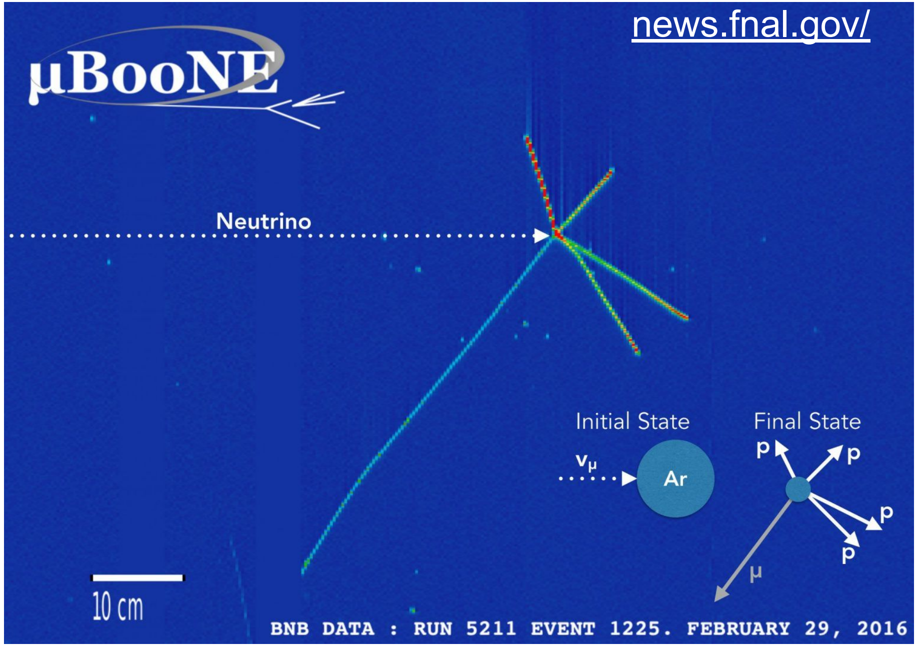
Neutrino interactions: *what, why, and how*



Kendall Mahn
Michigan State University

Snowmass CSS
July 20th 2022

Support from U.S. Department of Energy, award DE-SC0015903

Office of Science
U.S. Department of Energy

Outline

What are neutrino interactions?

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

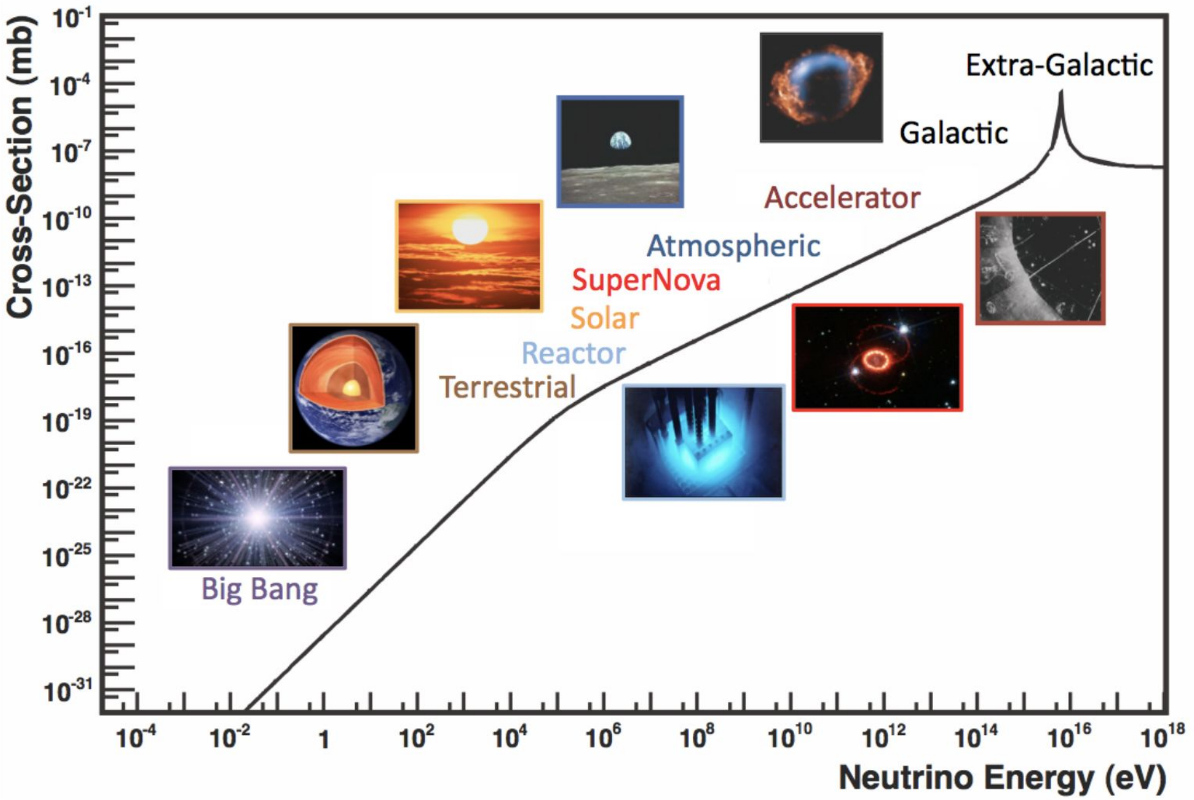
What are the plans to improve our understanding of neutrino interactions?

