ν-A Interactions

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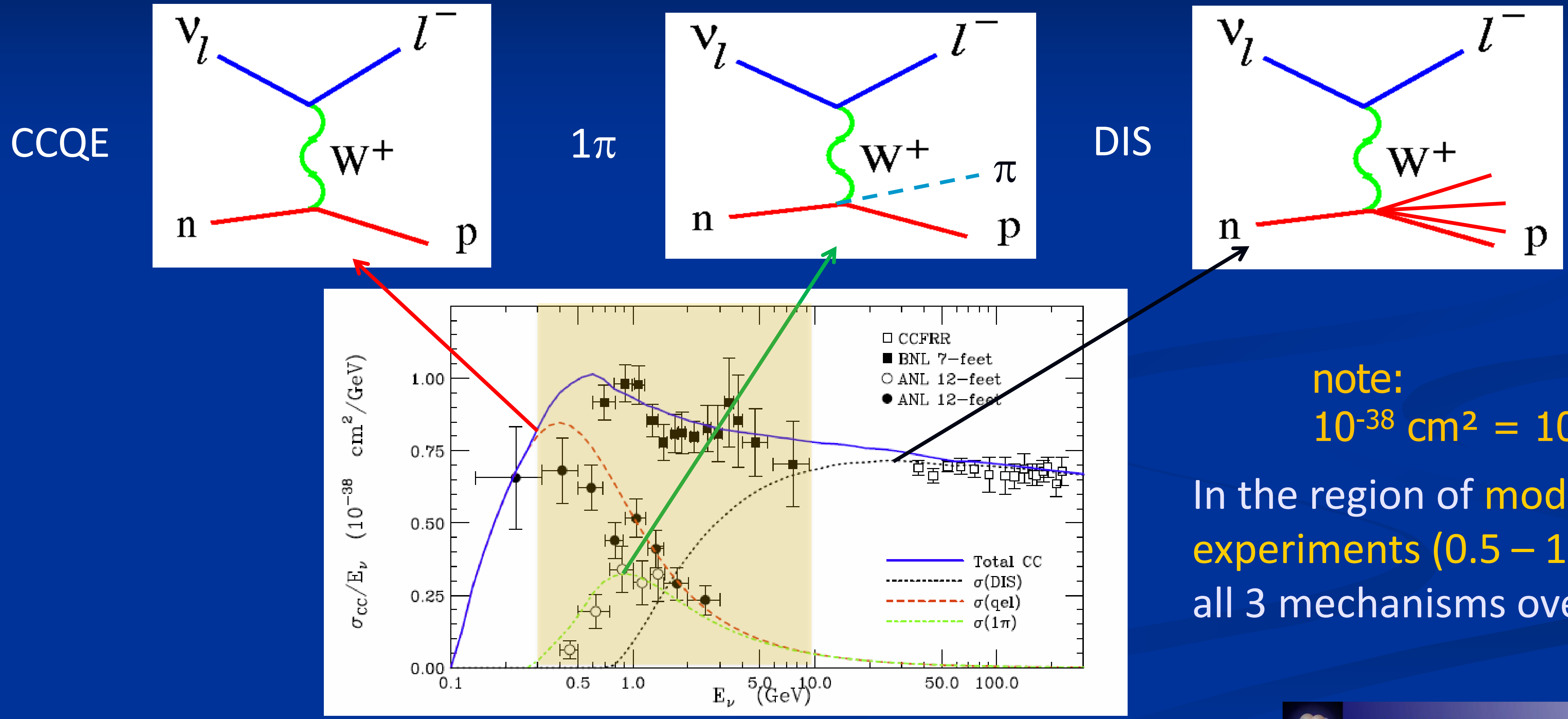
Neutrino-nucleon cross section

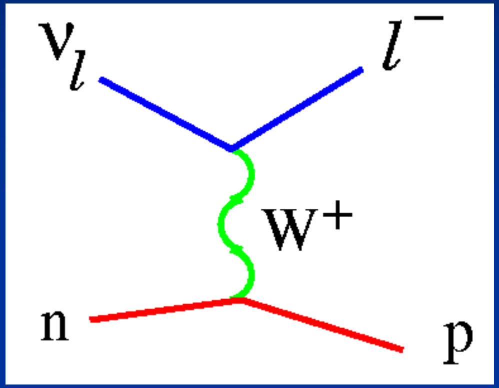


note:
10^{-38} cm² = 10^{-11} mb

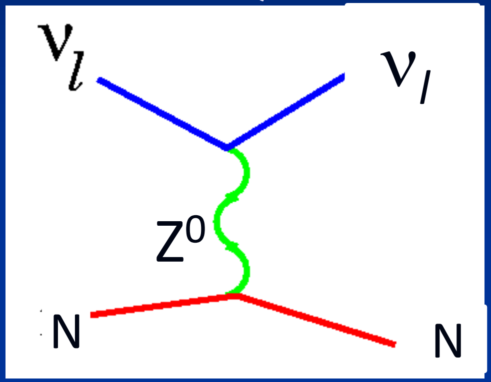
In the region of modern experiments (0.5 – 10 GeV) all 3 mechanisms overlap

Charged and Neutral Currents

CCQE



NCQE



Both processes favor interactions on neutrons:

