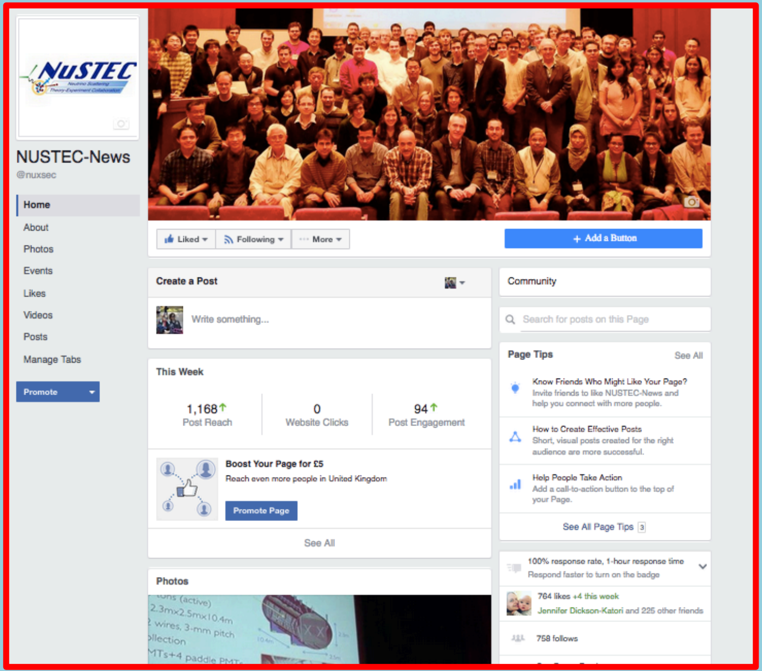
TK, Martini, arXiv:1611.07770 (JPhysG focus issue)

SIS and DIS Neutrino Interactions

Subscribe "NuSTEC News"
http://nustec.fnal.gov/
like "@nuxsec" or "NuSTEC-News" on Facebook
Twitter hashtag #nuxsec



Teppei Katori
Queen Mary University of London
IPPP-NuSTEC workshop, IPPP, Durham, Apr. 18, 2017

TK, Martini, arXiv:1611.07770 (JPhysG focus issue)

SIS and DIS Neutrino Interactions

Subscribe “NuSTEC News”
http://nustec.fnal.gov/
like “@nuxsec” or “NuSTEC-News” on Facebook
Twitter hashtag #nuxsec

outline

1. **Beyond CCQE and 1 pion production**
2. **Shallow inelastic scattering (SIS) and DIS**
3. **Neutrino hadronization**
4. **Conclusion**

Teppei Katori
Queen Mary University of London
IPPP-NuSTEC workshop, IPPP, Durham, Apr. 18, 2017

Bubble Chamber Cup 2017, April 9, Sheffield (IoP HEP annual meeting football match)

Queen Mary 0-2 Sheffield
Queen Mary 0-1 Manchester B
Queen Mary 0-∞ Birmingham A
Queen Mary 2-2 Liverpool B
Queen Mary 1-4 Manchester A

Liverpool A (again) won the game

1. Beyond CCQE and 1 pion production

2. Shallow inelastic scattering (SIS) and DIS

3. Neutrino hadronization

4. Conclusion

1. Flux-integrated differential cross-section

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

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

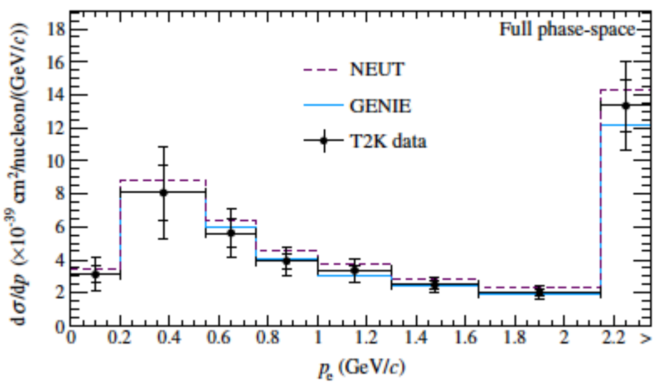
Now, all modern experiments publish flux-integrated differential cross-section
→ Detector efficiency corrected event rate
→ Flux and FSI are convoluted
→ Theorists can reproduce the data with neutrino flux tables from experimentalists
→ Minimum model dependent, useful for nuclear theorists

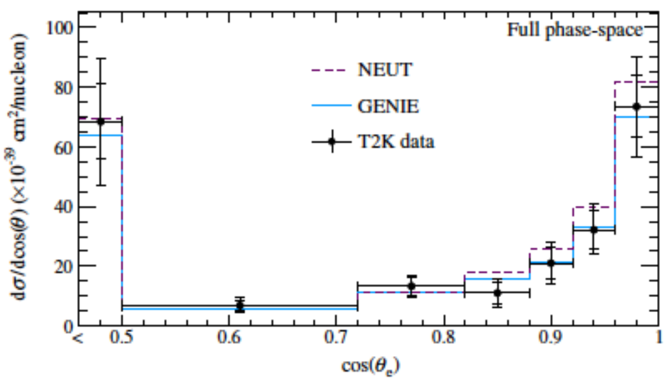
These data play major roles to study/improve neutrino interaction models by theorists

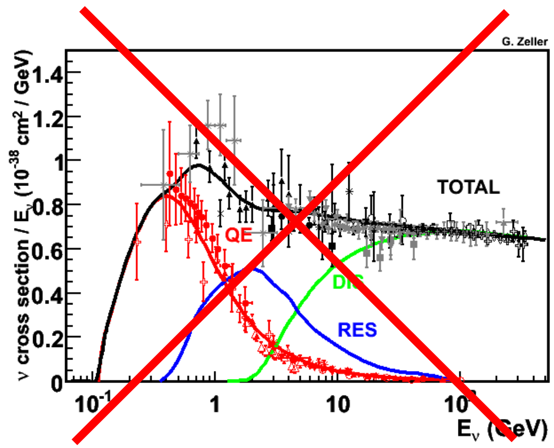
1. Flux-integrated differential cross-section

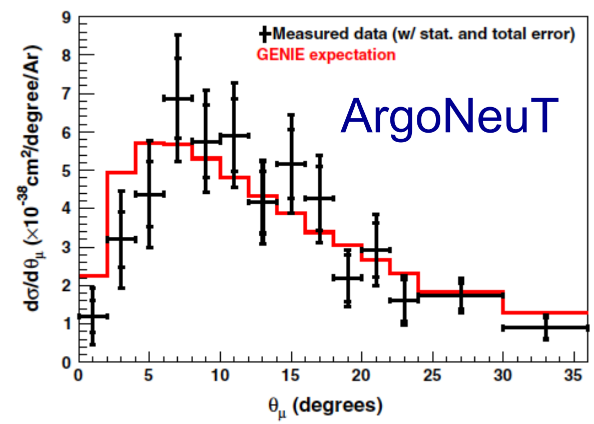
Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

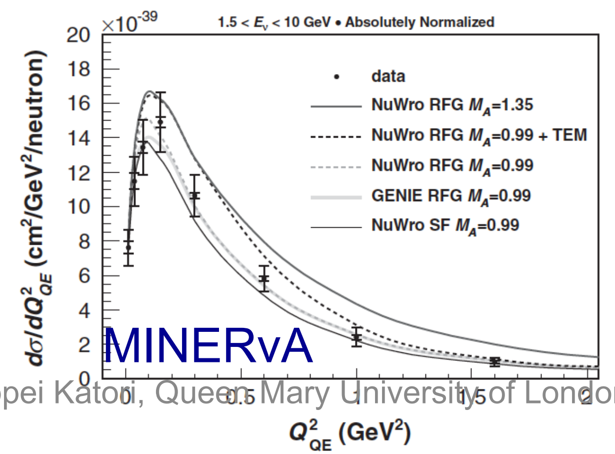
T2K



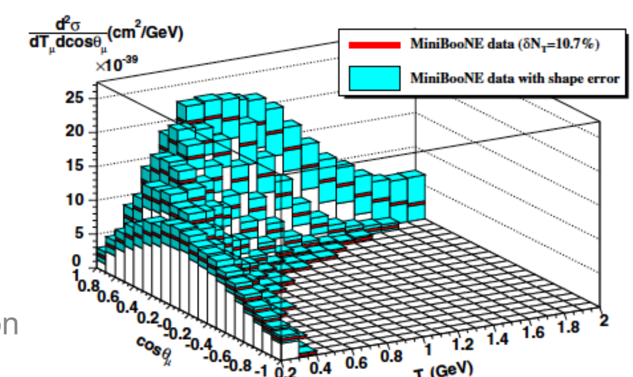








MiniBooNE



Queen Mary
University of London

1. Flux-integrated differential cross-section

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

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

$$\boxed{\frac{d\sigma}{dX}=\frac{1}{\Phi}\int\left(\frac{d^2\sigma}{dxdy}\right)\otimes\Phi(E_\nu)\otimes FSI}$$

Theorists

Experimentalists

$$\boxed{\left(\frac{d\sigma}{dX}\right)_i=\frac{\sum_j U_{ij}^{-1}(d_j-b_j)}{\Phi\cdot T\cdot\varepsilon_i\cdot\Delta X_i}}$$

flux-integrated differential cross-section data allow theorists and experimentalists talk first time in neutrino interaction physics history (cf, fiducial cross-section measurement in LHC)

1. Flux-integrated differential cross-section

Various type of flux-integrated differential cross-section data are available from all modern neutrino experiments.
→ Now PDG has a summary of neutrino cross-section data! (since 2012)

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{\sum_j U_{ij}^{-1}(d_j - b_j)}{\Phi \cdot T \cdot \varepsilon_i \cdot \Delta X_i}$$

Experimentalists

Theorists

$$\frac{d\sigma}{dX} = \frac{1}{\Phi}\int\left(\frac{d^2\sigma}{dxdy}\right)\otimes\Phi(E_\nu)\otimes FSI$$

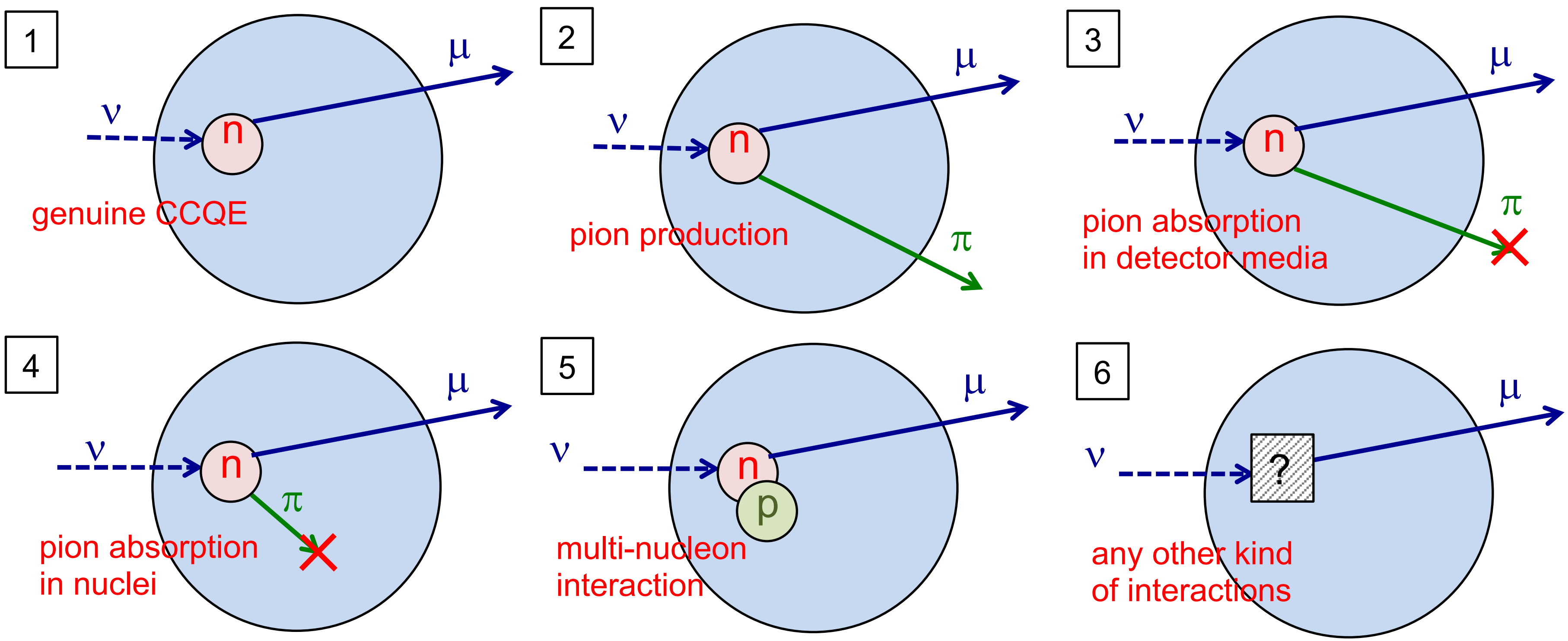
flux-integrated differential cross-section data allow theorists and experimentalists talk first time in neutrino interaction physics history (cf, fiducial cross-section measurement in LHC)

1. Topology-based cross section

Flux-integrated differential cross section also use topology-based cross-section

e.g.) CC0p cross section definition
- Complexity increase dramatically for multi-hadron final states

Genuine CCQE = (1)
CC0π = (1), (4), (5), (6)



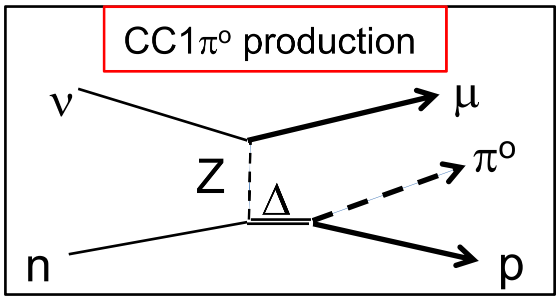
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

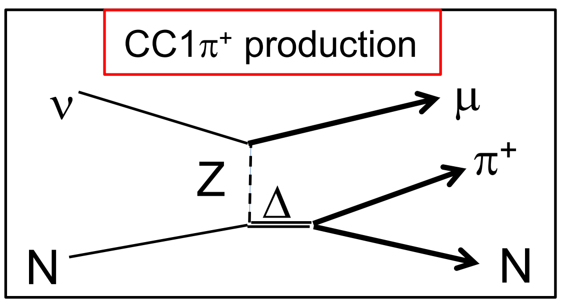
1. FSI and pion data

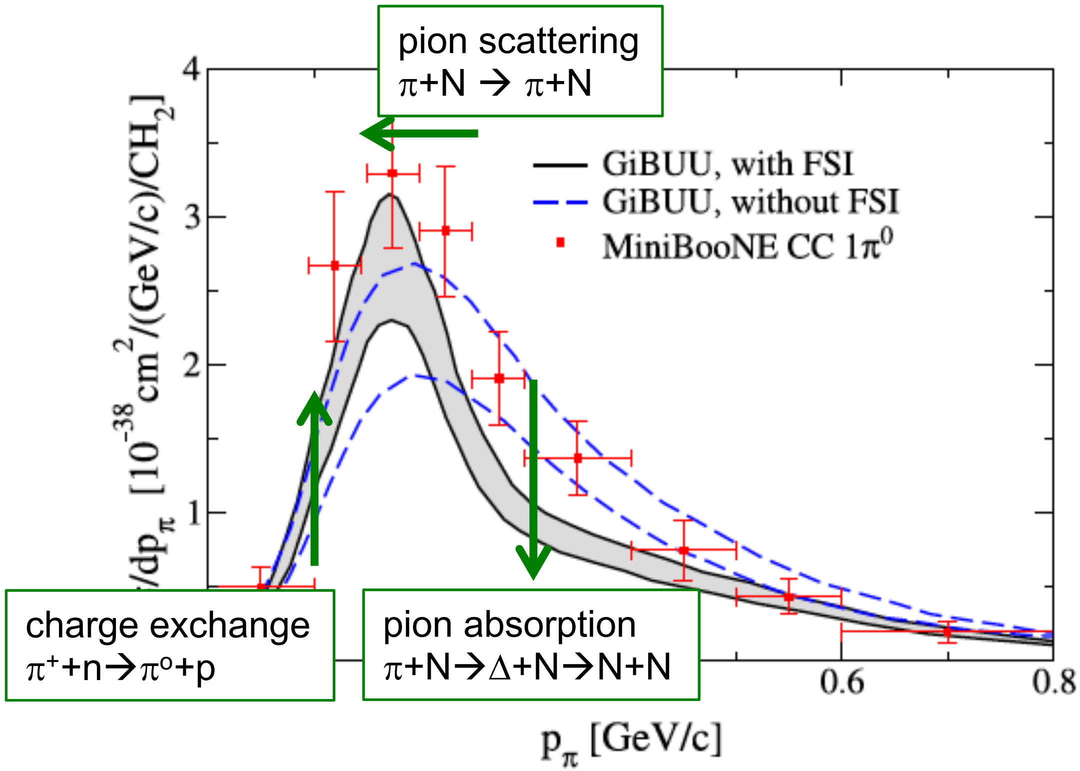
e.g.) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

Final state interaction

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







Interpretation of 1 pion production is already very complicated. Multi-hadron final state measurements by higher energy processes (SIS, DIS) is the completely new world for neutrino oscillation community!

