Nuclear Physics for Beyond the Standard Model Neutrino Physics

outline

1. Neutrino interaction physics - introduction
2. Charged-Current Quasi-Elastic (CCQE) interaction
3. Nucleon correlation physics in BSM physics
4. Neutrino interaction physics - future prospect
5. Conclusion

Teppei Katori @teppeikatori
King's College London
2020 JPS annual meeting, Nagoya, Mar. 18, 2020

Fun Timely Intellectual Adorable!

nuclear many-body problem

Leptonic CP violation

Neutrino oscillation

electron scattering

Spin physics

Gallium anomaly

NuSTEC News

Nucleon correlation

Neutrino-less double beta decay

EMC effect

Dark matter

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

Fun Timely Intellectual Adorable!

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

1. Next goal of high energy physics

Establish Neutrino Standard Model (νSM)
- SM + 3 active massive neutrinos

Unknown parameters of νSM
1. Dirac CP phase
2. θ_{23} (θ_{23}=40° and 50° are same for $\sin 2\theta_{23}$, but not for $\sin\theta_{23}$)
3. normal mass ordering $m_1<m_2<m_3$ or inverted mass ordering $m_3<m_1<m_2$
4. Dirac or Majorana
5. Majorana phase
6. Absolute neutrino mass

(4–6: not relevant to neutrino oscillation experiment(?))

We need higher precision neutrino experiments around 1-10 GeV.

Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

High energy beam (~few GeV)
- longer baseline (higher flux reduction)
- higher neutrino production
- higher interaction
- calorimetric energy reconstruction

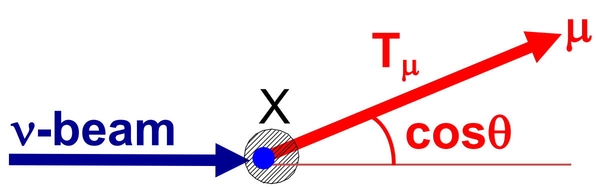
KING'S College LONDON

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

1. Next goal of high energy physics

Kinematics energy reconstruction

- problem: it assume 2-body neutrino interaction with single nucleon



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

Calorimetric energy reconstruction

- problem: you have to measure energy deposit from all outgoing particles

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

Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

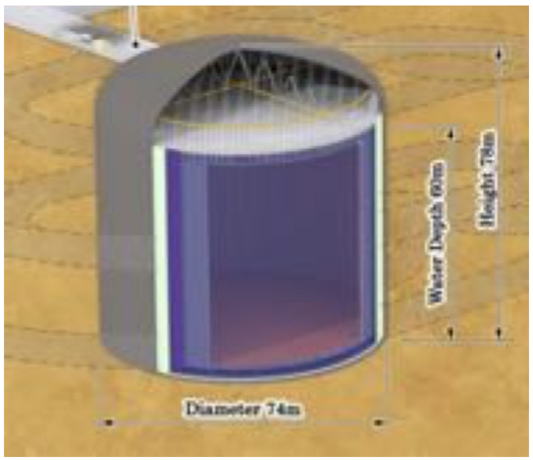
High energy beam (~few GeV)
- longer baseline (higher flux reduction)
- higher neutrino production
- higher interaction
- calorimetric energy reconstruction

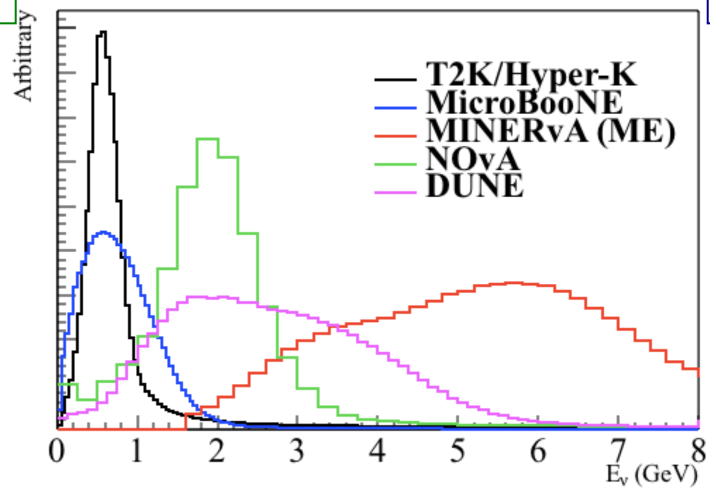
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

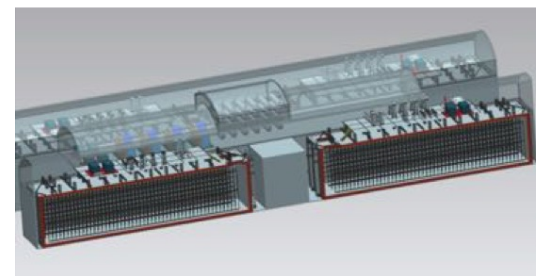
1. Next goal of high energy physics

Hyper-Kamiokande (Japan)
- Water target
- Narrow band 0.6 GeV
- Low spatial resolution
- High time resolution

DUNE (USA)
- Argon target
- wide band 1-4 GeV
- High spatial resolution
- Low time resolution







Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

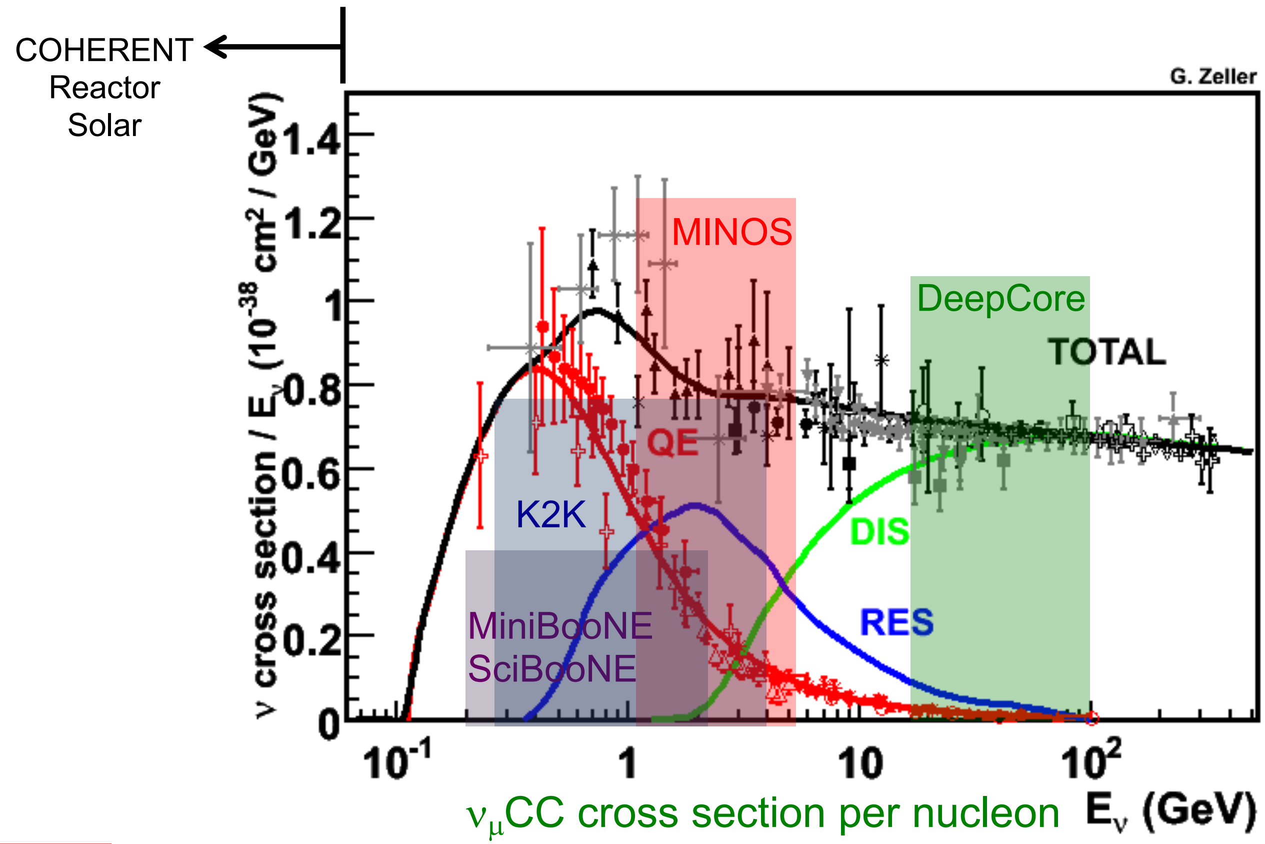
High energy beam (~few GeV)
- longer baseline (higher flux reduction)
- higher neutrino production
- higher interaction
- calorimetric energy reconstruction

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



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

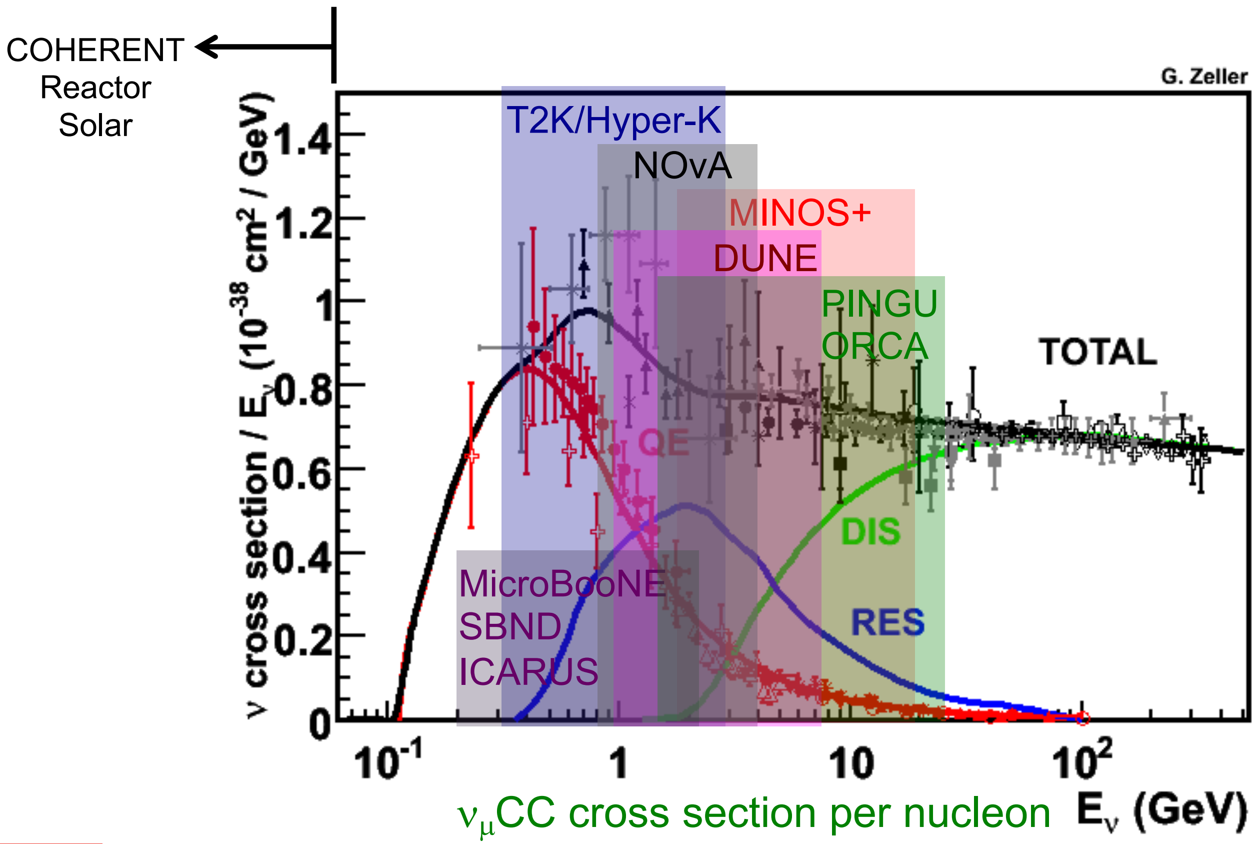
KING'S College LONDON

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

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



ν_μCC cross section per nucleon

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

1. Neutrino cross-section formula

Cross-section

- product of Leptonic and Hadronic tensor

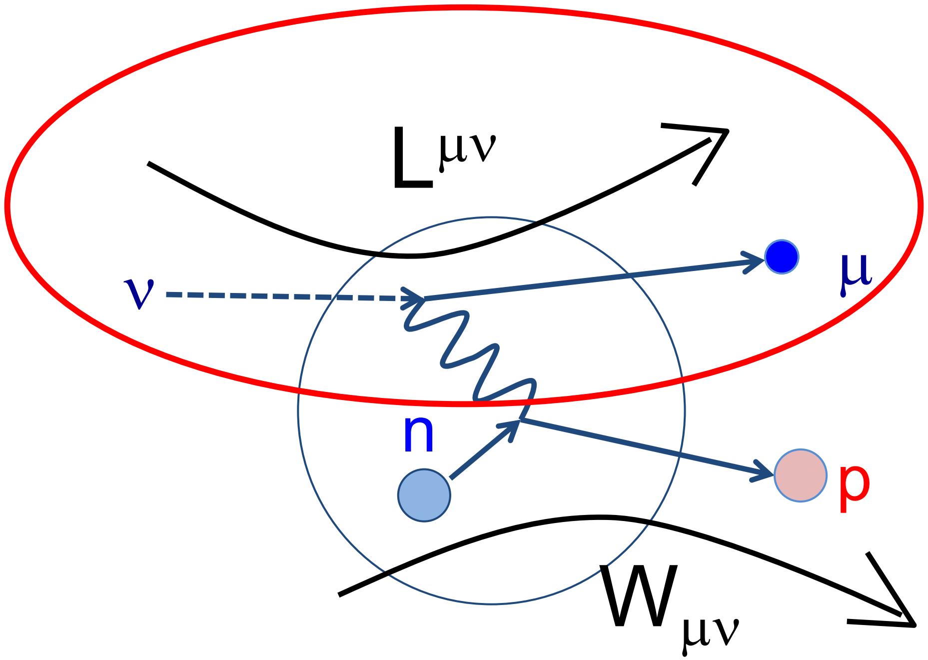
$$d\sigma \sim L^{\mu\nu} W_{\mu\nu}$$

Leptonic tensor

→ the Standard Model (easy)

Hadronic tensor

→ nuclear physics (hard)



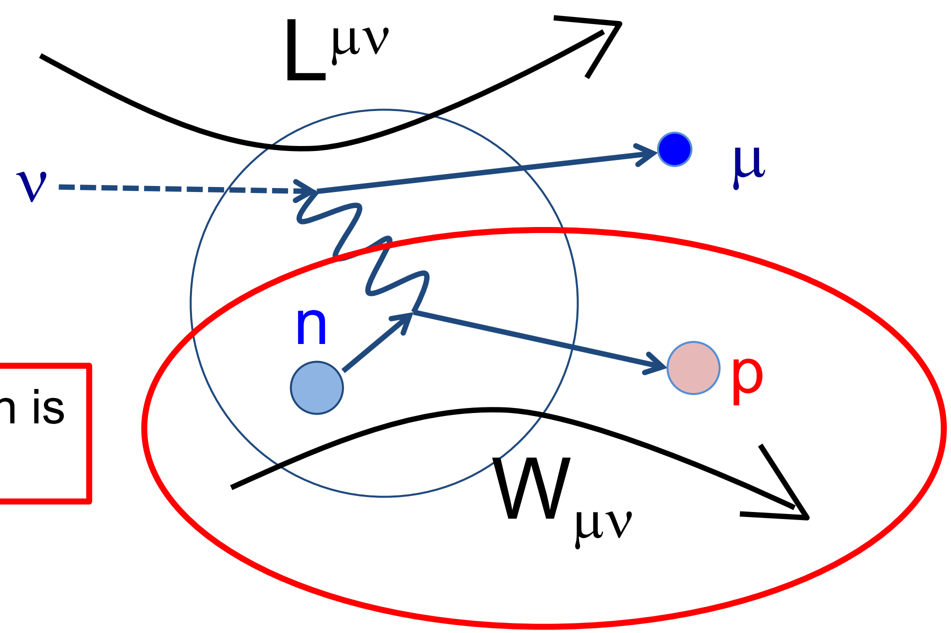
1. Neutrino cross-section formula

Cross-section
 - product of Leptonic and Hadronic tensor

$$d\sigma \sim L^{\mu\nu}W_{\mu\nu}$$

Leptonic tensor
 → the Standard Model (easy)

Hadronic tensor
 → nuclear physics (hard)



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

TK, Martini, JPhysG45(2017)1
NuSTEC white paper, Prog.Part.Nucl.Phys.100(2018)1

1. Neutrino interaction physics - introduction

2. Charged-Current Quasi-Elastic (CCQE) interaction

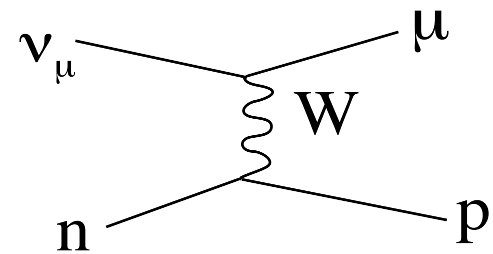
3. Nucleon correlation physics in BSM physics

4. Neutrino interaction physics - future prospect

5. Conclusions

2. Charged Current Quasi-Elastic scattering (CCQE)

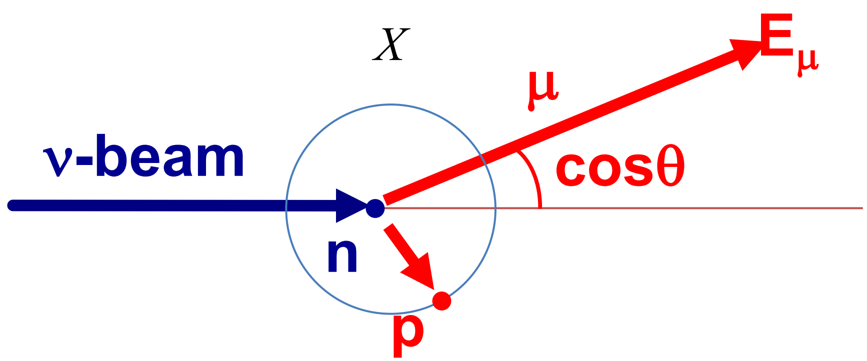
The simplest and the most abundant interaction around ~1 GeV.



