Neutrino-Nucleus Interactions and Oscillations

Ulrich Mosel

Institut für Theoretische Physik

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Physics Beyond the Standard Model

- Precision Physics at CERN LHC: 6.5 TeV protons, beam energy known within 0.1 % ➔ No evidence for BSM physics!
- Beams with broad energy distributions (> 100%) found evidence for BSM physics: neutrino oscillations -> neutrinos are massive ➔ 2005 Nobel Prize

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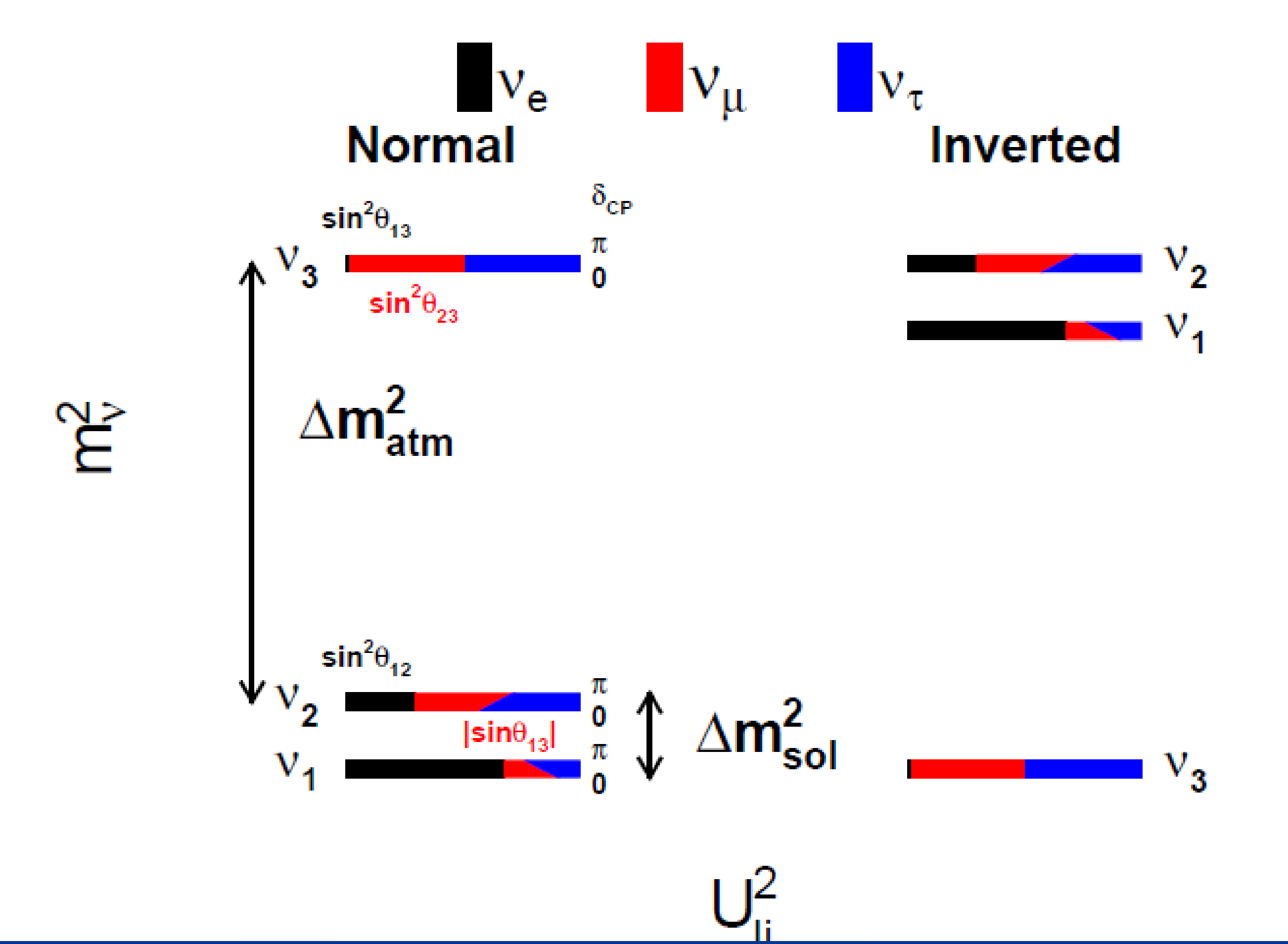
Neutrino Hierarchy

Know all mixing angles,
 not very precise
Do not know CP violating phase
Do not know mass hierarchy



