Experimental Challenges of Beam-based Neutrino Physic around 1-10 GeV

Teppei Katori
Queen Mary University of London
European strategy, IPPP, Durham, Apr. 17, 2018

Thank you everyone for all inputs to give this talk

This talk tries to be as general as possible, and the talk doesn't really represent my view

The talk is short, so please don't wait until the end but interrupt me any time if you want to make a comment

My view (=what I work on)

- T2K
- Hyper-Kamiokande
- IceCube
- NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

Experimental challenges of neutrino physics

We decided to do long baseline neutrino oscillation experiments (DUNE and Hyper-Kamiokande) for next ~15-20 years (?)

- Will these detectors be successfully measure δ_{CP} with 5σ?
  → simulation of hadrons and nuclear physics make many challenges

what are the interesting things to measure?

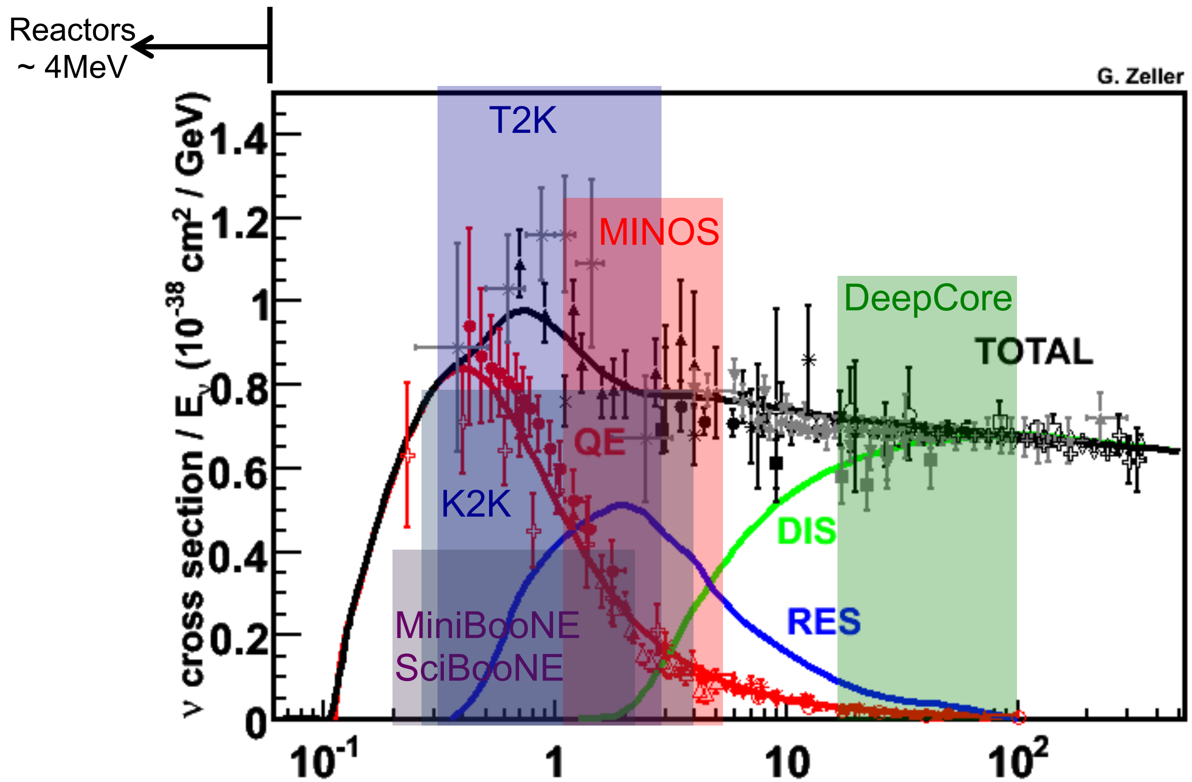
- we have high precision beams and high precision detectors, what do we want to do with them?
- Are these detectors expected to measure anything unexpected?
  → galactic supernova (are we crossing fingers for astrophysics?)
  → light dark matter particles (experiments are not optimized to measure them)

The real challenge is to find interesting physics which we can measure by these experiments (experiments should be as multi-purpose as possible)

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

Next generation neutrino oscillation experiments

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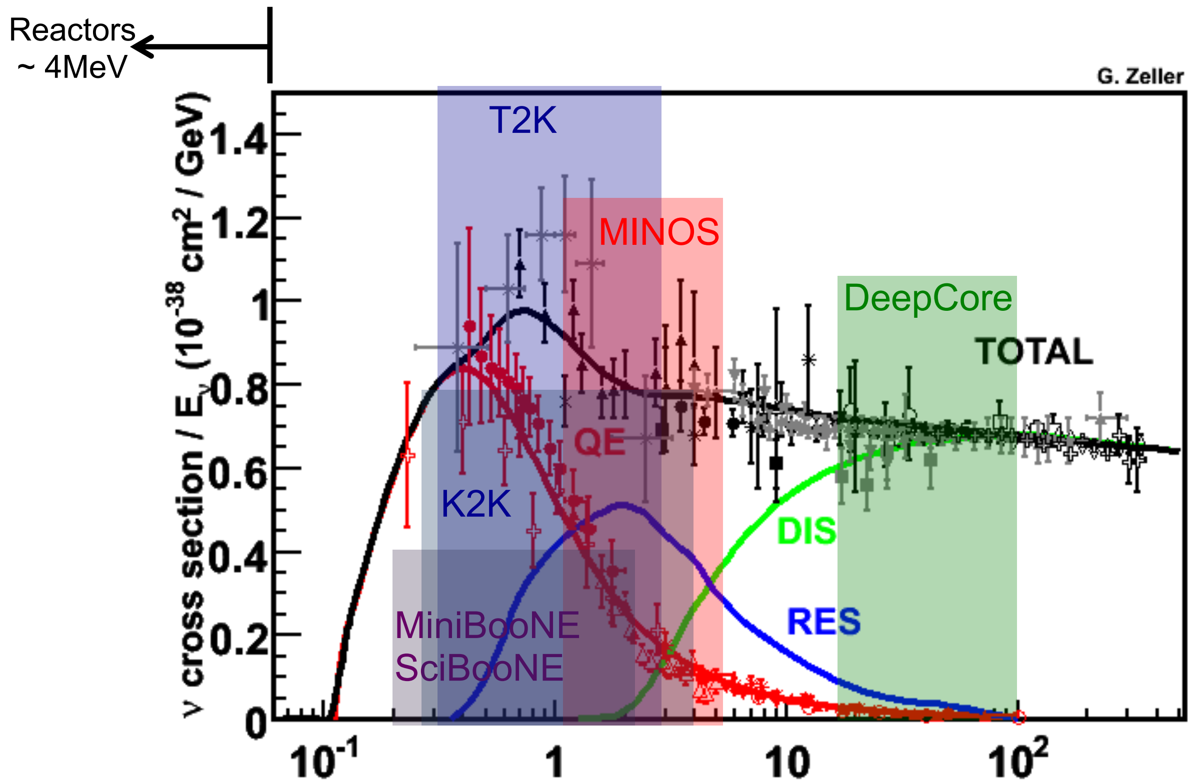

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Next generation neutrino oscillation experiments

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

Current and future oscillation experiments are all around 1-10 GeV

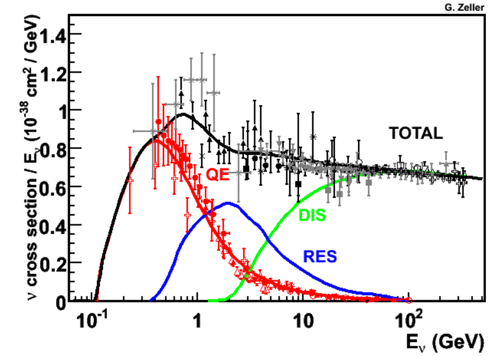
- not the easiest energy region to do many interesting physics
- interplay of many interaction types (QE, RES, DIS, etc) and their boundaries on various nuclear targets

We (=particle physicists) hate

- nuclear physics
- inclusive measurements (kinematics are not well-defined

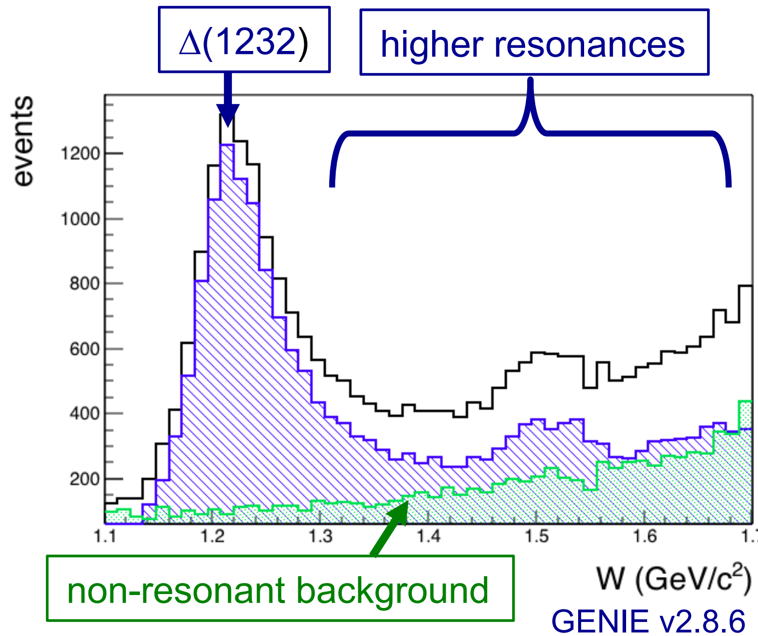
$$\boxed{P_{\mu\to e}(L/E)=\sin^2 2\theta\sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)}$$

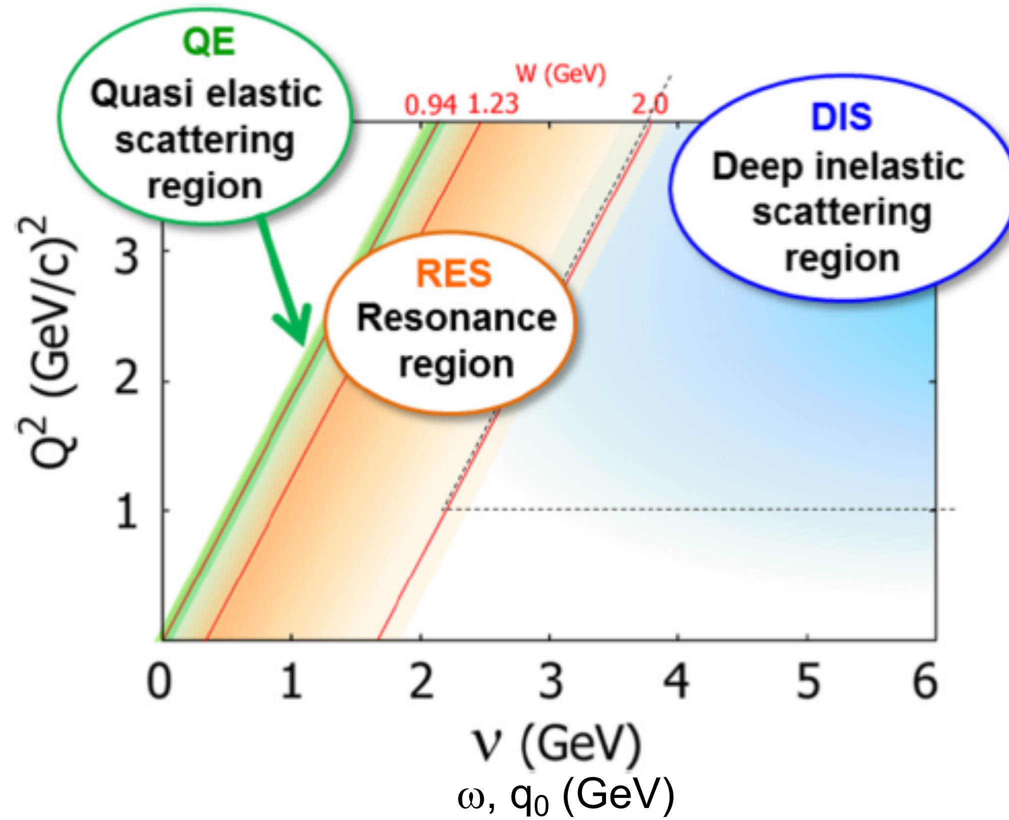
Nakamura et al.,Rep.Prog.Phys.80(2017)056301