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

Neutrino energy is reconstructed from the observed lepton kinematics
"QE assumption"

1. assuming neutron at rest
2. assuming interaction is CCQE



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

CCQE is the single most important channel of neutrino oscillation physics
T2K, NOvA, microBoonE, Hyper-Kamiokande…etc

KING'S College LONDON

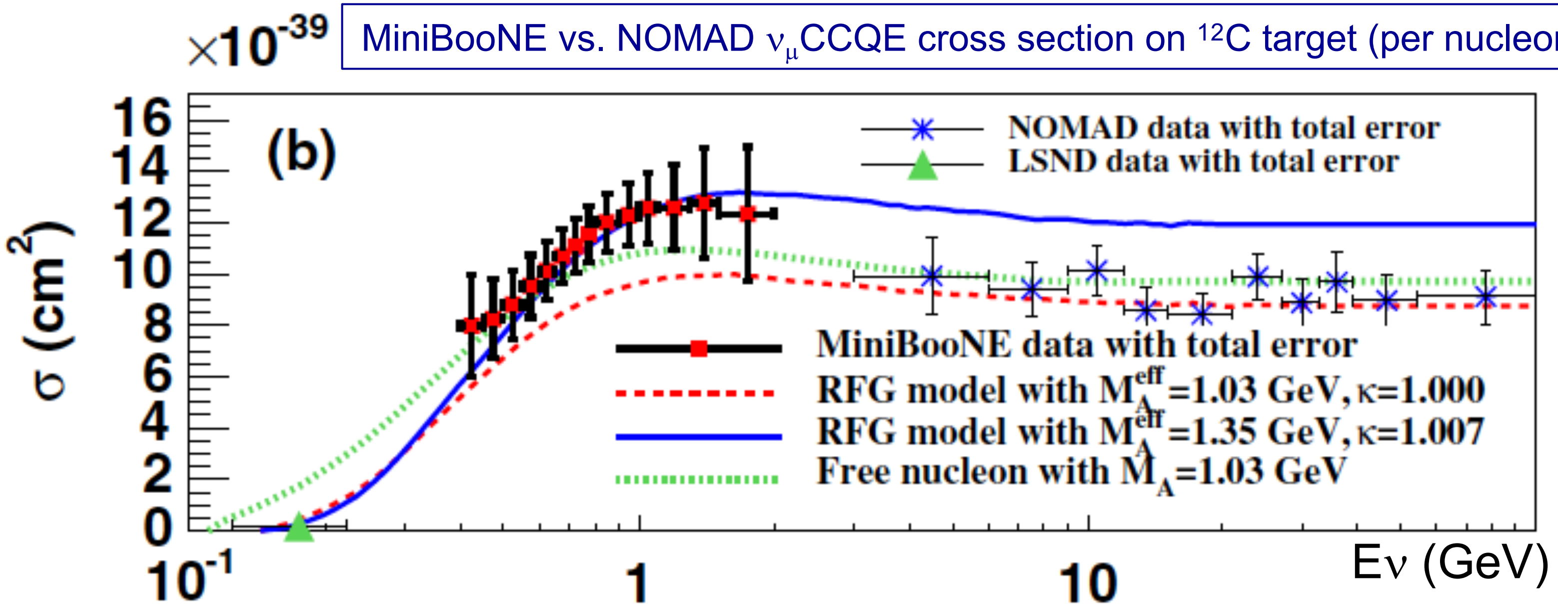
2. Charged Current Quasi-Elastic scattering (CCQE)

CCQE puzzle

1. low Q2 suppression → Low forward efficiency? (detector?)
2. high Q2 enhancement → Axial mass > 1.0 GeV? (physics?)
3. large normalization → Beam simulation is wrong? (flux?)

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

MiniBooNE vs. NOMAD ν_μCCQE cross section on ^{12}C target (per nucleon)



2. The solution of CCQE puzzle

Presence of 2-body current

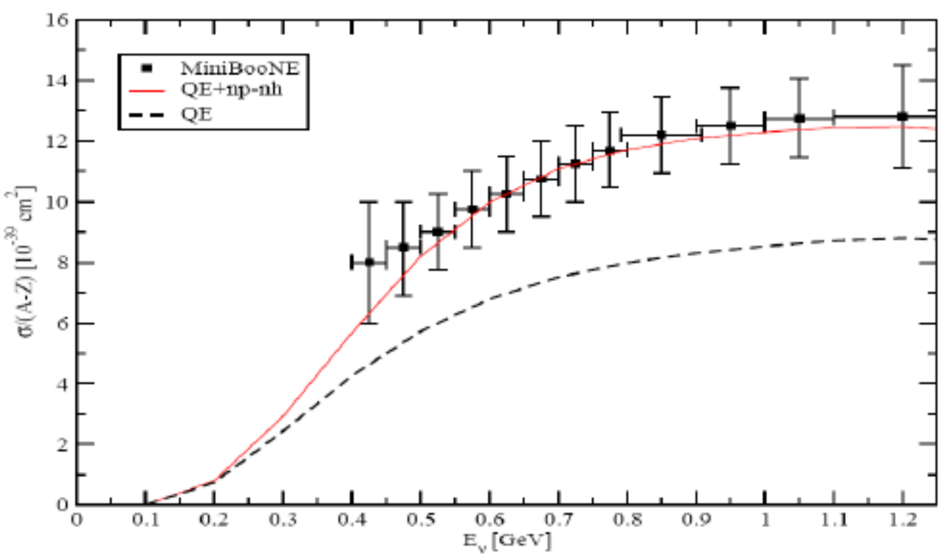
- Martini et al showed 2p-2h effect can add up 30-40% more cross section!

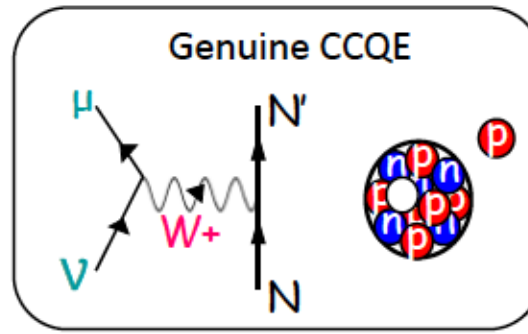
What experimentalists call "CCQE" is not genuine CCQE!

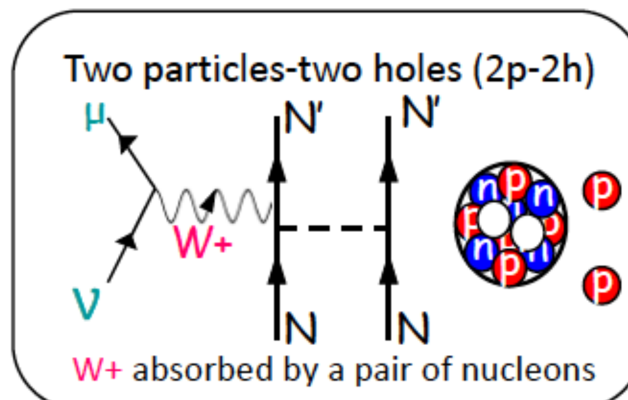
Marco Martini (Saclay)

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







Martini et al,PRC80(2009)065501
Nieves et al,PLB707(2012)72; NPA627(1997)543

2. The solution of CCQE puzzle

Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al

What experimentalists call "CCQE" is not genuine CCQE!

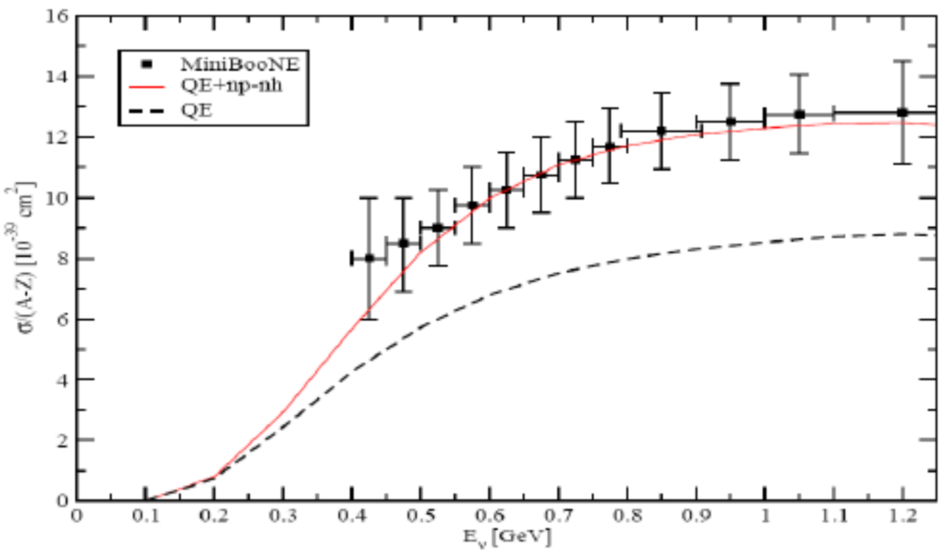
Marco Martini (Saclay)

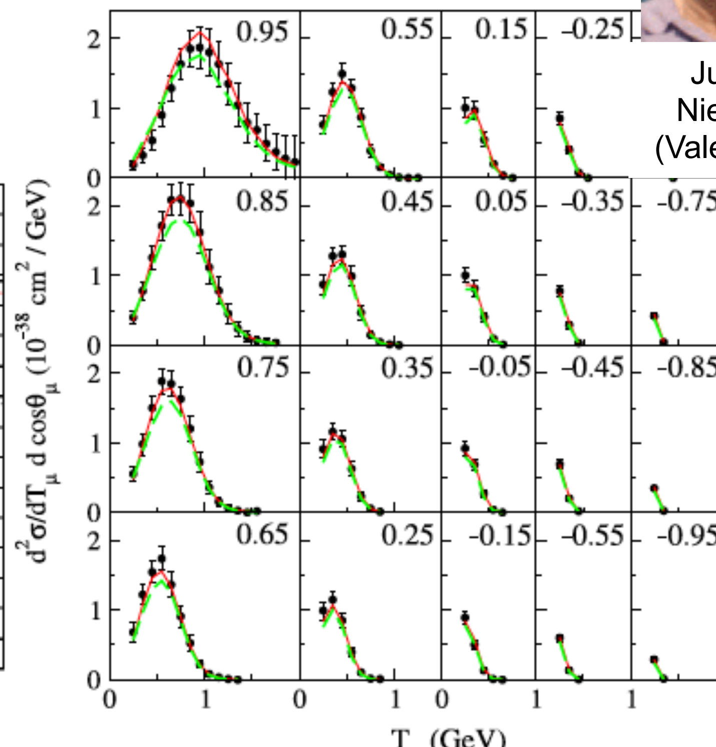
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

The model is tuned with electron scattering data (no free parameter)

Juan Nieves (Valencia)





Valencia model vs. MiniBooNE CCQE double differential cross-section data

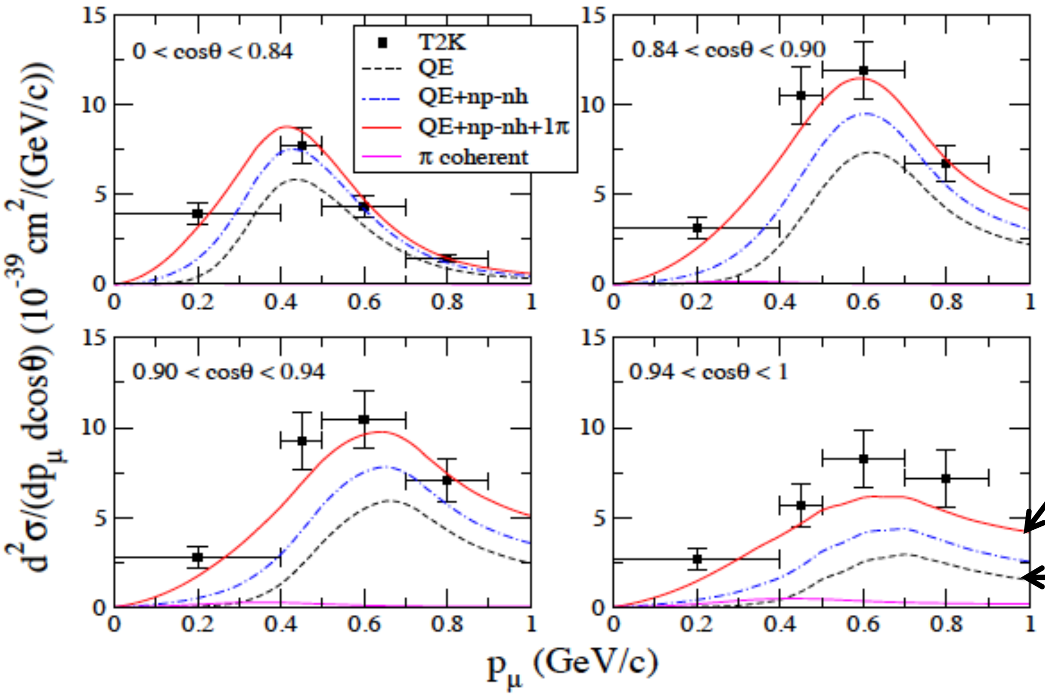
Martini et al,PRC80(2009)065501, PRC90(2014)025501
Nieves et al,PLB707(2012)72; NPA627(1997)543

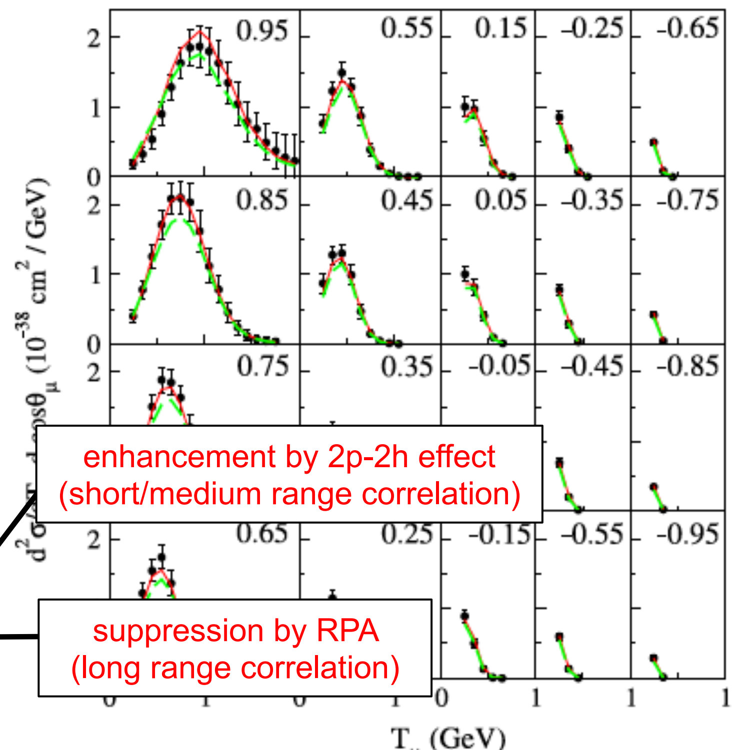
2. The solution of CCQE puzzle

Presence of 2-body current

- Martini et al showed 2p-2h effect can add up 30-40% more cross section!
- consistent result is obtained by Nieves et al
- The model can explain T2K data simultaneously

