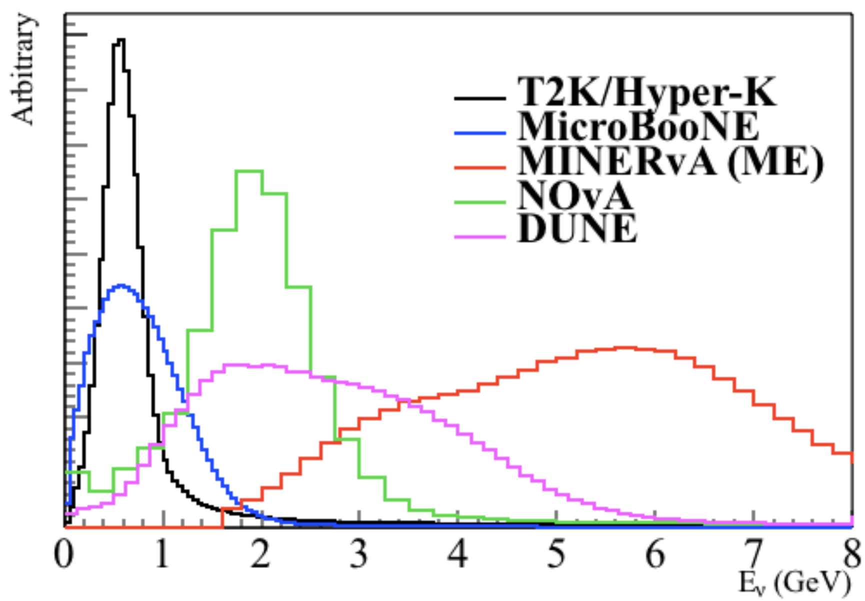
# 1. Typical neutrino beams for oscillation experiments



e.g.) J-PARC neutrino beam (T2K)
- pion decay-in-flight (high flux)
- off-axis beam (narrow band)
- but has components up to ~ 10 GeV
- typical beam 1-10 GeV
- ~4% normalization error (best case)



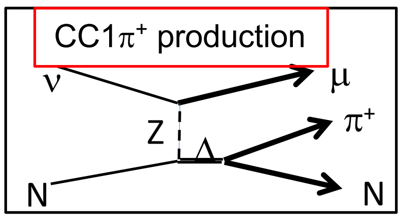

$$P_{\mu\to e}(L/E)=\sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

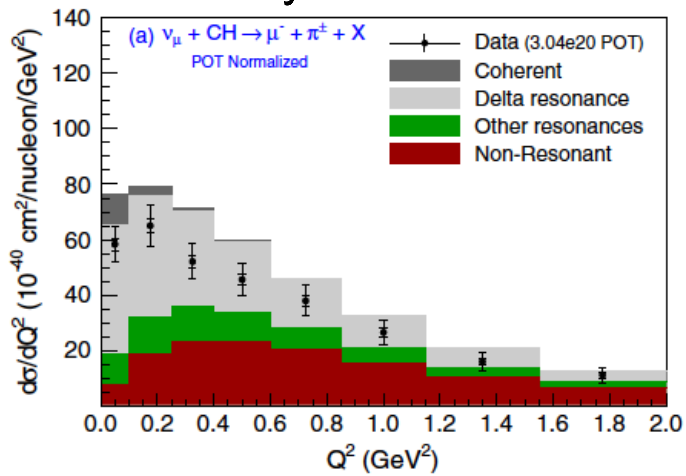
# 1. MINERvA FSI and cross section model tuning (2016)

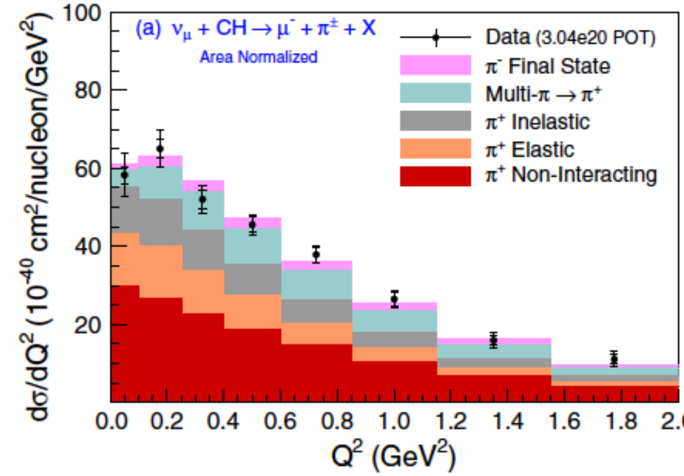
## MINERvA CC1$\pi^+$, $\bar{\nu}$CC1$\pi^o$, $\nu$CC1$\pi^o$ data simultaneous fit

