Neutrino interactions:
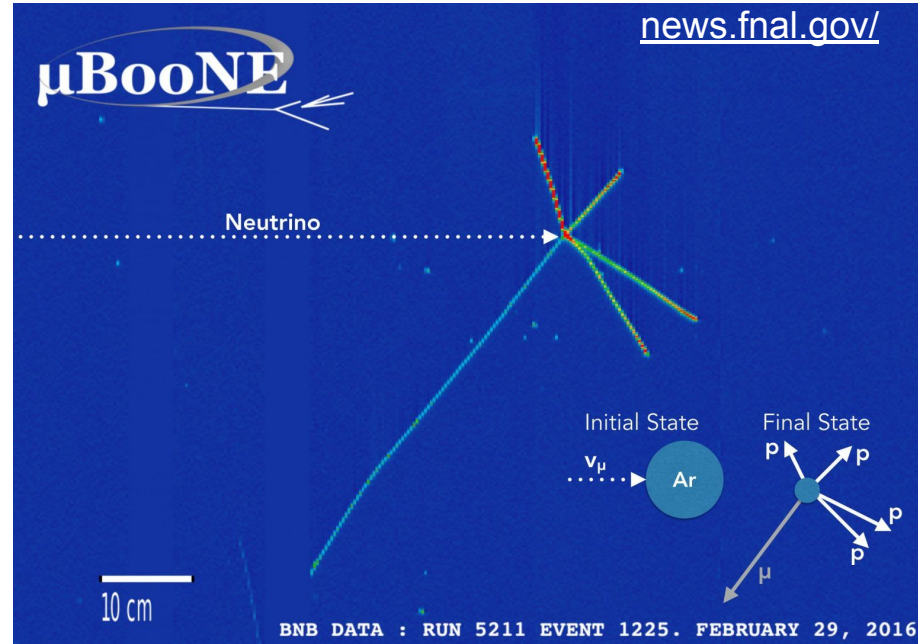## *what, why, and how*

Kendall Mahn
Michigan State University

Snowmass CSS,
July 20th 2022

news.fnal.gov/

μBooNE

Neutrino

Initial State

ν_μ Ar

Final State

p

p

p

p

μ

10 cm

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

1

Outline

What are neutrino interactions?

Why is an understanding of neutrino interactions essential to current and future physics programs?

What are the plans to improve our understanding of neutrino interactions?

Neutrino interactions are important to a broad variety of physics programs, and multiple efforts are underway to fully map out the open questions
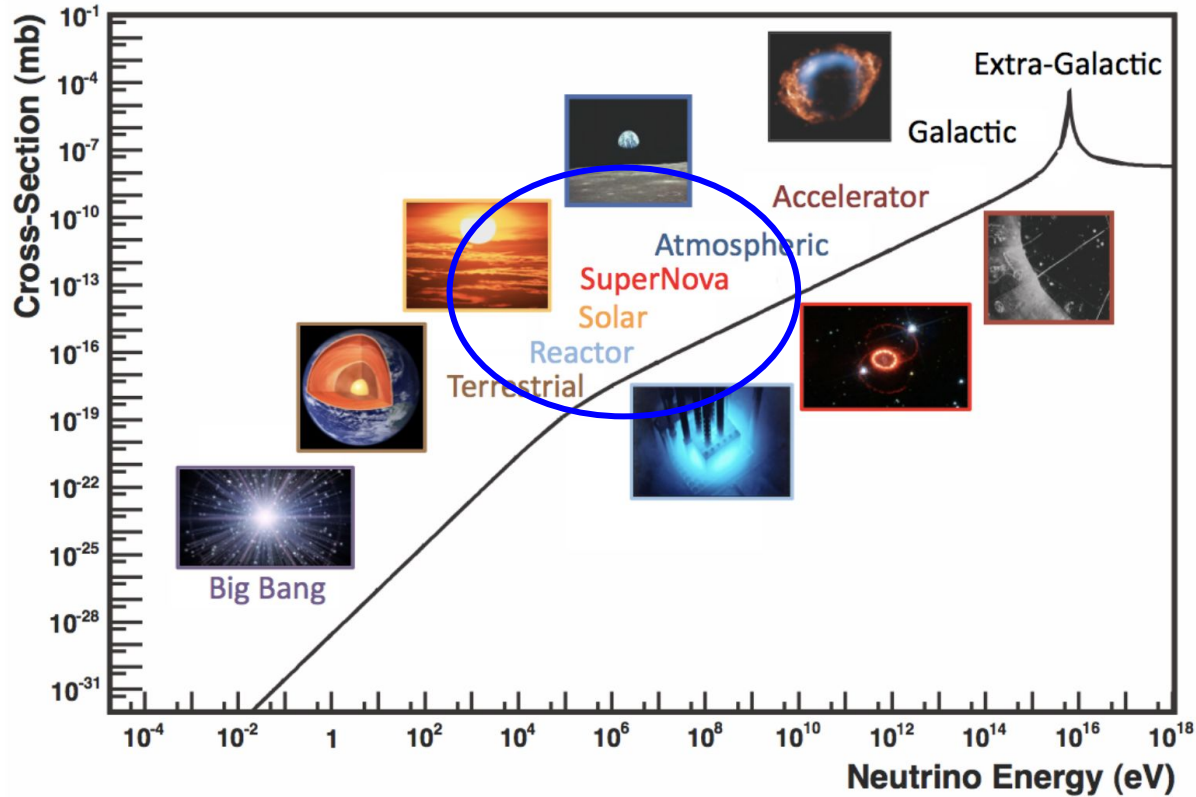
The scale of neutrino interactions

Rev. Mod. Phys. 84, 1307 (2012)
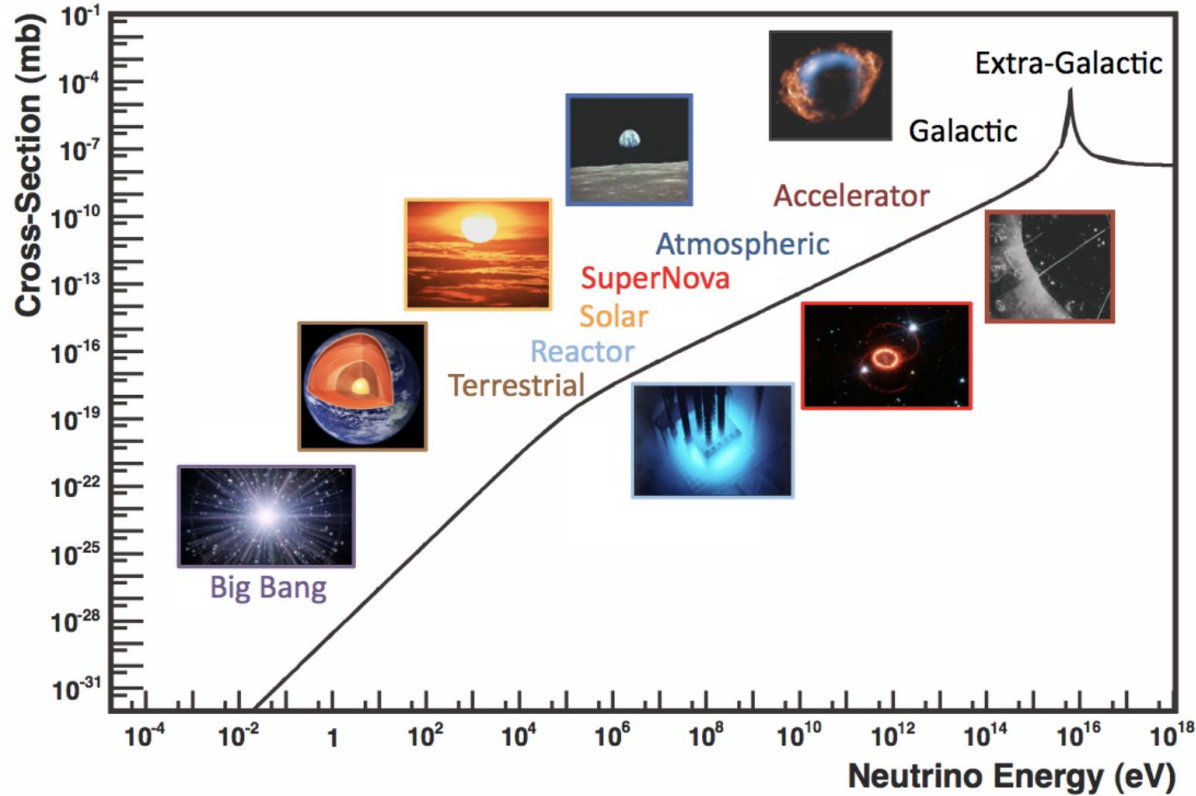
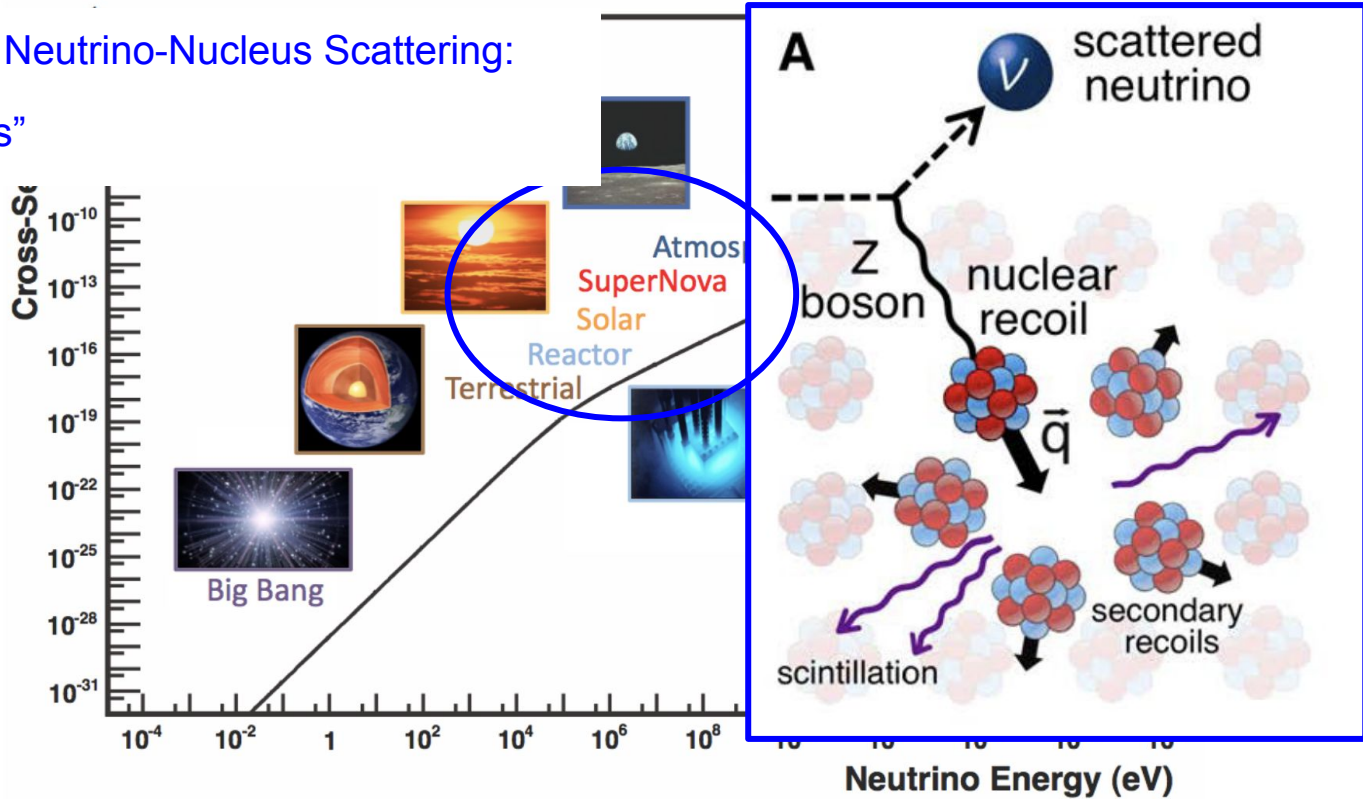# The scale of neutrino interactions: low energy, ~0-100 MeV

Rev. Mod. Phys. 84, 1307 (2012)

4

The scale of neutrino interactions: low energy, ~1-100 MeV

Coherent Elastic Neutrino-Nucleus Scattering:
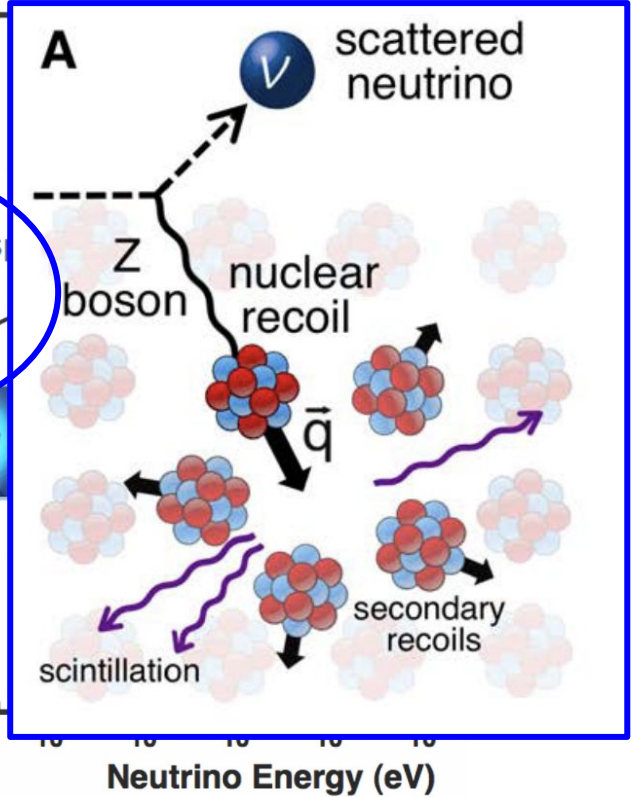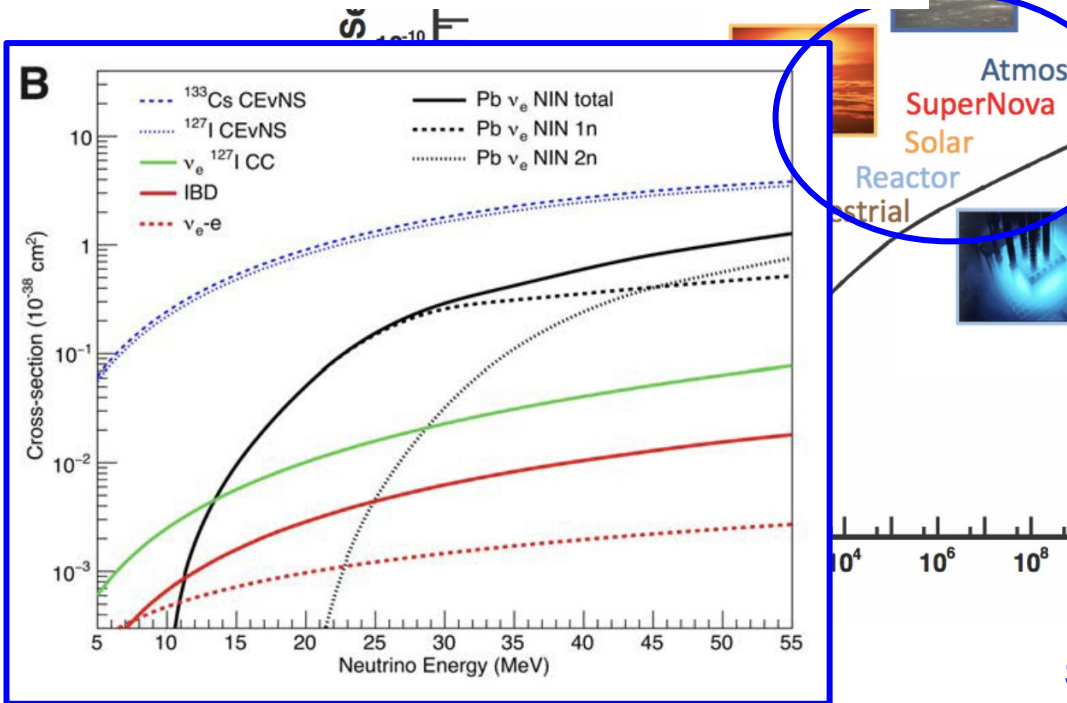
CEvNS - "Sevens"