- CCQE : charge conservation
- NCQE weak charge
  - neutron : $Q_{weak} = 1$
  - proton : $1 - 4\sin^2\theta_W$, Weinberg angle ~ 0.25 -> Q_{weak} ~ 0
- Electron scattering favors interaction with protons

Neutrino Oscillations

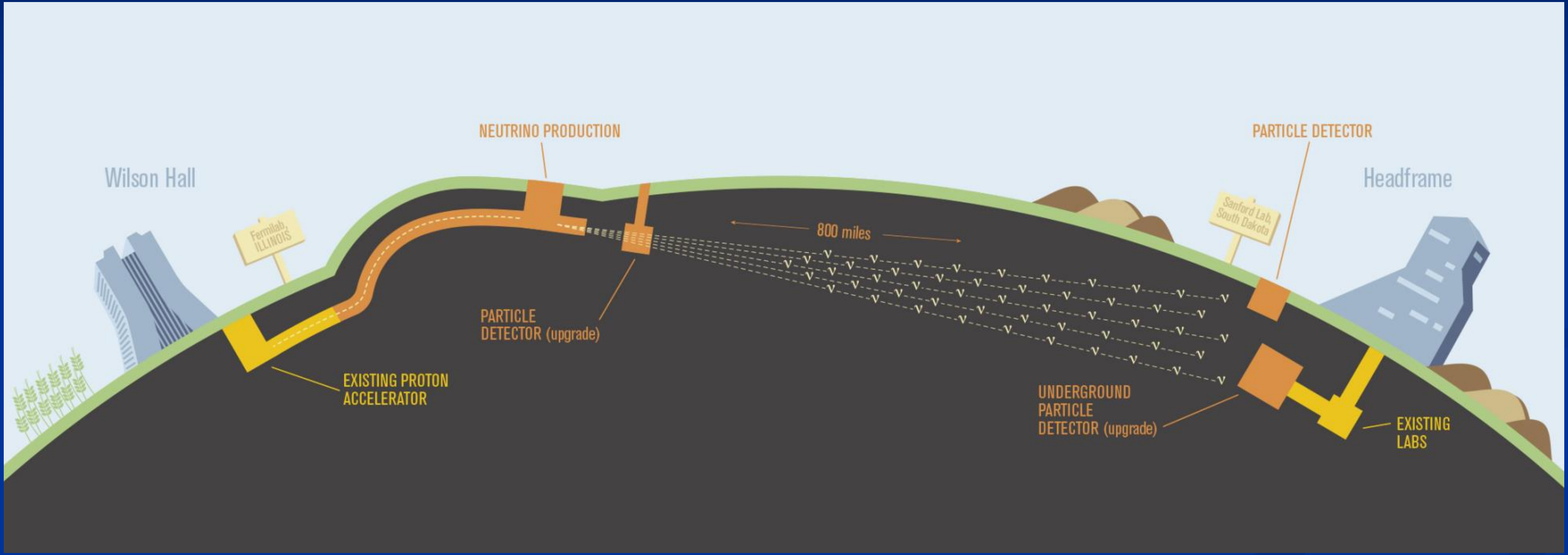
- 2-Flavor Oscillation:

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

Know: distance *L*, need energy E_ν
to determine mass difference Δm^2, *mixing angle* θ

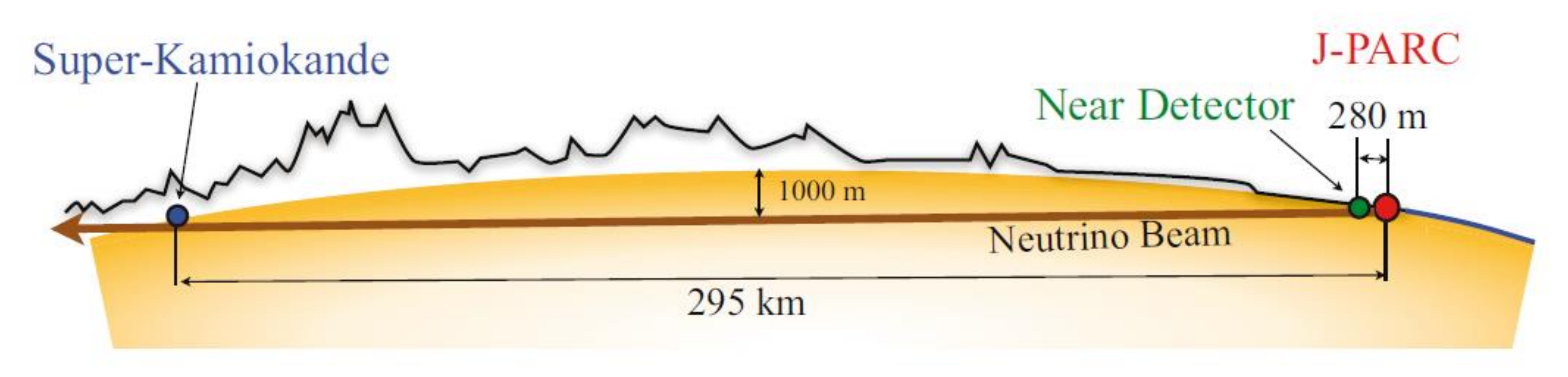
- Even more interesting:
3-Flavor Oscillation allows for CP violating
phase δ_{CP} → matter/antimatter puzzle, order of neutrino masses