Neutrino interactions are important to a broad variety of physics programs

Multiple, complementary approaches are underway to fully map out the open questions

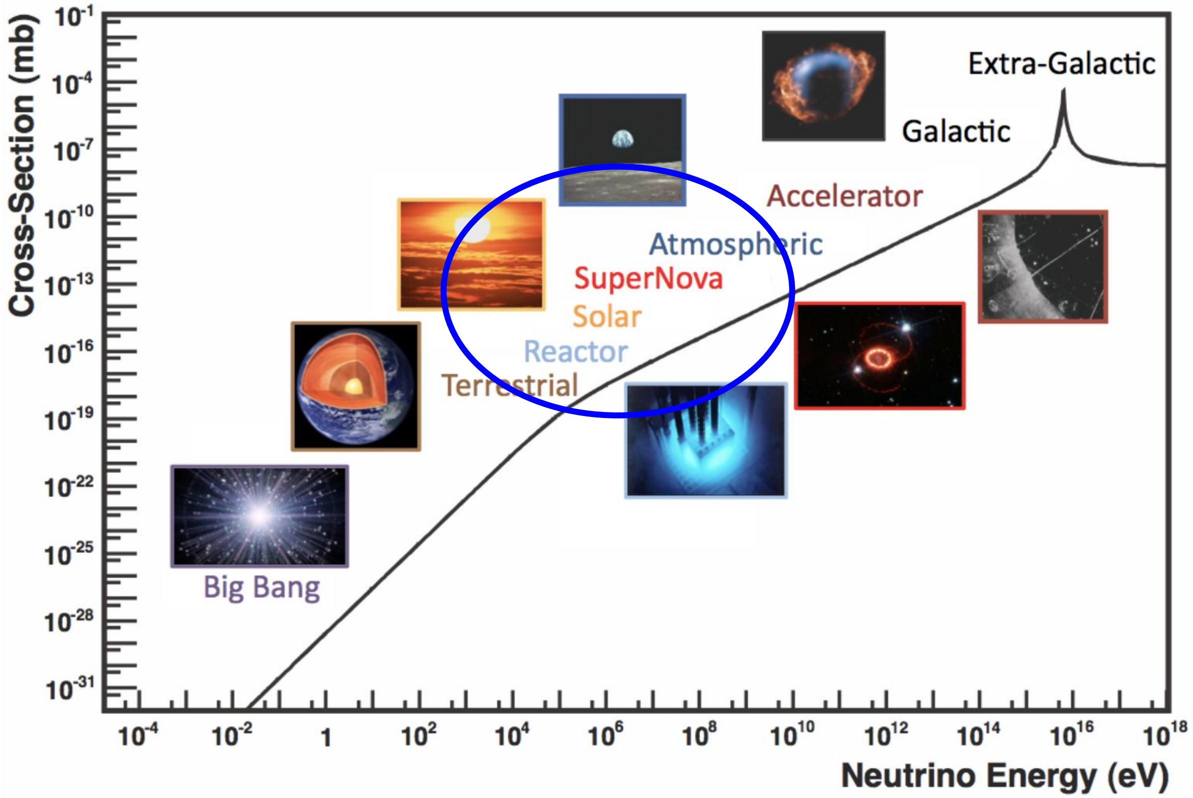
The scale of neutrino interactions

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



