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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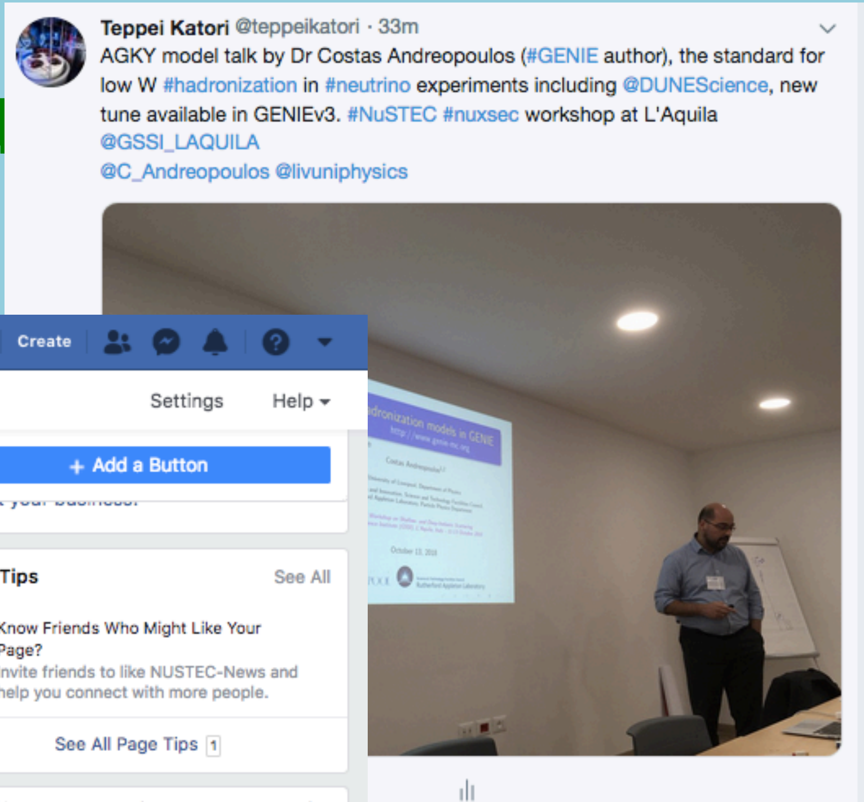
E-mail to listserv@fnal.gov, Leave the subject line blank, Type "subscribe nustec-news firstname lastname"

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

like “@nuxsec” on Facebook page, use hashtag #nuxsec

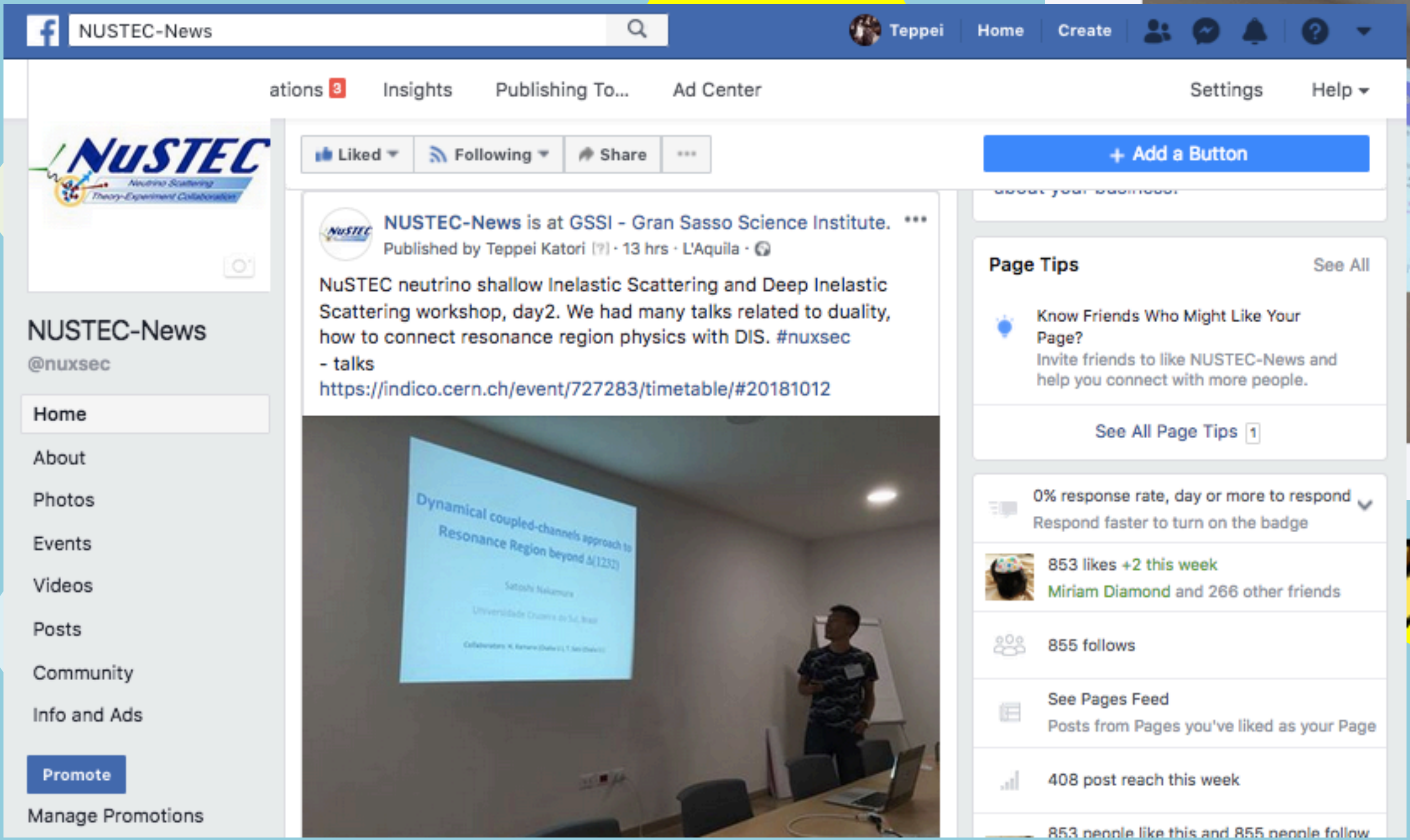
Fun Timely Intellectu



Teppei Katori @teppeikatori · 33m

AGKY model talk by Dr Costas Andreopoulos (#GENIE author), the standard for low W #hadronization in #neutrino experiments including @DUNEScience, new tune available in GENIEv3. #NuSTEC #nuxsec workshop at L'Aquila @GSSI_LAQUILA @C_Andreopoulos @livuniphysics

nuclear



NUSTEC-News

@nuxsec

NUSTEC-News is at **GSSI - Gran Sasso Science Institute.**

Published by Teppei Katori [?] · 13 hrs · L'Aquila ·

NuSTEC neutrino shallow Inelastic Scattering and Deep Inelastic Scattering workshop, day2. We had many talks related to duality, how to connect resonance region physics with DIS. #nuxsec
- talks
https://indico.cern.ch/event/727283/timetable/#20181012

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0% response rate, day or more to respond
Respond faster to turn on the badge

853 likes +2 this week
Miriam Diamond and 266 other friends

855 follows

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Posts from Pages you've liked as your Page

408 post reach this week

853 people like this and 855 people follow

Dark matter

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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
3. Neutrino hadronization process
5. Conclusion

Teppei Katori
Queen Mary University of London
NuSTEC nuS&DIS workshop, GSSI, L'Aquila, Italy, Oct. 11, 2018

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

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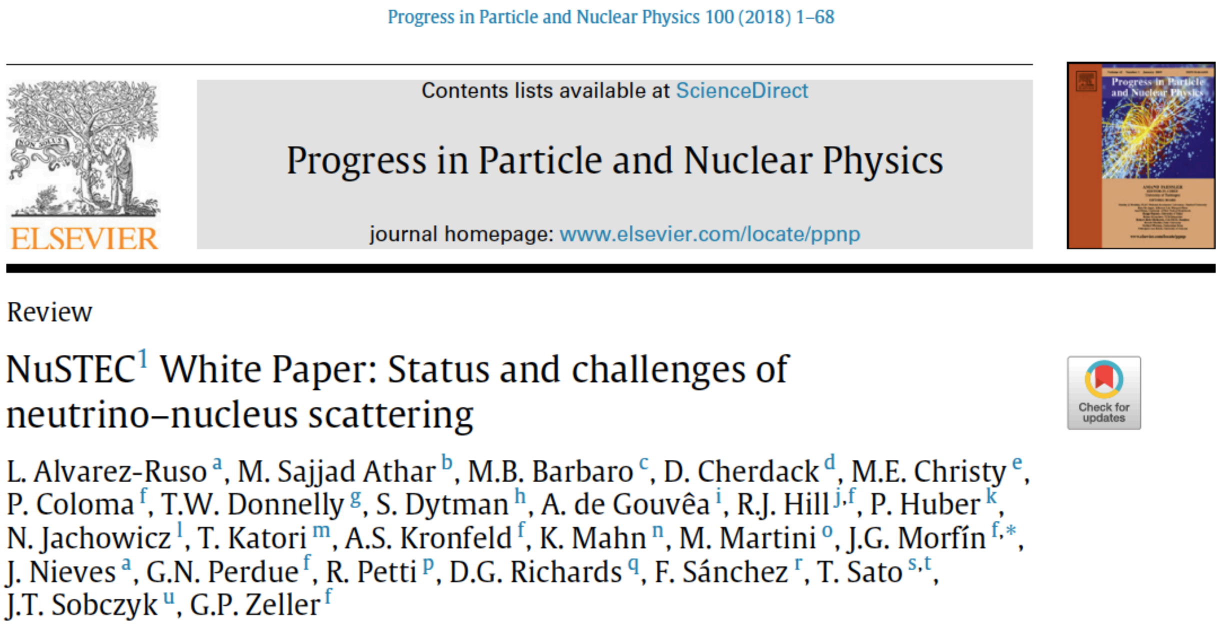

Progress in Particle and Nuclear Physics 100 (2018) 1–68

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Review

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

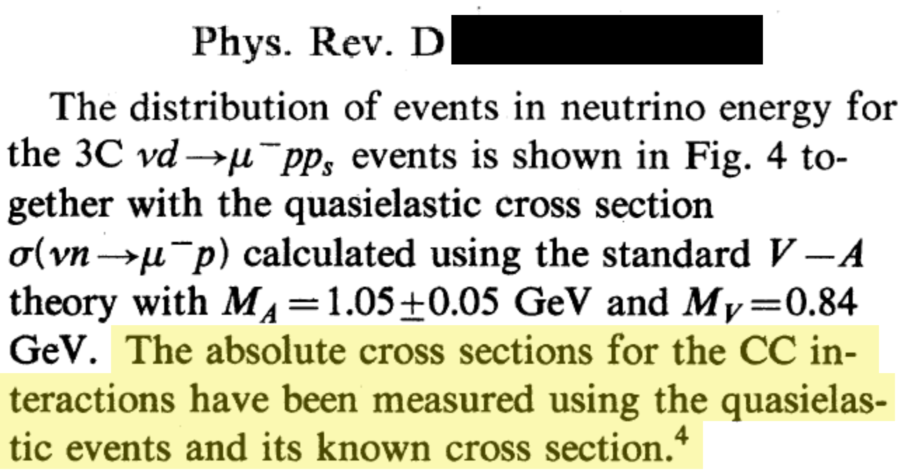
L. Alvarez-Ruso[a], M. Sajjad Athar[b], M.B. Barbaro[c], D. Cherdack[d], M.E. Christy[e], P. Coloma[f], T.W. Donnelly[g], S. Dytman[h], A. de Gouvêa[i], R.J. Hill[j,f], P. Huber[k], N. Jachowicz[l], T. Katori[m], A.S. Kronfeld[f], K. Mahn[n], M. Martini[o], J.G. Morfín[f,*], J. Nieves[a], G.N. Perdue[f],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

Jon Link, Fermilab Wine & Cheese seminar (2005)

Neutrino cross section measurement, 30 years ago

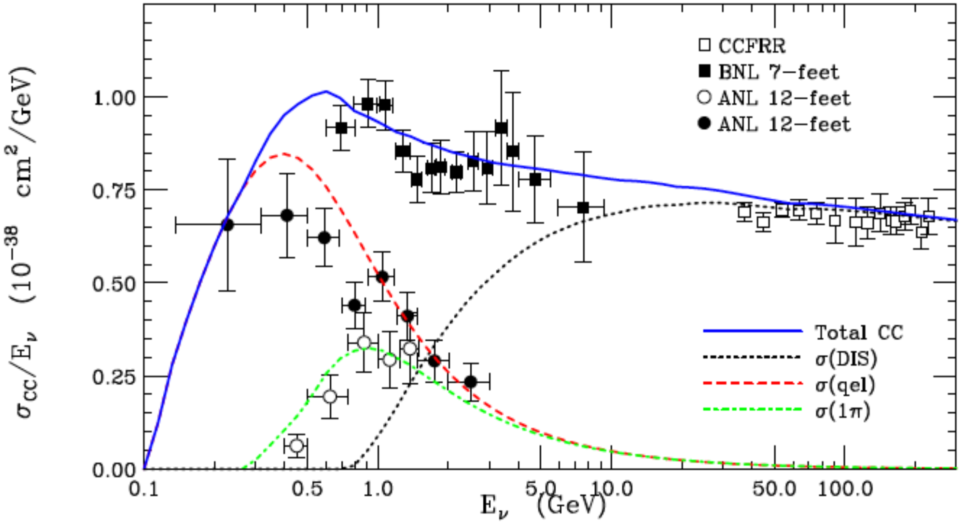
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate

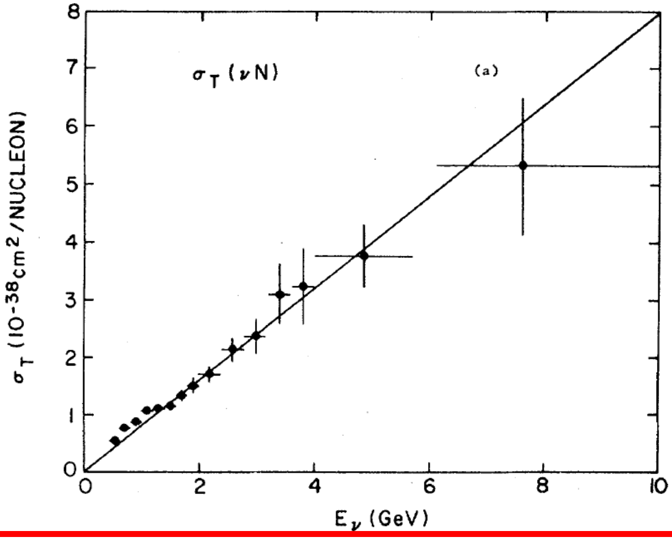
What you get? OF COURSE the cross section you assume!



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]





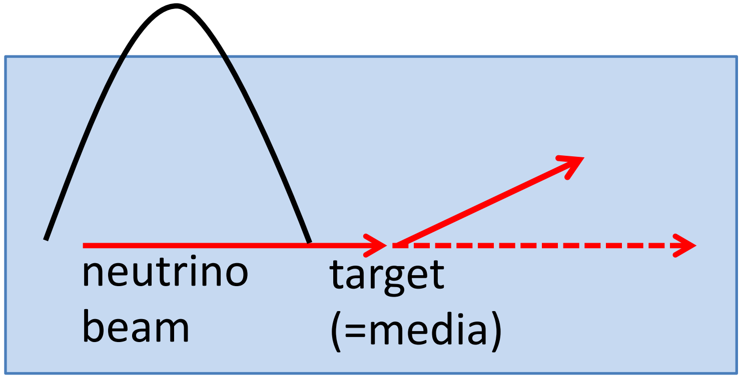
Progress of science is slow, but we have achieved so many things in last 30 years!

1. Typical neutrino detectors

Neutrino scattering

- Wideband beam

→ Need to predict every processes

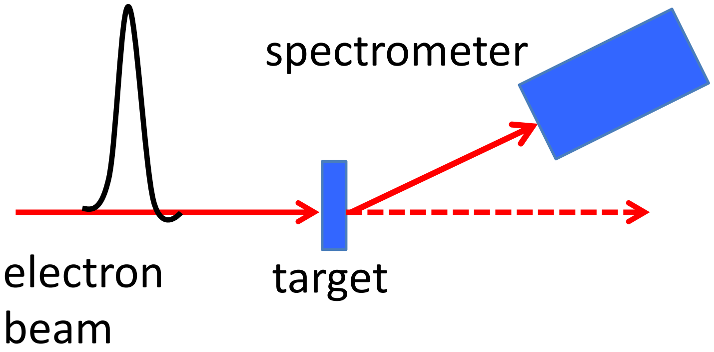


Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ kinematics is completely fixed



TK, Martini, JPhysG45(2017)1

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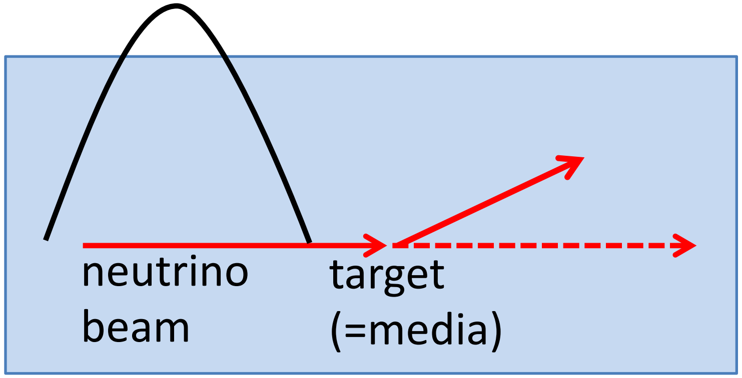

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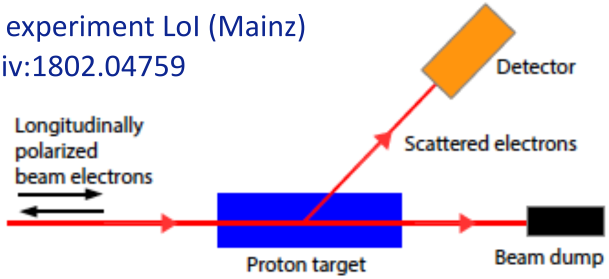

P2 experiment LoI (Mainz)
arXiv:1802.04759

TK, Martini, JPhysG45(2017)1

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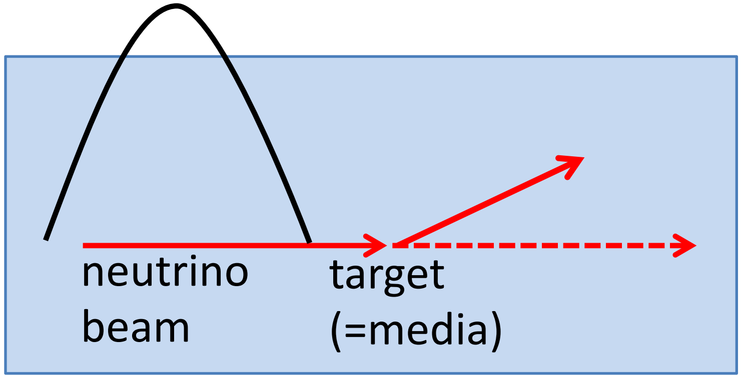
Neutrino scattering

- Wideband beam

→ Need to predict every processes



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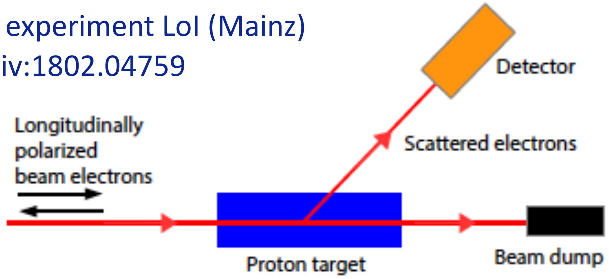


Incomplete kinematics

- Neutrino energy is reconstructed, not measured
- Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV are model dependent
- Large mass, coarse instrumentation, not every final state particles are measured