Shallow Inelastic Scattering (SIS)

SIS physics includes;
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS





Neutrino cannot choose kinematics

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

SIS physics

SIS physics includes;
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS

DCC model
- Total amplitude is conserved
- Channels are coupled (πN, $\pi\pi$N, etc)
- 2 pion productions ~10% at 2 GeV
- not available in neutrino event generators

DCC model vs. electro-pionproduction data

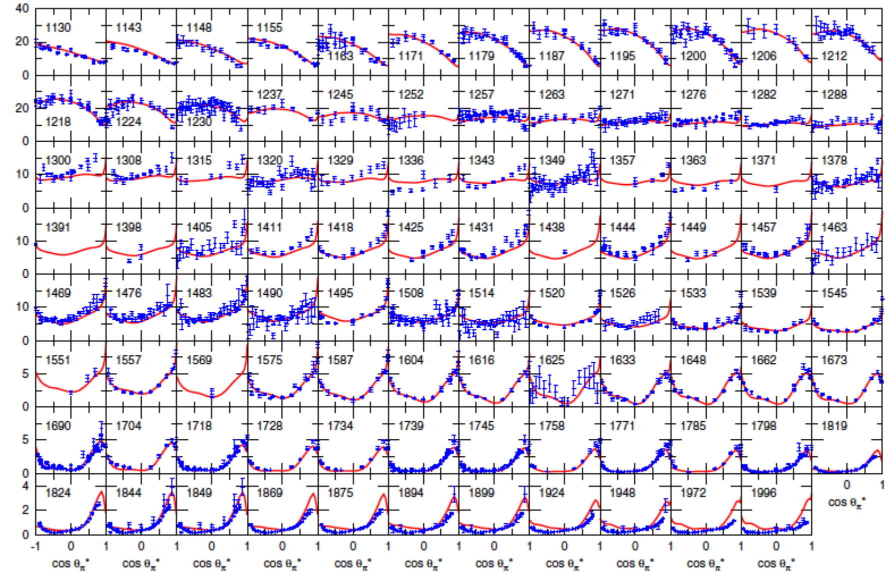
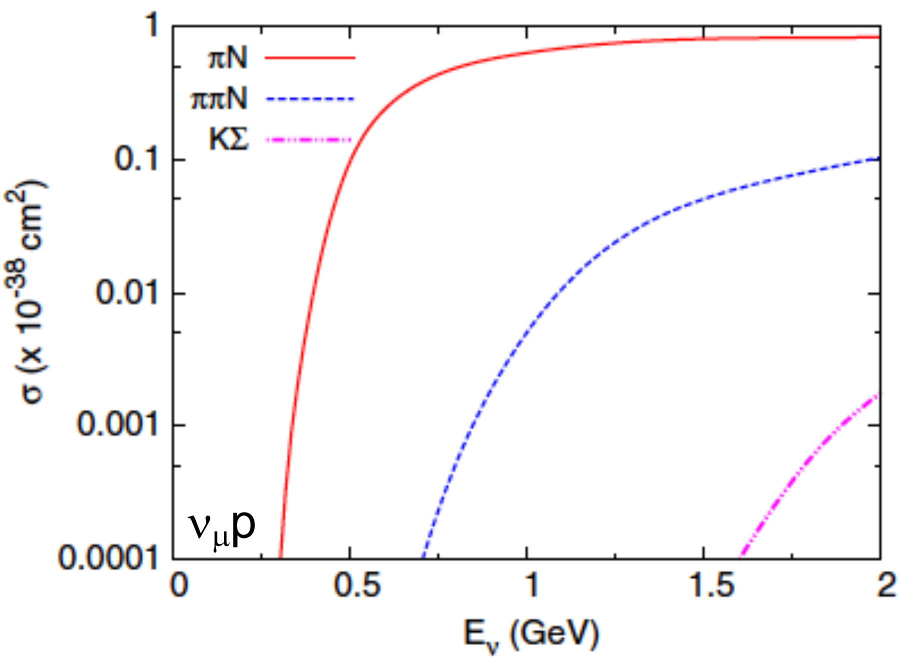
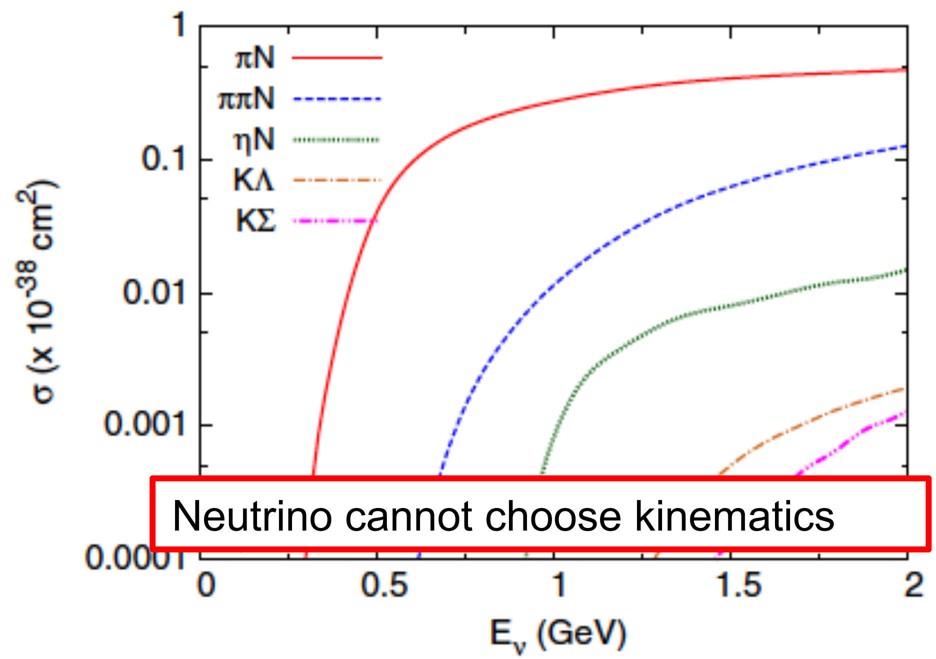


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].





Neutrino cannot choose kinematics

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

SIS physics

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

SIS physics includes;
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS

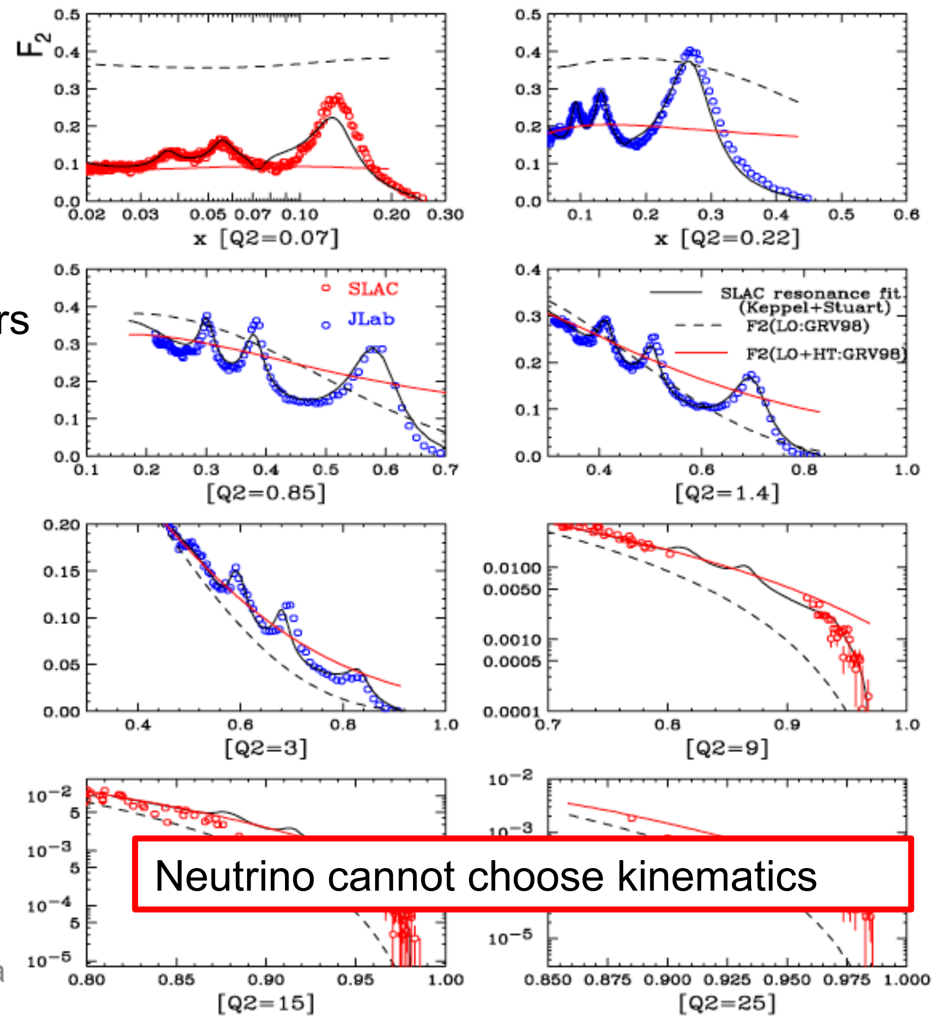
GRV98 LO PDF + Bodek-Yang correction
- GRV98 for low Q^2 DIS
- Bodek-Yang correction for QH-duality
- 20 years old, out-of-dated
- not sure how to implement systematic errors