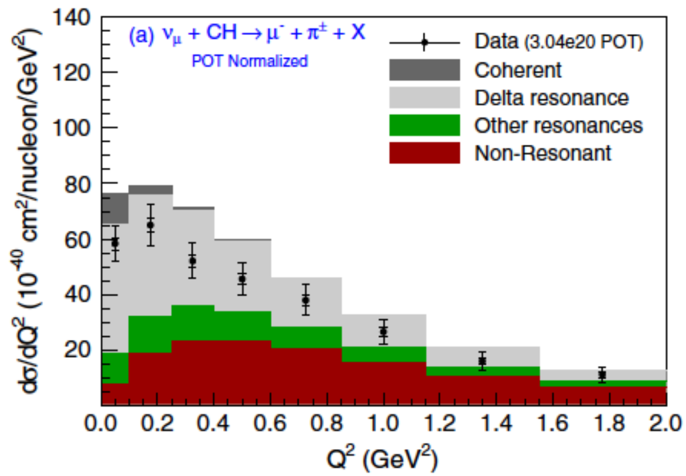
University of London

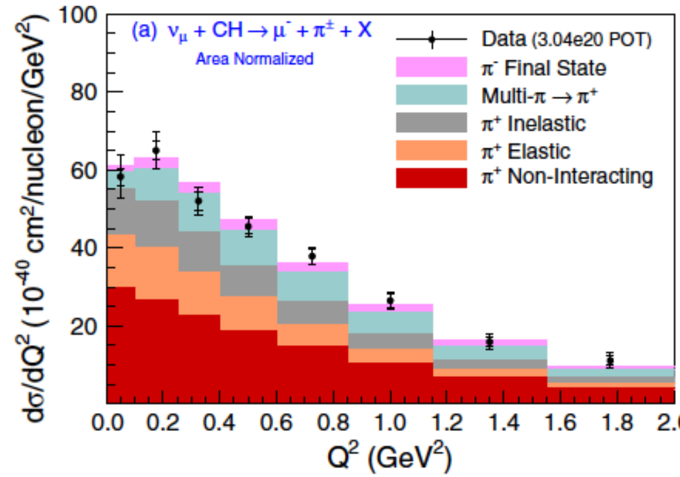
1. FSI tuning from pion data

FSI and MINERvA pion production data

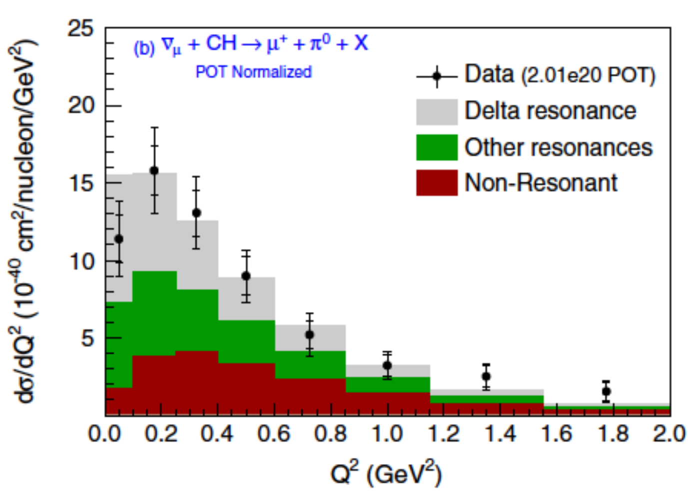
- this moment, there is no clear directionality to tune MC…

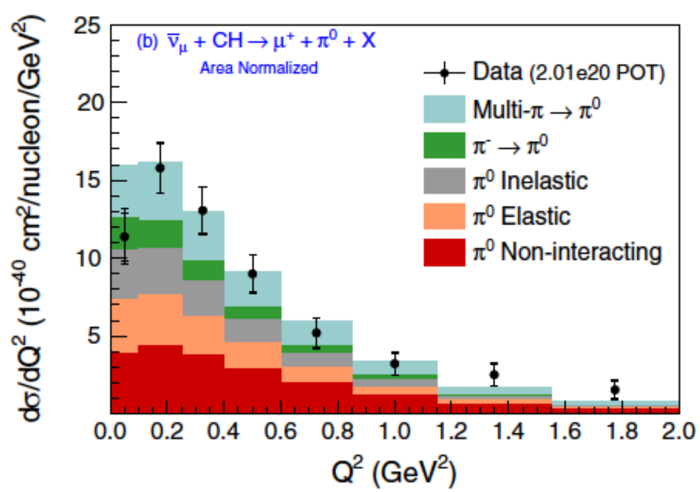
ν_μCC1π^+ data has better shape agreement with GENIE





anti-ν_μCC1π^o data has better normalization agreement with GENIE

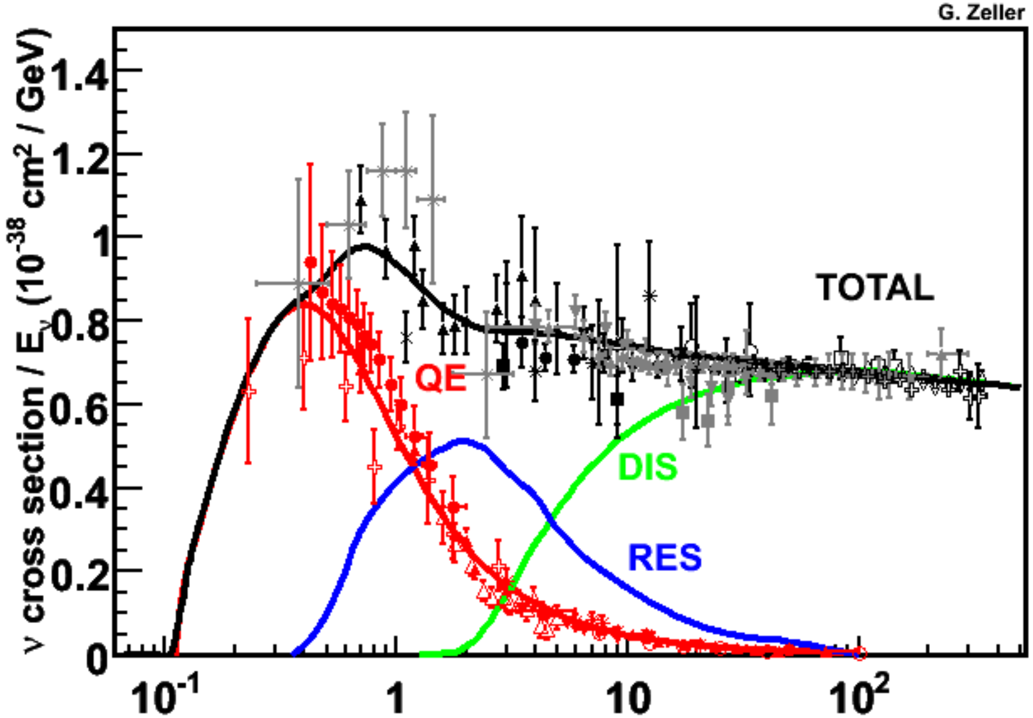




1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



ν_μCC cross section per nucleon

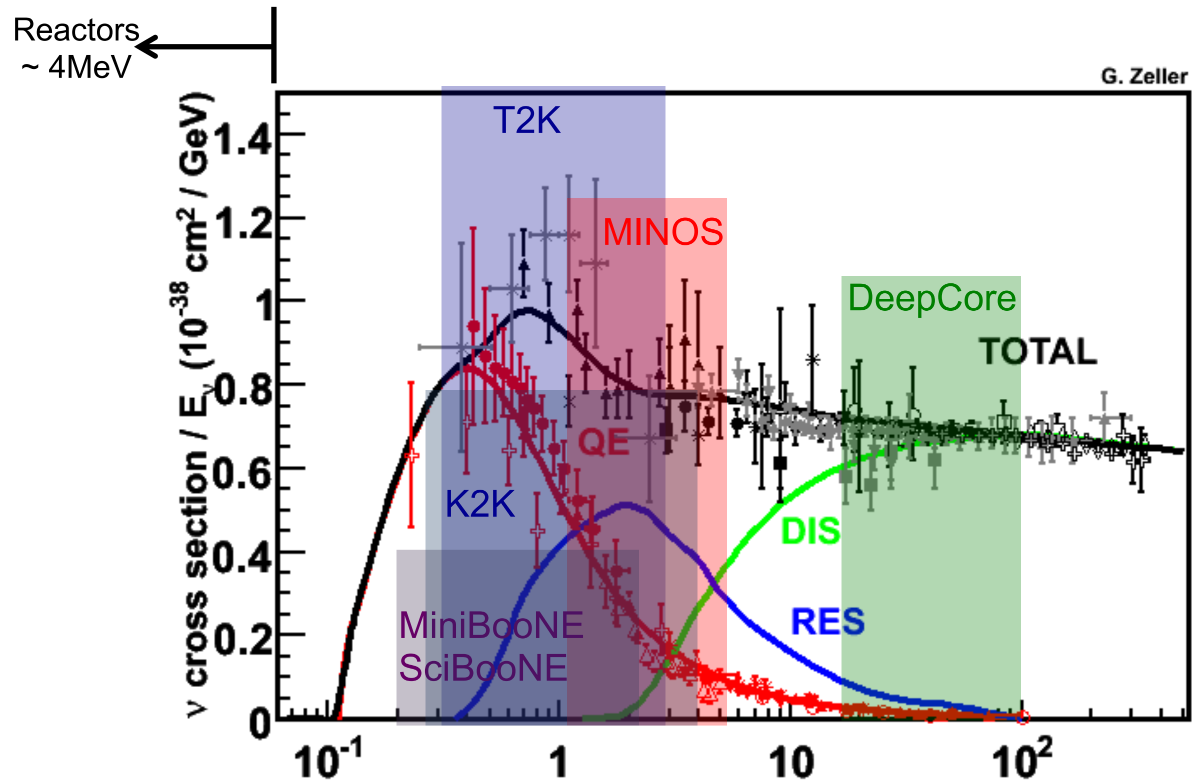
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



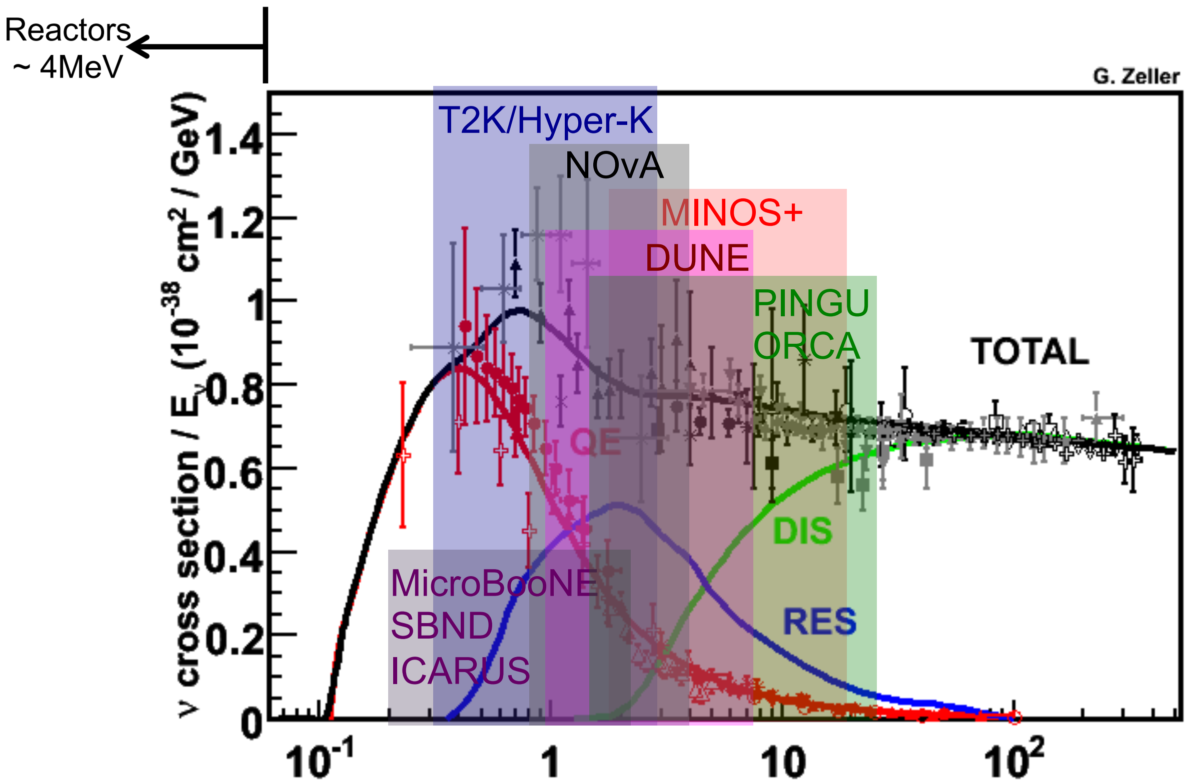
ν_μCC cross section per nucleon

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



ν_μCC cross section per nucleon

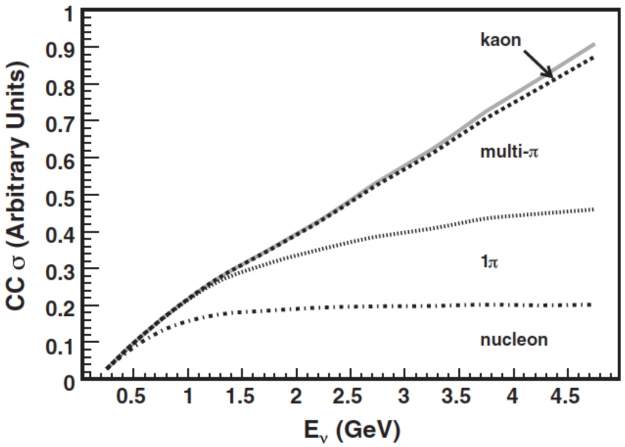
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

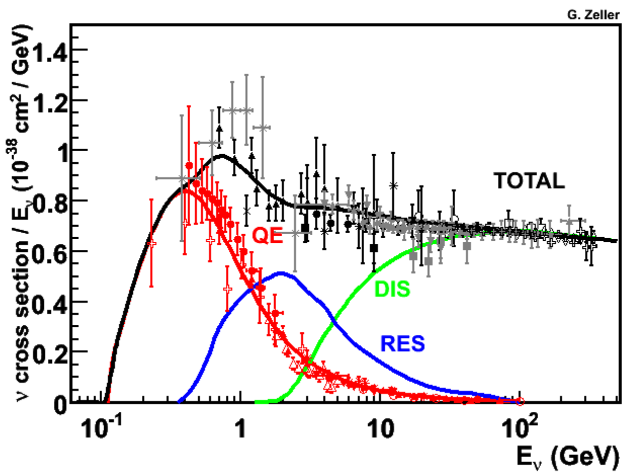
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307
TK and Martini, ArXiv:1611.07770

1. Next generation neutrino oscillation experiments

Energy > 2 GeV is important

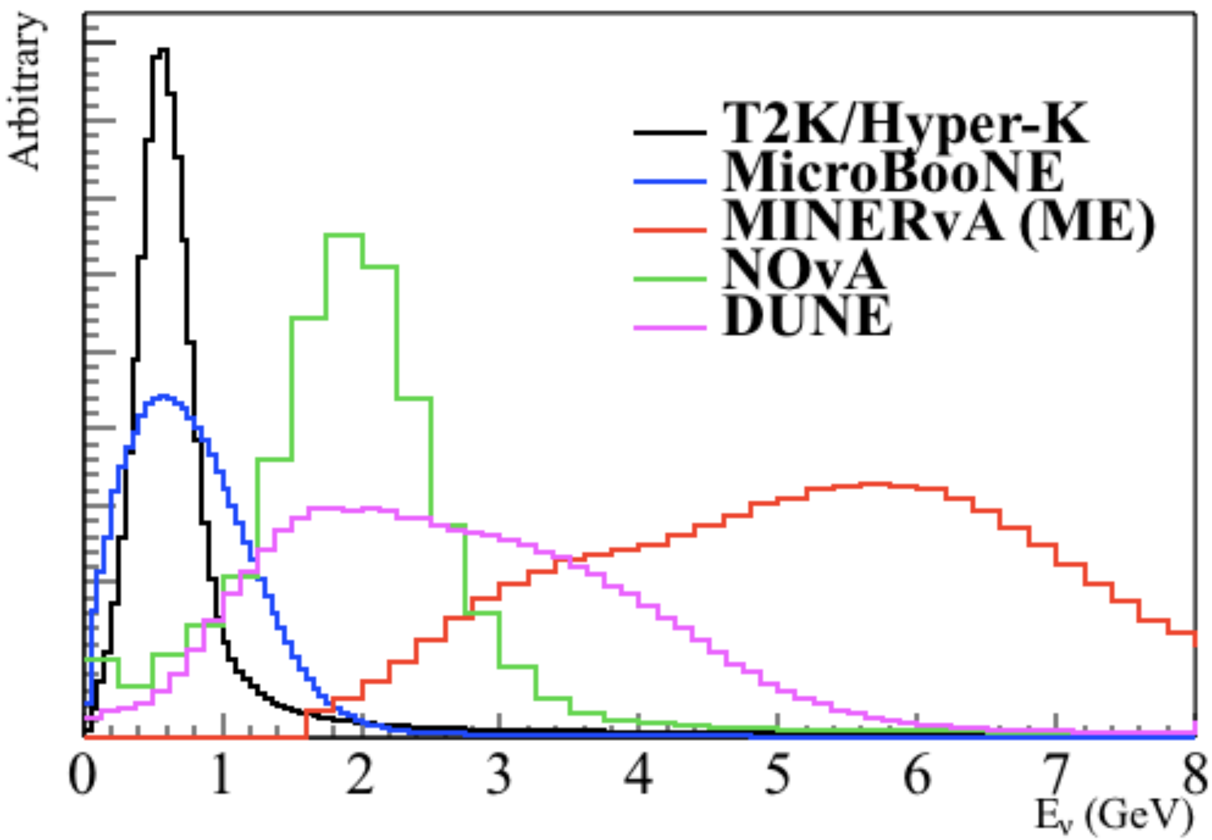
- T2K, NOvA, DUNE event rate per channel





GENIE v2.8.6

NOvA, CCQE=28%, RES=40%, DIS=32%
DUNE, CCQE=10%, RES=17%, DIS=73%



Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307
TK and Martini, ArXiv:1611.07770

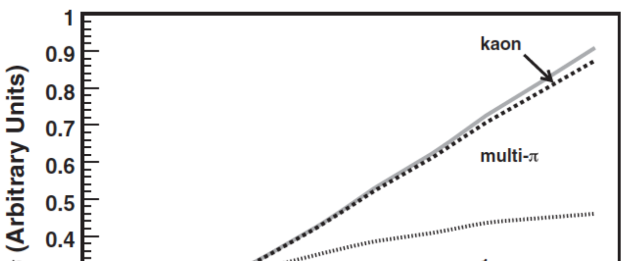
1. Next generation neutrino oscillation experiments