The scale of neutrino interactions: low energy, ~1-100 MeV

Coherent Elastic Neutrino-Nucleus Scattering:

CEvNS - "Sevens"

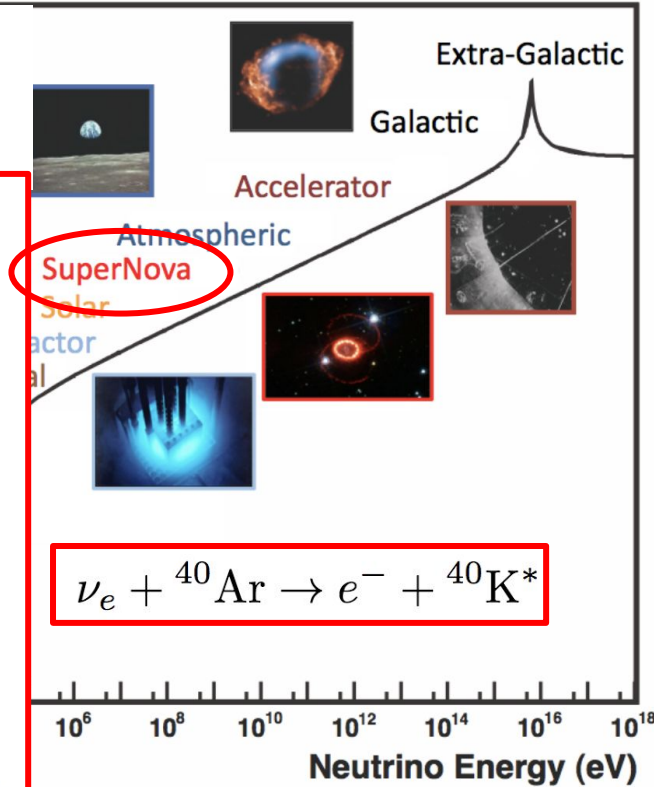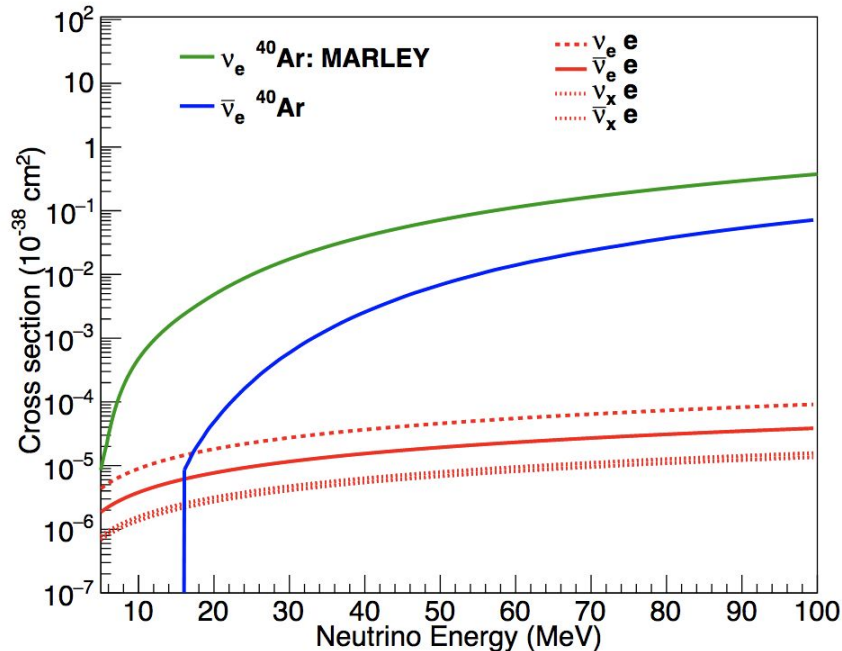# The scale of neutrino interactions: low energy, ~1-100 MeV

Charged current (CC) scattering cross section for Super Nova Burst (SNB)
Example from DUNE - arxiv 2008.06647

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

The scale of neutrino interactions: high energy,~20 GeV-1EeV

Rev. Mod. Phys. 84, 1307 (2012)
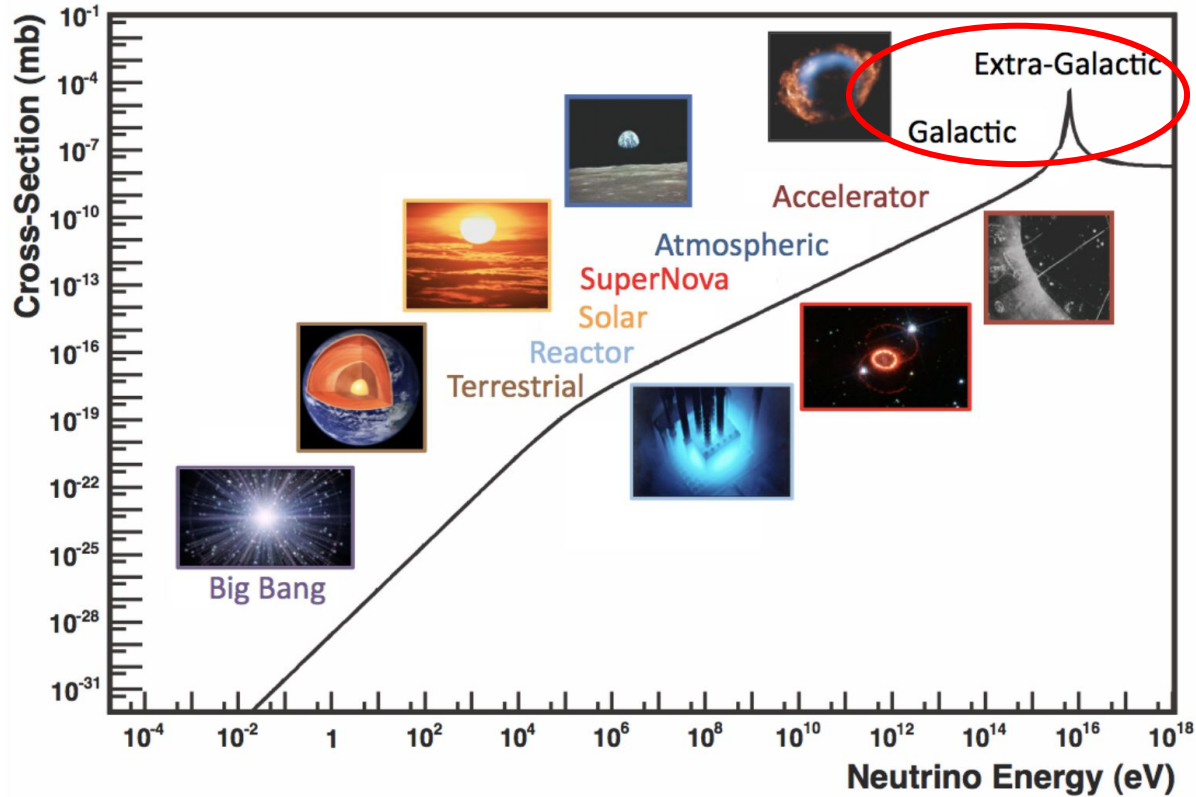
The scale of neutrino interactions: high energy,~20 GeV-1EeV

Example: IceCube detection of resonant W production (Glashow resonance, 6 PeV)
Nature 591, 220–224 (2021)
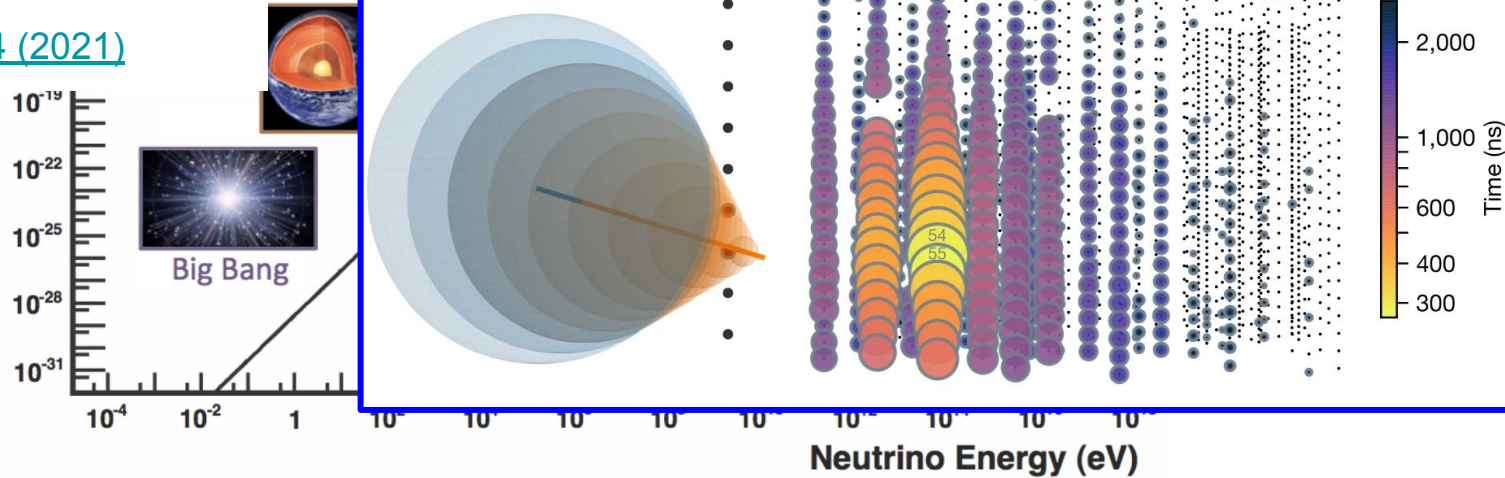
The scale of neutrino interactions: intermediate, ~0.1-20 GeV
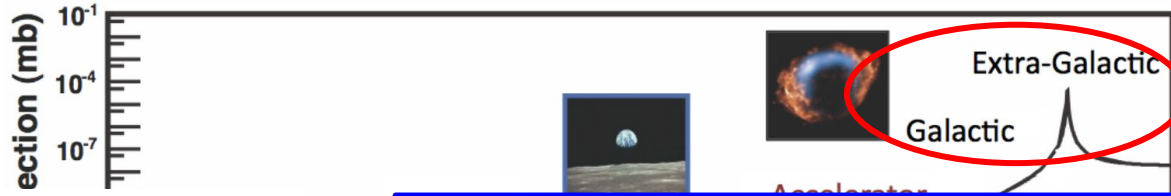

Rev. Mod. Phys.
84, 1307 (2012)
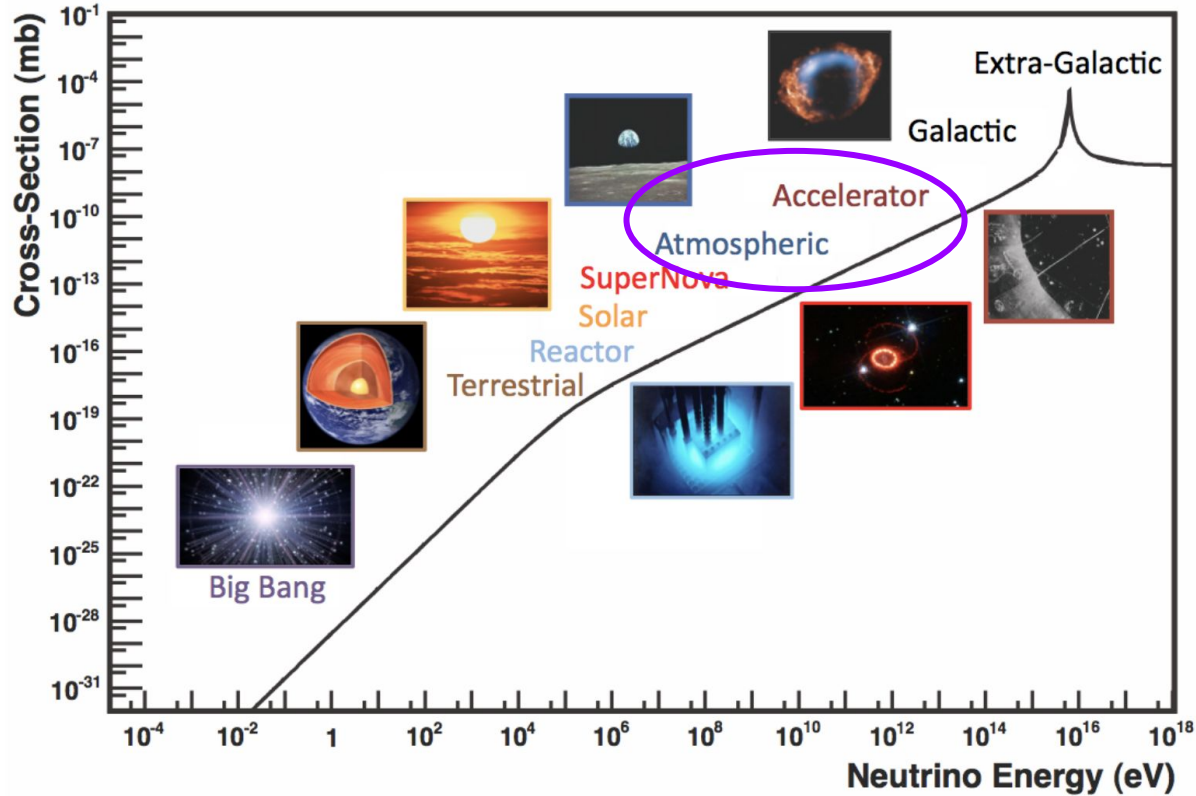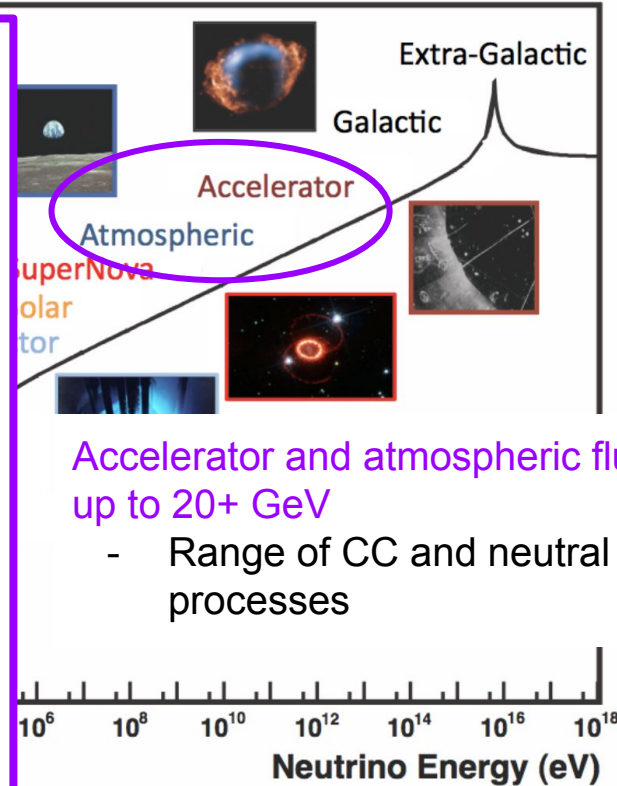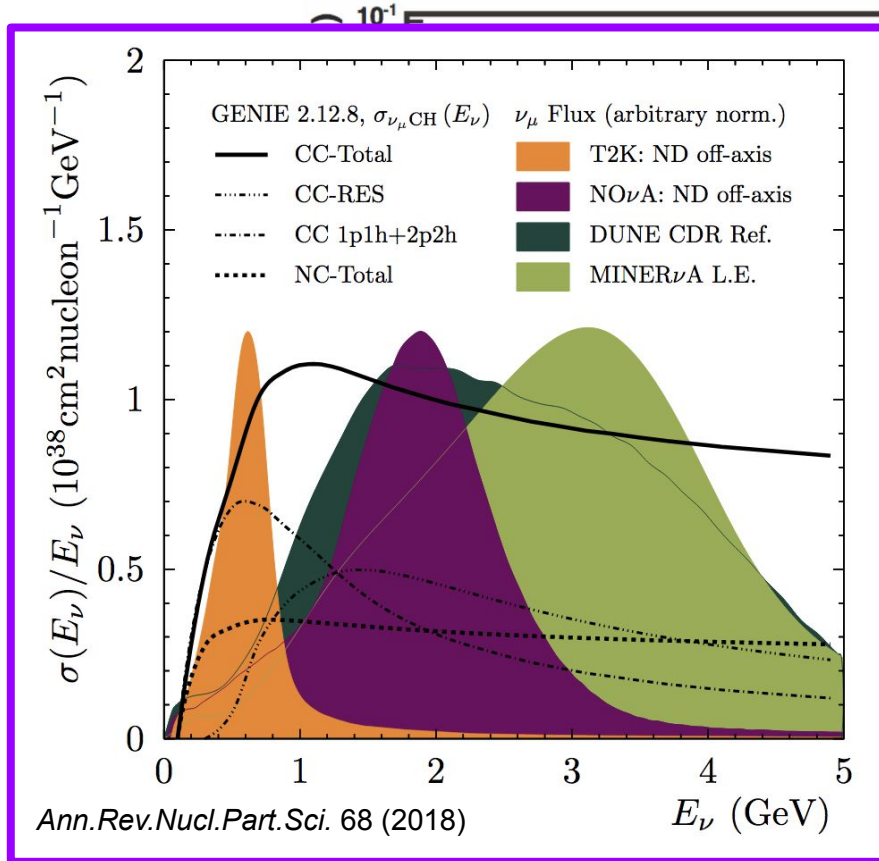
The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Ann.Rev.Nucl.Part.Sci. 68 (2018)

