Neutrino-Nucleus Interactions and Oscillations

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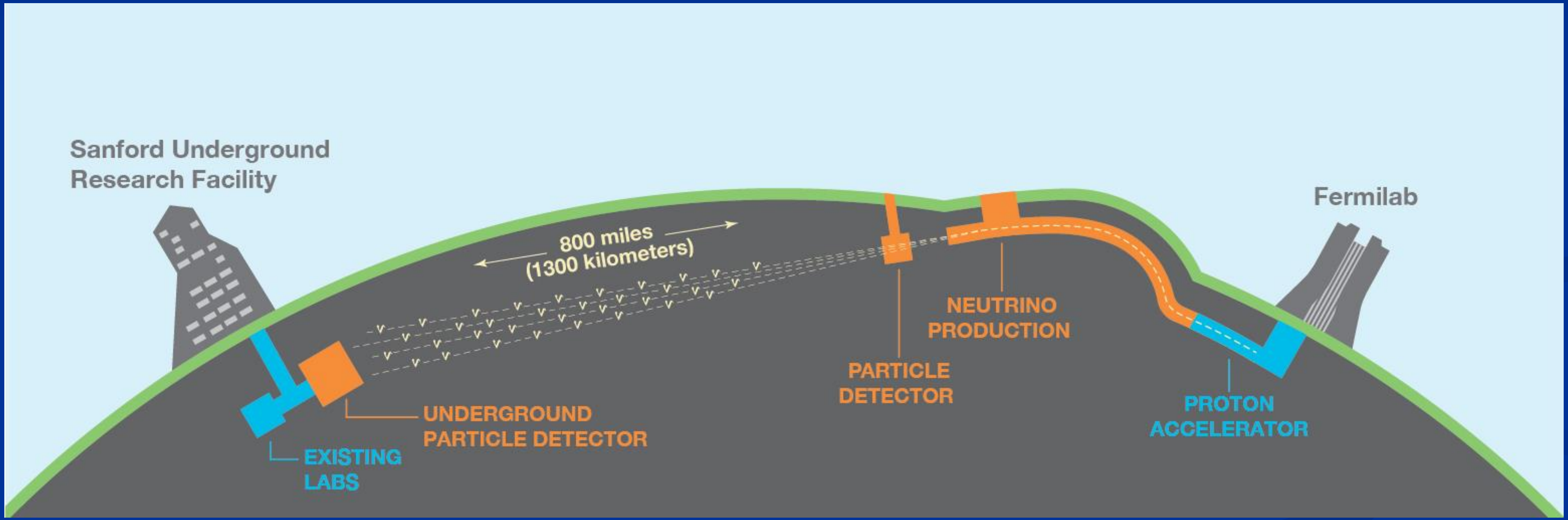
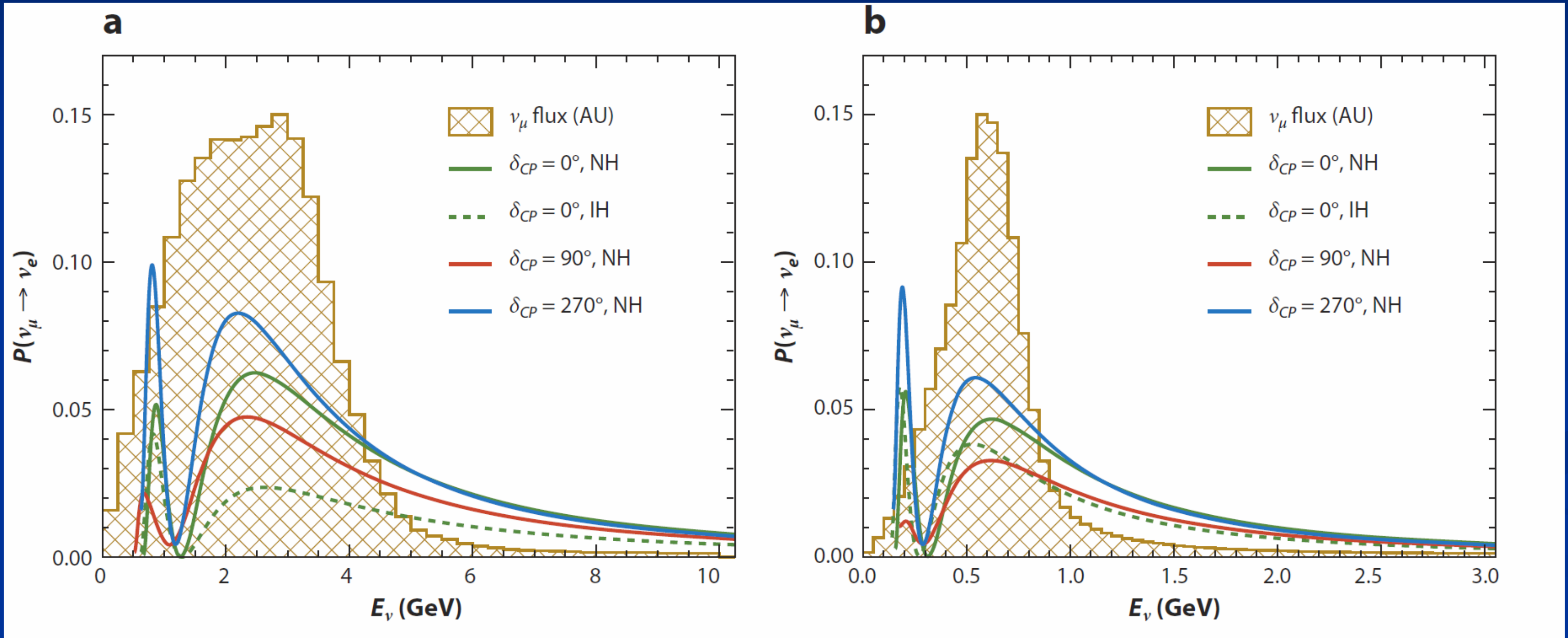
Long-Baseline Experiment: T2K and NOvA

Future (2027): DUNE



$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4 E_\nu}\right)$$



DUNE, 1300 km

HyperK (T2K) 295 km

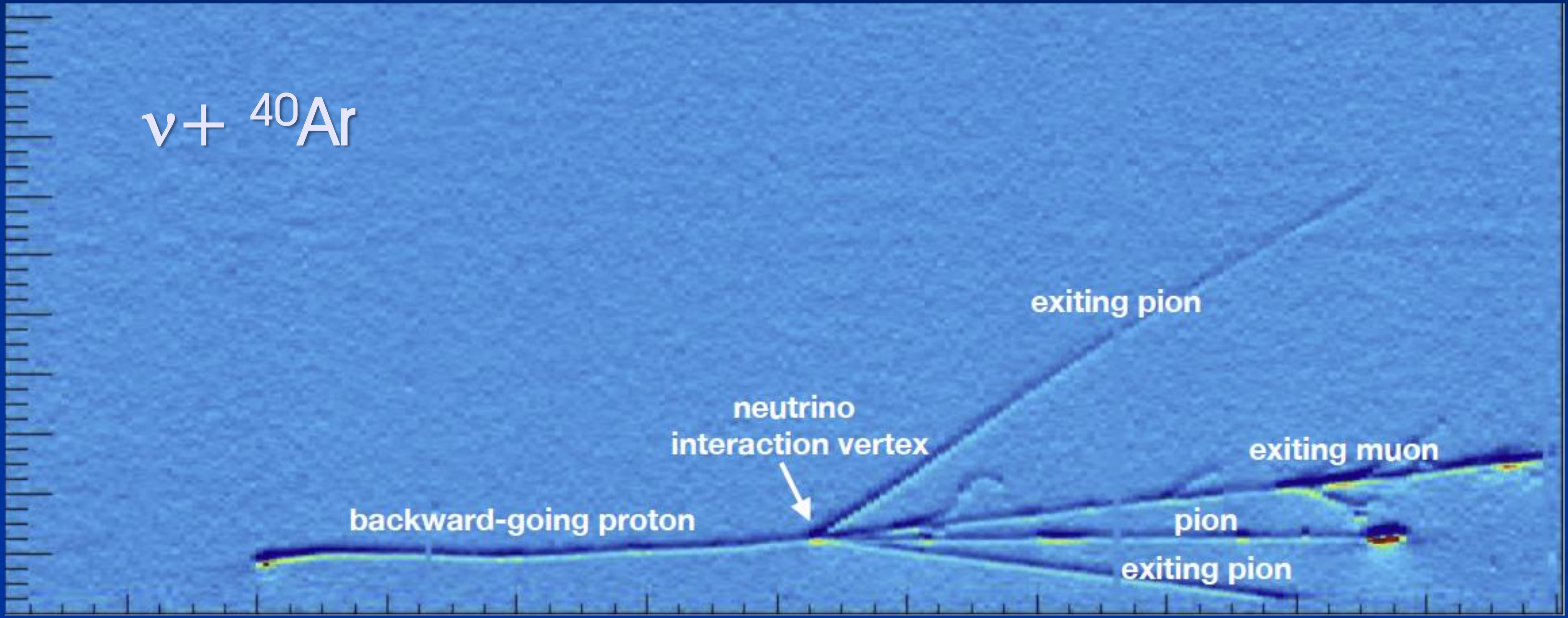
From:
Diwan et al,
Ann. Rev.
Nucl. Part. Sci 66
(2016)

