Nuclear Physics for Beyond the Standard Model Neutrino Physics

outline

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

Teppei Katori @teppeikatori
King's College London
Genova HEP seminar, University of Genova, May 3, 2023

All anomalies in particle physics are Strong interaction

1. Neutrino interaction physics - introduction

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

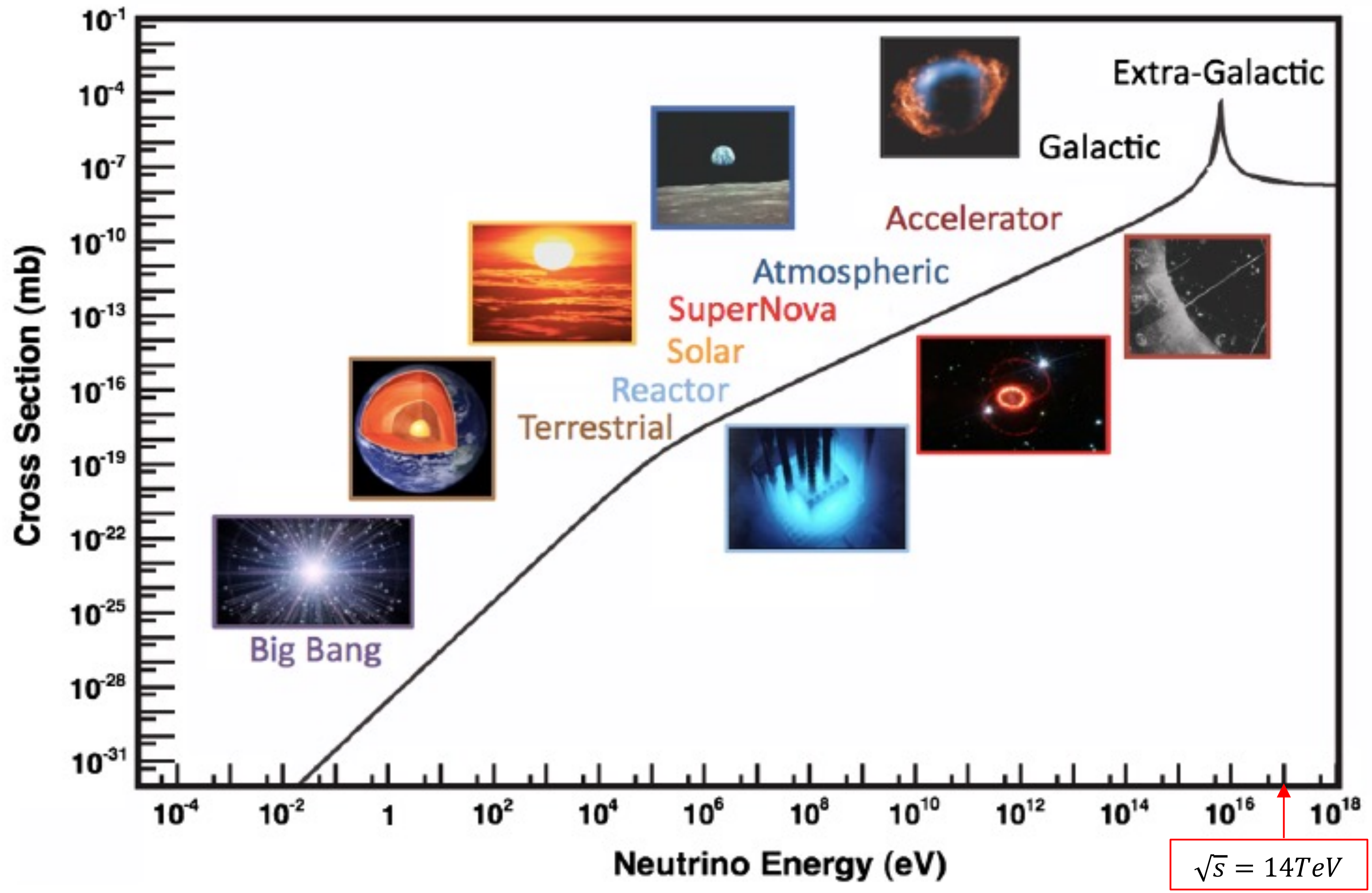
3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

5. Conclusions

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

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



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

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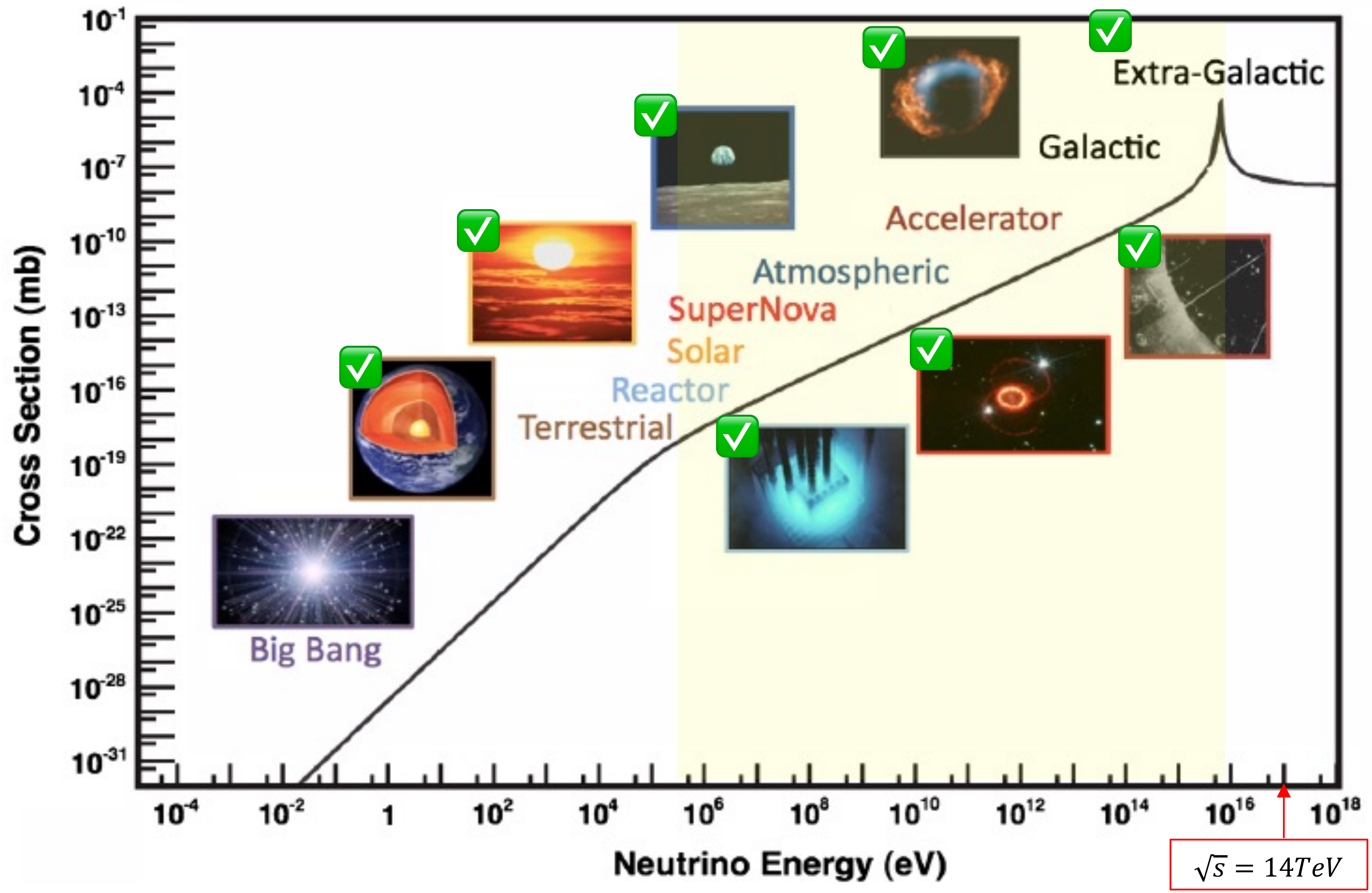

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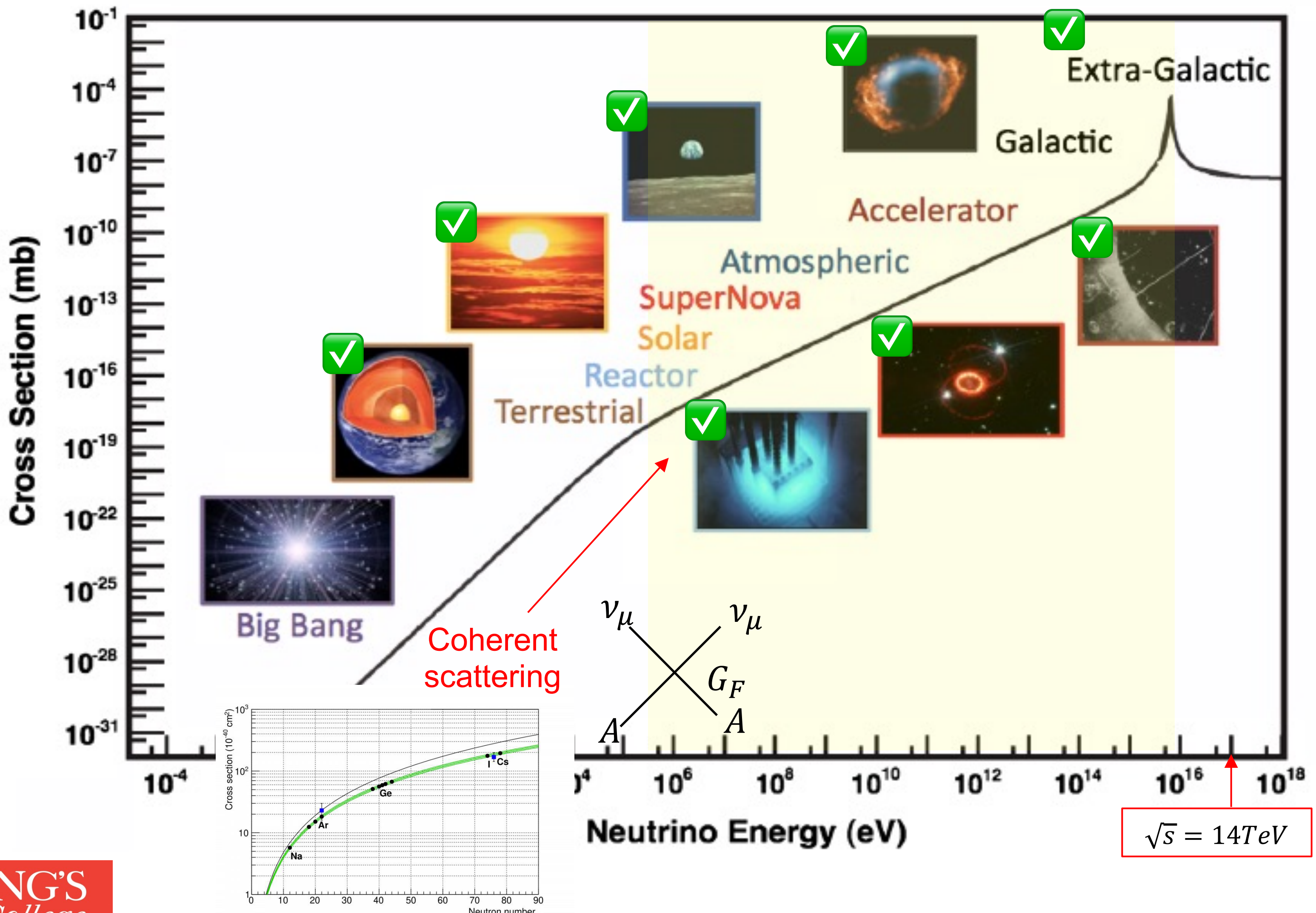

COHERENT, Science357(2017)1123
PRL126(2021)012002

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

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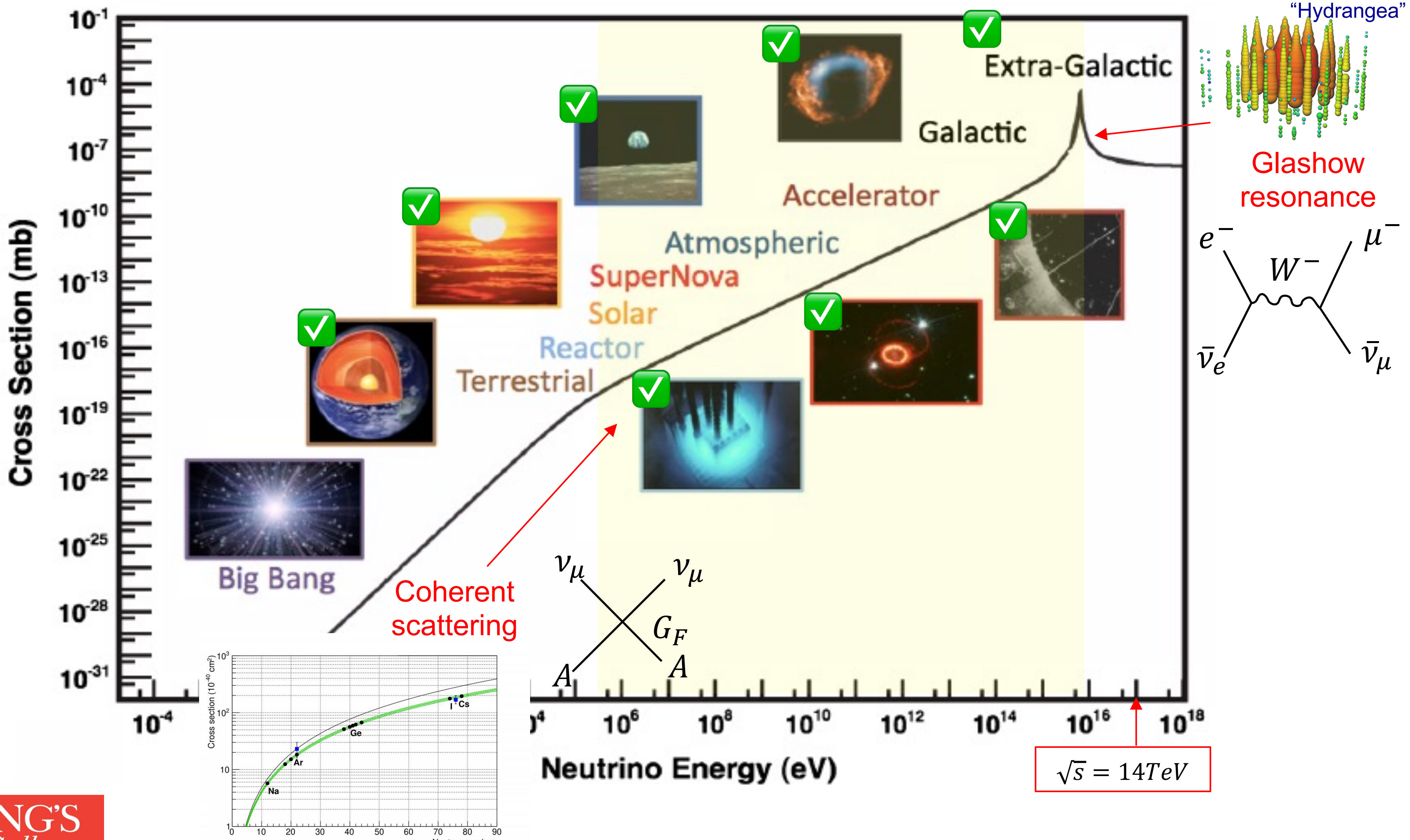
IceCube, Nature591(2021)220



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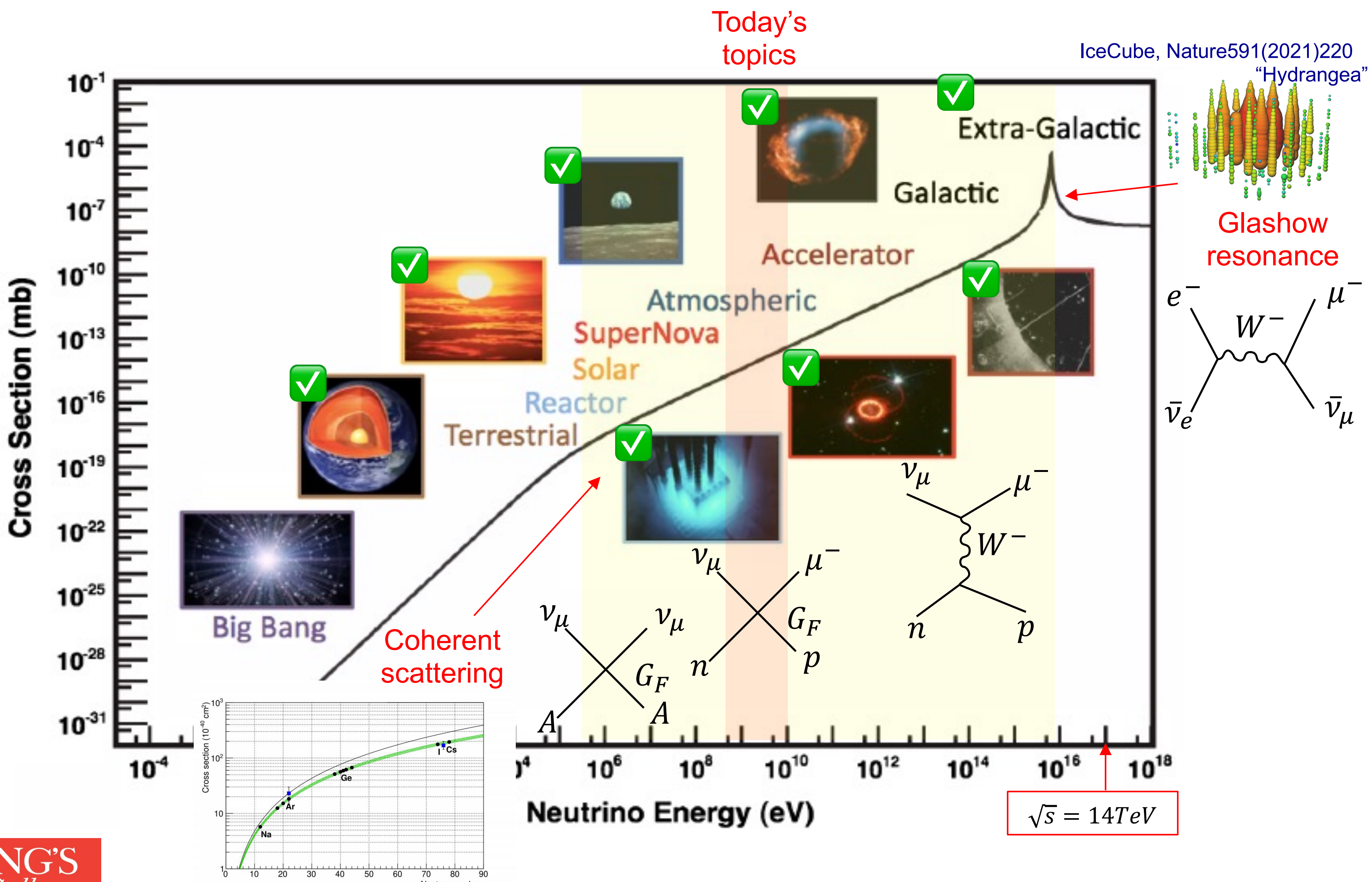

COHERENT, Science357(2017)1123
PRL126(2021)012002

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

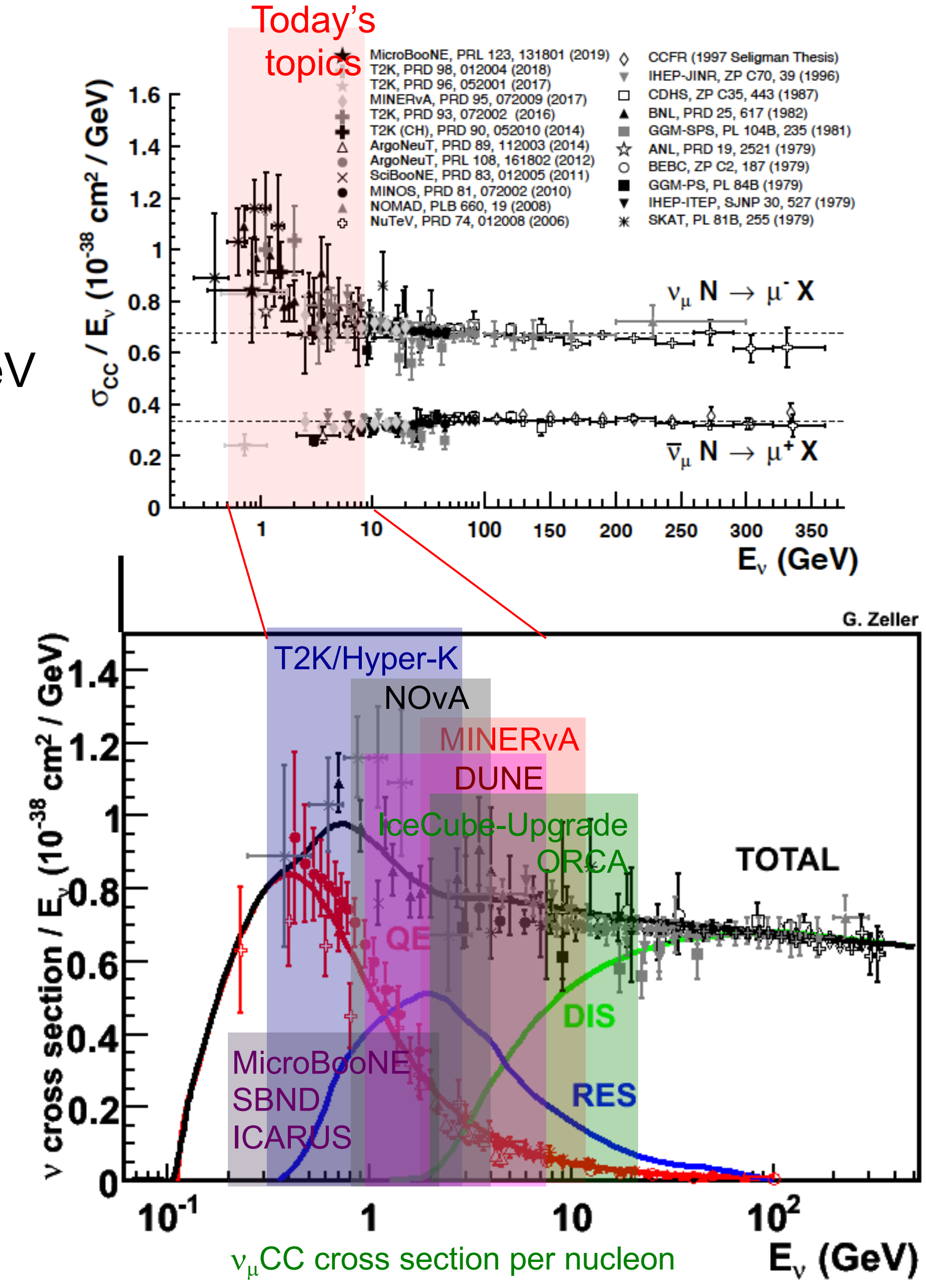

Table 52.2: Published measurements of neutrino and antineutrino CC inclusive cross sections from modern accelerator-based neutrino experiments.

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

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1. Neutrino interaction physics around 1-10 GeV

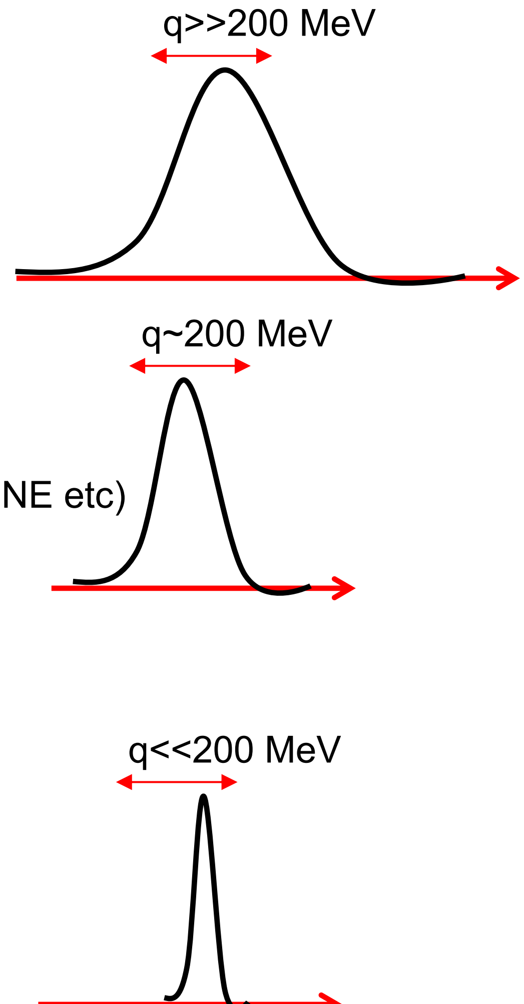
Size of wave packet ~ momentum transfer (~energy)

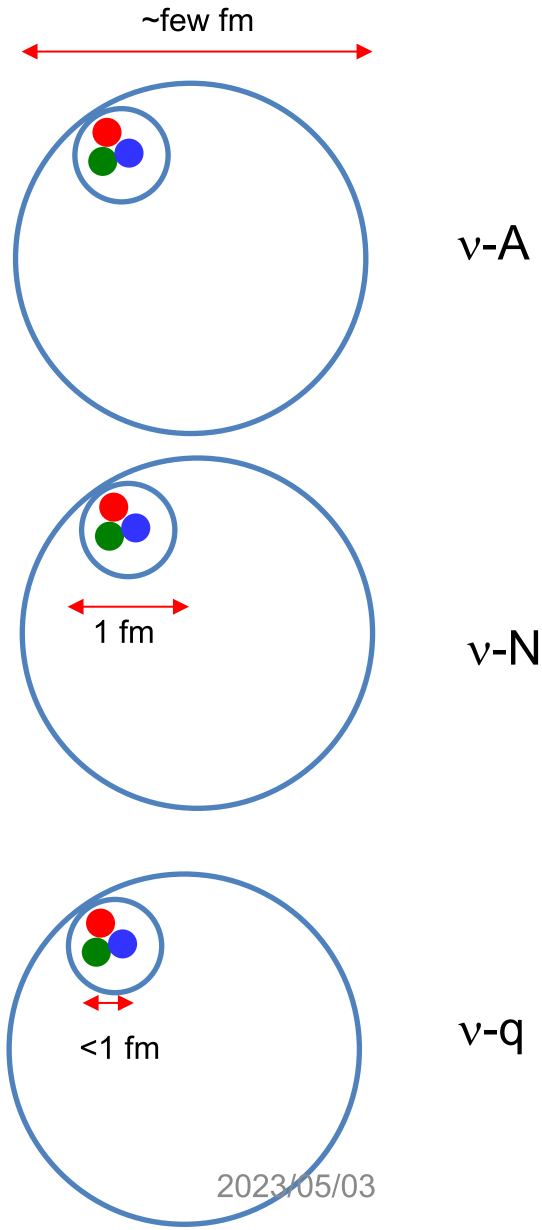
$\hbar c = 197\ MeV \cdot fm \rightarrow$ 200 MeV ~ 1 fm (size of nucleon)

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

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

>>1 GeV neutrino beam
(LHC, astrophysical)



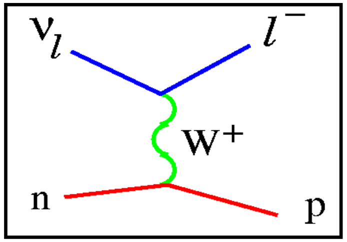


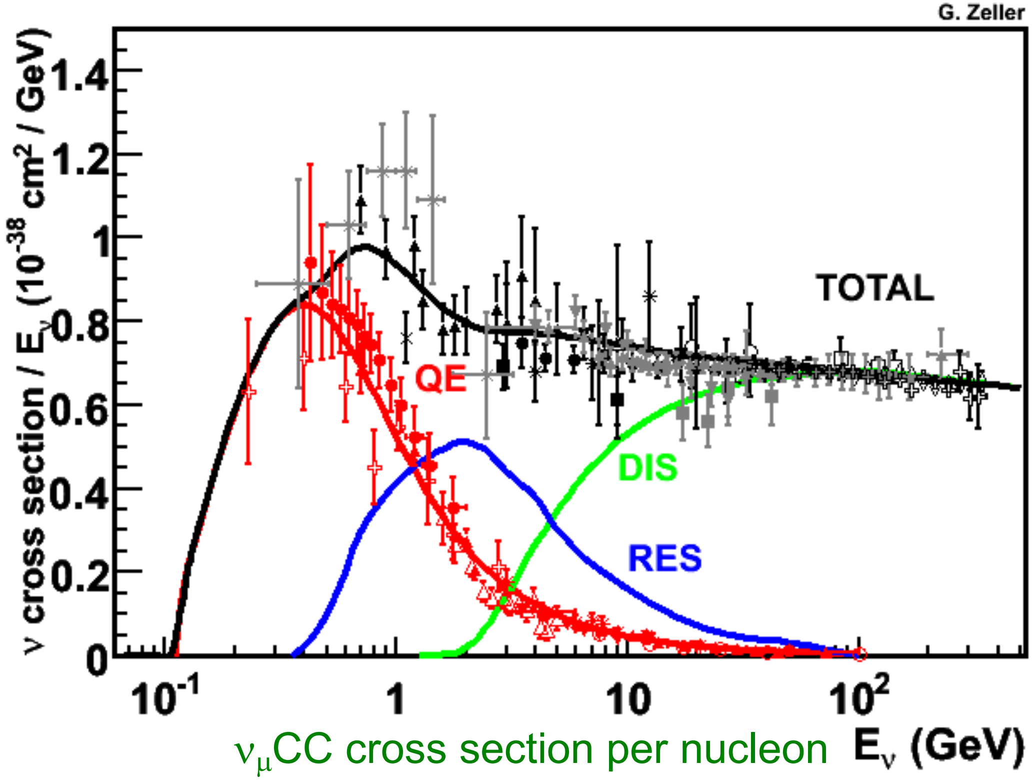
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

1. Neutrino interaction physics around 1-10 GeV

Neutrino interaction physics around 1-10 GeV
- degree of freedom change from nucleus → nucleon → parton
- There is no cut off (they all interfere)

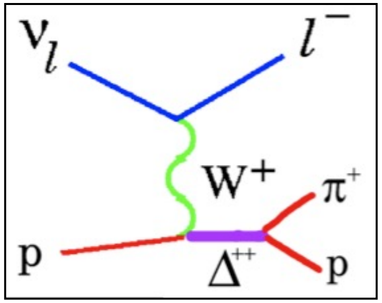
Quasi Elastic (QE)

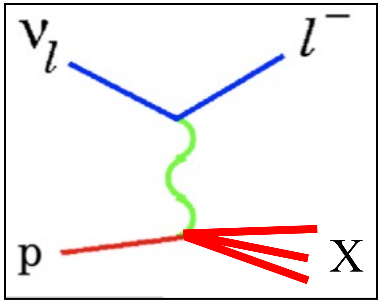




ν_μCC cross section per nucleon

baryonic RESonance





Deep Inelastic Scattering (DIS)

1. Next goal of high energy physics

Establish Neutrino Standard Model (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.