Neutrino interaction physics = incomplete measurement

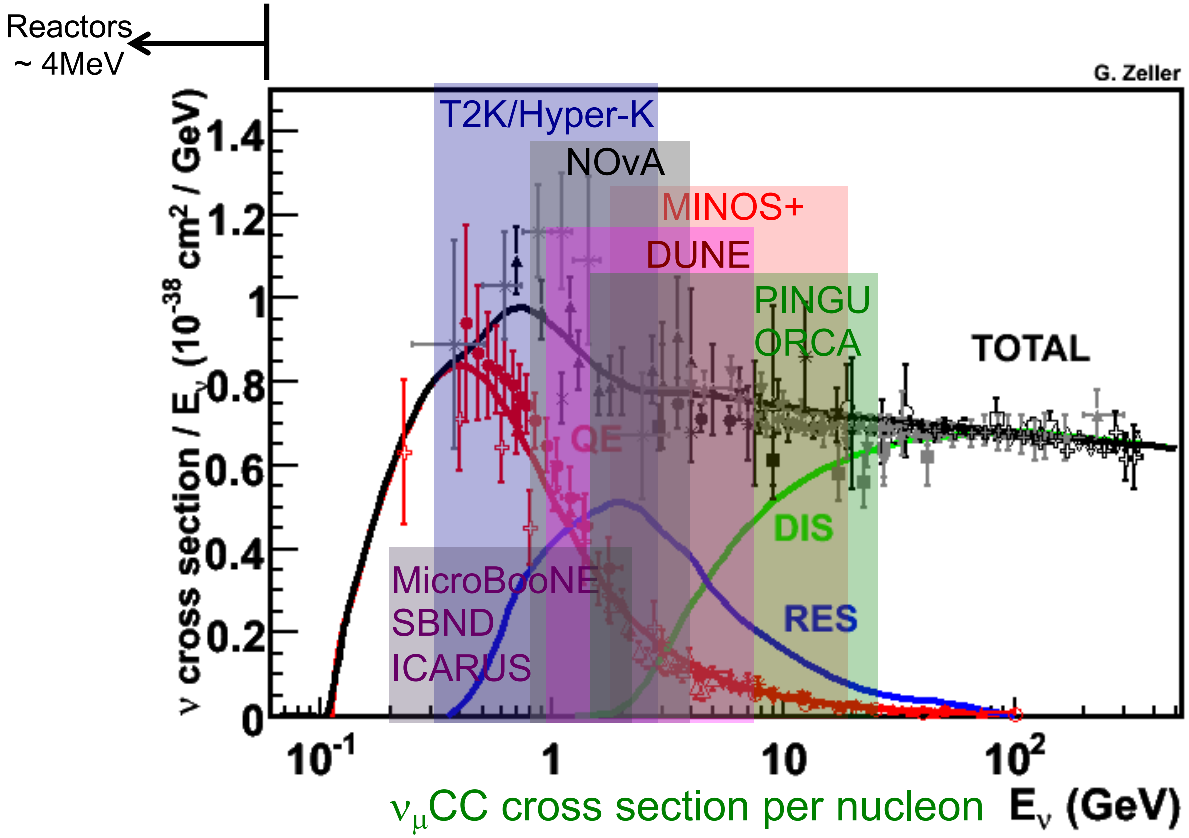
1. Neutrino kinematics are under-constrained
2. Neutrino cannot choose target, need simulations of all materials
3. Detectors are coarse, incomplete final state measurements

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments, present to future

- T2K, NOvA, Fermilab SBN, PINGU, ORCA, Hyper-Kamiokande, DUNE…



ν_μCC cross section per nucleon

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

MiniBooNE: PRD81(2010)092005, Martini et al,PRC80(2009)065501
TK and Martini, JPhysG45(2018)013001

1. Discovery of nucleon correlation in neutrino scattering

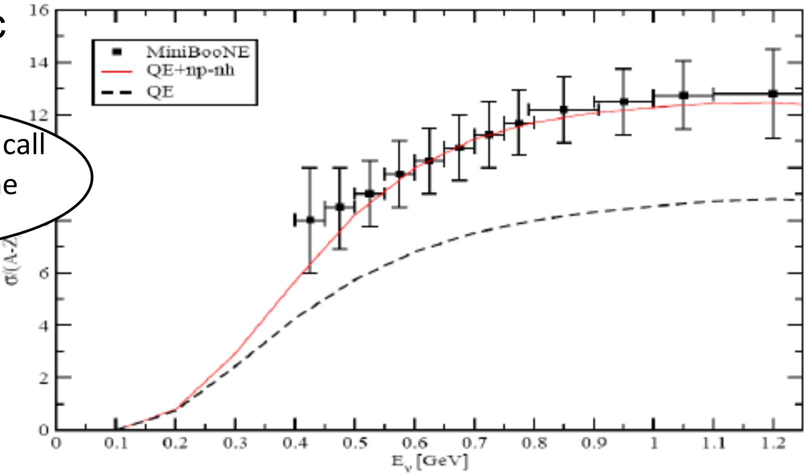
- Significant enhancement of cross section (10-30%) around 1 GeV
- Modify lepton kinematics and final state hadrons
- The hottest topic for T2K, MINERvA, MicroBooNE, etc

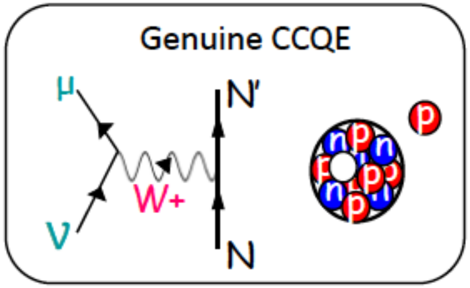
An explanation of this puzzle

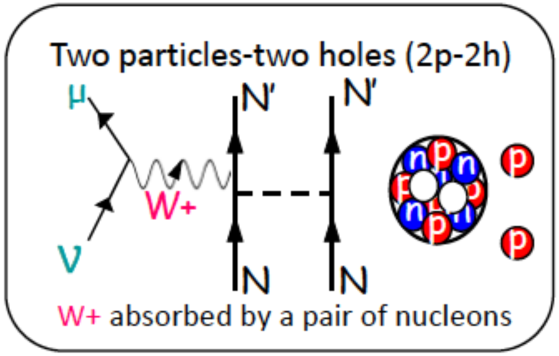
Inclusion of the multinucleon emission channel (np-nh)

What experimentalists call "CCQE" is not genuine CCQE!

Marco Martini (Saclay)



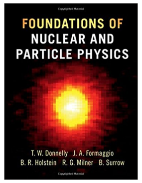




W+ absorbed by a pair of nucleons

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

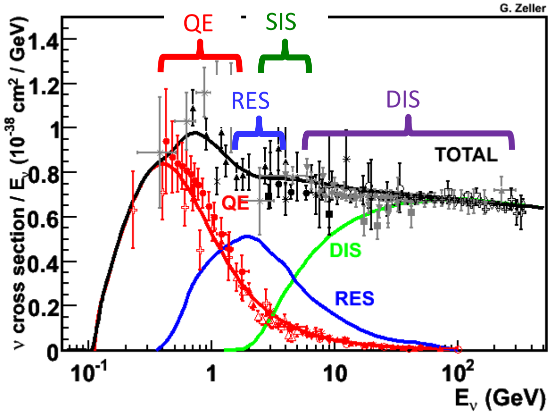
The first textbook of neutrino interaction physics!
"Foundation of Nuclear and Particle Physics"
- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow

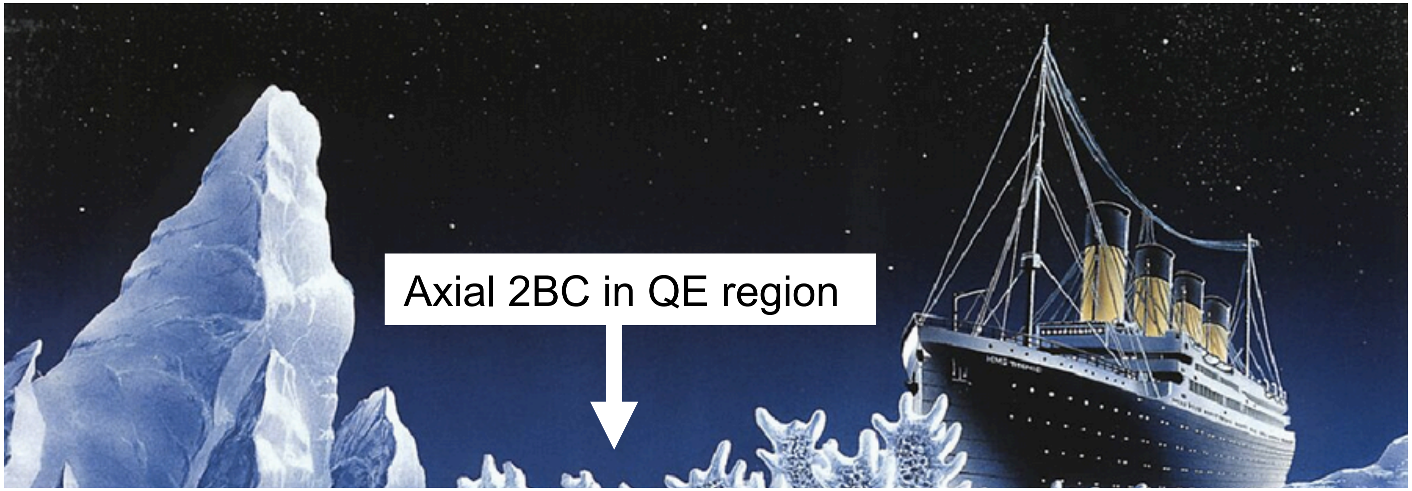


3: Sensitivity to oscillation parameter
Matt Muether
Christophe Bronner

1. Beyond QE peak

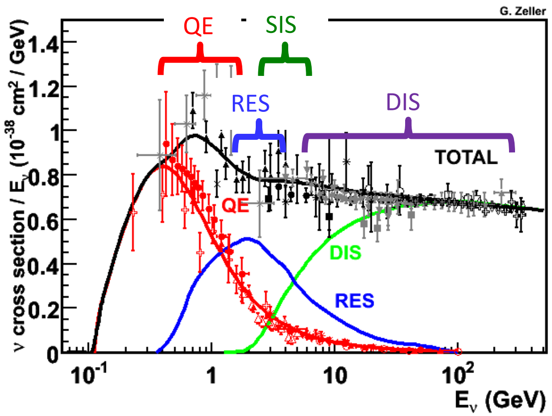
Axial 2-body current in QE region may be a tip of the iceberg…

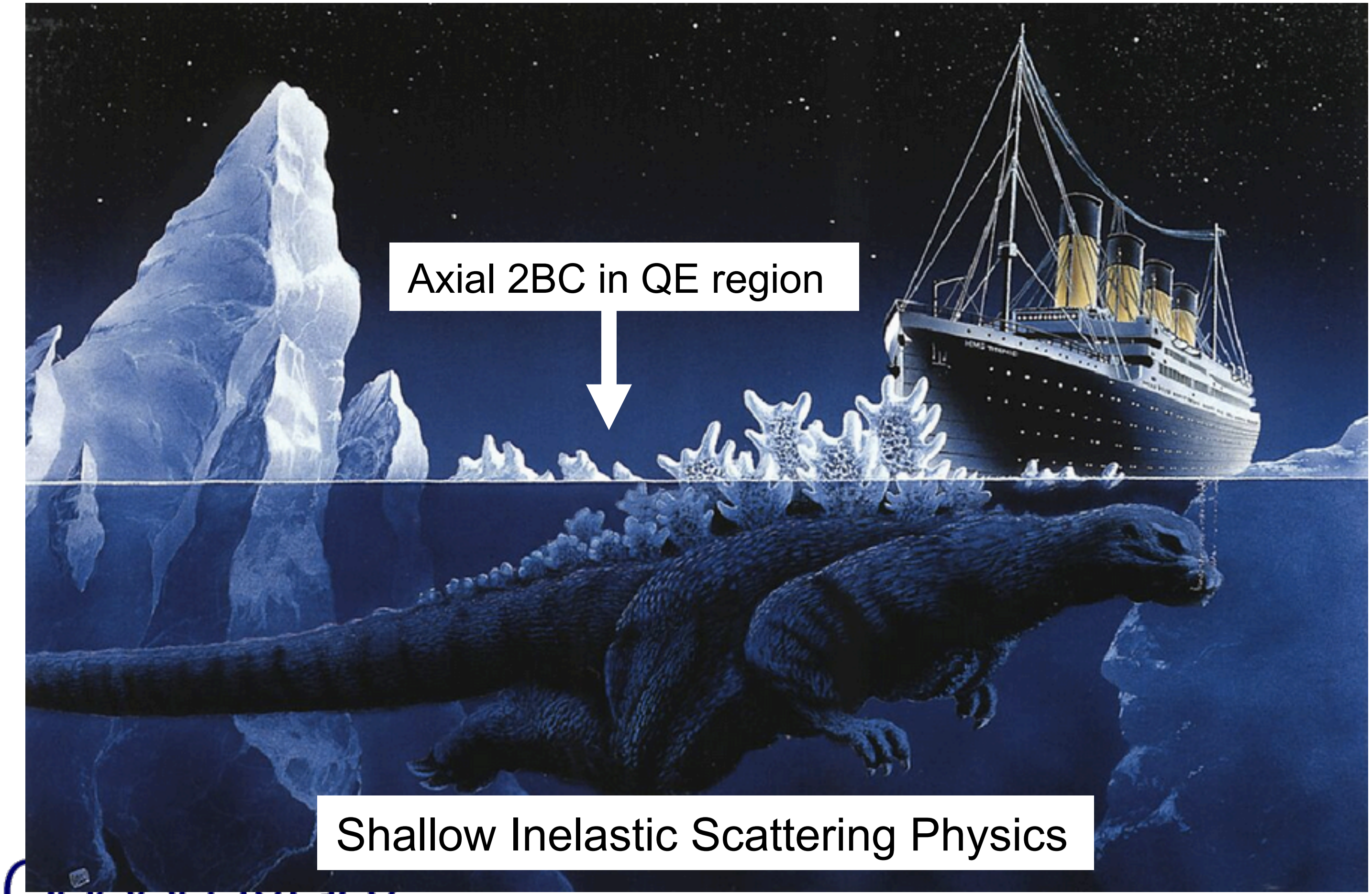




1. Beyond QE peak

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

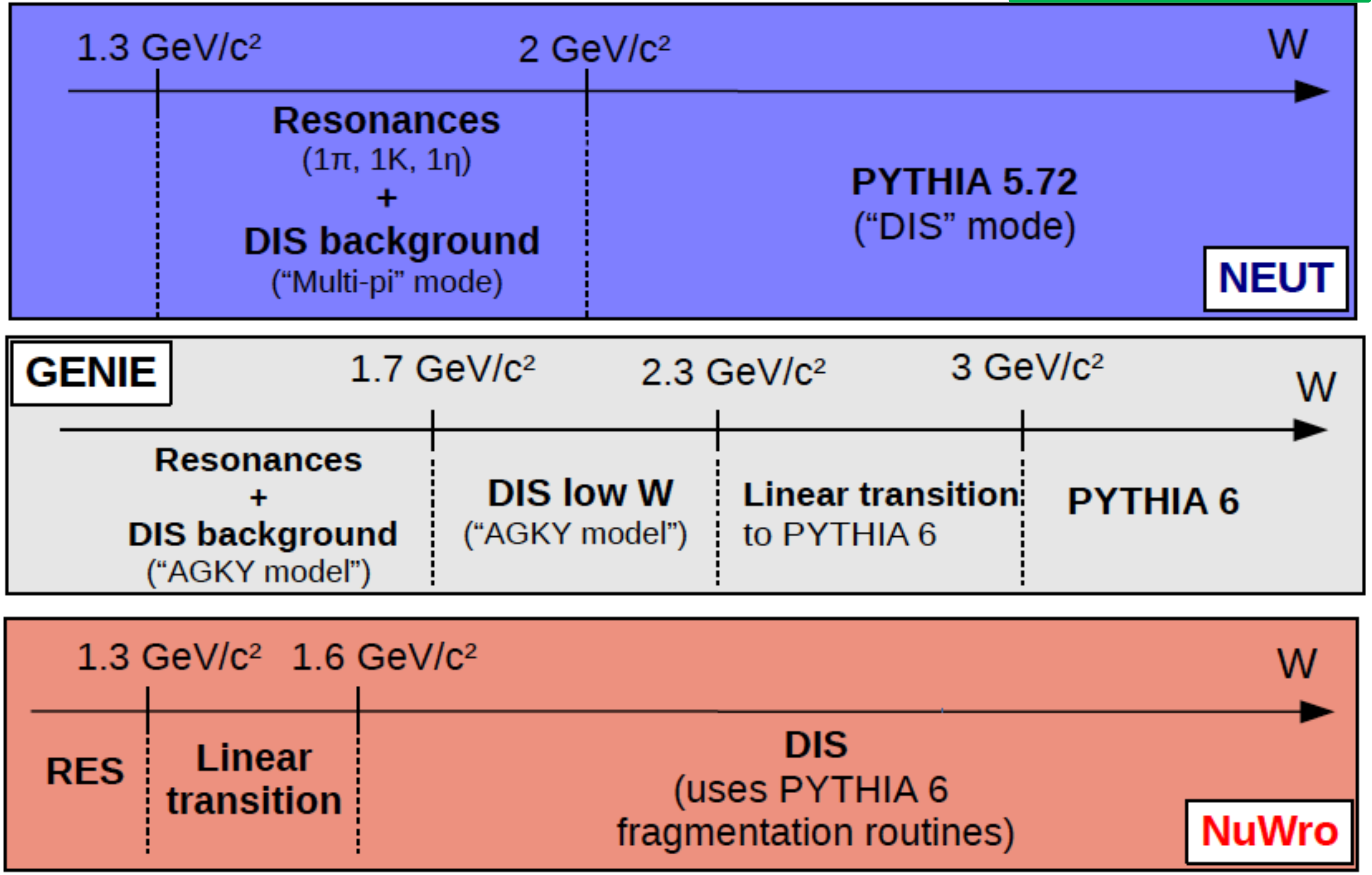




Axial 2BC in QE region

Shallow Inelastic Scattering Physics

Session 2: Generators
Kai Gallmeister
Julia Tena Vidal
Jan Sobczyk
Christophe Bronner



1.3 GeV/c^2 — 2 GeV/c^2 — W

Resonances
(1π, 1K, 1η)
+
DIS background
("Multi-pi" mode)

PYTHIA 5.72
("DIS" mode)

NEUT

GENIE

1.7 GeV/c^2 — 2.3 GeV/c^2 — 3 GeV/c^2 — W

Resonances
+
DIS background
("AGKY model")

DIS low W
("AGKY model")

Linear transition
to PYTHIA 6

PYTHIA 6

1.3 GeV/c^2 — 1.6 GeV/c^2 — W

RES

Linear transition

DIS
(uses PYTHIA 6
fragmentation routines)

NuWro

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

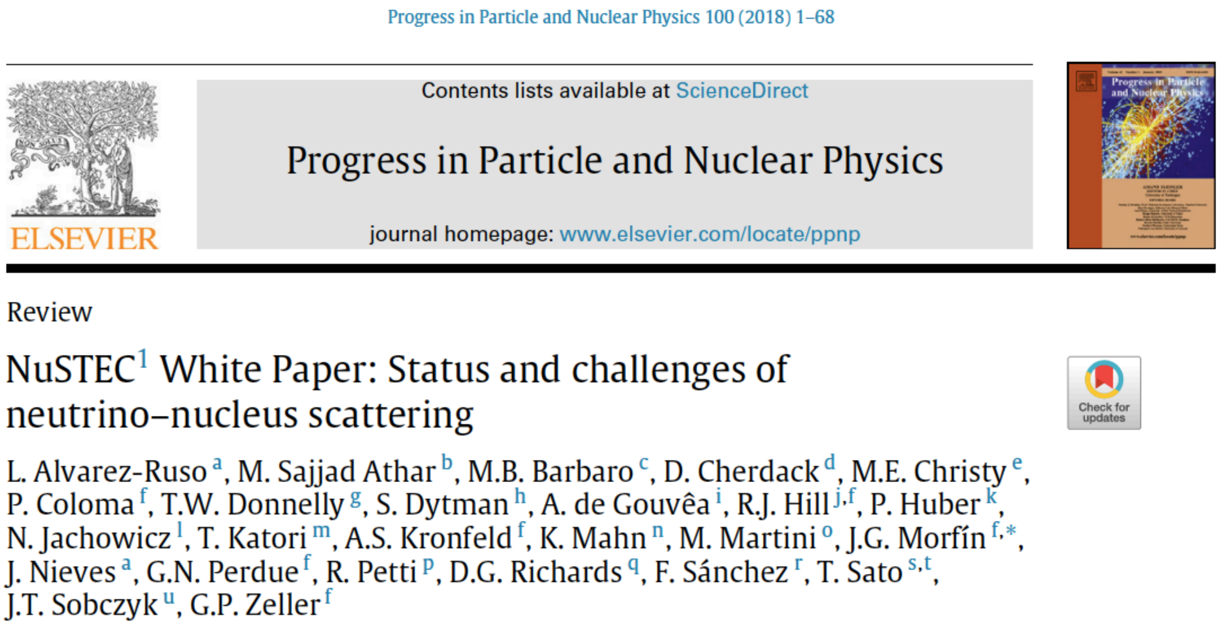
1. Neutrino interaction physics

2. Shallow-Inelastic scattering (SIS)

3. Nuclear-dependent DIS physics

4. Neutrino hadronization process

5. Conclusion



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Queen Mary
University of London

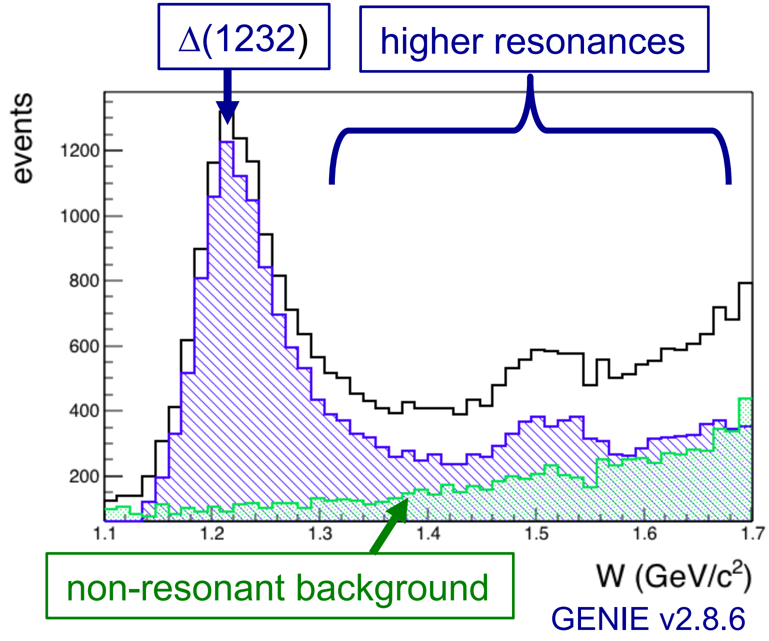
Nakamura et al.,Rep.Prog.Phys.80(2017)056301