Accelerator and atmospheric flux is ~0.1 GeV on up to 20+ GeV
- Range of CC and neutral current (NC) processes

Why are neutrino interactions important?

Energy regime

low energy, ~0-100 MeV
- CEvNS
- SNB
- Solar neutrinos

Interesting physics

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

Why are neutrino interactions important?

Energy regime

low energy, ~0-100 MeV
- CEvNS
- SNB
- Solar neutrinos
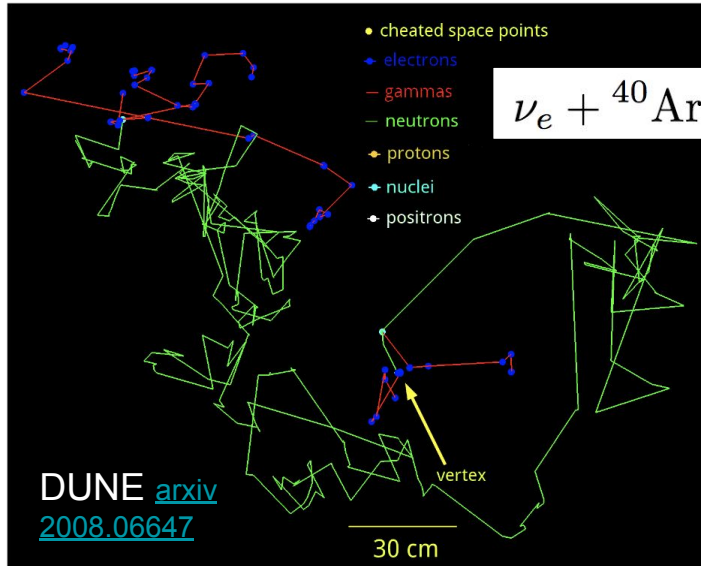
Interesting physics

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

Example of needed information about interactions for physics
- Semi inclusive predictions of SNB xsec

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

- cheated space points
- electrons
- gammas
- neutrons
- protons
- nuclei
- positrons

vertex

DUNE arxiv 2008.06647

30 cm

Quantification by DUNE: E. Conley, Nu@ORNL workshop

13

Why are neutrino interactions important?

Energy regime

intermediate energy, ~0.1-20 GeV
- Accelerator neutrinos
- Atmospheric neutrinos

Interesting physics

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Three flavor oscillation: θ_{23} octant, mass hierarchy, CP violation.
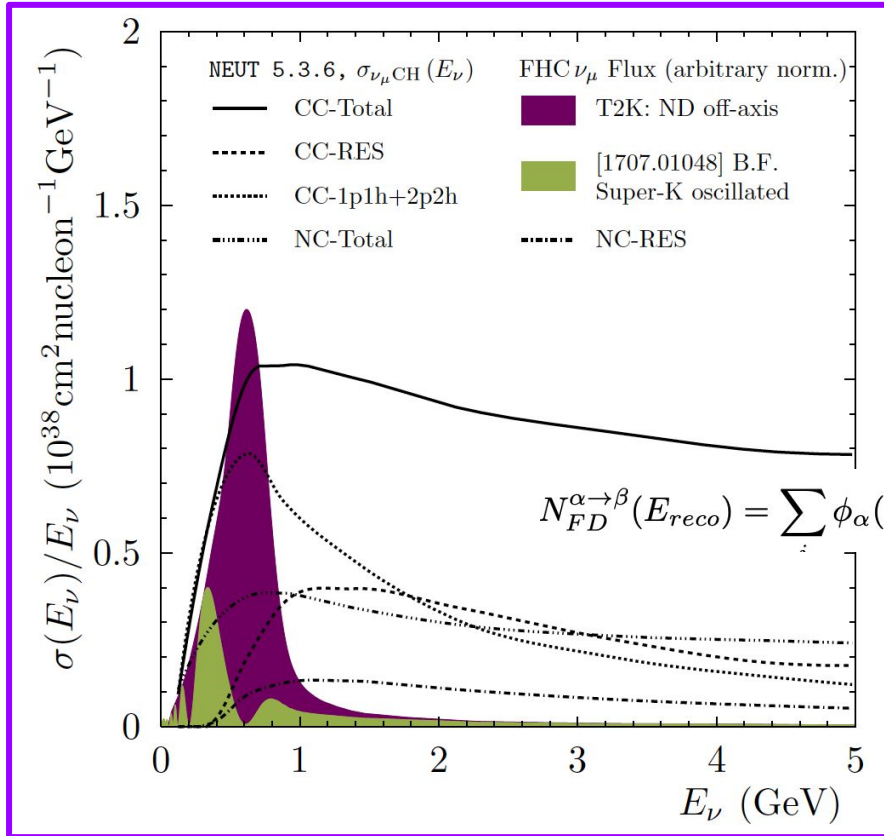Tests of neutrino mixing model

More BSM: proton decay

Why do interactions matter to experiments?

Example: Tokai-to-Kamioka (T2K) experiment

Basic challenges:

- Need prediction across energy for CC/NC

$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Fix formula to be easier to read, simpler

Why do interactions matter to experiments?
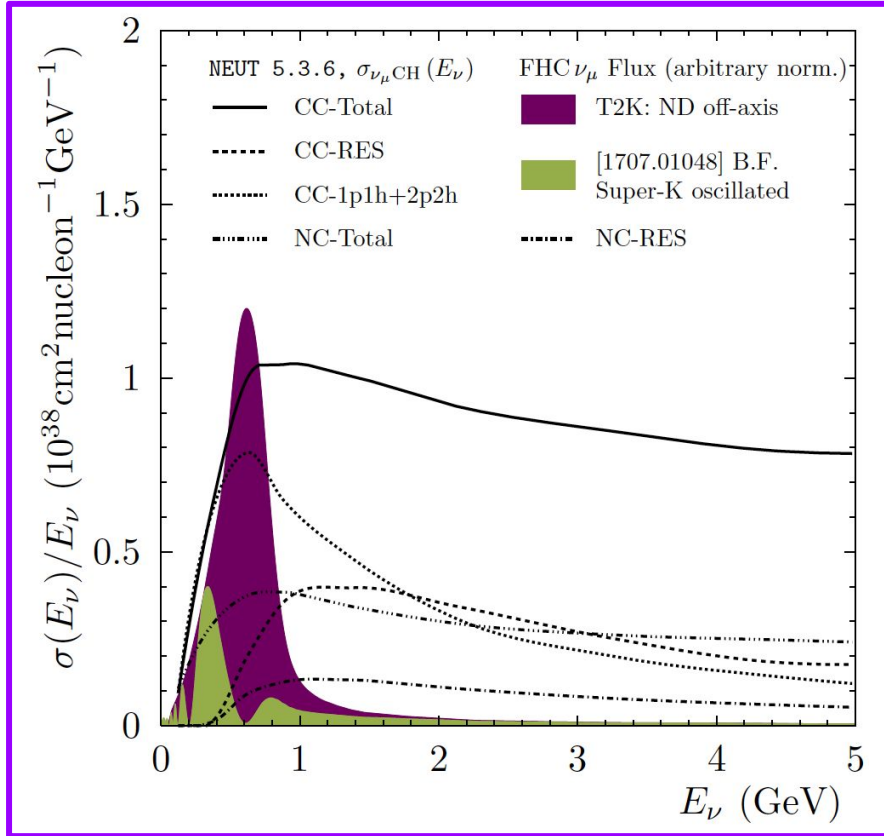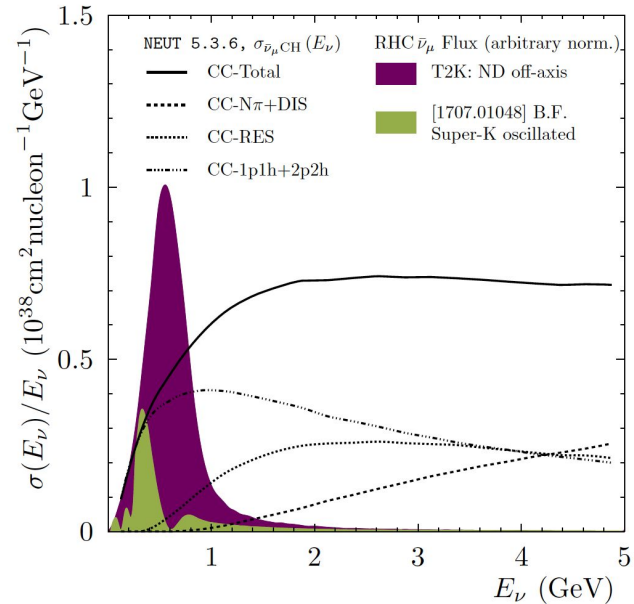

Example: Tokai-to-Kamioka (T2K) experiment
Basic challenges:
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- Need all flavors (neutrino, antineutrino, electron, muon, tau)

Why do interactions matter to experiments?

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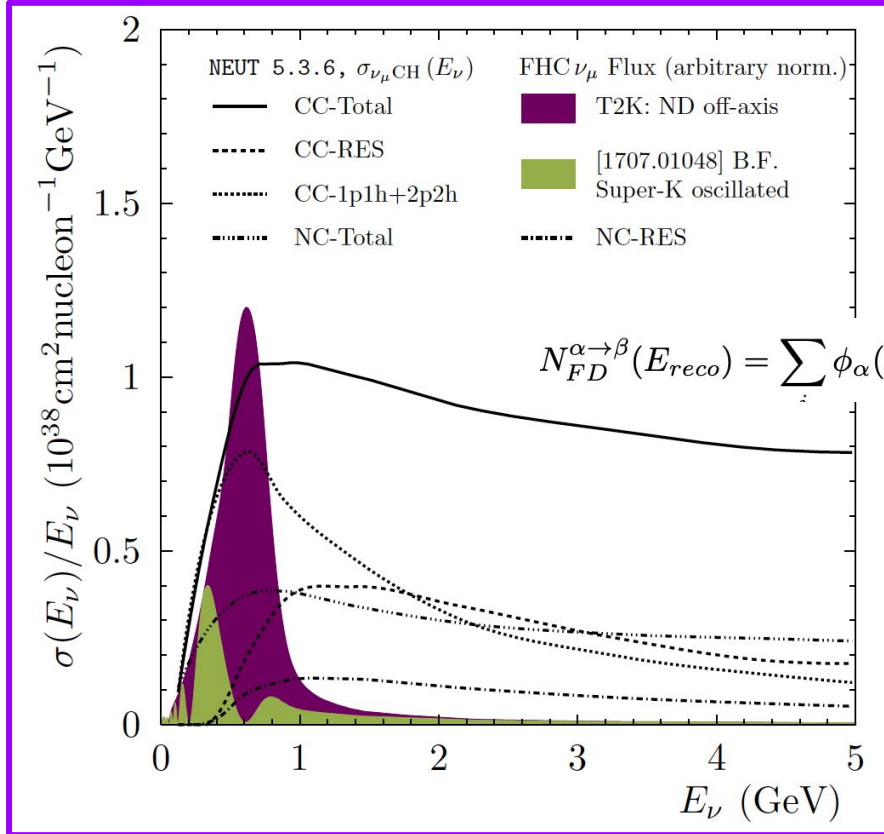
Example: Tokai-to-Kamioka (T2K) experiment

Basic challenges:
- Need prediction across energy for CC/NC
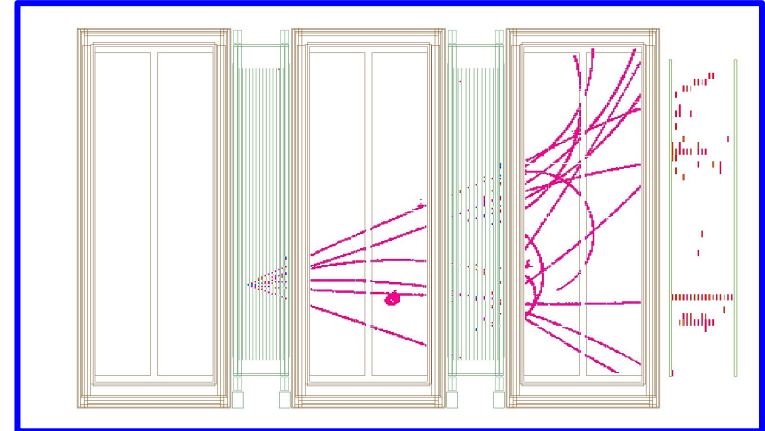- Need all flavors (neutrino, antineutrino, electron, muon, tau)
- Need exclusive measurements
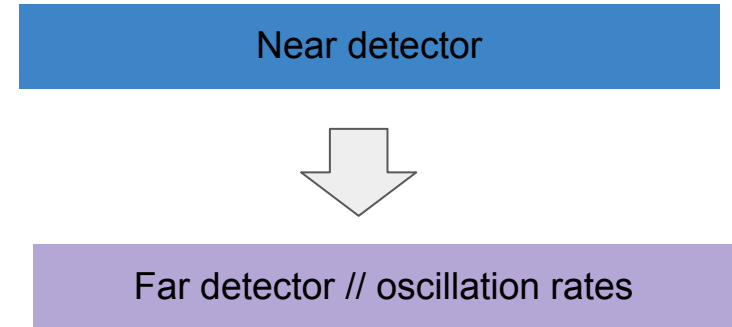
Role of "near detector" in oscillation experiments

$$N_{FD}^{\alpha \to \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

$$N_{ND}^{\alpha} E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

Current and future near detectors (ND) are designed to meet the needs of the experiment
- NOvA ND, T2K ND (new upgrade - arxiv 1901.03750)
- DUNE ND, Hyper-Kamiokande ND