DUNE (Flagship of US HEP)

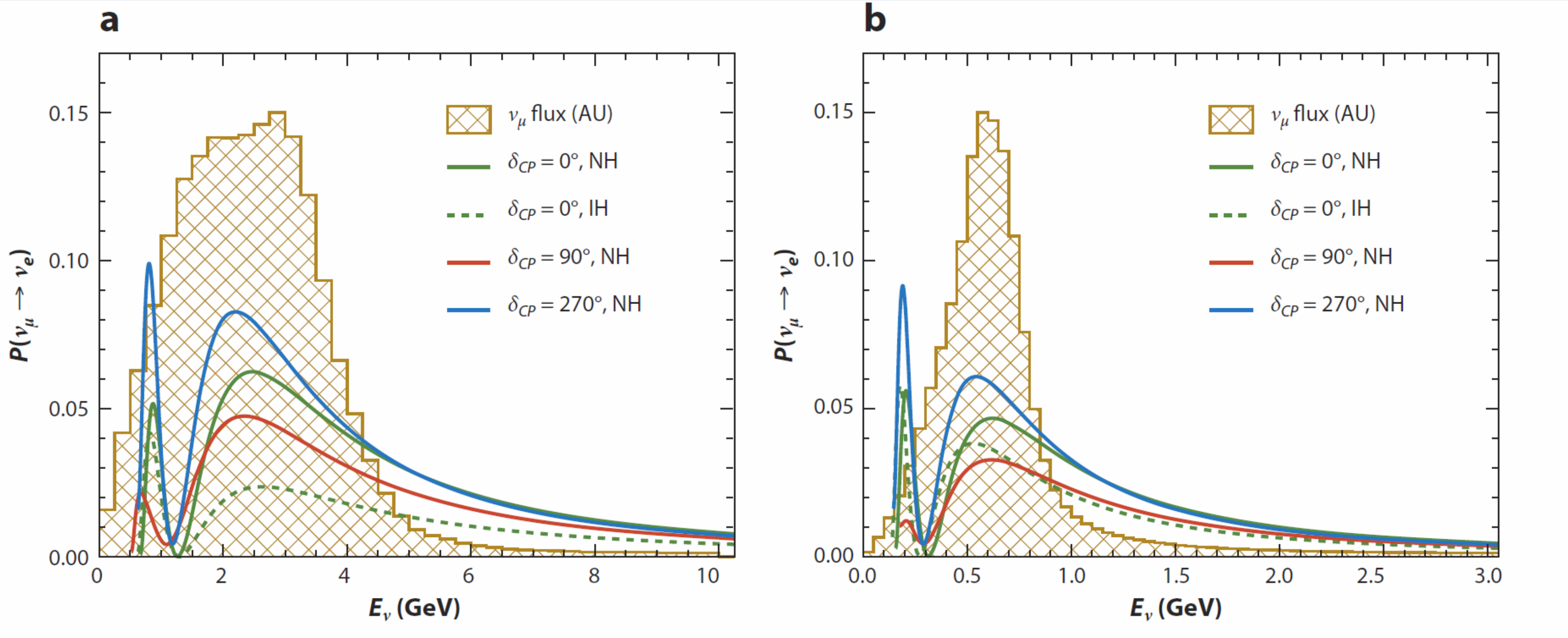


Also NovA experiment starts at Fermilab, ~ 800 km beam length

T2K Neutrino Beam



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%

Neutrino Beam Energy

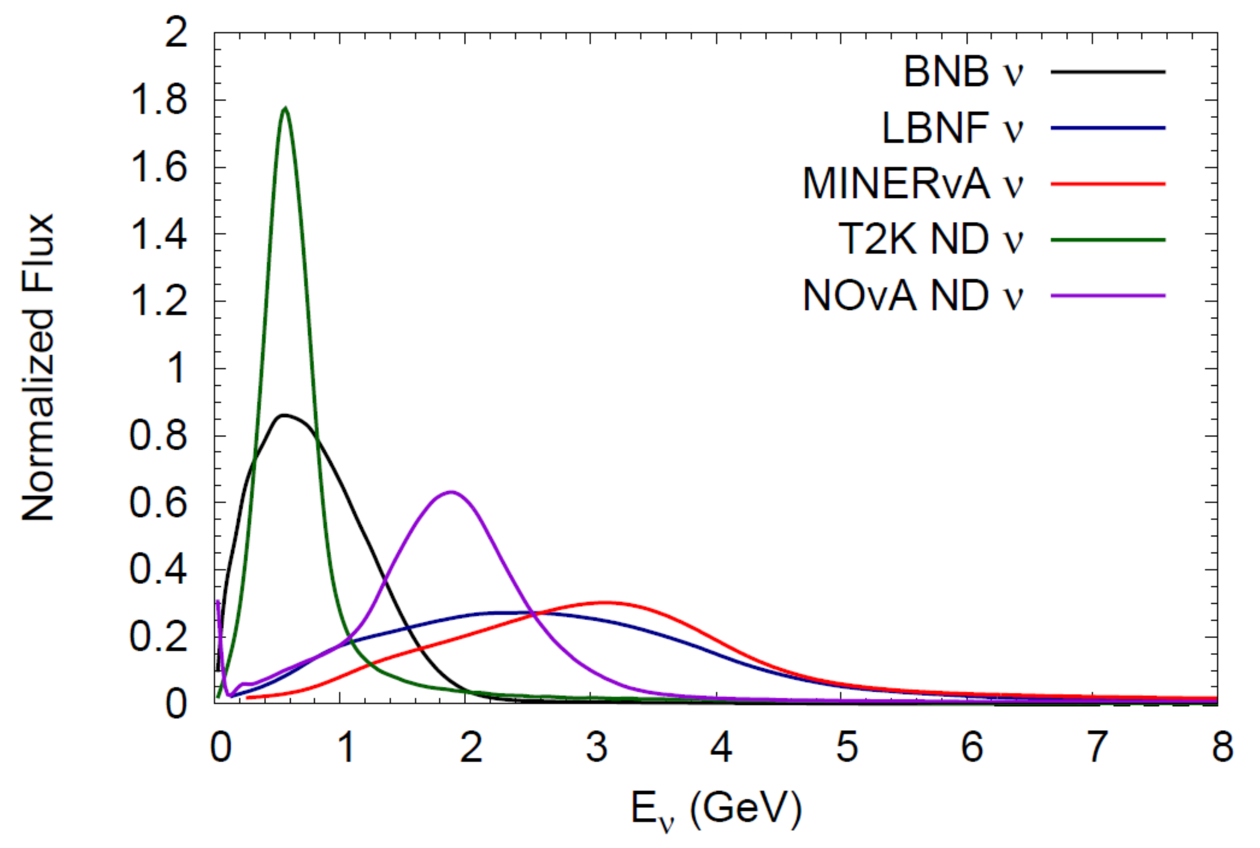
PROBLEM:

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: $\Delta E / E \sim 0.1\ \%$



Problem: Neutrino Energy

- The incoming neutrino energy on the abscissa of all such oscillation 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 → Need transport

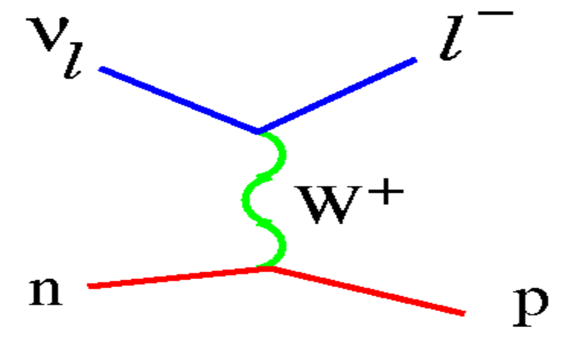
Energy Reconstruction

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

  2. Kinematical: through QE, needs event identification

Energy Reconstruction by QE