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

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

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

Proton F2 function GRV98-BY correction vs. data



Neutrino cannot choose kinematics

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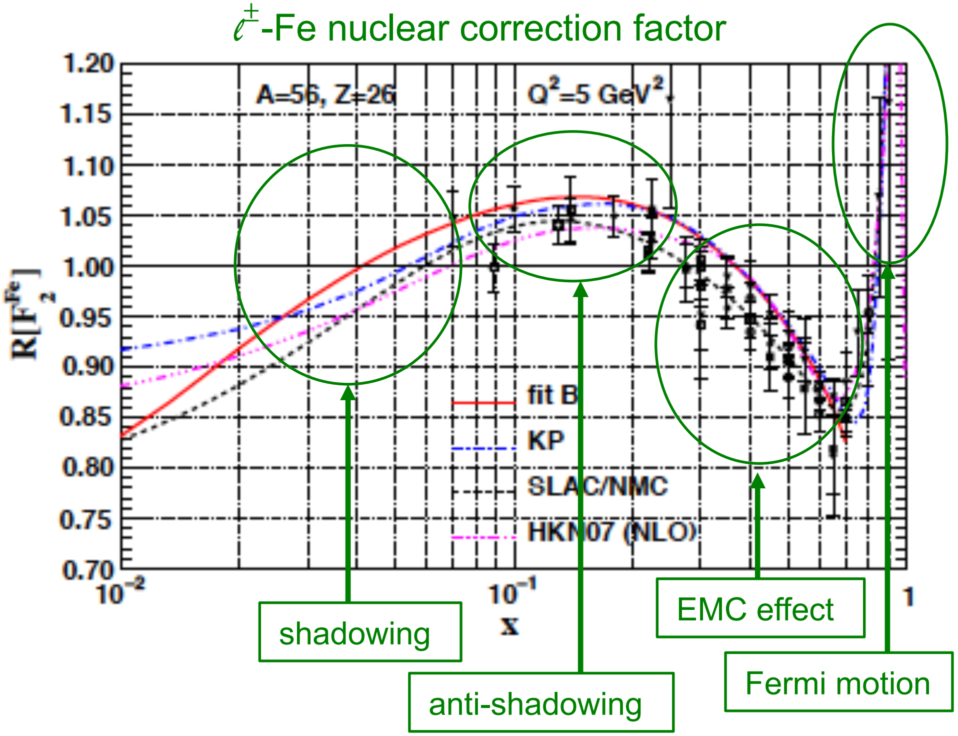
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028
nCTEQ, PRD80(2009)094004

SIS physics

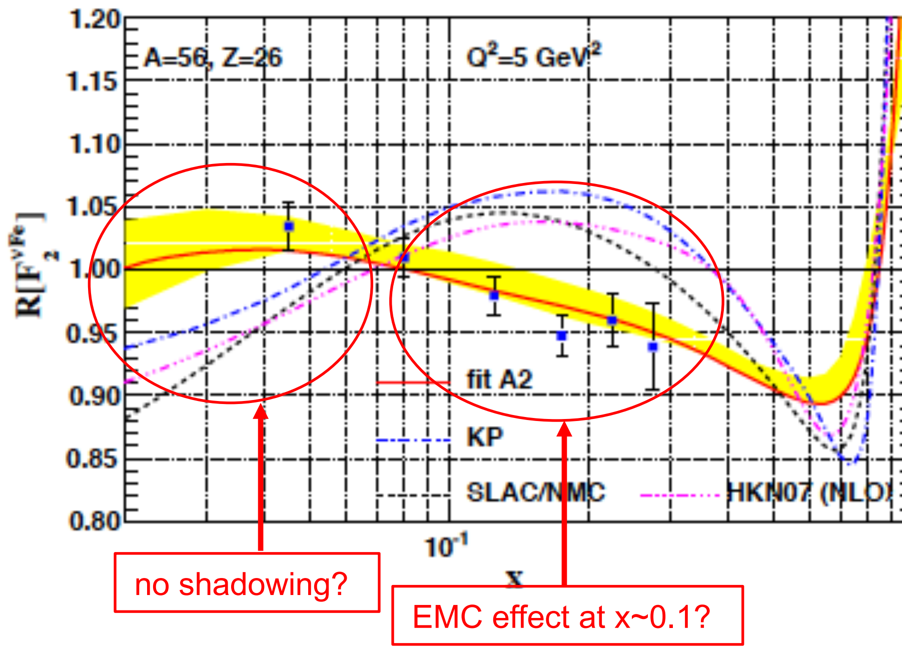
SIS physics includes;
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS

Nuclear PDF
- Shadowing, EMC effect, Fermi motion
- Various models describe charged lepton data
- Neutrino data look very different
- Not available in neutrino event generators

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



ν-Fe nuclear correction factor



Neutrino cannot choose target

MINERvA,PRD93(2016)071101

SIS physics

SIS physics includes;

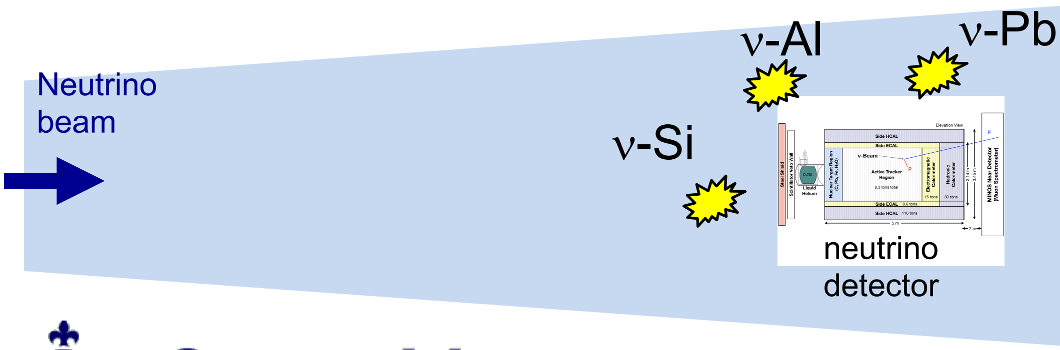
- Higher resonances and hadron dynamics
- low Q^2, low W DIS
- Nuclear dependent DIS

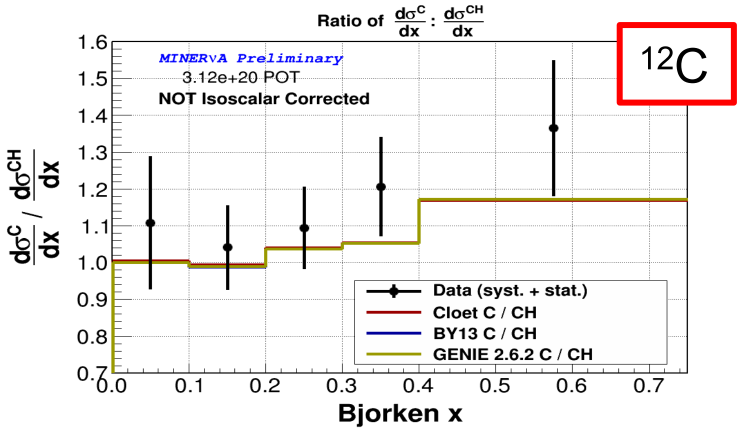
MINERvA DIS target ratio data (C, Fe, Pb)

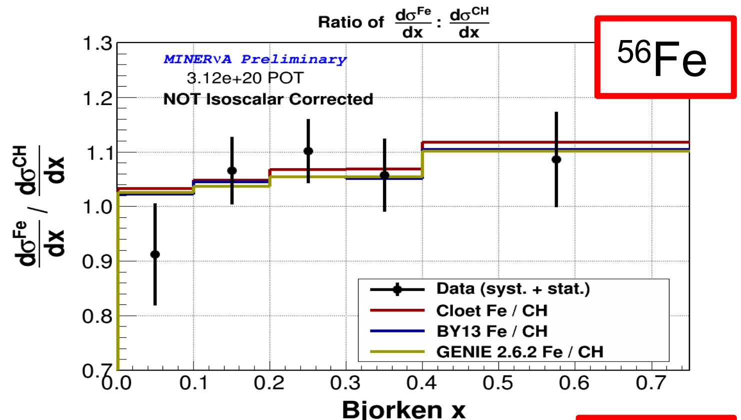
- MINERvA data reveal shadowing effect on neutrino may be larger than expected

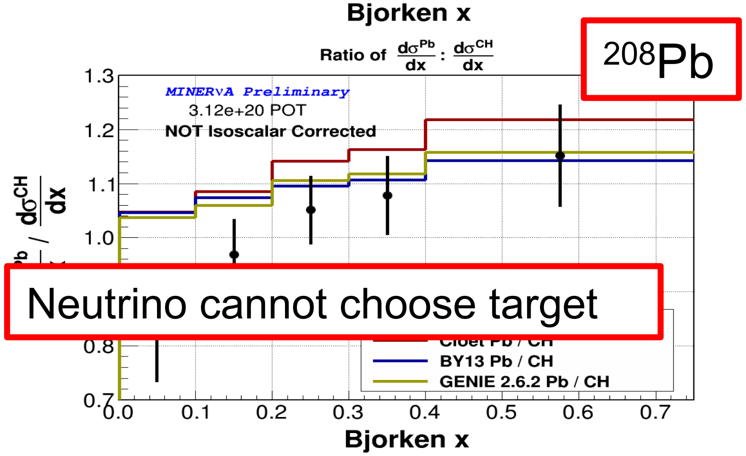
We care all nuclear targets

- 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.





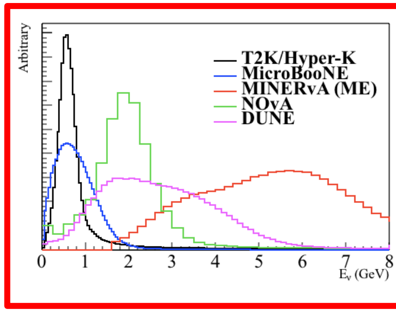




Neutrino cannot choose target

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

SIS model in GENIE

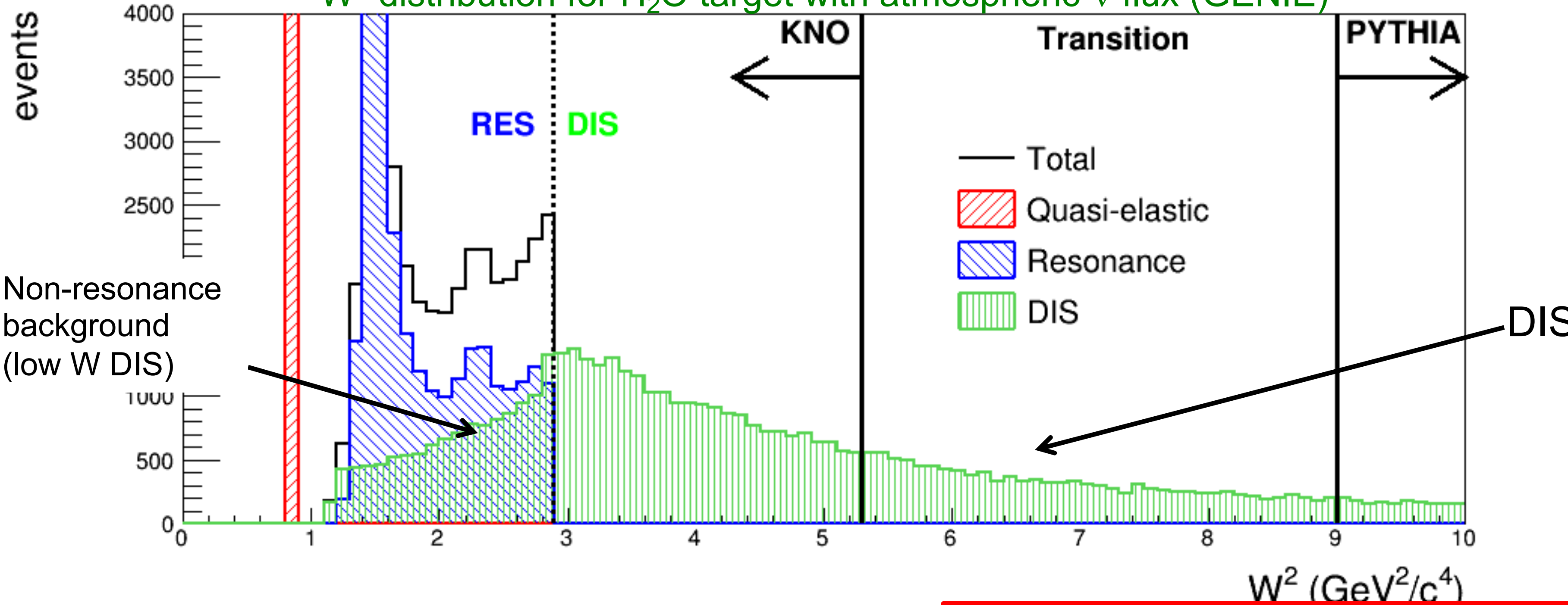


Cross section
W^2<2.9 GeV^2 : RES
W^2>2.9 GeV^2 : DIS
Hadronization (GENIE-AGKY model)
W^2<5.3GeV^2 : KNO scaling based model
2.3GeV^2<W^2<9.0GeV^2 : transition
9.0GeV^2<W^2 : PYTHIA6

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

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

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



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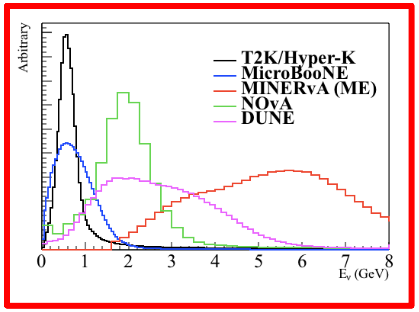
Typical “Frankenstein” style model!

