Neutrino-Nucleus Interaction Physics around 1-10 GeV

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

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King's College London

Neutrino Group seminar, Ruđer Bošković Institute, Zagreb, April 10, 2025

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

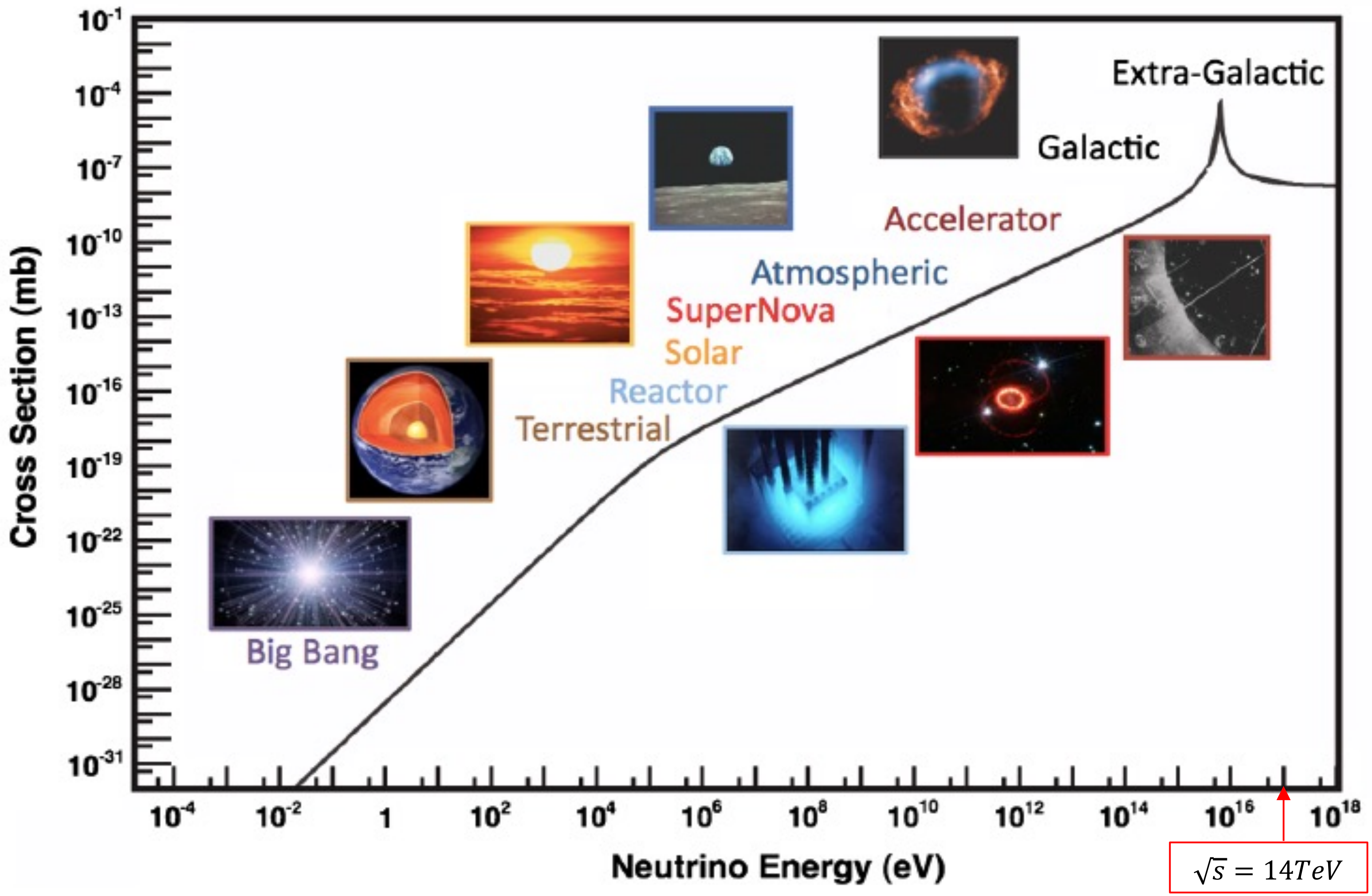
3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

5. Conclusions

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

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



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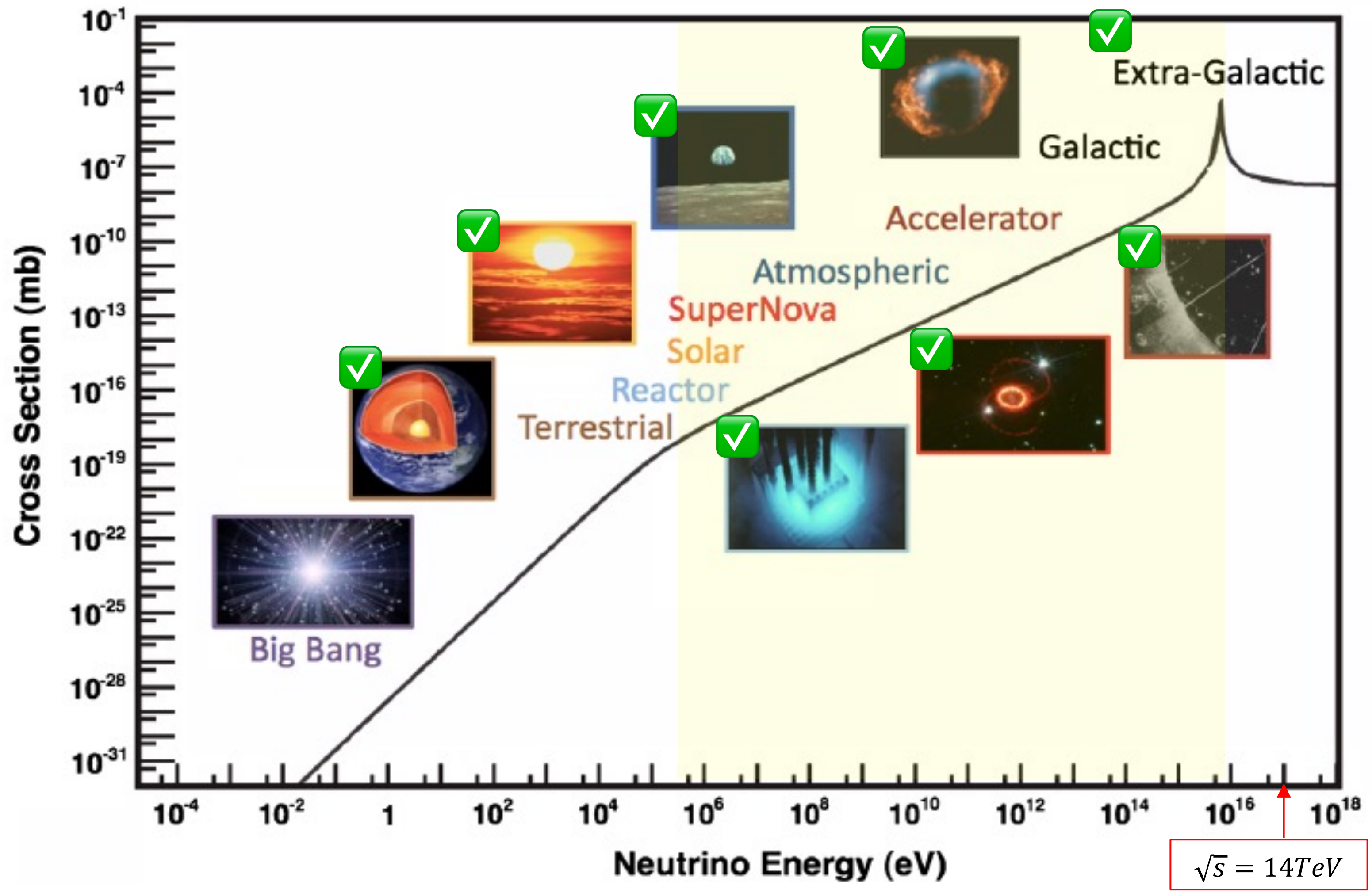

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

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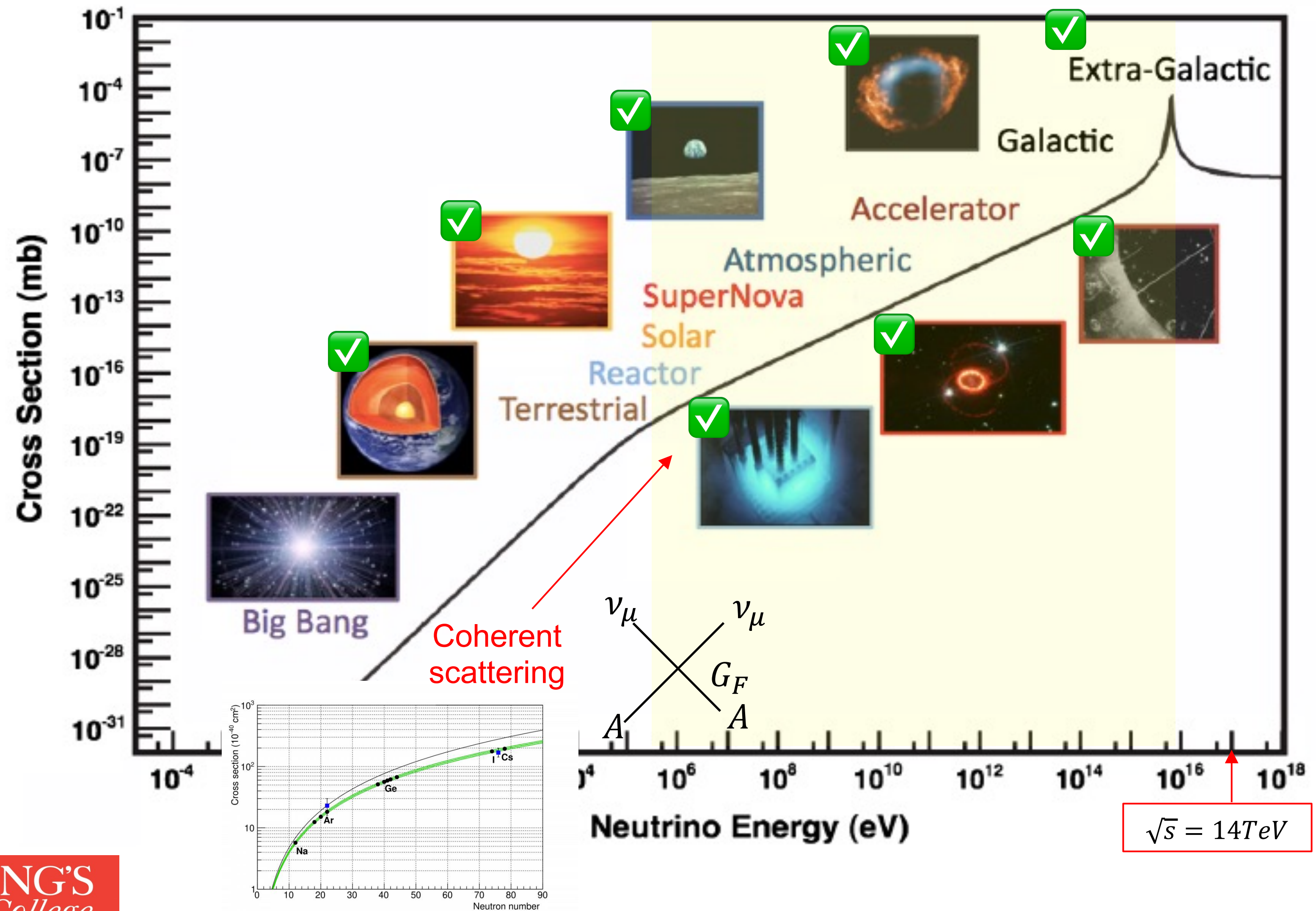
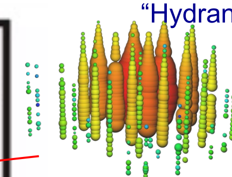
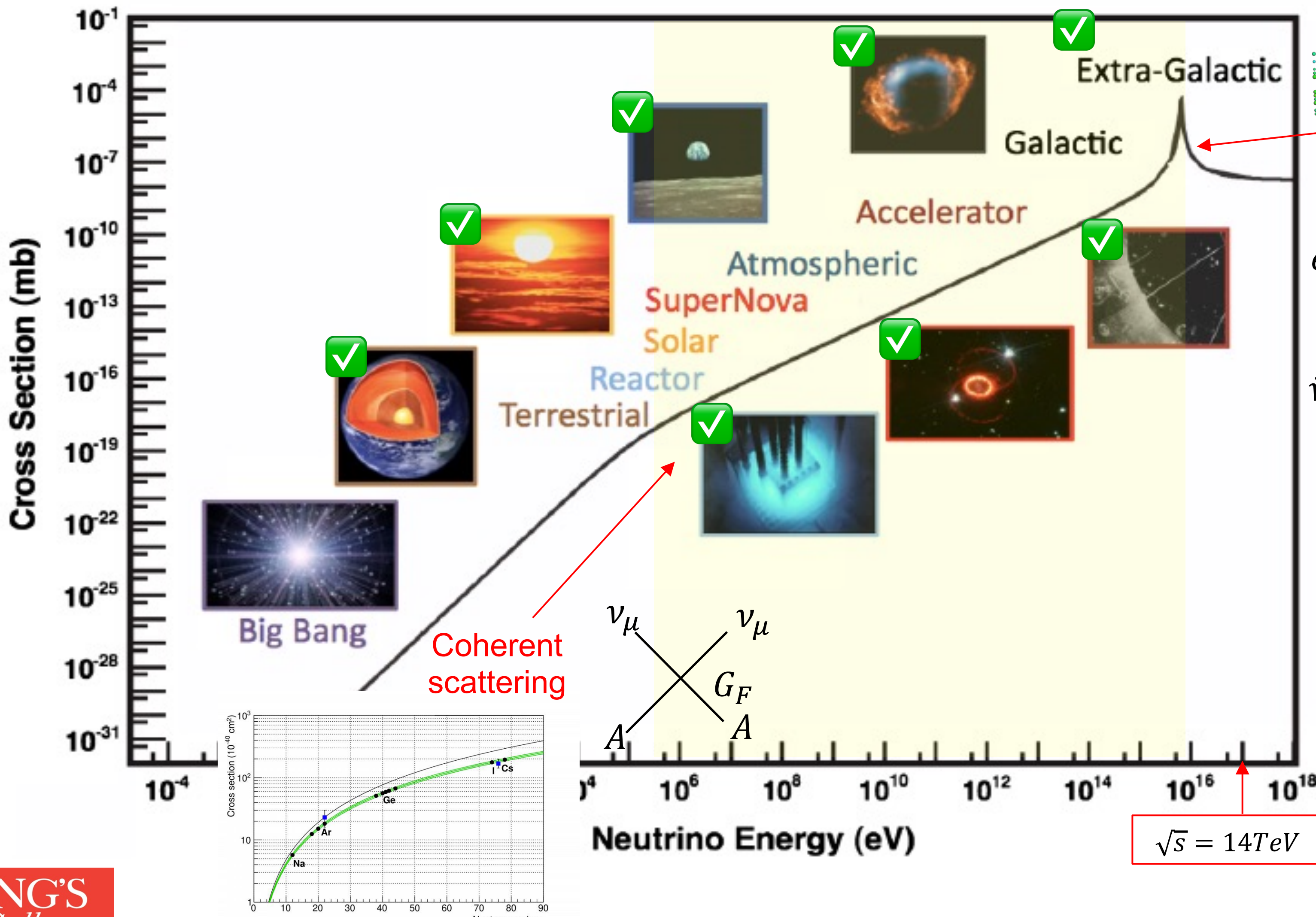


COHERENT, Science357(2017)1123
PRL126(2021)012002

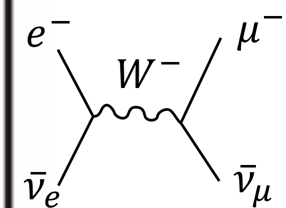
1. From eV to EeV: Neutrino cross sections across energy scales

IceCube, Nature591(2021)220
"Hydrangea"





Glashow resonance



$\sqrt{s} = 14TeV$

COHERENT, Science357(2017)1123
PRL126(2021)012002

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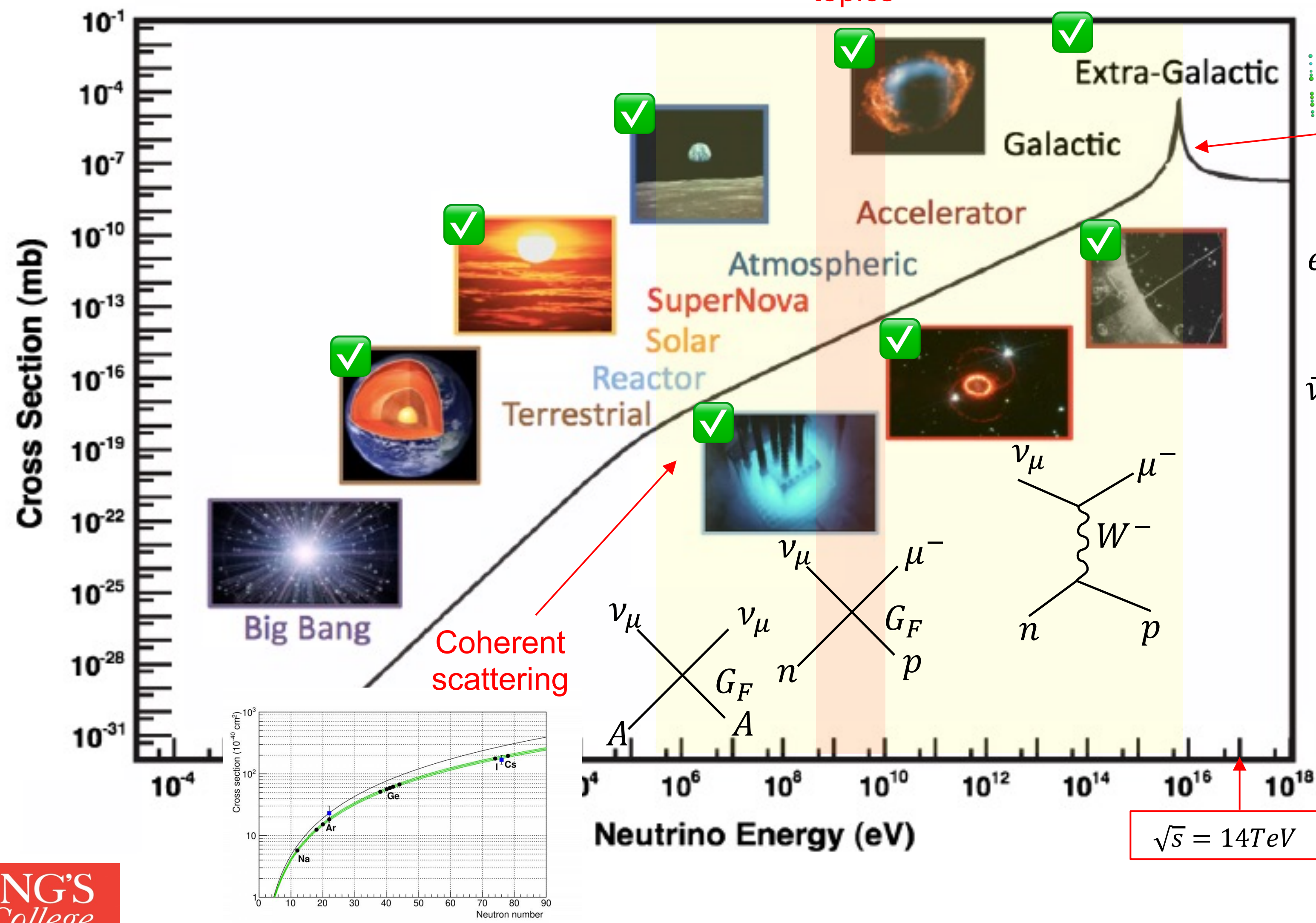
1. From eV to EeV: Neutrino cross sections across energy scales

Today's topics



Coherent scattering

COHERENT, Science357(2017)1123
PRL126(2021)012002

$\sqrt{s} = 14TeV$

IceCube, Nature591(2021)220
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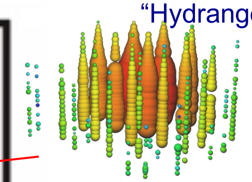

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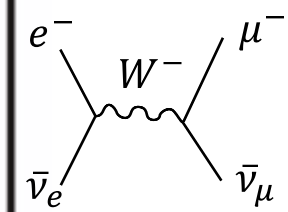

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1. PDG: Neutrino Cross Section Measurements

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

Focus of this talk is around a few GeV

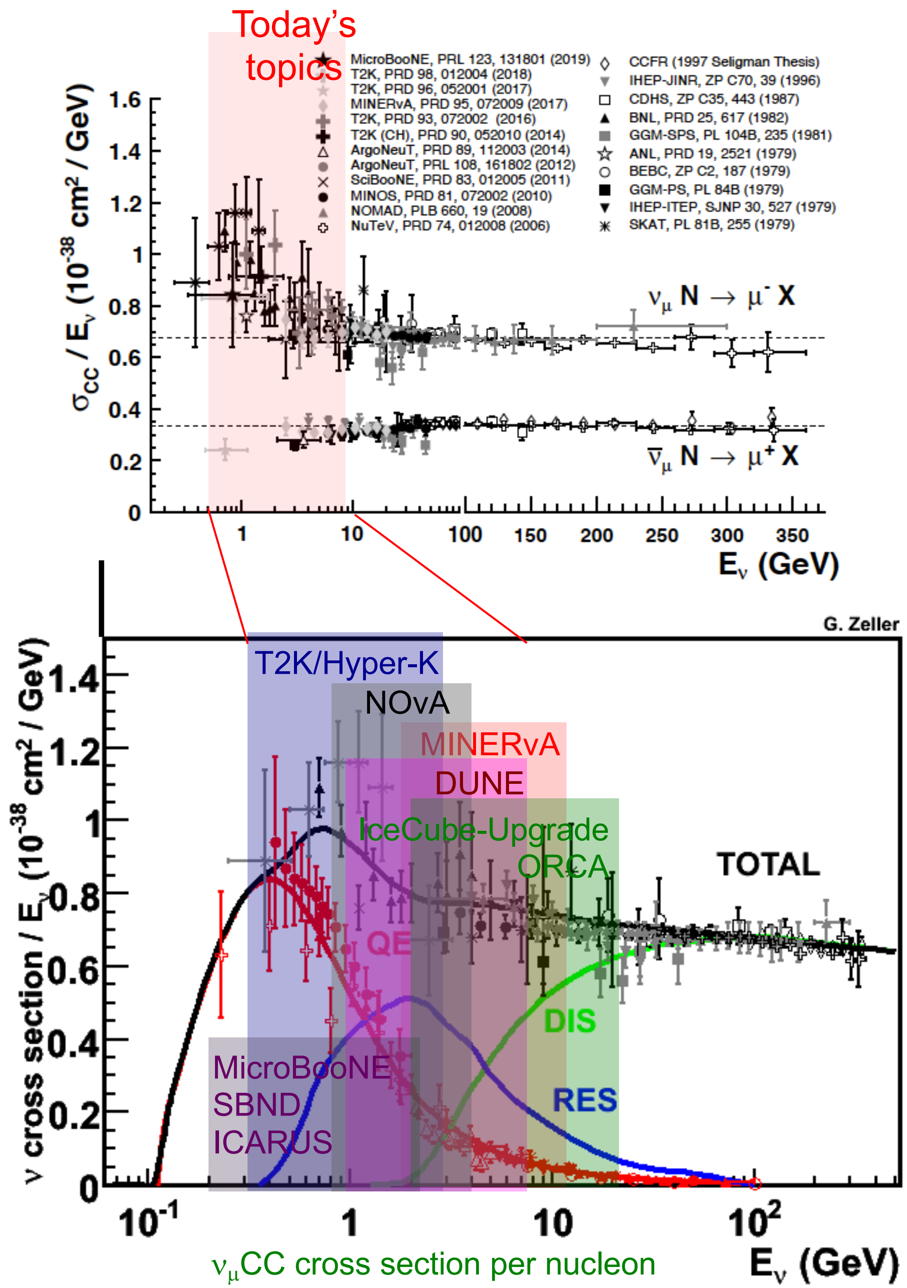


Table 52.2: Published measurements of neutrino and antineutrino CC inclusive cross sections from modern accelerator-based neutrino experiments.

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. Neutrino interaction physics around 1-10 GeV

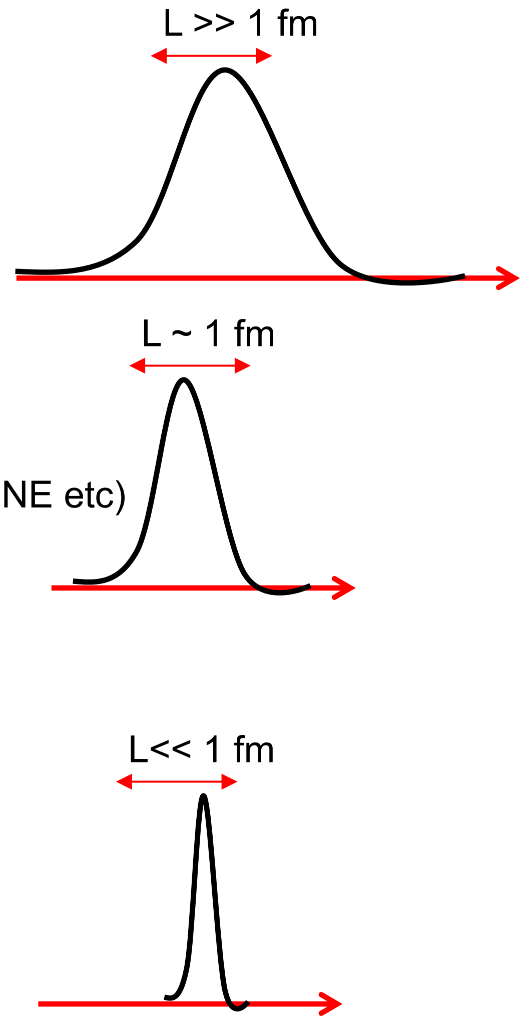
Size of wave packet ~ momentum transfer (~energy)

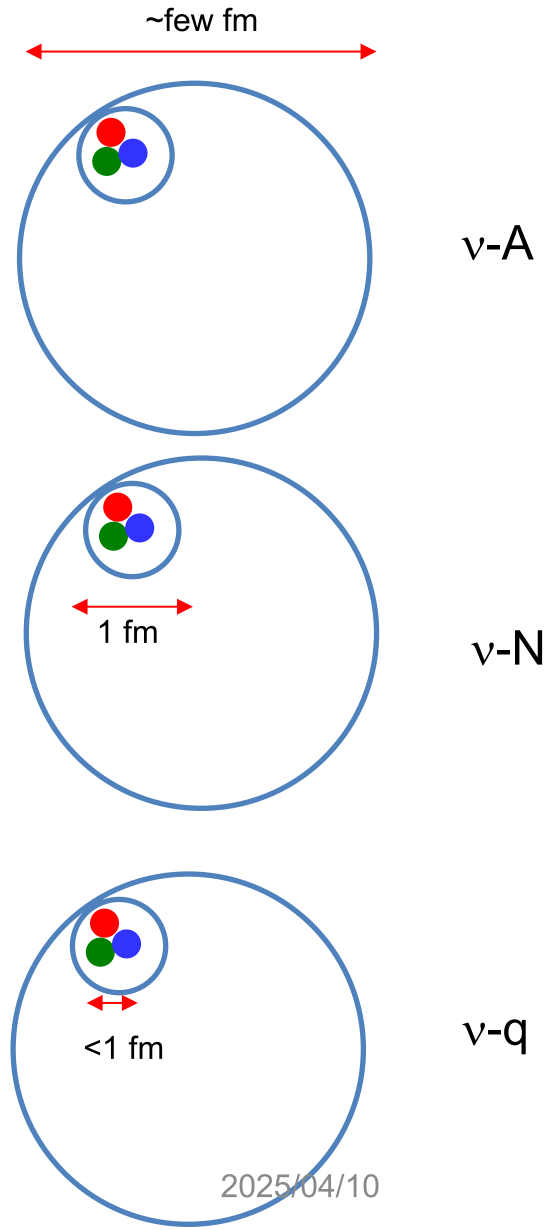
$\hbar c = 197\ MeV \cdot fm \rightarrow$ 200 MeV ~ 1 fm (size of nucleon)

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

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

>>1 GeV neutrino beam
(LHC, astrophysical)



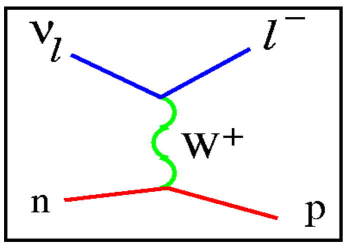


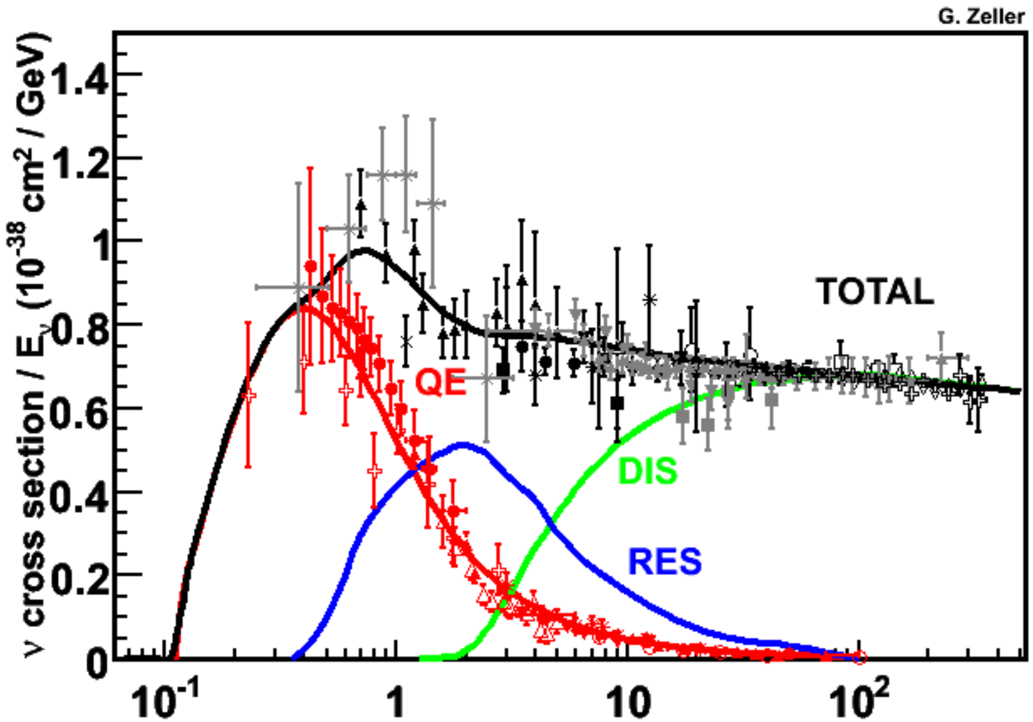
1. Neutrino interaction physics around 1-10 GeV

Neutrino interaction physics around 1-10 GeV

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

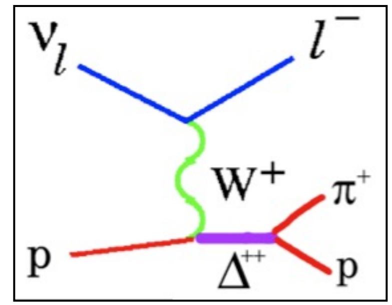
Quasi Elastic (QE)

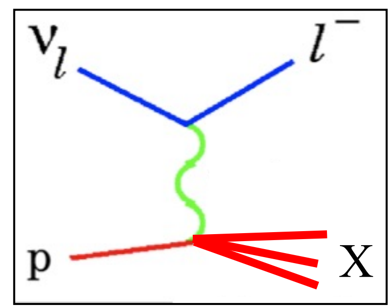




ν_μCC cross section per nucleon

baryonic RESonance





Deep Inelastic Scattering (DIS)

1. Next goal of high energy physics

Establish Neutrino Standard Model (nSM)

- SM + 3 active massive neutrinos

Unknown parameters of nSM

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)

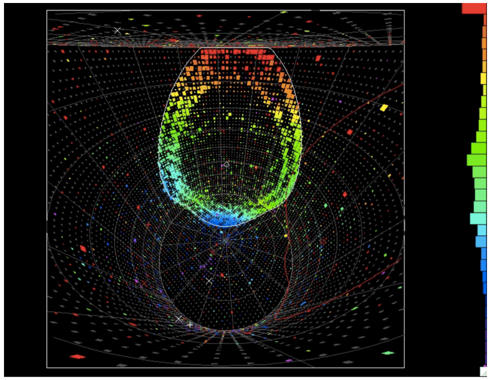
We need higher precision neutrino experiments around 1-10 GeV.