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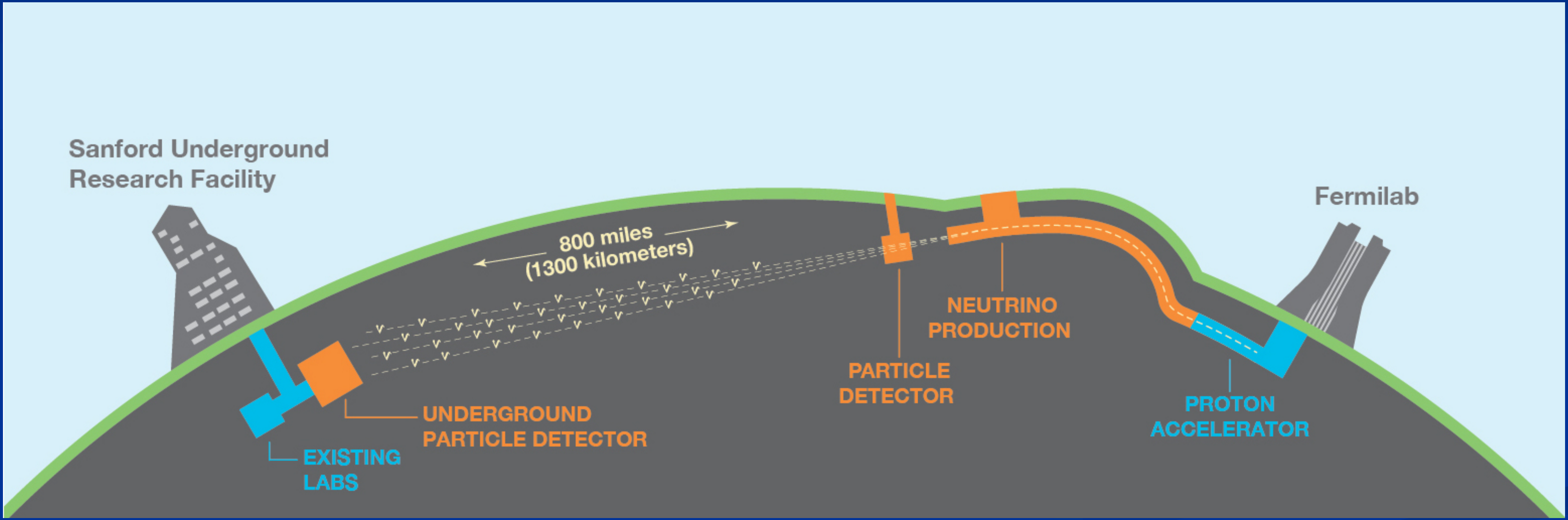
- The impossible experiment:
  - Beam lines are a few hundred kilometers long
  - Beam energies are wide from a few 100 MeV – 30 GeV, distribution not too well known
  - Beam is wide: about 1 m at its source, km at the target
  - Beam composition is not precisely known

Long-Baseline Experiment: T2K and NOvA

Future (2027): DUNE, joint CERN-FNAL 1.5 B$ project



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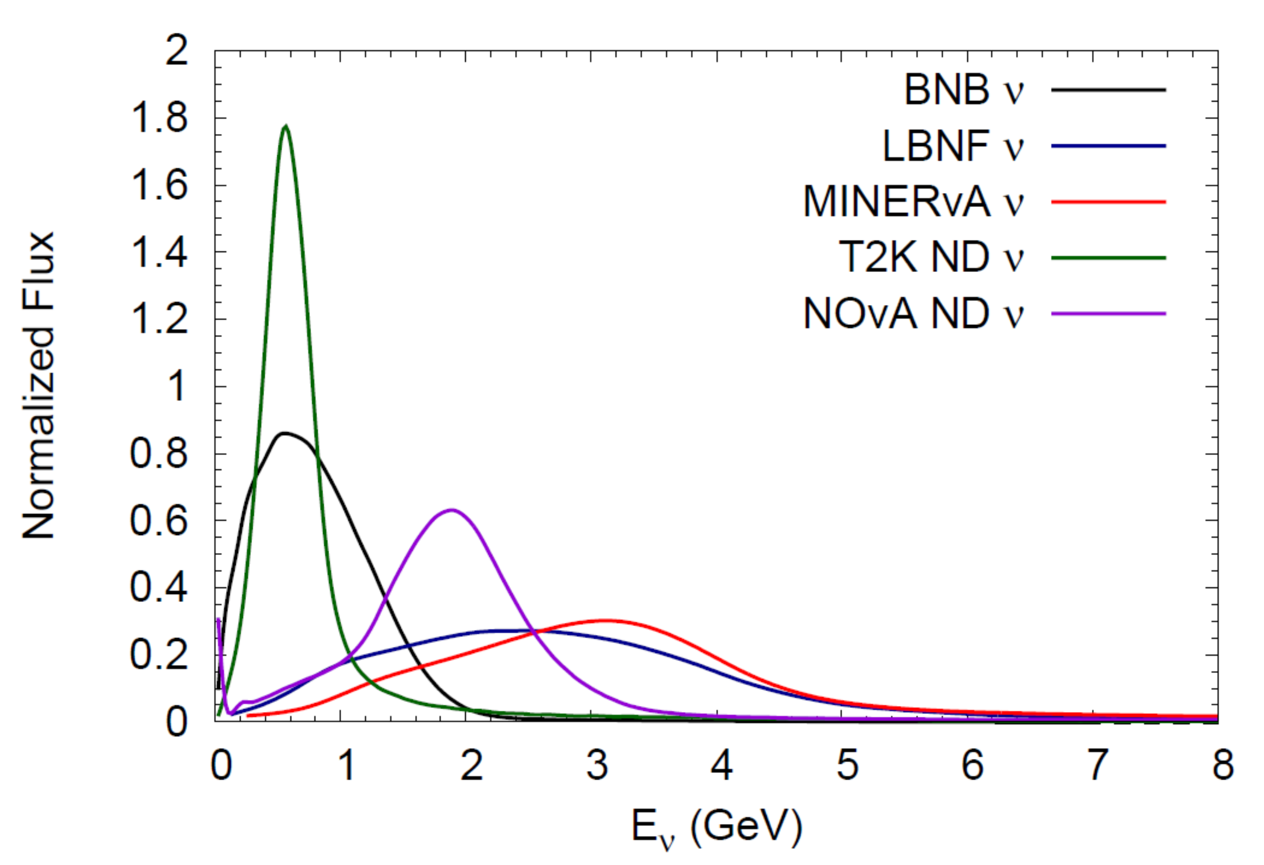
Oscillations and Neutrino Energy