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

SIS model in GENIE



Cross section

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There are 2 kind of "transitions" in SIS region
- cross-section
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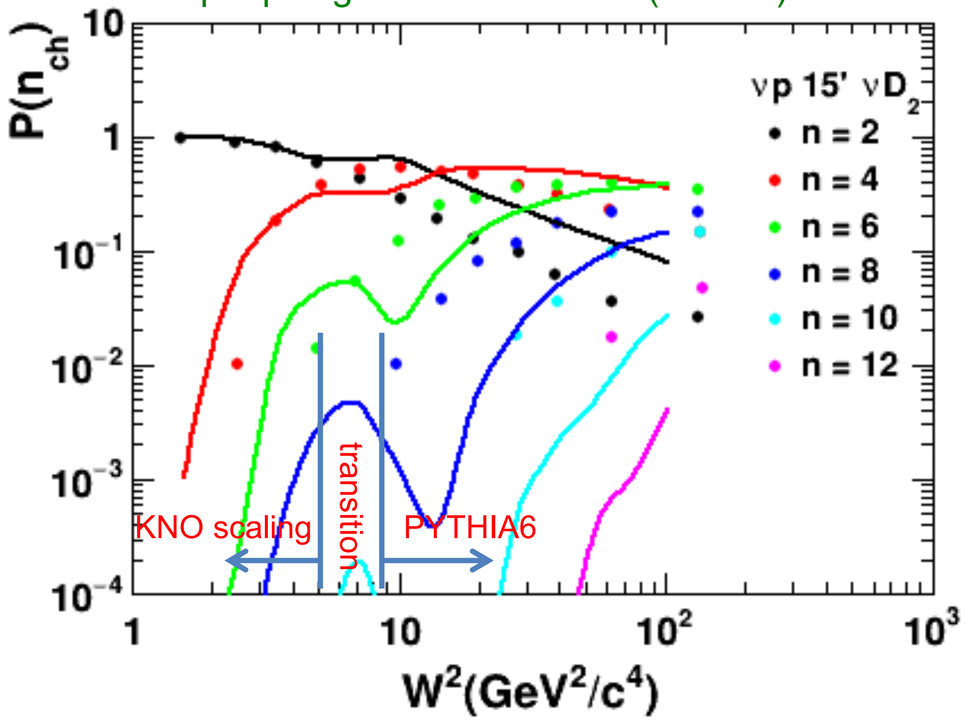
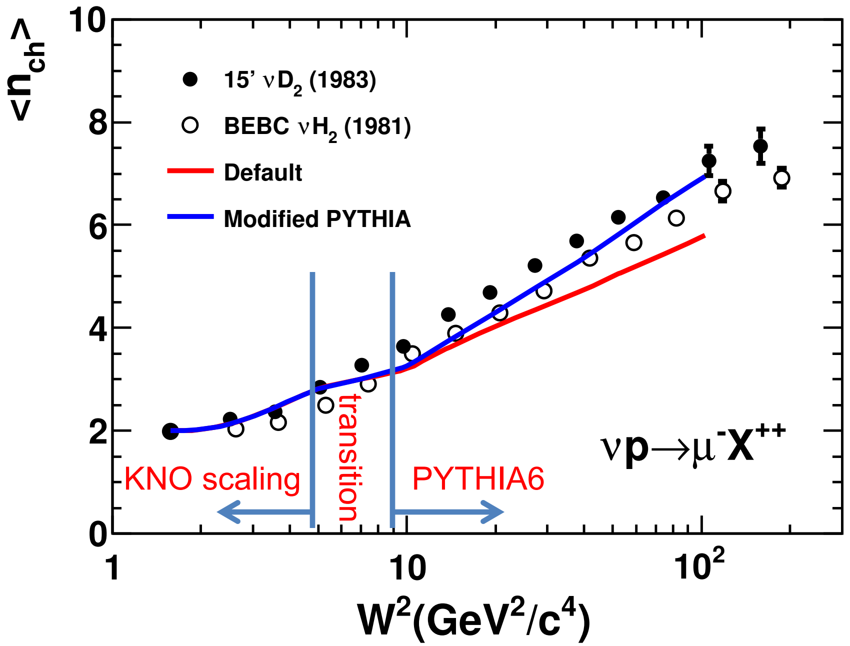
Very important energy region for NOvA, PINGU, ORCA, Hyper-K, DUNE…

ν-p topological cross section (GENIE)



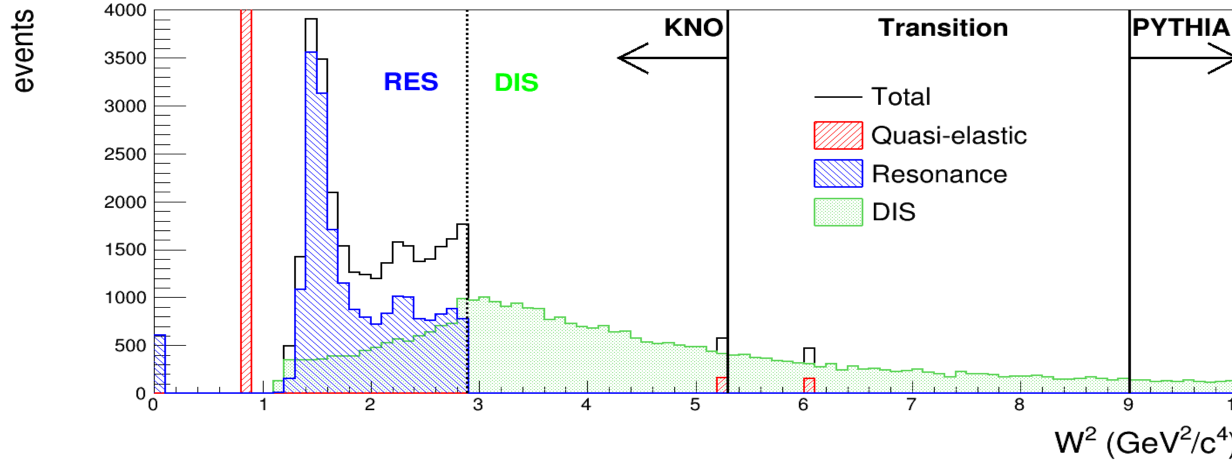
ν-p averaged charged hadron multiplicity (GENIE)



Typical "Frankenstein" style model!

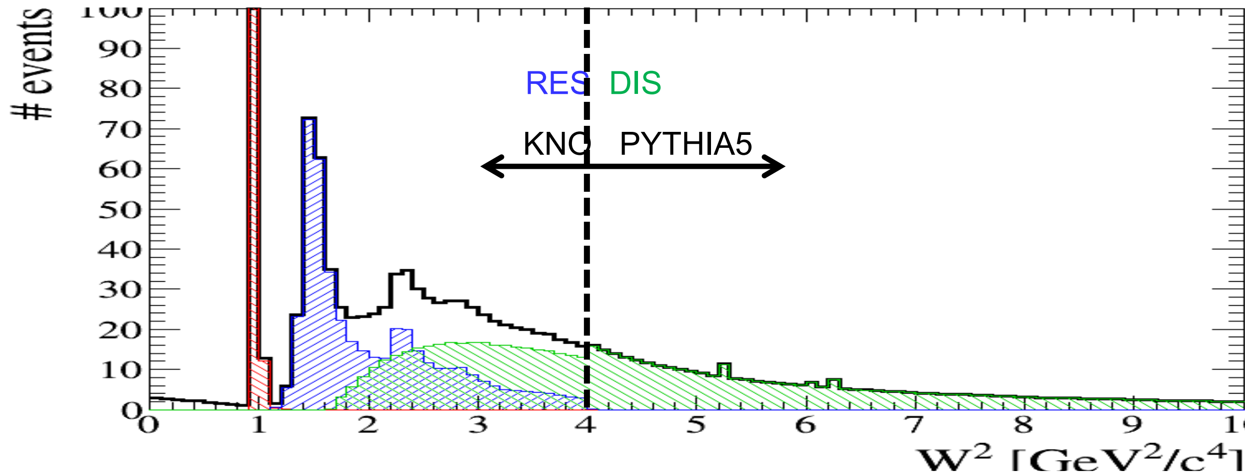
SIS is the least understood energy region and (dominant signals in DUNE)