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

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

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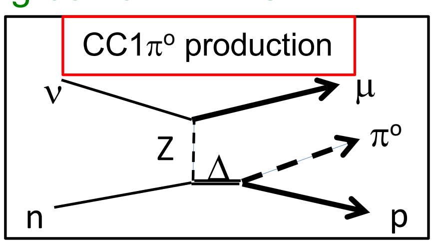
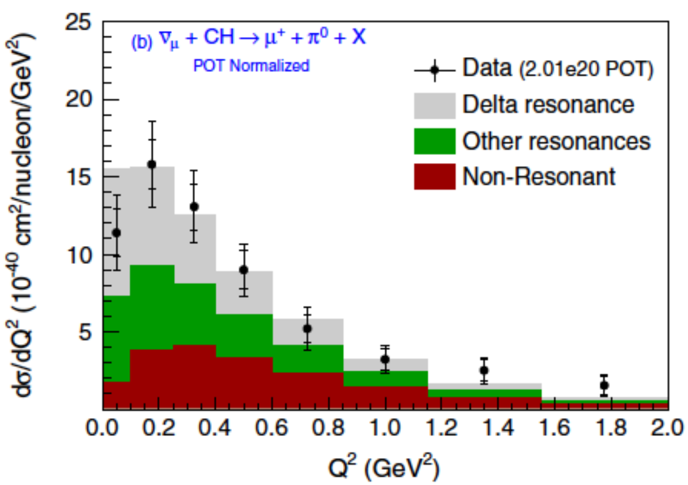
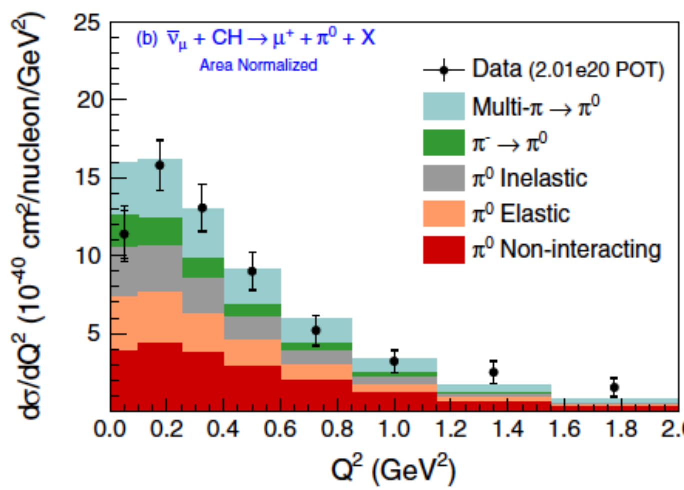


# 1. Neutrino cross section overview



GENIE uses “Frankenstein” model…, there are 2 transtions for both cross section and hadronization