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

Neutrinos on Nuclei

ArgoNeut Experiment

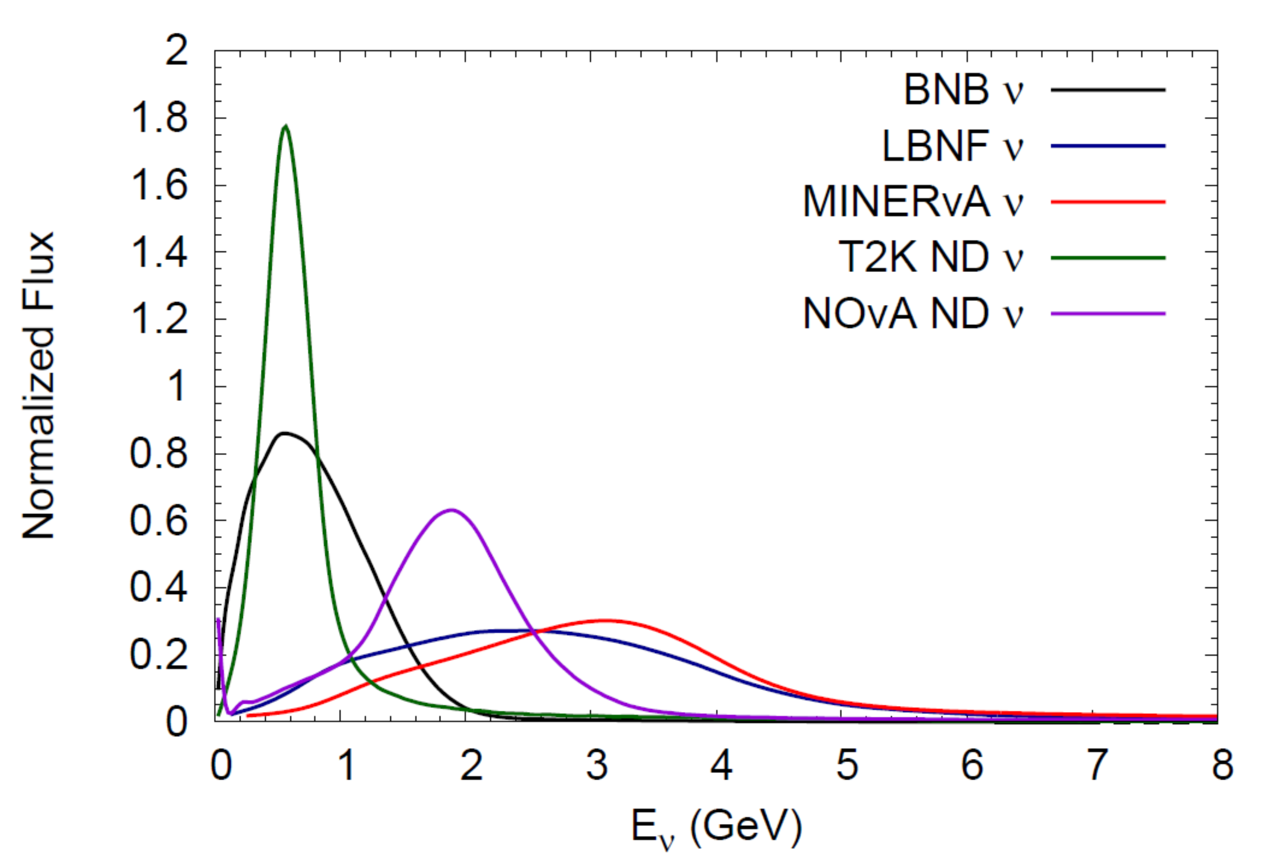


What is the ingoing state? Composition? Energy?

Oscillations and Neutrino Energy

PROBLEM:
Neutrinos are produced as secondary decay products of high-energy pA collisions

➔ They have broad energy distributions
Difference to any other high-energy and nuclear physics experiment!
LHC: $\Delta E / E \sim 0.1\ \%$



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Neutrino-Oscillations

Simplified: 2 Flavors only

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4 E_\nu} \right)$$

Energy must be reconstructed from hadronic final state, observed in less-than-perfect detectors
➔ Compute backwards from final state to incoming neutrino

Reaction mechanism must be known for reconstruction:
Nuclear Physics is essential, because targets are nuclei

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νA Reaction

- General structure: **approximately** factorizes

full event (four-vectors of all particles in final state)