GENIE



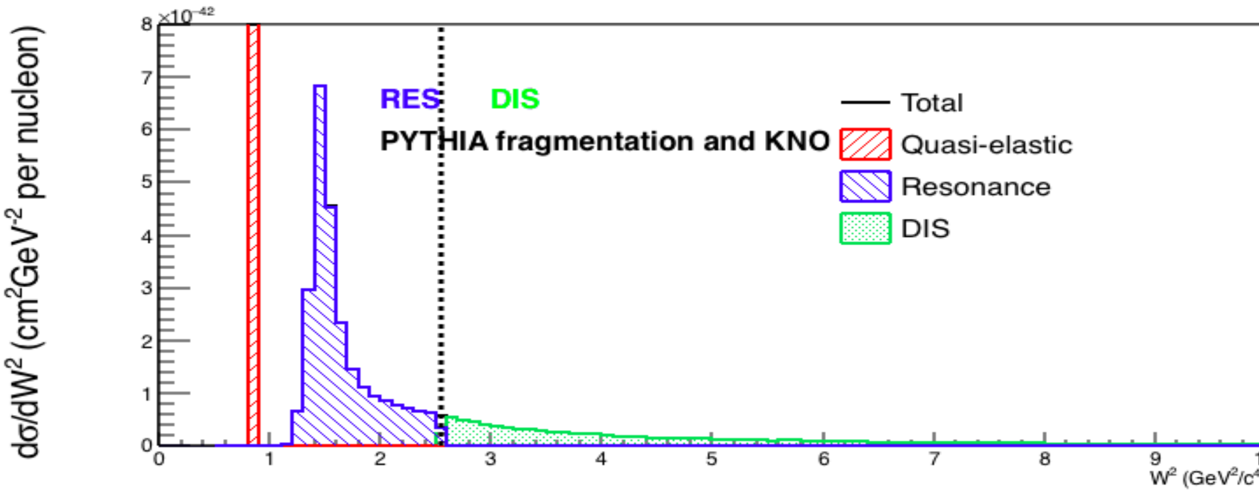
vs

NEUT



vs

NuWro



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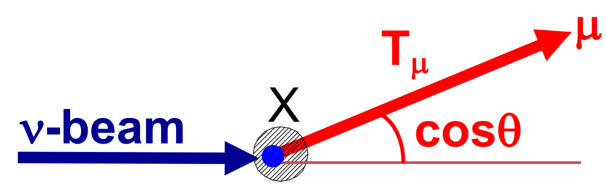
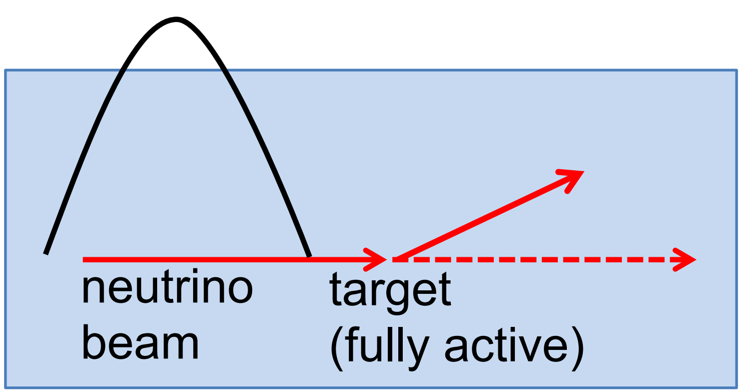
Neutrino detector features

Large mass, coarse instrumentation
- neutirno don't interact very often
- In general, not much R&D



Incomplete kinematics
- No one measure 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 the interaction is 2-body interaction

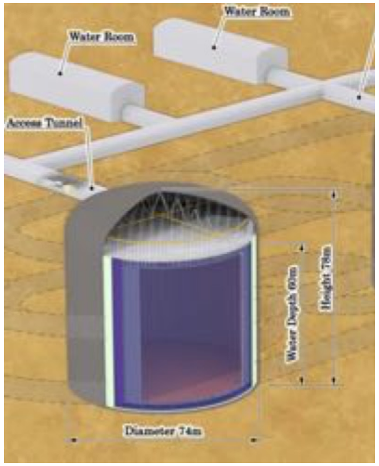
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

Water Cherenkov vs. LArTPC

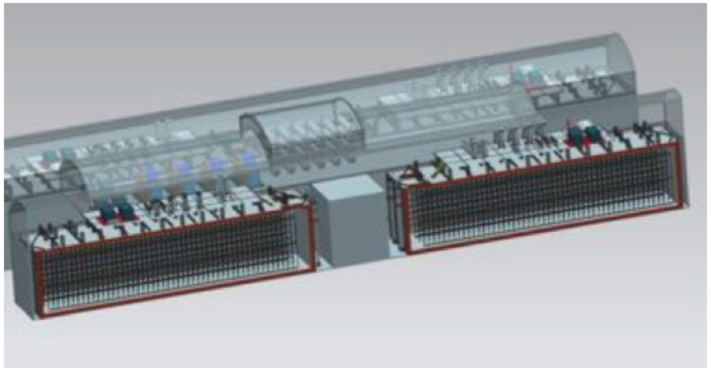
HyperK

- Known technology
- Large mass (190 kton)
- Low resolution
- Timing information
- Hard to measure hadrons
  → kinematic E reconstruction



DUNE

- Challenging (HV, purity, data size, etc)
- Small mass (40 kton)
- High resolution
- TPC has no timing information (~ms), but has scintillation light (~ns)
- Good hadron measurements
  → calorimetric E reconstruction



These 2 experiments are complementary

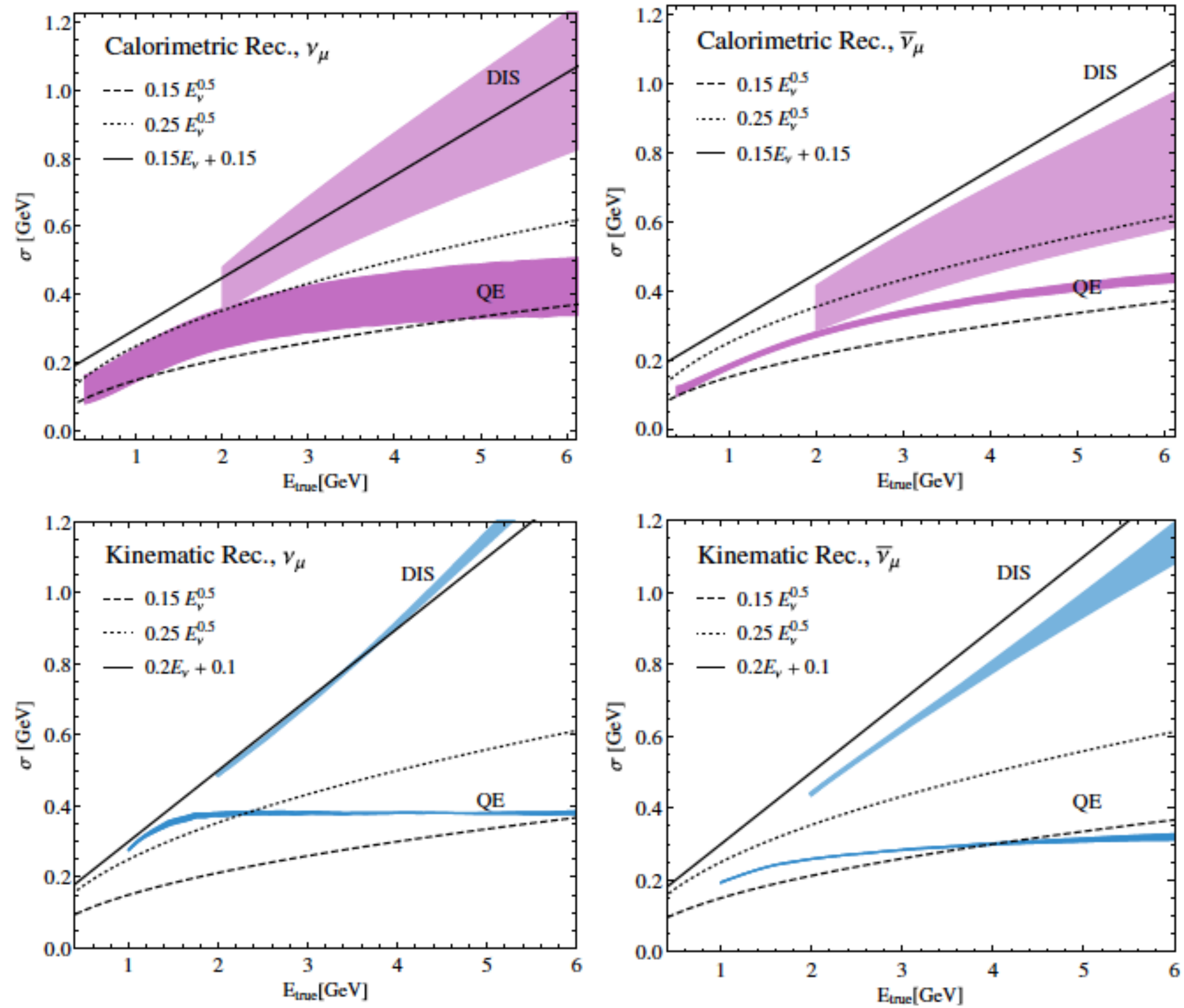
Ankowski et al, PRD92(2015)073014

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

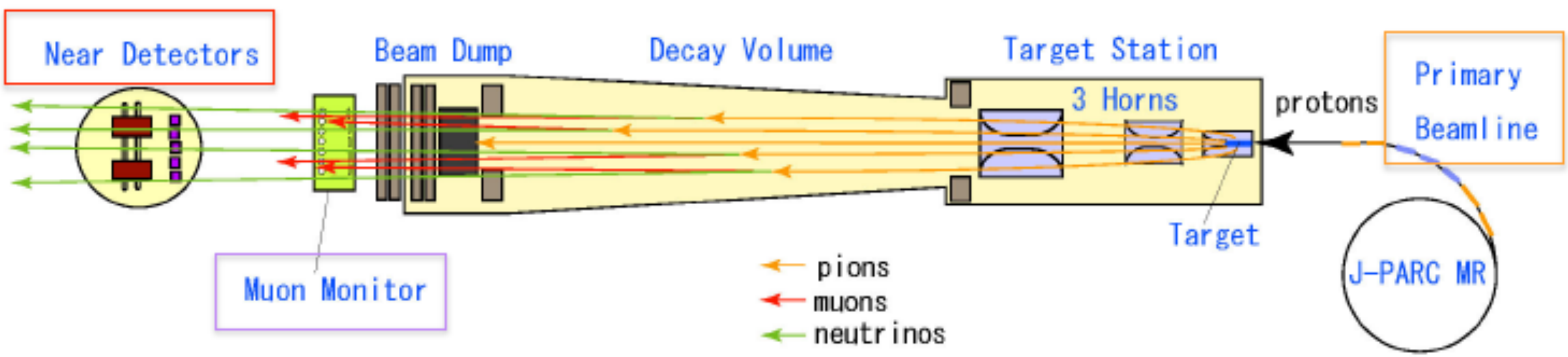
etc



Neutrino beam: traditional superbeam

J-PARC neutrino beam

- With careful monitoring and external measurements, J-PARC neutrino beam achieved ~4% absolute error. Probably this is good enough after the near detector constraint? (similar number is achievable by NuMI and DUNE beam). This is the maximum precision one can achieve by the traditional superbeam.



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

Another challenge: publications

CDF run II (2009)
- ~ 500 collaborators
- ~ 59 papers/year

(~1 paper/week)

T2K (2015)
- ~ 500 collaborators
- 11 papers/year

(<1 paper/month)

- 2 oscillation papers
- 6 cross section papers
- 2 phenomenology
- 1 detector/sensitivity

CMS (2015)
- ~ 2000 collaborators
- ~ 90 papers/year

(>1 paper/weak)

DUNE (2025?)
- ~1000 collaborators
- ? papers/year

Accelerator-based neutrino experiments have different community structure

Another challenge: software development

PYTHIA
- Standard for all collider experimentalists (?)
- manual > 9000 citation (after 12 years)

GENIE
- Standard simulation for all neutrino experimentalists
- the paper = 500 citation (after 7 years)

Costas Andreopoulos
(Liverpool)

Accelerator-based neutrino experiments have different community structure

Another challenge: not many physics topics

Galactic supernova?
Many studies in both HyperK and DUNE to prepare for the next galactic supernova (~3/100 years) → astrophysics is more interesting?

Solar neutrinos?
John Beacom presented a new idea to optimize DUNE to measure interesting things of solar neutrinos (NuPlatform meeting at CERN, Jan 2018)

Light dark matter search?
If we want to look for light dark matter particles from beam dump, beam dump may need to be optimized, also detector need to be optimized to measure NC elastic scattering.