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

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

Energy must be reconstructed from hadronic final state,

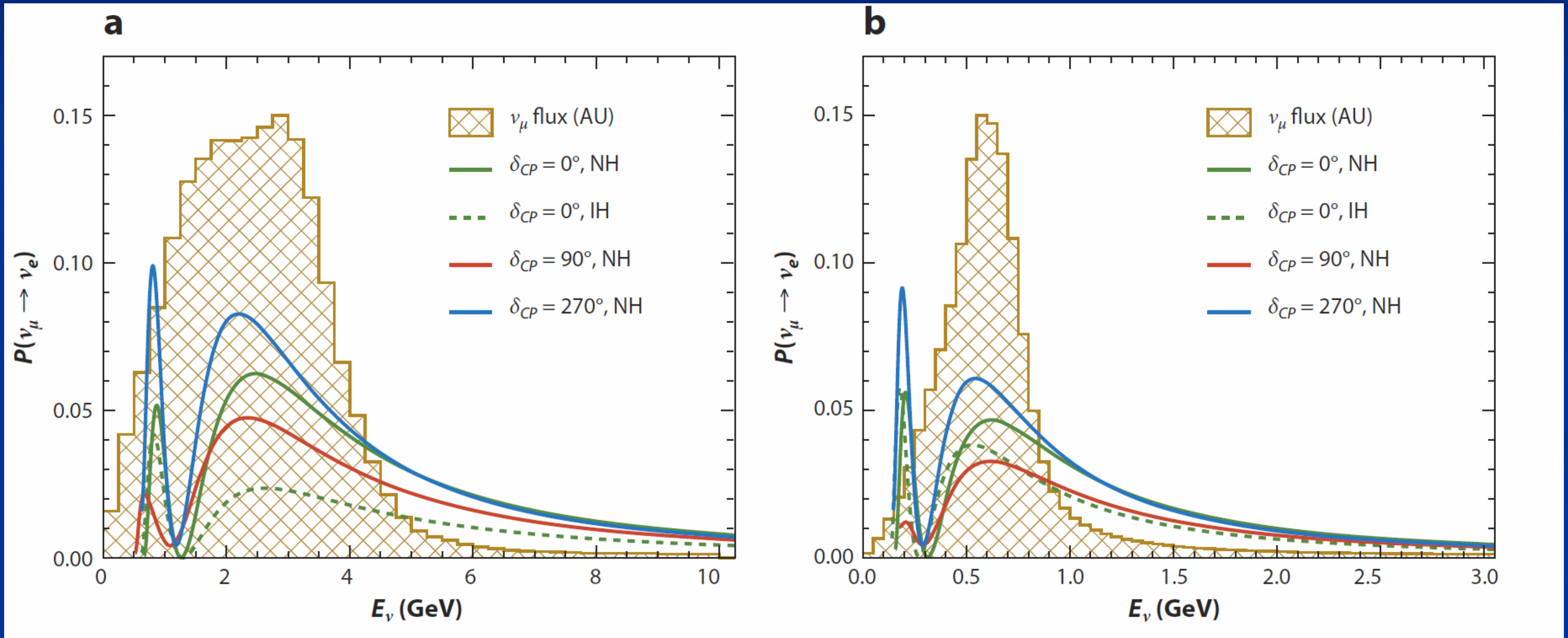
observed in less-than-perfect detectors

➔ Compute backwards from final state to incoming neutrino

Reaction mechanism must be known for reconstruction:

Nuclear Physics is essential, because targets are nuclei: C, O, Ar

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



DUNE, 1300 km

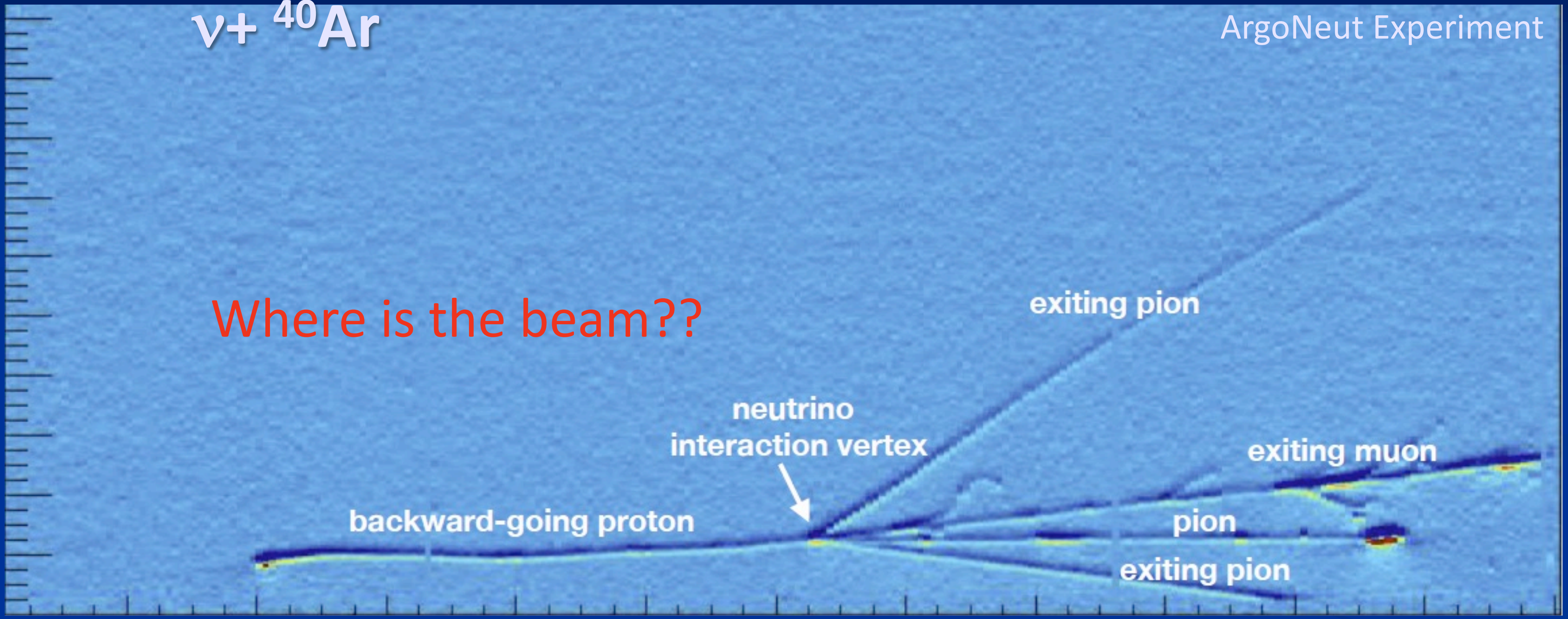
HyperK (T2K) 295 km

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 20%

Neutrinos on Nuclei



What is the ingoing state? Composition? Energy?
Must reconstruct from final state!

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

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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

