Neutrino Interactions with Nuclei

A Halloween Talk

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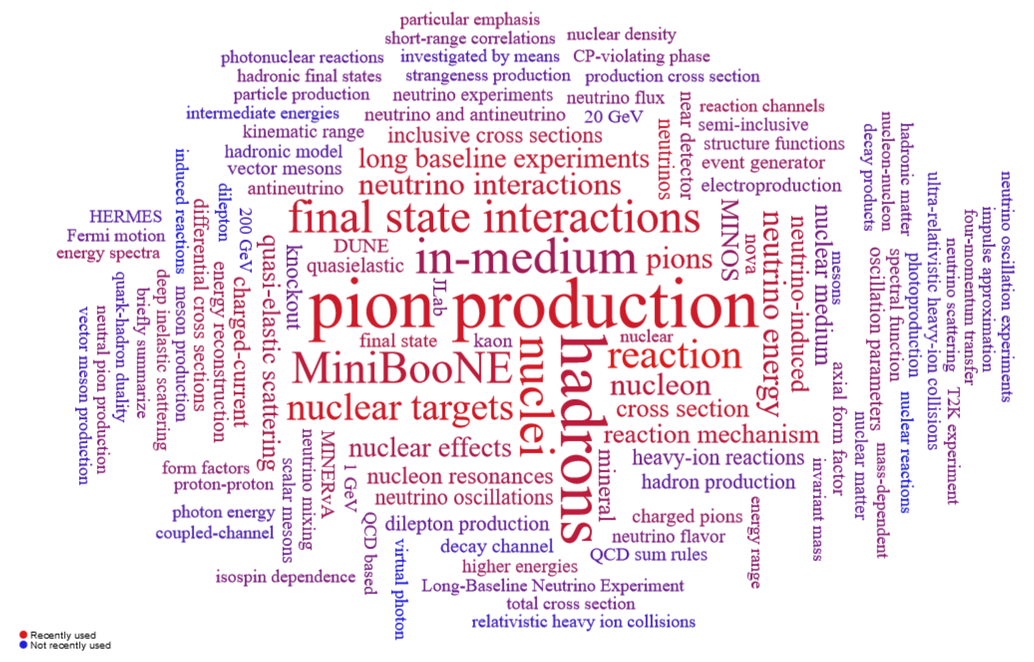
My Profile



Scimeter.org

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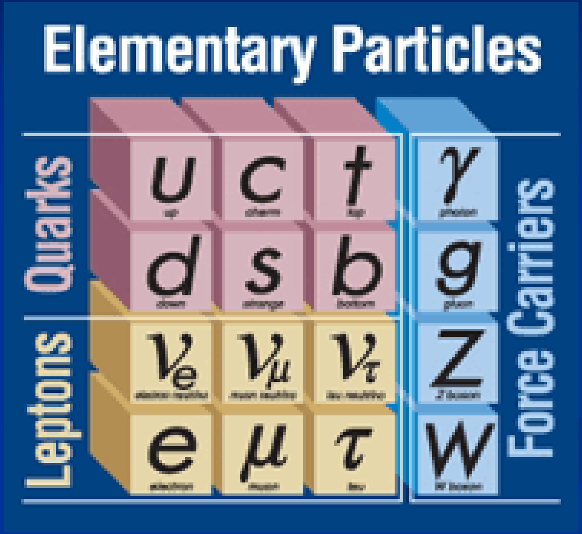
Contents

- Intro: neutrino masses and oscillations
- Detecting neutrinos: What do we know about neutrino-nucleon interactions?
- Long baseline experiments
- Where does nuclear physics come in?
- Summary

Building blocks of matter

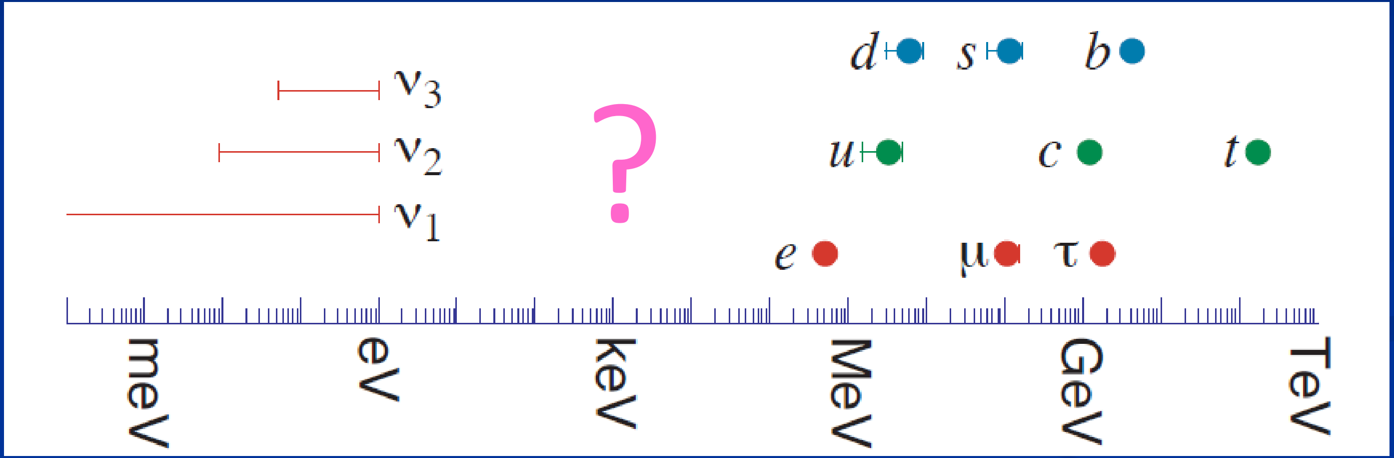


Textbook Knowledge (~ 2000):
Neutrinos are massless and only lefthanded

Neutrino Sources

1. Cosmic Neutrinos, energies up to multi TeV
2. Atmospheric neutrinos from decay of pions, muons produced in the upper atmosphere by cosmic rays, energies ~ 100 MeV – 10 GeV
3. Accelerator produced neutrinos, energies: 100 MeV – 100 GeV
4. Solar electron neutrinos from thermonuclear fusion, energies ~ up to 10 MeV, flux on earth: $10^{10}/(\mathrm{cm}^2\ \mathrm{sec})$
5. Reactor (anti-)neutrinos from fission, energies ~ 2 – 3 MeV
6. Geo-Neutrinos, energies a few MeV

Neutrinos are different!



Textbooks until ~ 2000: neutrinos are massless

Solar Neutrino Puzzle (SNP)

- Solar Neutrino Puzzle:
  thermonuclear processes in the sun produce lots of electron neutrinos (energies: a few Mev), but only ~½ of them are detected on earth.

- Where is the rest?

Neutrinos Oscillate: 2 Flavors

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\Theta_m & \sin\Theta_m \\ -\sin\Theta_m & \cos\Theta_m \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu_j(t)\rangle = |\nu_j(0)\rangle \, e^{-i(Et-p_j x)/\hbar}$$

$$p = \frac{1}{c}\sqrt{E^2 - m^2c^4} \approx \frac{1}{c}\left(E - \frac{m^2c^4}{2E}\right).$$

$$|\nu_j(L)\rangle = |\nu_j(0)\rangle \, e^{-i\frac{m_j^2c^4}{2E}\frac{L}{\hbar c}}$$

$$P(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta(0)|\nu_\alpha(L)\rangle|^2 \approx \sin^2\left(\frac{\Delta m^2c^4}{4E}\frac{L}{\hbar c}\right) \cdot \sin^2(2\Theta_m)$$

$\Delta m^2 = m_\alpha{}^2 - m_\beta{}^2$,

P indepdent of sign of Δm^2

Neutrino Oscillate: 2 Flavors

- 2-Flavor Oscillation (electron appearance probability)

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

Know: L, need E_ν to determine $\Delta m^2 = m_{\nu_e}{}^2 - m_{\nu_\mu}{}^2$, θ

- Even more interesting:
  3-Flavor Oscillation allows for CP violating
  phase δ_{CP} → matter/antimatter puzzle

Neutrino Oscillate: 3 Flavors

U : Pontecorvo-Maki-Nakagawa-Sakata matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

breaks CP invariance

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

$$c_{\alpha\beta} = \cos\theta_{\alpha\beta} \text{ and } s_{\alpha\beta} = \sin\theta_{\alpha\beta}.$$

Neutrino Oscillate: 3 Flavors

$$\begin{aligned}
P(\nu_\mu \to \nu_e) \;\simeq\;& \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
-\;& \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\;& \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\;& \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \\
\equiv\;& O_1 + O_2(\delta) + O_3(\delta) + O_4 \;.
\end{aligned}$$

$$\Delta = \frac{\Delta m^2_{21} L}{4E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \xi = \cos\theta_{13}\, \sin(2\theta_{12})\, \sin(2\theta_{23})$$

$$\hat{A} = \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}} \qquad \delta = \text{CP violating phase}$$

appearance probability

Vacuum
oscillation

Matter effects,
n_e = electron density
Depends on sign of Δ_{31}

Oscillation depends on difference of (squared) masses only

Sign Δ dependence connected with δ_{CP}

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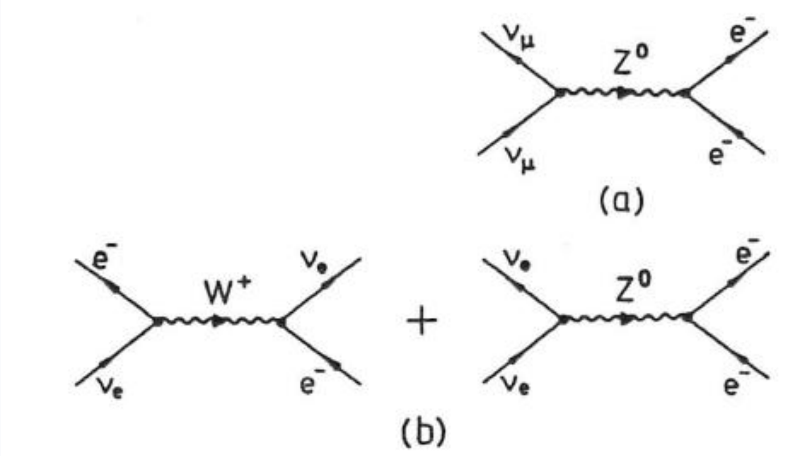
Neutrinos in Matter

Matter contains only electrons!