Completion of lepton mixing matrix elements
tau sector has the largest error, which mean we need t-appearance oscillation experiments (=atmospheric neutrino oscillation)

Anything else?

Accelerator-based neutrino experiments have different community structure

Conclusion

Subscribe “NuSTEC News”

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

We decided to do DUNE and Hyper-Kamiokande for next ~15-20 years (?)

- Will these detectors be successfully measure δ_{CP} with 5σ?
  → Neutrino interaction physics and nuclear physics make many challenges

- Are these detectors expected to measure anything unexpected?
  → galactic supernova? (are we crossing fingers for astrophysics?)
  → light dark matter particles? (detectors are not optimized to measure them)

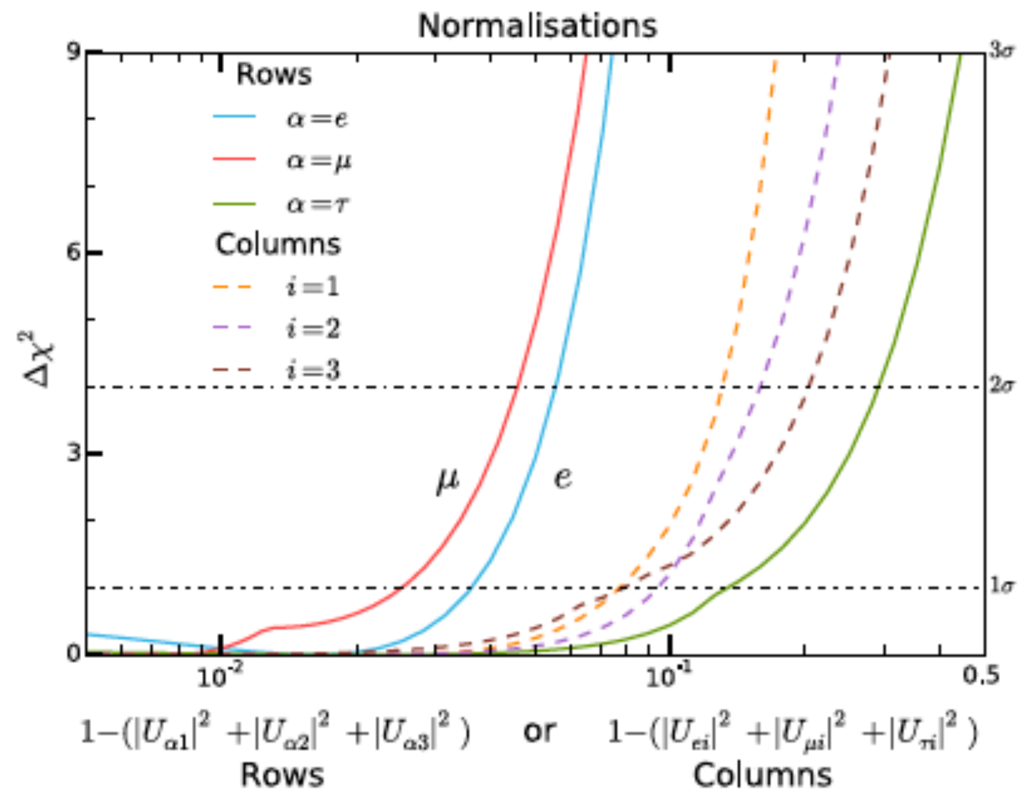
what are the interesting things to measure?
→ we have high precision beams and high precision detectors, what do we want to do with them?

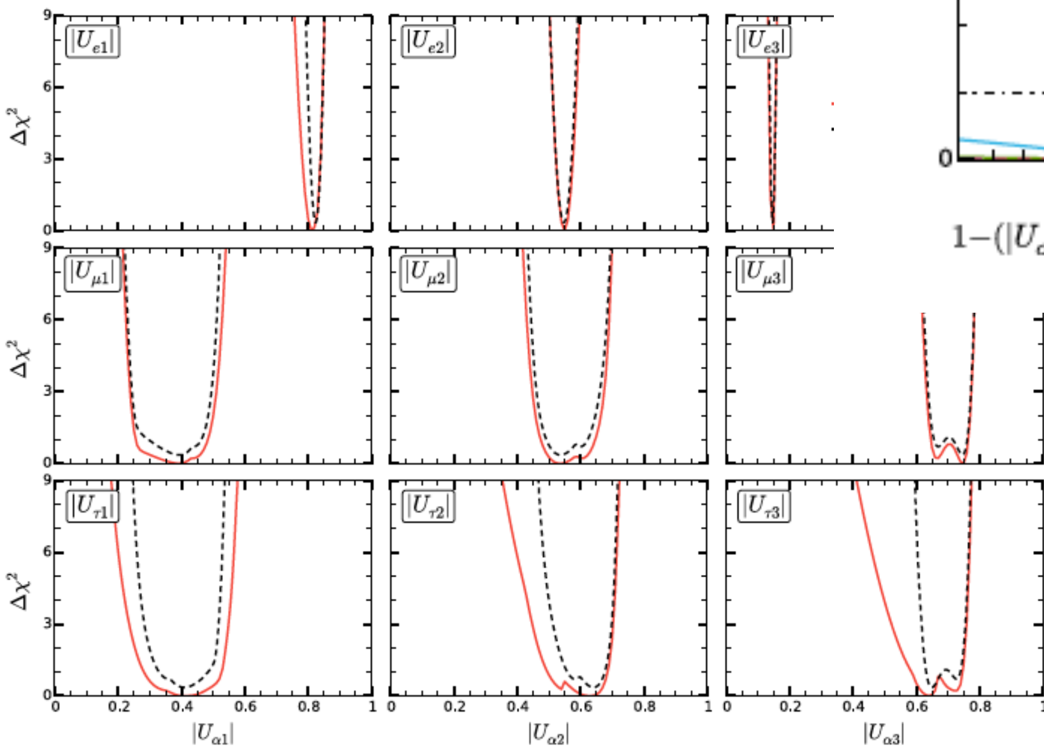
It is challenging is to find interesting physics which we can measure by these experiments (experiments should be as multi-purpose as possible)

Backup

1. τ-appearance to complete lepton mixing matrix

If we want to look for new physics from unitarity, we need τ-appearance oscillation experiment
→ atmospheric neutirno oscillation





Neutrino detector R&D

Water Cherenkov
- gadolinium doping (neutron counting)
- water-based scintillator (low-energy charged particle measurements)
- LAPPD, track reconstruction in water

High resolution detectors
- LArTPC: mm resolution with ionization (~ms), fast signal by scintillation (~ns)
- HPTPC: low mass, suitable for DUNE near detector
- SuperFGD: 3-d scintillator for high resolution tracker

All these are motivated to add hadron detection capability on neutrino detectors

Neutrino beam R&D

nuPRISM
- neutrino angular distribution measurement to understand final state particle distribution. This allows to study oscillation with skipping nuclear physics. (proposed to DUNE and HyperK)

ENUBET (tagged neutrino beam)
- monitor decay products to reconstruct beam neutrino energy

nuSTORM and Neutrino Factory
- ~1% precision on electron neutrino beam from muon decay in strage ring

Decay-at-Rest (DAR) neutirno beam
- mono-energetic neutrino beam (DAR of kaon, DAR on pion)

Beta beam
- Neutrinos from boosted isotope decay

Many of them are motivated to measure neutrino interactions more carefully

Jon Link, Fermilab Wine & Cheese seminar (2005)

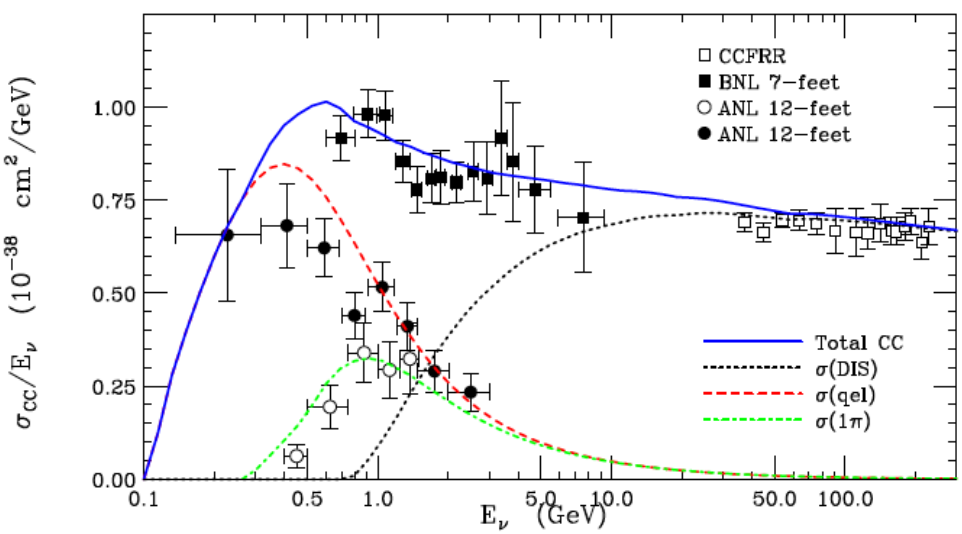
Dark age of neutrino interaction physics

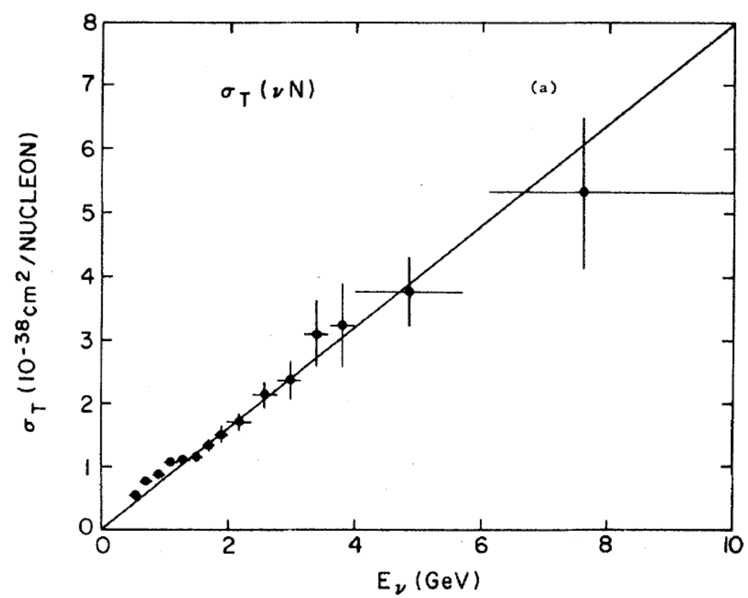
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate
→ you get the cross section which you assumed

Nobody really hasn't measured neutrino-nucleus cross section until recently.