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)*

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

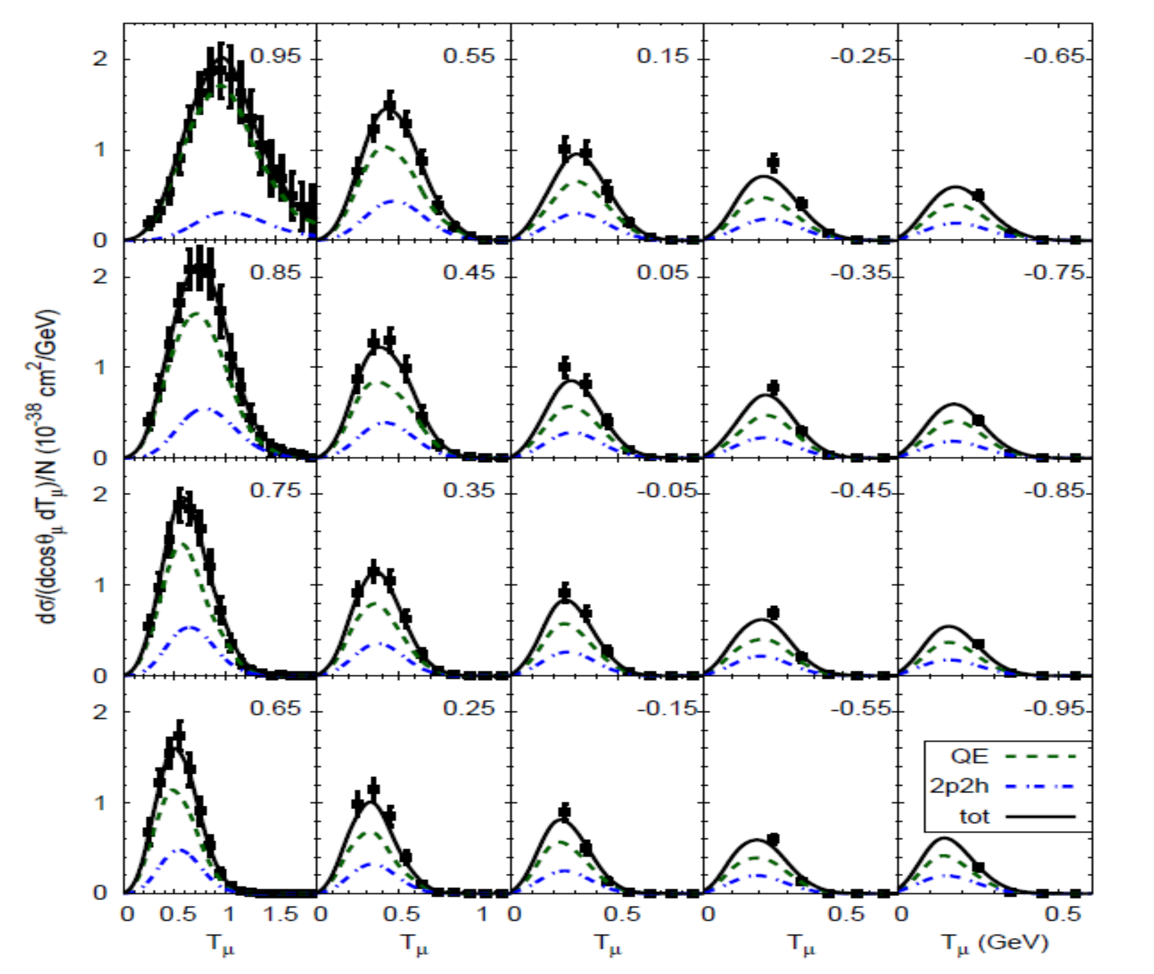
Spectral function

Phase space distribution

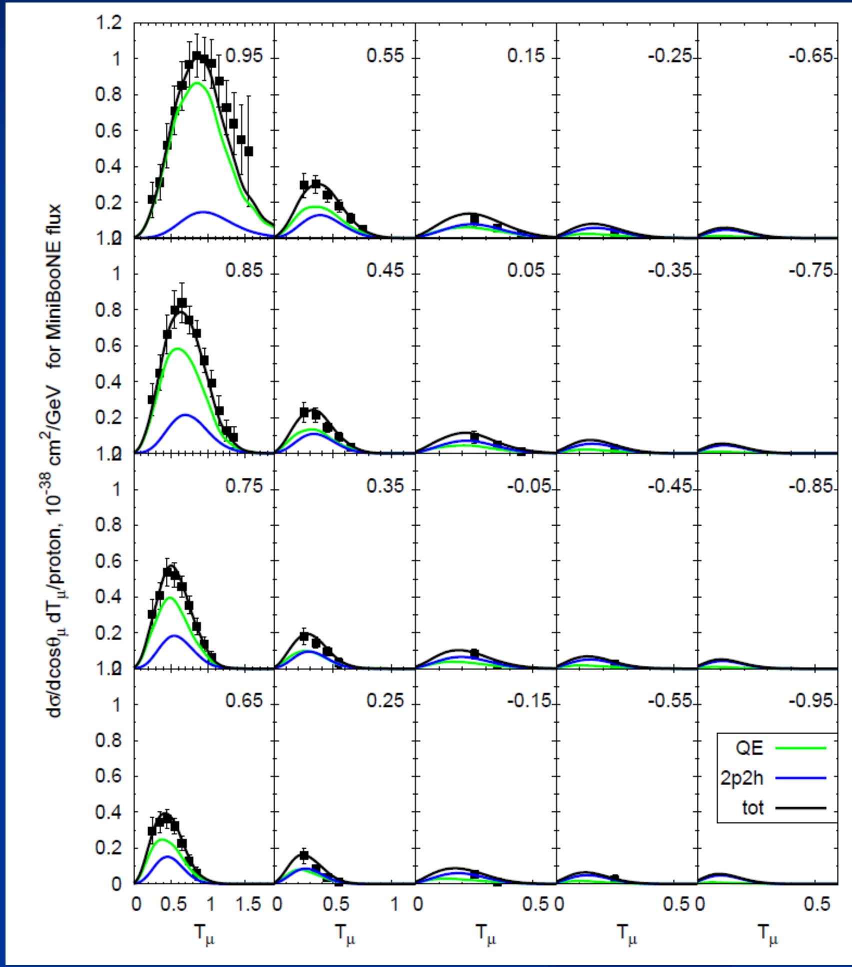
Kadanoff-Baym equations with BM offshell term