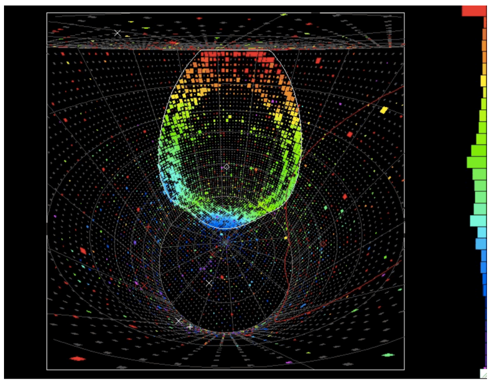
Low energy beam (~1 GeV)
- shorter baseline (lower flux reduction)
- lower neutrino production
- lower interaction rate
- kinematic energy reconstruction

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

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

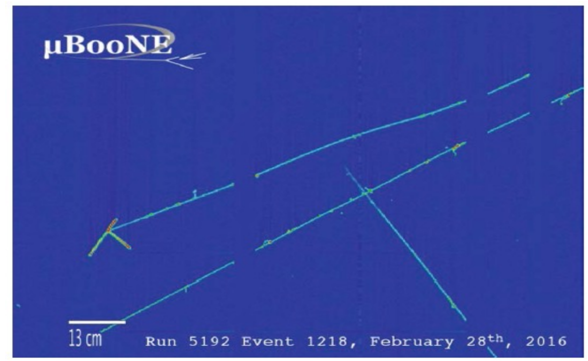
1. Next goal of high energy physics

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



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

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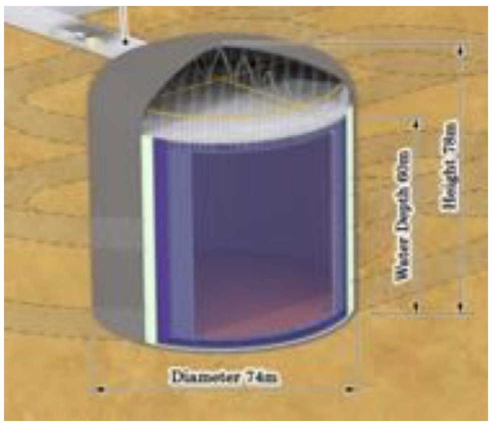
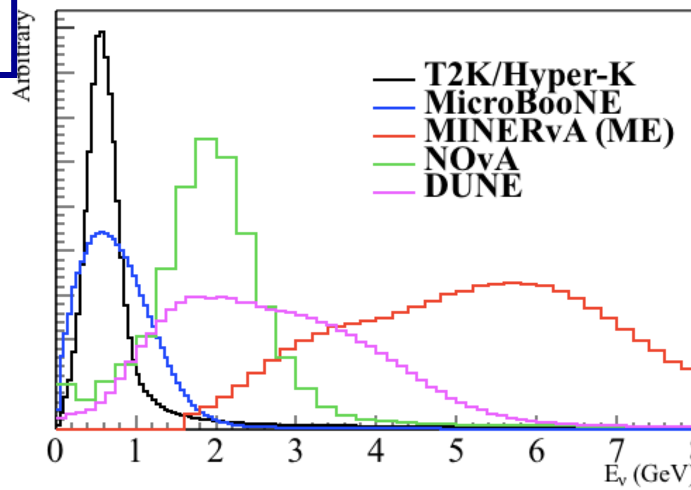
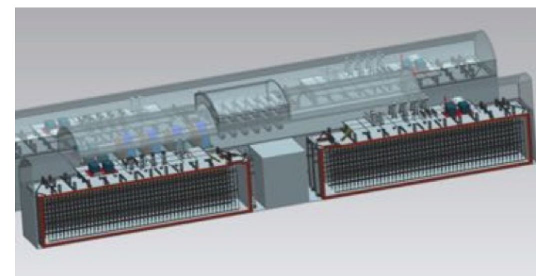
1. Next goal of high energy physics

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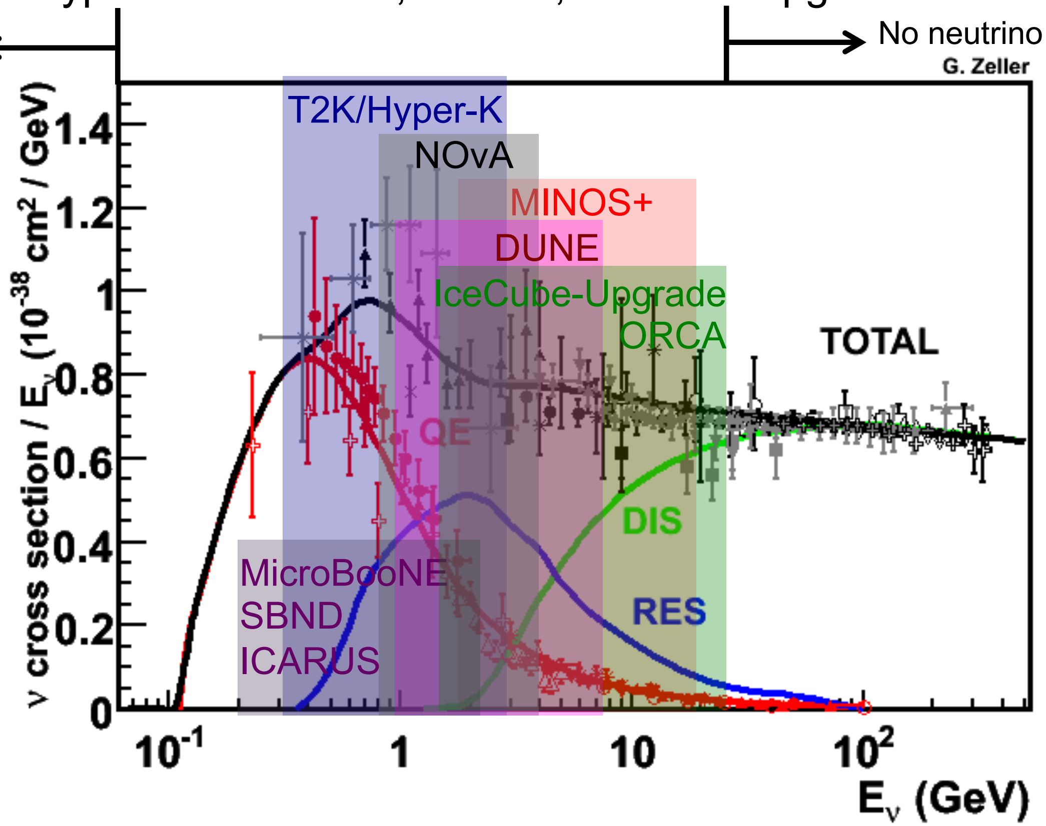
Formaggio and Zeller, Rev.Mod.Phys.84(2012)1307

1. Next generation neutrino oscillation experiments

Current and future neutrino oscillation experiments

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

Reactor and Solar neutrino oscillation



Neutrino oscillation length reaches ~12700km (diameter of Earth)

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

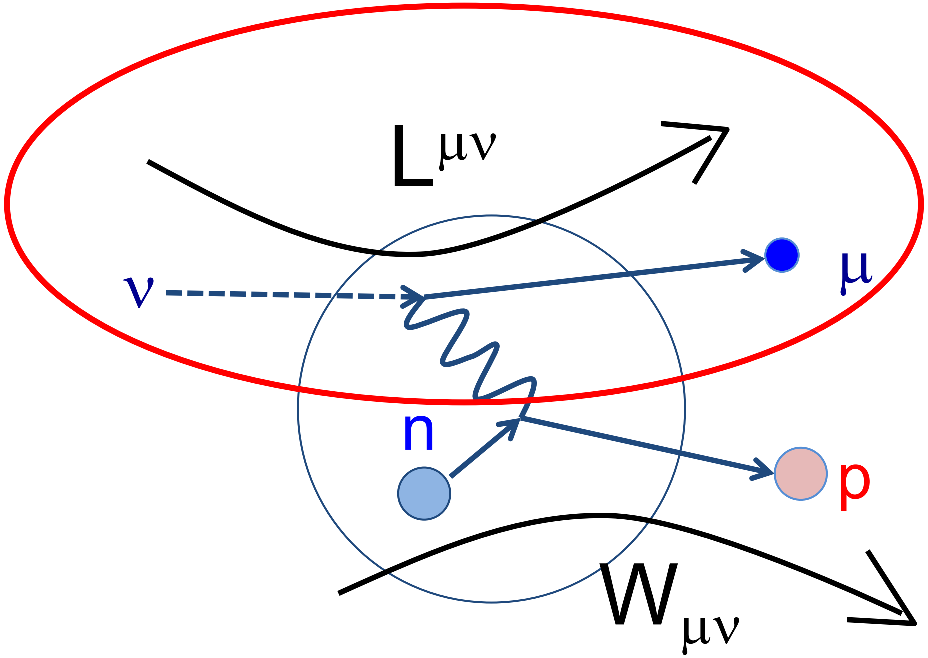
1. Neutrino cross-section formula

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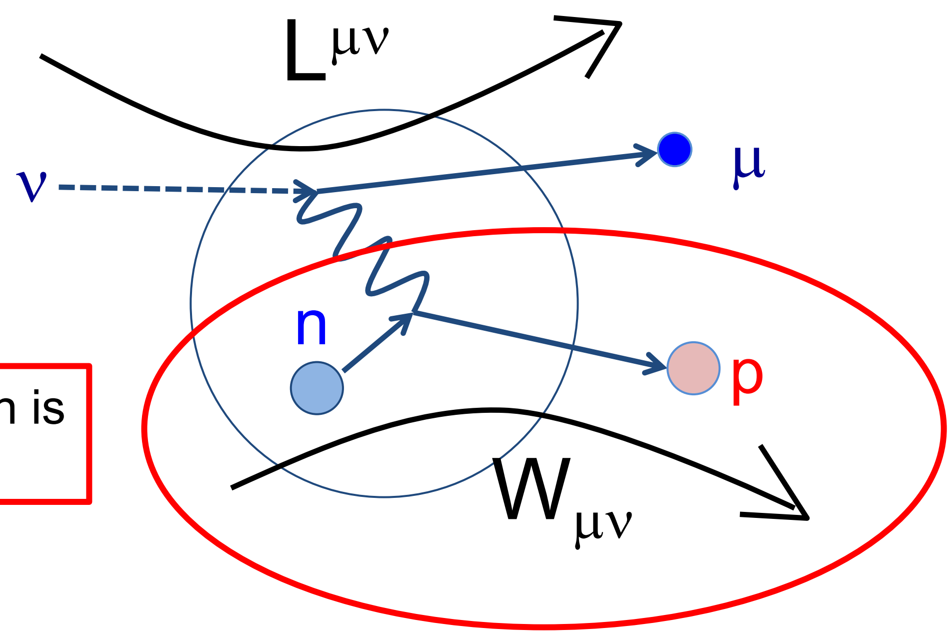
All complication of neutrino cross-section is how to model the hadronic tensor part



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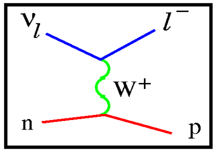
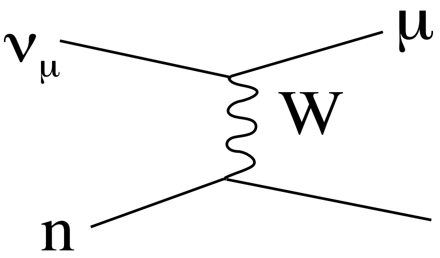
Quasi Elastic



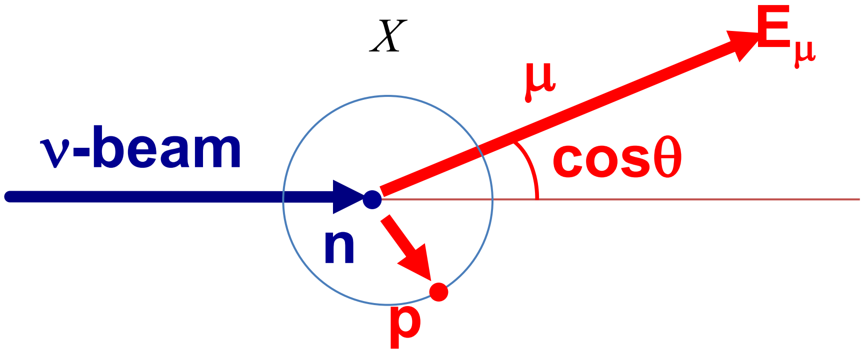
2. Charged Current Quasi-Elastic scattering (CCQE)

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

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



Neutrino energy is reconstructed from the observed lepton kinematics
"QE assumption"
1. assuming neutron at rest
2. assuming interaction is CCQE

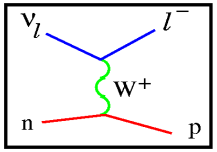


$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

2. CCQE puzzle

Quasi Elastic

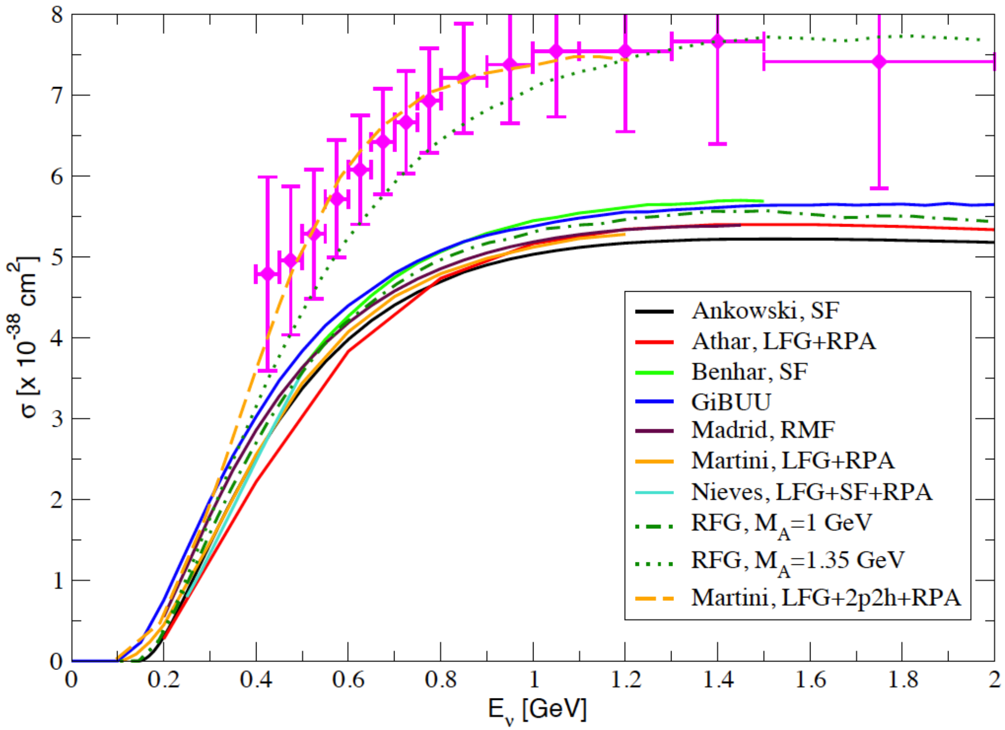


Simplest channel, but both shape and normalization disagree

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

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

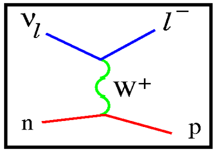
MiniBooNE ν_μCCQE cross section on ^{12}C target (per nucleon)



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

2. Solution of CCQE puzzle

Quasi Elastic

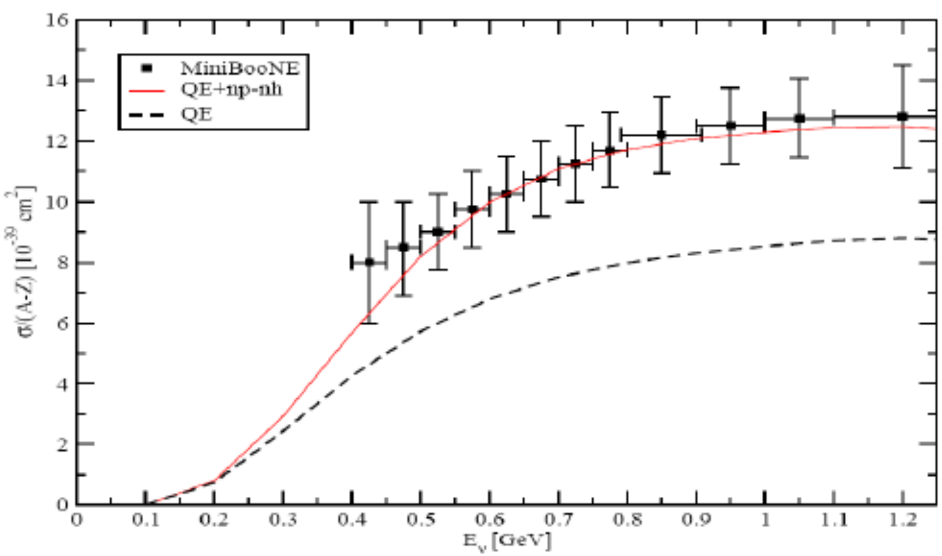


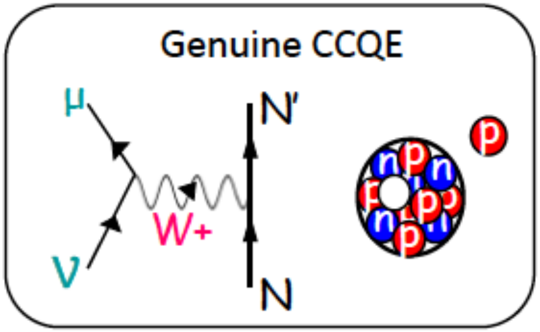
Presence of 2-body current

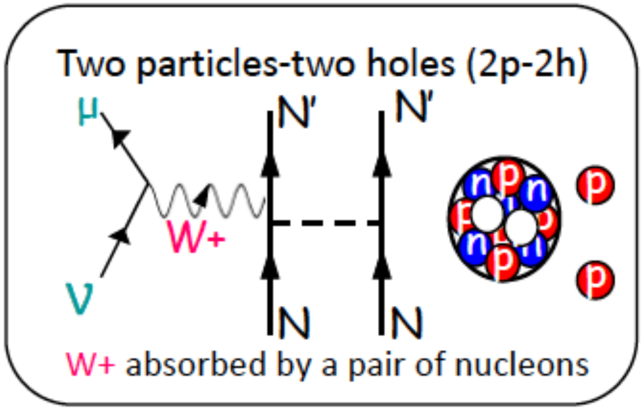
- CCQE is identified from single outgoing charged lepton events
- Significant fraction of events are not from 2-body neutrino-nucleon interactions
- Martini et al showed 2p-2h effect can add up ~30% more cross section

An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)







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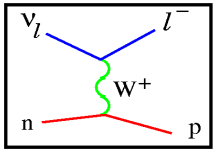
Quasi Elastic



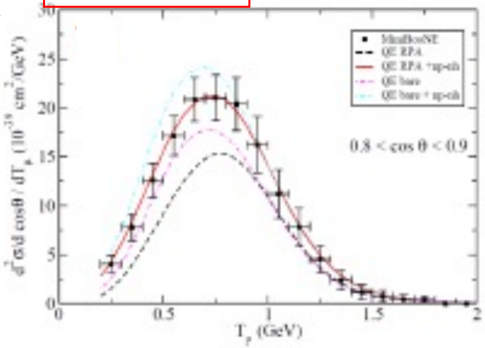
2. Models using 2p-2h

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

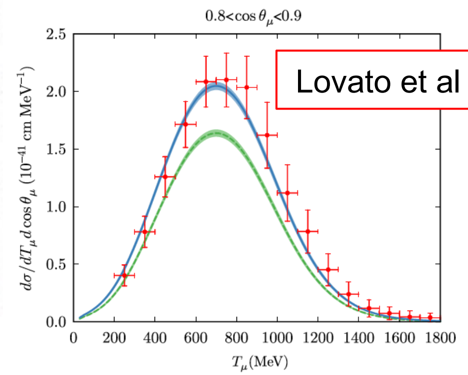
Martini et al – Lyon 2p2ph model
Nieves et al – Valencia 2p2h model
SuSAv2 – Superscaling+MEC
Giusti et al – Relativistic Green's function
Butkevich et al – RDWIA+MEC
Lovato et al – GFMC
Jachowicz et al – CRPA+MEC

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

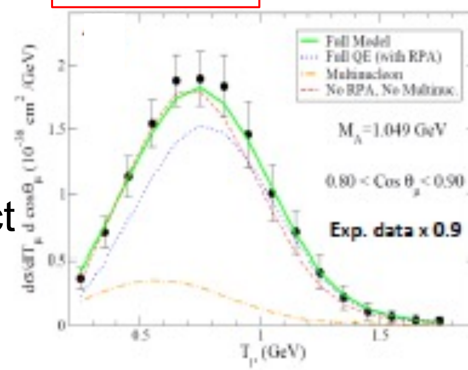
Martini et al



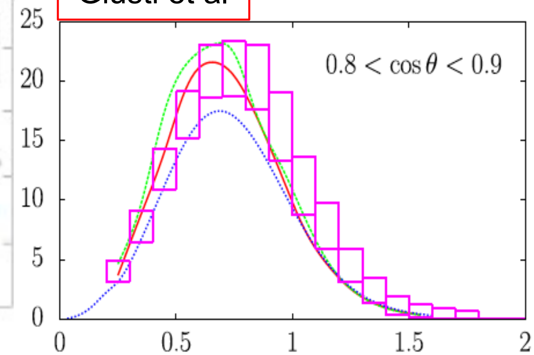
Lovato et al



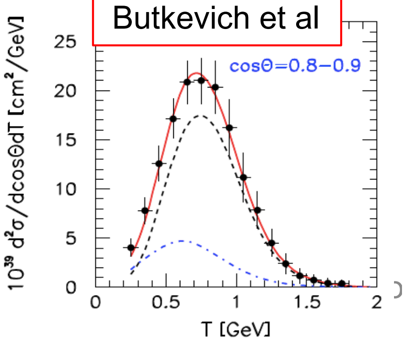
Nieves et al



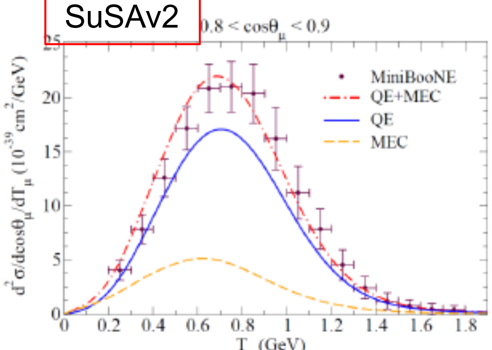
Giusti et al



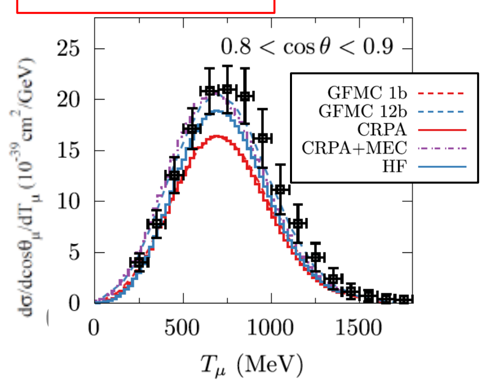
Butkevich et al



SuSAv2



Jachowicz et al



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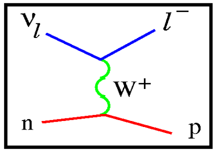
Wiringa et al, PRC51(1997)38, Pieper et al, PRC64(2001)014001
Lovato et al,PRX10(2020)031068 (2020)

2. Nucleon correlations in neutrino physics

Quasi Elastic



Ab-initio calculation

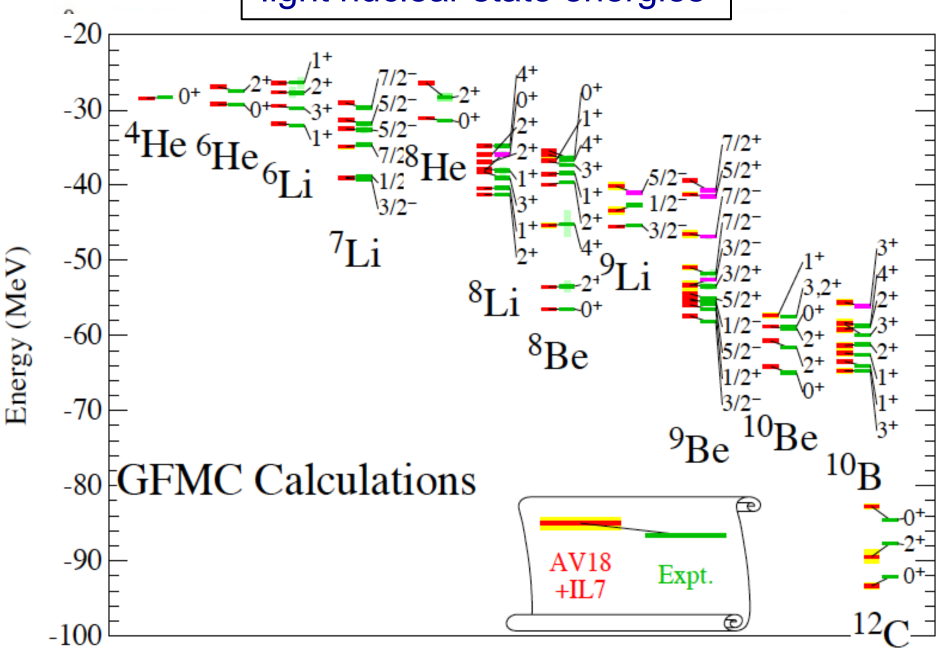
- Quantum Monte Carlo (QMC)
- Predicts energy levels of all light nuclei
- Consistent result with phenomenological models
- Ground state includes correct nucleon correlations

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

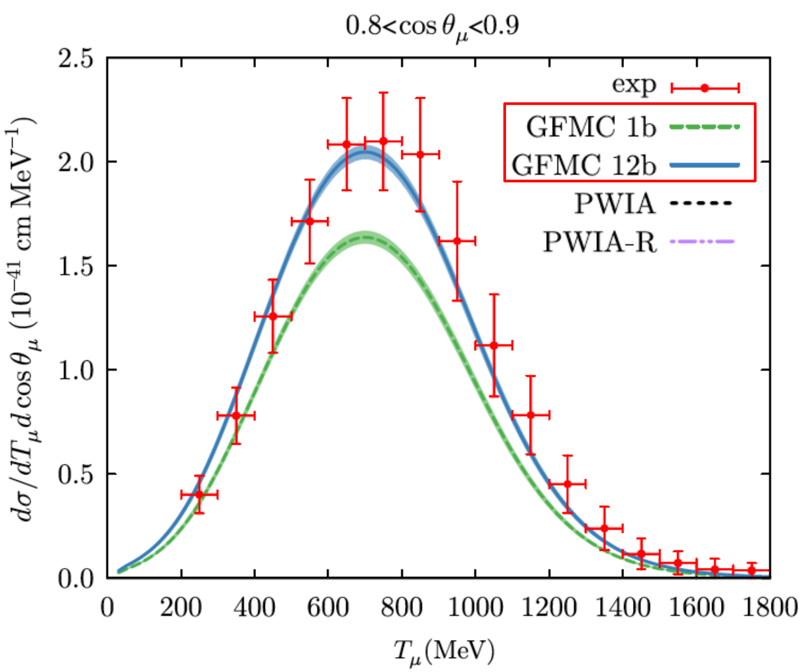
2N potential (Av18)

3N potential (IL7)

light nuclear state energies



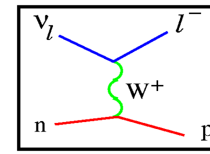
MiniBooNE CCQE cross-section



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

2. Nucleon correlations in neutrino physics

Quasi Elastic



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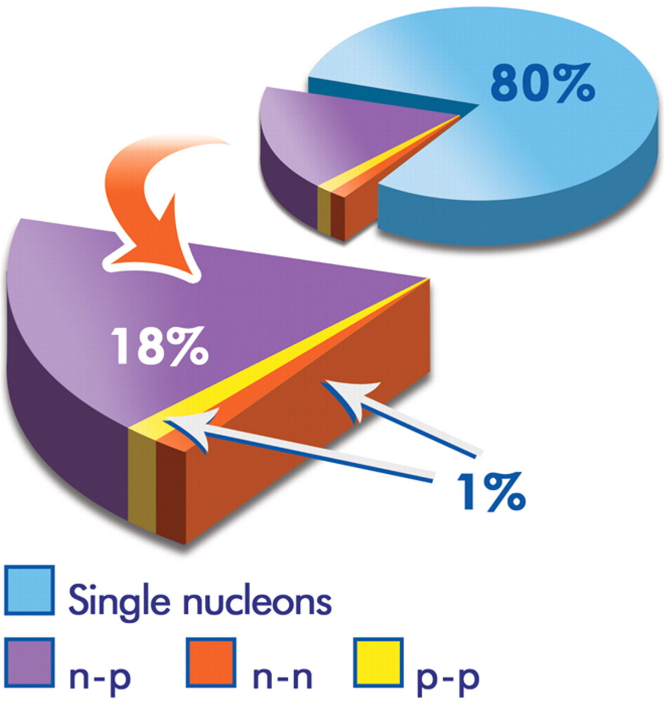
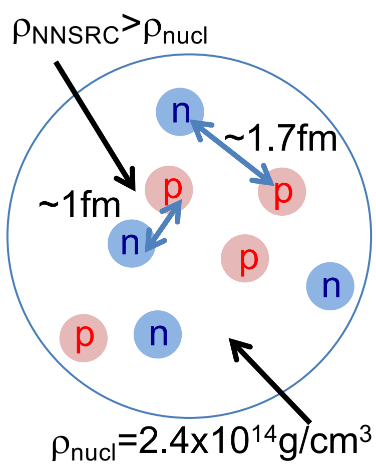




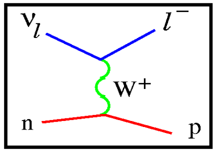
Physics of nucleon correlation

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

Nucleon correlation is a very hot topics!

NOvA, EPJC80,1119(2020)

Quasi Elastic

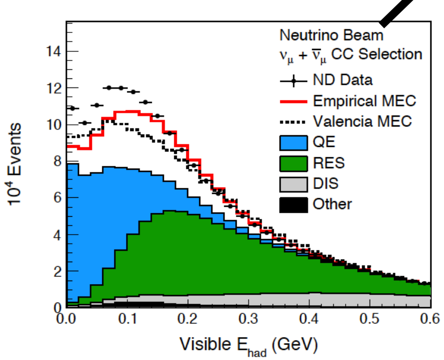


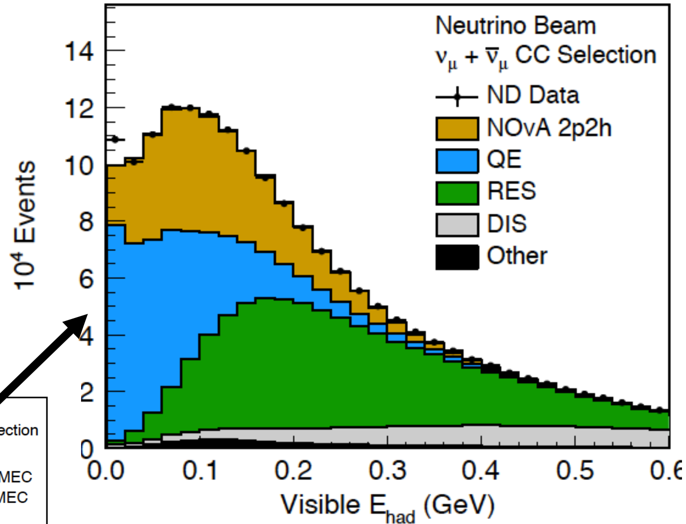
2. Nucleon correlations in neutrino physics

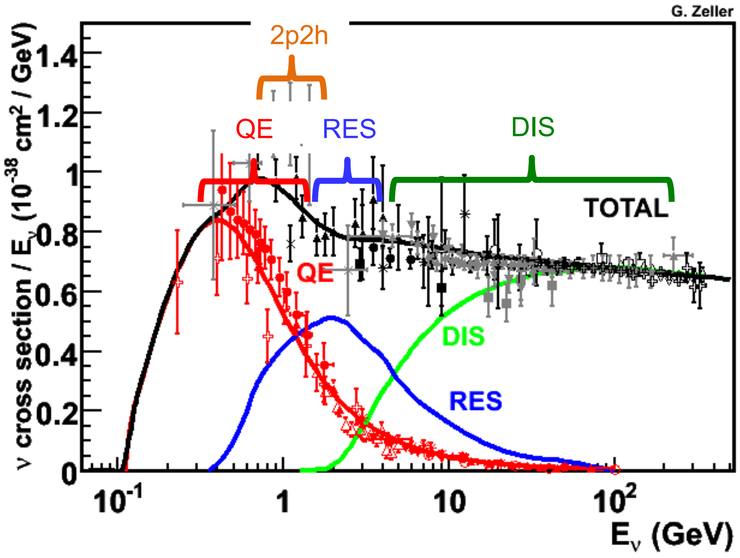
2-particle 2-hole (2p2h) effect

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

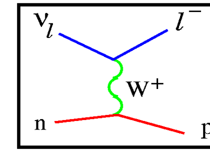
NOvA near detector data-MC comparison after fit







Quasi Elastic

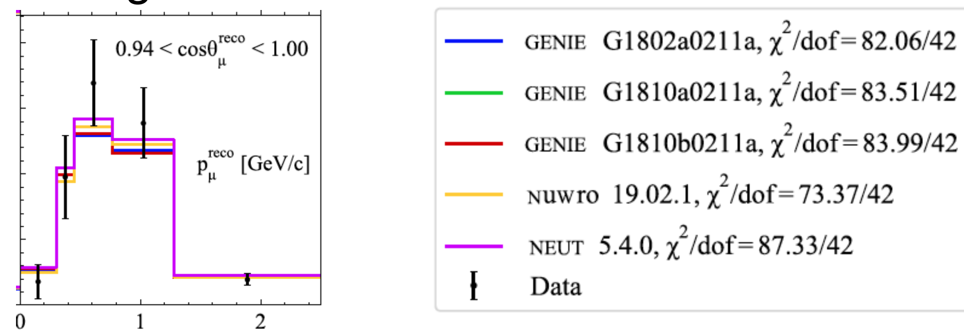


2. Data tension

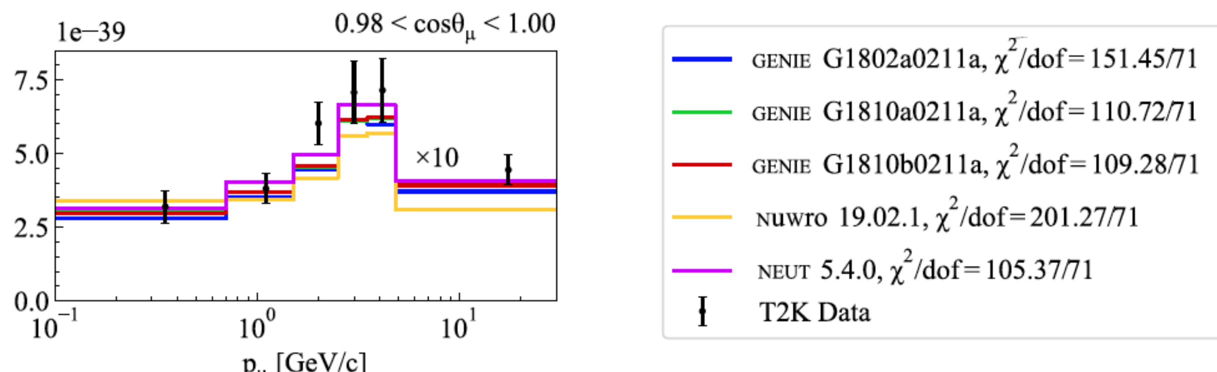
Data tension – external: T2K vs. MINERvA vs. MicroBooNE