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





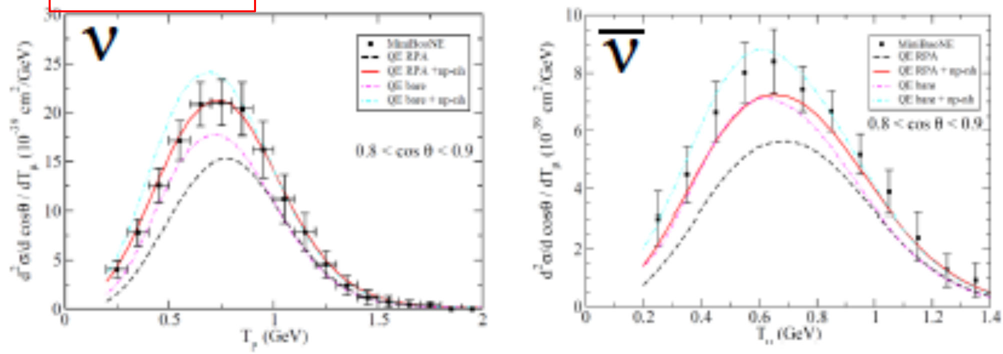
Valencia model vs. MiniBooNE CCQE double differential cross-section data

2. CCQE-like data, MiniBooNE (2019)

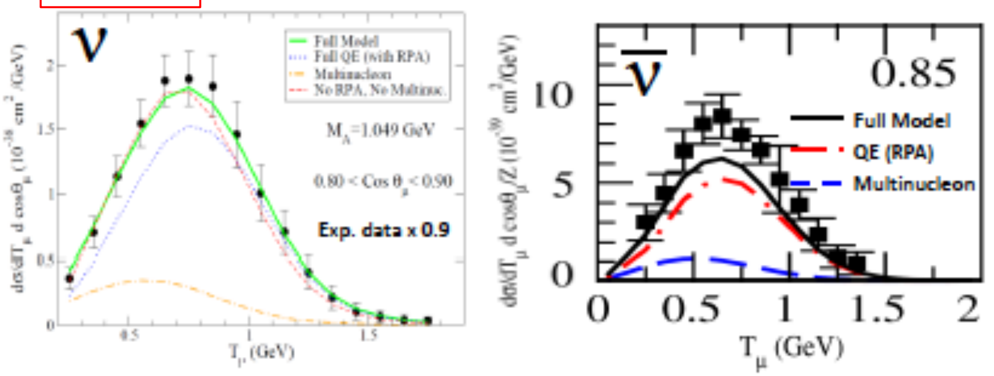
All groups agree qualitatively with MiniBooNE CCQE-like double differential data.

Martini – RPA+2p2h
Nieves – Valencia 2p2h model
SuSA – Superscaling+MEC
Giusti – Relativistic Green's function
Butkevich – RDWIA+MEC

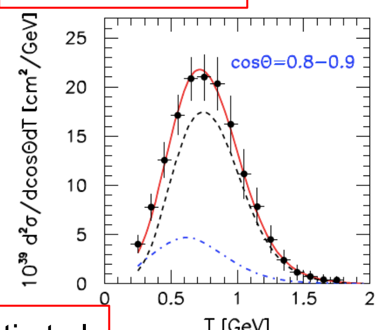
Martini et al



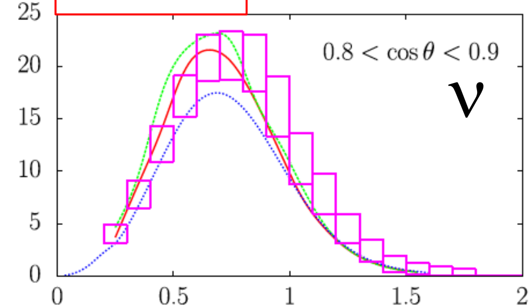
Valencia



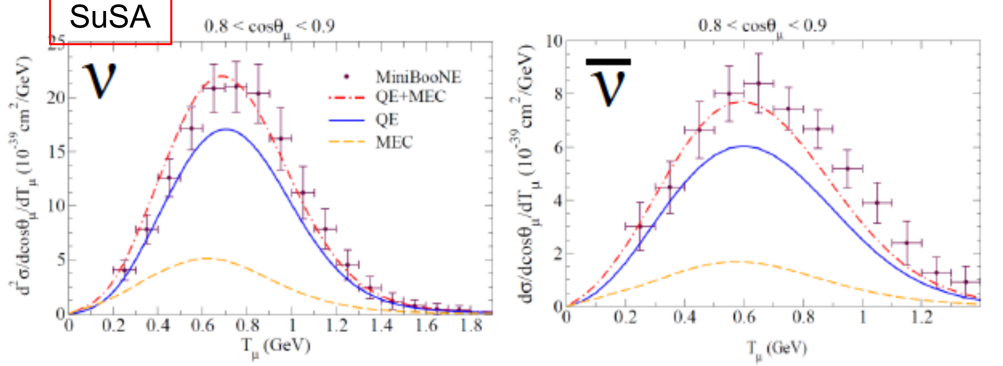
Butkevich et al



Giusti et al



SuSA



Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRL112(2014)182502, PRC91(2015)062501

2. The solution of CCQE puzzle

Ab initio calculation reproduce same feature

Alessandro Lovato
(Argonne/)

Ab-initio calculation

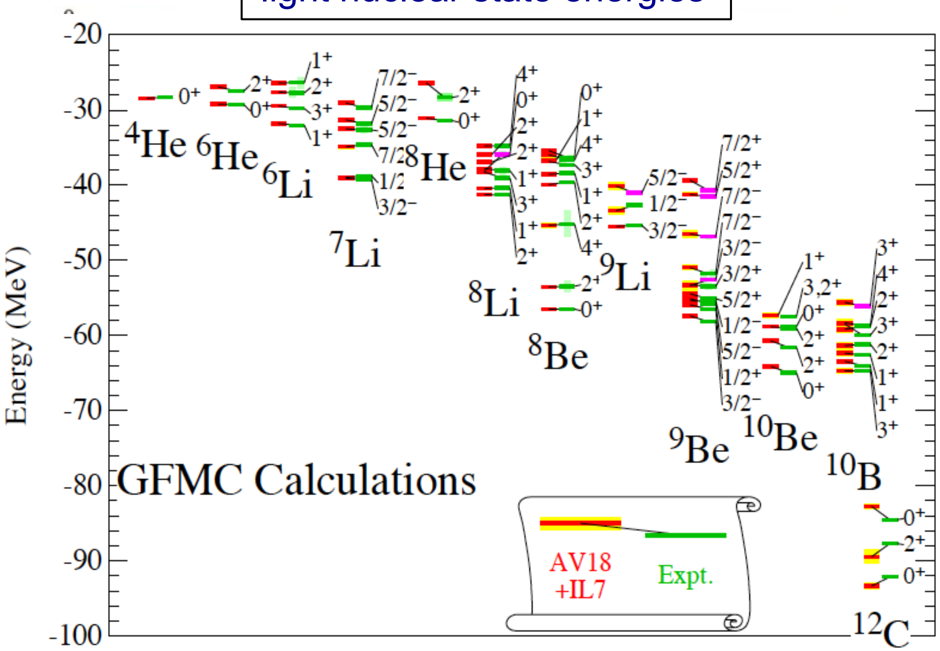
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Ground state includes correct nucleon correlations

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

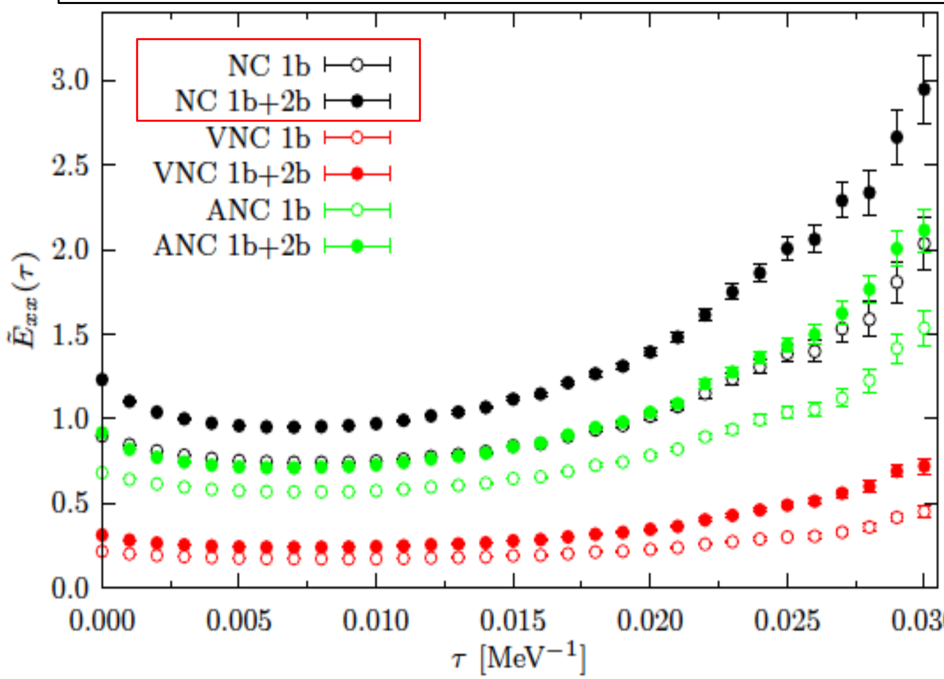
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



Neutrino NCQE scattering in ^{12}C response function



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

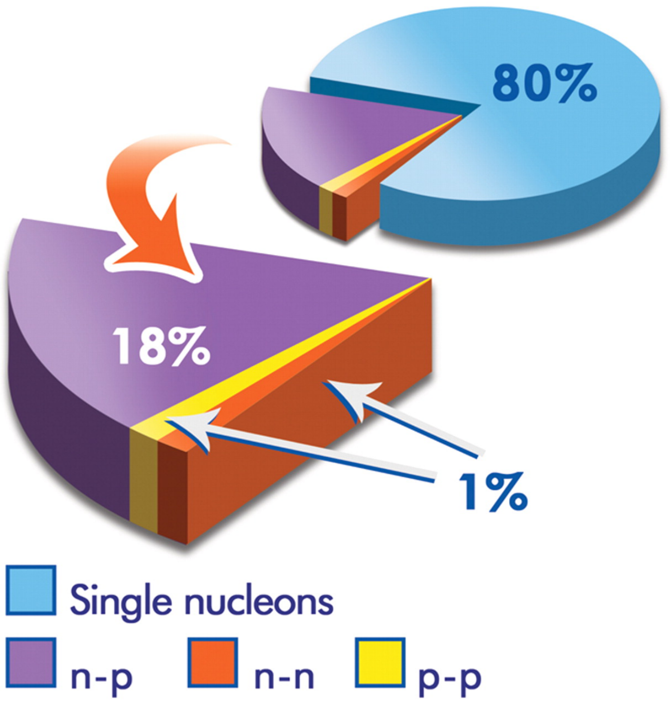
2. The solution of CCQE puzzle

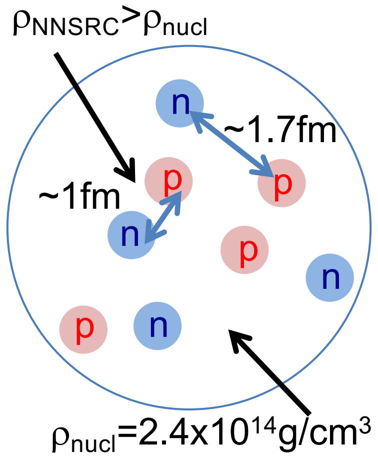
Ab-initio calculation
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Ground state includes correct nucleon correlations

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

2N potential (Av18)

3N potential (IL7)





Physics of nucleon correlation
- neutrino interaction
- EMC effect
- 0νββ
- Direct WIMP detection
- EMC effect
- etc

Nucleon correlation is a very hot topics!

TK, Martini, JPhysG45(2017)1
NuSTEC white paper, Prog.Part.Nucl.Phys.100(2018)1

1. Neutrino interaction physics - introduction

2. Charged-Current Quasi-Elastic (CCQE) interaction

3. Nucleon correlation physics in BSM physics

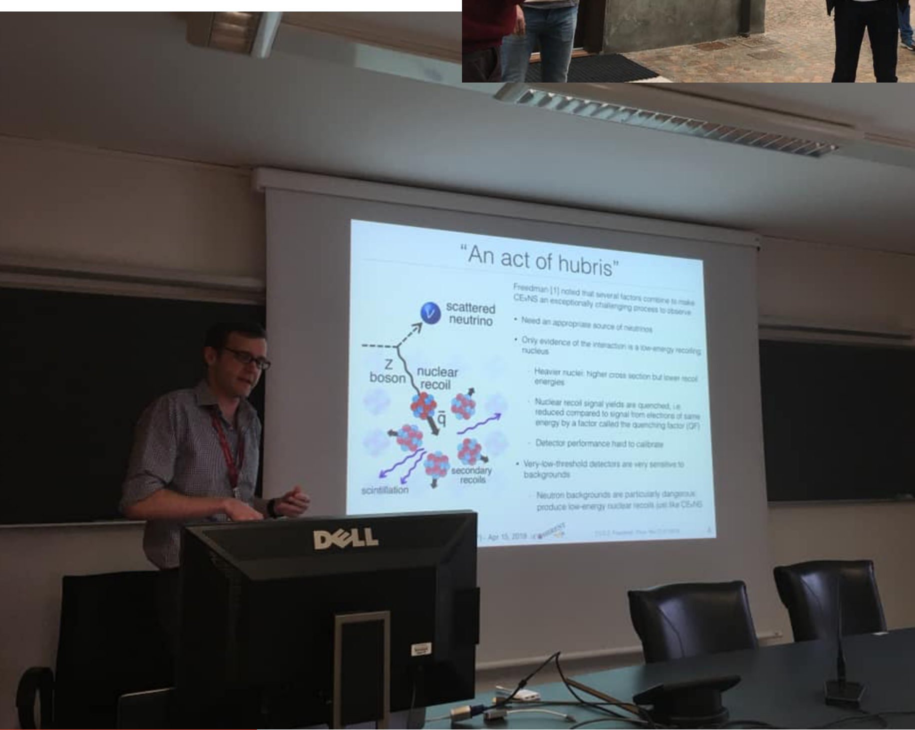
4. Neutrino interaction physics - future prospect