NC for all neutrino flavors

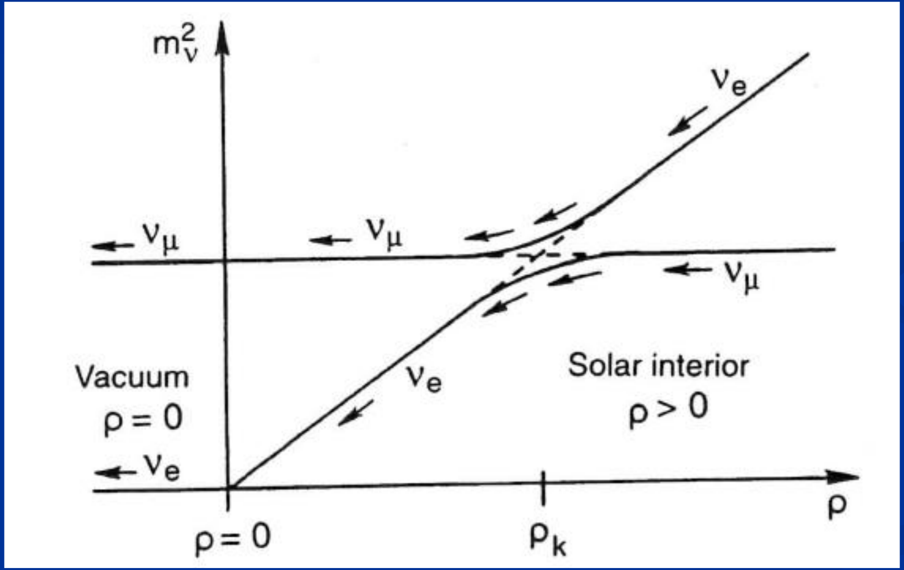
CC ony for electron neutrinos

CC leads to a forward-scattering amplitude only for electron neutrinos
→ Potential: $V = \mathrm{Sqrt}(2) * G_F * E_\nu * n_e$ only for e-neutrinos

Neutrinos in Matter

Potential for electron neutrino causes mass shift in medium:

Level Crossing:



Electron neutrinos coming from high densities to low ones can end up as muon neutrinos

MSW Effect

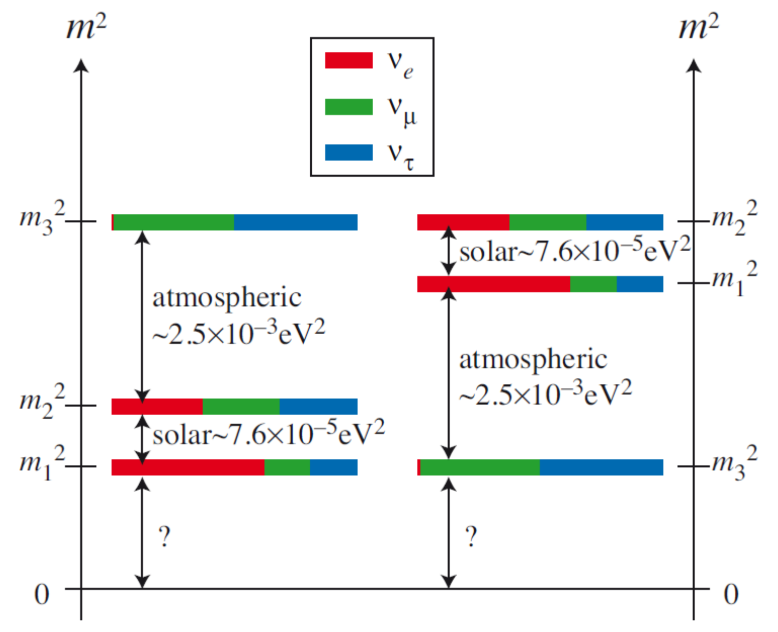
SNP Solution: Neutrinos have mass

- Super-Kamiokande compares atmospheric μ neutrinos from above (~ 10 km) and below (~ 12.000 km): see clear deficit in the latter → oscillation
- SNO uses detector filled with D_2O, measures
  ν_e + d -> e^- + p + p (CC, only e-neutrinos)
  ν + d -> ν + p + n (NC, all neutrinos)
  Ratio test directly oscillation hypothesis, solves solar neutrino puzzle by density effect.
- → Physics Nobel Prize 2015 (Kajita, McDonald)

What can(not) be measured with solar, atmospheric, reactor neutrinos?

- Atmospheric: mu -> tau neutrino oscillation (Kamiokande)
- Solar: electron -> mu neutrino, density effect (SNO)
- Reactor: e antineutrino disappearance, oscillation

What do we (not) know?



Normal hierachy inverted hierarchy

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Compare with

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

Open Problems (2018)

1. Is the CP violating phase /= 0 ?
2. What are the masses? What is the mass ordering?
3. Are Neutrinos Majorana or Dirac particles?
4. Where are the right-handed neutrinos?

LHC Experiments

- Beam composition perfectly known
- Beam energy known to about 0.01%
- Beam diameter ~ 1 micrometer at source
- Beamline ~ 27 km (LHC circumference)
- Beam diameter at detector ~ 1 micrometer
- Cross sections ~ 40 pb
- From all of this:
  no physics beyond the standard model

The Impossible Experiment

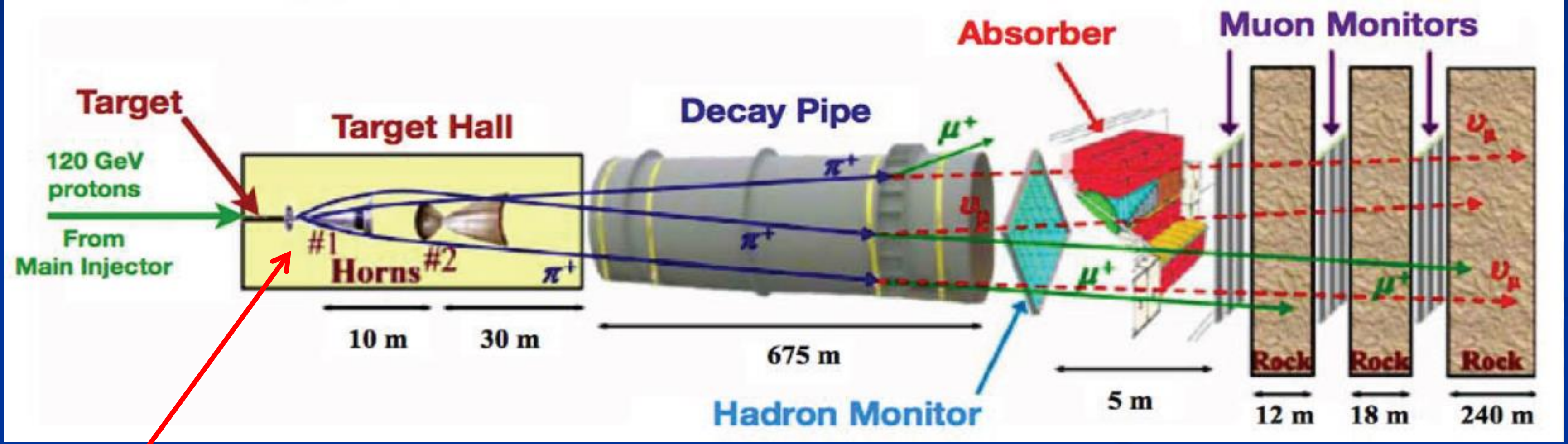
- Beam composition not fully known
- Beam energy badly known
- Beam diameter ~ 0.5 m at source
- Beamline ~ 300 – 1000 km
- Beam diameter ~ km m at detector
- Cross sections ~ 10^{-5} pb
- Only a small part of the final state known
- From all of this:

extract physics beyond the standard model!

Ongoing Long Baseline Experiments

- T2K (Japan), L ~ 300 km, E ~ 0.7 GeV
- NOvA (USA), L ~ 800 km, E ~ 2 GeV
- Planned: DUNE (~ 2027), L = 1300 km, E ~ 3.5 GeV