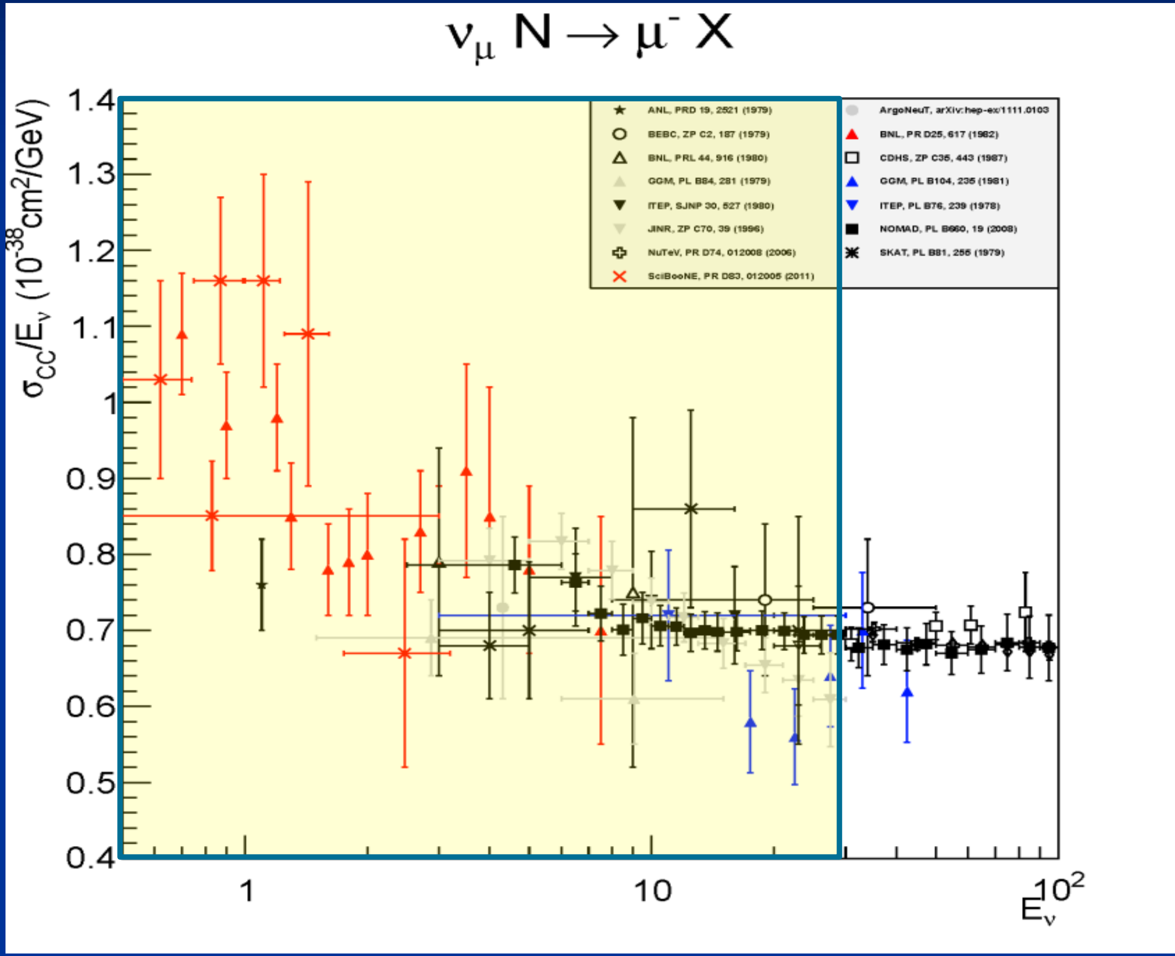
$$\cong$$

initial interaction *x* final state interaction

Determines inclusive X-section

Determines the final state particles

Neutrino-Nucleon Cross Sections



Experimental error-bars directly enter into nuclear cross sections and limit accuracy of energy reconstruction

BUT: this is only part of the problem,
The other part is FSI, since experiments use nuclear targets: H_2O (T2K), CH (NovA), Ar40 (DUNE)

Neutrino Cross Sections: Nucleus

- All targets in long-baseline experiments are nuclei: C, O, Ar, Fe
- Cross sections on the *nucleus*:
  - QE + final state interactions (fsi)
  - Resonance-Pion Production + fsi
  - Deep Inelastic Scattering → Pions + fsi
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and coh. pion production

Need for a Generator

- Need the full event for energy reconstruction
- Need to ‚compute backwards' from final state to initial incoming neutrino energy
- Need initial neutrino-nucleon interactions and hadron-hadron final state interactions
- Need to do this in the energy range 0 – 30 GeV

- All generators presently used (GENIE, NEUT) contain outdated nuclear physics (Fermi-Gas, no nuclear binding, Rein-Segal for resonances, crude fsi)

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- GiBUU was constructed with the aim to encode the „best possible“ theory: gibuu.hepforge.org
- „BEST POSSIBLE“ requires
  - All neutrino energies, -> relativistic from outset, includes resonances and DIS
  - All targets
  - Not just inclusive X-sections, but full events
  - Reasonable bound nuclear ground states

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- *Initial interactions:*
  - Mean field potential with local Fermigas momentum distribution, nucleons are bound (not so in generators!)
  - Initial interactions calculated by summing over interactions with all bound, Fermi-moving nucleons
  - 2p2h from electron phenomenology
- *Final state interaction:*
  - propagates outgoing particles through the nucleus using *quantum-kinetic transport theory*, fully relativistic (off-shell transport possible).
    Initial and final interactions come from the same Hamiltonian.
    CONSISTENCY of inclusive and semi-inclusive X-sections
- Calculations give final state phase space distribution of all particles, four-vectors of all particles → generator

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Pions

- Pion production amplitude
  = resonance contrib + background (Born-terms)
- Resonance contrib
  - *V* determined from e-scattering (MAID)
  - *A* from PCAC ansatz
- Background:
  - Up to about Δ obtained from effective field theory
  - Beyond Δ unknown
  - 2 pi BG totally unknown

Quantum-kinetic Transport Theory for FSI

On-shell drift term — Off-shell transport term — Collision term

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)\ .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

Spectral function

Phase space distribution

Kadanoff-Baym equations with BM offshell term

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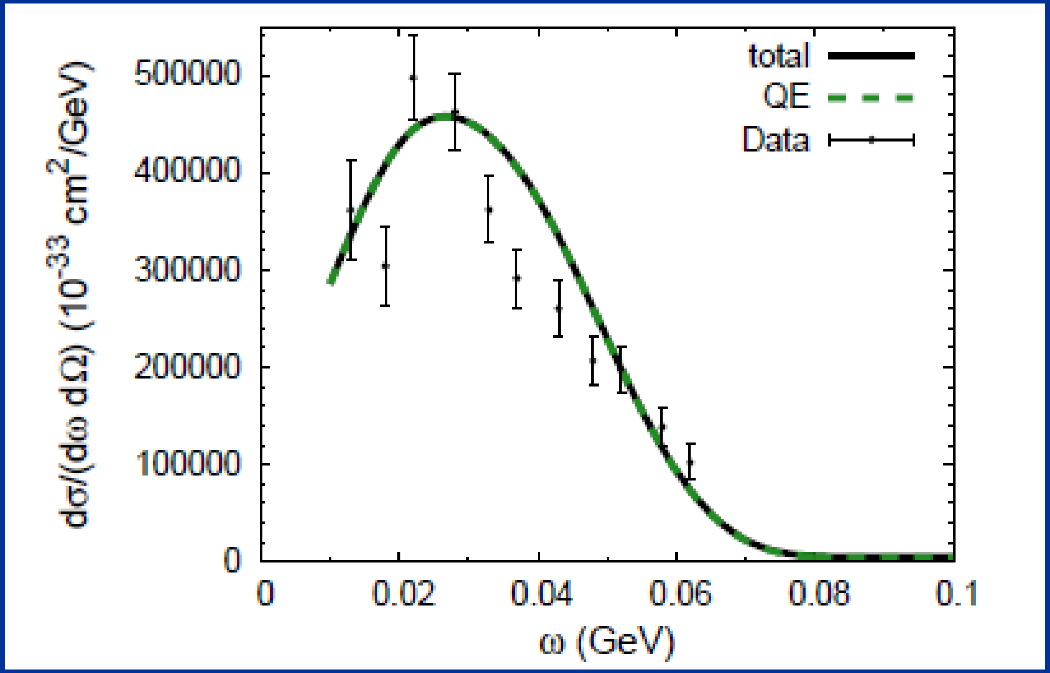
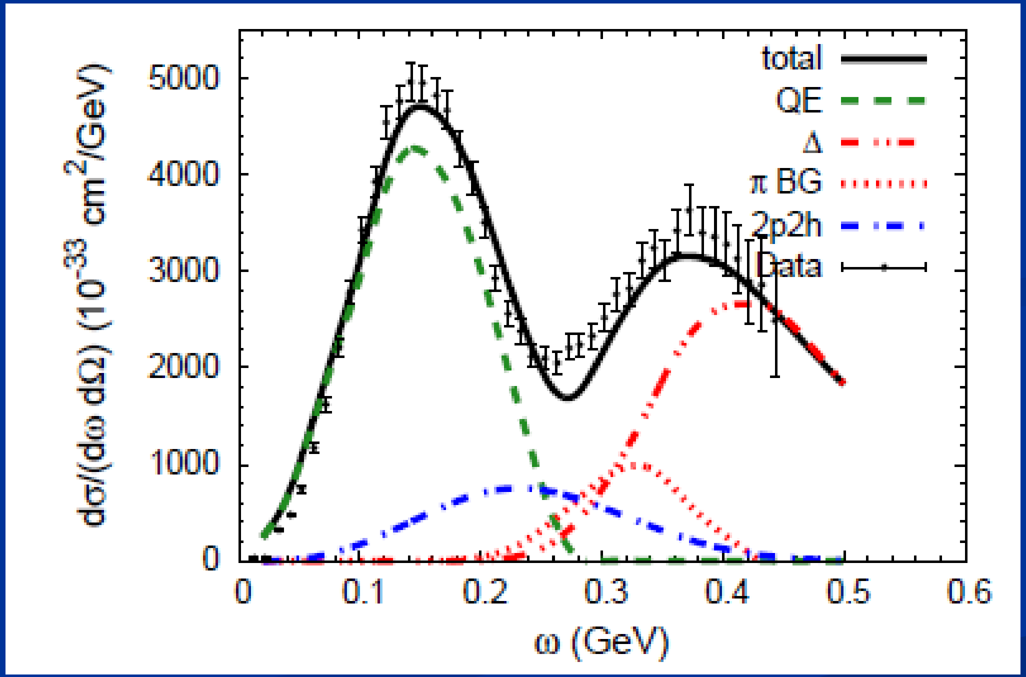
Test with Electron Data: QE + Res