5. Conclusions

3. Atomic nuclei as laboratories for BSM physics

ECT* workshop, 15 Apr. 15-19 2019, Trento, Italy
http://www.ectstar.eu/node/4436

Topics include;
- Neutrino physics
- EDM
- $0\nu\beta\beta$
- dark matter
- etc



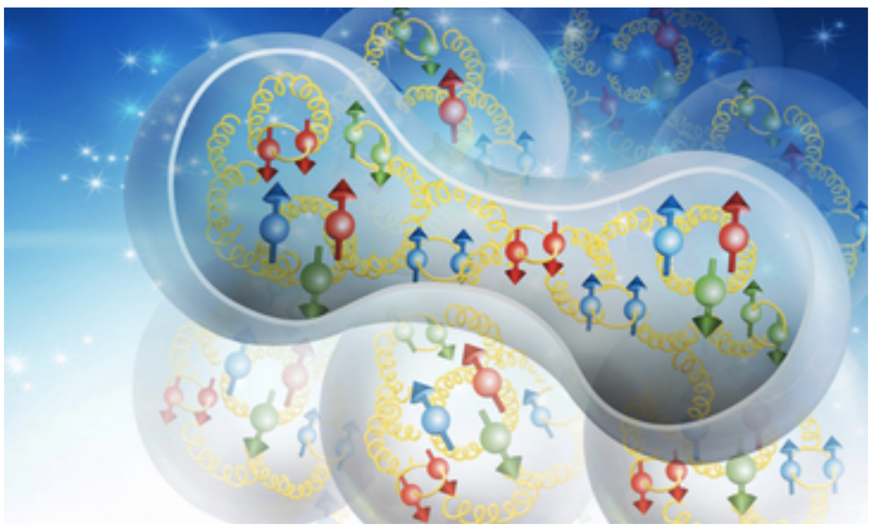
3. EMC effect

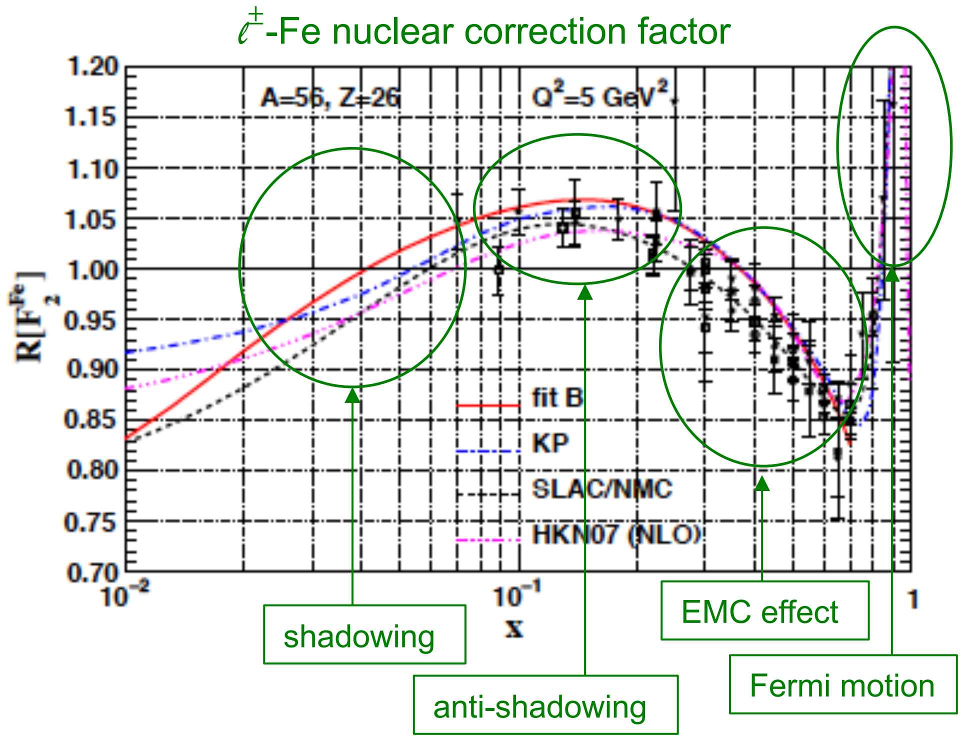
Nuclear dependent DIS
- First observed by the EMC experiment
- Structure function depends on nuclei

→ Quarks feel presence of other quarks in other nucleons

Fe-D ratio of F_2 structure function
- PDF is suppressed at x~0.6 (EMC effect)
- PDF is enhanced at x~0.1 (anti-shadowing)
- PDF is suppressed at x<0.1 (shadowing)

Nuclear physics makes very rich structure in particle physics!



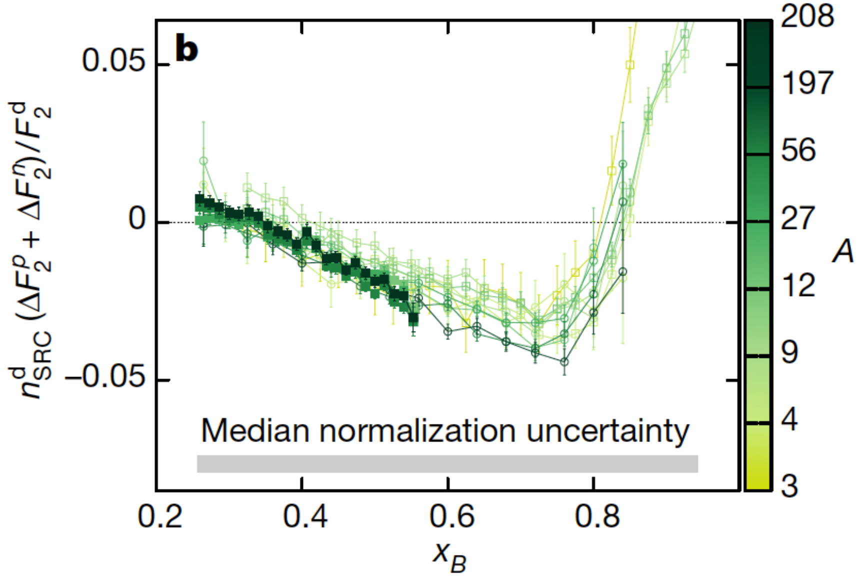


3. EMC effect

Nuclear dependent DIS
- First observed by the EMC experiment
- Structure function depends on nuclei

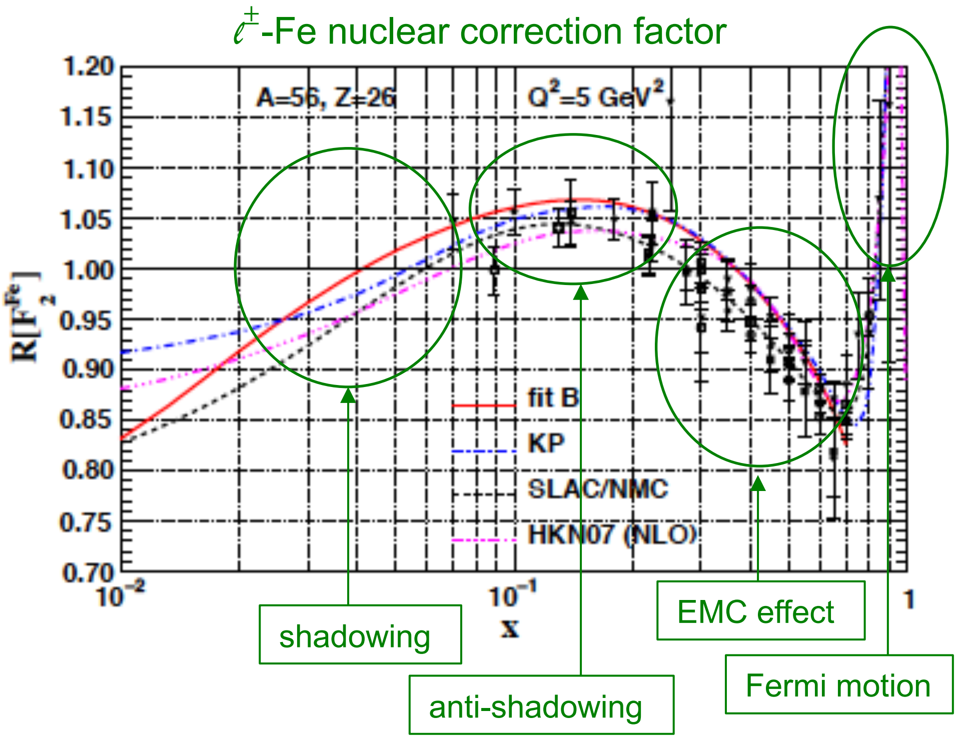
→ Quarks feel presence of other quarks in other nucleons

EMC effect can be modeled from the amount of correlated pairs in nuclei (CLAS in JLab).



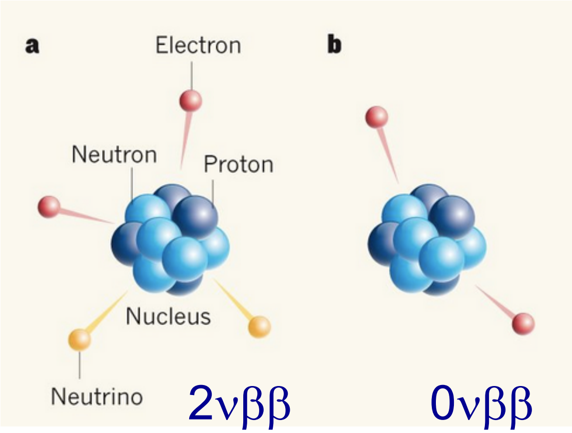
Fe-D ratio of F_2 structure function
- PDF is suppressed at x~0.6 (EMC effect)
- PDF is enhanced at x~0.1 (anti-shadowing)
- PDF is suppressed at x<0.1 (shadowing)

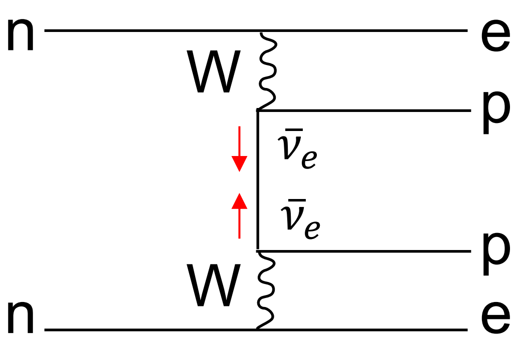
Nuclear physics makes very rich structure in particle physics!



3. Neutrino-less double beta decay ($0\nu\beta\beta$)

Majorana particle
- double beta decay ($2\nu\beta\beta$) is the second order nuclear process, possible only for few elements (^{82}Se, ^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe, etc)
- $0\nu\beta\beta$ is the lepton number violation process (BSM process)
- Expected half-life, $\tau(0\nu\beta\beta) > 10^{27}$ yrs ($>>10^{10}$ yrs ~ life of universe)

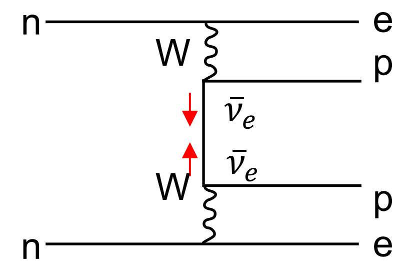




$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\,2}$$

Measured half-life of $0\nu\beta\beta$ process is related to effective Majorana mass ($m_{\beta\beta}^2$)
- Phase space
- Nuclear matrix element
- effective g_A

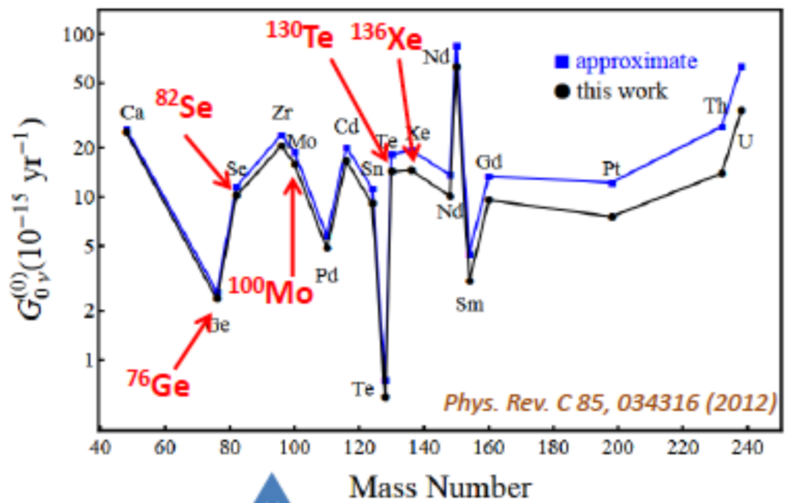
3. Neutrino-less double beta decay ($0\nu\beta\beta$)



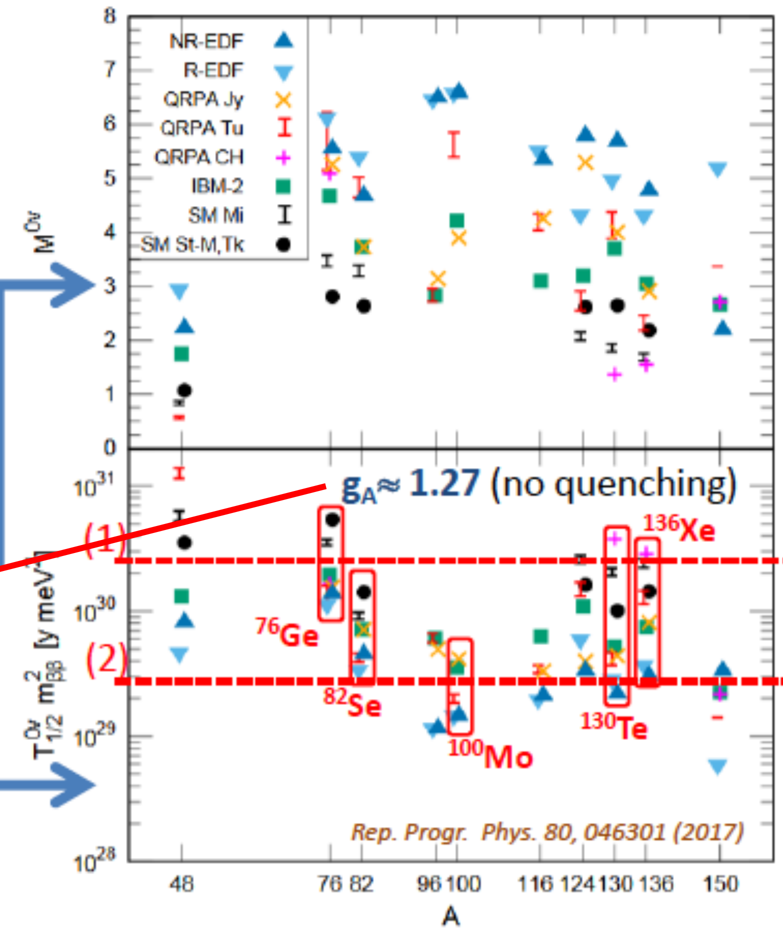
Majorana particle

- Measured half-life of $0\nu\beta\beta$ process is related to effective Majorana mass ($m_{\beta\beta}^2$)

Phase space: exactly calculable



Nuclear matrix elements: several models



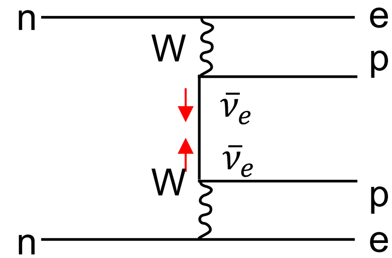
$$1/\tau = G(Q,Z)\, g_A^{\ 4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\ 2}$$

Nuclear physics gives large systematics
- Nuclear matric element calculation
- Nuclear quenching of g_A

KING'S College LONDON

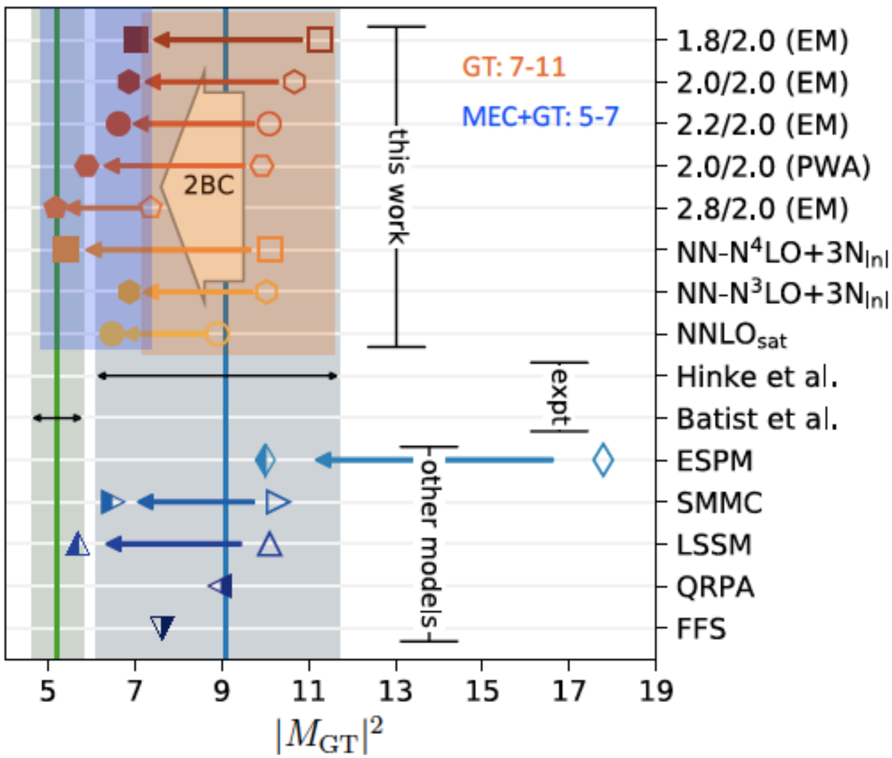
P. Gysbers, G. Hagen, et al, Nature Phys. 15(2019)428