**Cross section**

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

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

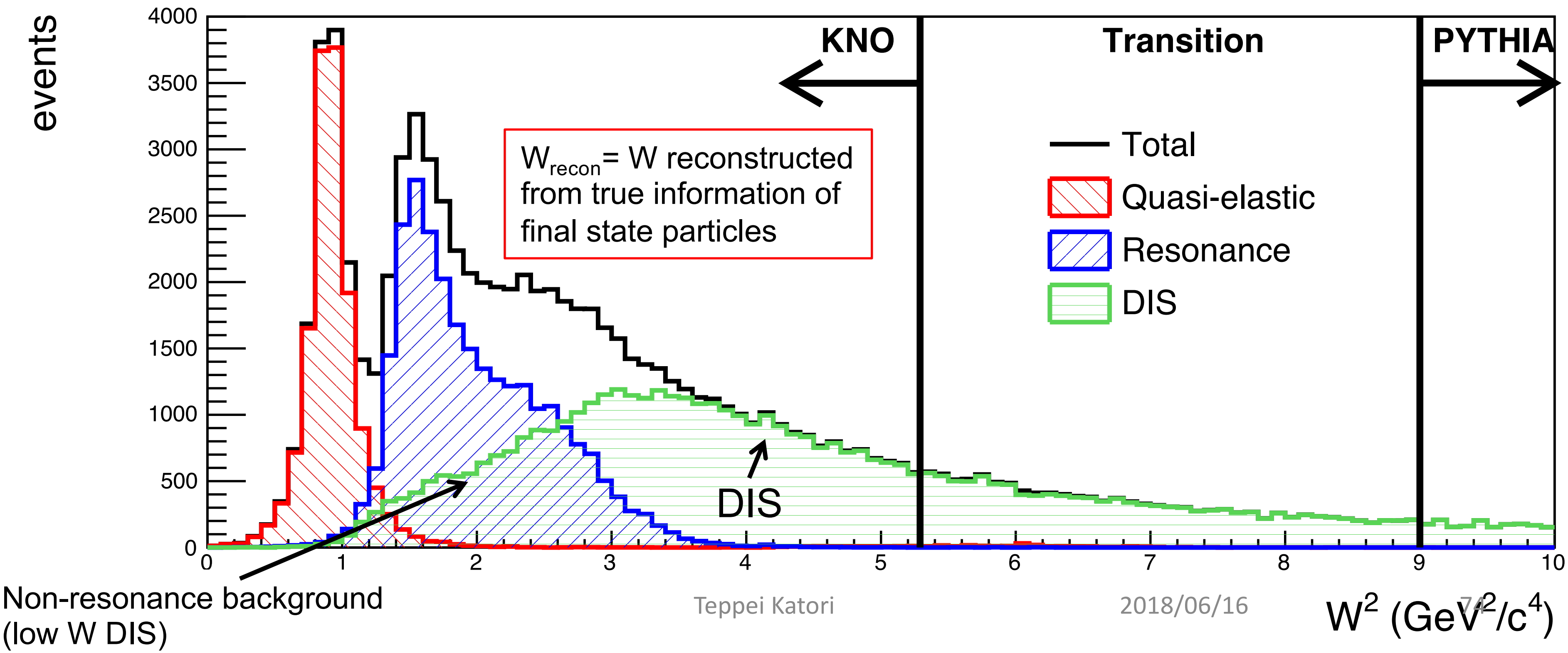
**Hadronization (AGKY model)**

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

5.3$GeV^2$<$W^2$<9.0$GeV^2$ : transition

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

$\nu_\mu$CC on $H_2O$ target with atmospheric neutrino flux in $W_{recon}$



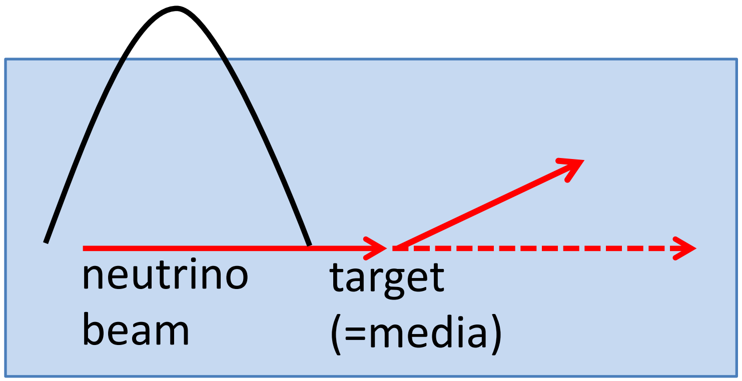
Ankowski et al, PRD92(2015)073014

# 1. Kinematic E reconstruction vs calorimetric E reconstruction

Neutrino scattering

- Wideband beam

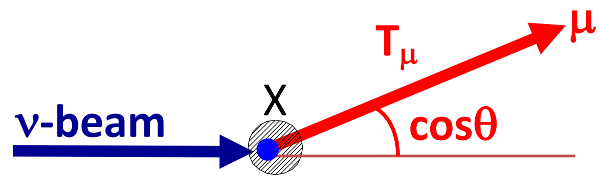
→ observables are inclusive




Incomplete kinematics

- Large mass, coarse instrumentation
- No one measures neutrino energy directly
- Reconstructing kinematics (Ev, Q2, W, x, y,...) in 1-10 GeV depends on interaction models

