Neutrino Event Generator

outline

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

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nuSTEP2024,国科大杭州高等研究院，杭州, May 18, 2024

1. Introduction

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

3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

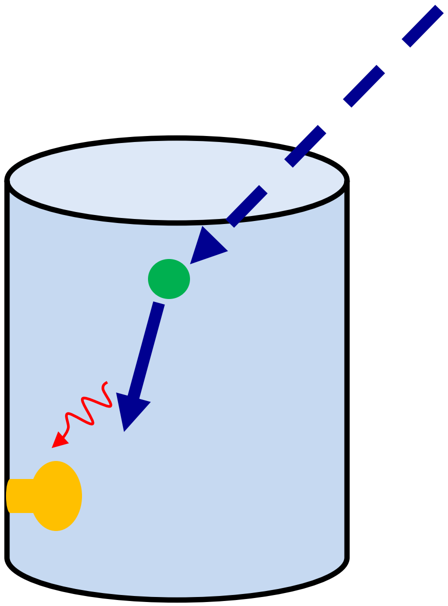
5. Conclusions

1. Why neutrino event generator?

Data

- Neutrinos interact with materials
- Particles propagate, and emit photons
- Photons are recorded by sensors

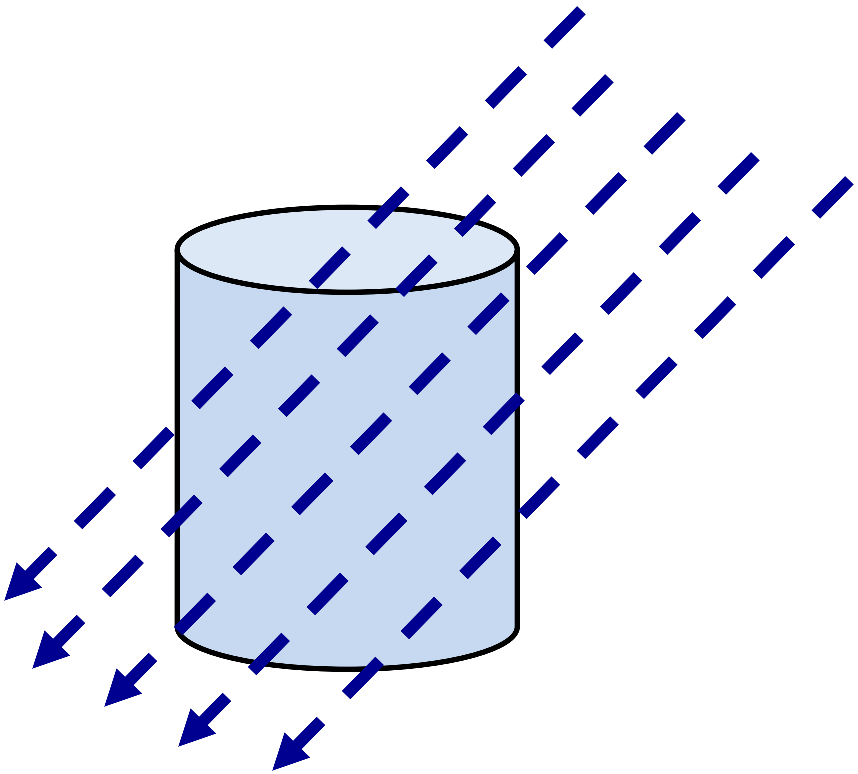
→ 1 event = 1 data trigger



Simulation

- If you try to simulate neutrino interaction by propagating neutrinos, you wait very long time to make 1 neutrino interaction

→ very inefficient simulation



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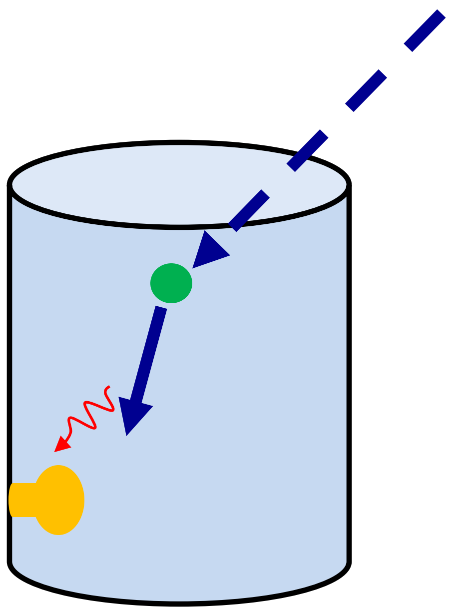
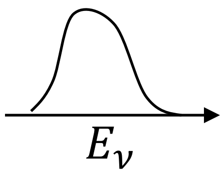


Simulation

- Flux prediction Φ(Eν)



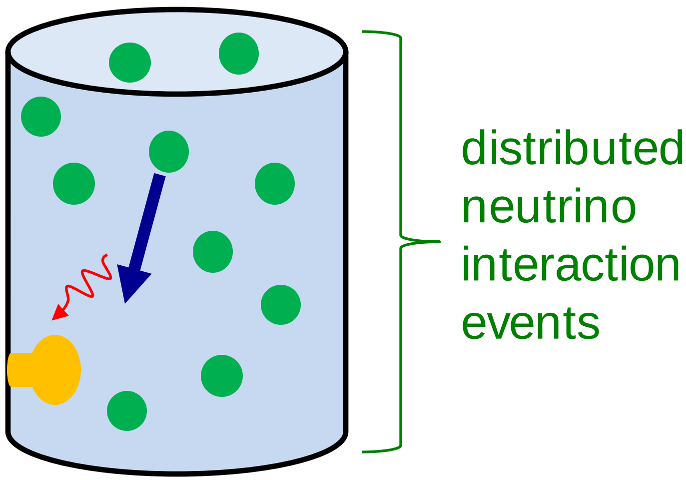
- Neutrino events are generated based on Φ(Eν) and cross-section σ(k,k')

→ Neutrino event generator

$$Events = \int \Phi \otimes \sigma \, dE_\nu$$

- Generated events are distributed in volume
- Particle & photon propagation by Geant4

→ 1 event = 1 neutrino interaction



1. Why neutrino event generator?

GENIE
https://github.com/GENIE-MC
- Used by Fermilab experiments

NEUT
(no public website)
- Used by Japanese neutrino experiments

NuWro
https://nuwro.github.io/user-guide/
- Independent generator

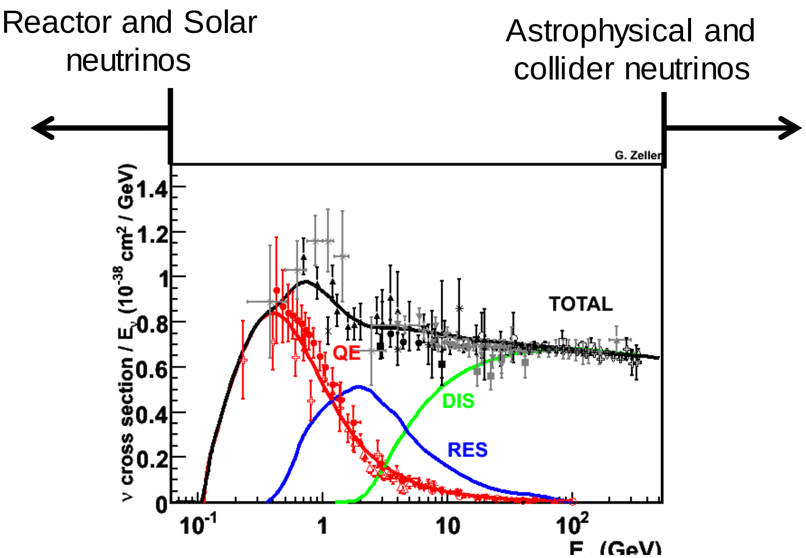
GIBUU
https://gibuu.hepforge.org/trac/wiki
- BUU transport to simulate hadron final states

NUISANCE
https://nuisance.hepforge.org/
- Data-Neutrino generator comparison framework

Achilles (New!)
https://arxiv.org/abs/2205.06378
- Theory-driven better factorization

Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307
NuSTEC, Prog.Part.Nucl.Phys.100(2018)1

1. Why neutrino event generator?



Fast simulation

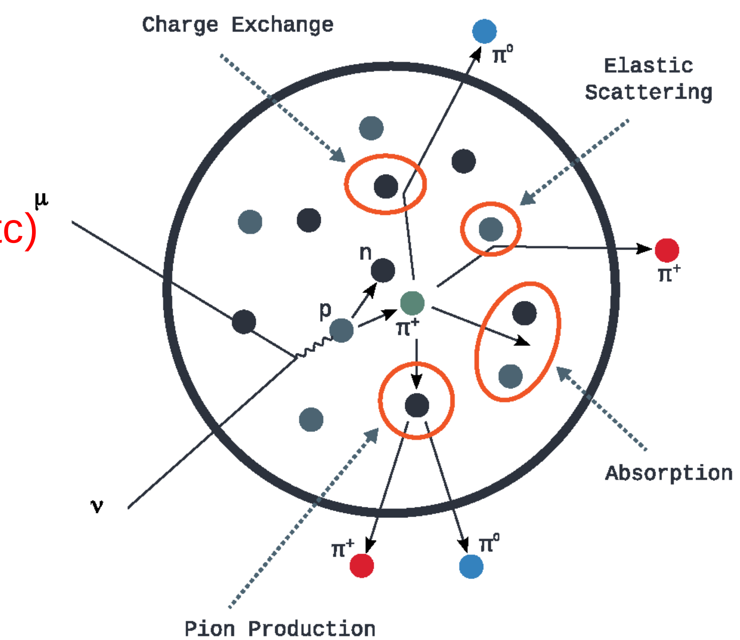
- Monte Carlo method

Merge models to cover all kinematic phase space

- Inverse beta decay (IBD)
- Charged-current quasi-elastic (CCQE)
- Resonance baryon production (RES)
- Deep-inelastic scattering (DIS)
- etc

Nuclear effects

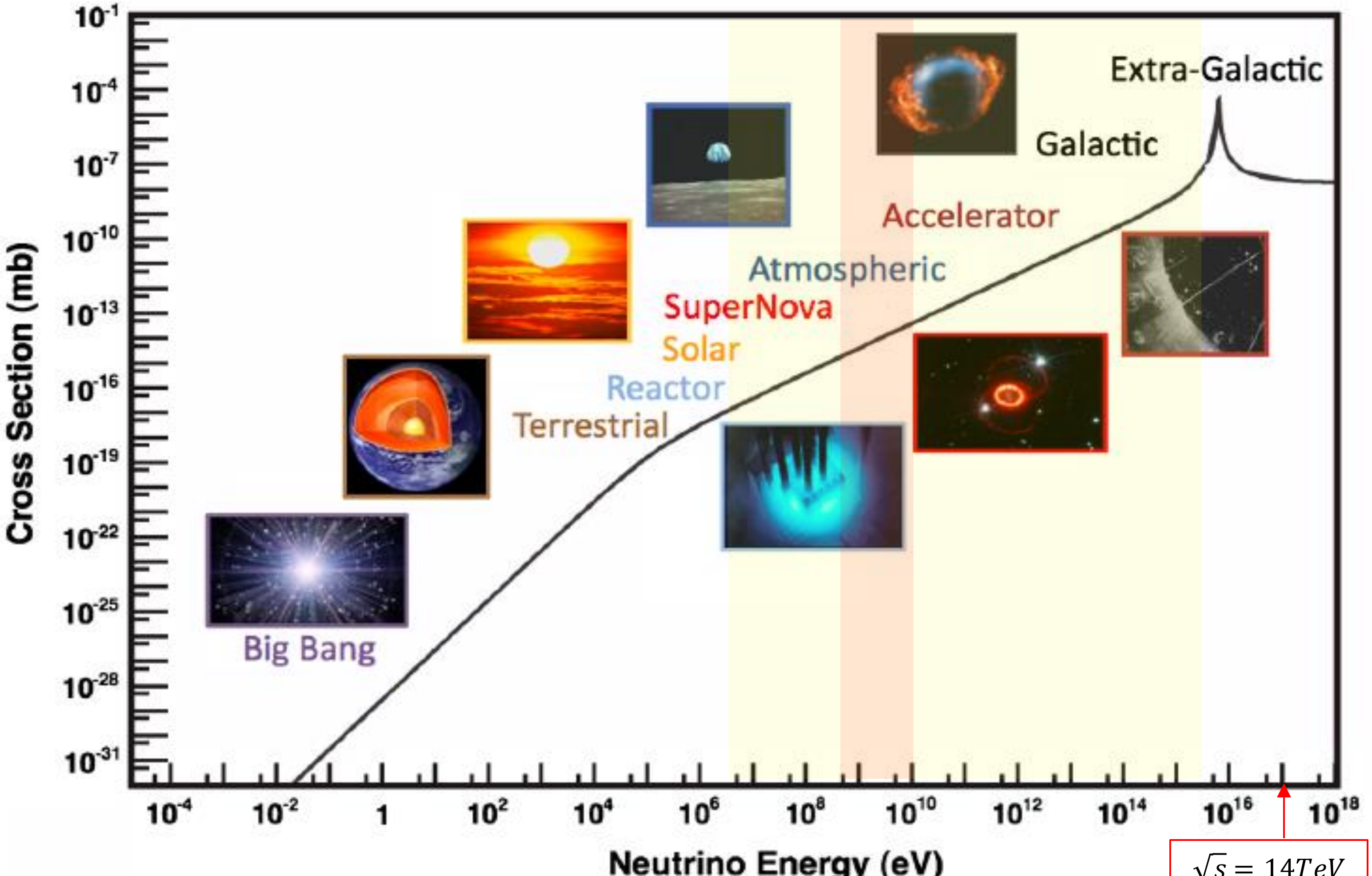
- Pauli blocking
- Fermi motion
- Final state interactions (scattering, absorption, etc)
- Nucleon correlations
- etc



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

1. Why neutrino event generator?

Accelerator-
based neutrinos



$\sqrt{s} = 14TeV$

1. Why neutrino event generator?

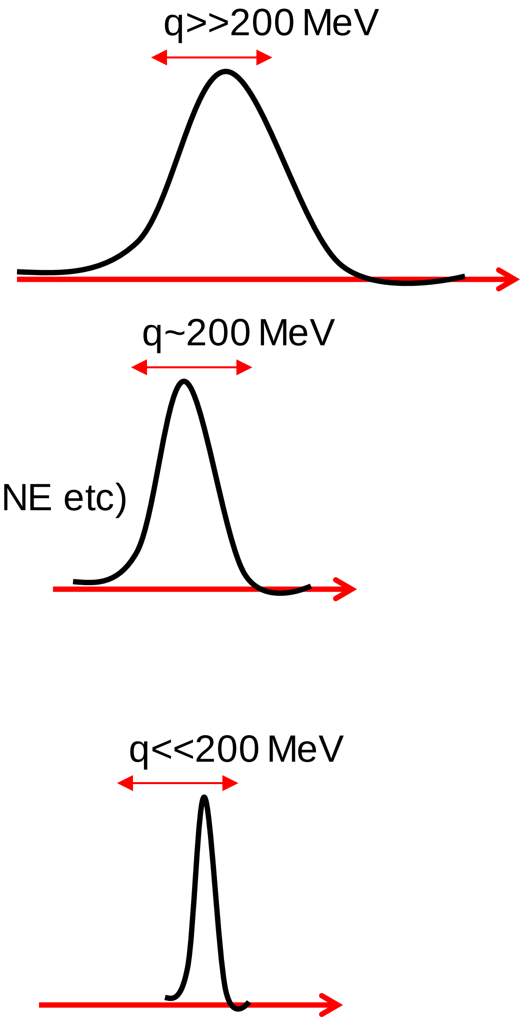
Size of wave packet ~ momentum transfer (~energy)

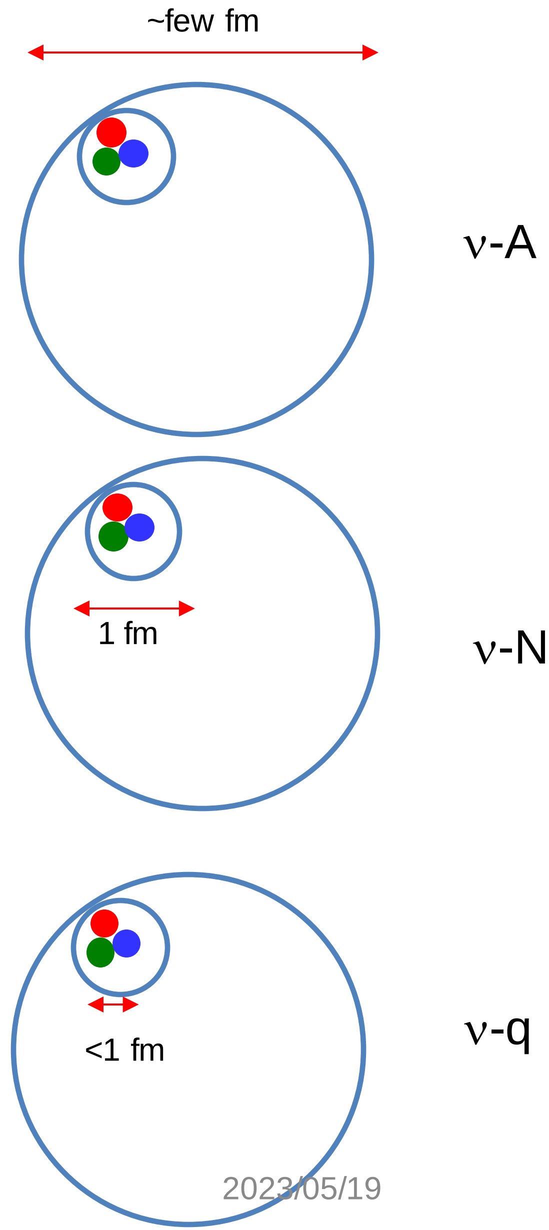
$\hbar c = 197\ MeV \cdot fm \rightarrow$ 200 MeV ~ 1 fm (size of nucleon)

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

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

>>1 GeV neutrino beam
(collider, astrophysical)





Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307
NuSTEC, Prog.Part.Nucl.Phys.100(2018)1

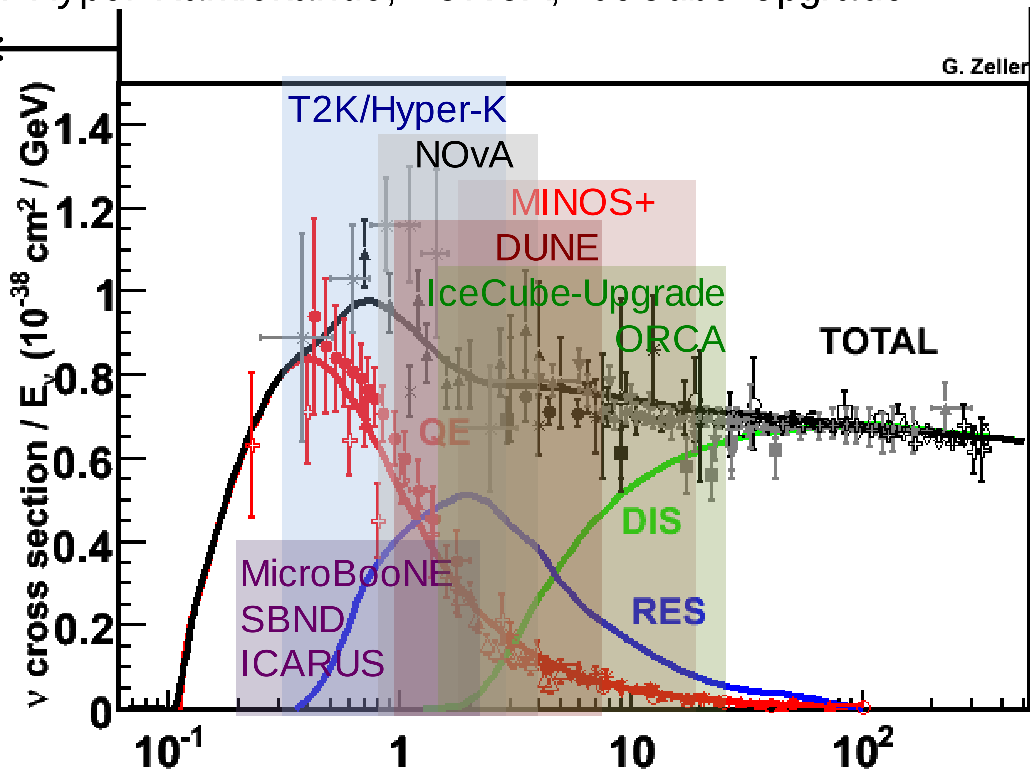
1. Why neutrino event generator?

Neutrino interaction physics around 1-10 GeV

- J-PARC: T2K, Hyper-Kamiokande,
- Fermilab: MicroBooNE/SBND/ICARUS, MINOS+, NOvA, DUNE
- Atmospheric: Hyper-Kamiokande, ORCA, IceCube-Upgrade

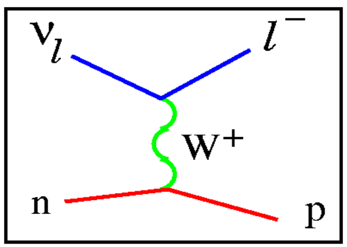
Reactor and solar neutrinos

Astrophysical and collider neutrinos

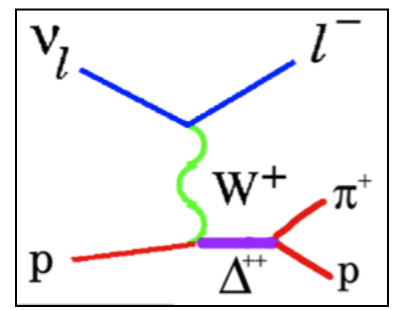


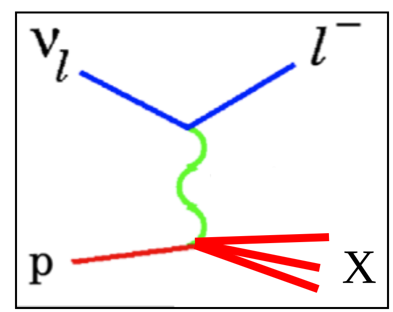
ν_μCC cross section per nucleon

Quasi Elastic (QE)



baryonic resonance (RES)





Deep Inelastic Scattering (DIS)

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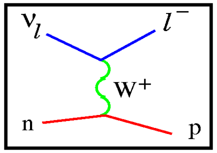
5. Conclusions

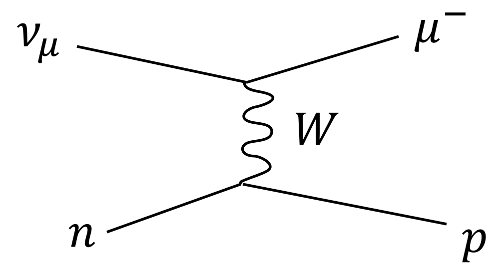
Quasi Elastic



2. Charged Current Quasi-Elastic scattering (CCQE)

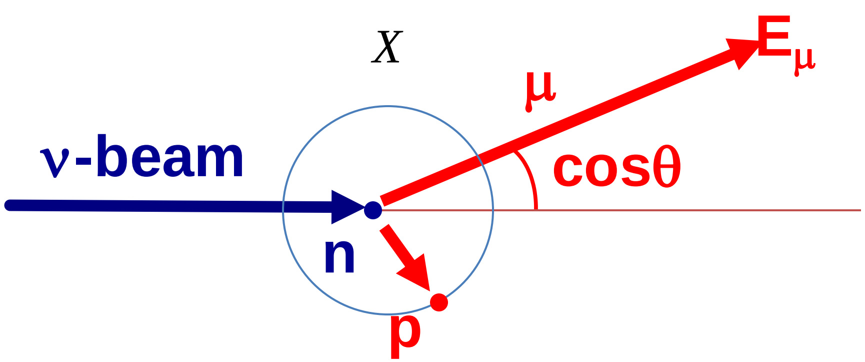
The simplest and the most abundant interaction around ~1 GeV.