Neutrino Source

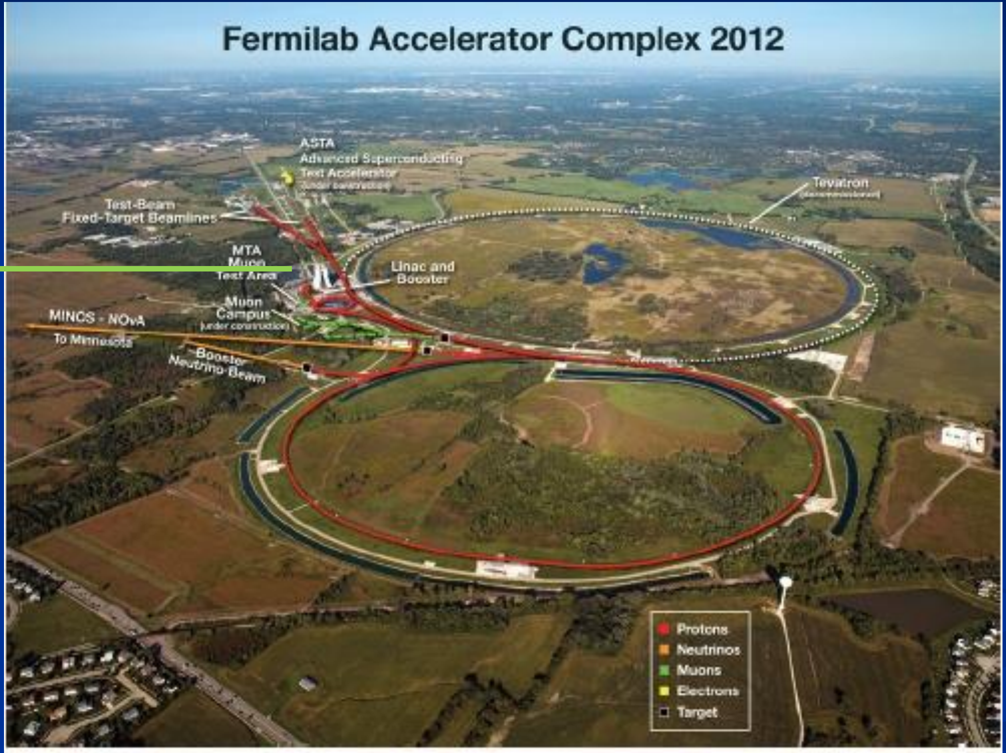


CBM Physics

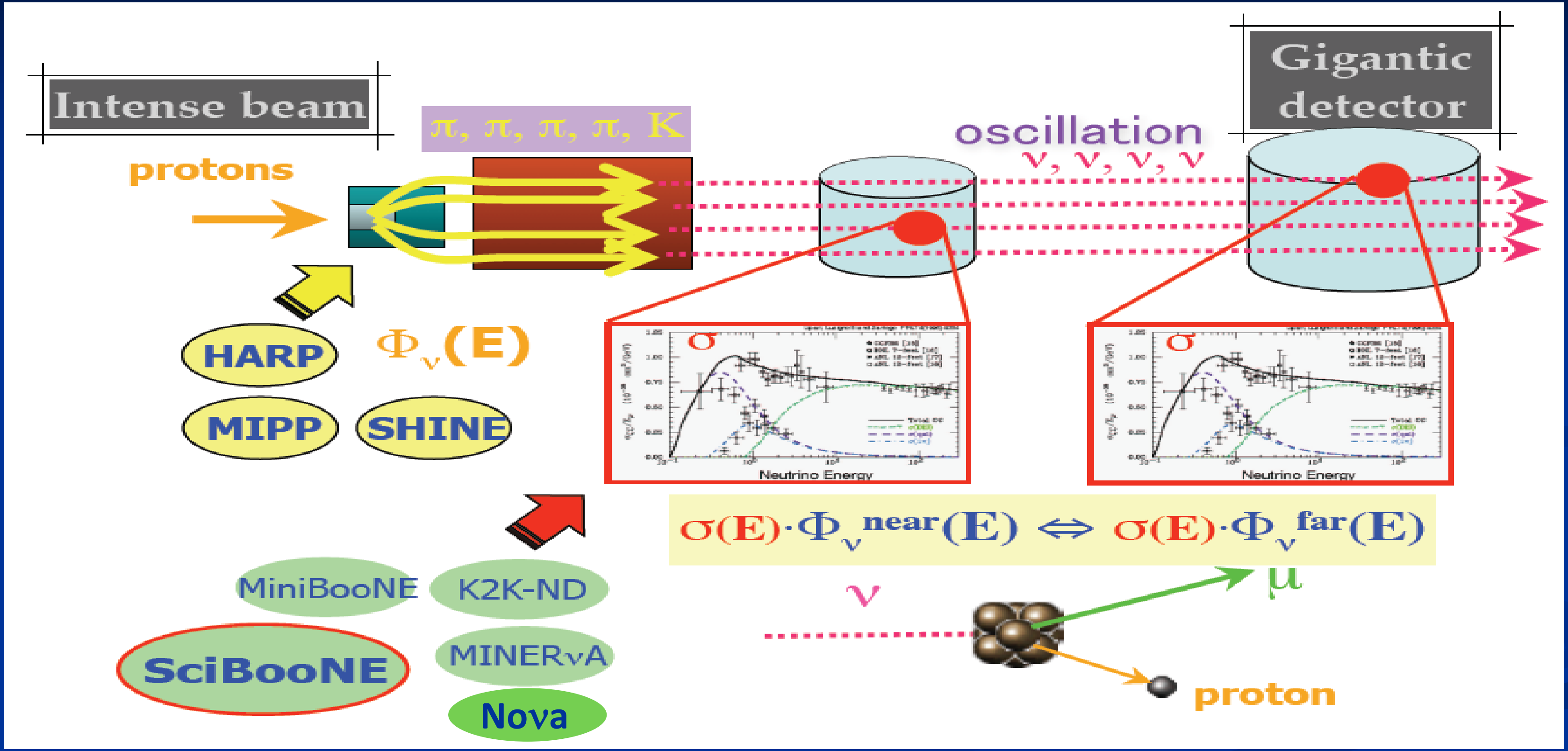
$$pC \rightarrow \pi^{+/-} \rightarrow \mu^{+/-}(\nu_\mu/\bar{\nu}_\mu)$$

Neutrino beams are broad in energy!

Long Baseline Experiment



Long Baseline Experiments



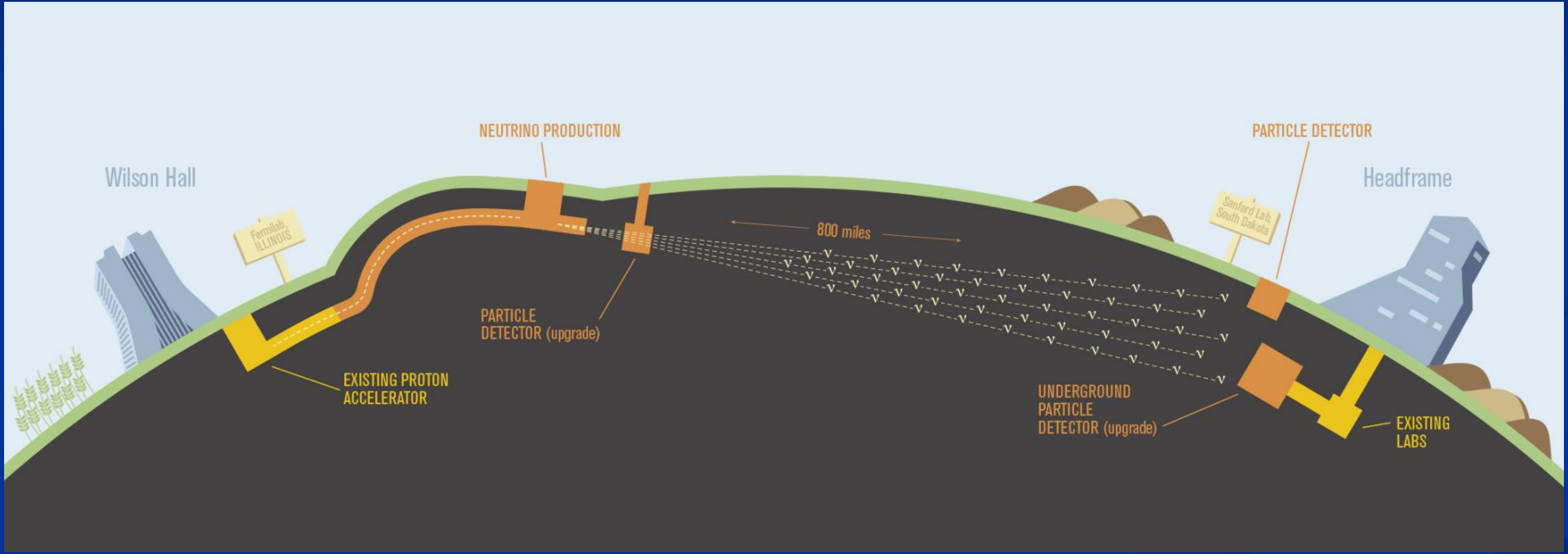
$$\sigma(E)\cdot\Phi_\nu^{near}(E) \Leftrightarrow \sigma(E)\cdot\Phi_\nu^{far}(E)$$

M. Wascko

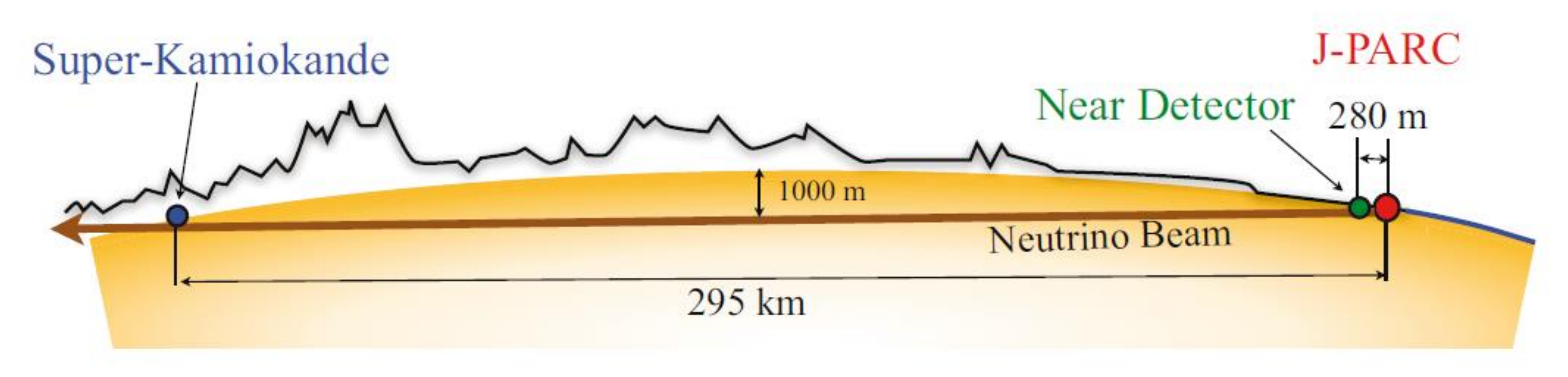
DUNE (= Deep Underground Neutrino Experiment)