Traditionally called “transition” region

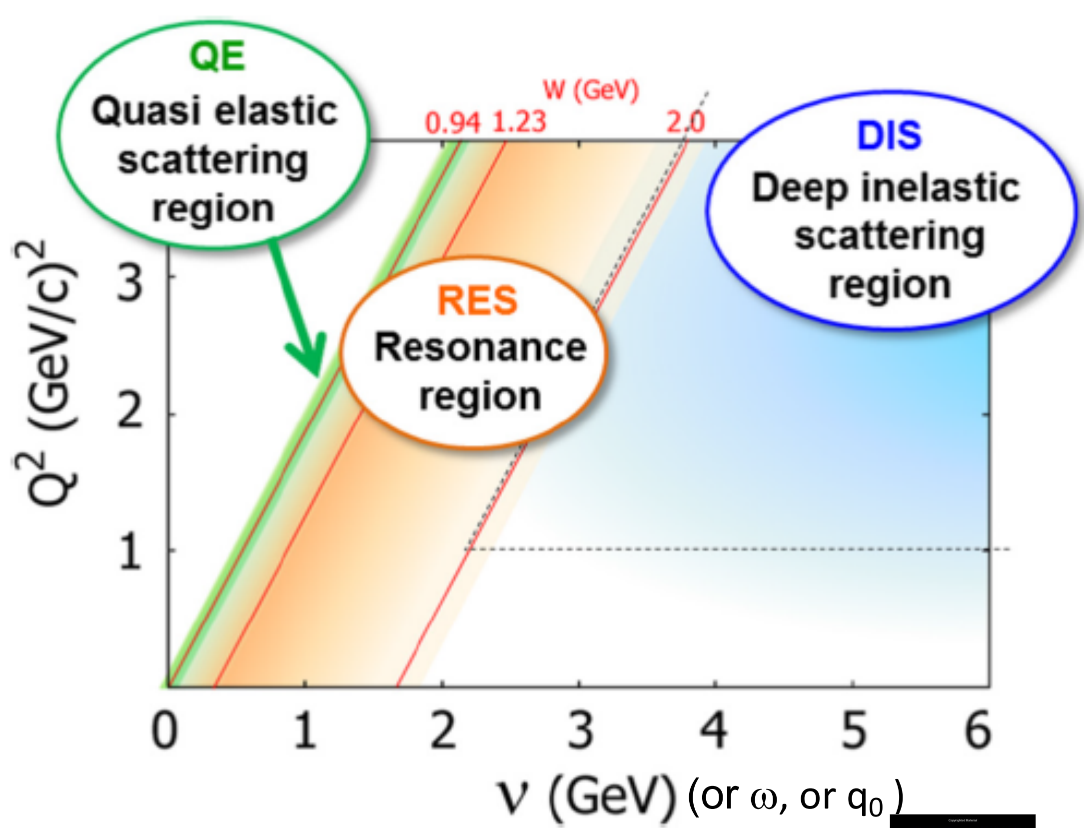
2. Sallow Inelastic Scattering (SIS) physics

Basic ingredients

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



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



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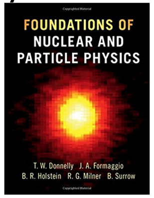

2. Physics of Δ resonance

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

Ulrich
Mosel
(Giessen)

Basic ingredients

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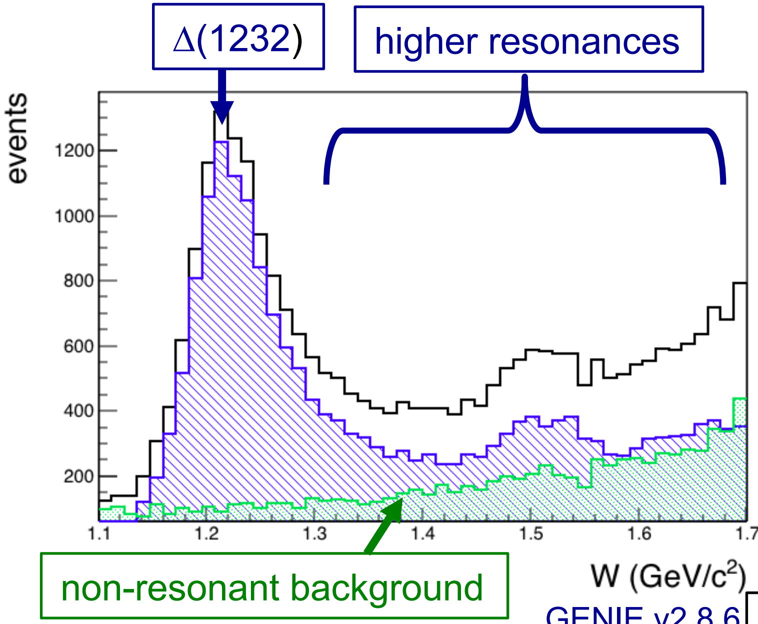
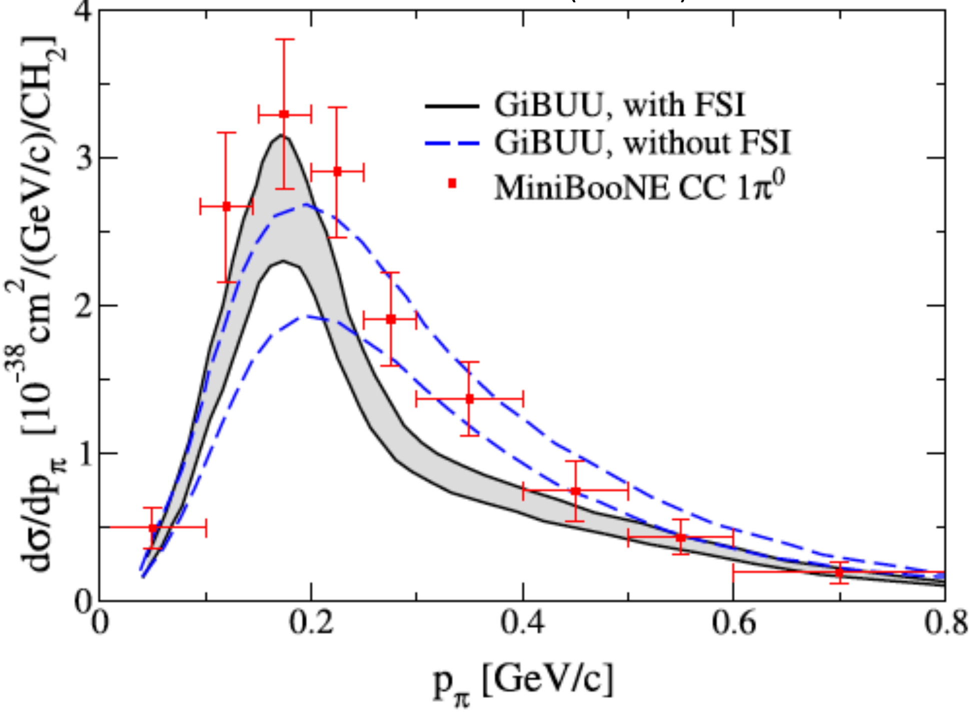
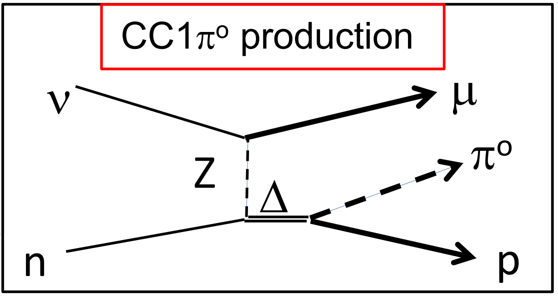


GENIE v2.8.6

MiniBooNE CC1π° data





Session 4: Pion production
Minoo Karbinezhad
Steve Dytman

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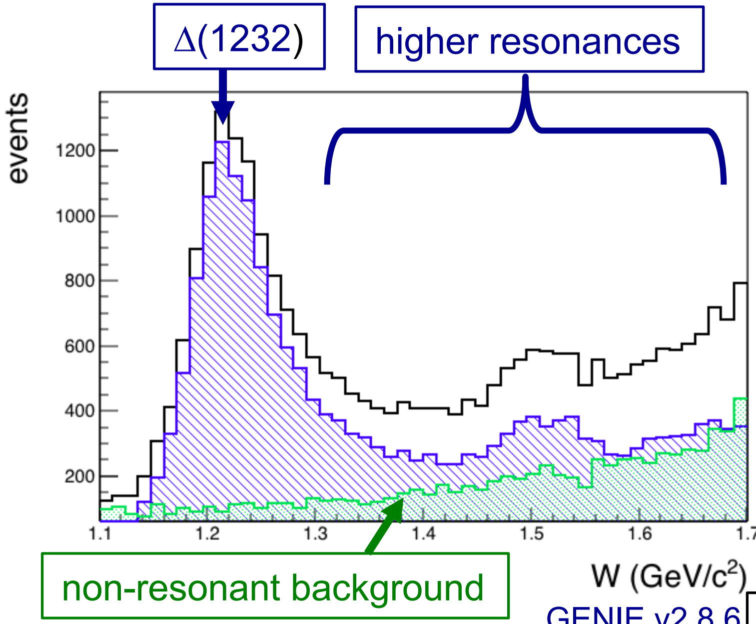
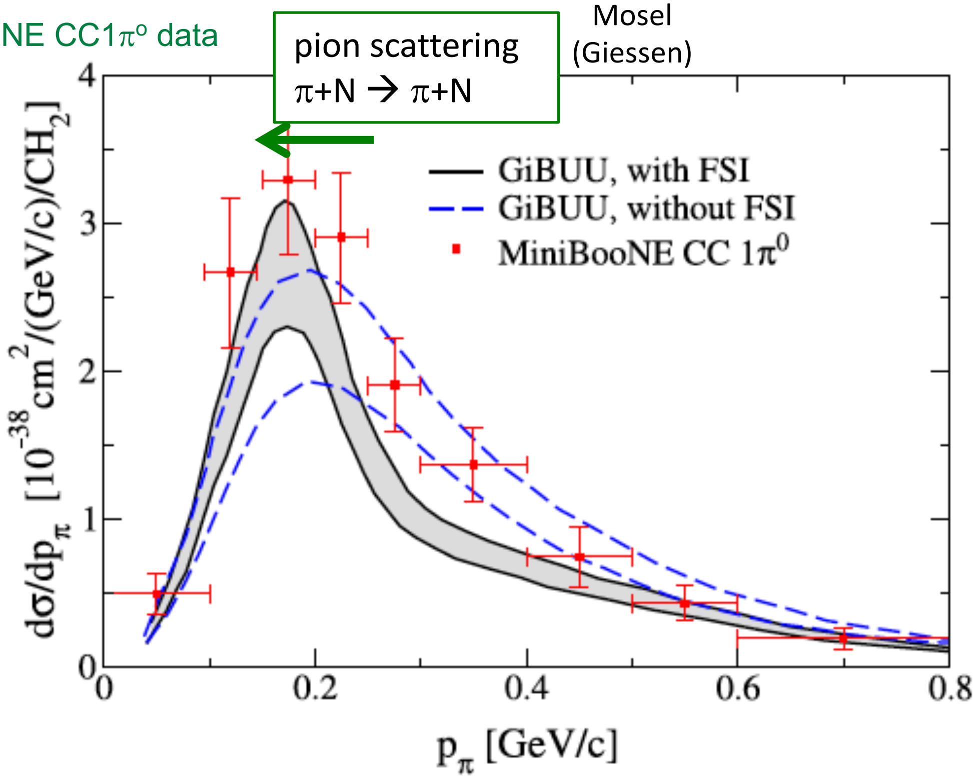


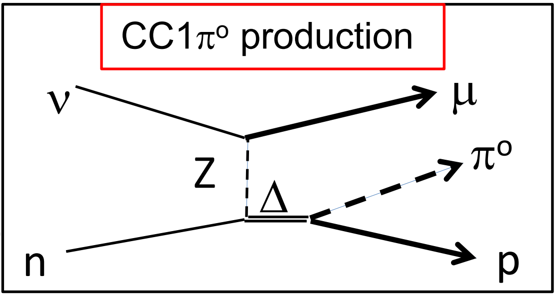
GENIE v2.8.6

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

Ulrich
Mosel
(Giessen)

MiniBooNE CC1π^o data





Session 4: Pion production
Minoo Karbinezhad
Steve Dytman

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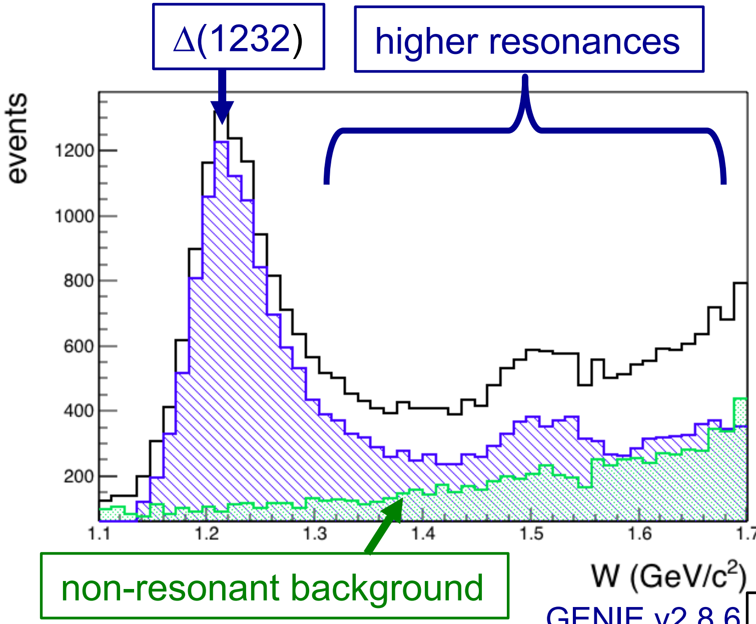
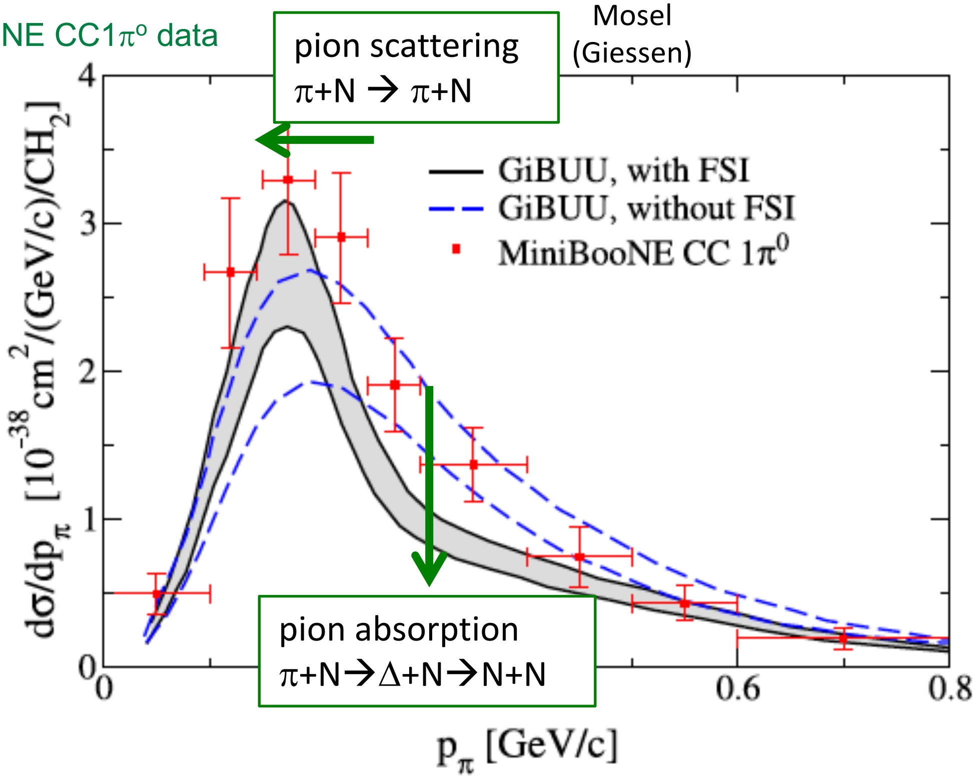
Mosel
(Giessen)

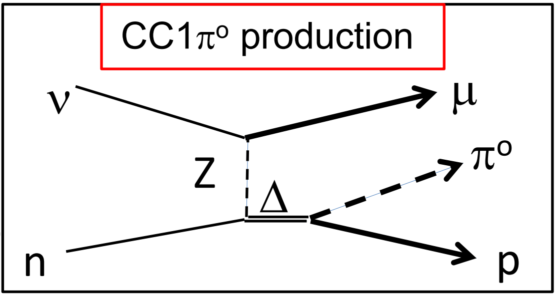


GENIE v2.8.6

MiniBooNE CC1π° data



CC1π° production



Session 4: Pion production
Minoo Karbinezhad
Steve Dytman

2. Physics of Δ resonance

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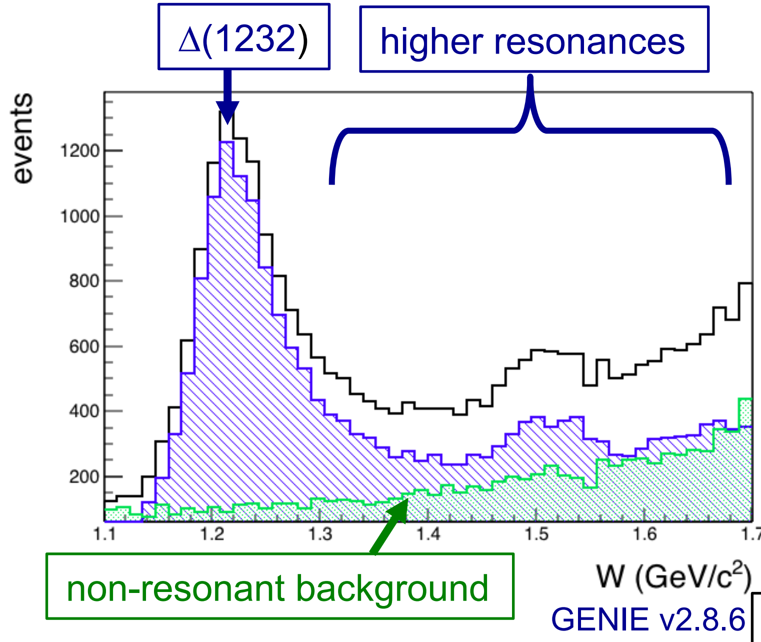
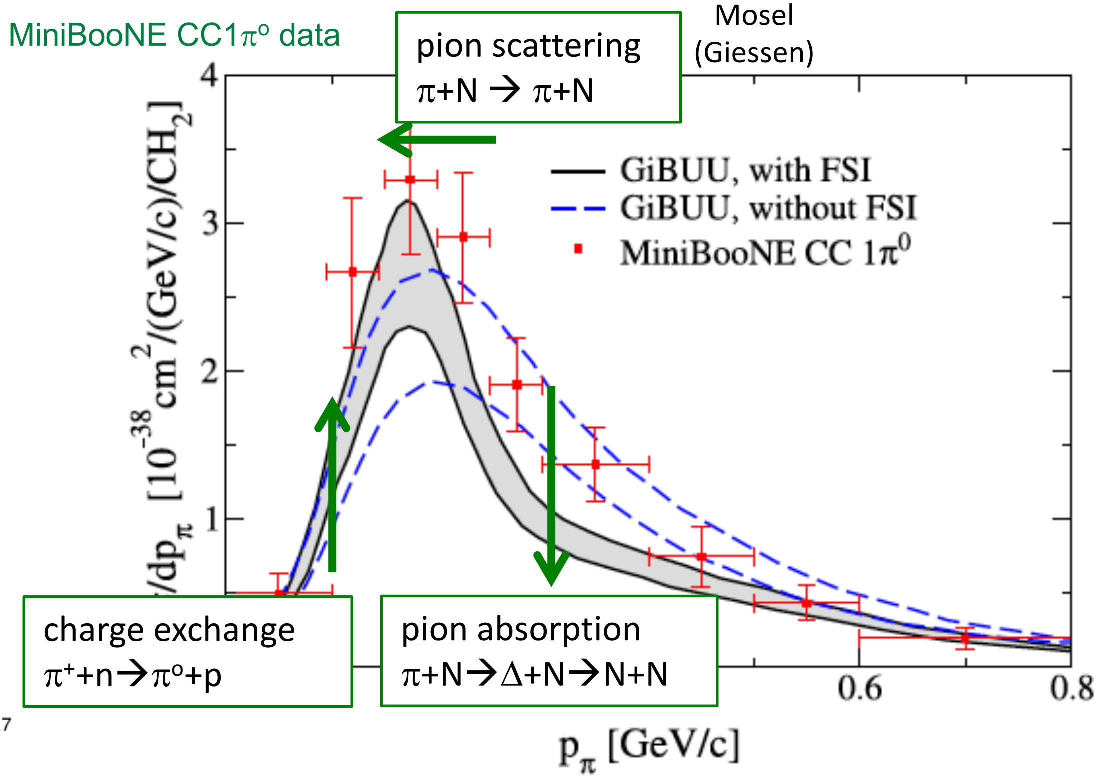
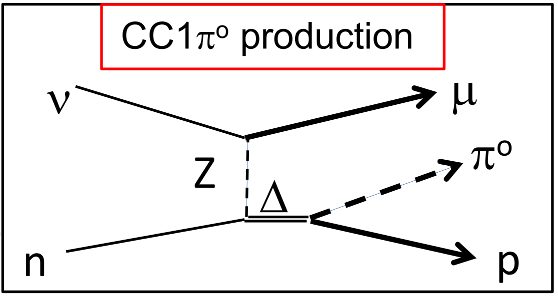
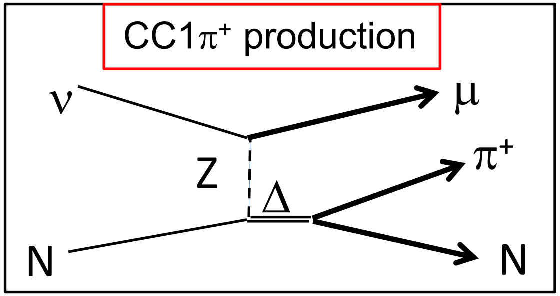
Giessen BUU transport model (GiBUU) describes final states of hadrons in nuclear media