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

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

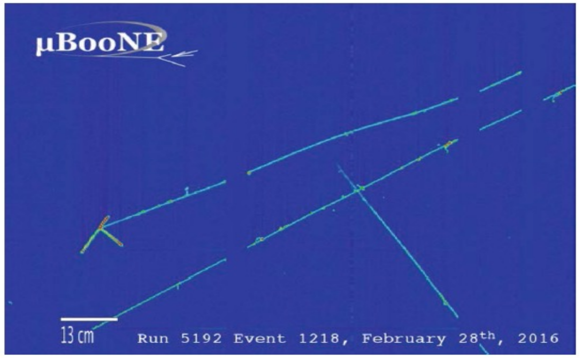
1. Next goal of high energy physics

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



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

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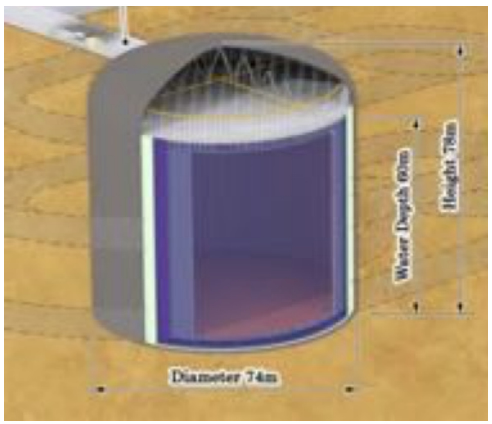
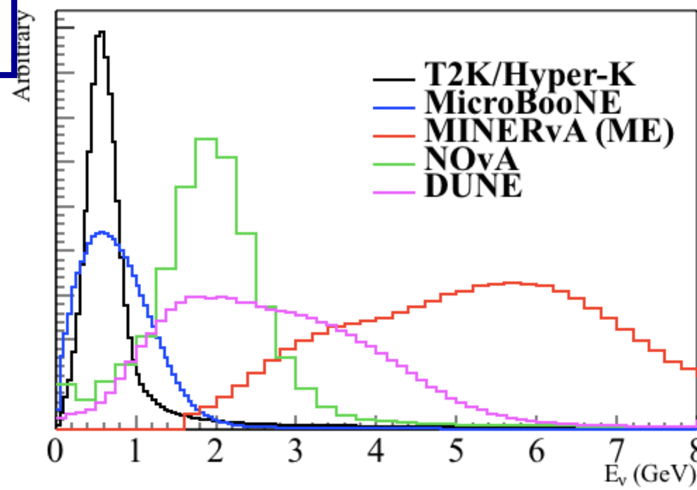
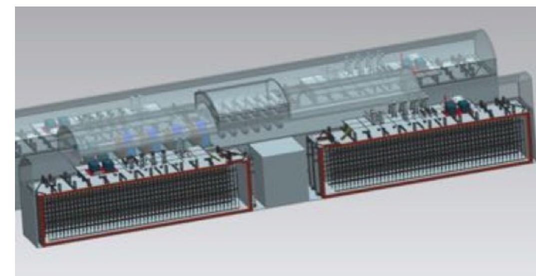
1. Next goal of high energy physics

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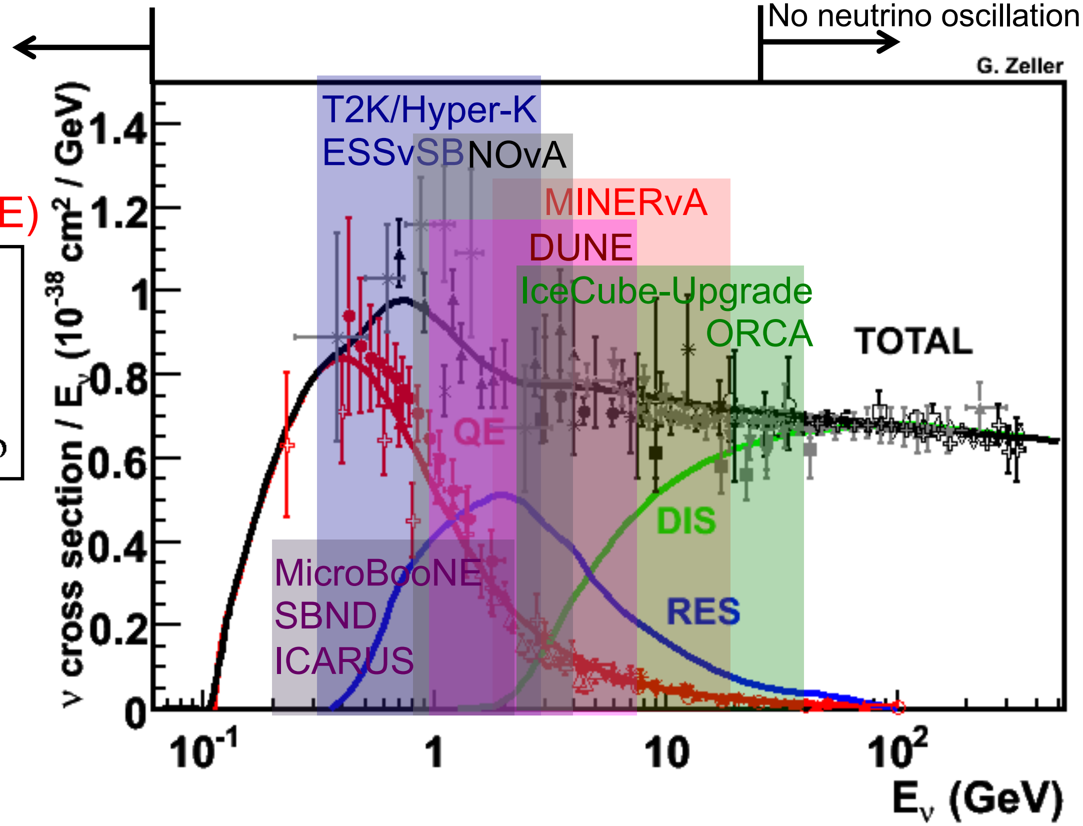
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

1. Next generation neutrino oscillation experiments

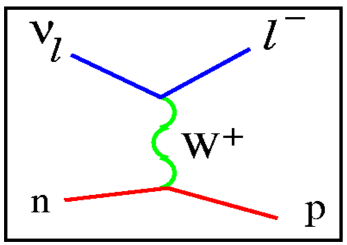
Current and future neutrino oscillation experiments

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

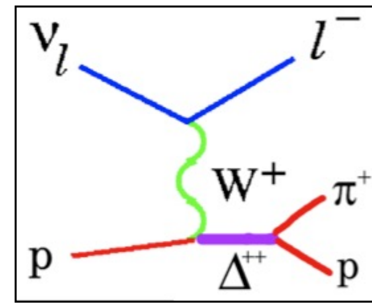
Reactor and Solar neutrino oscillation

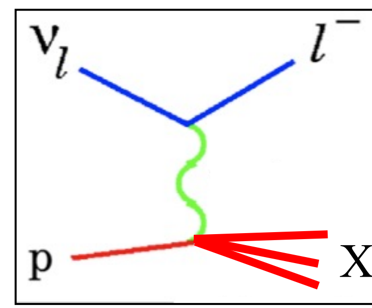


Quasi Elastic (QE)



baryonic RESonance





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

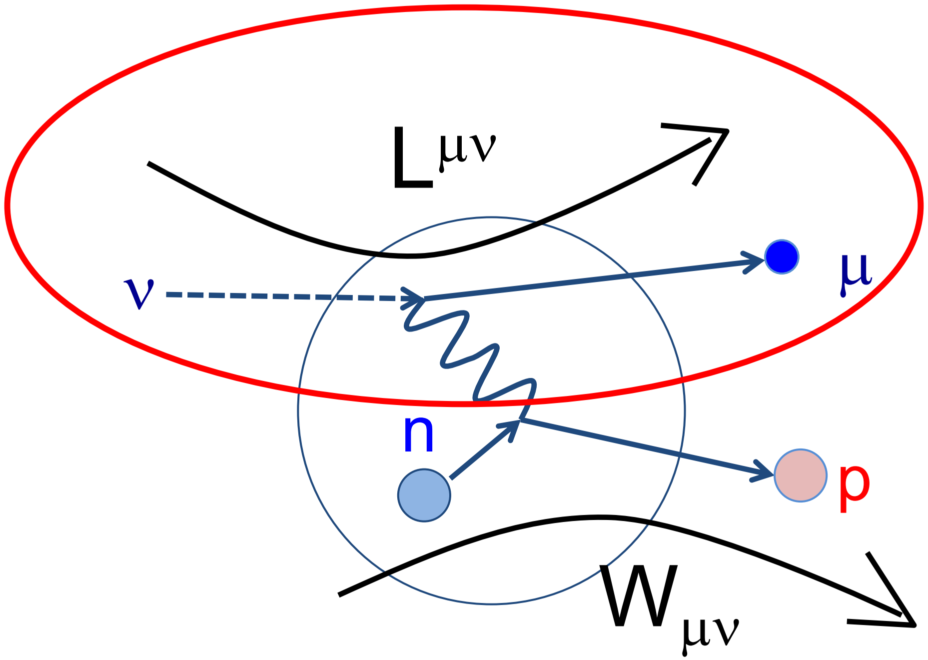
1. Neutrino cross-section formula

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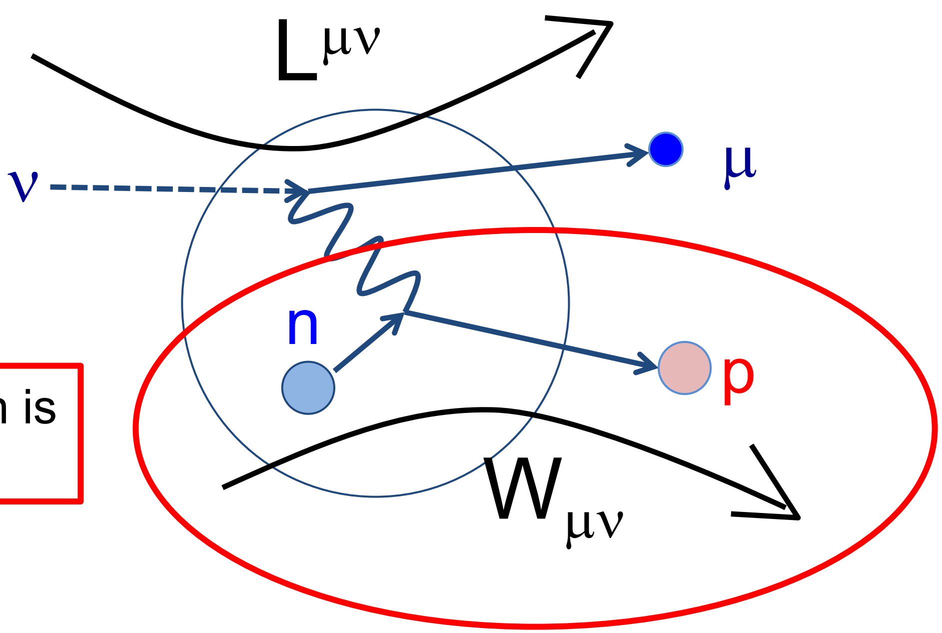
All complication of neutrino cross-section is how to model the hadronic tensor part



1. 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

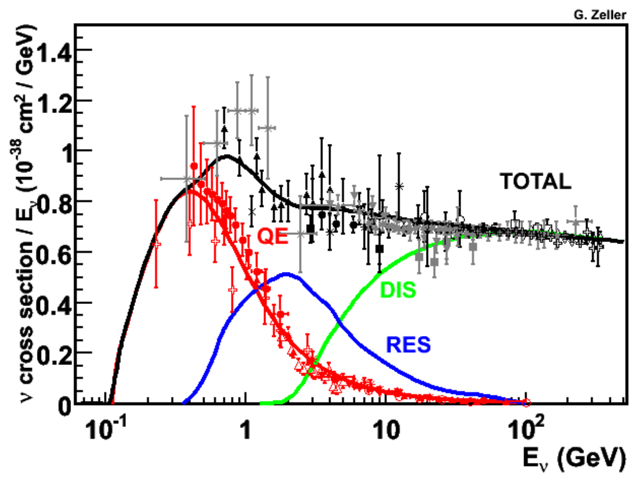
Achilles (New!)
https://arxiv.org/abs/2205.06378
- Theory-driven better factorization

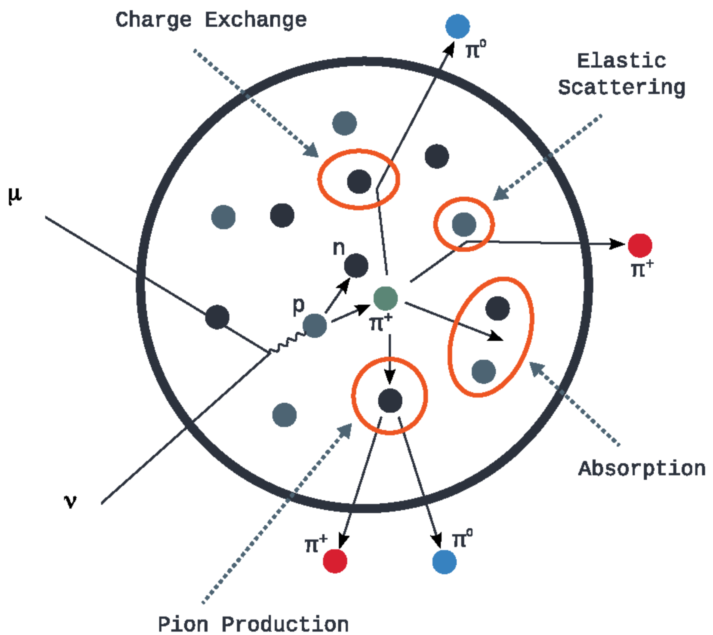
1. Neutrino event generator

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





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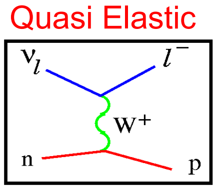
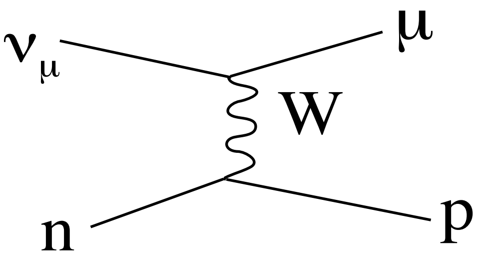


2. Charged Current Quasi-Elastic scattering (CCQE)

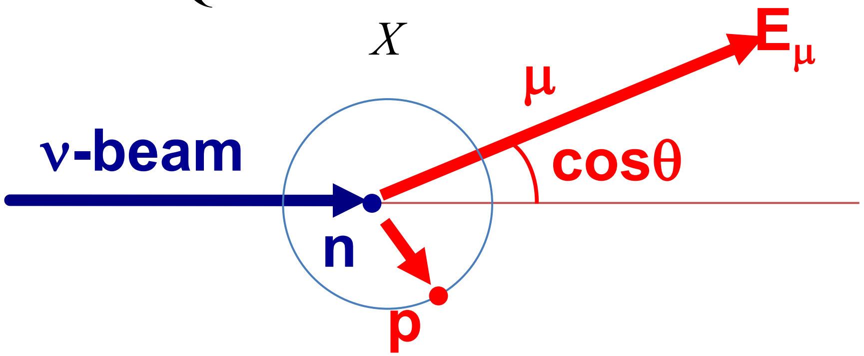
The simplest and the most abundant interaction around ~1 GeV.

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



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

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

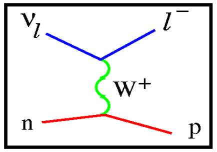


$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

MiniBooNE,PRD81(2010)092005

Quasi Elastic



2. CCQE puzzle

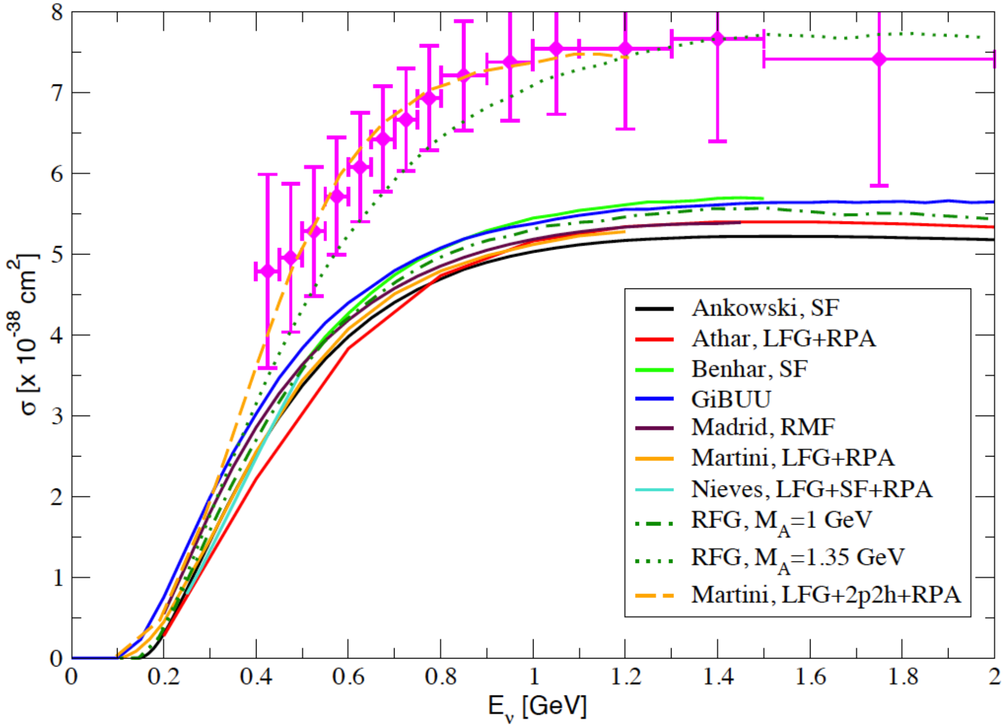
Simplest channel, but both shape and normalization disagree

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

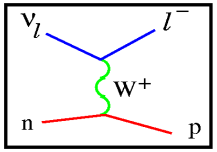
- Lepton universality = precise prediction for neutrino CCQE cross-section...?

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



2. Solution of CCQE puzzle

Quasi Elastic

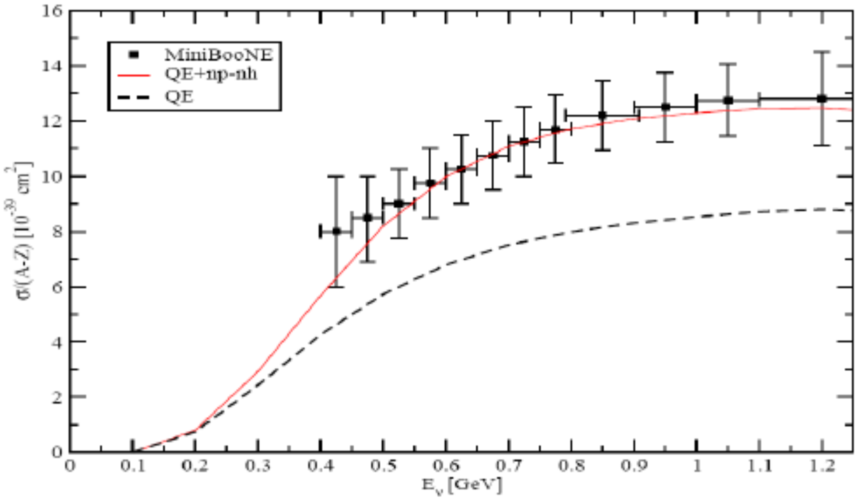


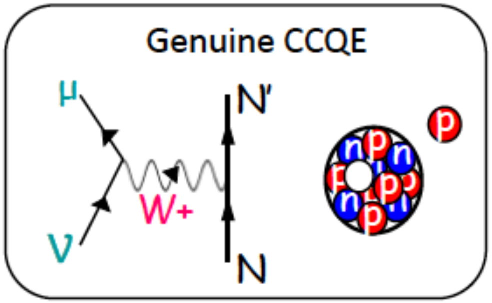
Presence of 2-body current

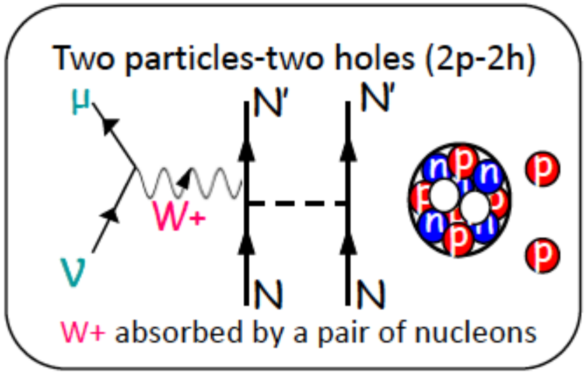
- CCQE is identified from single outgoing charged lepton events
- Significant fraction of events are not from 2-body neutrino-nucleon interactions
- Martini et al showed 2p-2h effect can add up ~30% more cross section

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)

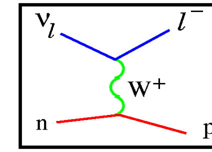






Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRX10(2020)031068 (2020)

Quasi Elastic



2. Nucleon correlations in neutrino physics

Ab-initio calculation

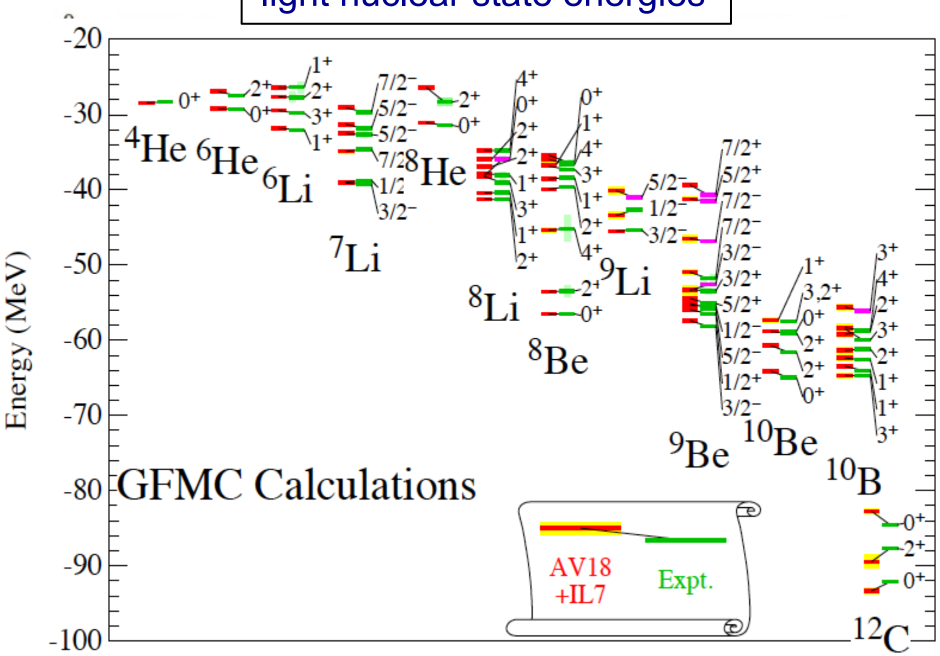
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Ground state includes correct nucleon correlations

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

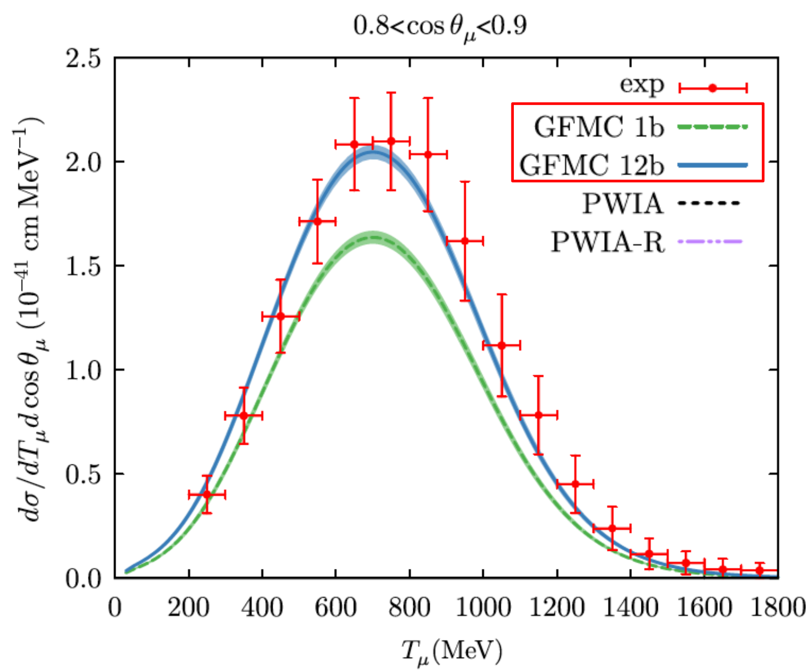
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



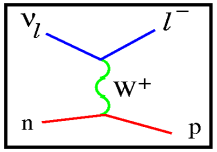
MiniBooNE CCQE cross-section



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

2. Nucleon correlations in neutrino physics

Quasi Elastic



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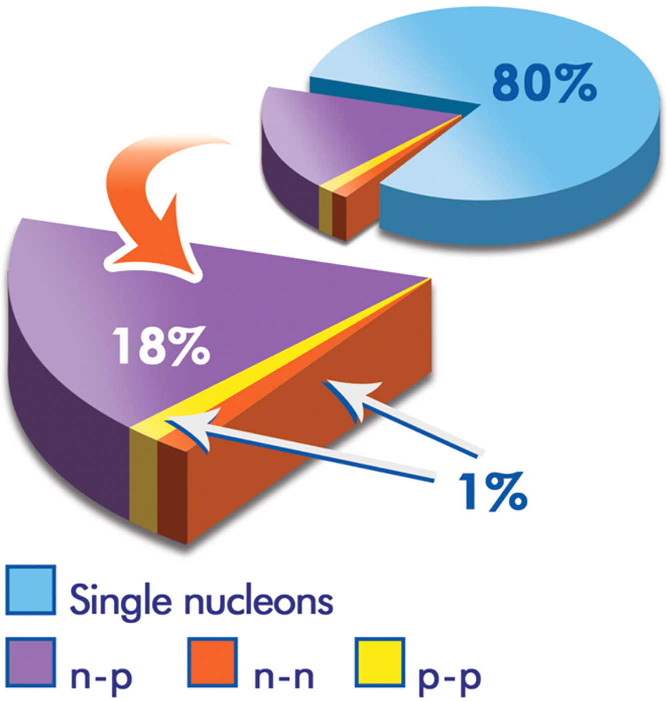
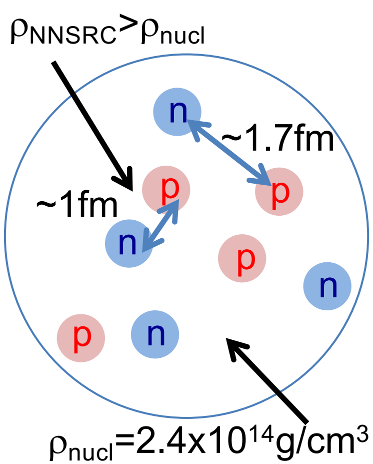


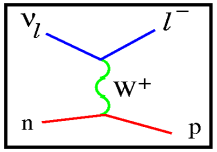


Physics of nucleon correlation

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

Nucleon correlation is a very hot topics!