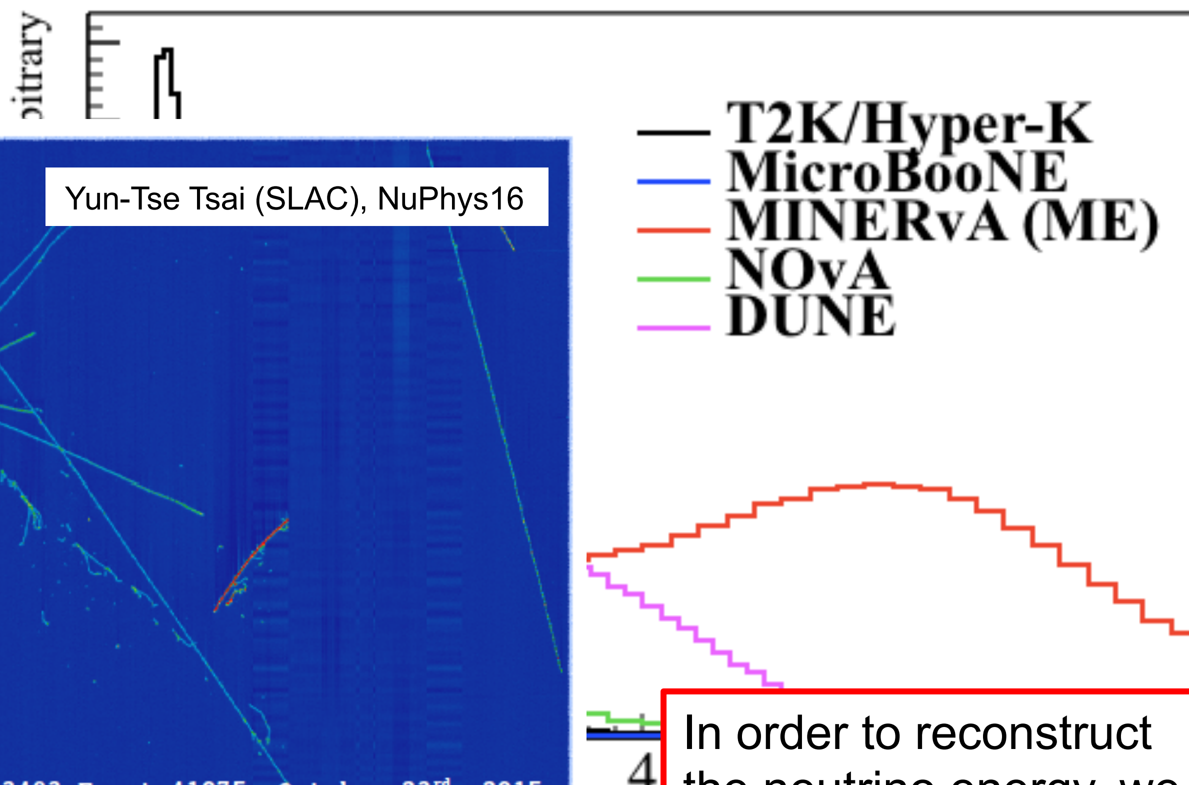
Energy > 2 GeV is important

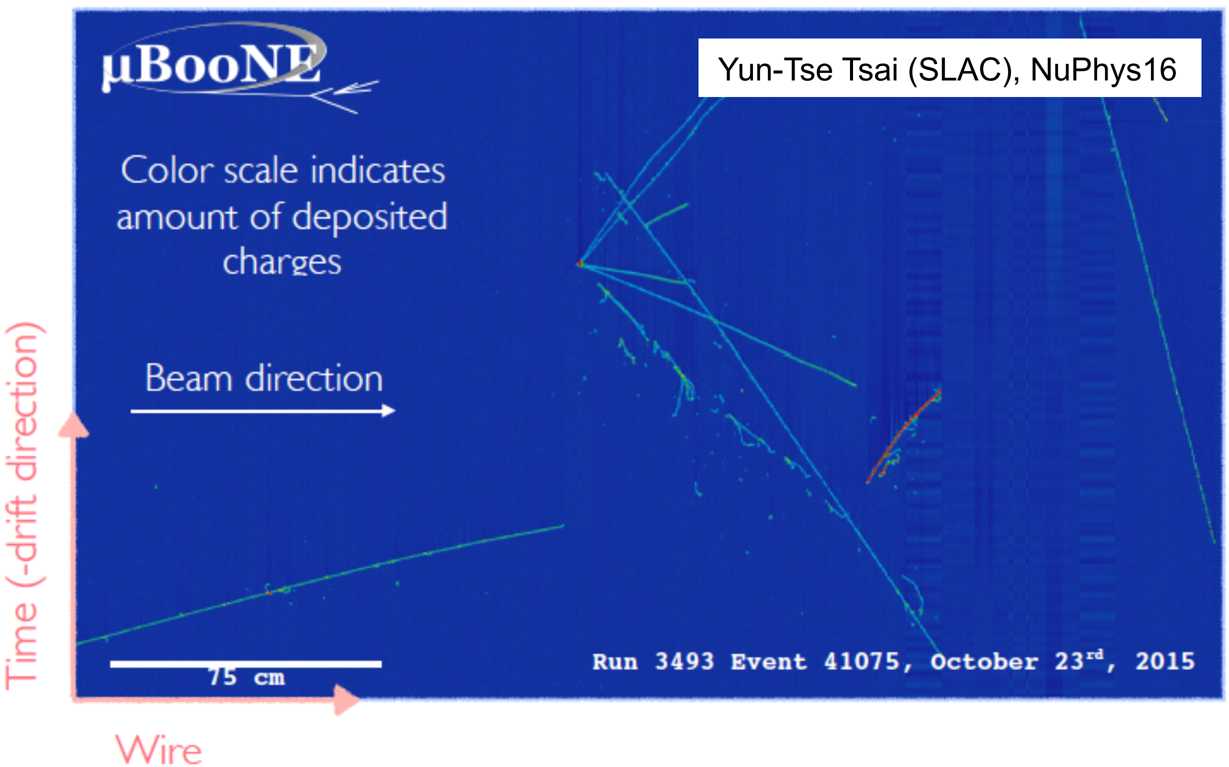
- T2K, NOvA, DUNE event rate per channel

GENIE v2.8.6

NOvA, CCQE=28%, RES=40%, DIS=32%
DUNE, CCQE=10%, RES=17%, DIS=73%







In order to reconstruct the neutrino energy, we need to add all "bits"

1. Introduction, summary

Beyond CCQE and 1 pion production processes

Current and future oscillation experiments have significant amount of higher energy processes with nuclear target

1. Flux-integrated differential cross-sections
- Flux and FSI are integrated
- topology-based cross-section

2. Final state interactions (FSIs)
- In general, we cannot access to primary vertex processes directly

3. Multi-hadron final state measurements
- Important for processes beyond CCQE and 1 pion production processes
- Theory, simulation, and measurement are all very premature

1. Beyond CCQE and 1 pion production

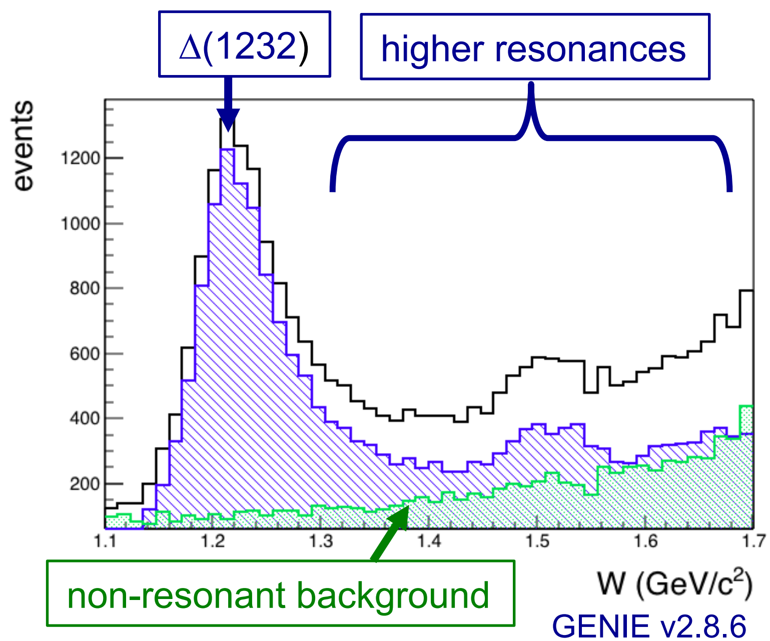
2. Shallow inelastic scattering (SIS) and DIS

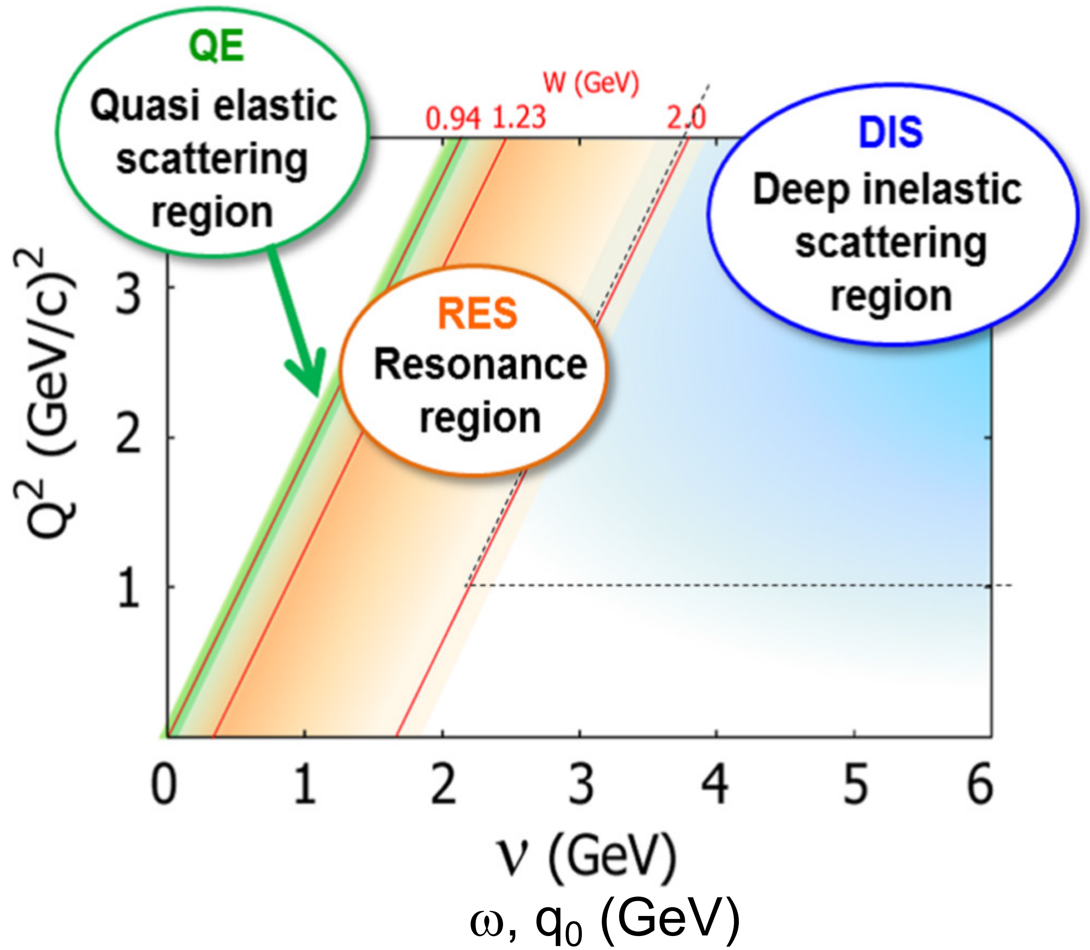
3. Neutrino hadronization

4. Conclusion

2. SIS region physics

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



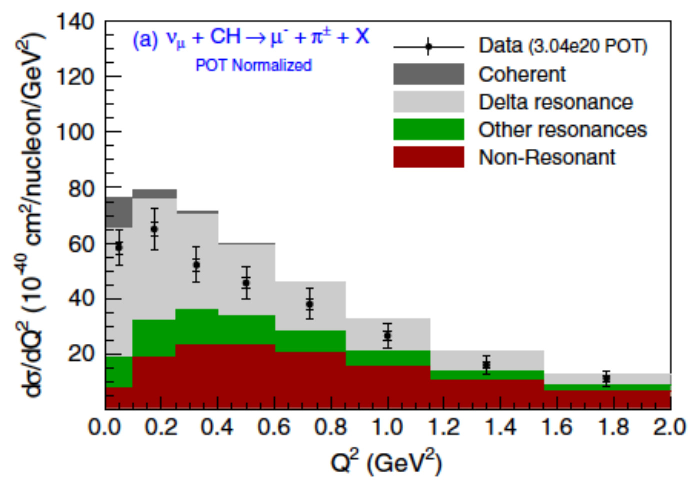


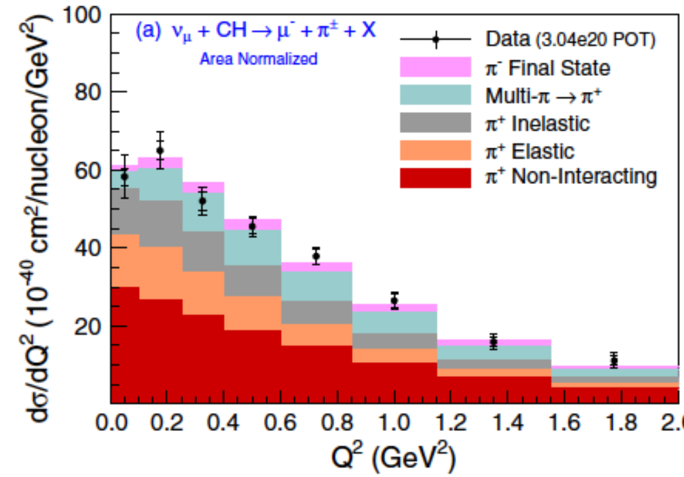
2. Tuning SIS region model

Non-resonant background and MINERvA pion production data

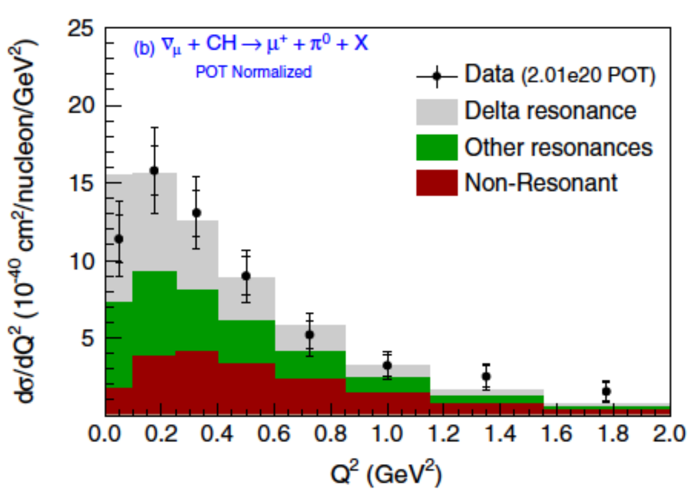
- this moment, there is no clear directionality to tune MC…
- Tuning down non-resonant background may be a solution to satisfy 2 data sets (?)

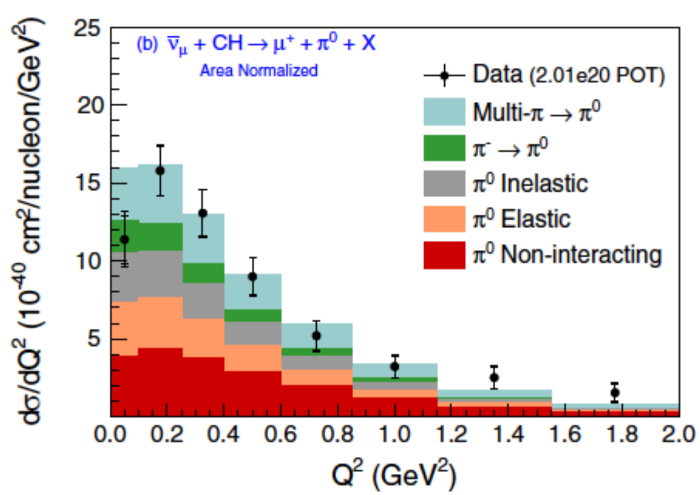
$\nu_\mu CC1\pi^+$ data has better shape agreement with GENIE