- Different kinematic coverage, different target

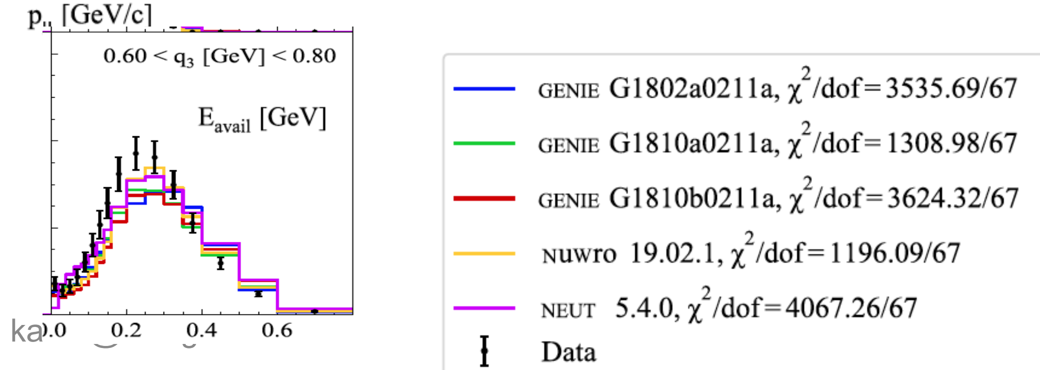
MicroBooNE CC inclusive double differential cross-section



T2K CC inclusive double differential cross-section



MINERvA CC inclusive double differential cross-section



KING'S College LONDON

1. Neutrino interaction physics - introduction

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

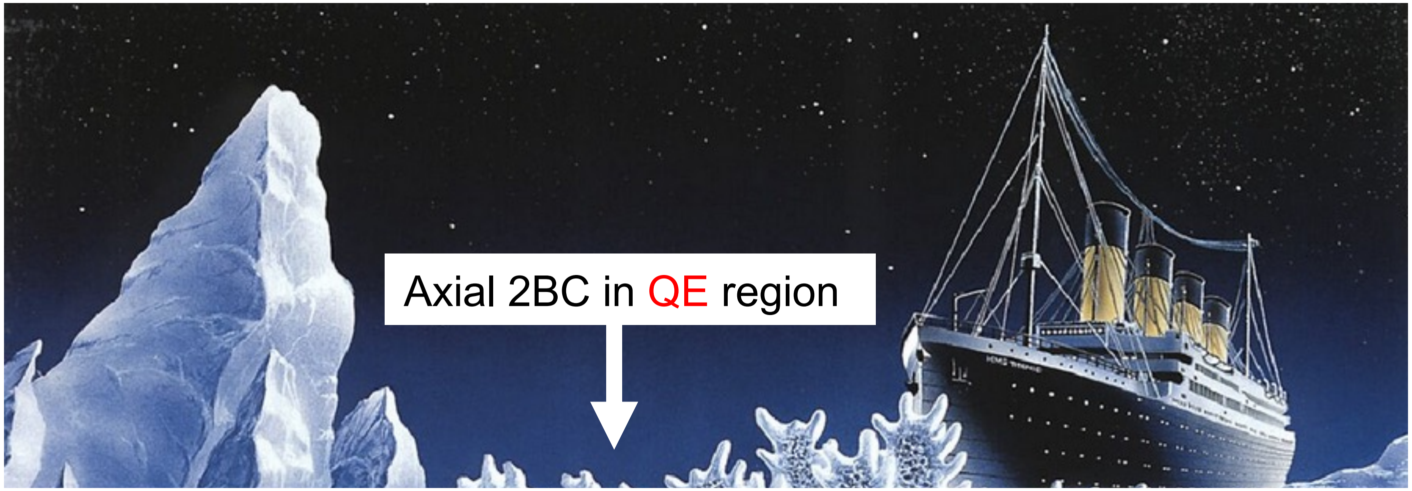
3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

5. Conclusions

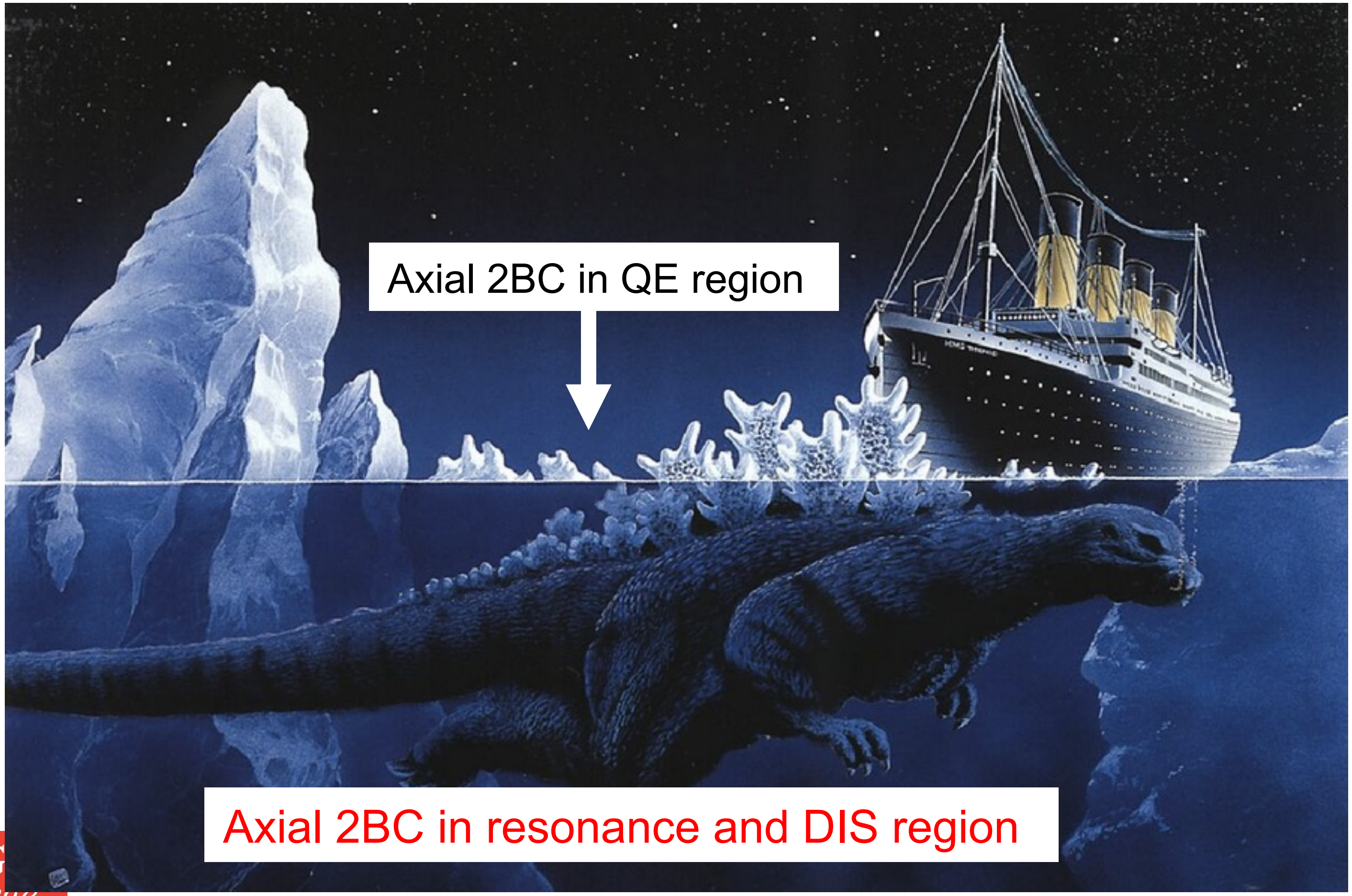
3. Beyond QE peak

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



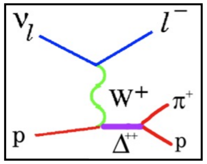
3. Beyond QE peak

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

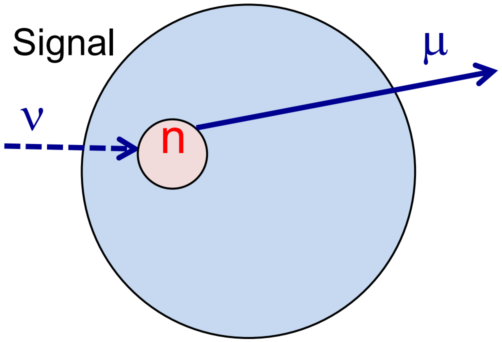


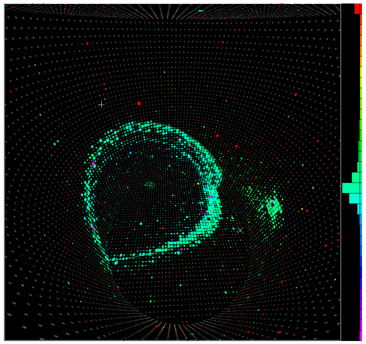
3. non-QE background (resonance pion production)

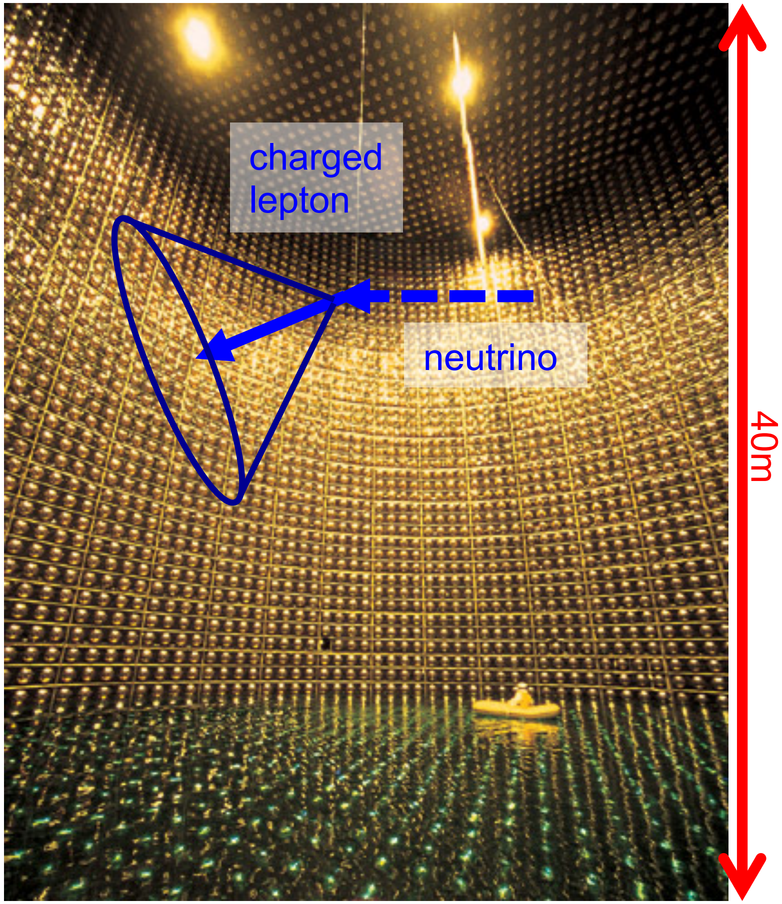
RESonance



non-QE background → shift spectrum





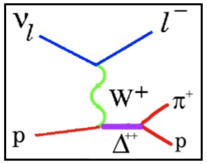


Typical neutrino oscillation detector
- Big and dense, to maximize interaction rate
- Coarsely instrumented, to minimize cost

(not great detector to measure hadrons)

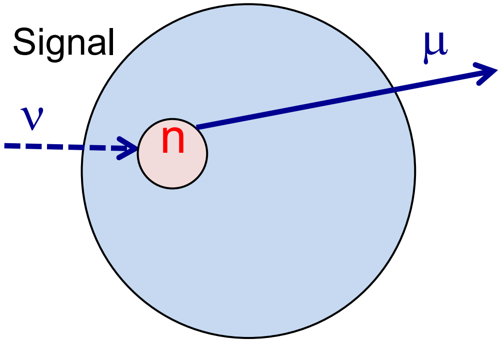
3. non-QE background (resonance pion production)

RESonance

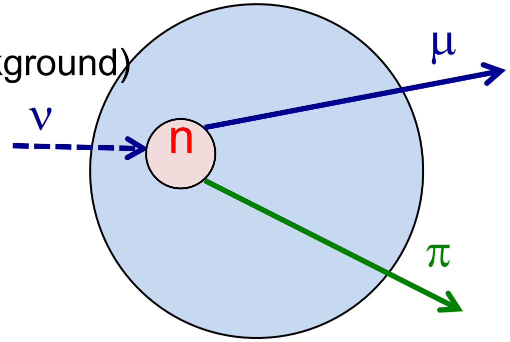


non-QE background → shift spectrum

Signal



Rejected
(not background)



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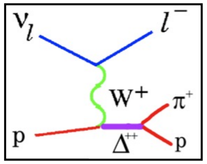

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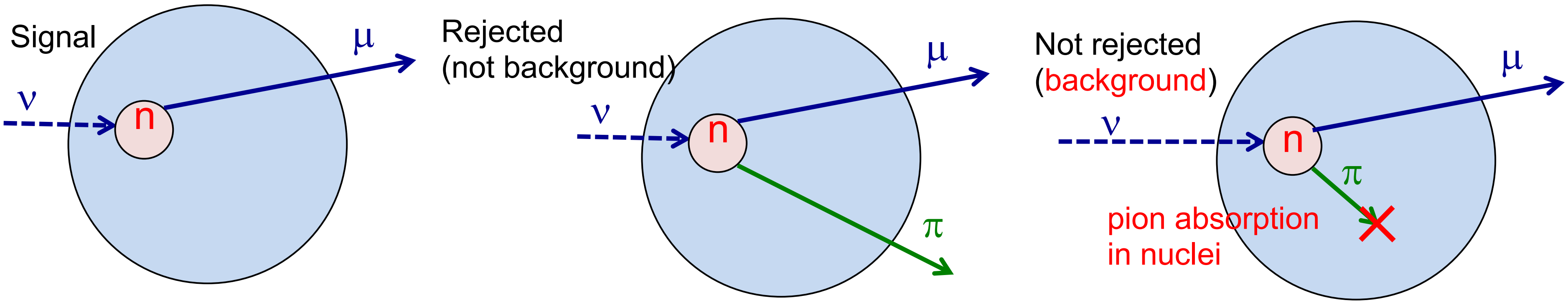

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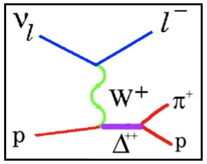

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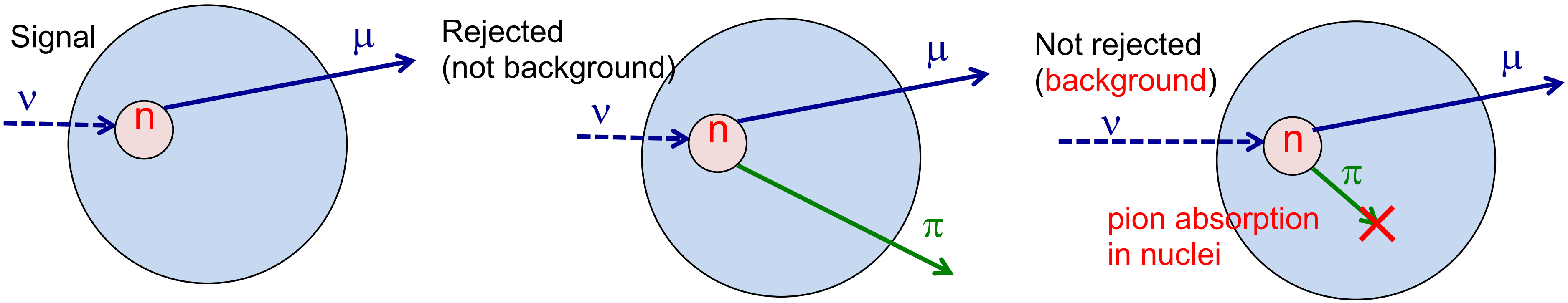
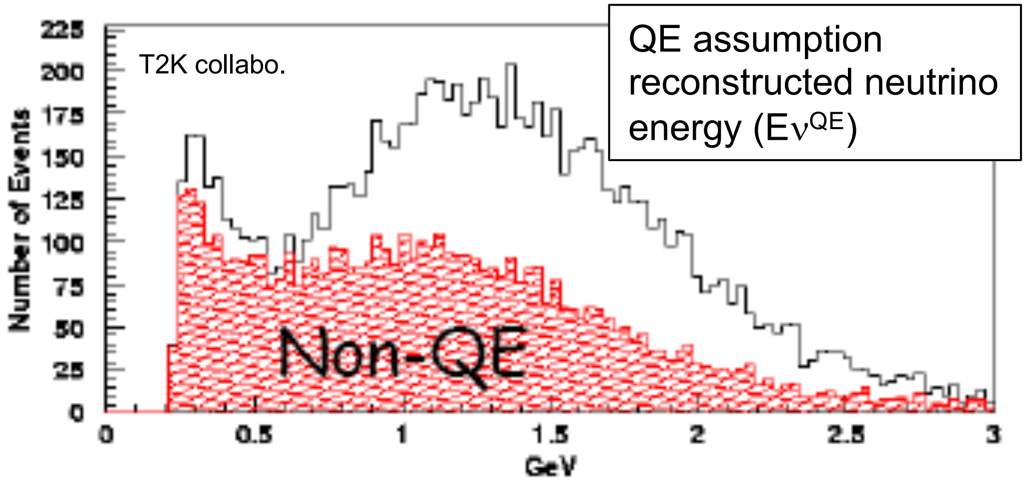
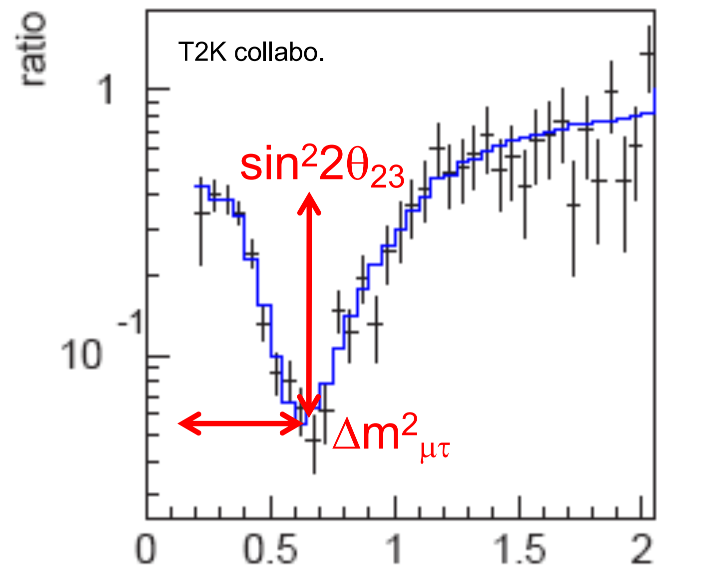




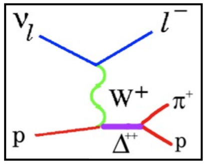


Solution: you need a good prediction of neutrino-induced pion production (hard)

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

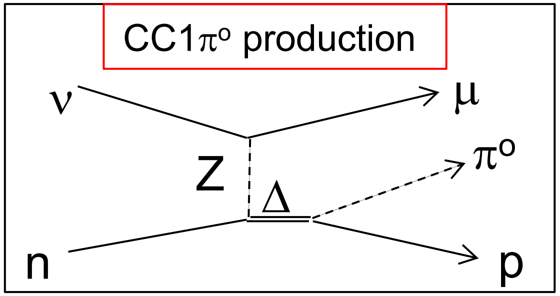
3. Pion puzzle

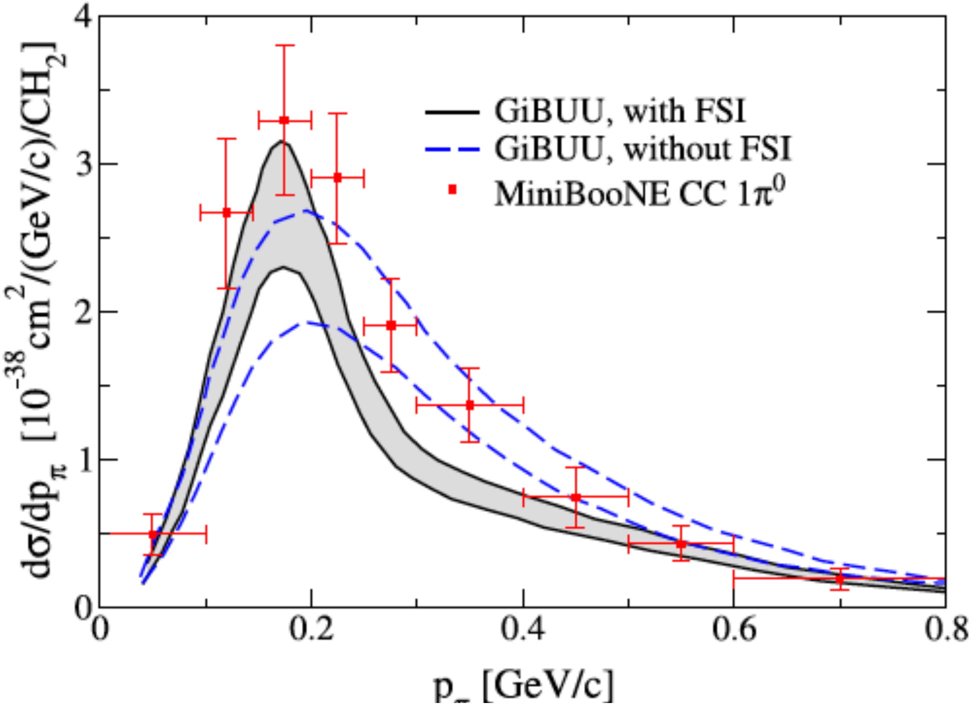
RESonance



Final state interaction

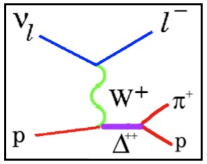
- Cascade model as a standard of the community
- Advanced models are not available for event-by-event simulation





ex) Giessen BUU transport model

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



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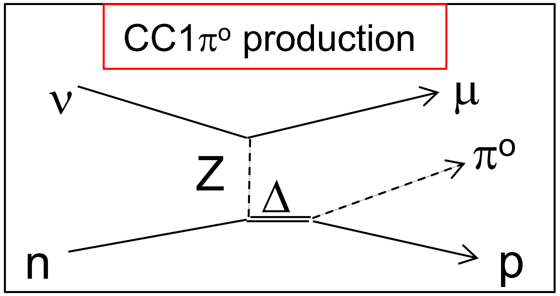

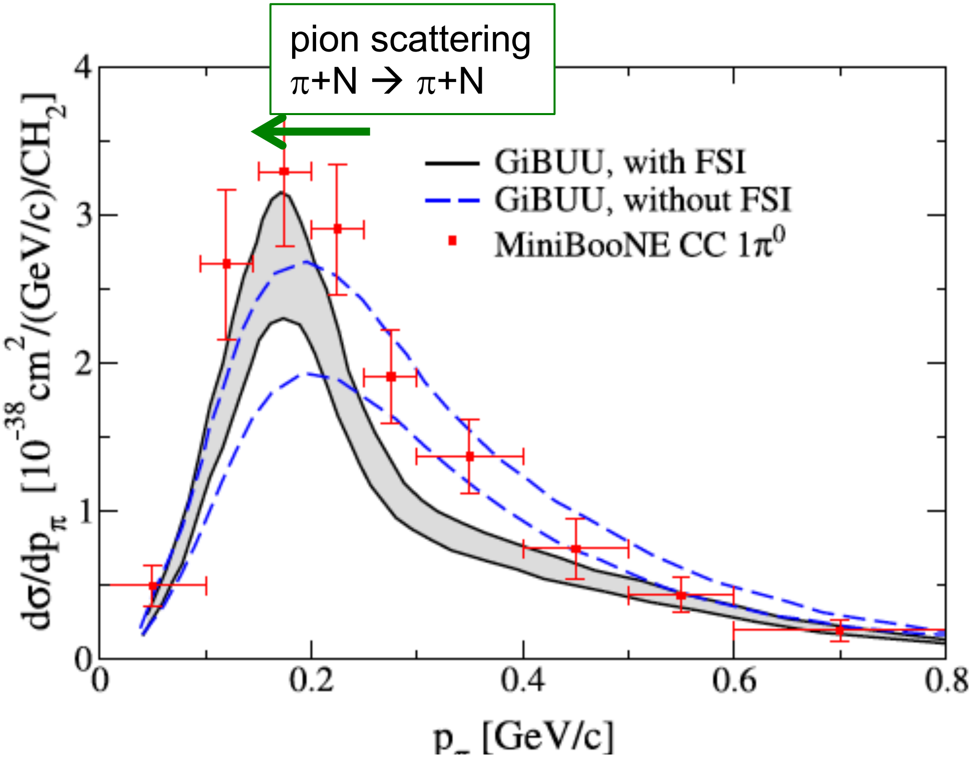

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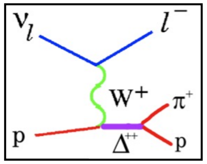

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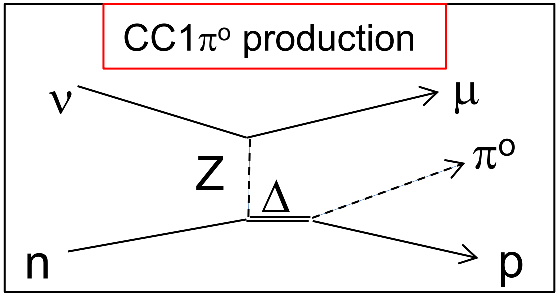

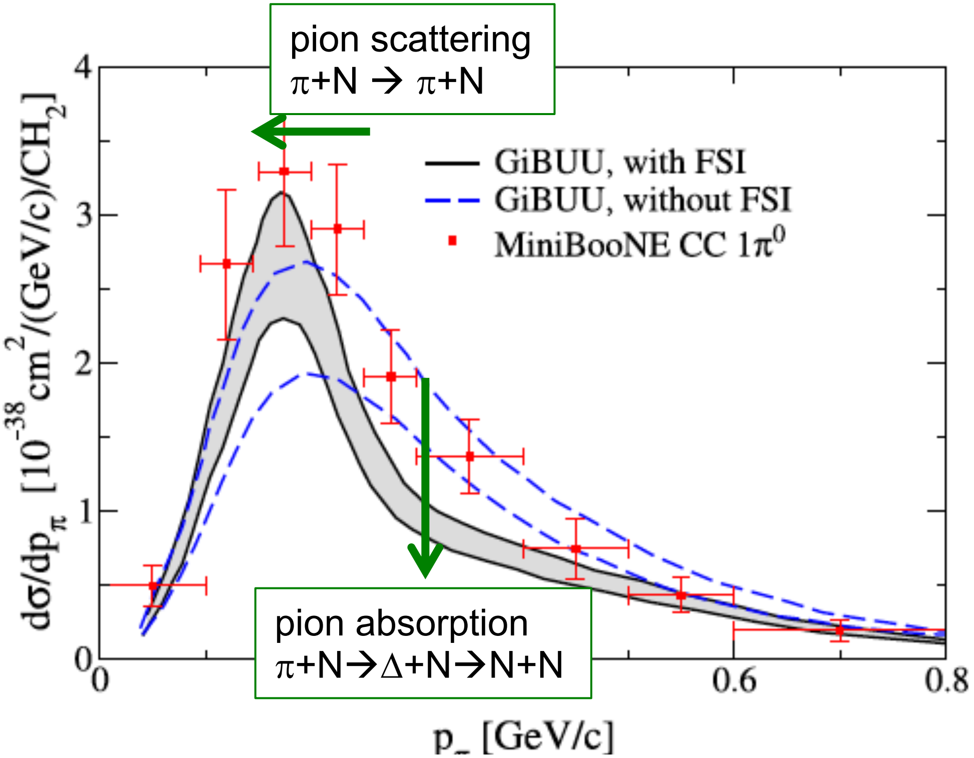

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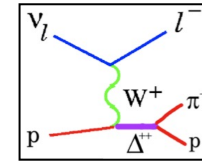

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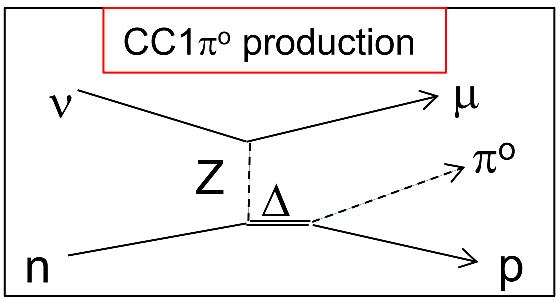
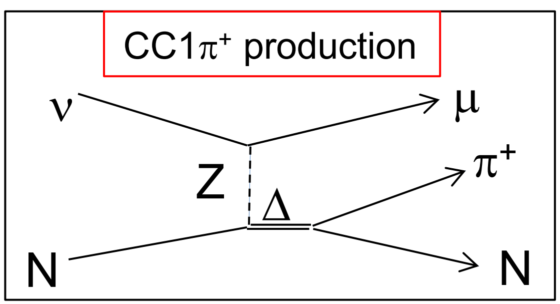
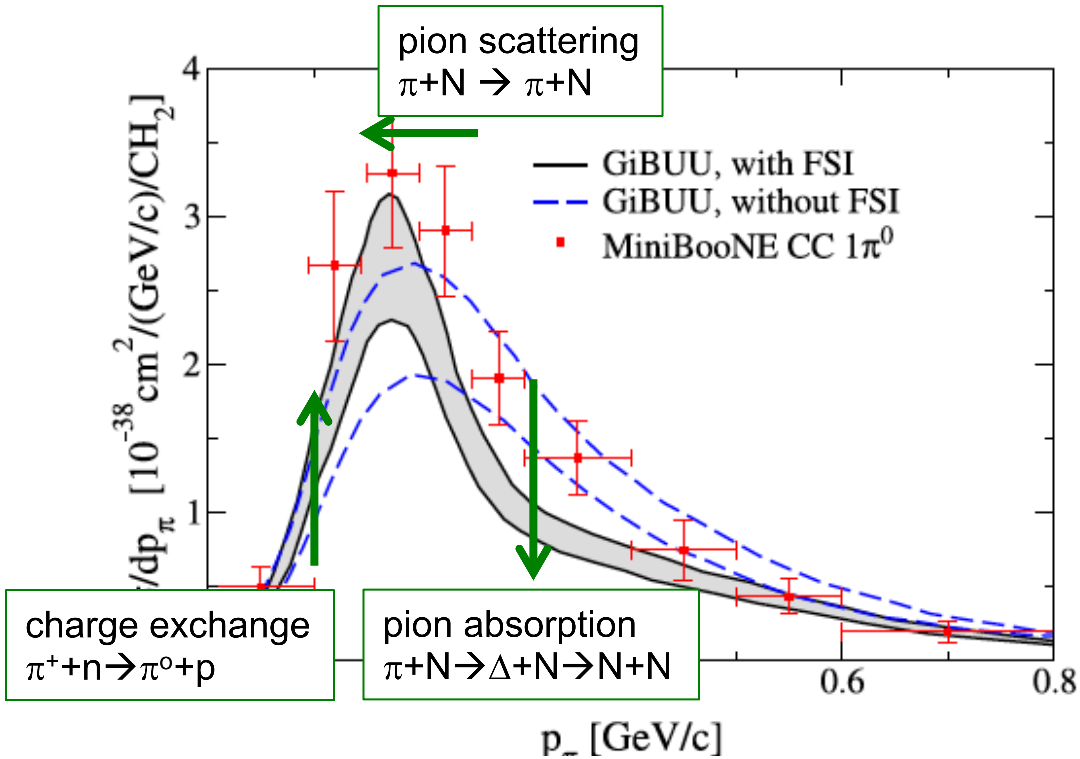


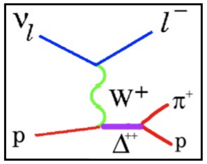




ex) Giessen BUU transport model
- Developed for heavy ion collision, and now used to calculate final state interactions of pions in nuclear media

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

3. Pion puzzle

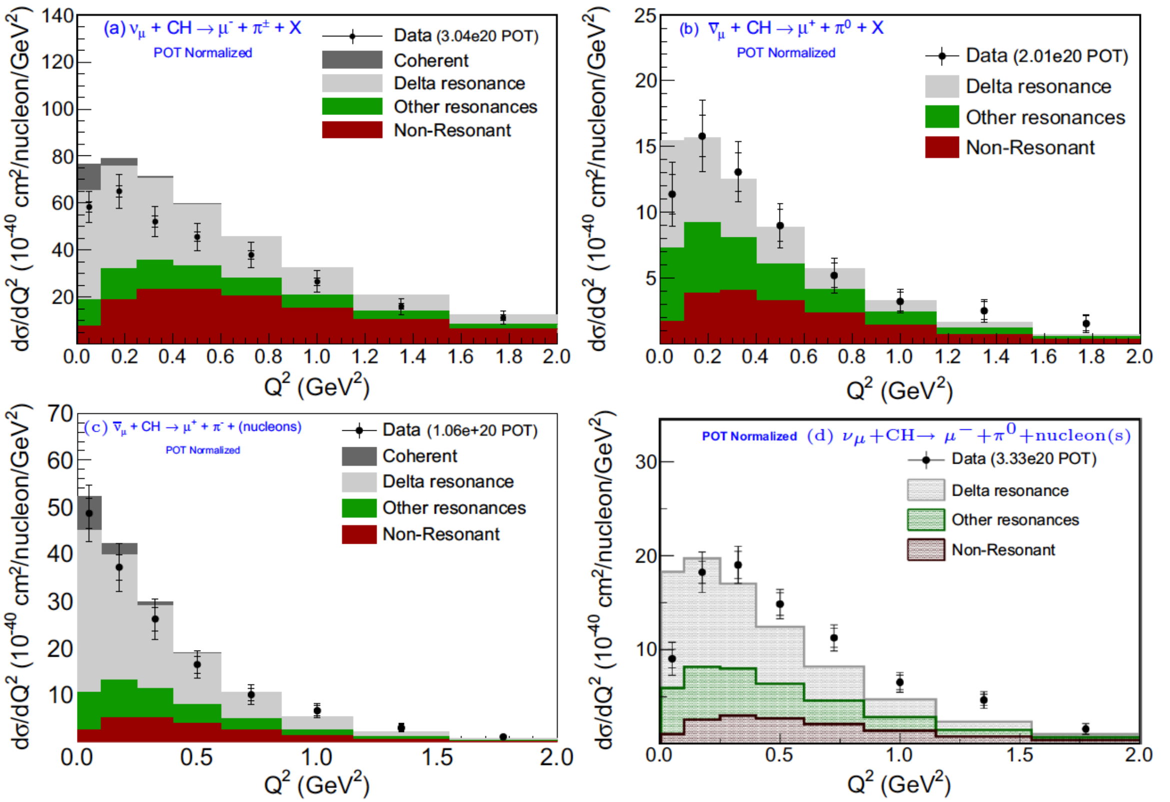


Data tension – internal: MINERvA pion data

- 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



You need to predict both
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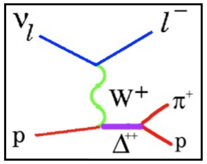
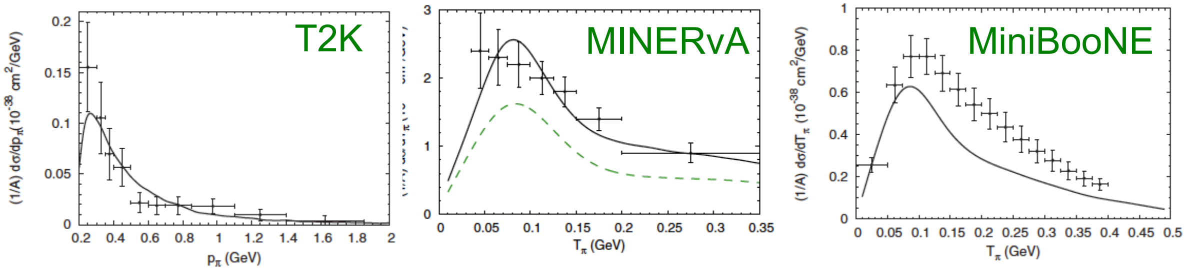