Quasi Elastic

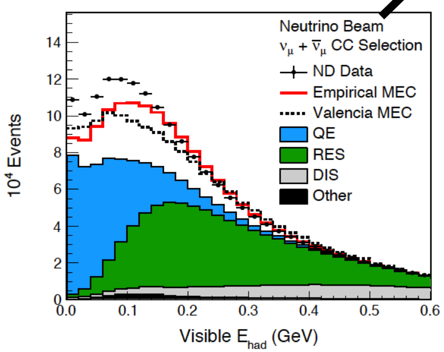


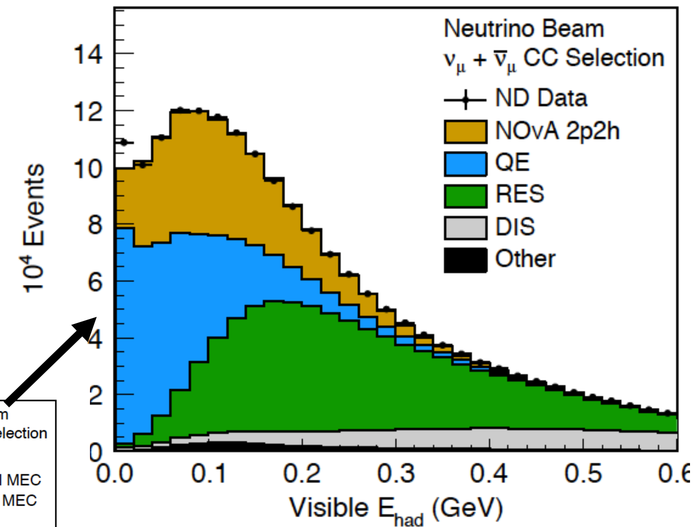
2. Nucleon correlations in neutrino physics

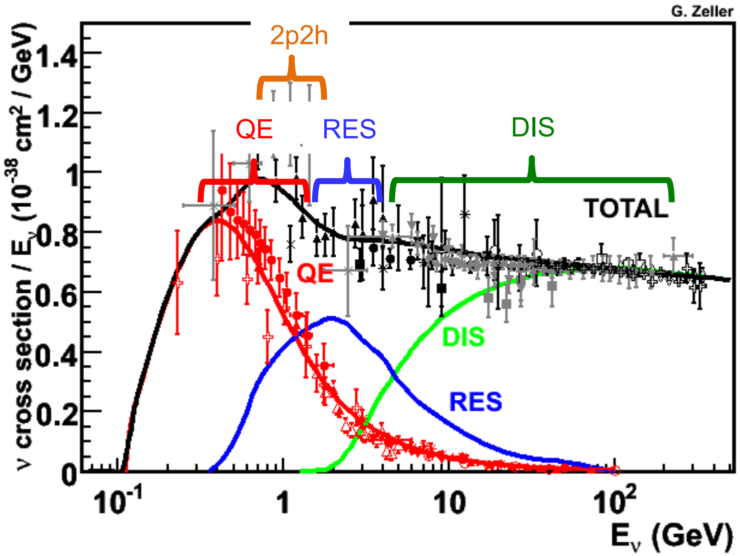
2-particle 2-hole (2p2h) effect

- Essential to describe data
- The biggest topic in nuxsec community (T2K, NOvA, MINERvA, MicroBooNE, etc)
- 2p2h models in generators don't describe data without heavy tuning
- High resolution detector (LArTPC, emulsion, etc) can find what is going on?

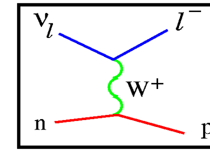
NOvA near detector data-MC comparison after fit







Quasi Elastic

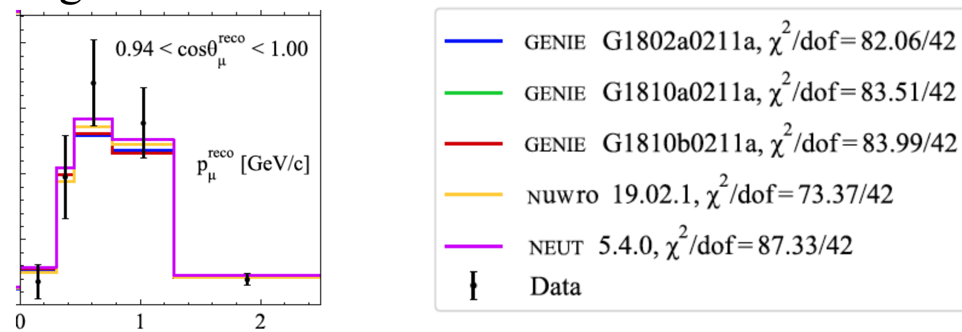


2. Data tension

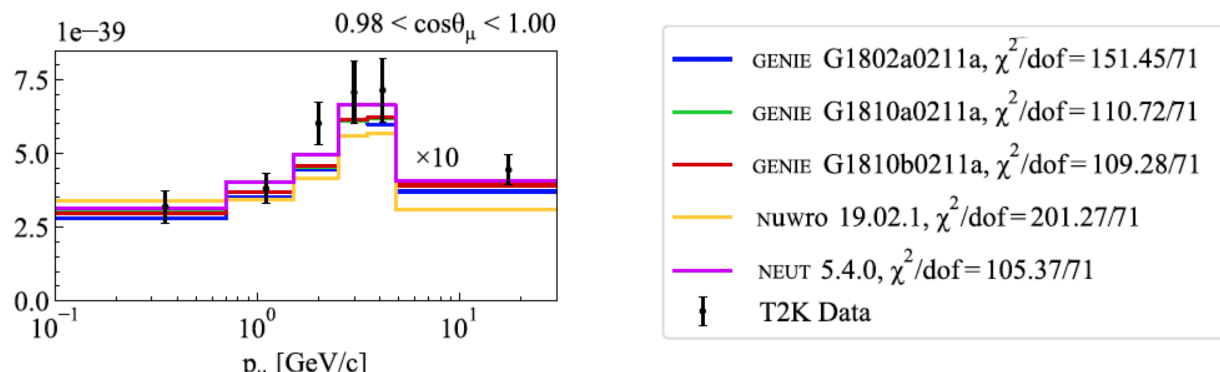
Data tension – external: T2K vs. MINERvA vs. MicroBooNE

- Different kinematic coverage, different target

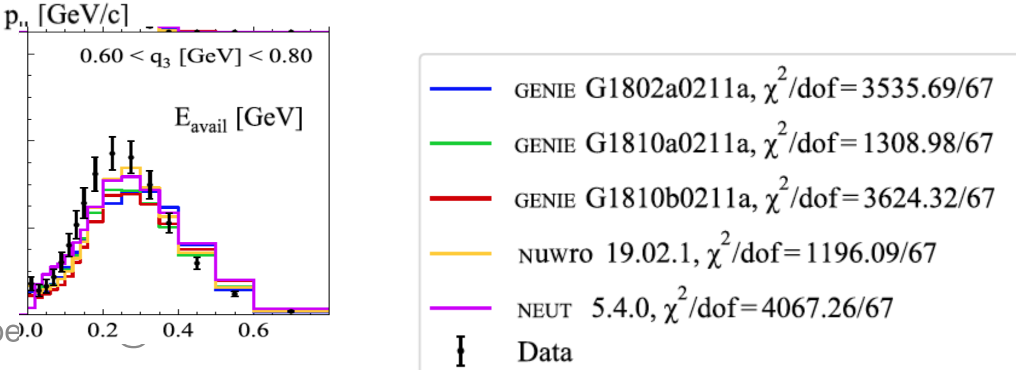
MicroBooNE CC inclusive double differential cross-section



T2K CC inclusive double differential cross-section



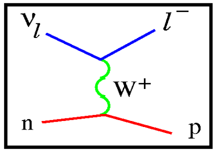
MINERvA CC inclusive double differential cross-section



KING'S College LONDON

Meyer, Walker-Loud, Wilkinson, Annu.Rev.Nucl.Part.Sci.72(2022)205
PNDNE, PRD109(2024)014503, PACS, PRD109(2024)094505

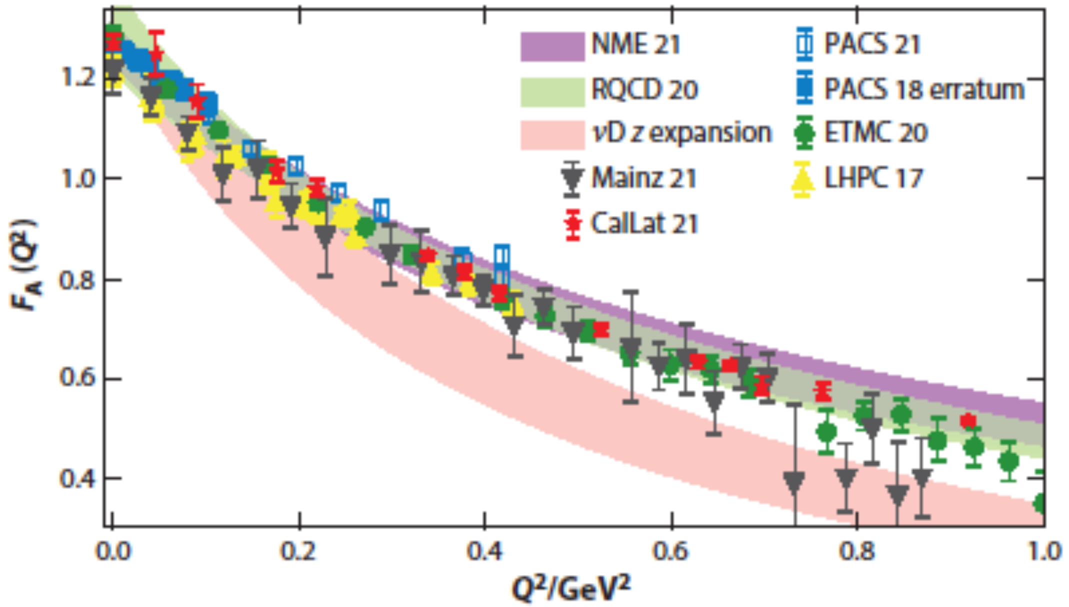
Quasi Elastic



2. Large axial mass?

Nucleon axial mass (nucleon parameter)

- 2p2h effect was interpreted with large $M_A^{QE} \sim 1.3$ GeV
- With 2p2h effect, we expect $M_A^{QE} \sim 1.0$ GeV
- Latest lattice QCD calculations suggests different value, $M_A^{QE} \sim 1.3$ GeV?
  - Role of 2p2h is smaller than expected?
  - $M_A^{QE} \sim 1.0$ GeV is supported by photo-pion production experiments
  - $M_A^{QE} \sim 1.0$ GeV is supported by neutrino bubble chamber data



Neutrino data anomalies are (mostly) by Strong interaction

1. Neutrino interaction physics - introduction

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

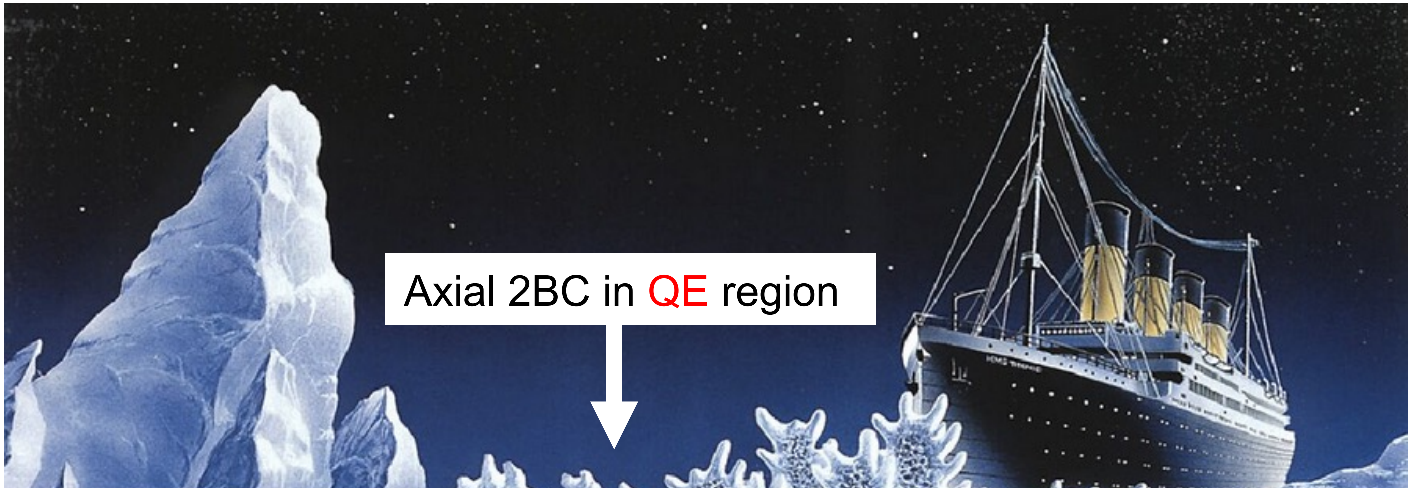
3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

5. Conclusions

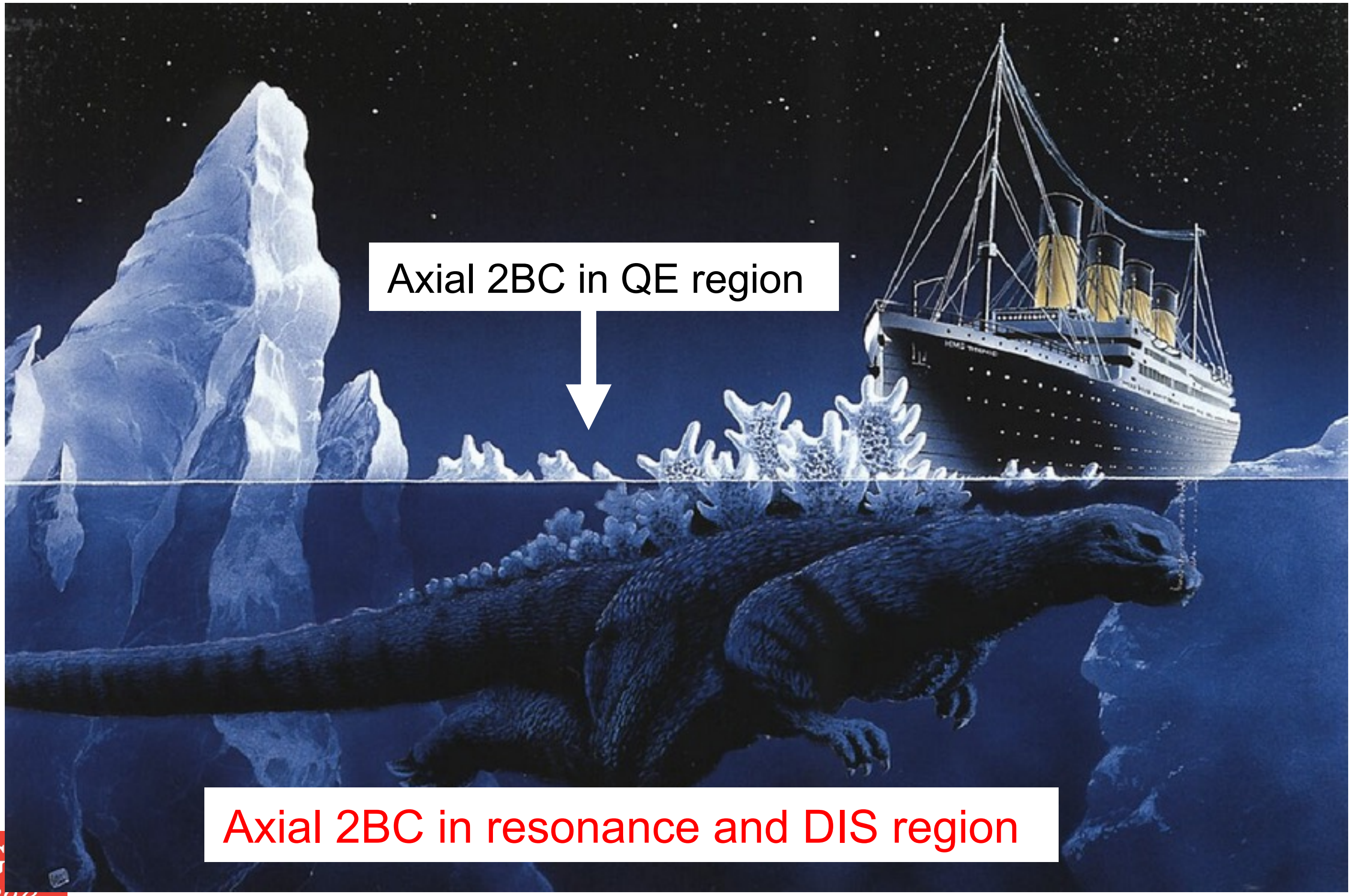
3. Beyond QE peak

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

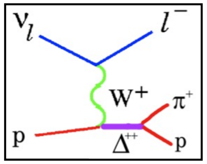


3. Beyond QE peak

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

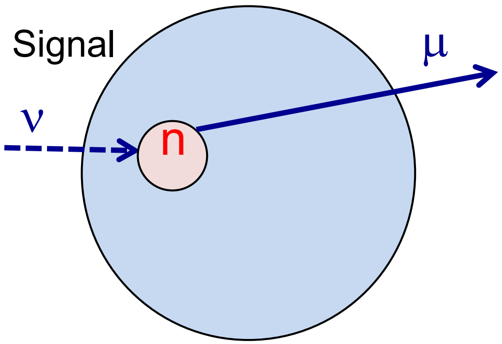


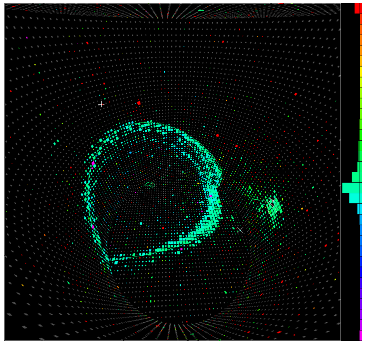
RESonance

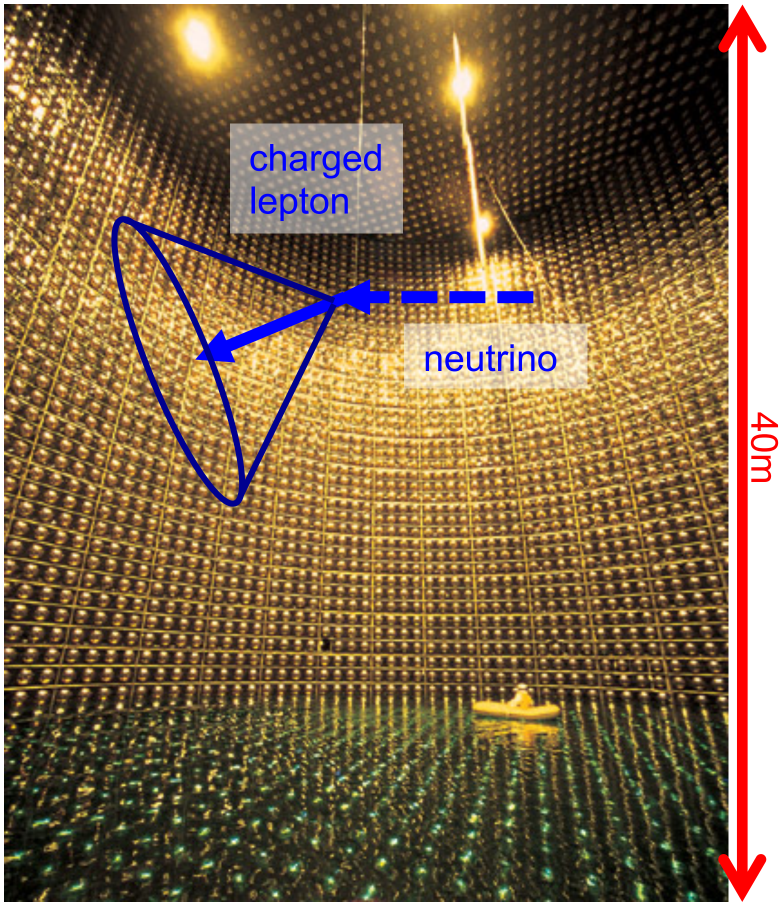


3. non-QE background (resonance pion production)

non-QE background → shift spectrum





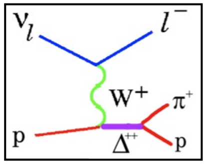


Water Cherenkov detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

3. non-QE background (resonance pion production)

RESonance



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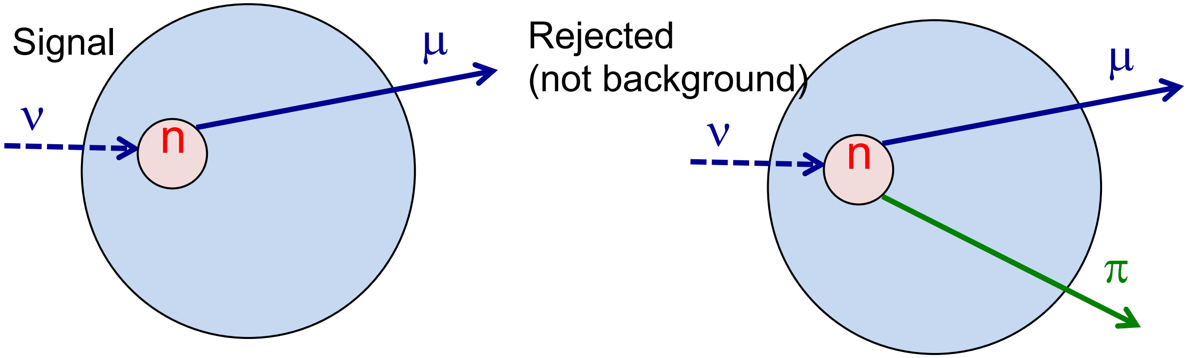

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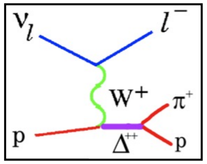
RESonance



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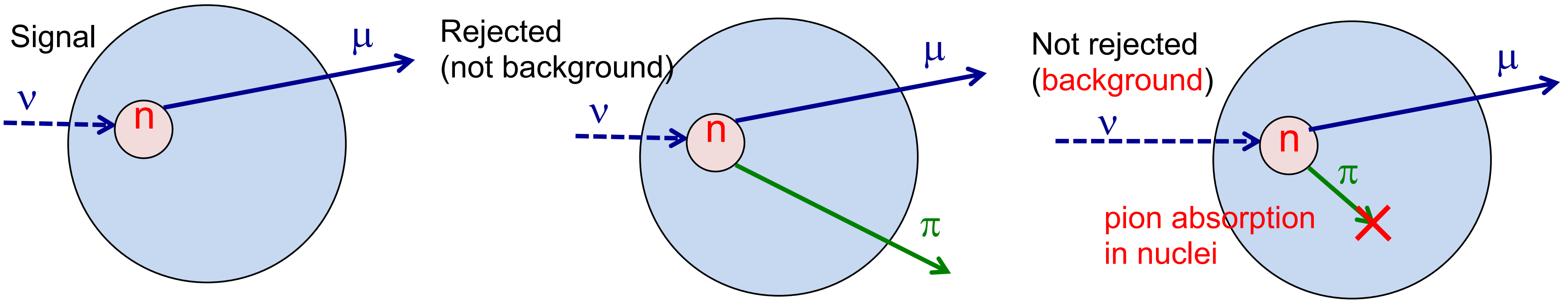

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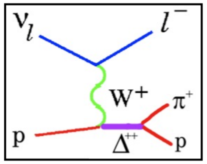

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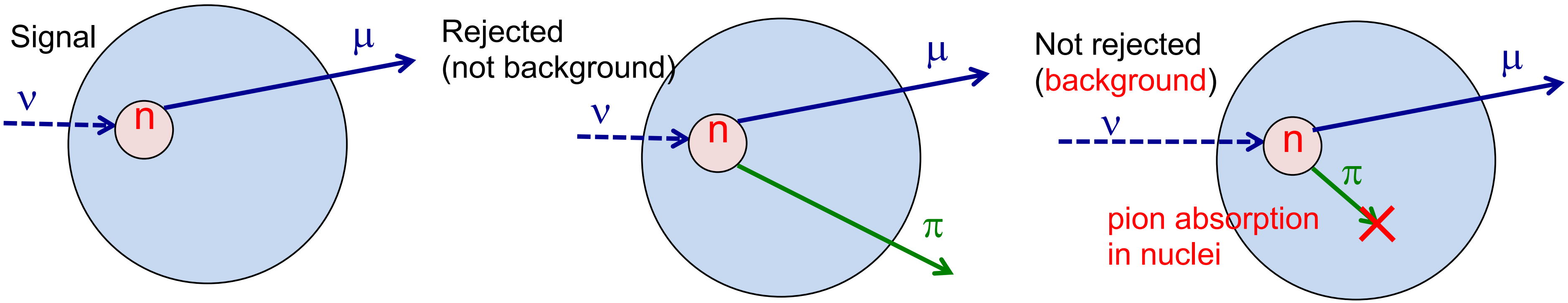
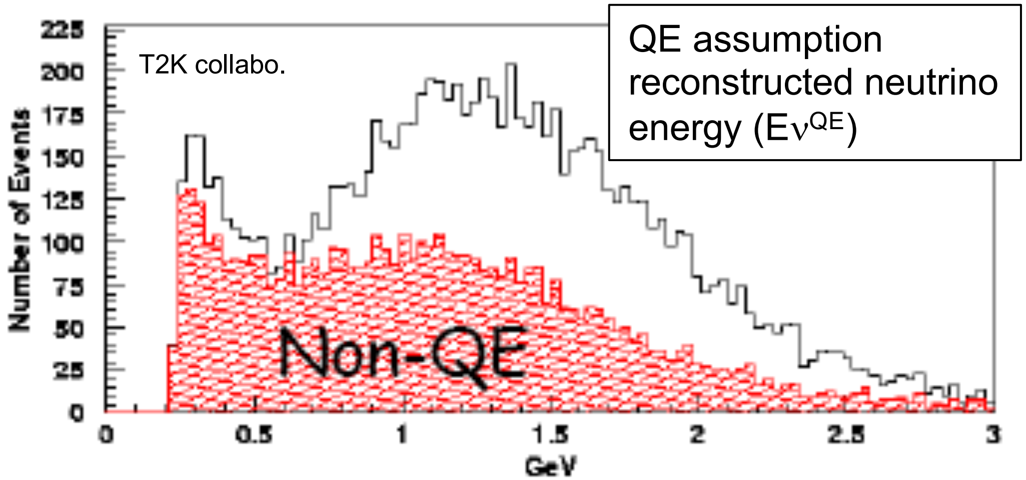
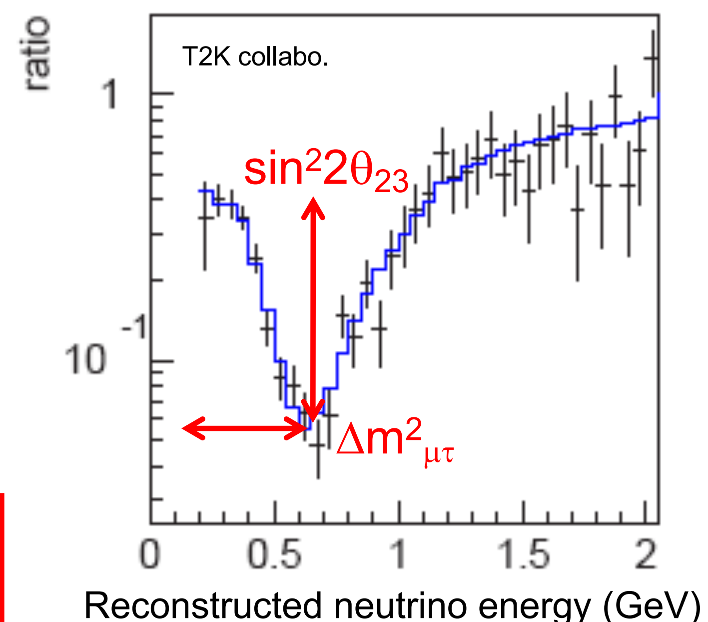
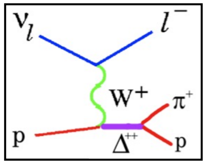