Beam: 700 kW, 60-120 GeV, 5 years ν + 5 years anti-ν
on-axis, wide band, upgradable to 2.3 MW
Baseline: 1300 km FNAL to Homestake

DUNE


NEUTRINO PRODUCTION
PARTICLE DETECTOR
Wilson Hall
Headframe
Fermilab ILLINOIS
Sanford Lab, South Dakota
800 miles
ν
PARTICLE DETECTOR (upgrade)
EXISTING PROTON ACCELERATOR
UNDERGROUND PARTICLE DETECTOR (upgrade)
EXISTING LABS

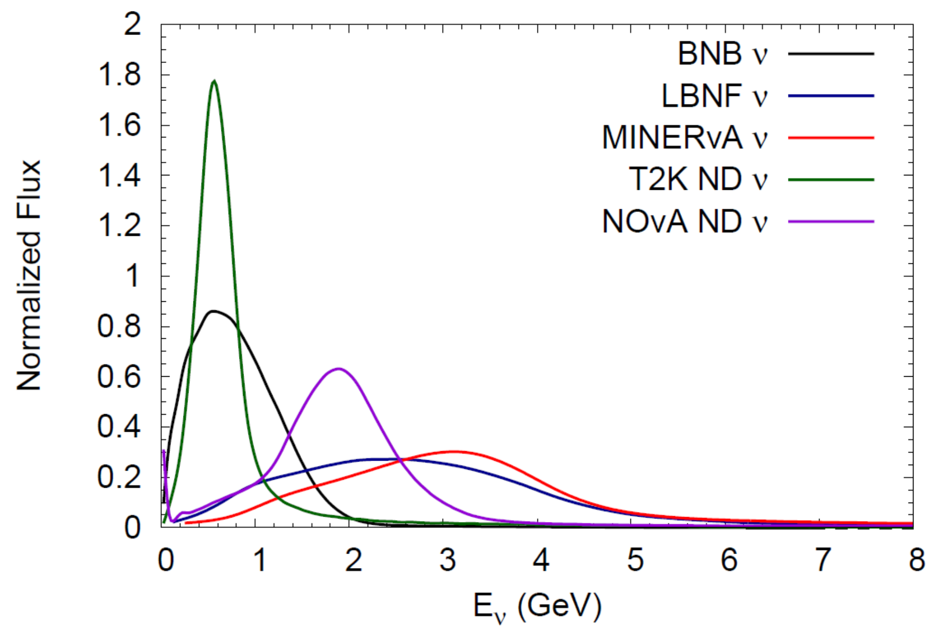
T2K Neutrino Beam



Oscillations and Neutrino Energy

PROBLEM:
Neutrinos are produced as secondary decay products of high-energy pA collisions, x-sections from hadron production experiments such as NA61/SHINE or HARP

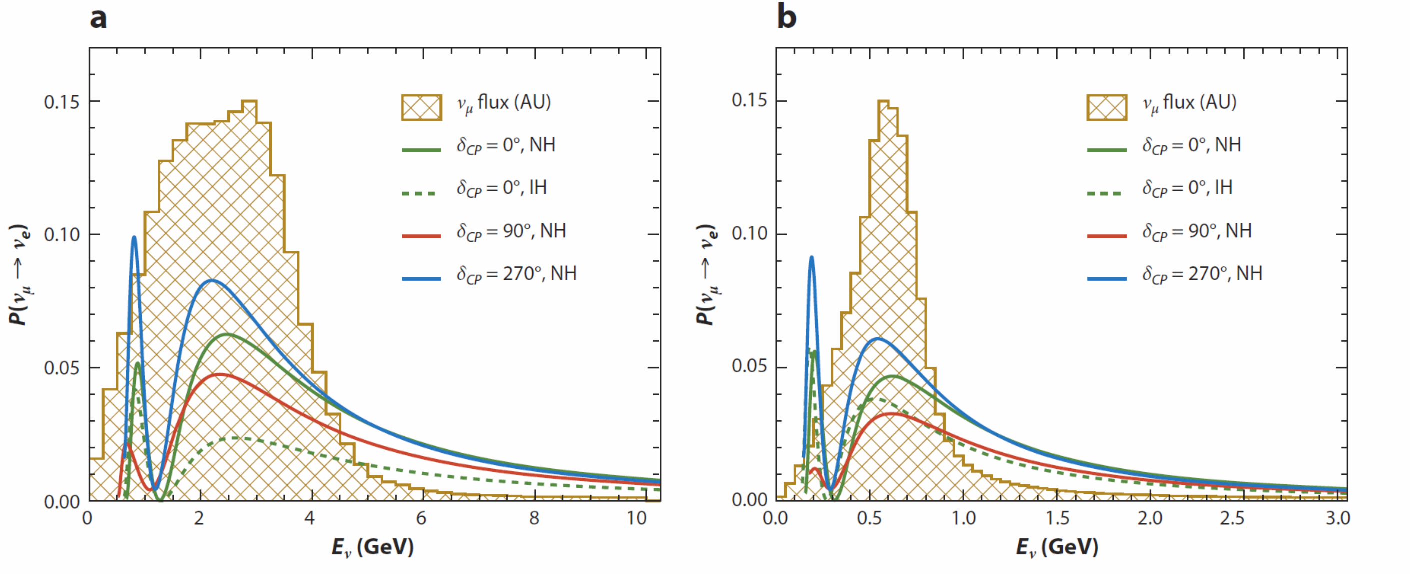
➔ They have broad energy distributions
Difference to any other high-energy and nuclear physics experiment!
LHC: $\Delta E / E \sim 0.1\ \%$



What is (not) measured in a LBL exp?

- LBL experiments measure only flux-averaged cross sections
- The neutrino energy is not measured
- Oscillation Patterns as function of neutrino energy must be reconstructed → needs nuclear theory and modeling
- Experiments require few % accuracy

Oscillation Signals as F(E_ν)



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

DUNE, 1300 km **HyperK (T2K) 295 km**

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

Ratios of event rates to about 10%

Problem: Neutrino Energy

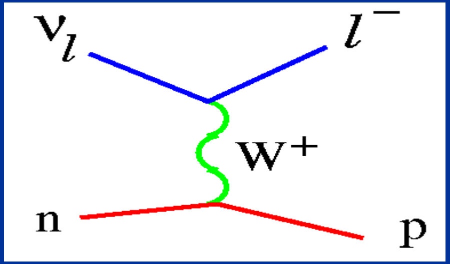
- The incoming neutrino energy on the abscissa of all such plots is not known, but must be reconstructed; very different from Nuclear Physics and High Energy Physics where the beam energy is accurately known.
- The reconstruction has to start from an only partially observed final state (detector limitations!) and proceeds from there ‚backwards' to the initial state.

Energy Reconstruction

- Oscillation analysis requires neutrino energy
- Energy reconstruction
  1. Calorimetric: measures energy of all outgoing particles, needs simulation of thresholds and non-measured events
  2. Through QE: needs event identification

Energy Reconstruction by QE

- In QE scattering on nucleon at rest, only *l +p*, no π: outgoing lepton determines neutrino energy

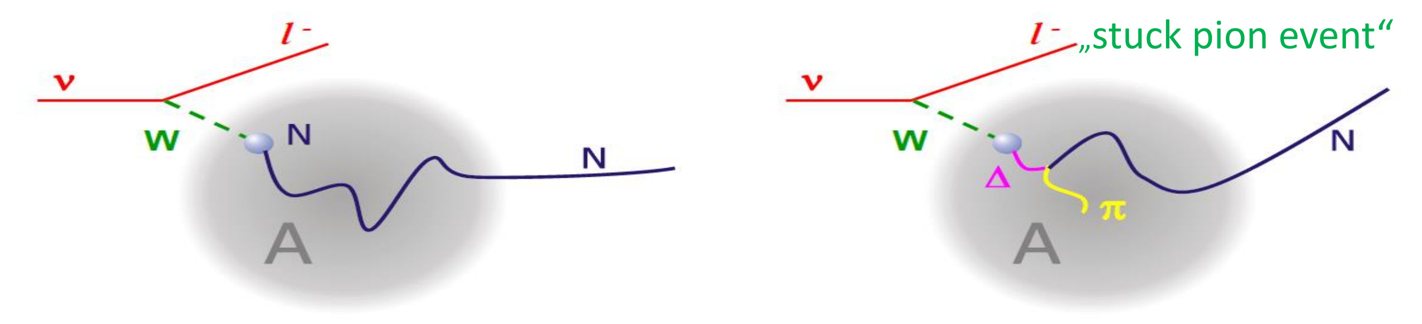


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

1. Nucleons are Fermi-moving
2. Final state interactions may hinder correct event identification

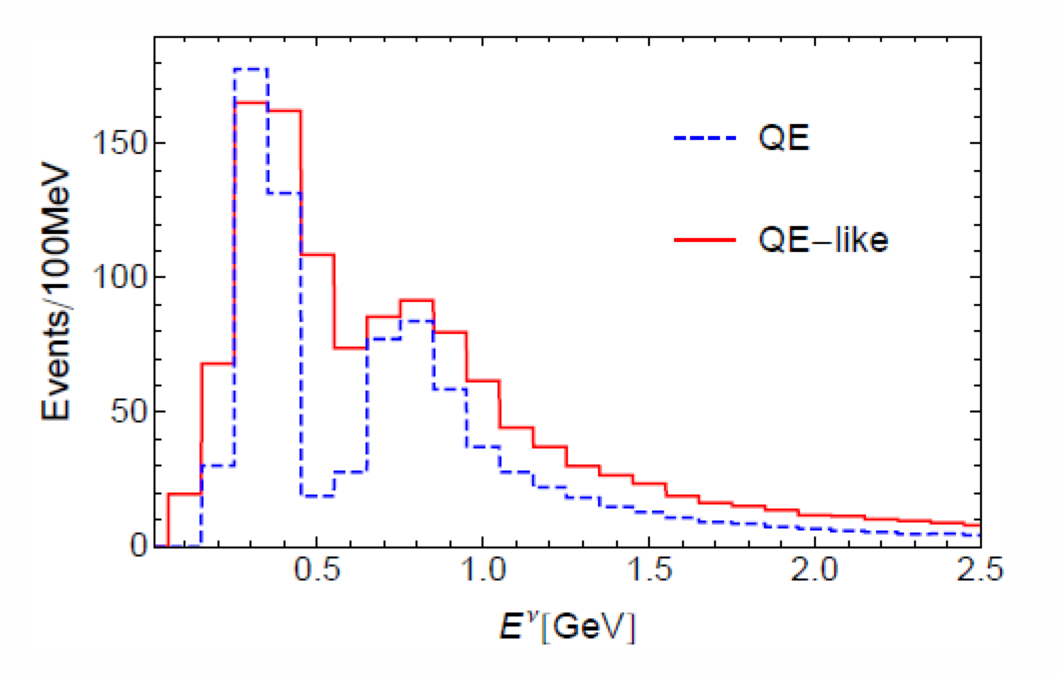
Final State Interactions in Nuclear Targets