Ulrich Mosel (Giessen)









Understanding of single pion production is already very tough

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

2. Physics of higher resonances

Basic ingredients

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4. low Q^2 , low W DIS
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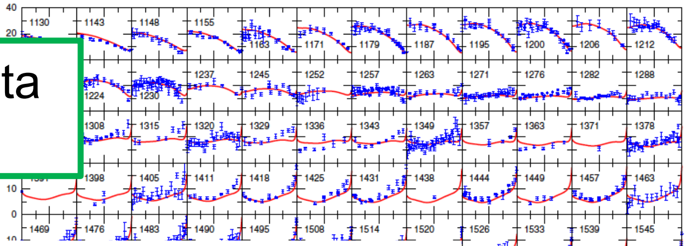
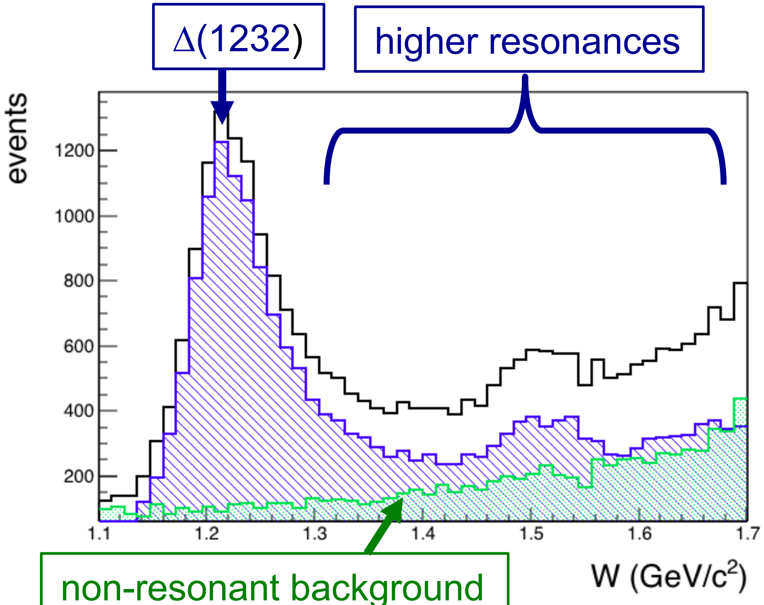
6. Neutrino hadronization

Session 4: Pion prod. W > Delta
Satoshi Nakamura

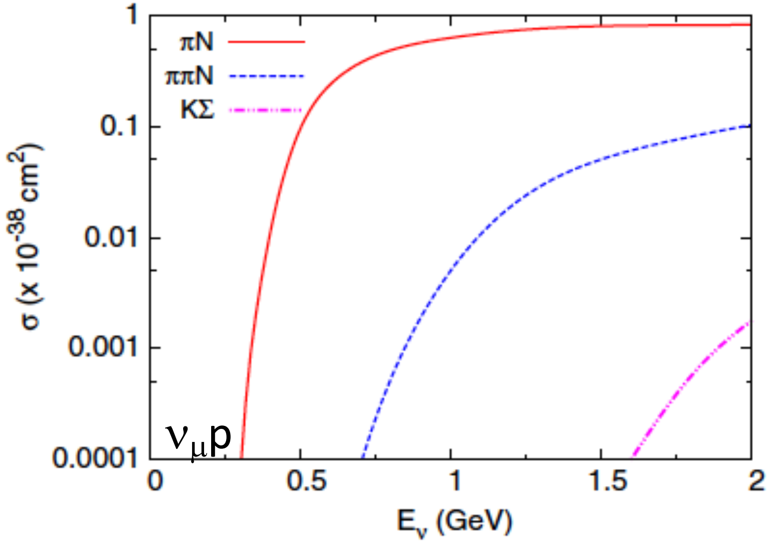
DCC model vs. electro-pion-production data



→ $\pi^- p$. The data are from Refs. [55–78].



GENIE v2.8.6



DCC model exclusive channel prediction

DCC model

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

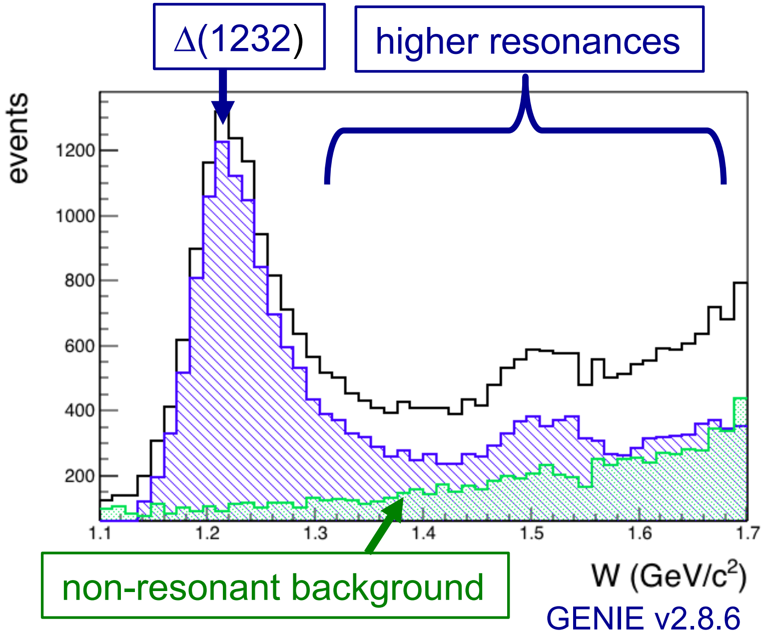
Role of high W resonances in neutrino experiments is not understood (and probably modeled incorrectly)

Rodrigues,Wilkinson,McFarland,EPJC76(2016)474

2. Physics of non-resonant background

Basic ingredients

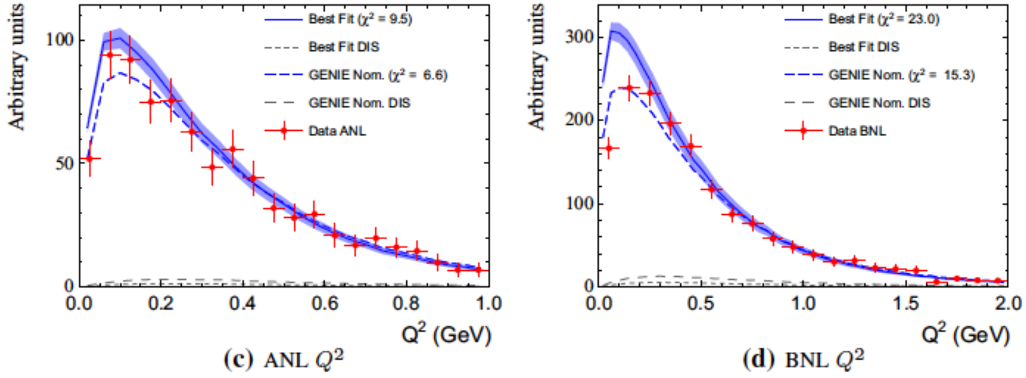
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS
6. Neutrino hadronization



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%.



(c) ANL Q^2

(d) BNL Q^2

If something is wrong beyond Delta, we usuallu blame non-resonant background

Teppei Katori, katori@fnal.gov

Session 4: Pion prod. W > Delta

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

2. Quark-Hadron Duality

5: Transition from SIS to DIS
Eric Christy
Manny Paschos
Huma Heidar
Natalie Jachowicz

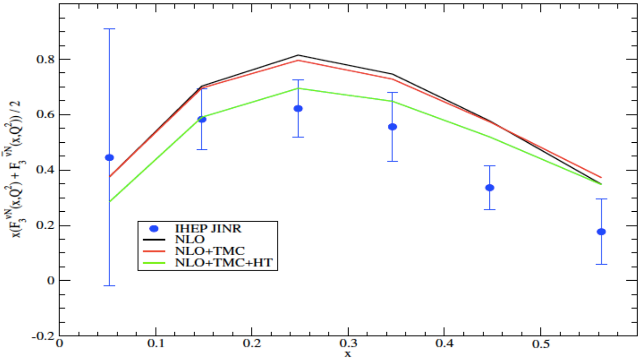
Basic ingredients

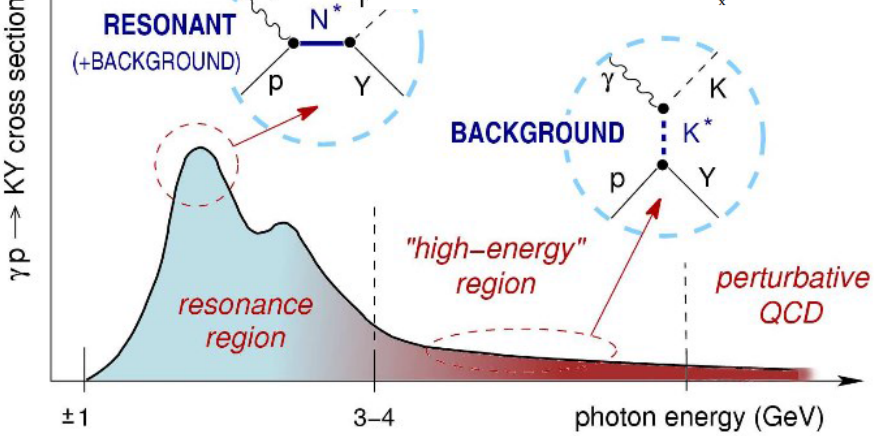
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS
6. Neutrino hadronization

"An average over the resonances is intimately related to the scaling curve"
- Manny Paschos (Dortmund)

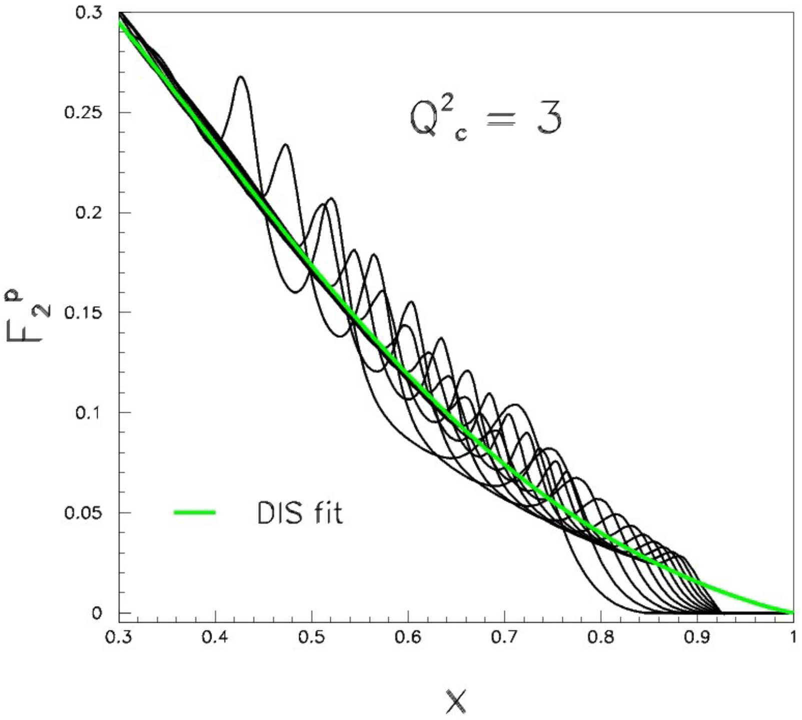
QH-duality

- Many studies





i@fnal.g



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

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2. higher resonances
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6. Neutrino hadronization

"… this cannot be true…"

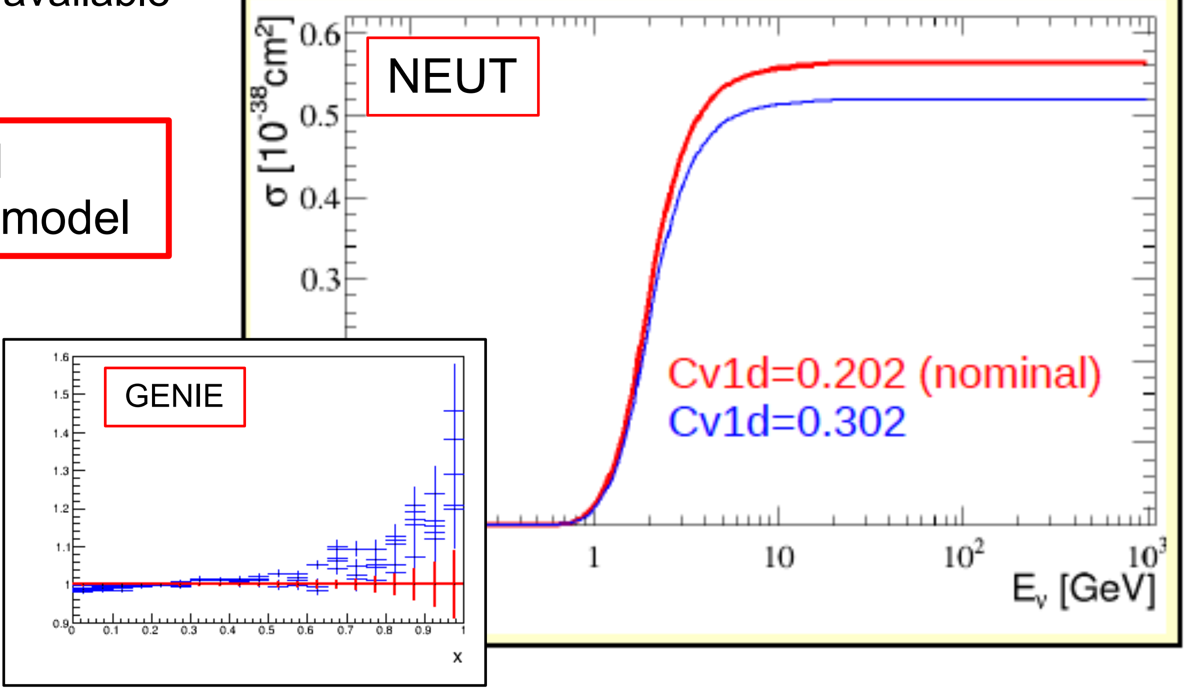
- Un-Ki Yang (Seoul National University)

QH-duality = Bodek-Yang model

- Many studies
- B-Y model is the only model available in neutrino generator

It is urgent to get correlated systematic errors from B-Y model

"Cv1d , Cv2d and Cs have very small effect on the χ^2 and hence have been neglected" D. Bhattacharya PhD's thesis



Christophe Bronner
Un-Ki Yang

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

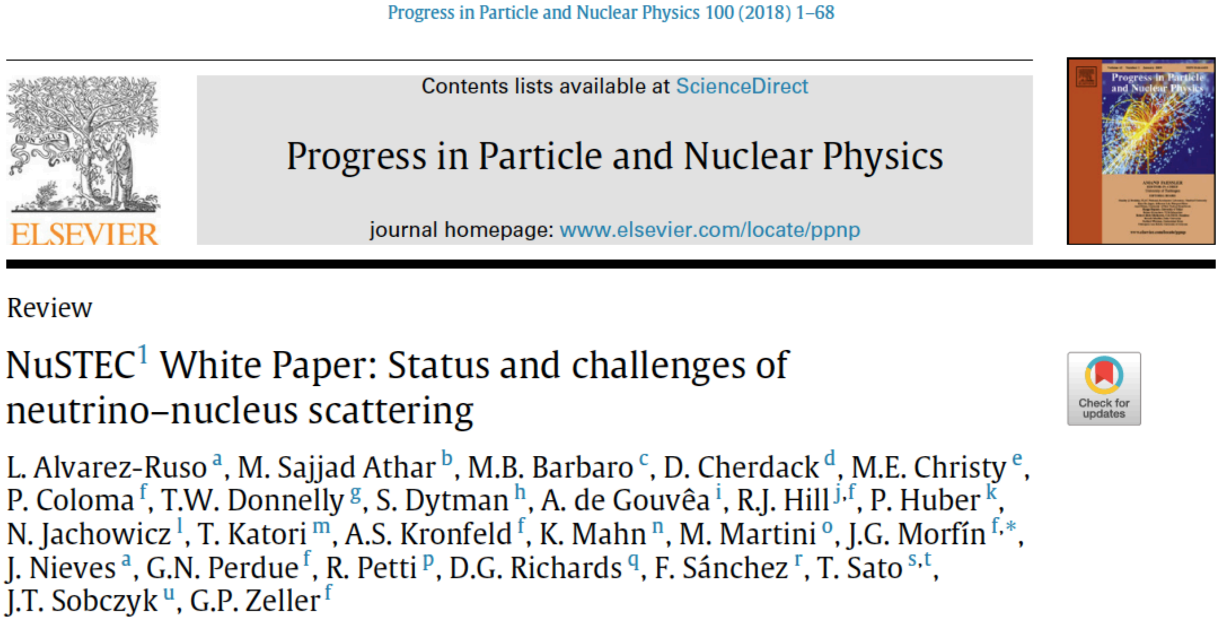
1. Neutrino interaction physics

2. Shallow-Inelastic scattering (SIS)

3. **Nuclear-dependent DIS physics**

4. Neutrino hadronization process

5. Conclusion



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

3. Nuclear dependent DIS process

6: nuclear medium effects
Sajjad Ather
Sergey Kulagin
Olek Kusina

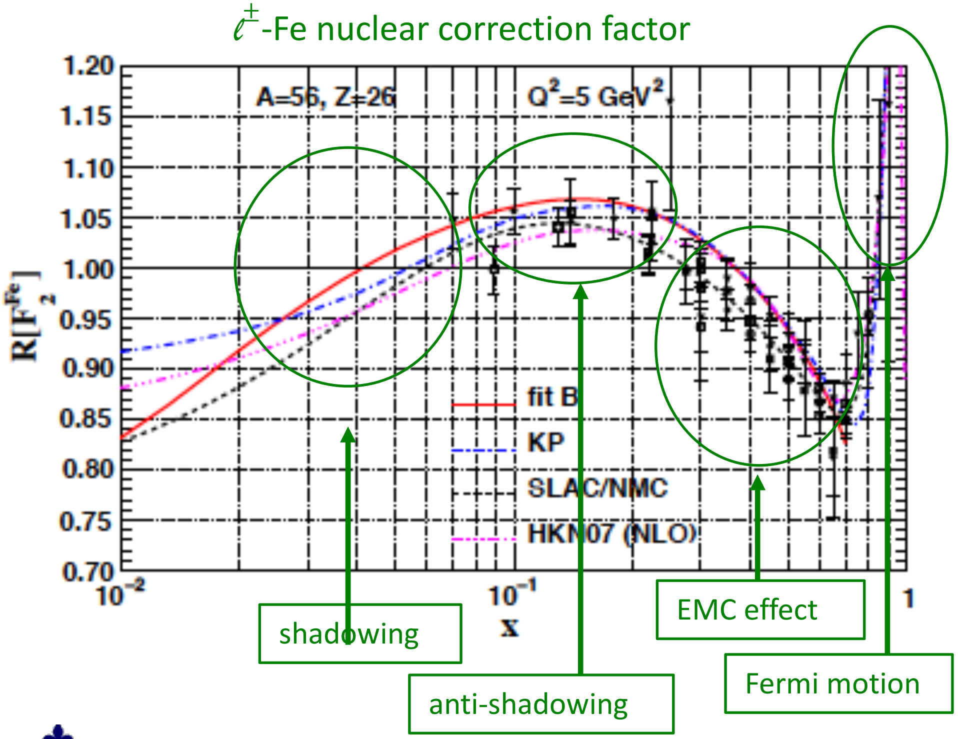
Basic ingredients

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

Nuclear PDF

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

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



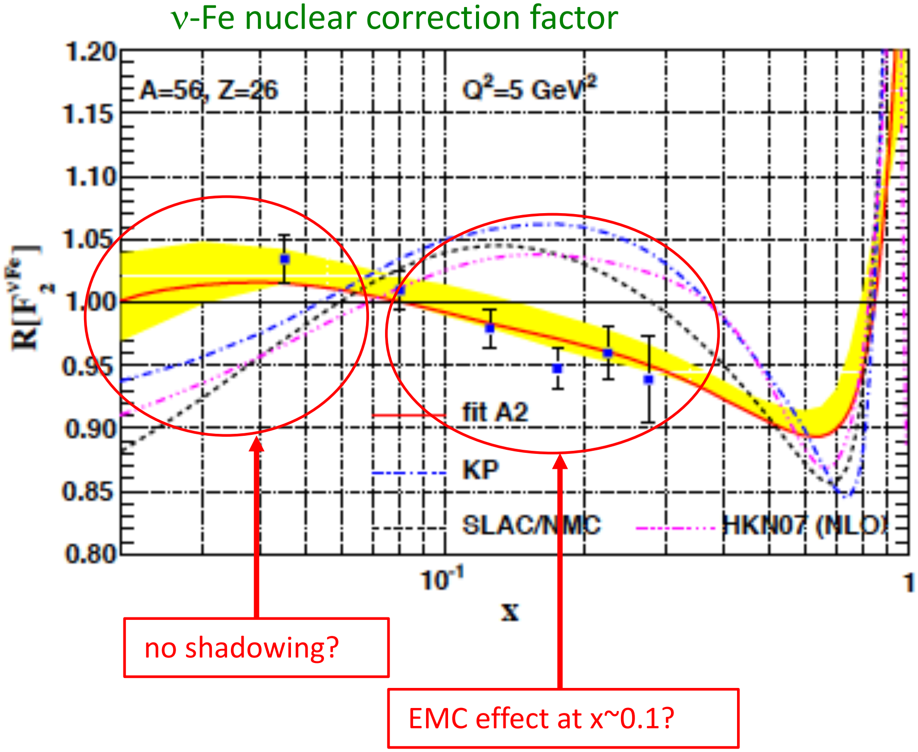
shadowing

anti-shadowing

EMC effect

Fermi motion

ν-Fe nuclear correction factor



no shadowing?