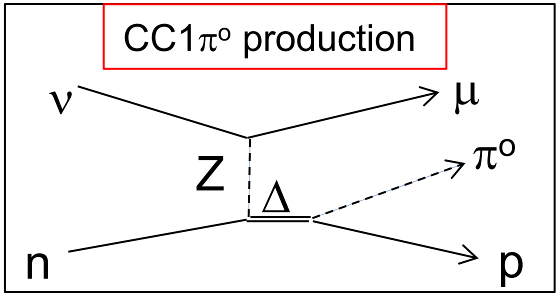
Solution: you need a good prediction of neutrino-induced pion production (hard)

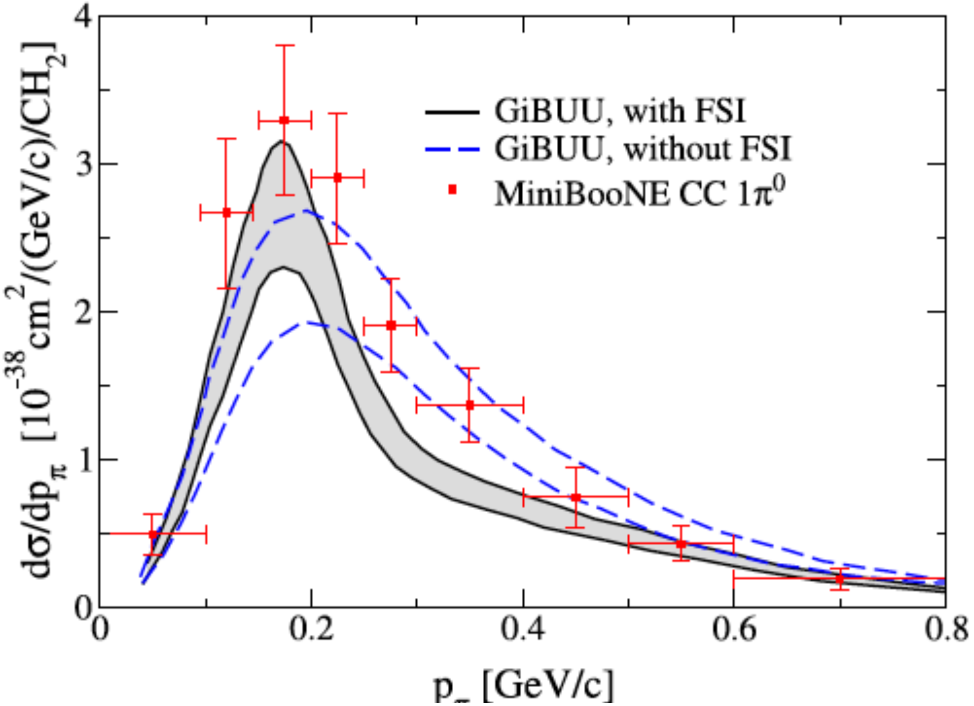


3. Pion puzzle

Final state interaction

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



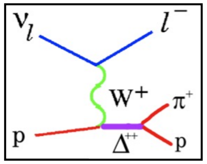


ex) Giessen BUU transport model

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

3. Pion puzzle

RESonance



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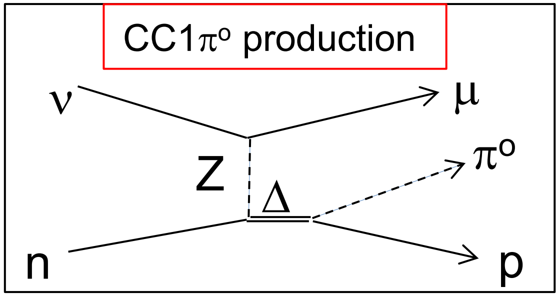

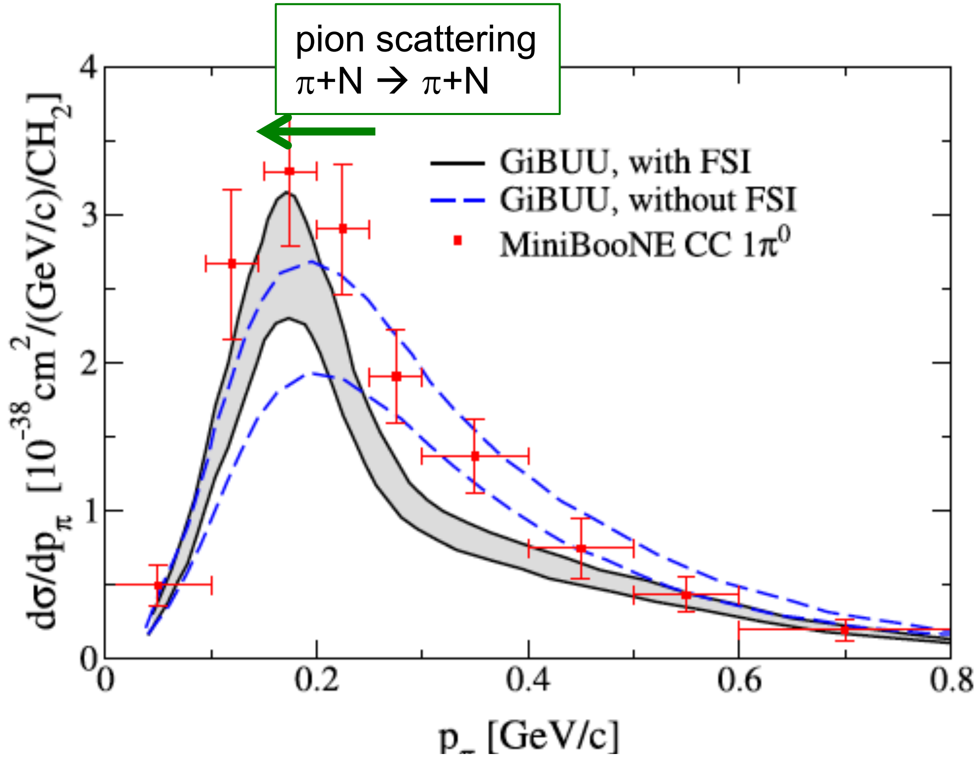

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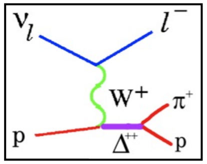

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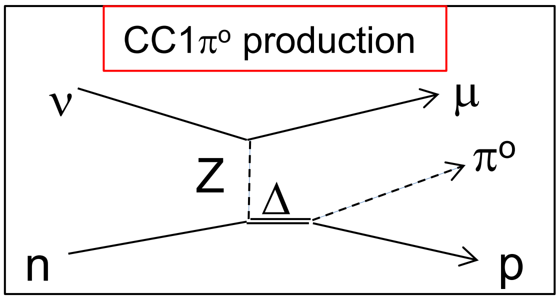

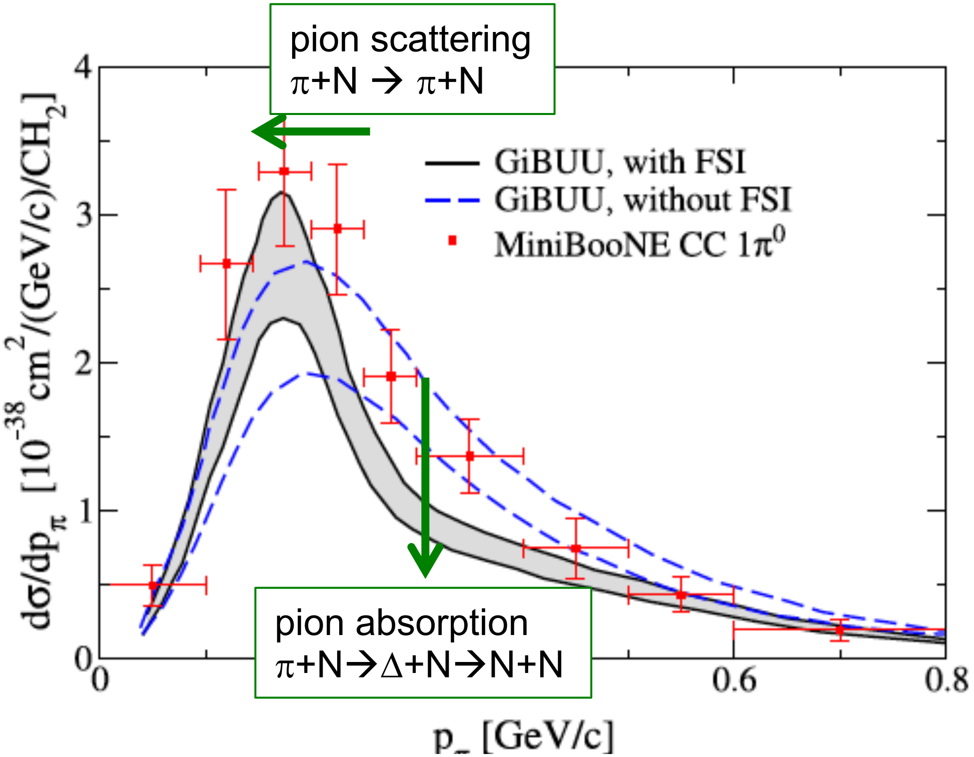

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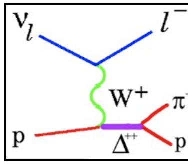
MiniBooNE,PRD83(2011)052009
Lalakulich et al,PRC87(2013)014602

3. Pion puzzle

RESonance



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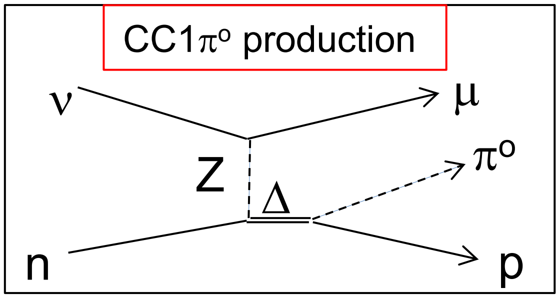
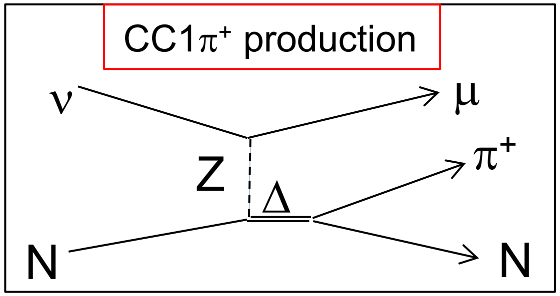
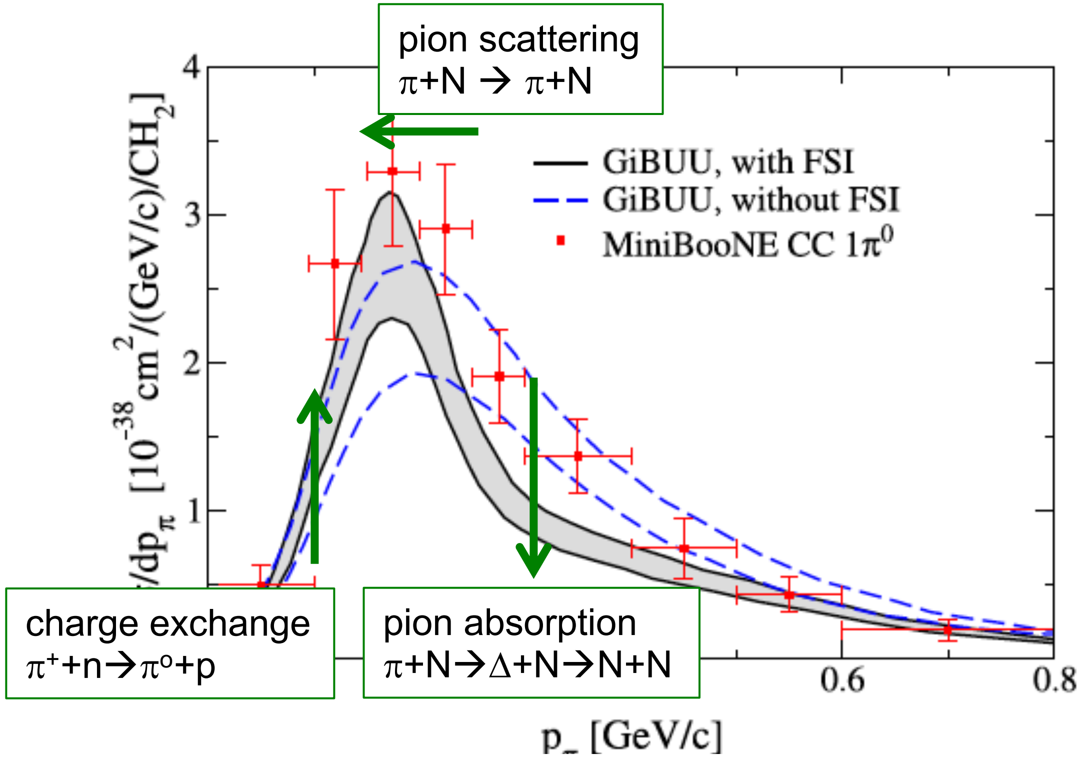


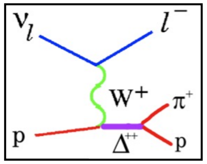




ex) Giessen BUU transport model

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

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



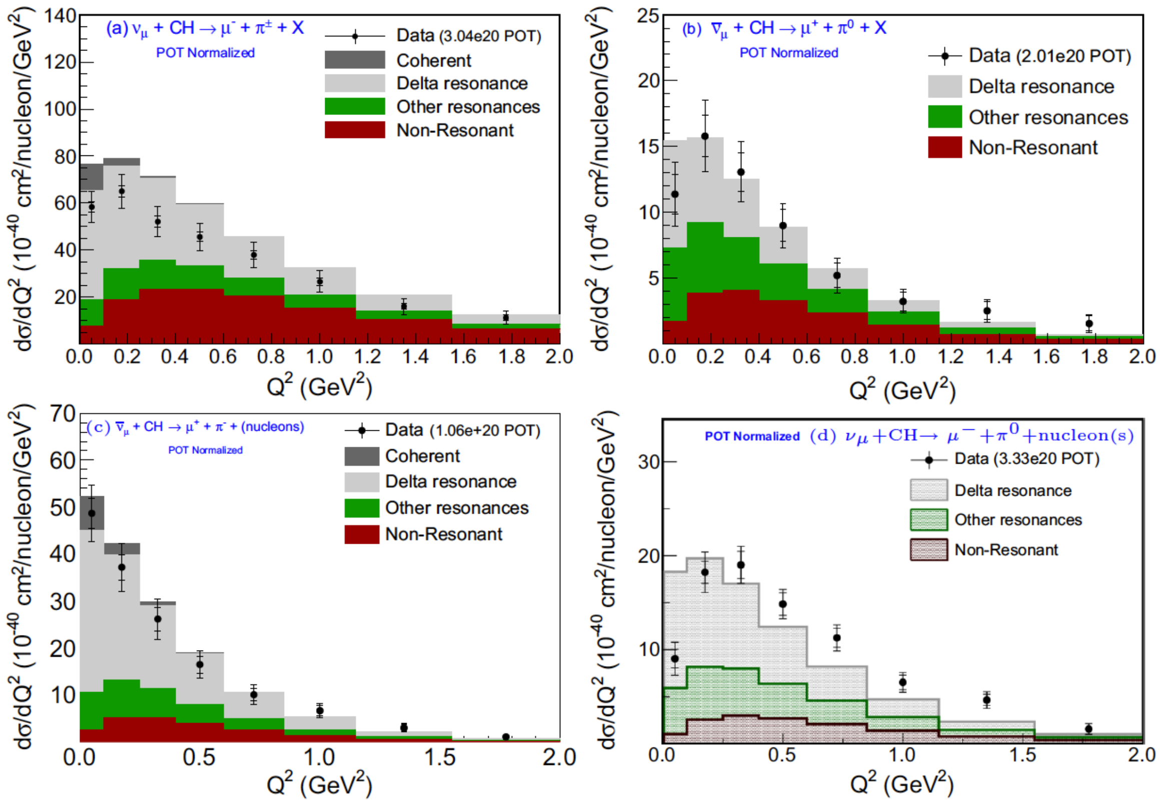
3. Pion puzzle

Data tension – internal: MINERvA pion data

- It is extremely difficult to tune pion and/or FSI parameters to fit all pion data
  - $\nu_\mu CC\pi^\pm$, low Q2 suppression, over-predicted
  - $\nu_\mu CC\pi^0$, strong low Q2 suppression
  - $\bar{\nu}_\mu CC\pi^-$, no low Q2 suppression
  - $\bar{\nu}_\mu CC\pi^0$, low Q2 suppression, under-predicted

The study relies of available knobs in the generator

It looks the simulation doesn't have good "knobs" to tune



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1. all pion production channels
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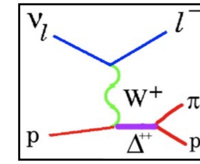
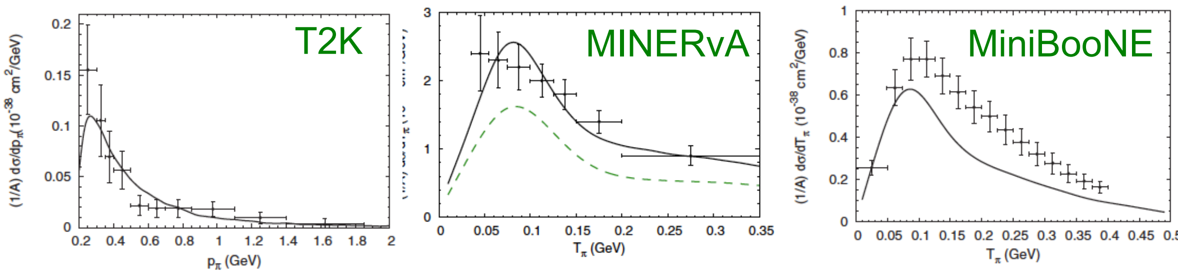


3. Data tension

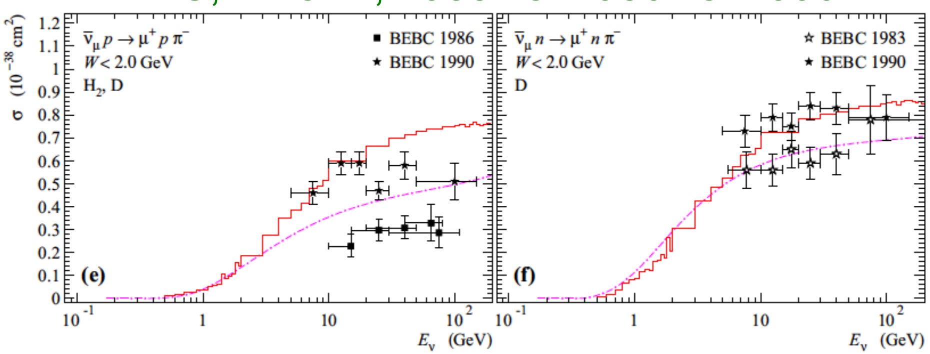
Data tension – external

- Tension between different experiments
- Tension between different targets
- Tension between different analyses

MiniBooNE vs. T2K vs. MINERvA (GiBUU)

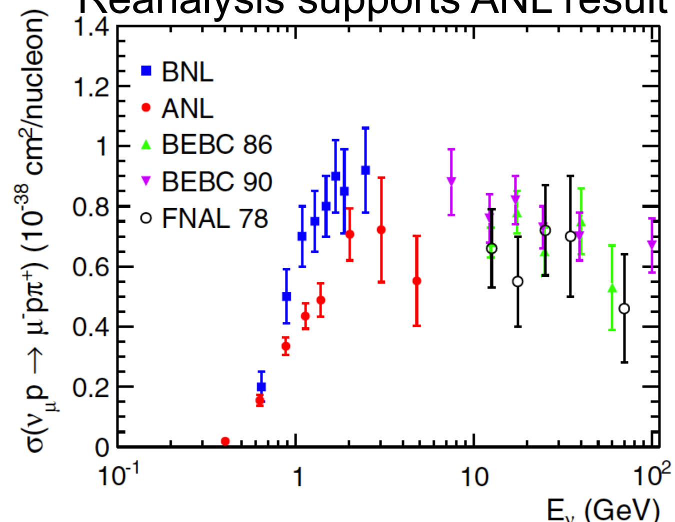


BEBC, H vs. D, 1983 vs. 1986 vs. 1990

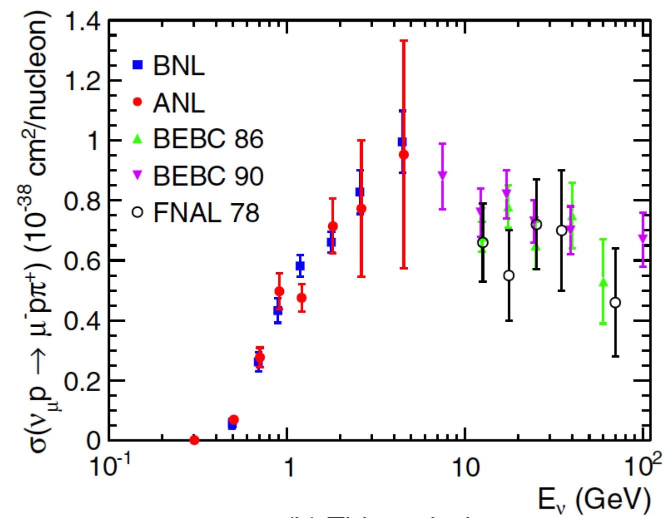


ANL vs. BNL data

Reanalysis supports ANL result



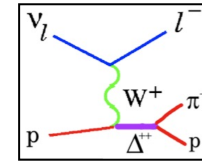
(a) Published



(b) Thisanalysis

teppei.katori@cern.ch

3. MiniBooNE low-energy excess



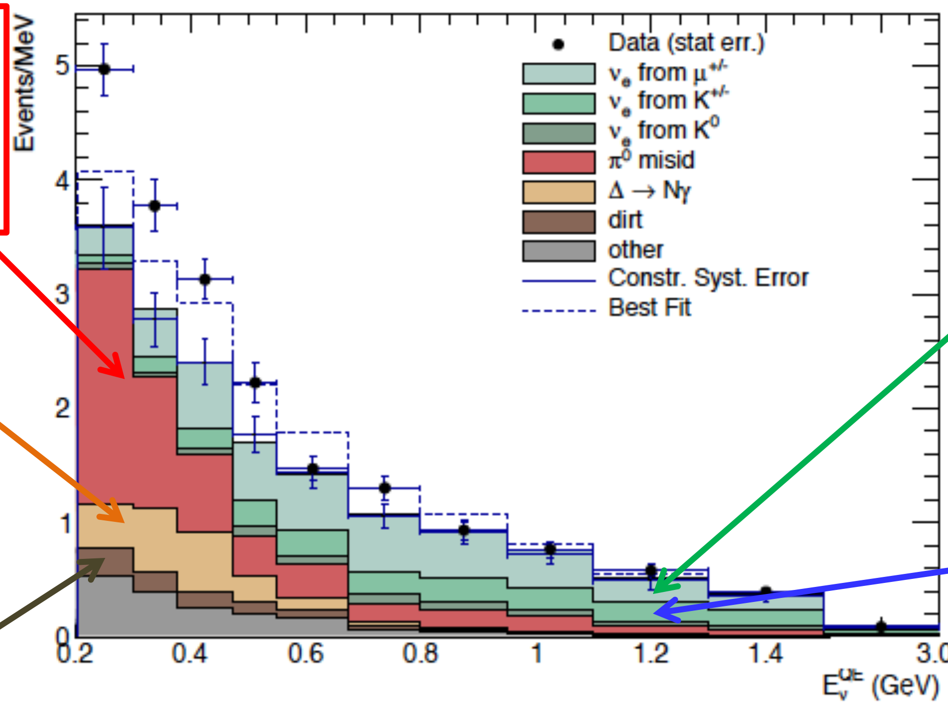
Short-baseline anomalies

- Collection of data suggesting existence of sterile neutrino in 1eV scale
- MiniBooNE has the single highest significance in all anomalies
- Resonance related backgrounds (NCπ^o, NCγ) are dominant at low-E ν_e candidate
- Important for future n_e appearance oscillation experiments, HyperK and DUNE)

Asymmetric π^o decay is constrained from measured NCπ^o rate ($\pi^o \rightarrow \gamma$)

Δ resonance rate is constrained from measured NCπ^o rate

dirt rate is measured from dirt data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from SciBooNE high energy ν_μ event measurement

1. Neutrino interaction physics - introduction

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

3. Neutrino baryonic resonance interaction

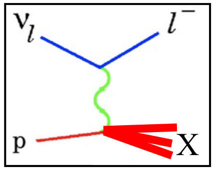
4. Neutrino shallow- and deep-inelastic scatterings

5. Conclusions

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

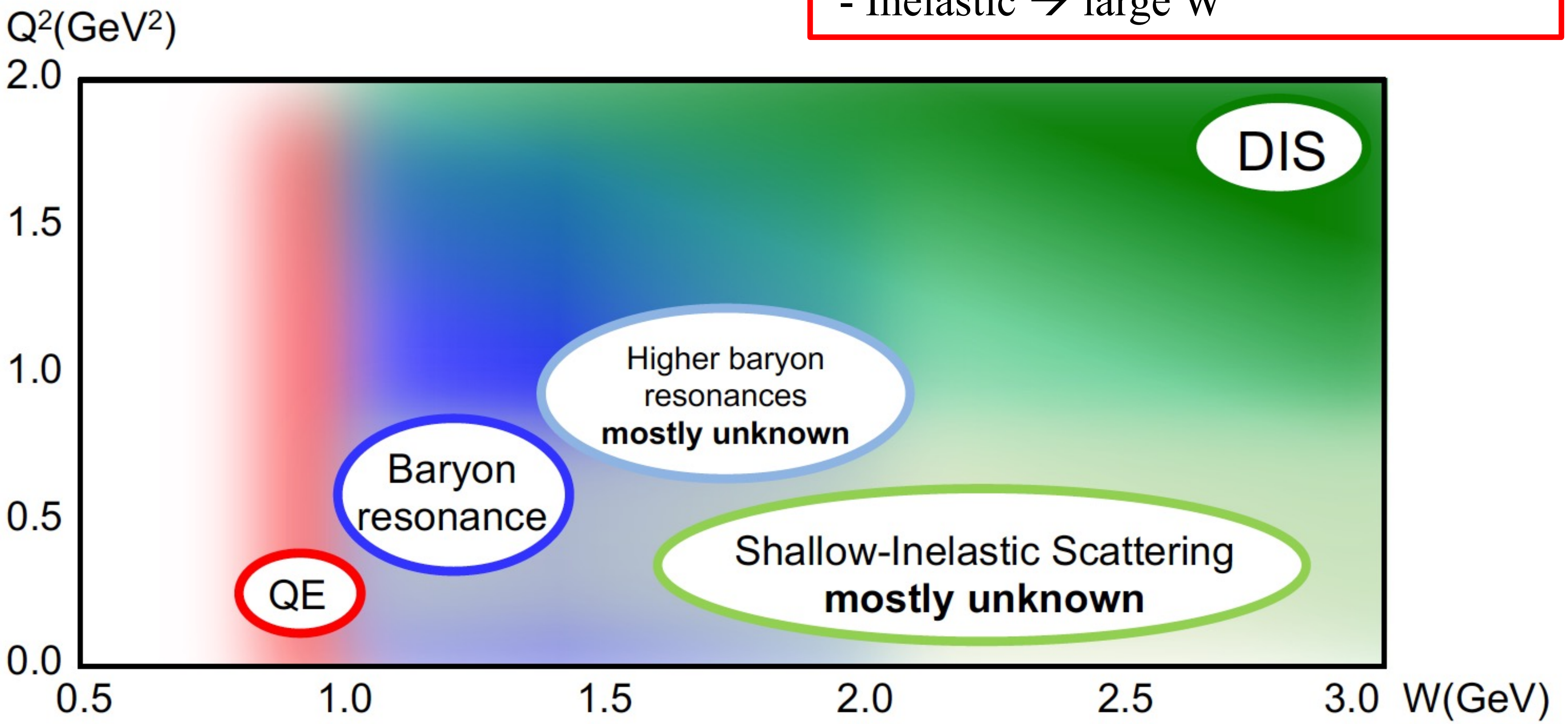


Cross section

- 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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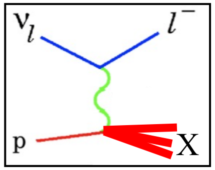

