Nuclear Physics for Beyond the Standard Model Neutrino Physics

outline

1. Neutrino interaction physics - introduction
2. Charged-Current Quasi-Elastic (CCQE) interaction
3. Neutrino baryonic resonance interaction
4. Neutrino shallow- and deep-inelastic scatterings
5. Conclusion

Teppei Katori @teppeikatori
King's College London
ICN seminar, UNAM, Nov. 17, 2021

Fun Timely Intellectual Adorable!

Neutrino oscillation

nuclear many-body problem

electron scattering

Spin physics

Leptonic CP violation

Gallium anomaly

NuSTEC News

Nucleon correlation

EMC effect

Neutrino-less double beta decay

Dark matter

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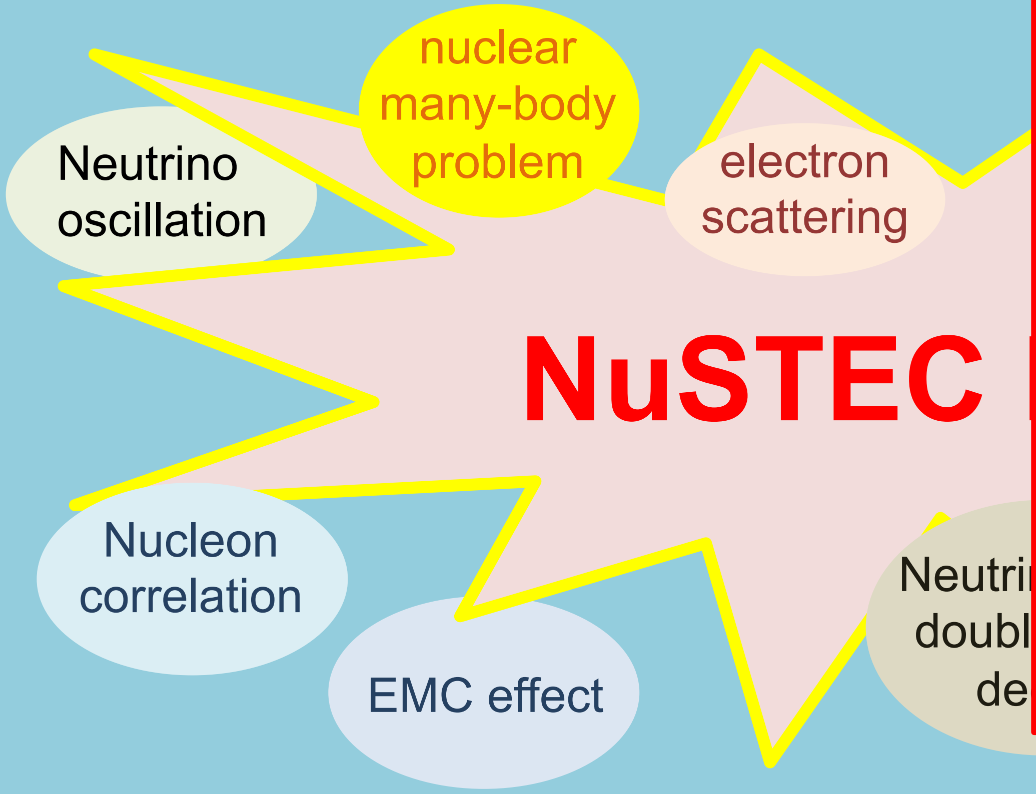

nuclear many-body problem

Neutrino oscillation

electron scattering

NuSTEC

Nucleon correlation

EMC effect

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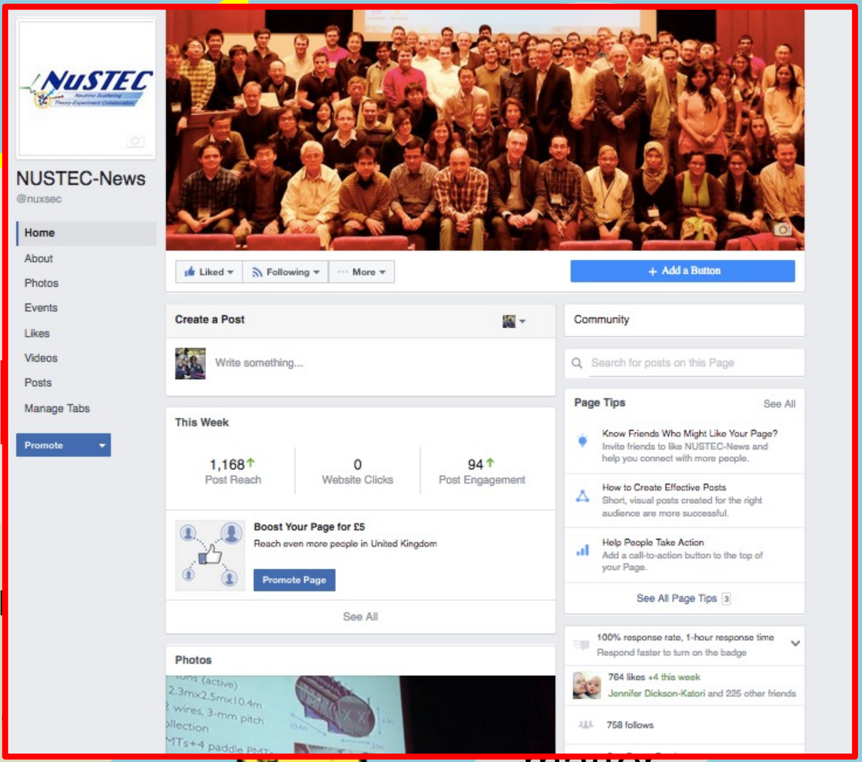
matter



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1. **Neutrino interaction physics - introduction**

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

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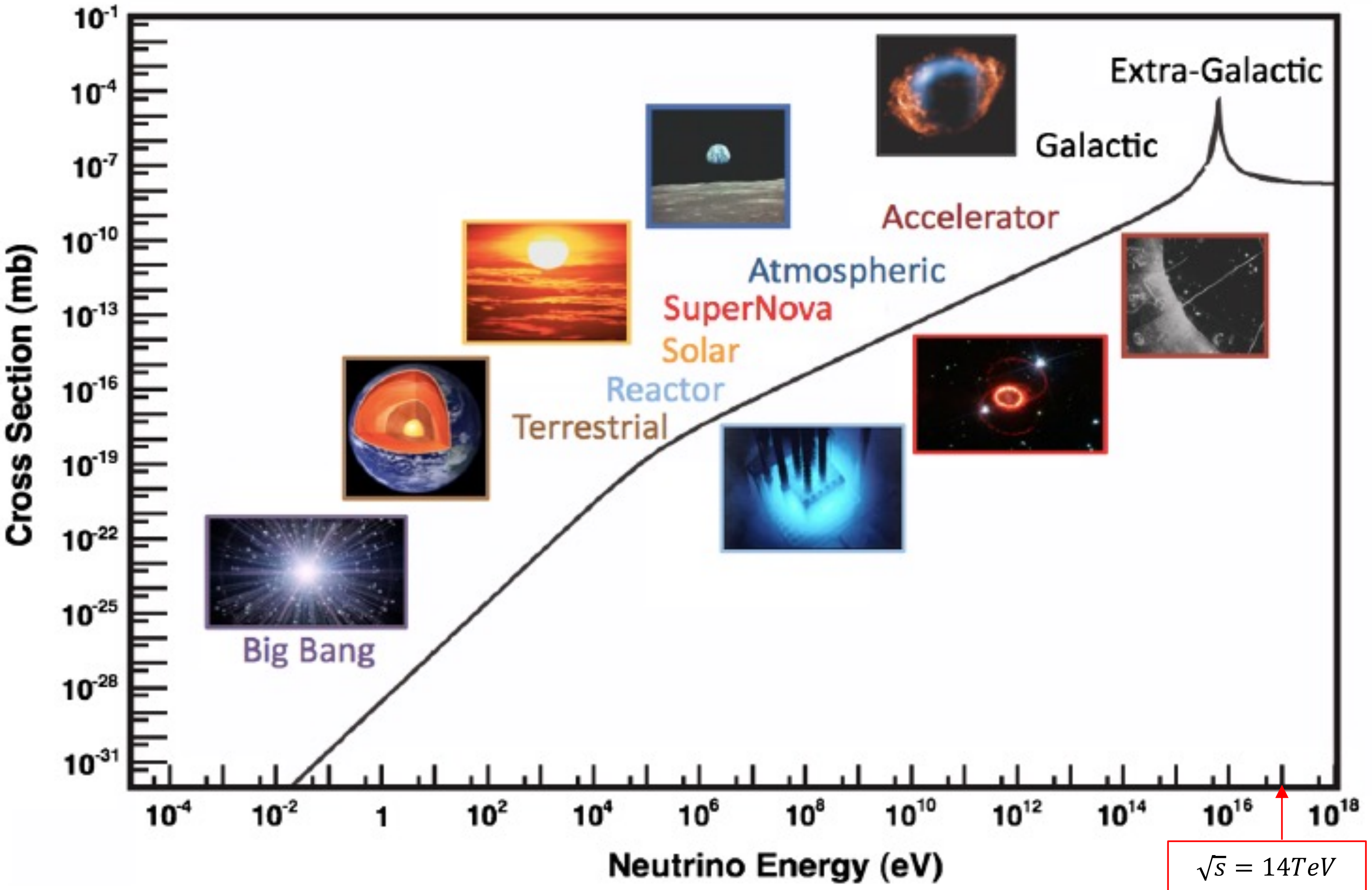
Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

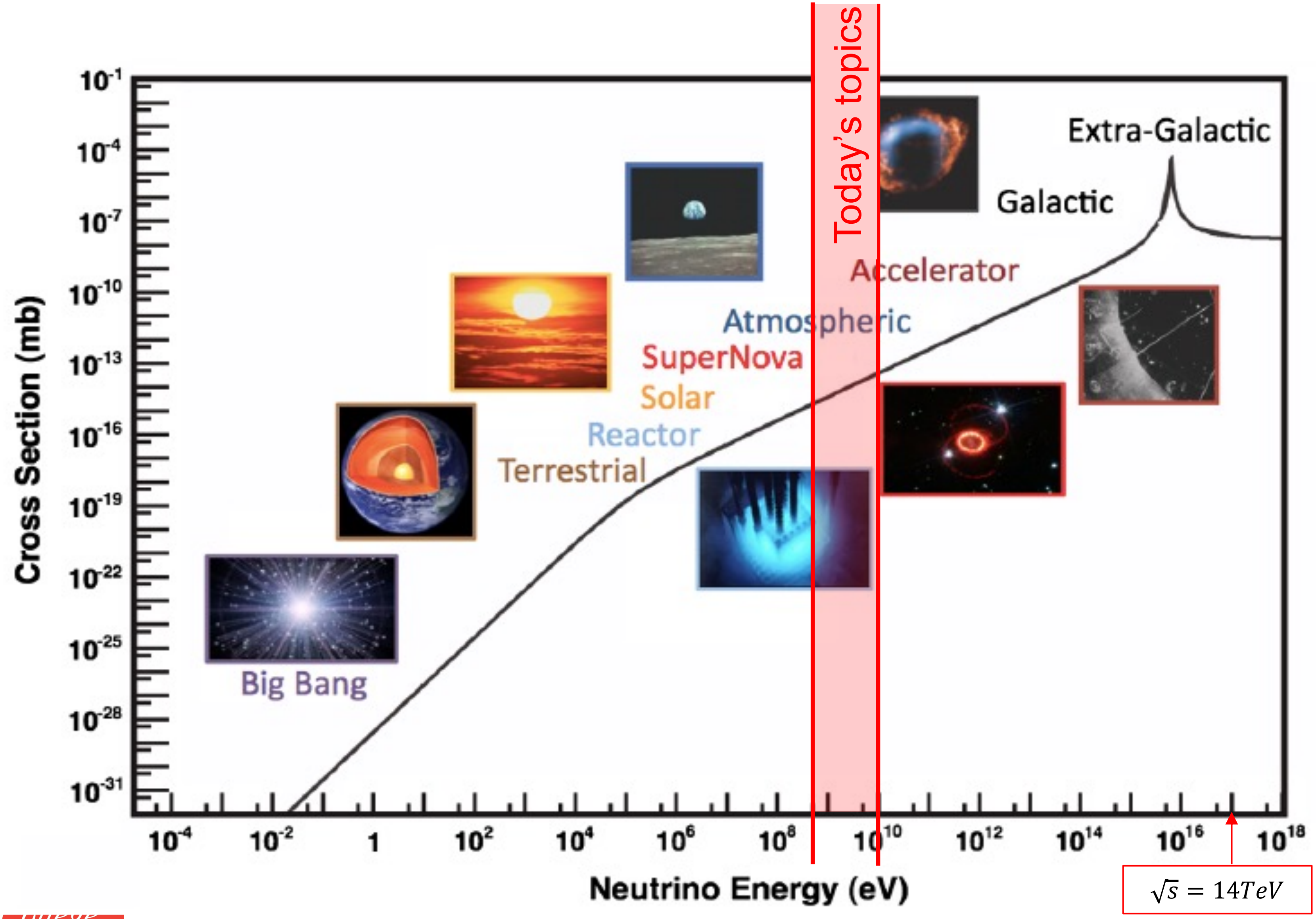
1. From eV to EeV: Neutrino cross sections across energy scales



$\sqrt{s} = 14TeV$

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

1. From eV to EeV: Neutrino cross sections across energy scales



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1. Neutrino interaction physics around 1-10 GeV

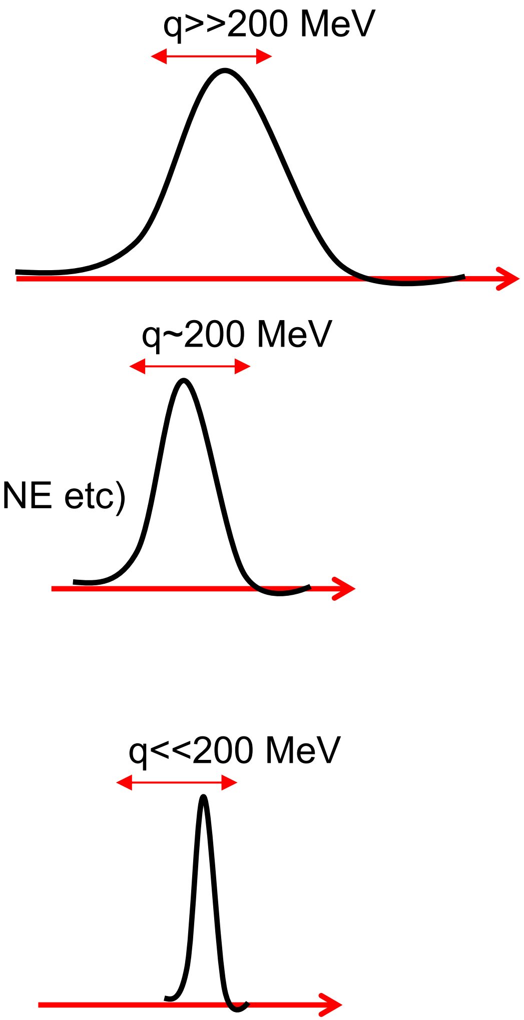
Size of wave packet ~ momentum transfer (~energy)

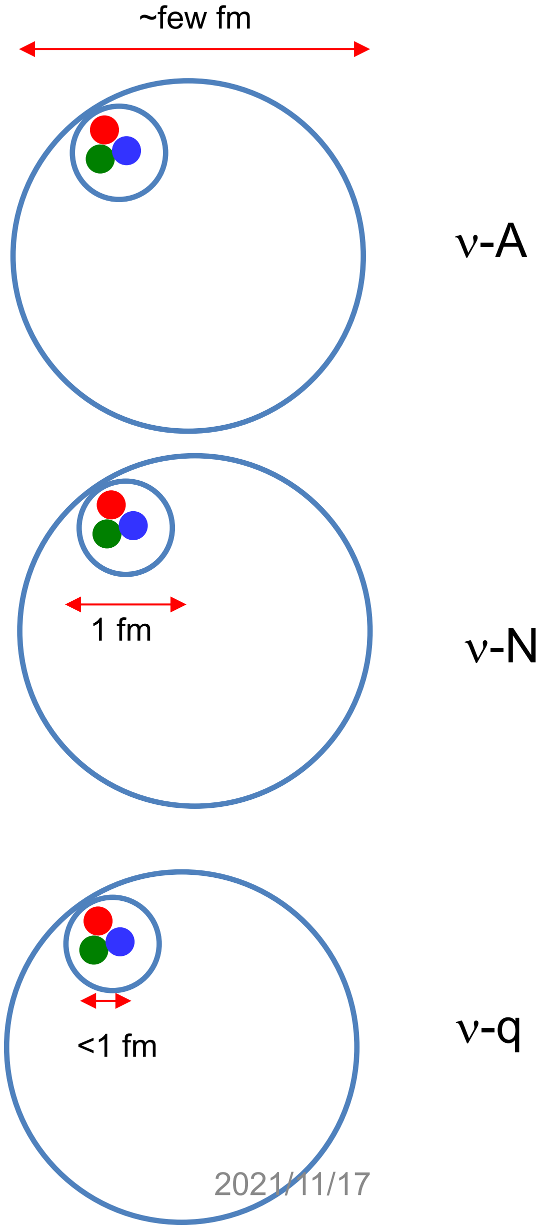
$\hbar c = 197\,MeV \cdot fm \rightarrow$ 200 MeV ~ 1 fm (size of nucleon)

<<1 GeV neutrino beam
(solar neutrinos, etc)

~1 GeV neutrino beam
(T2K, NOvA, HyperK, DUNE etc)

>>1 GeV neutrino beam
(LHC, astrophysical)





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

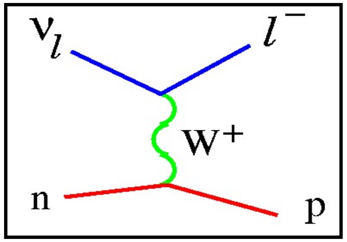
1. Neutrino interaction physics around 1-10 GeV

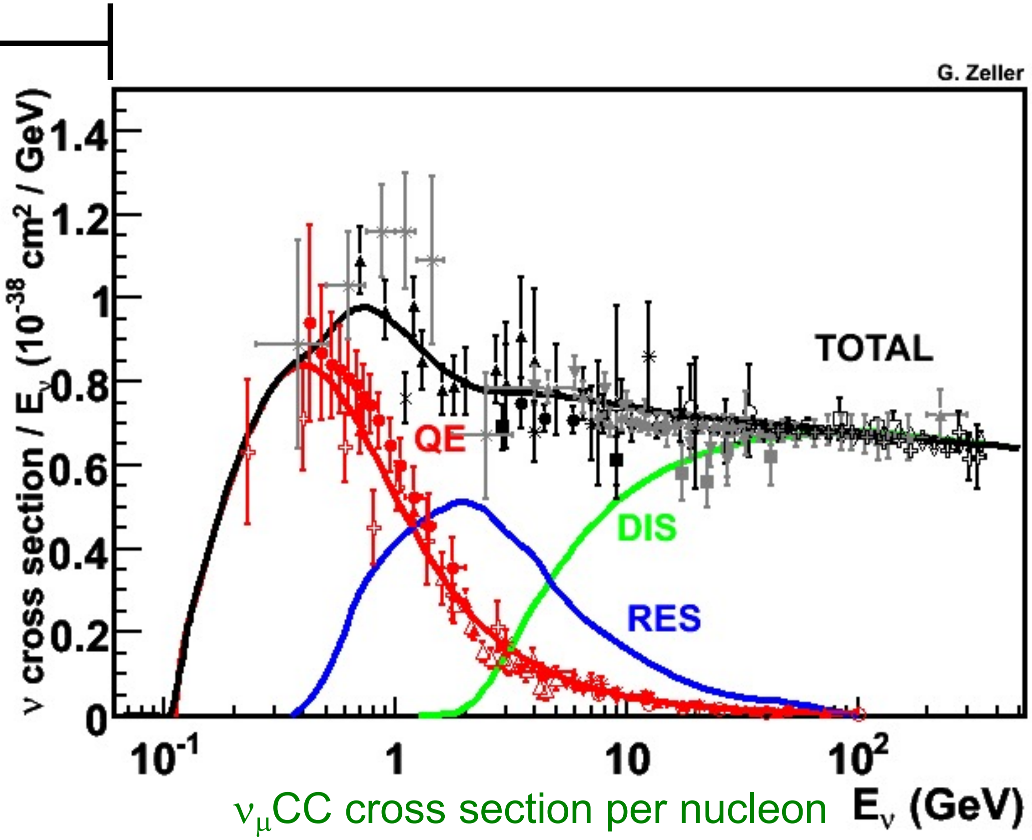
Neutrino interaction physics around 1-10 GeV

- degree of freedom change from nucleus → nucleon → parton
- There is no such thing (they all interfere)

COHERENT
Reactor
Solar

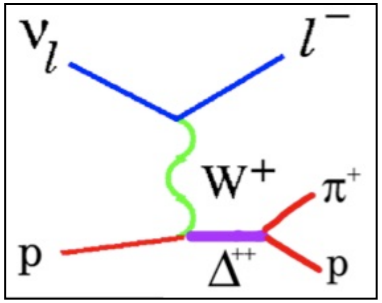
Quasi Elastic (QE)

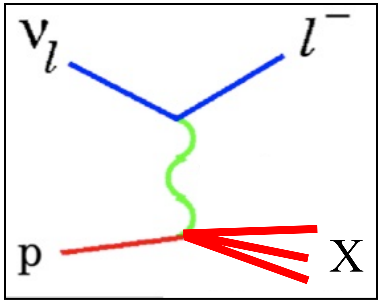




ν_μCC cross section per nucleon

baryonic
RESonance





Deep Inelastic
Scattering (DIS)

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.