- a necessary check for any generator development



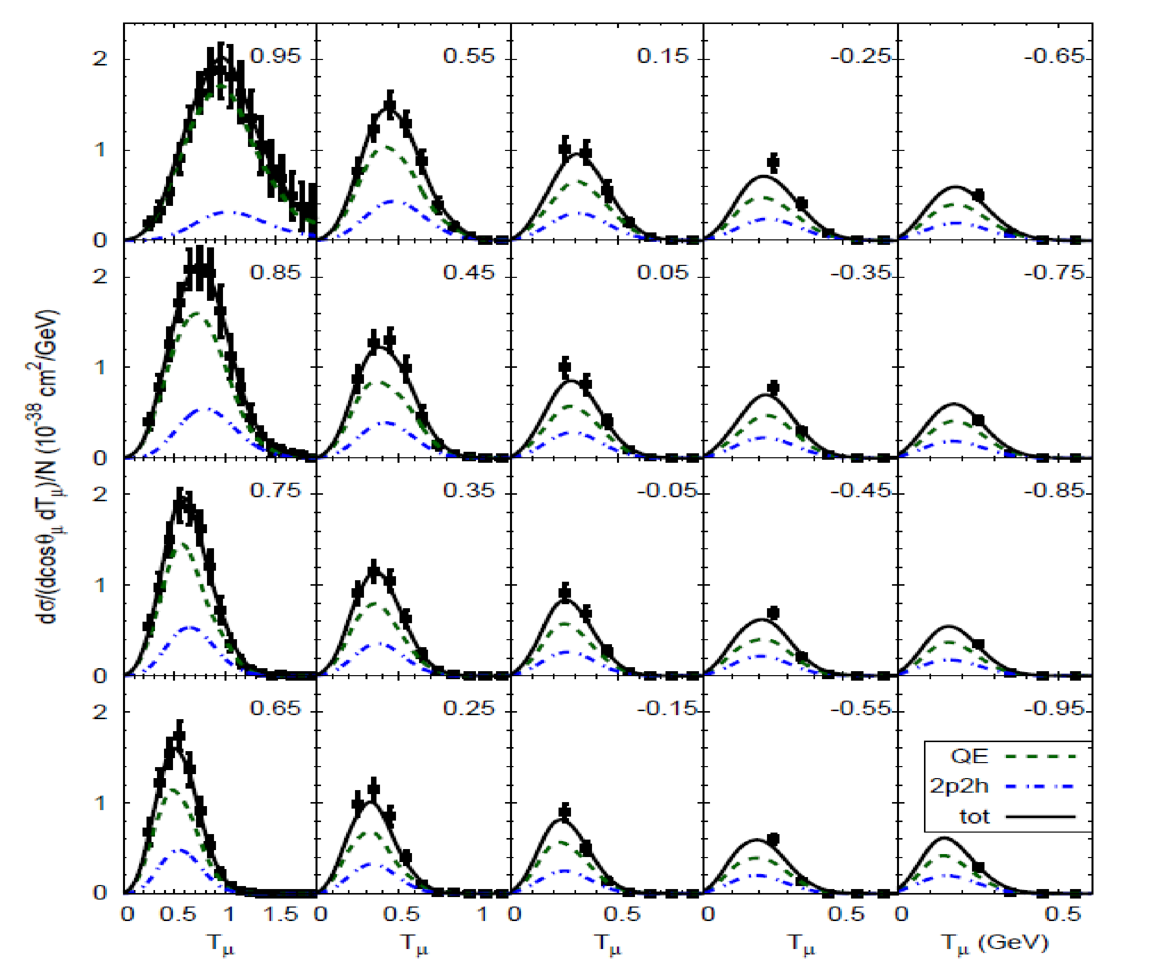
0.24 GeV, 36 deg, Q^2 = 0.02 GeV^2



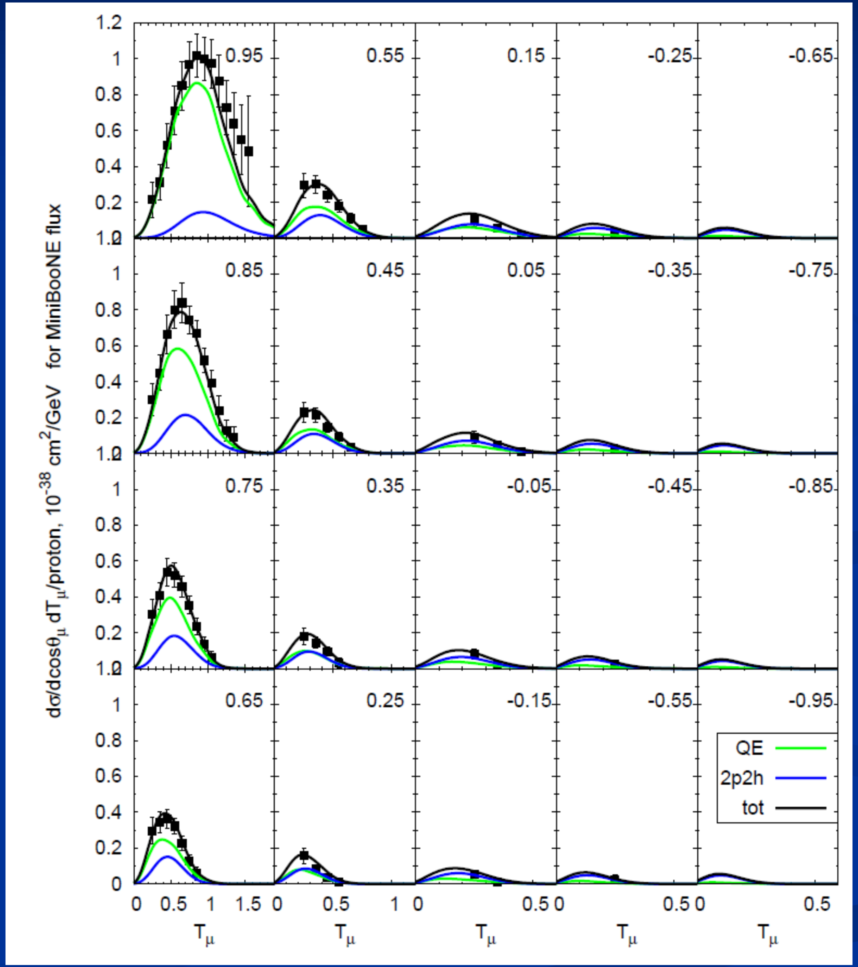
0.56 GeV, 60 deg, Q^2 = 0.24 GeV^2

MiniBooNE

ν



anti ν



GiBUU 2016: no data adjustment