The scale of neutrino interactions: low energy, ~0-100 MeV

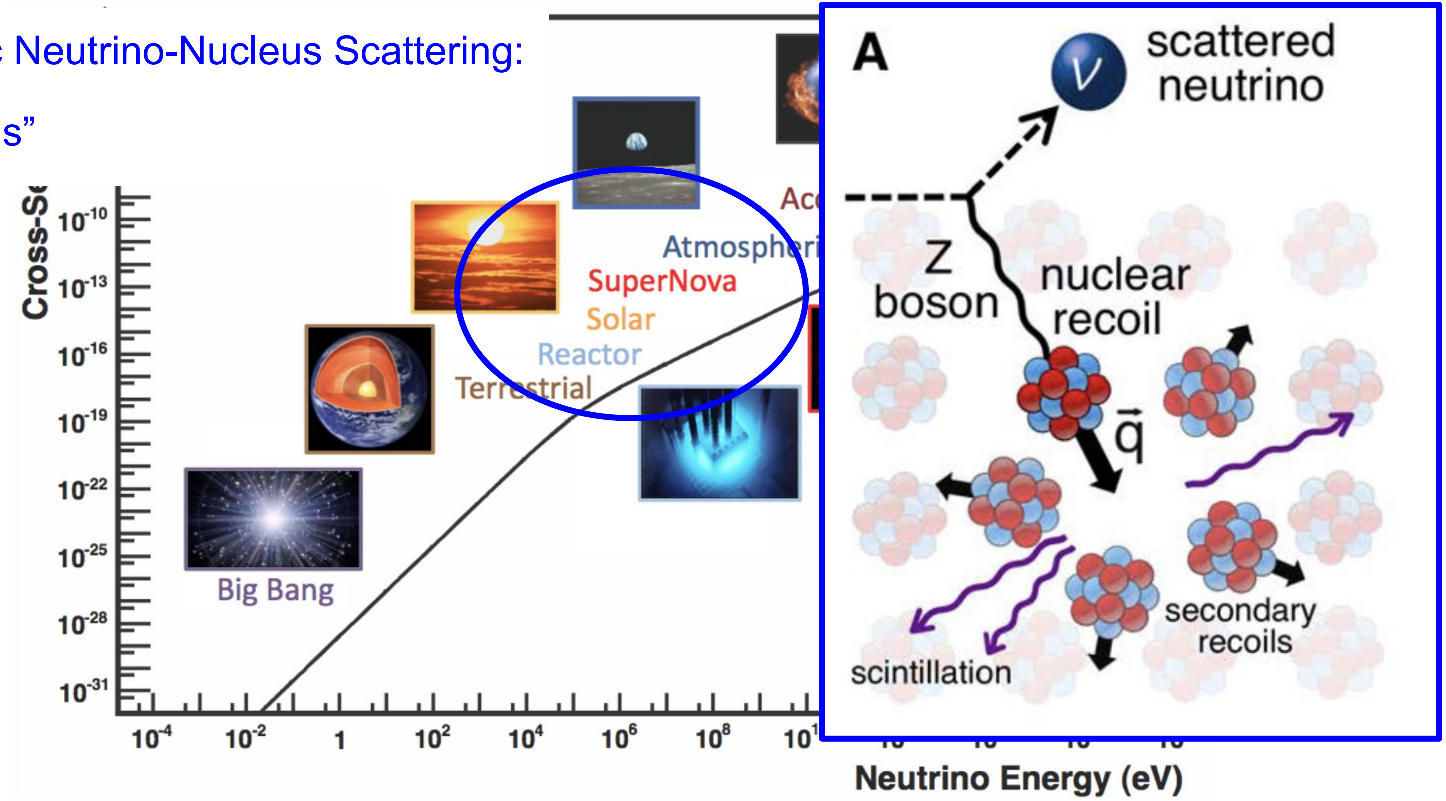
Rev. Mod. Phys. 84, 1307 (2012)



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

Coherent Elastic Neutrino-Nucleus Scattering:

CEvNS - “Sevens”