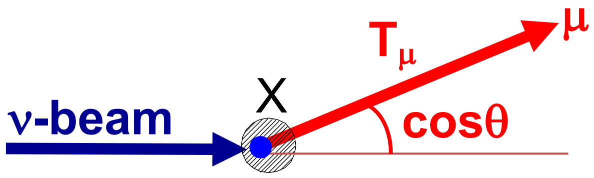
Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

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

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

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

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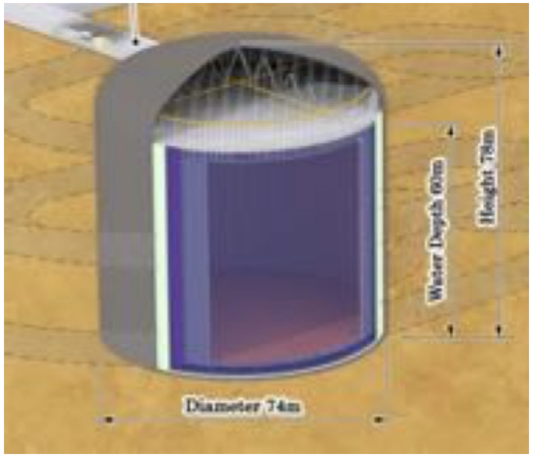
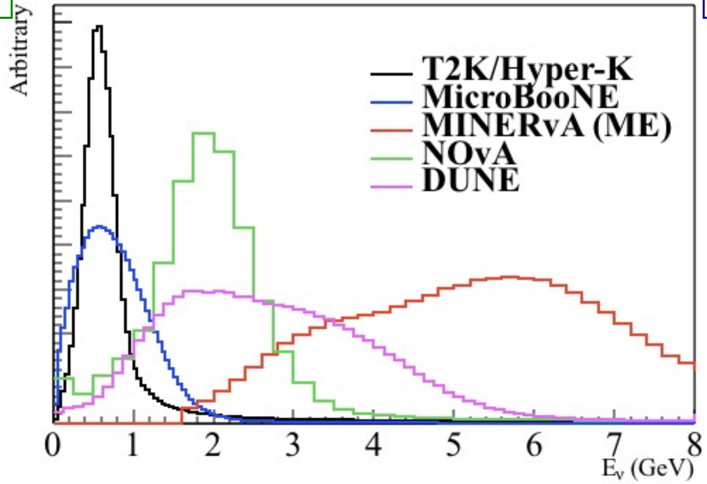
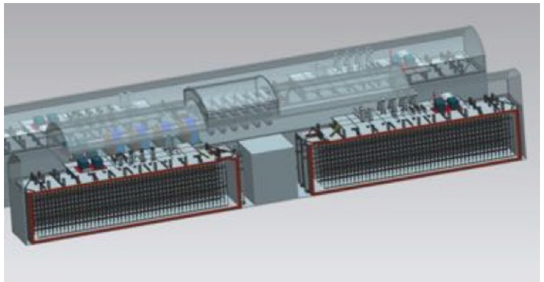
1. Next goal of high energy physics

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







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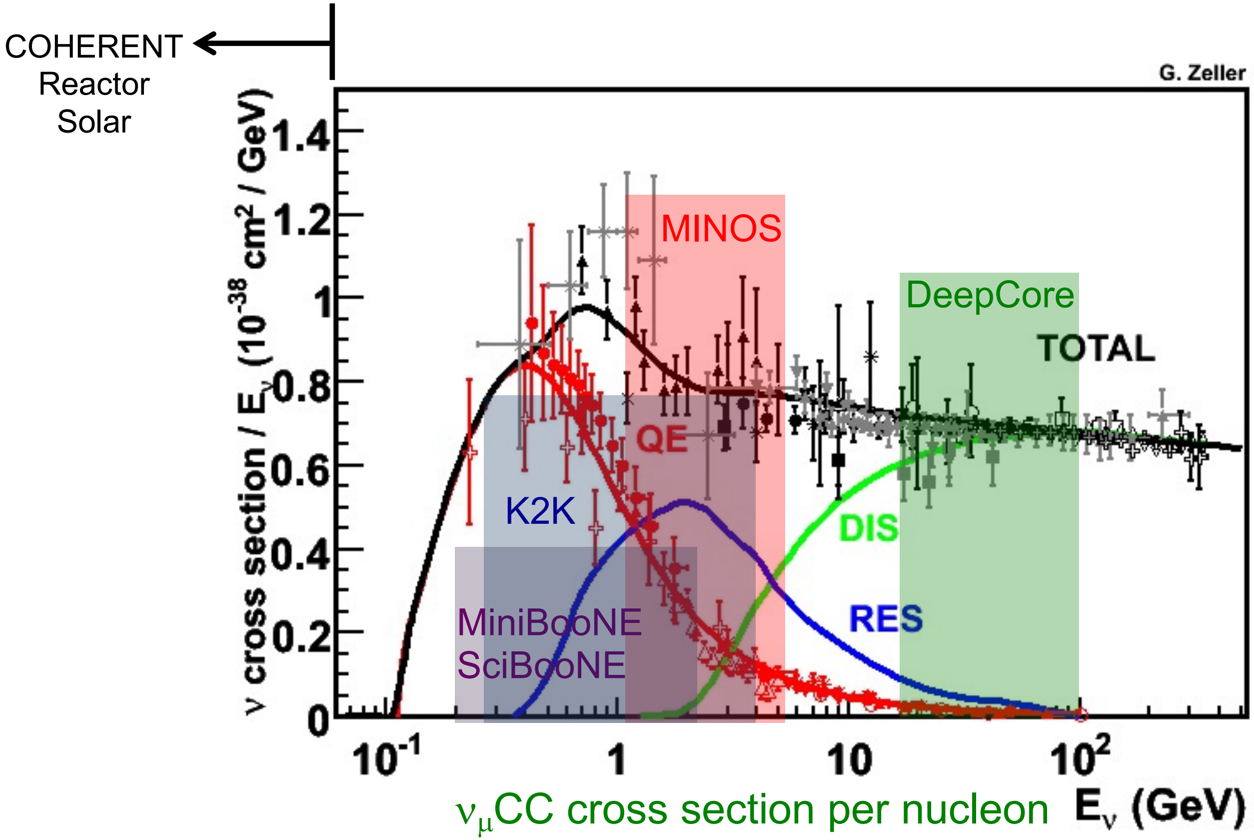
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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



ν_μCC cross section per nucleon

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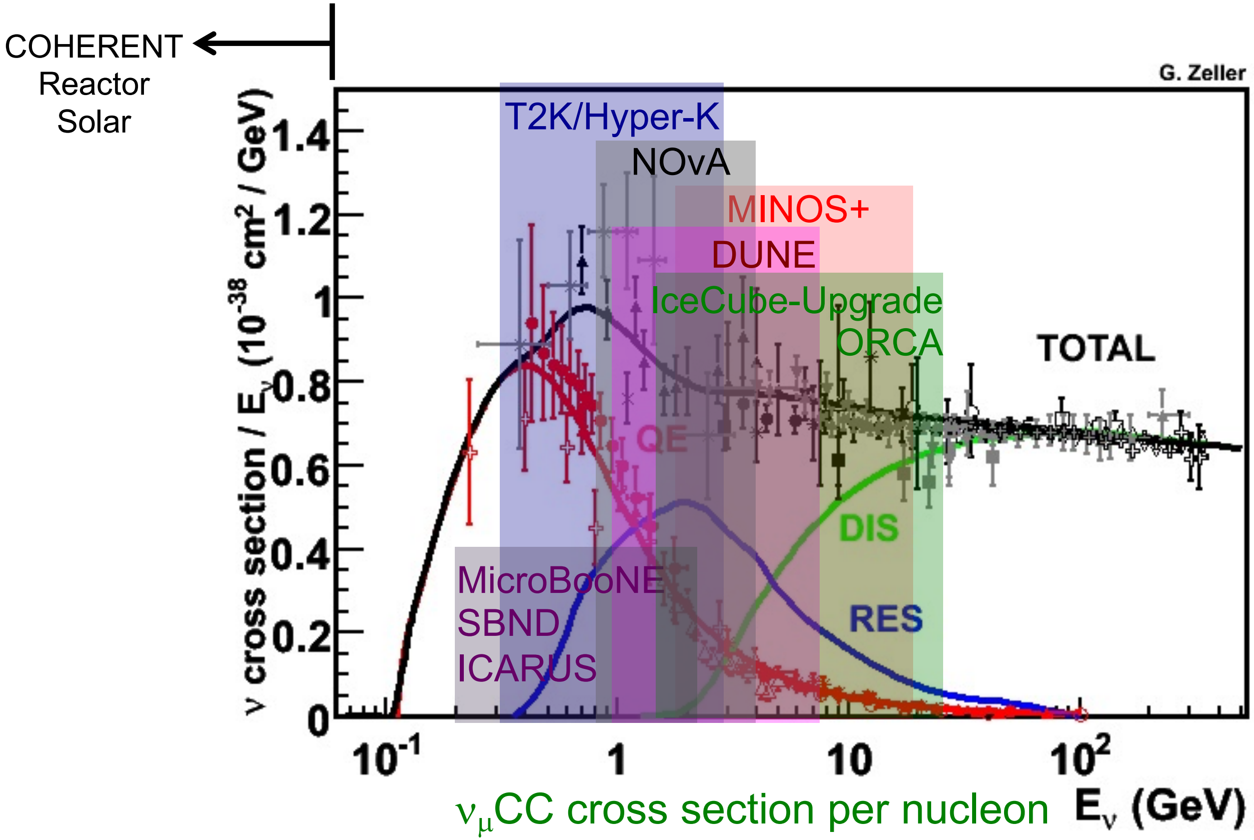

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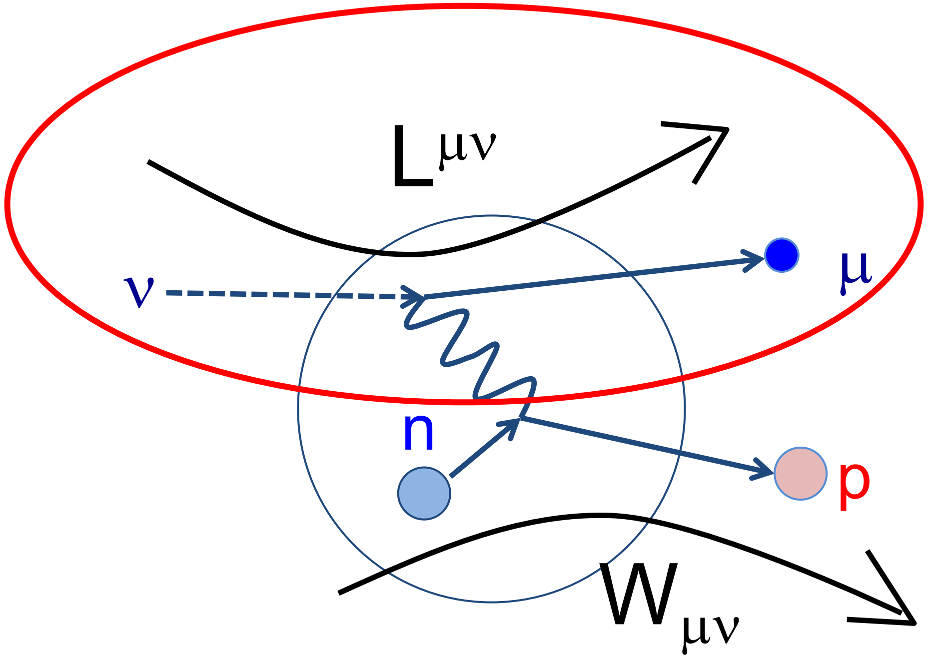
1. Neutrino cross-section formula

Cross-section
- product of Leptonic and Hadronic tensor

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

Leptonic tensor
→ the Standard Model (easy)

Hadronic tensor
→ nuclear physics (hard)



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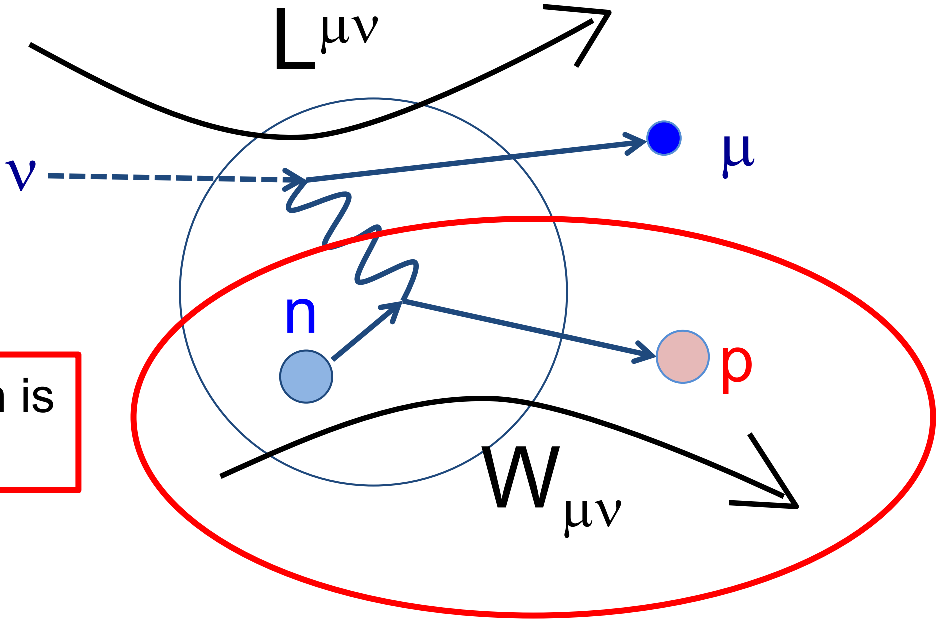
All complication of neutrino cross-section is how to model the hadronic tensor part



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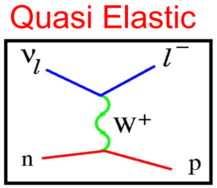
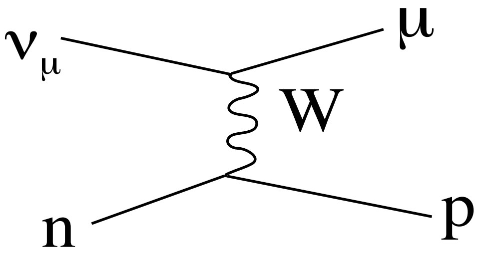
2. Charged Current Quasi-Elastic scattering (CCQE)

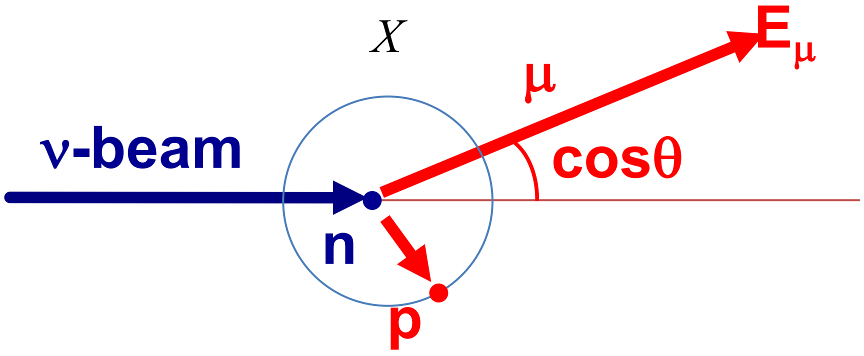


The simplest and the most abundant interaction around ~1 GeV.



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

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

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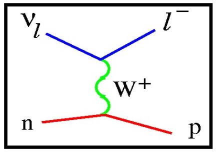
MiniBooNE,PRD81(2010)092005

2. CCQE puzzle

Quasi Elastic



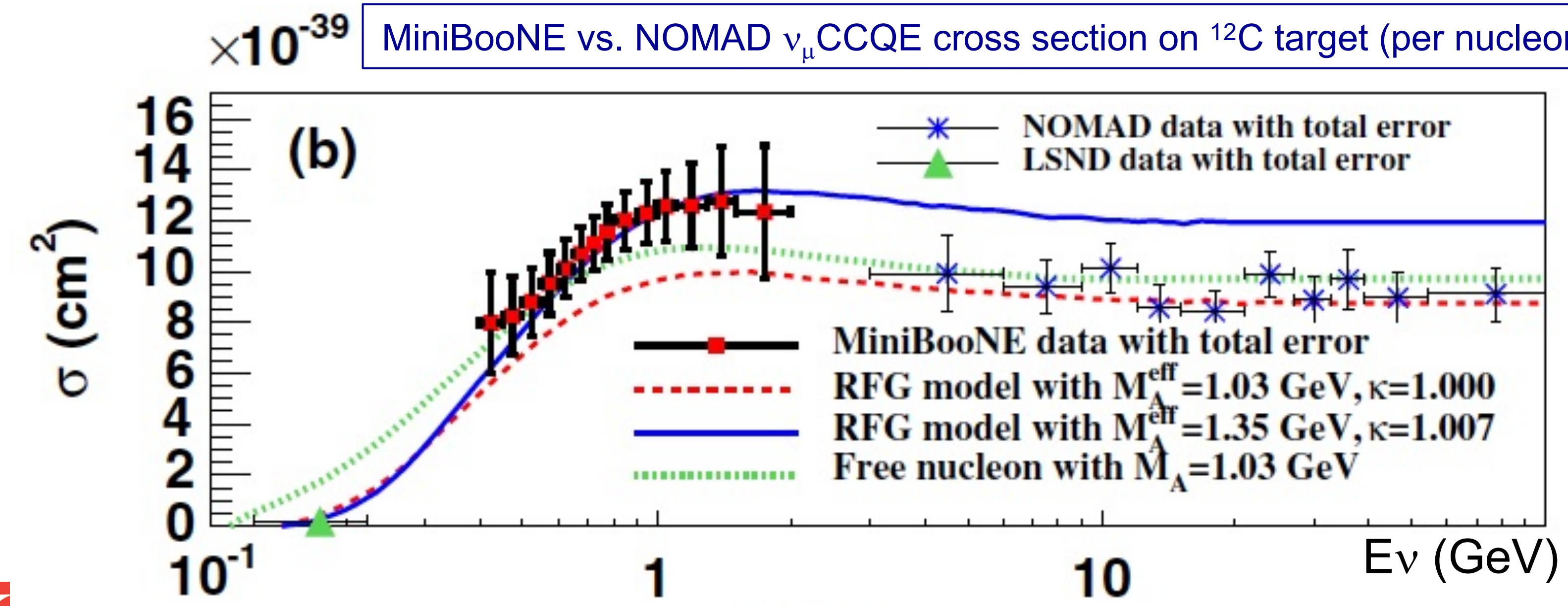
Simplest channel, but both shape and normalization disagree

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)



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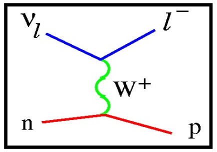
Martini et al,PRC80(2009)065501

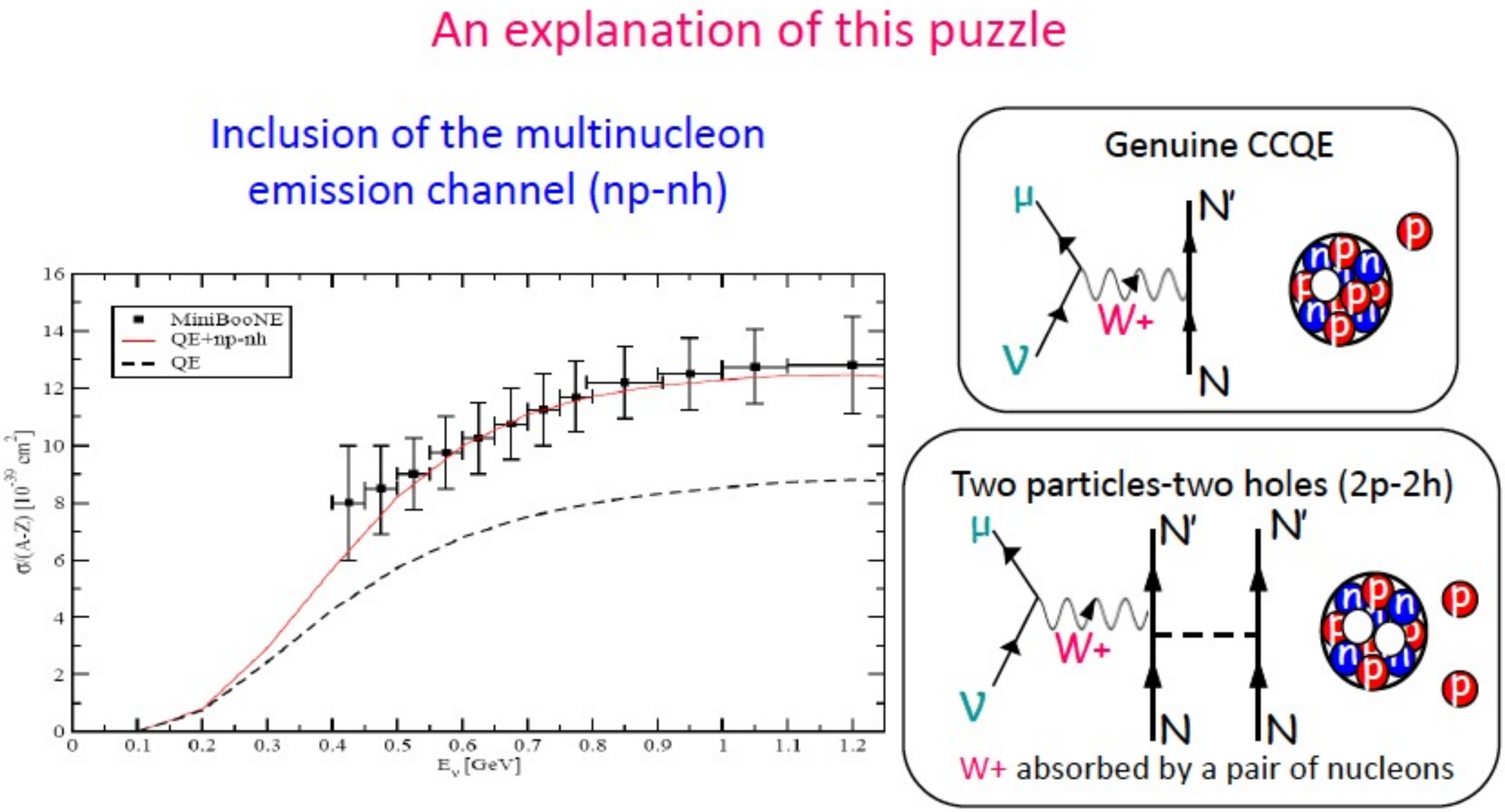
Quasi Elastic



2. Solution of CCQE puzzle

Presence of 2-body current

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



An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

Genuine CCQE

Two particles-two holes (2p-2h)

W+ absorbed by a pair of nucleons

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

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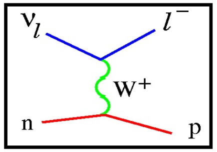
Quasi Elastic



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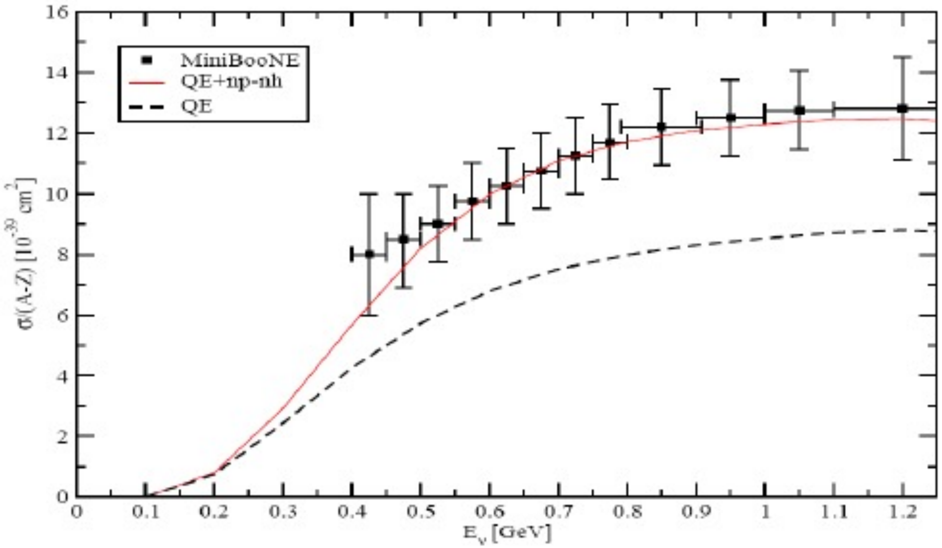