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

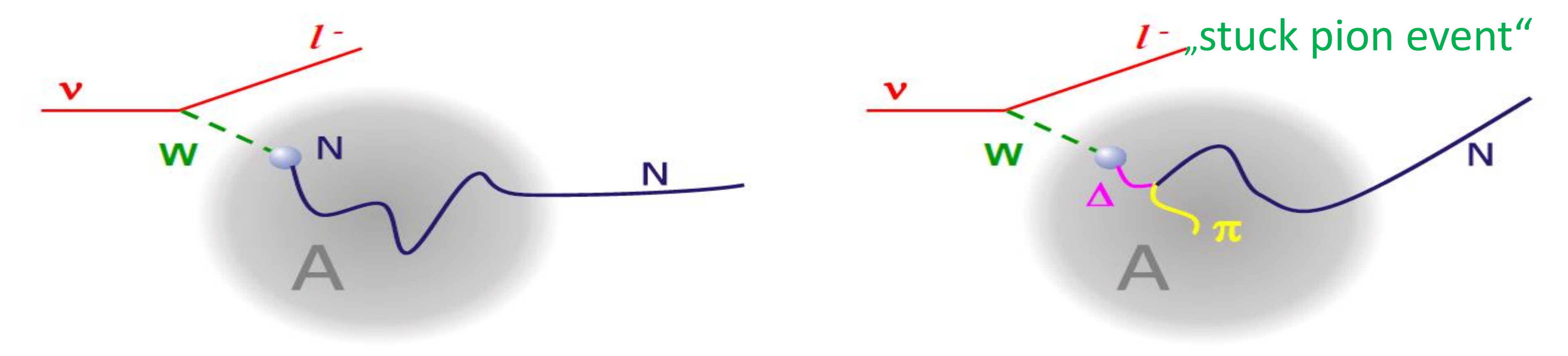


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets: C, O, ^{40}Ar

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

Final State Interactions in Nuclear Targets



„stuck pion event“

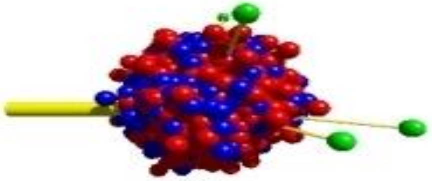
Complication to identify QE, always entangled with π production

Need Transport to sort out processes

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



Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym equations, allows for off-shell propagation
- 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 2021
  add. details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