anti-$\nu_\mu CC1\pi^o$ data has better normalization agreement with GENIE

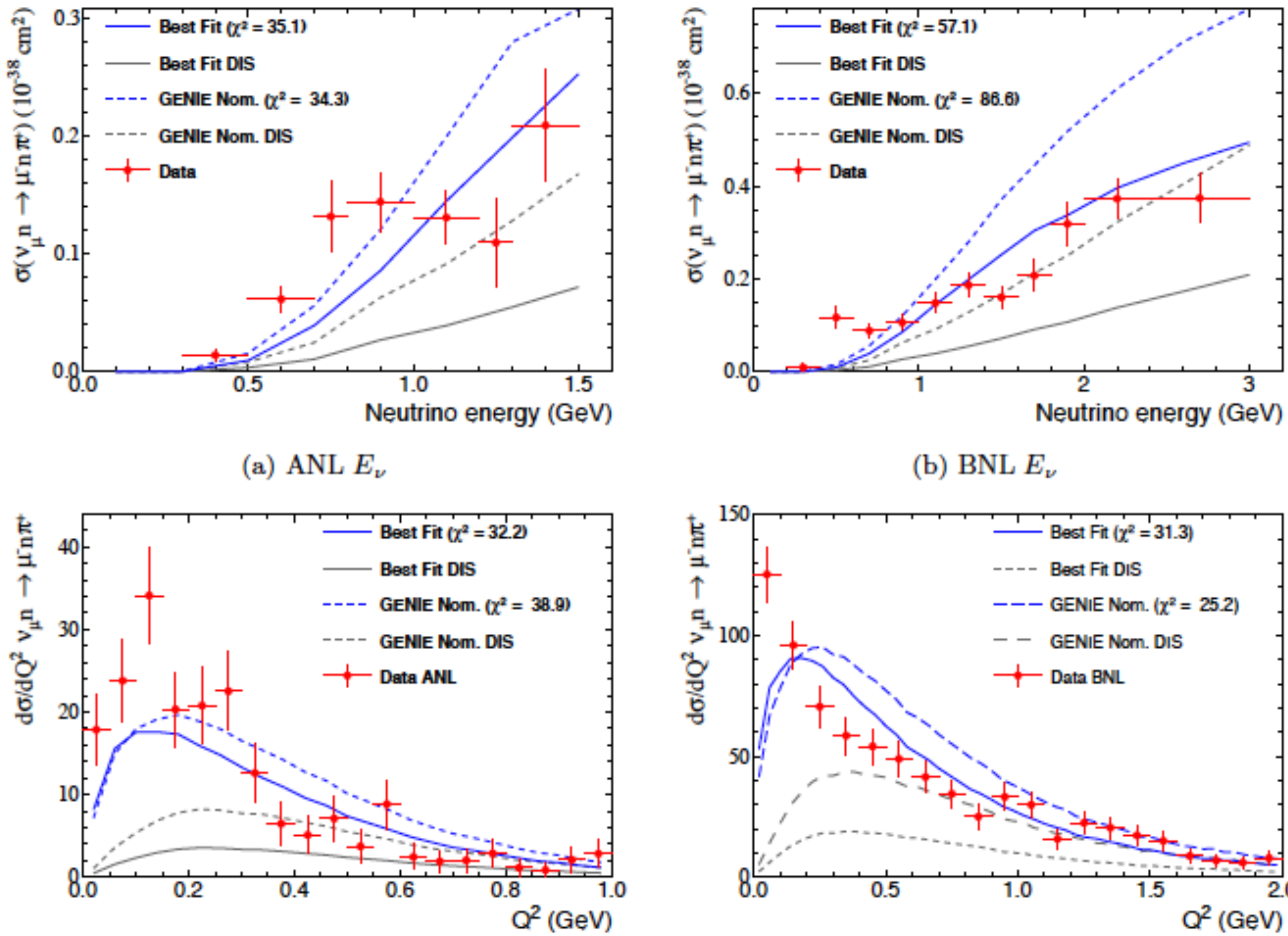




Queen Mary University of London

2. Tuning SIS region model

Bubble chamber data reanalysis
- non-resonant background is tuned down



(a) ANL E_ν (b) BNL E_ν

(c) ANL Q^2 (d) BNL Q^2

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

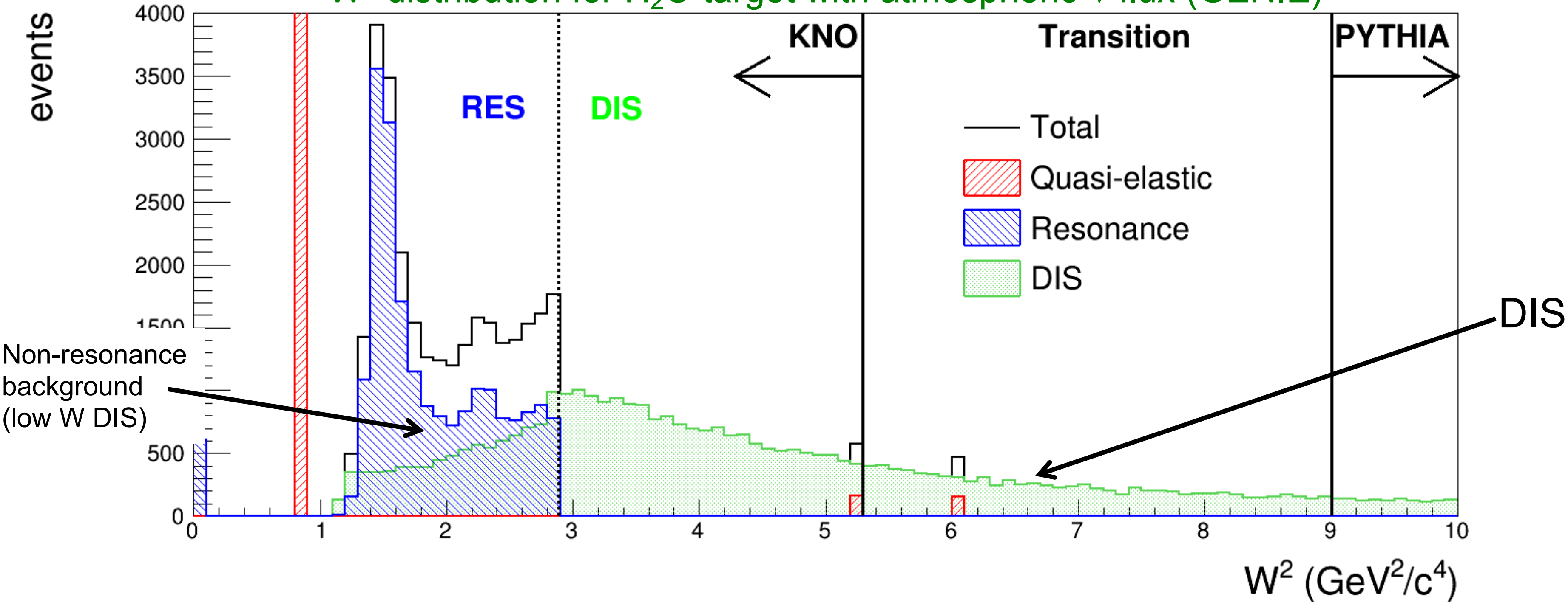
2. GENIE SIS model

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

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

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

GENIE v2.8.0



2. NEUT SIS model

Cross section

W^2<4 GeV^2 : RES

W^2>4 GeV^2 : DIS

Hadronization

W^2<4GeV^2 : KNO scaling based model

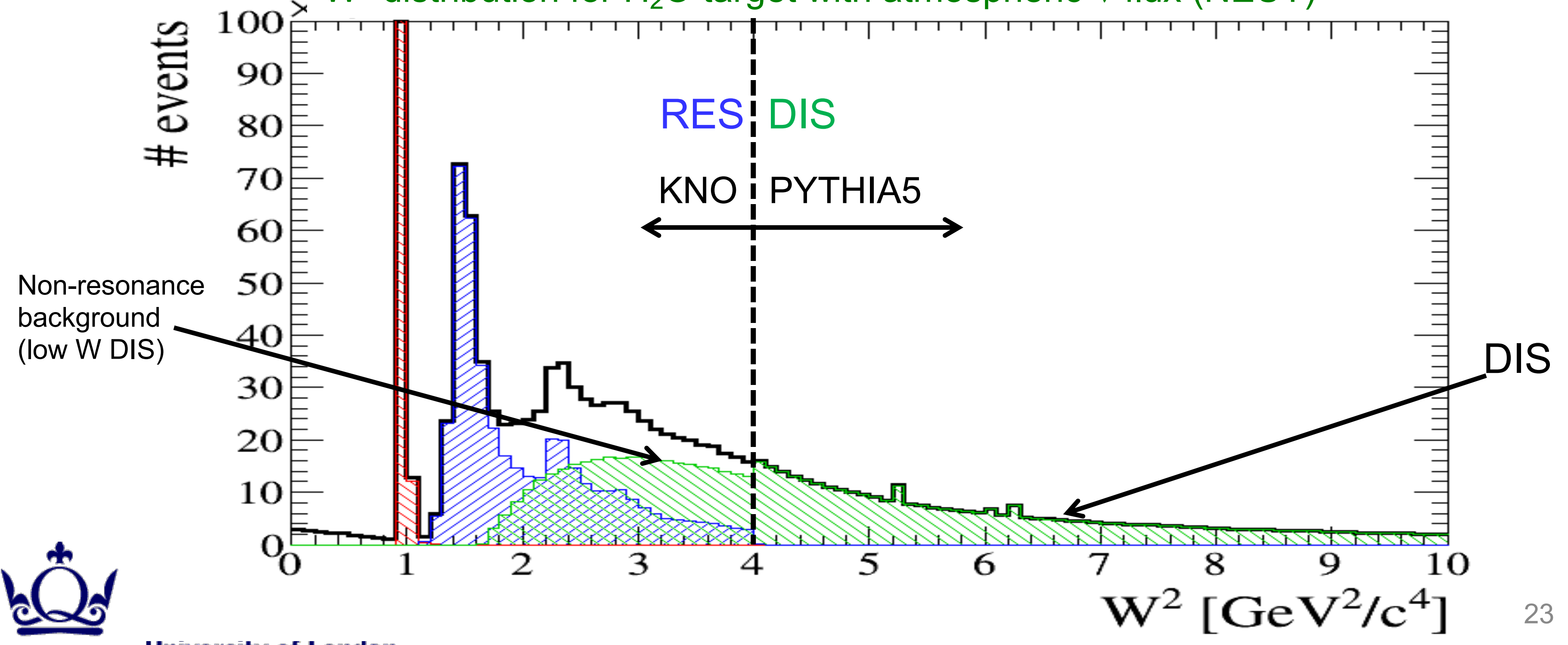
4GeV^2<W^2 : PYTHIA5

There are 2 kind of "transitions" in SIS region

- cross-section
- hadronization

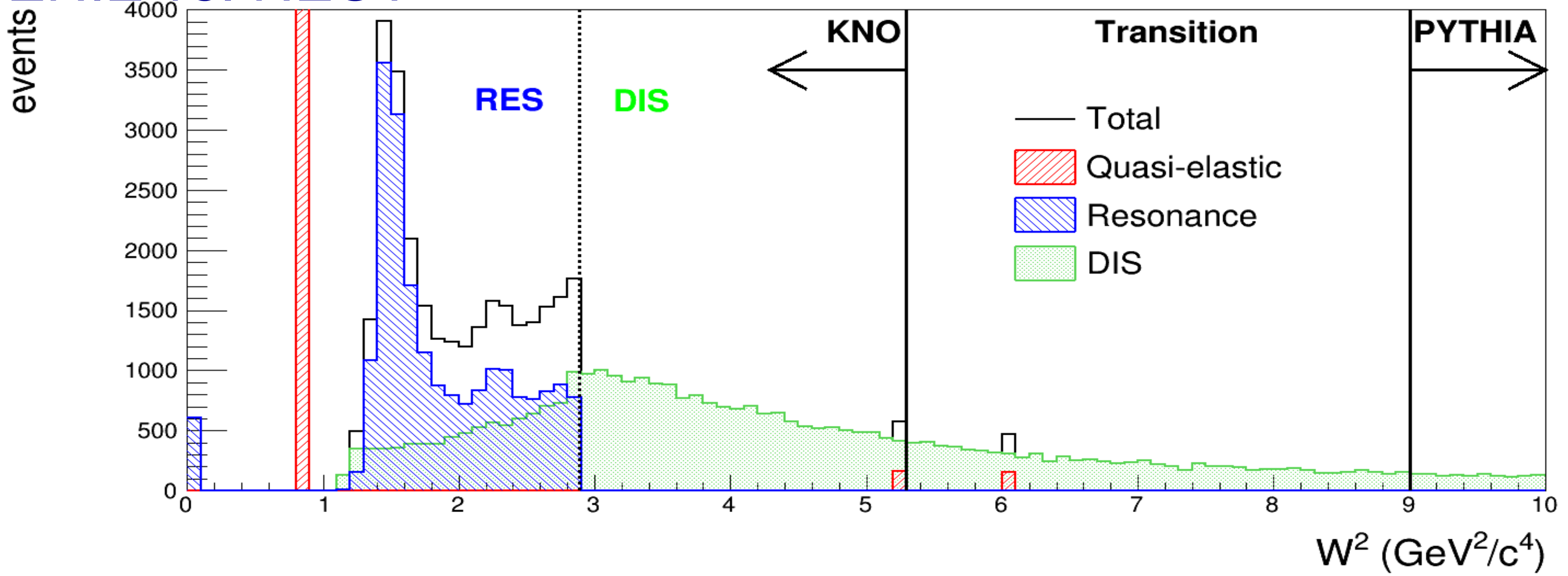
Christophe
Bronner
(IPMU)

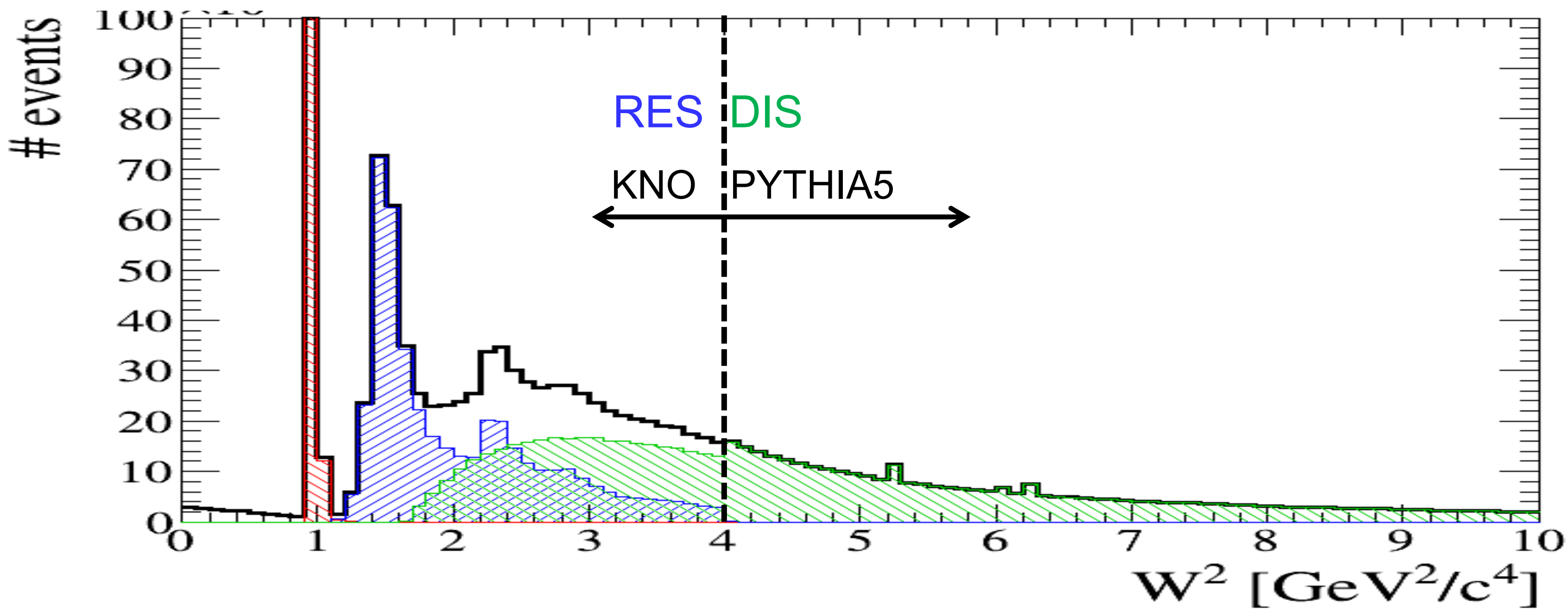
W² distribution for H_2O target with atmospheric-ν flux (NEUT)



University of London

2. GENIE vs. NEUT





2. SIS cross section model

Cross section

- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

2. SIS cross section model

Cross section
- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

DCC model
- Total amplitude is conserved
- Channels are coupled (πN, $\pi\pi N$, etc)
- 2 pion productions ~10% at 2 GeV

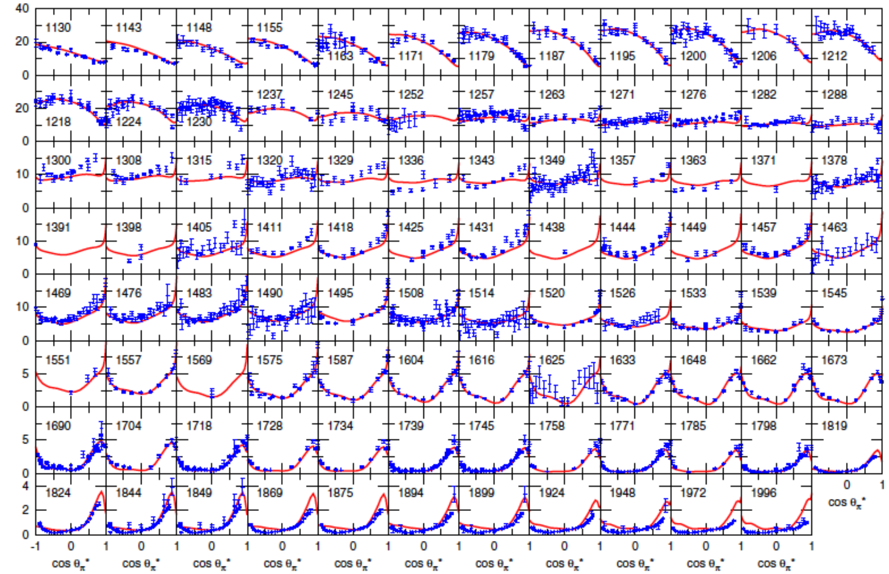
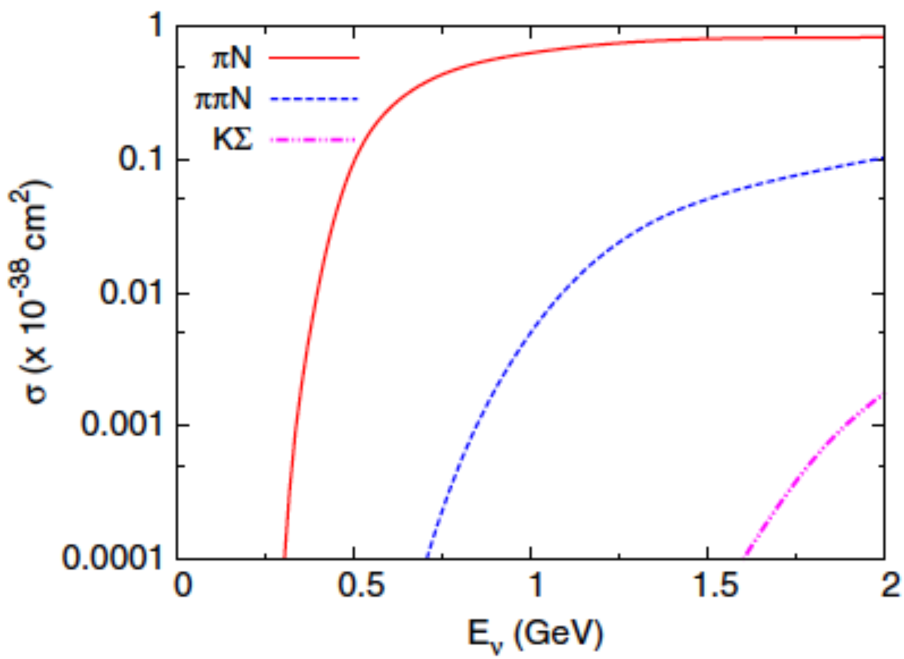
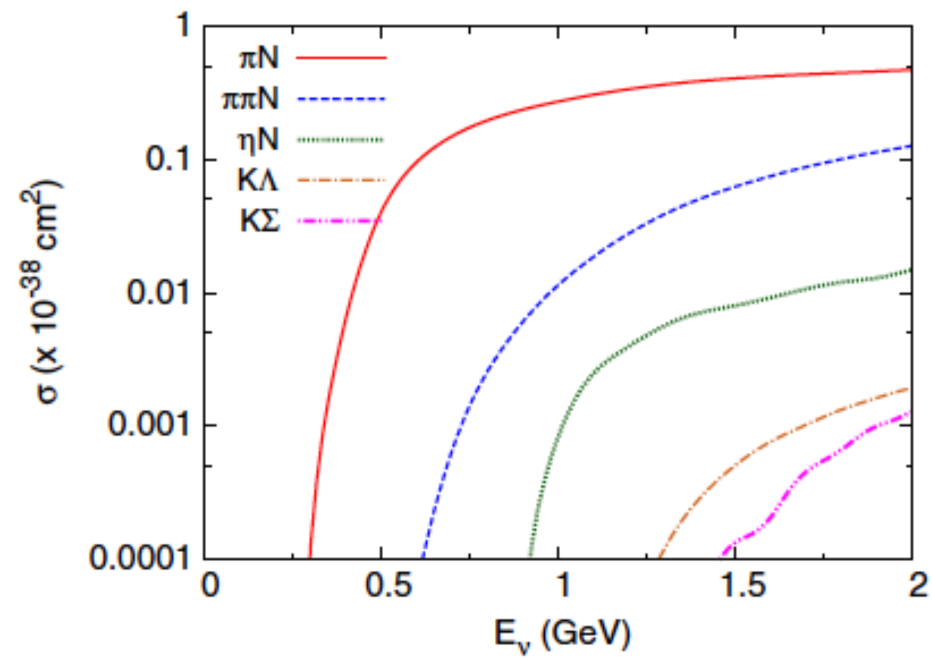


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega^*_\pi$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].





2. SIS cross section model

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

Cross section

- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

GRV98 LO PDF + Bodek-Yang correction

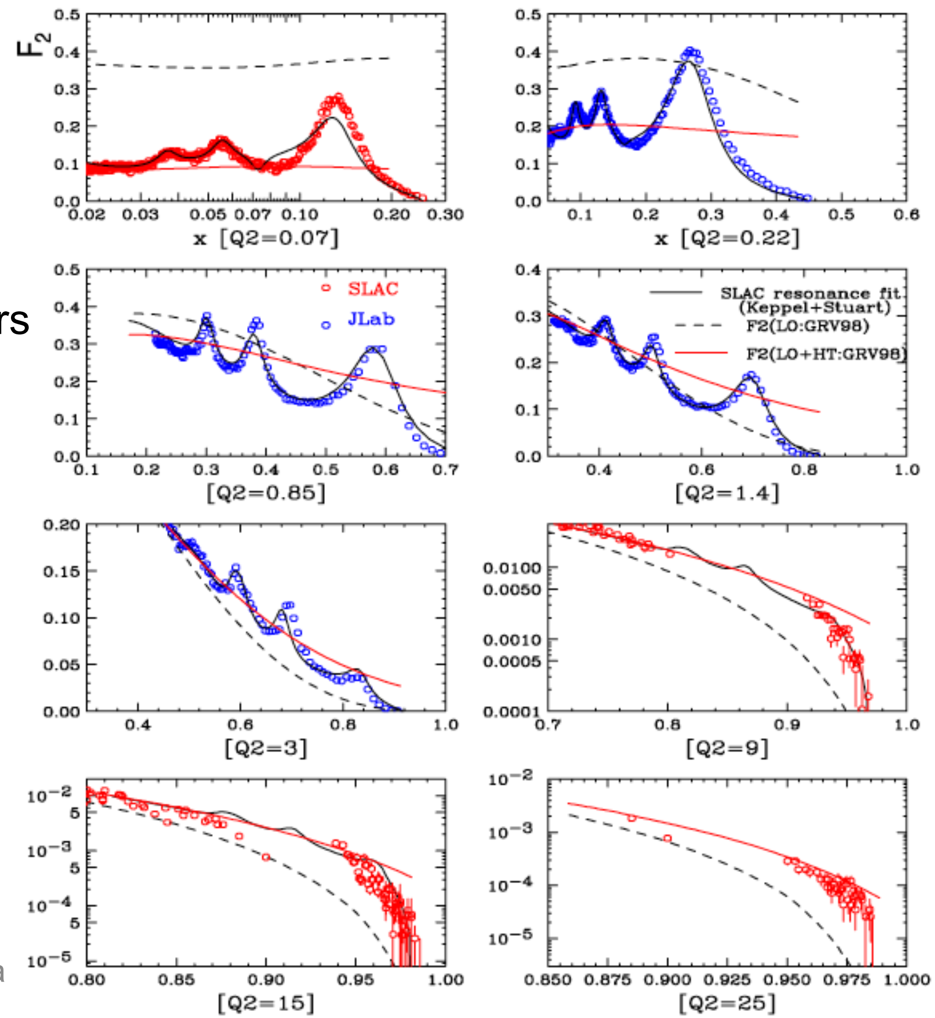
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data



Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11
NuTeV, PRD74(2006)012008

2. SIS cross section model

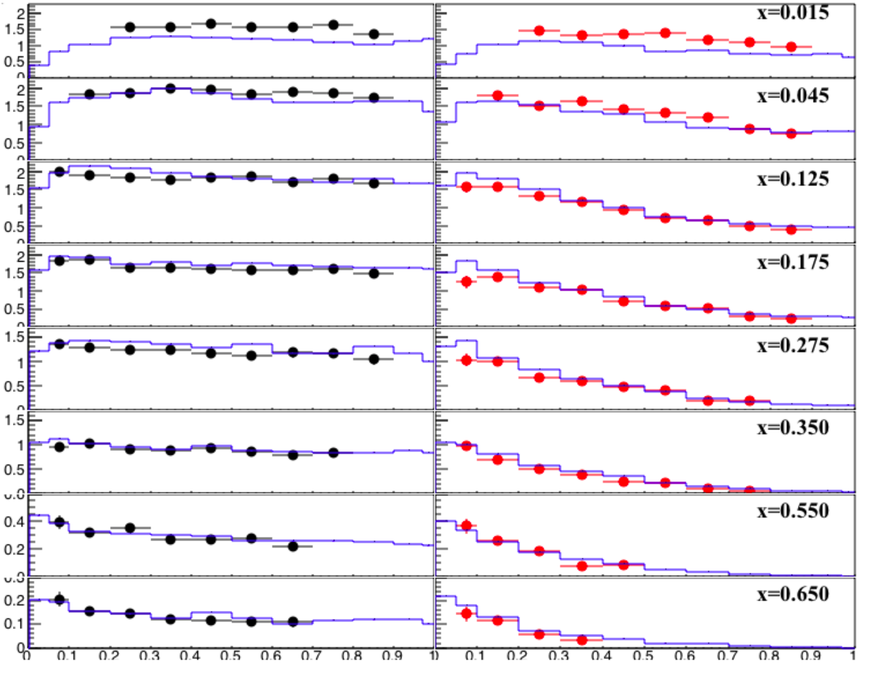
Shivesh Mandalia
(Queen Mary)

Cross section
- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

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

GENIE-NuTeV comparison
- GENIE use GRV98+BY correction
- GENIE can describe NuTeV data except very low x region
- Impact of data-MC low x disagreement is ~2% on total cross section in 30<E<360 GeV

150 GeV



NuTeV ν-Fe and antiν-Fe differential cross section (x, y, Eν)

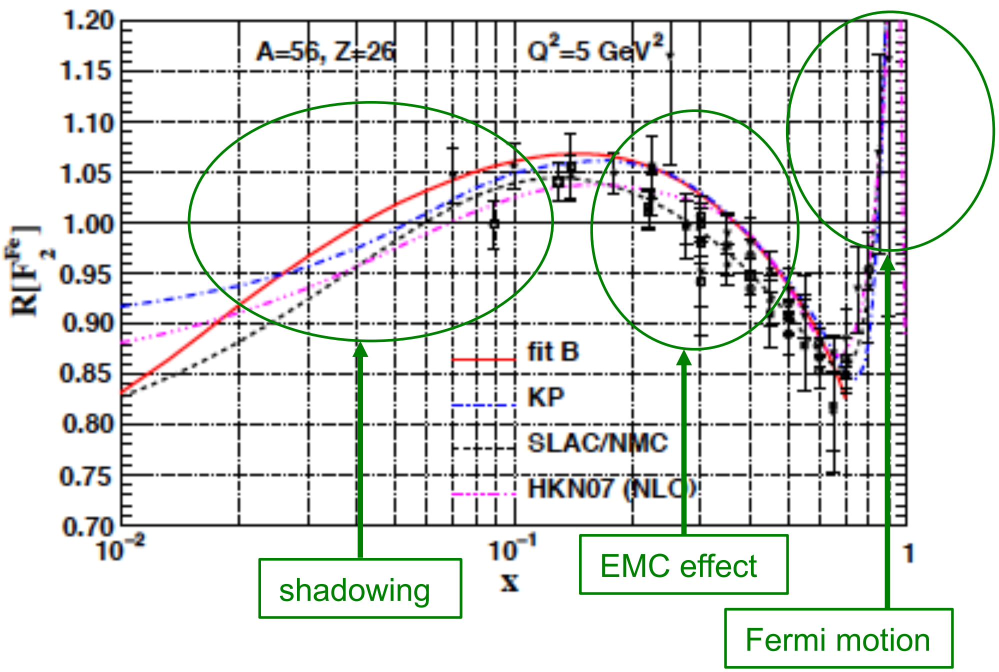
Model is verified with iron target, how about oxygen and argon?

2. SIS cross section model

Cross section
- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

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

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



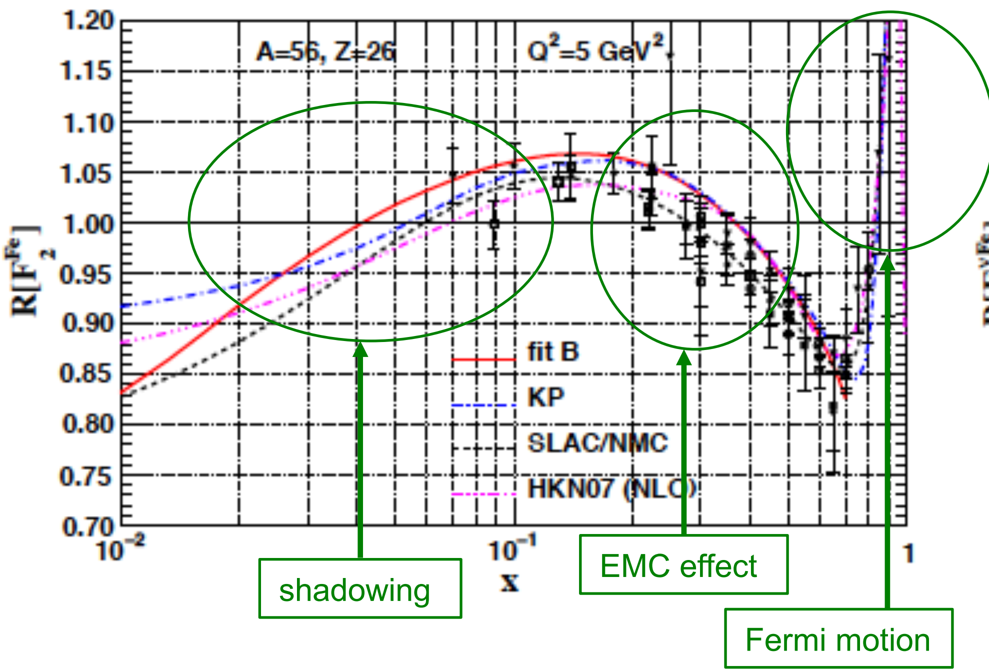
Jorge Morfin (Fermilab)

2. SIS cross section model

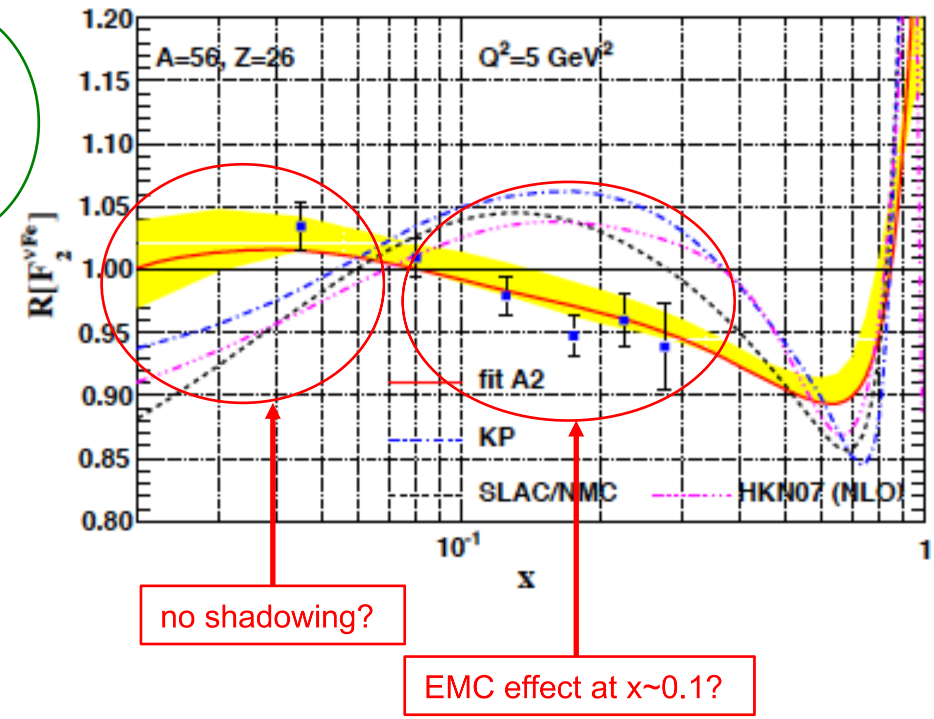
Cross section
- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

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

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



ν-Fe nuclear correction factor



2. SIS cross section model

Cross section

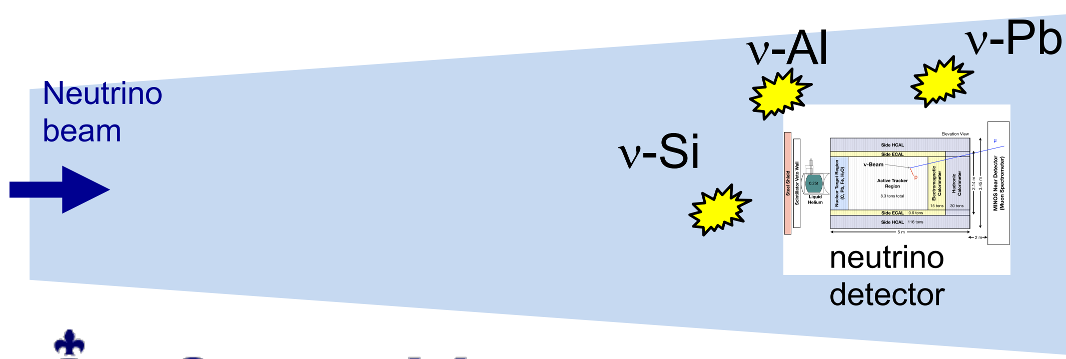
- Higher baryonic resonance
- low Q^2, low W DIS
- Nuclear dependent DIS

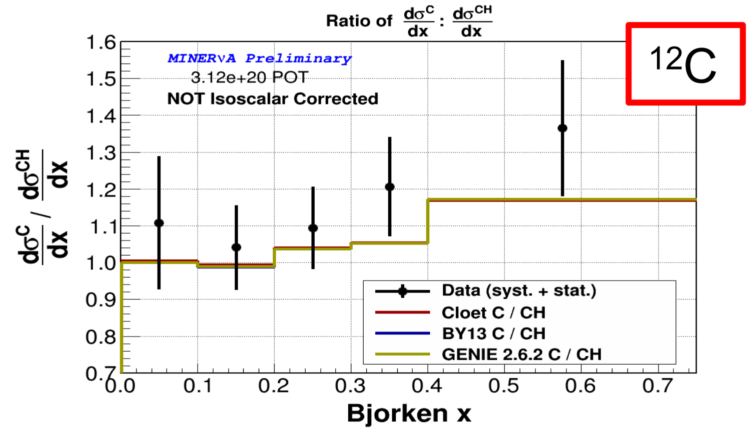
MINERvA DIS target ratio data (C, Fe, Pb)

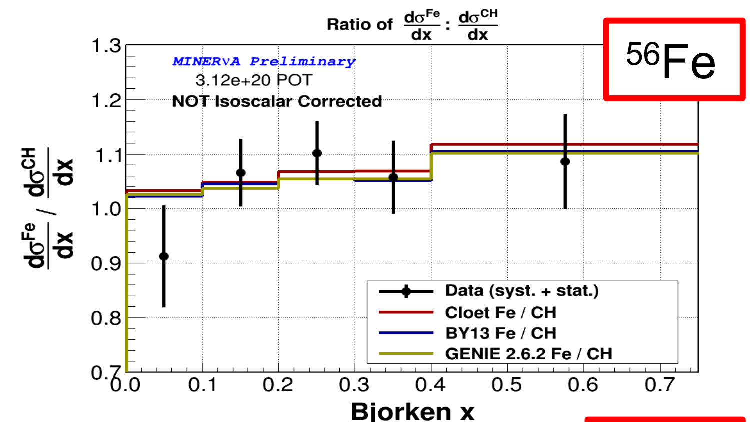
- MINERvA data reveal shadowing effect on neutrino may be larger than expected

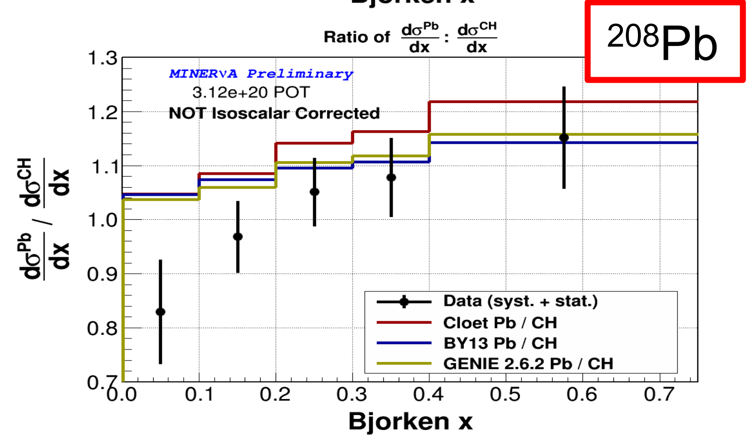
We care all nuclear targets

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









2. SIS cross section, summary

Three important physics beyond CCQE and 1 pion production

1. higher baryon resonance and how to compute the total amplitude

2. low Q^2 DIS and how to model resonance → DIS transition

3. nuclear dependent DIS

1. Beyond CCQE and 1 pion production

2. Shallow inelastic scattering (SIS) and DIS

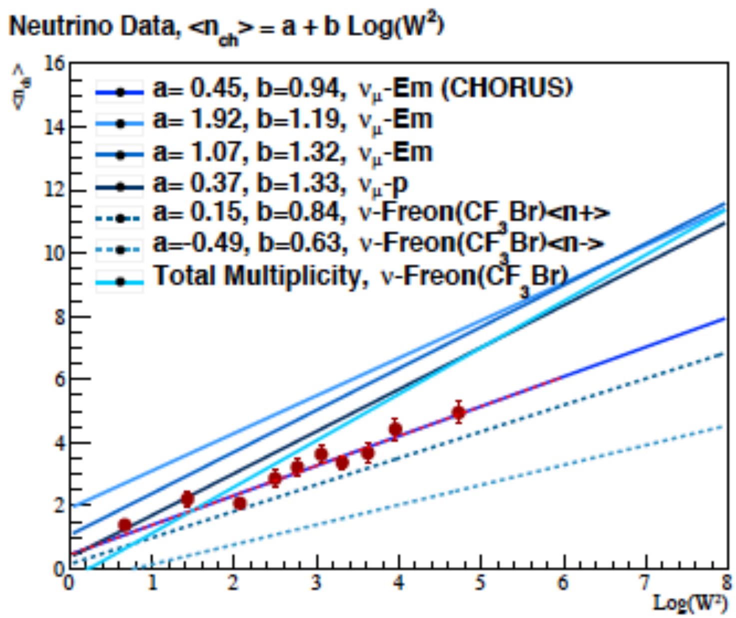
3. Neutrino hadronization

4. Conclusion

3. Neutrino low W hadronization model

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

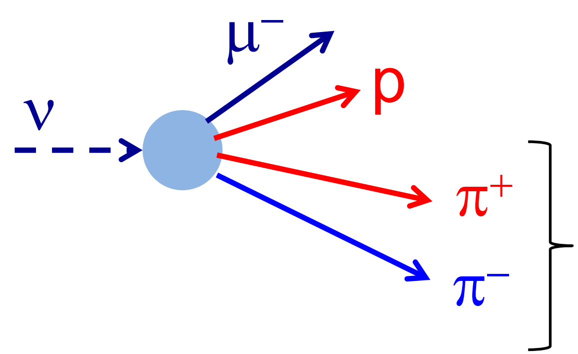
- Parameters extracted from data are used to model hadronization process
- The bubble chamber data are not consistent



Averaged charged hadron multiplicity

averaged charged hadron multiplicity

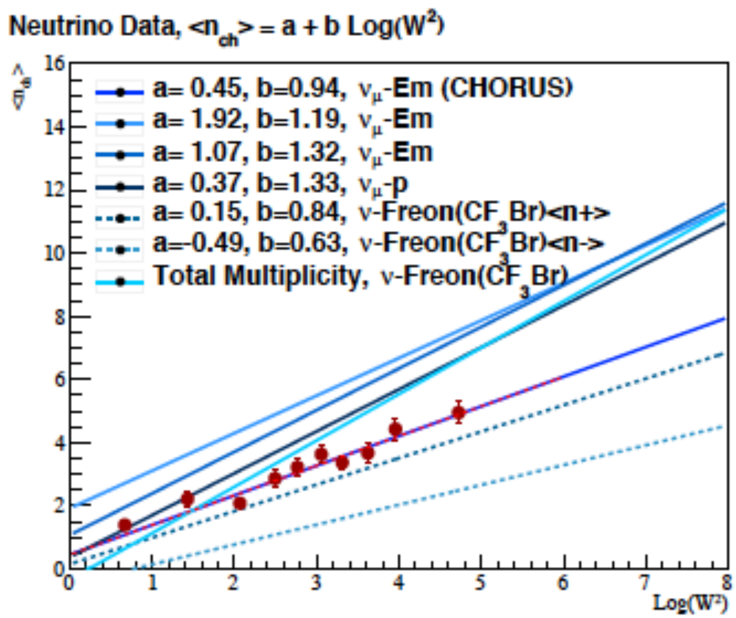
$$< n_{ch} >= a + bLog(W^2)$$



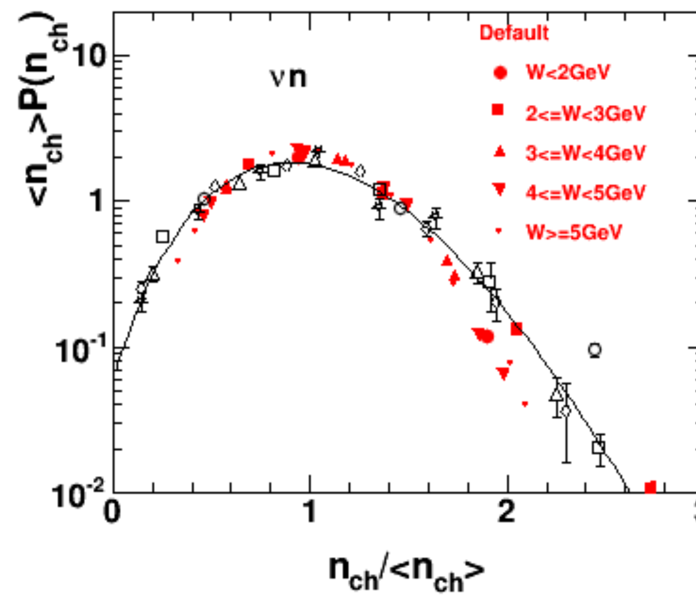
3. Neutrino low W hadronization model

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

- Parameters extracted from data are used to model hadronization process
- The bubble chamber data are not consistent