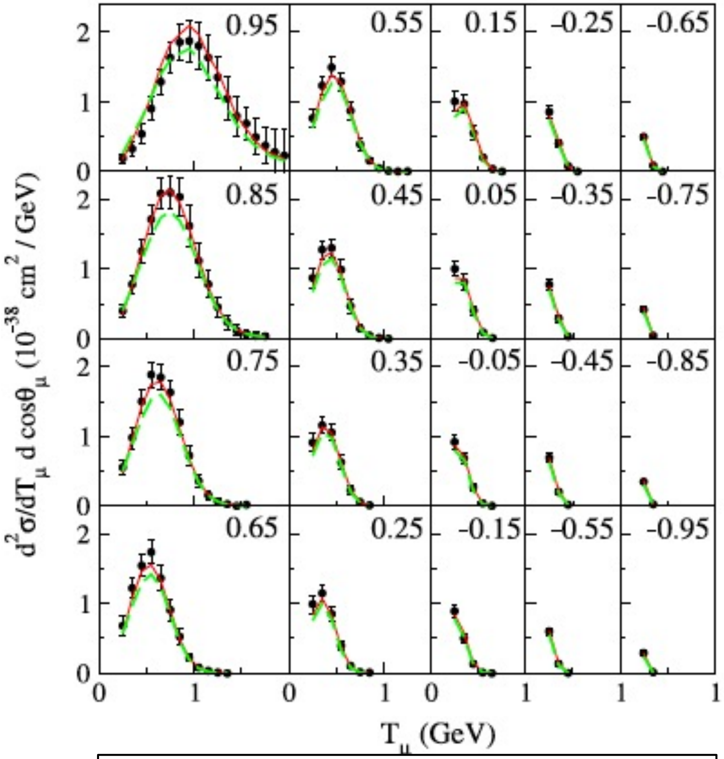

Valencia model vs. MiniBooNE CCQE double differential cross-section data

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

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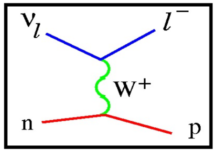
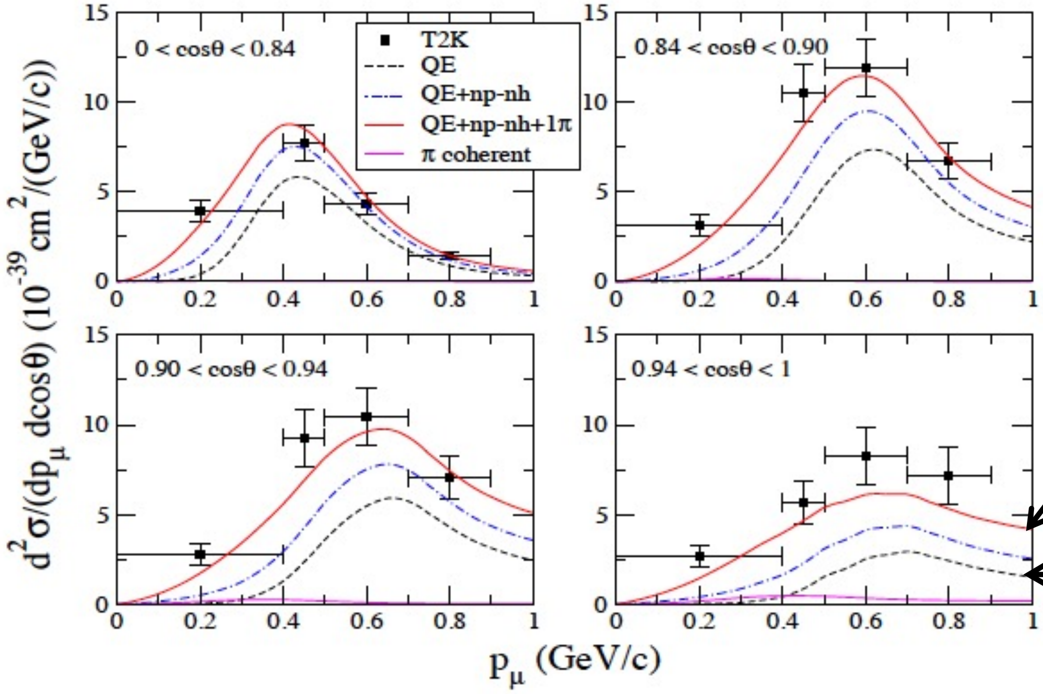
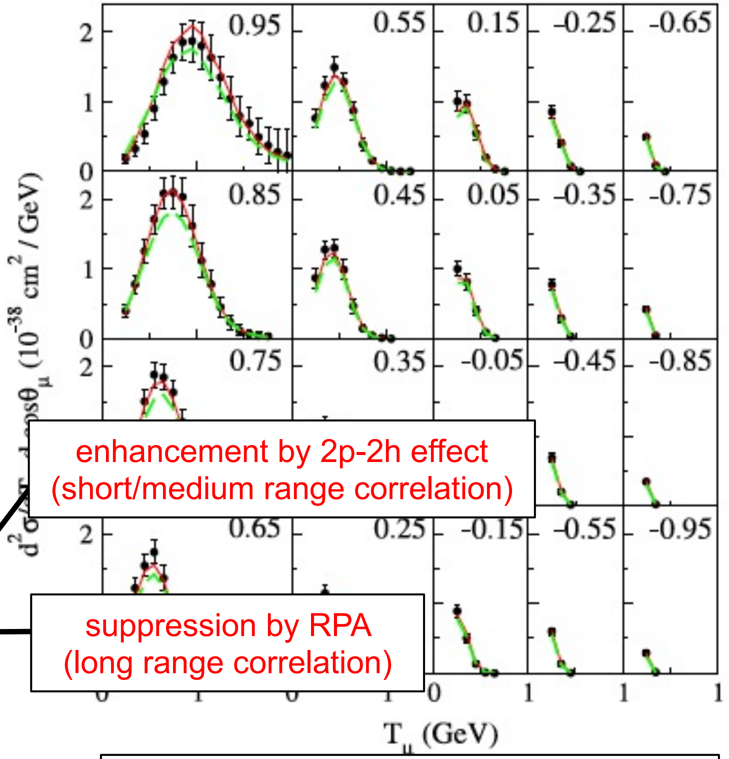


Presence of 2-body current

- 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





enhancement by 2p-2h effect
(short/medium range correlation)

suppression by RPA
(long range correlation)

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

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TK, Martini, JPhysG45(2017)1

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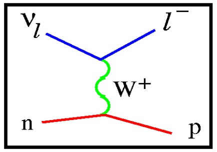
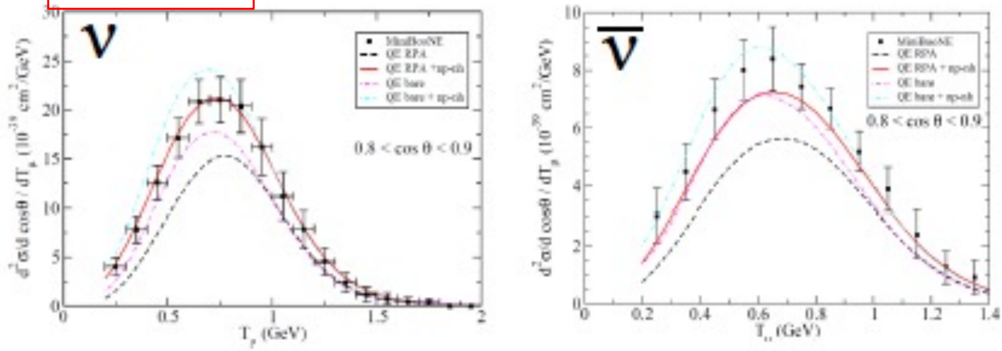


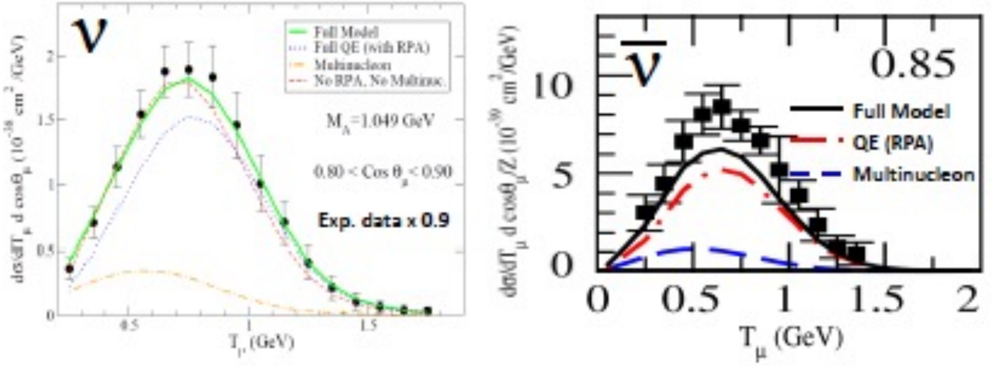
Many phenomenological models agree qualitatively with MiniBooNE CCQE-like double differential data.

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

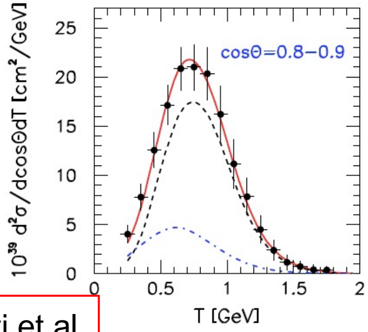
Martini et al



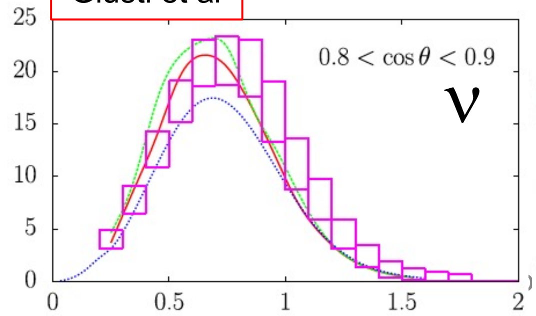
Valencia



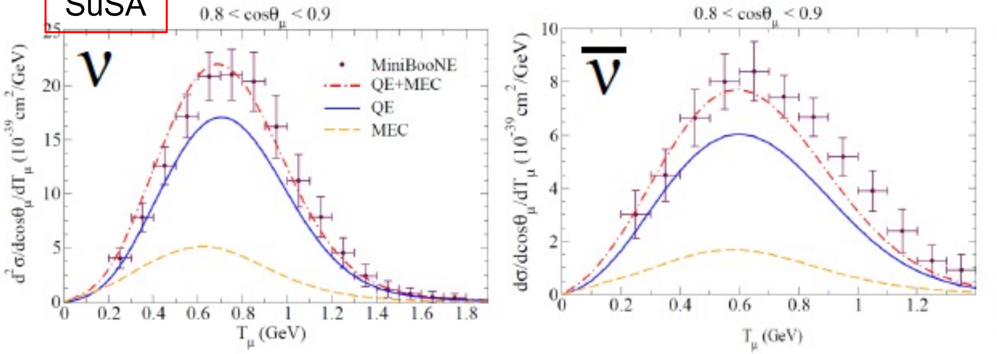
Butkevich et al



Giusti et al



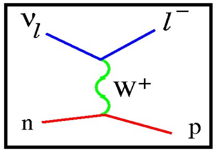
SuSA



Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRX10(2020)031068 (2020)

2. Nucleon correlations in neutrino physics

Quasi Elastic



Ab-initio calculation

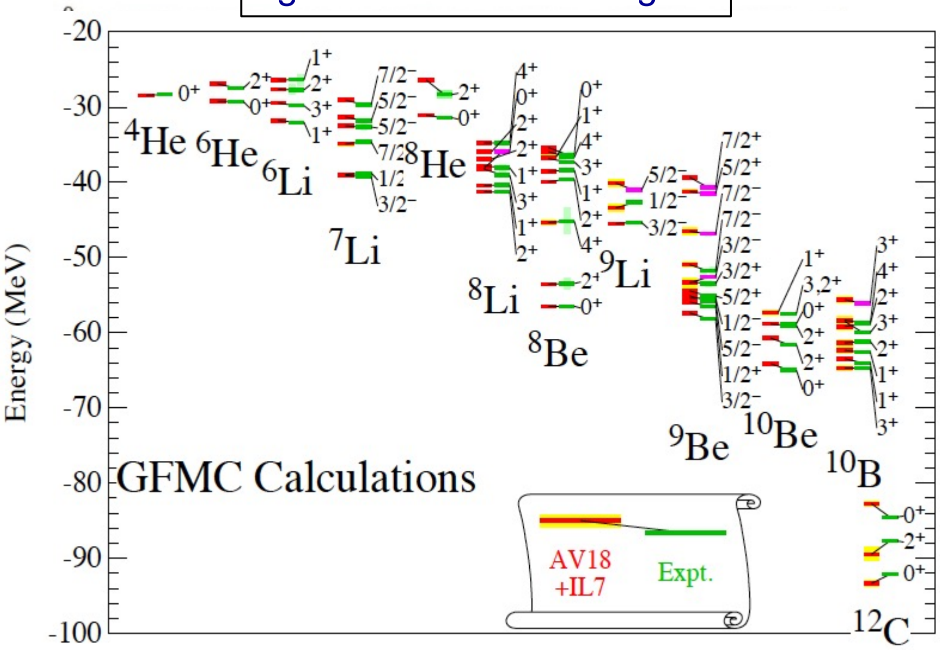
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Ground state includes correct nucleon correlations

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

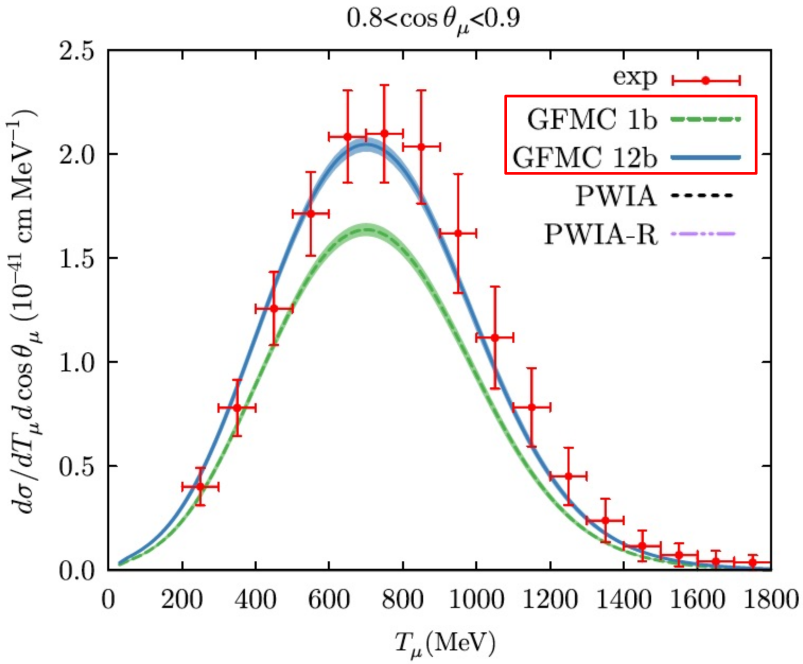
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



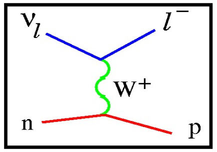
MiniBooNE CCQE cross-section



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

2. Nucleon correlations in neutrino physics

Quasi Elastic



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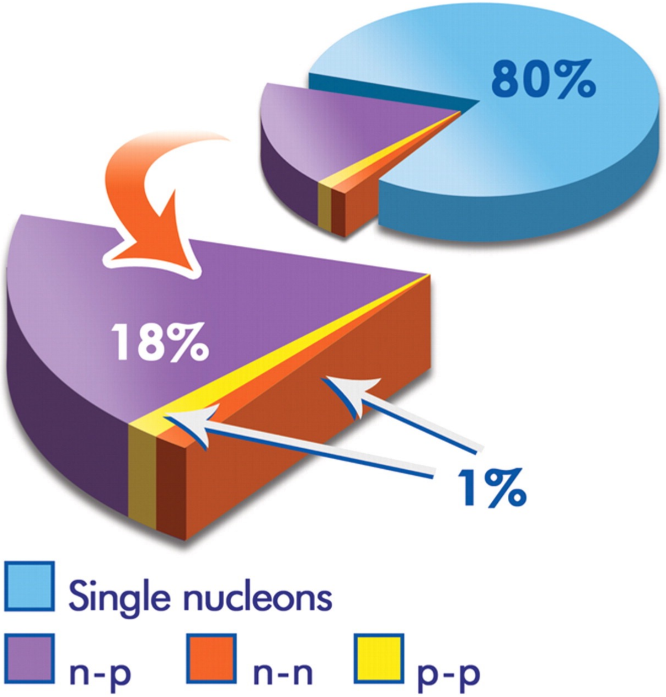
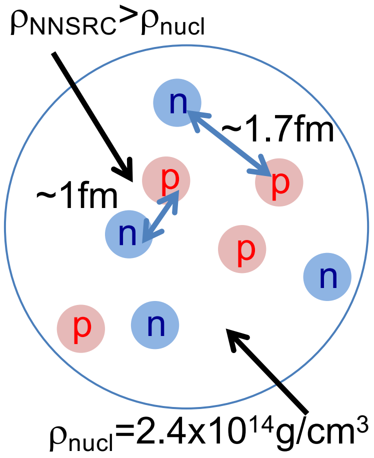
2N potential (Av18)

3N potential (IL7)





Physics of nucleon correlation

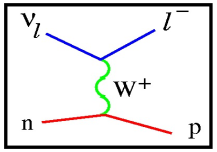
- neutrino interaction
- EMC effect
- $0\nu\beta\beta$
- Direct WIMP detection
- etc

katori@fna

Nucleon correlation is a very hot topics!

NOvA, EPJC80,1119(2020)

Quasi Elastic

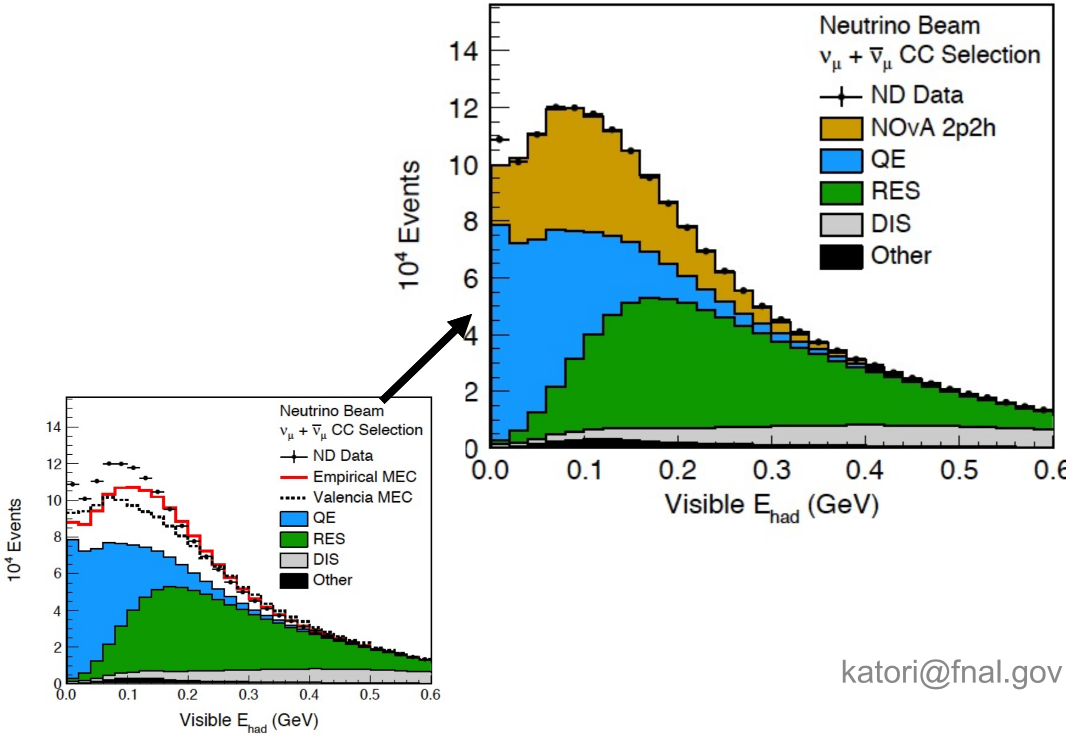


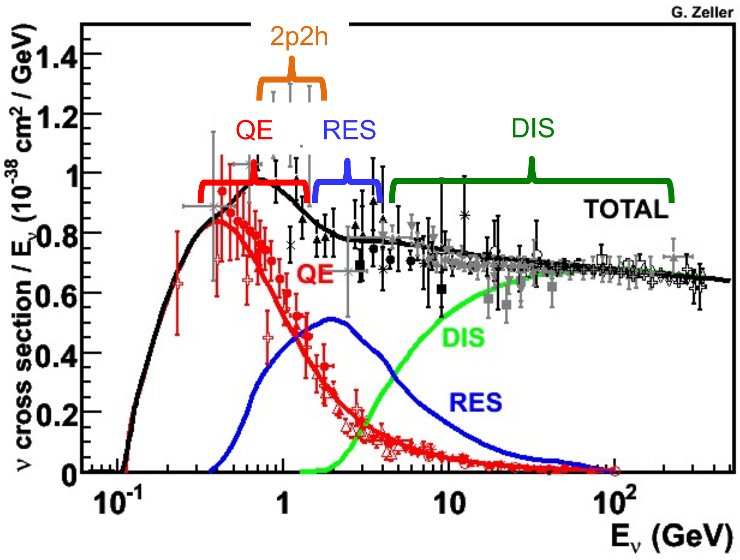
2. Nucleon correlations in neutrino physics

2-particle 2-hole (2p2h) effect

- Essential to describe data
- The biggest topic in nuxsec community (T2K, NOvA, MINERvA, MicroBooNE, etc)
- 2p2h models in generators don't describe data well?
- High resolution detector (LArTPC, emulsion, etc) can find what is going on?