MiniBooNE

ν



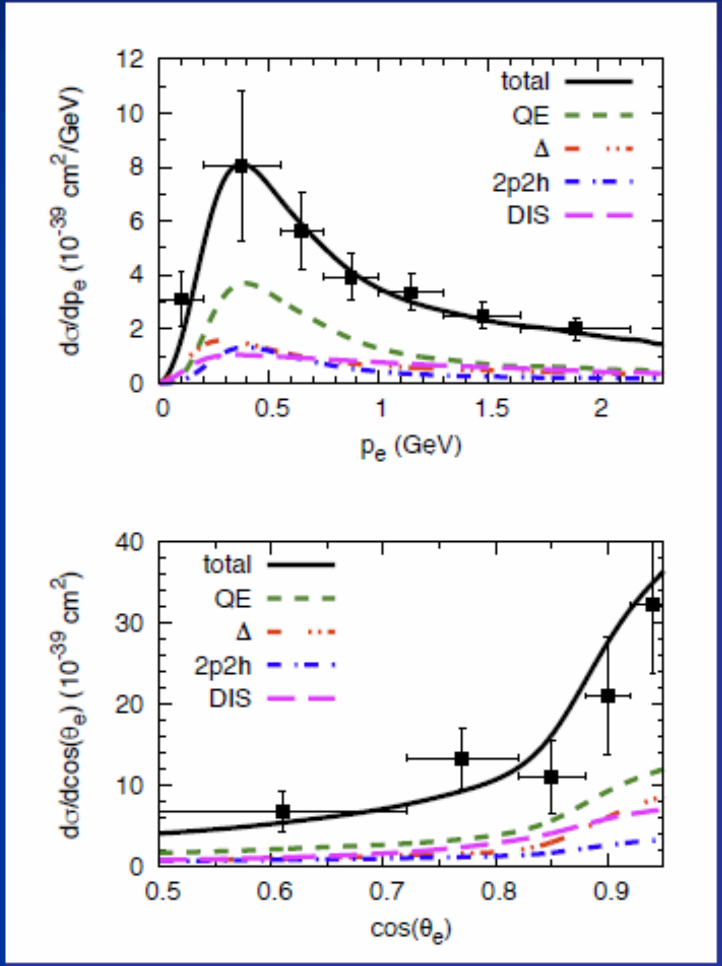
anti ν

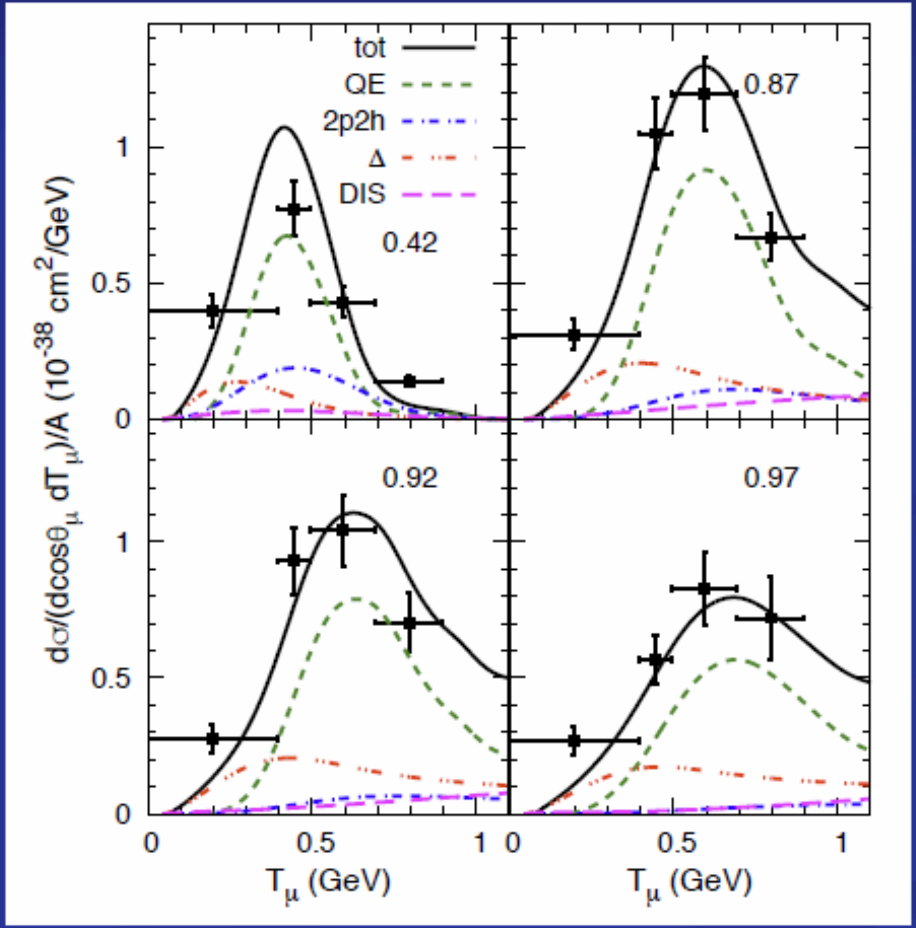


GiBUU 2016: no data adjustment

Comparison with T2K incl. Data

T2K, ν_e