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GiBUU

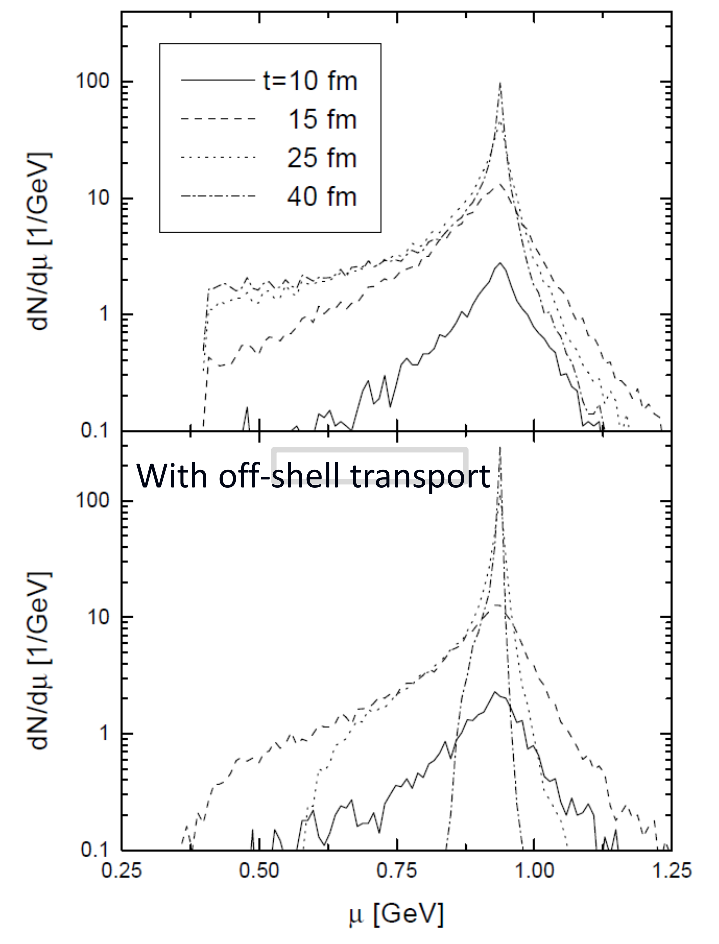
The Giessen Boltzmann-Uehling-Uhlenbeck Project

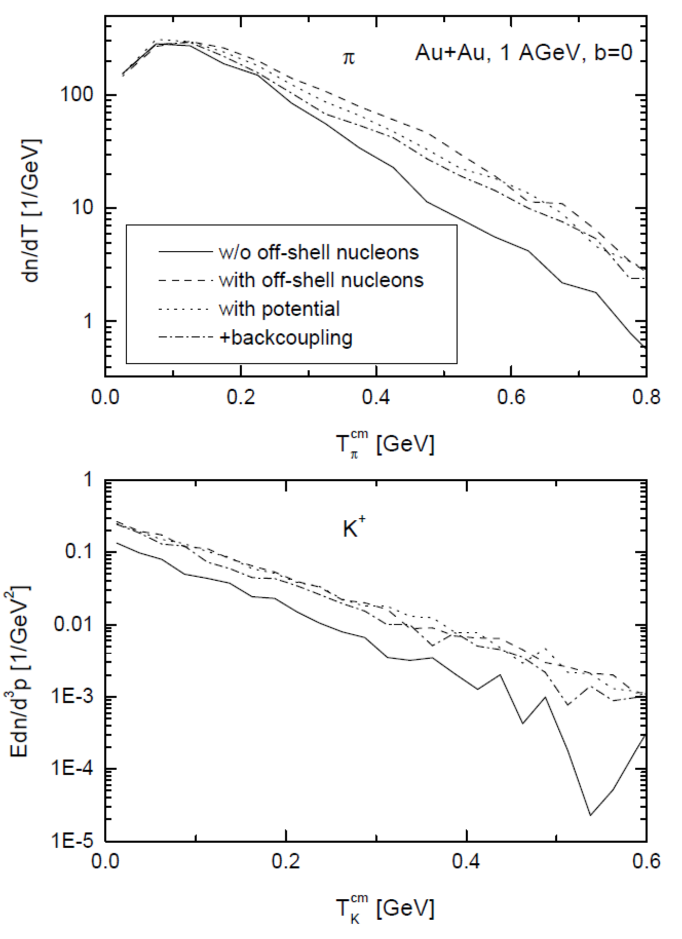
- **GiBUU** describes: (within the same unified theory and code)
  - heavy ion reactions, particle production and flow
  - pion and proton induced reactions on nuclei
  - photon and electron induced reactions on nuclei
  - neutrino induced reactions on nuclei

using the same physics input! And the same code!

NO TUNING!