3. Neutrino-less double beta decay (0νββ)



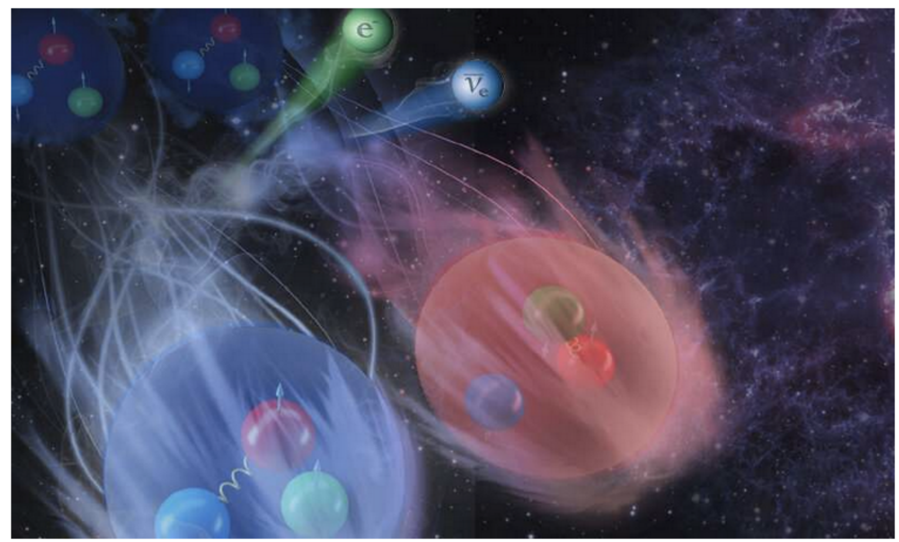
Beta decay quenching

- Axial coupling looks smaller in nuclei
- Ab initio calculation shows matrix element is suppressed due to nucleon 2-body current (2BC)
- Another uncertainty of 0νββ



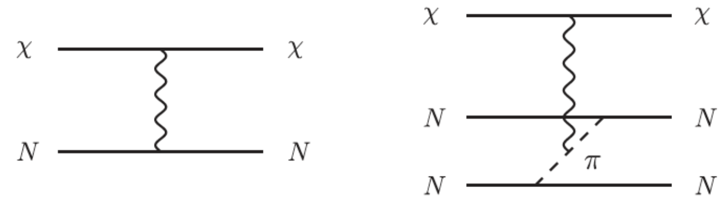
Physicists solve a beta-decay puzzle with advanced nuclear models

by Oak Ridge National Laboratory



Xenon 1T collaboration, PRL122(2019)071301
Hoferichter, et al, PLB746,410(2015)410, PRD94(2016)063505

3. Direct WIMP-pion scattering

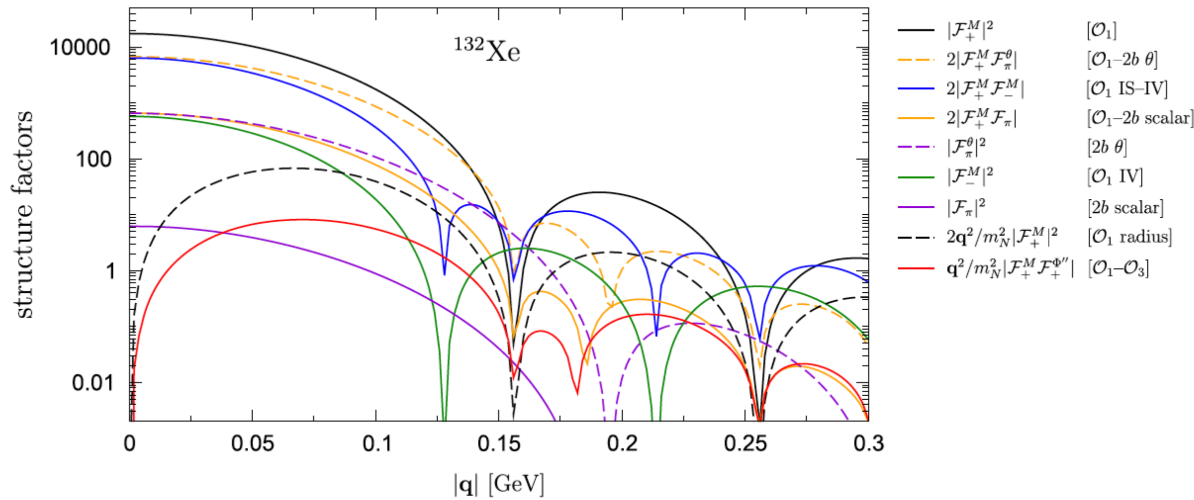


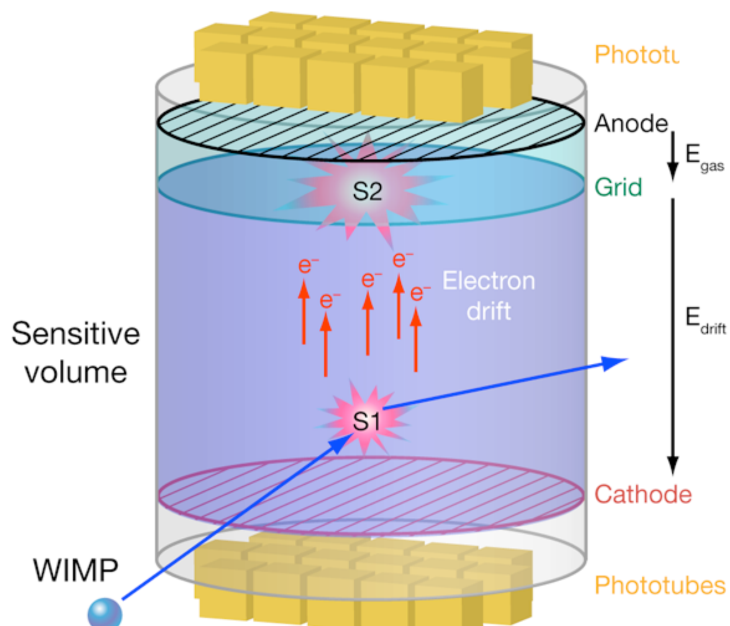
(a) (b)

Nuclear structure function

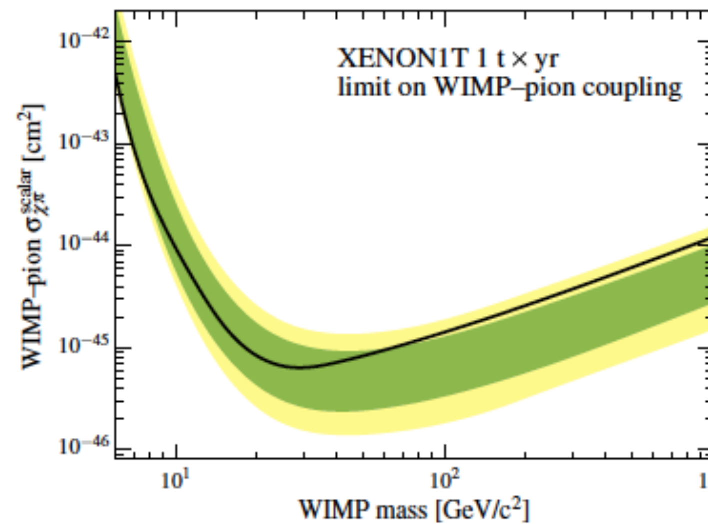
- WIMP interaction depends on nuclear structure function
- Chiral effective field theory including 2-body current
- Assuming leading contributions are zero, WIMP-pion scattering can be studied.

$$\frac{d\sigma^{SI}_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{1}{4\pi\mathbf{v}^2}\bigg|\left(c_+^M - \frac{\mathbf{q}^2}{m_N^2}\dot{c}_+^M\right)\mathcal{F}_+^M(\mathbf{q}^2) + c_\pi \mathcal{F}_\pi(\mathbf{q}^2) + c_\pi^\theta \mathcal{F}_\pi^\theta(\mathbf{q}^2) + \left(c_-^M - \frac{\mathbf{q}^2}{m_N^2}\dot{c}_-^M\right)\mathcal{F}_-^M(\mathbf{q}^2) + \frac{\mathbf{q}^2}{2m_N^2}\left[c_+^{\Phi''}\mathcal{F}_+^{\Phi''}(\mathbf{q}^2) + c_-^{\Phi''}\mathcal{F}_-^{\Phi''}(\mathbf{q}^2)\right]\bigg|^2,$$





katori@fnal.gov



Giunti et al, PRC83(2011)065504
Kostensalo et al, PLB795(2019)542

3. Gallium anomaly

Short-baseline neutrino anomaly

- 4 anomalies (Gallium anomaly Reactor anomaly, LSND excess, MiniBooNE excess) suggest presence of 1eV sterile neutrinos.

pp-neutrino experiment calibration

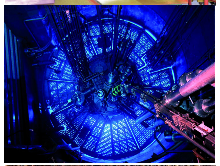
- SAGE and Gallex calibrated their gallium detectors by ^{37}Ar and ^{51}Cr neutrino sources.
- Both calibrations (1-3m source-detector distance) detected less neutrinos than predicted

New Neutrino - Gallium cross section

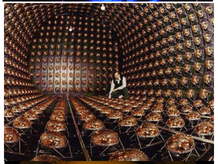
- Nuclear shell-model wave functions obtained with recently developed 2-nucleon interactions.

Gallium Anomaly, PLB795(2019)542 ($3.0\sigma \rightarrow 2.3\sigma$)

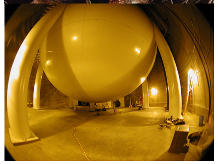
Direct tests of anomalies (no assumption of 1eV sterile)



Reactor Anomaly, PRC83(2011)054615 (2.8σ) → many experiments



LSND excess, PRD64(2001)112007 (3.8σ) → JSPS^2 experiment

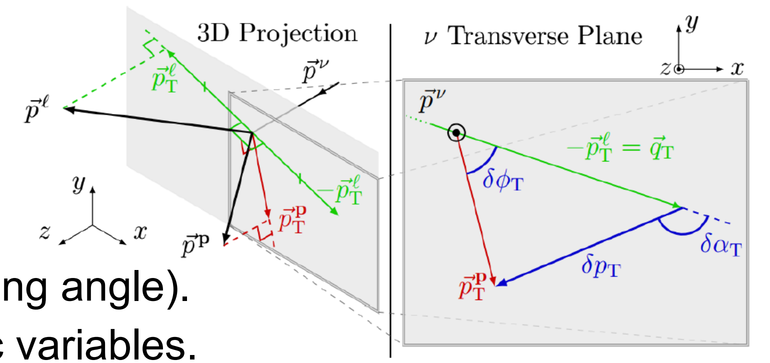


MiniBooNE excess, PRL121(2018)221801 (4.7σ) → MicroBooNE experiment

T2K, PRD98(2018)032003
MINERvA,PRD121(2018)022504

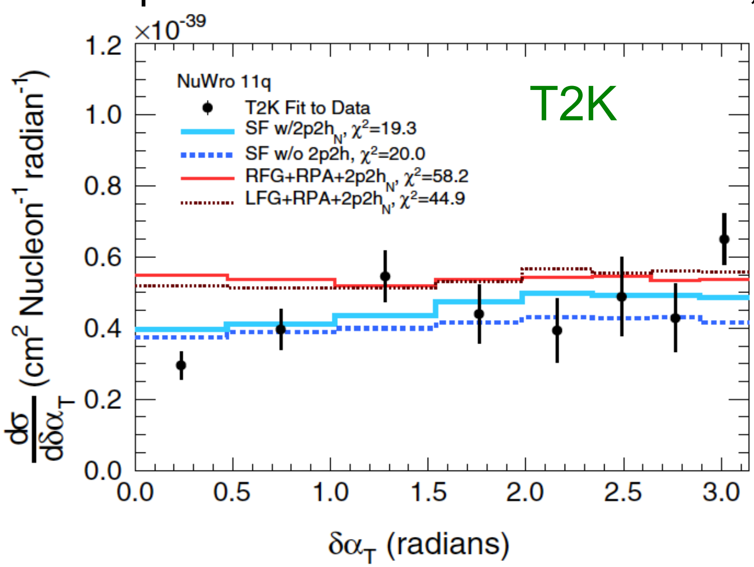
3. Neutrino hadron measurement for nuclear correlations

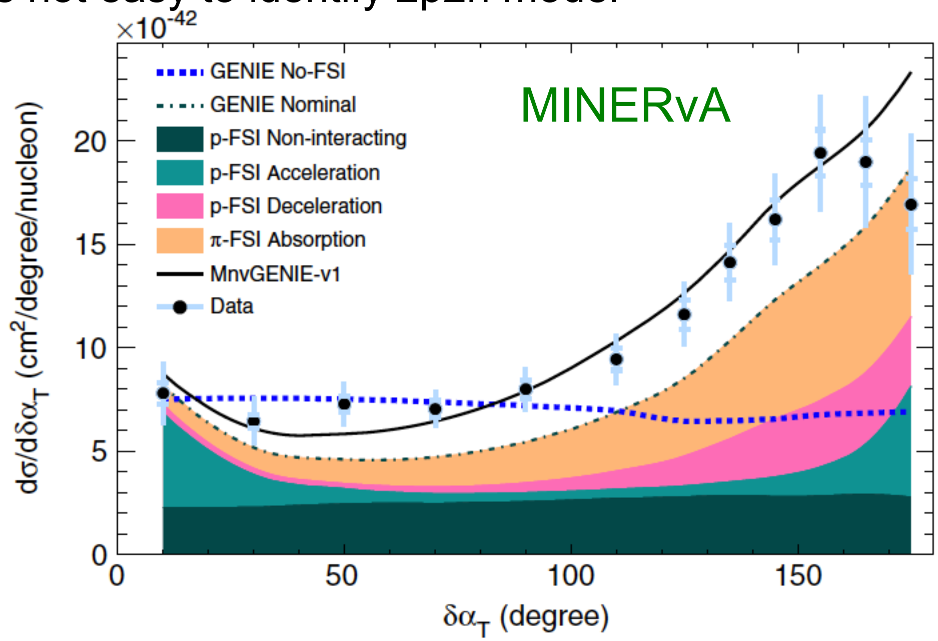
We want to constrain nuclear model from neutrino data
- Final state hadron measurement is the key



1 muon + 1 proton sample
- 5 dof (mu E and cosθ, proton E and cosθ, mu-p opening angle).
- Low statistics, and these are converted to 3 kinematic variables.

Data prefer advanced nuclear models, but it's not easy to identify 2p2h model

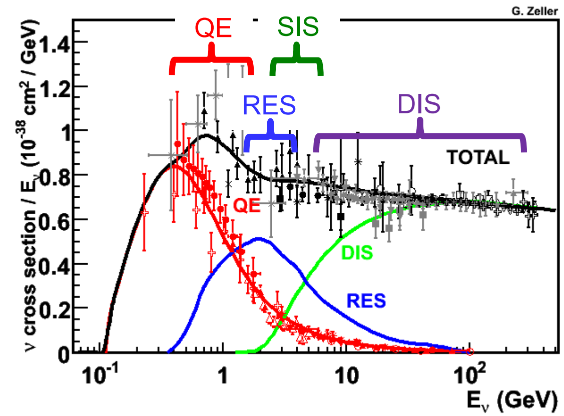


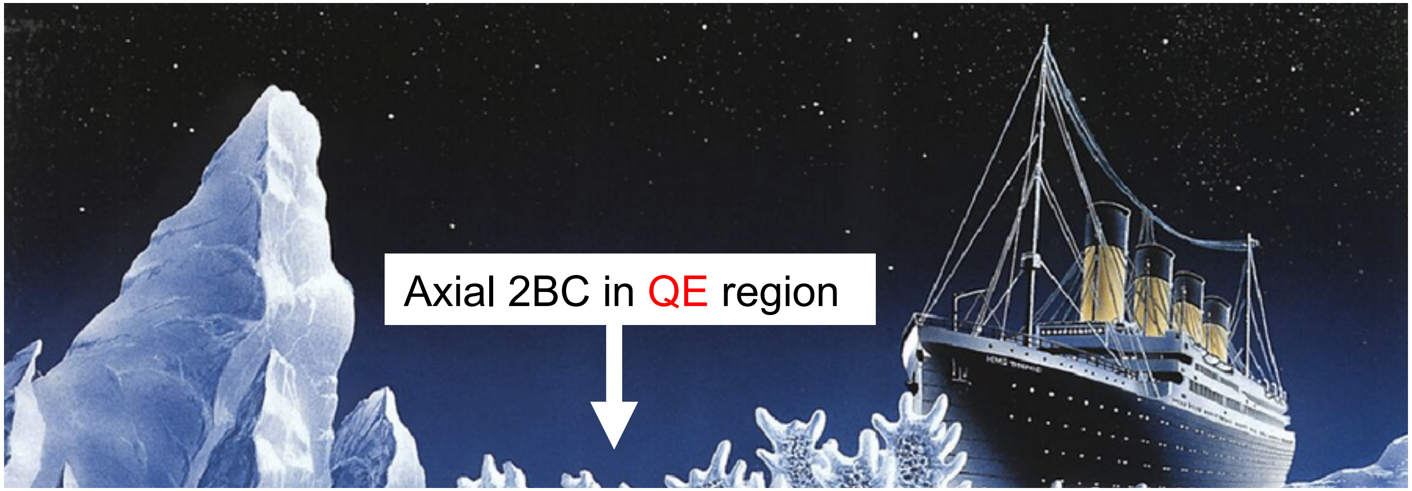


Importance of axial 2BC is understood qualitatively, we need more quantitative understanding!
(how much 2-body current? Any characteristic shapes in kinematic variables?)