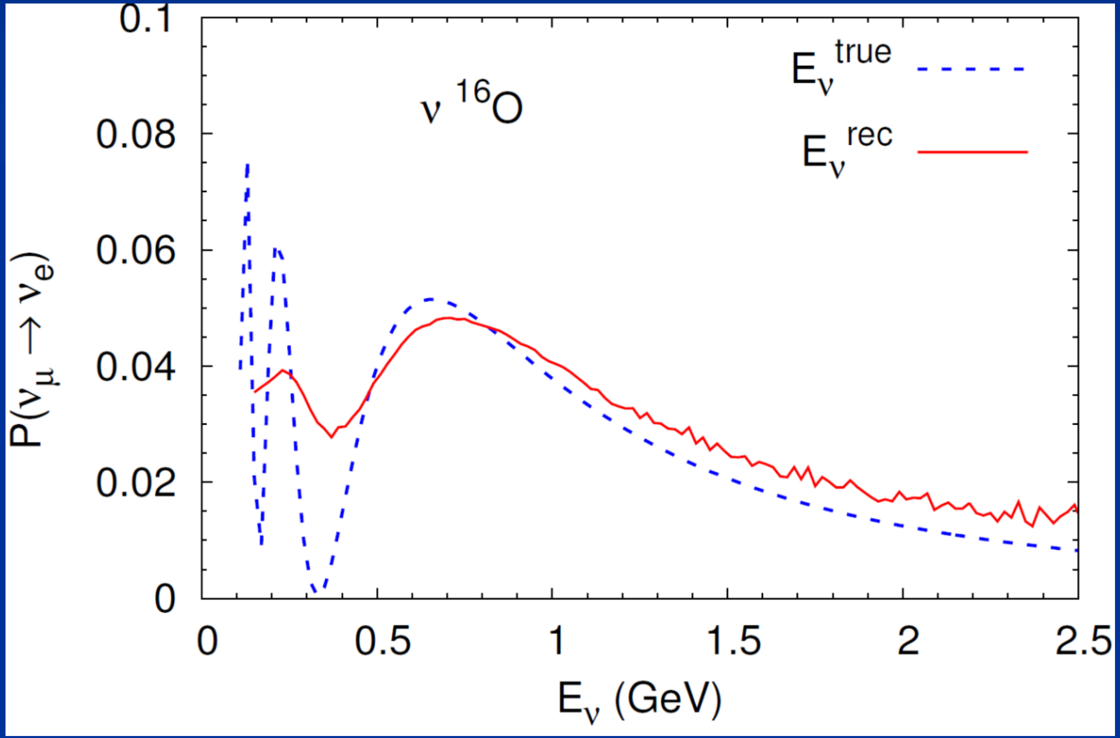


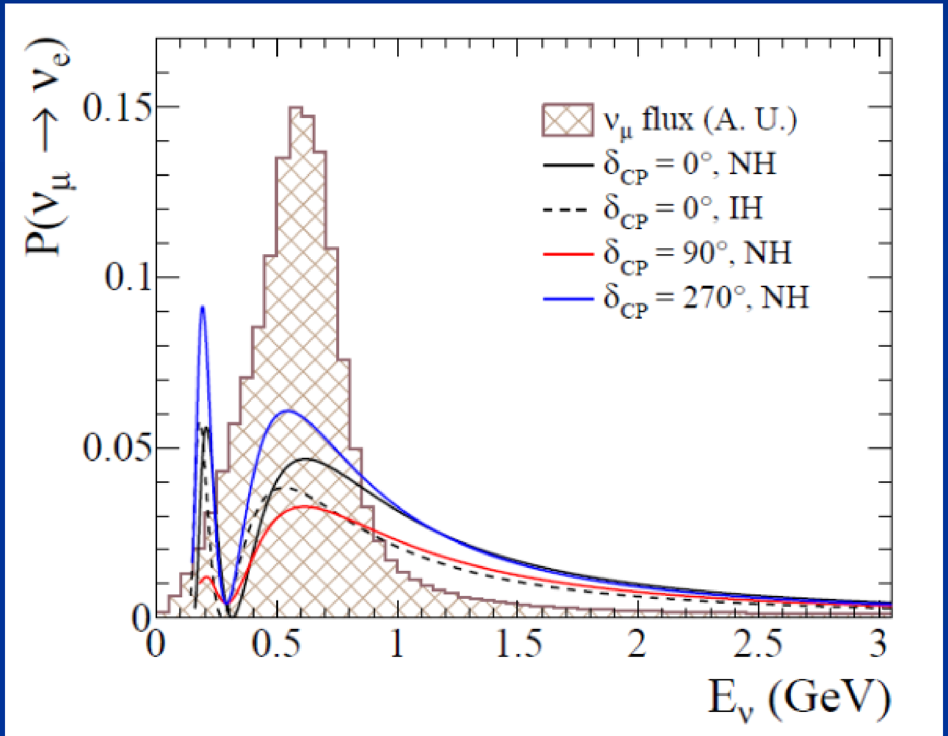


T2K, ν_μ

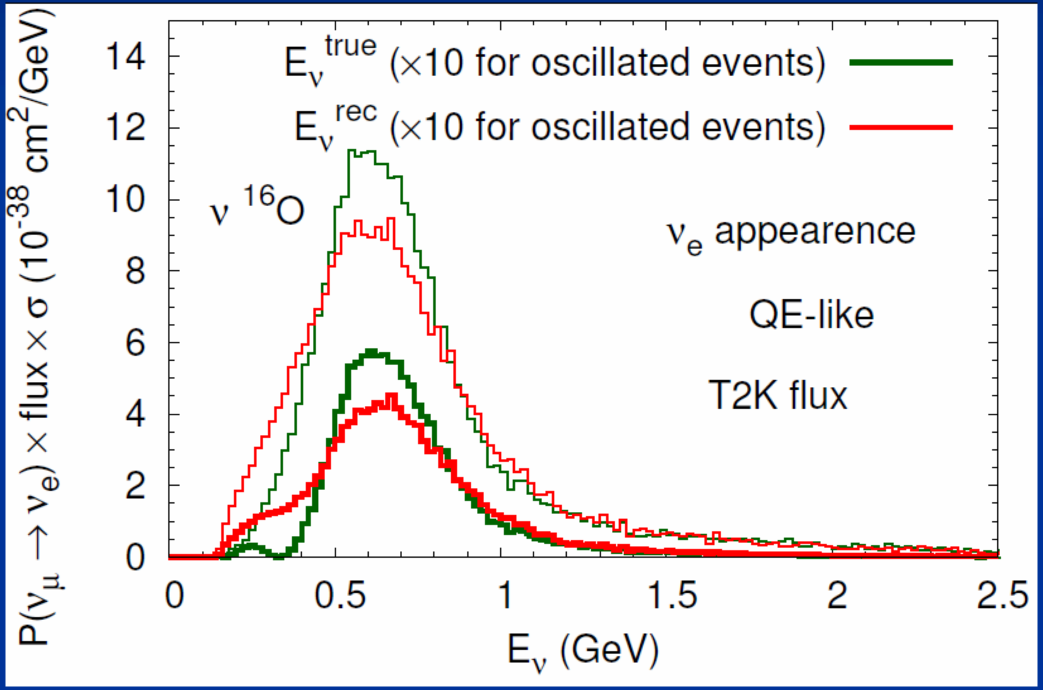
Agreement for different neutrino flavors