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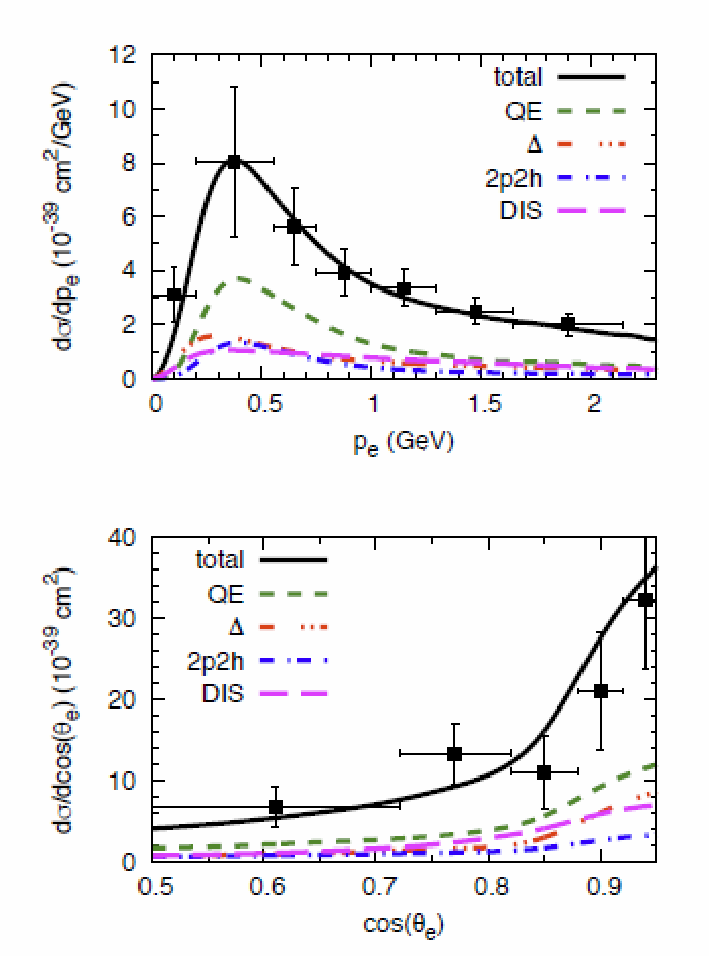
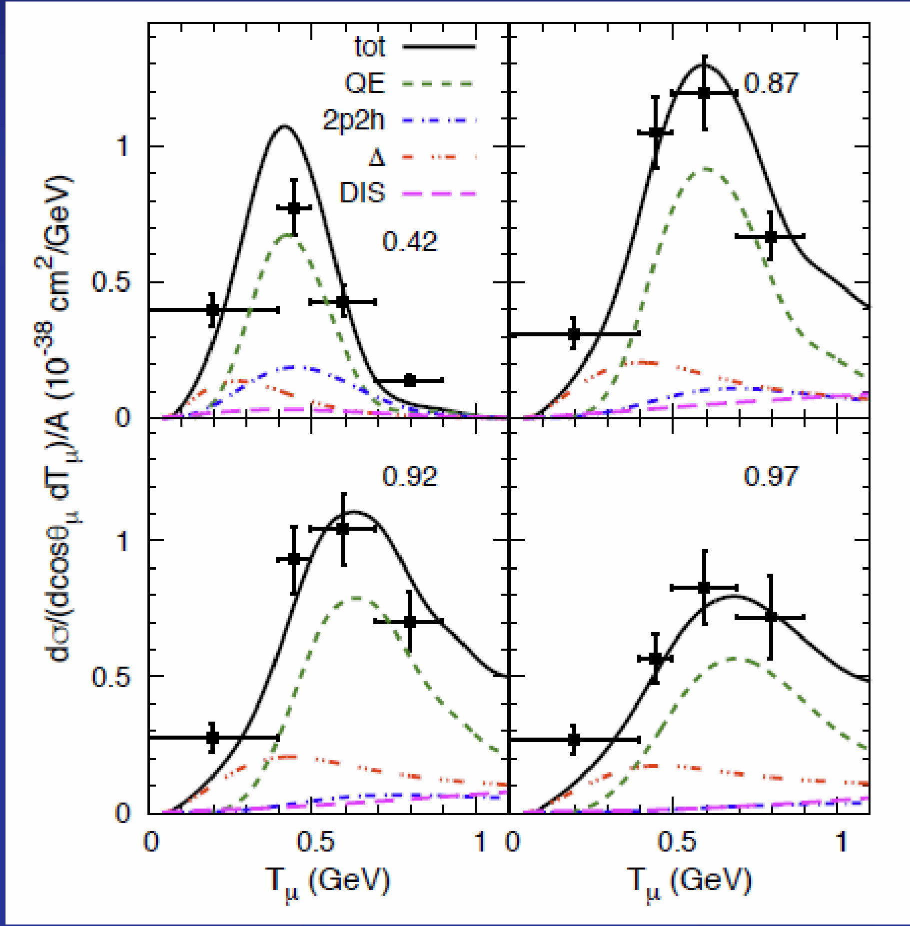
Comparison with T2K incl. Data

T2K, ν_e





T2K, ν_μ

Agreement for different neutrino flavors

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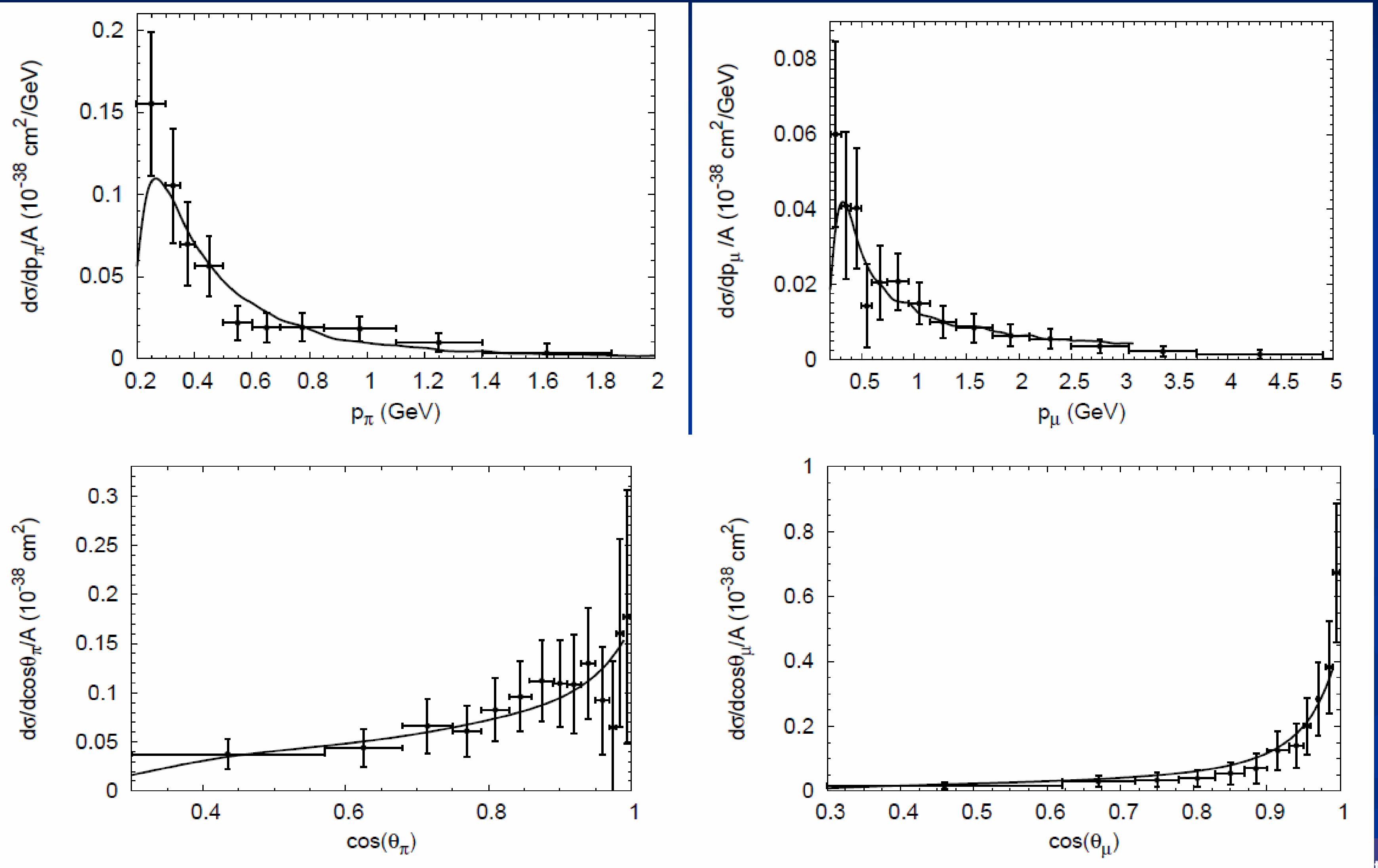
T2K ND280 Pions on Water