1. Kinematics energy reconstruction
 - problem: you have to assume neutrino interact with single nucleon




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

2. Calorimetric energy reconstruction
 - problem: you have to measure energy deposit from all outgoing particles

$$E_\nu^{Cal} = E_\mu + \sum_{i=1}^{all} E_{had}^i$$

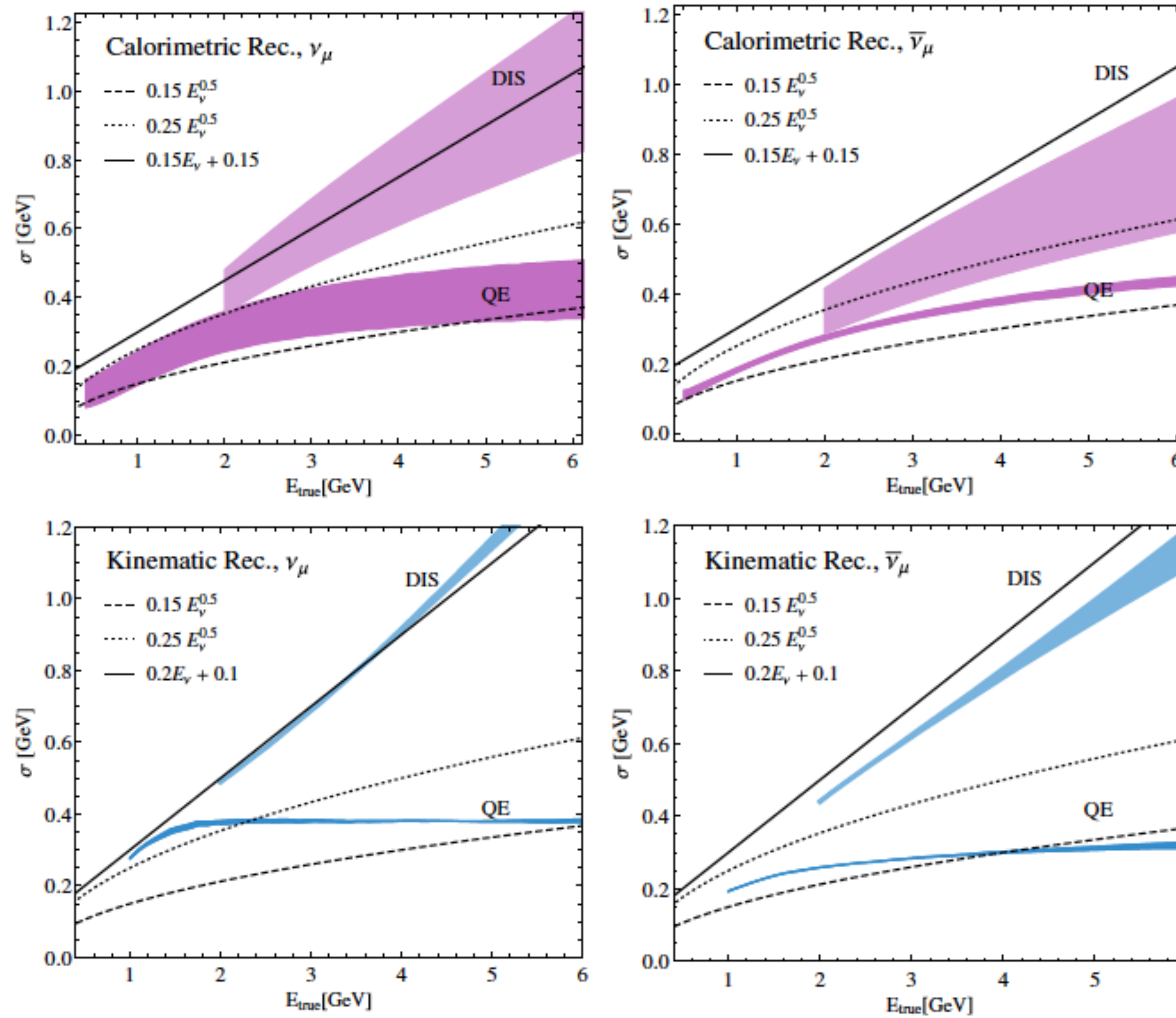
Ankowski et al, PRD92(2015)073014

# 1. Kinematic E reconstruction vs calorimetric E reconstruction

Calorimetric energy reconstruction suffers invisible hadrons (=neutrons)