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



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

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



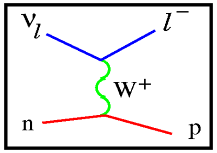
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

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

2. Nucleon correlations in neutrino physics

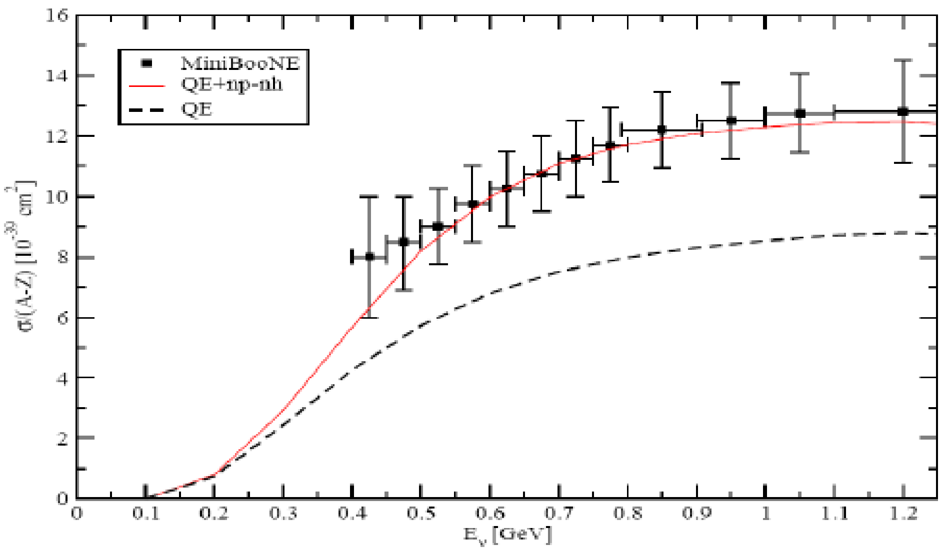
Quasi Elastic

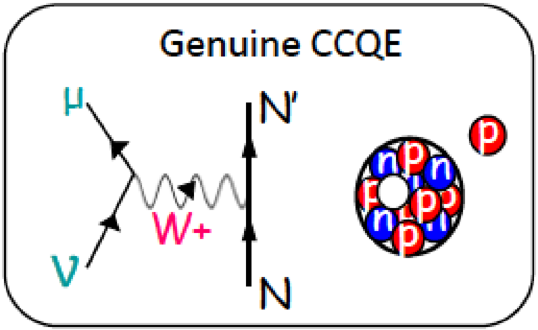


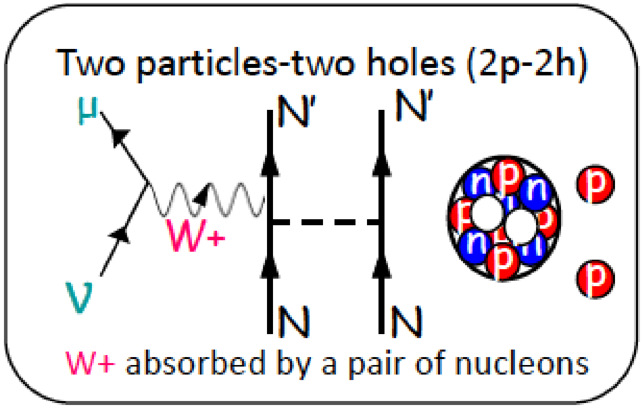
2-particle 2-hole (2p2h) effect

- CCQE is identified from single outgoing charged lepton events
- Significant fraction of events are not from 2-body neutrino-nucleon interactions
- 2p-2h effect can add up to ~30% more cross section

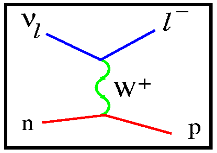
Inclusion of the multinucleon emission channel (np-nh)







Quasi Elastic

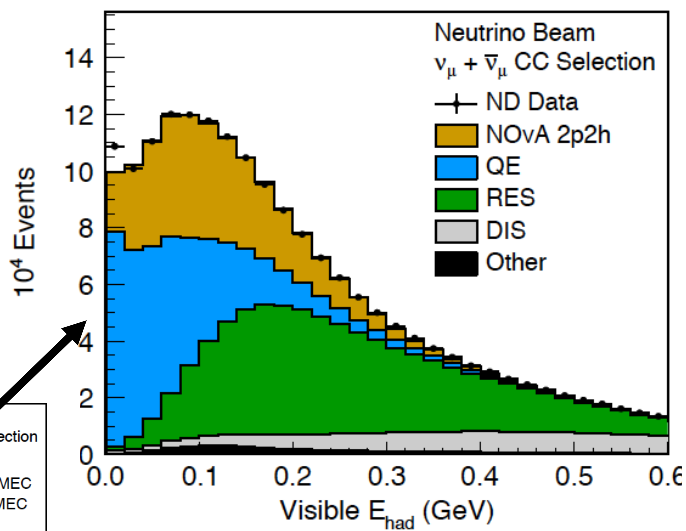


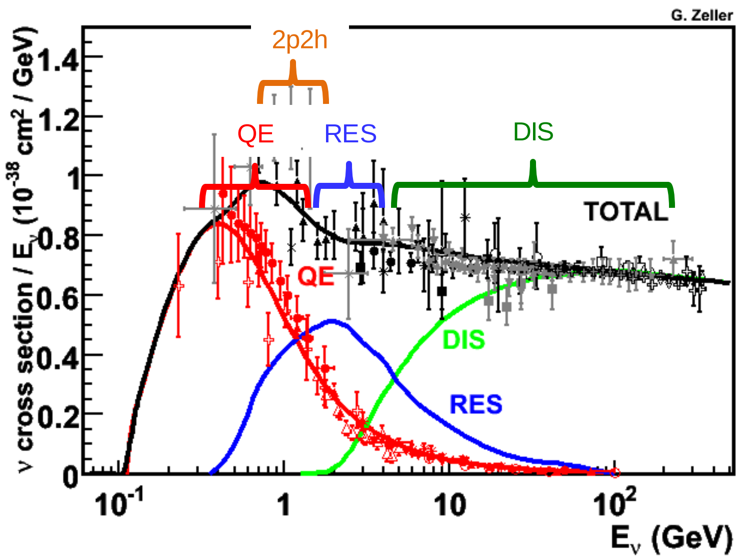
2. Nucleon correlations in neutrino physics

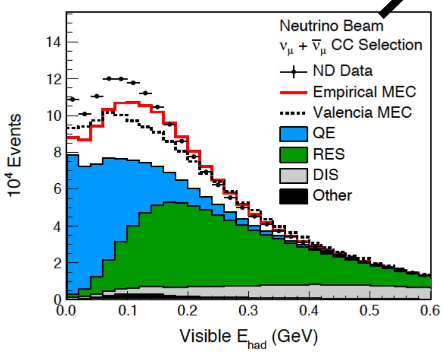
2-particle 2-hole (2p2h) effect

- Essential to describe data
- The biggest topic in nuxsec community (T2K, NOvA, MINERvA, MicroBooNE, etc)
- 2p2h models in generators often require data-driven tuning

NOvA near detector data-MC comparison after fit

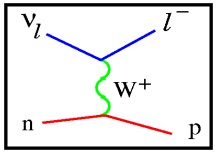


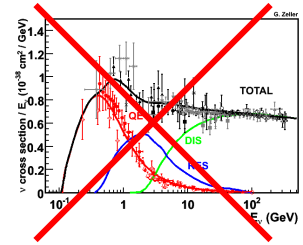




2. Generator tuning

Quasi Elastic

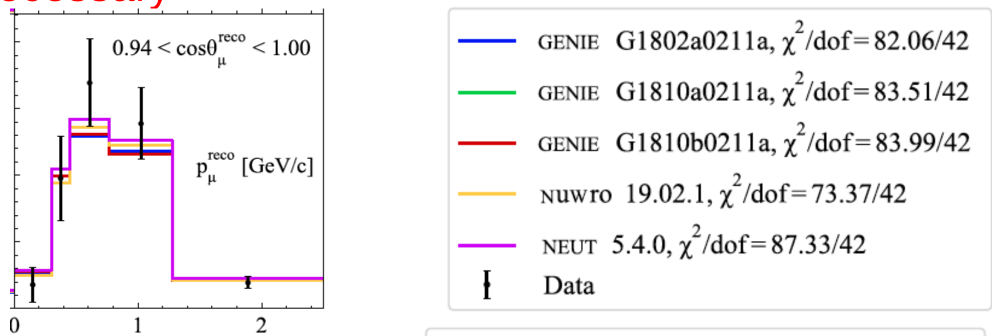




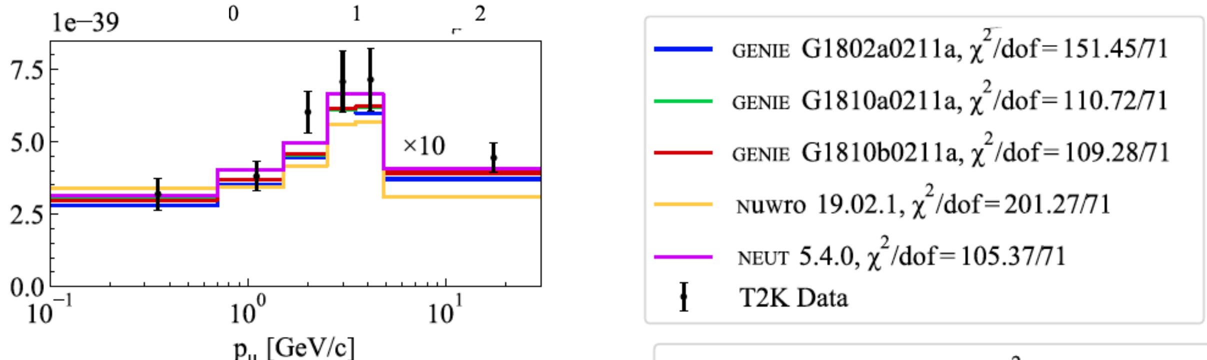
Data tension – external: T2K vs. MINERvA vs. MicroBooNE

- Different experiment cover different kinematic region
- Challenging to describe all experimental data simultaneously
- Internal tuning of generator models is necessary

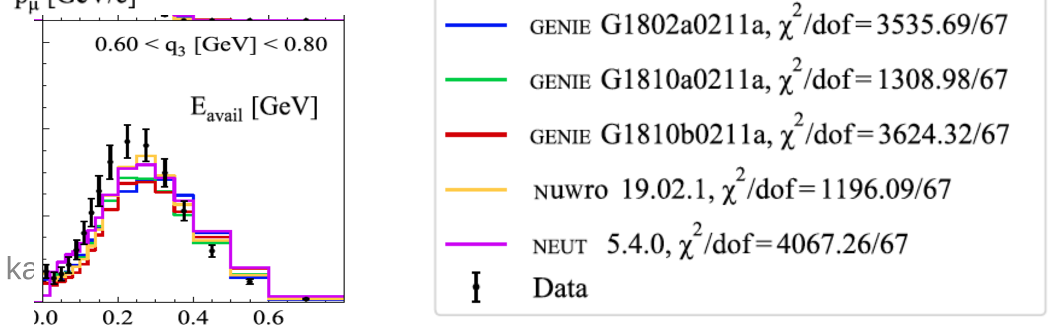
MicroBooNE CC inclusive double differential cross-section



T2K CC inclusive double differential cross-section



MINERvA CC inclusive double differential cross-section



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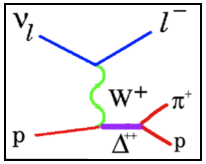
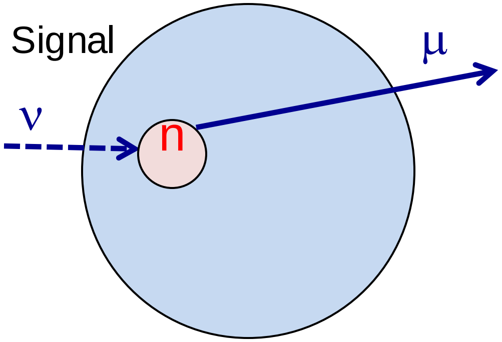
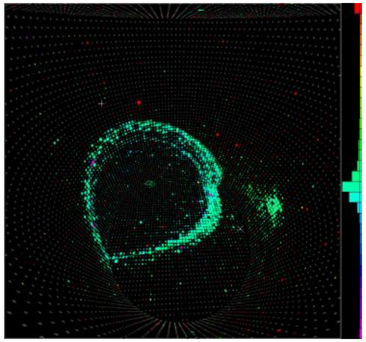
RESonance

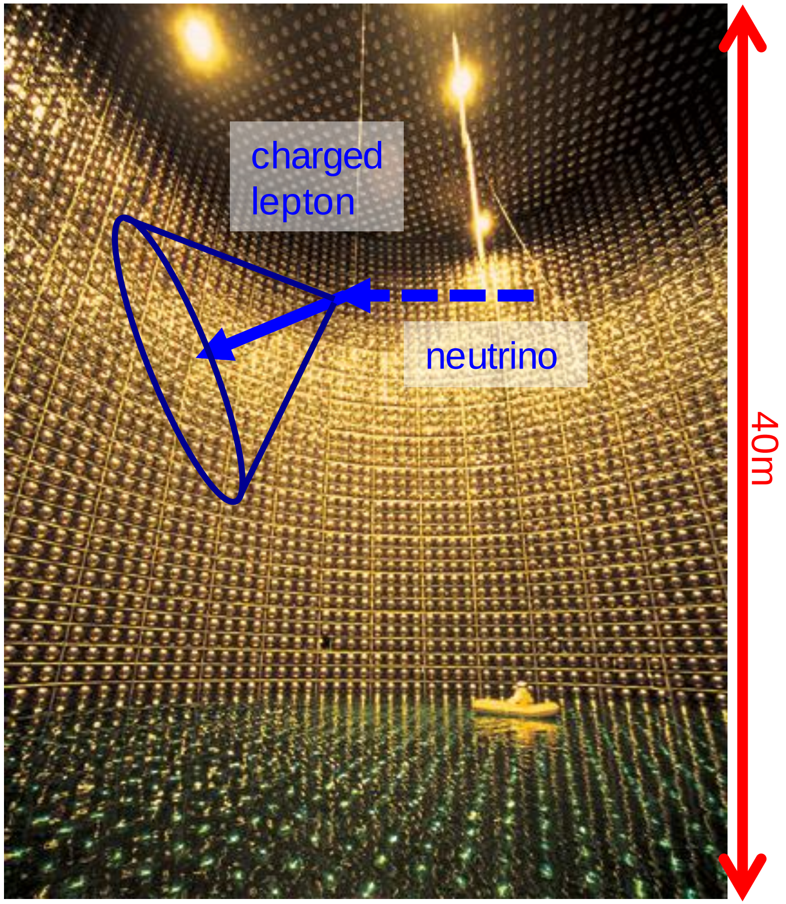


3. non-QE background (resonance pion production)

QE event = single lepton final state







Kinematic measurement of outgoing charged lepton
→ reconstruct neutrino energy

Background is all other channels with the same final state particles

3. non-QE background (resonance pion production)

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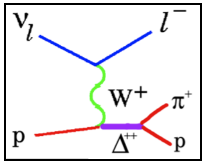

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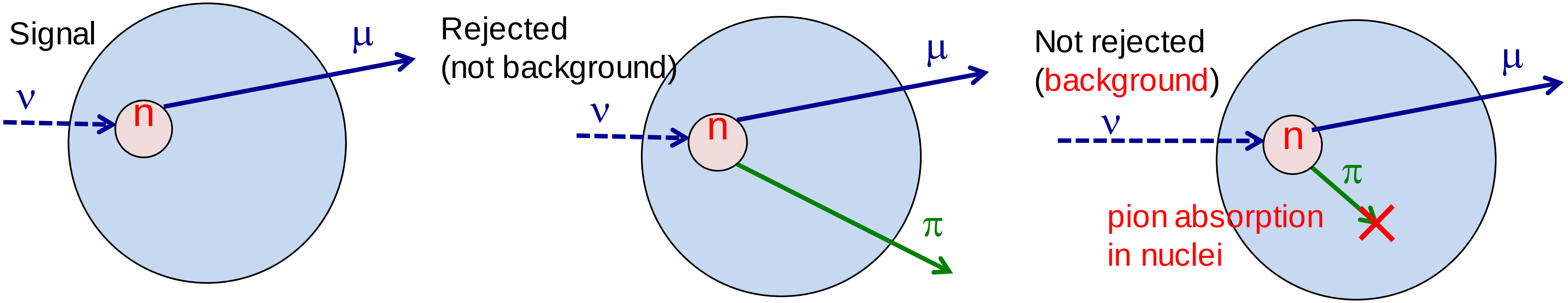

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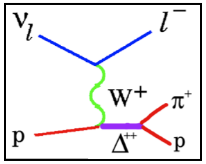
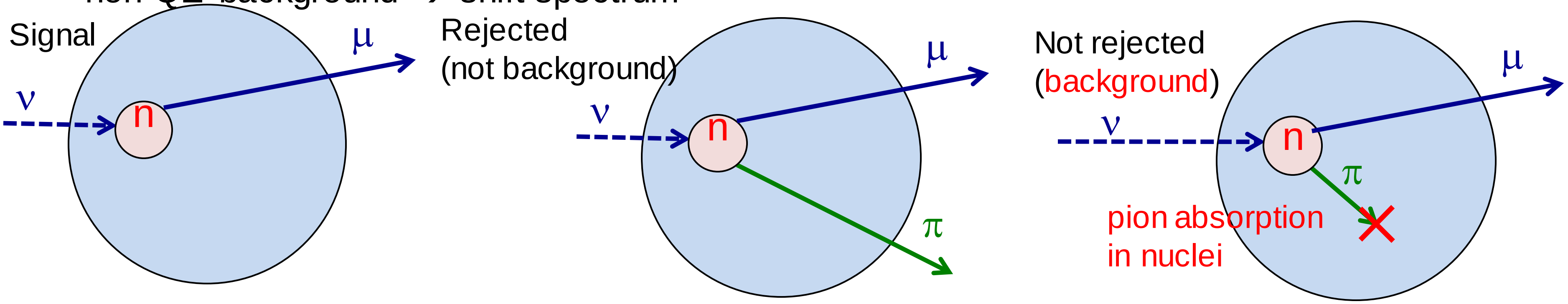
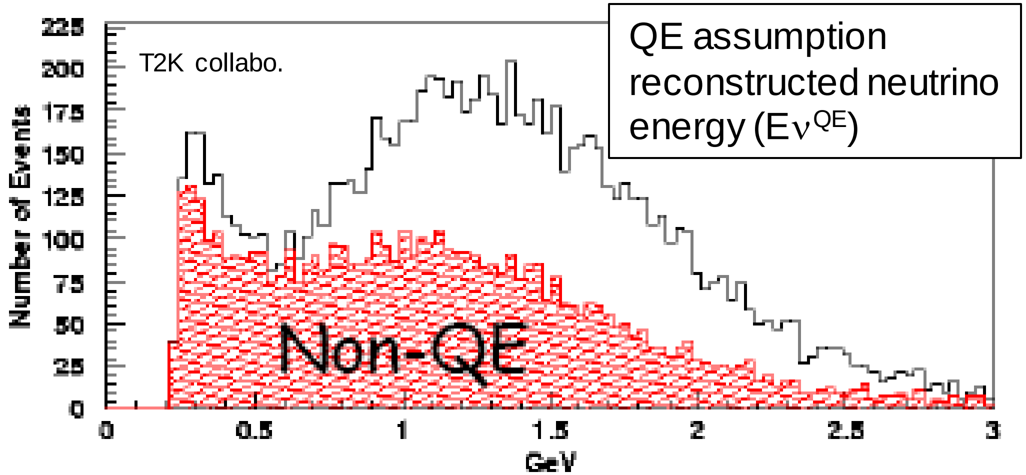
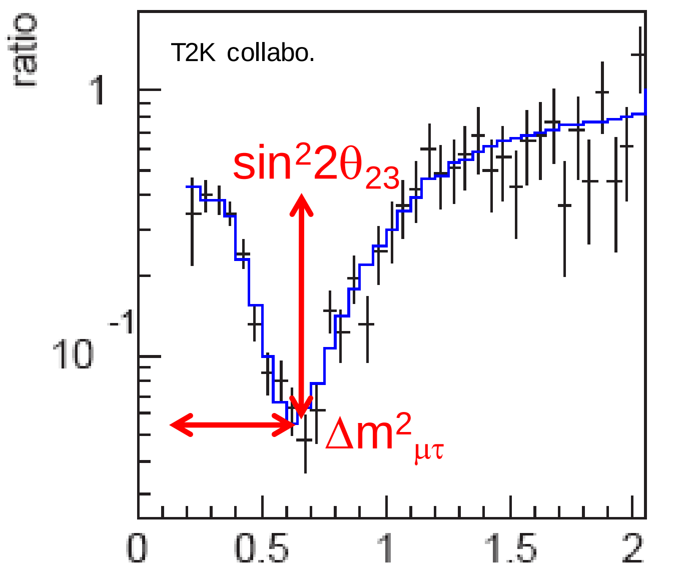


QE event = single lepton final state

- non-QE background → shift spectrum







Solution: simulate neutrino-induced pion production by event generator

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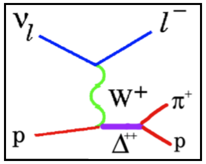
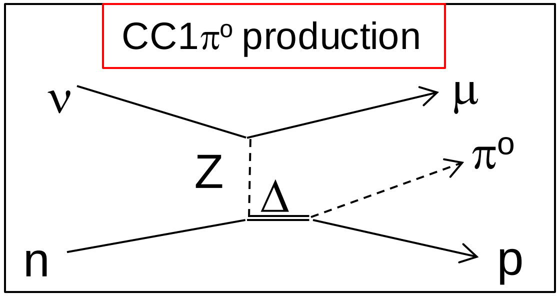
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

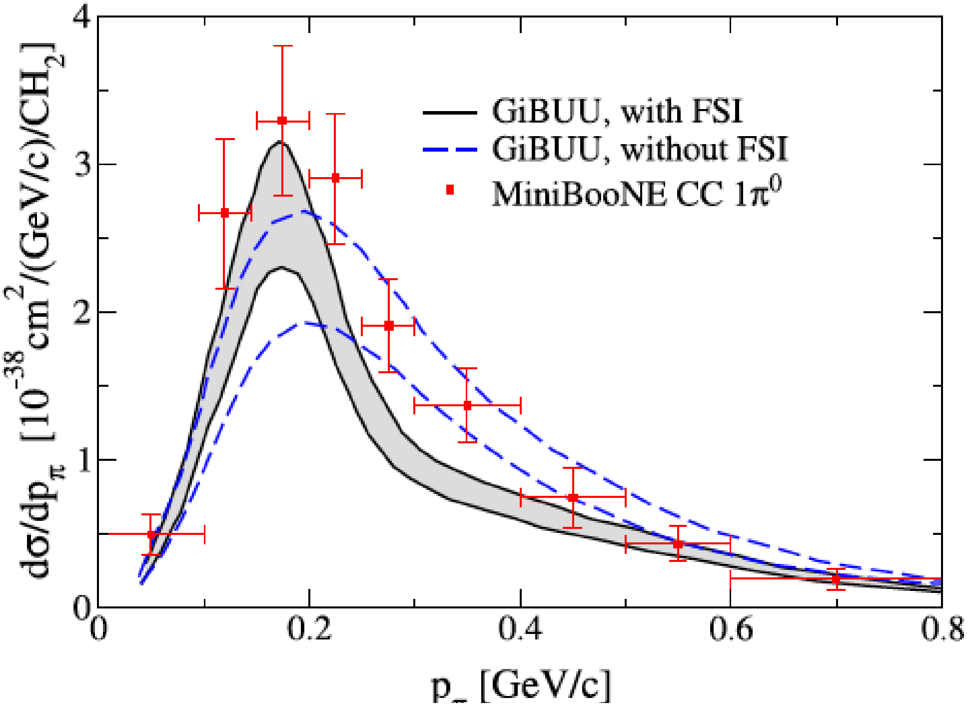


3. Single pion production

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
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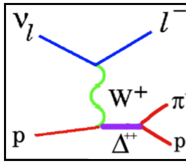

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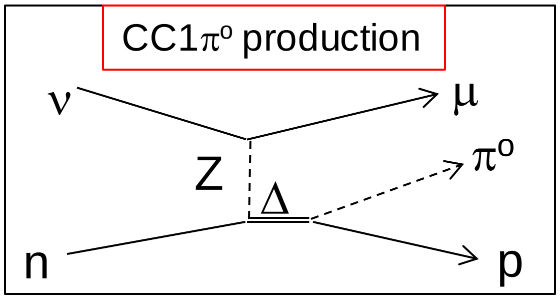