3. Data tension

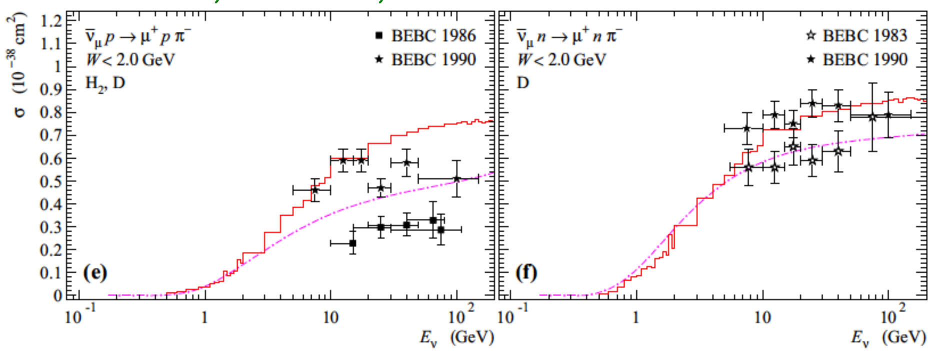
Data tension – external

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

MiniBooNE vs. T2K vs. MINERvA (GiBUU)

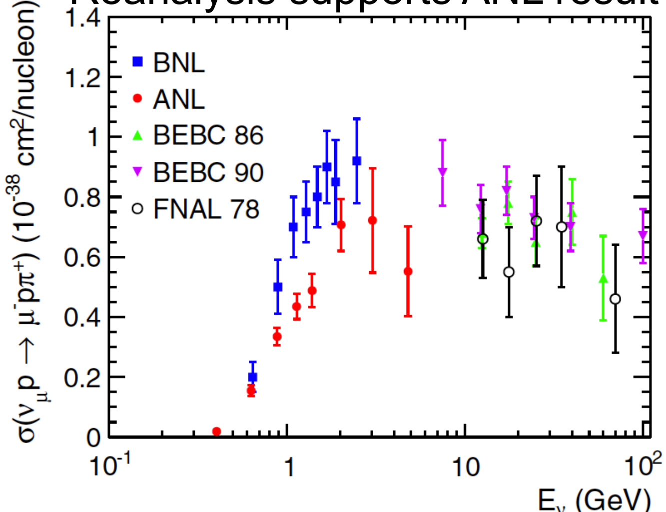


BEBC, H vs. D, 1983 vs. 1986 vs. 1990

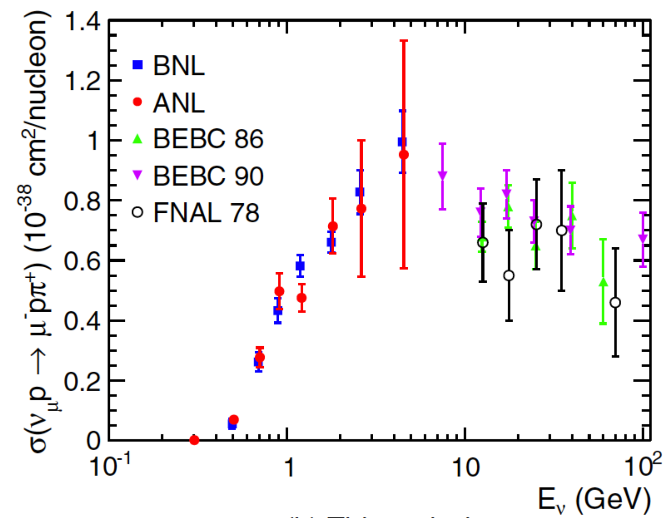


ANL vs. BNL data

Reanalysis supports ANL result

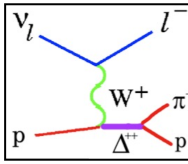


(a) Published



(b) Thisanalysis

katori@fnal.gov



3. MiniBooNE low-energy excess

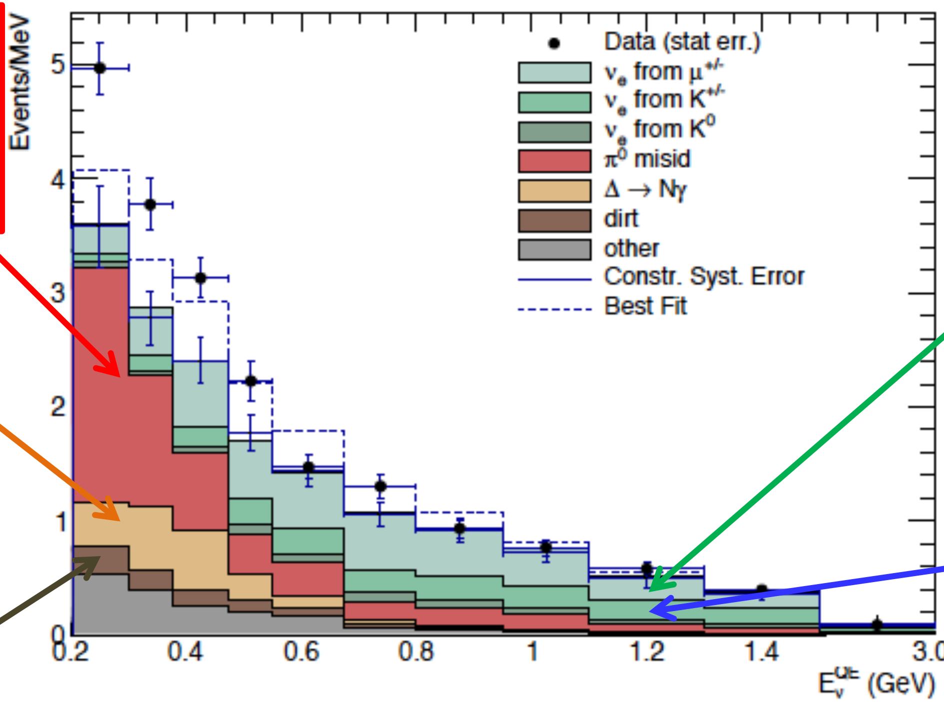
Short-baseline anomalies

- 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 ν_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

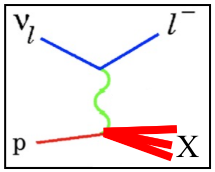
3. Neutrino baryonic resonance interaction

4. Neutrino shallow- and deep-inelastic scatterings

5. Conclusions

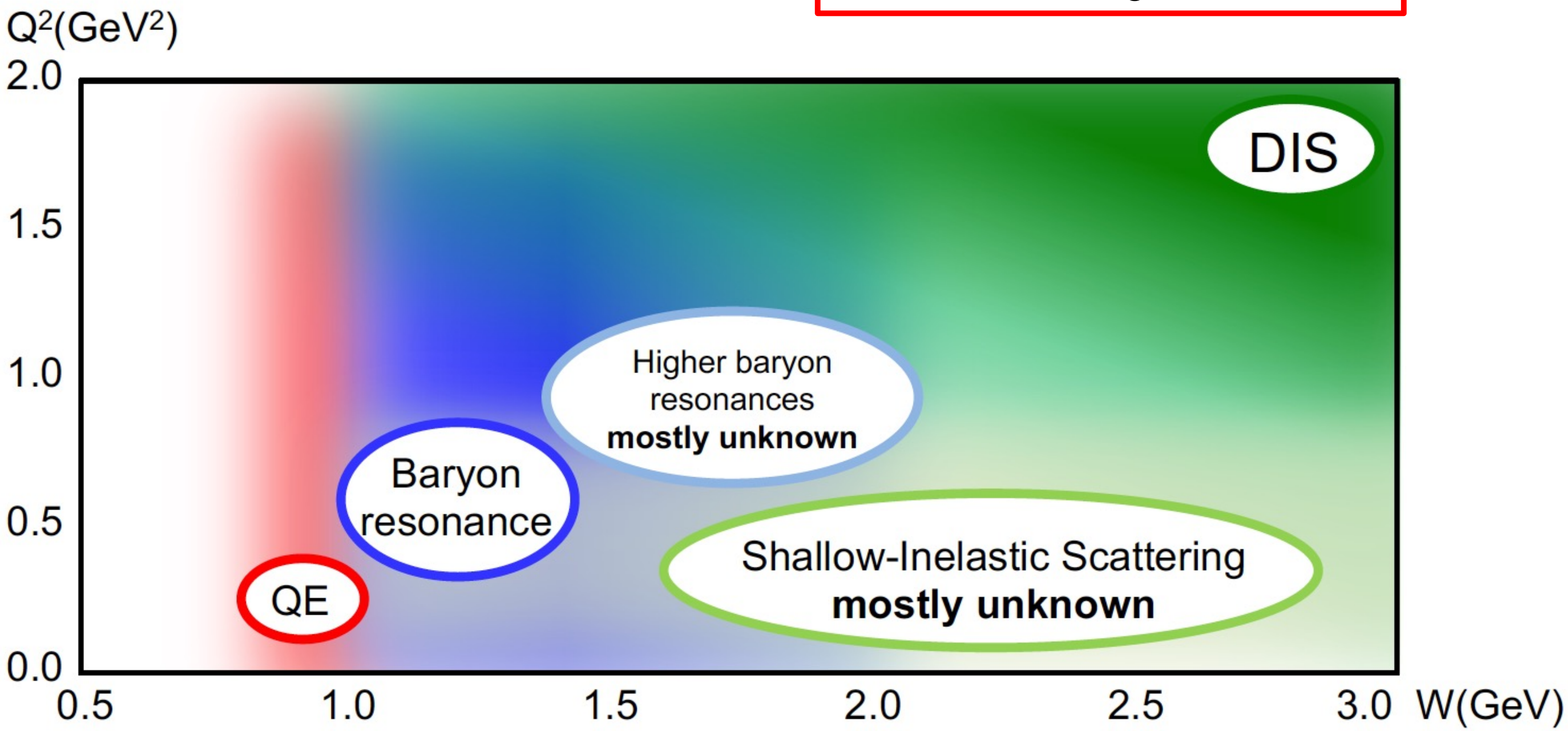
Nakamura et al,Rep.Prog.Phys.80(2017)056301, Sajjad Athar and Morfin, JPhysG48(2021) 034001
Snowmass21 LoI, ArXiv:2009.04285

4. Shallow Inelastic Scattering (SIS)



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



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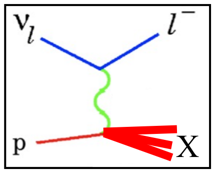

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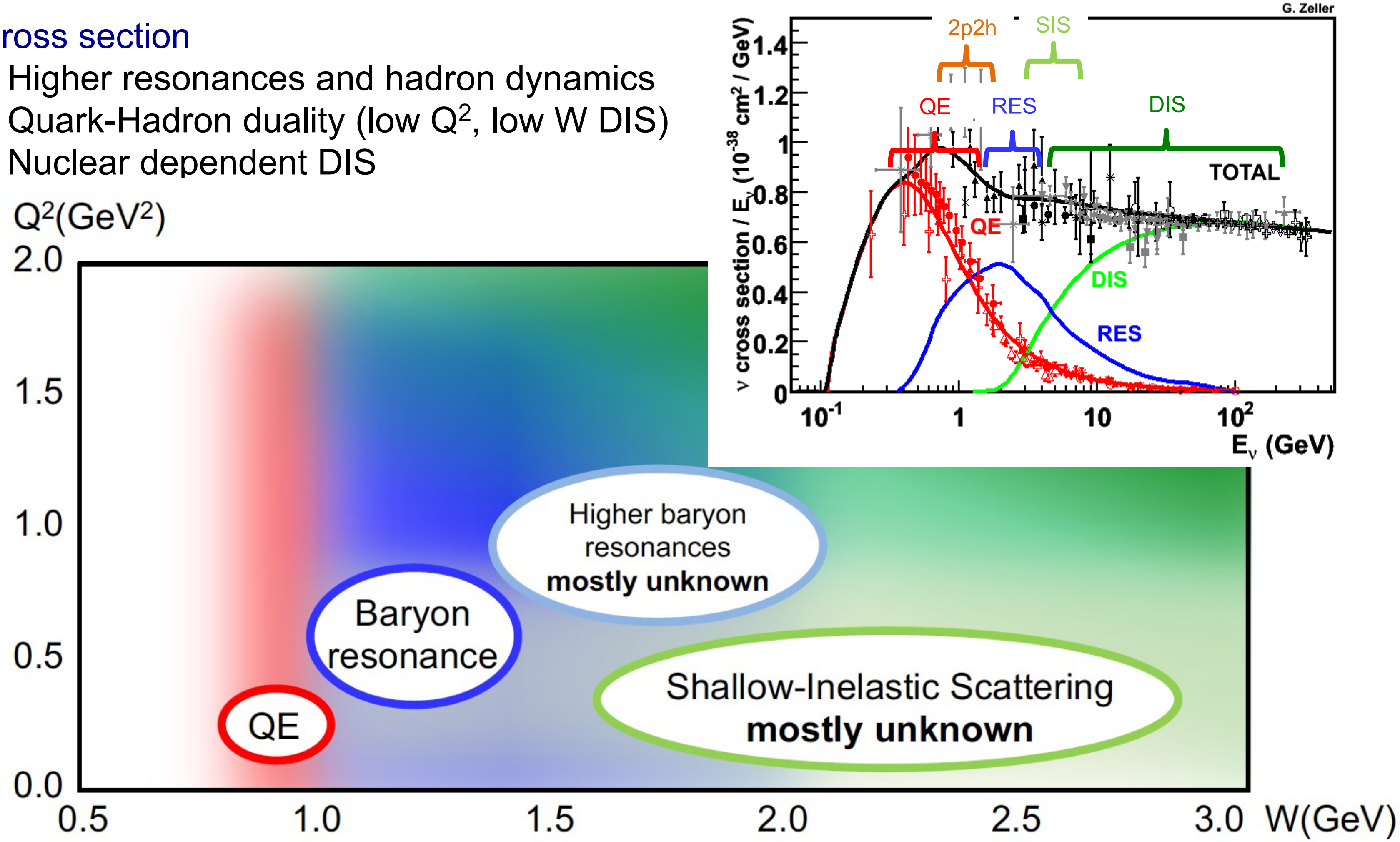
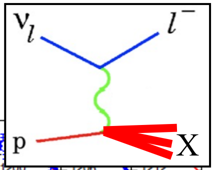


Nakamura et al,Rep.Prog.Phys.80(2017)056301

4. Higher baryonic resonances



Cross section
- Higher resonances and hadron dynamics
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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

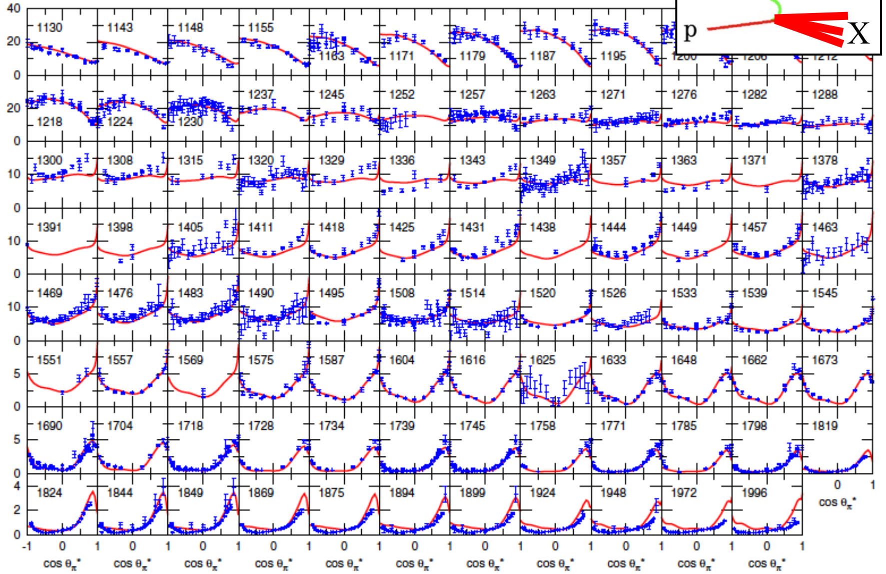
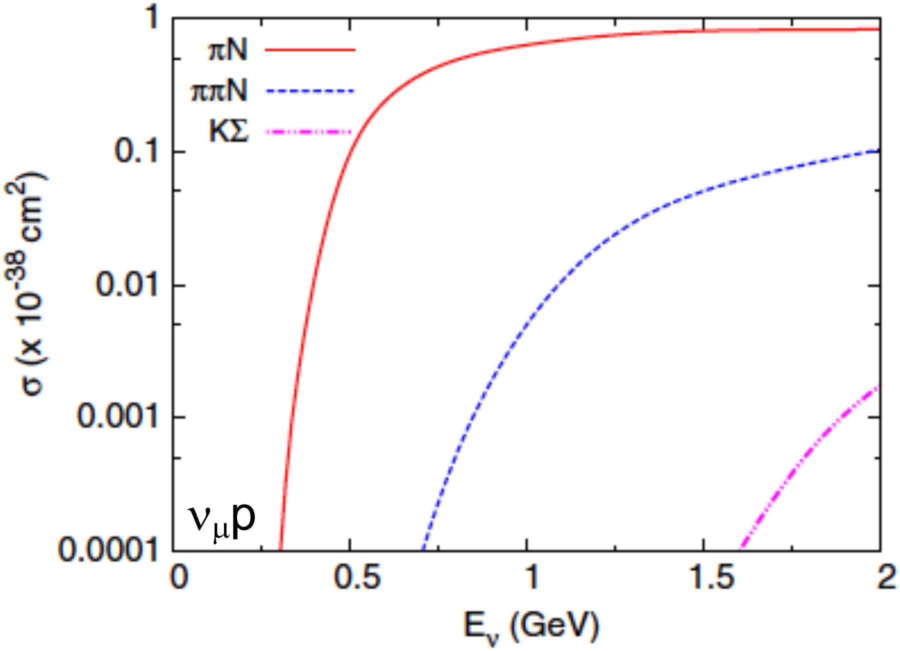
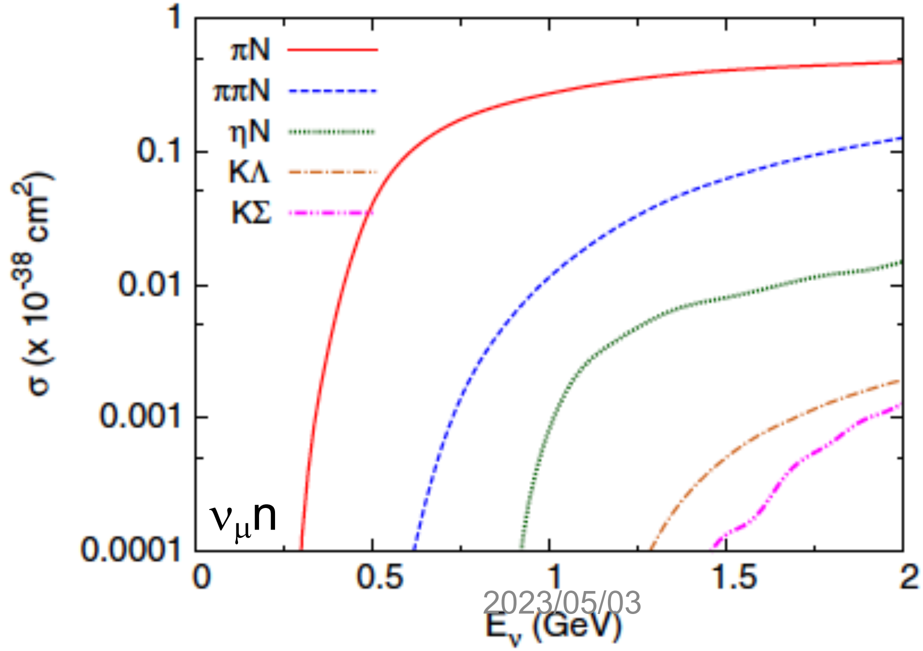


FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega_\pi^*$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].

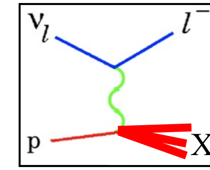




4. Quark-Hadron duality

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

DIS



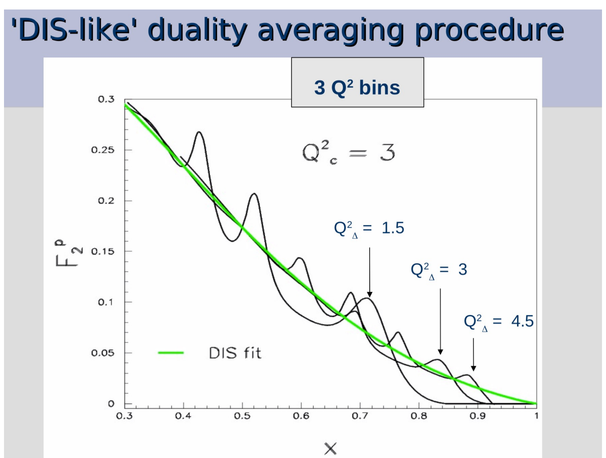
Cross section

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

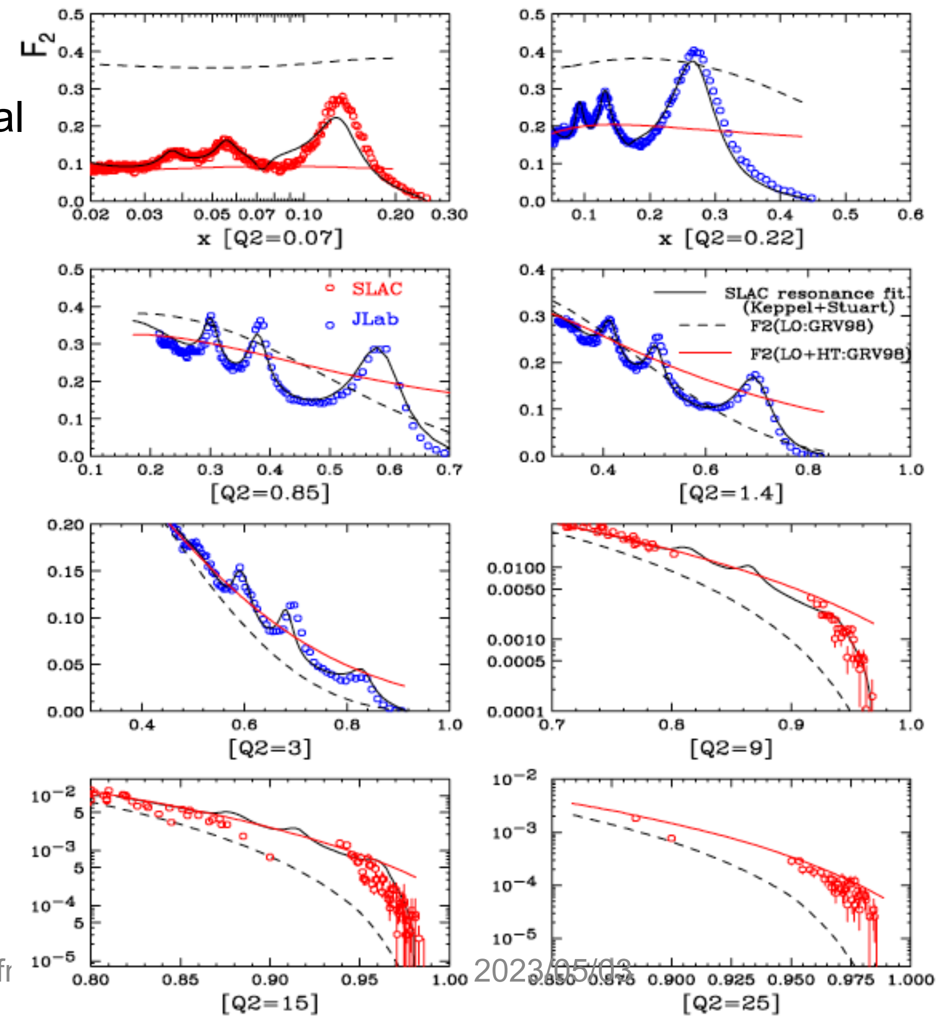
Bodek-Yang correction is a phenomenological model to reproduce duality-like behavior, accepted by all neutrino simulation

DIS ≠ Bjorken limit

DIS = Q^2 average of all resonances



Proton F2 function GRV98-BY correction vs. data

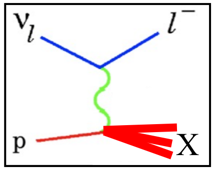


Christy, NuSTEC SIS workshop
https://nustec.fnal.gov/nuSDIS18/

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

4. Nuclear dependent DIS

DIS



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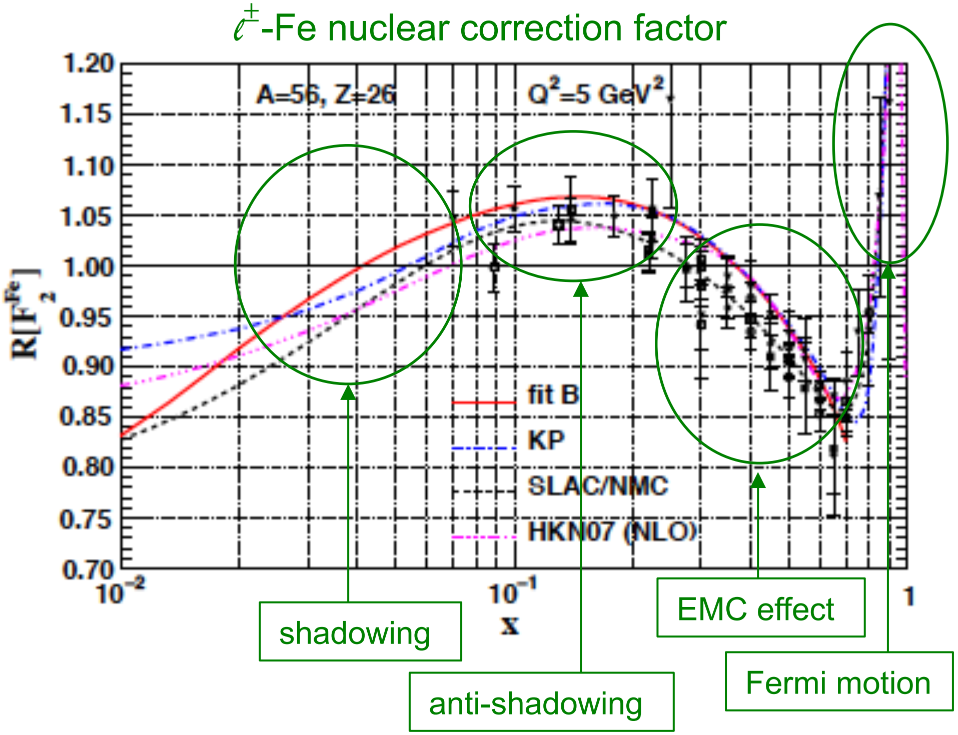
- Nuclear dependent DIS

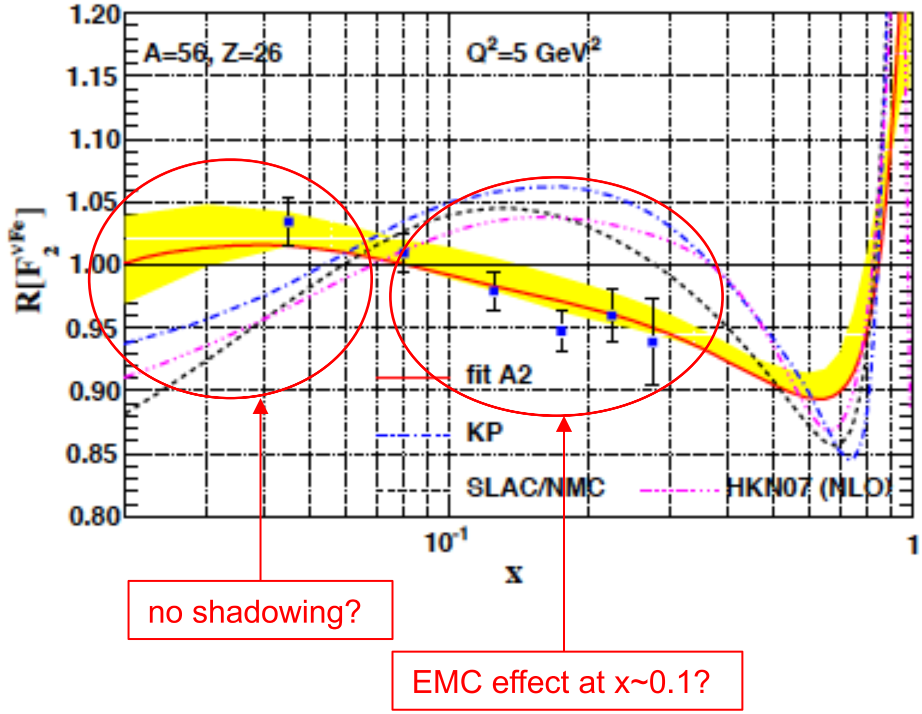
Nuclear PDF

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

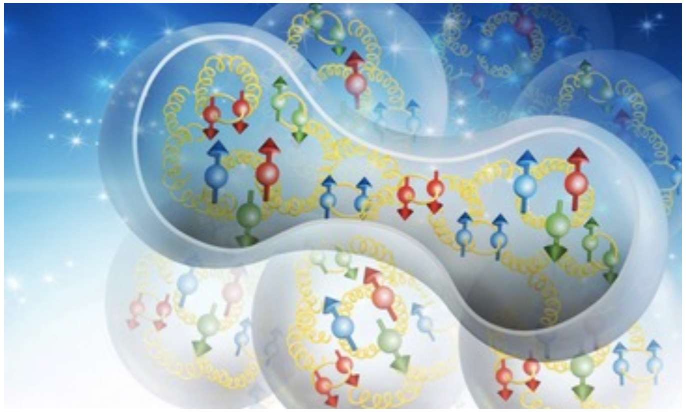
$\ell^{\pm}$-Fe nuclear correction factor

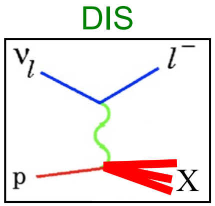


ν-Fe nuclear correction factor



4. EMC effect

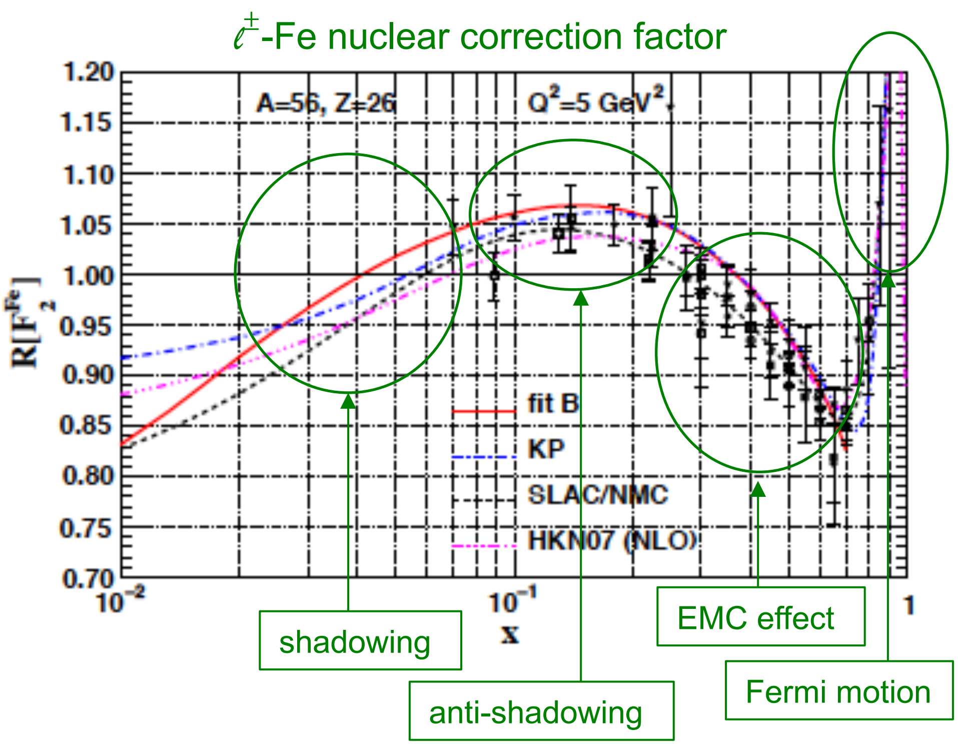




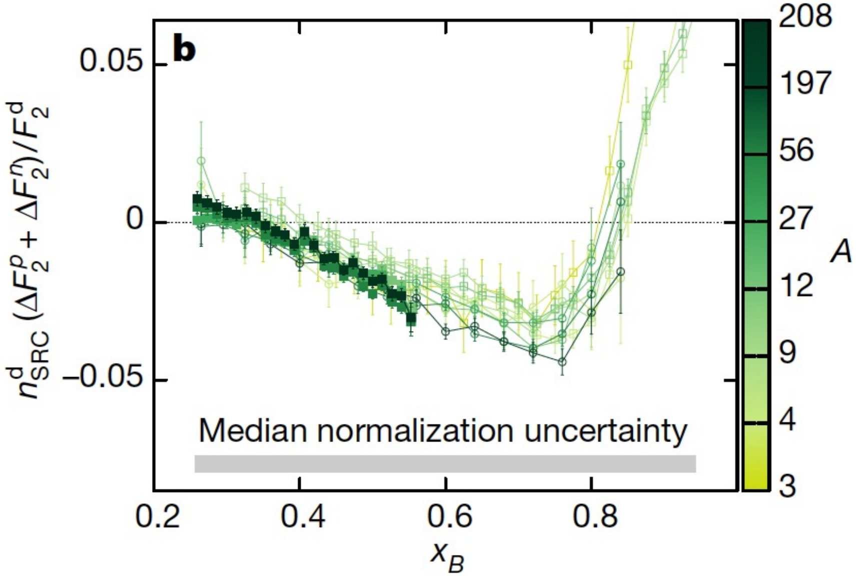
Nuclear dependent DIS

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

→ Quarks feel presence of other quarks in other nucleons



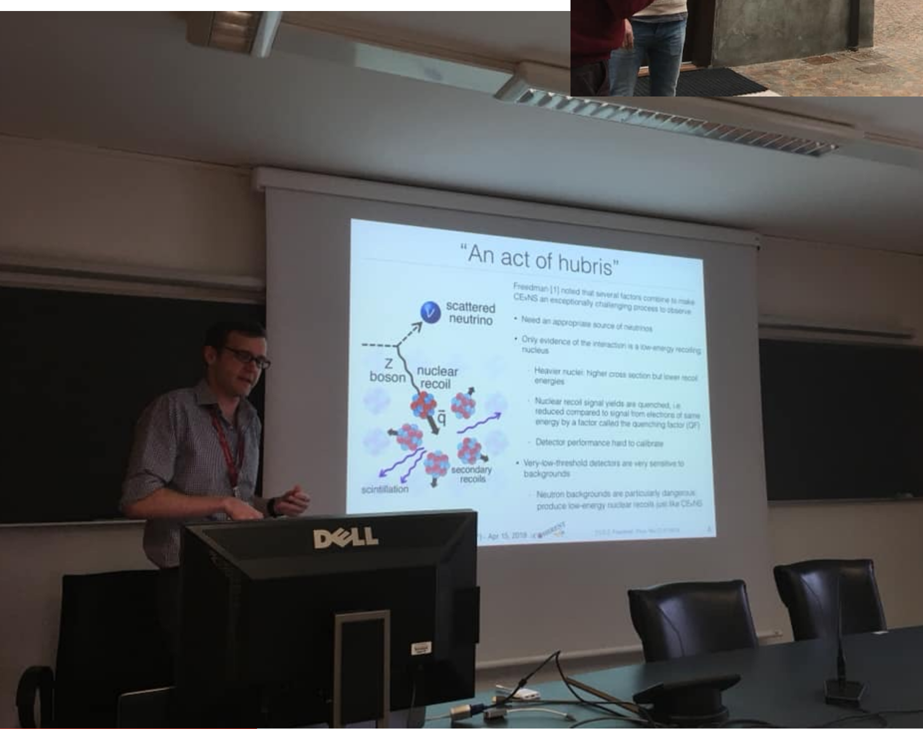
EMC effect can be modeled from the amount of correlated pairs in nuclei (CLAS in JLab).