EMC effect at x~0.1?

MINERvA,PRD93(2016)071101

3. Nuclear dependent DIS process

Basic ingredients

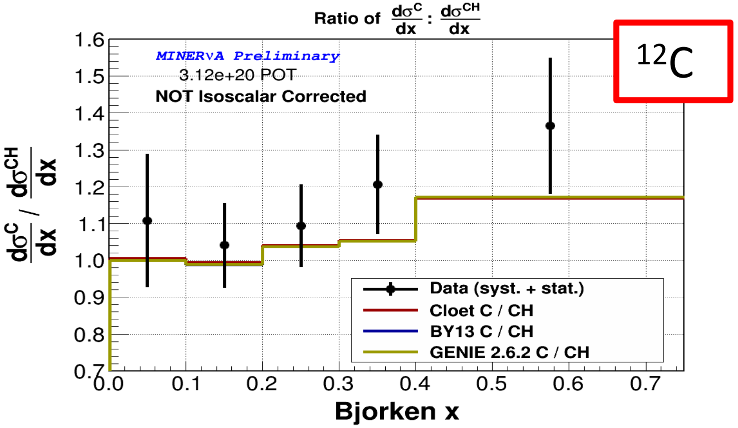
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low Q^2 , low W DIS
5. Nuclear dependent DIS
6. Neutrino hadronization

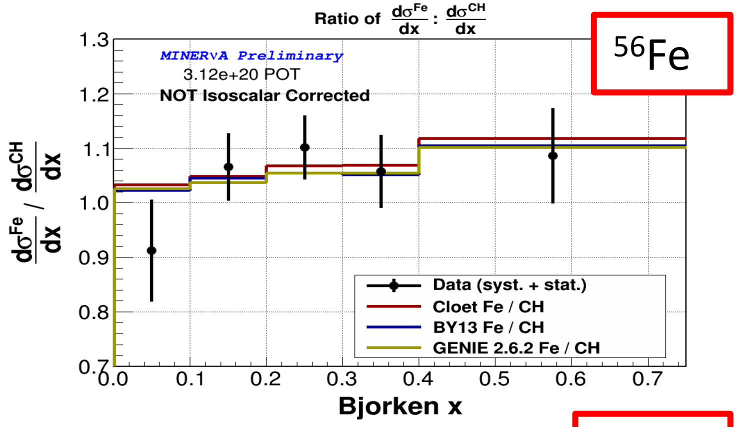
MINERvA DIS target ratio data (C, Fe, Pb)

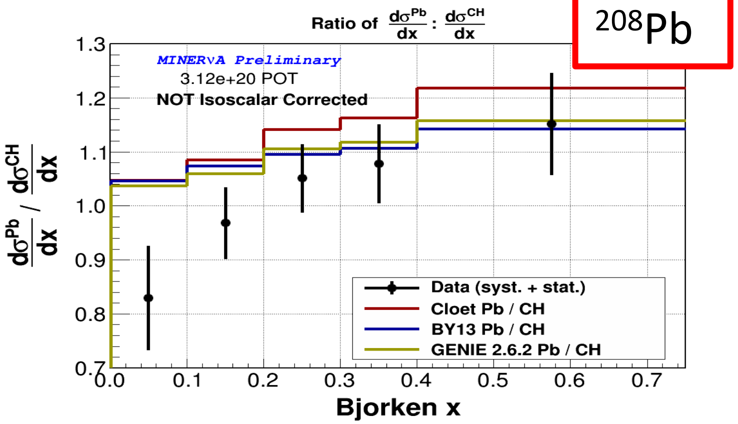
- MINERvA data reveal shadowing effect on neutrino may be larger than expected

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.







Teppei Katori, katori@fnal.g

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

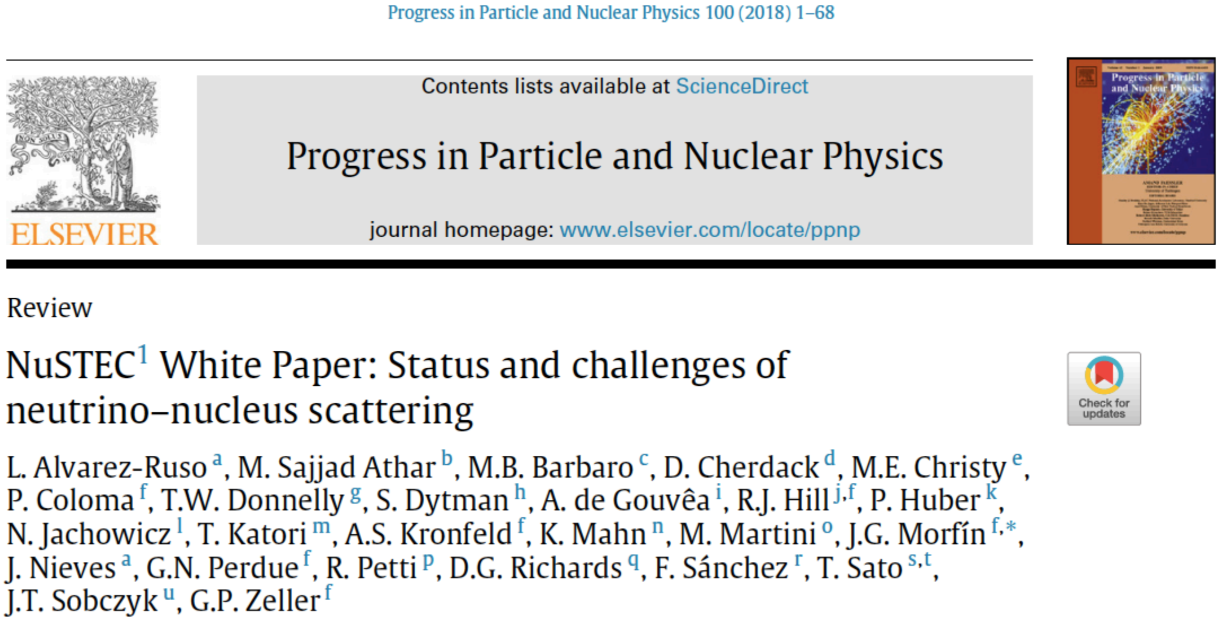
1. Neutrino interaction physics

2. Shallow-Inelastic scattering (SIS)

3. Nuclear-dependent DIS physics

4. **Neutrino hadronization process**

5. Conclusion



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Queen Mary
University of London

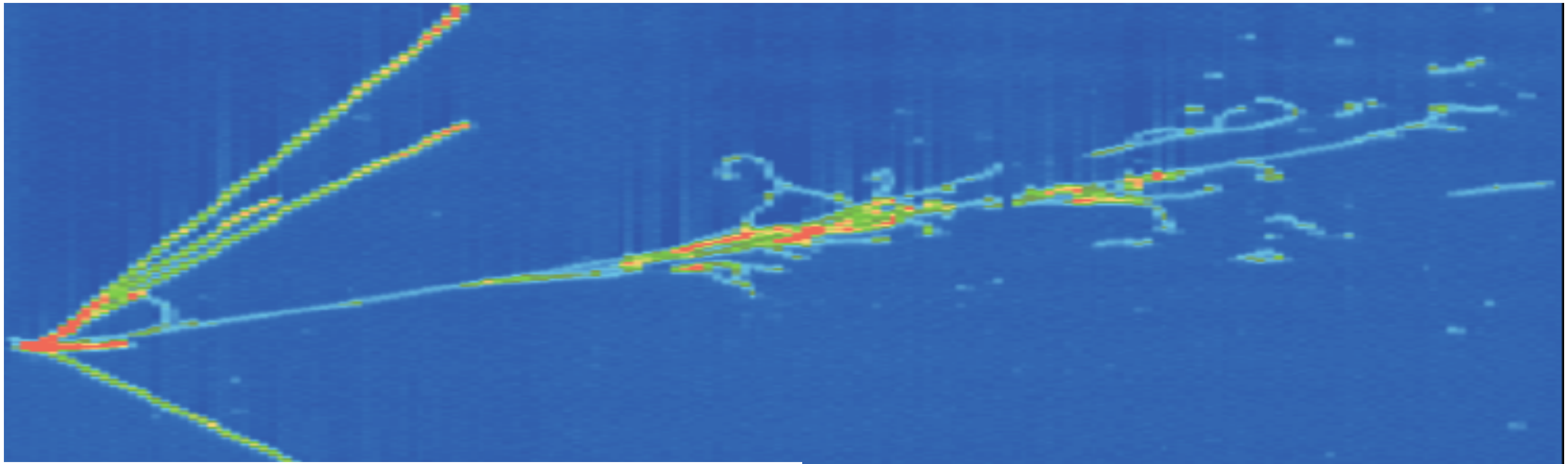
Guenette (MicroBooNE), Neutrino 2018

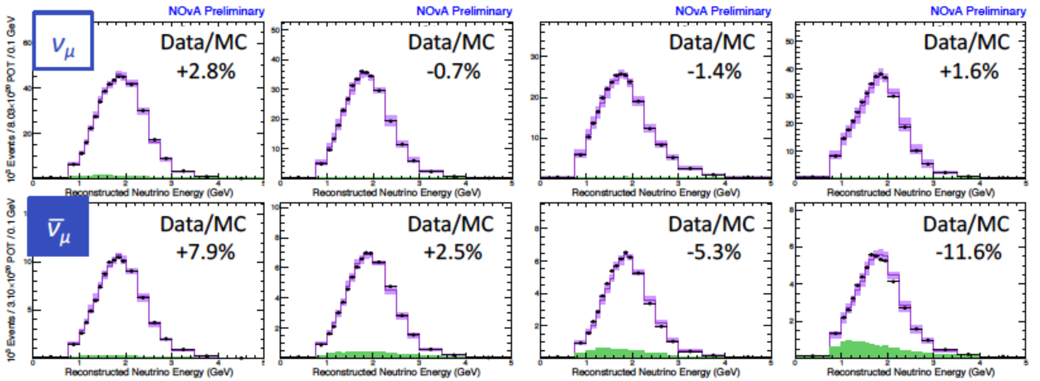
4. Neutrino hadronization

7: neutrino hadronization
Stefan Prestel
Costas Andreopoulos
Paola Sala
Kai Gallmesiter
Teppei Katori

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

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





Hadron shower measurement (c.f. NOvA) is probably not very sensitive to hadronization models

Matt Meuther

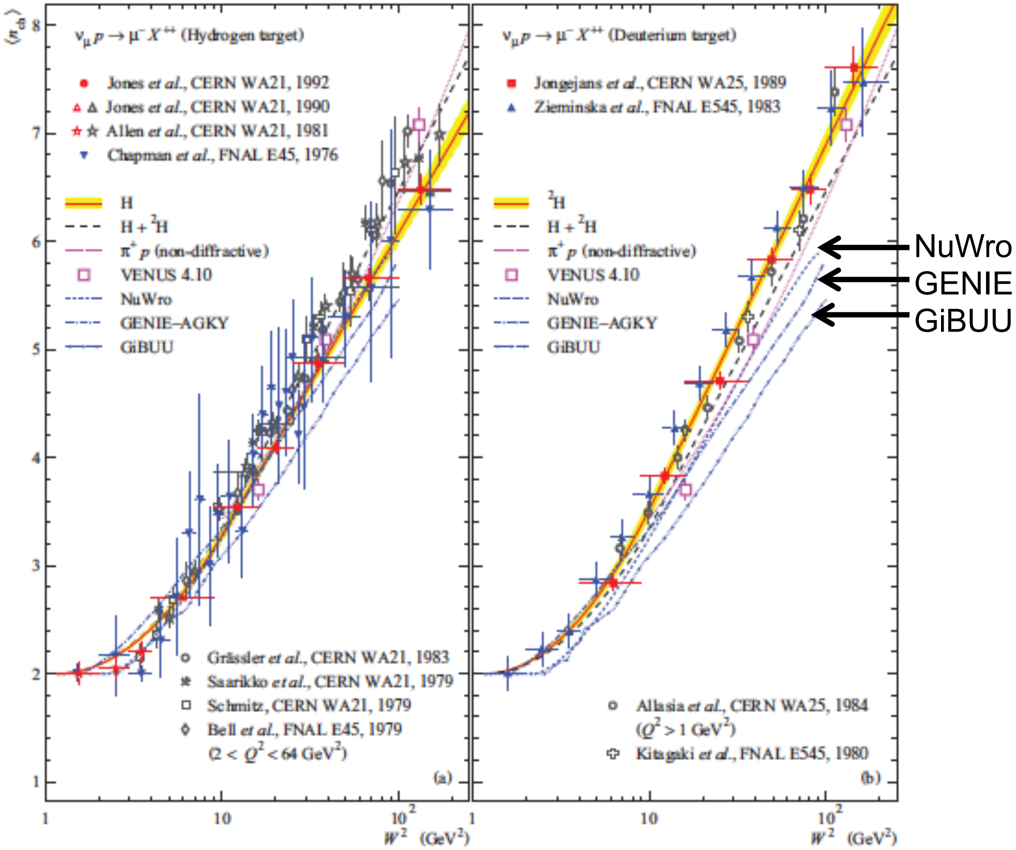
Kuzmin and Naumov, PRC88(2013)065501

4. PYTHIA neutrino hadronization

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)

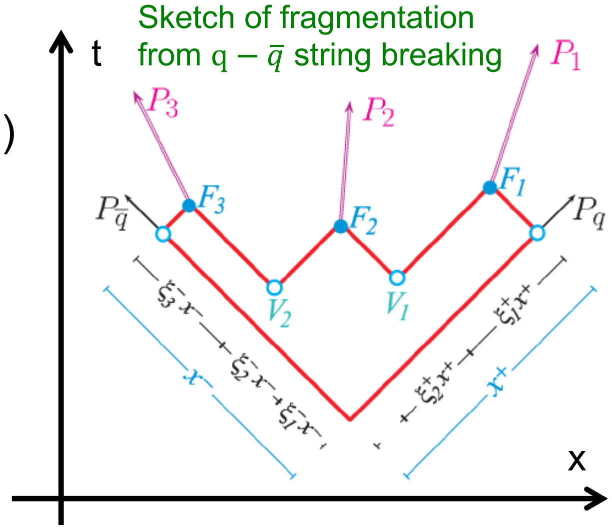


Average charged hadron multiplicity with function of W^2

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

4. PYTHIA neutrino hadronization

Shivesh Mandalia
(Queen Mary→Fermilab)


Sketch of fragmentation from $q-\bar{q}$ string breaking

Averaged charged hadron multiplicity <n_{ch}>

- PYTHIA6 with tuned Lund string function (Lund a ↑, Lund b ↓) can reproduce <n_{ch}> data both neutrino and antineutrino.

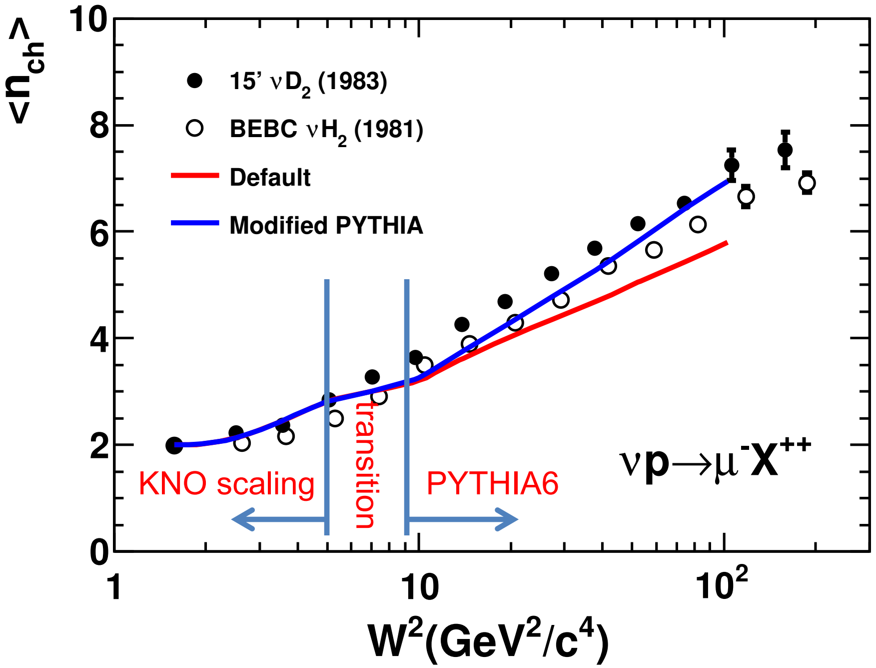
Lund string function

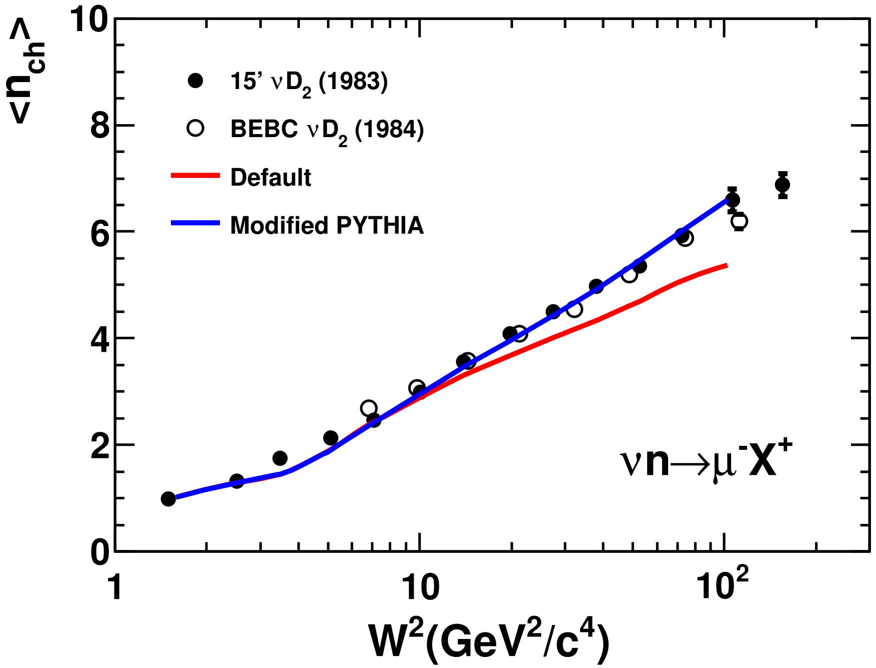
hadron energy distribution from iterative process

tunnelling probability

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

Neutrino average charged hadron multiplicity





TK et al, arXiv:1602.00083

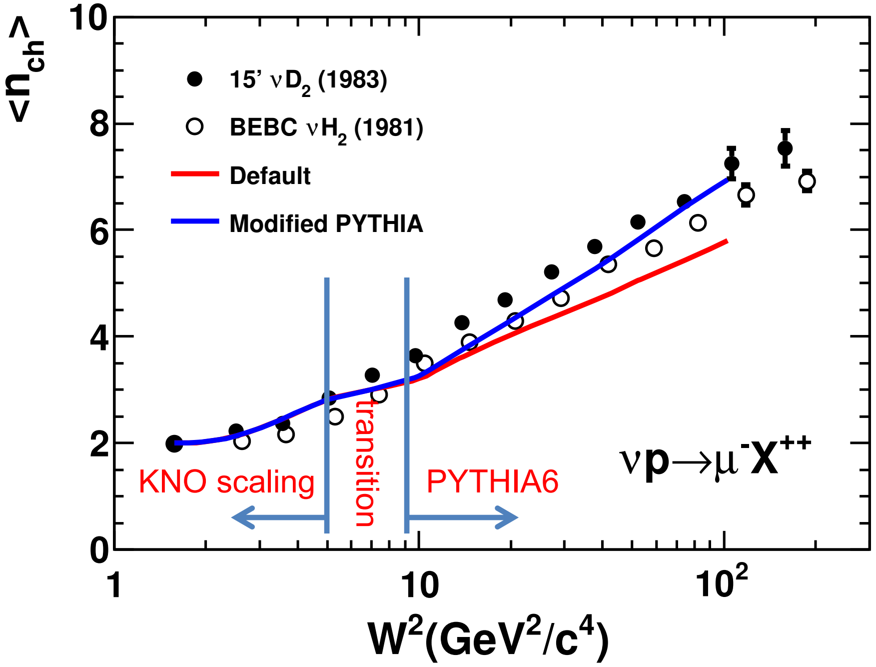
4. GENIE-PYTHIA8

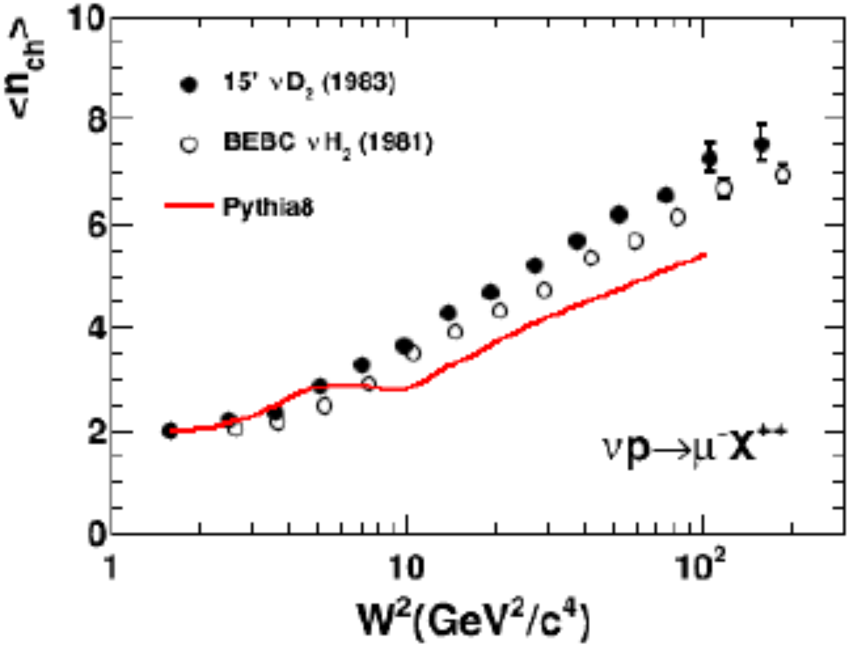
"We don't support PYTHIA6"
- Stephen Mrenna (Fermilab, PYTHIA author)