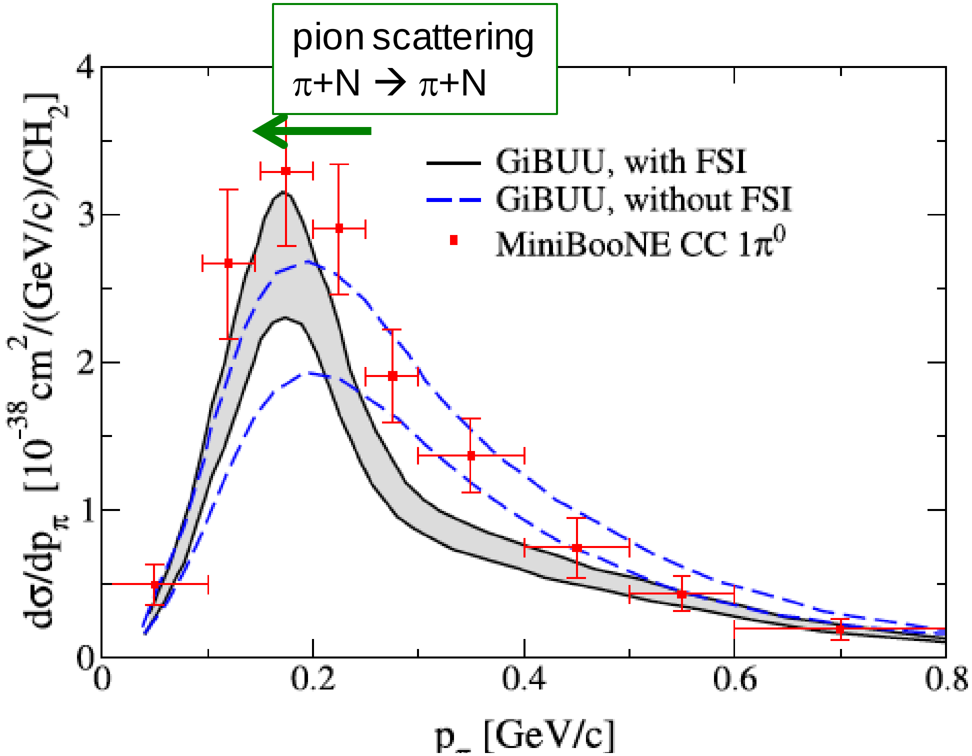

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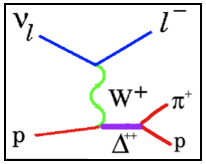

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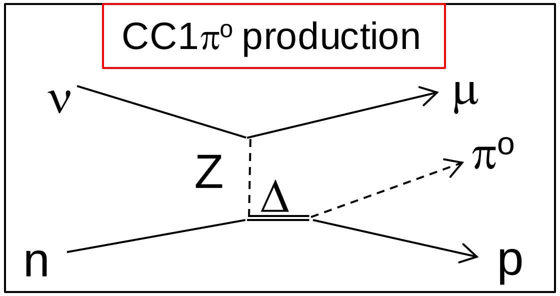

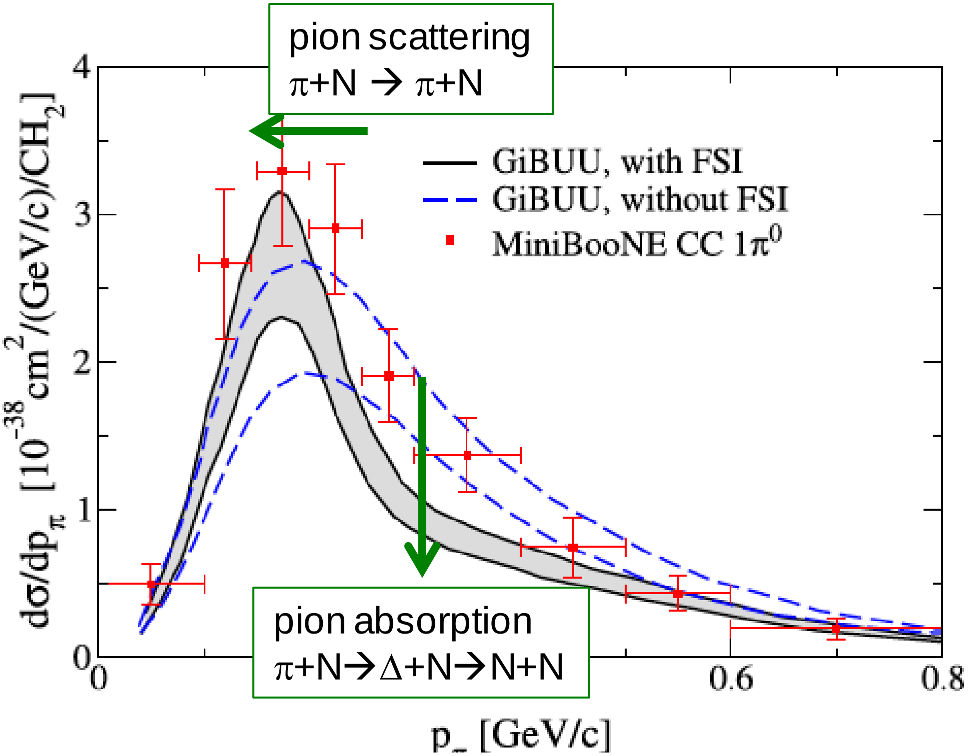

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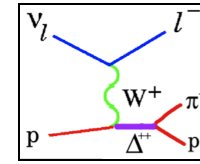

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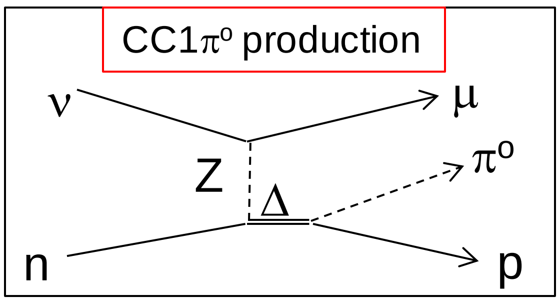
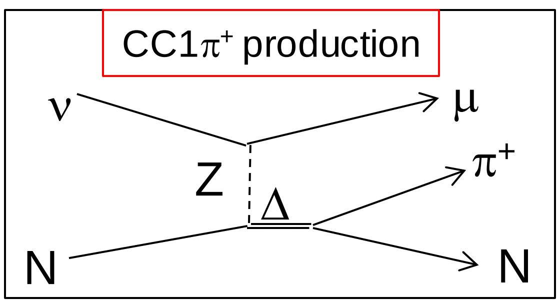
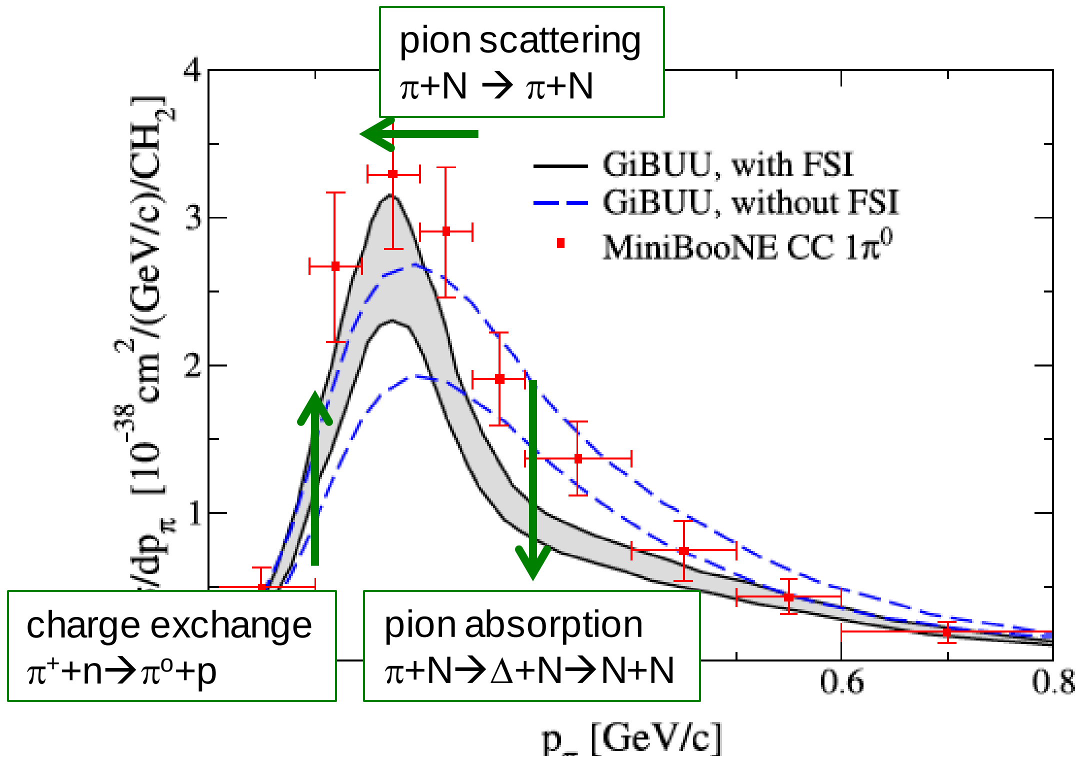
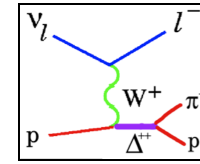






You need to predict both
1. all pion production channels
2. all final state interaction

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



3. Data tension

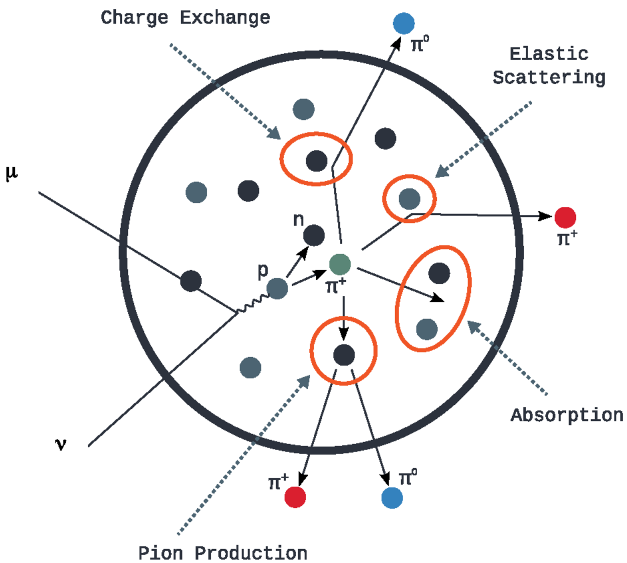
Data tension – internal: MINERvA pion data

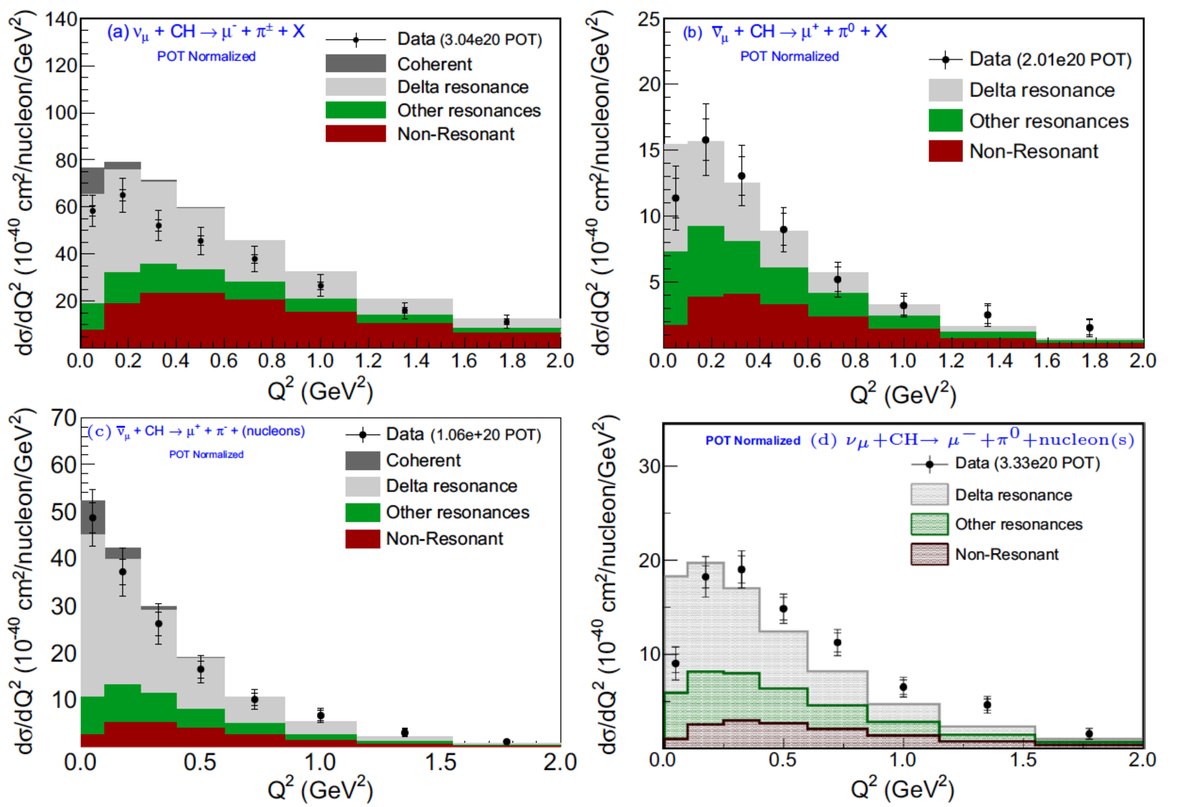
- Challenging to tune pion and FSI parameters to fit all data

$\nu_\mu CC\pi^\pm$ vs $\nu_\mu CC\pi^0$ vs $\bar{\nu}_\mu CC\pi^-$ vs $\bar{\nu}_\mu CC\pi^0$

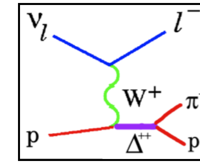
Simulating nuclear effects are hard

- Not much data for tuning
- Models may not be good,





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

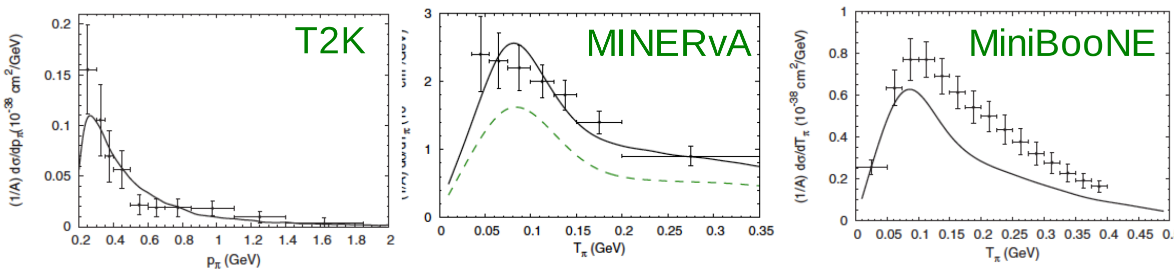


3. Data tension

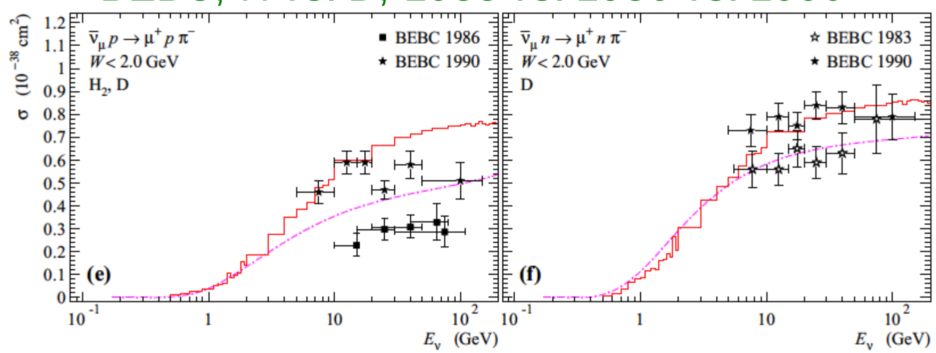
Data tension – external

- Tension between different experiments
- Tension between different targets

MiniBooNE vs. T2K vs. MINERvA (GiBUU)

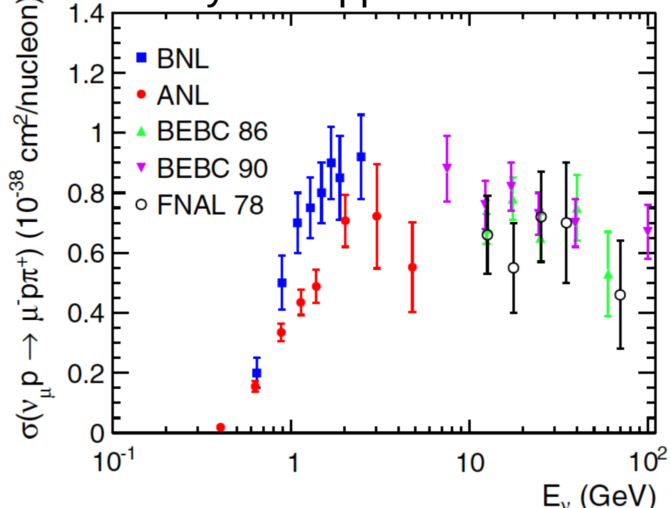


BEBC, H vs. D, 1983 vs. 1986 vs. 1990

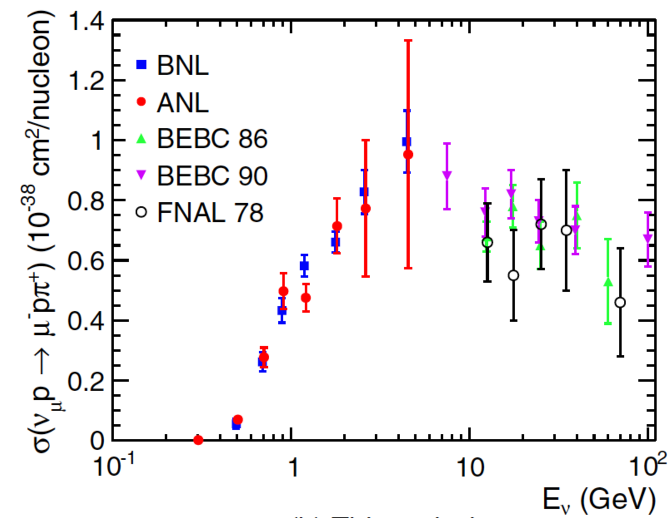


ANL vs. BNL data

Reanalysis supports ANL result



(a) Published



(b) Thisanalysis

katori@fnal.gov

1. Introduction

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

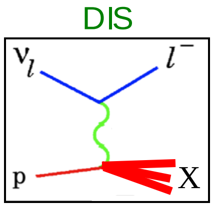
3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

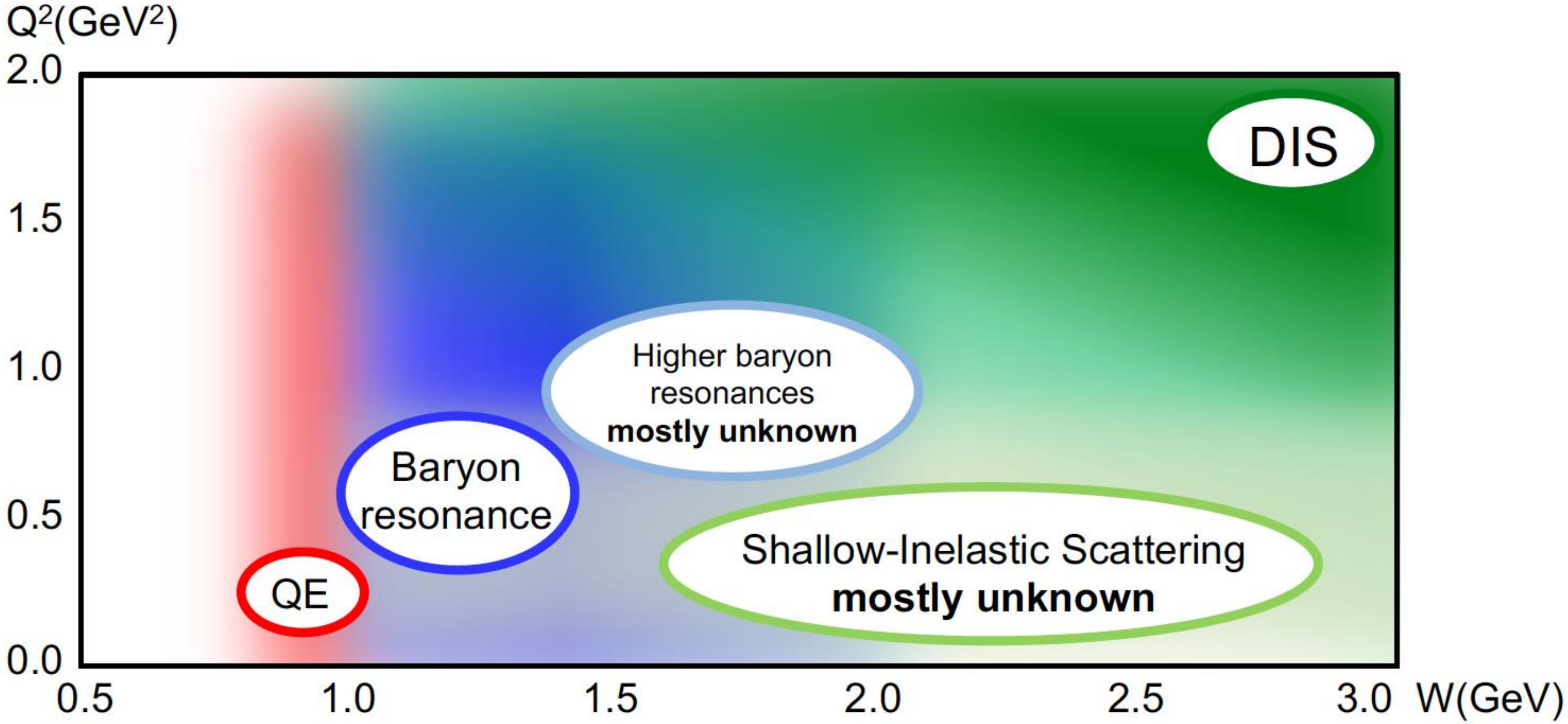
5. Conclusions

Nakamura et al,Rep.Prog.Phys.80(2017)056301, Sajjad Athar and Morfin, JPhysG48(2021) 034001
Snowmass21 white paper, ArXiv::2203.09030

4. Shallow Inelastic Scattering (SIS)

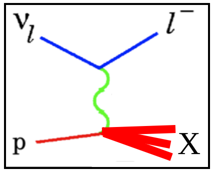


Shallow (low Q^2) inelastic (large W) scattering
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS