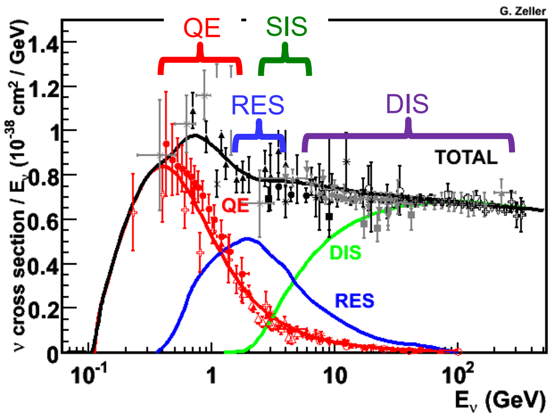
4. Atomic nuclei as laboratories for BSM physics

ECT* workshop, 15 Apr. 15-19 2019, Trento, Italy
https://www.ectstar.eu/workshops/atomic-nuclei-as-laboratories-for-bsm-physics/

Topics include;
- Neutrino interactions
- EMC effect
- $0\nu\beta\beta$
- Direct dark matter
- etc



4. NuInt conference series



https://nustec.fnal.gov/nuint-conference-series/

The main conference in the neutrino interaction physics community
- Every ~18 months
- The next one will be Spring 2024 in São Paulo (Brazil)

NuINT 2022

The 13th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Regions

October 24 to 29, 2022 (OFFLINE)

Hoam Faculty House
Seoul National University
Seoul, Korea

4. NuSTEC

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

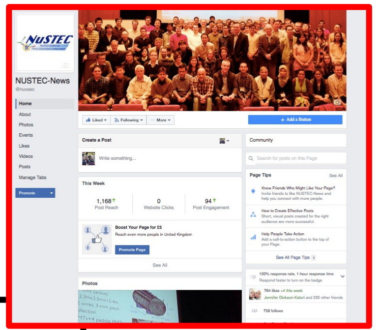
NuSTEC Workshop on Electron Scattering 2022 (Tel Aviv)
https://indico.fnal.gov/event/50863/

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

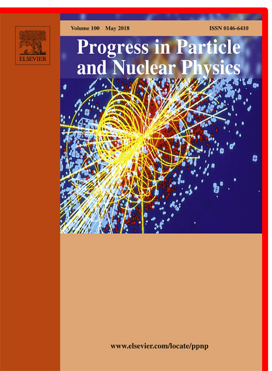
NuSTEC

- 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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(or just send e-mail to me, katori@FNAL.GOV)
like "@nuxsec" on Facebook page, use hashtag #nuxsec

Conclusion

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

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

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

Neutrino interaction physics beyond QE region is confusing.

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

Thank you for your attention!

Backup

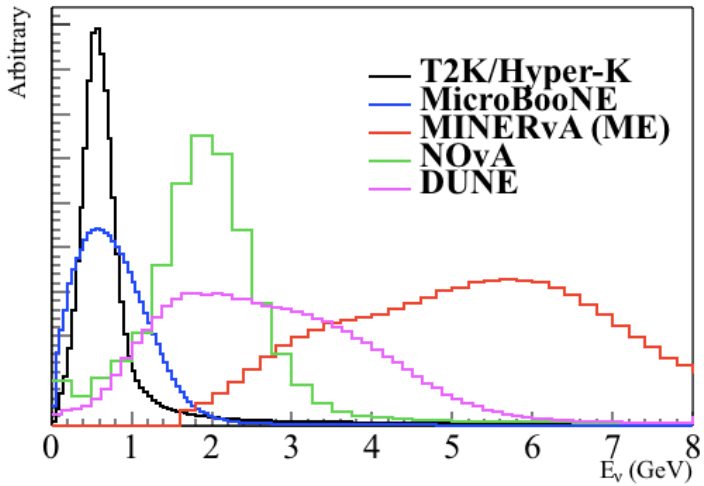
1. Next generation neutrino oscillation experiments

Neutrino oscillation experiments

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

We don't know the energy of incoming neutrinos…

- We need to simulate all physics from $E\nu=0$ to $E\nu$ ~few GeV
- We need to simulate all physics from $\omega,|\vec{q}|=0$ to $\omega,|\vec{q}|$~few GeV



Two rules of neutrino interaction physics

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

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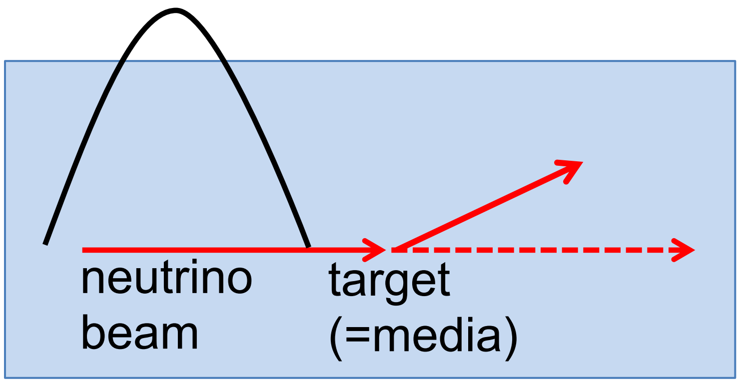
1. Typical neutrino detectors

Neutrino scattering

- Wideband beam

→ observables are inclusive



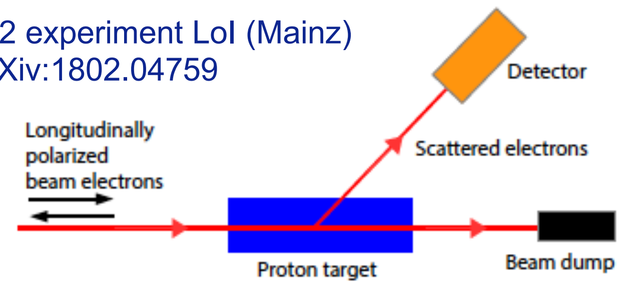
Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ kinematics is completely fixed

P2 experiment LoI (Mainz)
arXiv:1802.04759



Incomplete kinematics

- Large mass, coarse instrumentation
- No one measures neutrino energy directly
- Reconstructing kinematics (Ev, Q2, W, x, y,…) in 1-10 GeV depends on interaction models

Two rules of neutrino interaction physics

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

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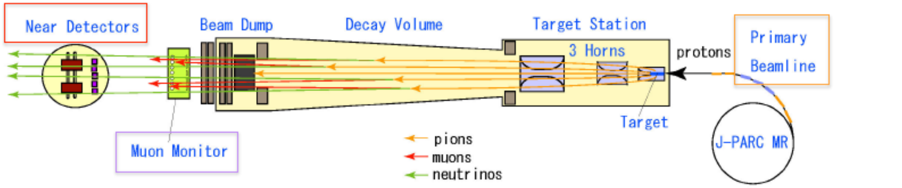
TK, Martini, JPhysG45(2017)1
Kowalik, NuInt18 (Toronto)

1. Typical neutrino beams for oscillation experiments

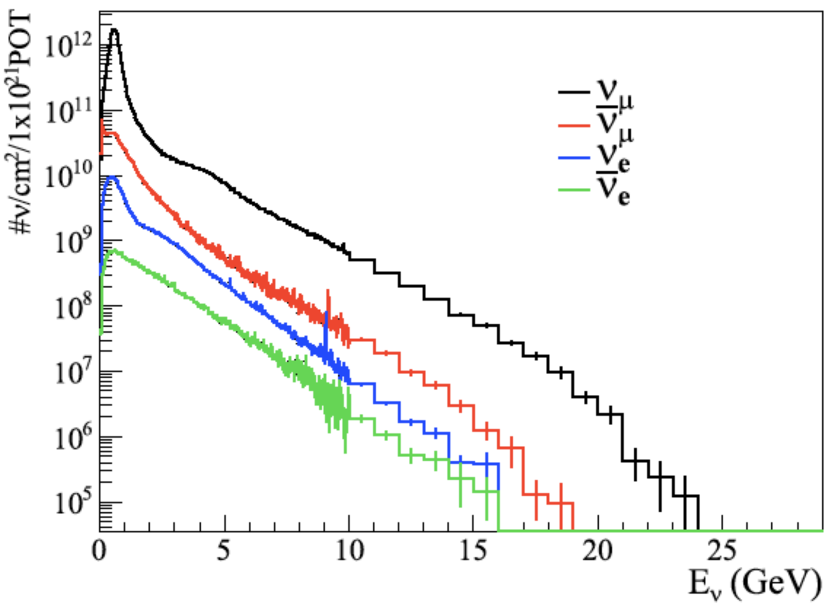
e.g.) J-PARC neutrino beam (T2K)
- pion decay-in-flight (high flux)
- off-axis beam (narrow band)
- but has components up to ~ 10 GeV
- typical beam 1-10 GeV
- ~4% normalization error (best case)

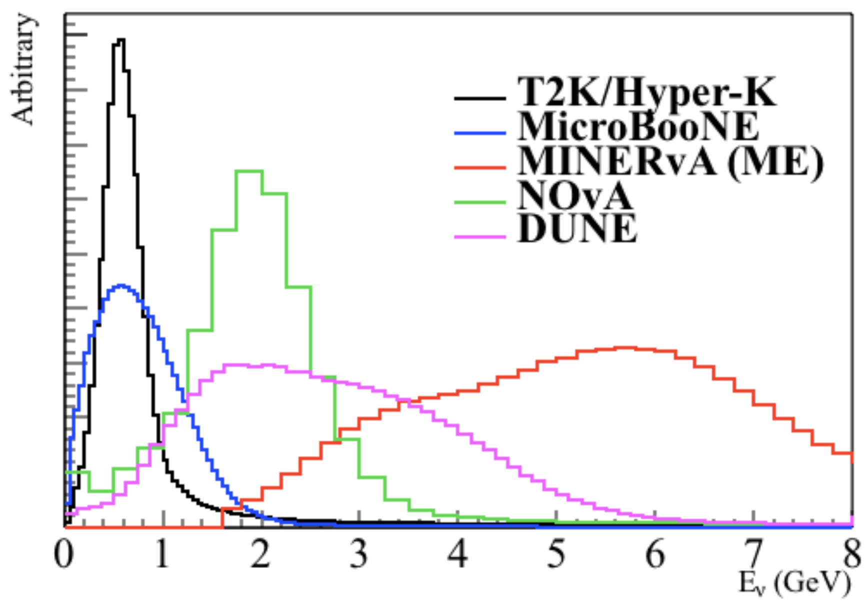


INGRID
monitors the stability of ν flux and direction

Muon Monitor
measures the muon profile after beam dump

Proton Beam Monitors
measure the proton beam intensity, direction





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

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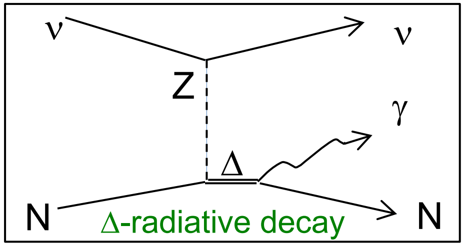
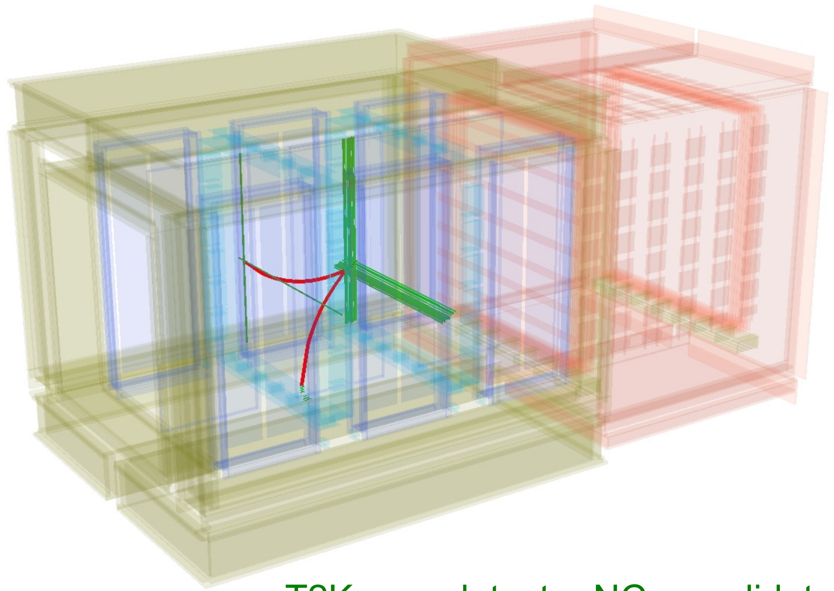
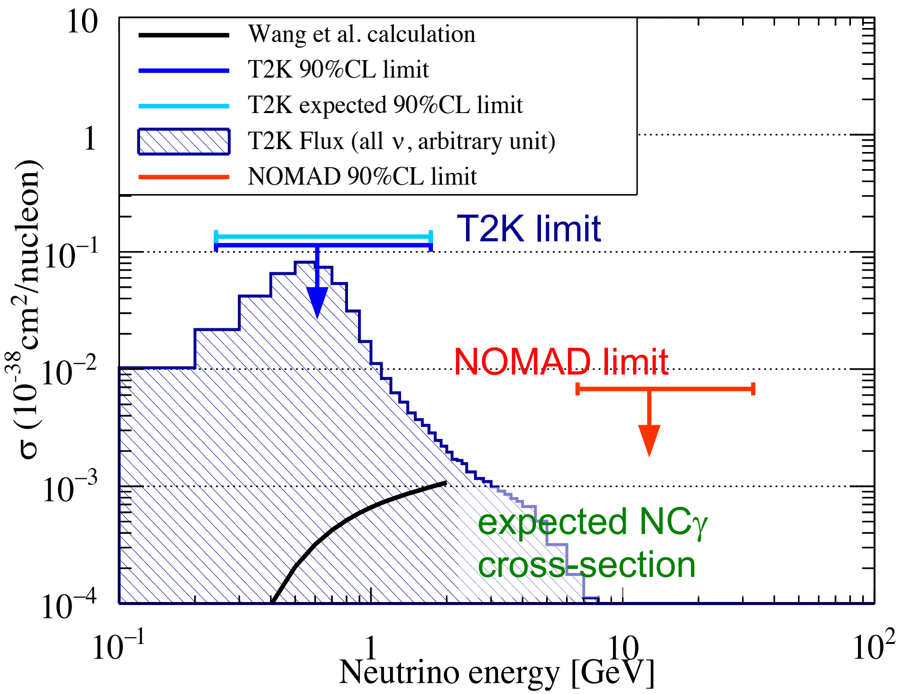
4. T2K Neutrino NC single photon production (NCγ)

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





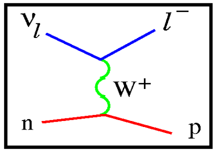
T2K near detector NCγ candidate



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

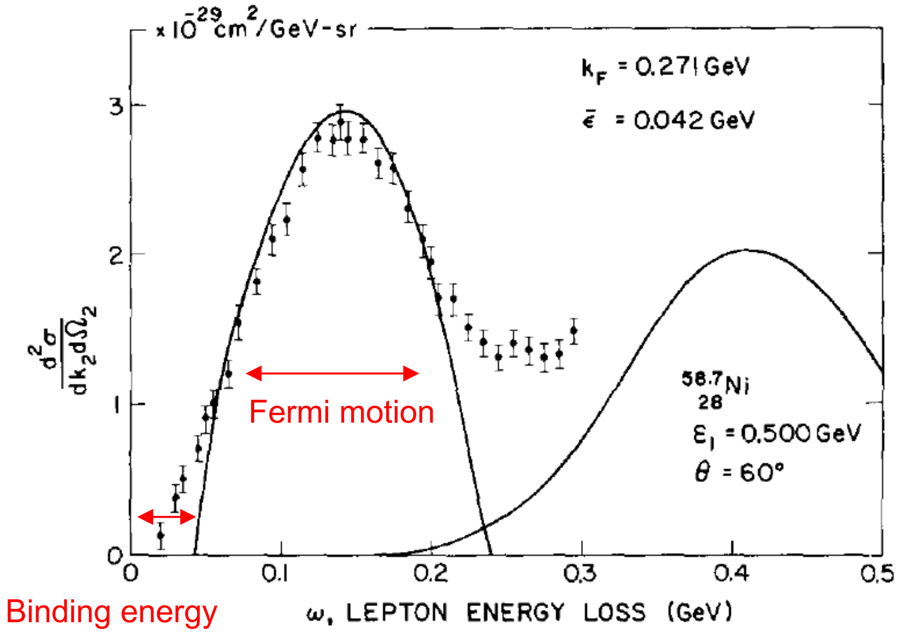
2. Fermi motion

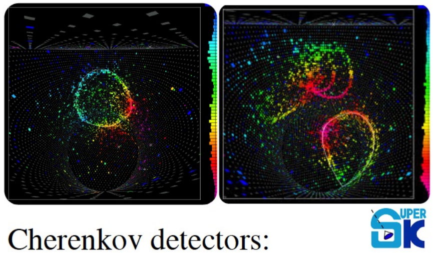
Quasi Elastic



Fermi motion

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



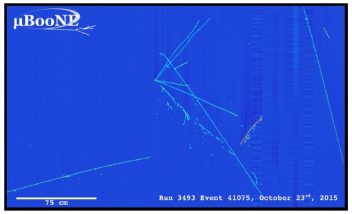


Cherenkov detectors:

Assuming QE interaction

Using lepton only

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



Tracking detectors:

Calorimetric sum

Using All detected particles

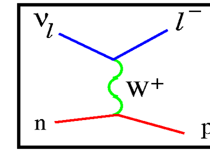
$$E_{cal} = E_l + E_p^{kin} + \epsilon$$

[1p0π]

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

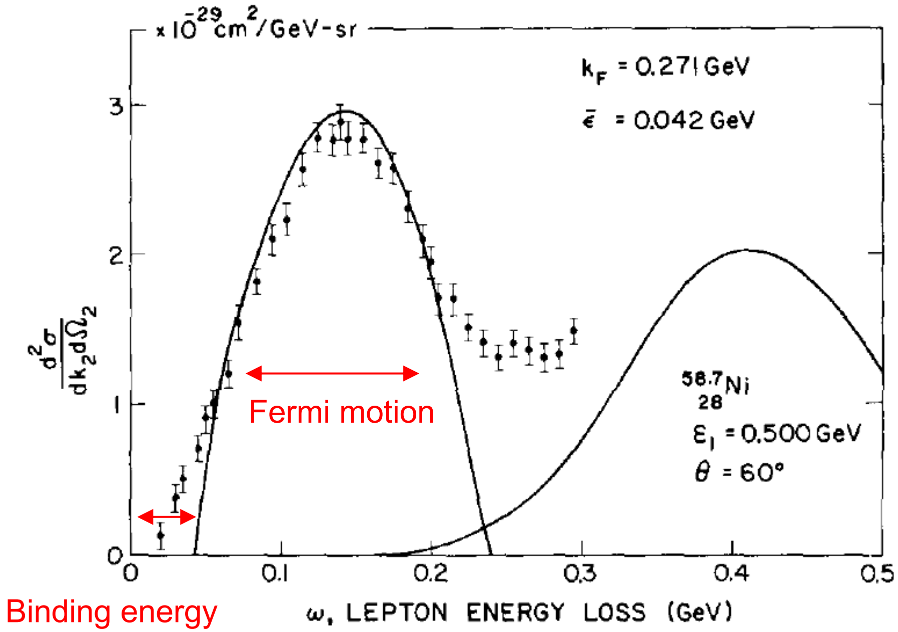
2. Pauli blocking

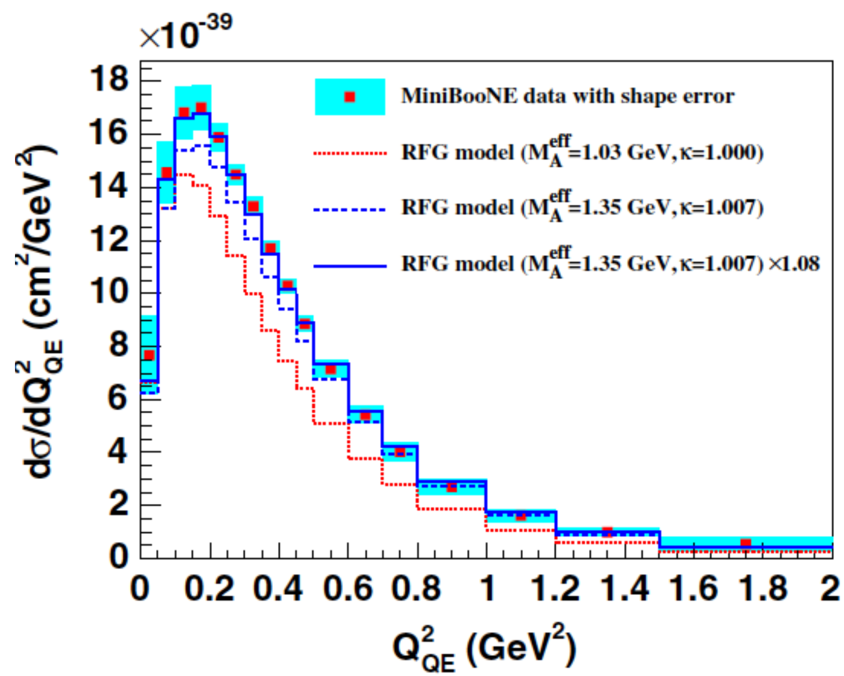
Quasi Elastic



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

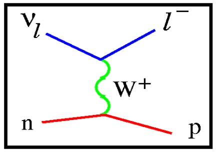




Smith and Moniz, NPB43(1972)605
Bodek and Cai, EPJC79(2019)293

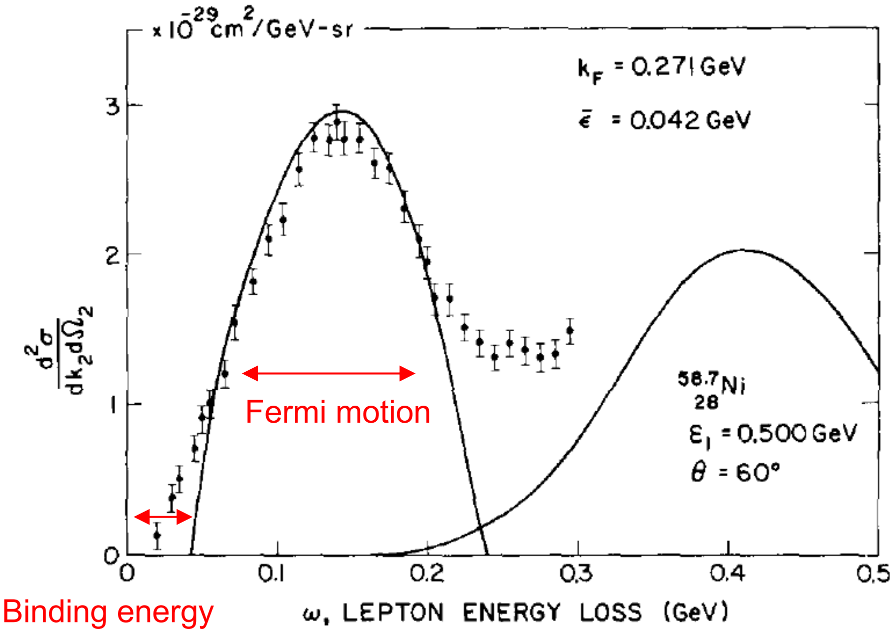
2. Nuclear Shell structure and binding energy

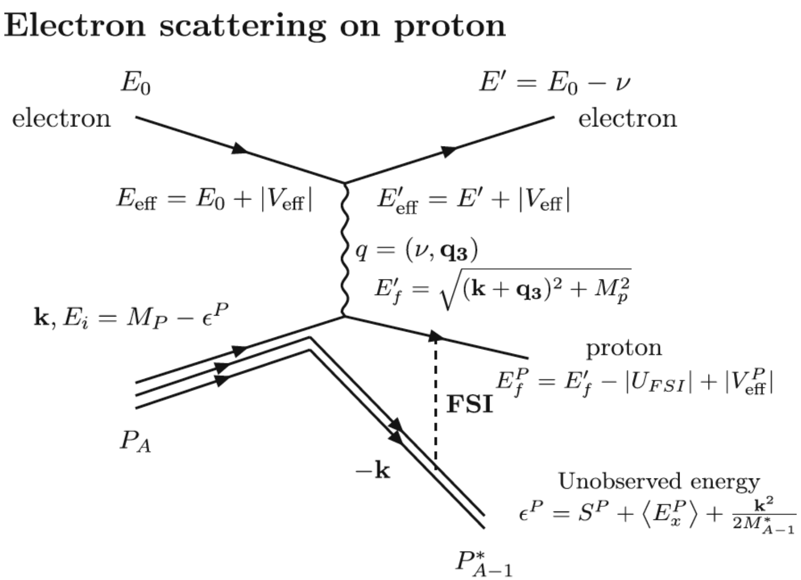
Quasi Elastic



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)





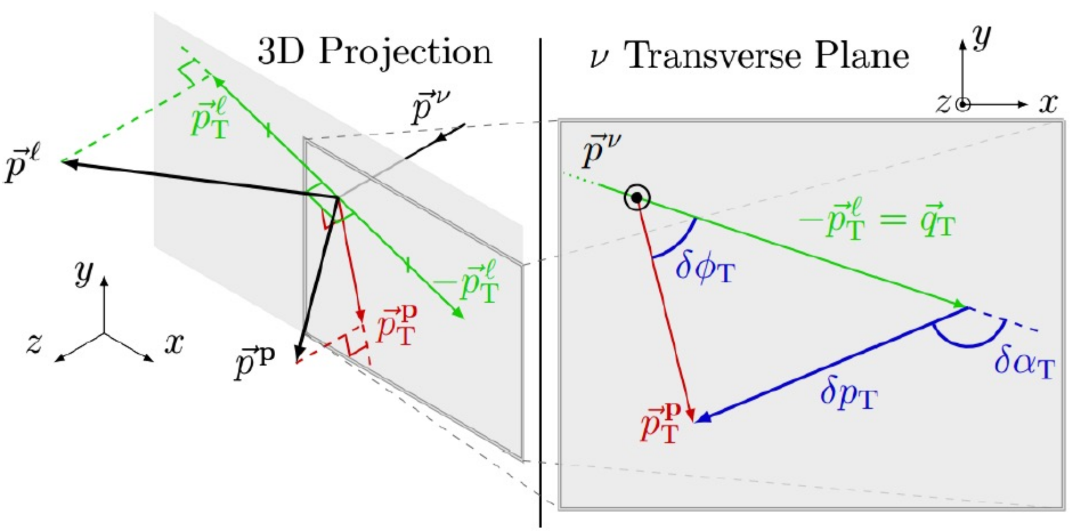
T2K, PRD98(2018)032003
MINERvA,PRL121(2018)022504

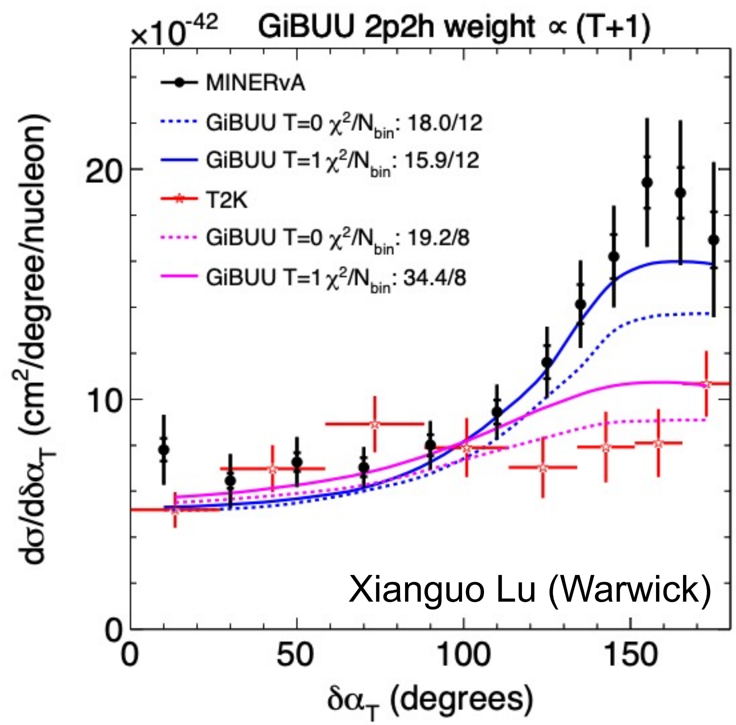
2. Nucleon correlations in neutrino physics

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

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

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





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

2. New paradigm of lepton scattering experiments

Flux-averaged differential cross-section

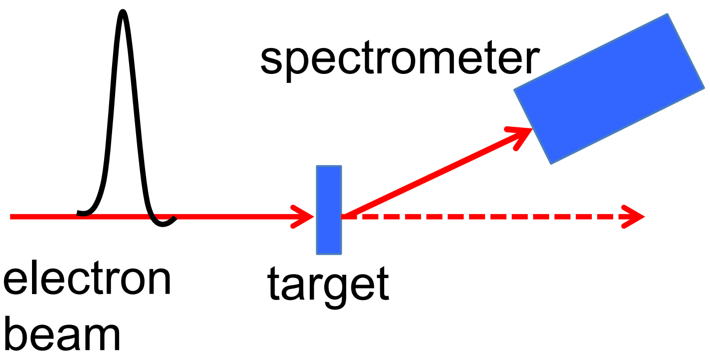
- Incomplete kinematics, reconstruction of Eν, Q2, q3, W, x, y,… depends on models

Electron scattering

- well defined energy, well known flux

→ reconstruct energy-momentum transfer

→ measure each process

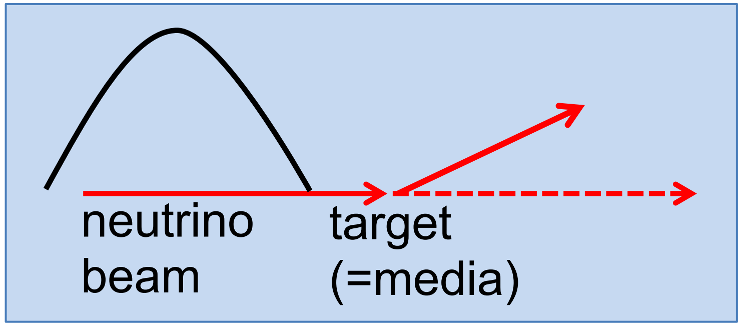


Neutrino scattering

- Wideband beam (unknown Eν)

→ cannot fix kinematics

→ inclusive measurement (CCQE, RES...)