PYTHIA8 → LHC era generator

- initial test shows PYTHIA8 have harder fragmentation model (consistent with LHC energy)
- HERMES style tuning (=shift fragmentation function by tuning Lund string function) can fix averaged charged hadron multiplicity.
- Ongoing problem: π^o-multiplicity and all hadron multiplicity dispersion

Neutrino average charged hadron multiplicity



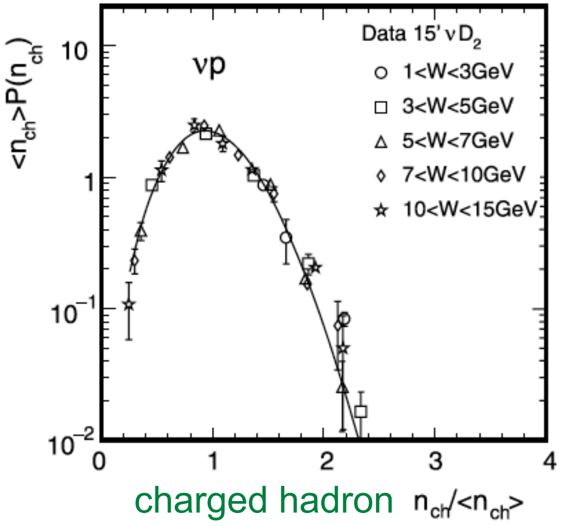


Zieminska et al (Fermilab 15'),PRD27(1993)47
AGKY model, EPJC63(2009)1

4. PYTHIA hadron multiplicity dispersion

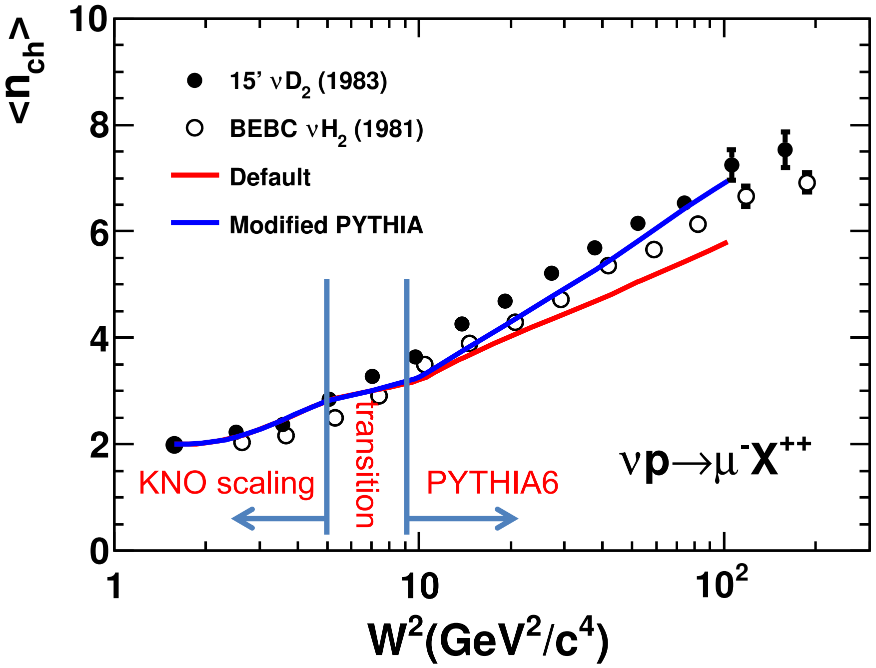
Bubble chamber topological cross section data

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.

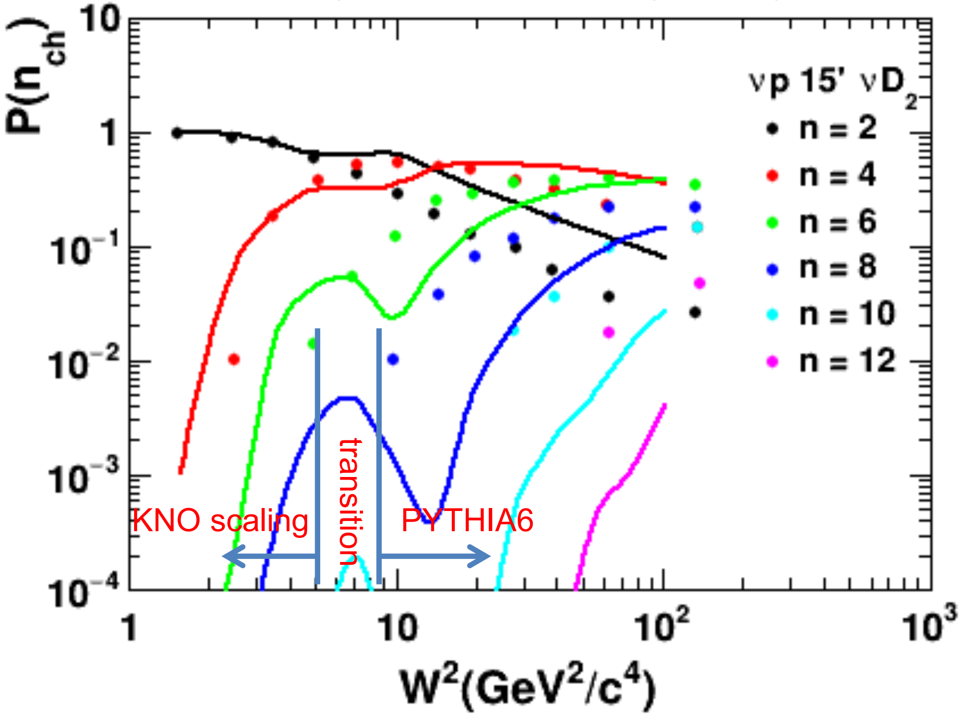


charged hadron multiplicity dispersion

Neutrino average charged hadron multiplicity



ν-p topological cross section (GENIE)



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

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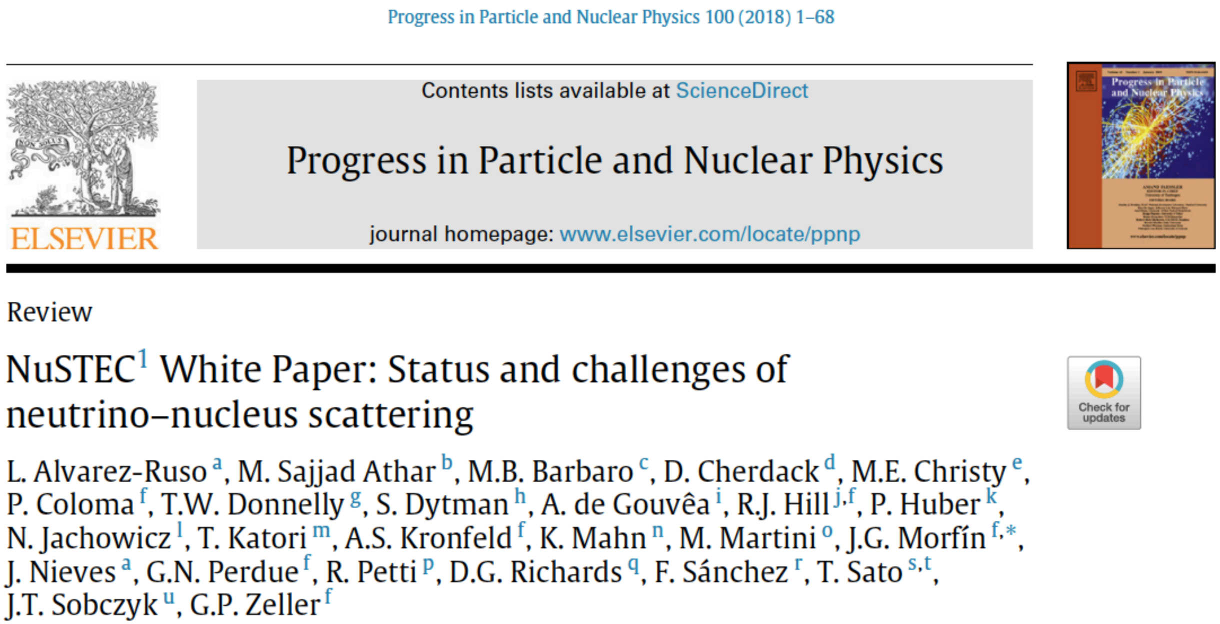

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Queen Mary
University of London

5. Conclusion: SIS systematics errors for ν-oscillation

Type	type of error
resonance	Single pion production
SIS	Non-resonant background
SIS	Bodek-Yang correction
SIS	Higher resonance
DIS	differential xs
DIS	A-scaling, empirical
DIS	A-scaling, nuclear PDF
Hadronization	low W averaged charged hadron multiplicity
Hadronization	high W averaged charged hadron multiplicity

Basic ingredients

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5. Conclusion: SIS systematics errors for ν-oscillation

Type	type of error	approach	ongoing issue	size of error
resonance	Single pion production	Form factors, external data on e and nu	MiniBooNE-MINERvA data tension	large, but studied well
SIS	Non-resonant background	External data on e and nu	Not many studies. Very phenomenological	???
SIS	Bodek-Yang correction	Change Bodek-Yang parameters by eyes	There is are correlations on model parameters	maybe large?
SIS	Higher resonance	???	MC must be wrong	???
DIS	differential xs	NuTeV-GENIE comparison (bottom-up)	Disagreement seen only at very low x (<0.03)	1-2% by GENIE
DIS	A-scaling, empirical	MINERvA-GENIE (bottom-up)	No understanding MINERvA data	maybe large?
DIS	A-scaling, nuclear PDF	From nuclear PDF, CT10? nCTEQ? (top-down)	GRV98 is only compatible with B-Y correction	expected to be small
Hadronization	low W averaged charged hadron multiplicity	Change AGKY model parameters	Not many data.	maybe large?
Hadronization	high W averaged charged hadron multiplicity	bubble chamber-PYTHIA comparison	Lund string function need to be tune for lowE	1-2% by GENIE

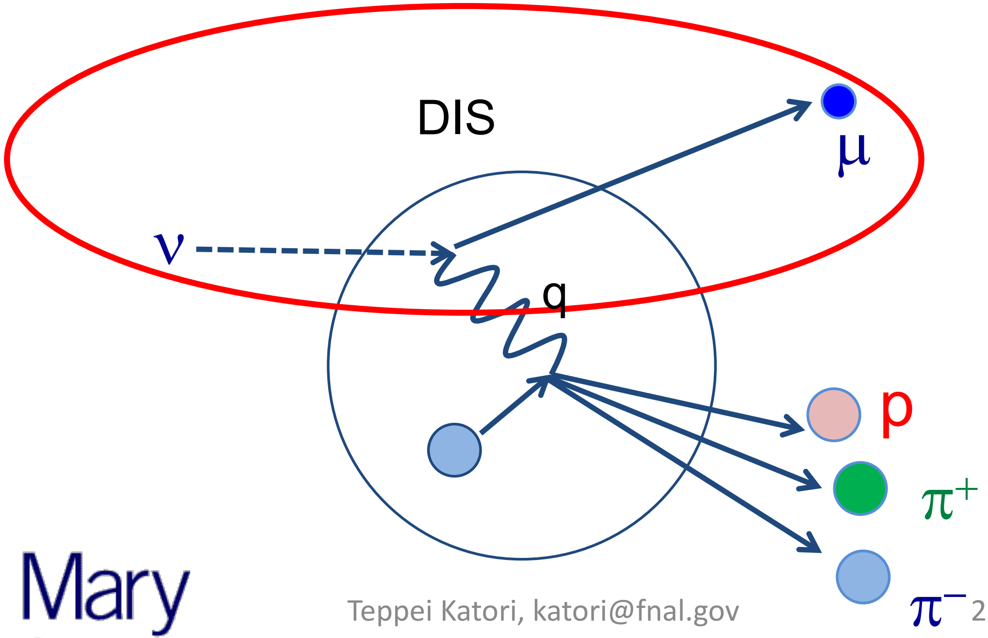
Some of systematic errors are identified to be dangerous…,
- What kind of systematic errors do we have on nuSIS&DIS?

Back up

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



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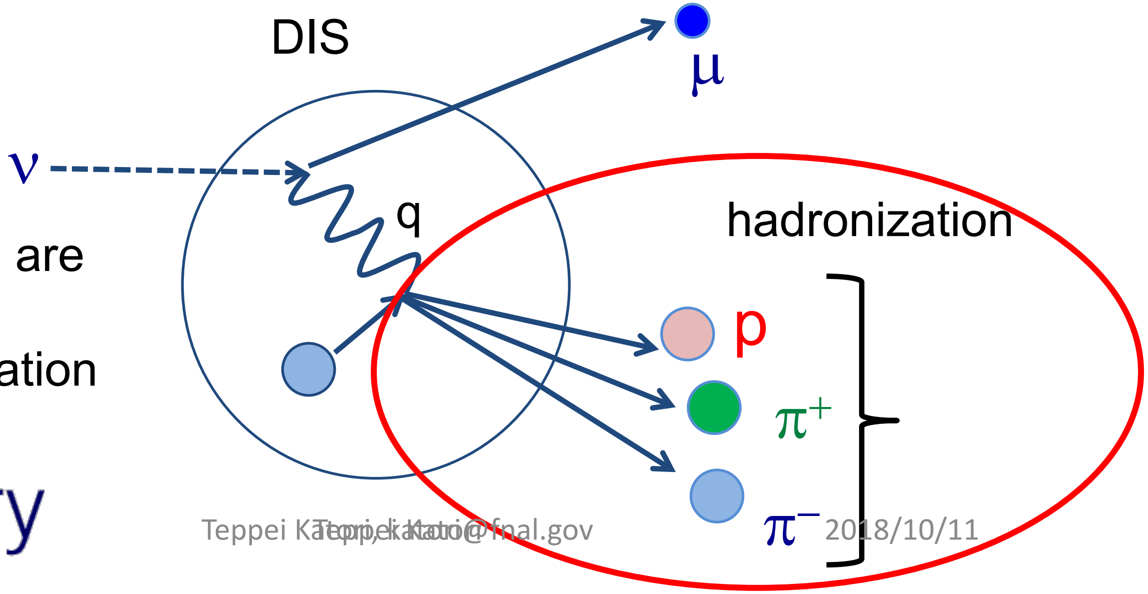
Neutrino hadronization

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



DIS and Hadronization are usually modelled independently in simulation

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

1. Neutrino DIS cross section overview

Neutrino Deep Inelastic Scattering (DIS)

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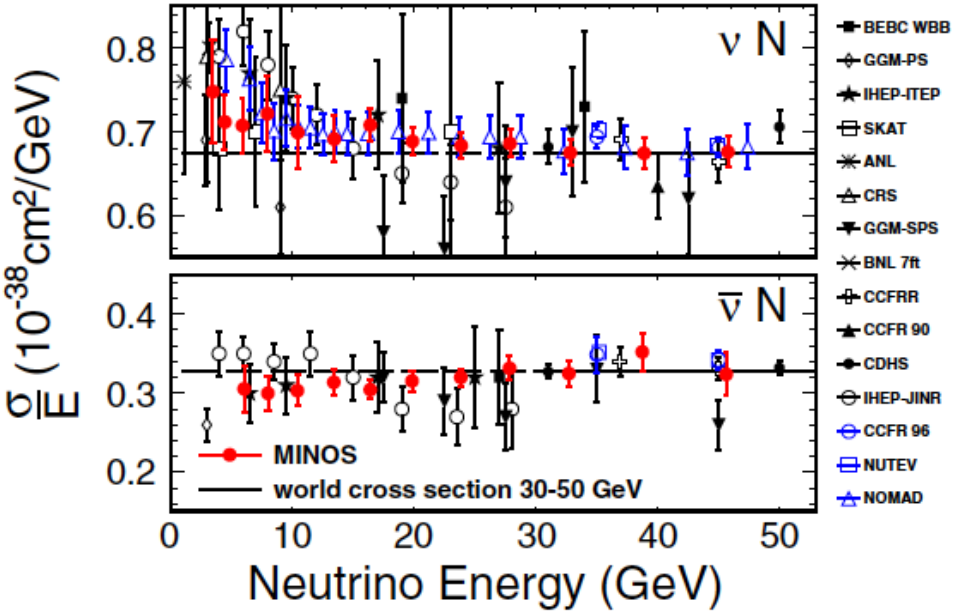
- DIS differential cross section is function of x and y
- DIS total cross section is function of Eν, integrated in x and y

Neutrino hadronization

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

DIS 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



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

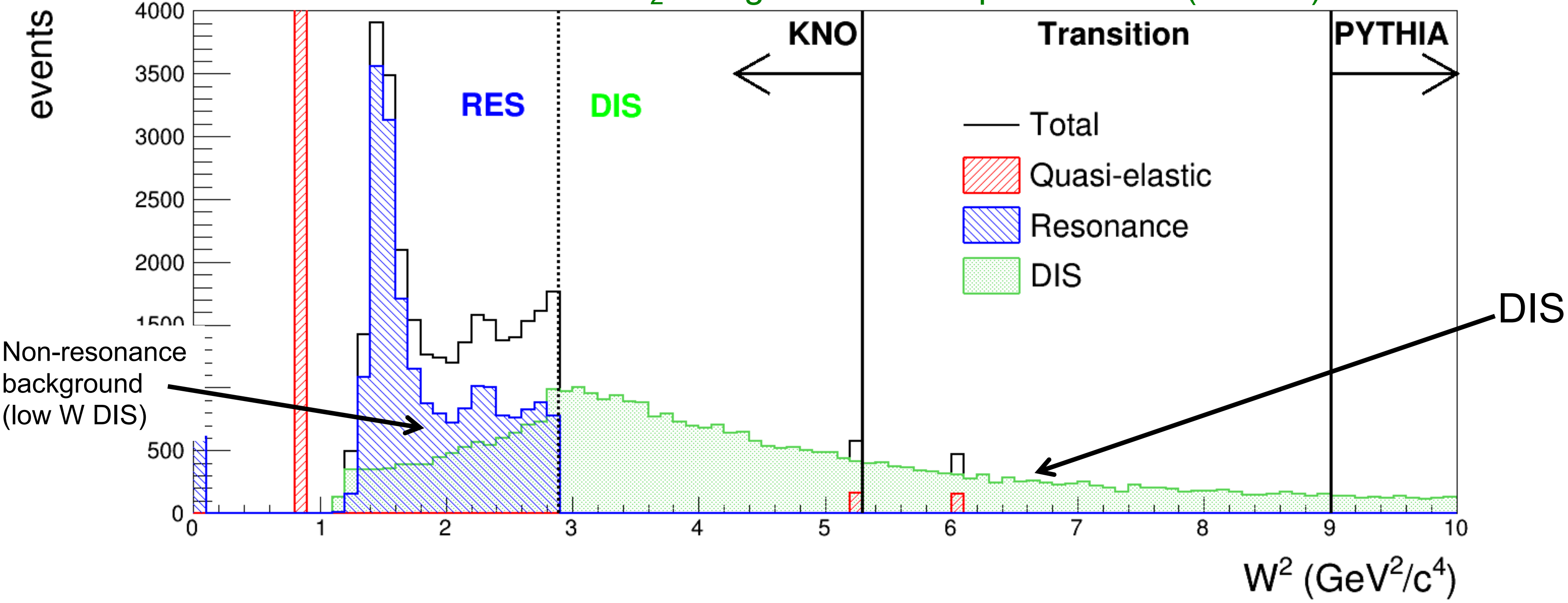
Hadronization

$W^2 < 5.3$GeV^2 : KNO scaling based model
2.3GeV$^2 < W^2 < 9.0$GeV^2 : transition
9.0GeV$^2 < W^2$: PYTHIA6