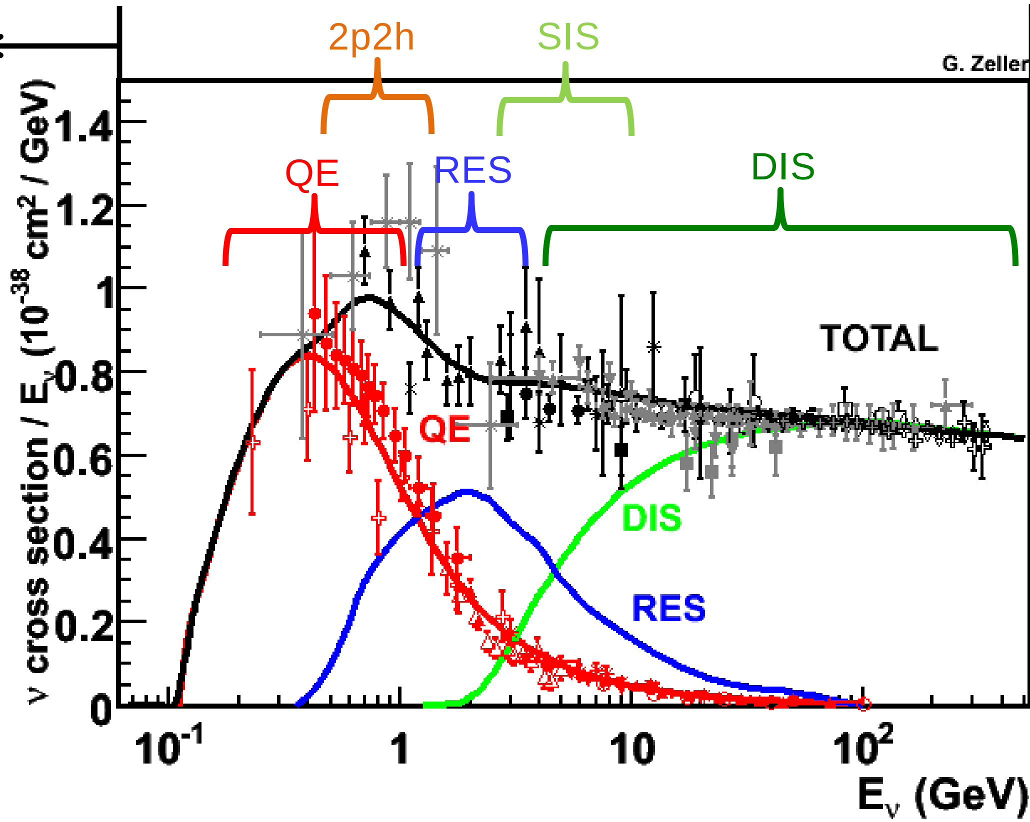
4. Shallow Inelastic Scattering (SIS)

DIS



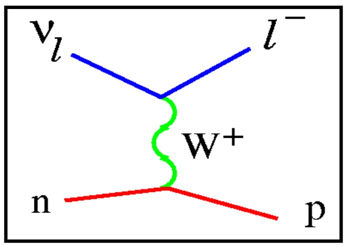
Shallow (low Q^2) inelastic (large W) scattering
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

Reactor and Solar neutrino oscillation

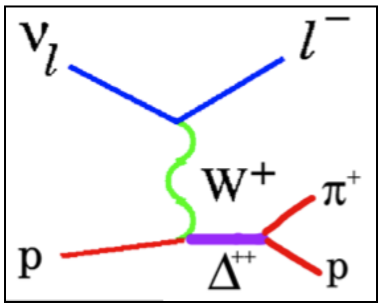


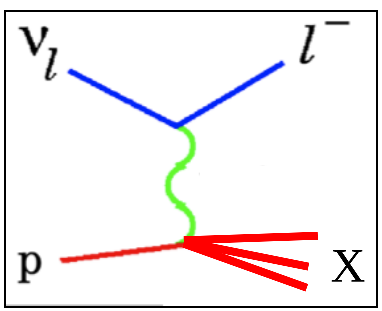
Astrophysical and collider neutrinos

Quasi Elastic (QE)



baryonic RESonance





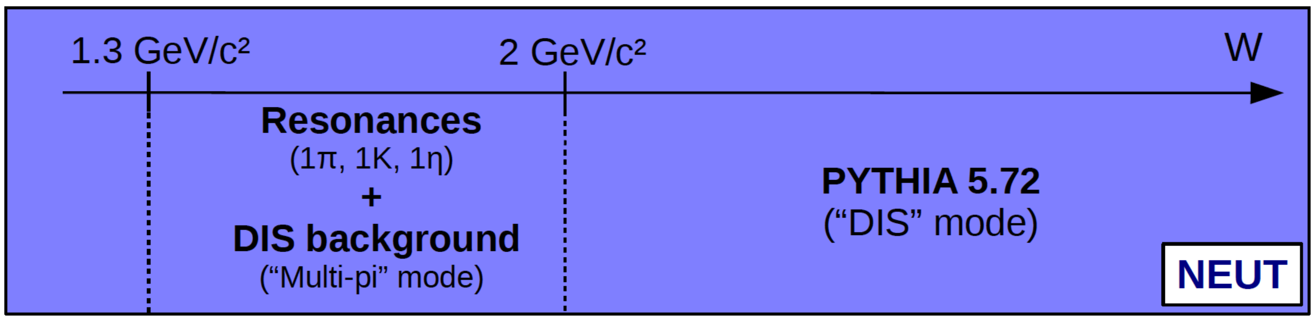
Deep Inelastic Scattering (DIS)

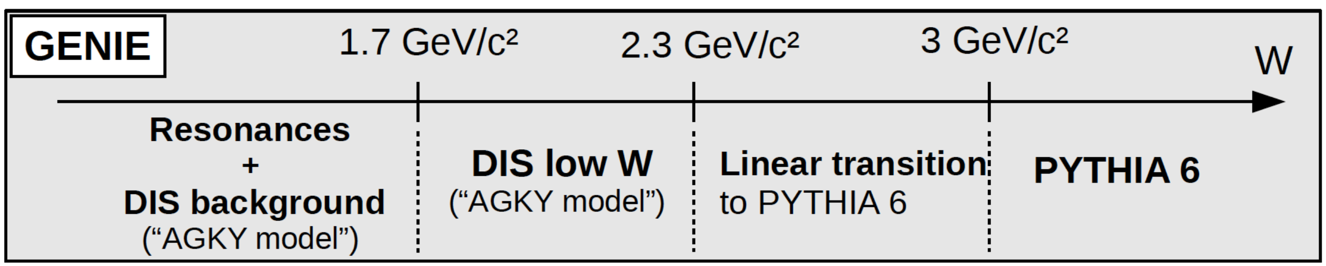
Nakamura et al,Rep.Prog.Phys.80(2017)056301, Sajjad Athar and Morfin, JPhysG48(2021) 034001
Snowmass21 white paper, ArXiv::2203.09030, NuSTEC nuSIS workshop, ArXiv:1907.13252

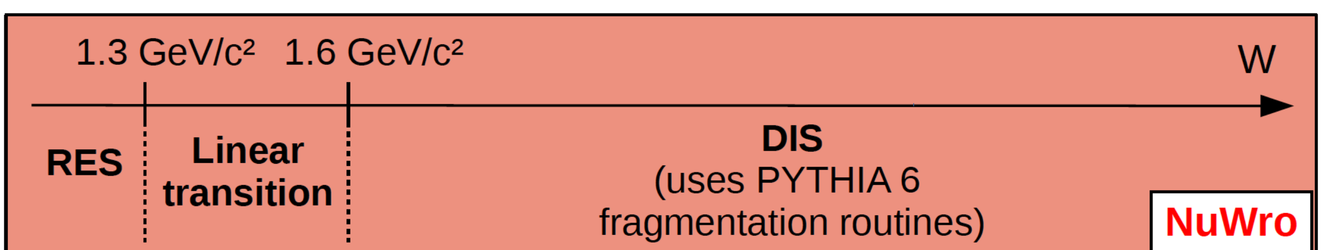
4. SIS in event generators

Shallow (low Q^2) inelastic (large W) scattering

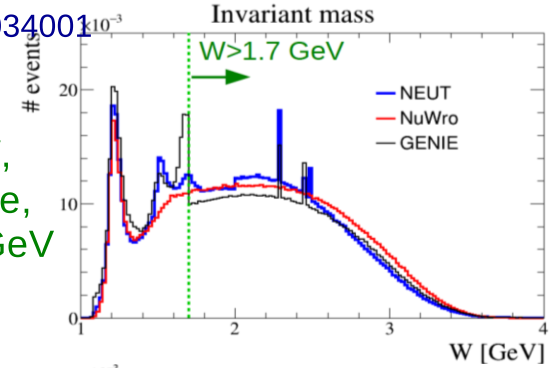
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS
- Difficult to connect different models

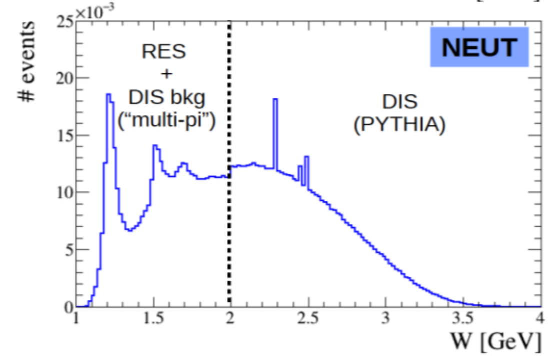


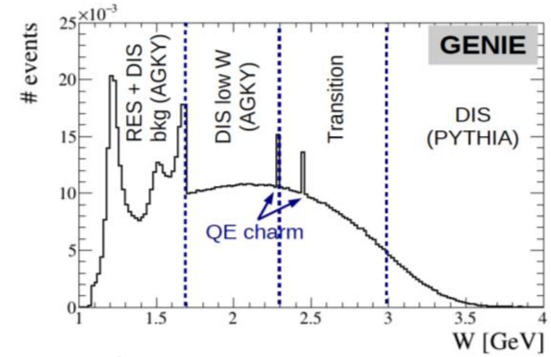


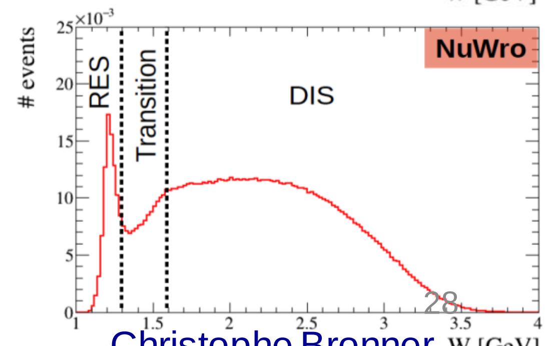


True W,
ν_μ on Fe,
Eν=6 GeV









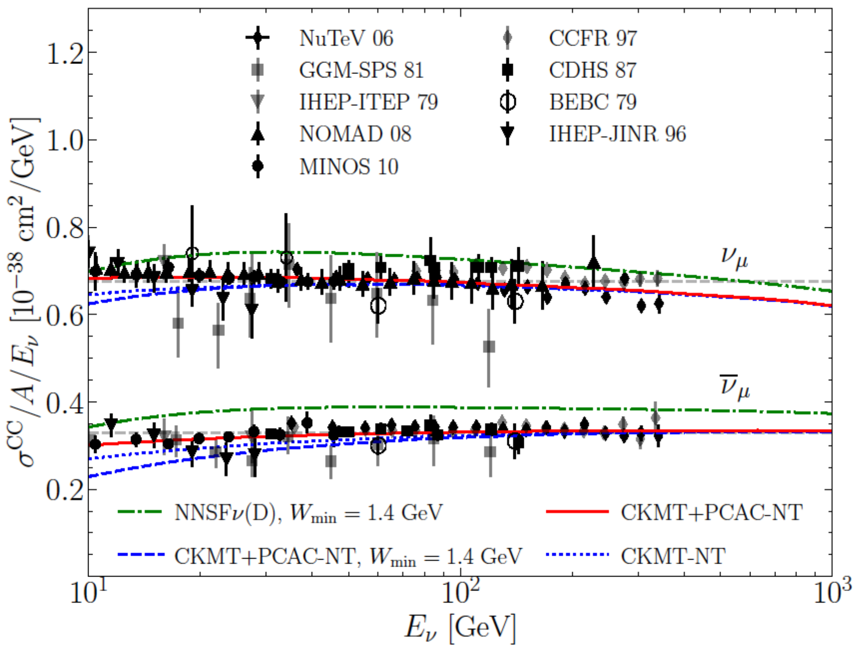
Christophe Bronner

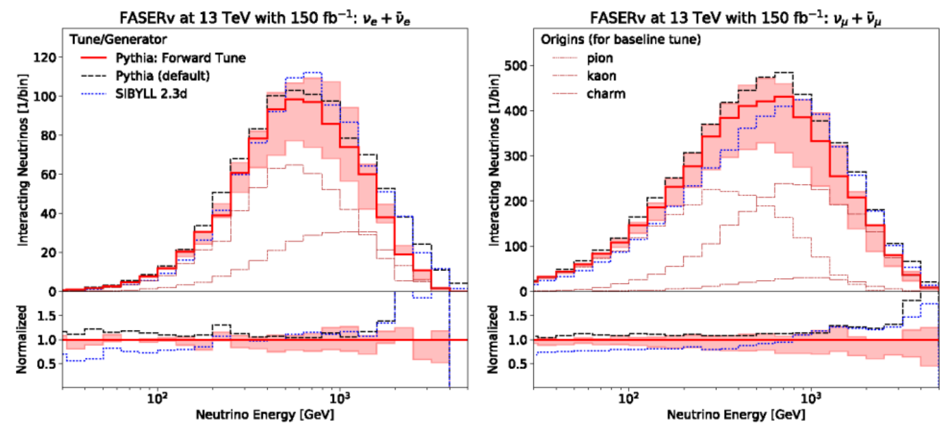
Fieg,Kling,Schulz,Sjöstrand,PRD109(2024)016010, FASERnu,ArXiv:2403.12520
Garcia,Gauld,Heijboer,Rojo,JCAP09(2020)025,Jeong and Reno,ArXiv:2307.09241

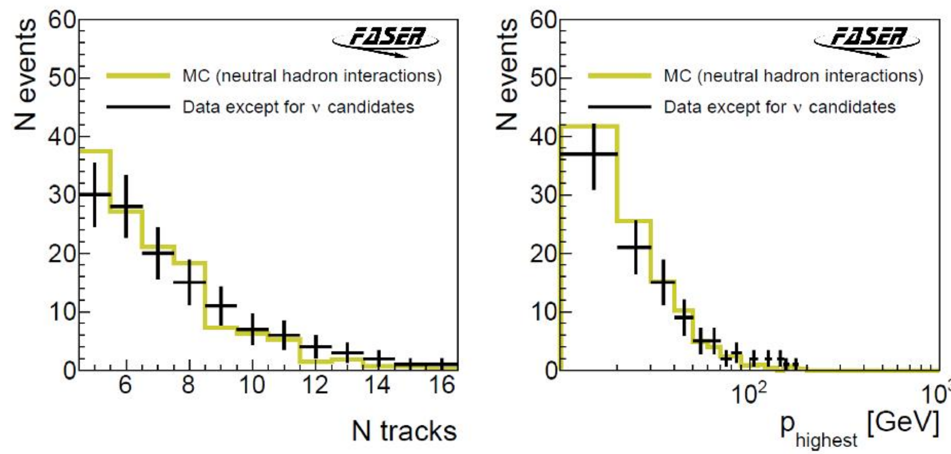
4. DIS in event generators

DIS cross-section model
- CSMS for neutrino telescopes
- NNSFnu in GENIE

High-energy neutrino production
- Forward production hadronization tuning
- Collider and atmospheric neutrinos







NuSTEC

NuSTEC 2024 summer school at CERN
https://indico.cern.ch/event/1331901

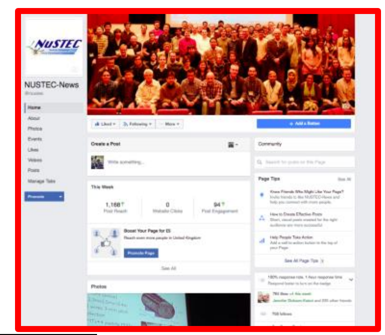
Neutrino Scattering Theory-Experiment Collaboration
https://nustec.fnal.gov/

NuSTEC CTGWG seminar and CEWG meetings
https://indico.fnal.gov/category/990/

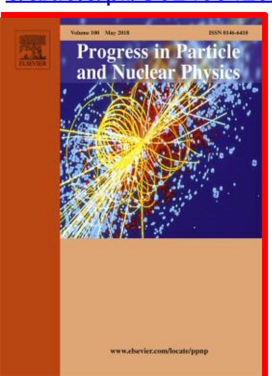
NuSTEC

- Cross-theory-generator WG (CTGWG)
- Workshops and Schools
- Cross-experiment WG (CEWG)
- Publications
- Long-term community planning
- Outreach

NuSTEC-News Facebook page
https://www.facebook.com/nuxsec



NuSTEC, PPNP100(2018)1
https://www.sciencedirect.com/science/article/pii/S0146641018300061



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Conclusion

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Neutrino event generator is a fundamental tool for neutrino experiments including the long-base neutrino oscillation experiments

1 to 10 GeV neutrino interaction measurements are crucial to successful next-generation neutrino oscillation experiments

Recent new neutrino interaction models show nuclear and hadron physics are important in neutrino event generators

Thank you for your attention!

Backup

1. PDG: Neutrino Cross Section Measurements

PDG has a summary of neutrino cross-section data since 2012!

Focus of this talk is around a few GeV

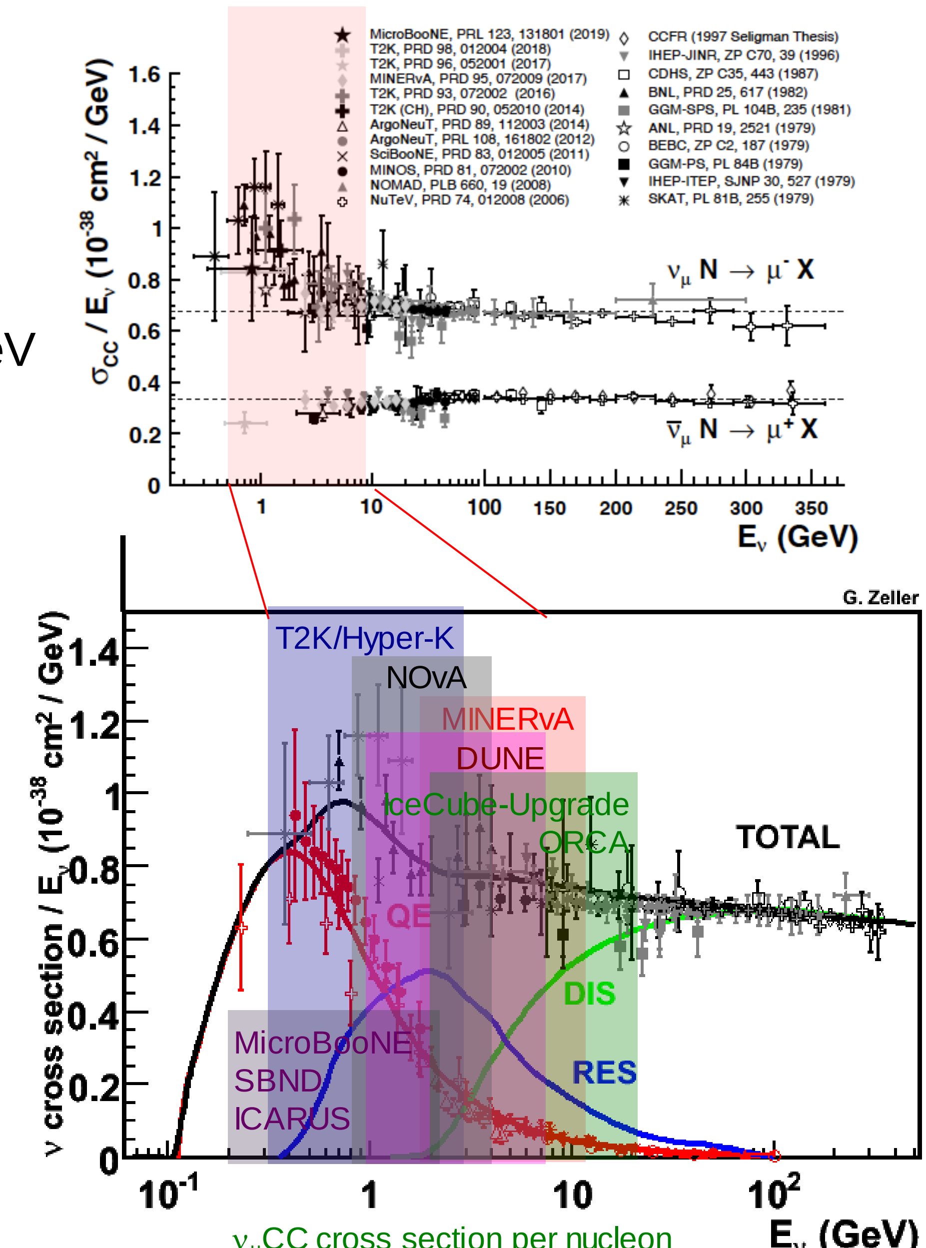


Table 52.2: Published measurements of neutrino and antineutrino CC inclusive cross sections from modern accelerator-based neutrino experiments.

experiment	measurement	target
ArgoNeuT	ν_μ [6, 7], $\bar{\nu}_\mu$ [7]	Ar
MicroBooNE	ν_μ [8, 26], ν_e [22]	Ar
MINERνA	ν_μ [9–11, 16, 17, 27], $\bar{\nu}_\mu$ [27], $\bar{\nu}_\mu/\nu_\mu$ [28]	CH, C/CH, Fe/CH, Pb/CH
MINOS	ν_μ [29], $\bar{\nu}_\mu$ [29]	Fe
NINJA	ν_μ [12], $\bar{\nu}_\mu$ [12]	H_2O
NOMAD	ν_μ [30]	C
SciBooNE	ν_μ [31]	CH
T2K	ν_μ [13, 14, 32–34], ν_e [23–25], $\bar{\nu}_\mu/\nu_\mu$ [15]	CH, H_2O, Fe

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 phases (x2)
6. Absolute neutrino mass

(4.–6.) not relevant to neutrino oscillation experiment

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

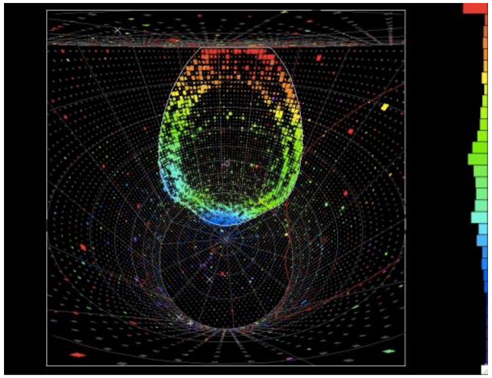
Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

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

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

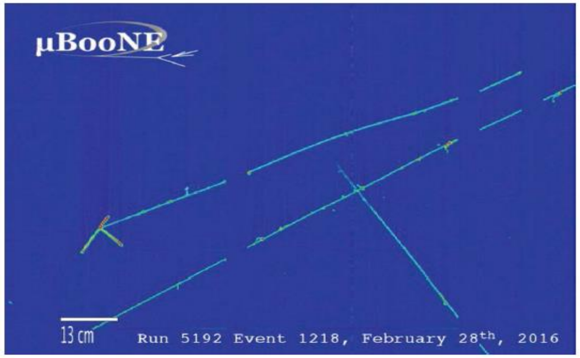
1. Next goal of high energy physics

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 need 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)
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High energy beam (~few GeV)
- longer baseline (higher flux reduction)
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$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

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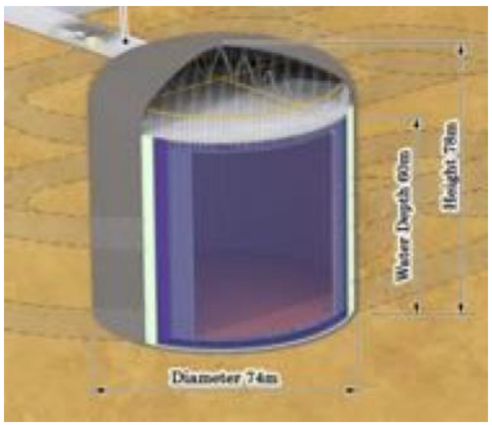
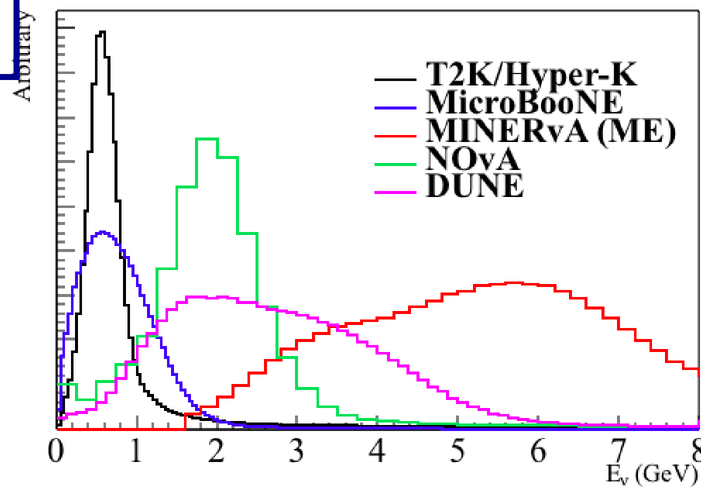
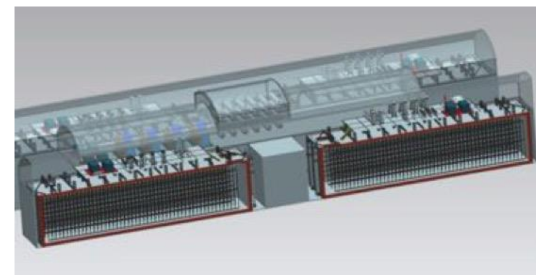
1. Next goal of high energy physics