NOvA near detector data-MC comparison after fit





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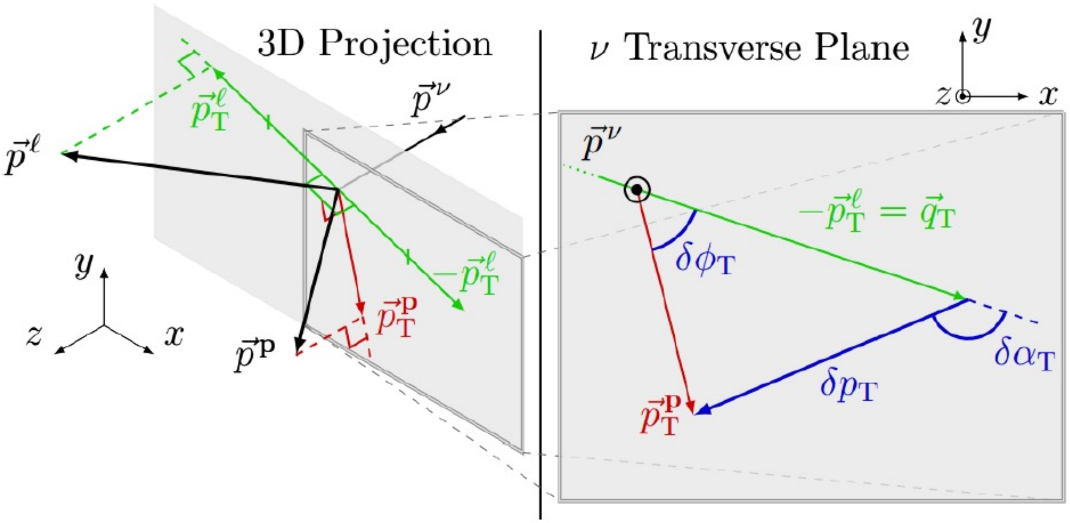
T2K, PRD98(2018)032003
MINERvA,PRL121(2018)022504

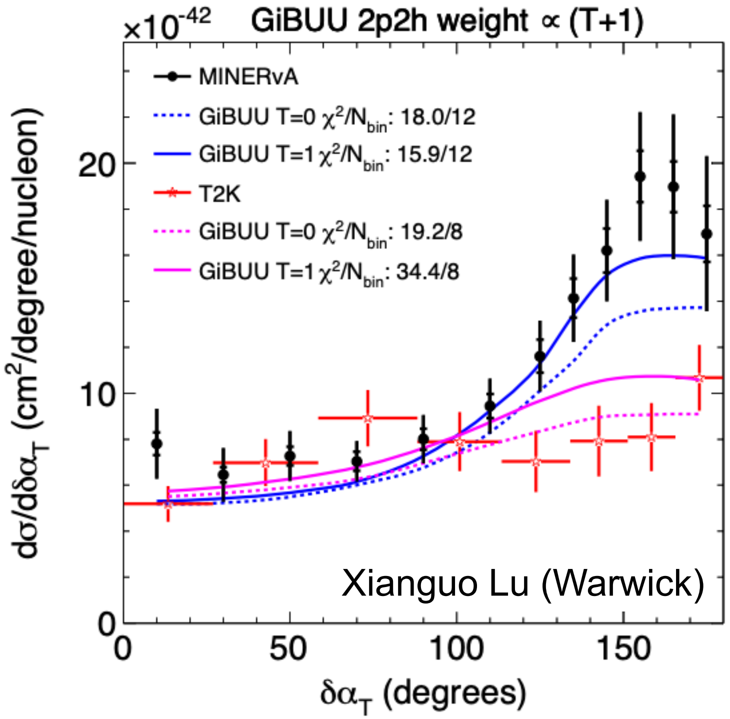
2. Nucleon correlations in neutrino physics

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





Xianguo Lu (Warwick)

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

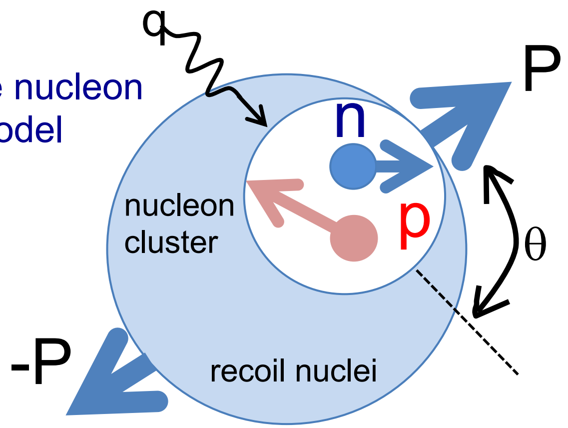
MicroBooNE,PRL125(2020)201803

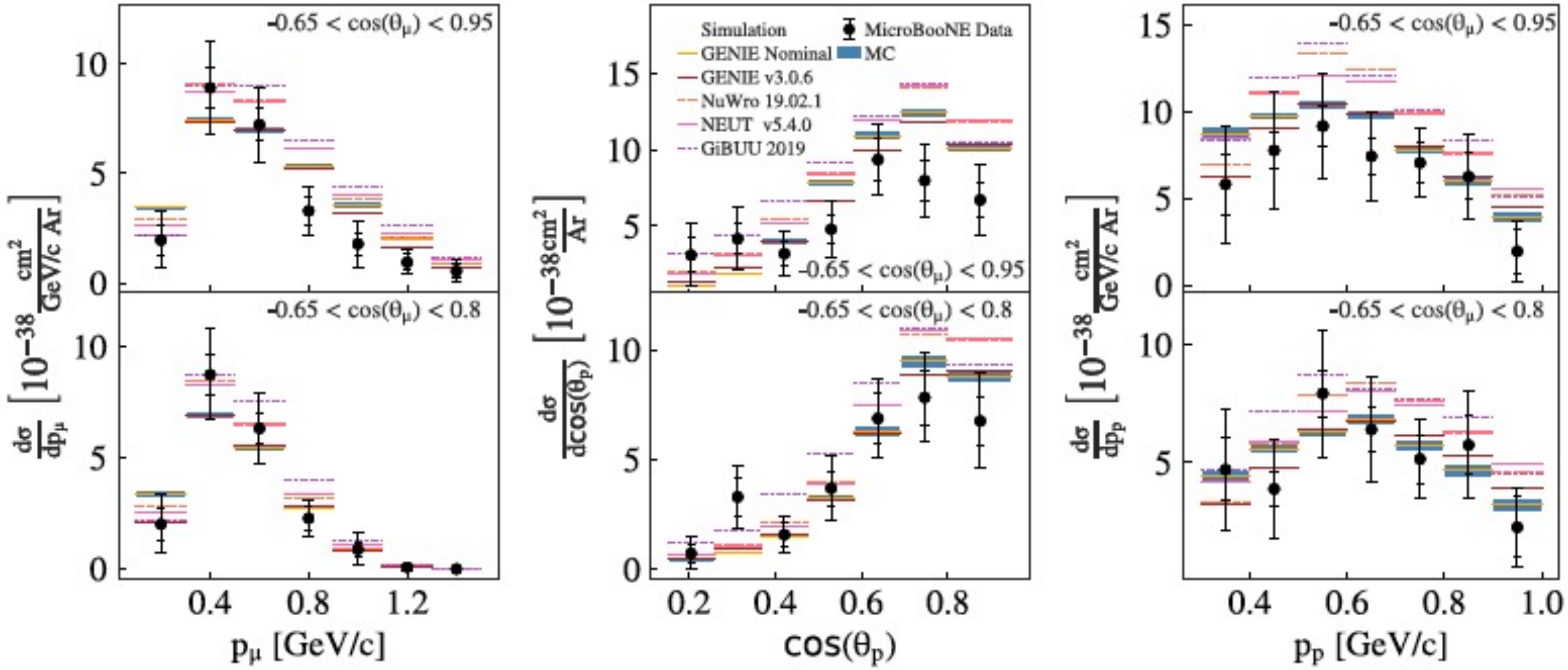
2. Nucleon correlations in neutrino physics

There is a strong belief in experimental community that hadron final states tell everything about 2p2h…

We need prediction of hadronic final states from theorists
- double differential cross-section = lepton kinematics
- final hadron multiplicity/kinematics = home-made

home-made nucleon emission model





1. Neutrino interaction physics - introduction
2. Charged-Current Quasi-Elastic (CCQE) interaction
3. **Neutrino baryonic resonance interaction**
4. Neutrino shallow- and deep-inelastic scatterings
5. Conclusions

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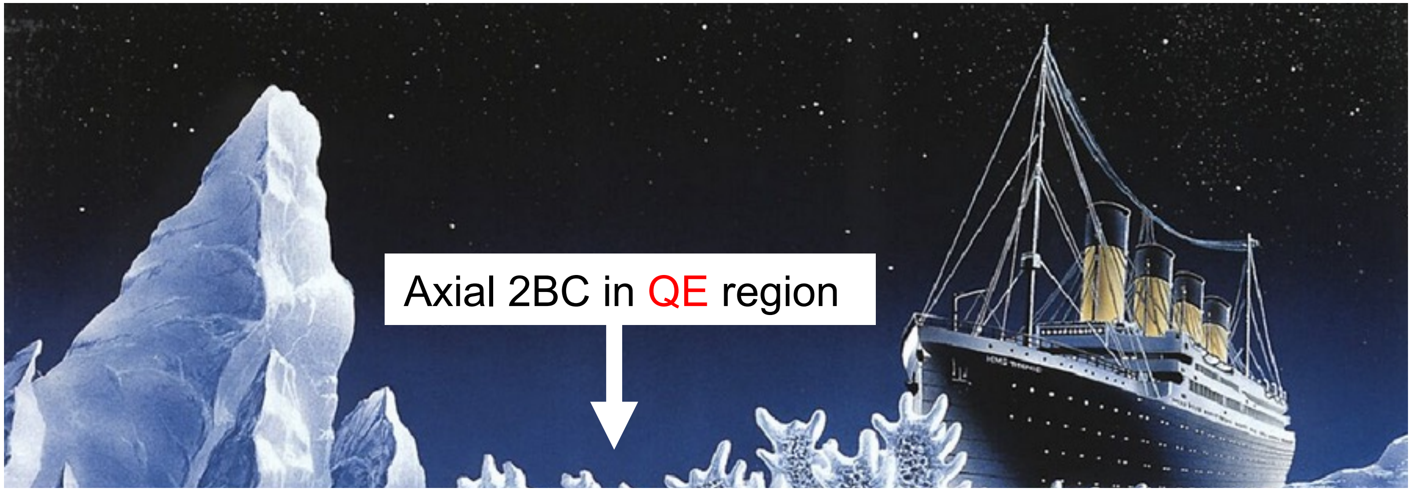
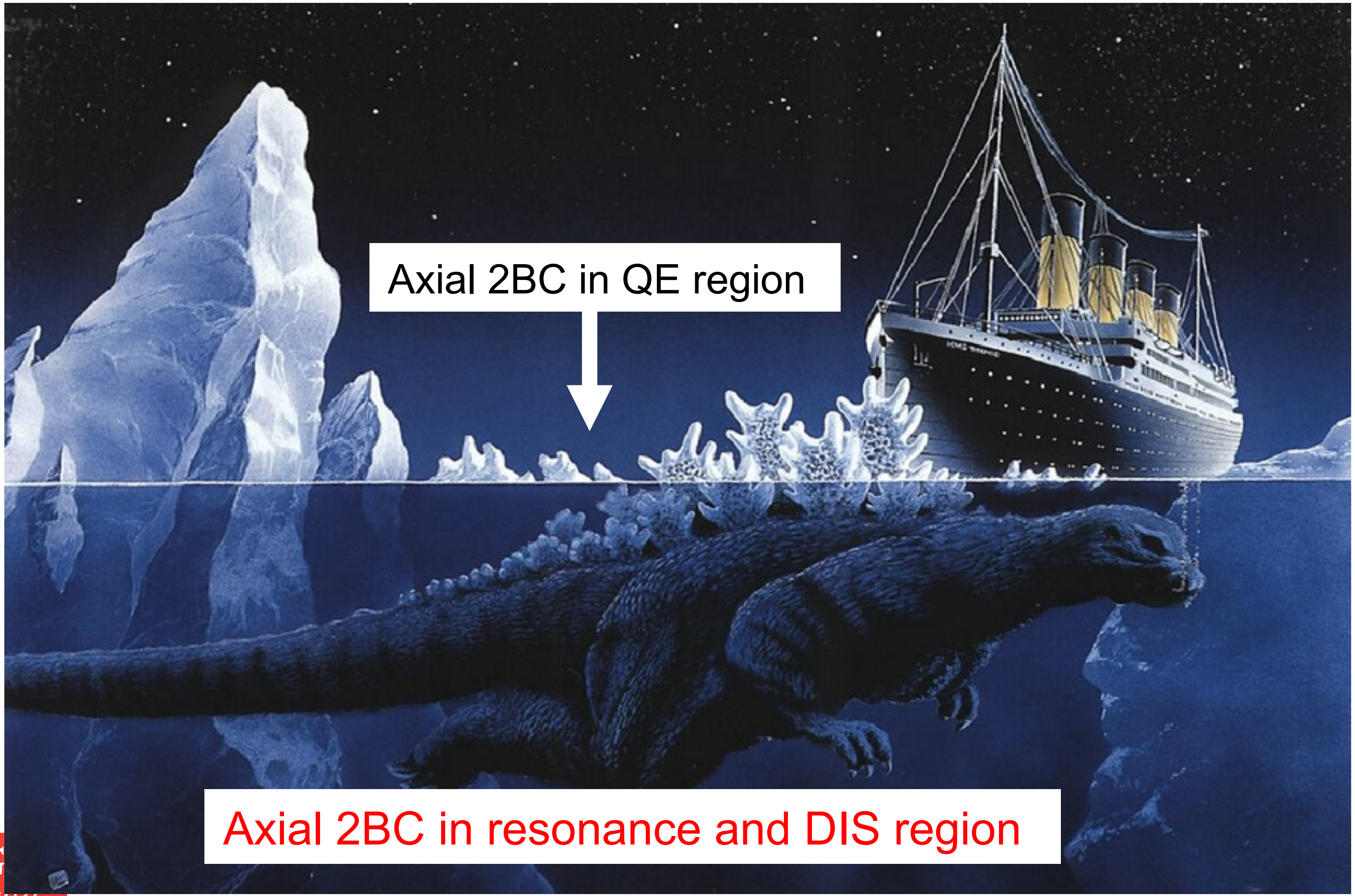
3. Beyond QE peak

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 a tip of gozilla!



Axial 2BC in QE region

Axial 2BC in resonance and DIS region

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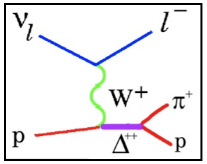
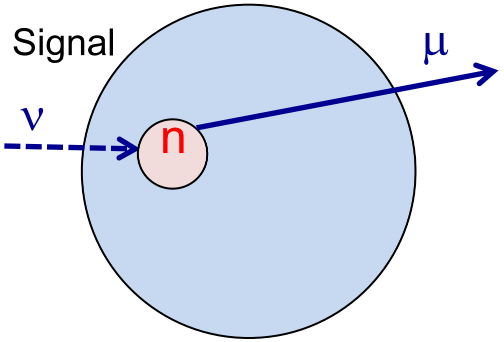
3. non-QE background (resonance pion production)

RESonance



non-QE background → shift spectrum



Neutrino energy is reconstructed from the observed lepton kinematics

“QE assumption”

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

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

(not great detector to measure hadrons)

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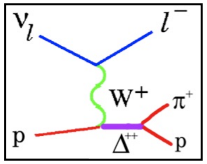
RESonance



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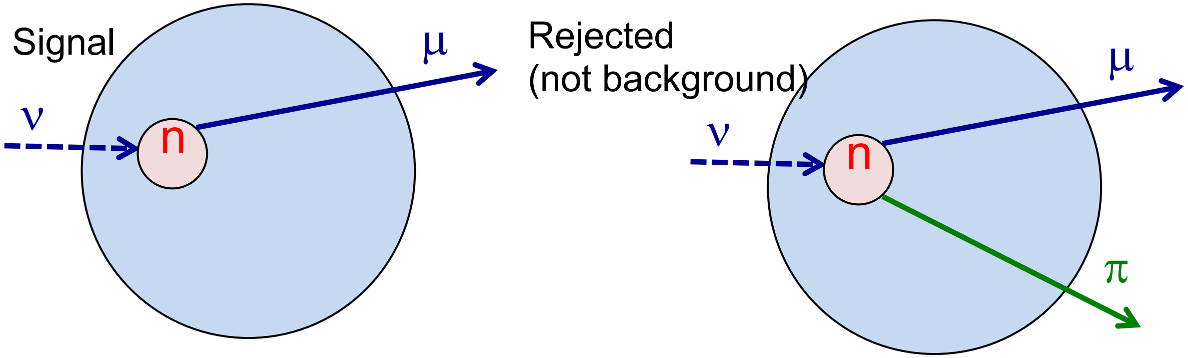

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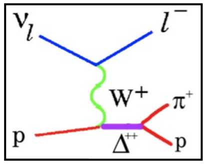

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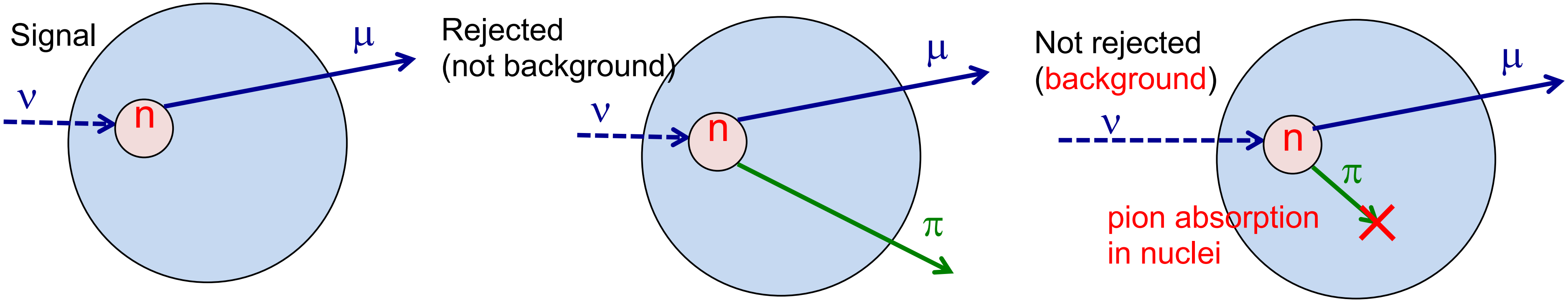
non-QE background → shift spectrum



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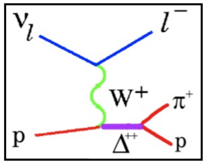
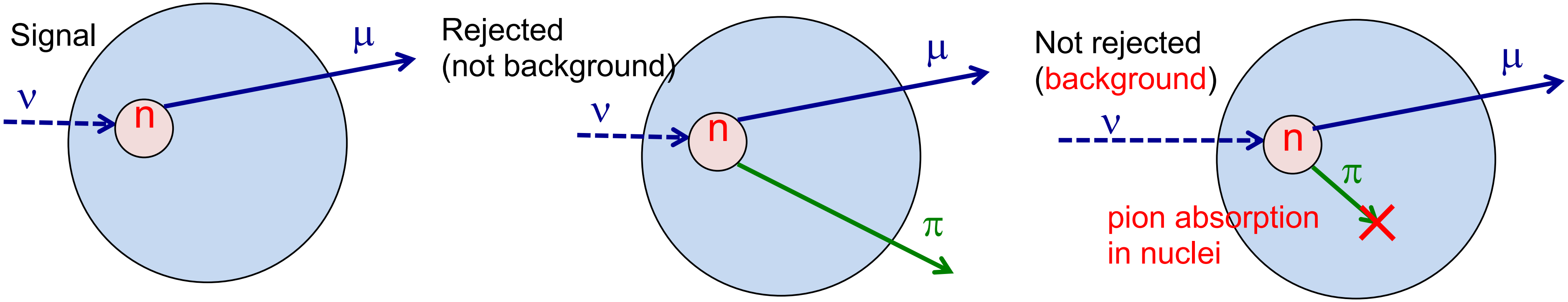
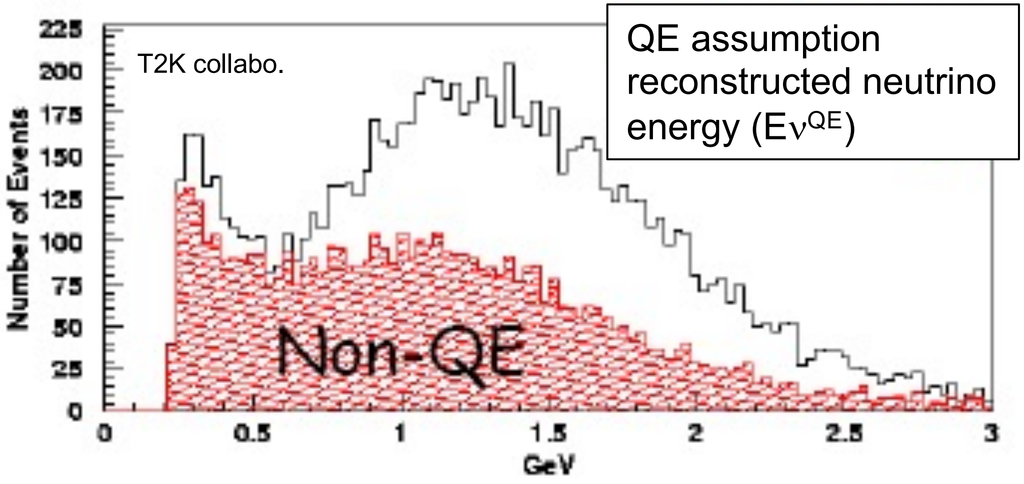
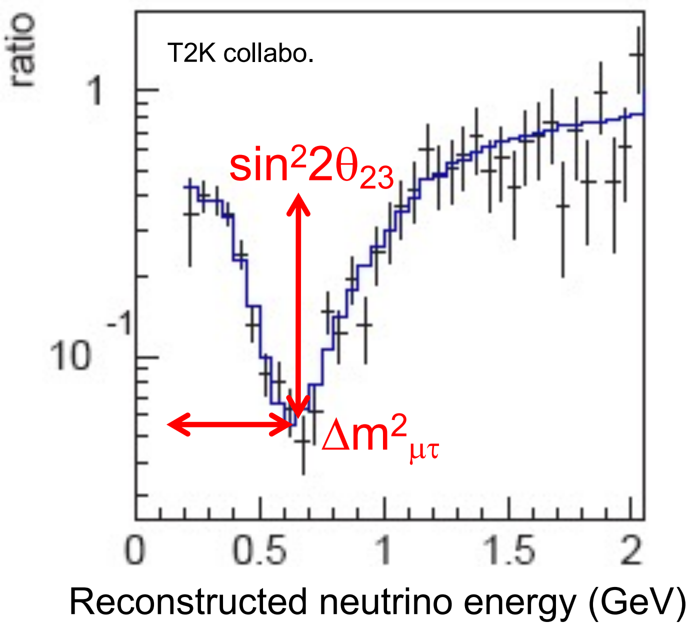


non-QE background → shift spectrum





QE assumption reconstructed neutrino energy ($E\nu^{QE}$)



Solution: you need a good prediction of out-going hadron final states (hard)

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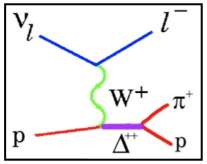
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