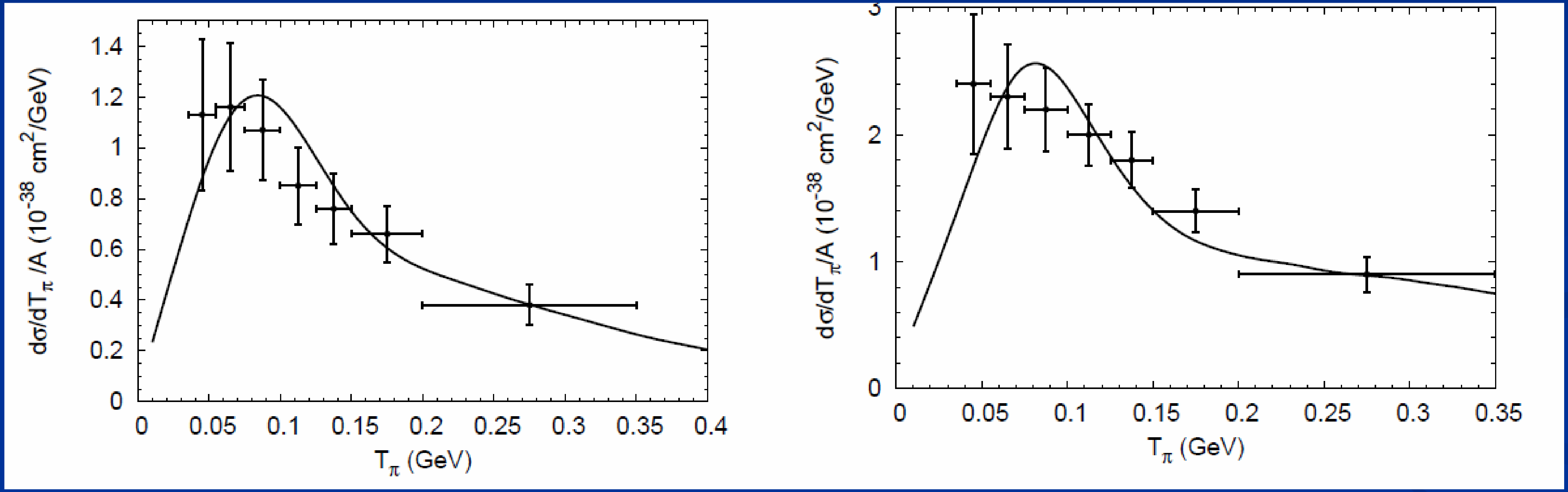


Data: T2K ND

Phys.Rev. D95 (2017) no.1, 012010

MINERvA Pions

CC charged pions



W < 1.4 GeV

W < 1.8 GeV, multiple pions

Sensitivity of T2K to Energy Reconstruction

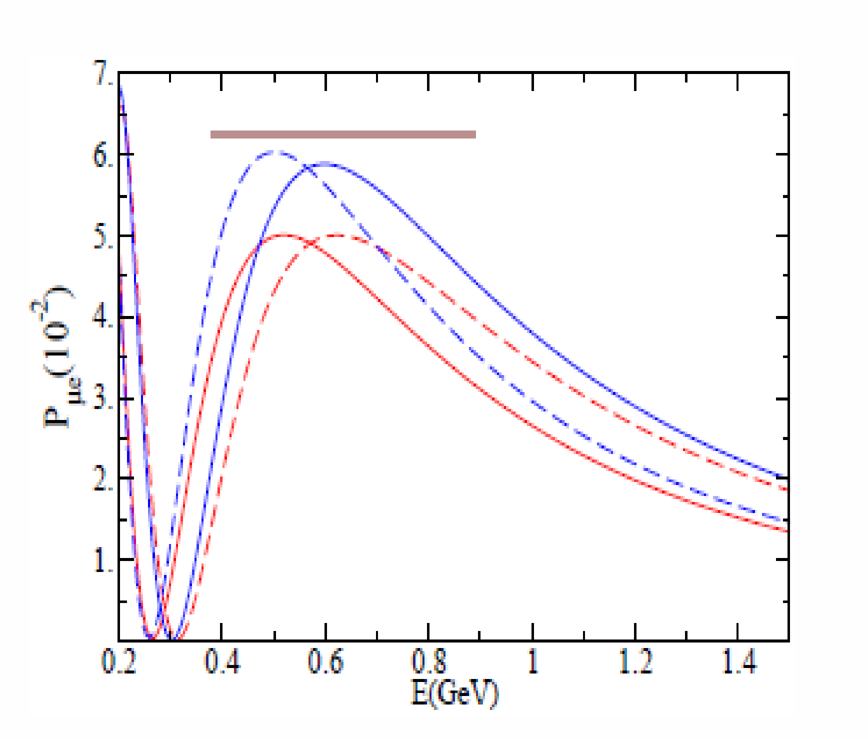
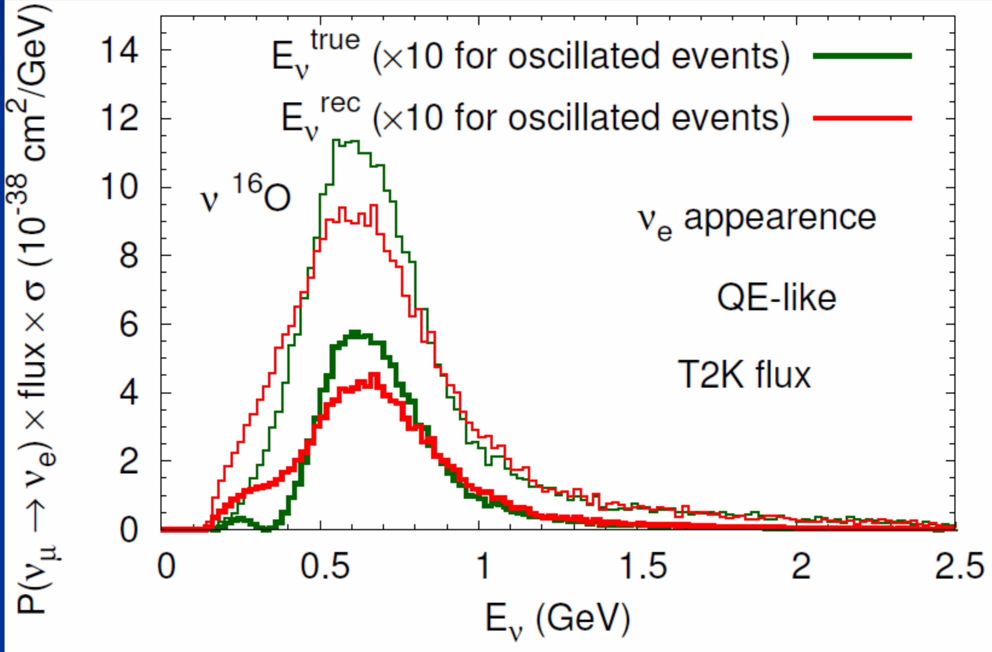


Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

D.J. Ernst et al., arXiv:1303.4790 [nucl-th]