ND provide stability monitoring, improved event rate prediction, and reduce shared systematic uncertainties

Near detector

Far detector // oscillation rates

Role of "near detector" in oscillation experiments

$$N_{FD}^{\alpha \to \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

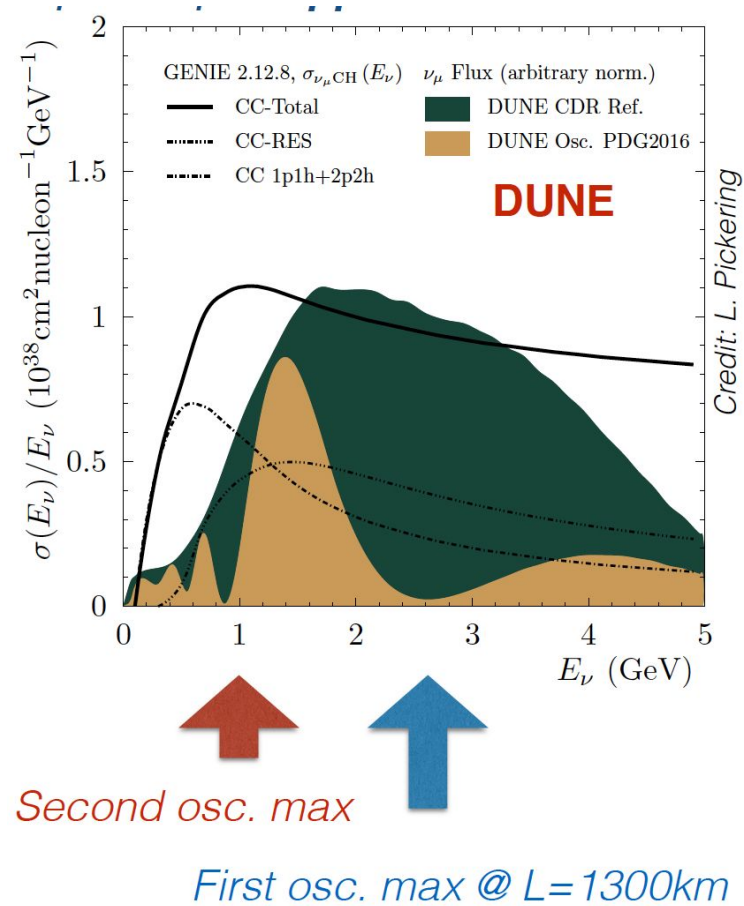$$N_{ND}^\alpha E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\alpha^i(E_{true}) \times \epsilon_\alpha(E_{true}) \times R_i(E_{true}; E_{reco})$$

Example: DUNE Near Detector (ND complex) - arxiv 2103.13910

- Liquid Argon (ND-LAr)
- Gaseous detector (ND-GAr)
- And beam monitoring (SAND)
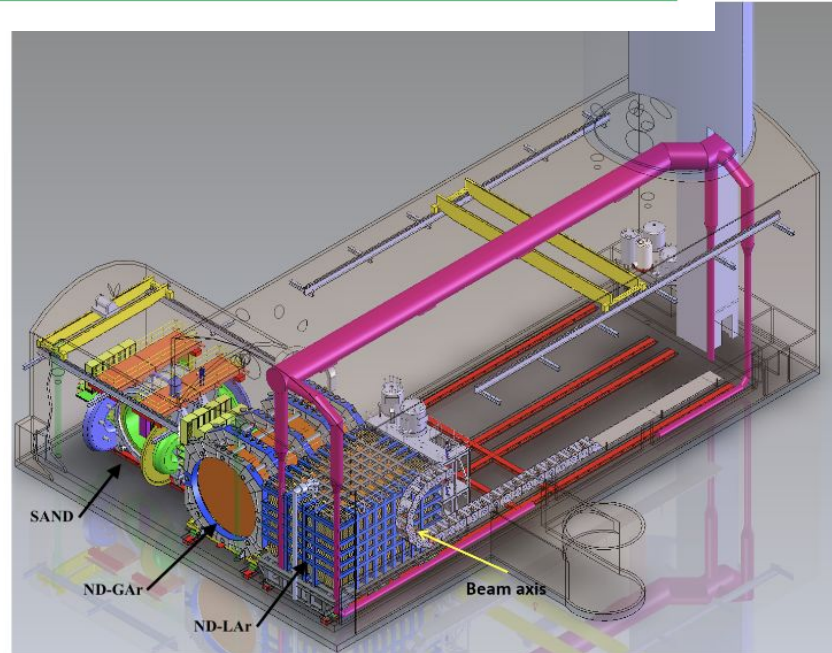
19

Why neutrino interactions matter - DUNE example
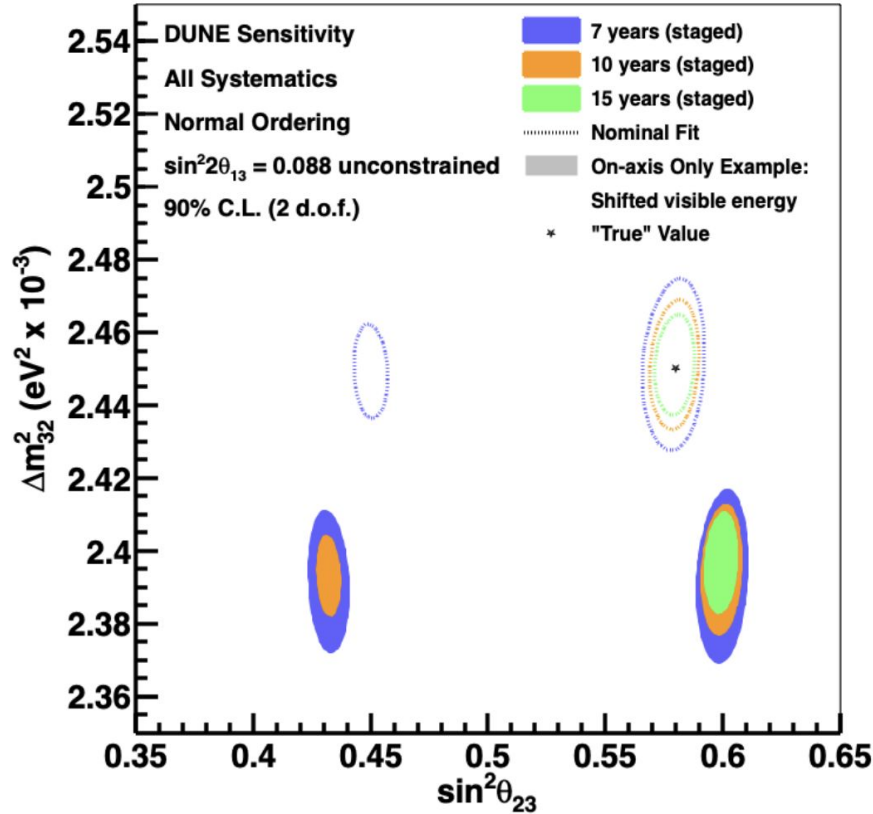

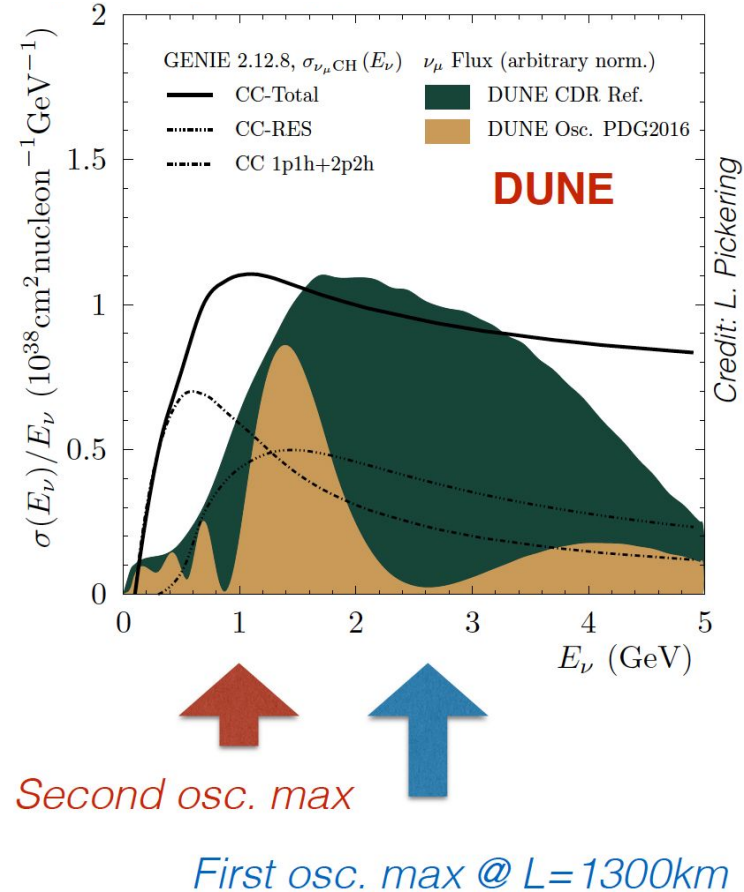Second osc. max

First osc. max @ L=1300km

Why neutrino interactions matter - DUNE example

DUNE Physics TDR arxiv. 2002.03005

Possibility of bias in key oscillation parameters

Credit: L. Pickering

Second osc. max

First osc. max @ L=1300km

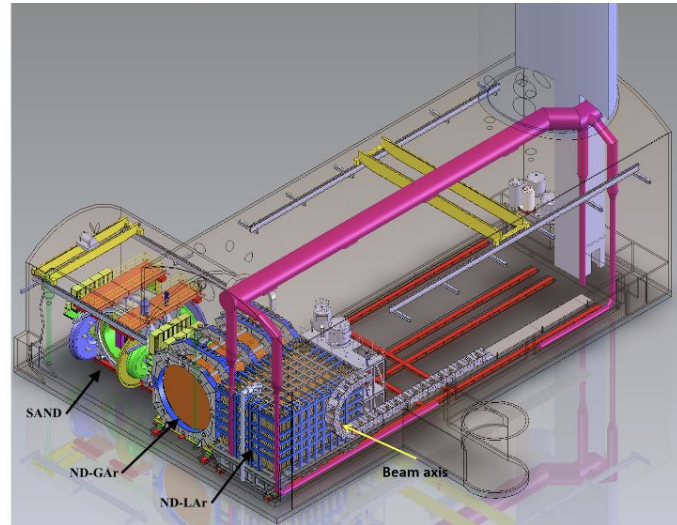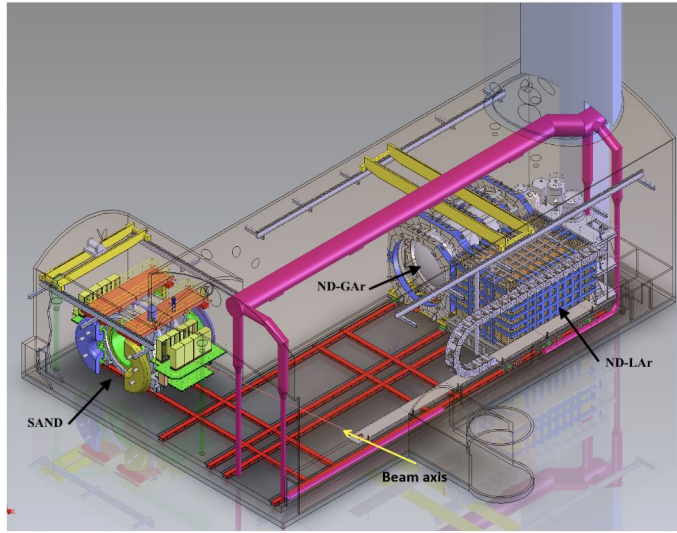# New approach: PRISM

GENIE 2.12.10, DUNE FD TDR CV Tune
— CC Inclusive   — CC 1p1h+2p2h
— CC Res 1π   — CC DIS
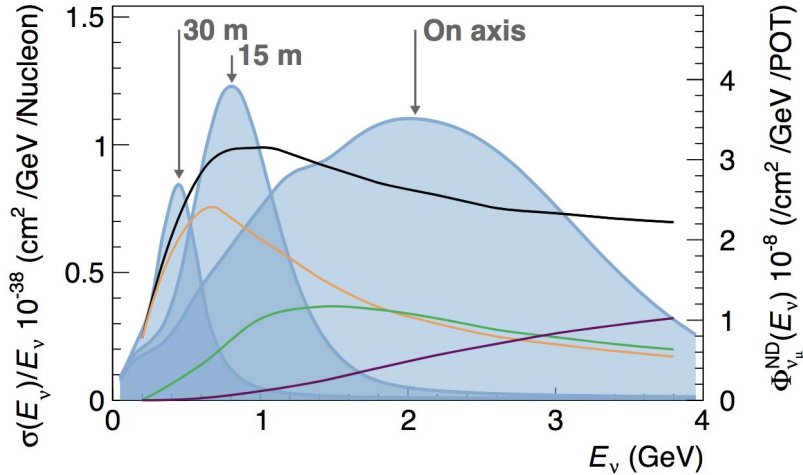
Place detectors at different
positions relative to beam
to measure different energy
spectra arxiv 2103.13910

PRISM provides robustness against mismodelling
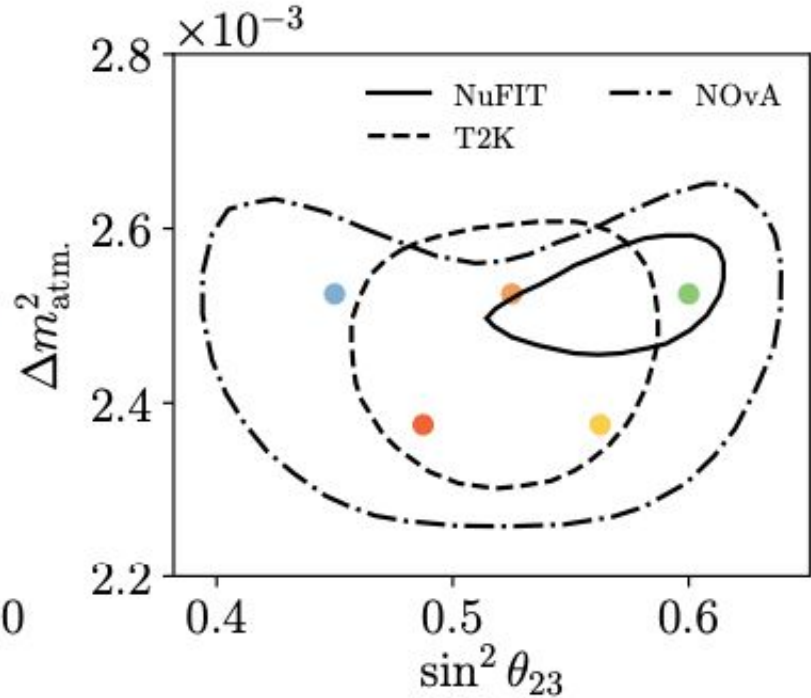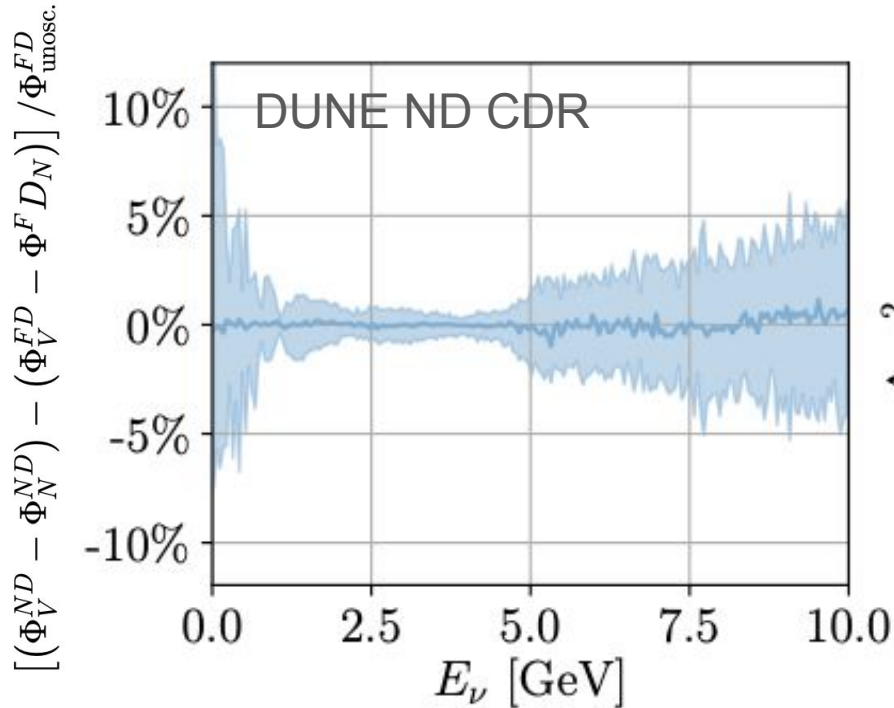
Allows for novel nuclear physics studies