Averaged charged hadron multiplicity



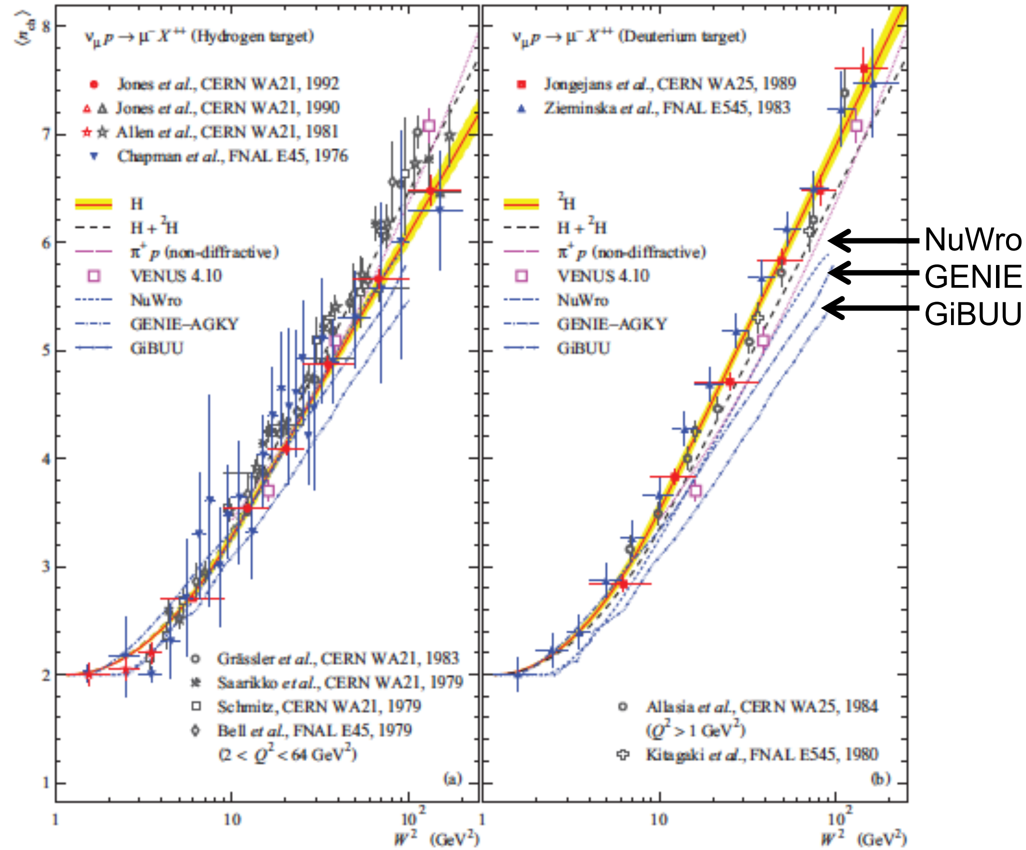
KNO scaling law of charged hadron multiplicity

3. Neutrino 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 W²

3. HERMES tuned PYTHIA6

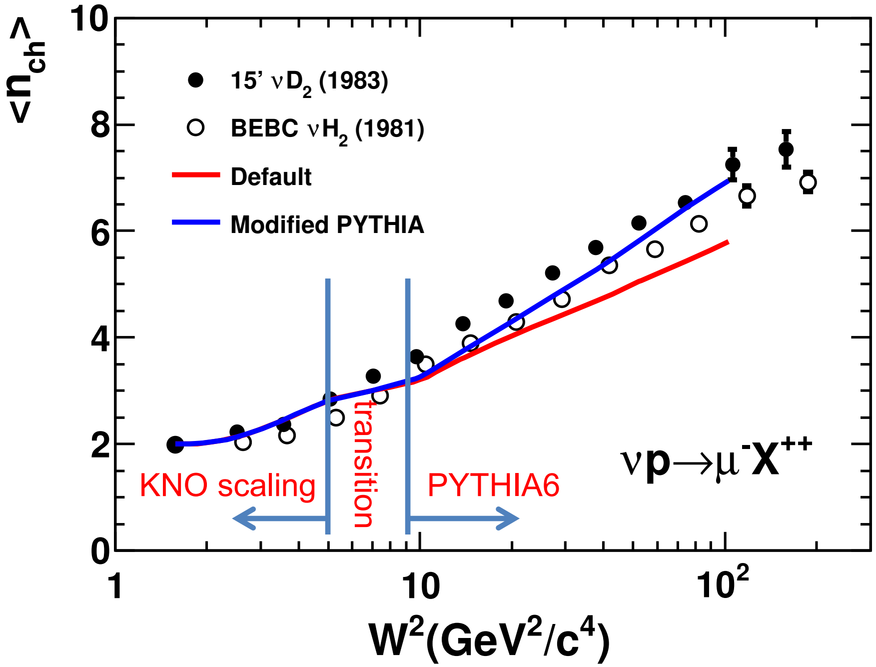
PARJ41 = Lund "a" parameter
PARJ42 = Lund "b" parameter

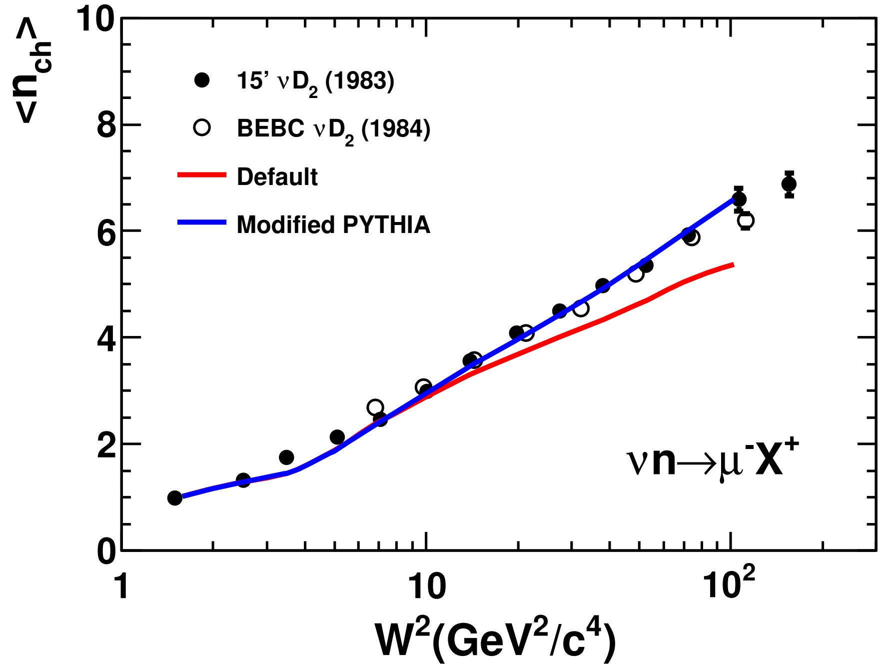
Averaged charged hadron multiplicity $<n_{ch}>$
- Lund-scan increases $<n_{ch}>$ (→ better agreement with bubble chamber data) both neutrino and antineutrino.

Red: PYTHIA default
Blue: Lund-scan

Parameter	PYTHIA	GENIE	Lund-scan	$\Delta q(x)$	2004c
PARJ1	0.10		0.02		0.029
PARJ2	0.30	0.21	0.25	0.20	0.283
PARJ11	0.50		0.51		
PARJ12	0.60		0.57		
PARJ21	0.36	0.44	0.42	0.37	0.38
PARJ23	0.01			0.03	
PARJ33	0.80	0.20	0.47		
PARJ41	0.30		0.68	1.74	1.94
PARJ42	0.58		0.35	0.23	0.544
PARJ45	0.50		0.74		1.05

Neutrino average charged hadron multiplicity





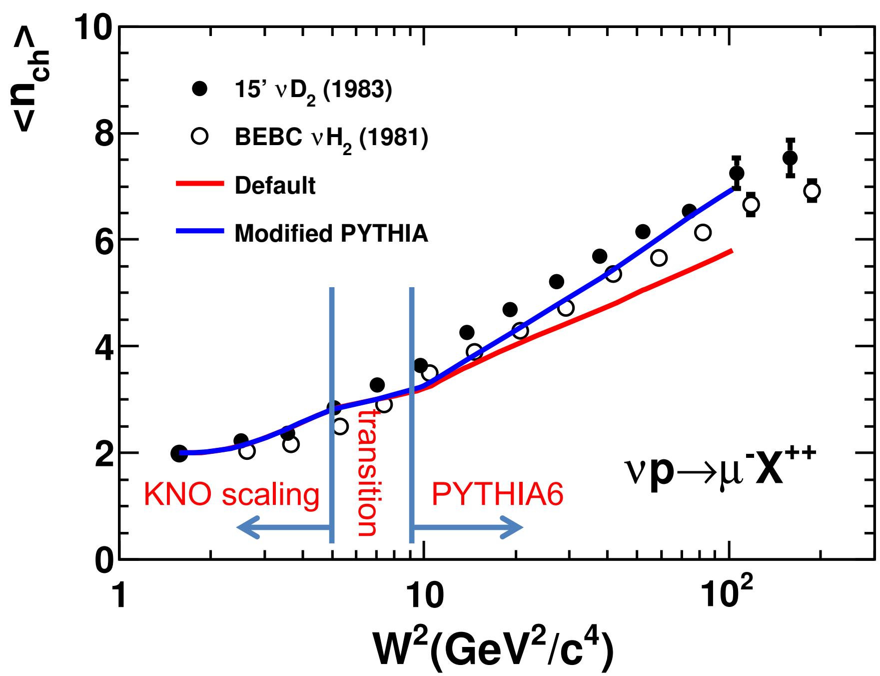
3. HERMES tuned PYTHIA6

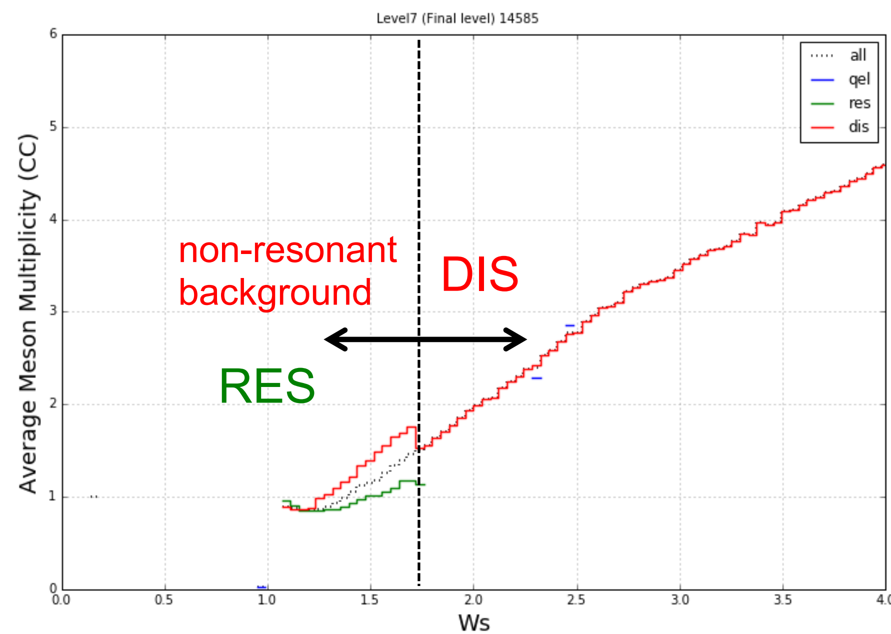
Averaged charged hadron multiplicity $\langle n_{ch} \rangle$
- Lund-scan increases $\langle n_{ch} \rangle$ (→ better agreement with bubble chamber data) both neutrino and antineutrino.

Red: PYTHIA default
Blue: Lund-scan

Making continuous curve is not easy at the transition region of models…

Neutrino average charged hadron multiplicity



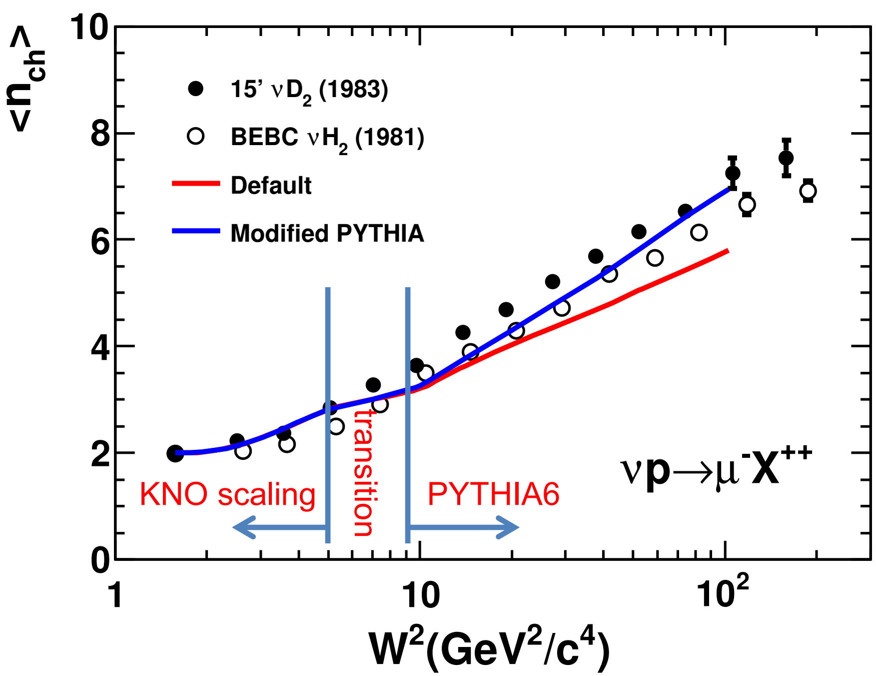


3. Hadron multiplicity

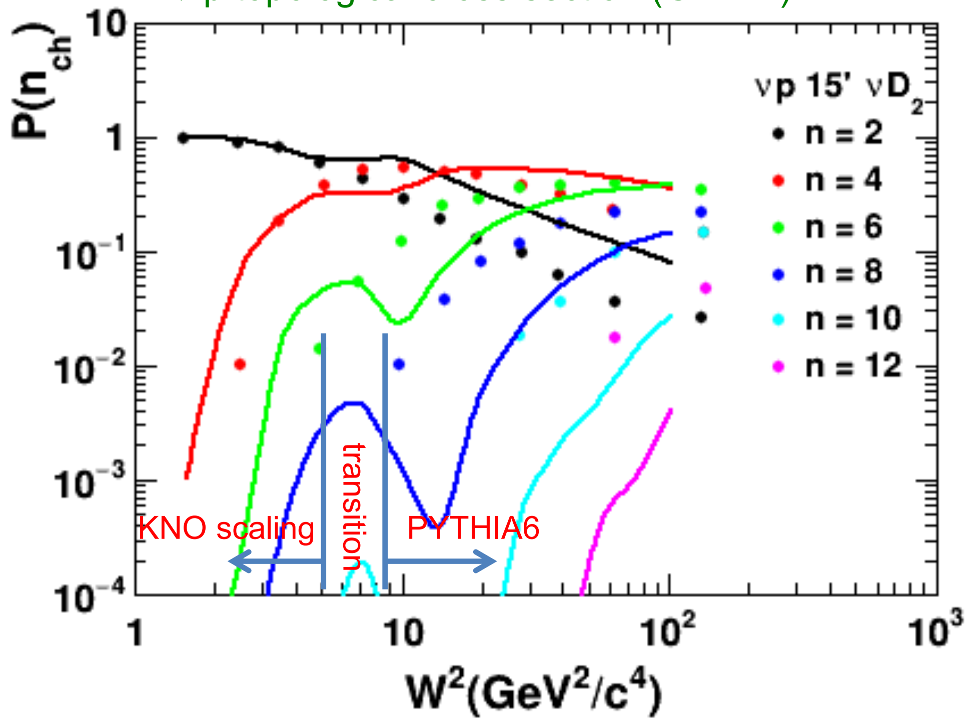
Bubble chamber topological cross section data

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.

Neutrino average charged hadron multiplicity



ν-p topological cross section (GENIE)



3. Hadronization, summary

Two important processes

1. Low W hadronization process based on empirical model (KNO scaling)

2. High W hadronization process from particle physics (PYTHIA, etc)

… and how to connect them

1. Beyond CCQE and 1 pion production

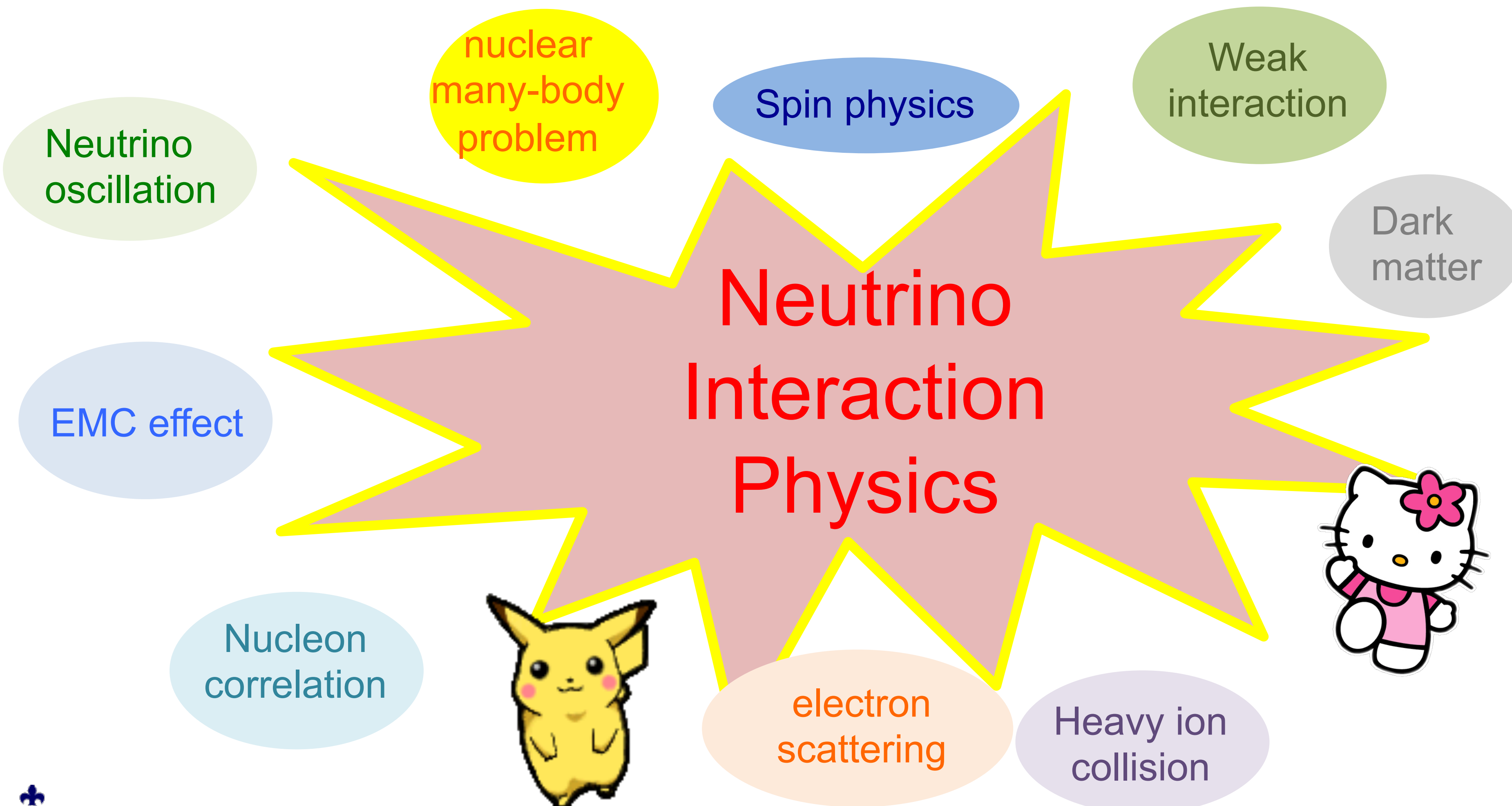
2. Shallow inelastic scattering (SIS) and DIS

3. Neutrino hadronization

4. Conclusion

Physics of Neutrino Interactions

Tremendous amount of activities, new data, new theories…



NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

NuSTEC promotes the collaboration and coordinates efforts between
- theorists, to study neutrino interaction problems
- experimentalists, to understand nu-A and e-A scattering problems
- generator builders, to implement, validate, tune, maintain models

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

1) NuSTEC Structure

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

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

NuSTEC school

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

NuSTEC school 17, Fermilab (Nov. 2017, TBA)

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

Lectures of NuSTEC school 15, Okayama, Japan (Nov. 8-14, 2015)

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

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

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

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

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

Lecture 11 Neutrino Oscillation Experiments (TBA)

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

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

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

Lecture 14, 17 Generator (TBA)

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

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

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

Conclusion

Subscribe “NuSTEC News”
http://nustec.fnal.gov/
like “@nuxsec” or “NuSTEC-News” on Facebook
Twitter hashtag #nuxsec

Flux-integrated differential cross-sections play a major role for model tuning
- flux and FSI are integrated, topology-based cross-sections

Processes beyond CCQE and 1 pion production are important. We need to correctly connect and/or add correct models.