3. Beyond QE peak

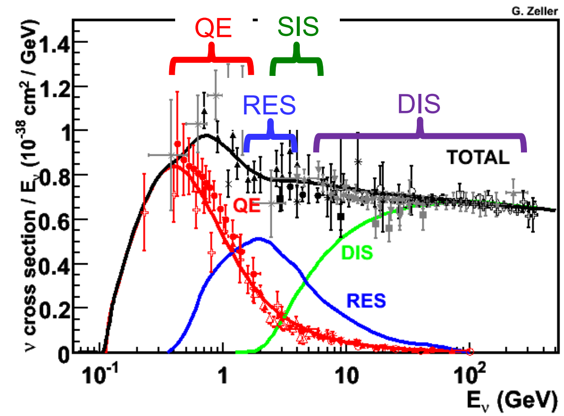
Axial 2-body current in QE region may be a tip of the iceberg…

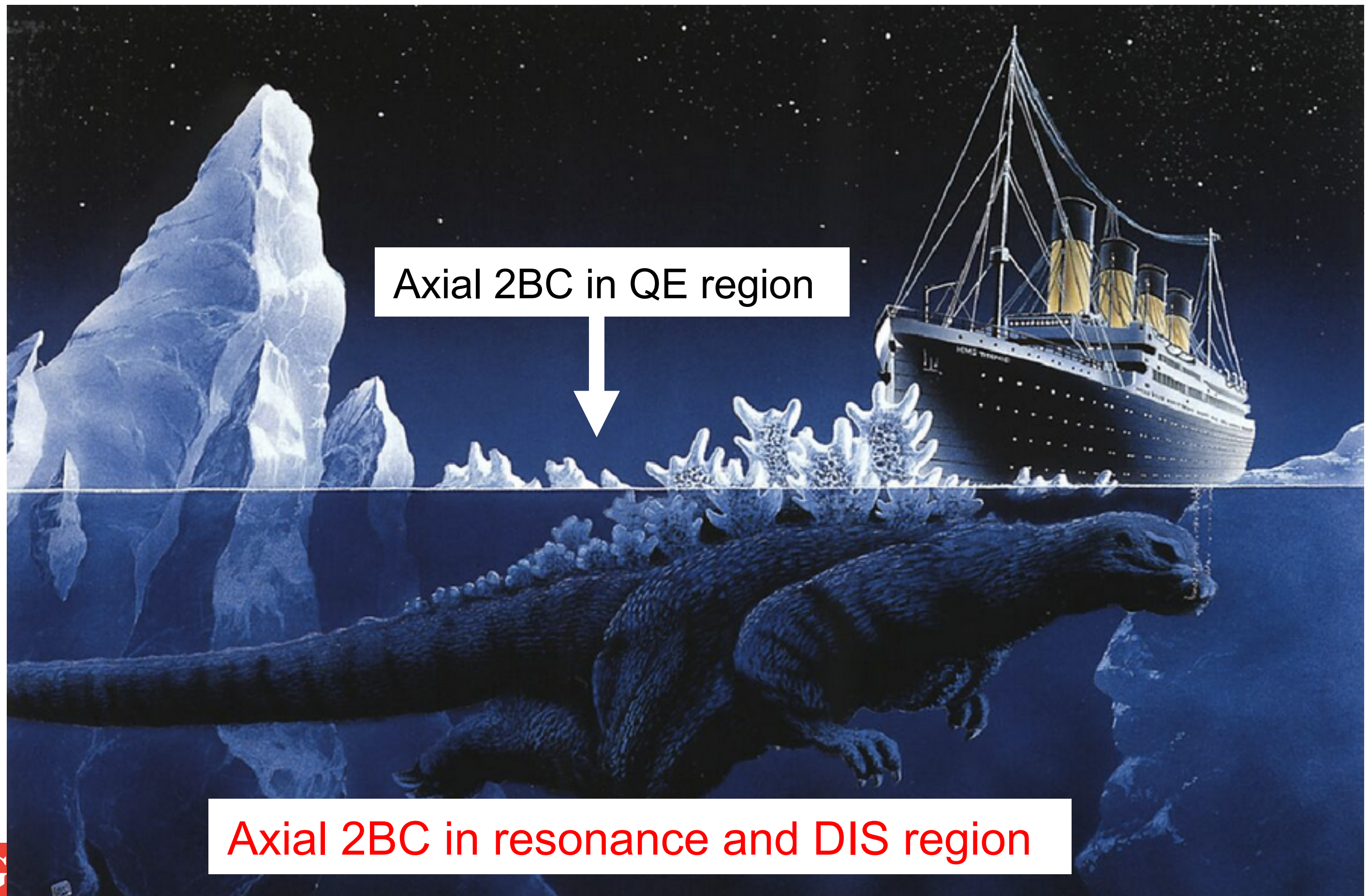




3. Beyond QE peak

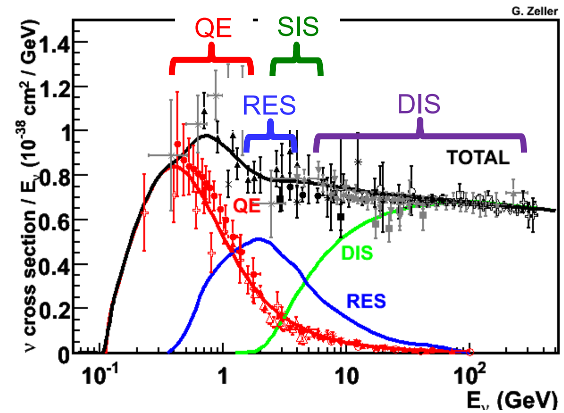
Axial 2-body current in QE region may be a tip of the iceberg…, or maybe tip of gozilla!





MINERvA,PRD100(2019)072005

3. Pion puzzle (2019)



MINERvA try to fit 4 different data set to tune MC…, and it is very hard

Strong tensions between data set
- Both cross section models and FSI models are important
- MC doesn't have enough freedom to fit all (or models may be wrong)

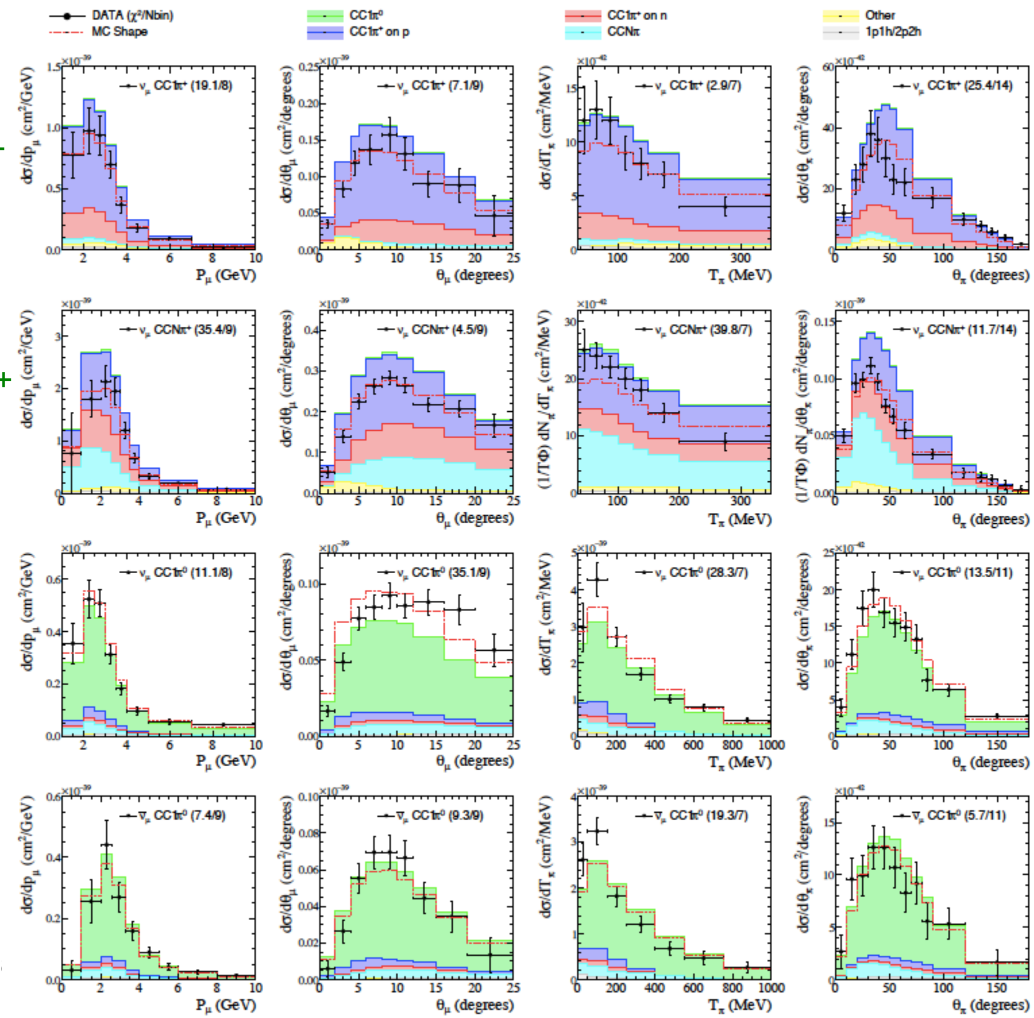
Few GeV neutrino experiments don't have good hadron final state predictions (cf. CCQE).

$\nu_\mu CC1\pi^+$

$\nu_\mu CCN\pi^+$

$\nu CC1\pi^o$

$\bar{\nu} CC1\pi^o$



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

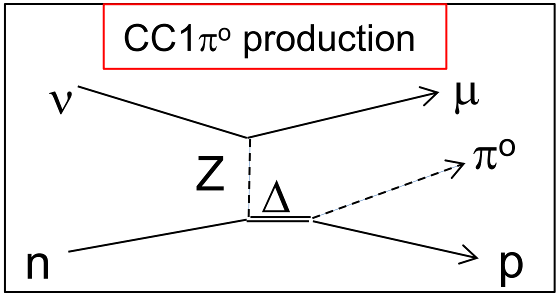
3. Pion puzzle (2019)

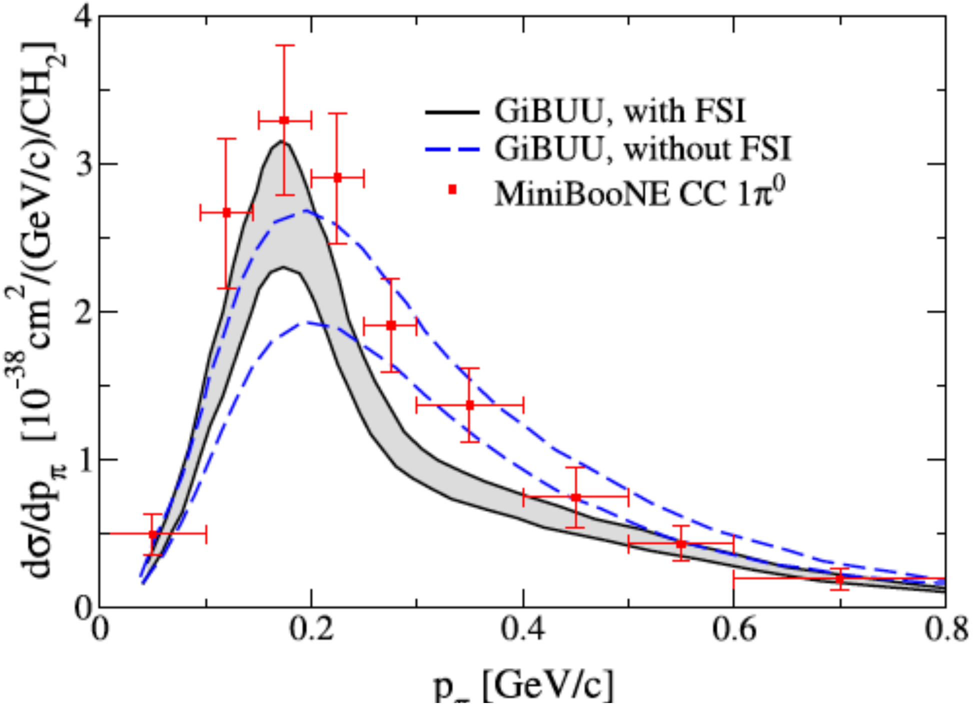
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

Ulrich Mosel (Giessen)

Final state interaction

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





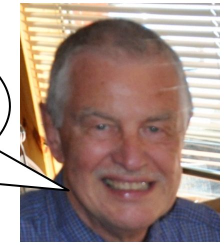
ex) Giessen BUU transport model

- 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

3. Pion puzzle (2019)

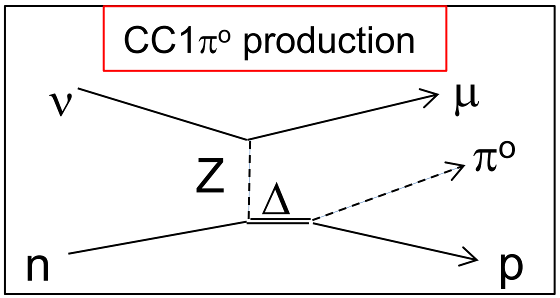
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

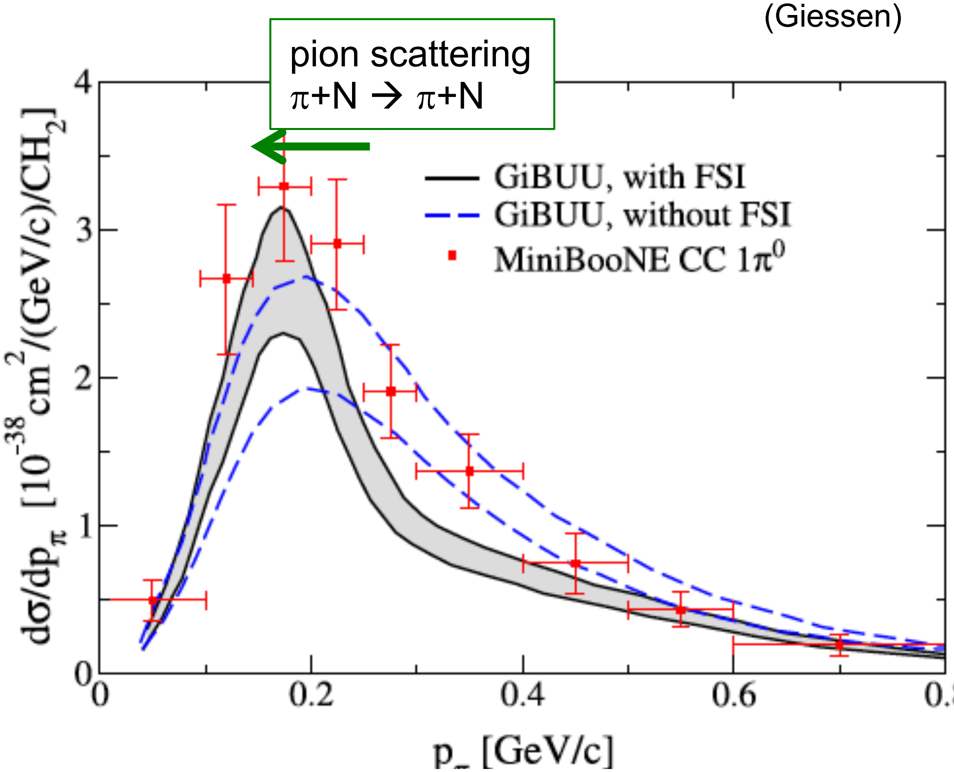


Ulrich Mosel (Giessen)

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

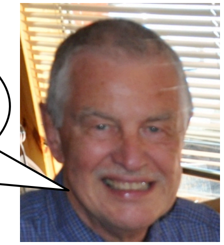
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