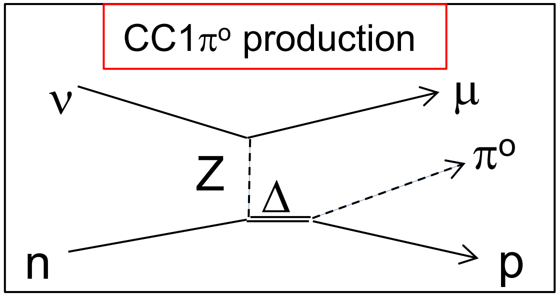
3. Pion puzzle

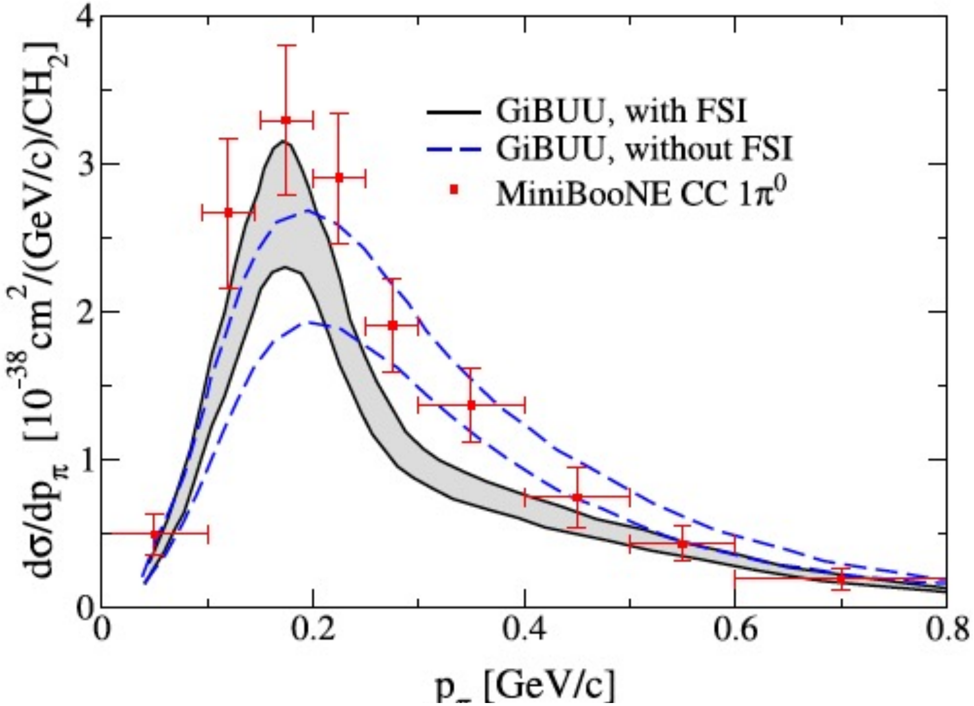
RESonance



Final state interaction

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





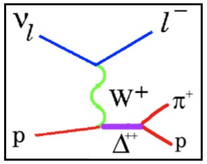
ex) Giessen BUU transport model

- 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

RESonance



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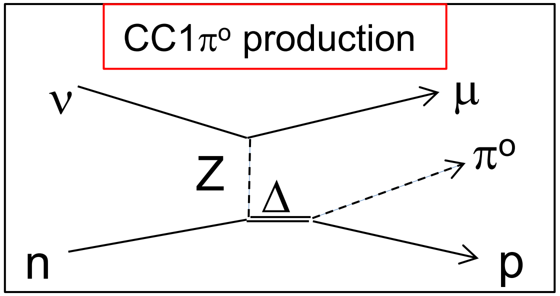
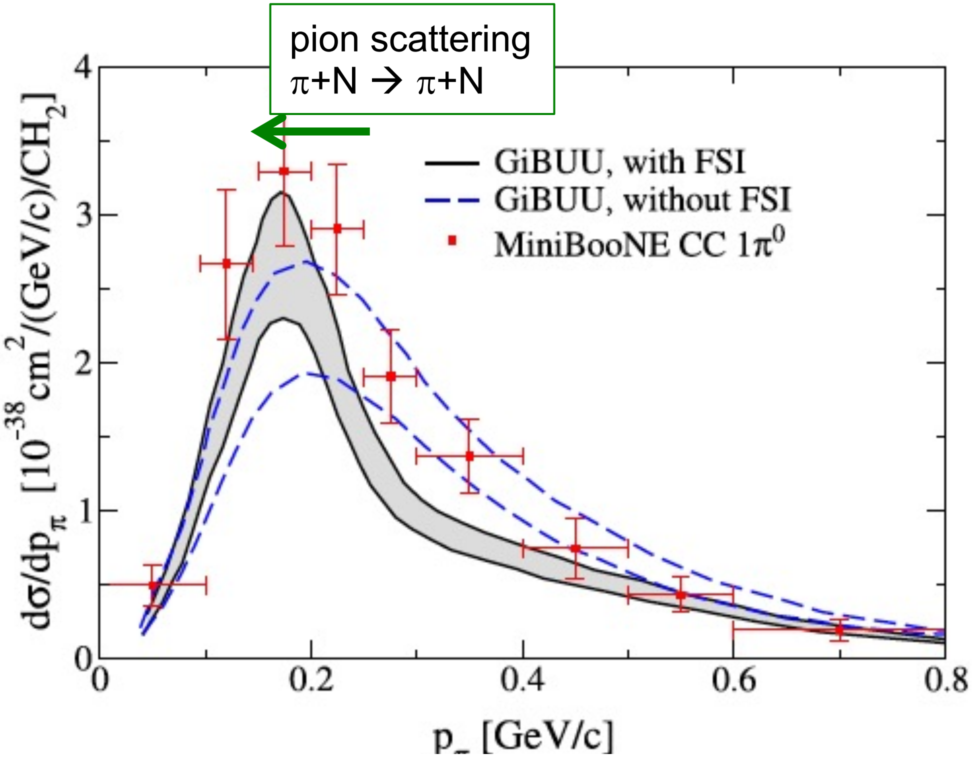

CC1π° production


pion scattering
π+N → π+N

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

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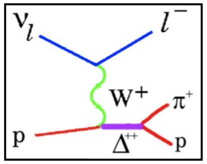
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

3. Pion puzzle

RESonance



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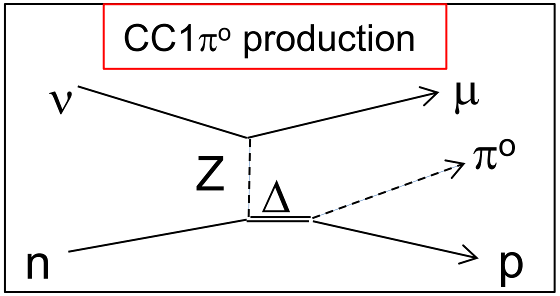
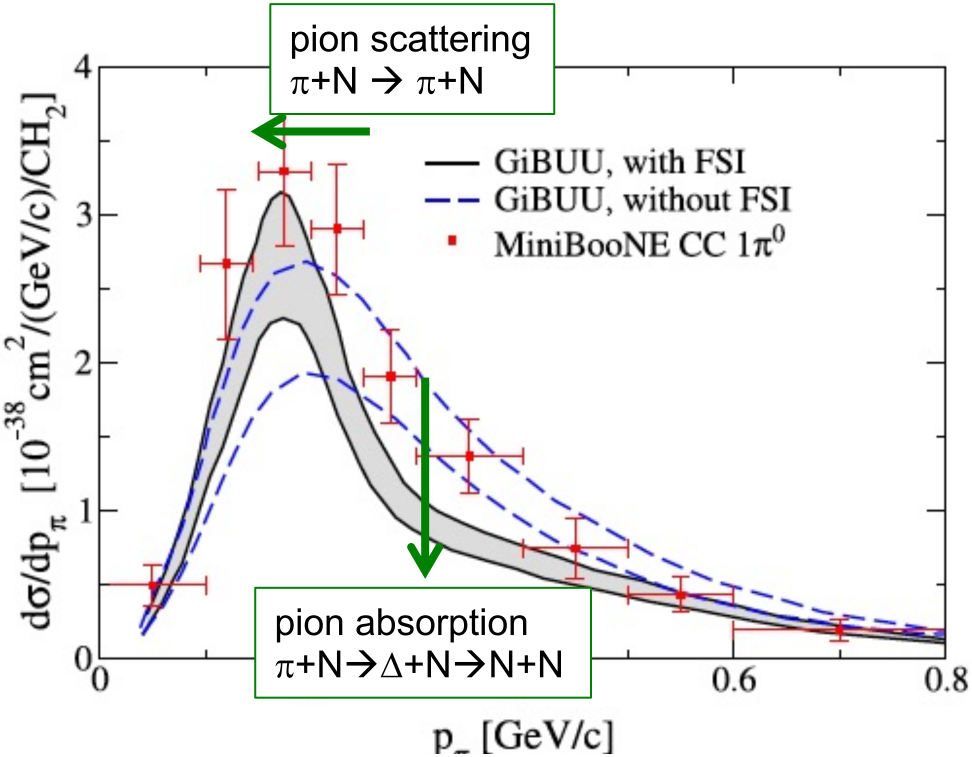

CC1π° production


pion scattering
π+N → π+N

pion absorption
π+N→Δ+N→N+N

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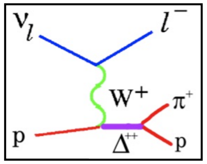
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

3. Pion puzzle

RESonance



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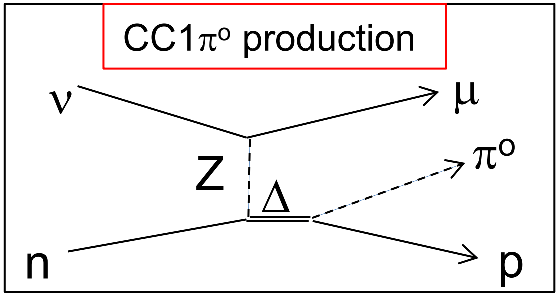
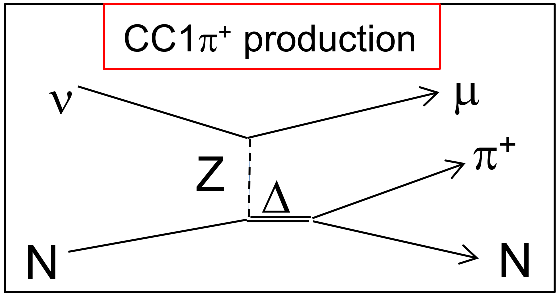
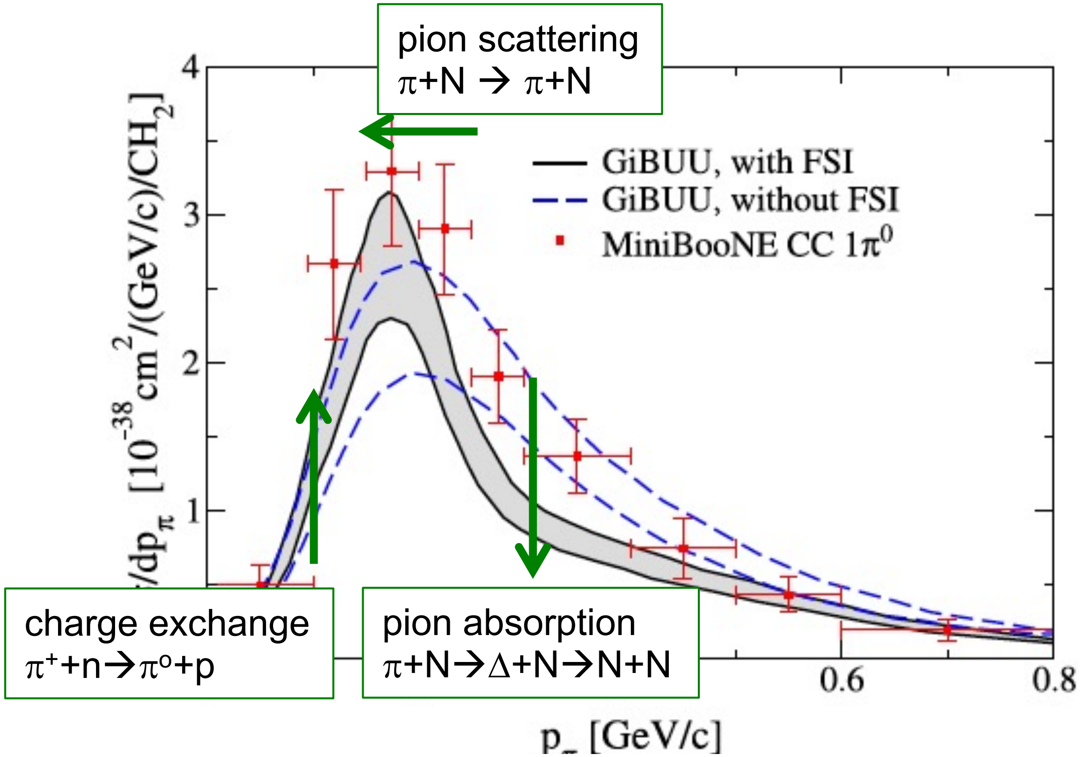






pion scattering
π+N → π+N

charge exchange
π⁺+n→π°+p

pion absorption
π+N→Δ+N→N+N

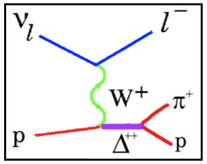
ex) Giessen BUU transport model

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

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

MINERvA,PRD100(2019)072005

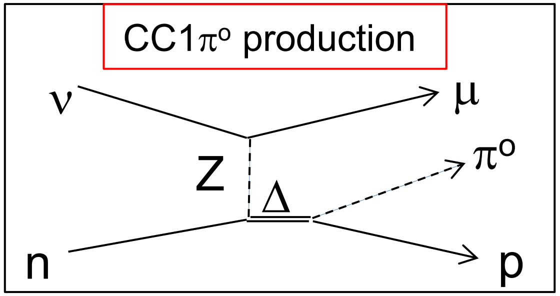
RESonance

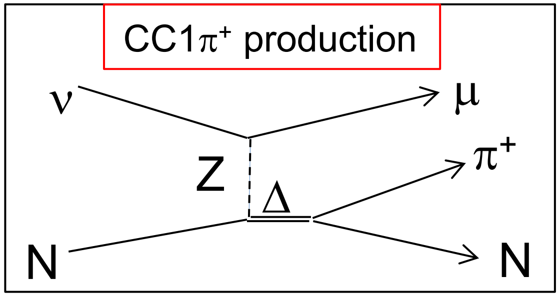


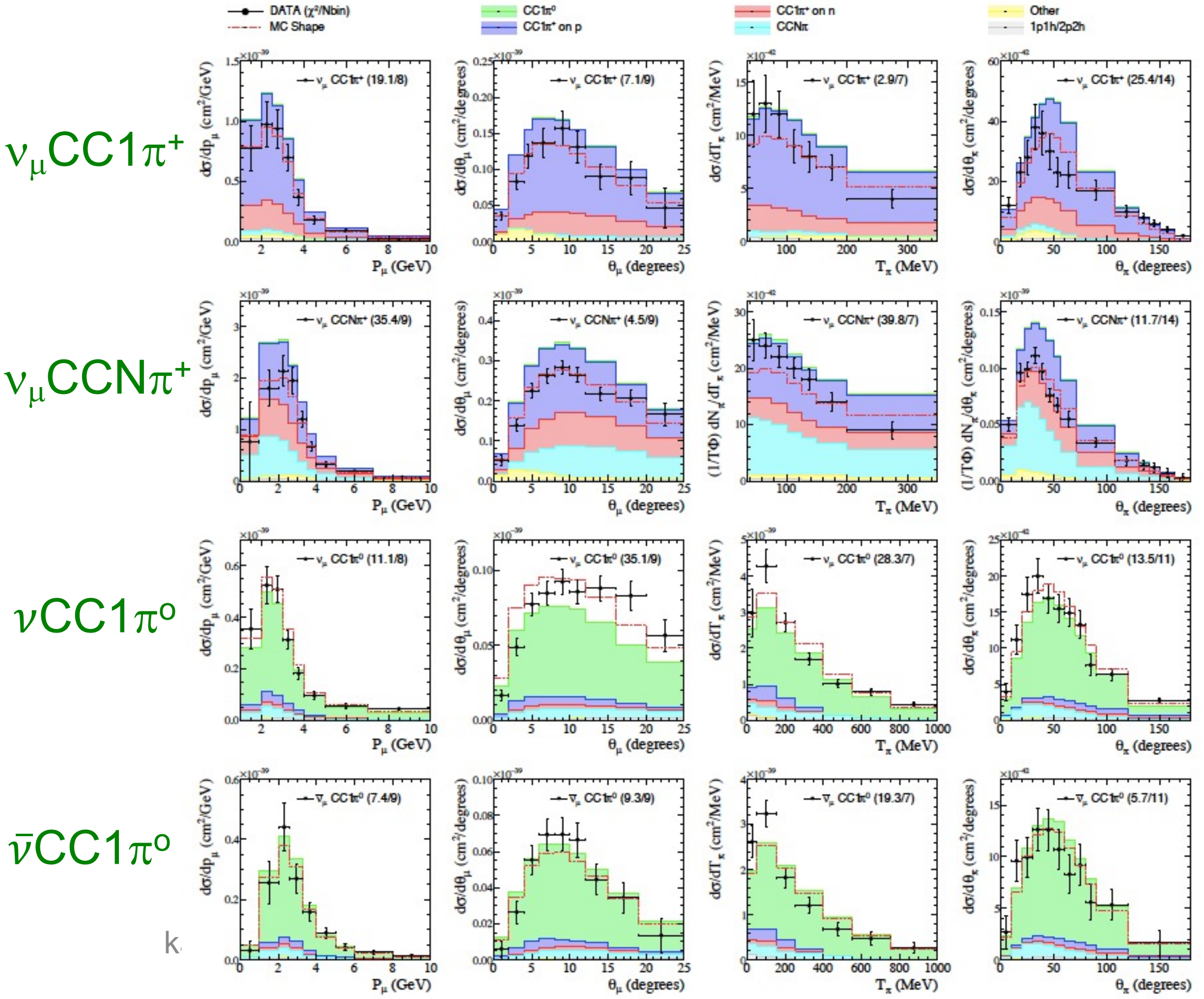
3. Pion puzzle

MINERvA try to fit 4 different data set to tune MC

- Strong tensions between data set
- Both cross section and FSI models need to be improved







You need to predict both

1. pion production model
2. final state interaction

1. Neutrino interaction physics - introduction

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

3. Neutrino baryonic resonance interaction

4. **Neutrino shallow- and deep-inelastic scatterings**

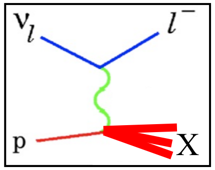
5. Conclusions

katori@fnal.gov

Nakamura et al,Rep.Prog.Phys.80(2017)056301, Sajjad Athar and Morfin, JPhysG48(2021) 034001
Snowmass21 LoI, ArXiv:2009.04285

4. Shallow Inelastic Scattering (SIS)

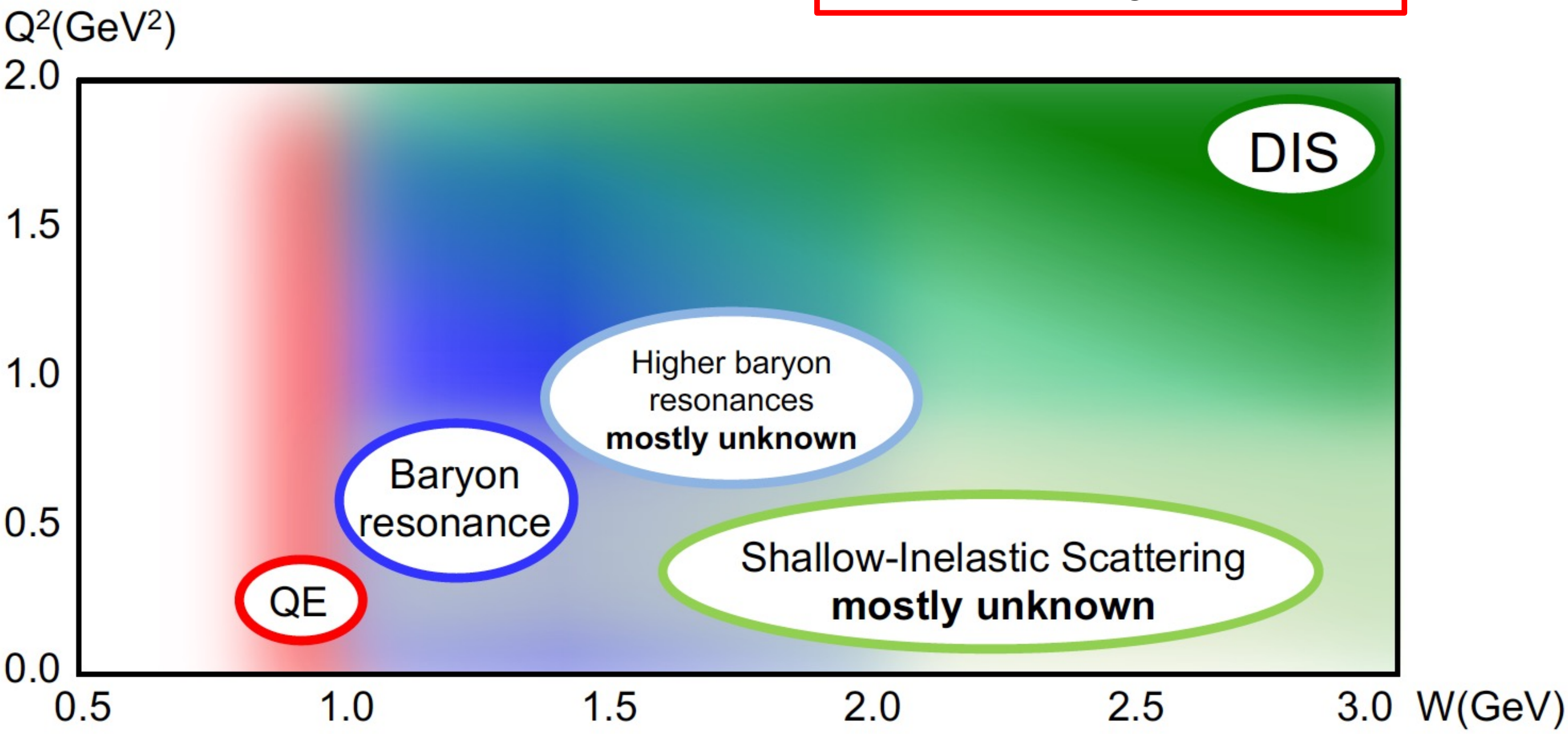
DIS



Cross section

- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

Neutrino experiments around 1-10 GeV are not quite DIS yet
- Shallow → low Q^2
- Inelastic → large W



Nakamura et al,Rep.Prog.Phys.80(2017)056301, Sajjad Athar and Morfin, JPhysG48(2021) 034001
Snowmass21 LoI, ArXiv:2009.04285

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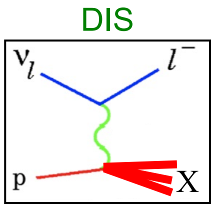