It largely depends on neutrino interaction and hadron simulation
- multiplicity
- kinematics
- nuclear effect
  - re-scattering
  - charge exchange
  - baryonic resonance
  - nucleon correlation

etc



T2K collaboration, PRL118(2017)151801

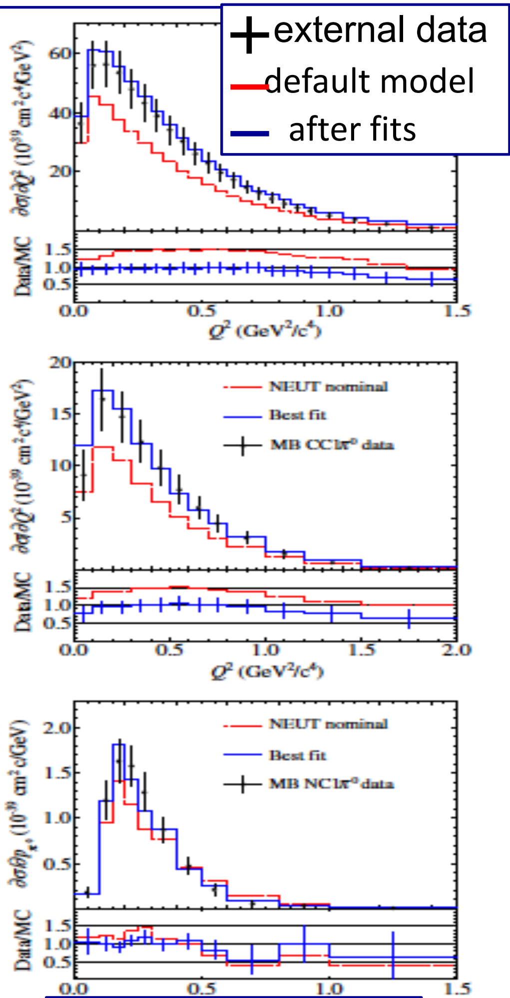


# 1. e.g.) T2K oscillation experiments

External constraint

MiniBooNE, MINERvA, SciBooNE

K2K, MINOS, Bubble chambers




External data fit

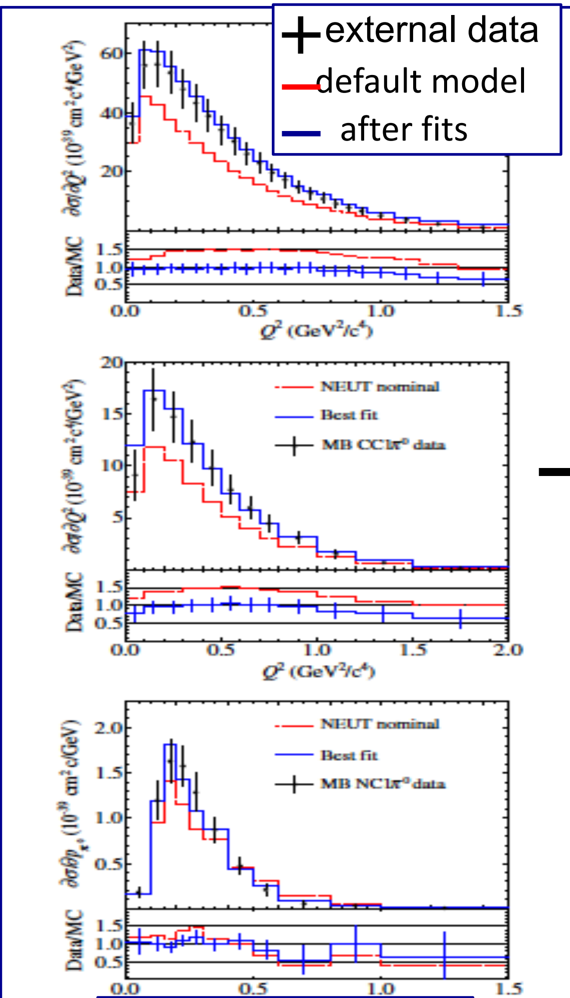
External data give initial guess of cross-section systematics