3. Pion puzzle (2019)

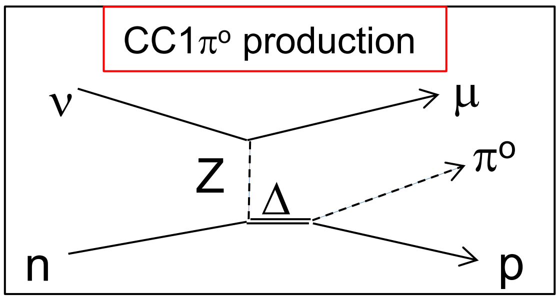
Final state interaction

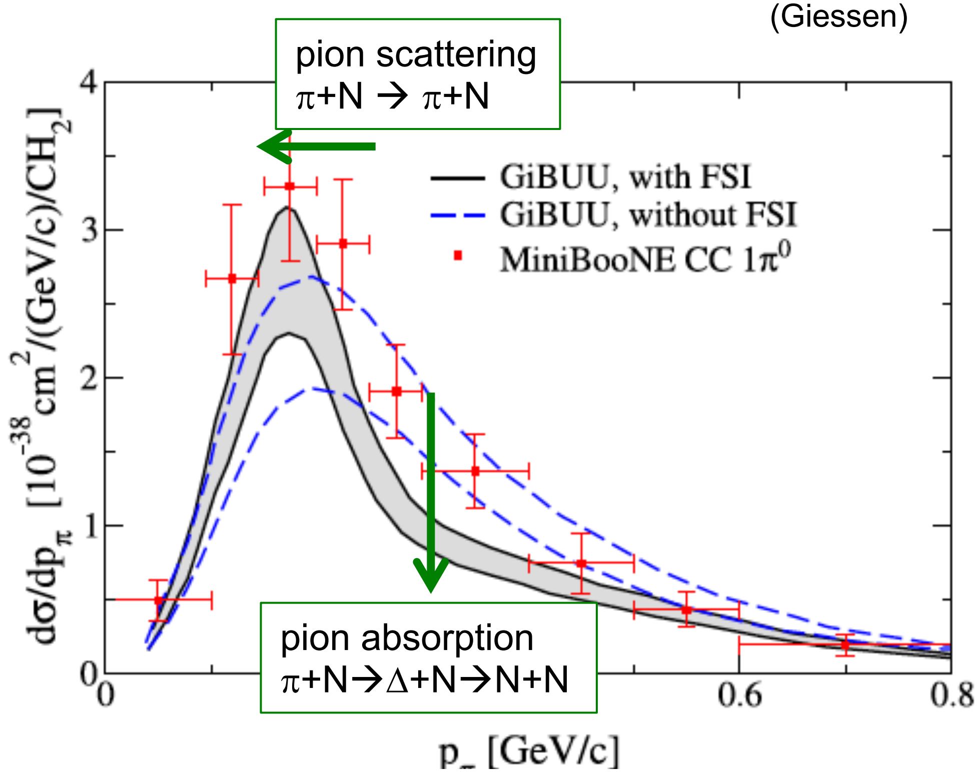
- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation

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



Ulrich Mosel (Giessen)





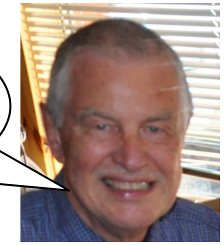
ex) Giessen BUU transport model

- 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

3. Pion puzzle (2019)

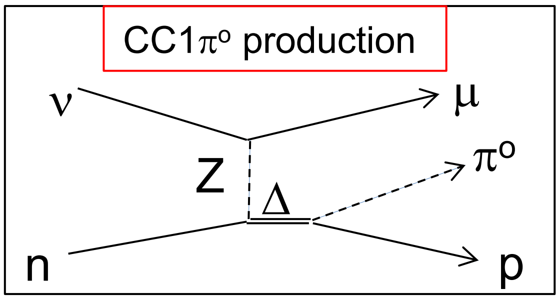
For long baseline oscillation experiments, theory has to be able to describe the full final states of all particles!

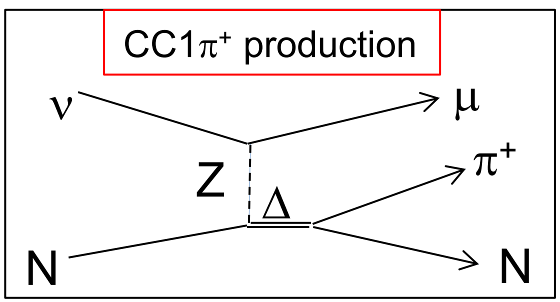


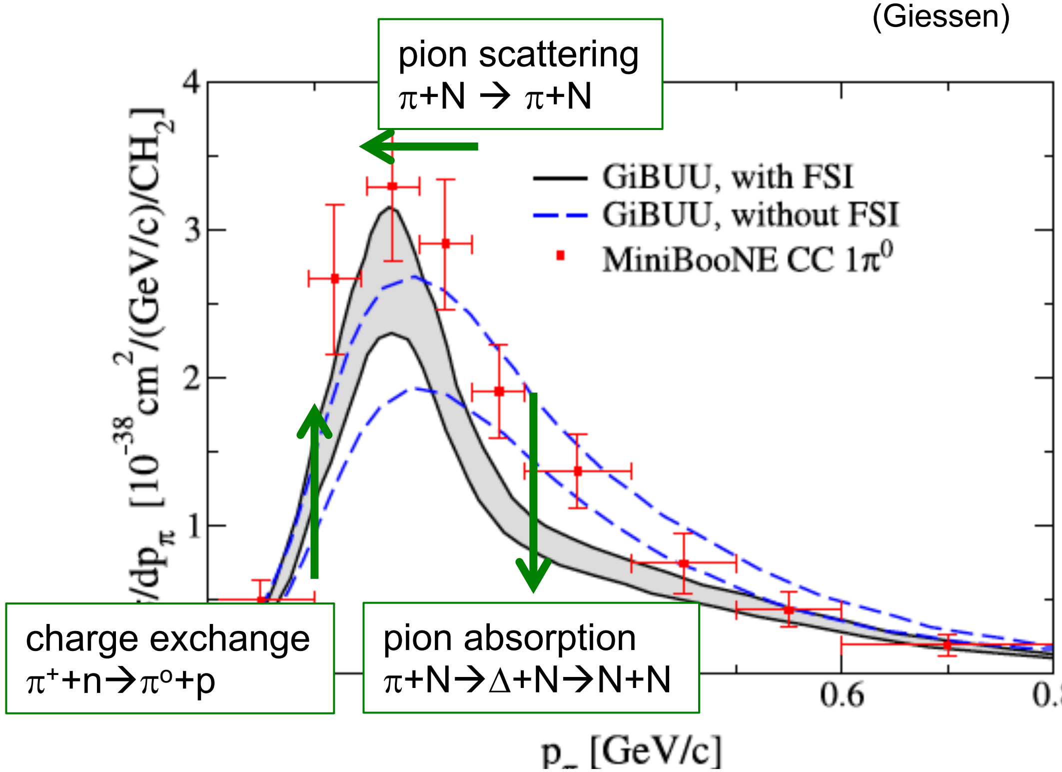
Ulrich Mosel (Giessen)

Final state interaction

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





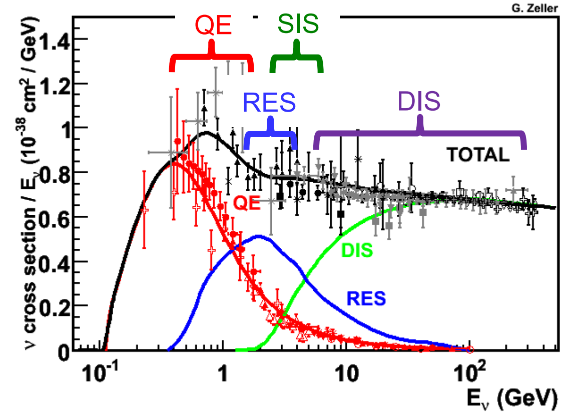


You need to predict both
1. pion production model
2. final state interaction

ex) Giessen BUU transport model

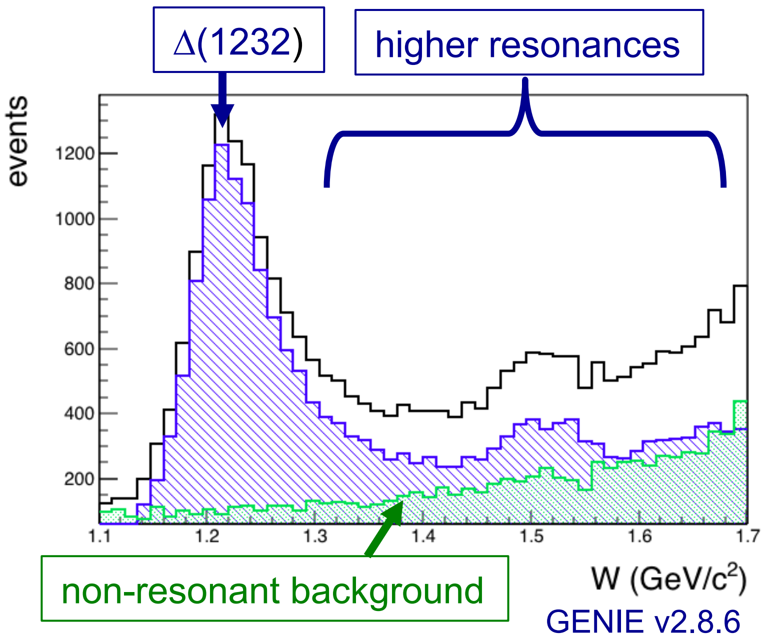
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

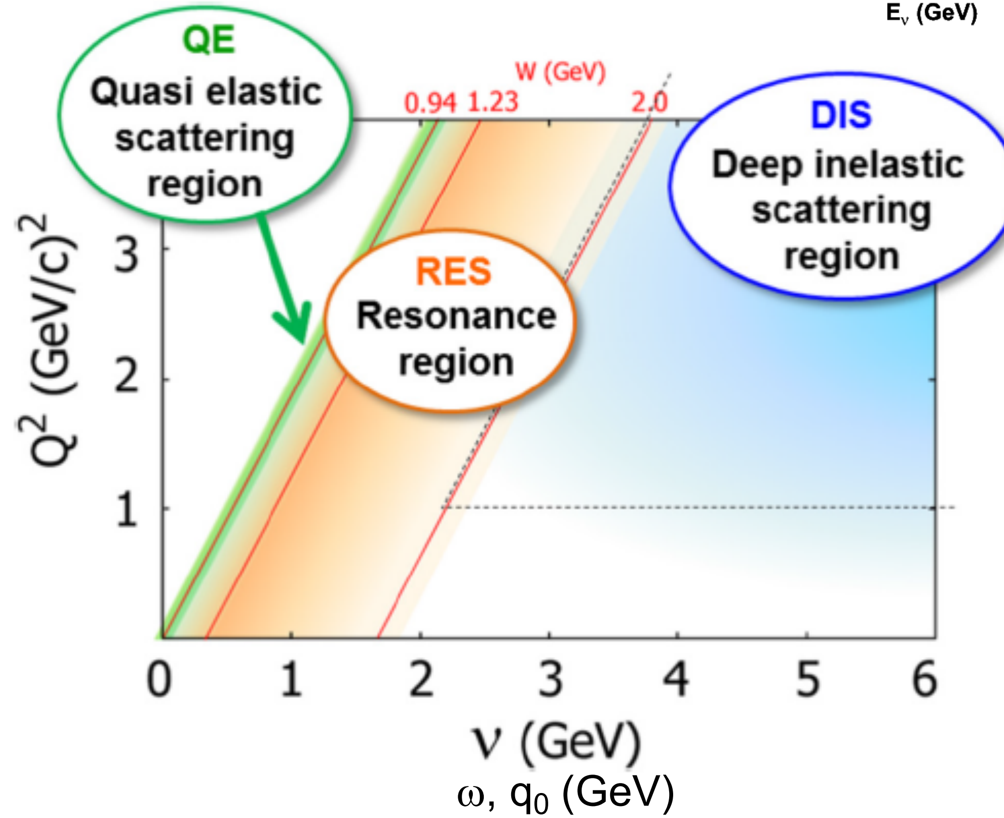
3. Shallow inelastic scattering (SIS)



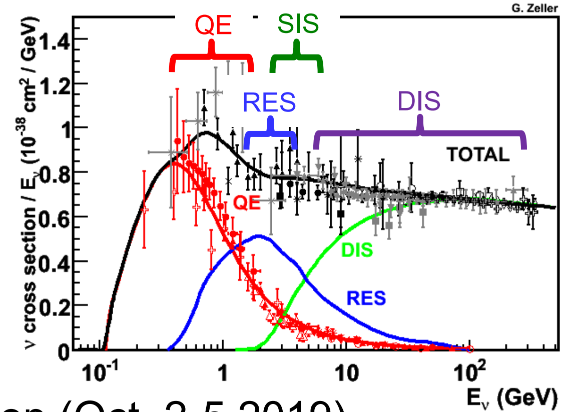
Ingredients of SIS physics

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





3. NuSTEC workshops



NuSTEC pion workshop (Oct. 2-5 2019)
the University of Pittsburgh, USA
https://nustec.fnal.gov/pion19/

NuSTEC SIS workshop (Oct. 11-13 2018)
L'Aquila, Italy
https://nustec.fnal.gov/nuSDIS18/
Summary paper (https://arxiv.org/abs/1907.13252)

Neutrino hadron production channels
- Background for oscillation measurement at HyperK
- Signal and background for oscillation measurement in DUNE
- Background for proton decay
- Signal and background for BSM physics search

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

Conclusion

1 to 10 GeV neutrino interaction measurements are crucial to successful next-generation neutrino oscillation experiments (DUNE, Hyper-K)

Nucleon correlation physics drastically change neutrino cross sections, both size and shape.

Recent new models and theories show nucleon correlation physics is important in many sub-fields of particle physics.

Neutrino interaction physics beyond QE region is confusing.

Future neutrino interaction measurements should focus on high-statistics neutrino hadron production measurements. This is the key to understand neutrino interaction models and nuclear effect.

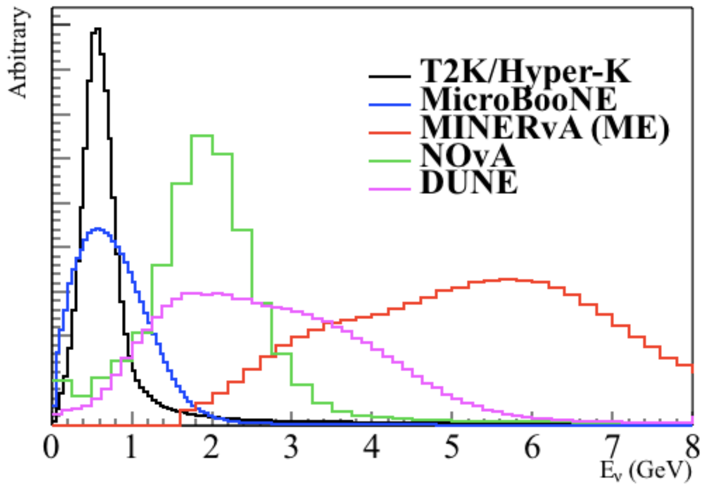
Thank you for your attention!