Khachatryan et al., Nature 599(2021)565

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

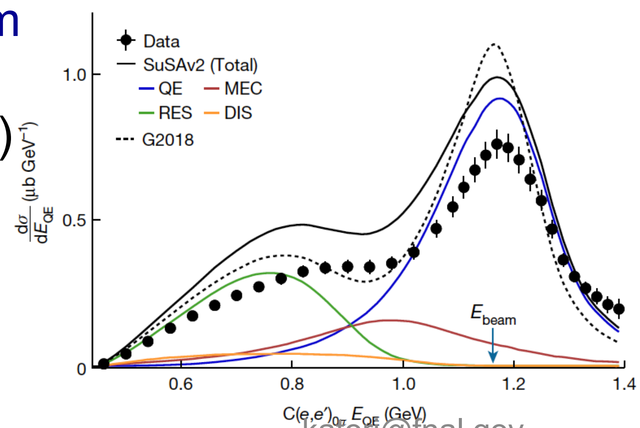
Neutrino experiment don't reconstruct Ev (and Q2) with great precision

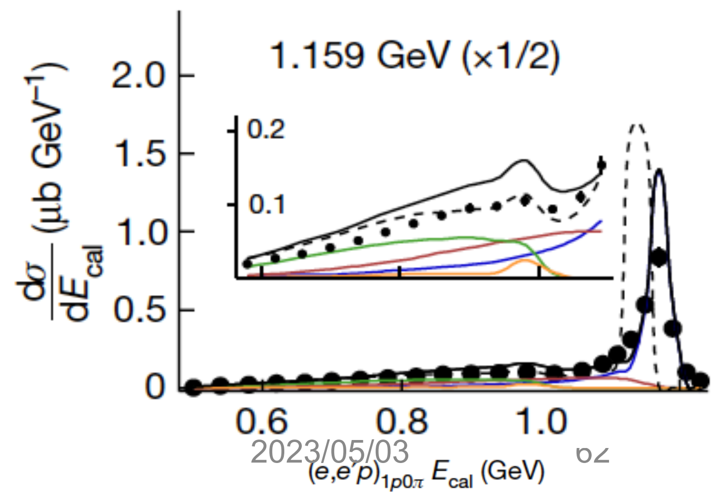
$$E_\nu^{QE} = \frac{ME_\nu - 0.5m_\mu^2}{M - E_\mu + p_\mu cos\theta}$$

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

Reconstructed beam electron energy spectrum by

- QE kinematic (HyperK)
- Calorimetric (DUNE)





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

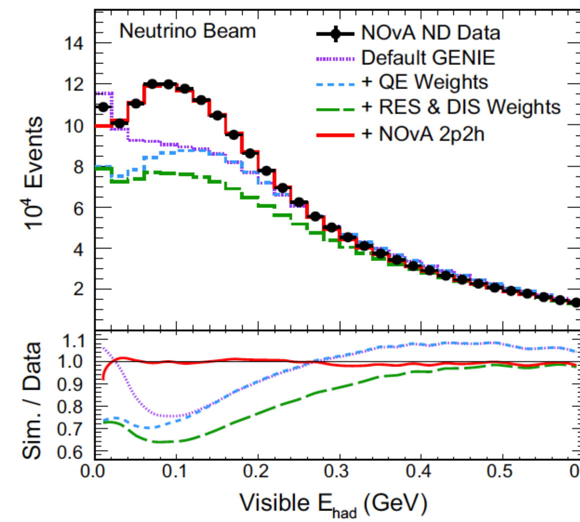
2. New paradigm of lepton scattering experiments

Flux-averaged differential cross-section

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

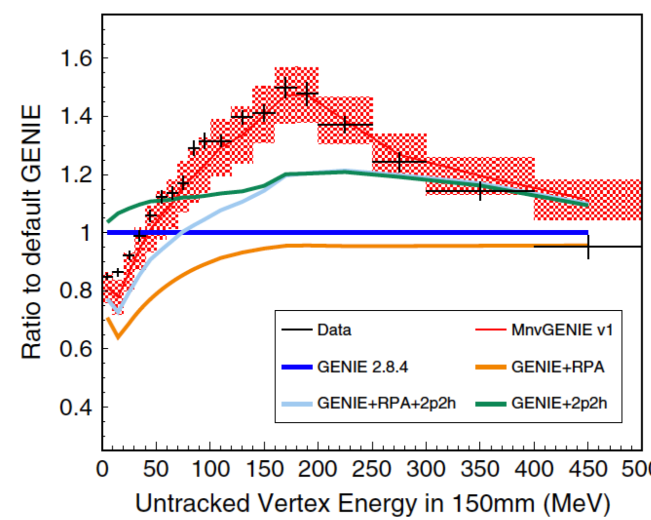
Visible hadronic energy deposit: E_{had}, E_{avail}

- 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)



MINERvA, PRL116(2016)071802,PRD99(2019)012004,EPJST230(2021) 4243, PRL121(2018)022504
NOvA, EPJC80(2020)1119 , Buizza Avanzini et al., PRD105(2022)092004, T2K, PRD98(2018)032003,

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}

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

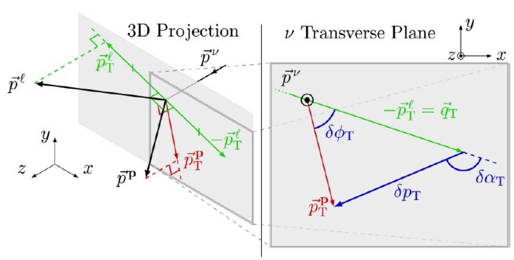
Vertex activity

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

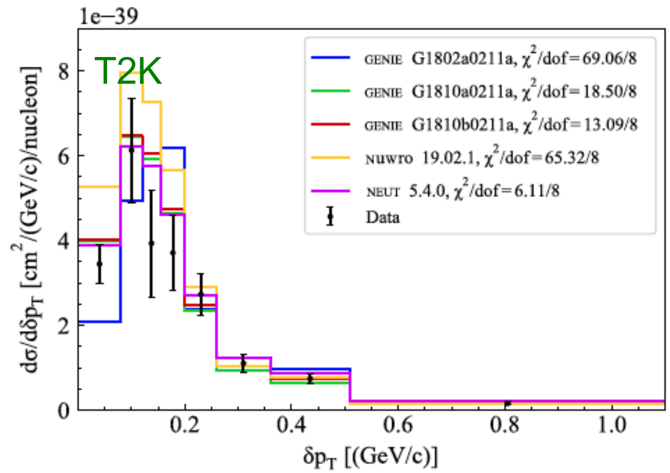
Transverse kinematic Imbalance (TKI) variables

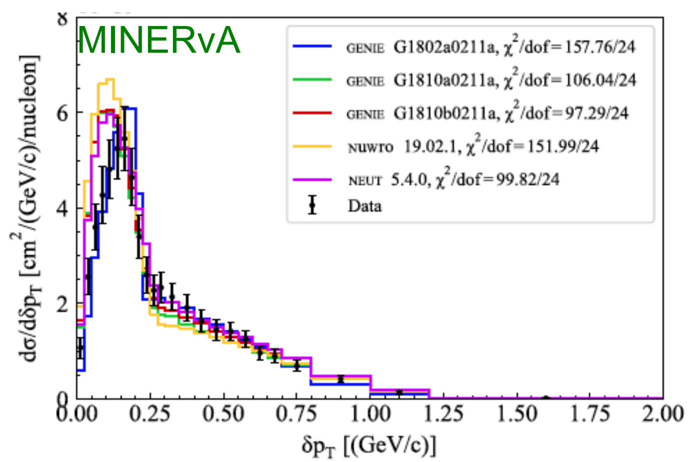
δP_T ~ nucleon momentum distribution

$\delta\alpha_T$ ~ FSI



nal.gov





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2. Generator implementation is our bottleneck

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

Hadron variables
- Visible hadronic energy deposit: E_{had}, E_{avail}
- Vertex activity
- Transverse kinematic Imbalance (TKI) variables

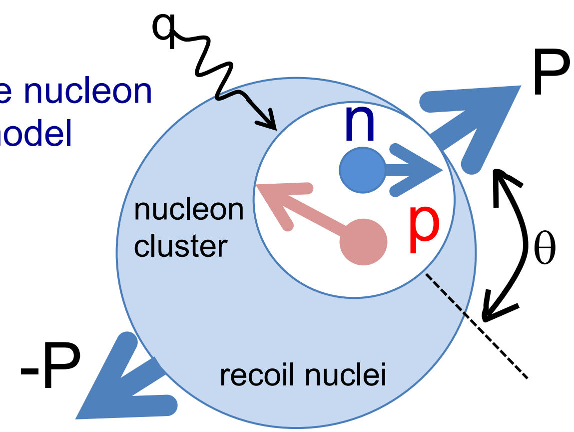
Hadrons are affected by FSIs
- Without implementing in generators, theoretical nuclear models cannot be compared with data
- Generator implementation is continuously a problem of our community

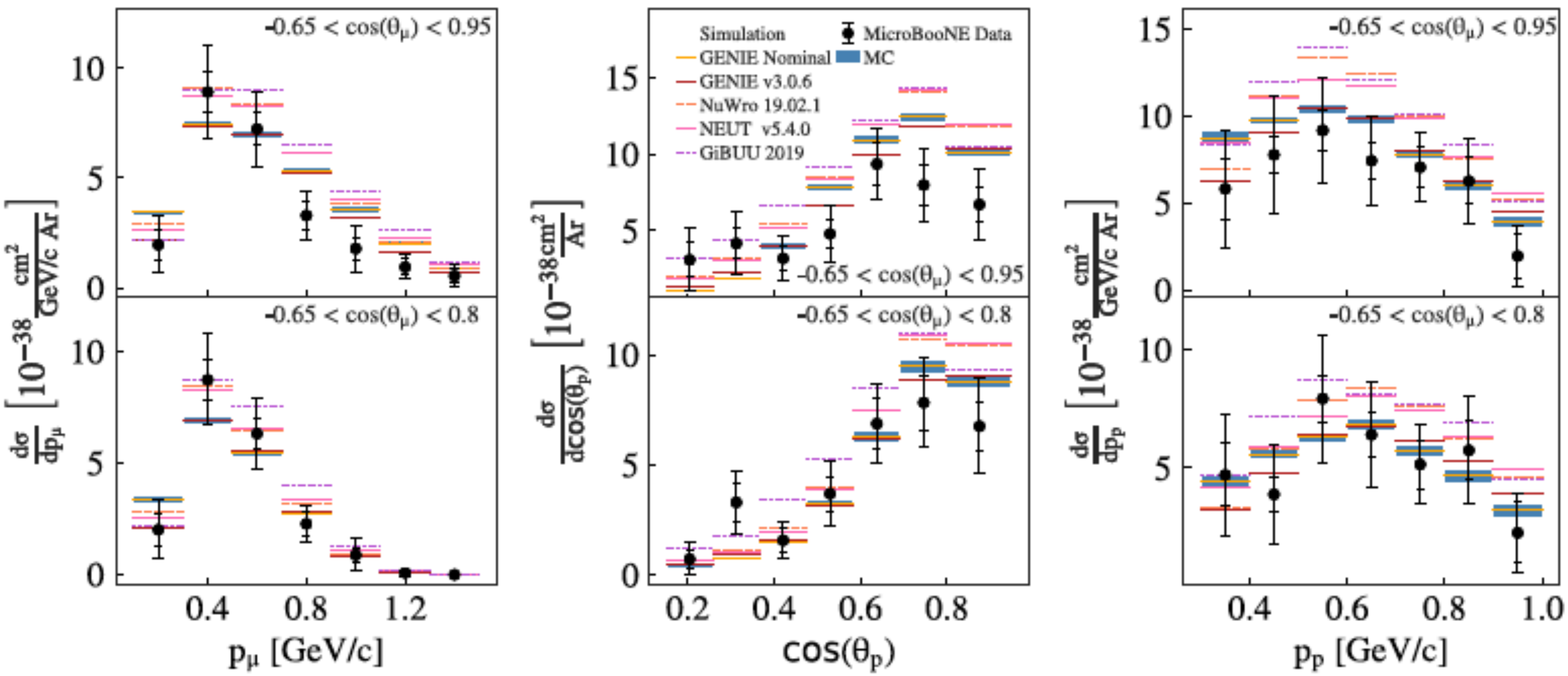
2. Nucleon correlations in neutrino physics

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

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

home-made nucleon emission model

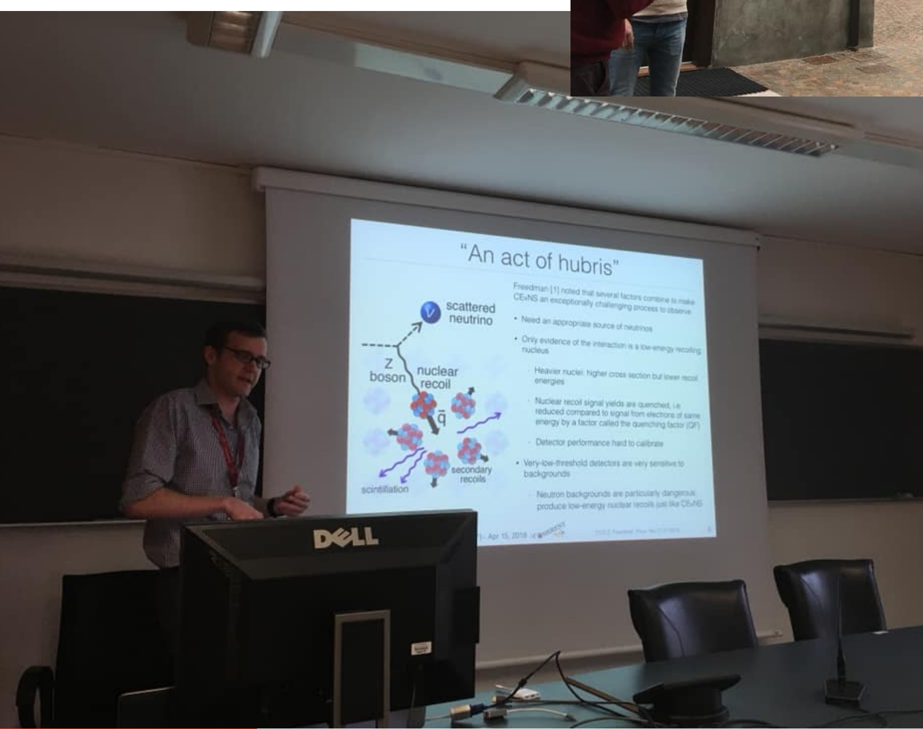




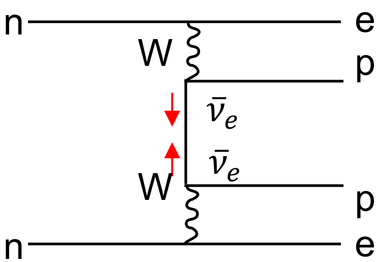
4. Atomic nuclei as laboratories for BSM physics

ECT* workshop, 15 Apr. 15-19 2019, Trento, Italy
https://www.ectstar.eu/workshops/atomic-nuclei-as-laboratories-for-bsm-physics/

Topics include;
- Neutrino interactions
- $0\nu\beta\beta$
- Direct dark matter
- EMC effect
- etc

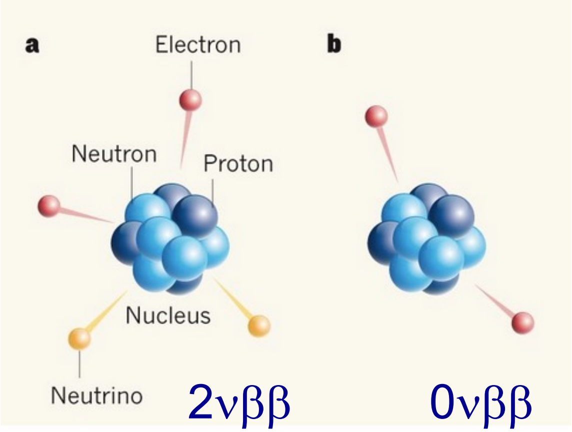


4. Neutrino-less double beta decay ($0\nu\beta\beta$)



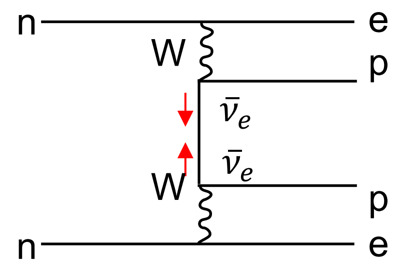
Majorana particle

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



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

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

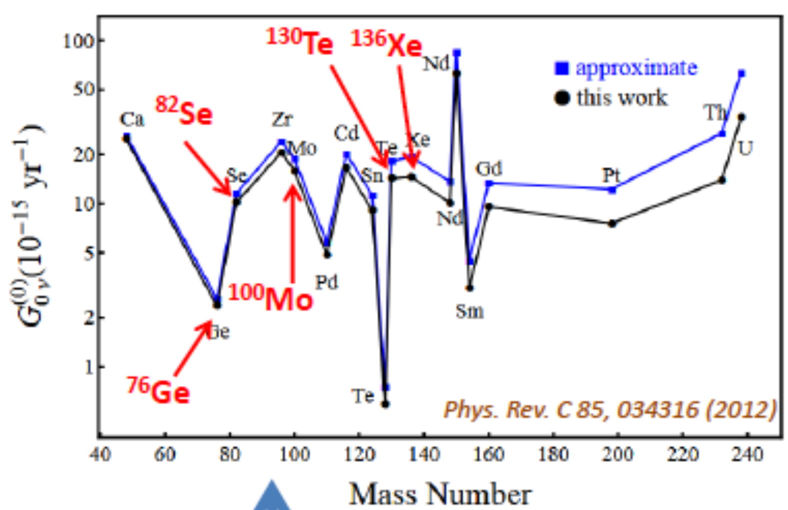


4. Neutrino-less double beta decay (0νββ)

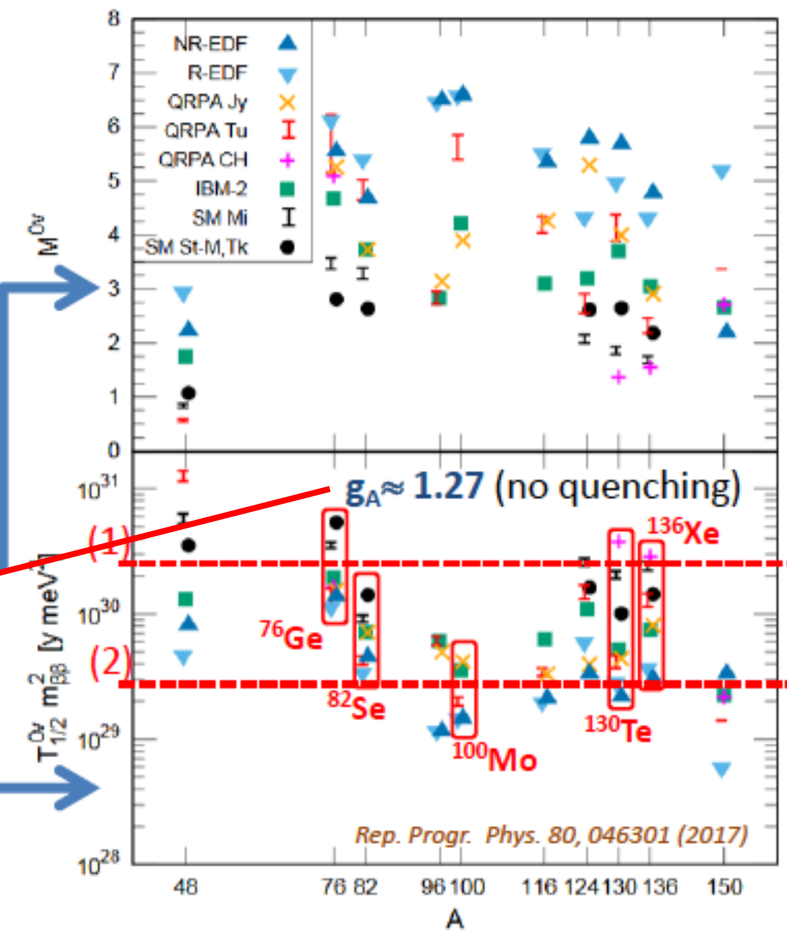
Majorana particle

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

Phase space: exactly calculable



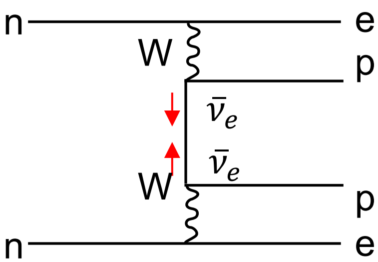
Nuclear matrix elements: several models



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

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

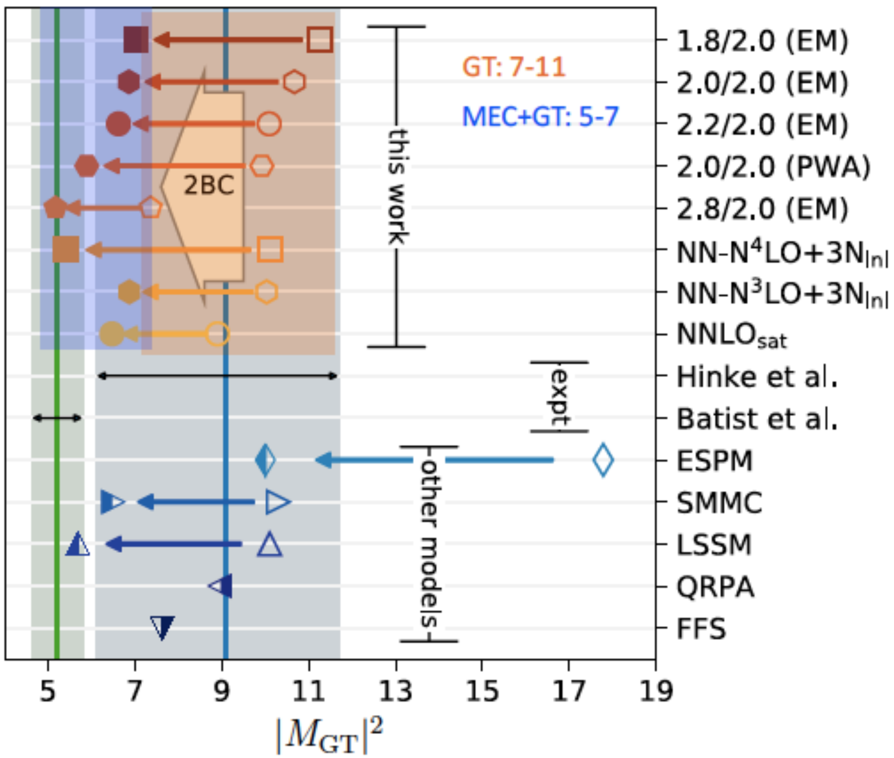
P. Gysbers, G. Hagen, et al, Nature Phys. 15(2019)428



4. Nucleon correlation and 0νββ

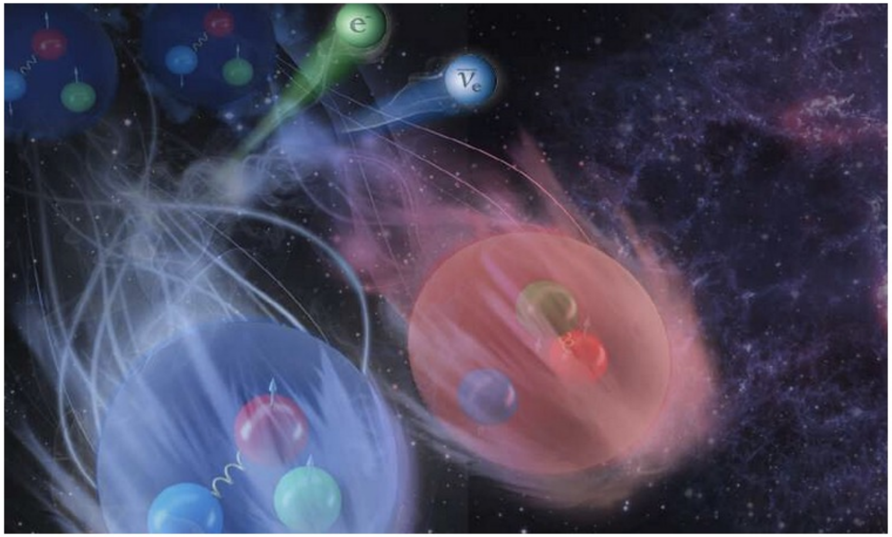
Beta decay quenching

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



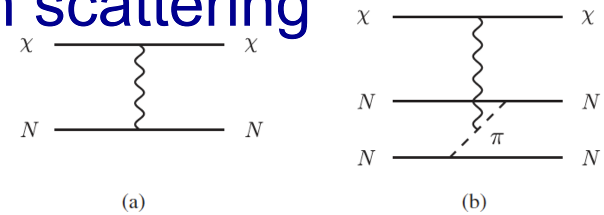
Physicists solve a beta-decay puzzle with advanced nuclear models

by Oak Ridge National Laboratory



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

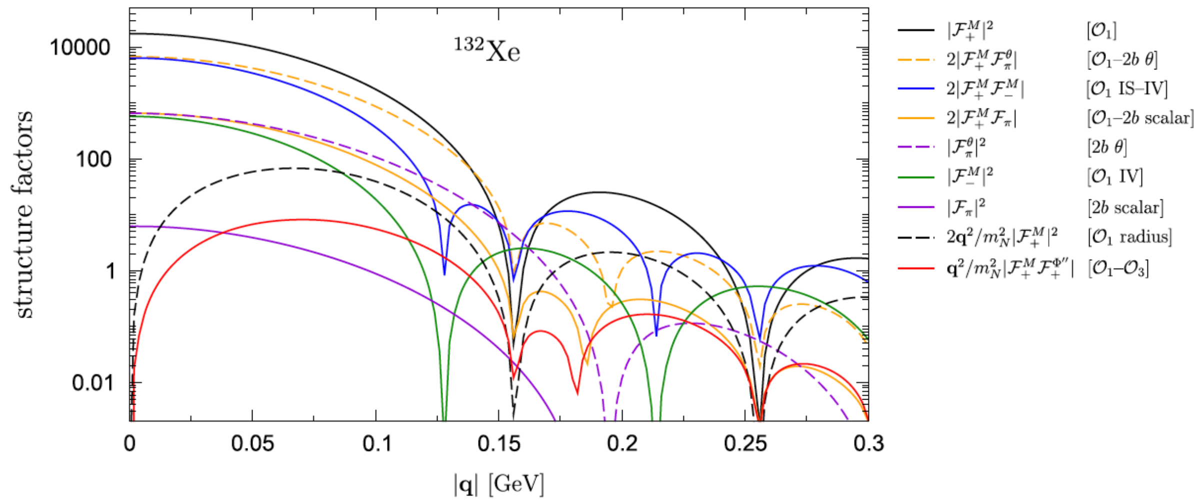
4. Nucleon correlation and Direct WIMP-pion scattering

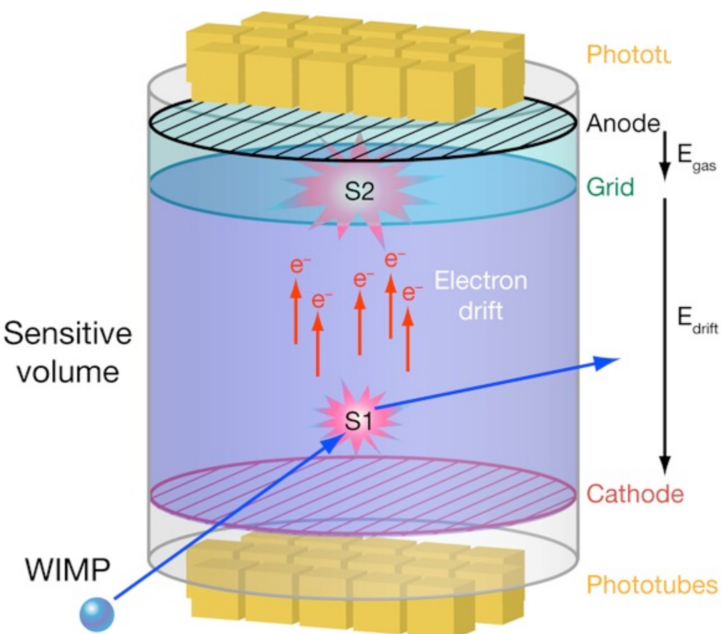


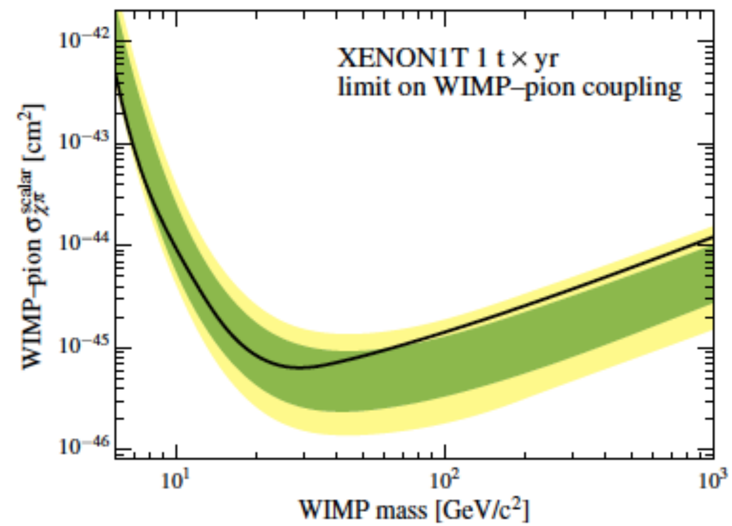
Direct WIMP-pion interaction

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

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

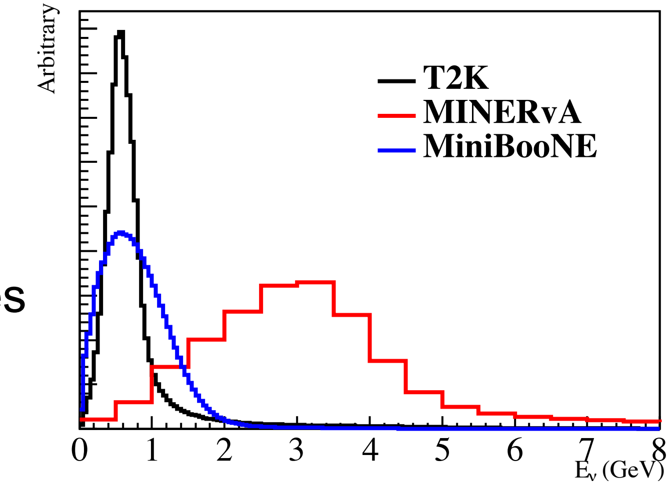






MiniBooNE, PRL100(2008)032301,PRD81(2010)092005:88(2013)032001

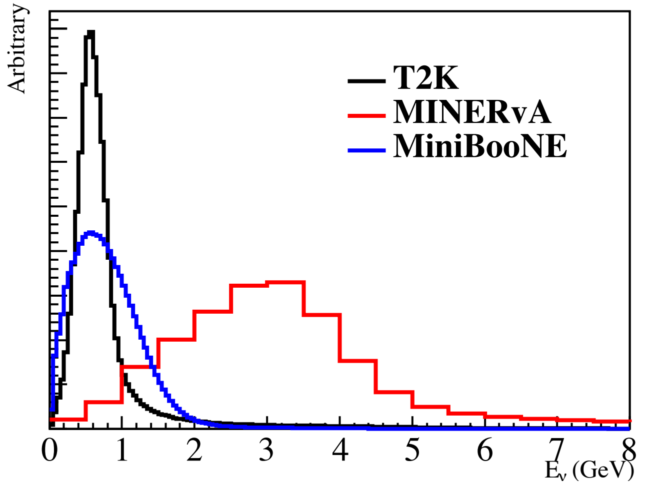
5. MiniBooNE



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)