Other DUNE detectors (ND-GAr, SAND) also have unique measurement opportunities

The role of external experiments
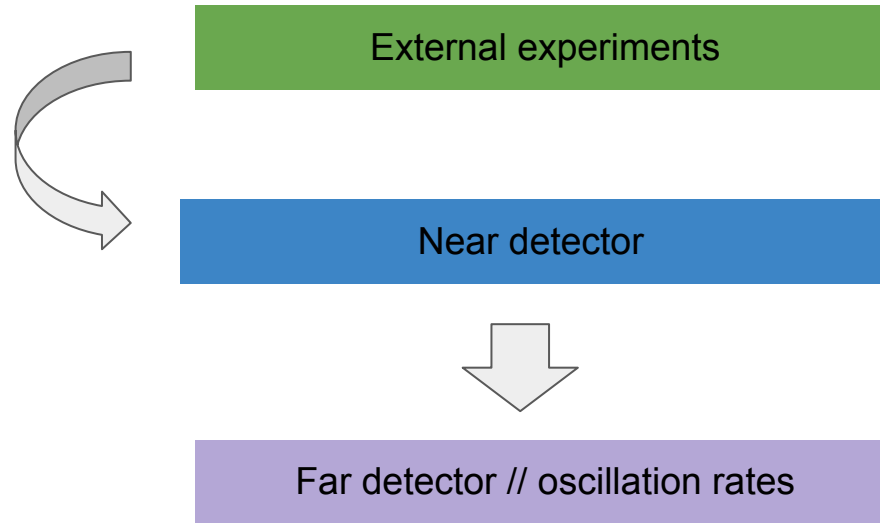
External experiments are important; determine parameterization, uncertainties.
- Electron scattering
- Pion scattering
- Neutrino H/D data
- Neutrino nucleus scattering

External experiments: electron scattering

WP on electron scattering
and neutrino physics:
arxiv 2203.06853

Inclusive measurements do not cover all the needed
phase space for future experiments, like DUNE

External experiments: electron scattering

WP on electron scattering and neutrino physics: arxiv 2203.06853

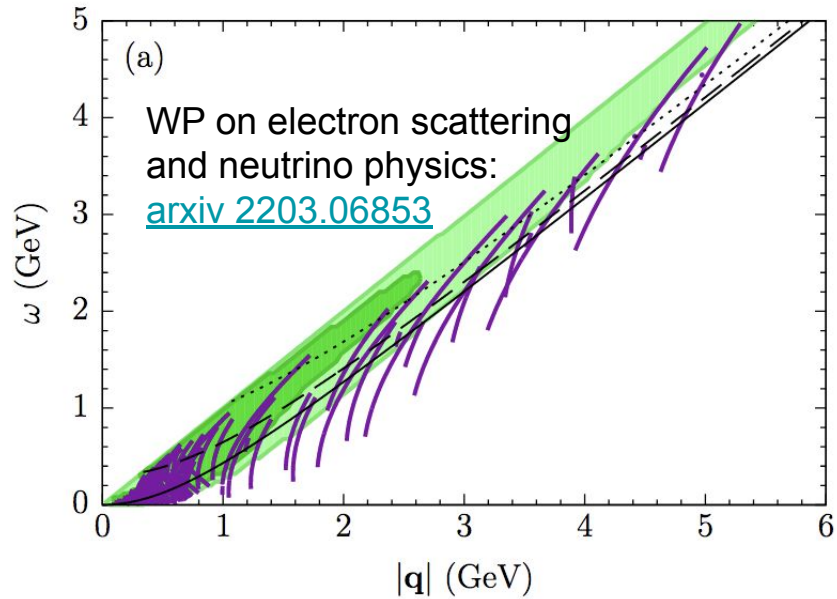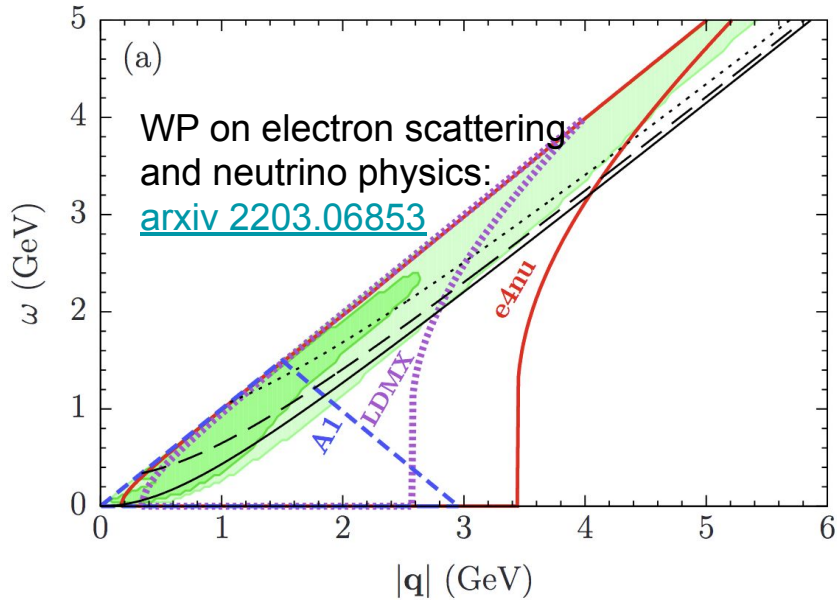| Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	$E_e = 2.222$ GeV $15.5° \leq \theta_e \leq 21.5°$ $-50.0° \leq \theta_p \leq -39.0°$	Ar, Ti Al, C	(e, e') e, p in the final state
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	$E_e = 1, 2, 4, 6$ GeV $\theta_e > 5°$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	$E_e = 4.0, 8.0$ GeV $\theta_e < 40°$	W, Ti, Al	(e, e') e, p, n, π, γ in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	50 MeV $\lesssim E_e \leq 1.5$ GeV $7° \leq \theta_e \leq 160°$	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
A1 (eALBA) (Planned)	$E_e = 500$ MeV - few GeV	C, CH Be, Ca	(e, e')

Semi inclusive, exclusive electron scattering measurements constrain vector piece of cross section
- Measurements critical where ND constraints are not applicable (e.g. BSM)
- High multiplicity final state characterization, range of targets (nuclear effects)

Exciting new experimental programs focused on this problem; complementary to ND

External experiments: neutrinos on nuclei

Experiment	Flavor	ν_μ Flux Peak (GeV)	Target
T2K	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$	0.6,0.8,1	CH, H_2O, Fe
NOvA	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$	2	CH_2
DUNE	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$	PRISM: 0.5-3	H,C,Ar
HK IWCD	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$	PRISM: 0.4-1	H_2O
MicroBooNE	ν_μ, ν_e	0.3,0.8	Ar
SBND	ν_μ, ν_e	0.8 (PRISM: 0.6-0.8)	Ar
ICARUS	ν_μ, ν_e	0.3,0.8	Ar
MINERvA	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$	3.5,6	He, C, CH, H_2O, Fe, Pb
ANNIE	$\nu_\mu, \overline{\nu}_\mu$	0.6	CH, H_2O
NINJA	$\nu_\mu, \overline{\nu}_\mu$	1	H_2O, Fe
FPF	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e, \nu_\tau, \overline{\nu}_\tau$	700 GeV	W, Ar
nuSTORM	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$	PRISM: 0.8-3	CH, H_2O, Ar, TBD
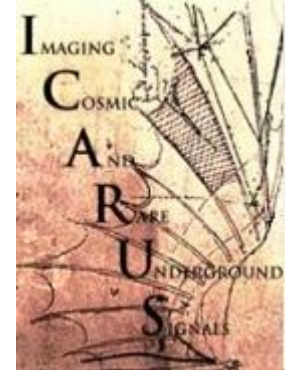
Let's not forget low energy!

Experiment	Source	Target	Time
COHERENT	πDAR	Na, Ar, Ge, CsI,	2014 -
Coherent CAPTAIN Mills	πDAR	Ar	
JSNS^2	πDAR		
ESS	πDAR		
CHILLAX	Reactor	Ar	
CONNIE	Reactor	Si	
CONUS	Reactor	Ge	
MINER	Reactor	Ge, Si	
NEON	Reactor	Na	
NUCLEUS	Reactor		
NUXE	Reactor	Xe	
PALEOCCENE	Paleo		
Ricochet	Reactor	Ge, Zn	
RED-100	Reactor	Xe	
NuGen	Reactor		
SBC	Reactor	Ar	
TEXONO	Reactor	Ge	
NEWSG	Reactor	H, He, C, Ne	

Multiple measurements underway or planned for CEvNS - arxiv 2203.07361

Complementary interplay with Parity Violating Electron Scattering - arxiv 2203.06853
- Determination of form factor from PVES can be used (with theory) to improve predictions and reach of CEvNS programs

Summary

A robust understanding of neutrino interactions is important to answer many of the open questions we face today:

BSM: sterile neutrinos, light dark matter, NSI, precision tests of SM

Astrophysics: supernova bursts, solar models

Three flavor oscillation: θ_{23} octant, mass hierarchy, CP violation.
Tests of neutrino mixing model

More BSM: proton decay

Summary

A robust understanding of neutrino interactions is important to answer many of the open questions we face today

There are multiple efforts planned or underway, to inform theory and simulation:

- Measurements from the current near detector program (T2K, NOvA), short baseline program (SBN), and external measurements (MINERvA, ANNIE, NINJA, nuSTORM, and more)
- Future experiments, like DUNE, have incorporated neutrino interaction measurements into their (near detector) design
- External measurements, including electron scattering and H/D targets, are complementary to information at near detectors
- For low energy, CEvNS measurements in combination with PVES, will provide a new channel for physics
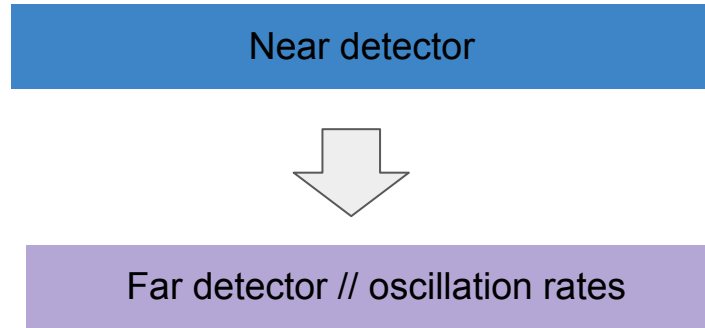
Backup

New approach: PRISM

GENIE 2.12.10, DUNE FD TDR CV Tune
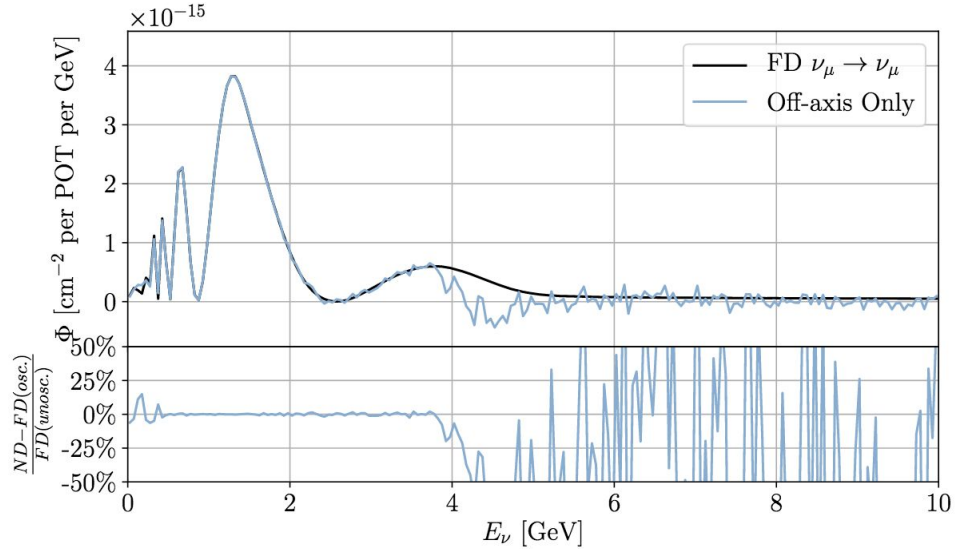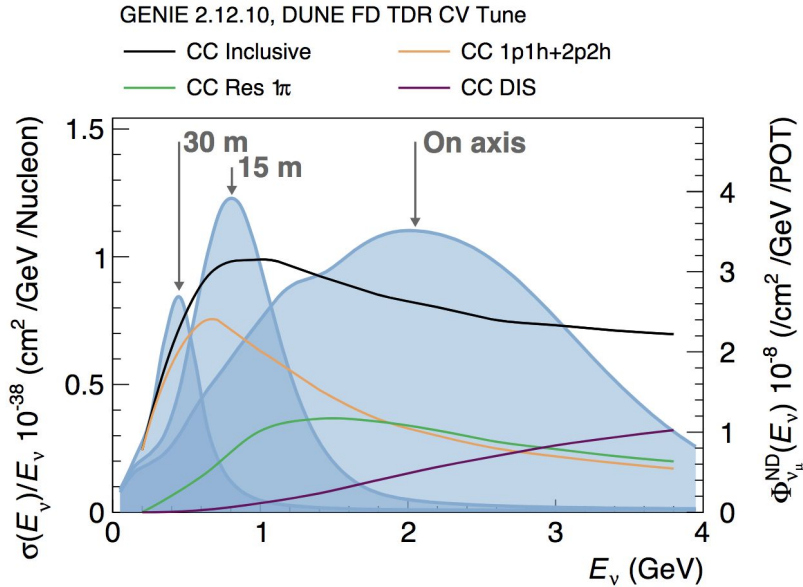
Combine spectra for an oscillation-matched flux

Current plans of oscillation experiments

Near detector

⬇

Far detector // oscillation rates

Current and future ND are designed to meet the needs of the experiment
- NOvA ND, T2K ND (new upgrade - arxiv 1901.03750)
- DUNE ND, Hyper-Kamiokande ND

External experiments:

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS

sbn.fnal.gov/

ANNIE

annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

Parting gifts of data
preservation, ultimate
measurements

NINJA

Recent: Phys. Rev. D 102, 072006

External experiments: Short Baseline Neutrino Program

SBN - arxiv 903.04608
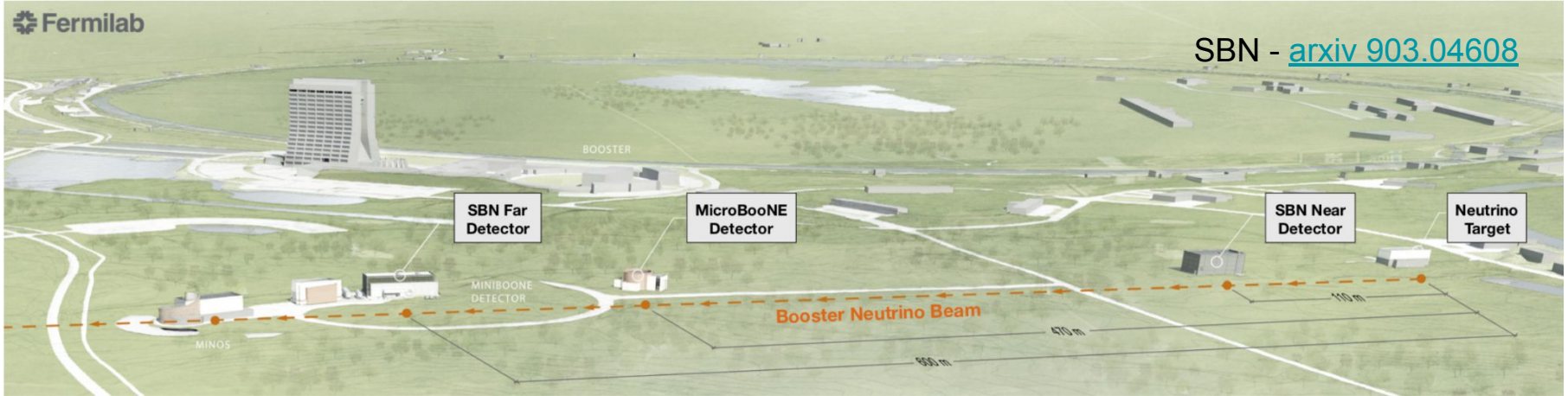
MicroBooNE: first high-statistics measurements of neutrino interactions on Ar

SBND: compare slices in detector for a PRISM-like effect

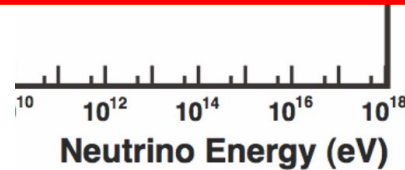**ICARUS:** Extra feature: enhanced ν_e cross section capability from NuMI beam
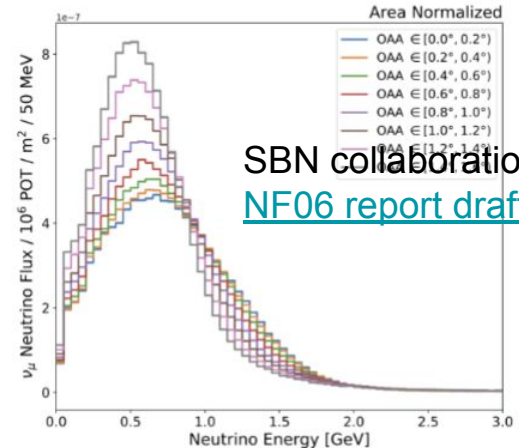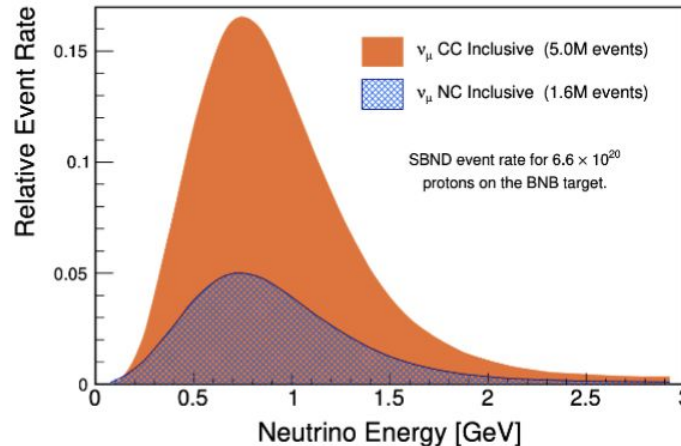
SBN collaboration, NF06 report draft

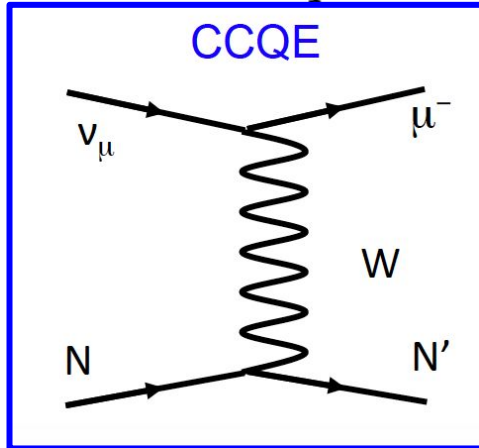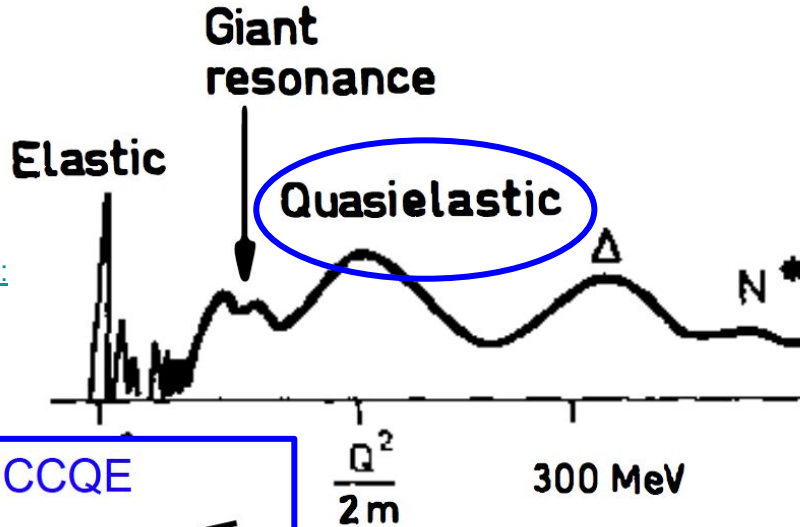# The scale of neutrino interactions: high energy,~20 GeV-1EeV
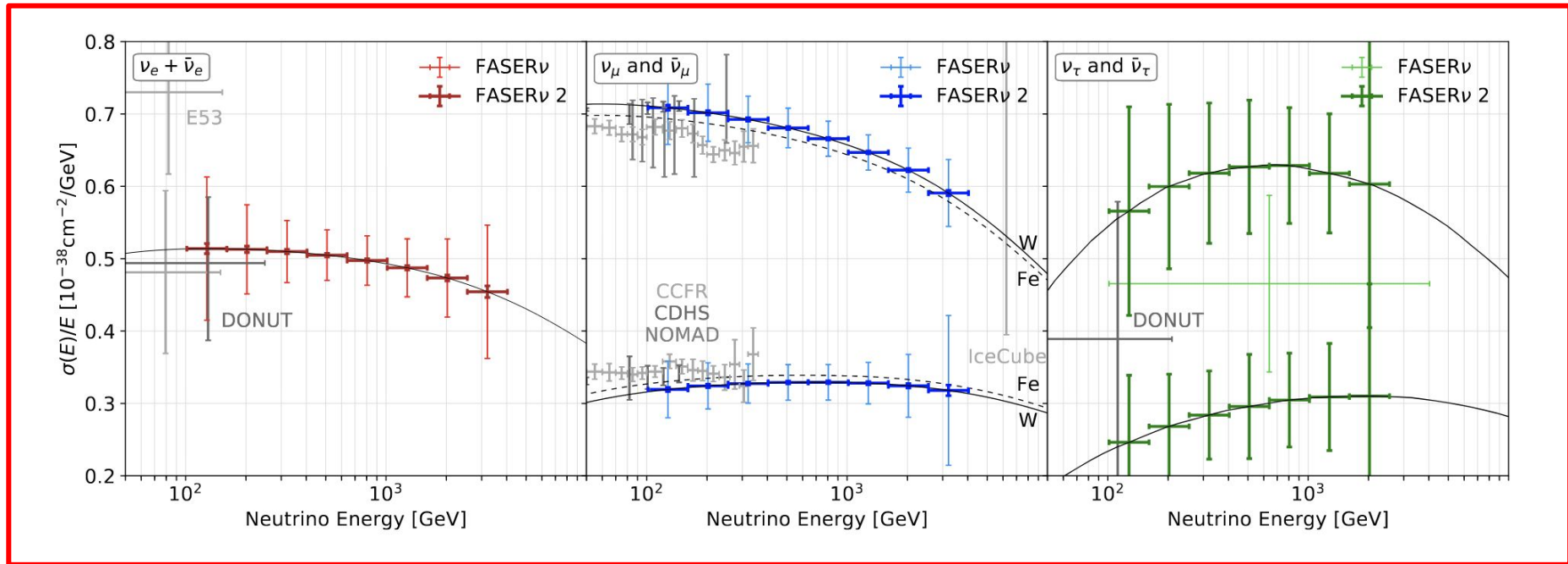
Example: Forward Physics Facility cross section measurements at LHC measurements of deep inelastic scattering (DIS)
- White Paper (WP): arxiv 2109.10905.pdf

The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Elastic

Giant resonance

Quasielastic

Δ

N^*

$\frac{Q^2}{2m}$ 300 MeV

CCQE

ν_μ μ^-

W

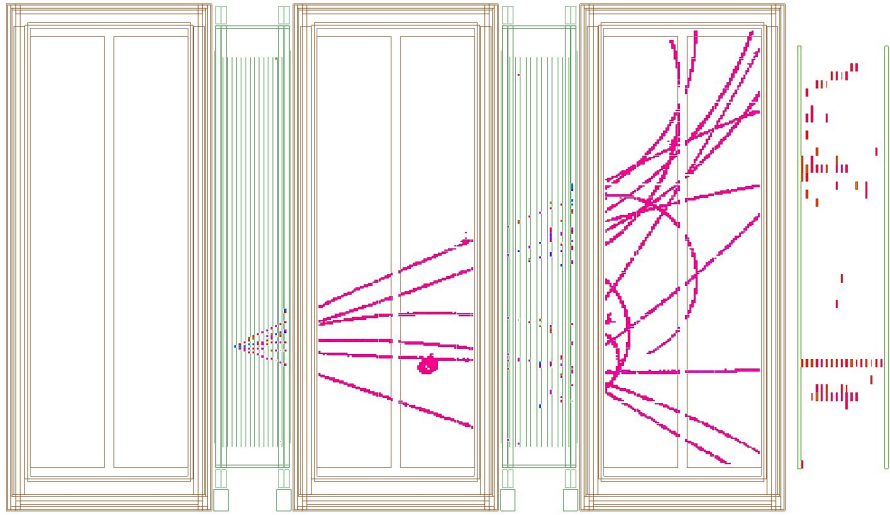N   N'

Charged current quasiela...

Observables:
- lepton in final state, ...
  antineutrino (+)
- Outgoing proton (ne...
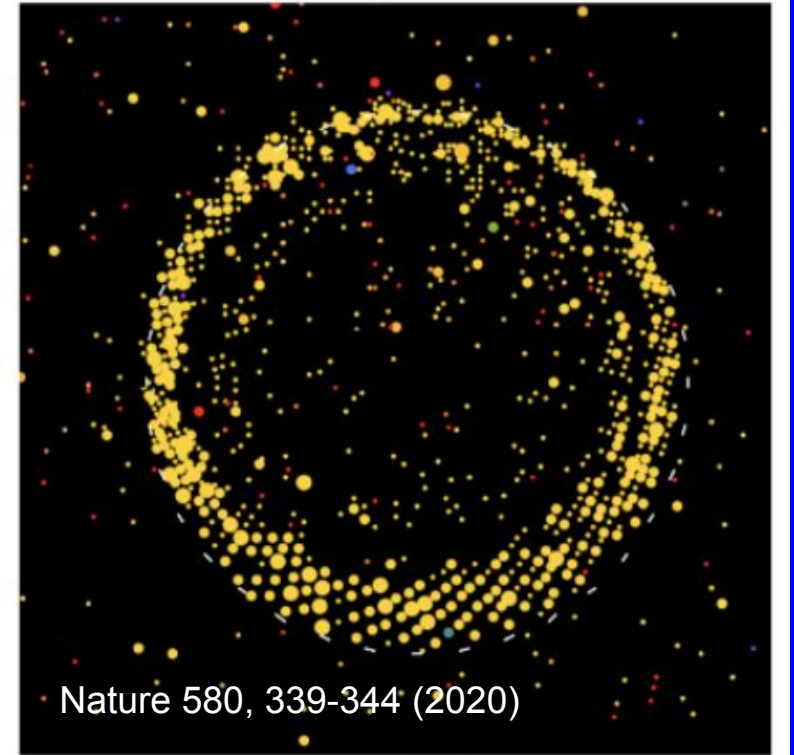
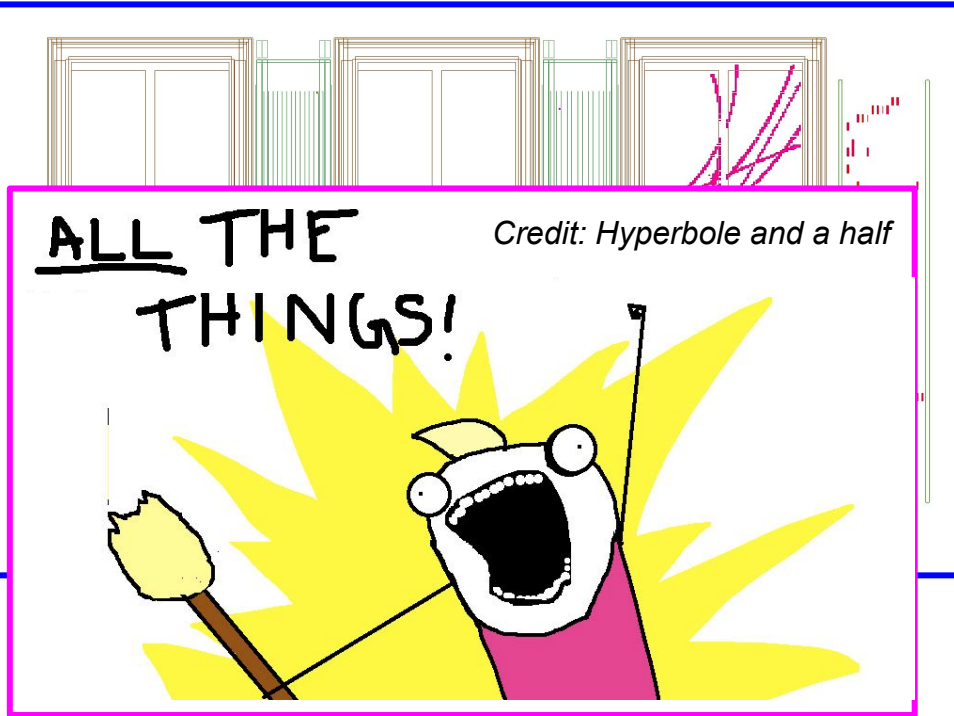Nature 580, 339-344 (2020)

ν_μ-like

Why exclusive?

Example of a multiparticle shower, T2K ND280 detector

Models predict final state particles, and associate those to the correct final state

The cross section model is important for **efficiency** and for the **true-reco relationship** (R) and energy estimators

$$N_{FD}^{\alpha \to \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

Why exclusive?