Complication to identify QE, always entangled with π production

Nuclear Targets (K2K, MiniBooNE, T2K, MINOS, Minerva, ….)

Deterioation of QE Signal



P. Coloma, P. Huber,
arxiv 1307.1203

QE-like:
in Cerenkov counter
nucleons not seen,
0 pions required

Generators

- Generators are needed for this ‚backwards calculation'
- The accuracy of the energy reconstruction and thus the precision of any neutrino mixing parameters depends crucially on the precision of these generators
- Generators must be an integral part of any experiment
- Generators must be able to handle:
  - the extended target size complications
  - the primary neutrino-nucleus interaction
  - the final state interactions

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

A wake-up call for the high-energy physics community:

“Wake up, Dr. Erskine—you’re being transferred to low energy physics.”

Low-Energy Nuclear Physics determines response of nuclei to neutrinos

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Quantum-Kinetic Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations
- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from gibuu.hepforge.org, new version GiBUU 2017
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

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GiBUU

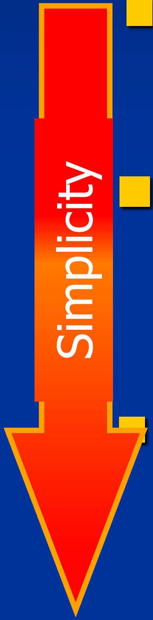
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** describes: (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions on nuclei
  - photon and electron induced reactions on nuclei
  - neutrino induced reactions on nuclei

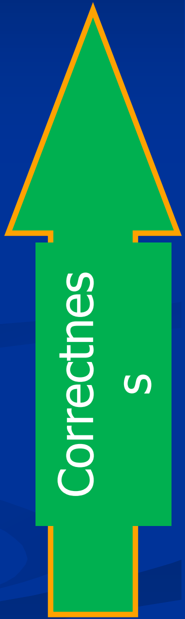
using the same physics input! And the same code!

NO TUNING!

Theoretical Basis of GiBUU


Simplicity

- Kadanoff-Baym equation   (1960s)
  - full equation not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models: GiBUU
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s)
- Cascade models (typical event generators, GENIE, NEUT, NuWro, …)
  - no mean-fields, primary interactions and FSI not consistent, reweighting of different interaction types, ….


Correctnes s

Quantum-kinetic Transport Theory

$$\overbrace{\mathcal{D}F(x,p)}^{\text{On-shell drift term}} - \overbrace{\mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}}}^{\text{Off-shell transport term}} = \overbrace{C(x,p)}^{\text{Collision term}} .$$

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

H contains
mean-field
potentials

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

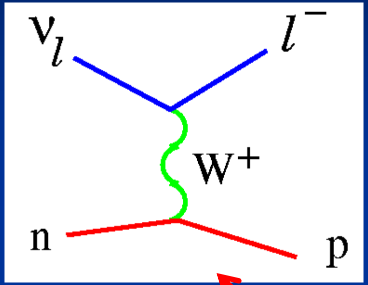
$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

Spectral function

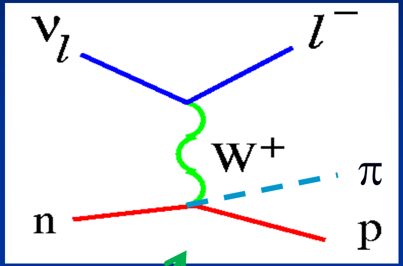
Phase space distribution

Neutrino-Nucleon Cross Section

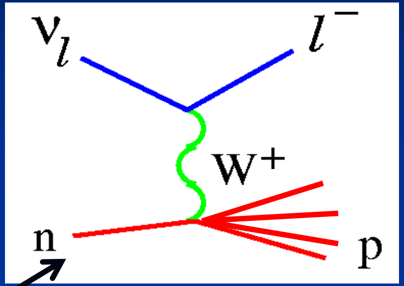
CCQE

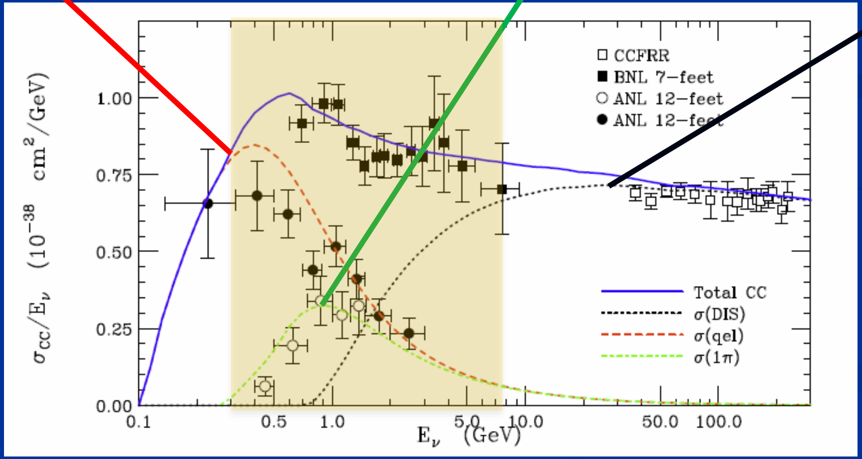


1π



DIS

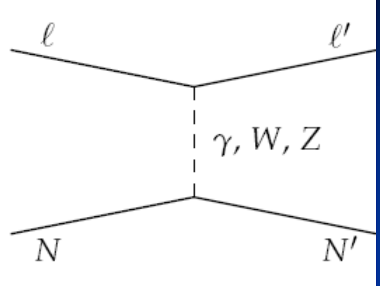




note:
10^{-38} cm² = 10^{-11} mb

In the region of modern experiments (0.5 – 10 GeV) all 3 mechanisms overlap

Quasielastic Scattering



$$J^{\mu}_{QE} = \left(\gamma^{\mu} - \frac{\not{q}\, q^{\mu}}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_{\alpha} F_2^V + \gamma^{\mu}\gamma_5 F_A + \frac{q^{\mu}\gamma_5}{M_N} F_P$$

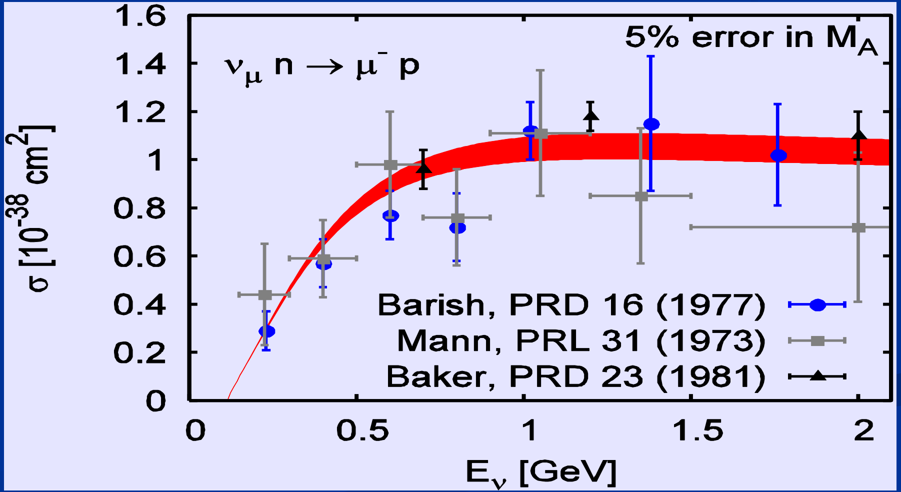
- Vector form factors from *e* –scattering
- axial form factors

F_A ⇔ F_P and $F_A(0)$ via **PCAC**

dipole ansatz for F_A with

M_A= 1 GeV:

$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$



ITP 10/2018

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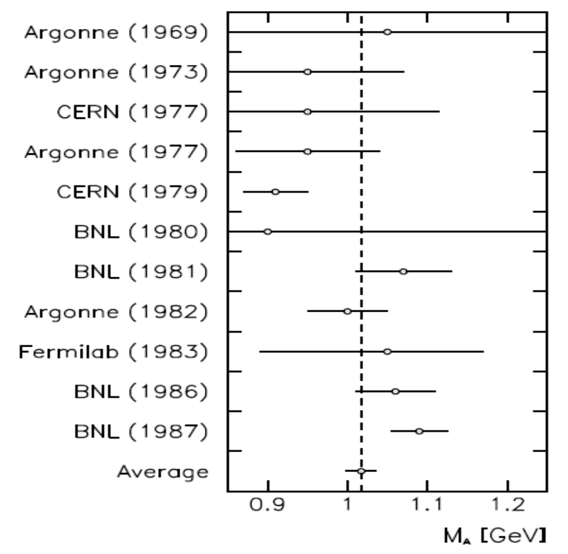
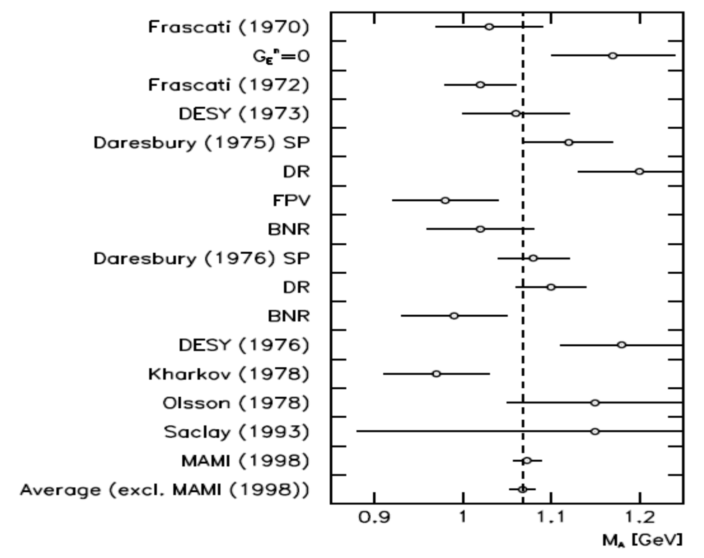
Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data





M_A ≅ 1.02 GeV world average

M_A ≅ 1.07 GeV world average

Dipole ansatz is simplification, not good for vector FF

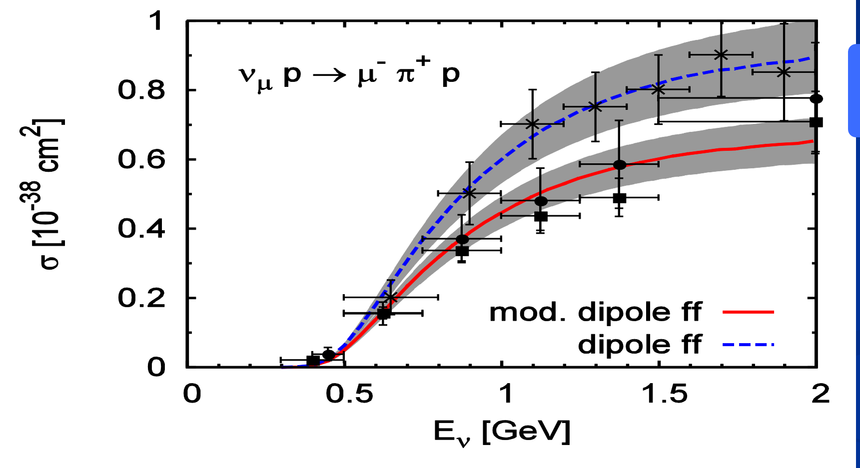
Pion Production

- 13 resonances with W < 2 GeV, non-resonant single-pion background, DIS
- pion production dominated by **P_{33}(1232) resonance**:

$$
\begin{aligned}
J^{\alpha\mu}_{\Delta} = \quad & \left[\frac{C_3^V}{M_N}\left(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu\right) + \frac{C_4^V}{M_N^2}\left(g^{\alpha\mu} q\cdot p' - q^\alpha p'^\mu\right) + \frac{C_5^V}{M_N^2}\left(g^{\alpha\mu} q\cdot p - q^\alpha p^\mu\right)\right]\gamma_5 \\
& + \frac{C_3^A}{M_N}\left(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu\right) + \frac{C_4^A}{M_N^2}\left(g^{\alpha\mu} q\cdot p' - q^\alpha p'^\mu\right) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^\alpha q^\mu
\end{aligned}
$$

- **$C^V(Q^2)$** from electron data (MAID analysis with CVC)
- **$C^A(Q^2)$** from fit to neutrino data (experiments on hydrogen/deuterium),
  so far only C^A_5 determined, for other axial FFs only educated guesses

Pion Production



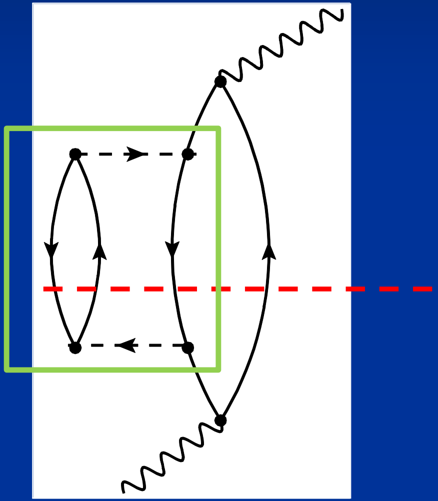
10 % error in $C_5^A(0)$

data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)

discrepancy between elementary data sets
→impossible to determine 3 axial formfactors

2p-2p excitations and spectral functions

2nd ampl. squared



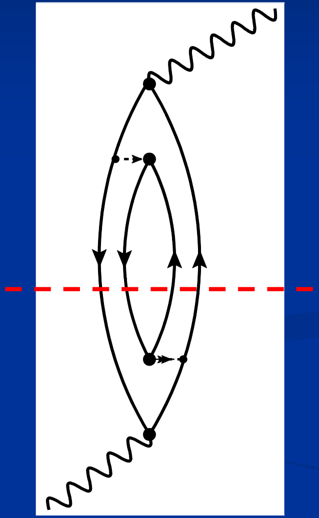
hole
selfenergy
Σ

Cutkosky
cut

Spectral Function

$$\mathcal{A} \propto \frac{\Im\Sigma}{(p^2 - M^2 - \Re\Sigma)^2 + (\Im\Sigma)^2}$$