Effects of off-shell transport on particle production





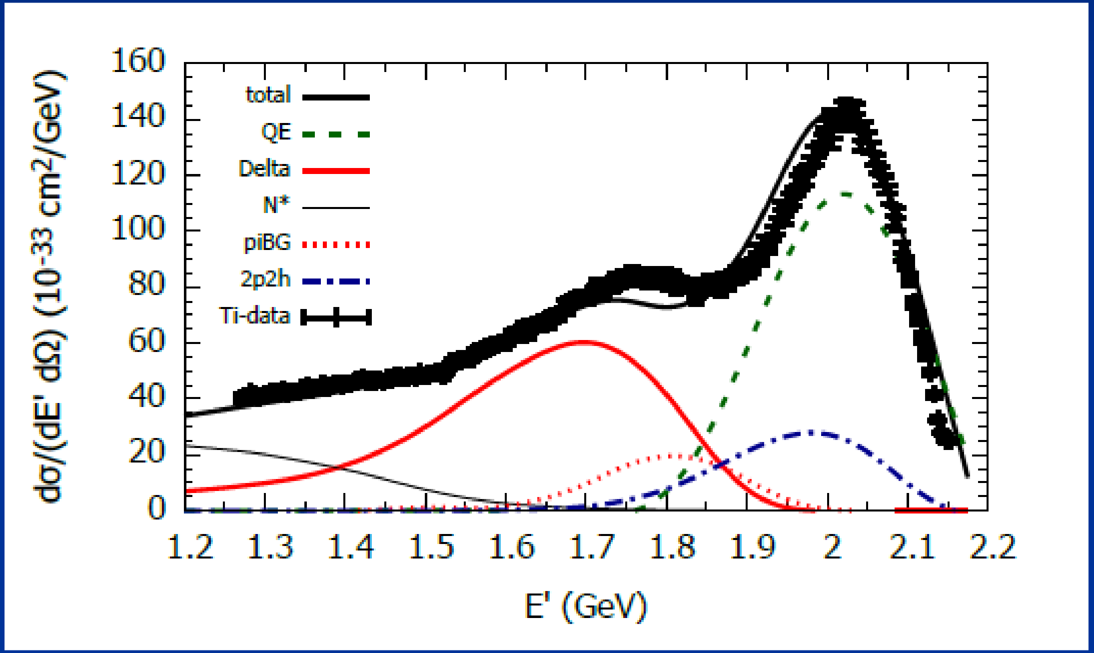
Off-shell effects affect both absolute X-sections and spectra, because effective threshold are affected.

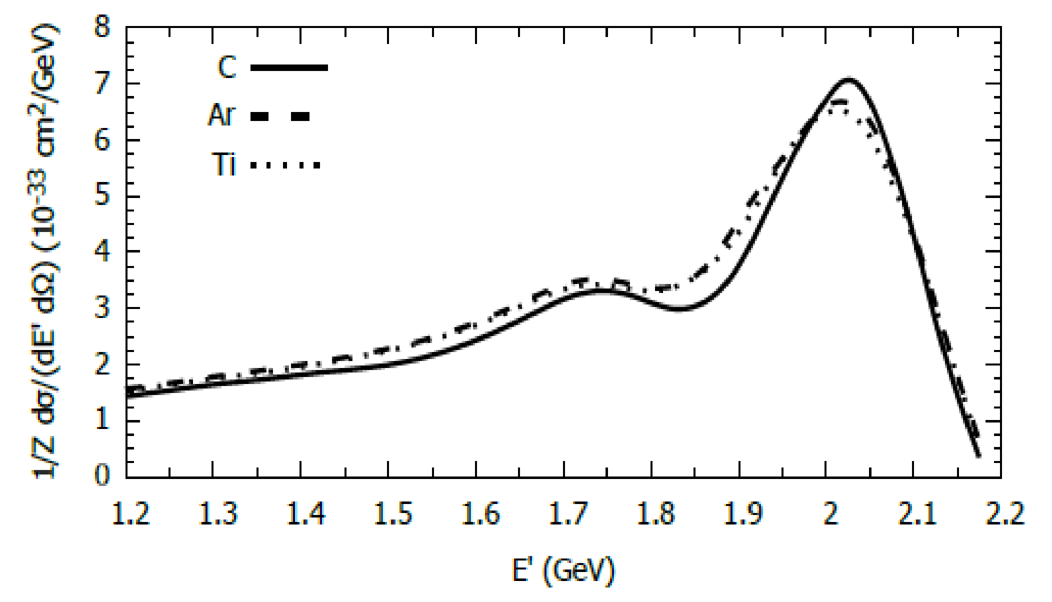
From:
Effenberger, Mosel,
Phys. Rev. C60 (1999) 051901