5. MiniBooNE



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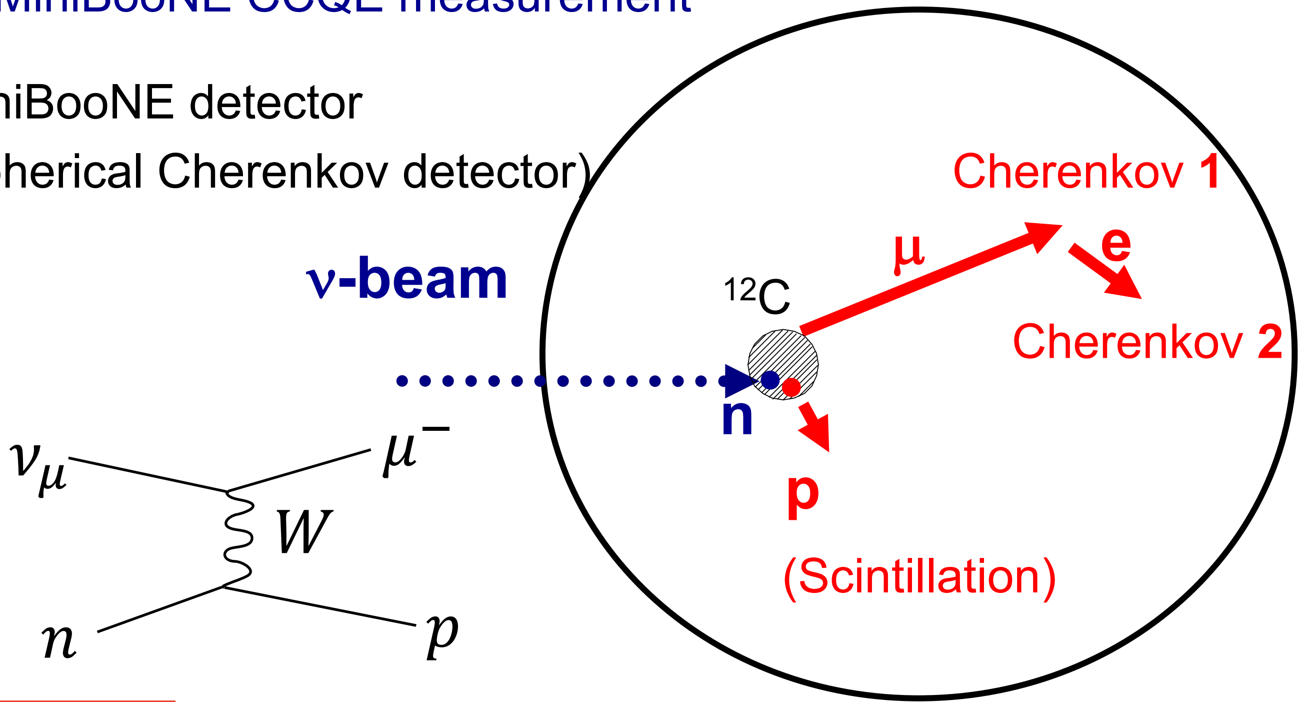
MiniBooNE CCQE measurement

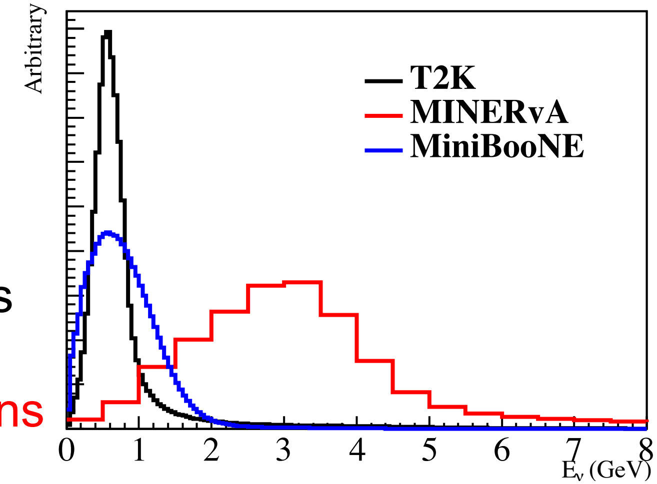
MiniBooNE detector
(spherical Cherenkov detector)



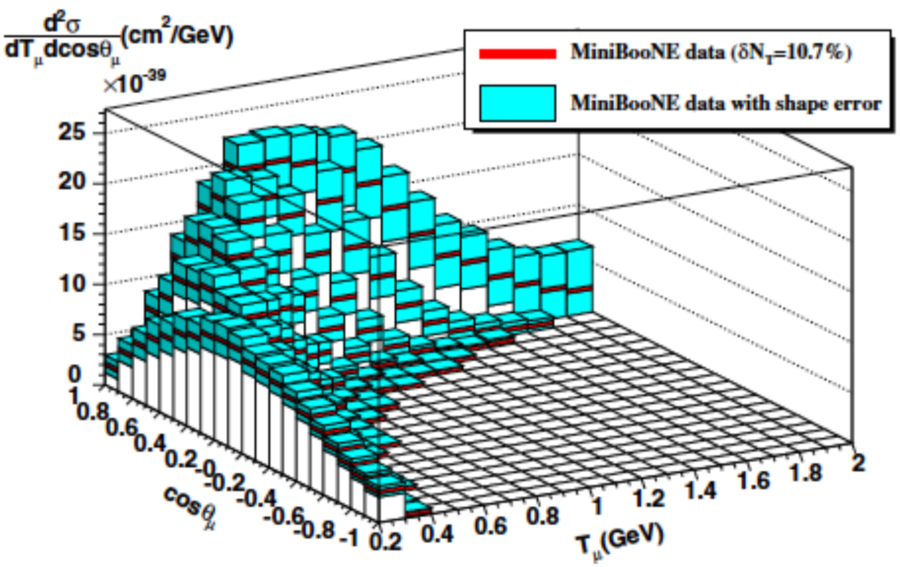
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

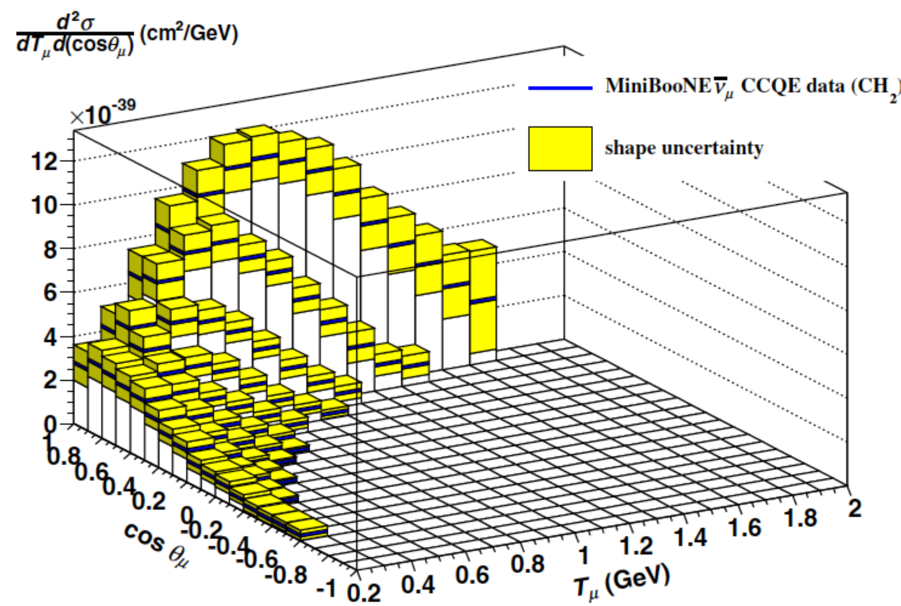
5. MiniBooNE

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



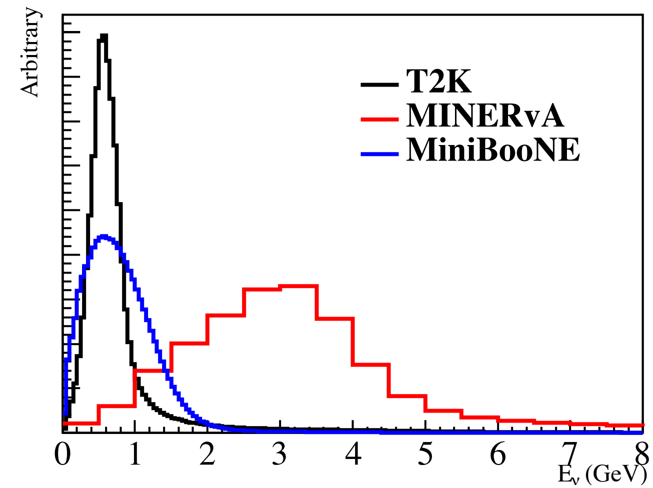
neutrino and anti-neutrino CCQE-like double differential cross sections

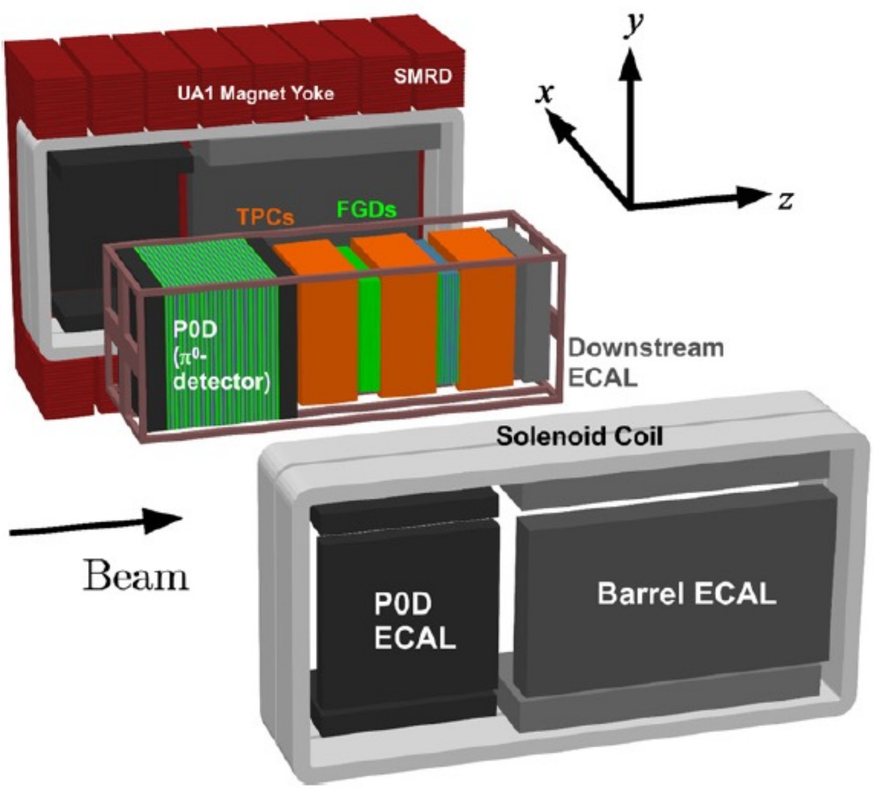


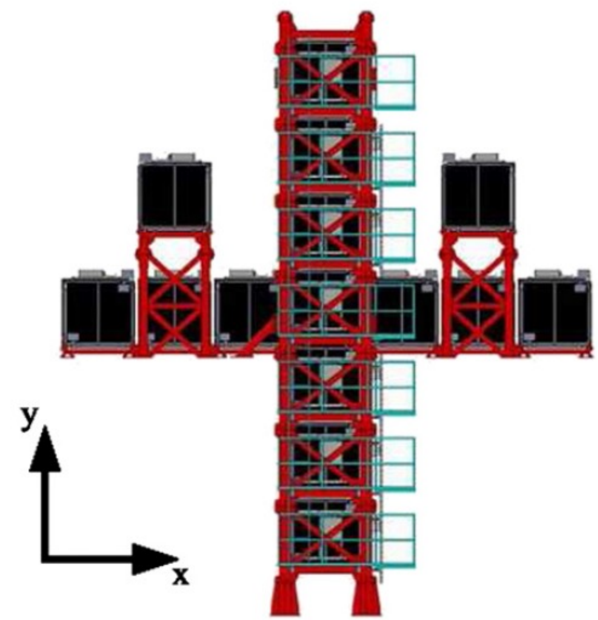


5. T2K near detector complex

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)







T2K, NIMA659(2011)106, T2K,PRD93(2016)112012

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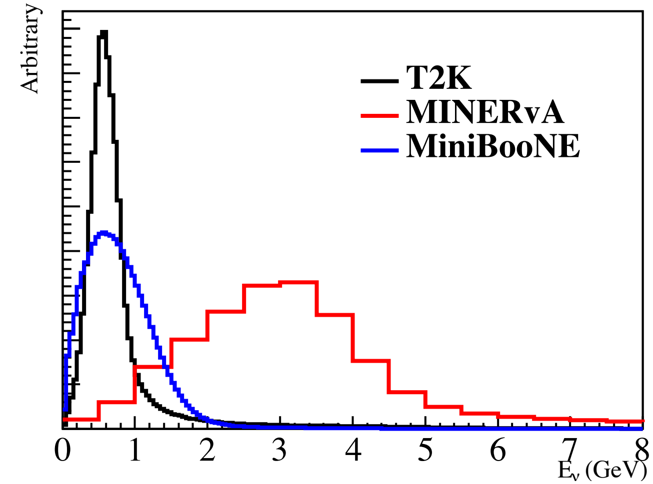

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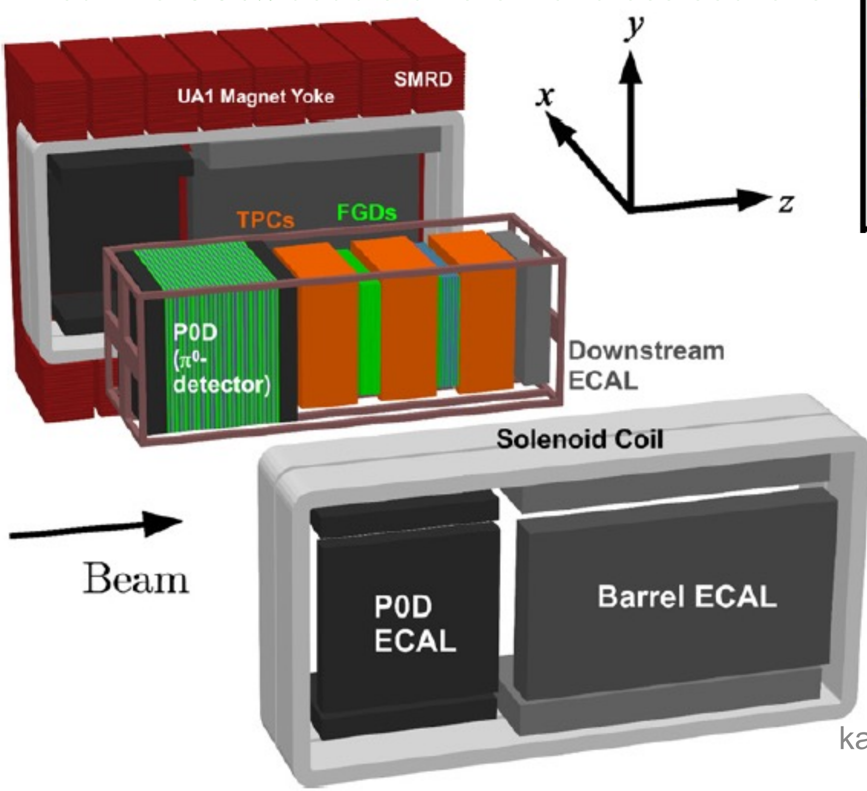
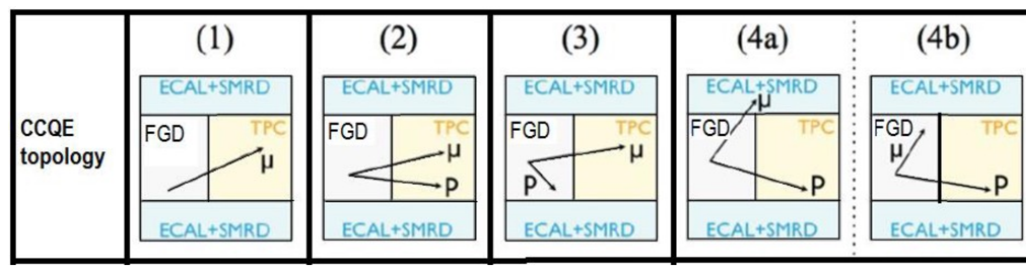
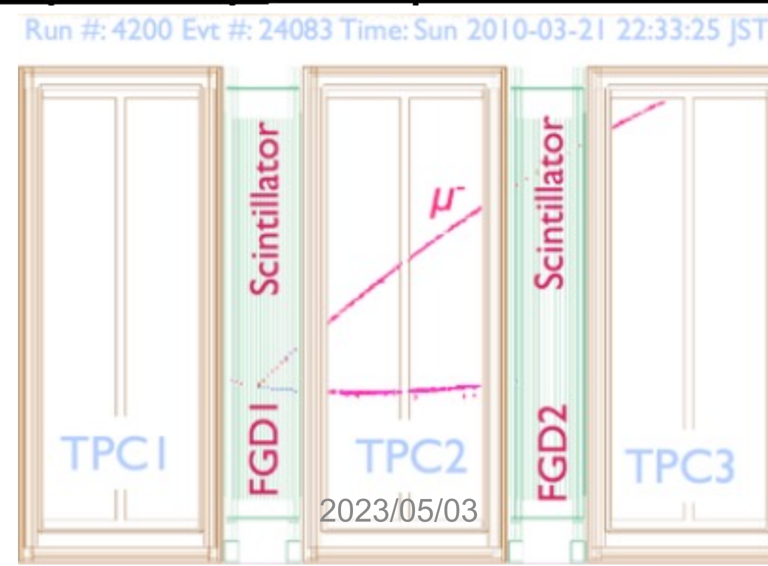
neutrino CC0π double differential cross sections







T2K, NIMA659(2011)106, T2K,PRD93(2016)112012

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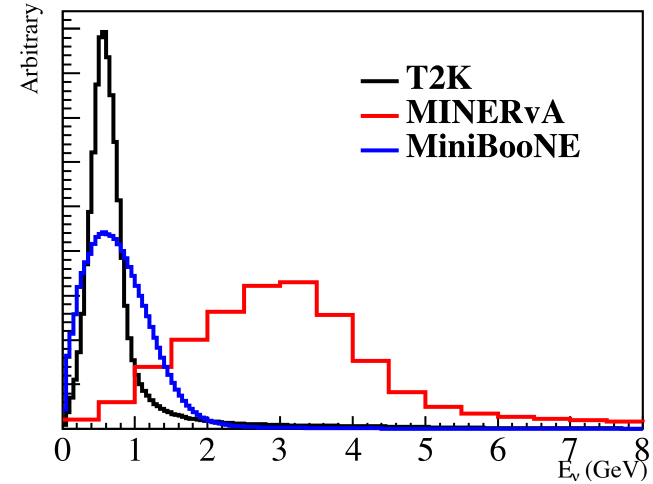

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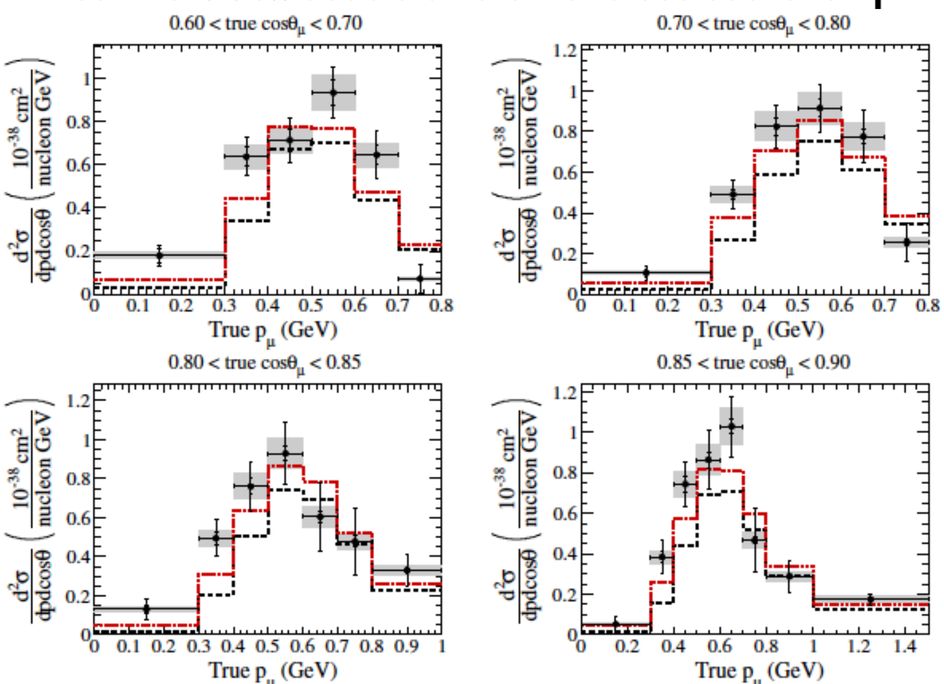

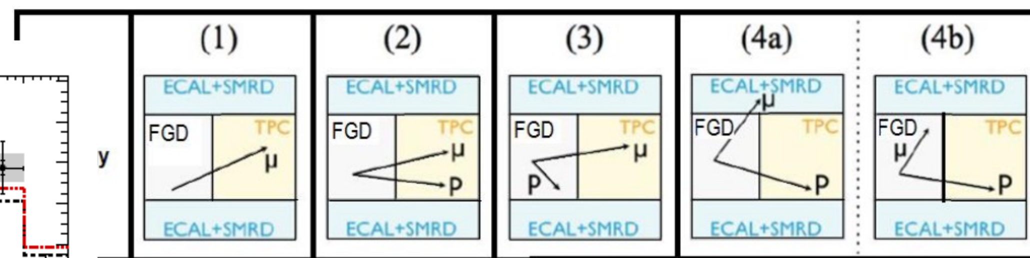

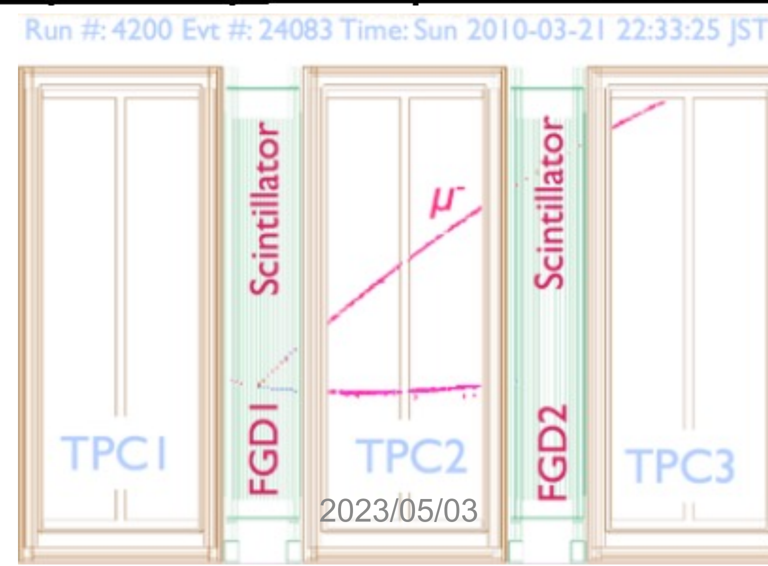

T2K, NIMA659(2011)106, T2K,PRD93(2016)112012
PRD98(2018)032003

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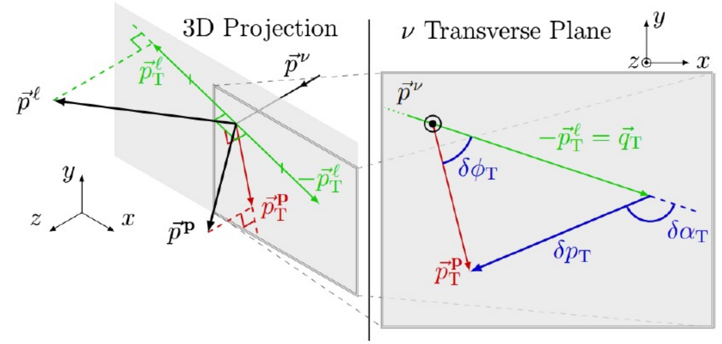

INGRID, FGD, P0D, ECal, TPC, SMRD

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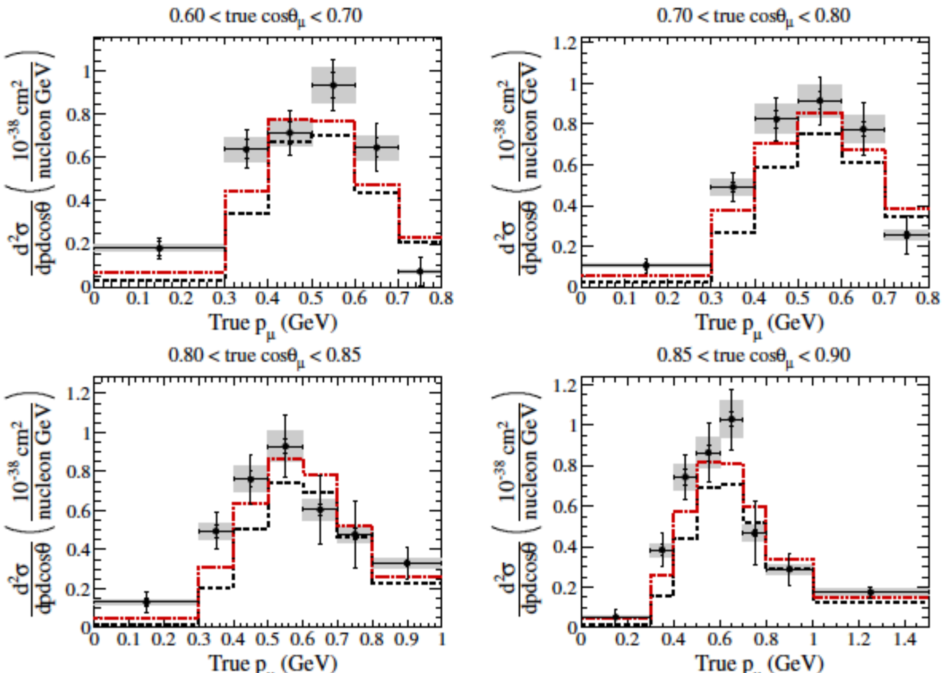
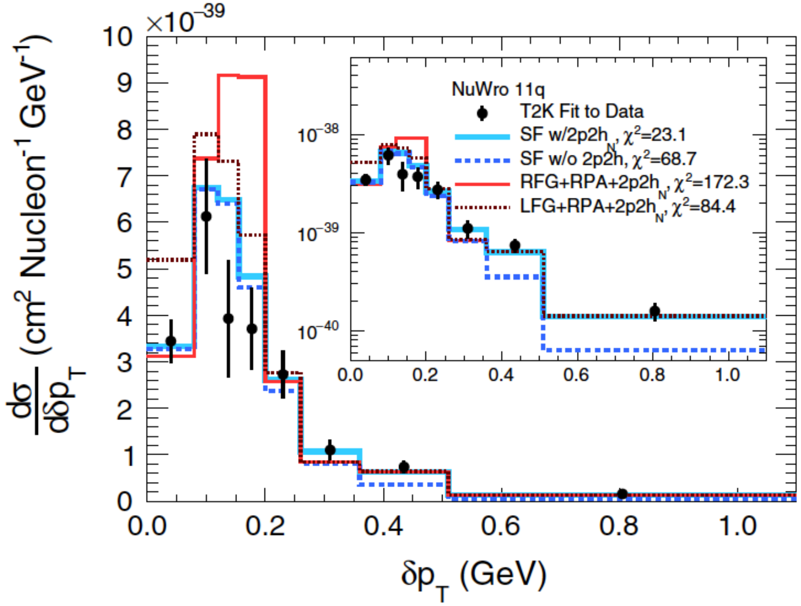
neutrino CC0π double differential cross sections



neutrino CC0π1p differential cross sections



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

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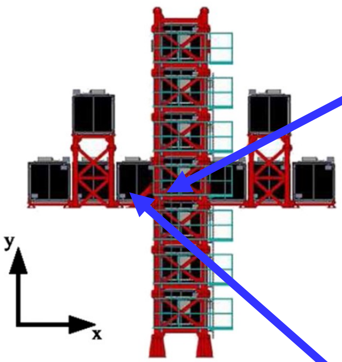
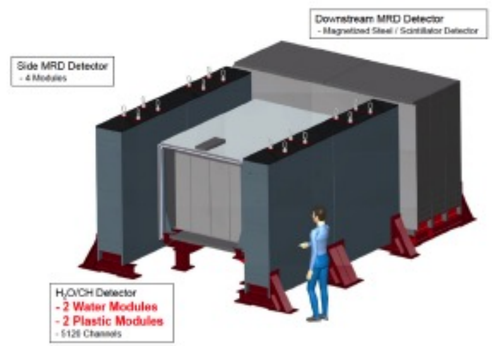
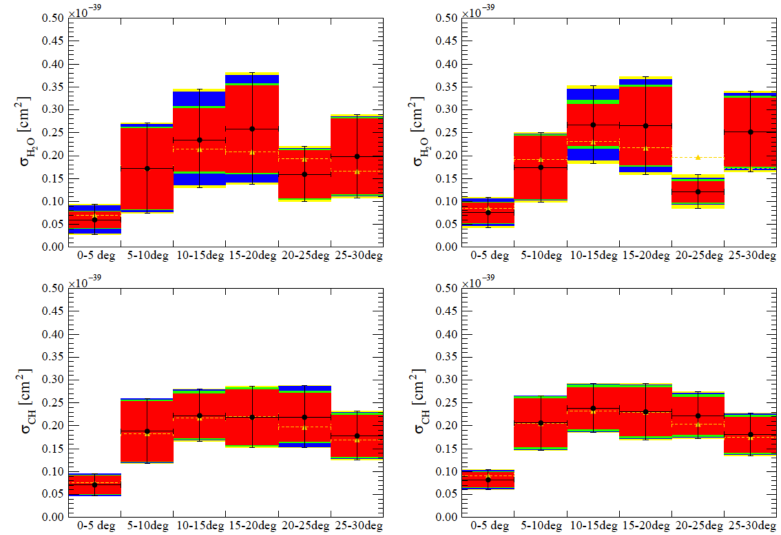
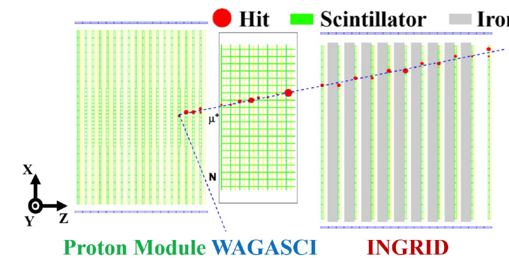


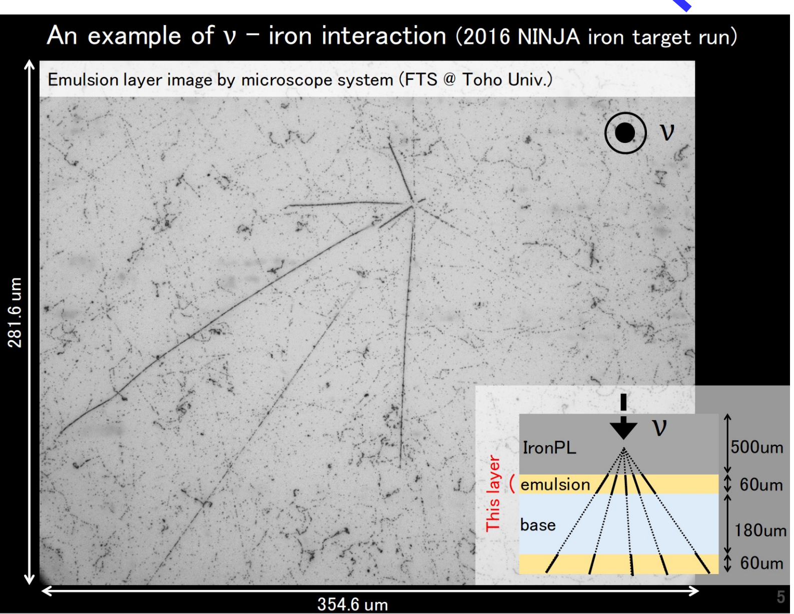
WAGASCI
- water target

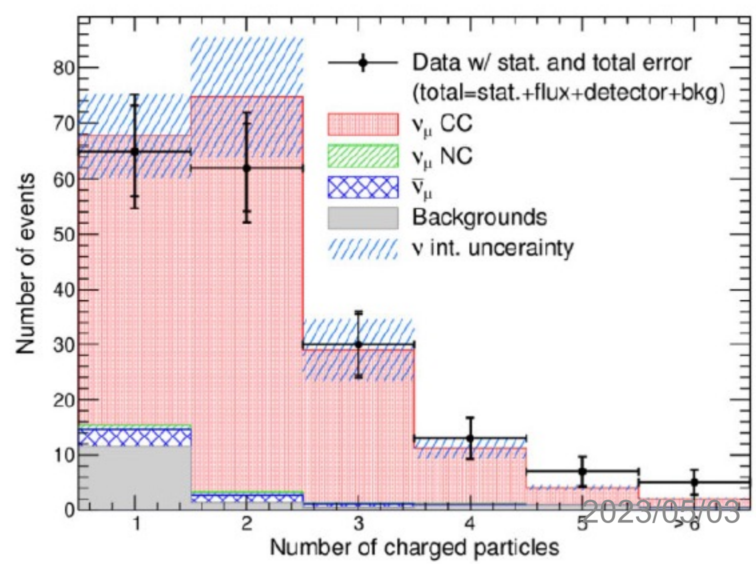






NINJA
- emulsion detector
- Multiple hadron tracks





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

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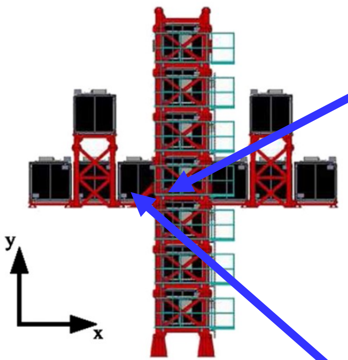

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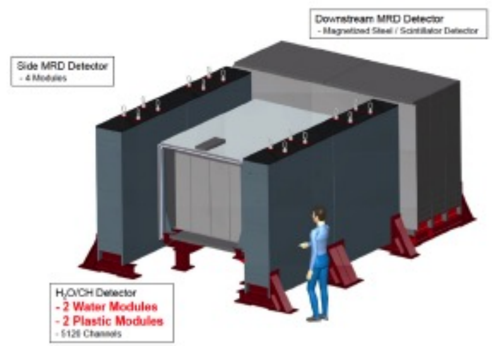