Interference term squared

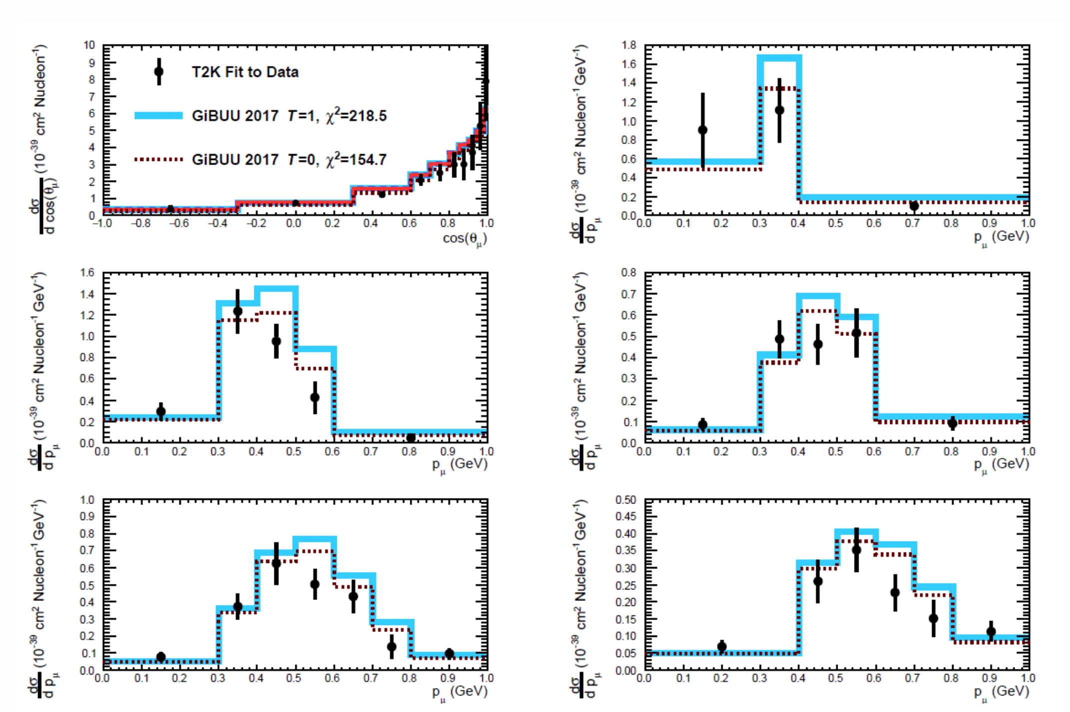


No selfenergy,
Vertex correction,
not included in spectral
function

Vertex correction
Not contained in spectral function

T2K Inclusive Cross Section

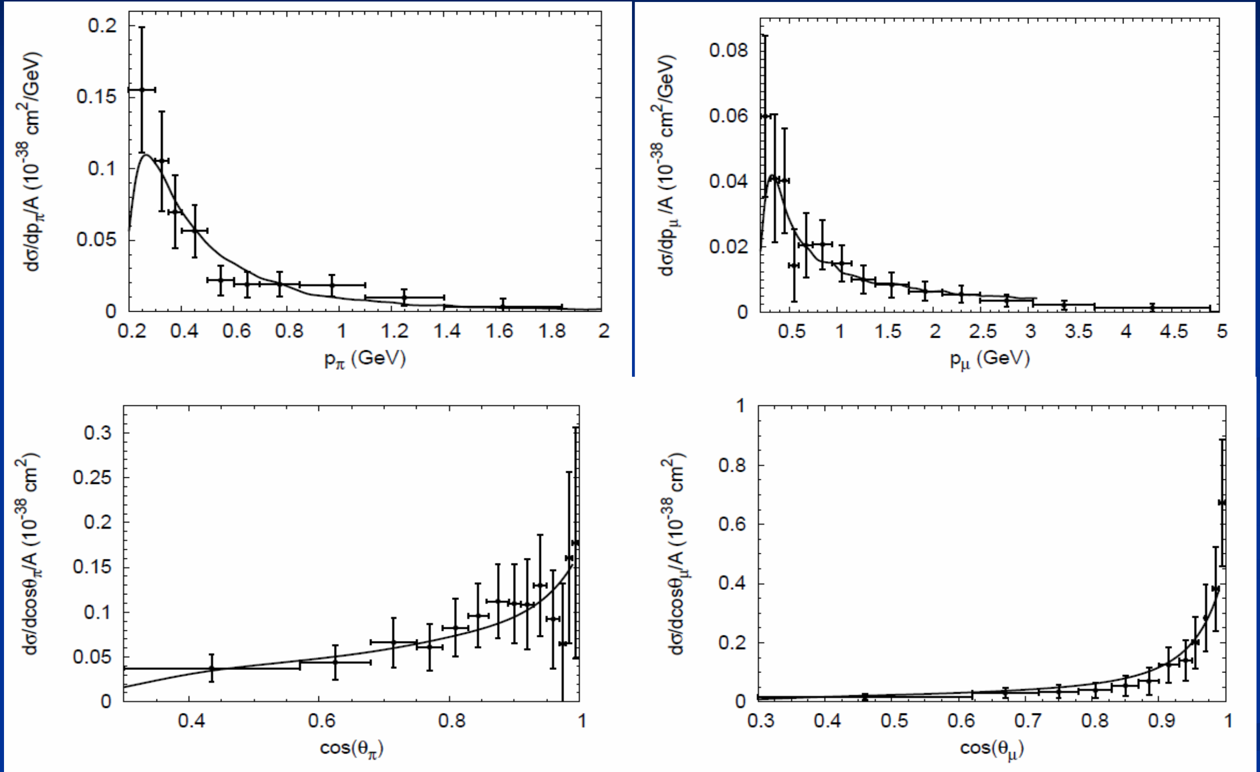
Target:
CH



Dolan et al,
arXiv:1804.09488

Poster:
S. Dolan et al
Wednesday, #104

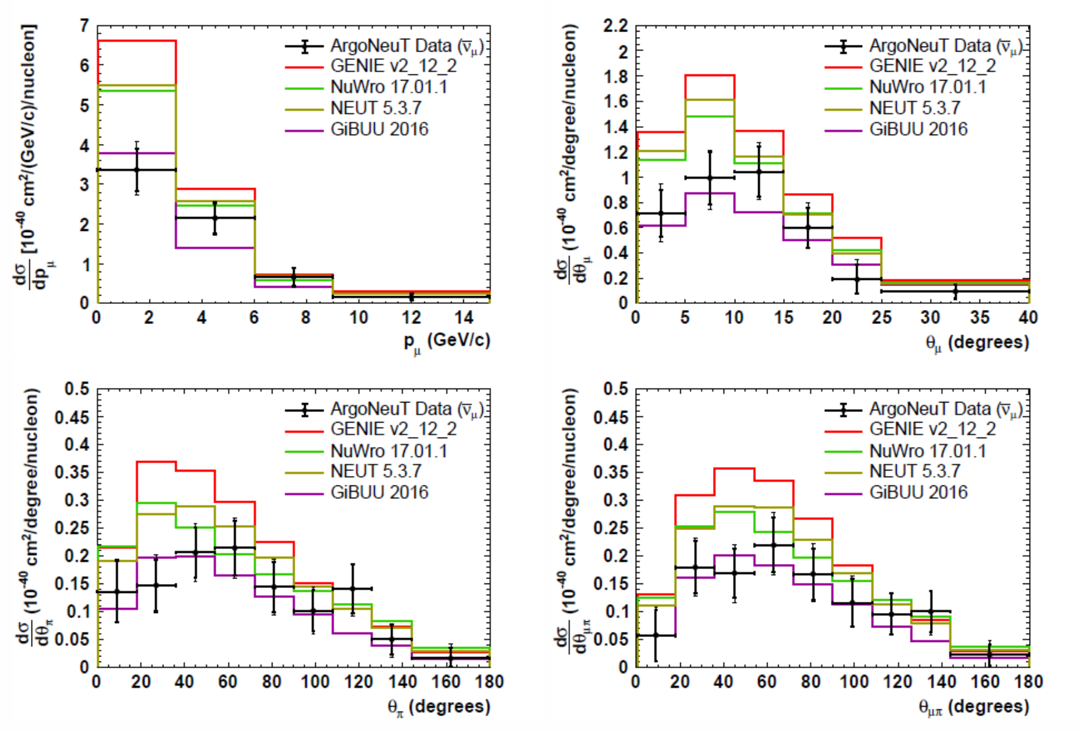
T2K ND280 Pi+



H_2O target

Mosel, Gallmeister,
Phys.Rev. C96 (2017) no.1, 015503

Pion Production on LAr



ArgoNeut

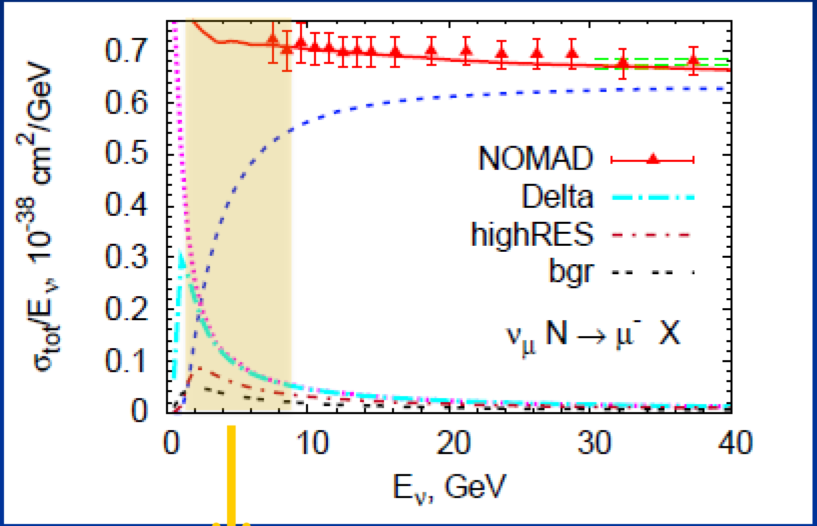
arXiv:1804.10294

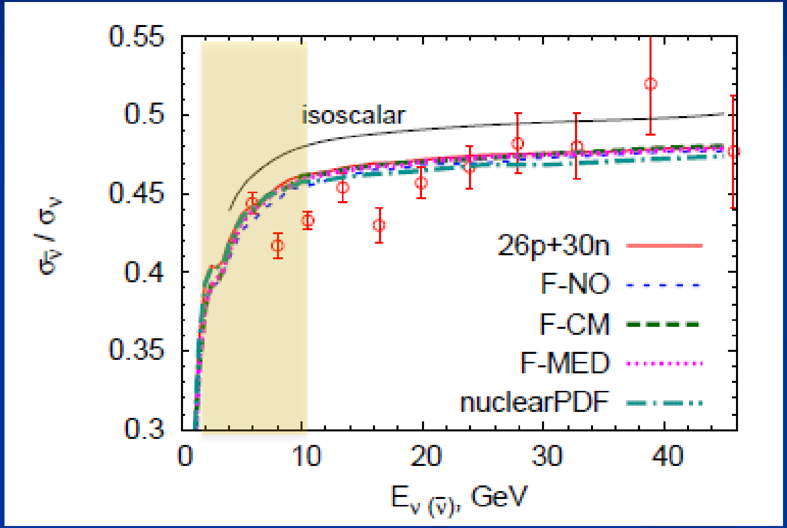
Antineutrinos

Excellent agreement of GiBUU with Ar data

NO Tune

SIS - DIS





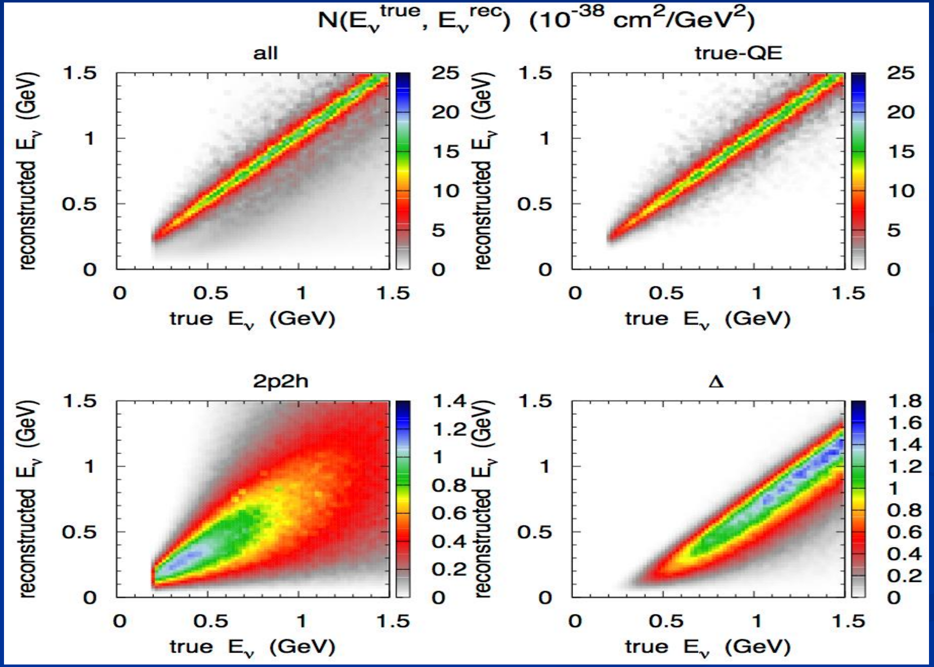
Shallow Inelastic Scattering,
interplay of different reaction mechanisms → Ambiguity to switch