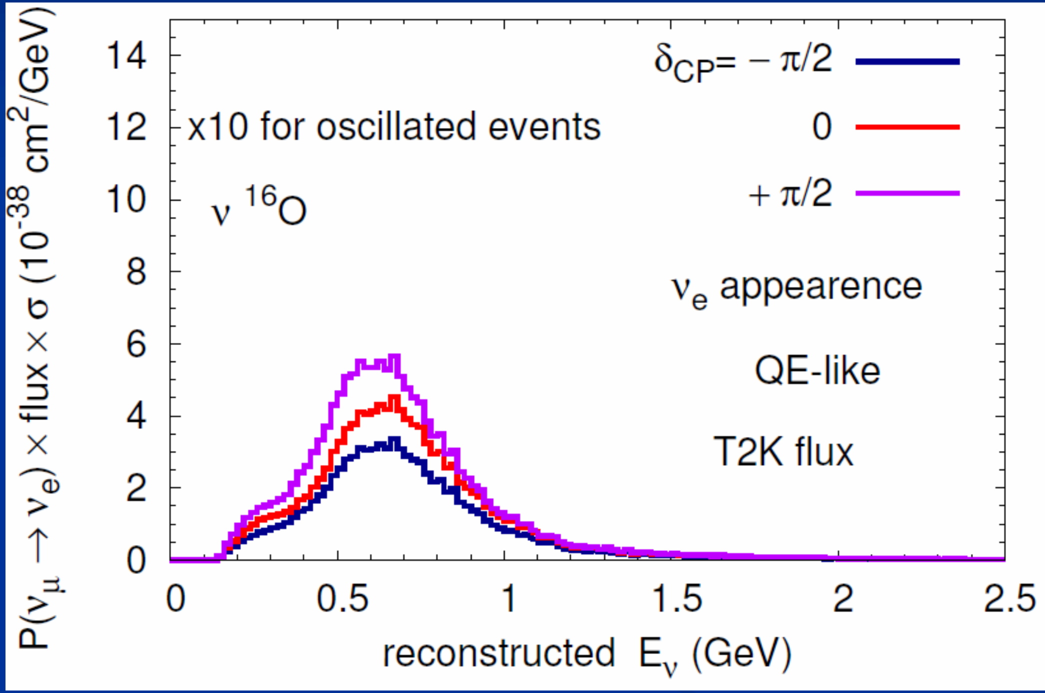
Reconstruction in T2K





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



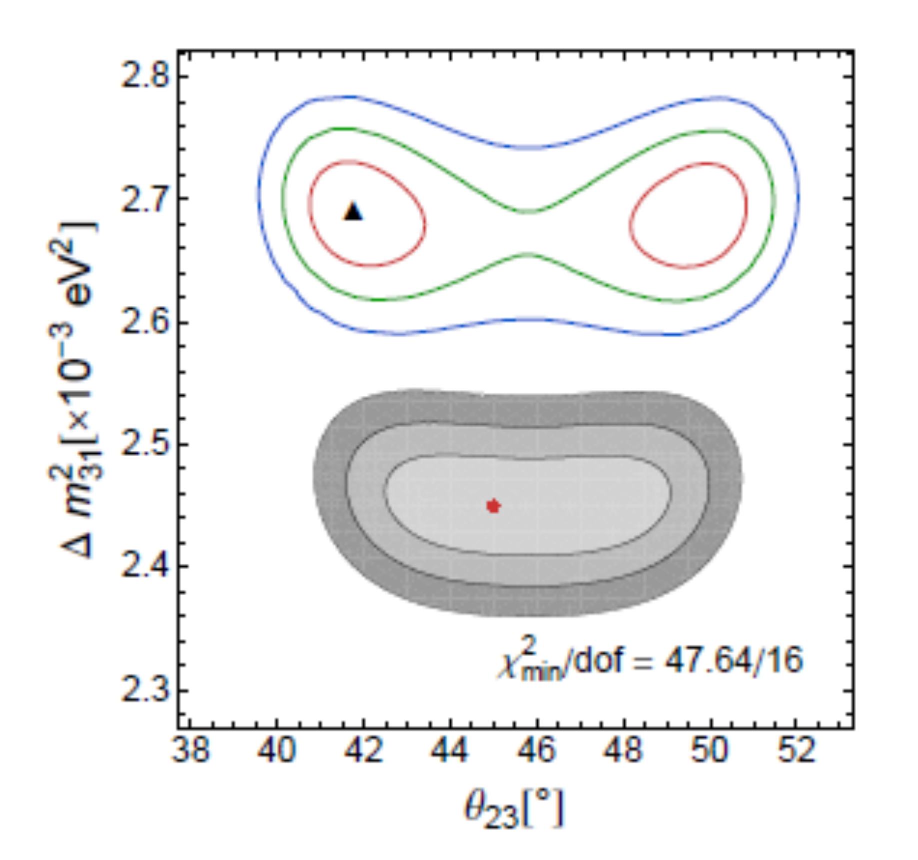


Uncertainties due to energy reconstruction as large as δ_{CP} dependence

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

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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. Only partially known because detectors are less-than-perfect.
- Backwards calculation from this partially known final state requires command both of initial neutrino-nucleus reactions and of hadronic final state interactions
- Present models can do this to about 10- 20 % → not good enough
- Precision neutrino long-baseline physics requires better state-of-the-art generators
- GiBUU is one such attempt
- BACK to PRECISION PHYSICS: not so much for experiment, but for theory

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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
     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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