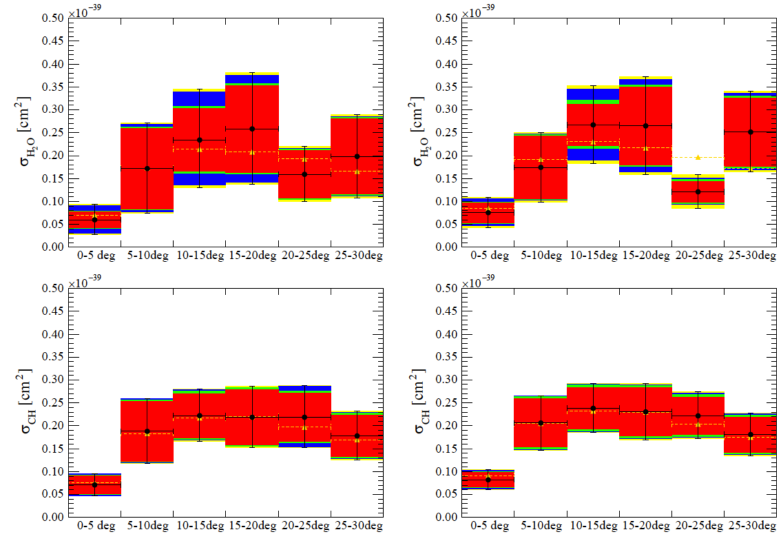

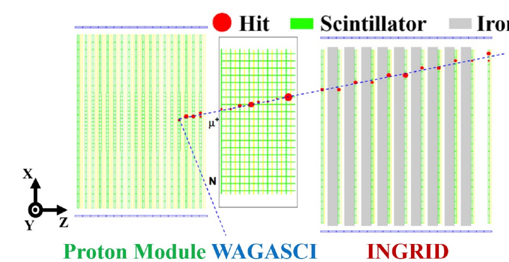

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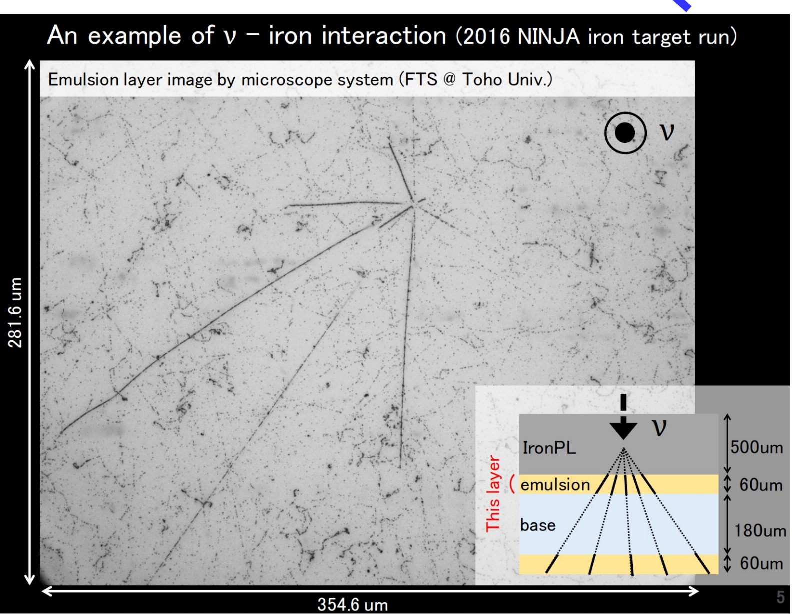
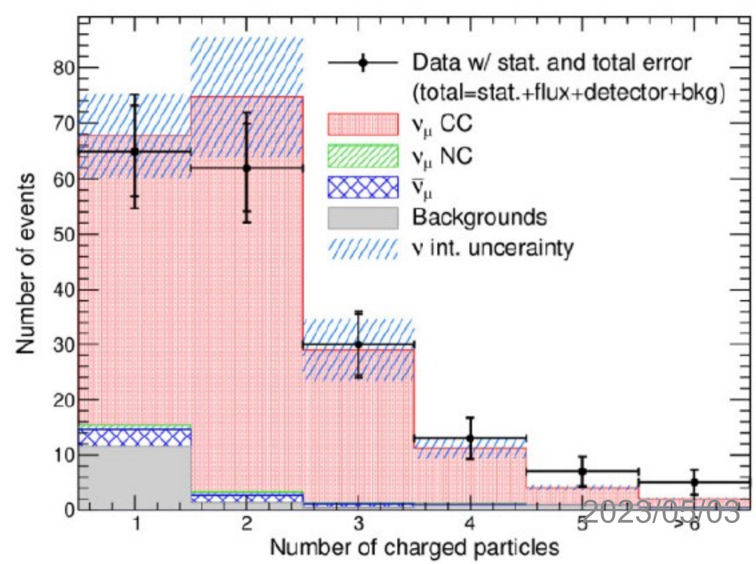
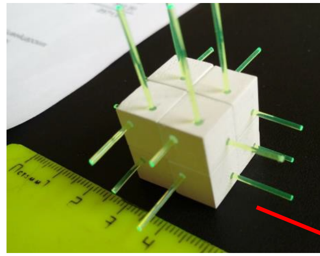
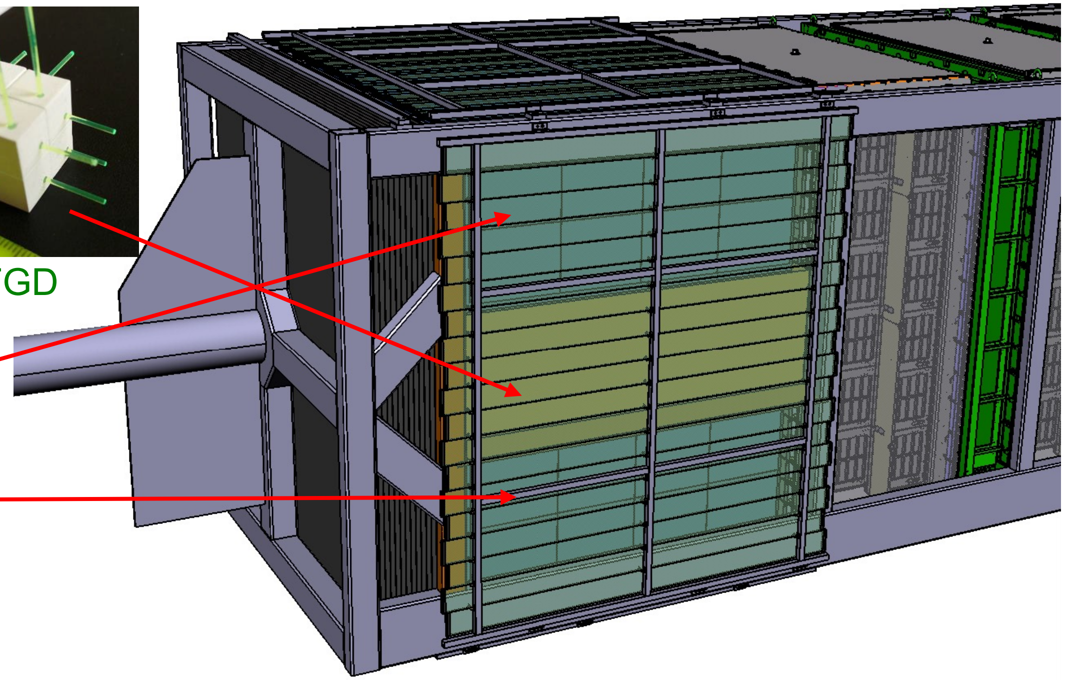




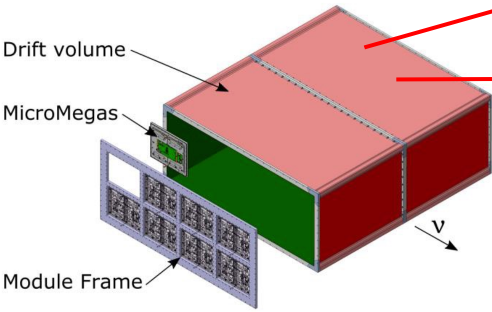
5. ND280 Upgrade



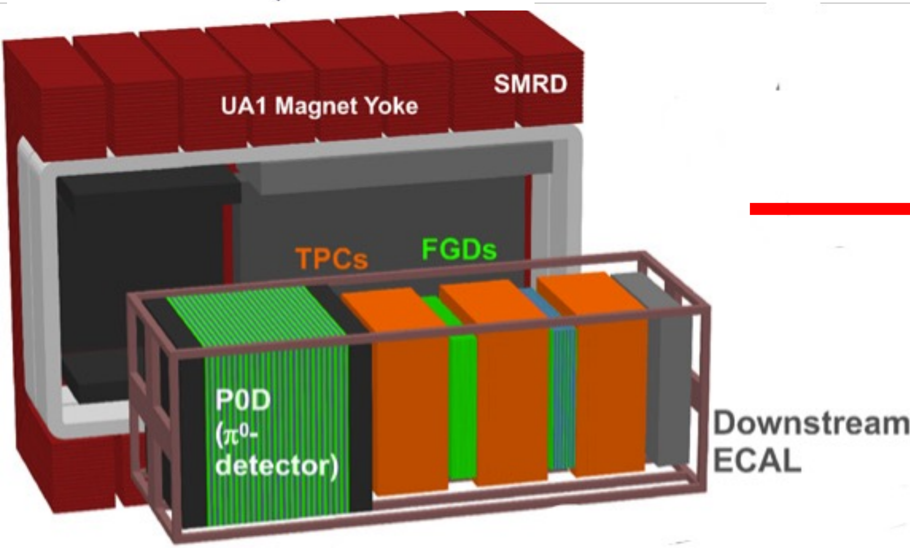
SuperFGD

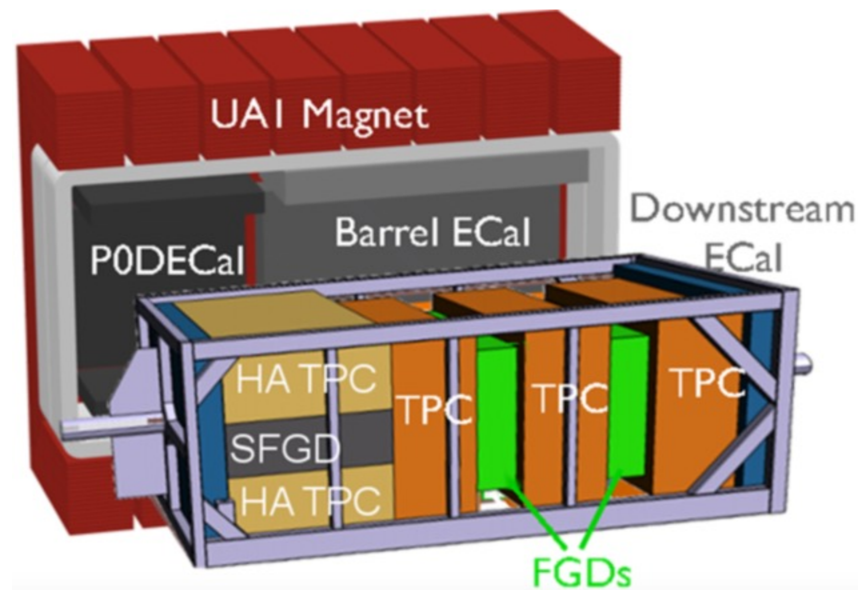


ND280 Upgrade
- Out: P0D detector
- In: High Angle TPC (HATPC)
- In: SuperFGD



High Angle TPC



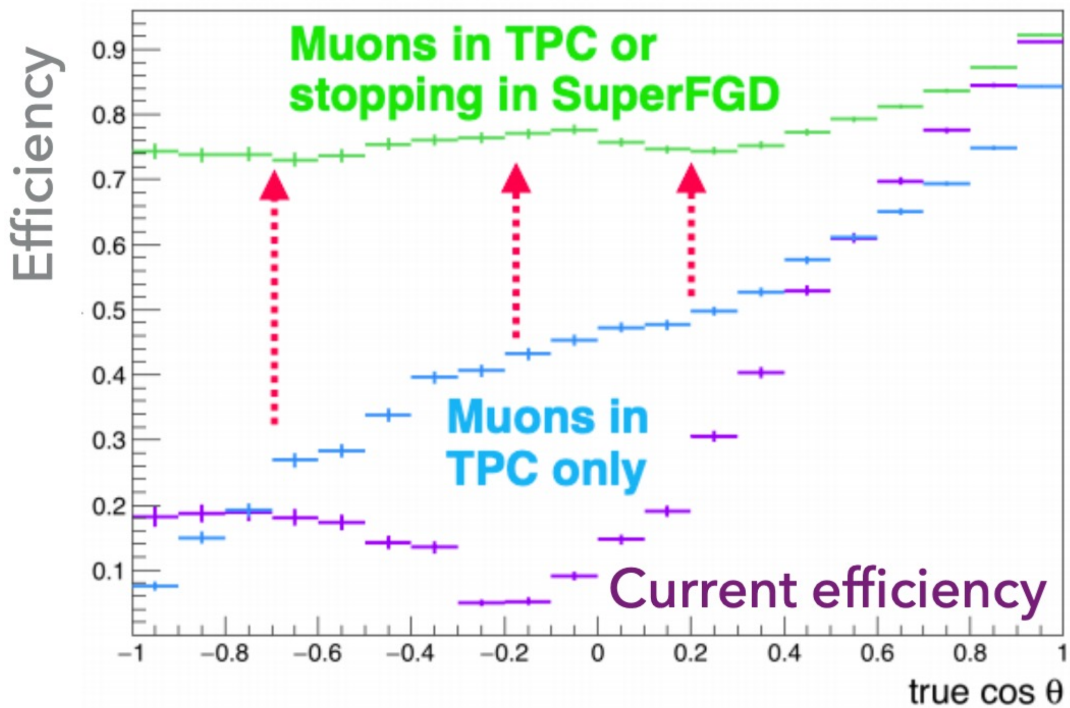


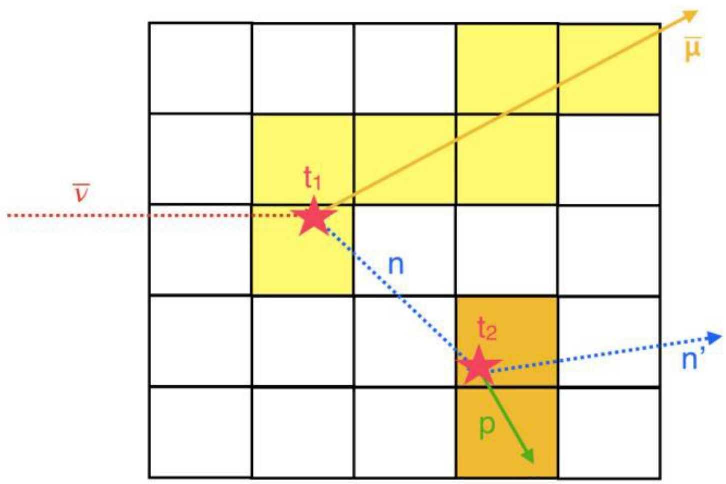
5. ND280 Upgrade

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

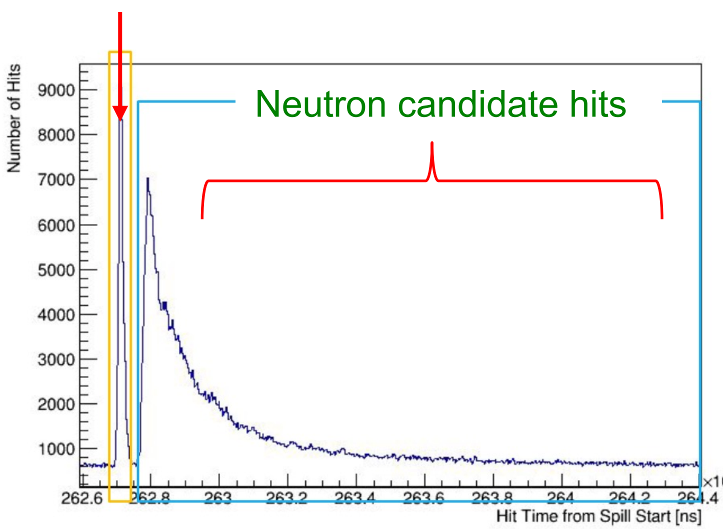
4π coverage
- It matches with Hyper-K phase space

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





t_0 (γ-ray)

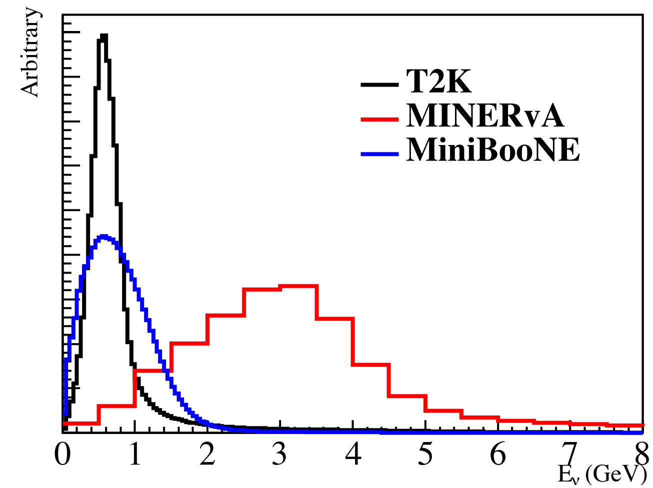


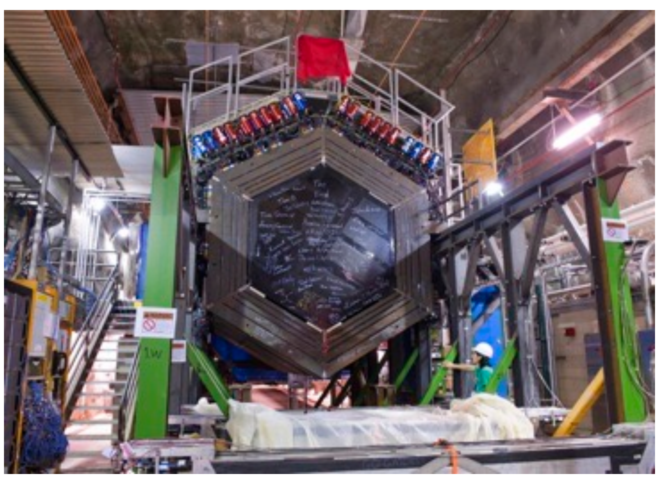
MINERvA, PRL111(2013)022501:022502

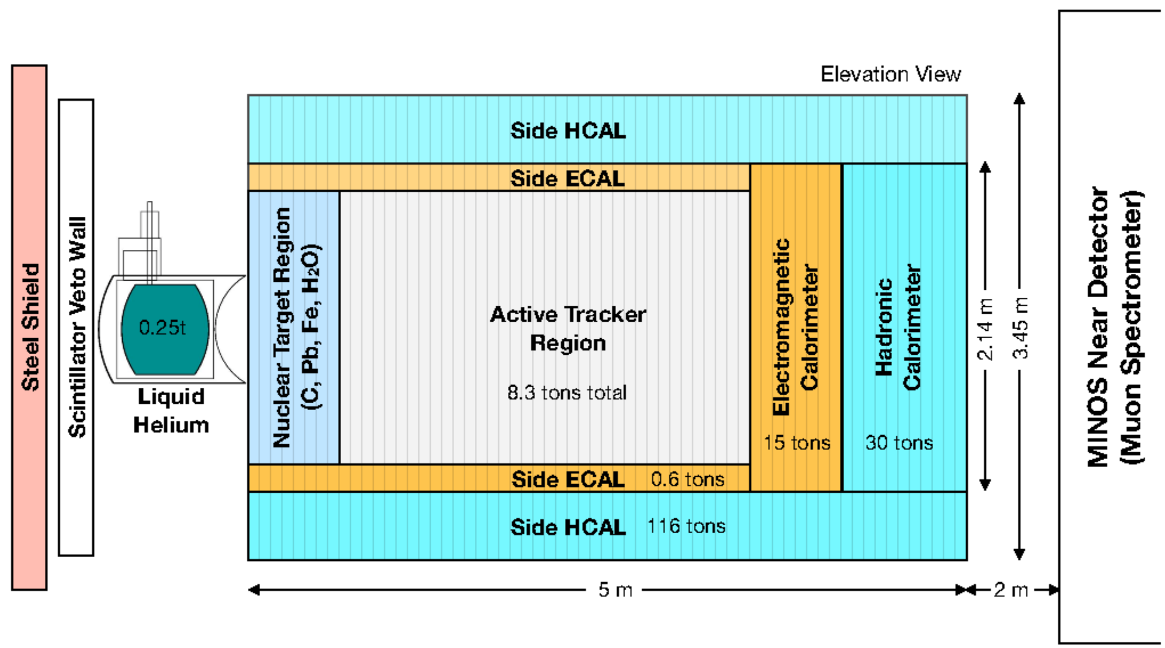
5. MINERvA

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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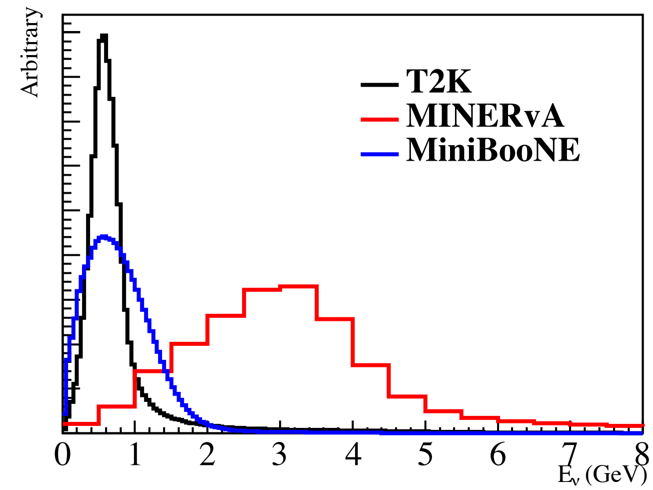

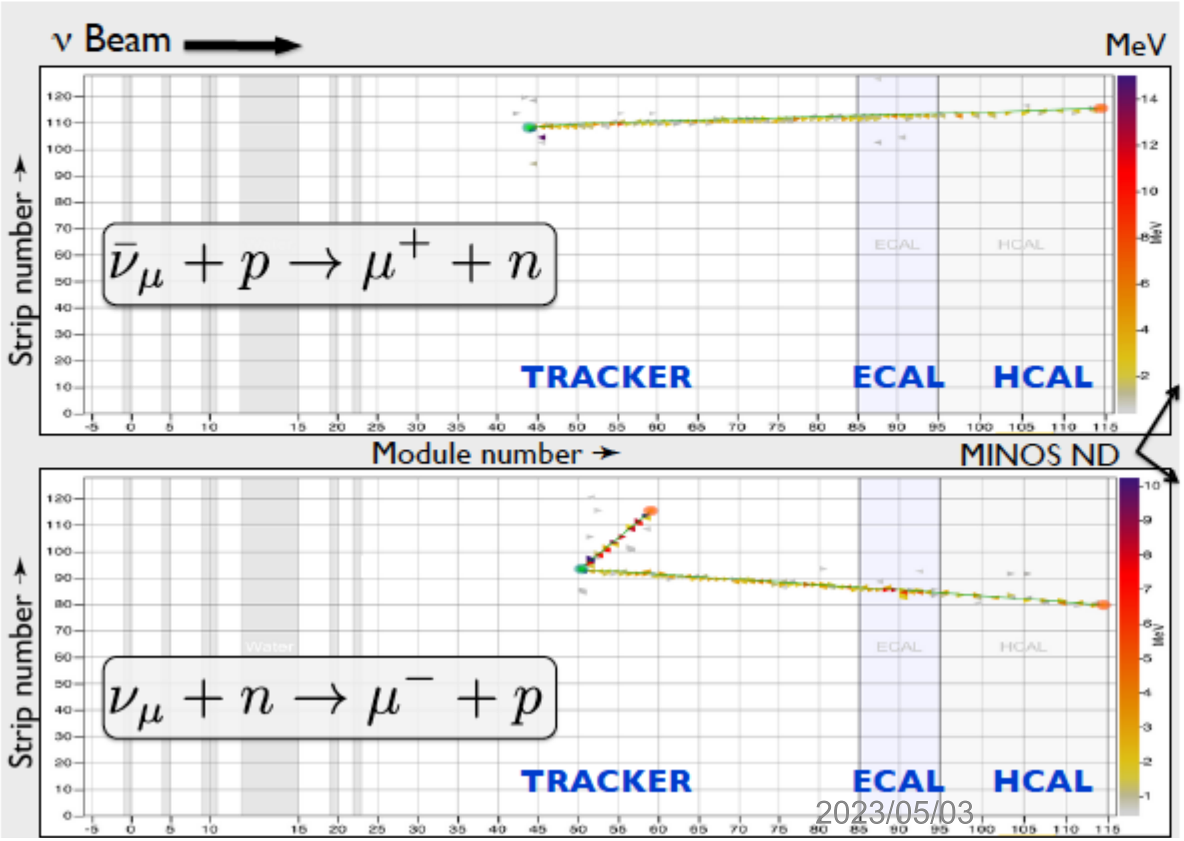

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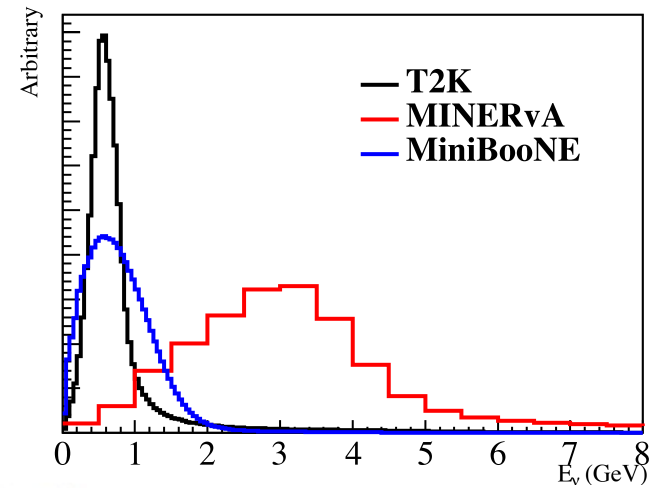

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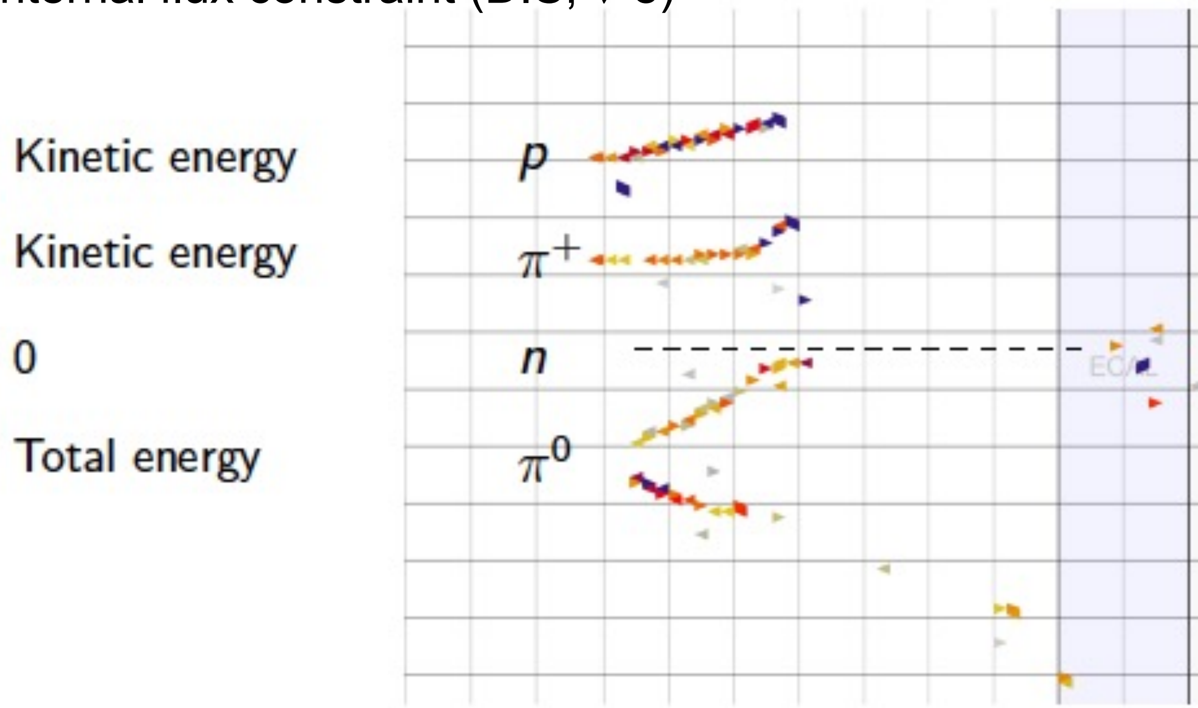


Beam test + better scintillator
→ good hadron measurement
→ kinematics is completely fixed

model-dependent

visible hadron energy
↓
total hadron energy
↓
Eν
↓
Q2

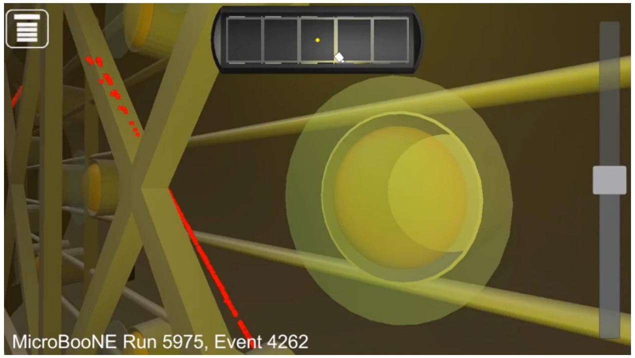
On average, we see *available* hadronic energy $E_{\mathrm{avail}} \neq q_0$:

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

MicroBooNE, JINST12(2018)PO2017
VENu, http://venu.physics.ox.ac.uk/

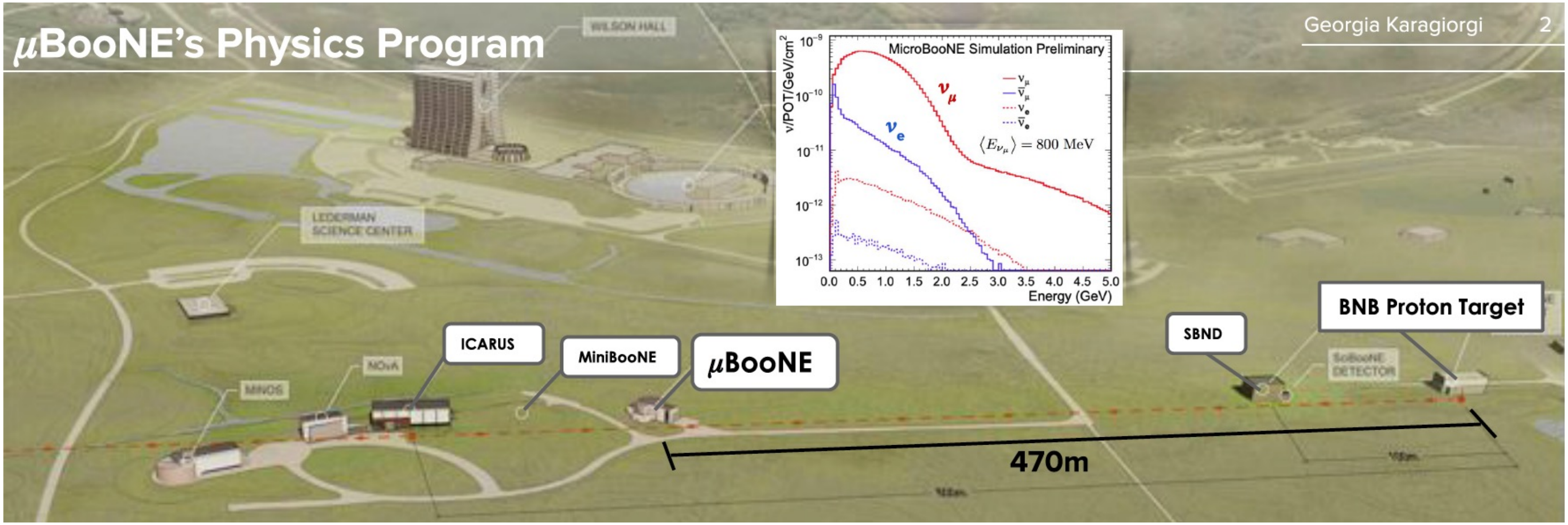
5. MicroBooNE

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



86ton LArTPC

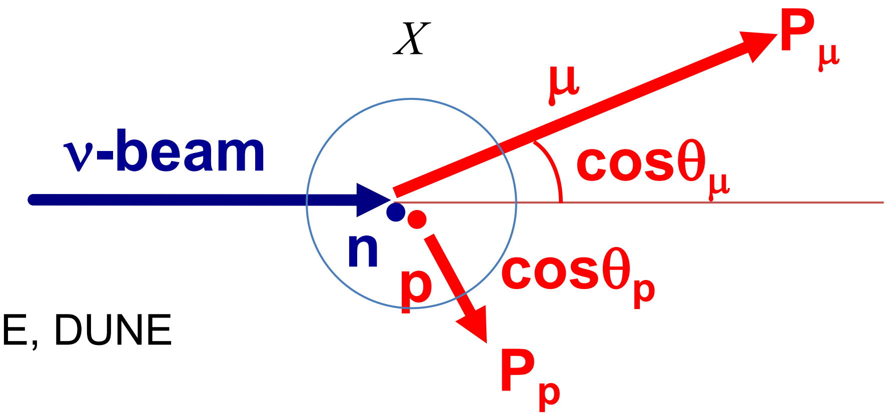
- <E>~800 MeV BNB on-axis beam
- Single phase LArTPC, 3-wire-plane reading
- 3mm pitch
- photon detection system
- ArgoNeuT, LArIAT, SBND, ICARUS, protoDUNE, DUNE



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