1. higher baryonic resonance
2. low Q^2 DIS
3. nuclear dependent DIS
4. low W hadronization
5. high W hadronization

Role of hadron simulation is getting more important.

We need models working in all kinematic region. Neutrino experiment is always “inclusive” comparing with electron scattering (nuclear physics) and collider physics (particle physics). Cross-section and hadronization processes should make sense in any Q^2 and W region.

Conclusion

Subscribe "NuSTEC News"
http://nustec.fnal.gov/
like "@nuxsec" or "NuSTEC-News" on Facebook
Twitter hashtag #nuxsec

Neutrino oscillation

electron scattering

many-body problem

Weak interaction

Neutrino Interaction Physics

EMC effect

Nucleon correlation

Spin physics

Dark matter

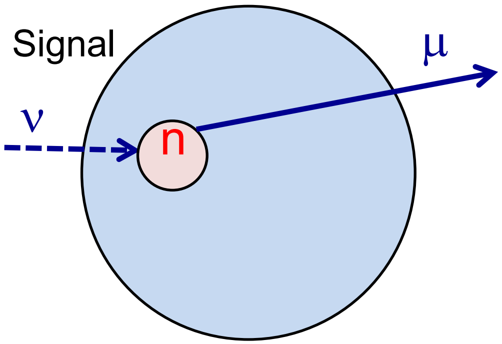
Heavy ion collision

Thank you for your attention!

Backup

3. non-QE background

non-QE background → shift spectrum

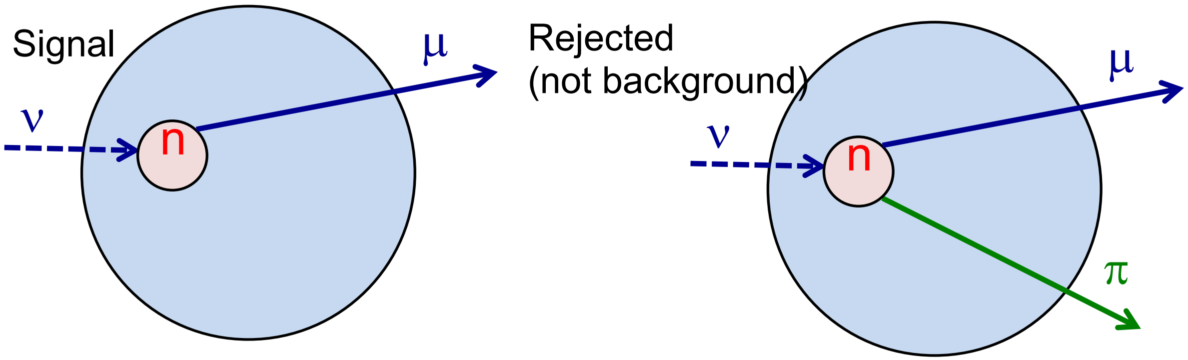


Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

3. non-QE background

non-QE background → shift spectrum

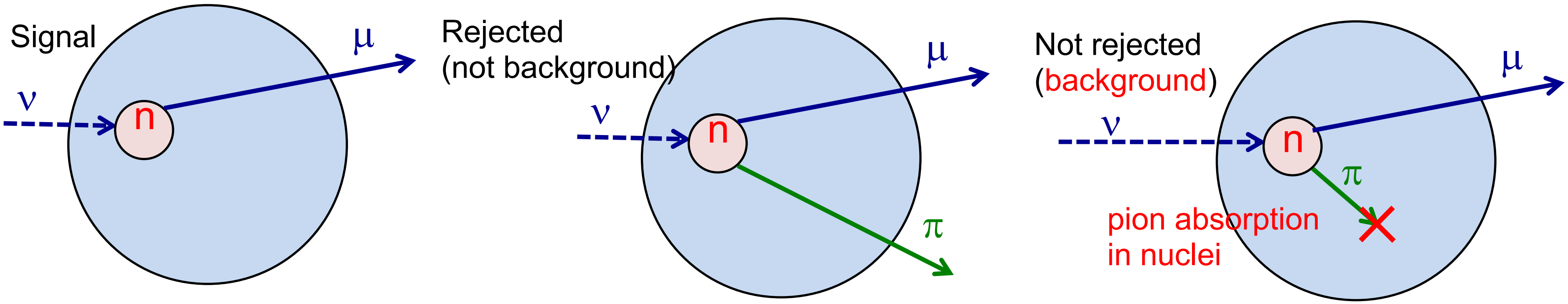


Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

3. non-QE background

non-QE background → shift spectrum

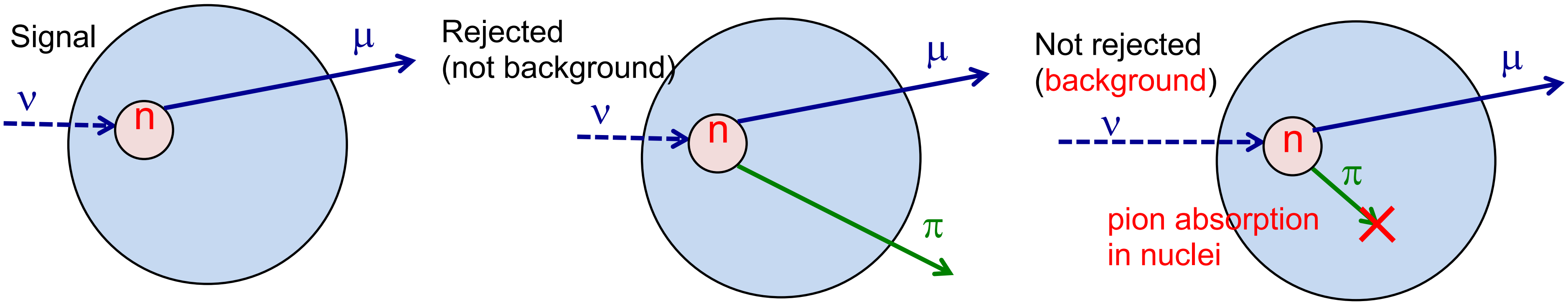


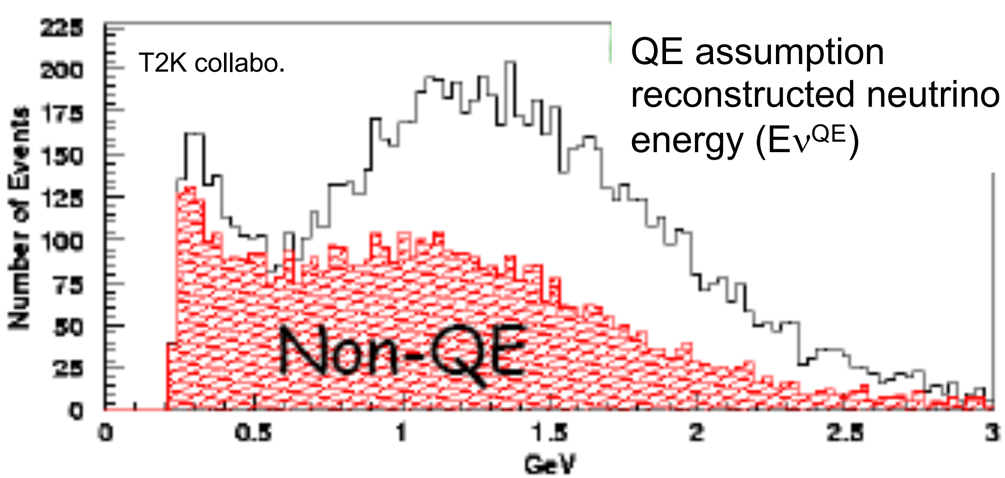
Typical neutrino detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

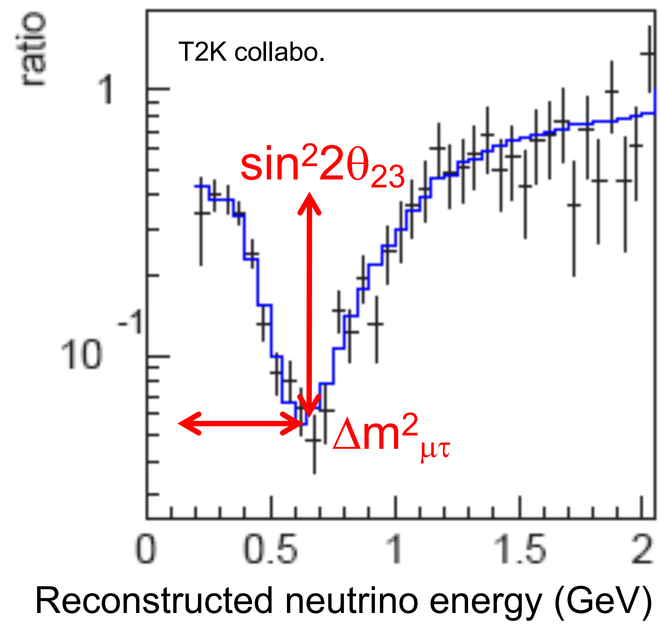
(not great detector to measure hadrons)

3. non-QE background

non-QE background → shift spectrum



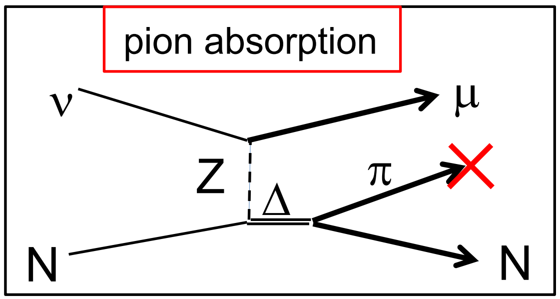




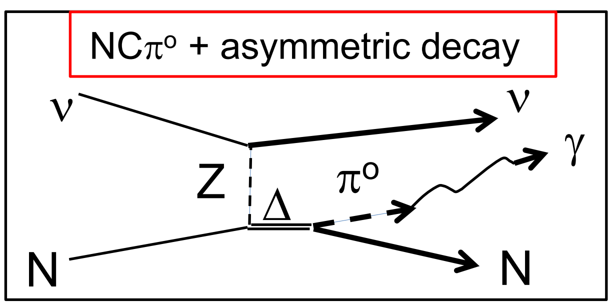
3. non-QE background

Understanding of neutrino pion production is important for oscillation experiments

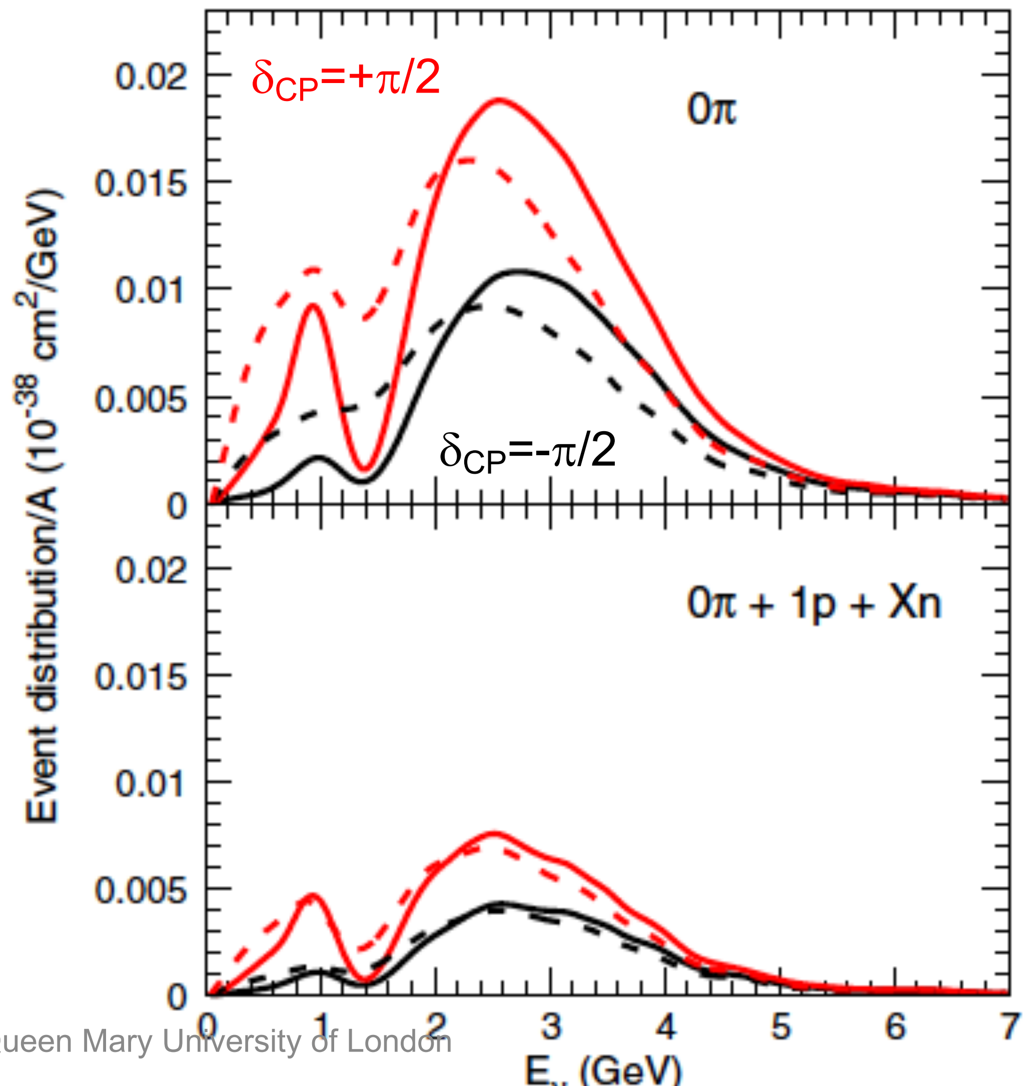
Pion production for ν_μ disappearance search
- Source of mis-reconstruction of neutrino energy



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



DUNE true vs. reconstructed Eν spectrum



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

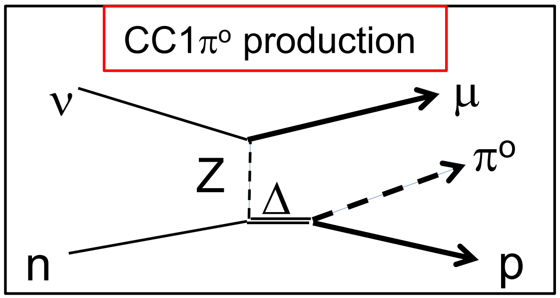
1. FSI and pion data

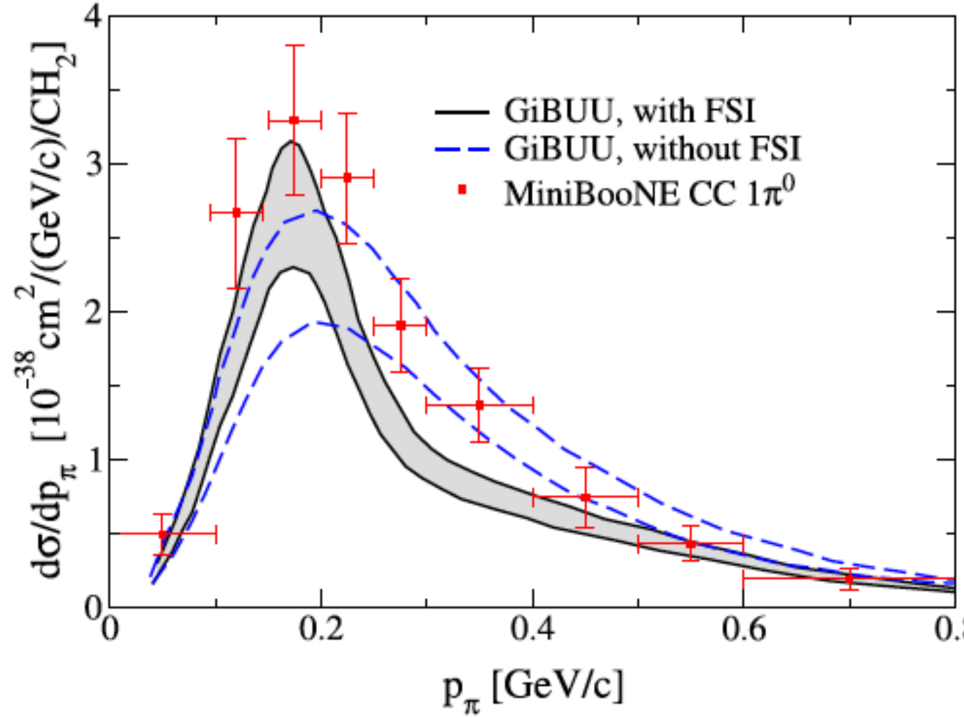
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

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





ex) Giessen BUU transport model

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

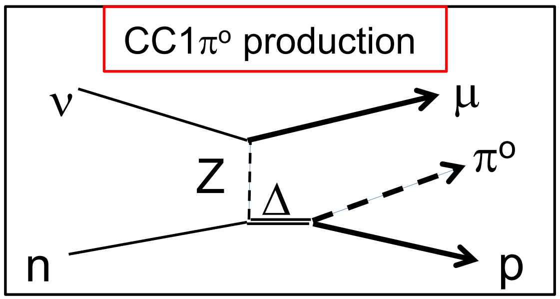
1. FSI and pion data

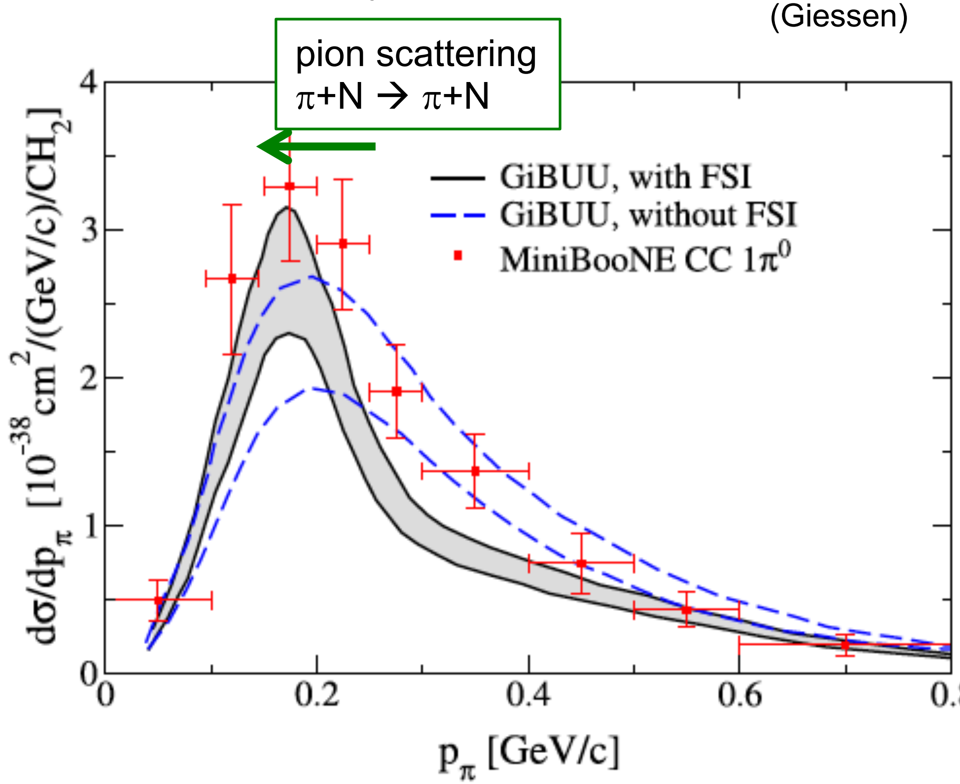
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