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

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

GENIE v2.8.0



Non-resonance background (low W DIS)

DIS

2. NEUT SIS model

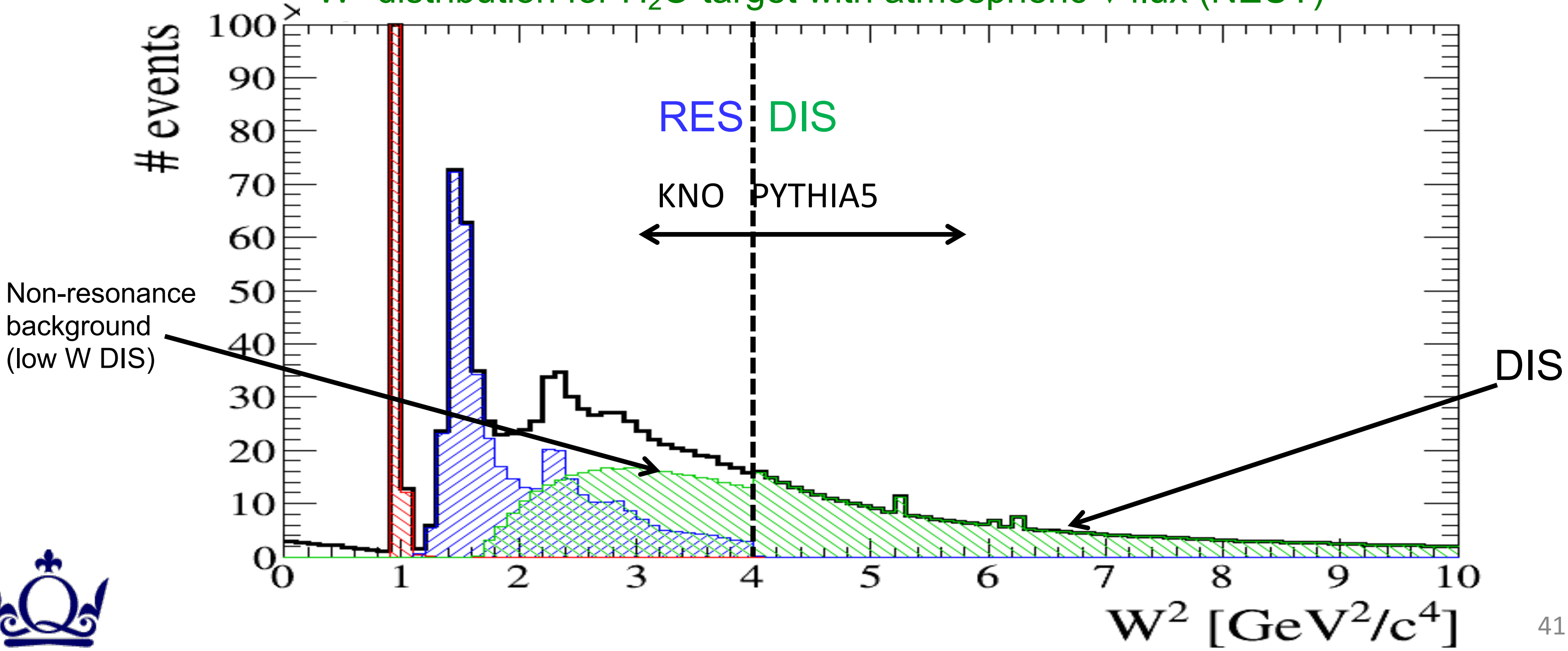
NEUT is the generator used by all Japanese neutrino programs (T2K, SuperK, etc)

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

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



Non-resonance background (low W DIS)

DIS

University of London

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

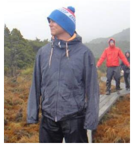
Hadronization

- PYTHIA fragmentation
- KNO scaling

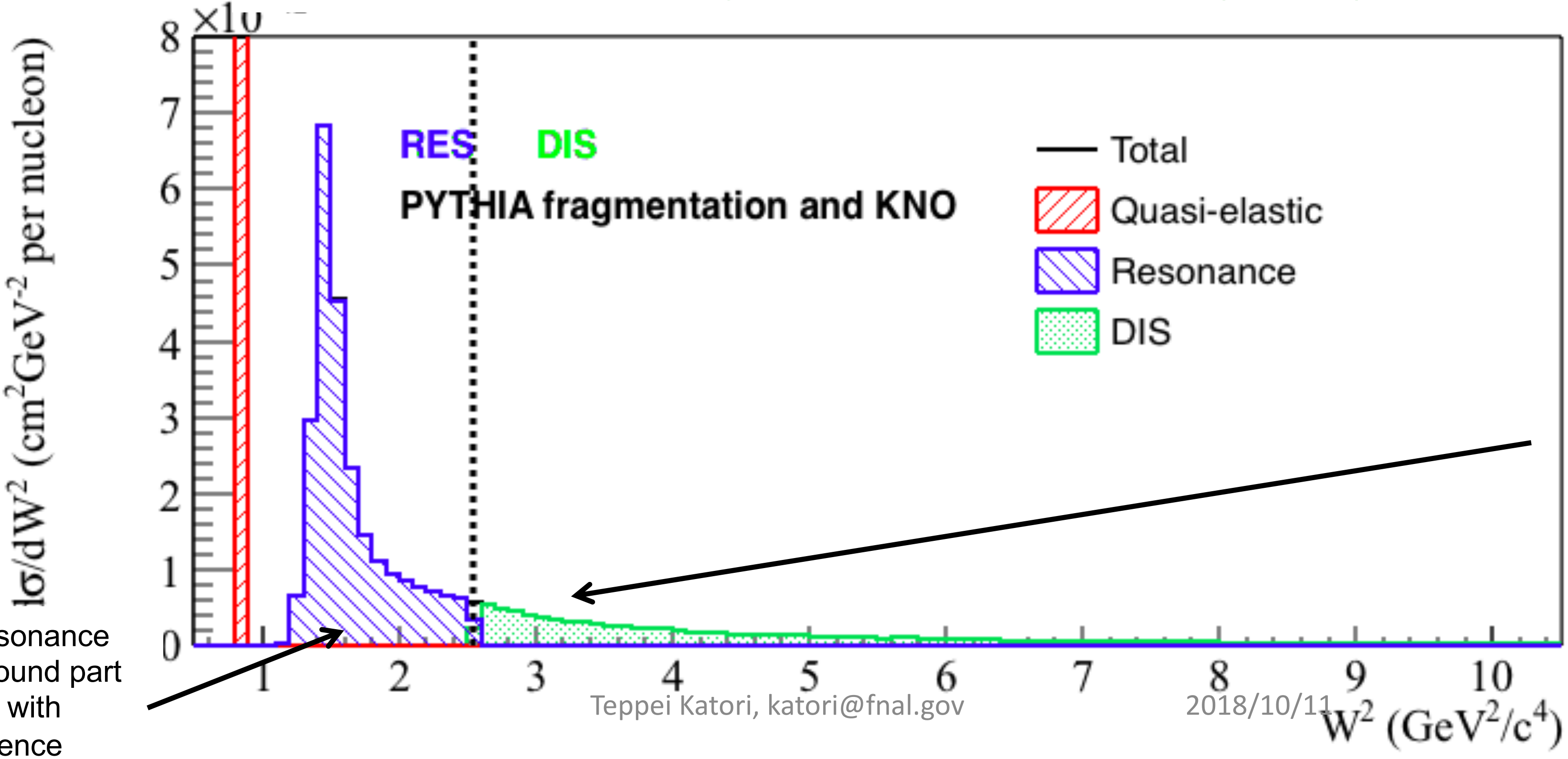
There are 2 kind of "transitions" in SIS region

- cross-section
- hadronization

File made by
Luke Pickering
(MSU)



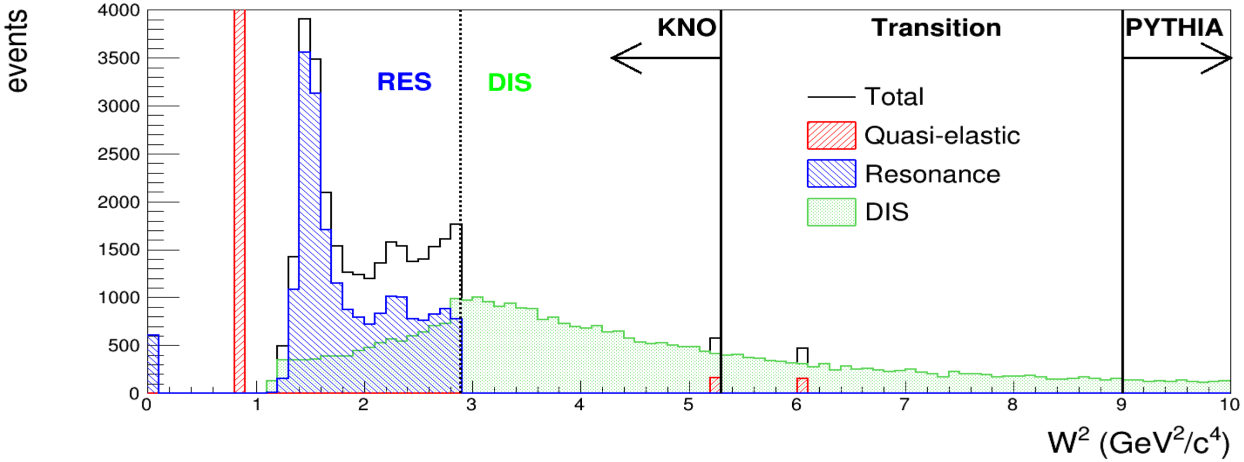
W^2 distribution for H_2O target with atmospheric-ν flux (NuWro)



DIS

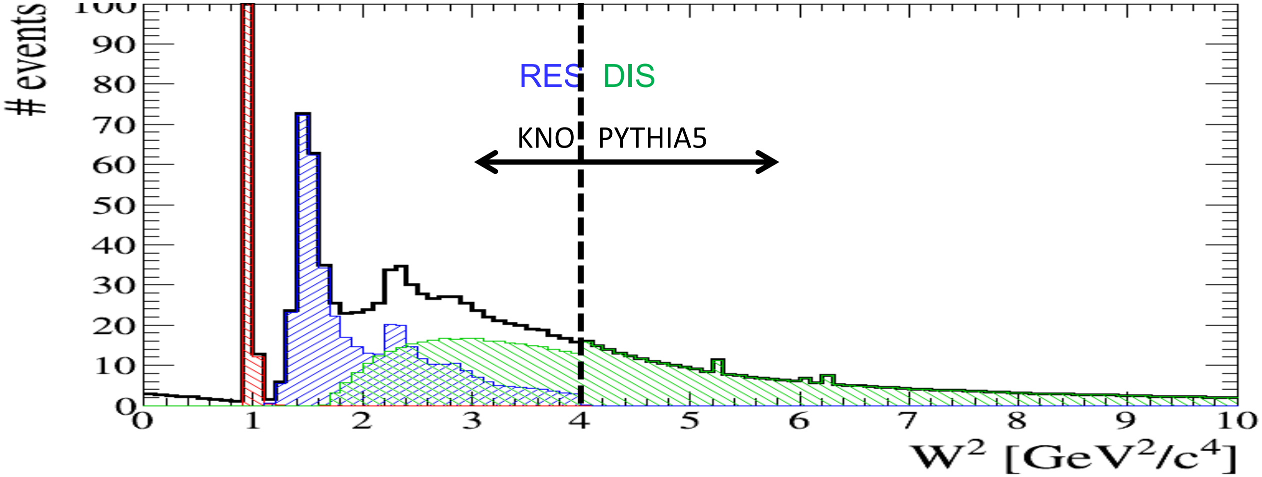
Non-resonance background part of RES with interference

GENIE



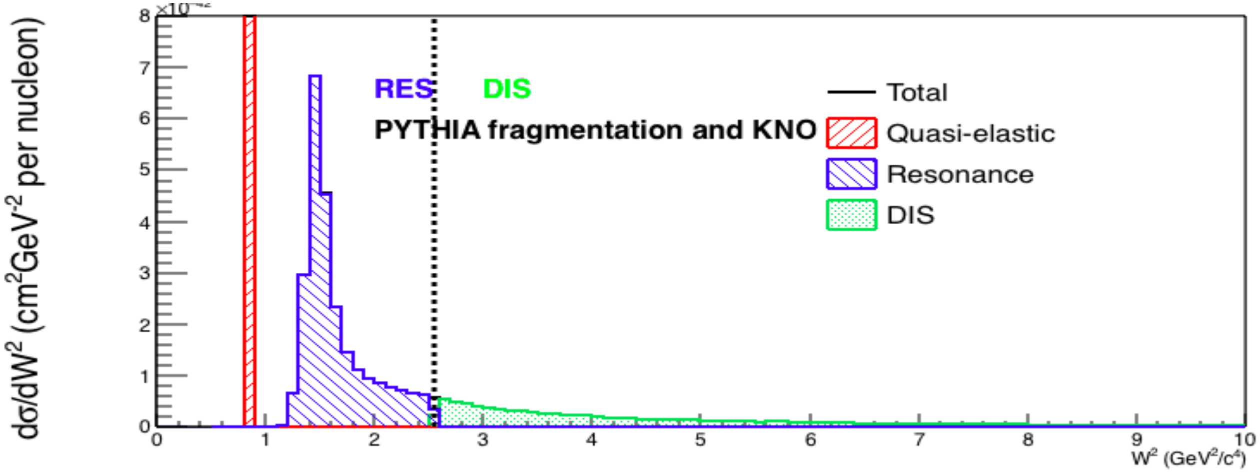
vs

NEUT



vs

NuWro



Queen Mary
University of London

TK and Mandalia, JPhysG42(2015)115004, arXiv:1602.00083

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

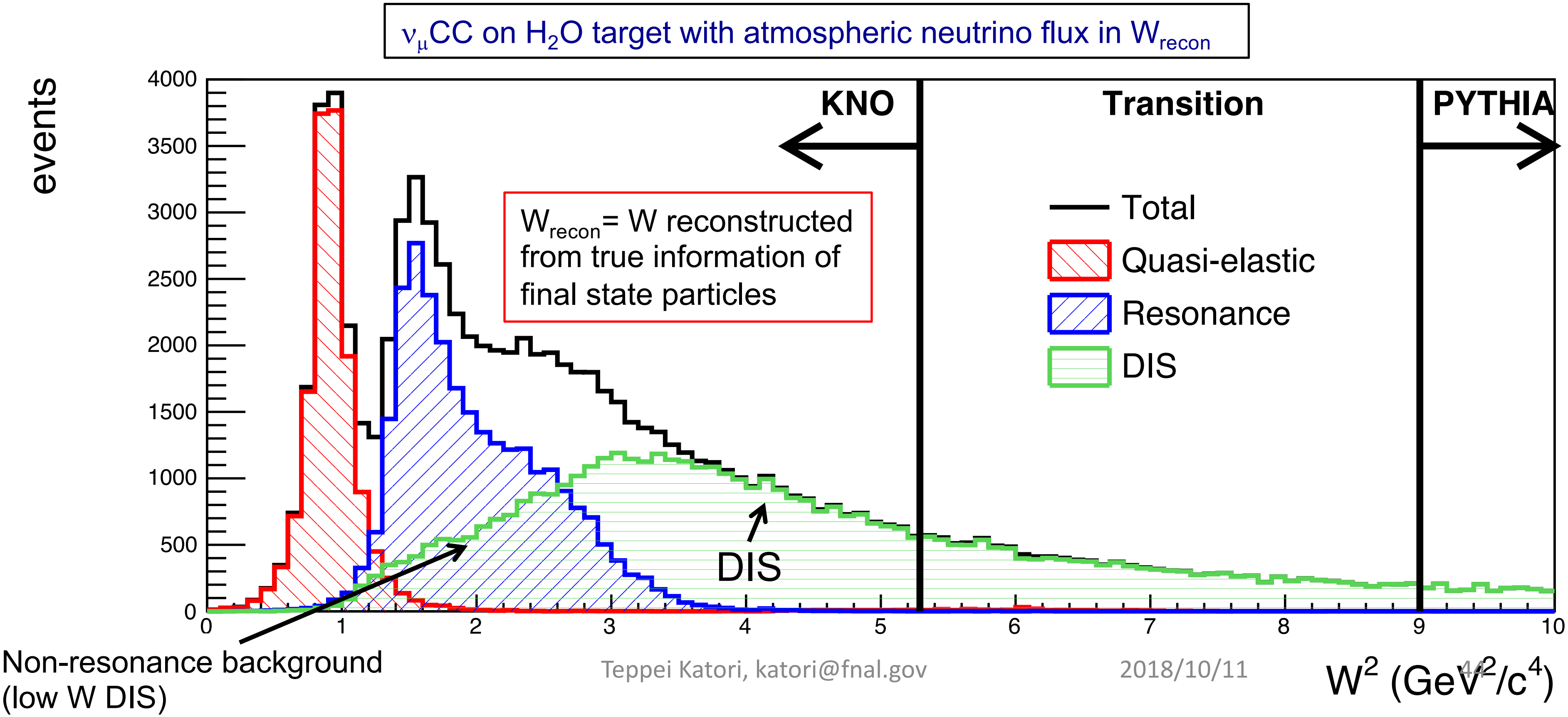
$W^2>2.9$ GeV^2 : DIS

Hadronization (AGKY model)

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

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

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

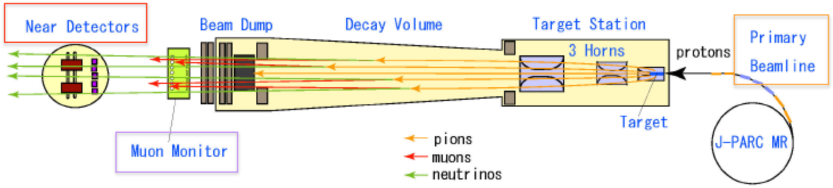


TK, Martini, JPhysG45(2017)1
Kowalik, NuInt18 (Toronto)

1. Typical neutrino beams for oscillation experiments

e.g.) J-PARC neutrino beam (T2K)

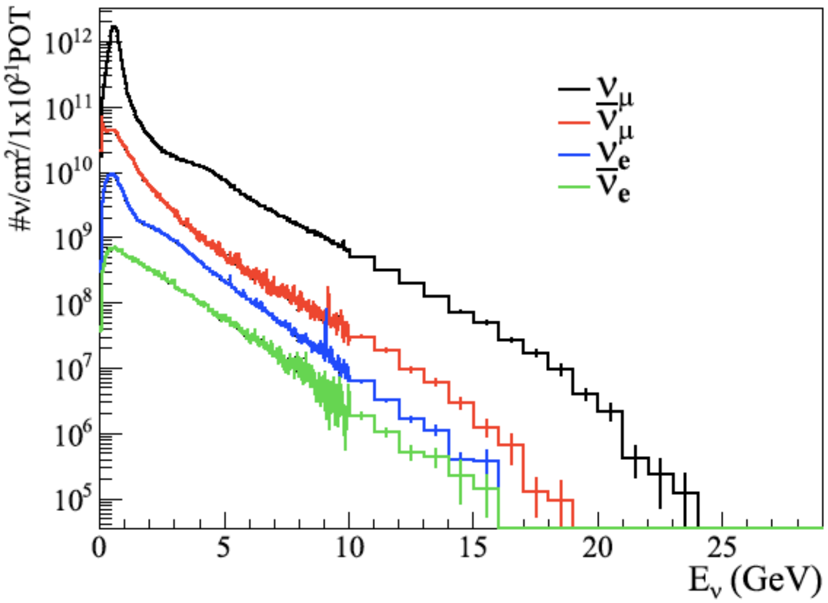
- pion decay-in-flight (high flux)
- off-axis beam (narrow band)
- but has components up to ~ 10 GeV
- typical beam 1-10 GeV
- ~4% normalization error (best case)