Collisional broadening of nucleons
=> short range correlations

GiBUU Results: Electrons

Inclusive X-sections





Mosel, Gallmeister: *Phys.Rev.C* 99 (2019) 6, 064605

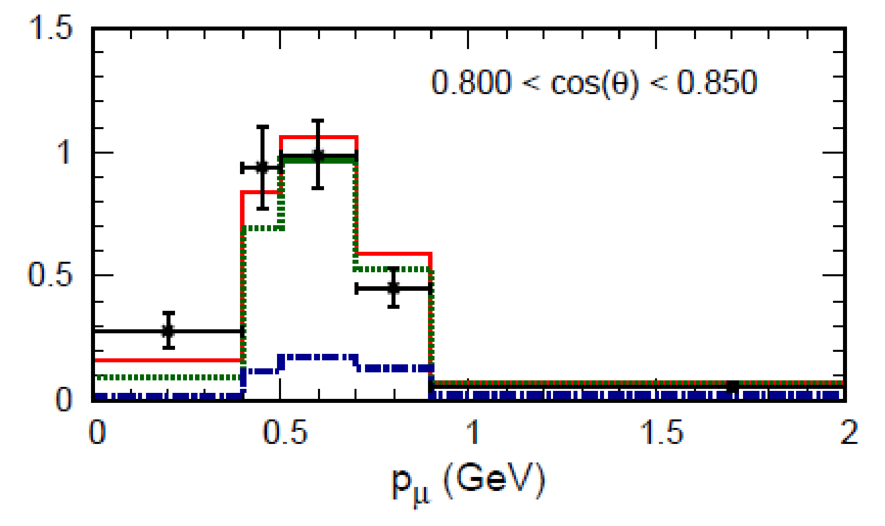
Target: Ti48, E = 2.222 GeV, 15.541 deg

Z-scaling of X-sections

Data are sensitive to proton momentum distributions

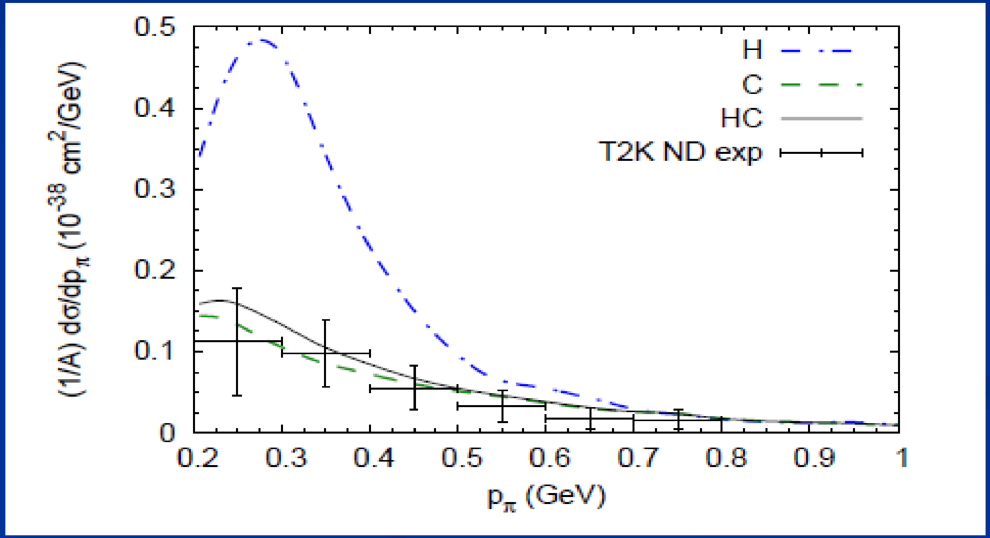
GiBUU Results: Neutrinos

Mosel, Gallmeister: *Phys.Rev.C* 97 (2018) 4, 045501



T2K: 0-pion (CCQE-like) on H2O target

Mosel, Gallmeister: *Phys.Rev.C* 96 (2017) 1, 015503



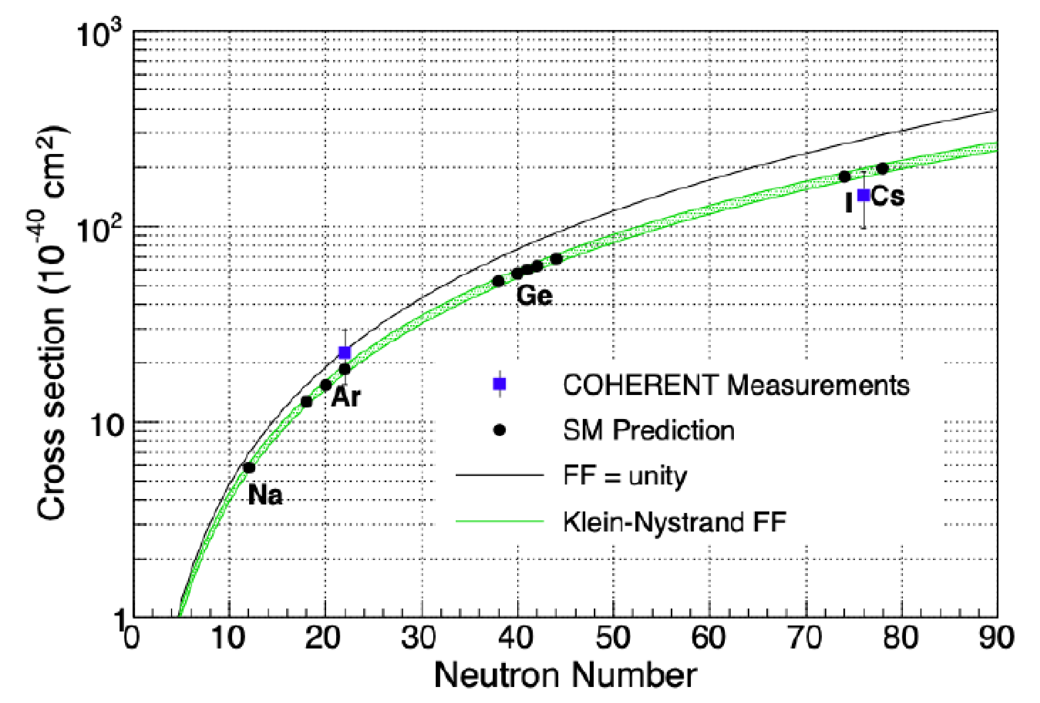
T2K: pion production on CH target

Coherent Neutrino Scattering

$$\frac{d\sigma}{dE} \sim \frac{G_F^2 \cdot M}{2\pi} \cdot \frac{Q_W^2}{4} \cdot F^2(Q) \cdot \left(2 - \frac{M \cdot E}{E_\nu^2}\right)$$