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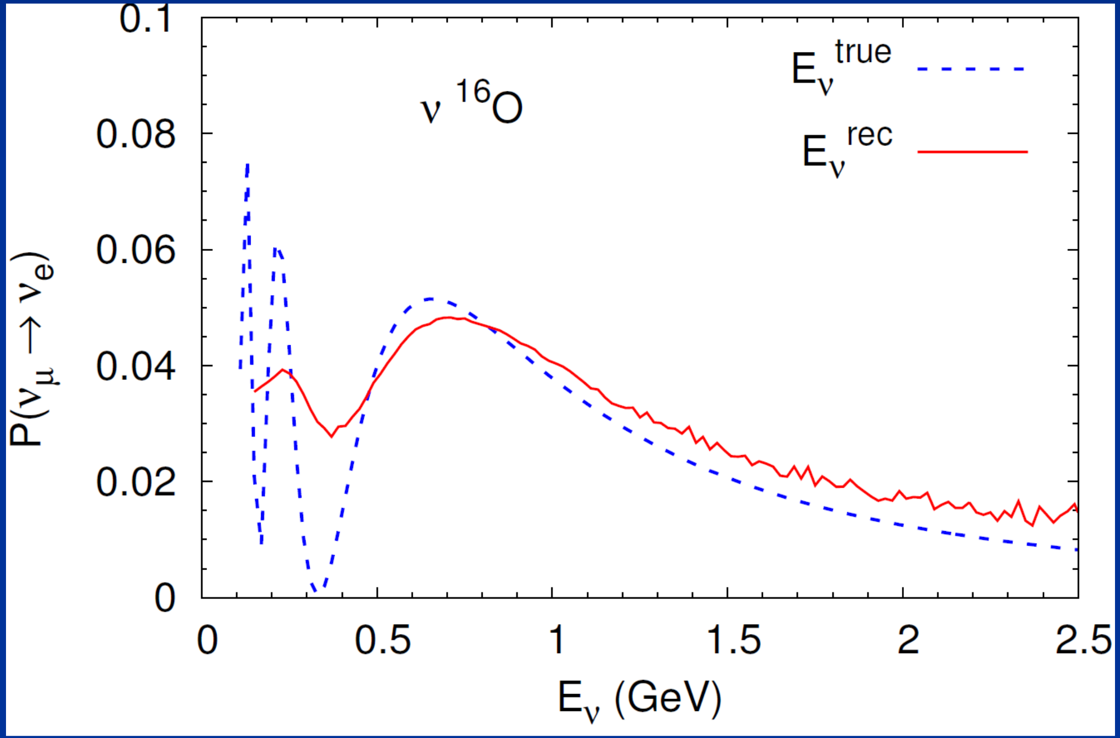
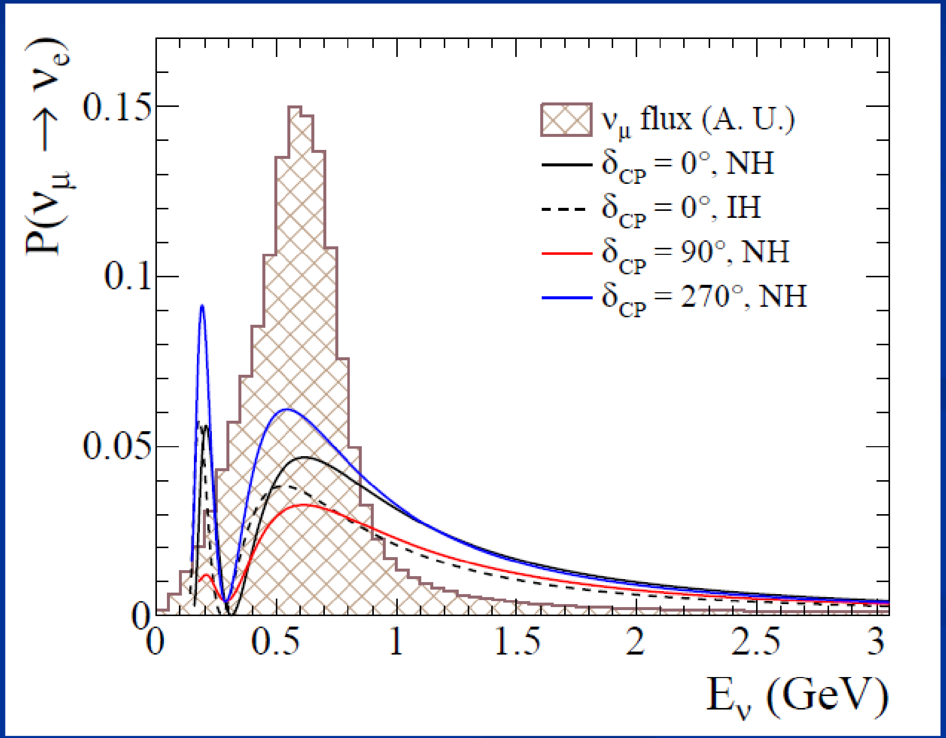
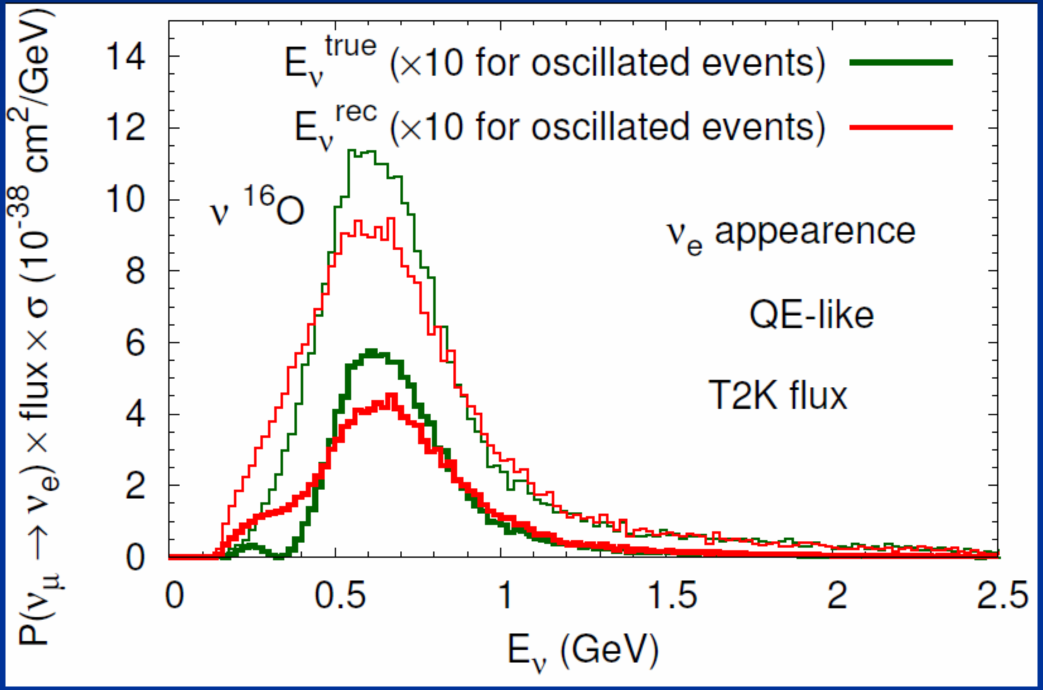
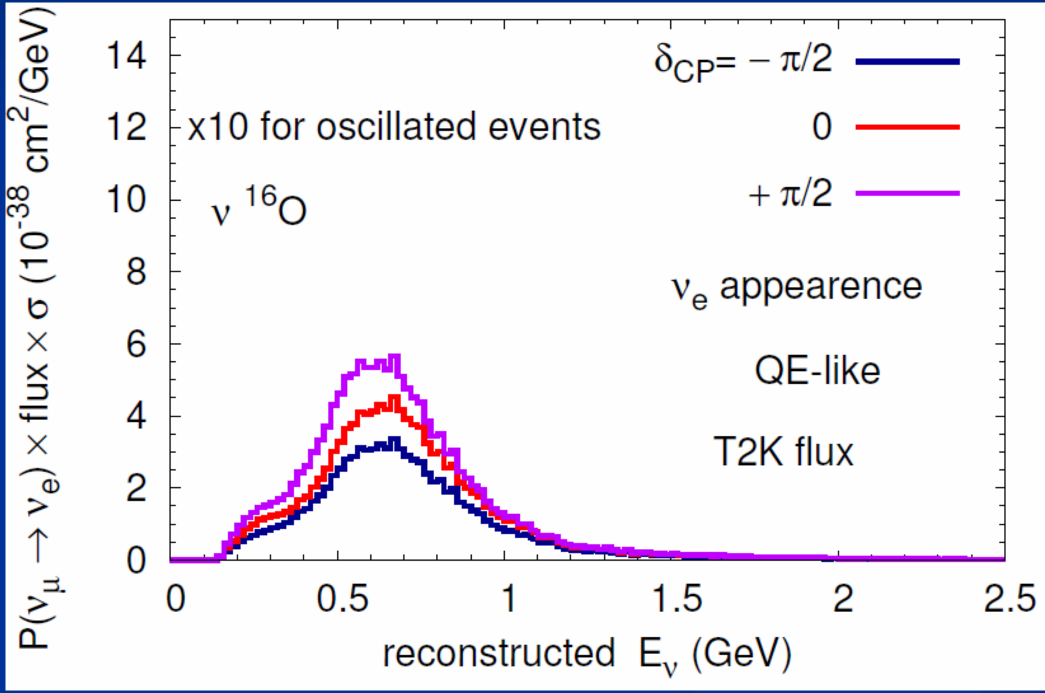
Reconstruction in T2K