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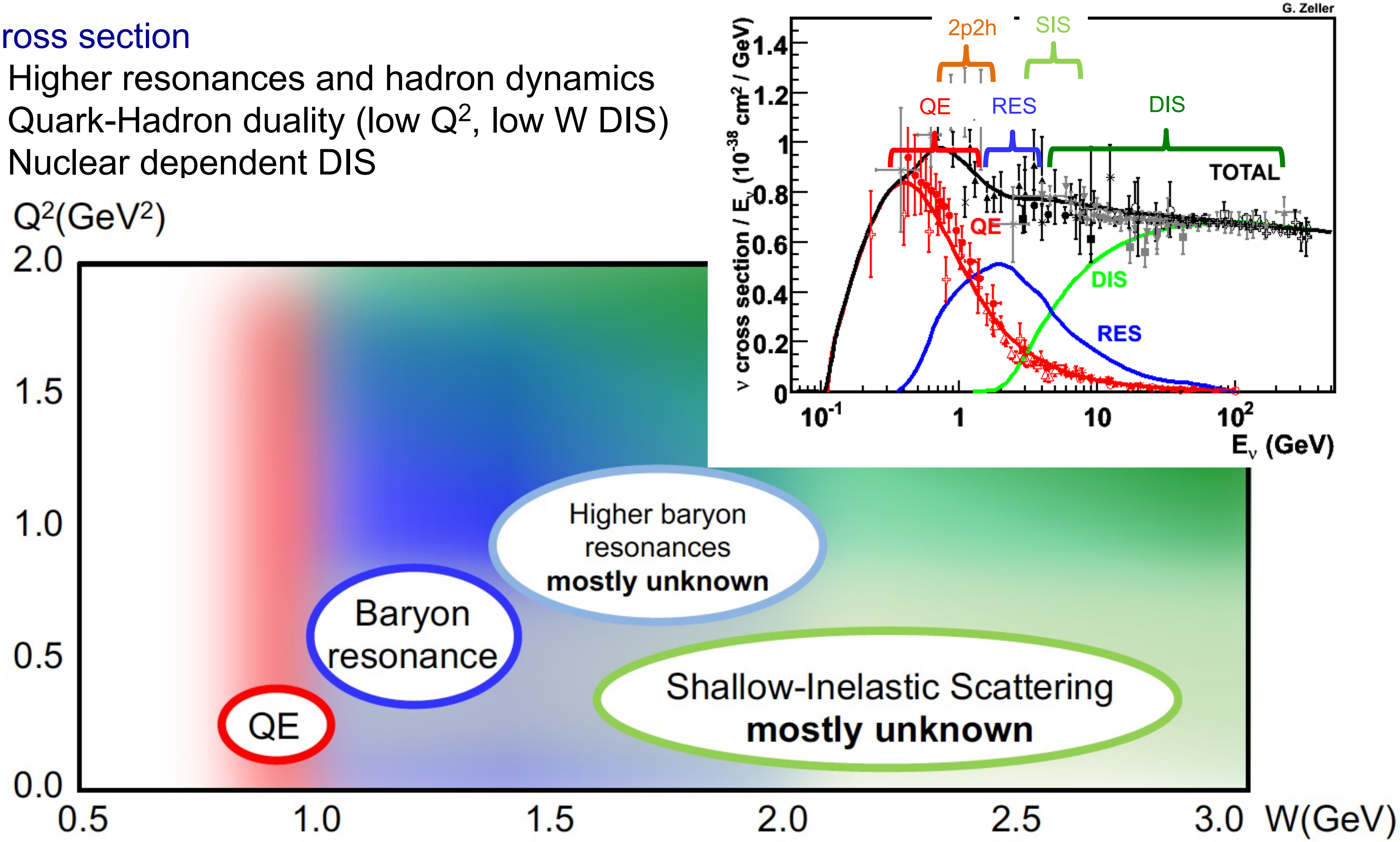
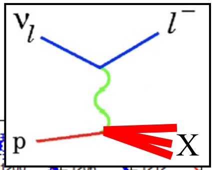


Nakamura et al,Rep.Prog.Phys.80(2017)056301

4. Higher baryonic resonances

DIS



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

DCC model vs. electro-pionproduction data

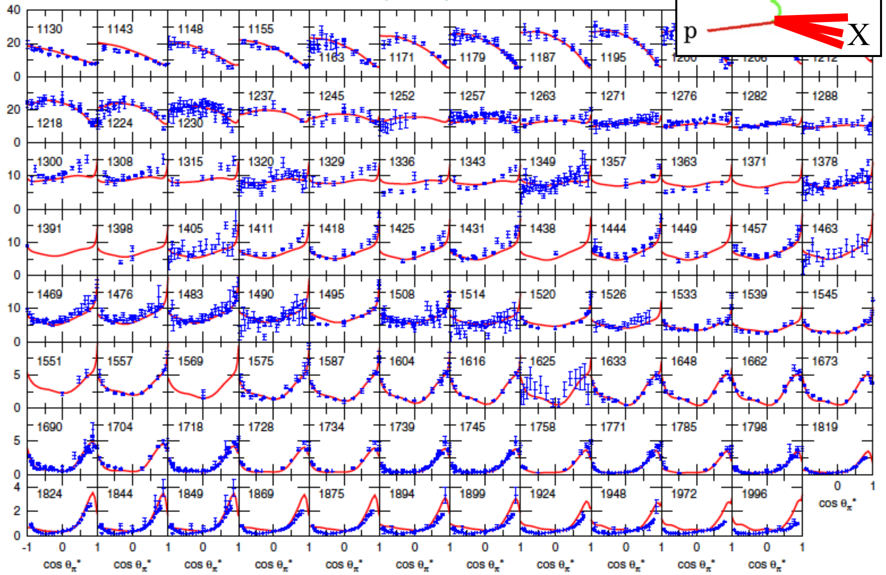
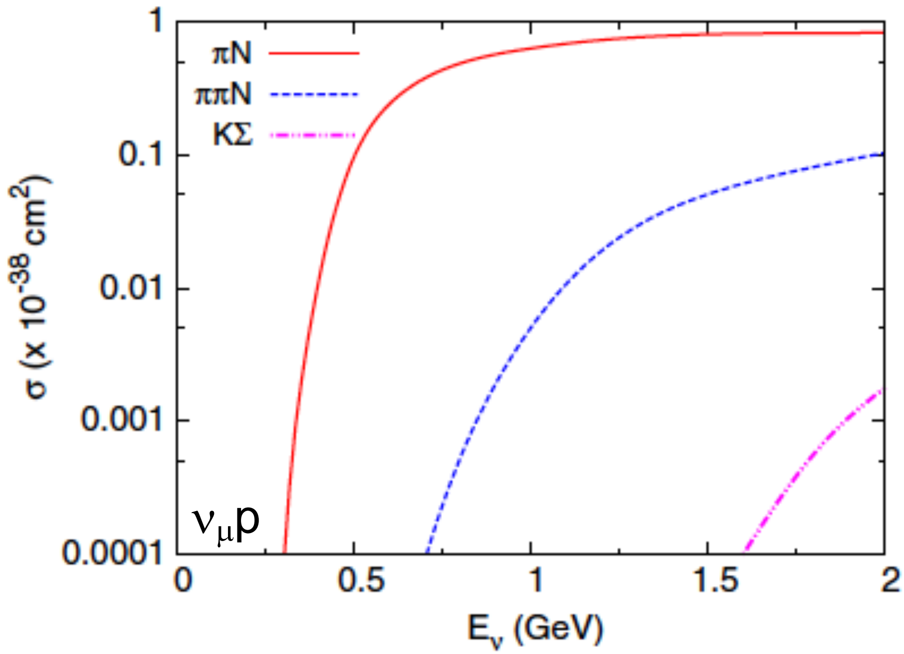
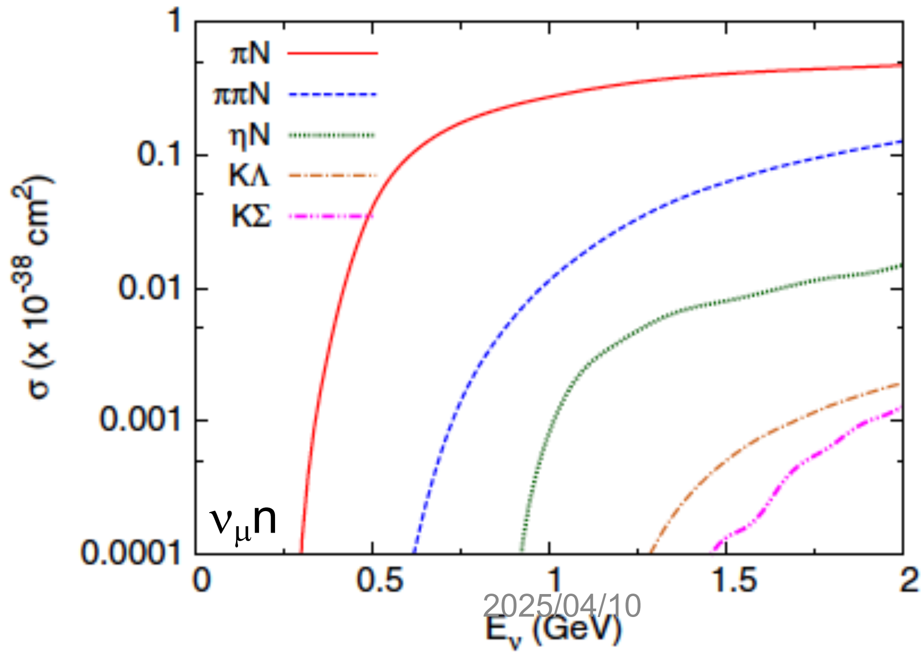


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

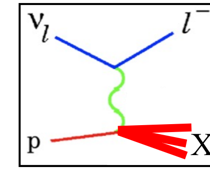




4. Quark-Hadron duality

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

DIS

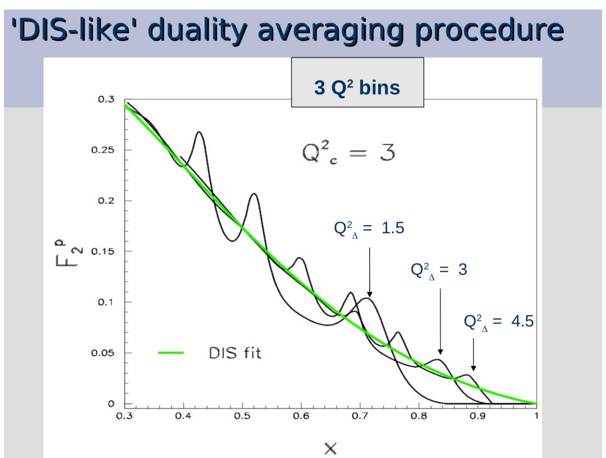


Cross section

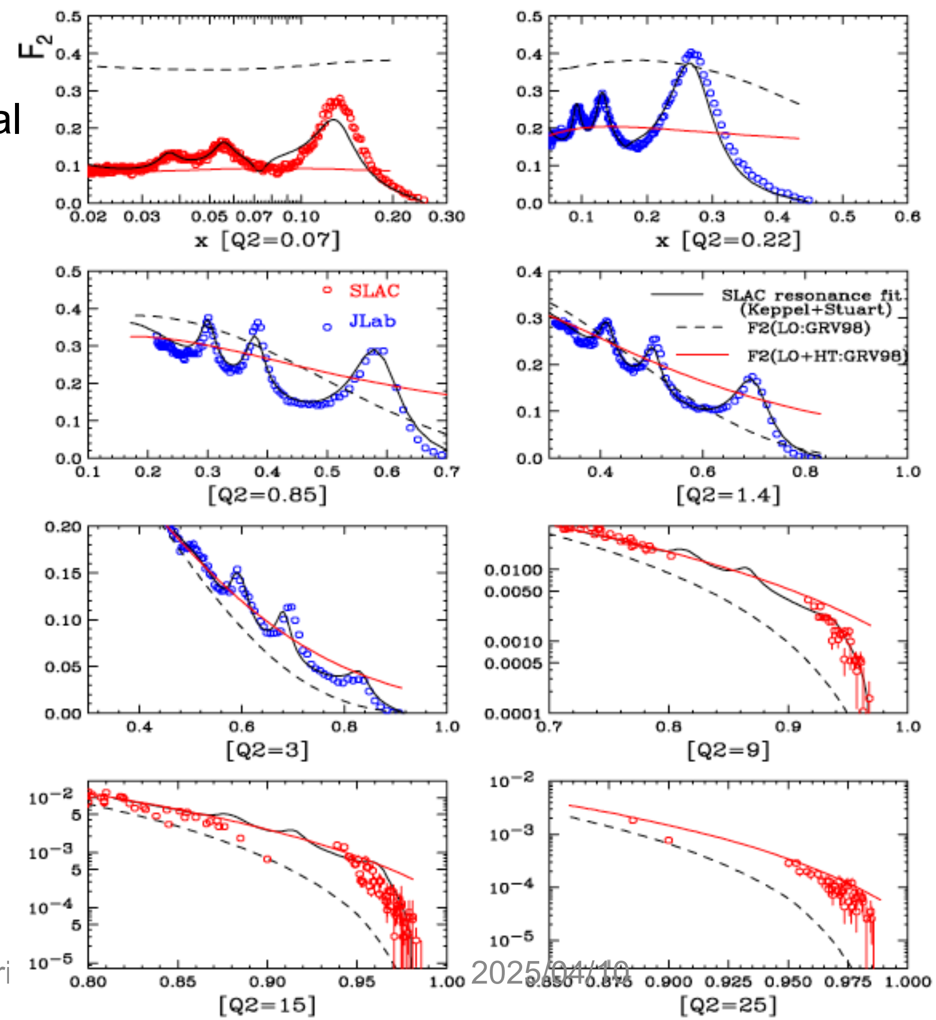
- Higher resonances and hadron dynamics
- Quark-Hadron duality (low Q^2, low W DIS)
- Nuclear dependent DIS

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



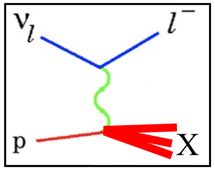
Proton F2 function GRV98-BY correction vs. data



Christy, NuSTEC SIS workshop
https://nustec.fnal.gov/nuSDIS18/

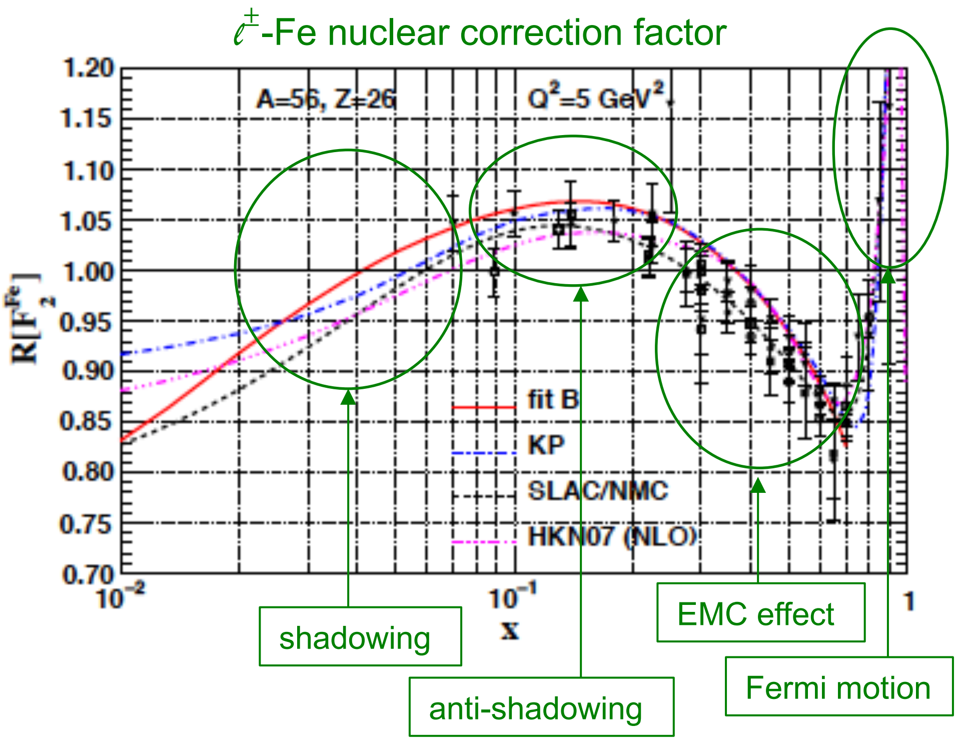
nCTEQ, PRD80(2009)094004
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028

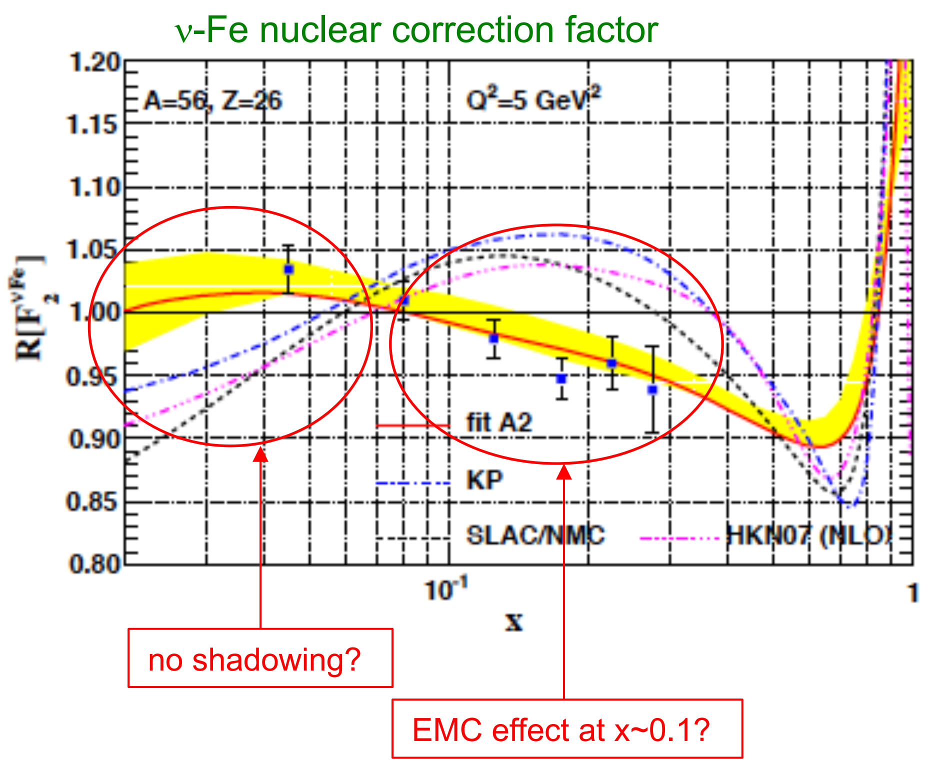
4. Nuclear dependent DIS



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





AGKY model, EPJC63(2009)1, GENIE, PRD105(2022)012009, Snowmass21, SciPostPhys,16(2024)130
TK, Mandalia, JPhysG42(2015)115004

4. Low-W hadronization model

KNO-scaling based model

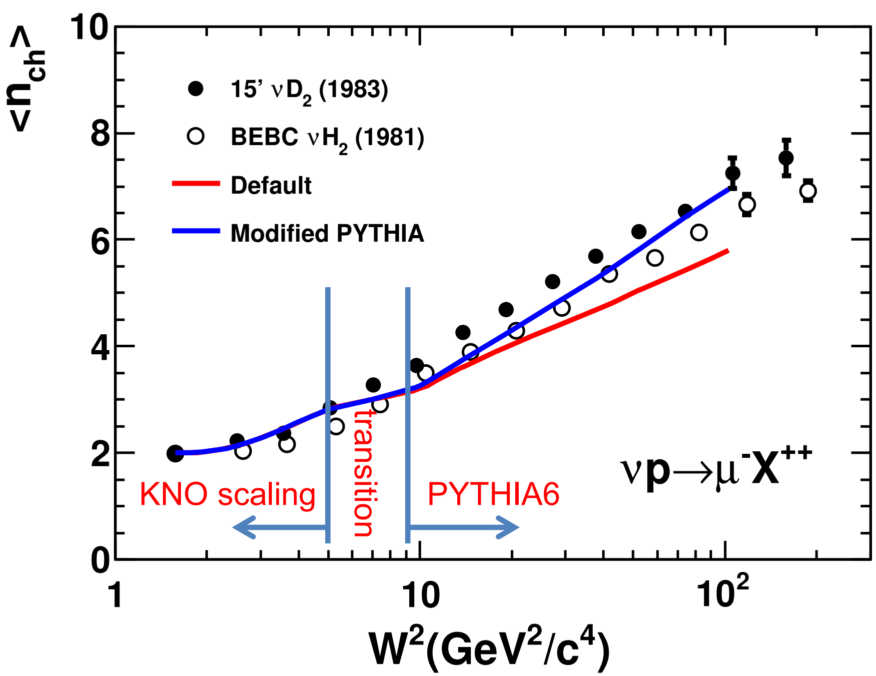
- Data-driven model
- Averaged charged hadron multiplicity $<n_{ch}>$
- Averaged neutral hadron multiplicity is chosen from isospin
- Variance of multiplicity is chosen from KNO-scaling law.

$$\langle n_{ch}\rangle = a_{ch} + b_{ch} \cdot \ln(W^2)$$

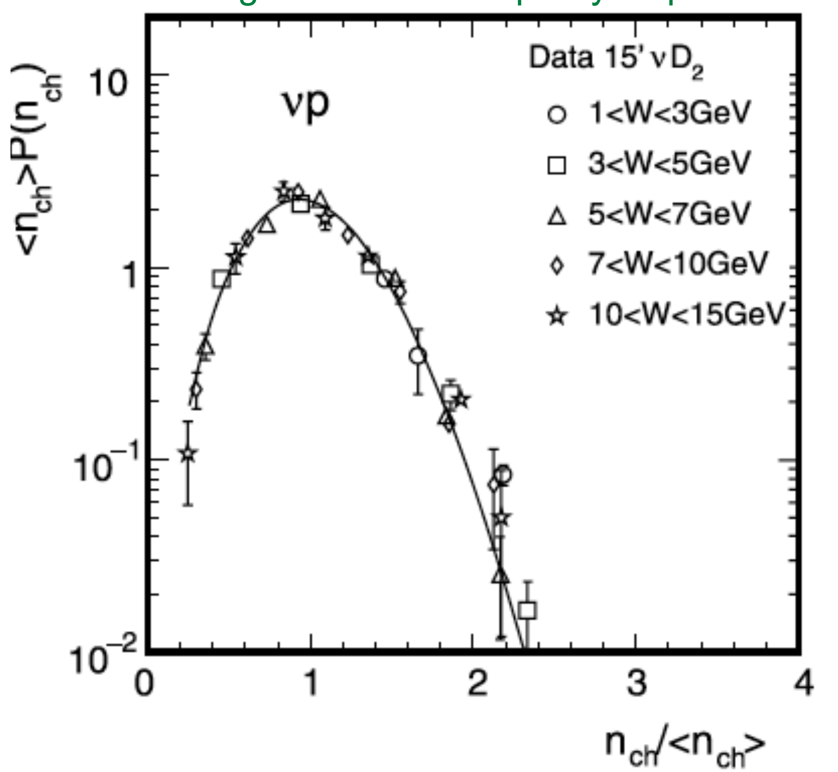
$$\pi^+ + \pi^-: \pi^0 = 2:1$$

$$\langle n\rangle \cdot P(n) = \frac{2e^{-c} c^{cn/\langle n\rangle+1}}{\Gamma(cn/\langle n\rangle + 1)}$$

Neutrino average charged hadron multiplicity



charged hadron multiplicity dispersion



4. High-W hadronization

PYTHIA6

- Lund string function to model $q-\bar{q}$ evolution
- Tuned function can reproduce <n_{ch}> data
- So far, PYTHIA tuning cannot fix dispersion discrepancy between Low-W and high-W hadronization models

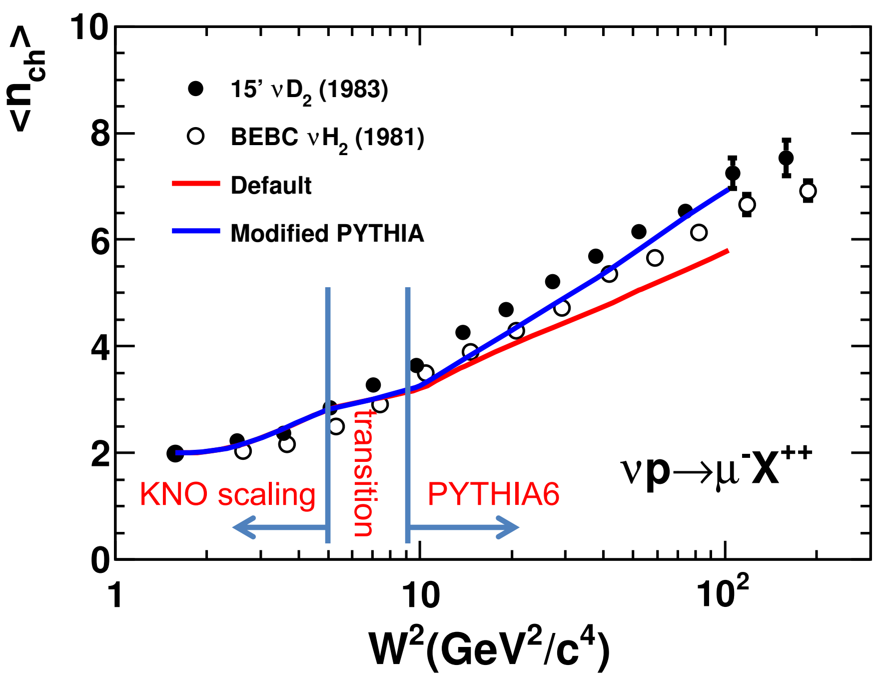
Lund string function

hadron energy distribution from iterative process

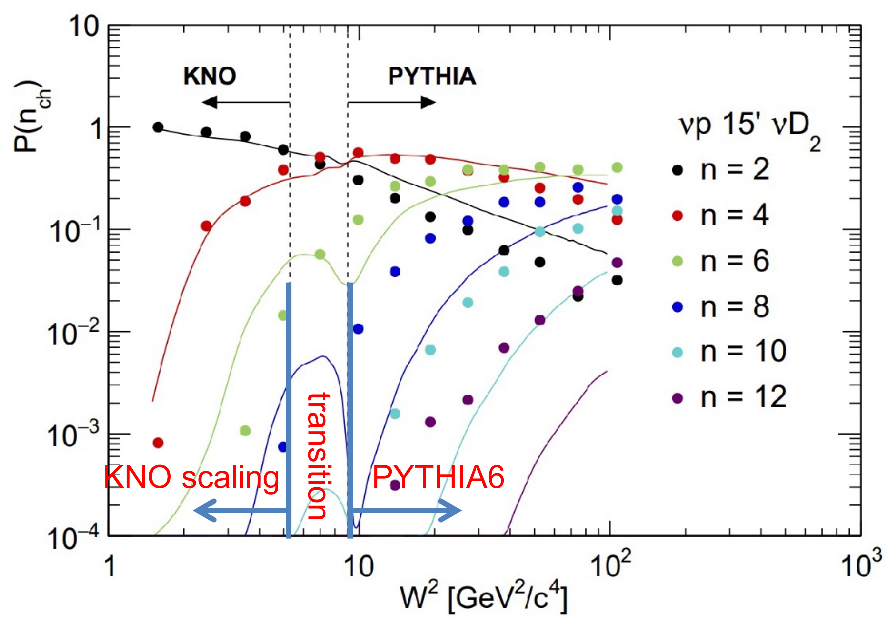
tunnelling probability

$$f(z) \propto z^{-1}(1-z)^a \cdot exp(-bm_\perp^2/z)$$

Neutrino average charged hadron multiplicity



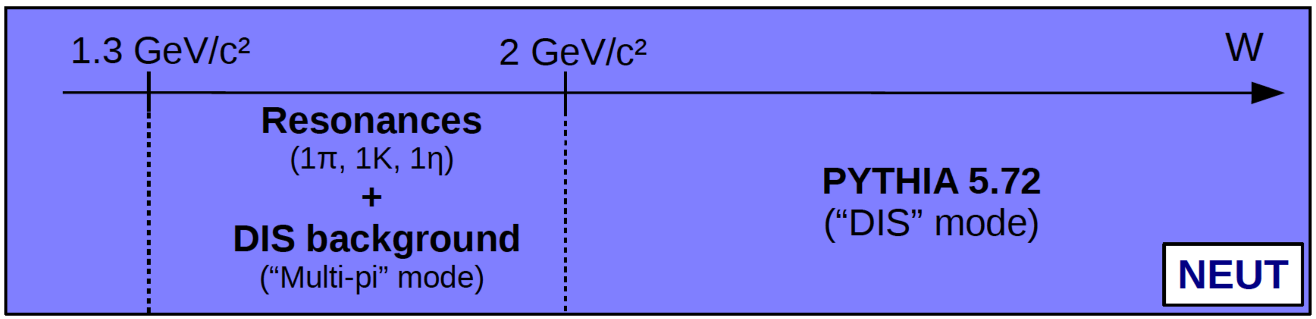
ν-p topological cross section (GENIE)