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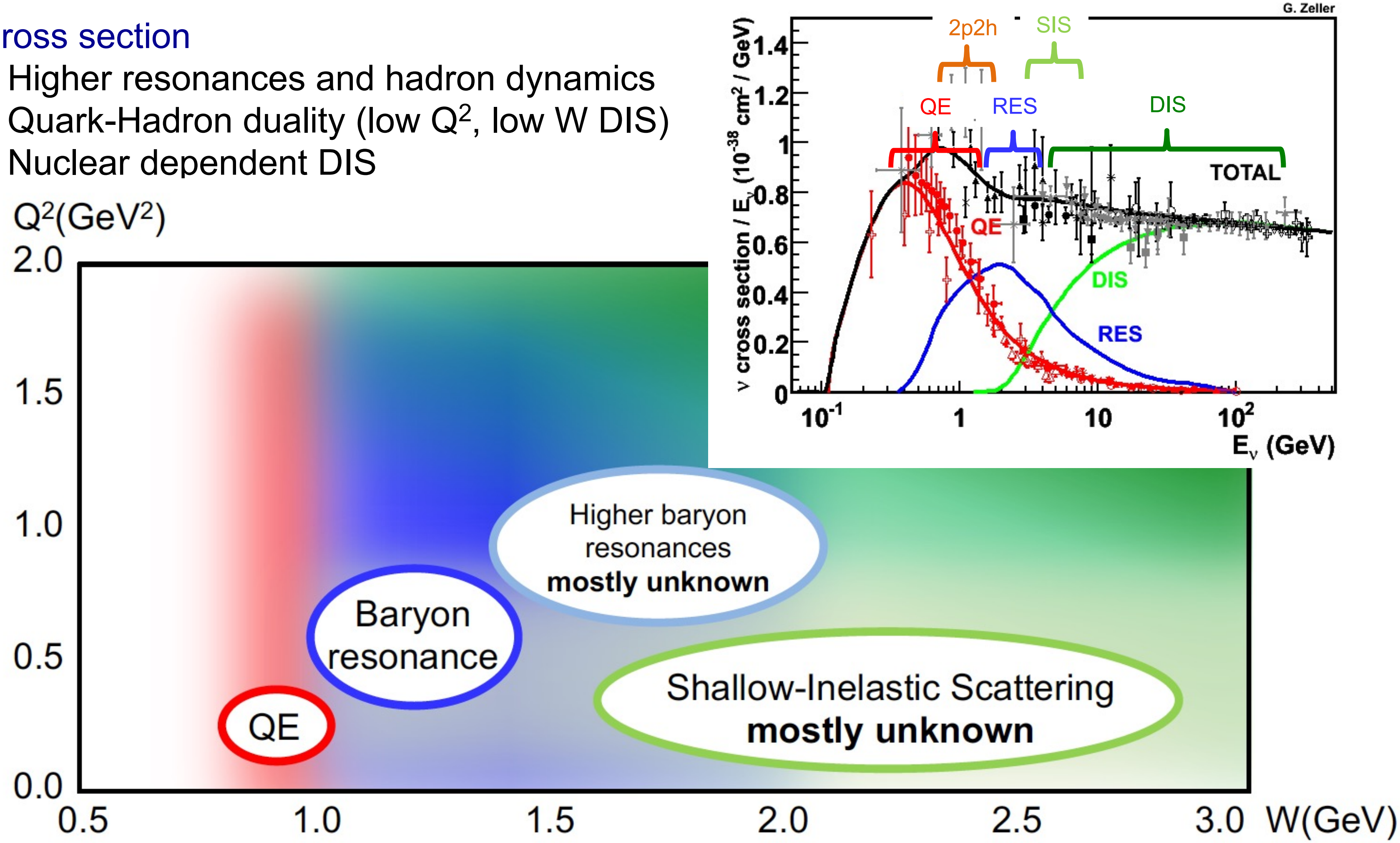


Nakamura et al,Rep.Prog.Phys.80(2017)056301

4. Higher baryonic resonances

Cross section

- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

DCC model

- Channels are coupled (πN, $\pi\pi$N, etc), total amplitude us conserved
- Most of axial form factors are unknown

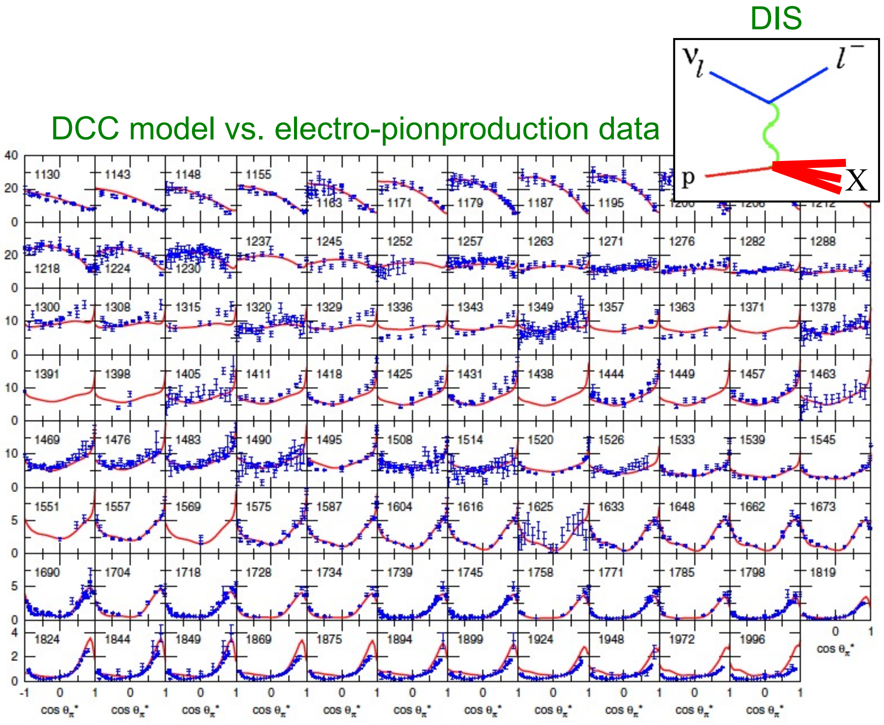
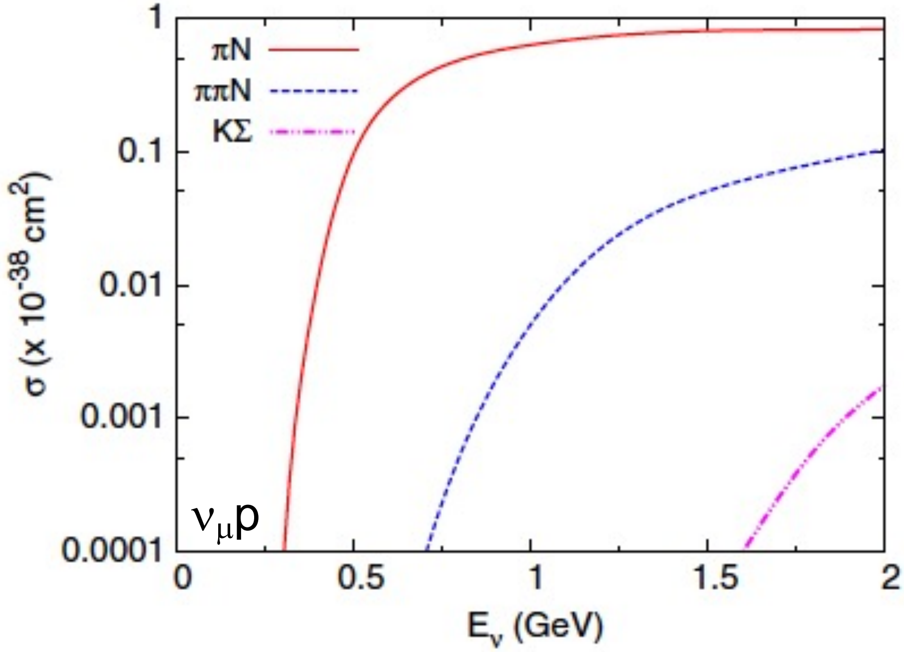
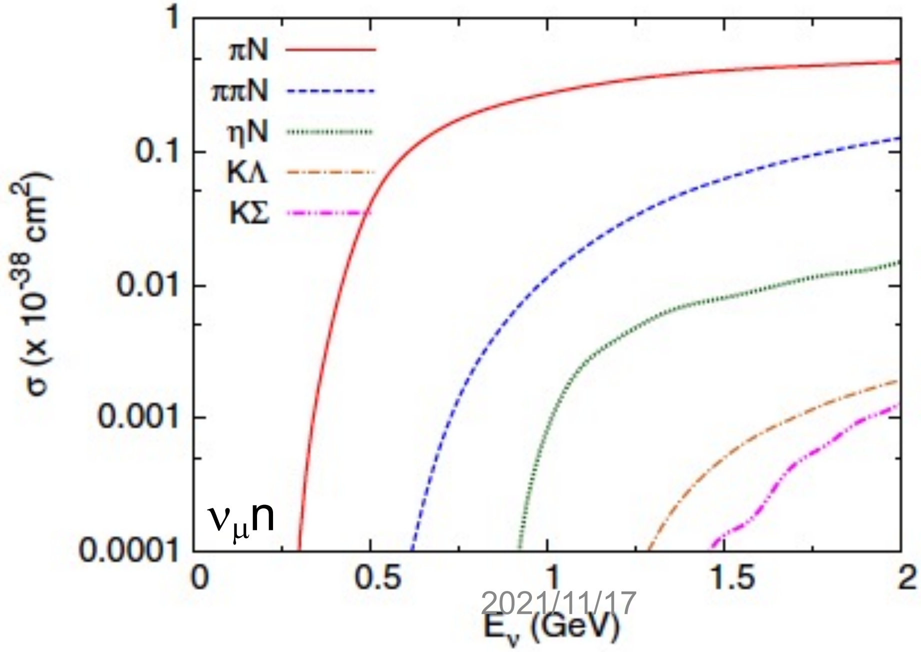


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].



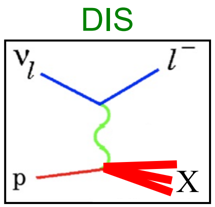


Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11

4. Quark-Hadron duality

Nachtmann variable

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



Cross section

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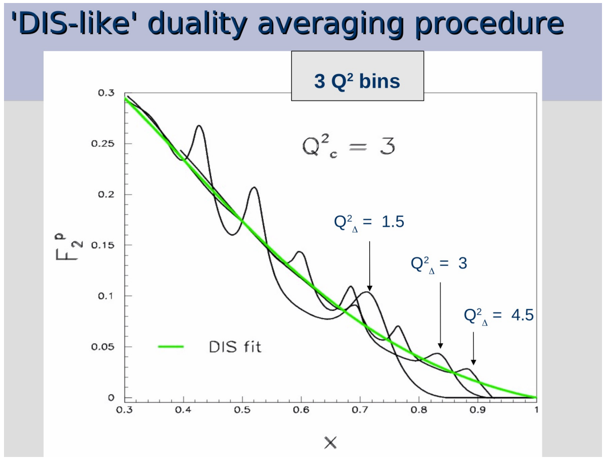
- Nuclear dependent DIS

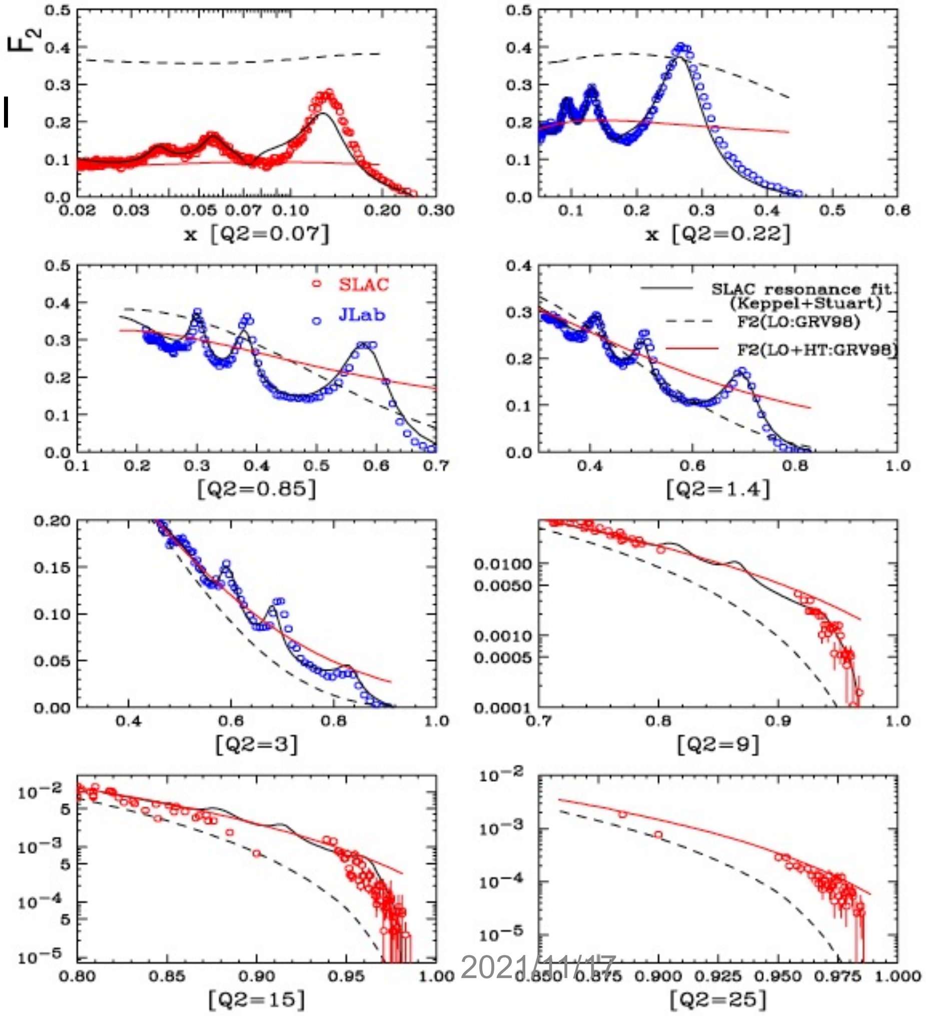
Bodek-Yang correction is a phenomenological model to reproduce duality-like behavior, accepted by all neutrino simulation

DIS ≠ Bjorken limit

DIS = Q^2 average of all resonances



Proton F2 function GRV98-BY correction vs. data

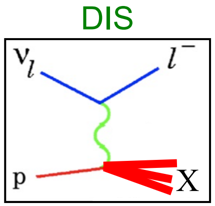


Christy, NuSTEC SIS workshop

https://nustec.fnal.gov/nuSDIS18/

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

4. Nuclear dependent DIS



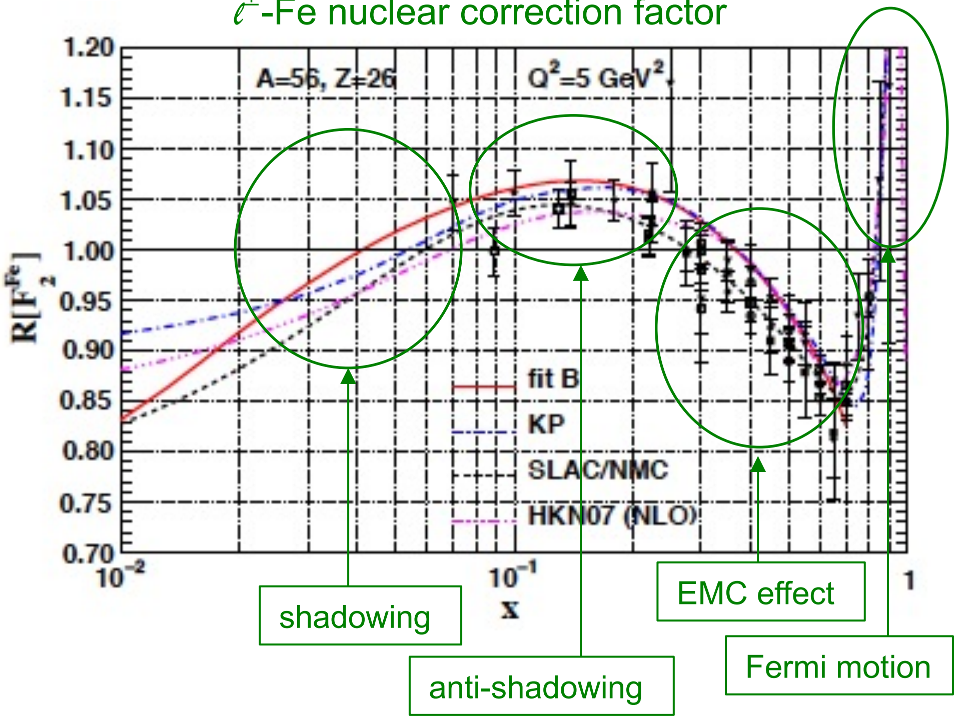
Cross section

- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

Nuclear PDF

- Shadowing, EMC effect, Fermi motion
- Likely due to nucleon dynamics in nucleus
- Various models describe charged lepton data
- Neutrino data look very different

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



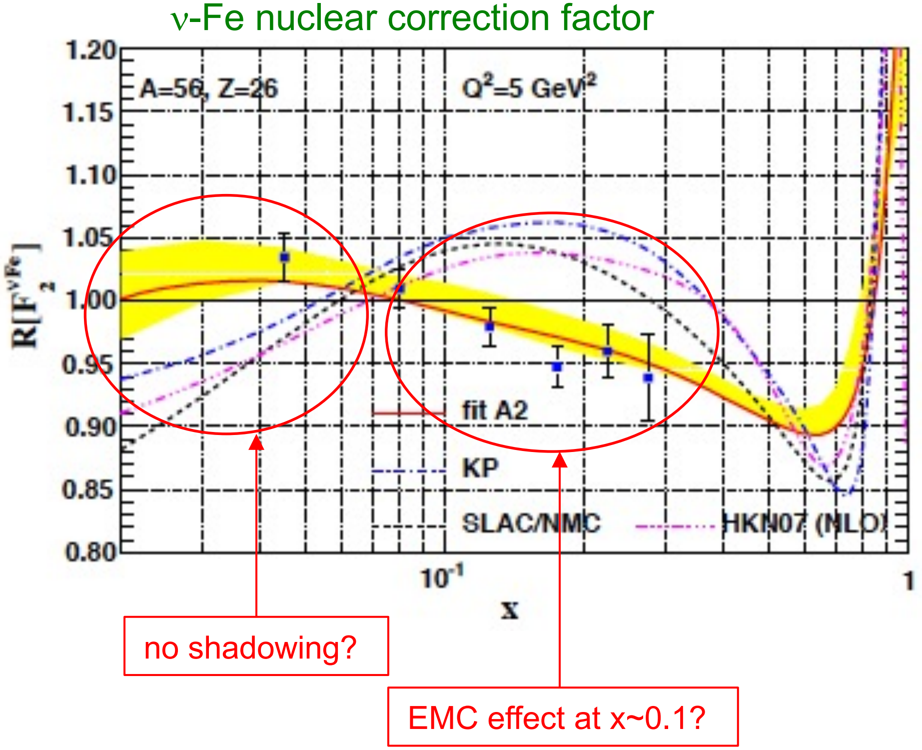
shadowing

anti-shadowing

EMC effect

Fermi motion

ν-Fe nuclear correction factor



no shadowing?

EMC effect at x~0.1?

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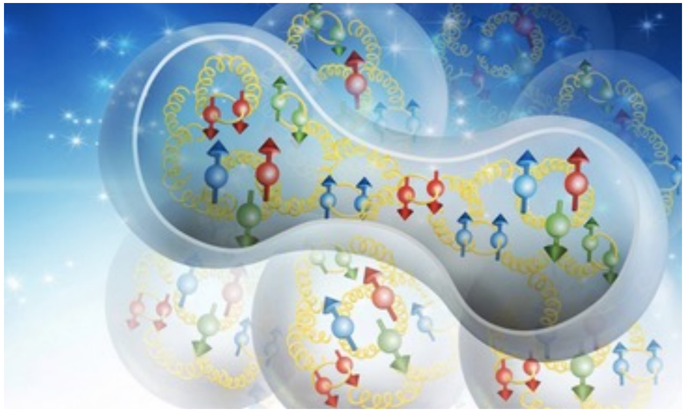
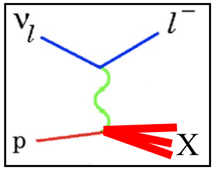
2021/11/17

nCTEQ, PRD80(2009)094004
Weinstein et al, PRL106(2011)052301, Nature 566 (2019) 354,

4. EMC effect



DIS

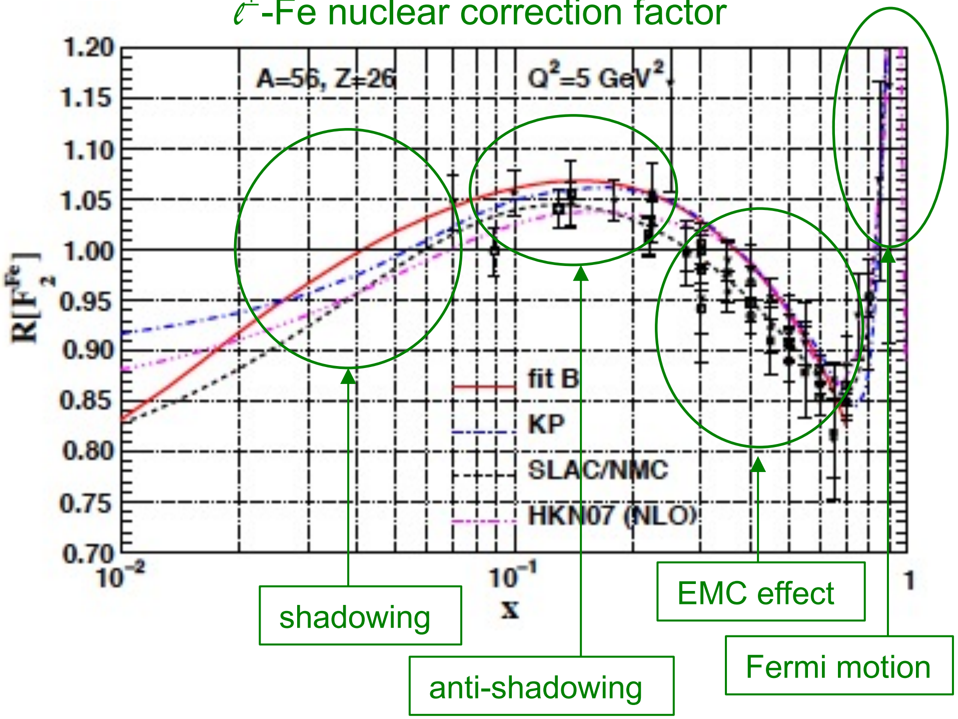


Nuclear dependent DIS

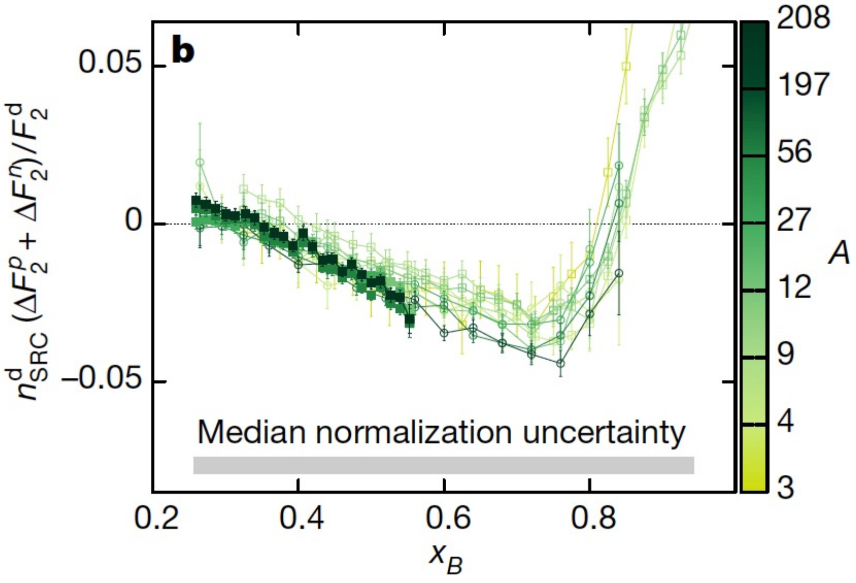
- First observed by the EMC experiment
- Structure function depends on nuclei