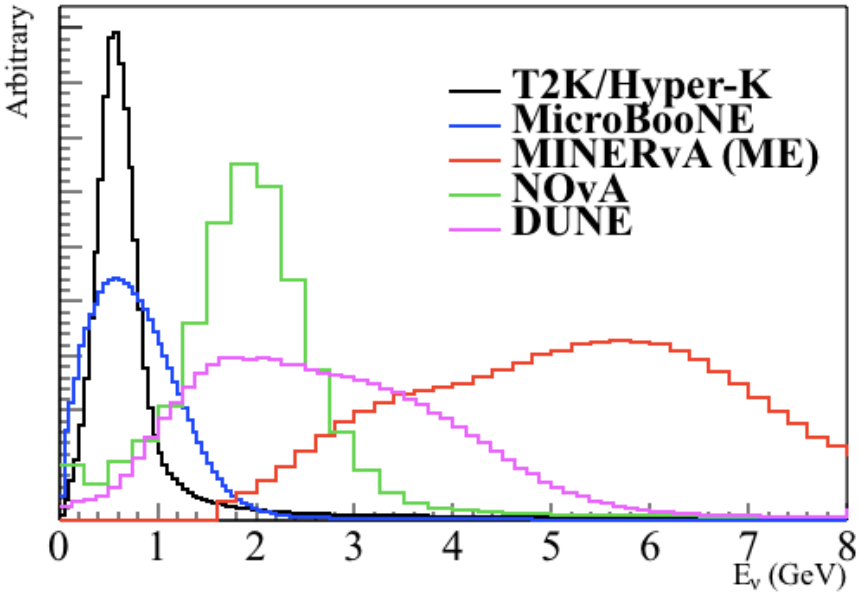


INGRID
monitors the stability of ν flux and direction

Muon Monitor
measures the muon profile after beam dump

Proton Beam Monitors
measure the proton beam intensity, direction





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

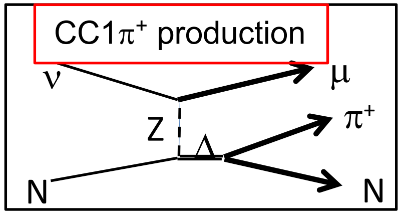
MINERvA,PRD94(2016)052005

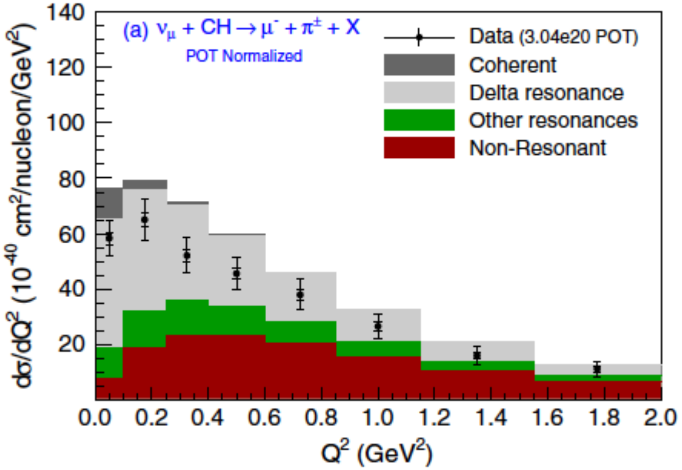
1. MINERvA FSI and cross section model tuning (2016)

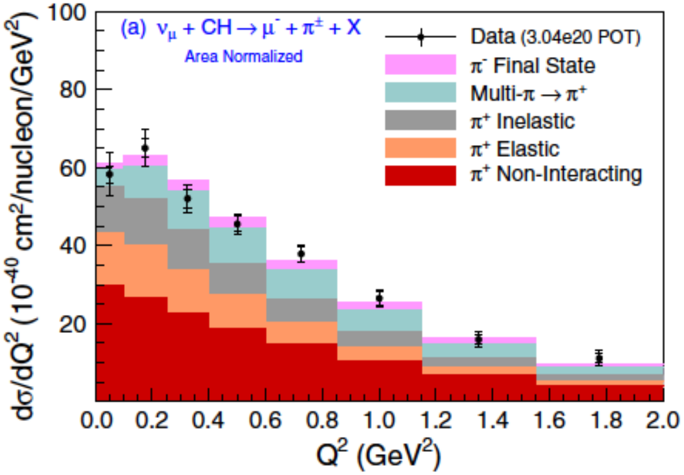
MINERvA CC1π^+, $\bar{\nu}$CC1π^o, νCC1π^o data simultaneous fit

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

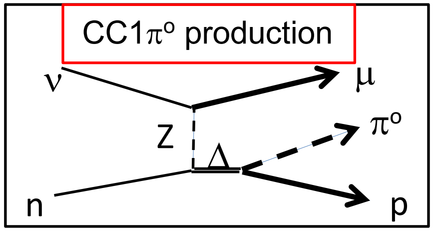
ν_μCC1π^+ data has better shape agreement with GENIE

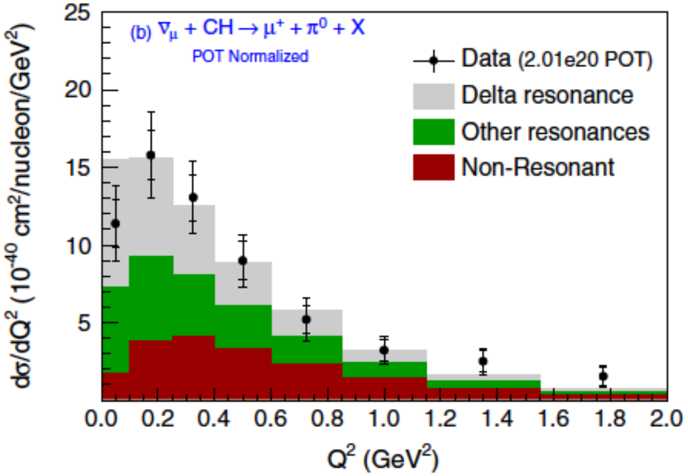


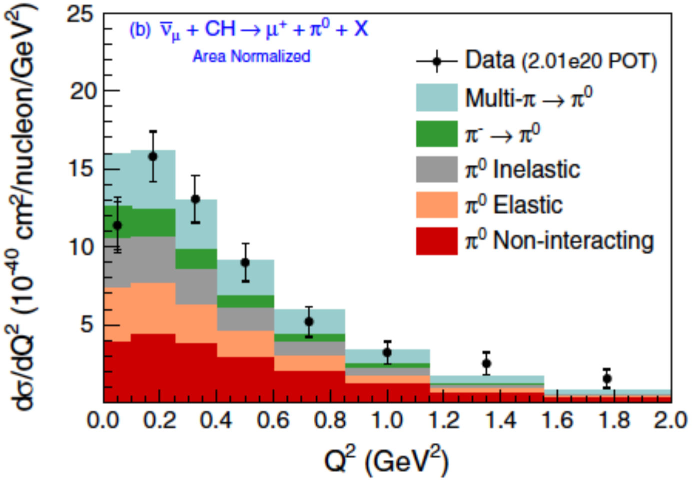




$\bar{\nu}$CC1π^o data has better normalization agreement with GENIE







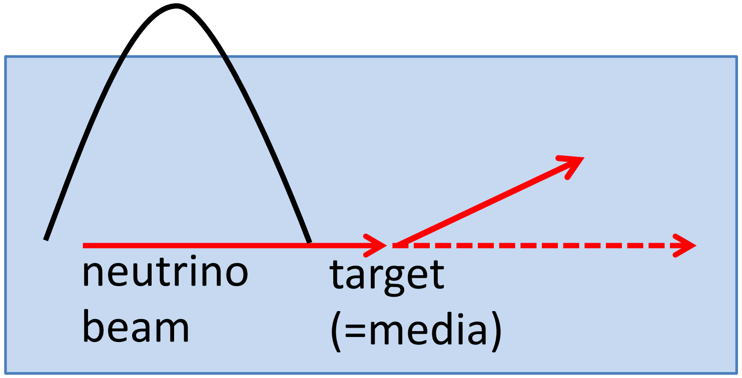
Benhar et al, Rev.Mod. Phys.80(2008)189, PRL105(2010)132301

1. Typical neutrino detectors

Neutrino scattering

- Wideband beam

→ Measure all reactions

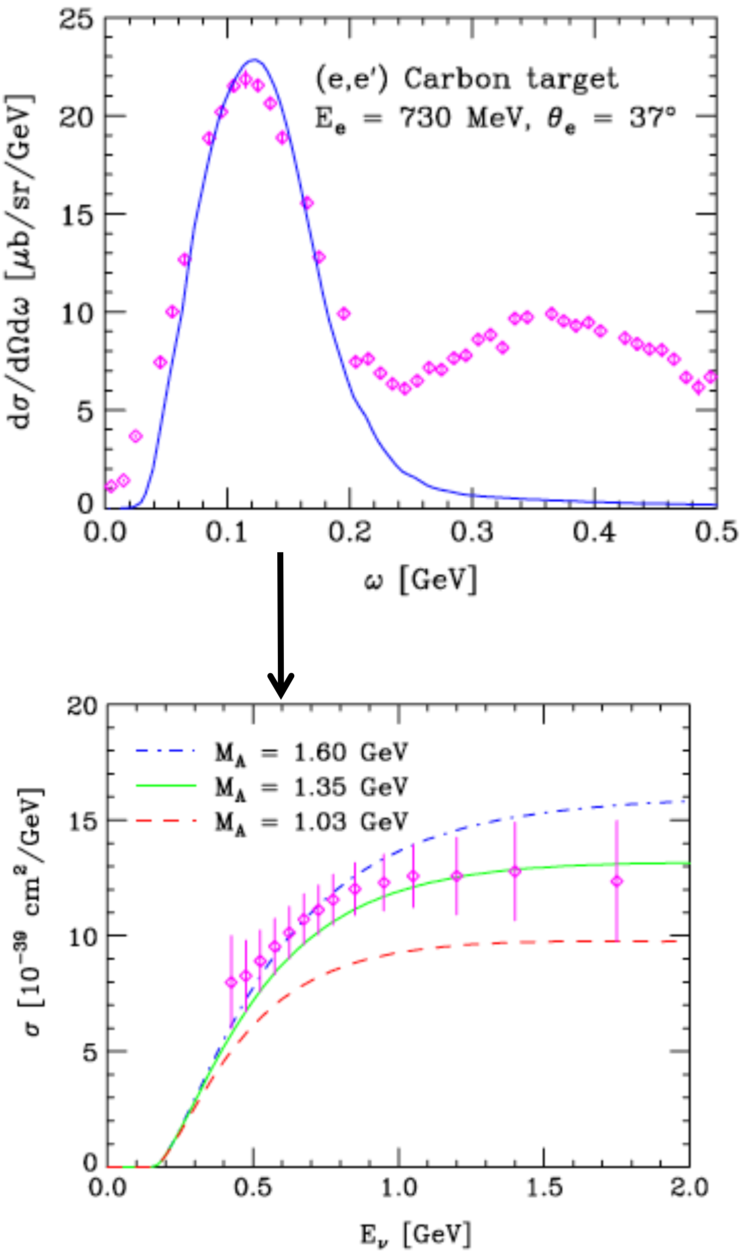


neutrino beam

target (=media)

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



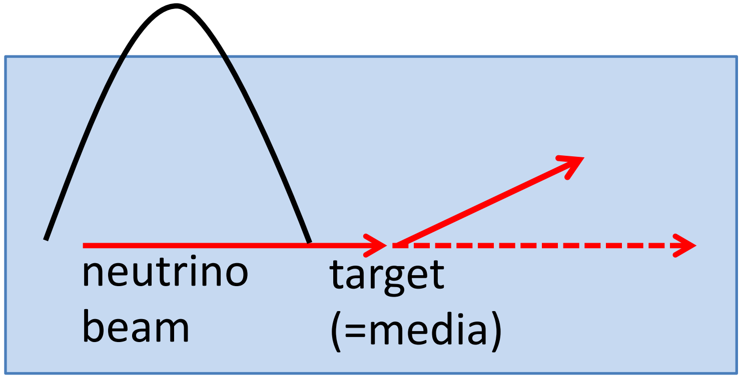
Benhar et al, Rev.Mod. Phys.80(2008)189, PRL105(2010)132301

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

Omar Benhar (Rome I)

→ Measure all reactions



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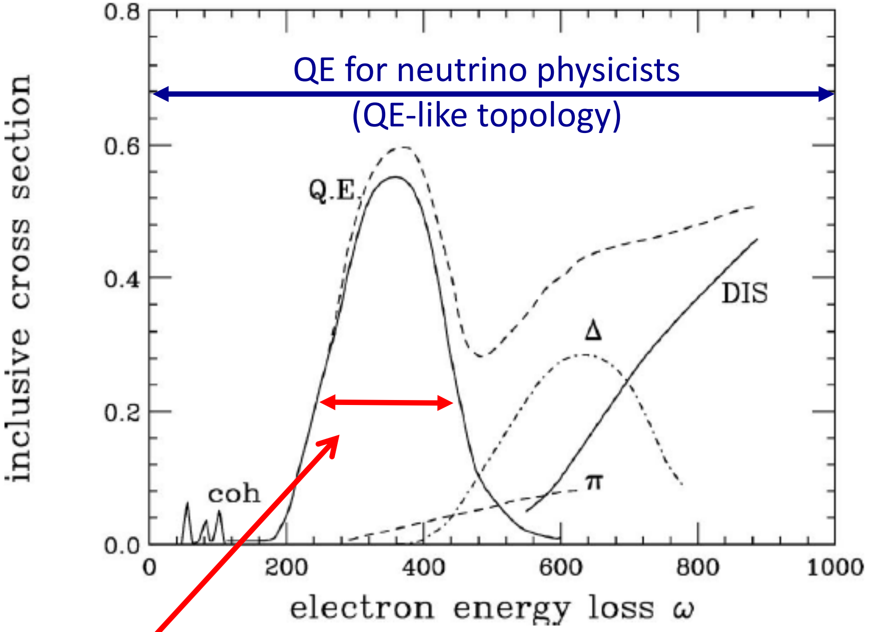
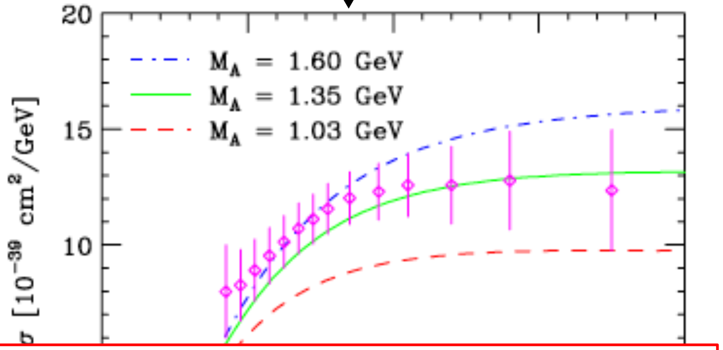


QE for neutrino physicists (QE-like topology)

QE for nuclear physicists (genuine QE)



Two rules of neutrino interaction physics

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

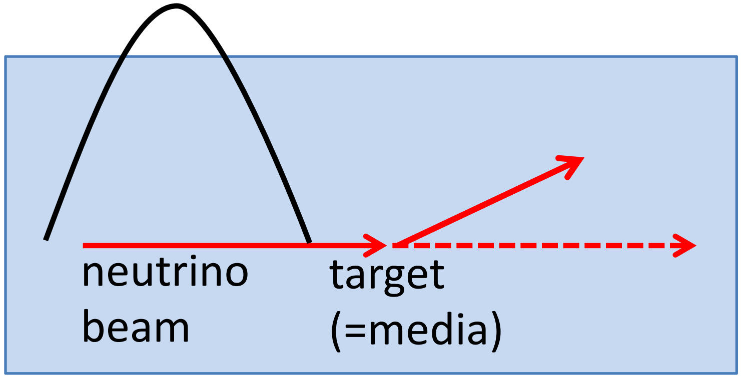
Ankowski et al, PRD92(2015)073014

1. Kinematic E reconstruction vs calorimetric E reconstruction

Neutrino scattering

- Wideband beam

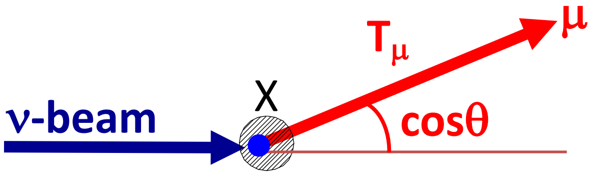
→ observables are inclusive



Incomplete kinematics

- Large mass, coarse instrumentation
- No one measures neutrino energy directly
- Reconstructing kinematics (Eν, 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

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

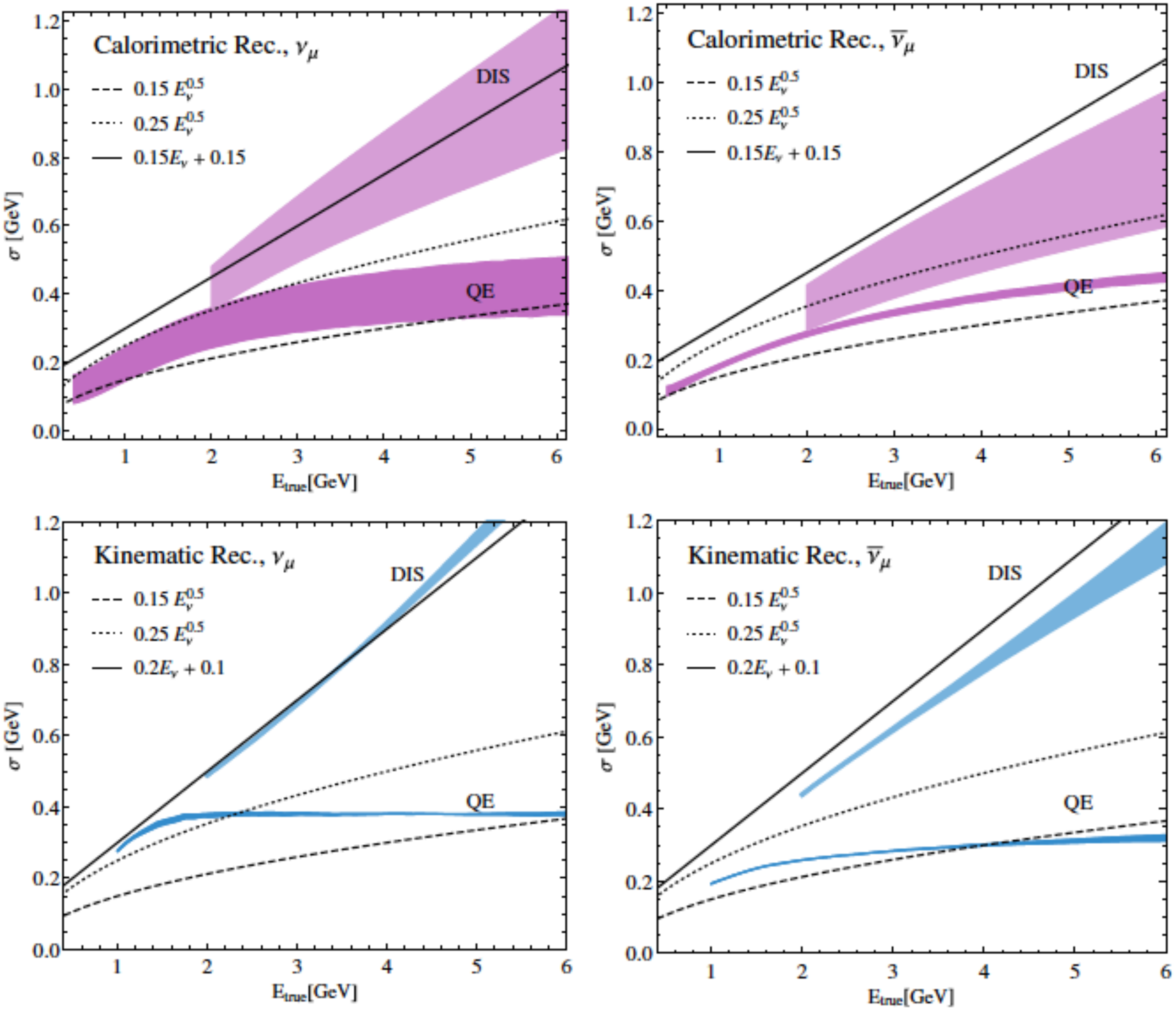
Ankowski et al, PRD92(2015)073014

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



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.

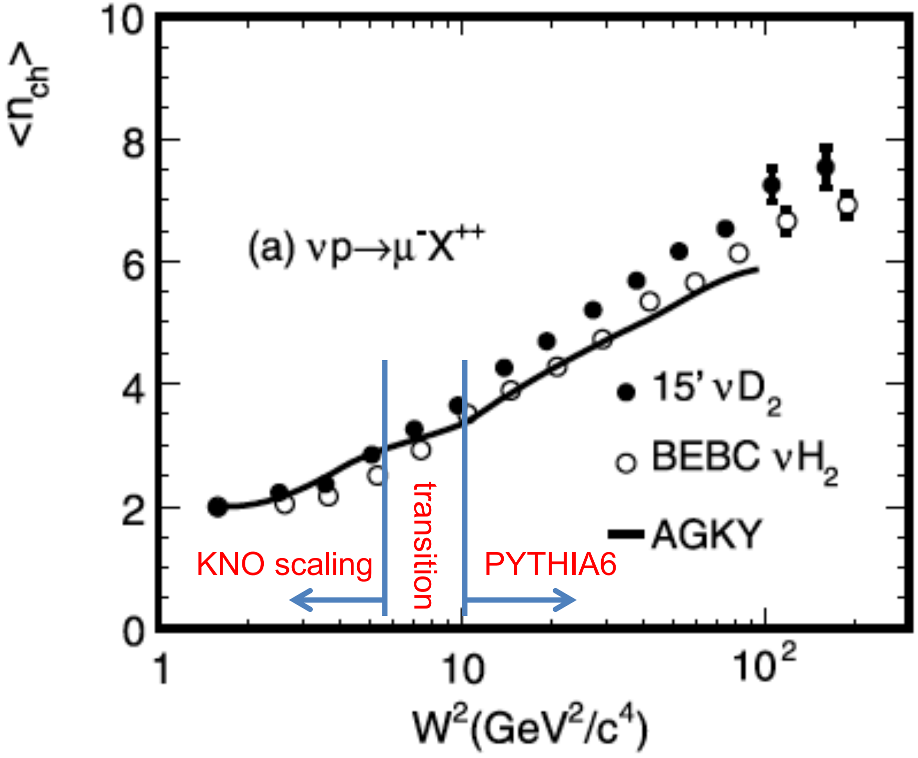
KNO-scaling based model (low W hadronization)

- 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.

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

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

averaged charged hadron multiplicity



charged hadron multiplicity dispersion