Credit: Hyperbole and a half

Example of a multiparticle shower,
T2K ND280 detector

Models predict final state particles, and associate those to the correct final state

The cross section model is important for **efficiency** and for the **true-reco relationship** (R) and energy estimators

… oh and I also want multiple target materials (H, C, O, Ar…)

$$N_{FD}^{\alpha \to \beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

External experiments: neutrino scattering on H/D

Resolve current discrepancies in nuclear data with improved, complementary H, D measurements

WP on opportunities for new measurements - arxiv 2203.11298

- Using DUNE ND (GAr, SAND)
- New bubble chamber based experiments at FNAL - arxiv 2203.11319
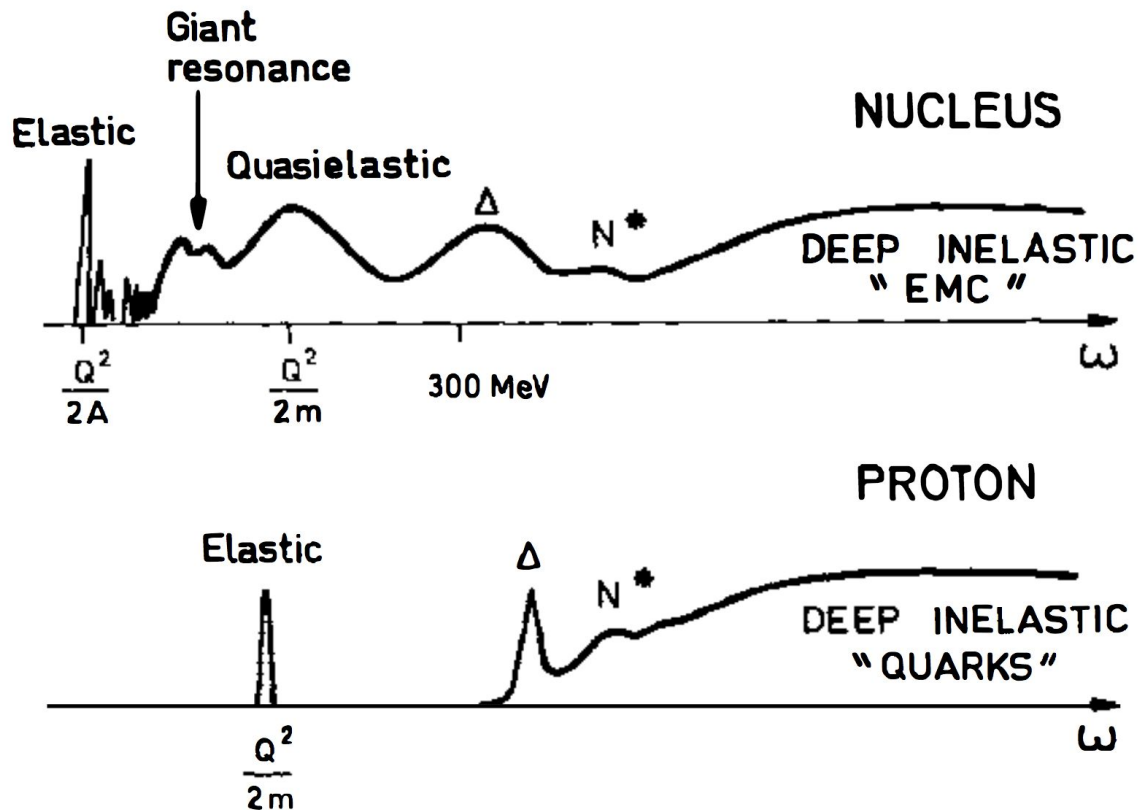
External experiments: Neutrinos from Stored muons (nuSTORM)

NuSTORM feasibility study
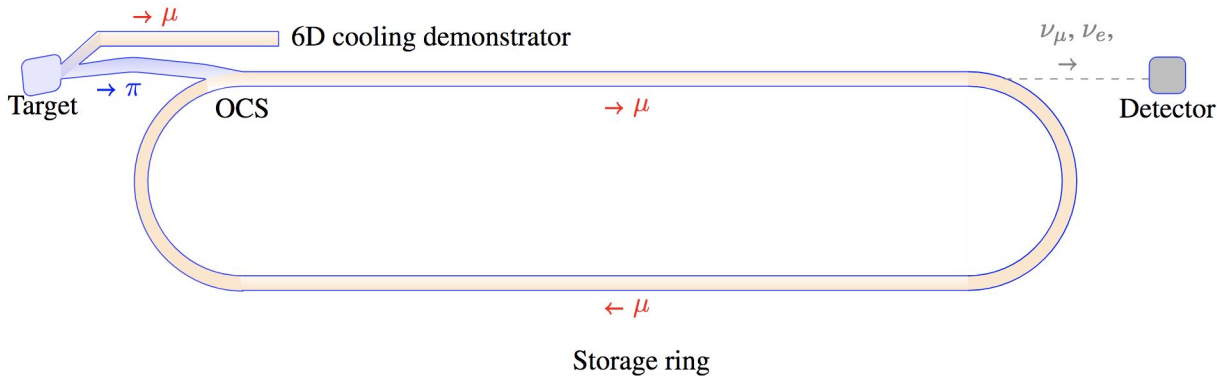
Muon decay based beam, provides 1% level flux uncertainties

Precision ν_e / ν_μ (and antineutrino) cross section measurements

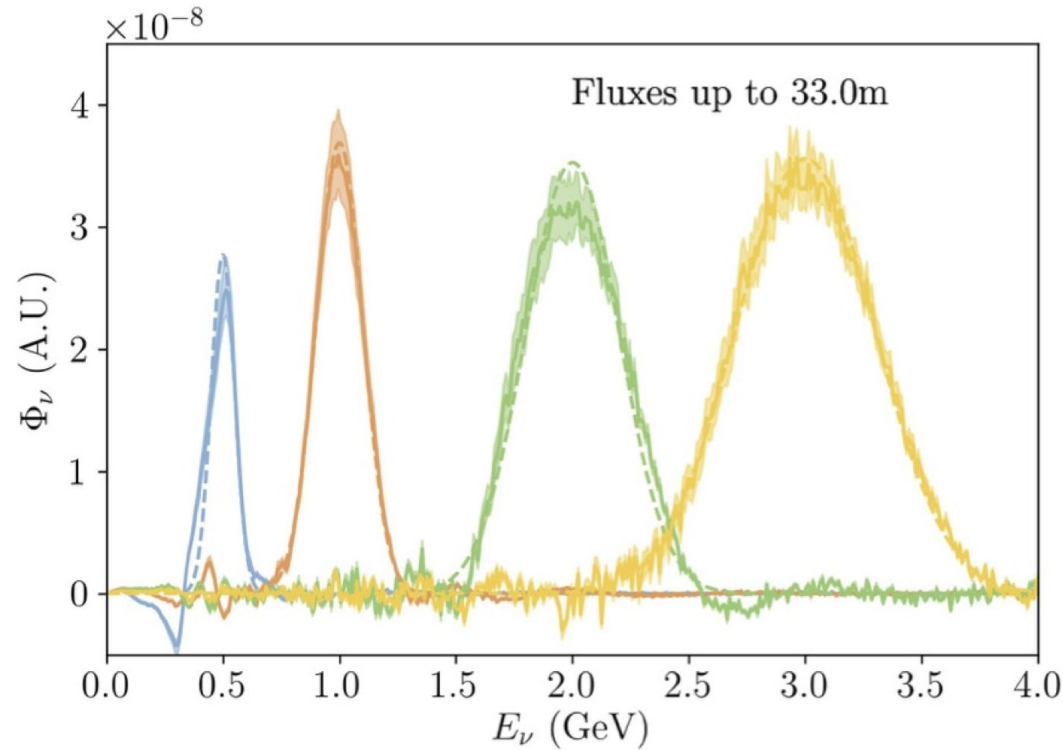CPV measurements depend on electron neutrino-antineutrino asymmetry
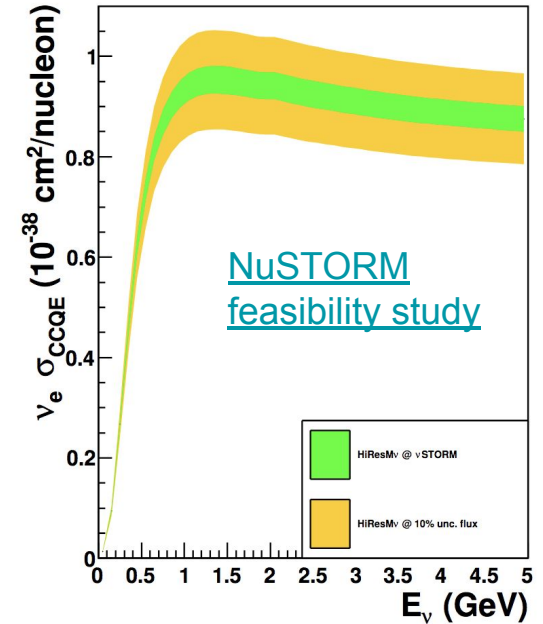
WP: arxiv 2203.07545

Another view of the necessity of precision modelling

From: DUNE ND CDR:

https://arxiv.org/pdf/2103.13910.pdf

What we learn at the ND: parameter constraints
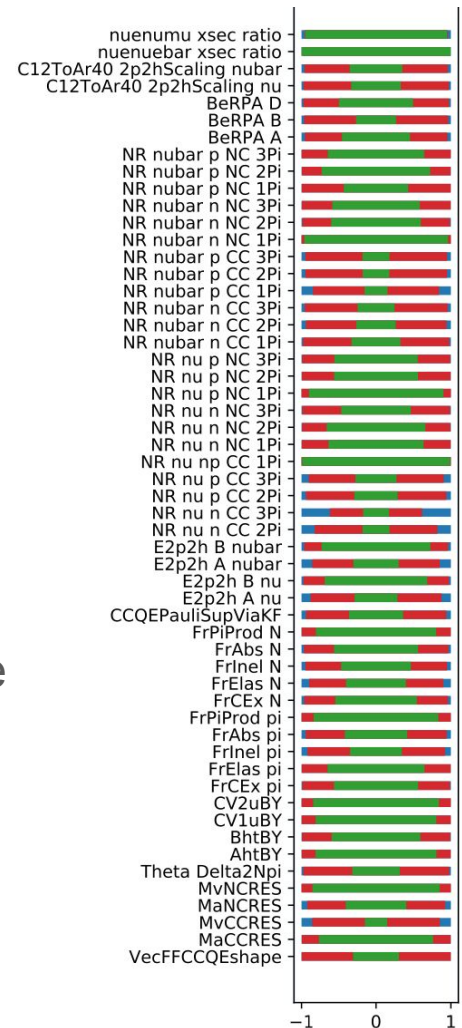
From: DUNE Physics TDR, Fig 5.34

https://arxiv.org/pdf/2002.03005.pdf

What's not obvious here:

- Important measurements needed by THEORY from electron scattering
- How the model development needs go with time (iterative process takes time, this is at the end)
- What if the model is wrong? (PRISM, electron scattering)

■ Prior   ■ FD-only   ■ ND+FD

Why is electron scattering a key component of the current and future program?

From: Electron scattering white paper https://arxiv.org/abs/2203.06853 - *credit of many here!*

To have a robust model requires multiple tests of the model

- *Elec scattering is highly complementary to the ND program, and enhances ND physics reach in a novel way;*
- *Resonance region expected to be very important - major discrepancies and need for electron measurements for theory*
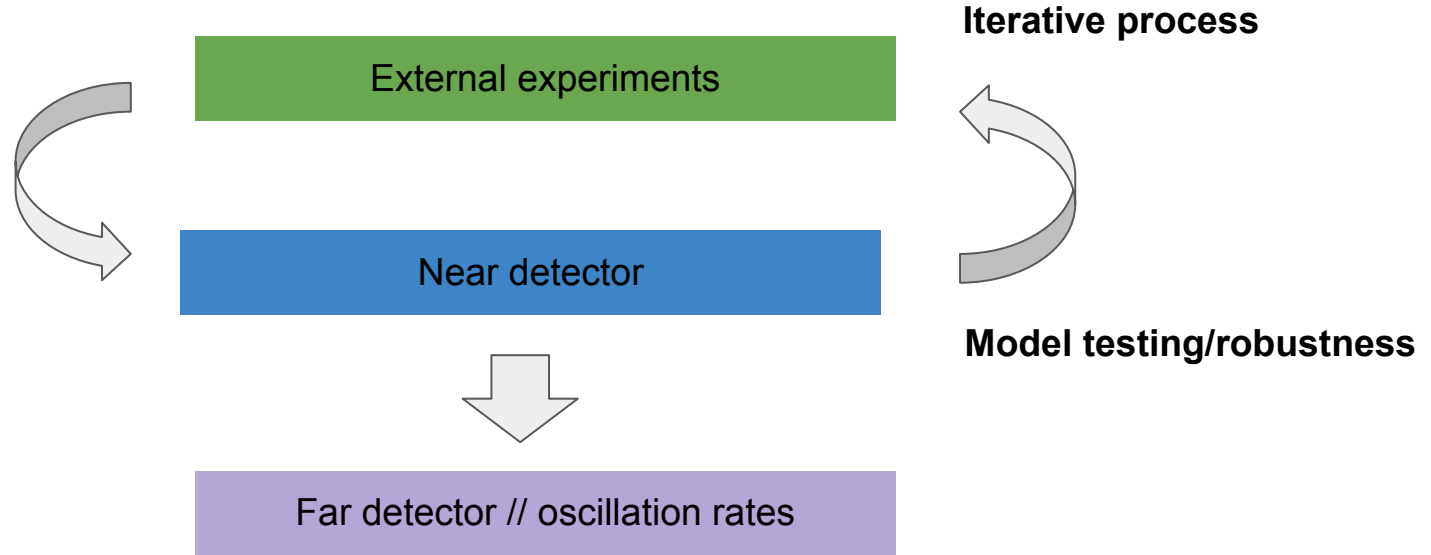
We know next to nothing in transition region, which is also where the power of PRISM decreases

- *need H/D measurements and need to build a basic and complete model of multiplicity and final state composition; atm nu physics may also really need this region*

Both of these problems need TIME and DATA to confront

- *mature state of T2K/NOvA combined with electron scattering program is exciting*