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]





SIS-DIS workshop at GSSI, Italy

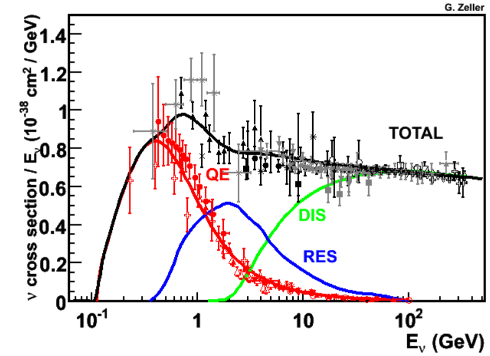
No one is willing to talk about SIS physics

2018 October 15-19: NuInt 18, GSSI, Italy
The main conference of ν-interaction physics

2018 October 11-13: nuSDIS, GSSI, Italy
A Workshop on SIS-DIS physics (TBA)

SIS model is hard in many ways…
- higher resonances model
- low Q^2 DIS model
- A-dependent DIS model
- neutrino hadronization model
- resonance → DIS transition

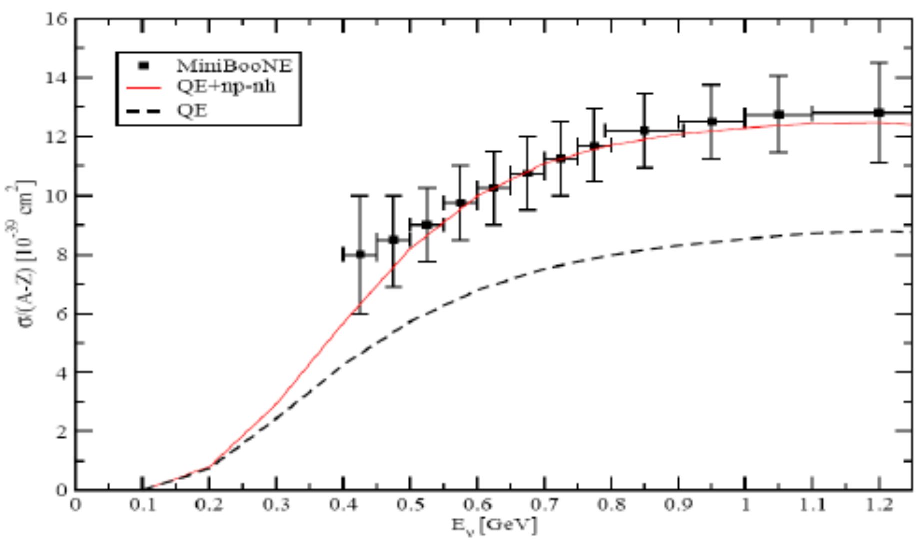
4. CCQE for oscillation physics

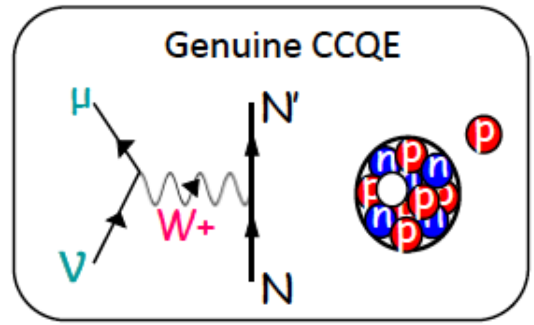


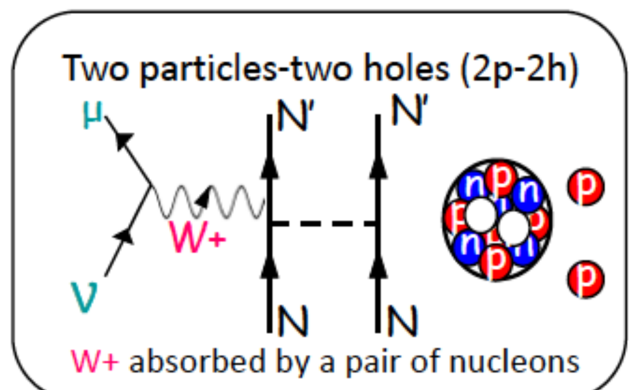
- Most common interaction around 1 GeV
- Simple 2-body interaction (in a simple world)
- All experiments measured higher late
- Nucleon correlation contribute ~30% of CCQE-like final states

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







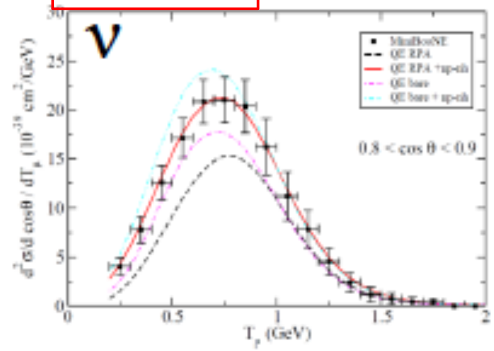
Martini et al, PRC84(2011)055502, Nieves et al, PLB707(2012)72
Meucci et al, PRL107(2011)172501, Megias et al.,PRD94(2016)093004

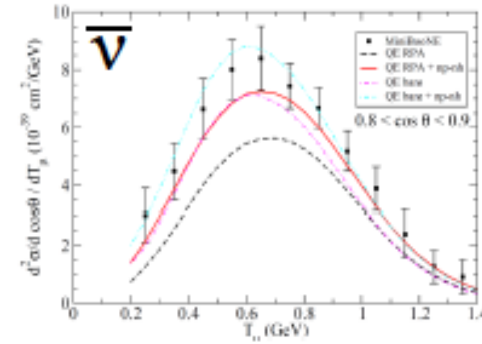
4. CCQE-like data (2016)

CCQE
Resonance
SIS

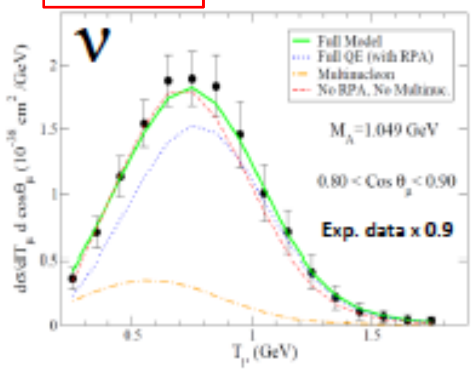
All nuclear calculation agree qualitatively with MiniBooNE and MINERvA CCQE-like double differential data.

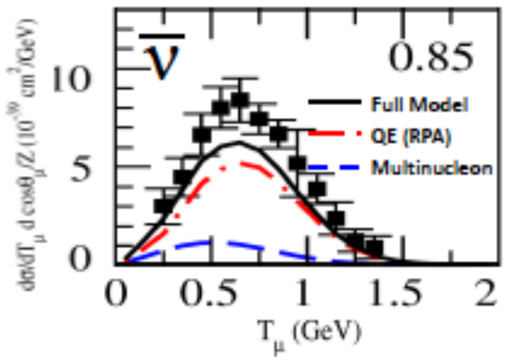
Martini et al



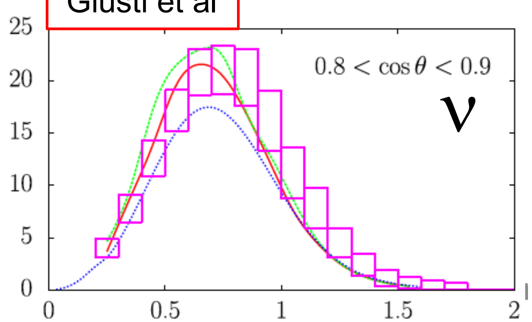


Valencia

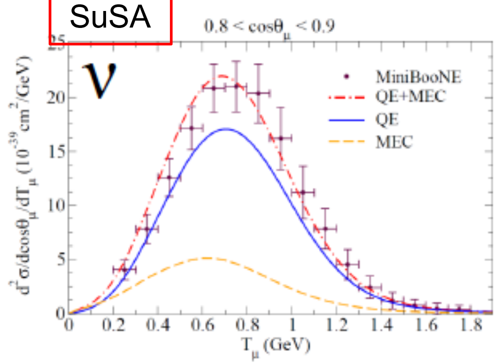


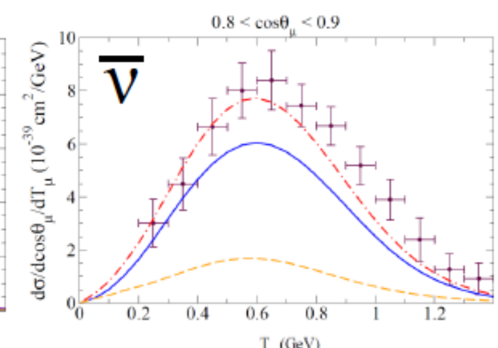


Giusti et al



SuSA





Queen Mary
University of London

Wilkinson et al.,PRD93(2016)072010
MINERvA, arXiv:1803.09377

4. CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation
- Valencia MEC model is available in NEUT
- Implemented in GENIE, officially ready for GENIE v2.12

This moment…
Valencia MEC model does not fit T2K, Super-K, MINERvA data very well, people are working very hard to understand what is going on

large M_A error → large nuclear effect error

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

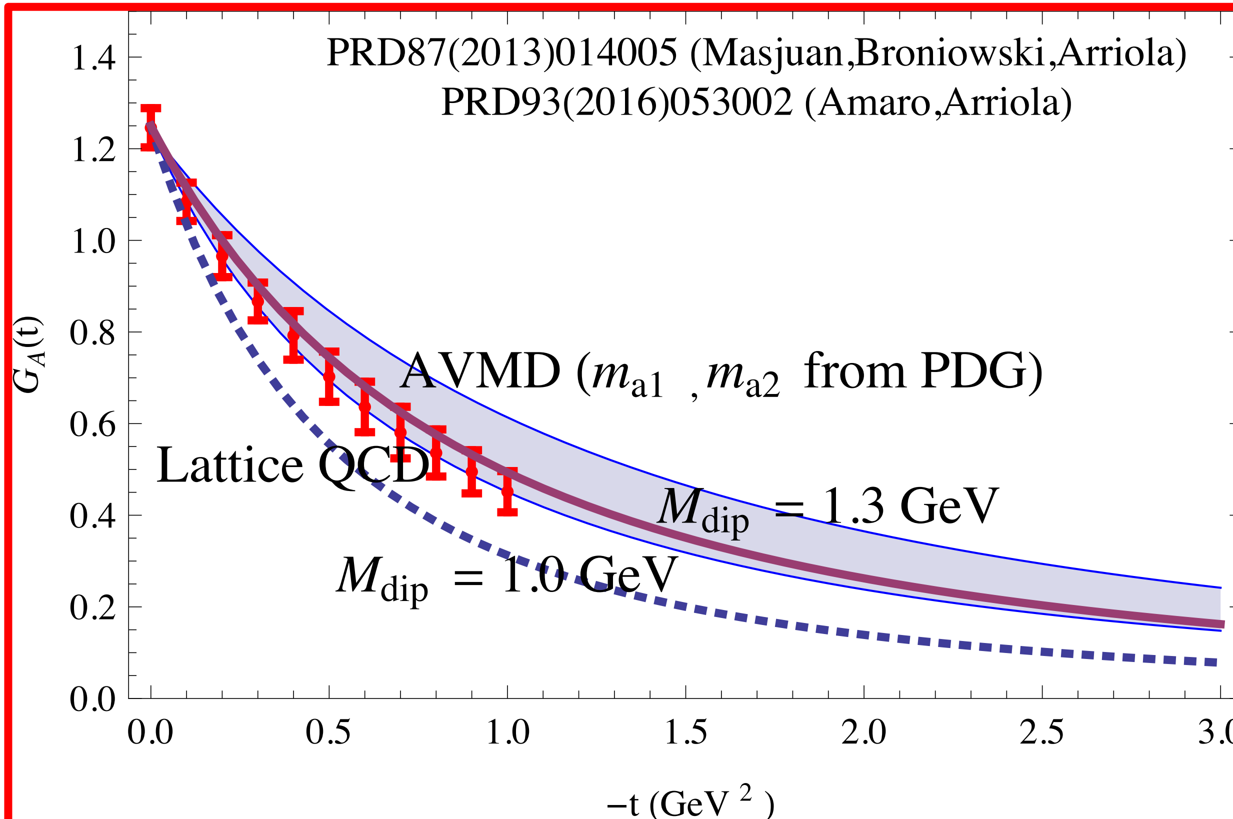
Amaro et al.,PRD93(2016)053002
Alexandrou et al., PRD88(2013)014509