# 1. e.g.) T2K oscillation experiments

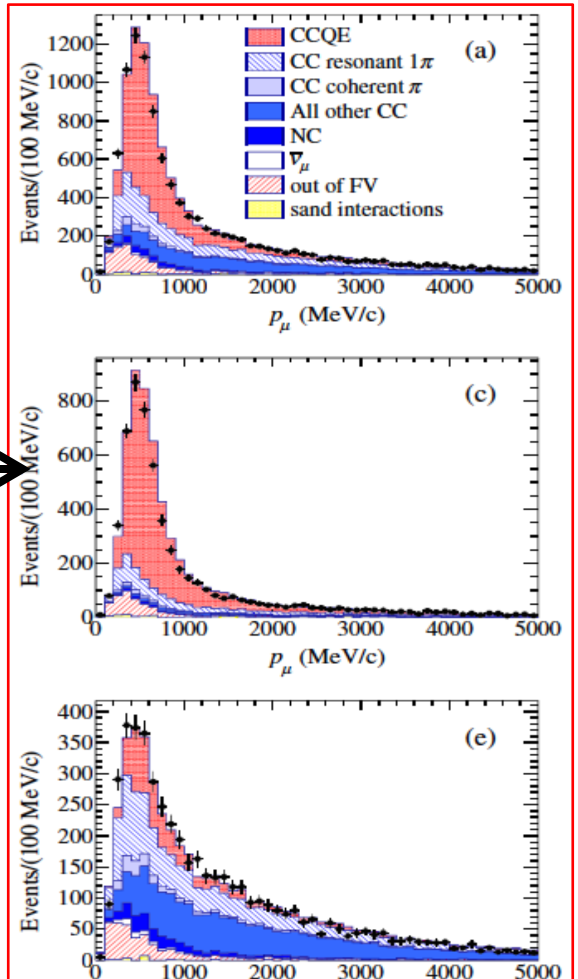


**External constraint**
MiniBooNE, MINERvA, SciBooNE
K2K, MINOS, Bubble chambers

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




External data fit




T2K ND280 data fit

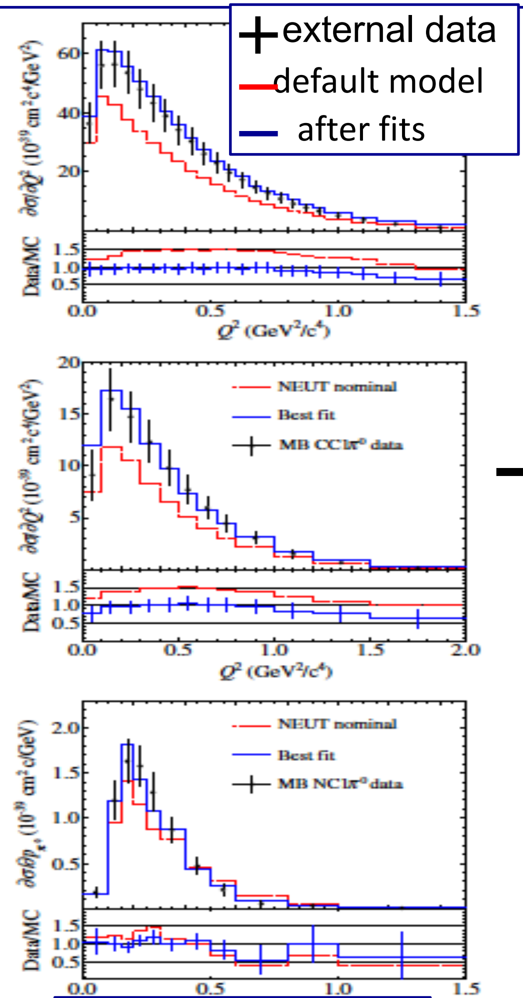
Constraint from internal data find actual size of cross-section errors