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





ex) Giessen BUU transport model

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

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

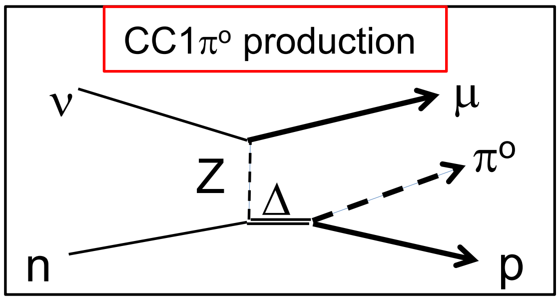
1. FSI and pion data

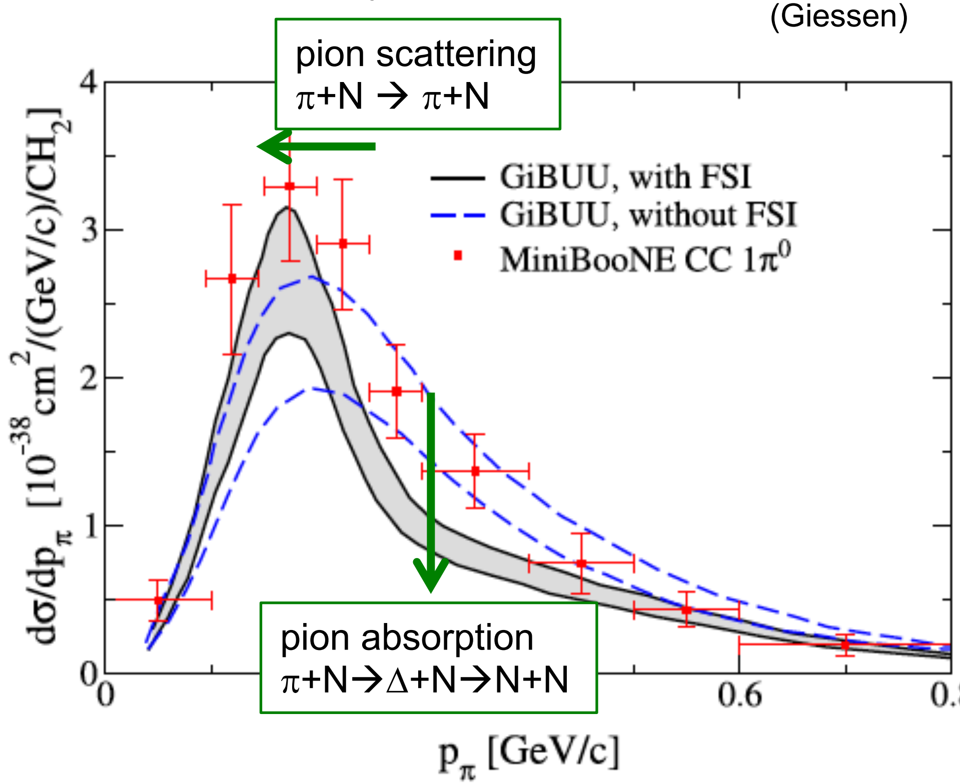
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

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





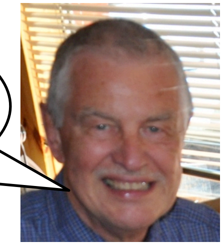
ex) Giessen BUU transport model

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

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

1. FSI and pion data

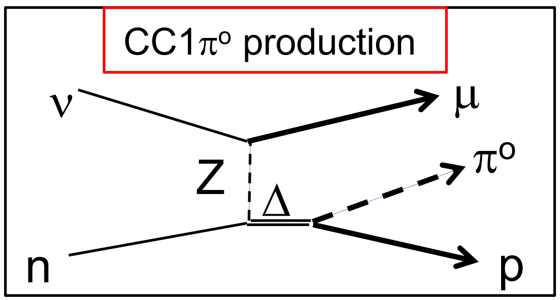
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

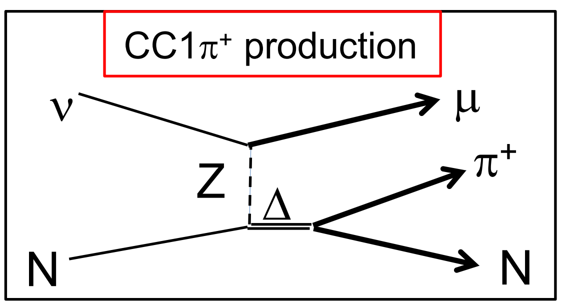


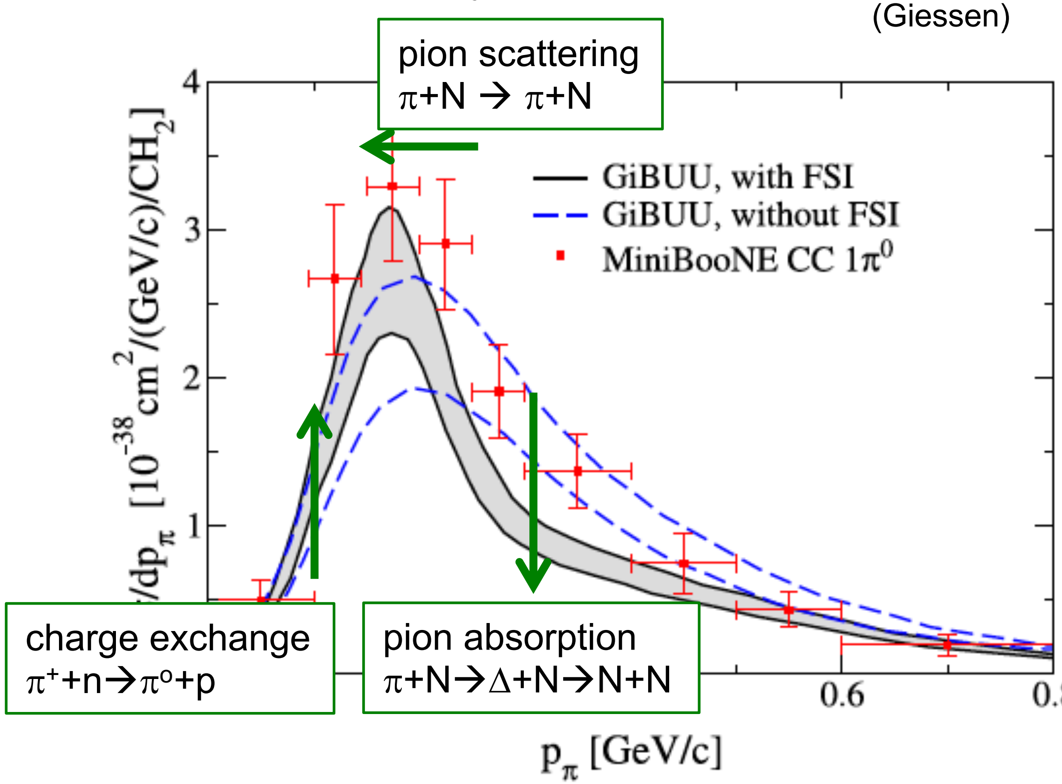
Ulrich Mosel (Giessen)

Final state interaction

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







ex) Giessen BUU transport model

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

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

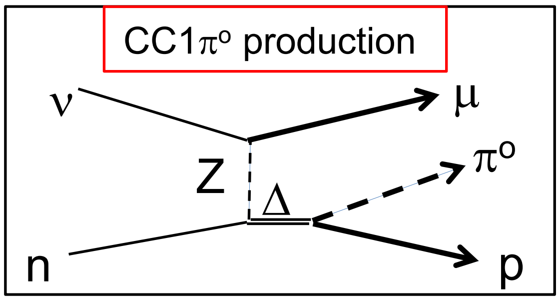
1. FSI and pion data

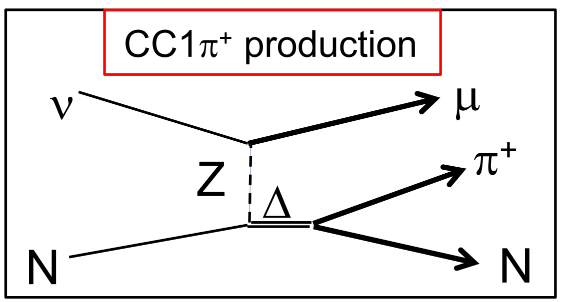
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

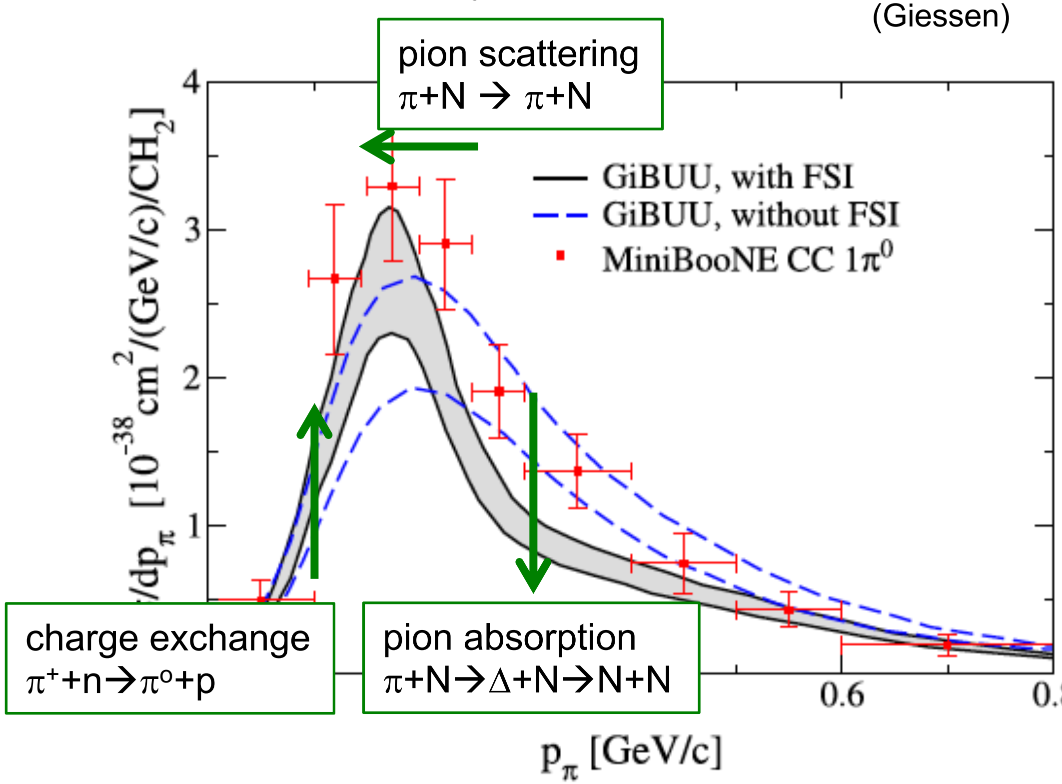
Ulrich Mosel (Giessen)

Final state interaction

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







Interpretation of 1 pion production is already very complicated. Multi-hadron final state measurements by higher energy processes (SIS, DIS) is the completely new world for neutrino oscillation community!

University of London

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

2. GENIE SIS model

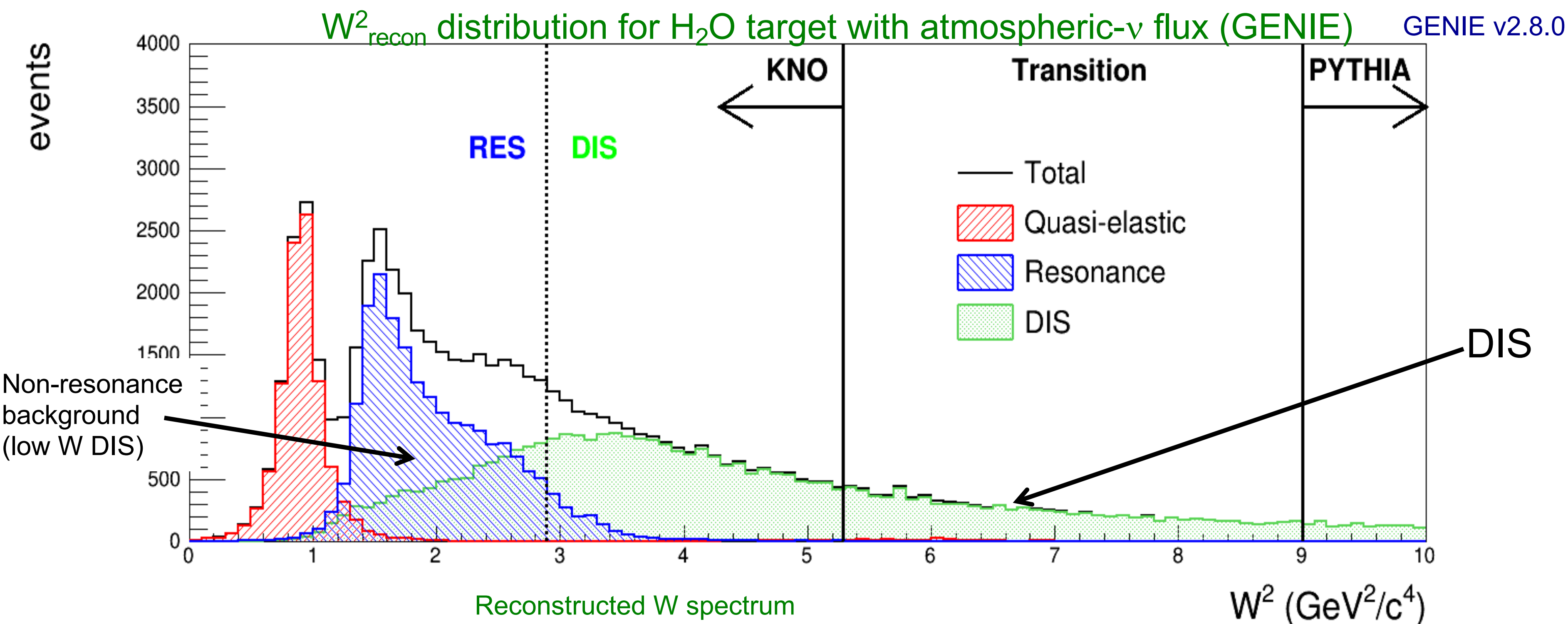
Cross section

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

Hadronization

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

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



Reconstructed W spectrum
→ measurable W distribution with 100% efficiency detector

Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11
NuTeV, PRD74(2006)012008

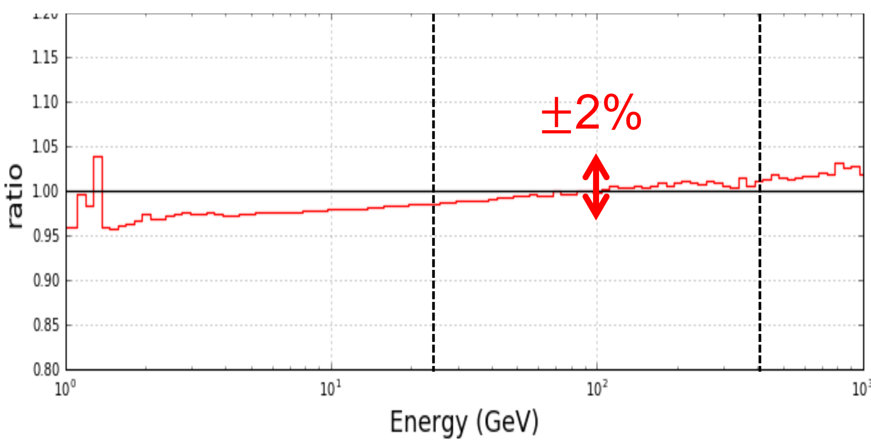
2. SIS region physics

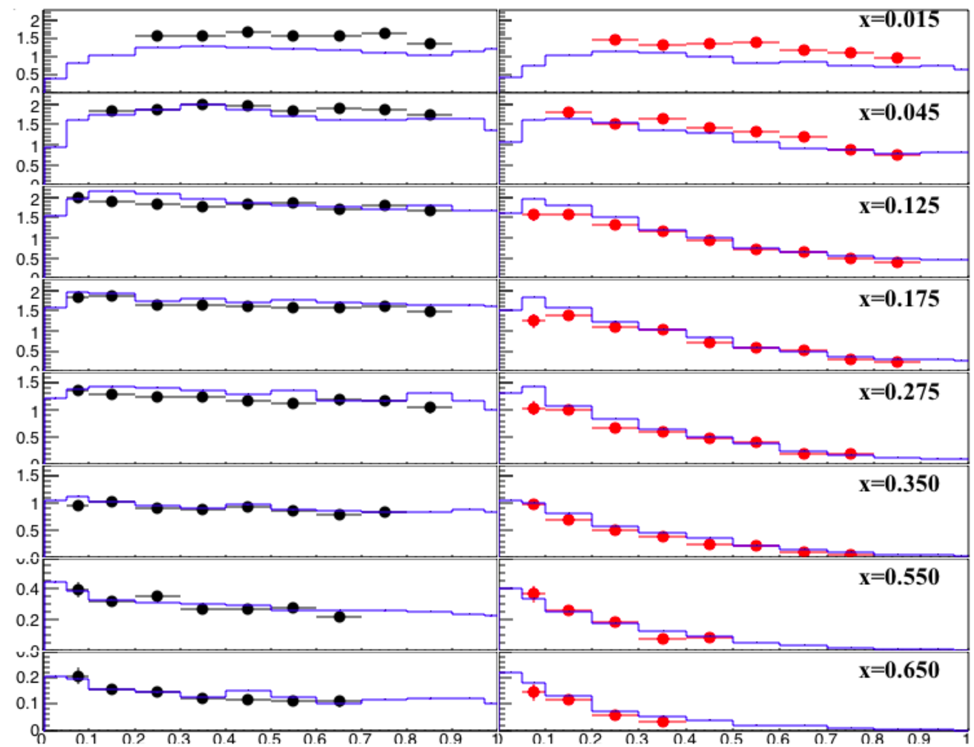
Shivesh Mandalia
(Queen Mary)

GENIE-NuTeV comparison

- GENIE use GRV98 LO PDF +Bodek-Yang correction
- GENIE can describe NuTeV data except very low x region
- Impact of data-MC low x disagreement is ~2% on total cross section in 30<E<360 GeV

150 GeV





NuTeV ν-Fe and antiν-Fe differential cross section (x, y, Eν)