4. CCQE for oscillation physics

CCQE
Resonance
SIS

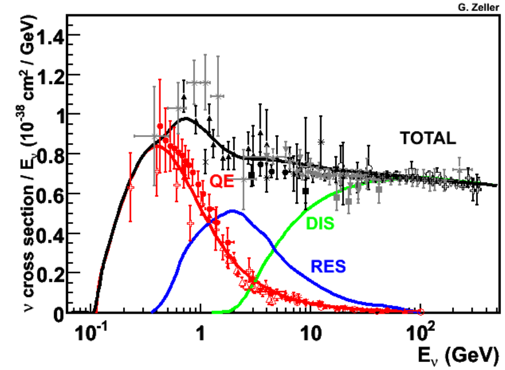
Community is converged: the origin of CCQE puzzle is multi-nucleon correlation?
- Lattice QCD prefers large MA
- Some top down axial form factor model prefers harder spectrum (~large MA)

The community is still confused with neutrino-nucleon scattering theory…



Wilkinson et al,PRD90(2014)112017,Graczyk et al,PRD80(2009)093001
MINERvA,PRD94(2016)052005

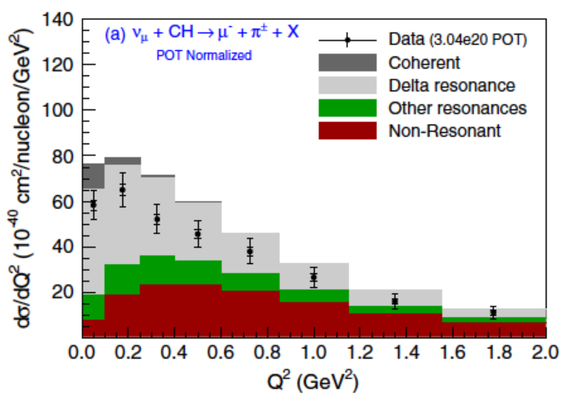
4. Baryonic resonance for oscillation physics

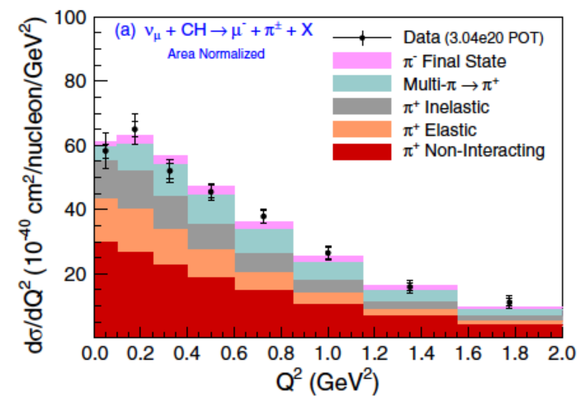


Recent fit on re-analyzed ANL-BNL data shows on $C^A_5(0)$ error is 6%. This would give ~6-10% error on M_A^{RES} for experimentalist.

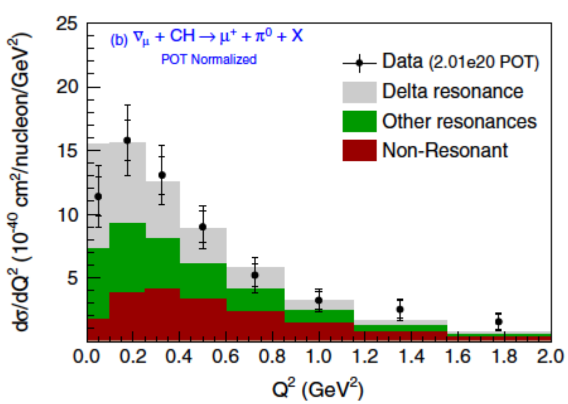
However, this small error on M_A^{RES} cannot cover the discrepancy between MiniBooNE-MINERvA (pion puzzle). First of all, model errors cannot explain new MINERvA data. In the end, baryonic resonance error is kept 30% or higher.

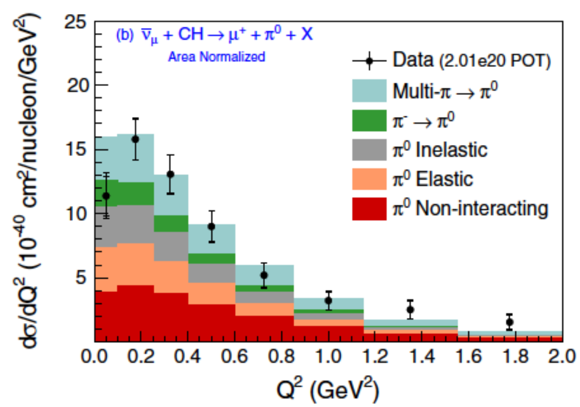
$\nu_\mu CC1\pi^+$ data has better shape agreement with GENIE





$\bar{\nu}CC1\pi^o$ data has better normalization agreement with GENIE

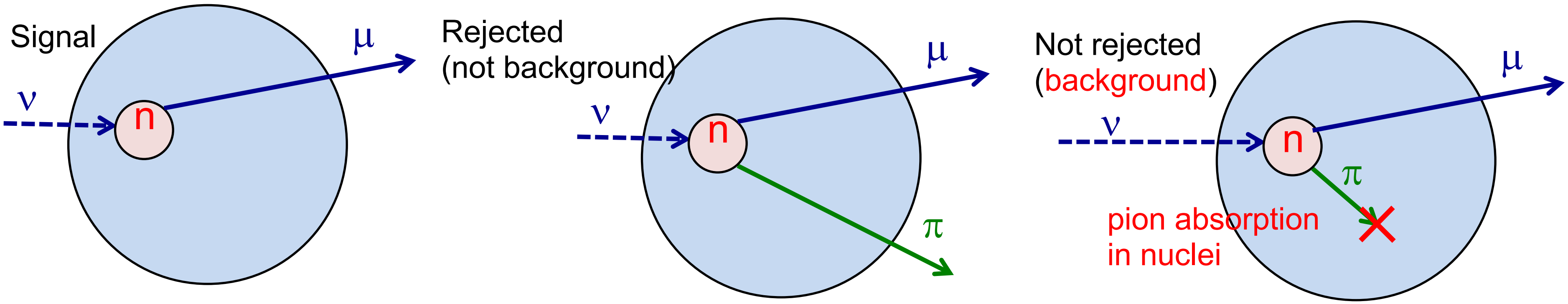


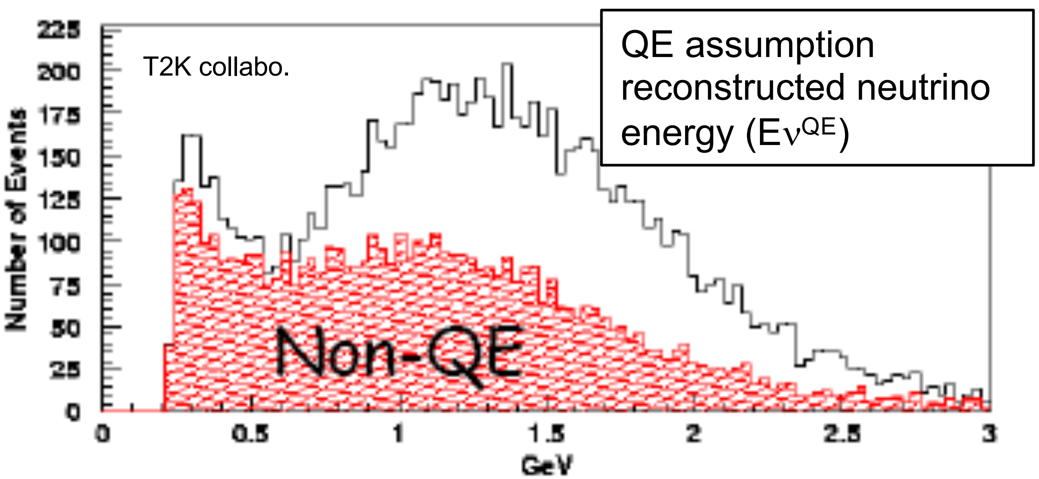


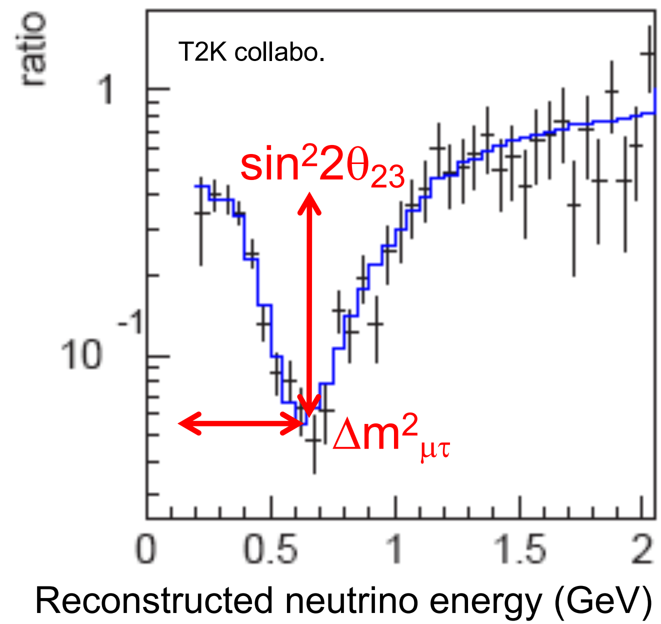
4. Pion production background

CCQE
Resonance
SIS

non-QE background → shift spectrum





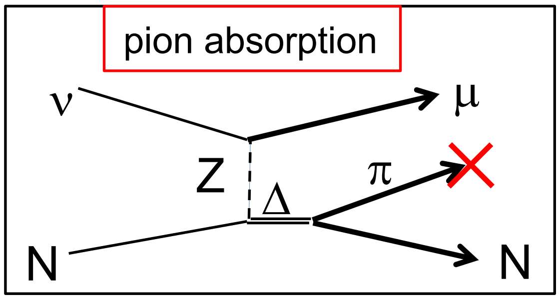


Coloma et al,PRL111(2013)221802
Mosel et al,PRL112(2014)151802

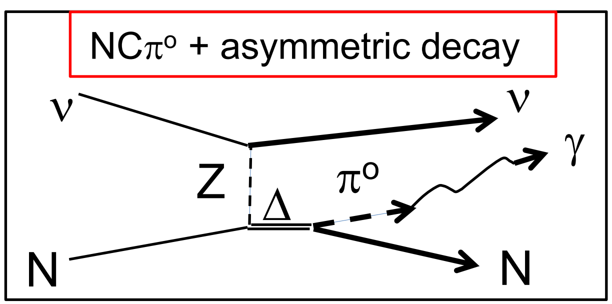
4. Pion production background

CCQE
Resonance
SIS

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