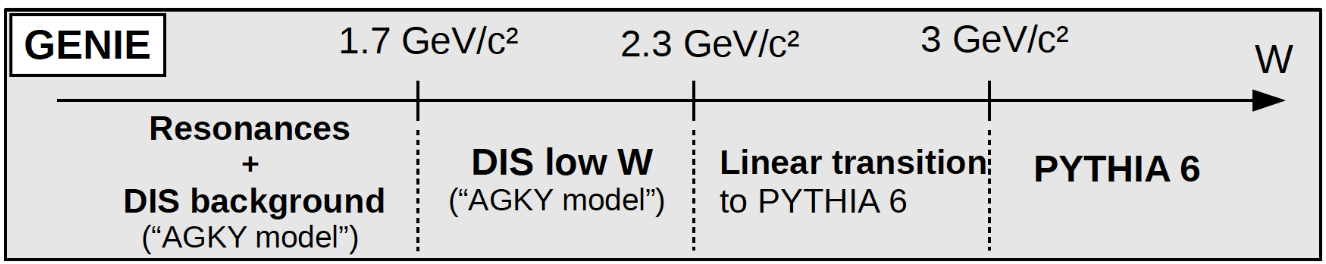


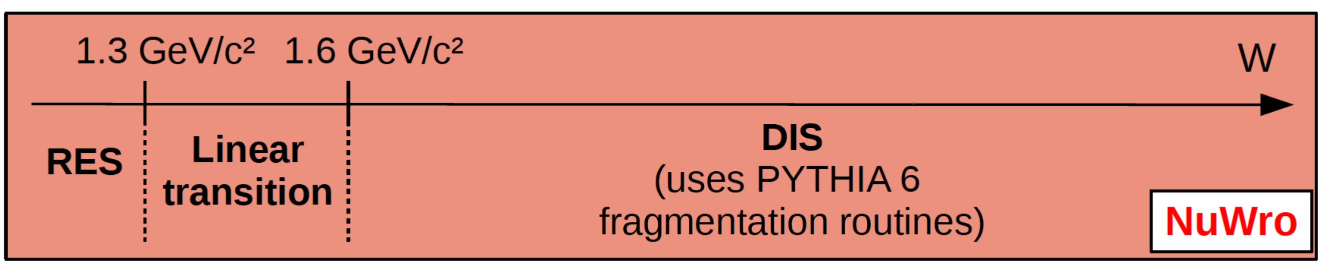
Nakamura et al,Rep.Prog.Phys.80(2017)056301, Sajjad Athar and Morfin, JPhysG48(2021) 034001
Snowmass21 white paper, ArXiv::2203.09030, NuSTEC nuSIS workshop, ArXiv:1907.13252

1. SIS in event generators

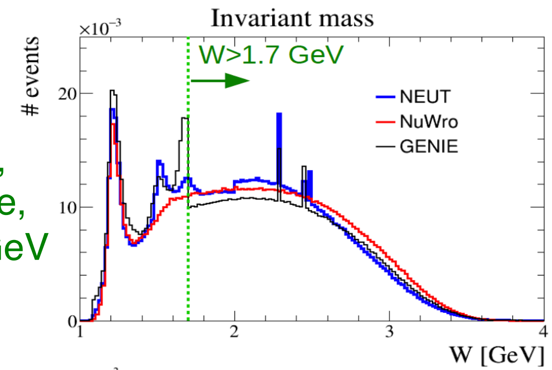
Difficult to connect different models
- Cross-section models
- Hadronization models

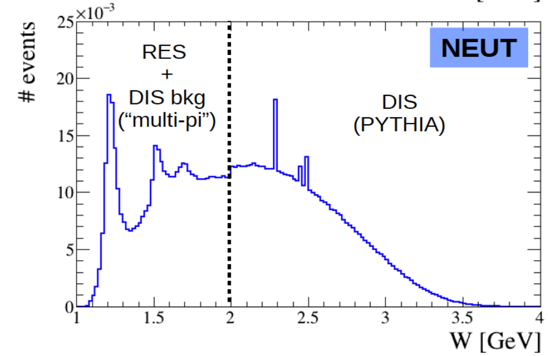


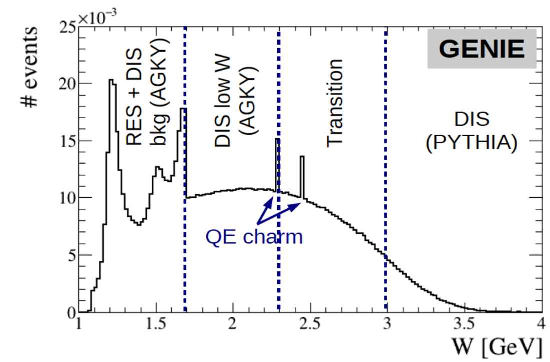


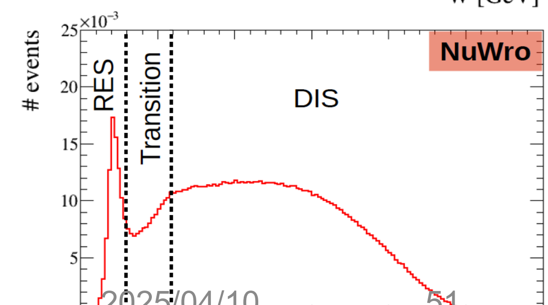


True W,
ν_μ on Fe,
Eν=6 GeV









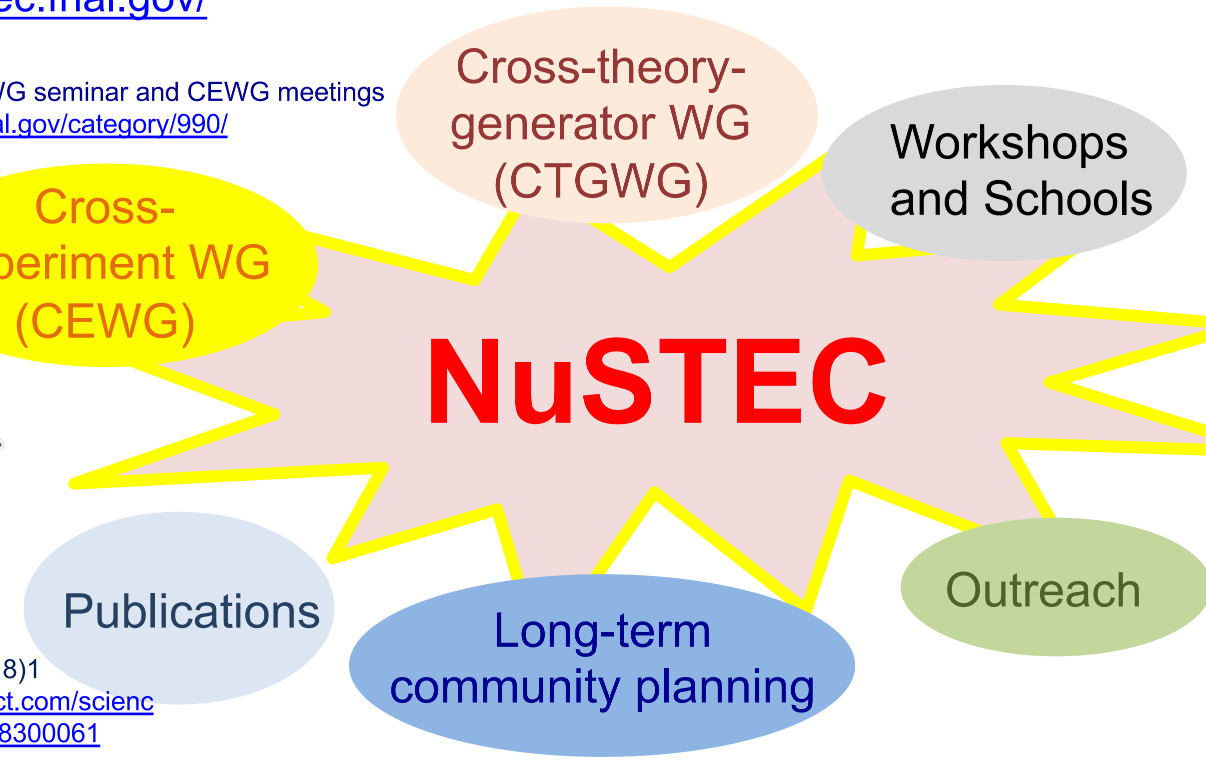
Christophe Bronner

4. NuSTEC

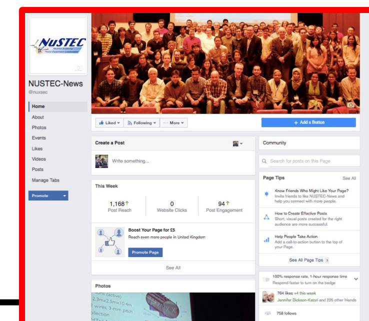
NuInt conference series
- Oct. 6-10 2025, Mainz (Germany)
https://nustec.fnal.gov/nuint-conference-series/

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

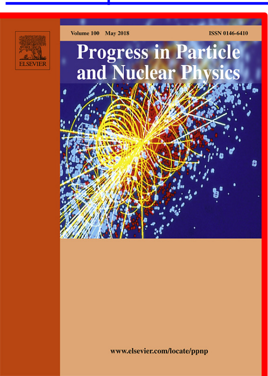
NuSTEC CTGWG seminar and CEWG meetings
https://indico.fnal.gov/category/990/



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

Nucleon correlation physics drastically change neutrino cross sections in QE dominant region.

Currently, the community don't understand tensions in resonant single pion production data.

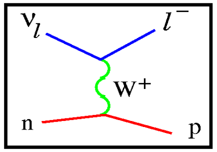
Systematic errors on SIS and DIS region are important for future experiments.

Thank you for your attention!

Backup

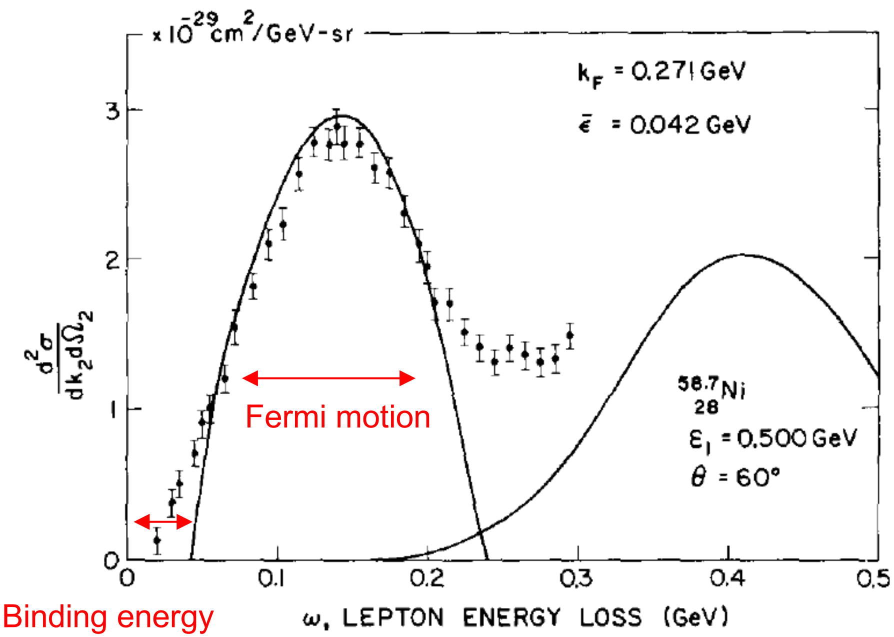
Smith and Moniz, NPB43(1972)605
Ashkenazi (Neutrino 2020), https://zenodo.org/record/3959538

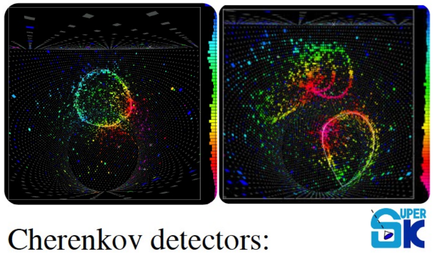
2. Fermi motion



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)



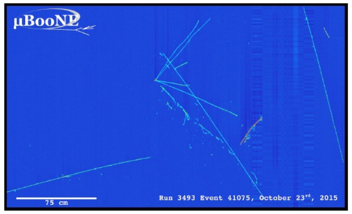


Cherenkov detectors:

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

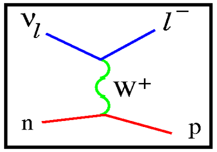
$$E_{cal} = E_l + E_p^{kin} + \epsilon$$

[1p0π]

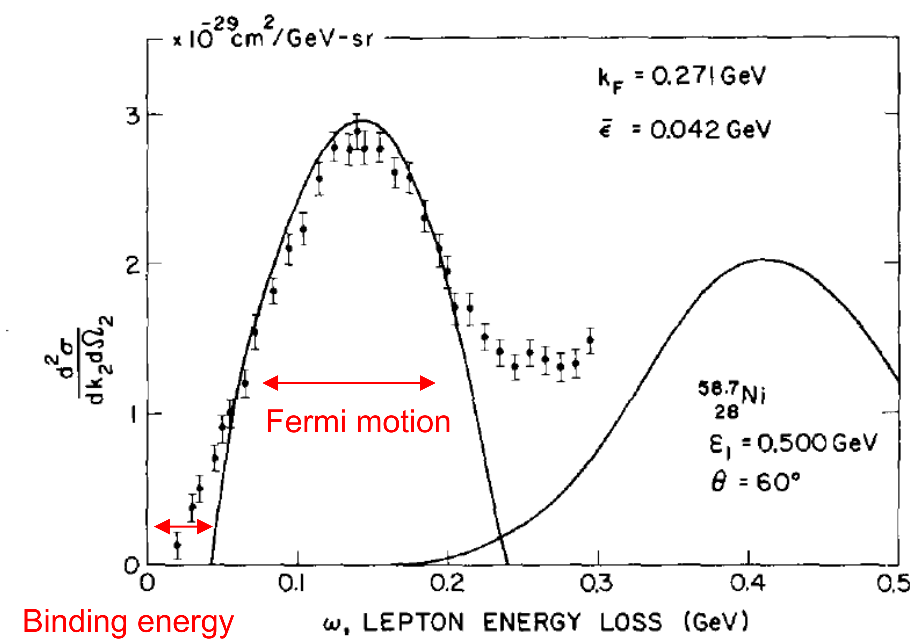
Smith and Moniz, NPB43(1972)605
MiniBooNE, PRD81(2010)092005

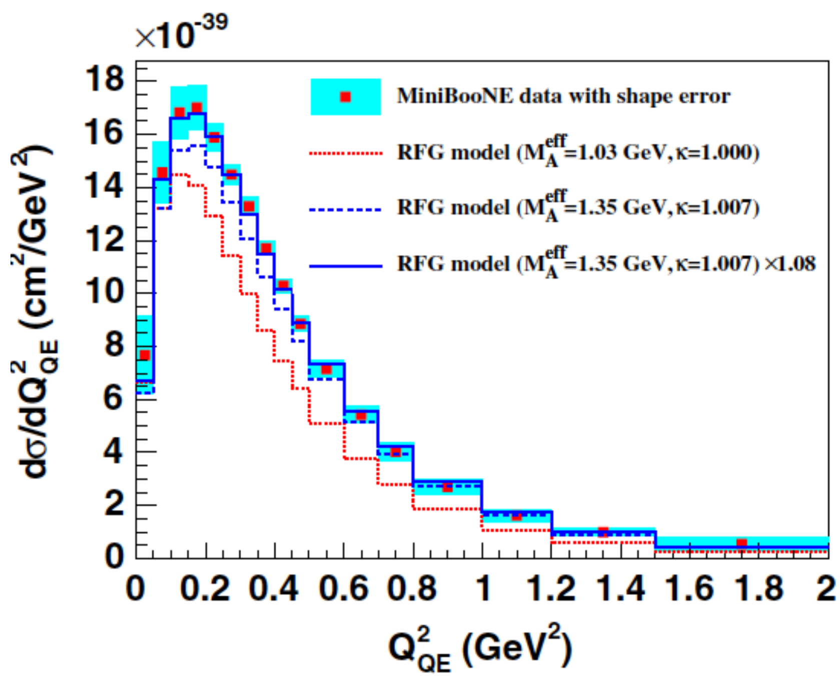
2. Pauli blocking

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

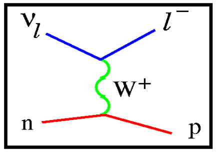




Smith and Moniz, NPB43(1972)605
Bodek and Cai, EPJC79(2019)293

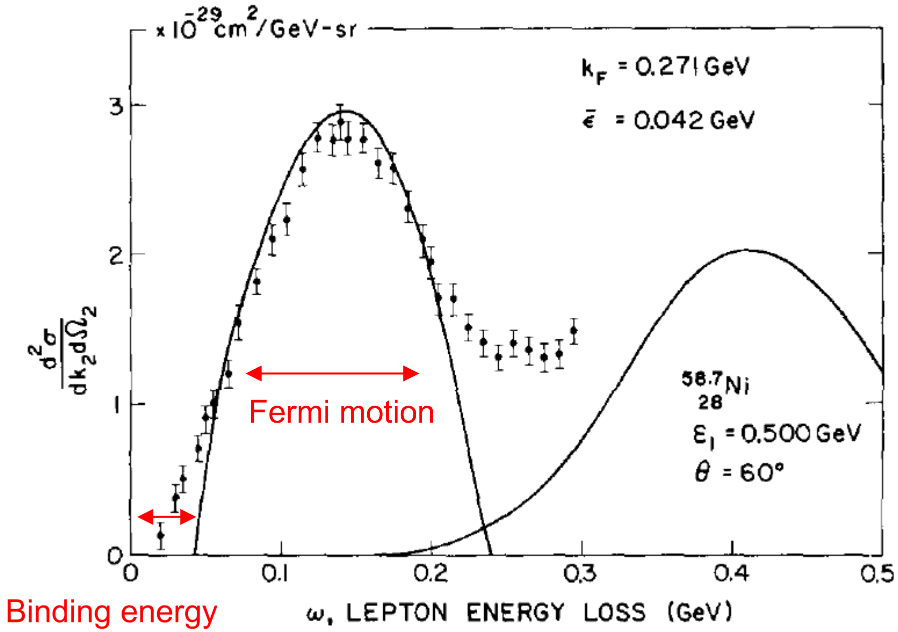
2. Nuclear Shell structure and binding energy

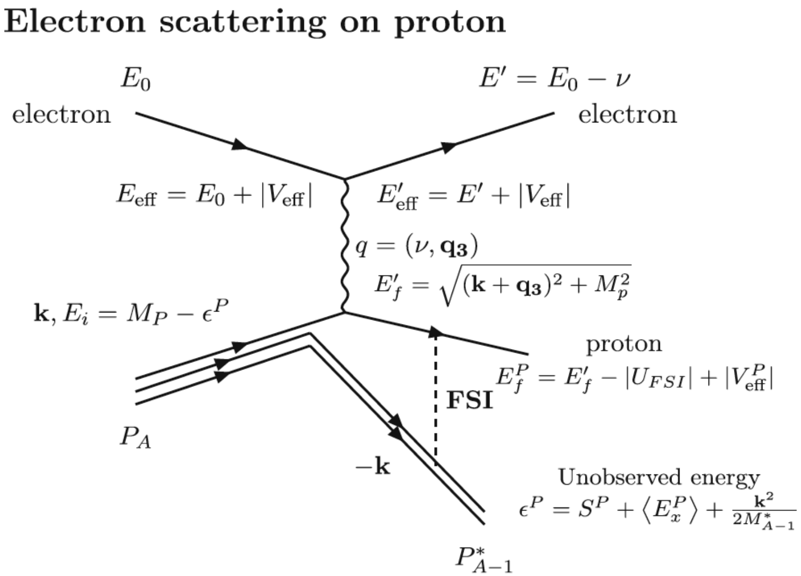
Quasi Elastic



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. 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

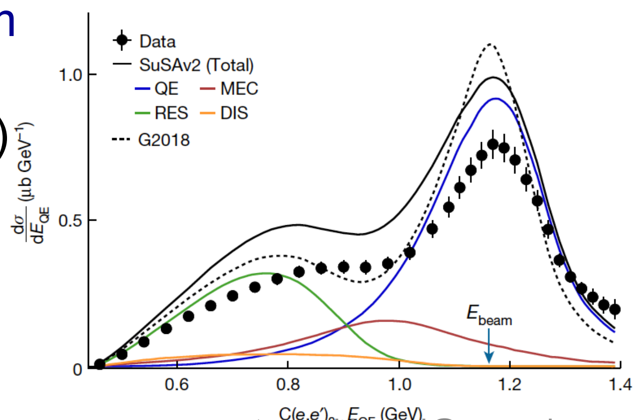
Neutrino experiment don't reconstruct Ev (and Q2) with great precision

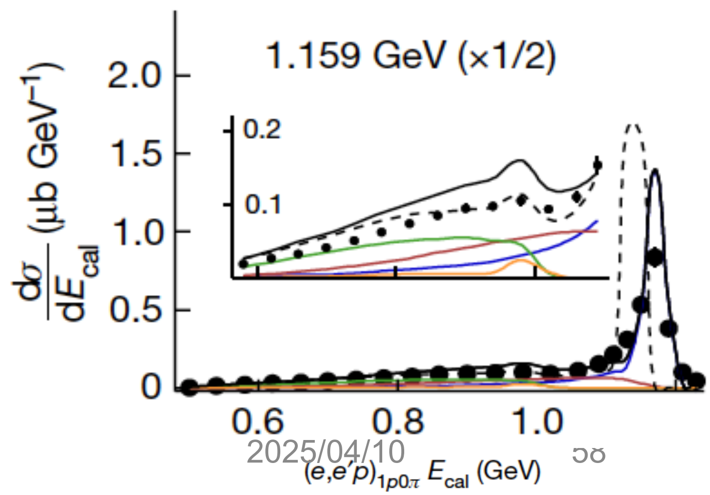
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

Reconstructed beam electron energy spectrum by

- QE kinematic (HyperK)
- Calorimetric (DUNE)

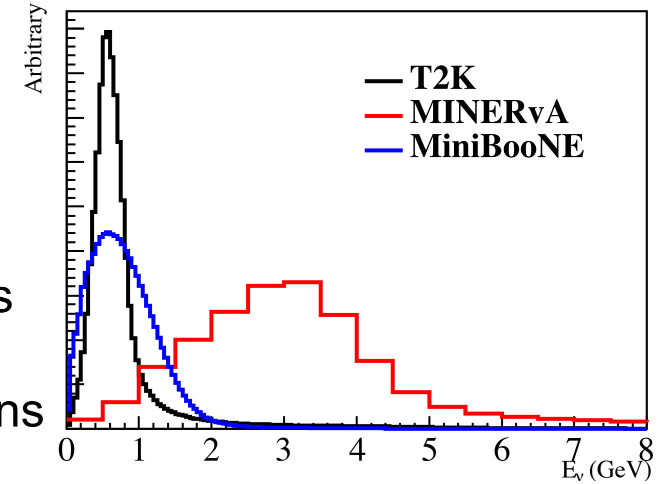




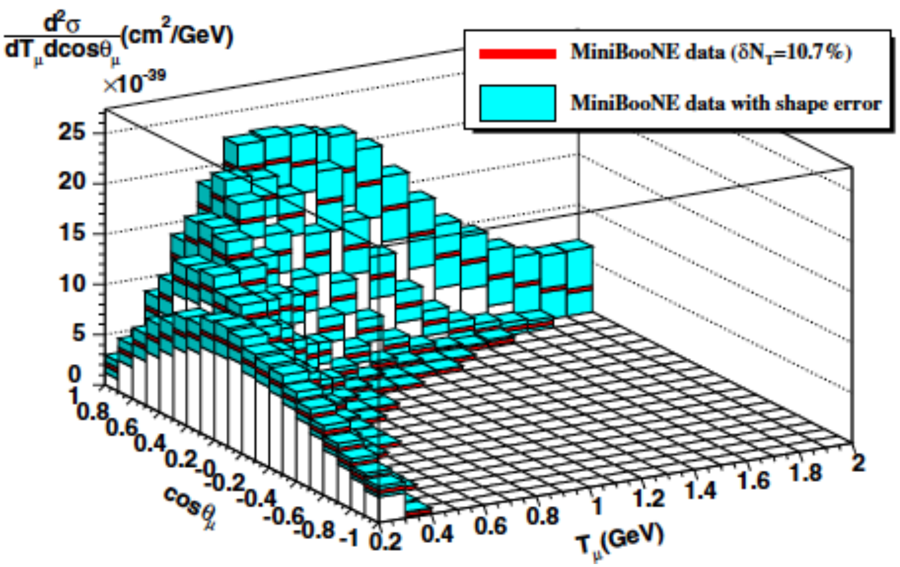
5. MiniBooNE

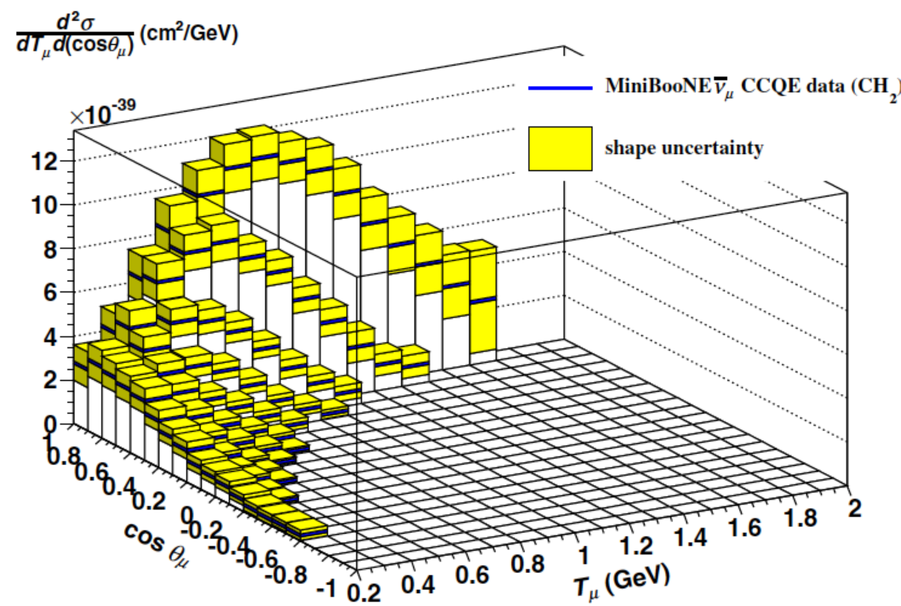
Mineral oil (CH_2) Cherenkov detector

- 4π coverage, <E>~800 MeV beam up to 2 GeV
- Measure Cherenkov radiations from charged particles
- Some calorimetric (scintillation)
- Measured first flux-integrated differential cross sections
- Solved CCQE puzzle

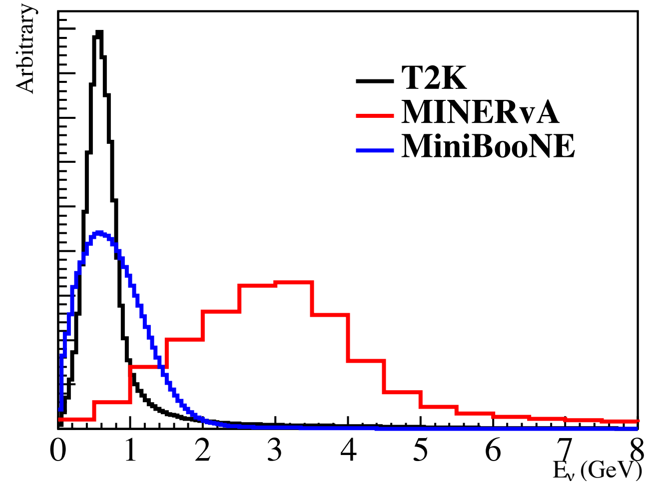


neutrino and anti-neutrino CCQE-like double differential cross sections



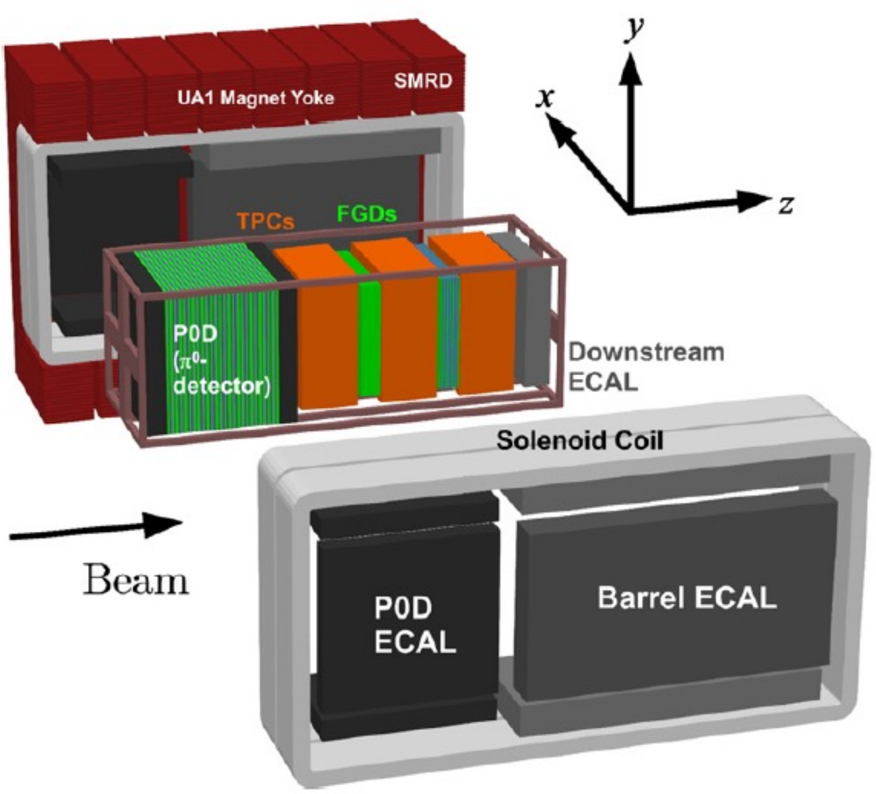


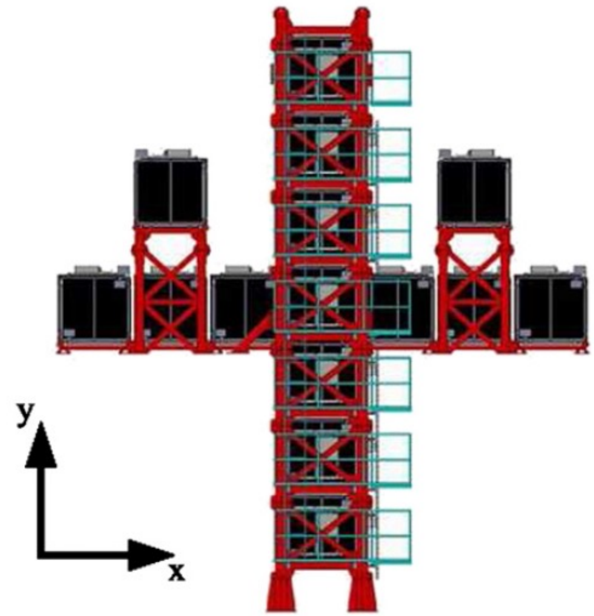
5. T2K near detector complex



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)