Oscillation signal in T2K
δ_{CP} sensitivity of appearance exps



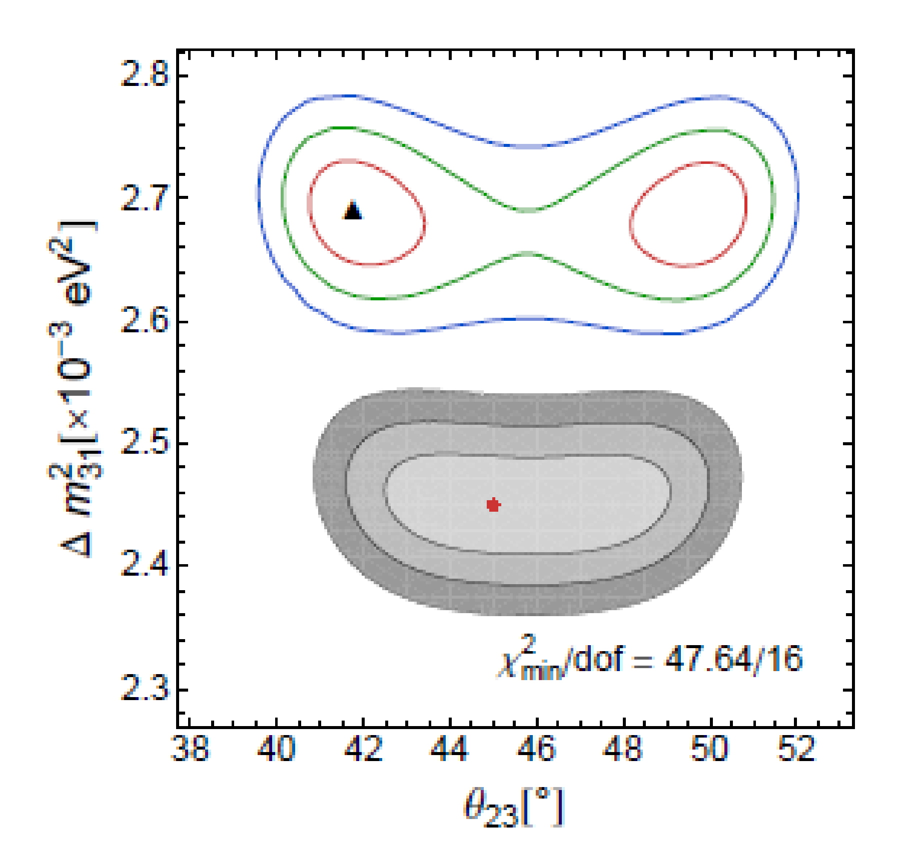


Uncertainties due to energy reconstruction
as large as δ_{CP} dependence

Generator Dependence of Oscillation Parameters

GiBUU-GENIE

GiBUU-GiBUU



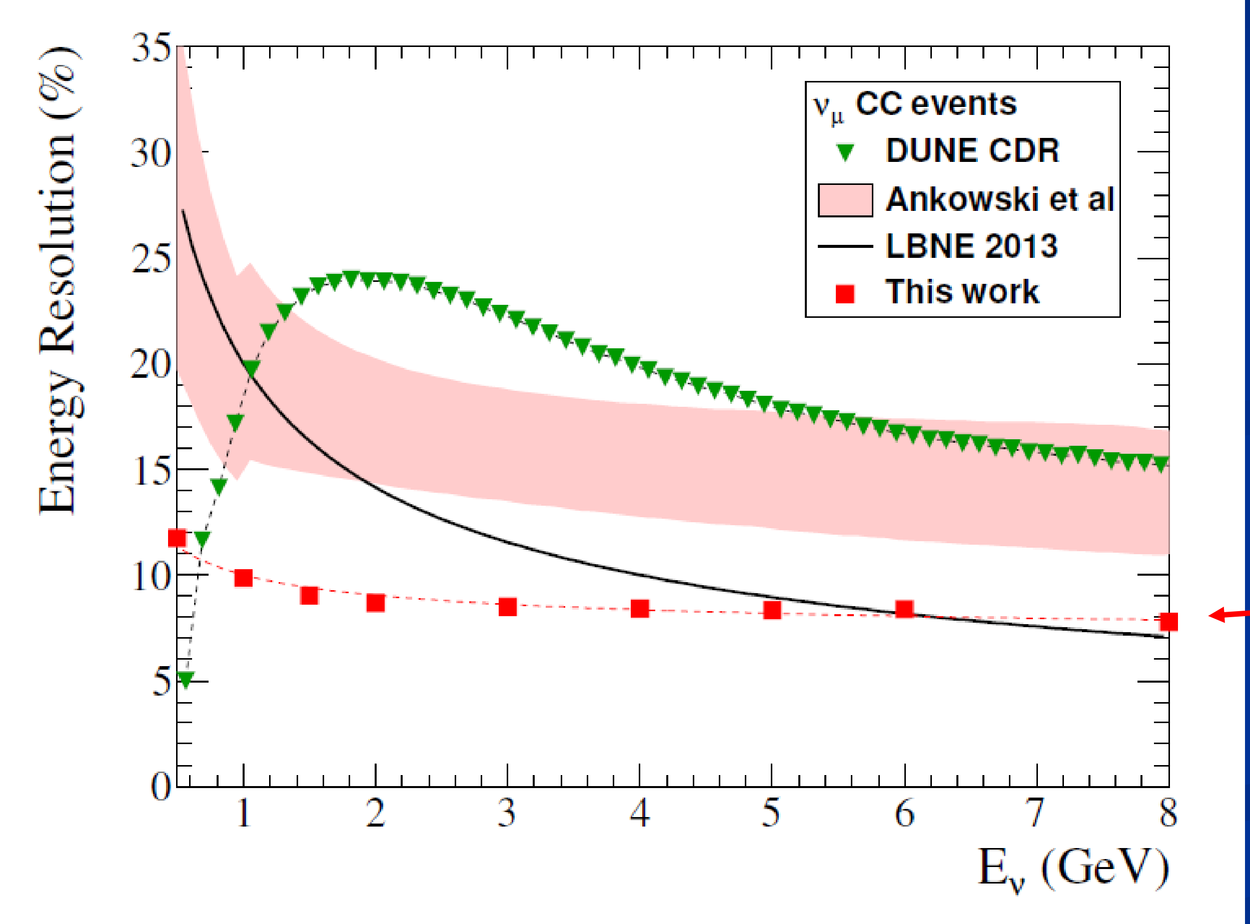
Generator: GENIE

Nature: GiBUU

T2K Flux

From: P. Coloma et al, Phys.Rev. D89 (2014) 073015

Energy Reconstruction



From de Romeri et al, JHEP 1609 (2016) 030

Uses ND info

Summary

- Extraction of neutrino properties requires knowledge of neutrino energy to about 5% accuracy.
- In long-baseline experiments the incoming neutrino energy must be reconstructed from final state. Final state is only partially known because detectors are less-than-perfect.
- Backwards calculation from this partially known final state requires command both of hadronic final state interactions and of initial neutrino-nucleus reactions
- Present models can do this to about 10% → not good enough
- Precision neutrino long-baseline physics requires better state-of-the-art generators
- GiBUU is one such attempt

GiBUU: References

- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains the latest changes in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators
  4. Mosel et al, Phys.Rev. C96 (2017) no.1, 015503
     pion production comparison of MiniBooNE, T2K and MINERvA

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