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

DUNE (USA)
- Argon target
- 1300 km baseline
- wide band 1-4 GeV
- High spatial resolution
- Low time resolution







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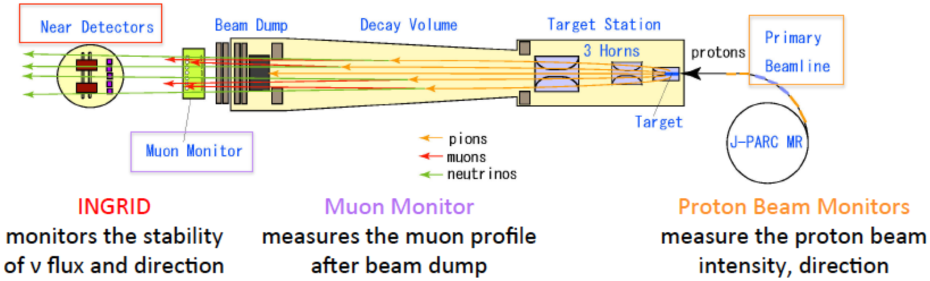
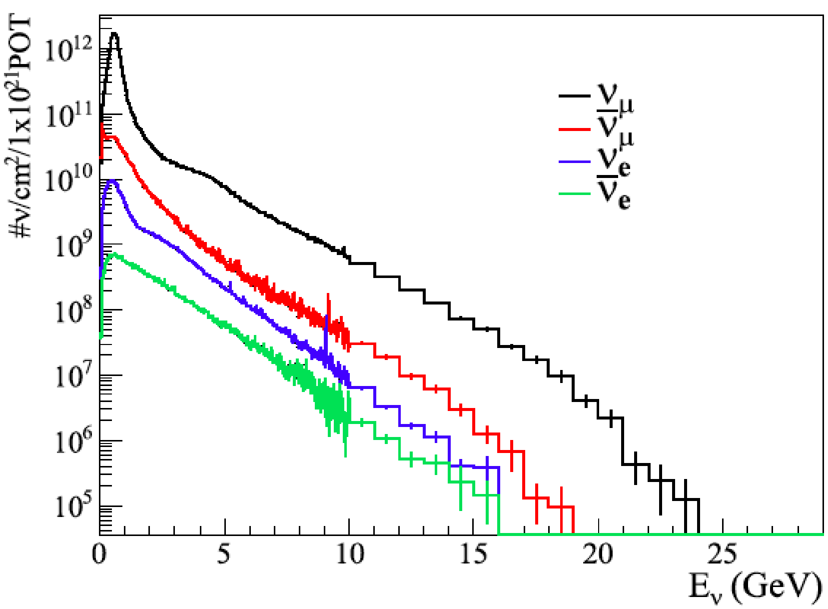
$$P_{\mu\to e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

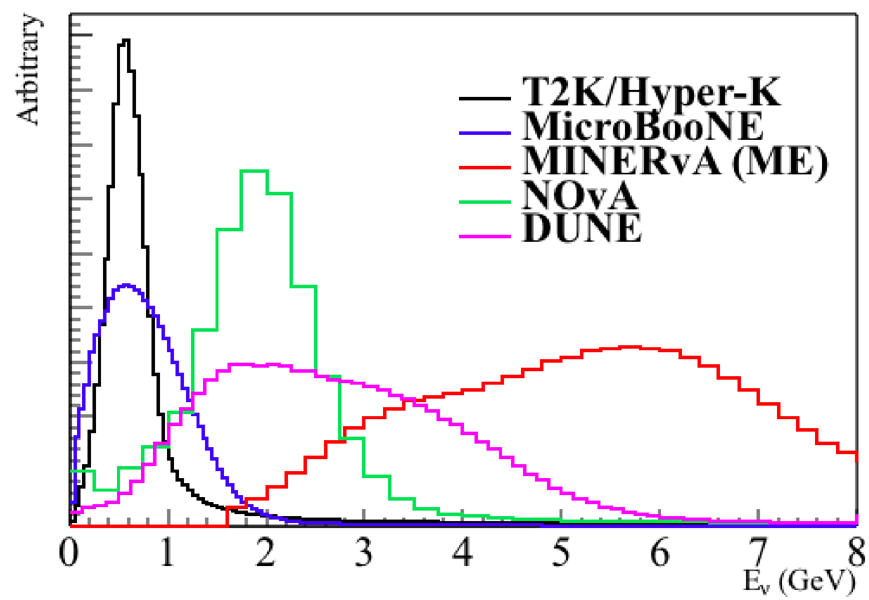
TK, Martini, JPhysG45(2017)1
Kowalik, NuInt18 (Toronto)

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)





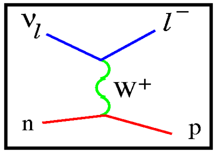


$$P_{\mu\to e}(L/E)=\sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

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

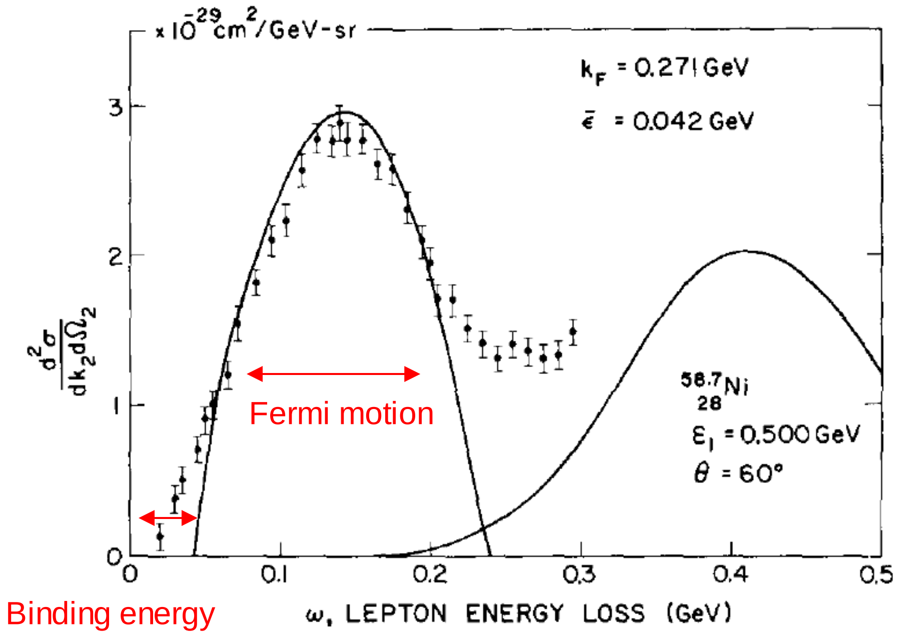
2. Fermi motion

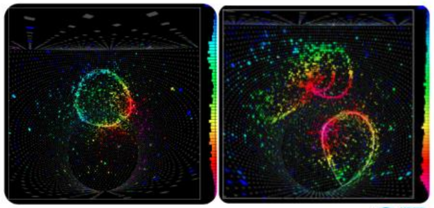
Quasi Elastic



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)



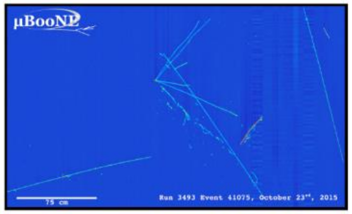


Cherenkov detectors:

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

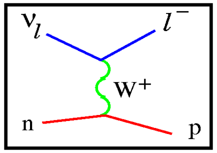
$$E_{\text{cal}} = E_l + E_p^{\text{kin}} + \epsilon$$

[1p0π]

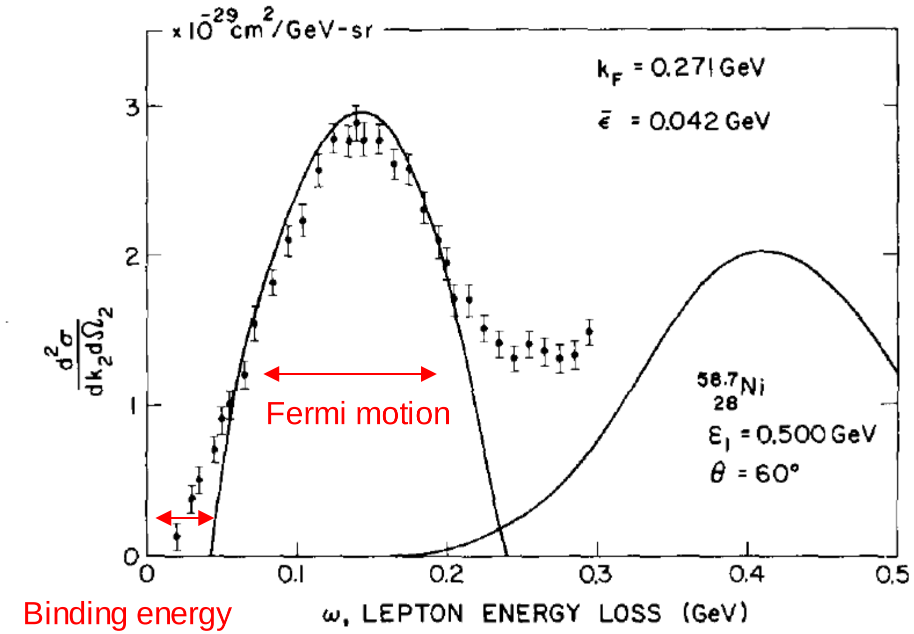
Smith and Moniz, NPB43(1972)605
MiniBooNE, PRD81(2010)092005

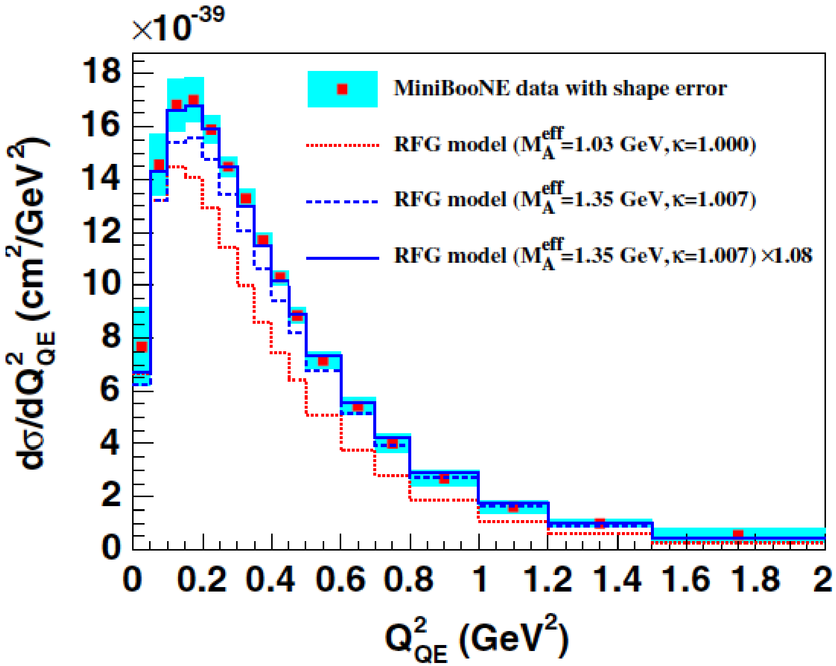
2. Pauli blocking

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

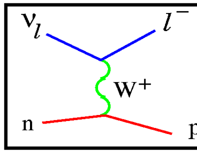




Smith and Moniz, NPB43(1972)605
Bodek and Cai, EPJC79(2019)293

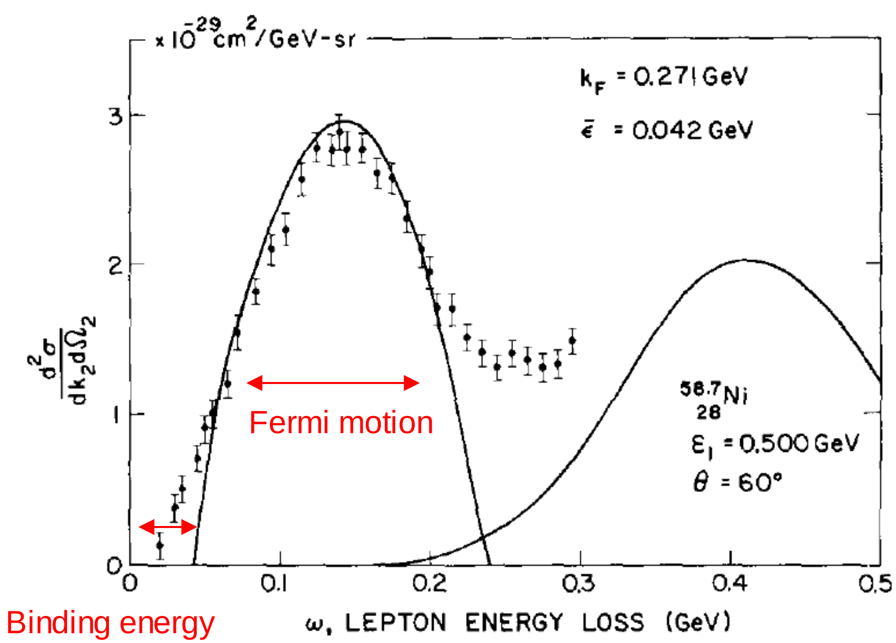
2. Nuclear Shell structure and binding energy

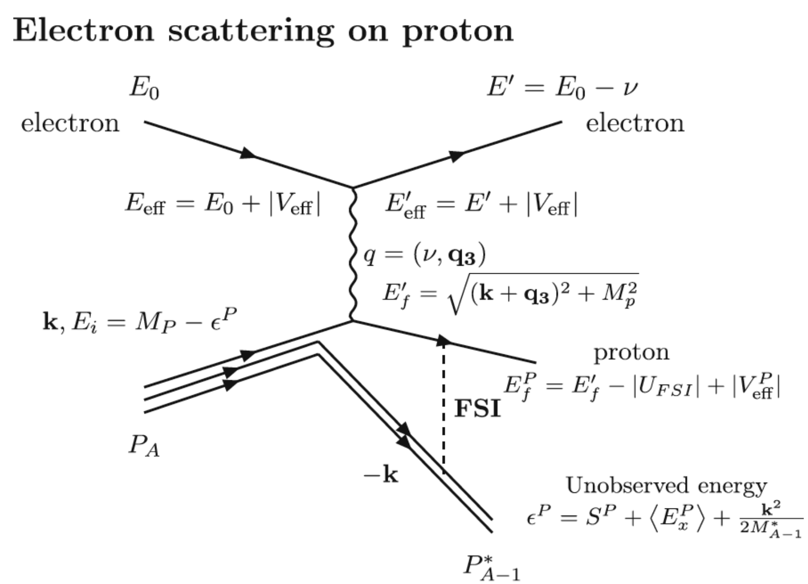
Quasi Elastic



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)



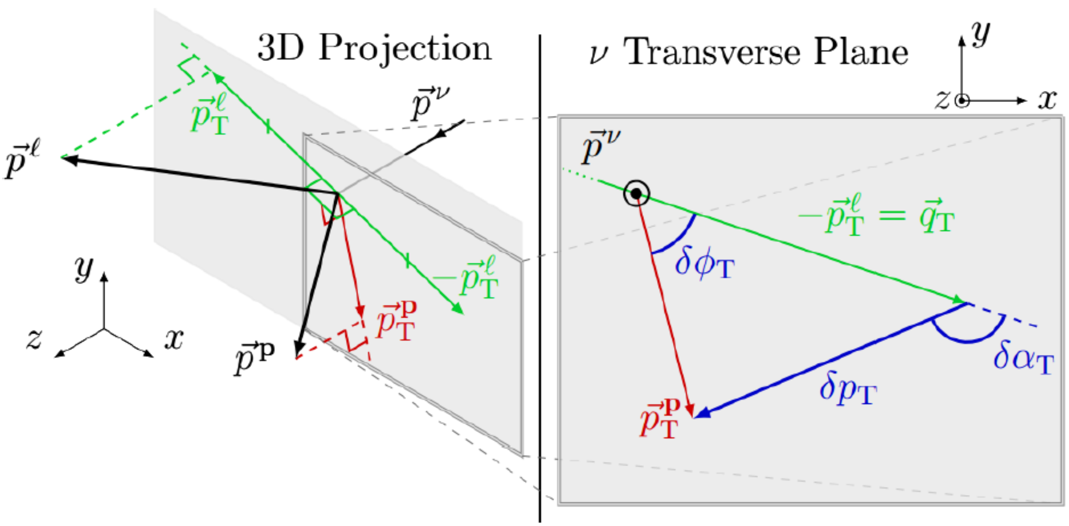


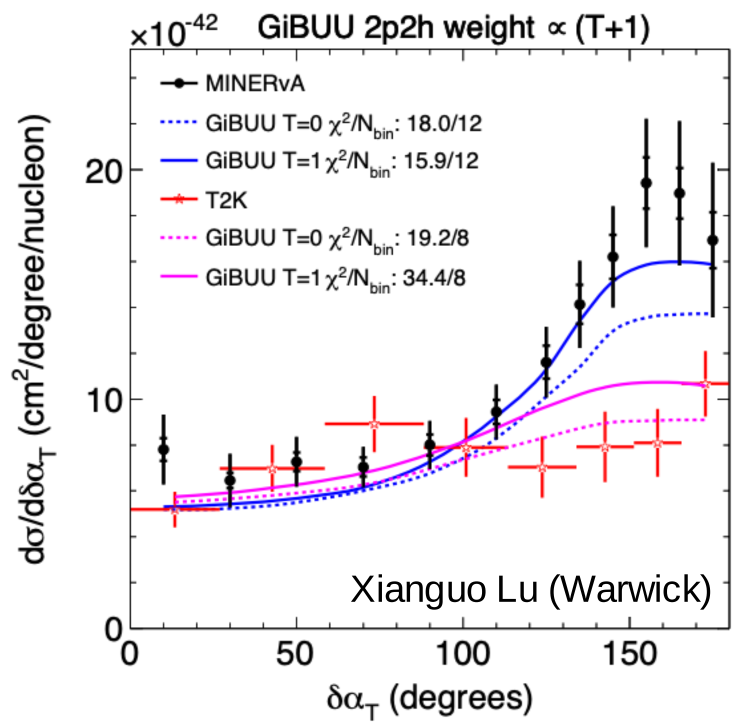
2. Nucleon correlations in neutrino physics

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.

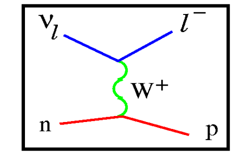
Data prefer advanced nuclear models, but it's not easy to identify which 2p2h model is right





Importance of axial 2BC is understood qualitatively, we need more quantitative understanding

Quasi Elastic

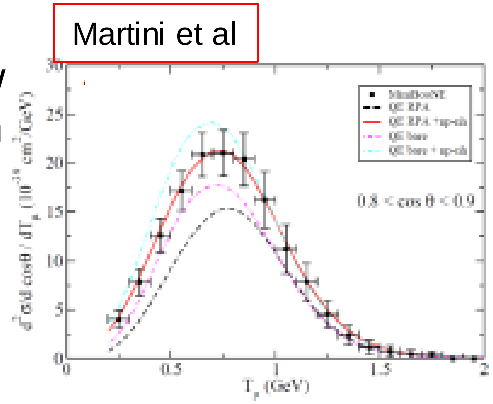


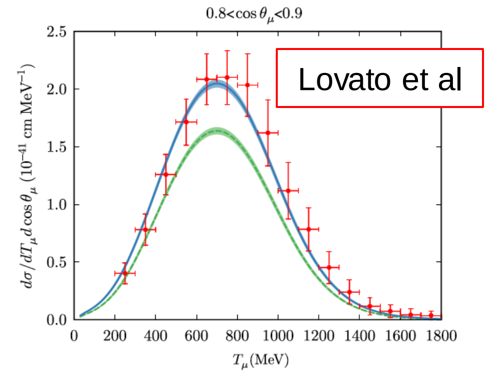
2. Models using 2p-2h

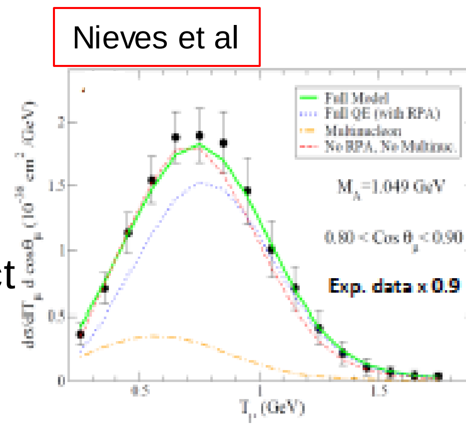
Flux-averaged differential cross-sections allow nuclear theorists to compare their models with data without implementing them in generators

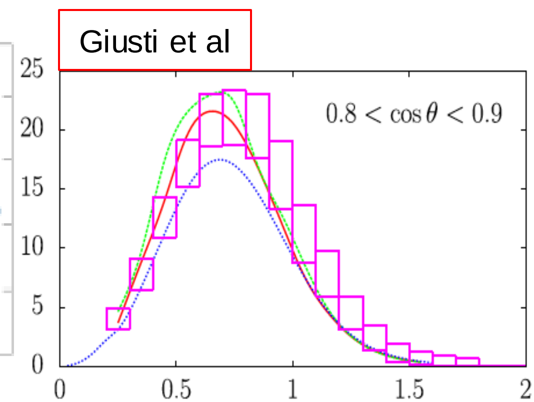
Martini et al – Lyon 2p2ph model
Nieves et al – Valencia 2p2h model
SuSAv2 – Superscaling+MEC
Giusti et al – Relativistic Green's function
Butkevich et al – RDWIA+MEC
Lovato et al – GFMC
Jachowicz et al – CRPA+MEC

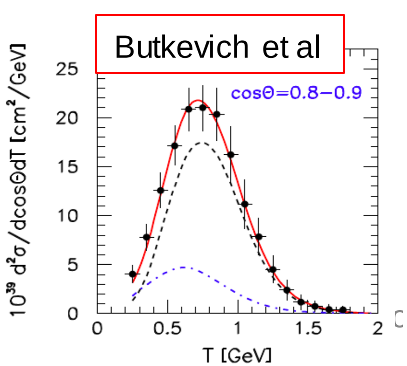
All models can fit with data, are they all correct models?