5. T2K near detector complex

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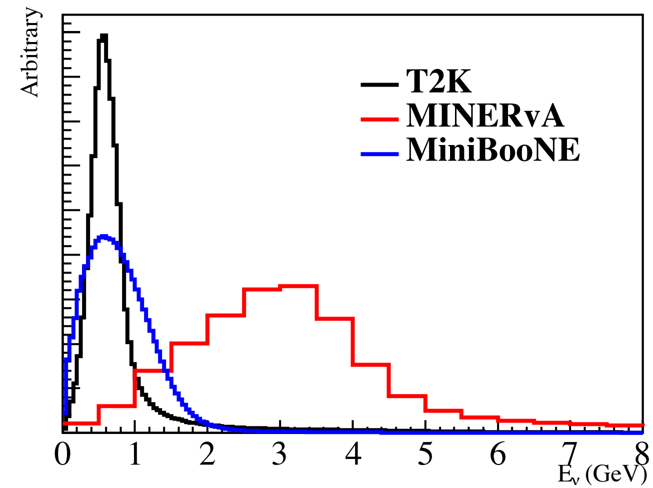
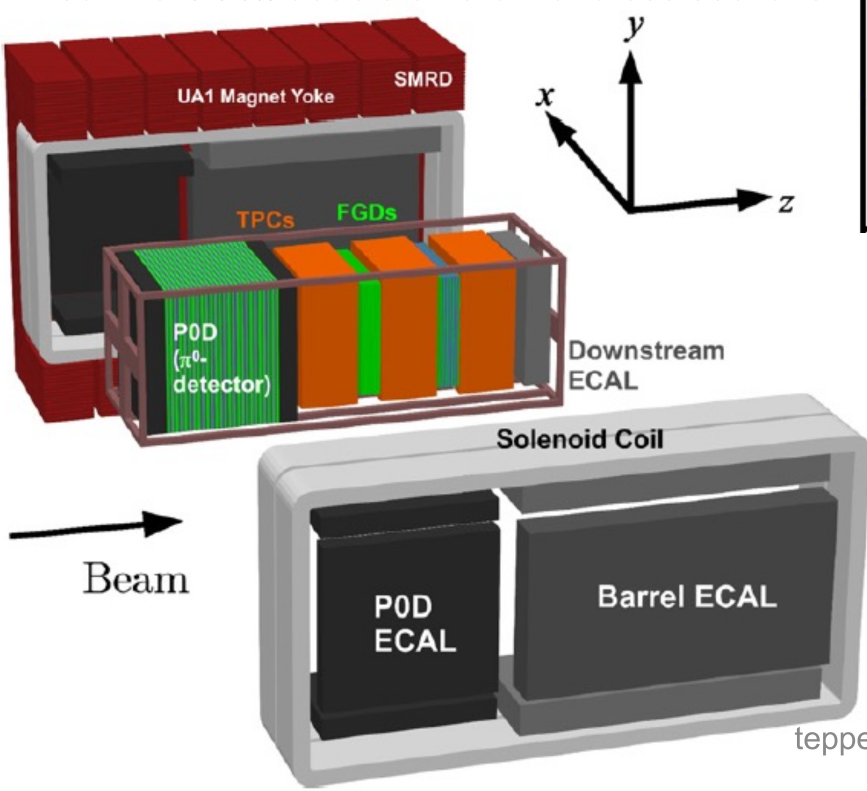
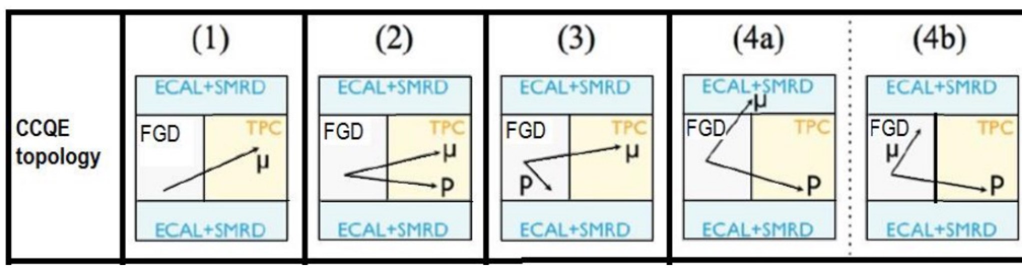
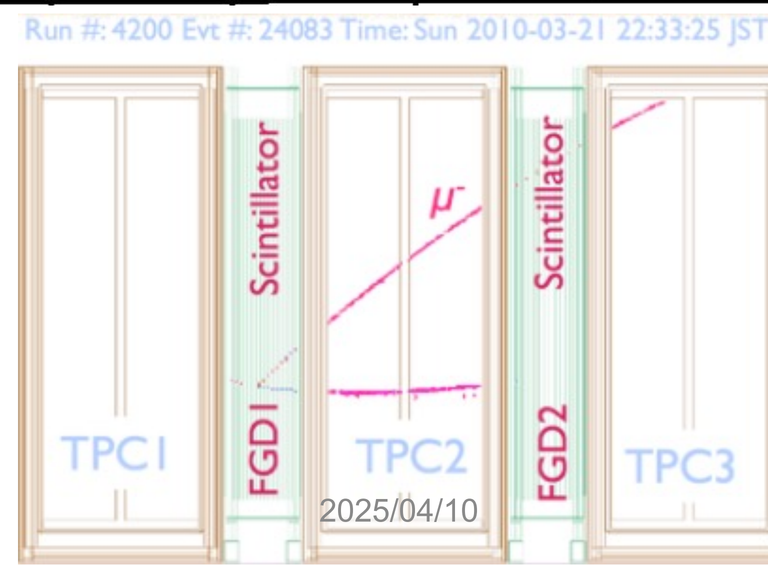


neutrino CC0π double differential cross sections







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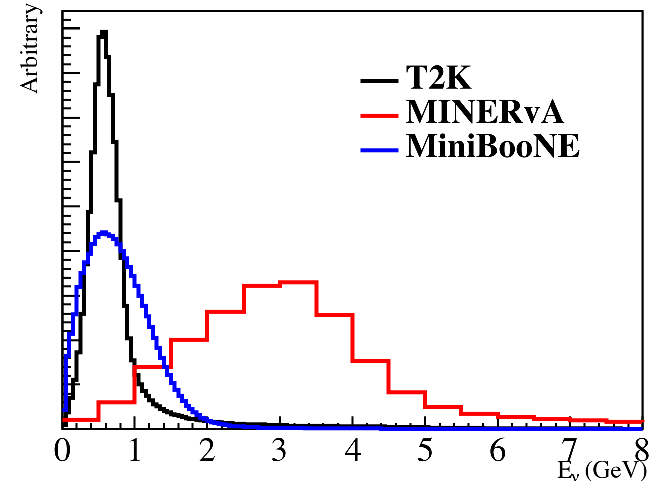

INGRID, FGD, P0D, ECal, TPC, SMRD

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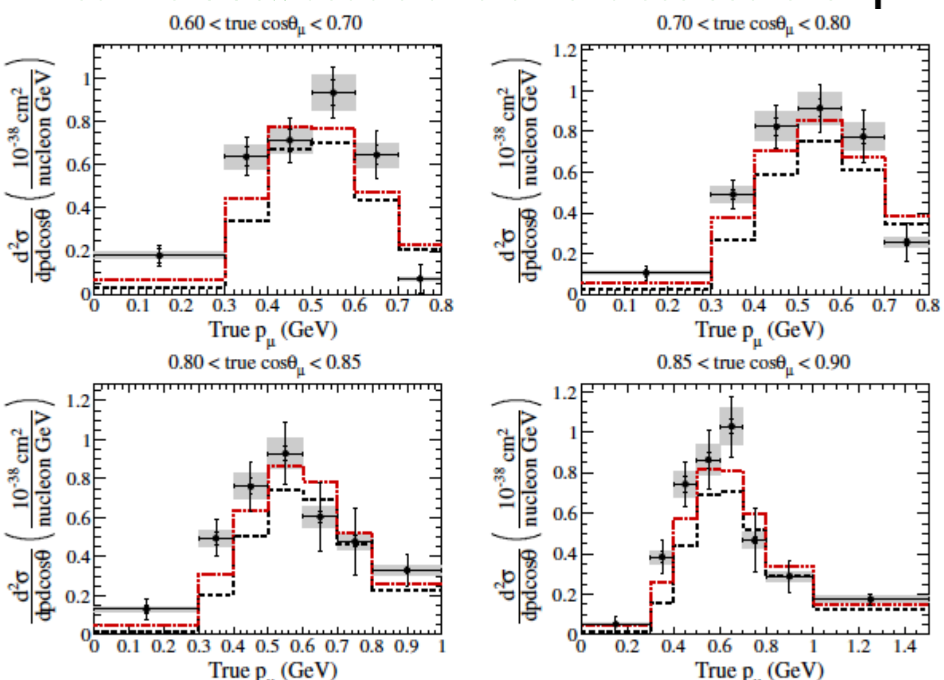
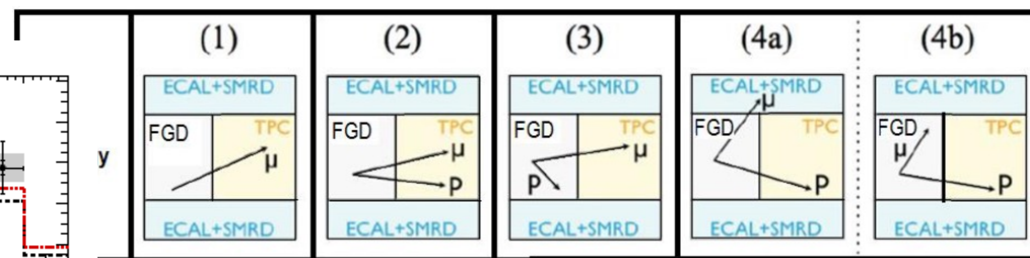
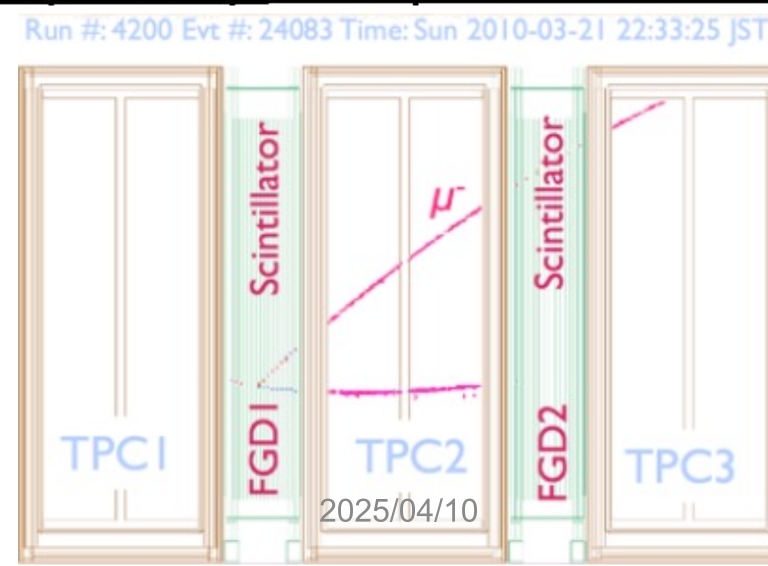
neutrino CC0π double differential cross sections

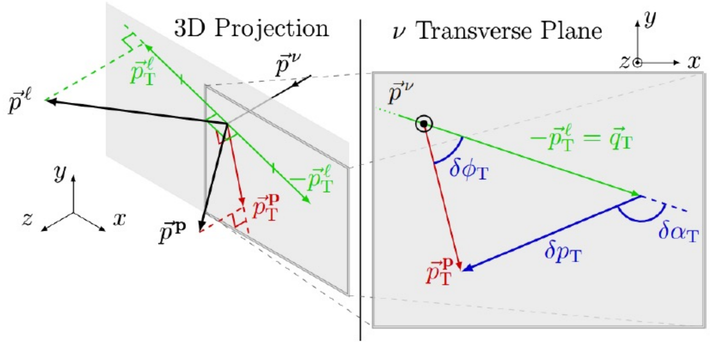






T2K, NIMA659(2011)106, T2K,PRD93(2016)112012
PRD98(2018)032003

5. T2K near detector complex



INGRID, FGD, P0D, ECal, TPC, SMRD

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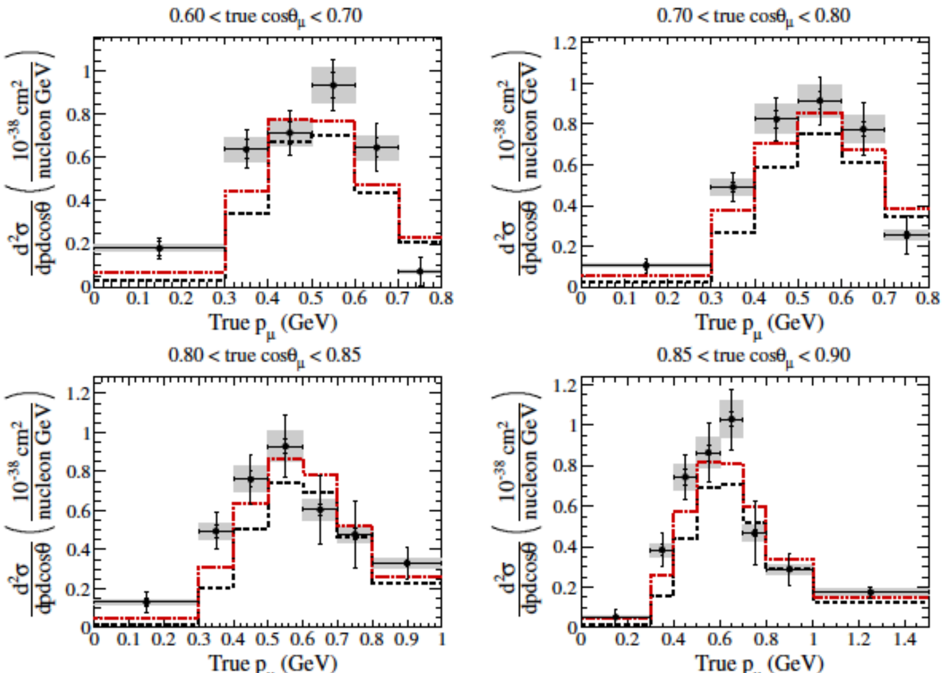
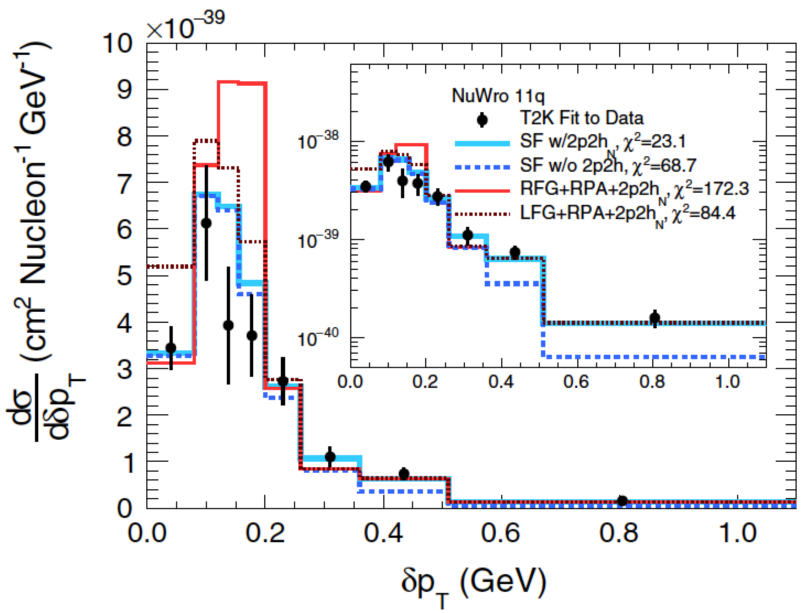
neutrino CC0π double differential cross sections

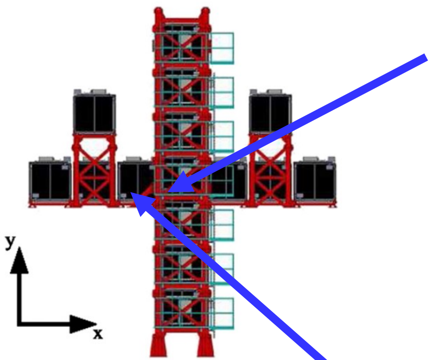


neutrino CC0π1p differential cross sections

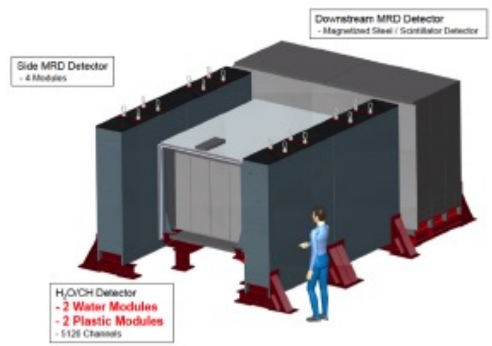


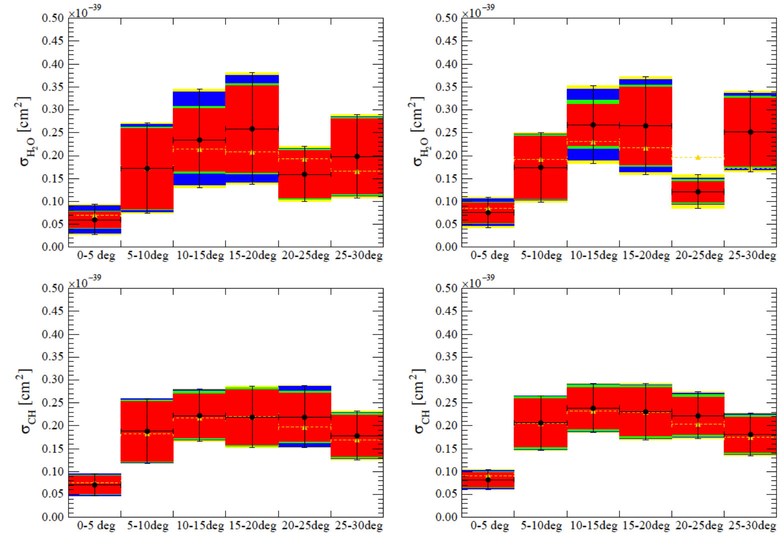
WAGASCI,PTEP(2019)093C02
NINJA, PTEP2021(033C01)

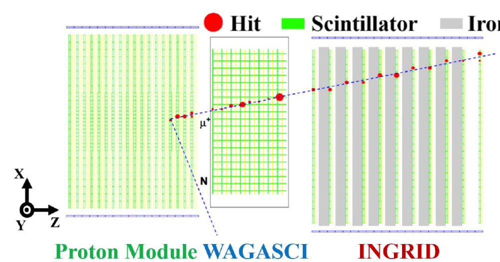
5. T2K near detector complex



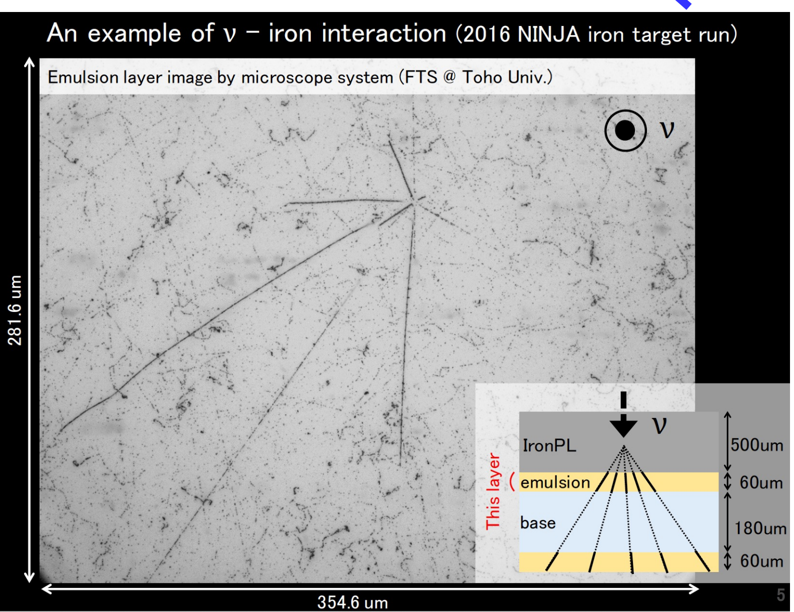
WAGASCI
- water target

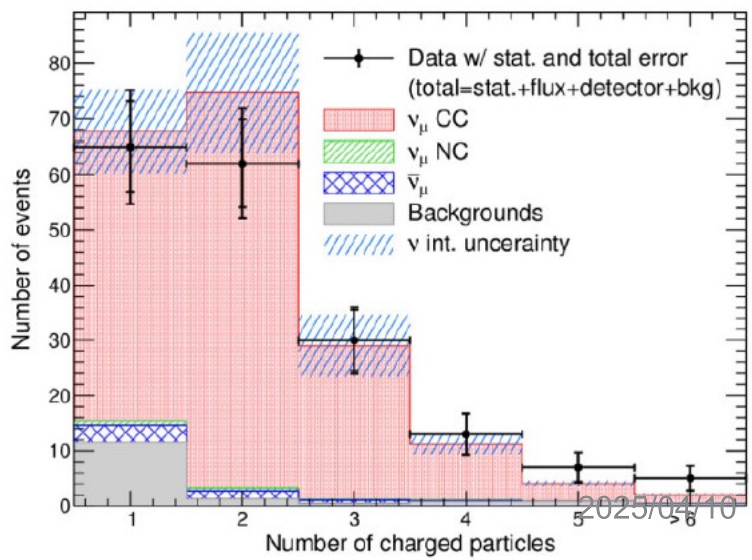






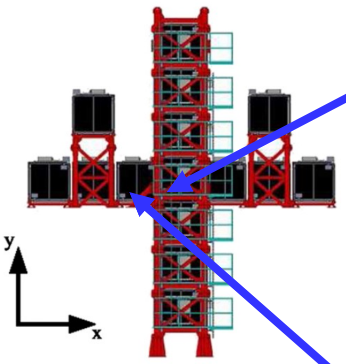
NINJA
- emulsion detector
- Multiple hadron tracks



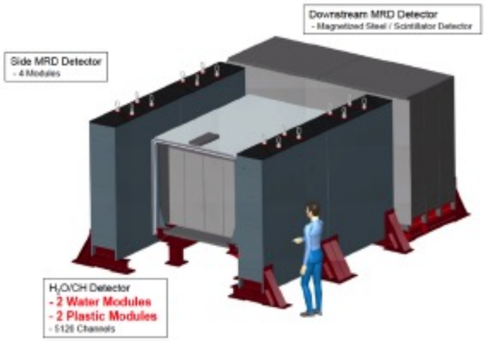


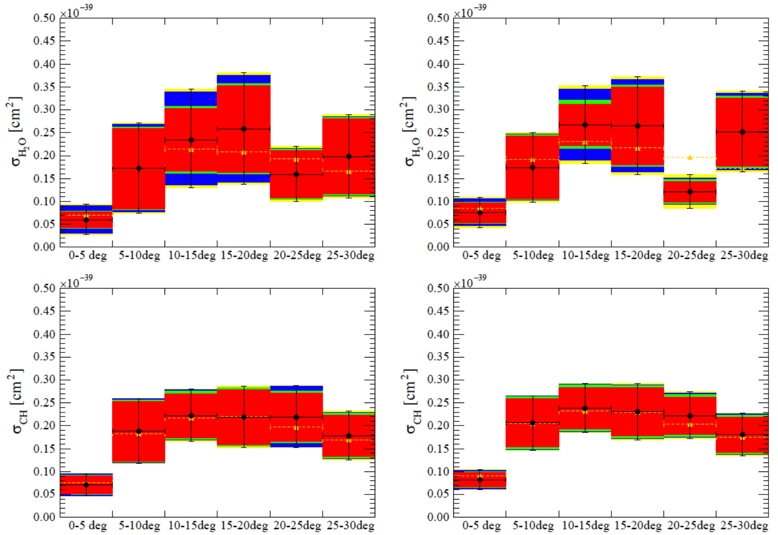
WAGASCI,PTEP(2019)093C02
NINJA, PTEP2021(033C01)