$\sigma \propto Q_W^2 \propto (N - (1 - 4 \cdot \sin^2\theta_W)Z)^2$ $\sin^2\theta_W$ ~1/4 ➔ $\sigma \propto N^2$.

CEνNS Experiment:
Neutrinos from decay
of pions at rest ~ 30 MeV

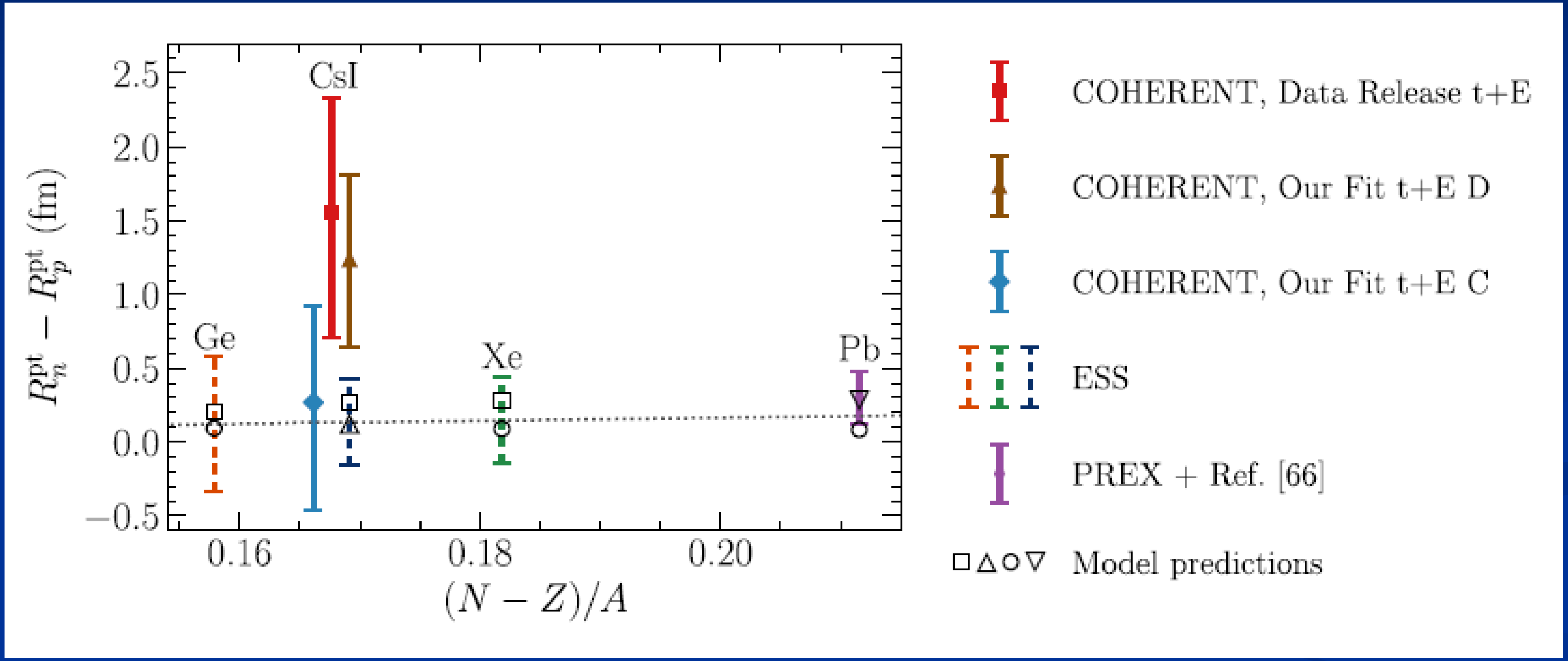


T.M. Undaguita, lecture notes, 2021

F²(Q) contains info on neutron distribution
(PREX measures only at Momentum transfer)

Coherent Neutrino Scattering

Coherent
errors are only
experimental,
no model
dependence



P. Coloma et al, *JHEP* 02 (2020) 123

Other experiments running:
TEXONO: reactor in Taiwan
CONNIE: reactor in Brazil
CONUS: reactor in Germany

Other experiments planned:
MINER in Texas, US
NUCLEUS at reactor Chooz, France
Ricochet at ILL, France
RED at reactor, Russia

Summary

- Extraction of fundamental neutrino properties (masses, CP violating phase, mass ordering) from long-baseline experiments requires an incoming-energy reconstruction

- Energy reconstruction requires a quantitatively reliable description of final state interactions → state-of-the-art transport is needed

- Combination of electron and neutrino experiments gives info on proton vs neutron distributions in nuclei