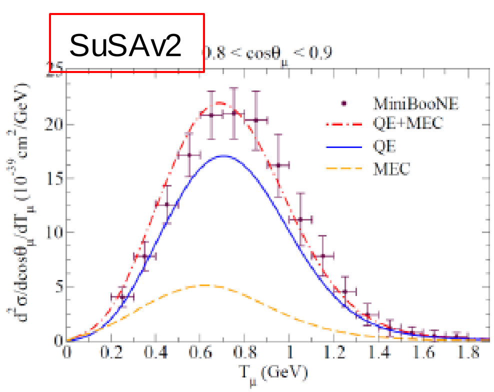


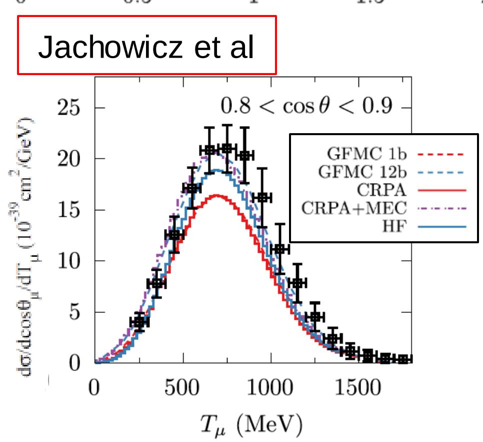










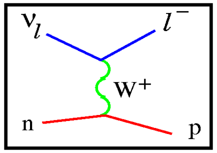


KING'S College LONDON

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

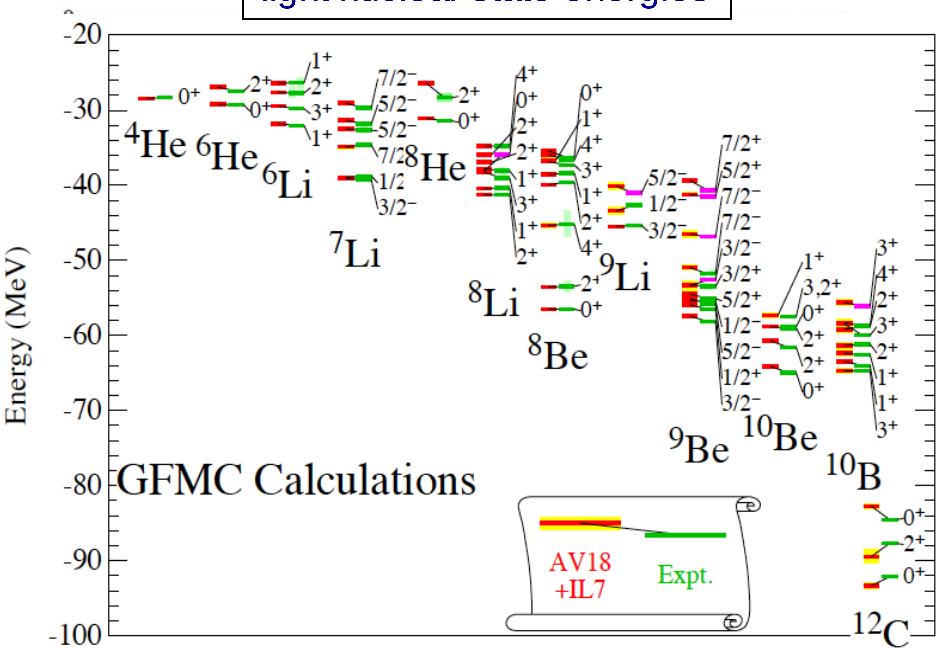
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Ground state includes correct nucleon correlations

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

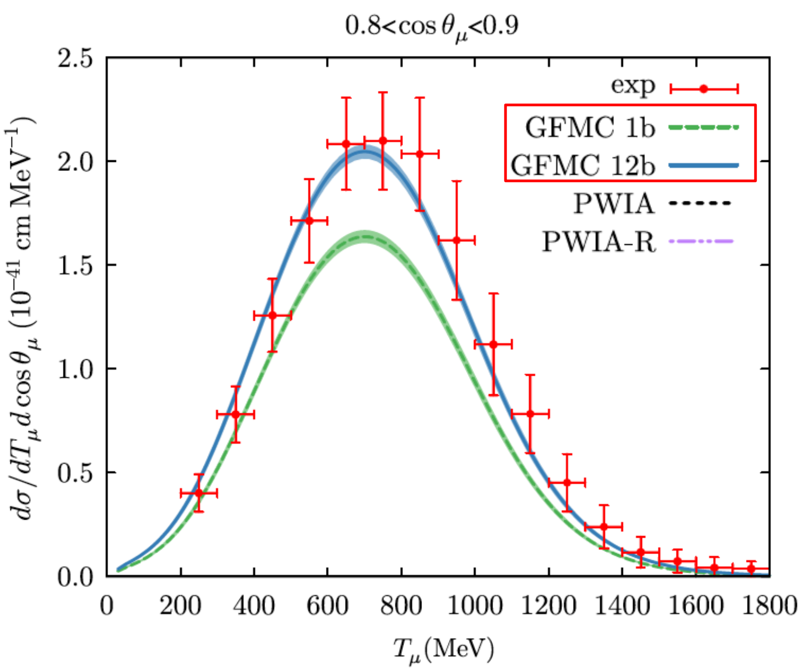
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



MiniBooNE CCQE cross-section



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

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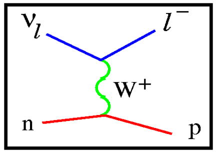

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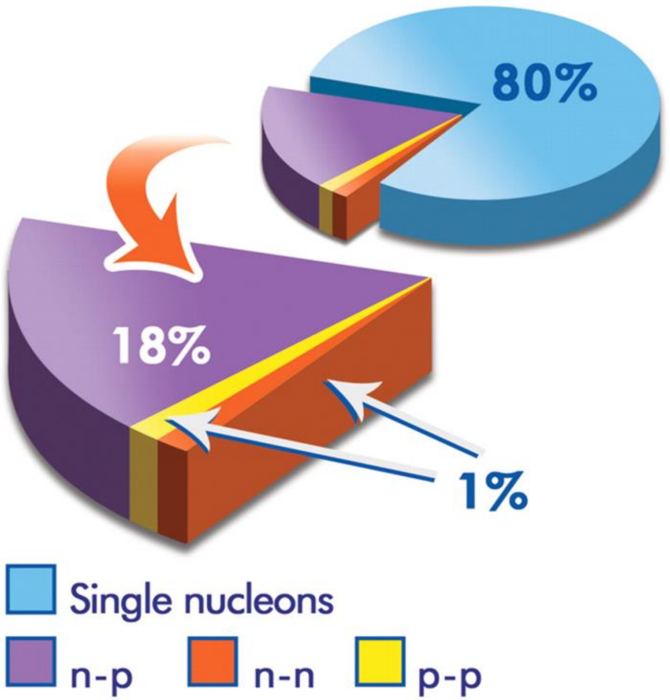
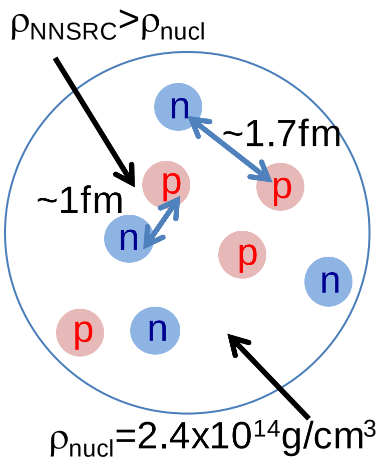
2N potential (Av18) — 3N potential (IL7)





Physics of nucleon correlation

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

Nucleon correlation is a very hot topics!

Benhar et al, PRL105(2010)132301, EPJST230(2021)4309
TK, Martini, JPhysG45(2017)1

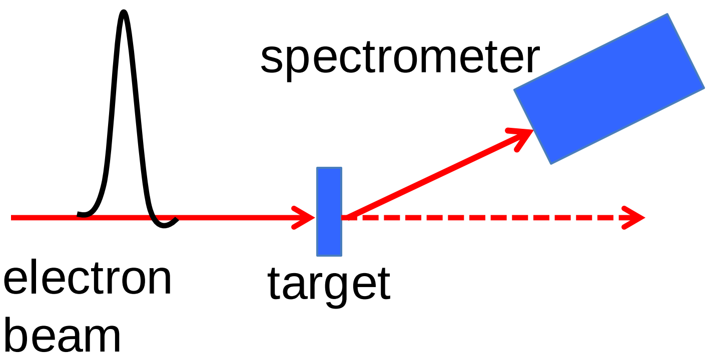
2. New paradigm of lepton scattering experiments

Flux-averaged differential cross-section
- Incomplete kinematics, reconstruction of Ev, Q2, q3, W, x, y,… depends on models

Electron scattering
- well defined energy, well known flux

→ reconstruct energy-momentum transfer

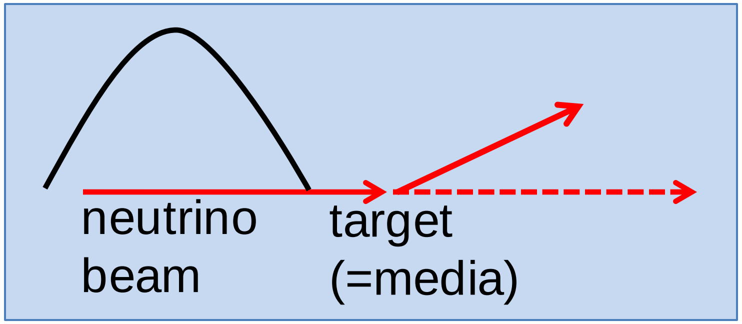
→ measure each process



Neutrino scattering
- Wideband beam (unknown Ev)

→ cannot fix kinematics

→ inclusive measurement (CCQE, RES...)



Khachatryan et al., Nature 599(2021)565

2. New paradigm of lepton scattering experiments

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Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ measure each process

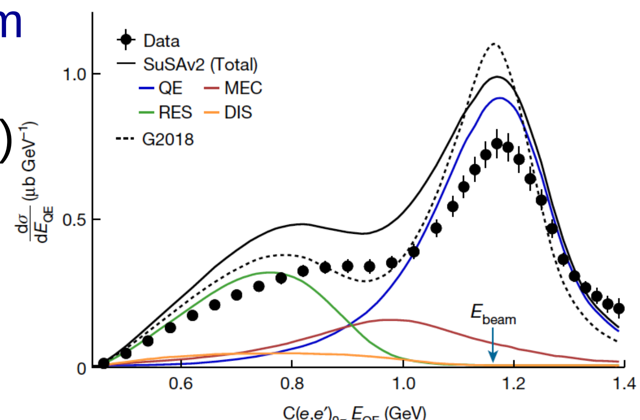
Neutrino experiment don’t reconstruct Ev (and Q2) with great precision

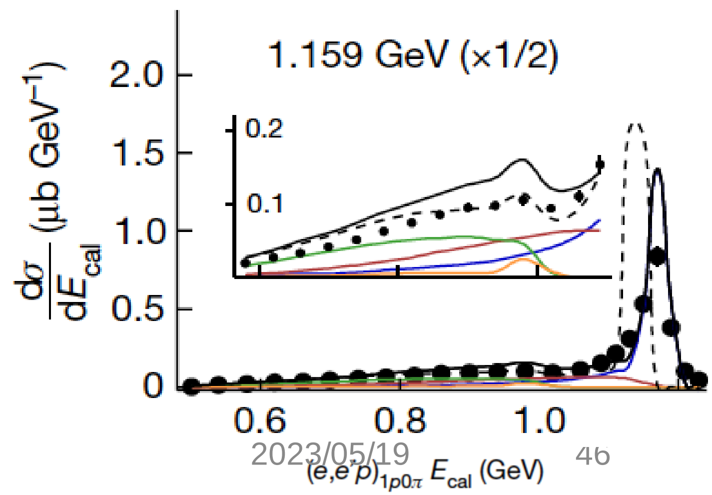
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

Reconstructed beam electron energy spectrum by

- QE kinematic (HyperK)
- Calorimetric (DUNE)





MINERvA, PRL116(2016)071802,PRD99(2019)012004
NOvA, EPJC80(2020)1119

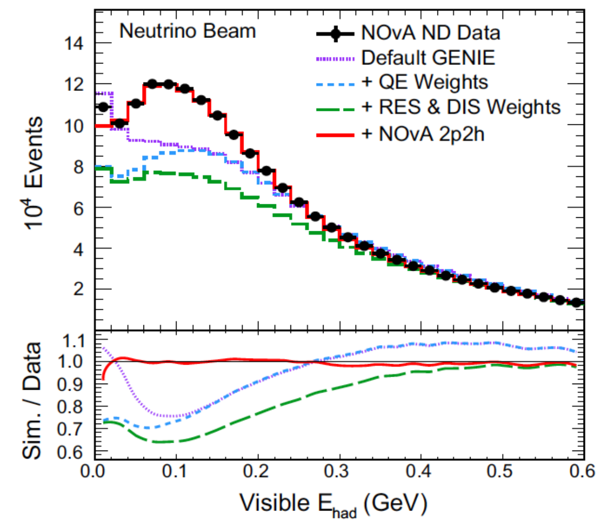
2. New paradigm of lepton scattering experiments

Flux-averaged differential cross-section

- Incomplete kinematics, reconstruction of Ev, Q2, q3, W, x, y,… depends on models
- New kinematic variables from hadrons

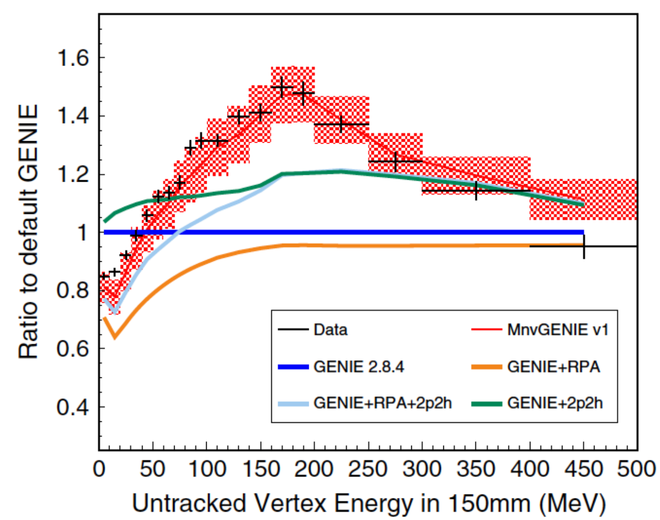
Visible hadronic energy deposit: E_{had}, E_{avail}

- Sum of all hadron energy deposit
- Strongly correlated to energy transfer (q_0 or ω or ν)
- Sensitive to 2p2h



Vertex activity

- Some of all hadronic activities around the vertex
- Low energy nucleons (=2 nucleon emission)



2. New paradigm of lepton scattering experiments

These studies suggest no nuclear models fit neutrino data without tuning

Flux-averaged differential cross-section

- Incomplete kinematics, reconstruction of Ev, Q2, q3, W, x, y,… depends on models
- New kinematic variables from hadrons

Visible hadronic energy deposit: E_{had}, E_{avail}

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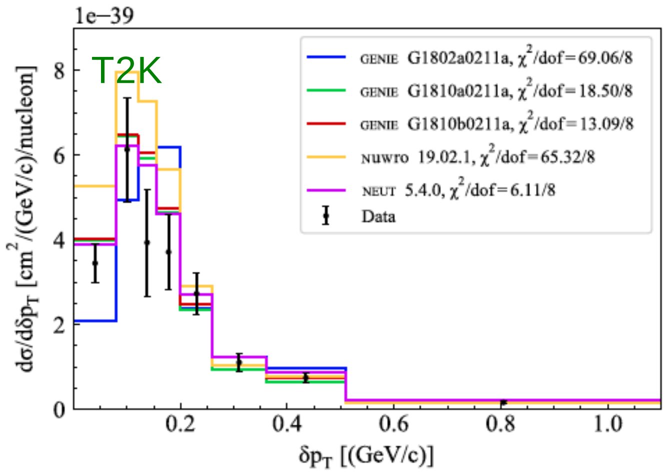

Vertex activity

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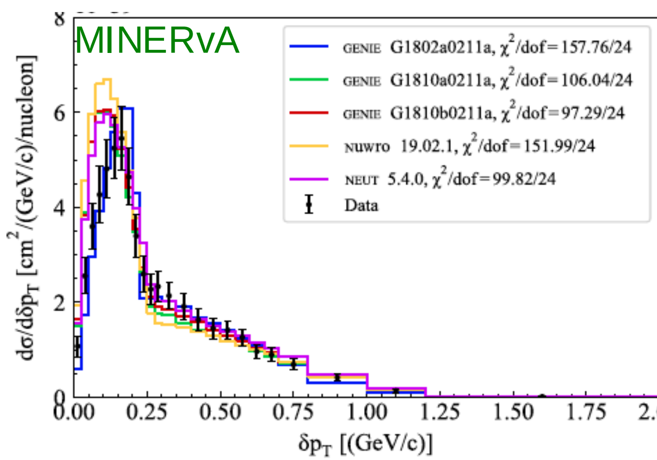
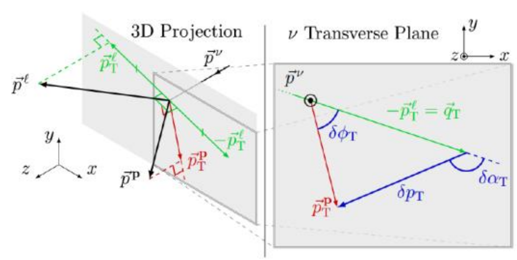


Transverse kinematic Imbalance (TKI) variables

δP_T ~ nucleon momentum distribution

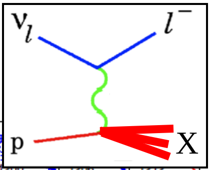
$\delta\alpha_T$ ~ FSI



nal.gov

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

4. Higher baryonic resonances



DCC model vs. electro-pionproduction data

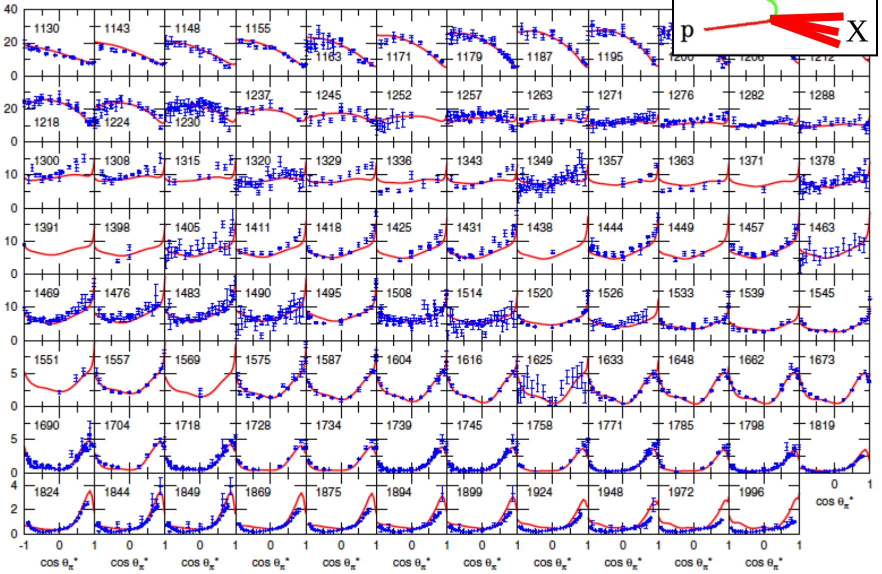


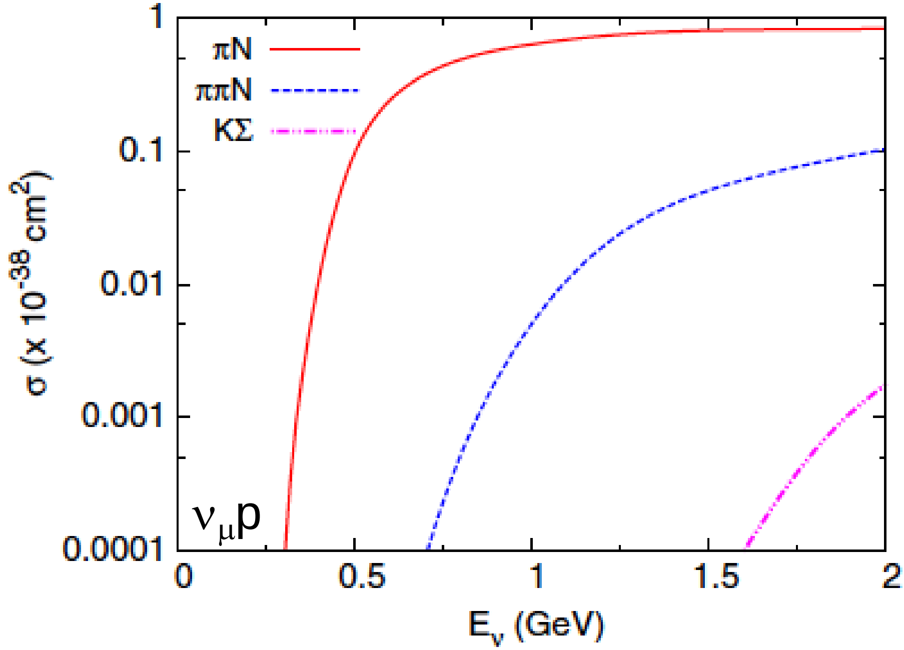
FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega^*_\pi$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

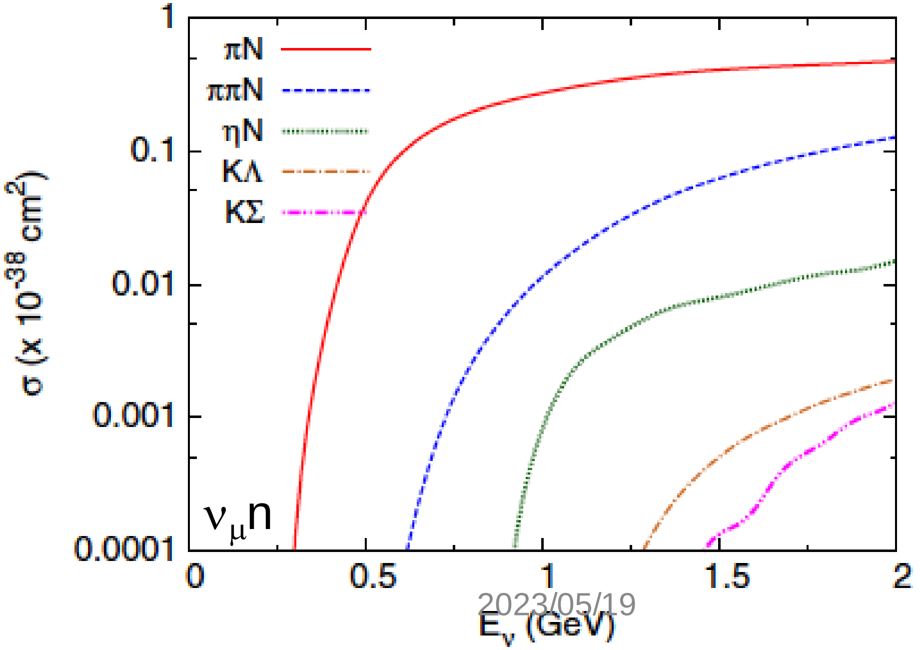
Cross section

- 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

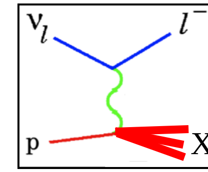




4. Quark-Hadron duality

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

DIS



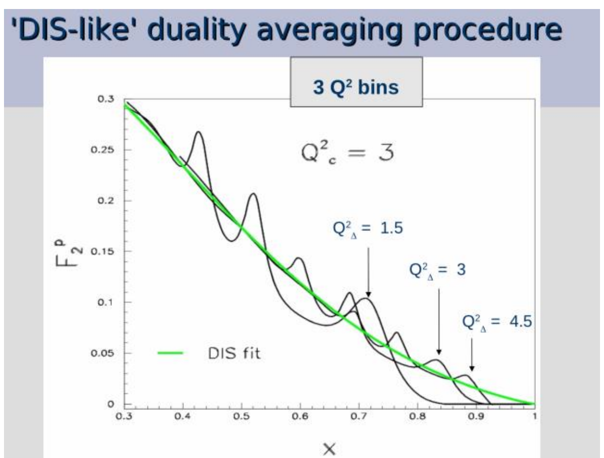
Cross section

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

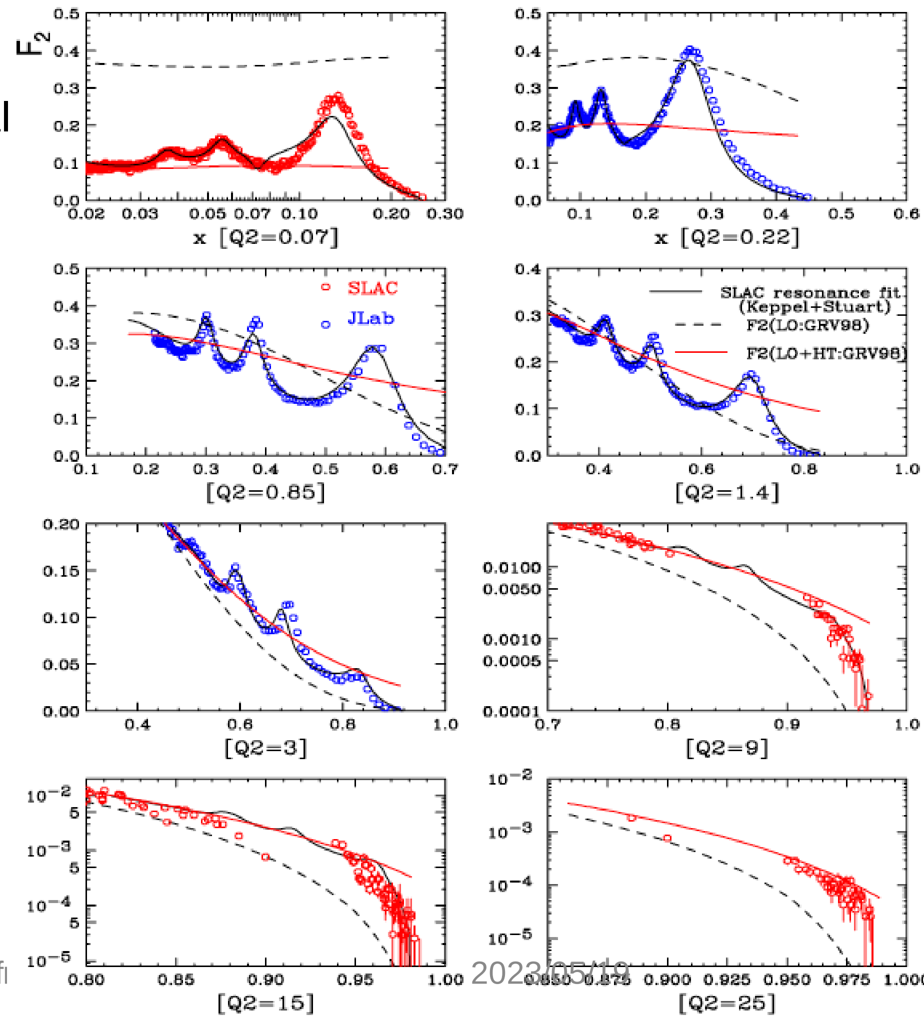
Bodek-Yang correction is a phenomenological model to reproduce duality-like behavior, accepted by all neutrino simulation