Oscillation and Energy Reconstruction

GiBUU is Nature

- GiBUU is used to simulate nature: generate events with known, *true energy*
- Analyze these events with exp. methods, obtain *reconstructed energy* for each event
- Compare event rates as functions of true and reconstructed energies

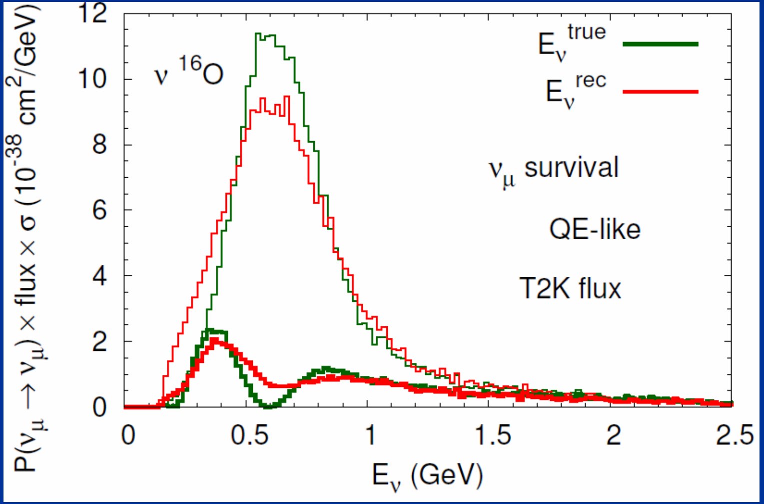
Migration Matrix for C and MB flux



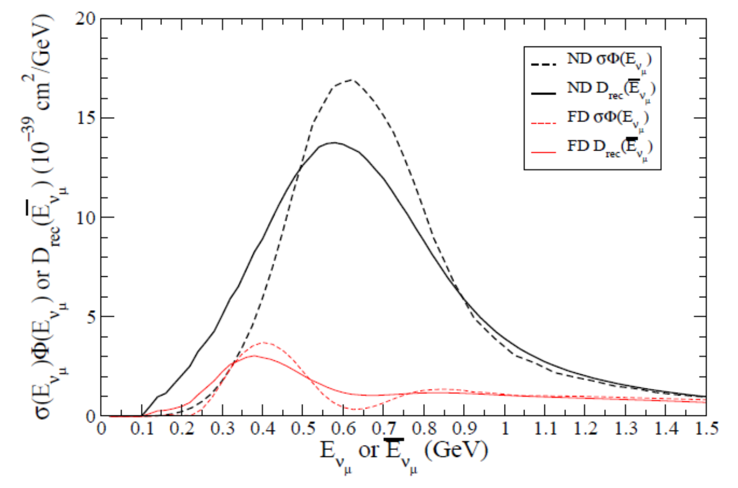
Distributions
for 0 pion events!

Oscillation signal in T2K

ν_μ disappearance



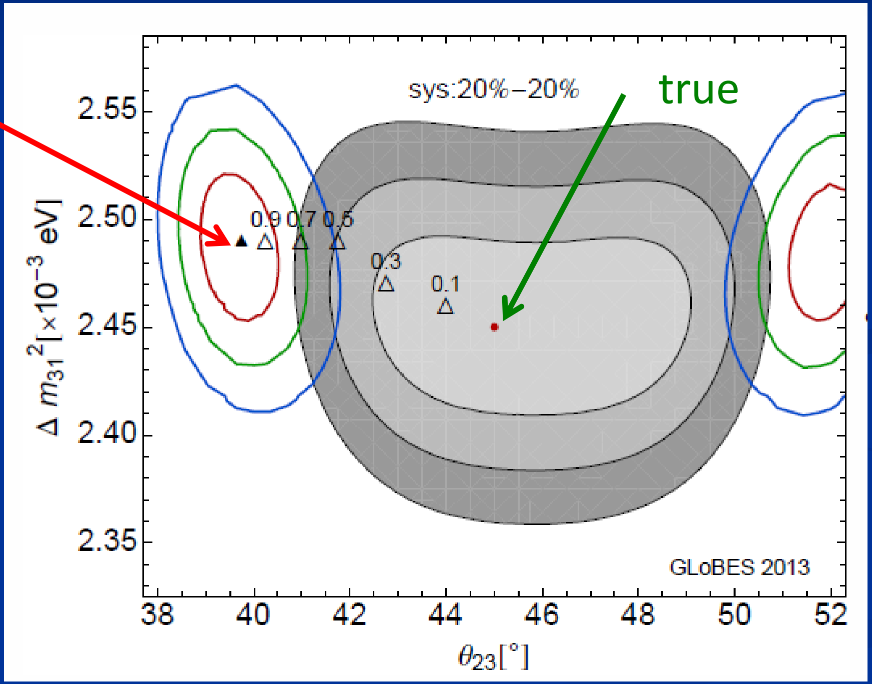
GiBUU



Martini

Sensitivity of oscillation parameters to nuclear model

reconstructed
from naive
QE dynamics

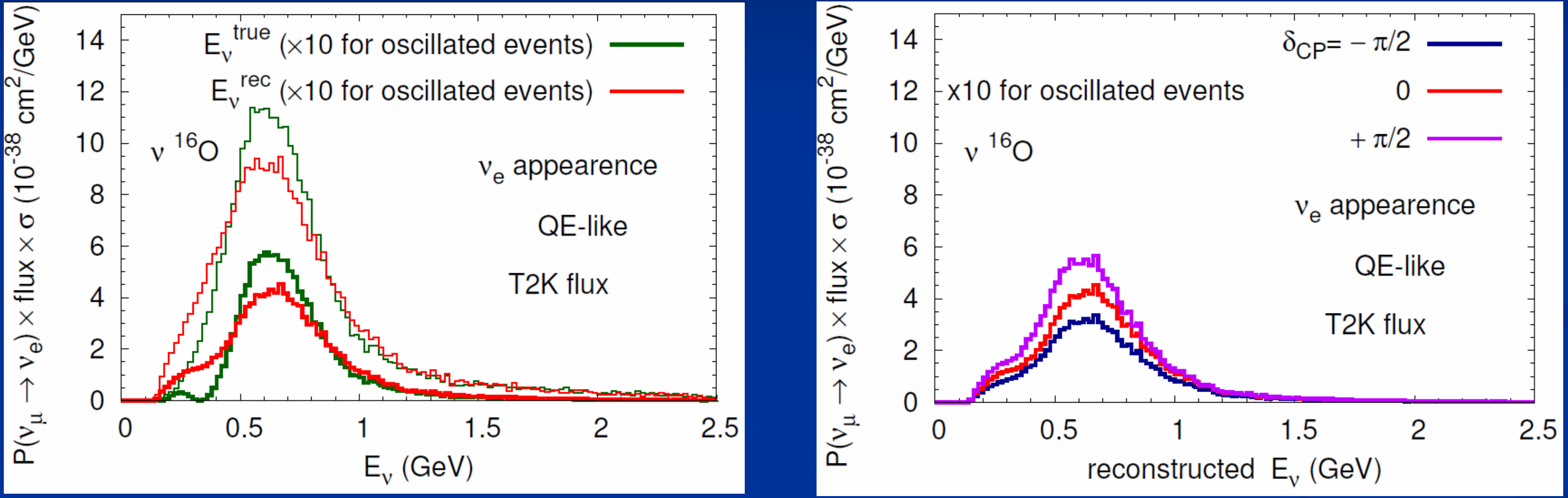


P. Coloma, P. Huber,
arXiv:1307.1243, July 2013

Analysis based on GiBUU

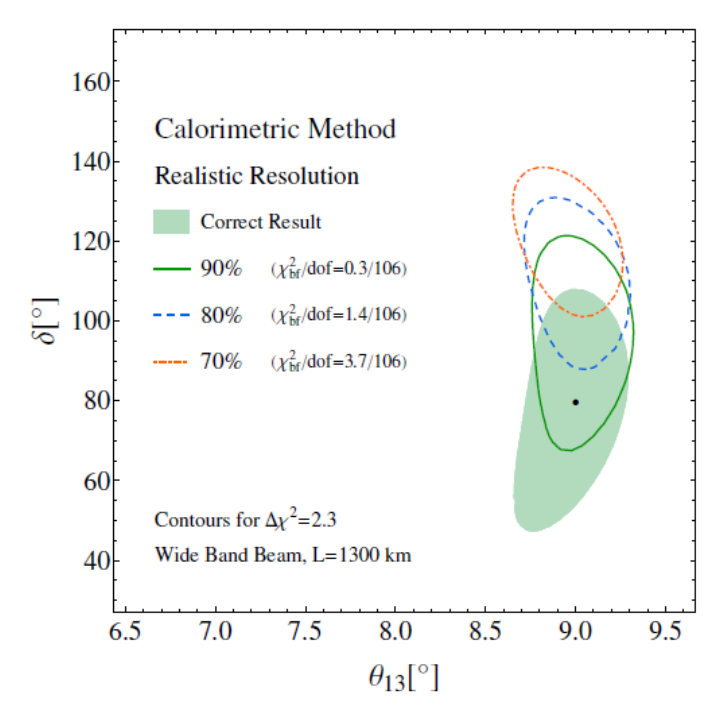
T2K

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



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

Extraction of Oscillation Parameters



Oscill parameters in dependence on % of true missing energy for DUNE

Ankowski et al,
Phys.Rev. D92 (2015) 091301

Summary I

- Energy reconstruction is essential for precision determination of neutrino oscillation parameters (and nu-hadron cross sections)
- Neutrino energy must be known within about 50 (T2K) or 100 (DUNE) MeV
- Nuclear effects complicate the energy reconstruction
- Need state-of-the-art generators for reconstruction, with predictive power and no artificial degrees of freedom

Summary II

- Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
- This joint effort has to be funded as integral part of experiments

- Transport Theory has to find its way into neutrino generators!

GiBUU

- 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
- The work reported here was done in collaboration with Kai Gallmeister and Olga Lalakulich