T2K collaboration, PRL118(2017)151801



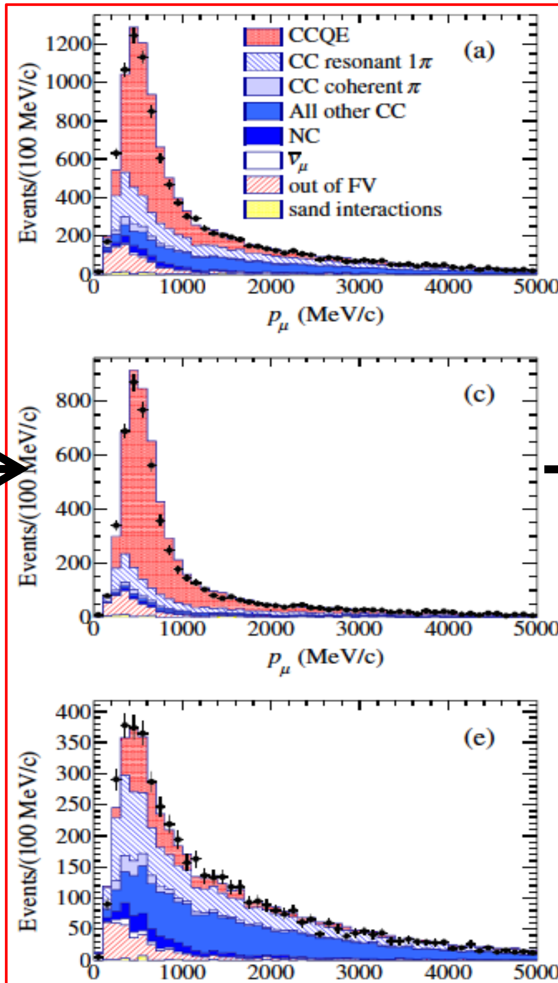
# 1. e.g.) T2K oscillation experiments

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




External data fit

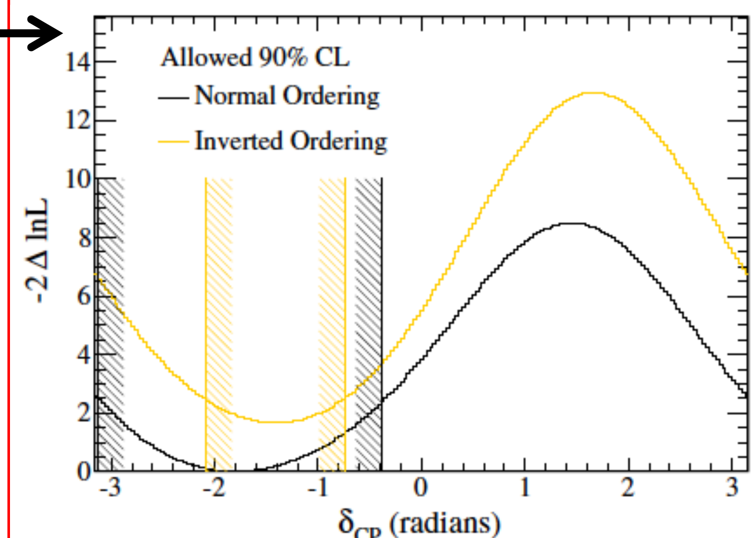
**Internal constraint**
Near detector
oscillation non-sensitive channels




T2K ND280 data fit

Neutrino interaction model is a large systematics of neutrino oscillation experiment

| Source (%) | $\nu_\mu$ | $\nu_e$ | $\bar{\nu}_\mu$ | $\bar{\nu}_e$ |
|---|---|---|---|---|
| ND280-unconstrained cross section | 0.7 | 3.0 | 0.8 | 3.3 |
| Flux and ND280-constrained cross section | 2.8 | 2.9 | 3.3 | 3.2 |
| Super-Kamiokande detector systematics | 3.9 | 2.4 | 3.3 | 3.1 |
| Final or secondary hadron interactions | 1.5 | 2.5 | 2.1 | 2.5 |
| Total | 5.0 | 5.4 | 5.2 | 6.2 |




oscillation result

# 4. DIS-hadronization errors, summary

- Goal is to make event weight with function of Ev, x, y, etc, for IceCube oscillation program
- Some of systematic errors are identified to be dangerous

| | DIS or Hadronization | type of error | approach | size |
|---|---|---|---|---|
| some study (MSU) | DIS | Bodek-Yang correction | play with Bodek-Yang parameters (by eyes) | maybe large? |
| done | DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | 1-2% by GENIE study |
| under investigation | DIS | A-scaling | MINERvA-GENIE (bottom-up) | maybe large? |
| some study (MSU) | DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | expected to be tiny |
| under investigation | Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | maybe large? |
| done JPhysG42(2015)115004 | Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | 1-2% by GENIE study |