→ Quarks feel presence of other quarks in other nucleons

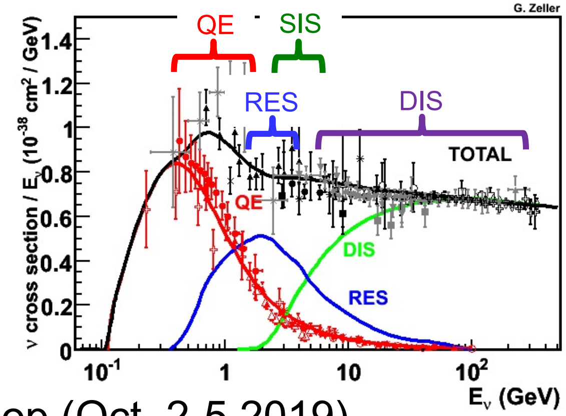
$\ell^\pm$-Fe nuclear correction factor



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



4. NuSTEC workshops



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

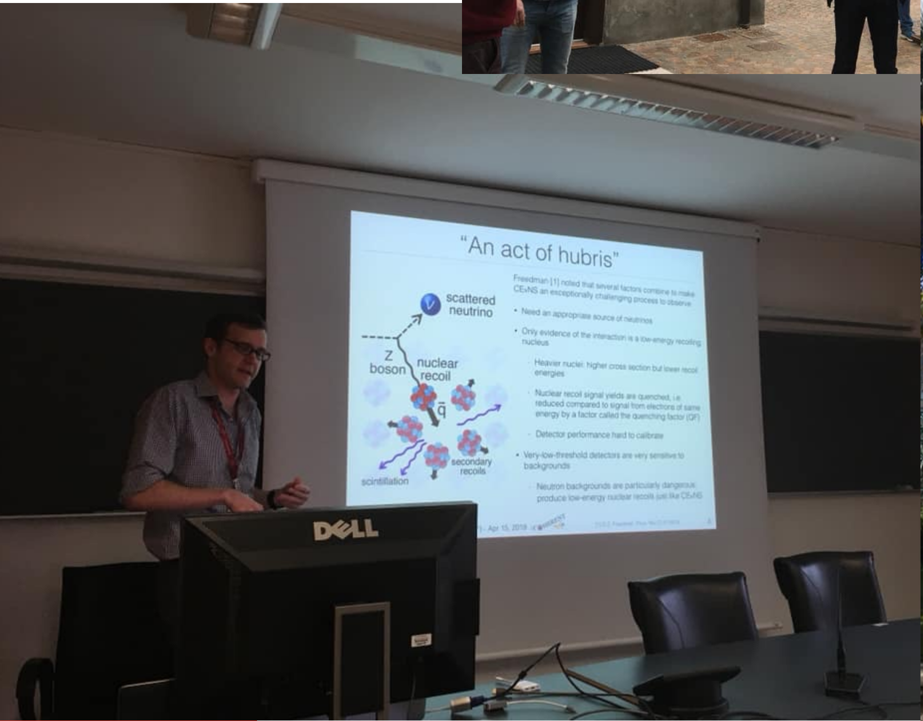
NuSTEC SIS workshop (Oct. 11-13 2018)
L'Aquila, Italy
https://nustec.fnal.gov/nuSDIS18/
Summary paper (https://arxiv.org/abs/1907.13252)

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

4. Atomic nuclei as laboratories for BSM physics

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

Topics include;
- 2p2h
- EMC effect
- $0\nu\beta\beta$
- dark matter
- etc



"An act of hubris"

Freedman [1] noted that several factors combine to make CEνNS an exceptionally challenging process to observe
- Need an appropriate source of neutrinos
- Only evidence of the interaction is a low-energy recoiling nucleus
  - Heavier nuclei: higher cross section but lower recoil energies
  - Nuclear recoil signal yields are quenched, i.e. reduced compared to signal from electrons of same energy by a factor called the quenching factor (QF)
  - Detector performance hard to calibrate
- Very-low-threshold detectors are very sensitive to backgrounds
  - Neutron backgrounds are particularly dangerous: produce low-energy nuclear recoils just like CEνNS

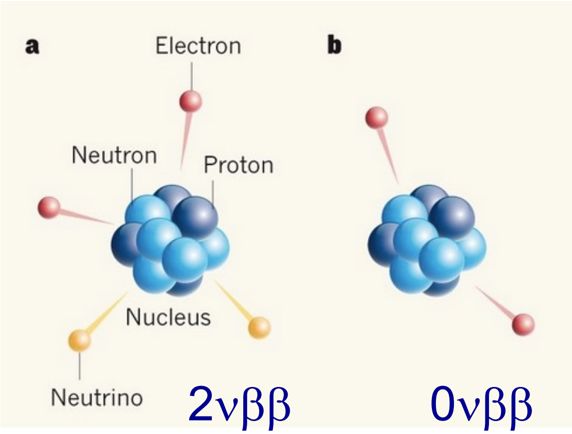
Apr 15, 2019

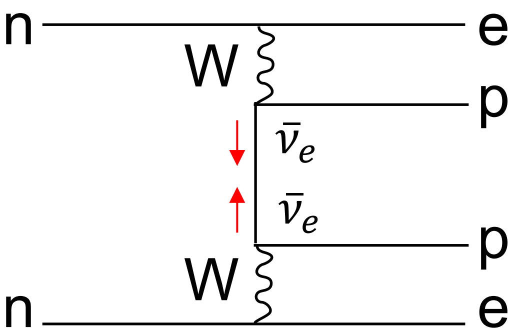
Giuliani, Neutrino 2018

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

Majorana particle

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

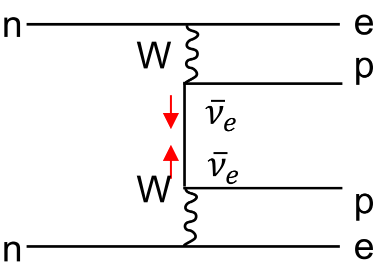




$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2\, m_{\beta\beta}^{\;2}$$

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

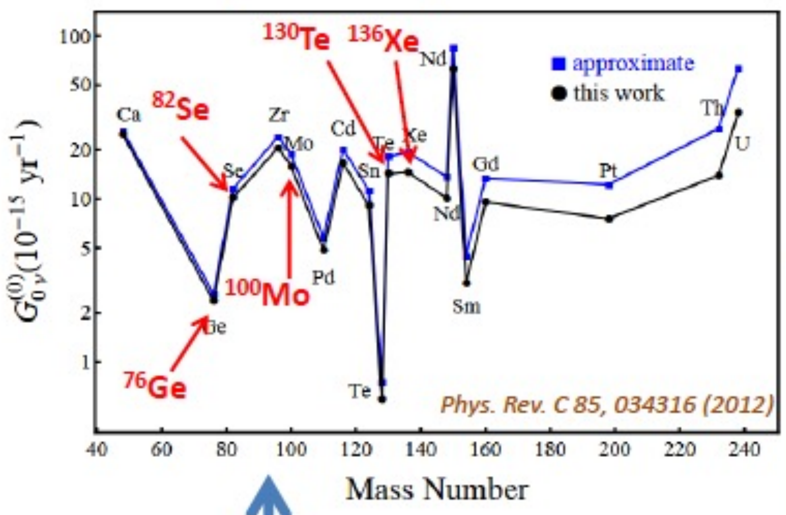
4. Neutrino-less double beta decay (0νββ)



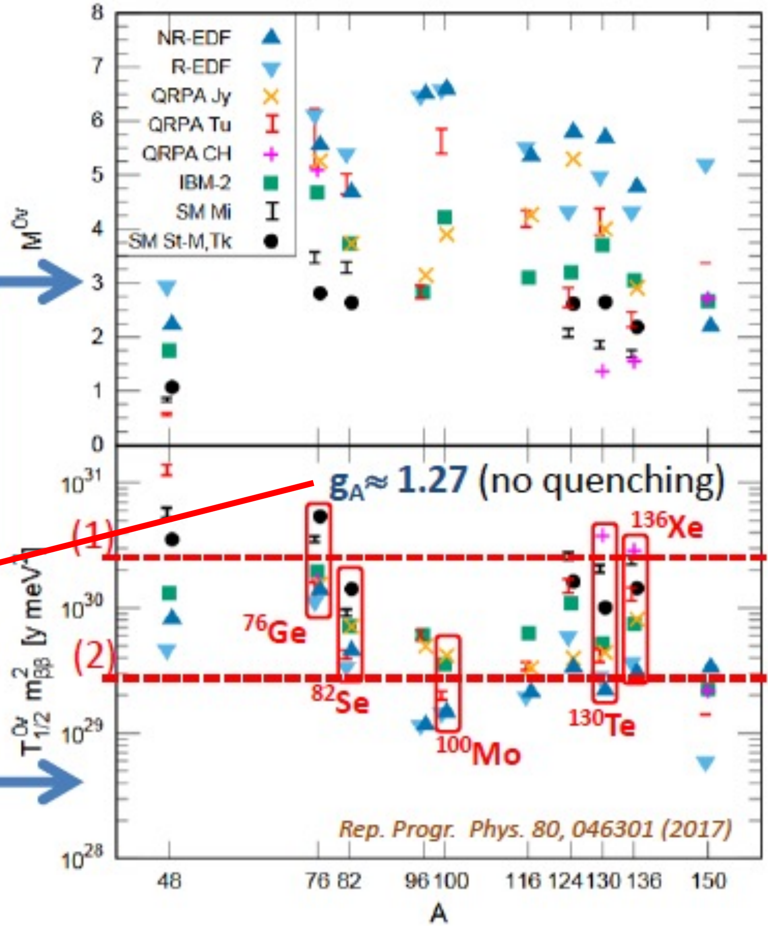
Majorana particle

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

Phase space: exactly calculable



Nuclear matrix elements: several models

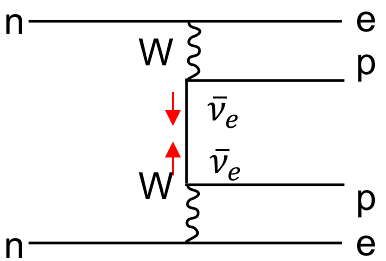


$$1/\tau = G(Q,Z)\, g_A{}^4 |M_{nucl}|^2\, m_{\beta\beta}{}^2$$

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

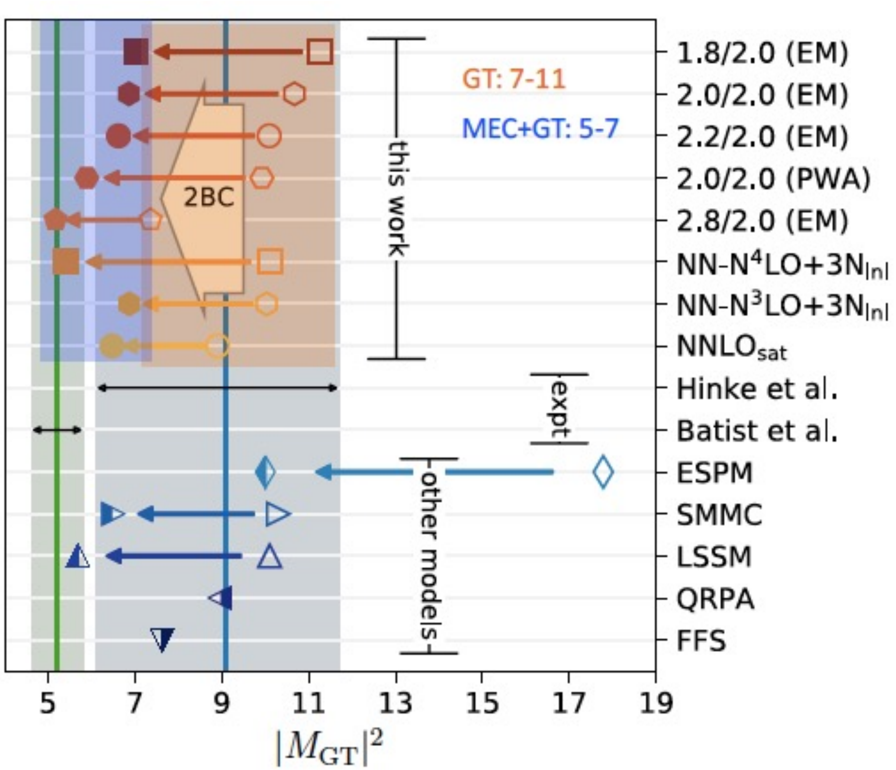
P. Gysbers, G. Hagen, et al, Nature Phys. 15(2019)428

4. 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

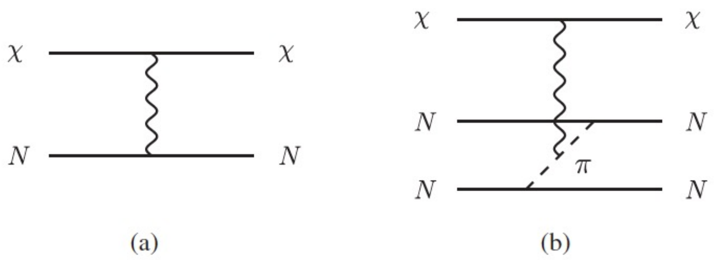


Physicists solve a beta-decay puzzle with advanced nuclear models

by Oak Ridge National Laboratory

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

4. Direct WIMP-pion scattering



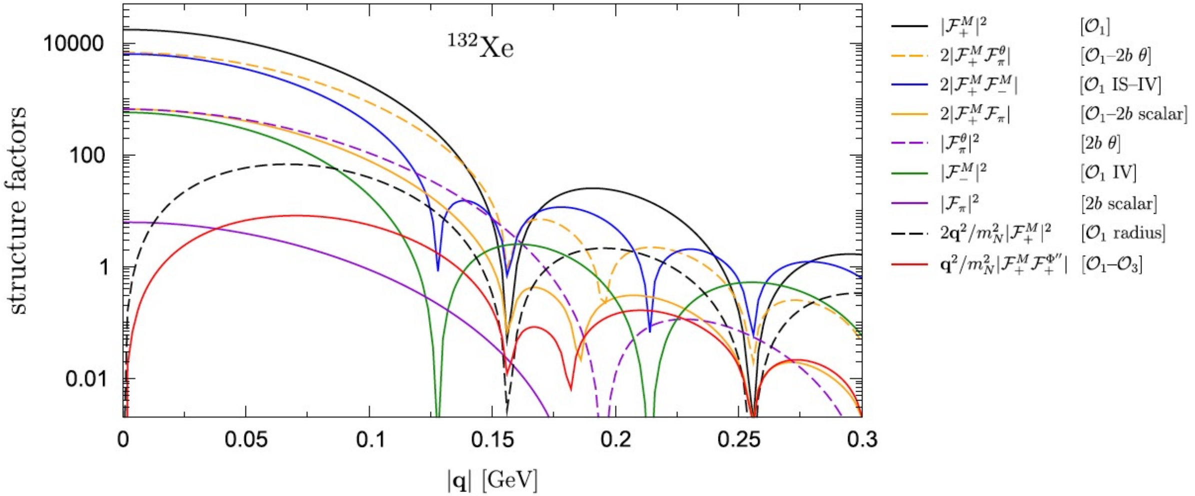
(a)

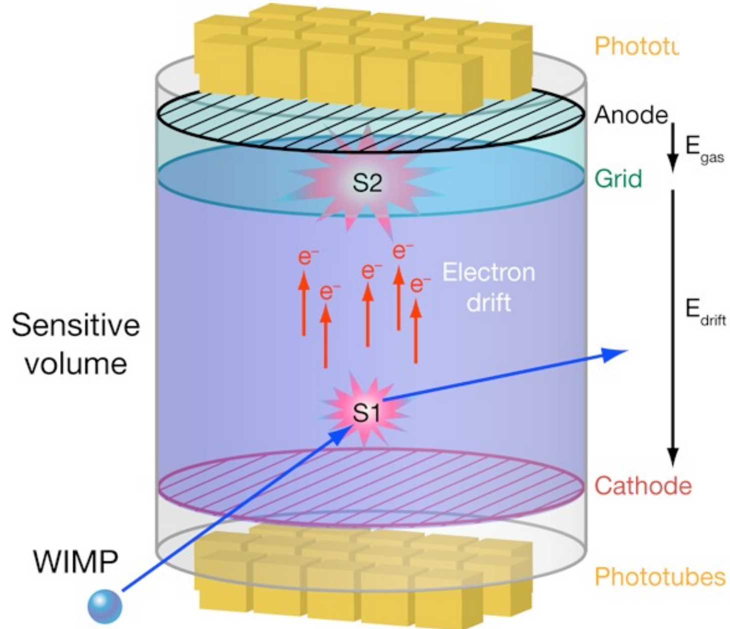
(b)

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.

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





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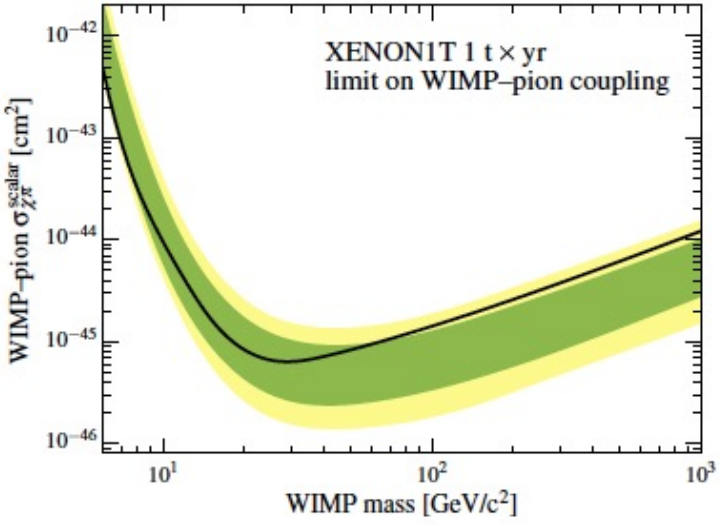

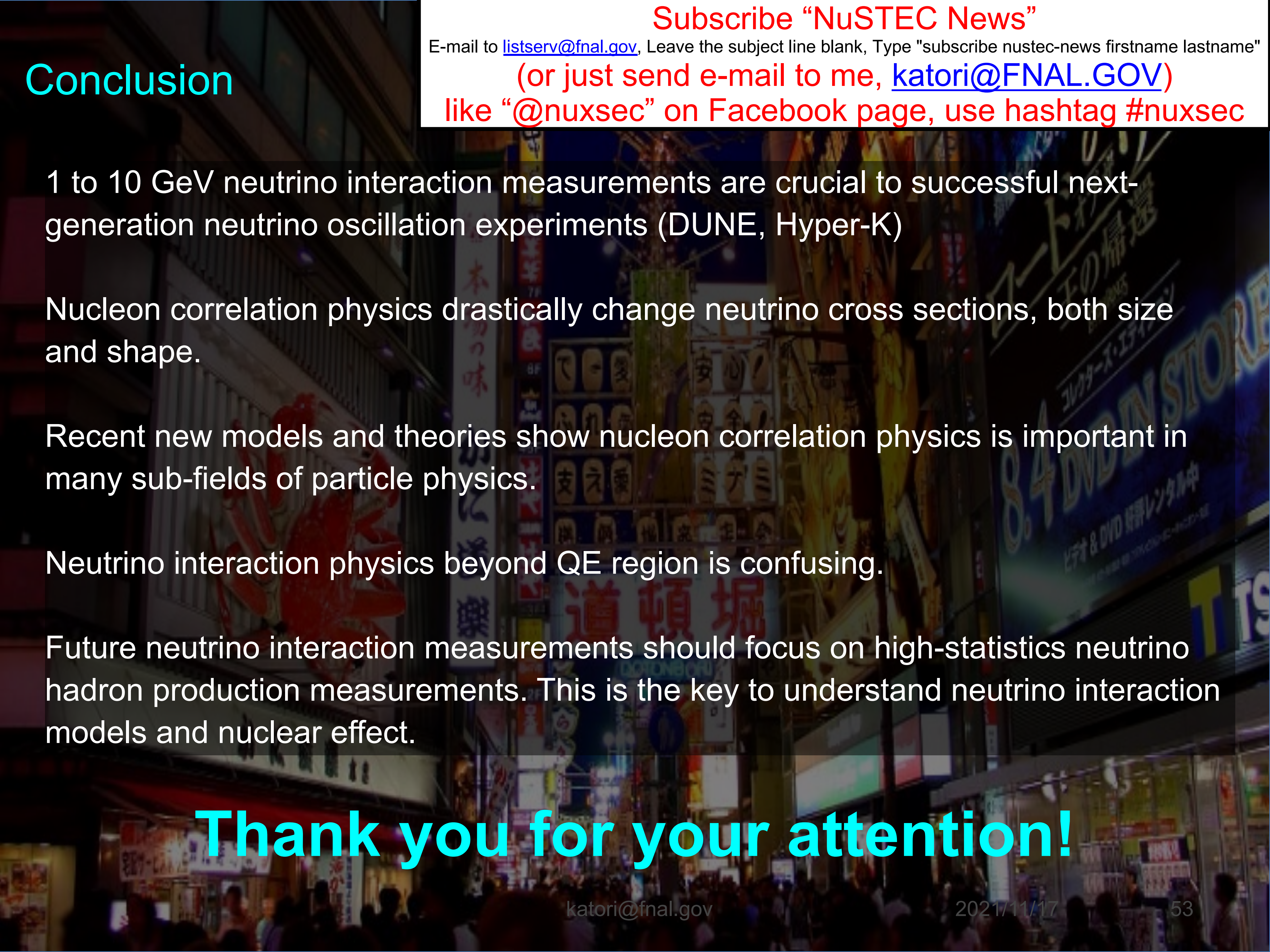

Conclusion

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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

katori@fnal.gov

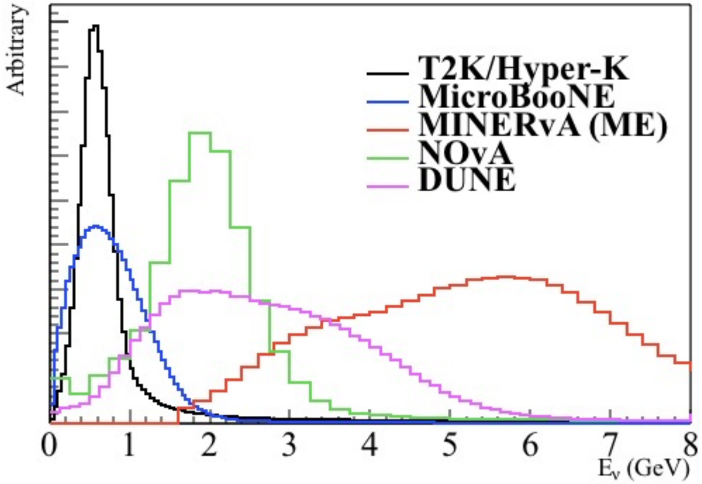
1. Next generation neutrino oscillation experiments

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 $E\nu=0$ to $E\nu$ ~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