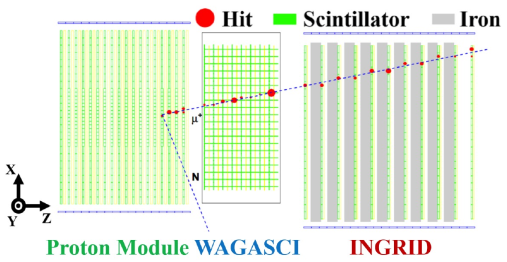
5. T2K near detector complex



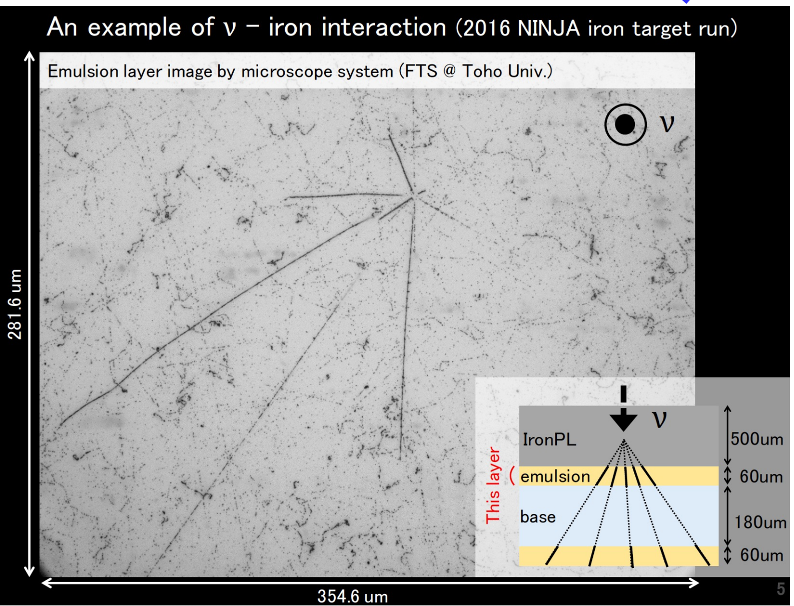
WAGASCI
- water target

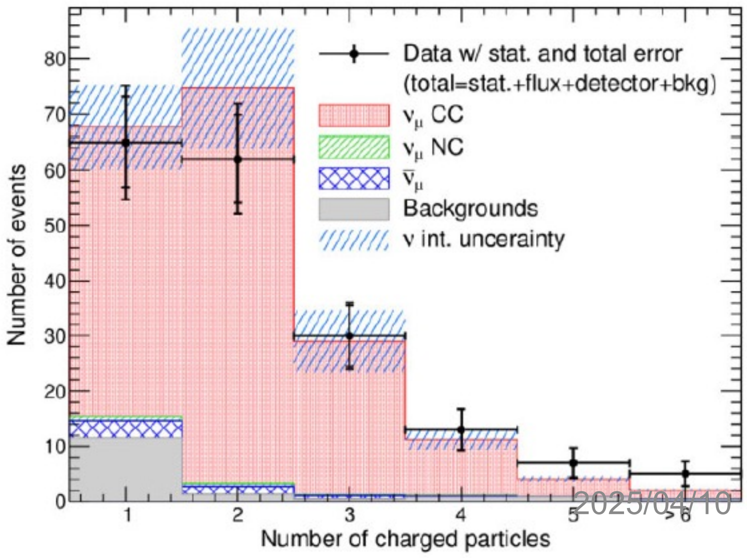




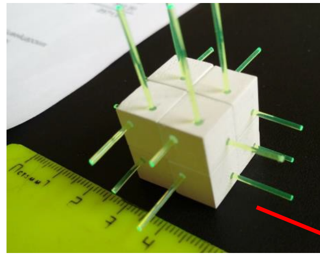


NINJA
- emulsion detector
- Multiple hadron tracks

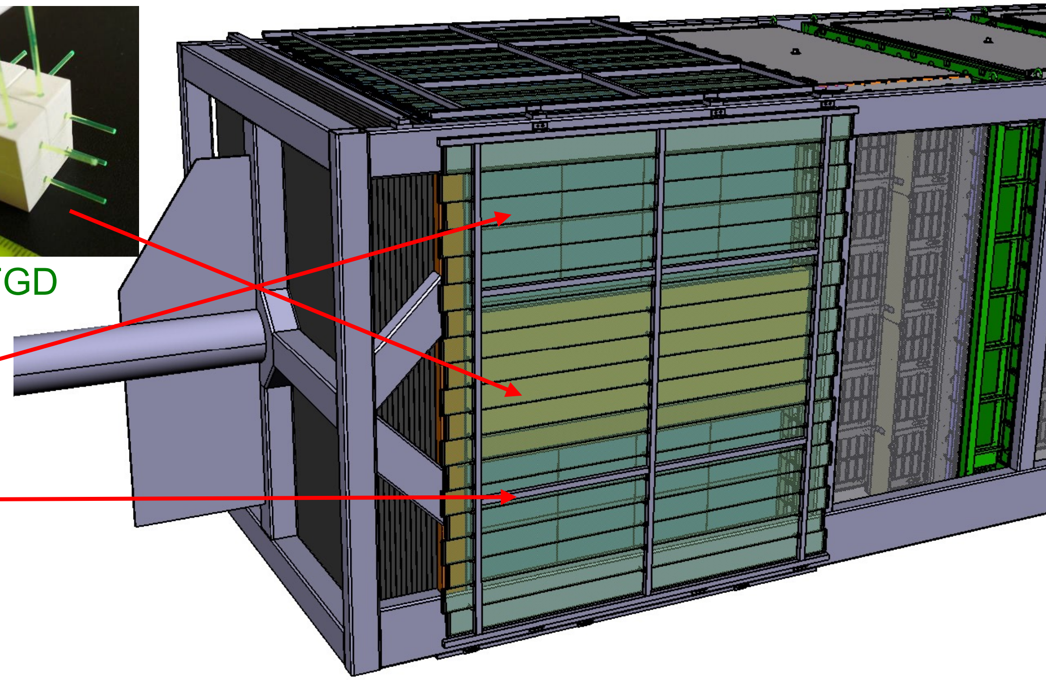




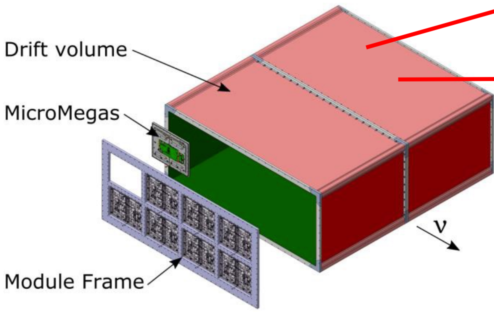
5. ND280 Upgrade



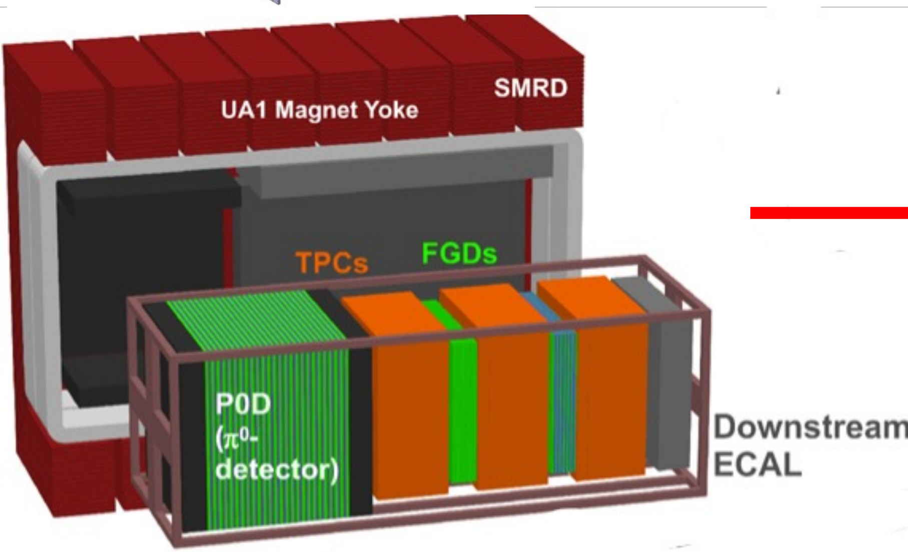
SuperFGD

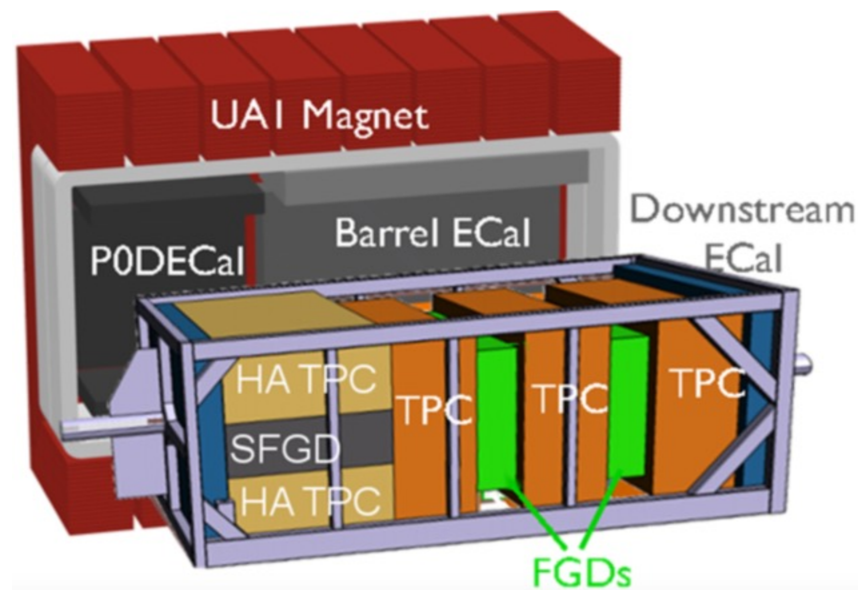


ND280 Upgrade
- Out: P0D detector
- In: High Angle TPC (HATPC)
- In: SuperFGD



High Angle TPC



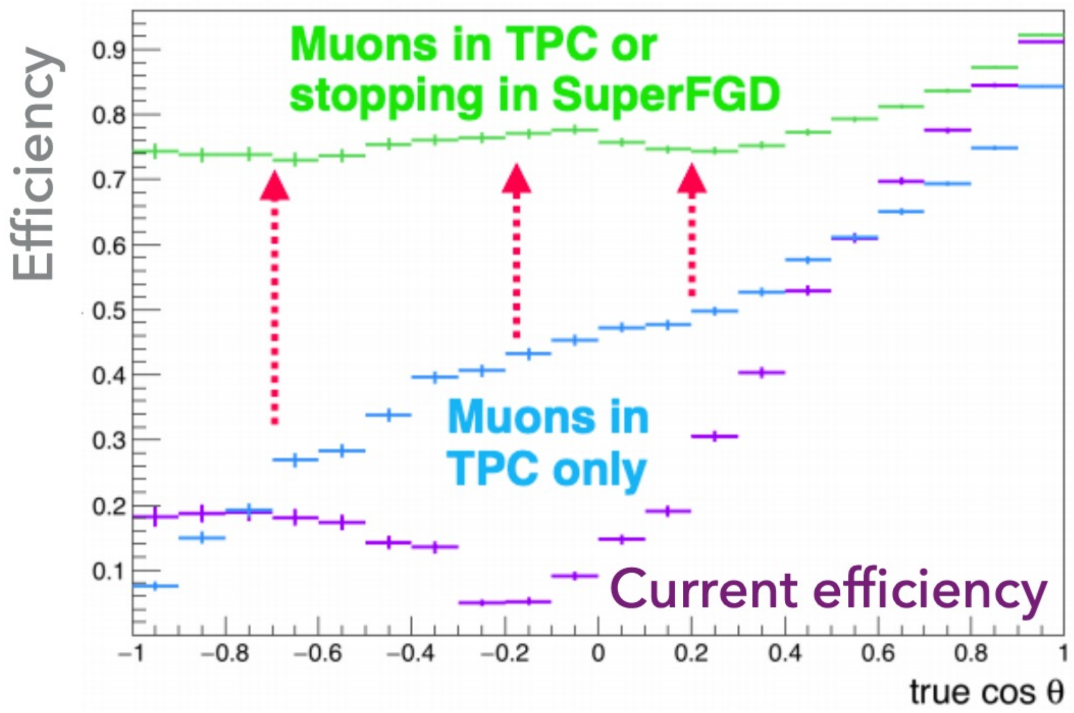


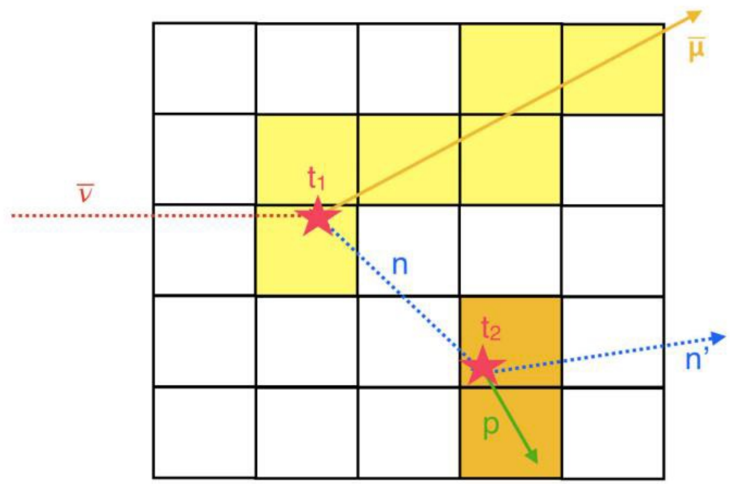
5. ND280 Upgrade

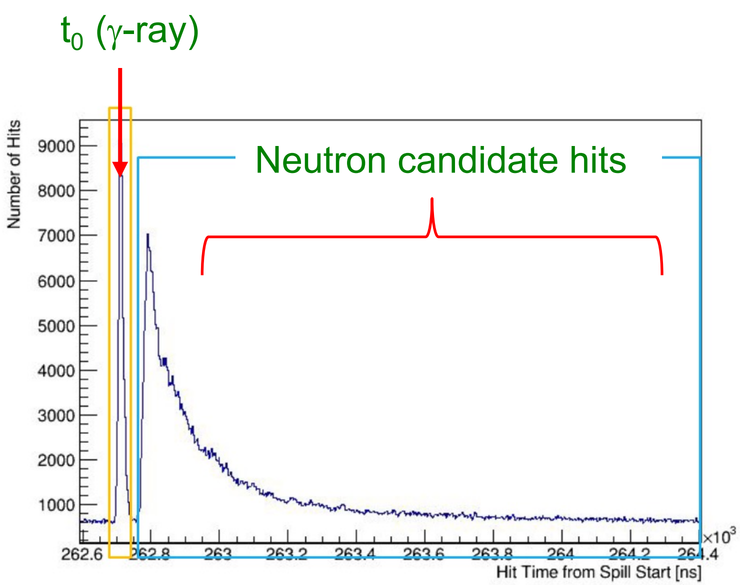
ND280 Upgrade
- Out: P0D detector
- In: High Angle TPC (HATPC)
- In: SuperFGD

4π coverage
- It matches with Hyper-K phase space

Neutron tagging
- SuperFGD beam test at LANL
- ToF to measure energy

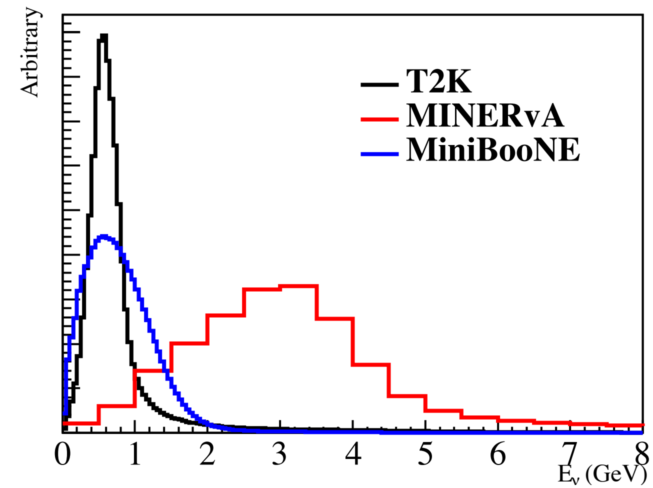


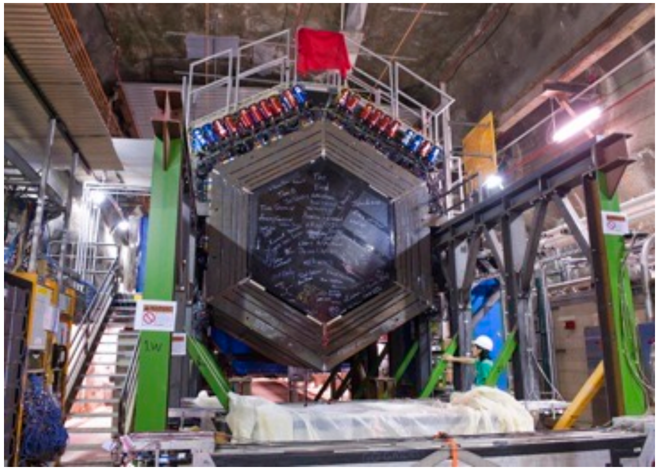


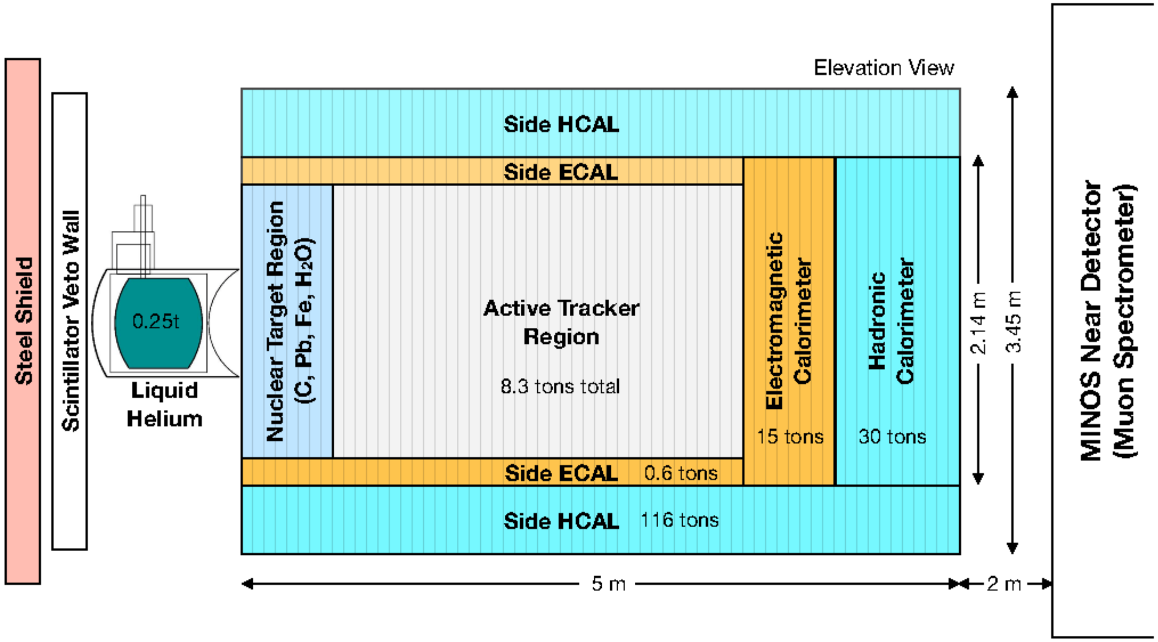


5. MINERvA

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)







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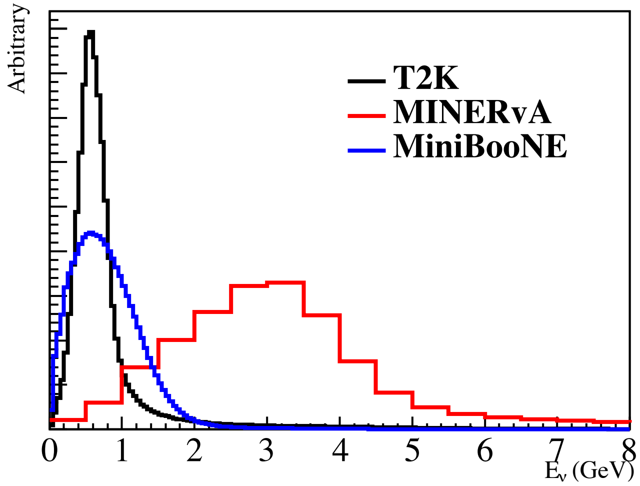

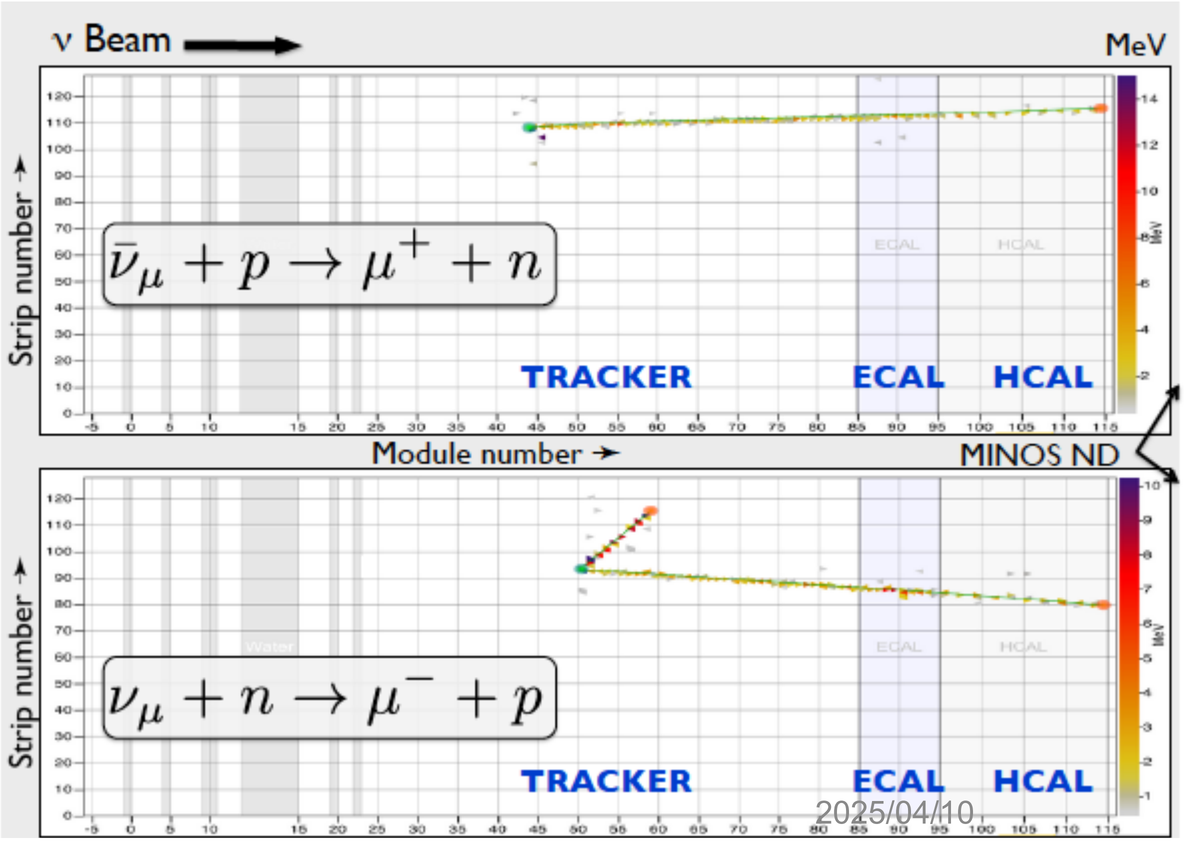

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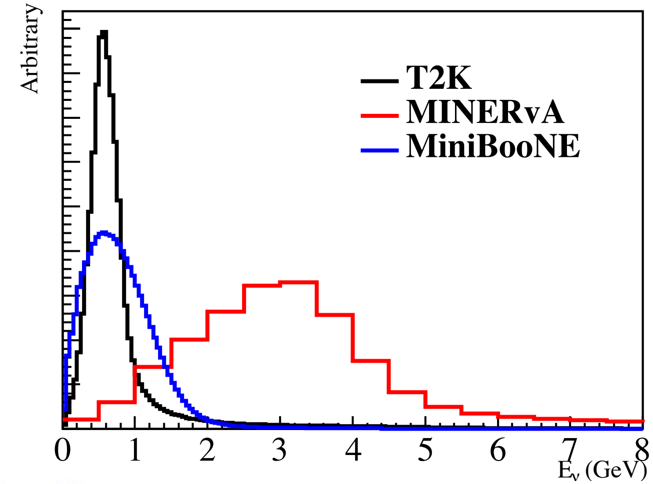

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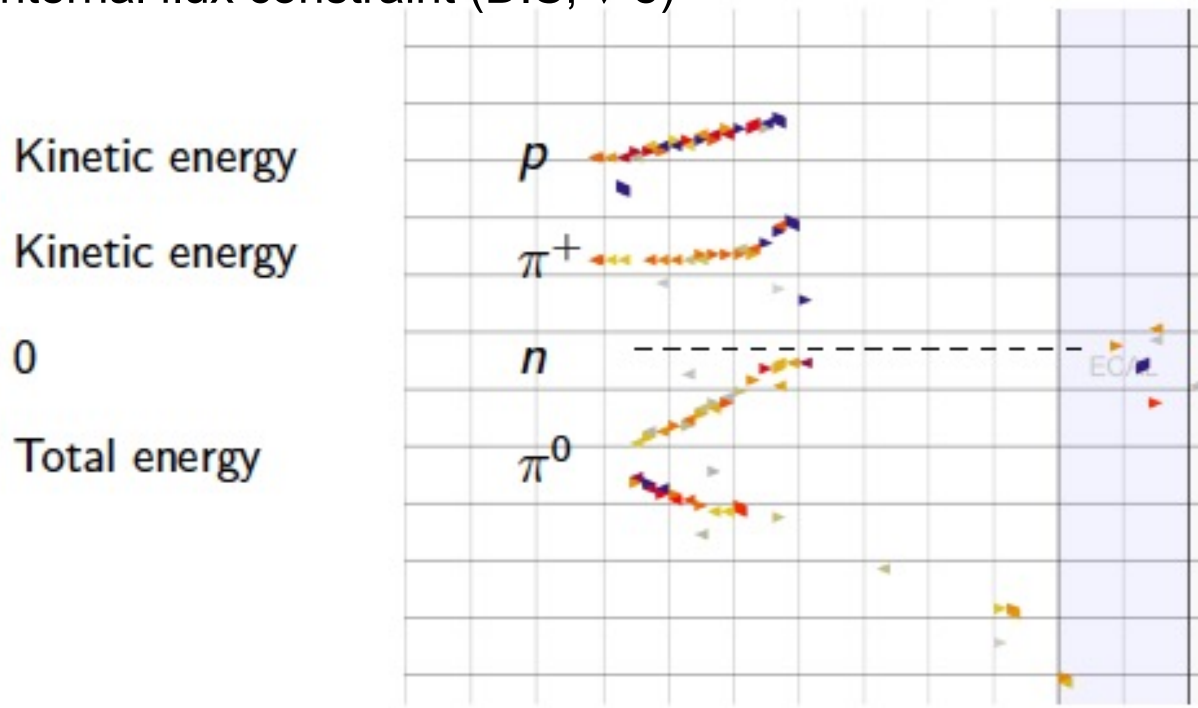


Beam test + better scintillator
→ good hadron measurement
→ kinematics is completely fixed

model-dependent

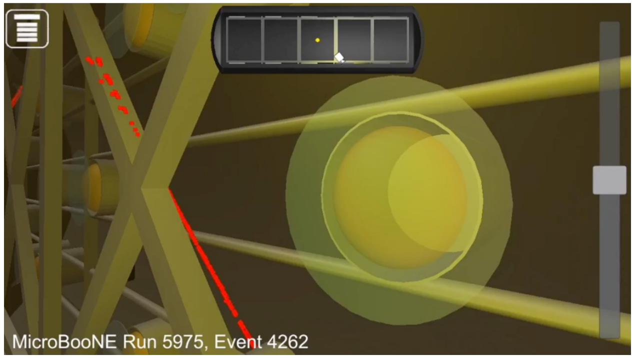
visible hadron energy
↓
total hadron energy
↓
Eν
↓
Q2

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

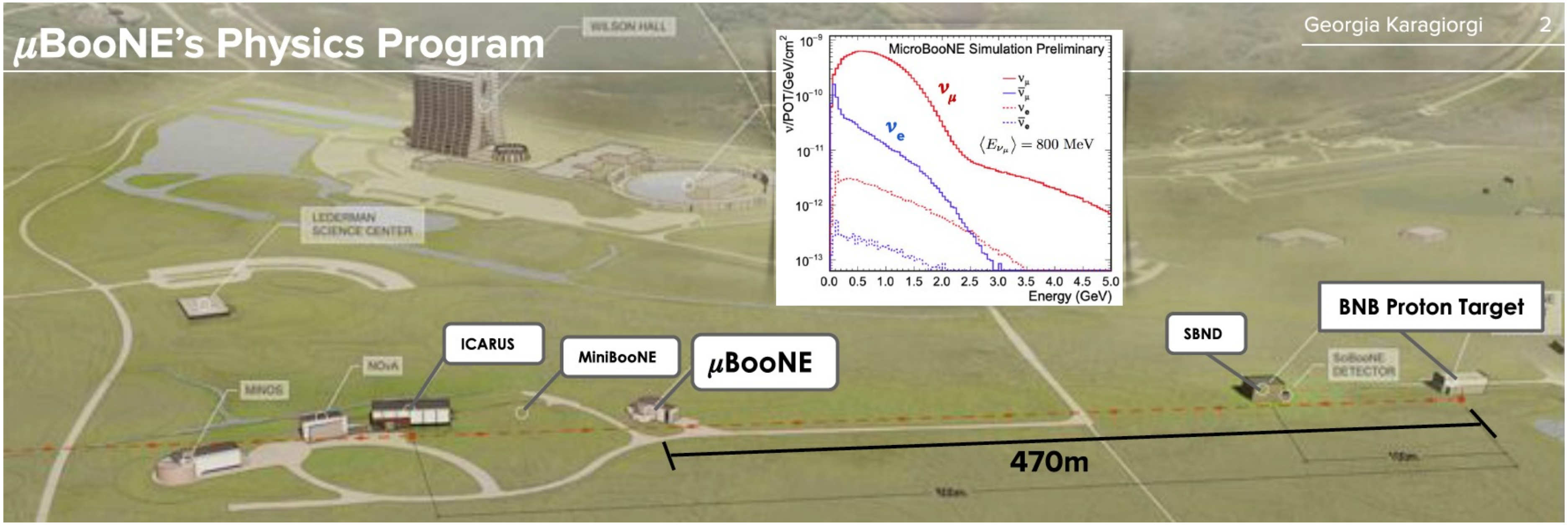
$$E_{avail} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

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

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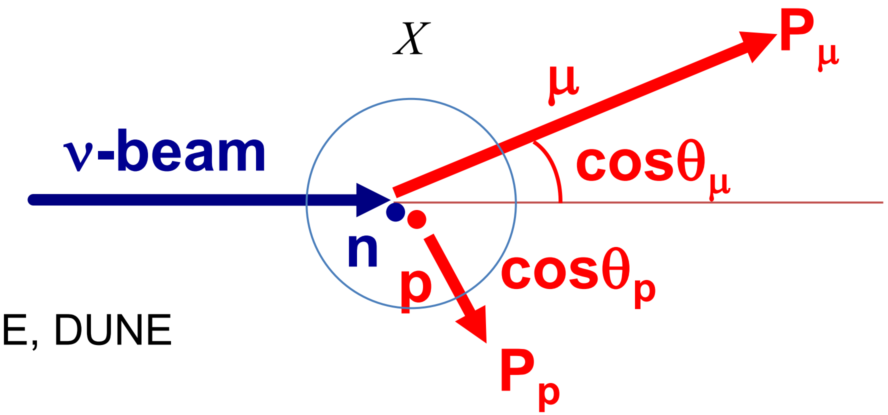

MicroBooNE CC mu+p differential cross section

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