Backup

1. Next generation neutrino oscillation experiments

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

We don't know the energy of incoming neutrinos…
- We need to simulate all physics from Eν=0 to Eν ~few GeV
- We need to simulate all physics from $\omega,|\vec{q}|$=0 to $\omega,|\vec{q}|$~few GeV



Two rules of neutrino interaction physics
1. Neutrinos cannot choose kinematic
2. Neutrino kinematics are not fully determined

KING'S College LONDON

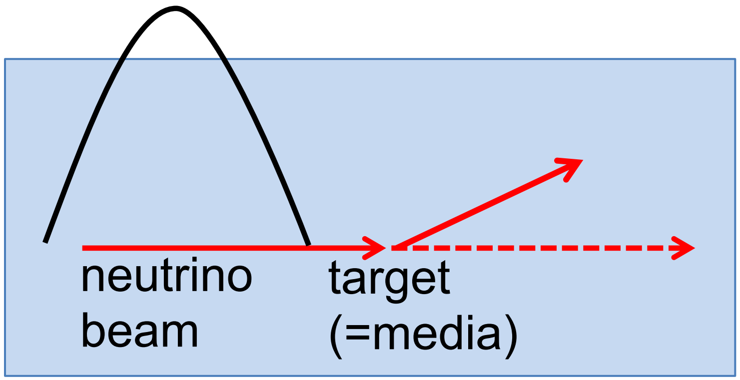
TK, Martini, JPhysG45(2017)1

1. Typical neutrino detectors

Neutrino scattering

- Wideband beam

→ observables are inclusive



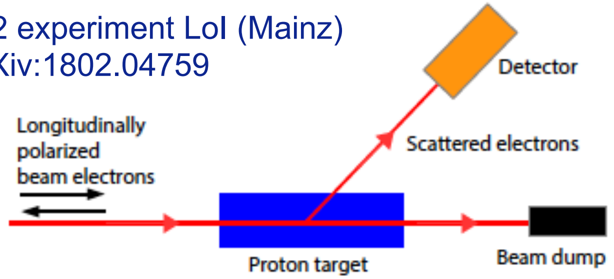
Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ kinematics is completely fixed

P2 experiment LoI (Mainz)
arXiv:1802.04759



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

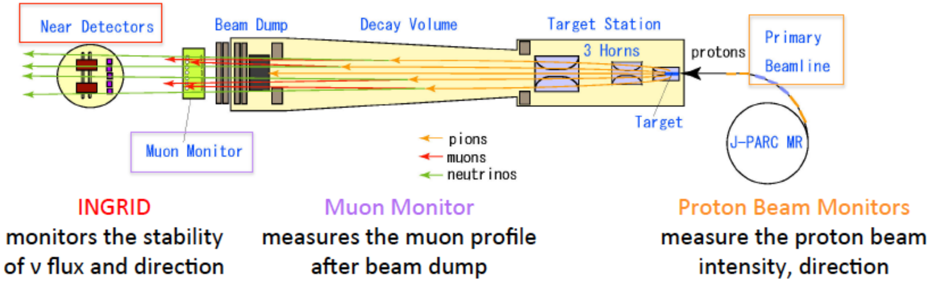
Two rules of neutrino interaction physics

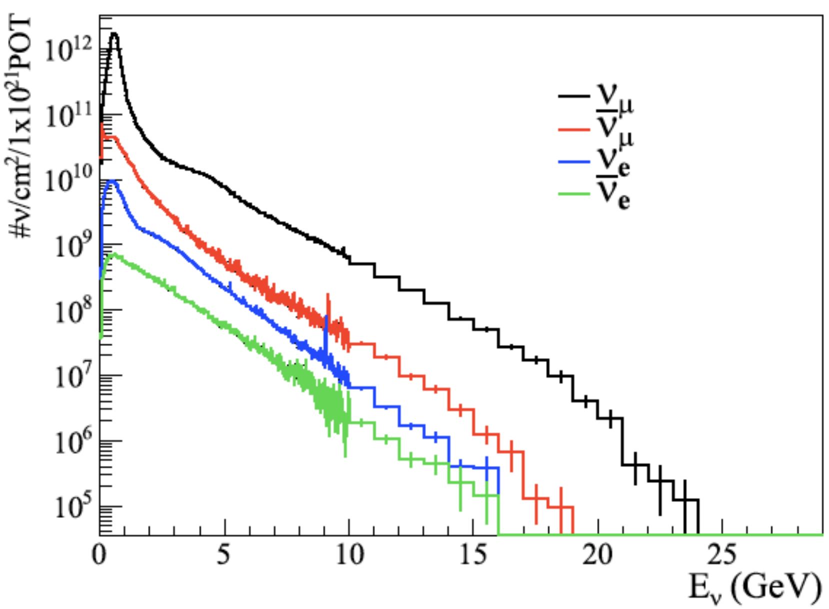
1. Neutrinos cannot choose kinematic
2. Neutrino kinematics are not fully determined

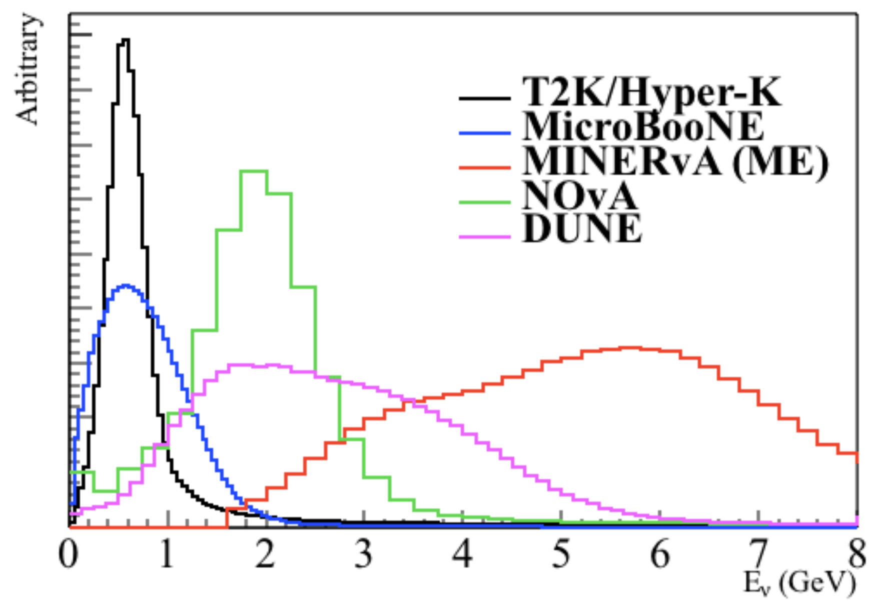
TK, Martini, JPhysG45(2017)1
Kowalik, NuInt18 (Toronto)

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)







KING'S College LONDON

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

2. Summary of CCQE for oscillation physics

Community is converged: the origin of CCQE puzzle is multi-nucleon correlation

This moment…
New nuclear models available in simulations do not quantitatively describe T2K and MINERvA CCQE μ+p data

large M_A error → large 2p2h error

It is crucial to have correct CCQE, 2p2h, pion production models to understand data simultaneously. Otherwise M_A error stays around 20-30%.

We have good theorists who make models, and good experimentalists who measure data, but we are still lacking people between them.

Ankowski et al, PRD92(2015)073014

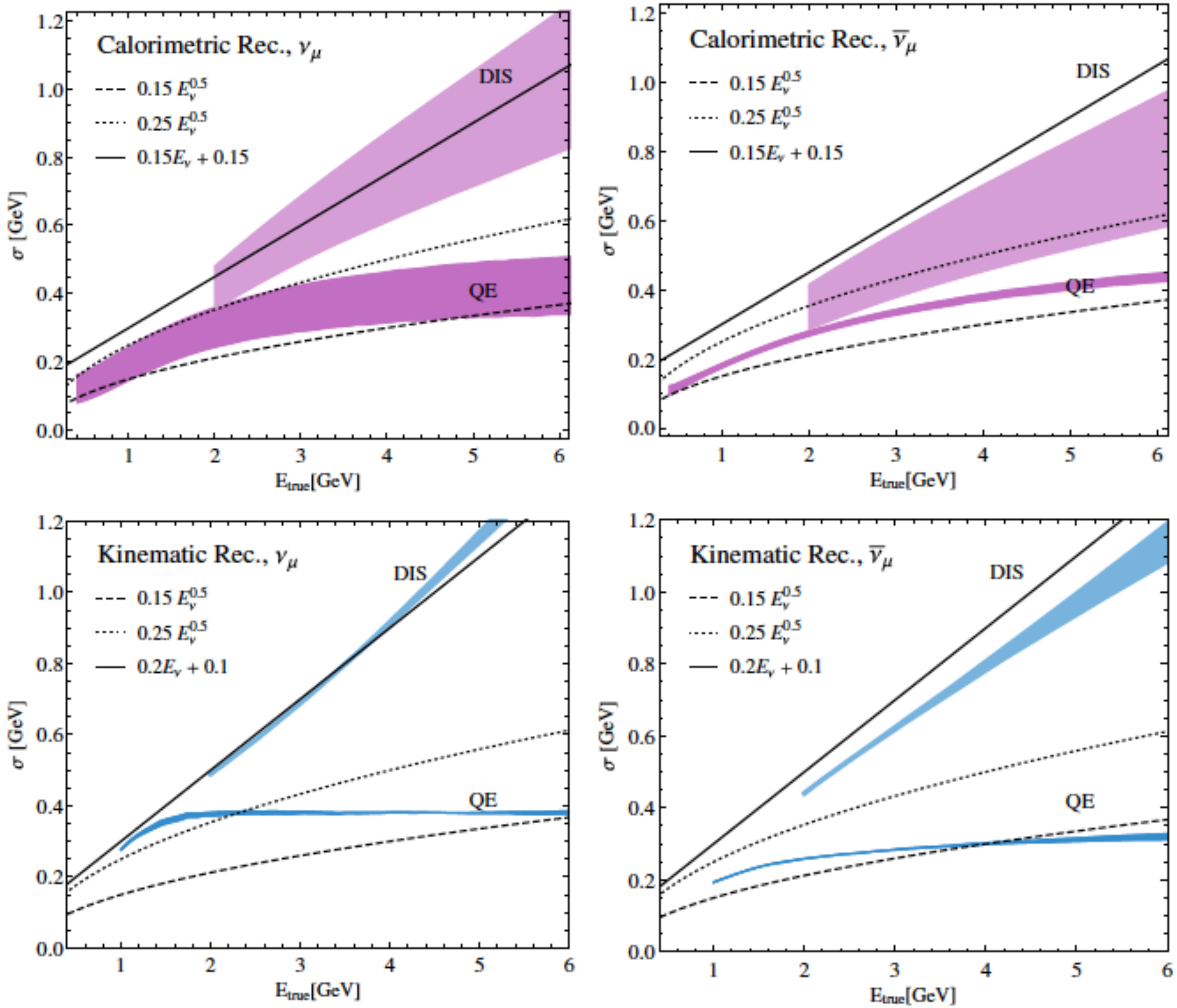
2. Kinematic E reconstruction vs calorimetric E reconstruction

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



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

4. SIS-DIS model

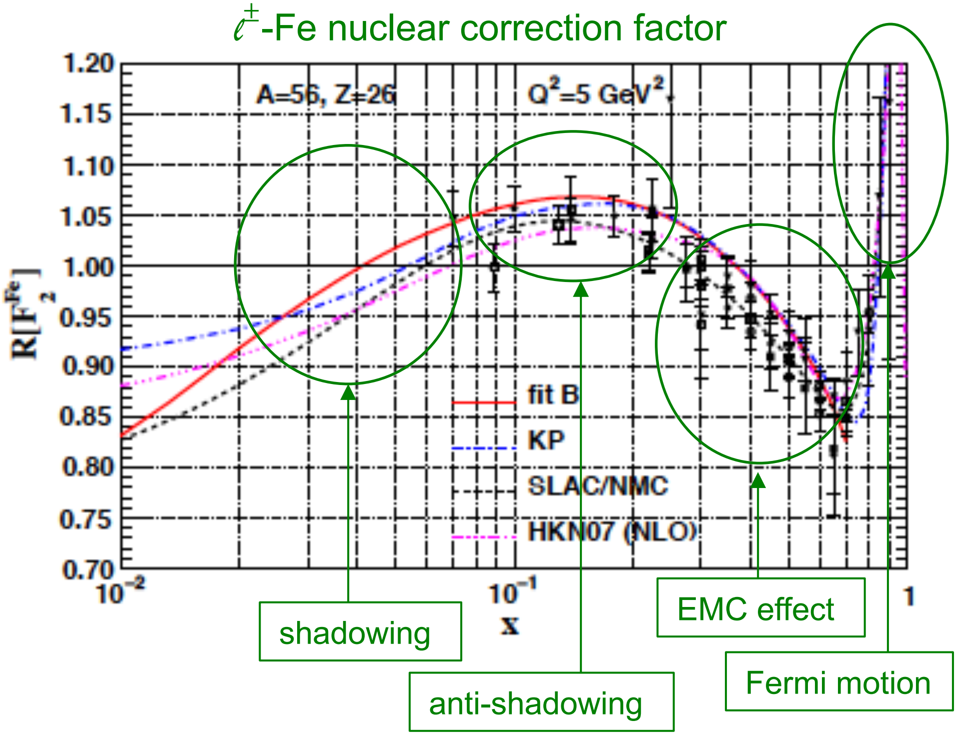
Cross section

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

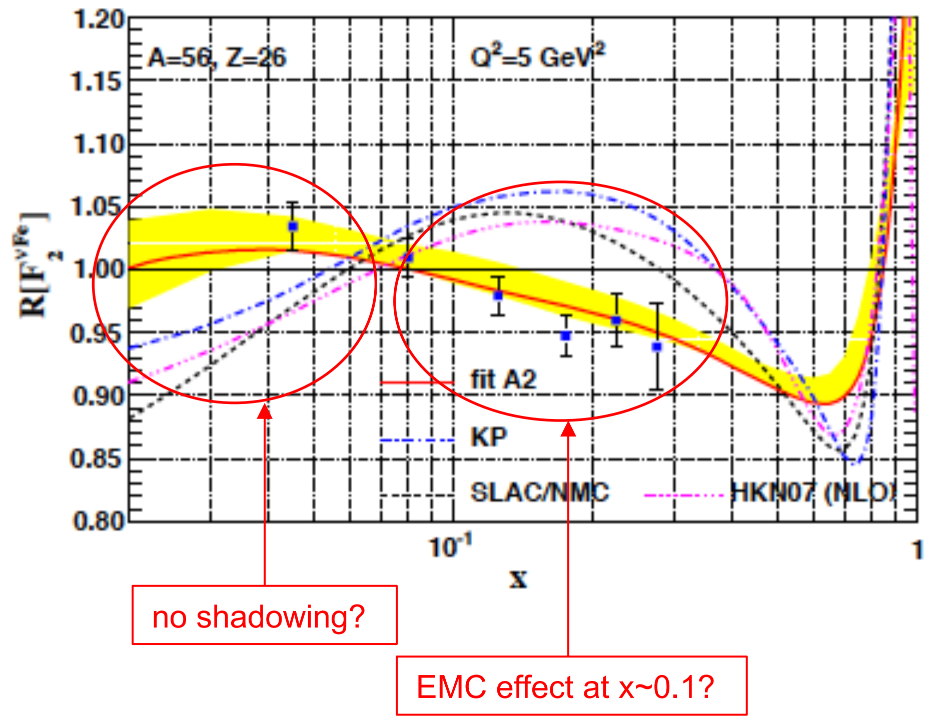
Nuclear PDF

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

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



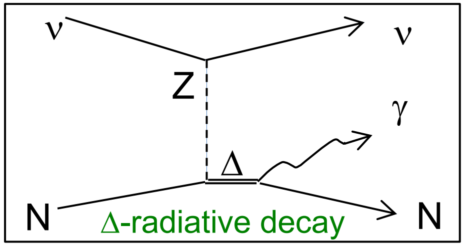
ν-Fe nuclear correction factor

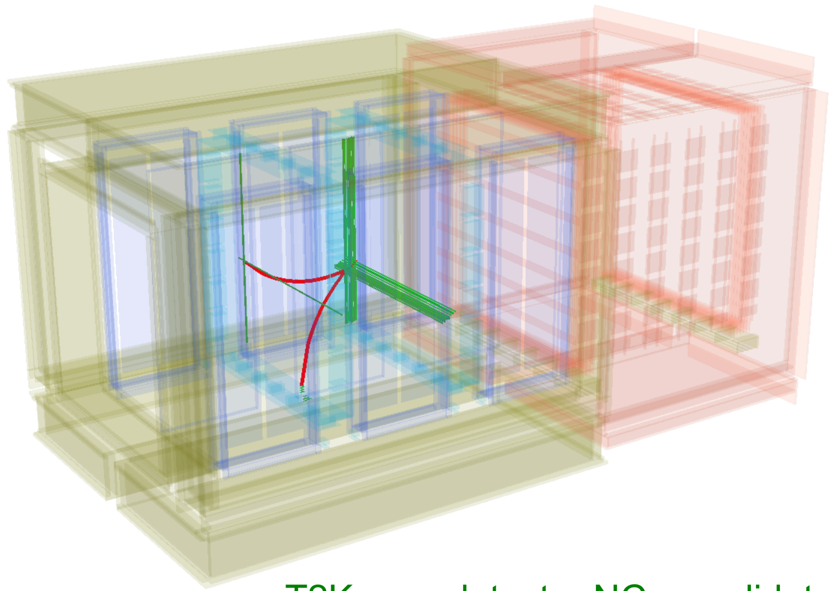


KING'S College LONDON

4. T2K Neutrino NC single photon production (NCγ)

Neutrino induced NC single photon production (NCγ) process is not experimentally identified. NCγ is misID background for every electron-neutrino appearance oscillation experiment. T2K and NOMAD set limits on this process, but ~x3 higher cross-section can explain all MiniBooNE excess.





T2K near detector NCγ candidate