DIS ≠ Bjorken limit

DIS = Q^2 average of all resonances



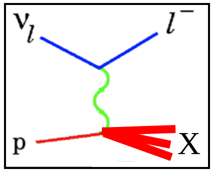
Proton F2 function GRV98-BY correction vs. data



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

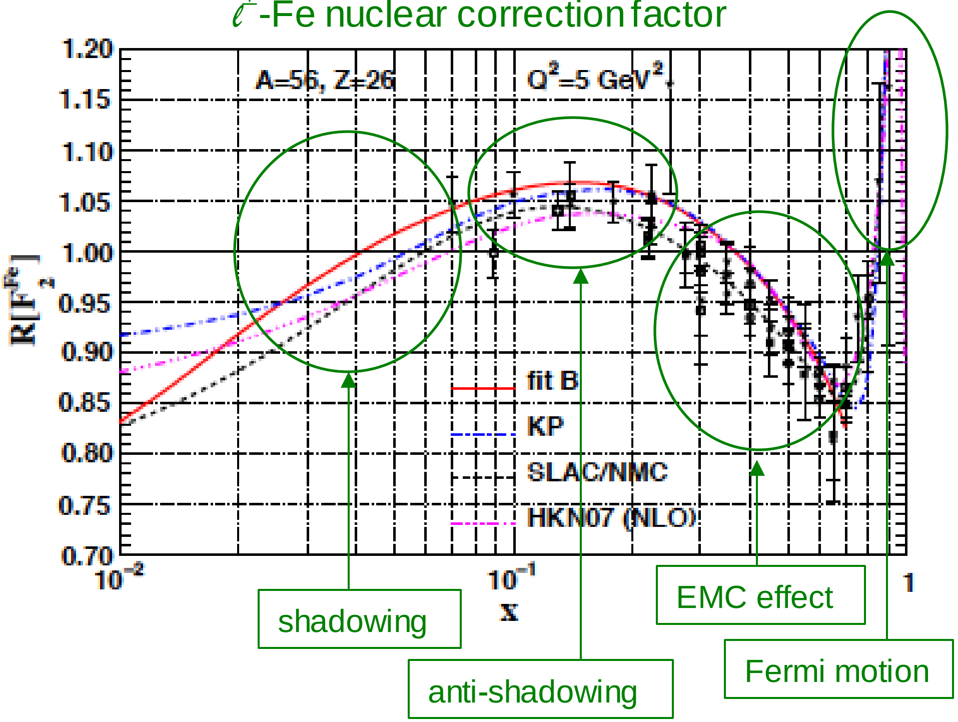
4. Nuclear dependent DIS



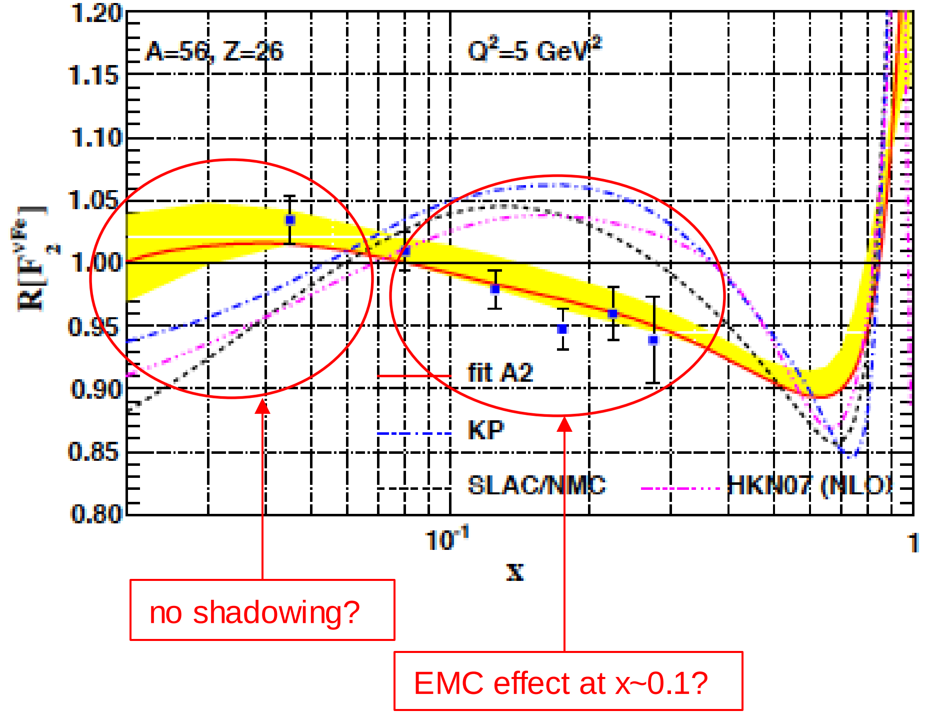
Cross section
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

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

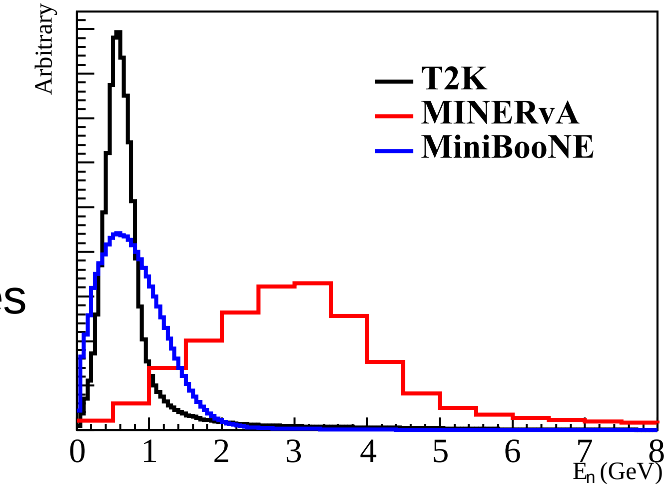


ν-Fe nuclear correction factor



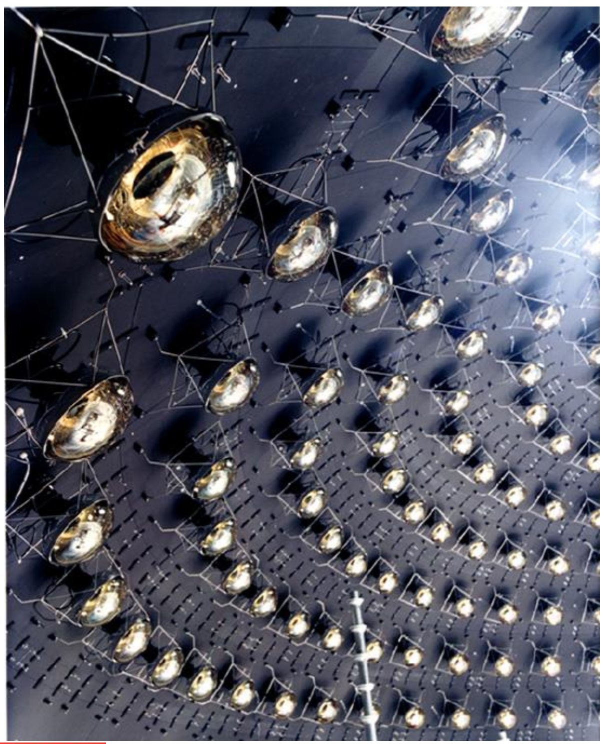
MiniBooNE, PRL100(2008)032301,PRD81(2010)092005:88(2013)032001

5. MiniBooNE



Mineral oil (CH_2) Cherenkov detector

- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Measure Cherenkov radiations from charged particles
- Some calorimetric (scintillation)



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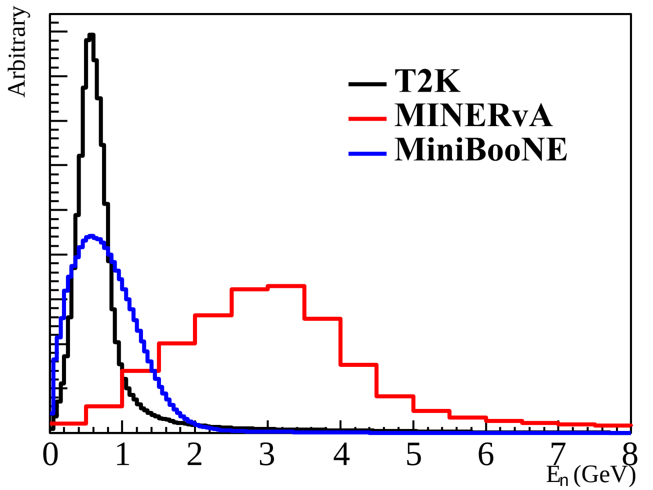
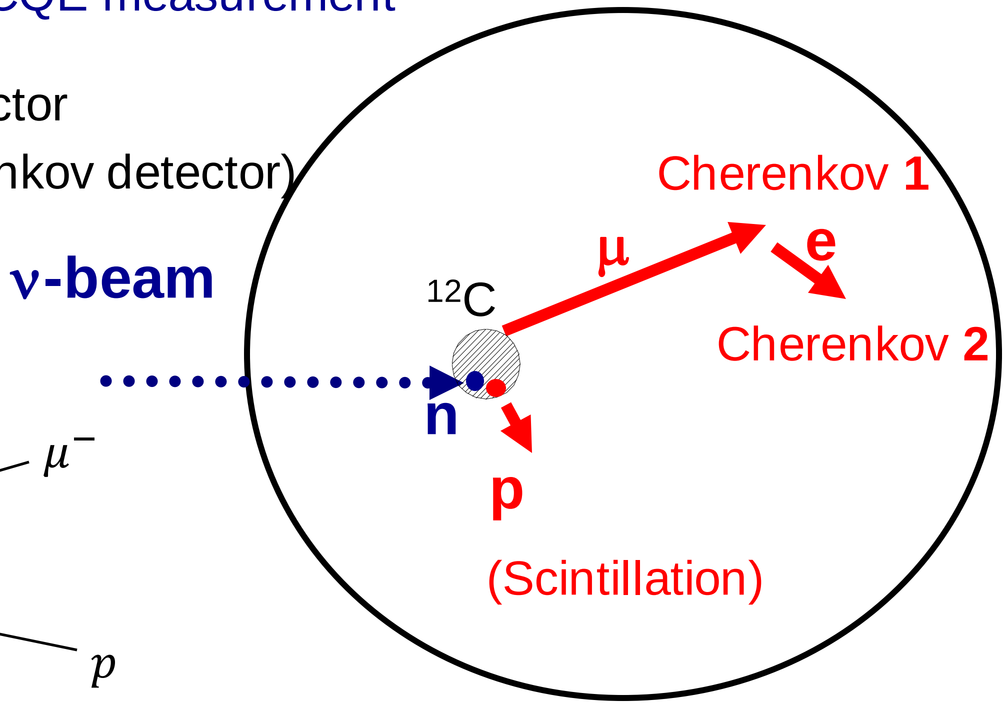
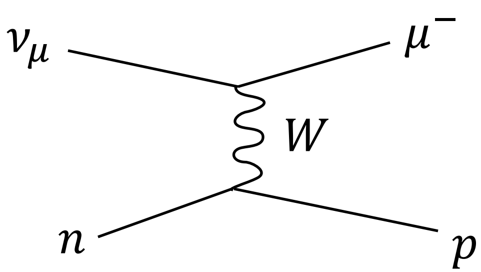


MiniBooNE CCQE measurement

MiniBooNE detector
(spherical Cherenkov detector)



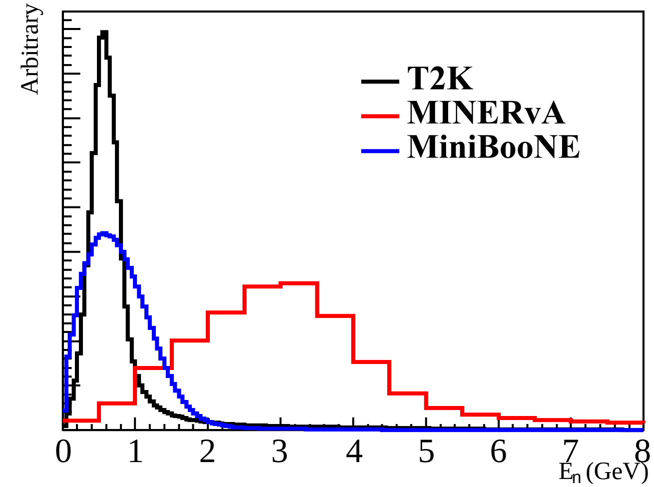


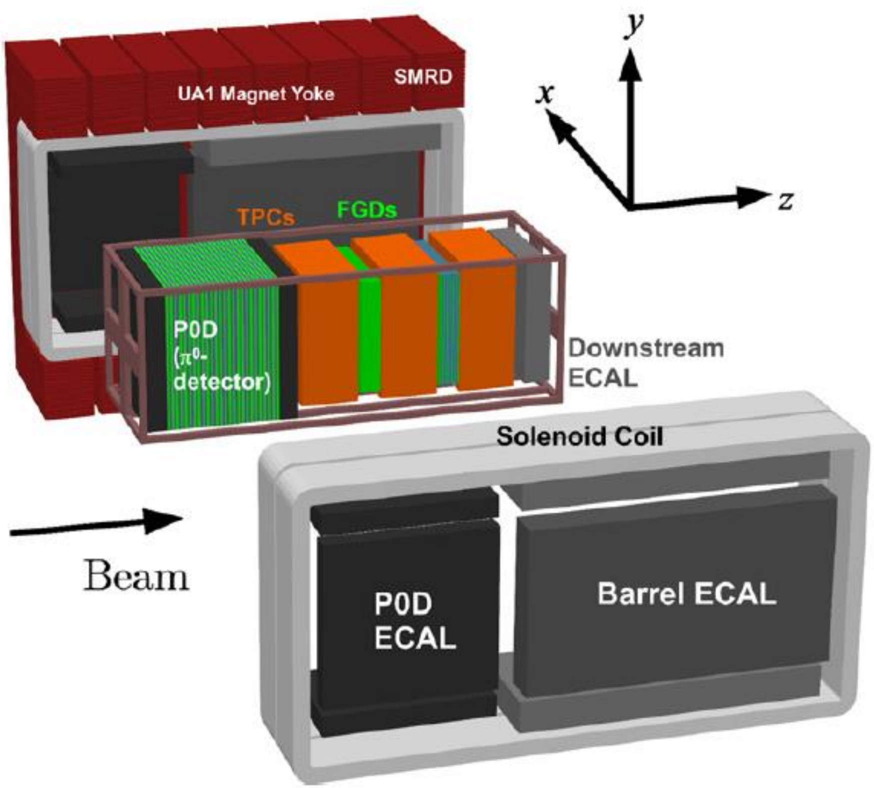
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

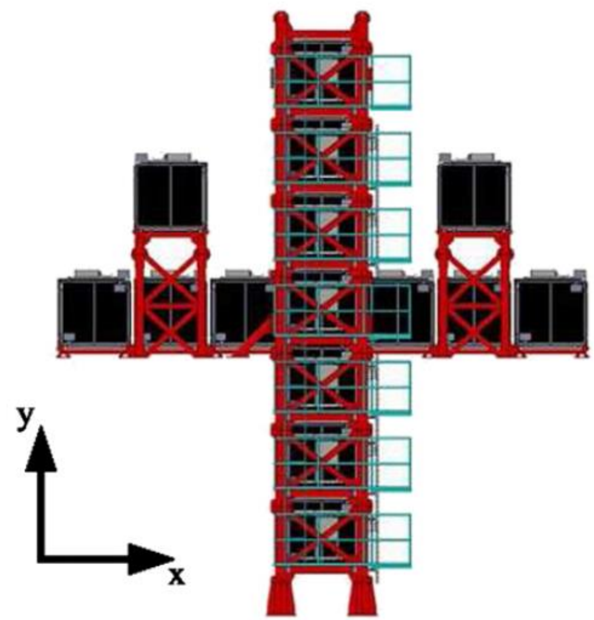
T2K, NIMA659(2011)106

5. T2K near detector complex

INGRID, FGD, P0D, ECal, TPC, SMRD
- Plastic scintillation trackers (except gas TPC)
- 0.2T magnet for momentum measurement
- <E>~600 MeV off-axis beam
- variety of targets (CH, H_2O, Pb, Ar)
- Limited coverage (combination of sub-detectors)







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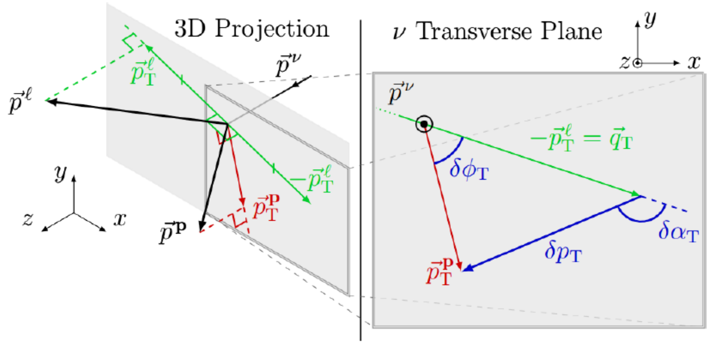

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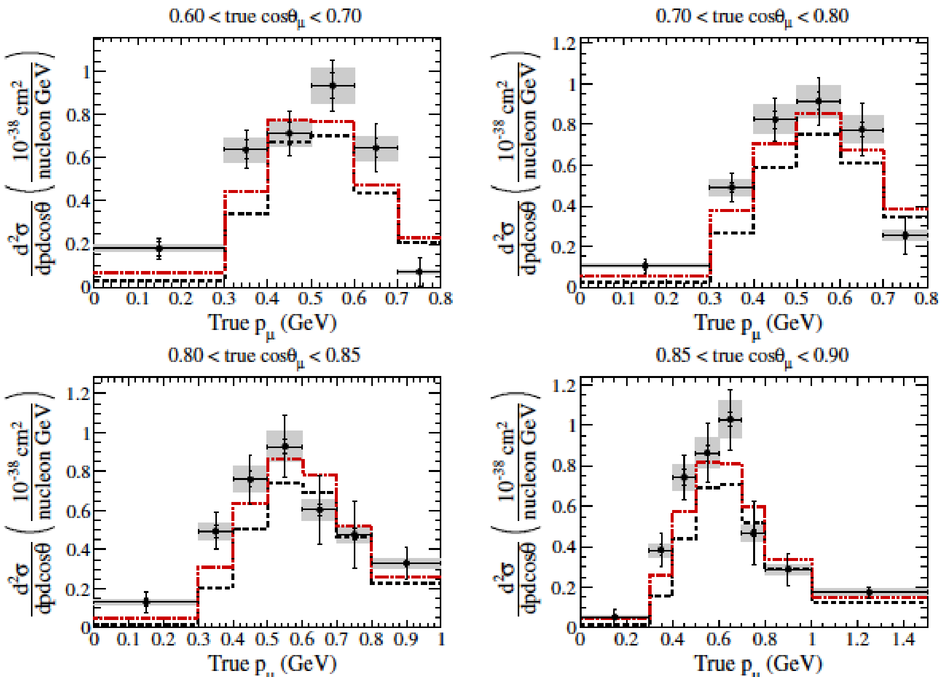
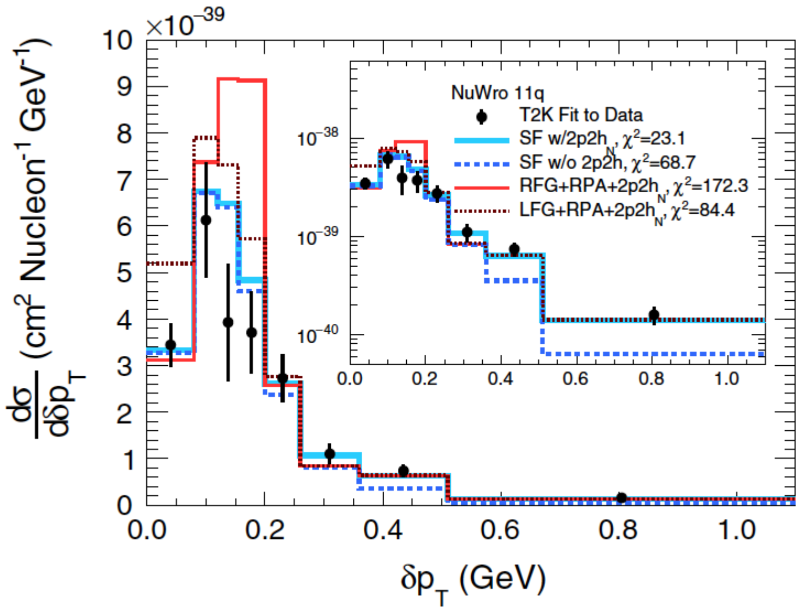
neutrino CC0π double differential cross sections



neutrino CC0π1p differential cross sections



WAGASCI,PTEP(2019)093C02
NINJA, PTEP2021(033C01)