Time is key to understand open questions

Iterative process

External experiments

Near detector

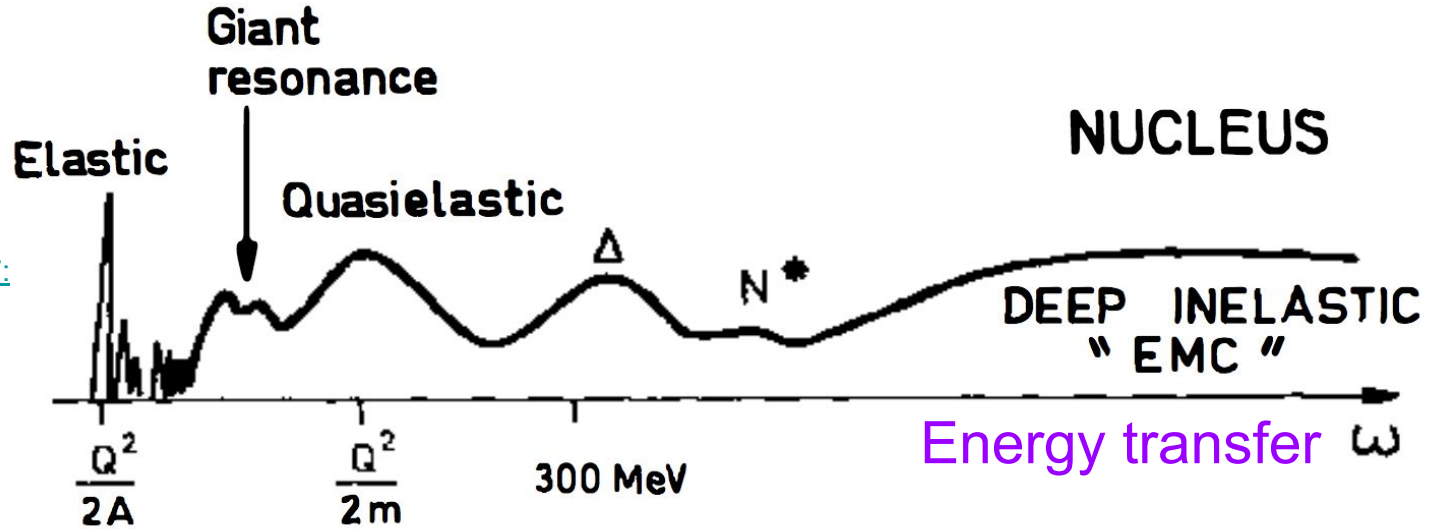**Model testing/robustness**

Far detector // oscillation rates

External experiments are important; determine parameterization, uncertainties.
- Electron scattering
- Pion scattering
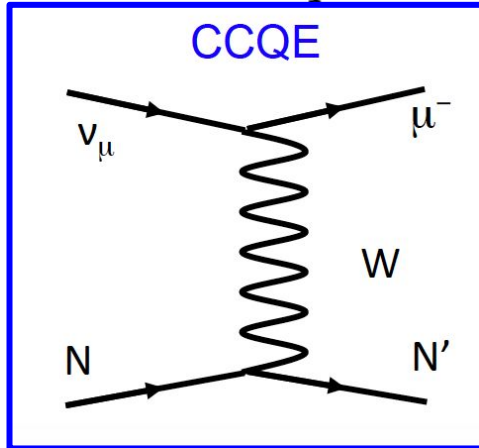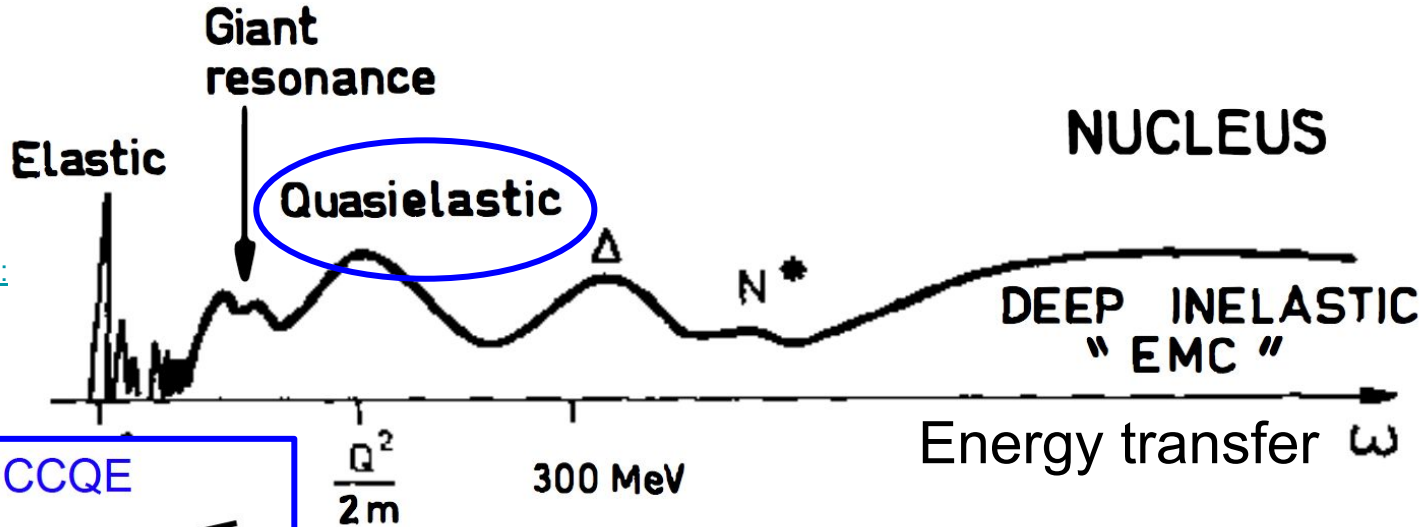- Neutrino H/D data
- Neutrino nucleus scattering

The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Ann. Rev. Nucl. Part.Sci.1987.37: 133-76

The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Giant resonance

Elastic

Quasielastic

NUCLEUS

Δ

N^*

DEEP INELASTIC "EMC"

Energy transfer ω

$\dfrac{Q^2}{2m}$

300 MeV

CCQE

ν_μ μ^-

W

N   N'

Charged current quasielastic scattering

Observables:
- lepton in final state, charge determines neutrino (-) or antineutrino (+)
- Outgoing proton (neutron)

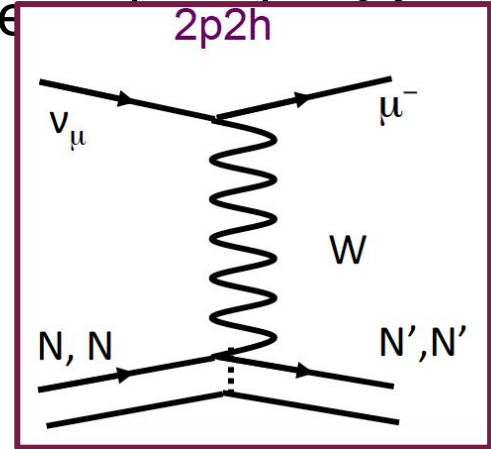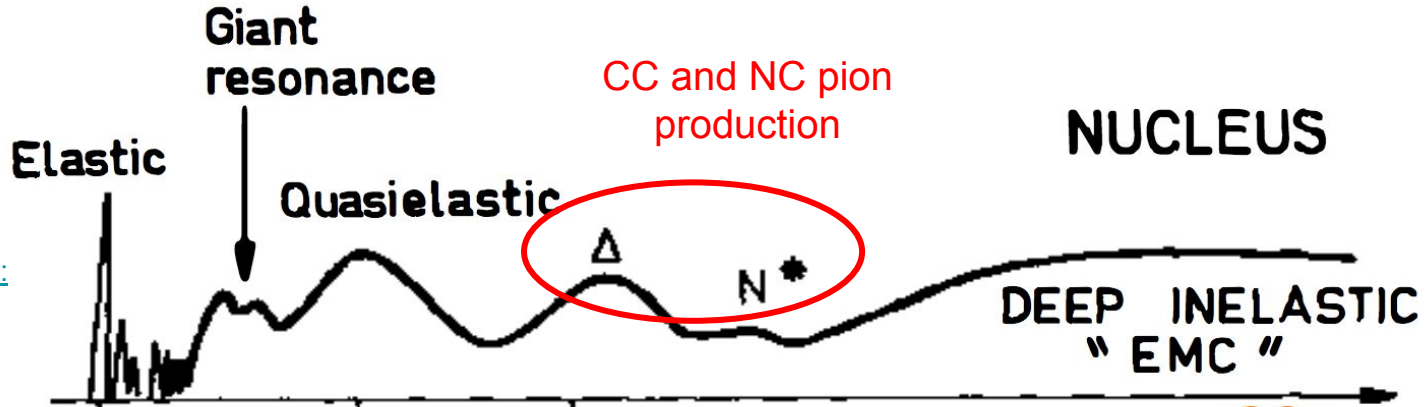# The scale of neutrino interactions: intermediate, ~0.1-20 GeV

CCQE

2p2h
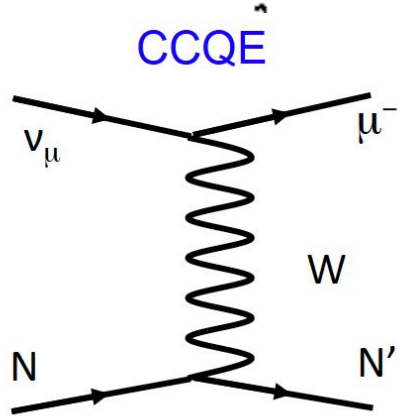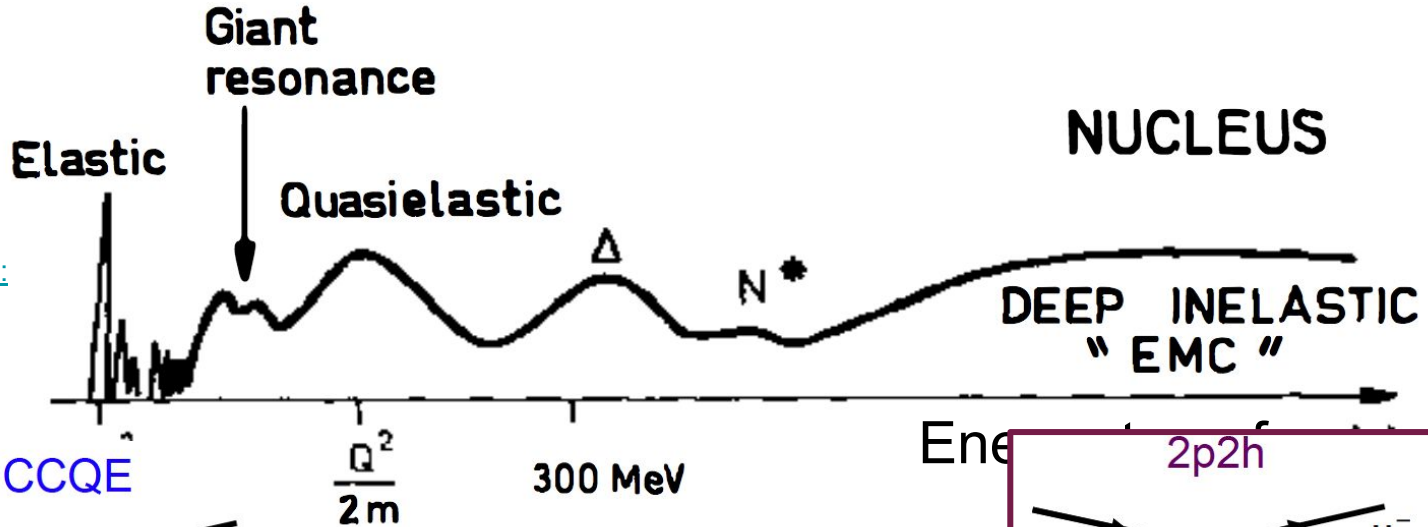
Multinucleon scattering

Similar observables:
- lepton in final state
- Outgoing protons (neutrons)

The scale of neutrino interactions: intermediate, ~0.1-20 GeV
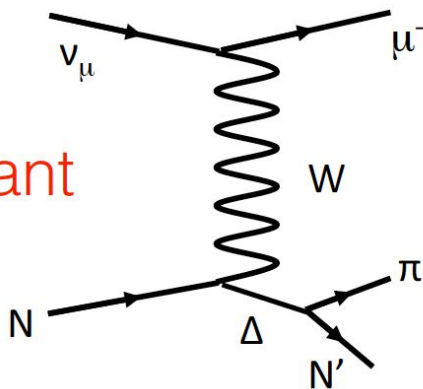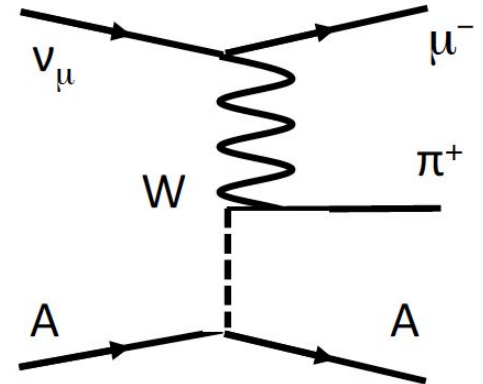

Ann. Rev. Nucl. Part.Sci.1987.37: 133-76

49

The scale of neutrino interactions: intermediate, ~0.1-20 GeV

Giant resonance

Elastic

Quasielastic

Shallow inelastic scattering and deep inelastic scattering

NUCLEUS

Ann. Rev. Nucl. Part.Sci.1987.37: 133-76

Δ

N^*

DEEP INELASTIC "EMC"

Energy transfer ω

Example of a multiparticle shower, T2K ND280 detector

50
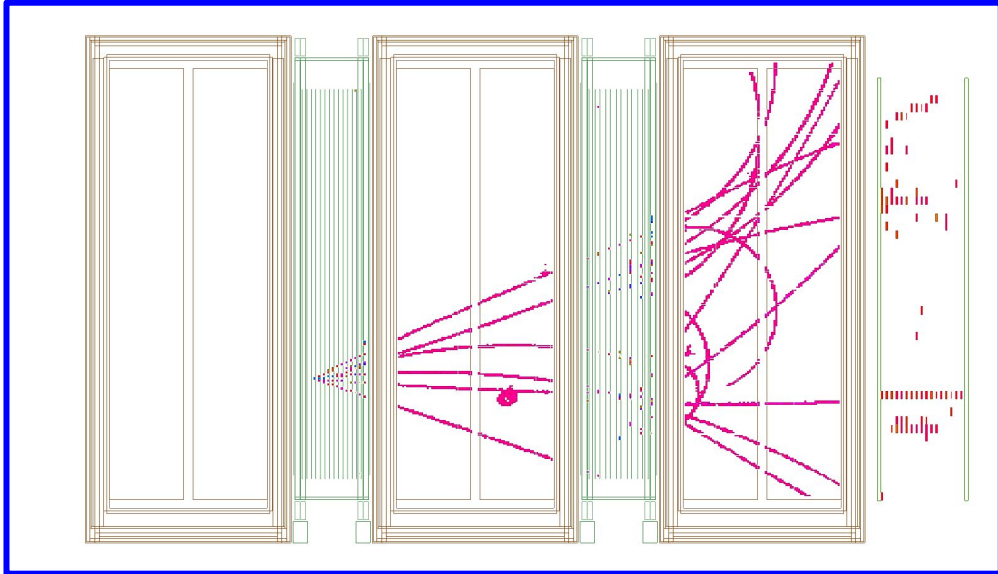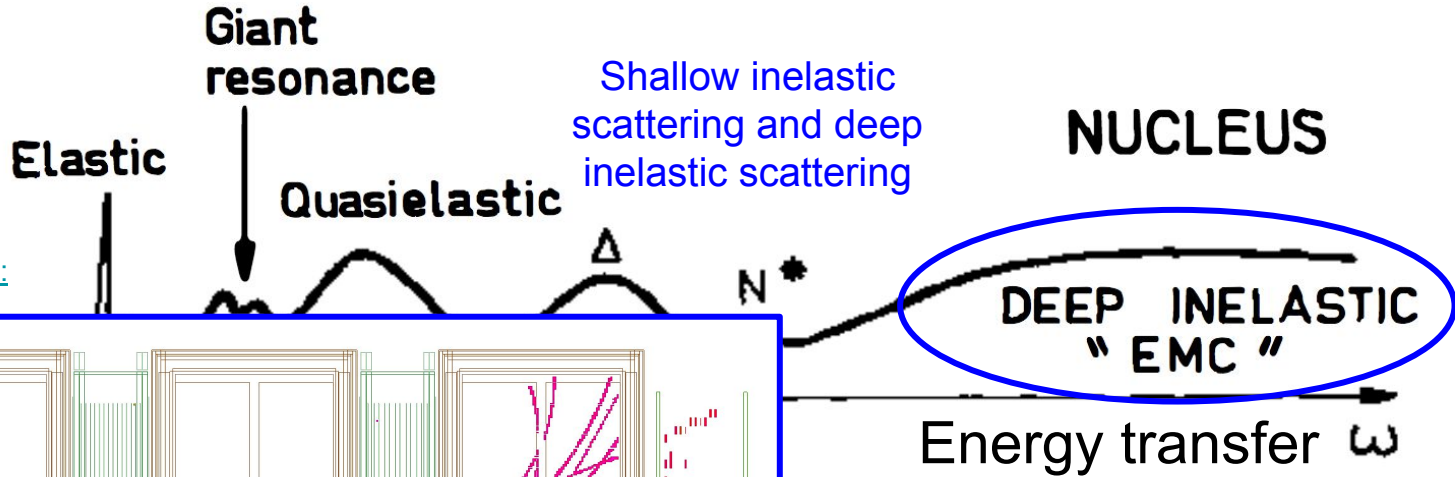
External experiments: neutrinos on nuclei

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS

sbn.fnal.gov/

ANNIE

annie.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

NINJA

Recent: Phys. Rev. D 102, 072006