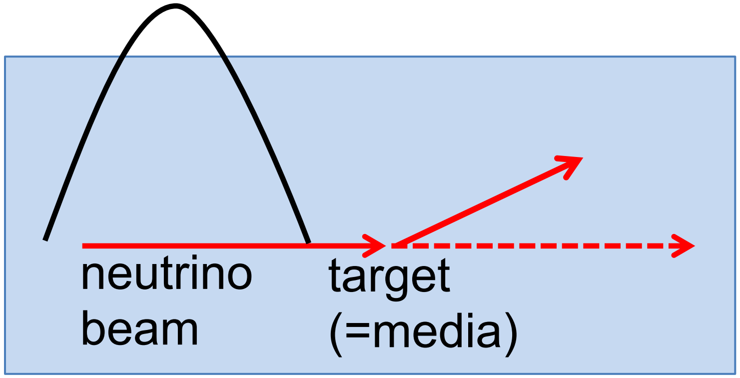
TK, Martini, JPhysG45(2017)1

1. Typical neutrino detectors

Neutrino scattering

- Wideband beam

→ observables are inclusive



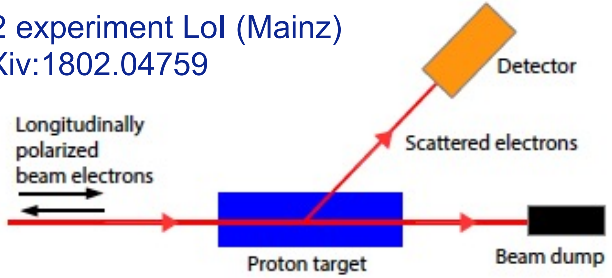
Electron scattering

- 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

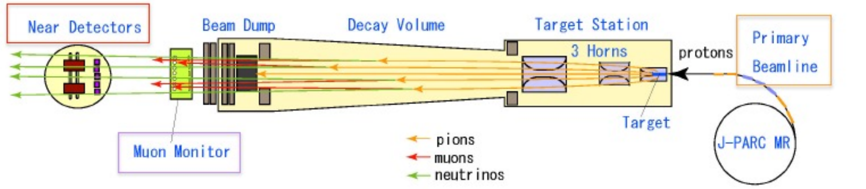
1. Neutrinos cannot choose kinematic
2. Neutrino kinematics are not fully determined

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

1. Typical neutrino beams for oscillation experiments

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

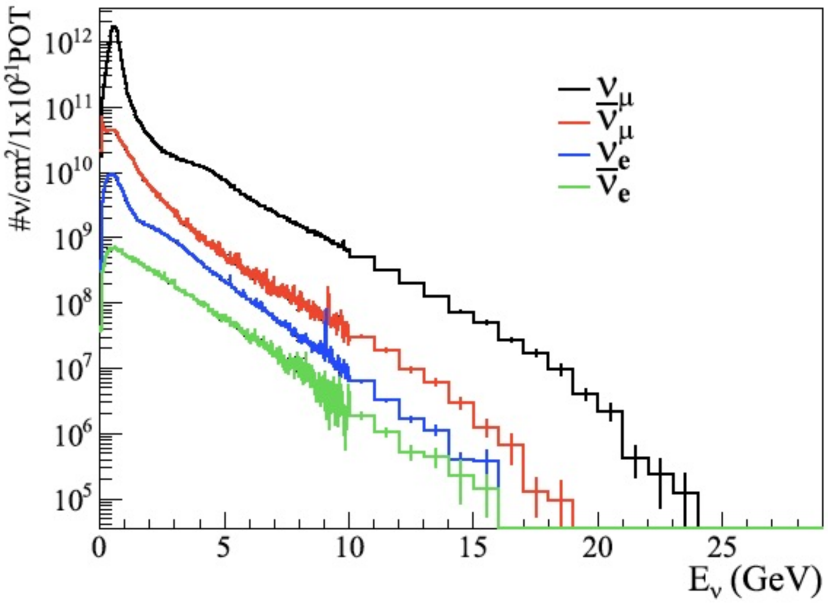
- pion decay-in-flight (high flux)
- off-axis beam (narrow band)
- but has components up to ~ 10 GeV
- typical beam 1-10 GeV
- ~4% normalization error (best case)

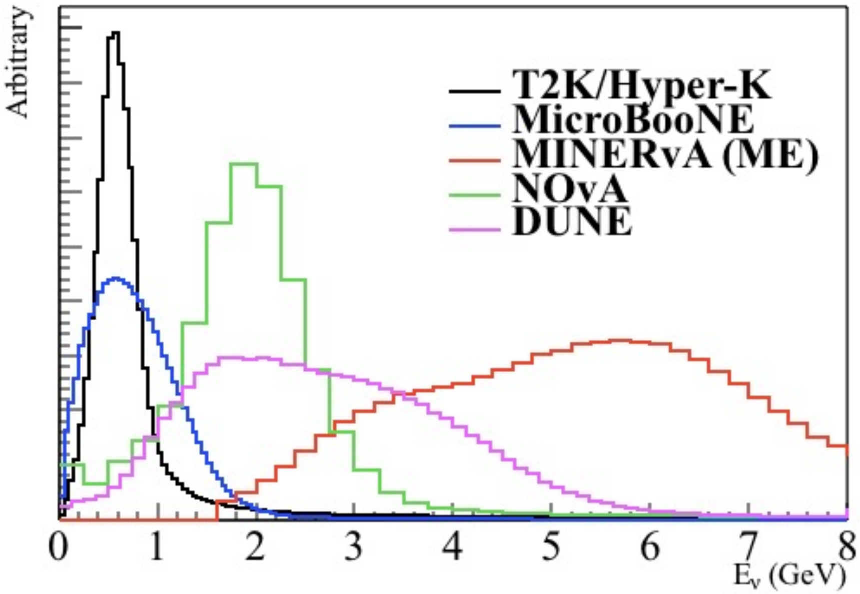


INGRID
monitors the stability of ν flux and direction

Muon Monitor
measures the muon profile after beam dump

Proton Beam Monitors
measure the proton beam intensity, direction





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

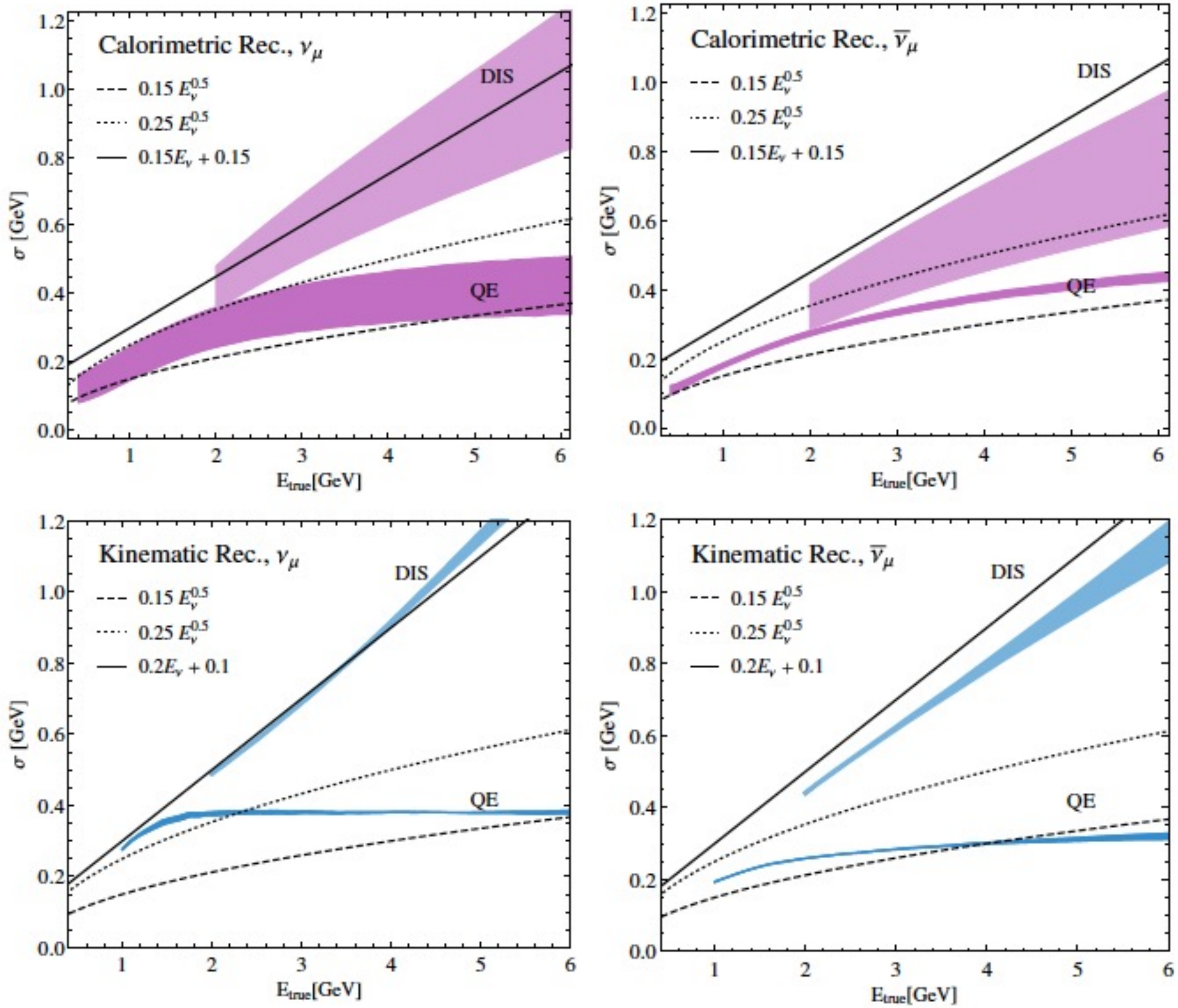
Ankowski et al, PRD92(2015)073014

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

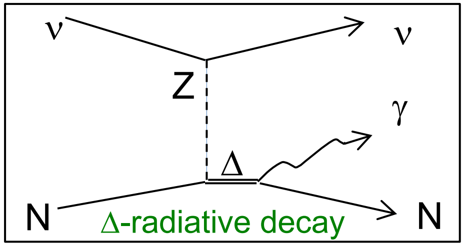
etc

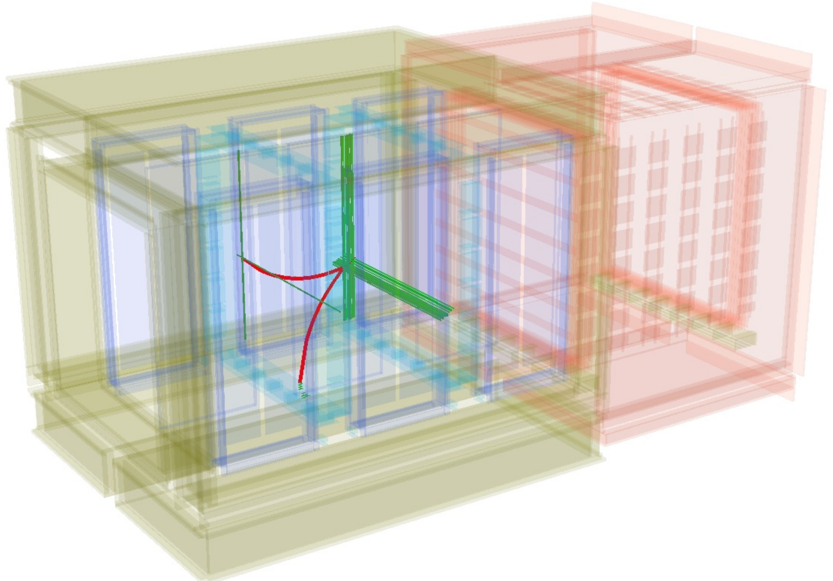


T2K, JPhysG46 (2019) 08LT01

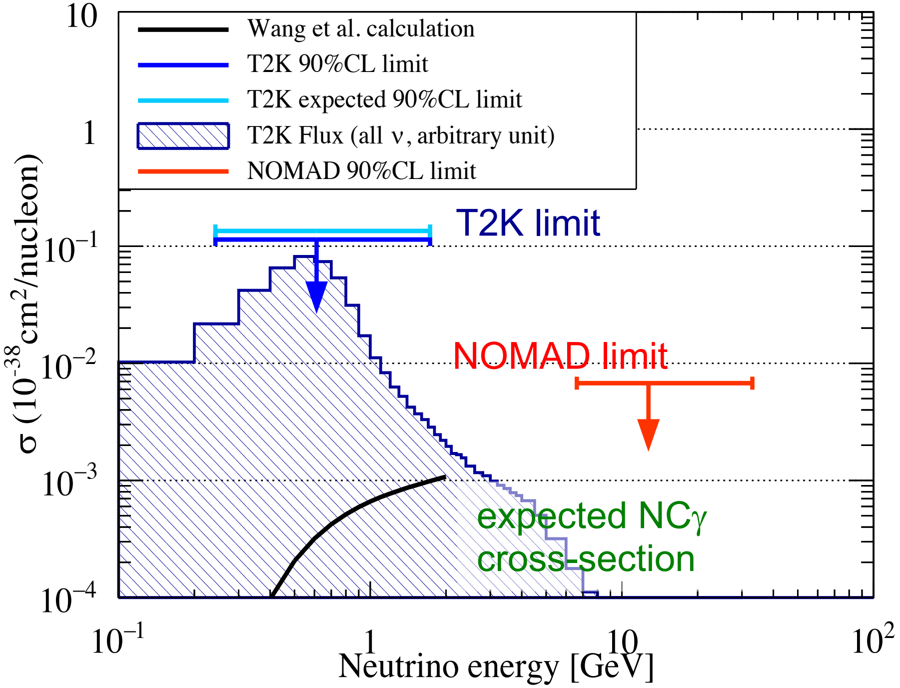
4. T2K Neutrino NC single photon production (NCγ)

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.





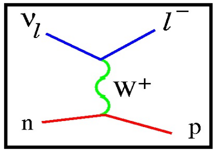
T2K near detector NCγ candidate



Smith and Moniz, NPB43(1972)605
Ashkenazi (Neutrino 2020), https://zenodo.org/record/3959538

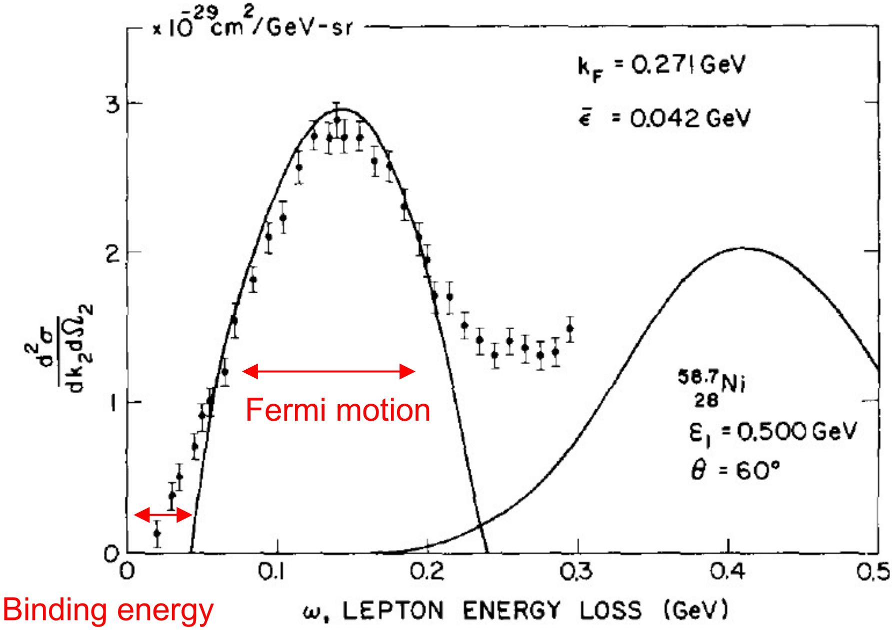
2. Fermi motion

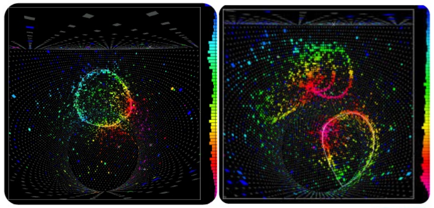
Quasi Elastic



Fermi motion

- Measured energy is smeared from the true energy if you assume nucleon at rest
- High resolution detector can measure all outgoing hadrons
  → initial nucleon momentum can be reconstructed (no Fermi motion smearing)



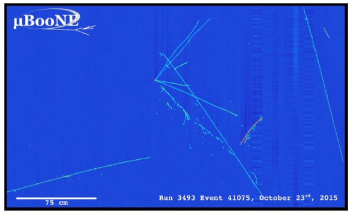


Cherenkov detectors:

Assuming QE interaction

Using lepton only

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2(M - E_l + |k_l|\cos\theta_l)}$$



Tracking detectors:

Calorimetric sum

Using All detected particles

$$E_{\mathrm{cal}} = E_l + E_p^{\mathrm{kin}} + \epsilon$$

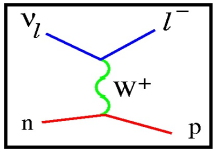
[1p0π]

katori@fnal.gov

Smith and Moniz, NPB43(1972)605
MiniBooNE, PRD81(2010)092005

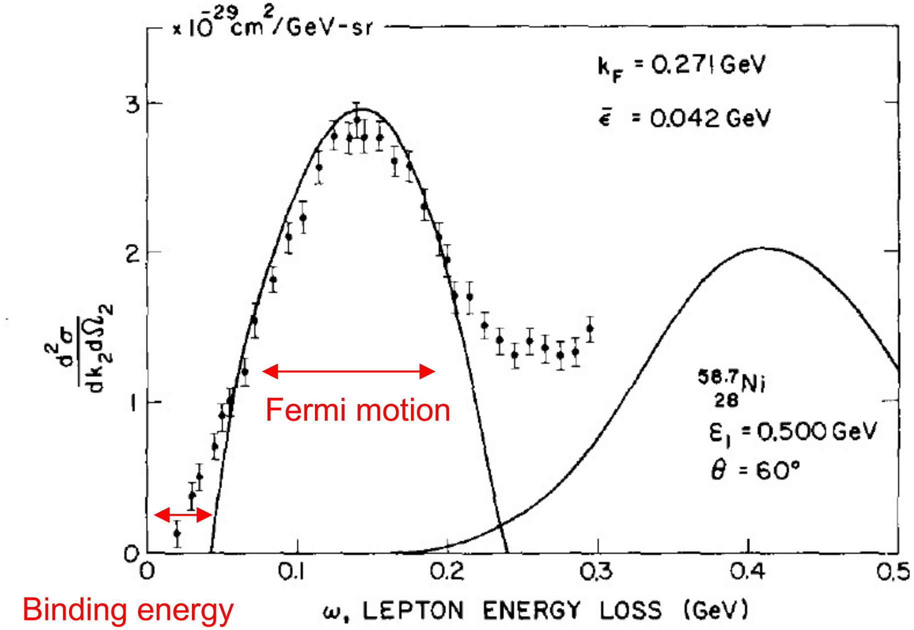
2. Pauli blocking

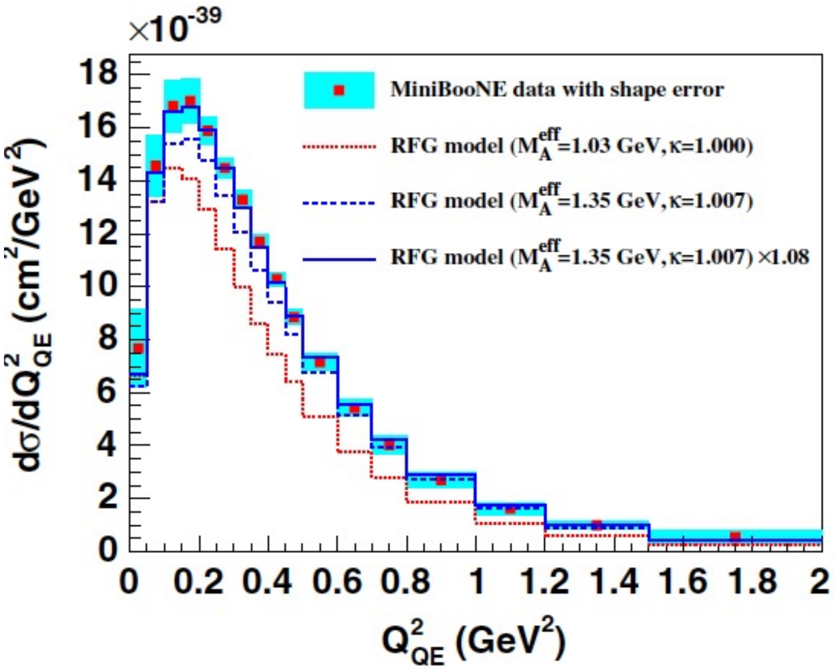
Quasi Elastic



Pauli blocking

- Low momentum transfer reaction is forbidden.
- data show more suppression than what Pauli blocking can → RPA(?)
- In the global Fermi gas model, Pauli blocking looks unphysical

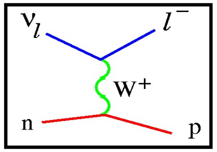




Smith and Moniz, NPB43(1972)605
Bodek and Cai, EPJC79(2019)293

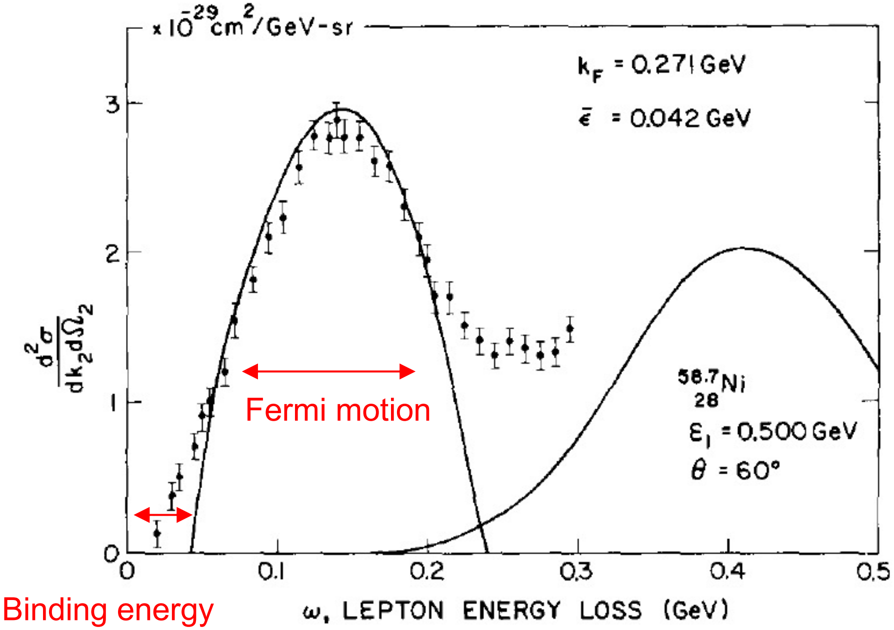
2. Nuclear Shell structure and binding energy

Quasi Elastic



Binding energy ~ unobserved energy

- Energy to cost to release 1 nucleon, not constant
- Separation energy + excitation energy + recoil energy
  - Separation energy: energy to release 1 nucleon from the shell (~15 MeV, depends)
  - Excitation energy: energy used to excite leftover target nucleus (~1 MeV)
  - Recoil energy: kinetic energy of recoil target nucleus (~2-3 MeV)



Binding energy