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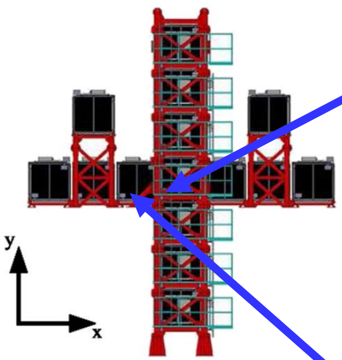
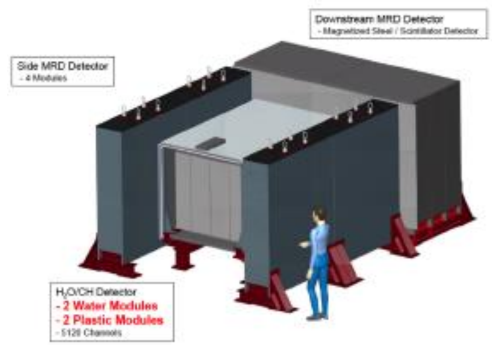
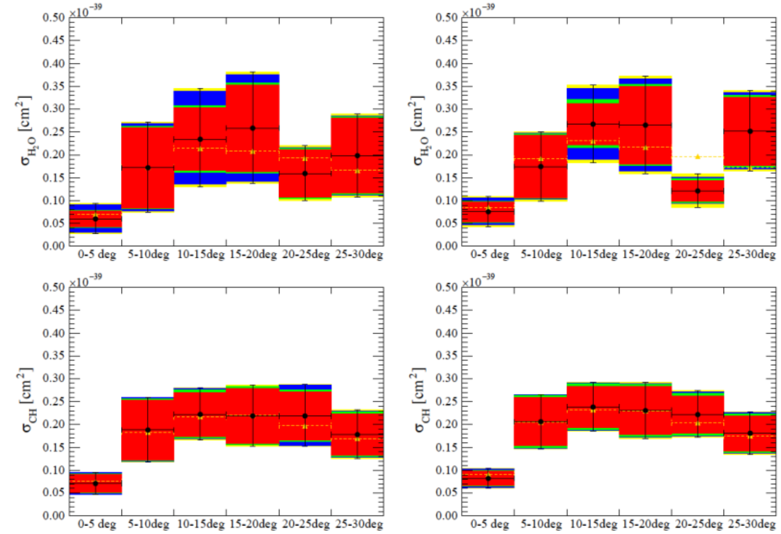
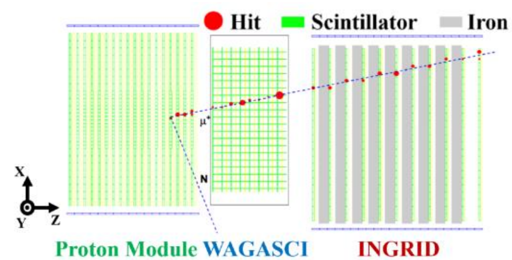


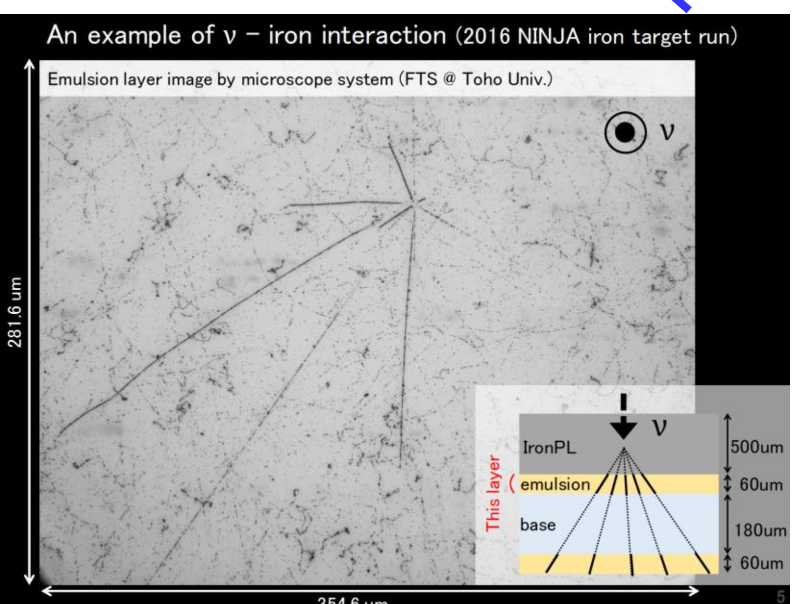
WAGASCI
- water target

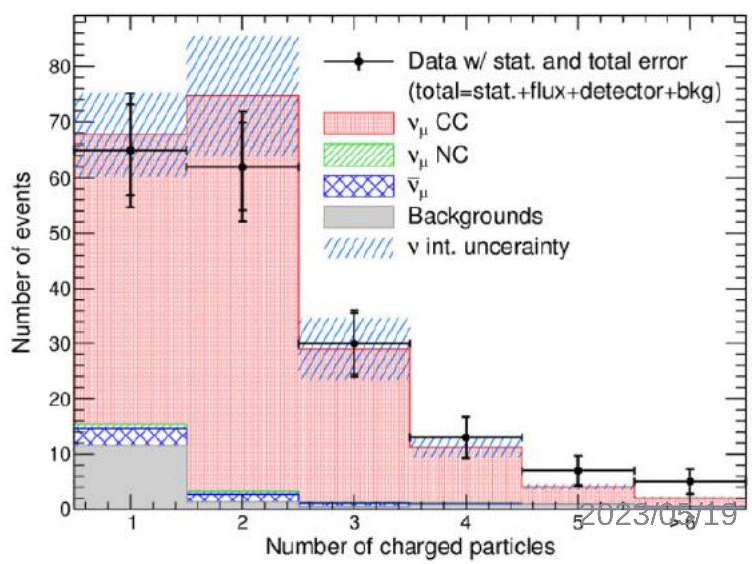




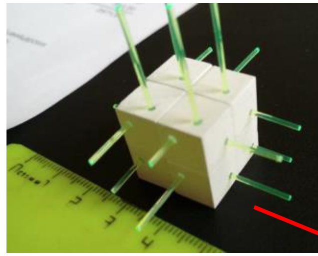


NINJA
- emulsion detector
- Multiple hadron tracks

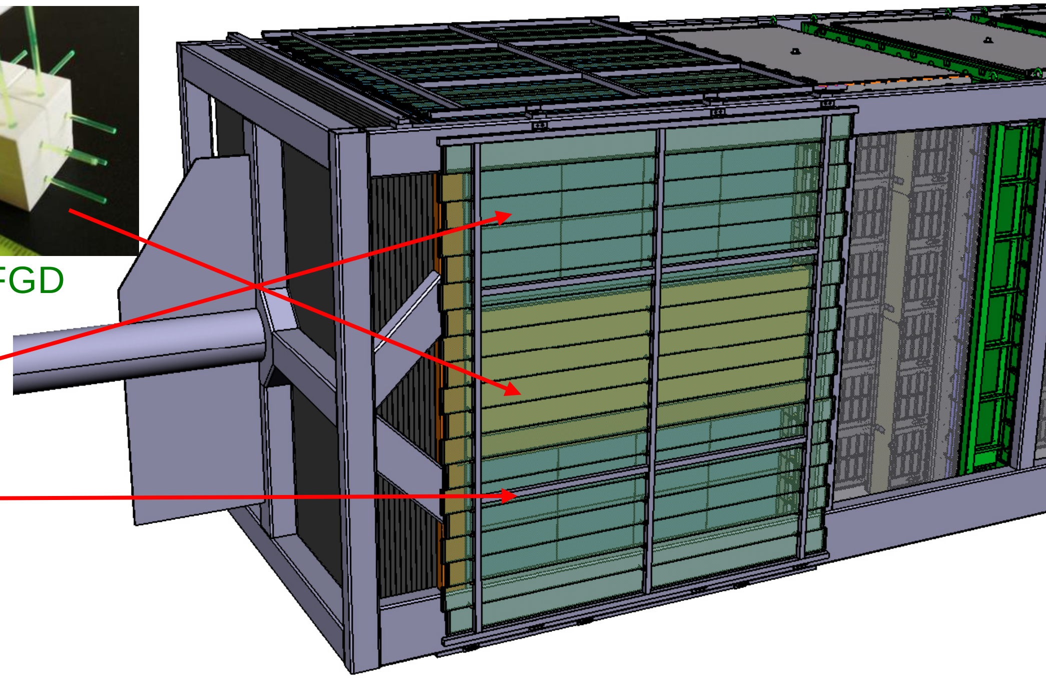




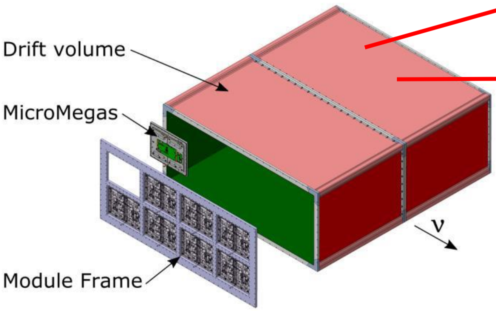
5. ND280 Upgrade



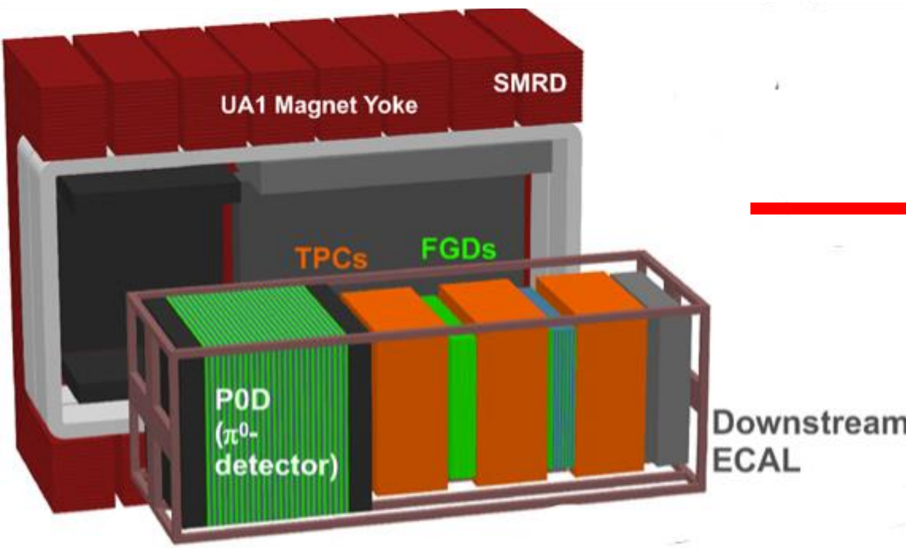
SuperFGD

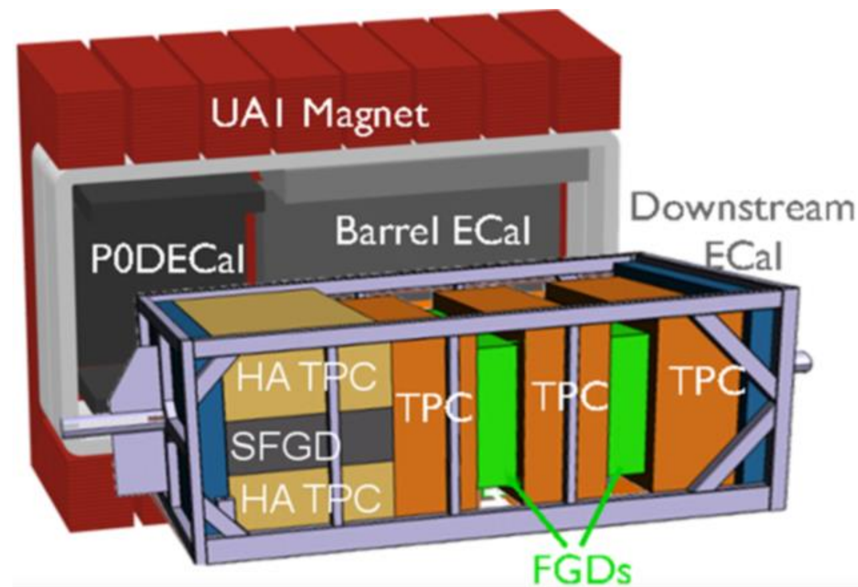


ND280 Upgrade
- Out: P0D detector
- In: High Angle TPC (HATPC)
- In: SuperFGD

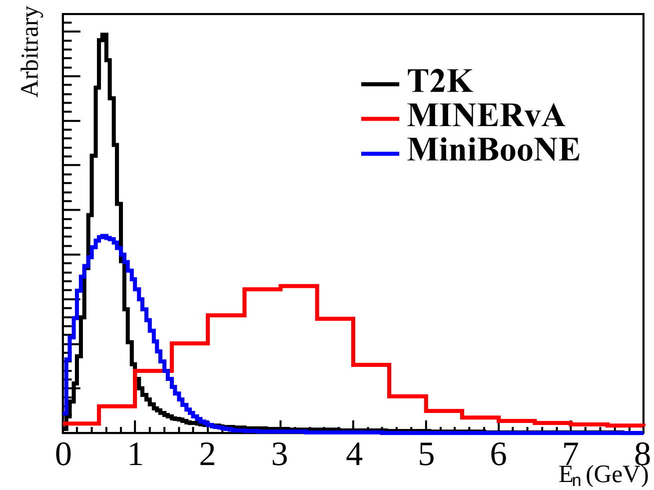


High Angle TPC



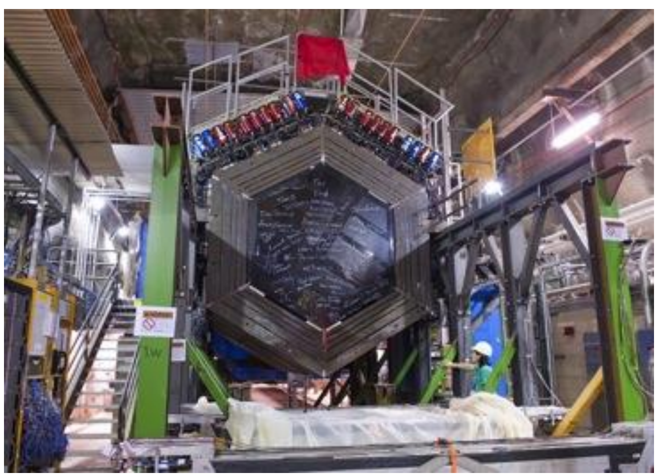


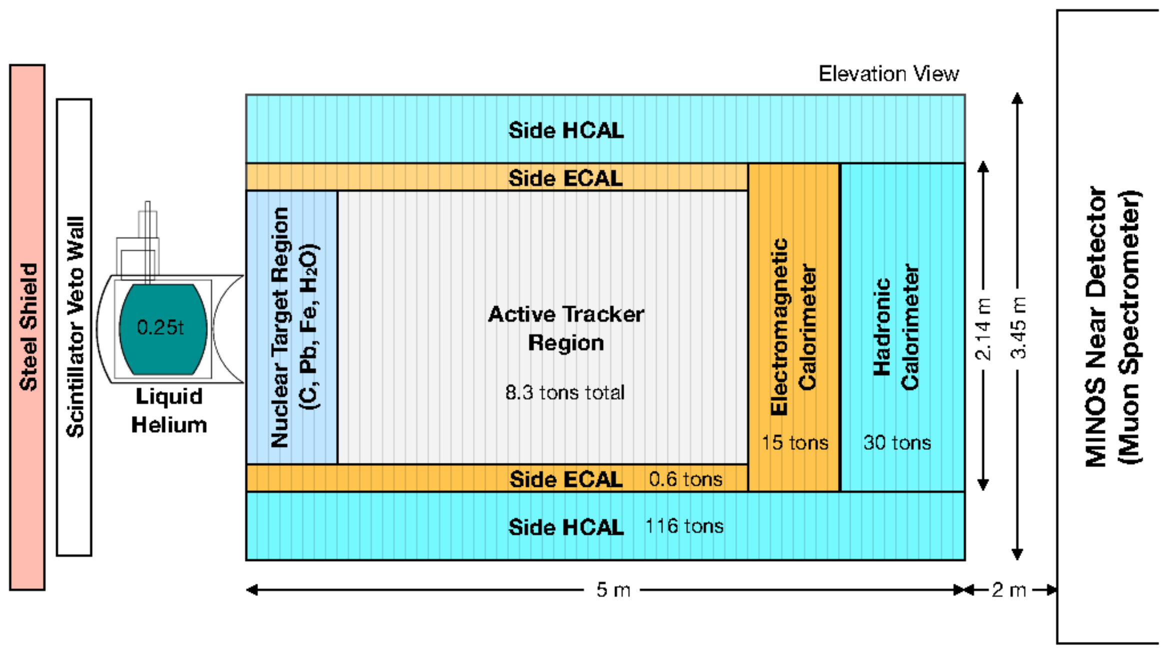
5. MINERvA



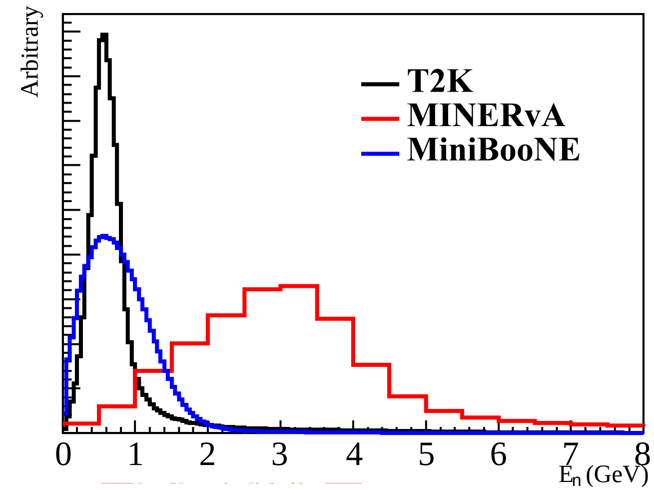
Scintillation tracker

- <E>~3.5 GeV on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)





5. MINERvA



Scintillation tracker

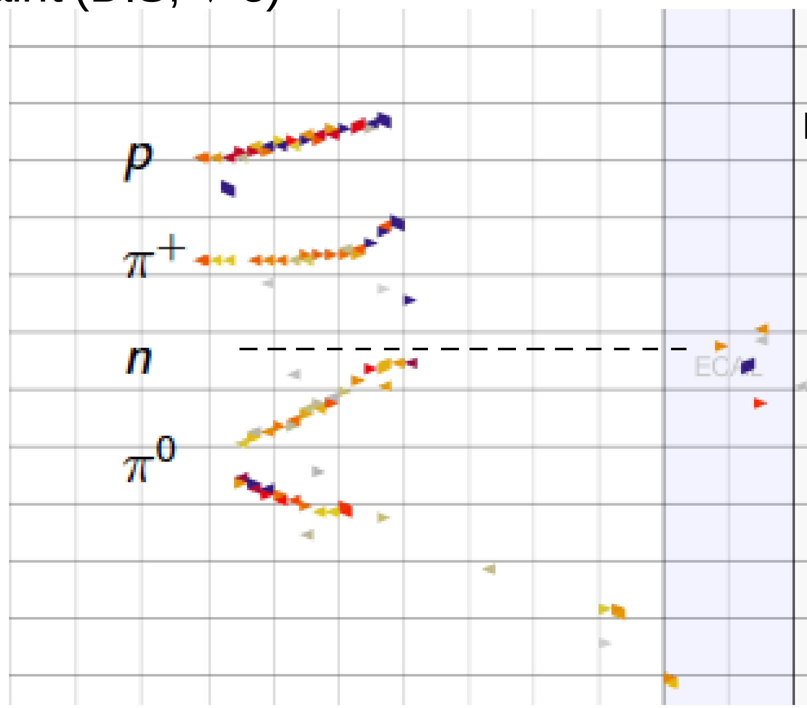
- <E>~3.5 GeV on-axis beam
- variety of targets (CH, Pb, Fe)
- Small acceptance due to MINOS ND
- charge separation by MINOS ND
- internal flux constraint (DIS, ν-e)

Kinetic energy

Kinetic energy

0

Total energy



Beam test + better scintillator
→ good hadron measurement
→ kinematics is completely fixed

model-dependent

visible hadron energy

↓

total hadron energy

↓

Eν

↓

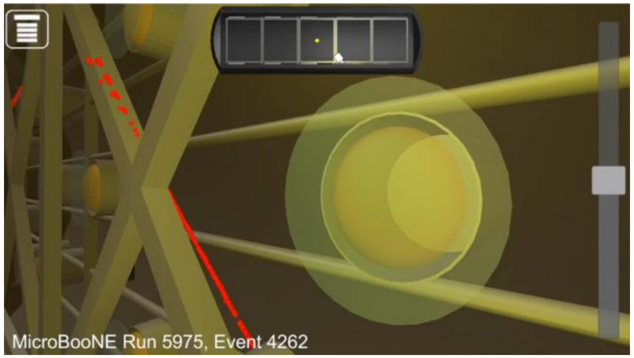
Q2

On average, we see *available* hadronic energy $E_{avail} \neq q_0$:

$$E_{avail} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

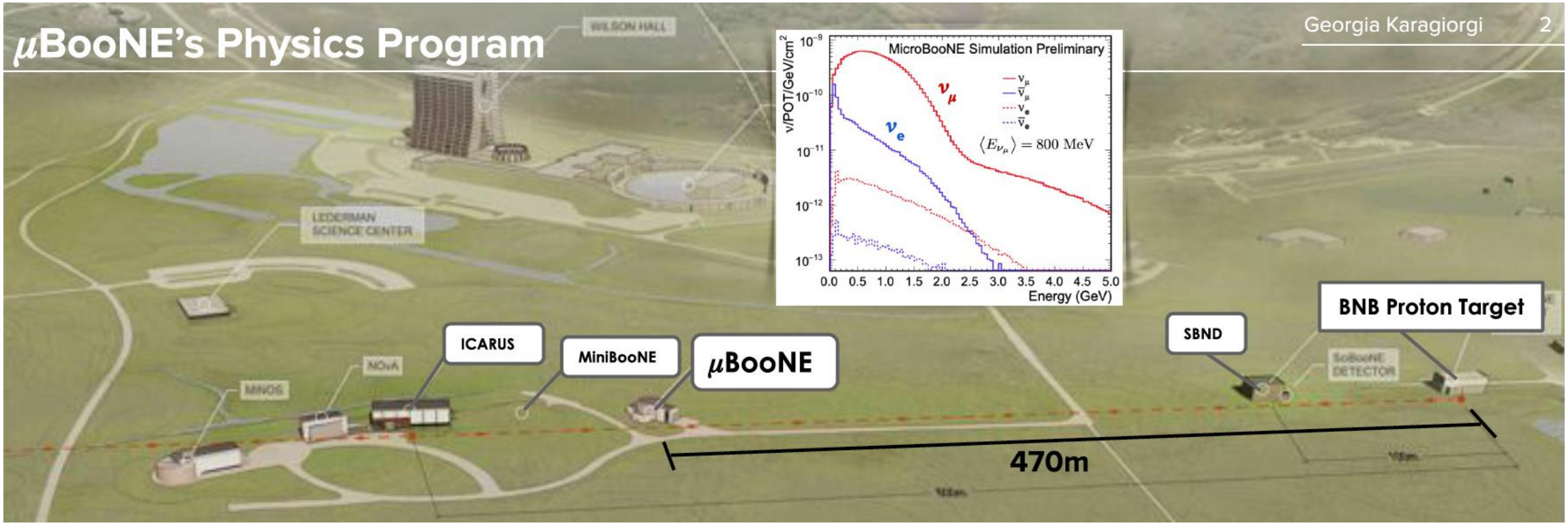
5. MicroBooNE

VENu (Virtual Environment of Neutrinos)
http://venu.physics.ox.ac.uk/
- smart phone app for MicroBooNE data

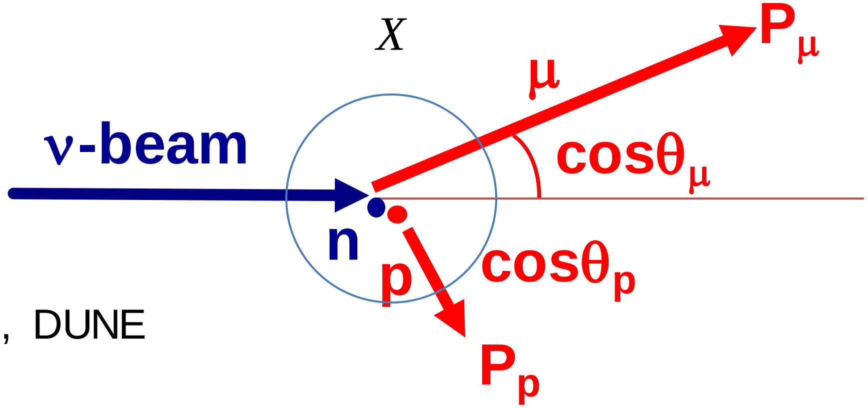


86ton LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system
- ArgoNeuT, LArIAT, SBND, ICARUS, protoDUNE, DUNE



5. MicroBooNE



86ton LArTPC

- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system
- ArgoNeuT, LArIAT, SBND, ICARUS, protoDUNE, DUNE

MicroBooNE CC mu+p differential cross section

Outgoing proton kinematics are measured to reconstruct Fermi motion

Multiple Coulomb scattering to estimate escaping muon energy

Large cosmic ray background, but mostly understood

Low statistics for hadron measurements