Science, Vol 357, 6356, pp. 1123-1126

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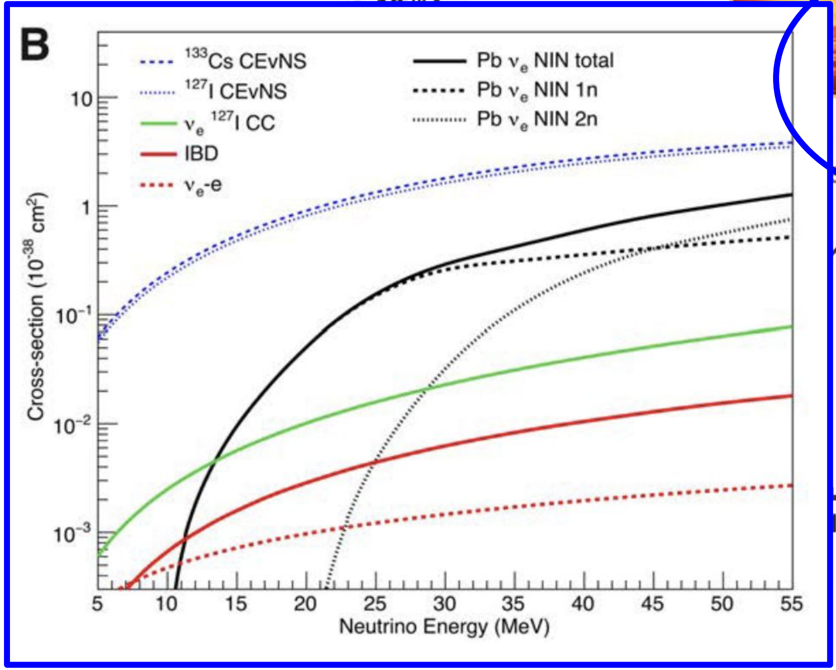
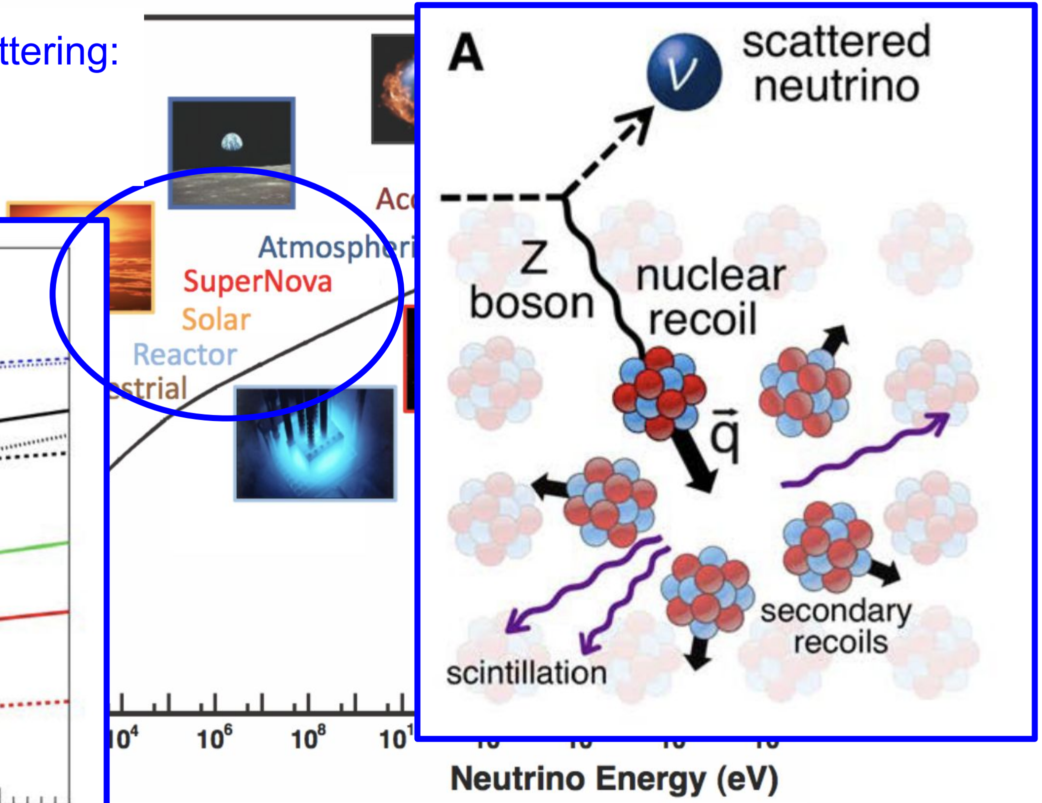
Coherent Elastic Neutrino-Nucleus Scattering:

CEvNS - “Sevens”



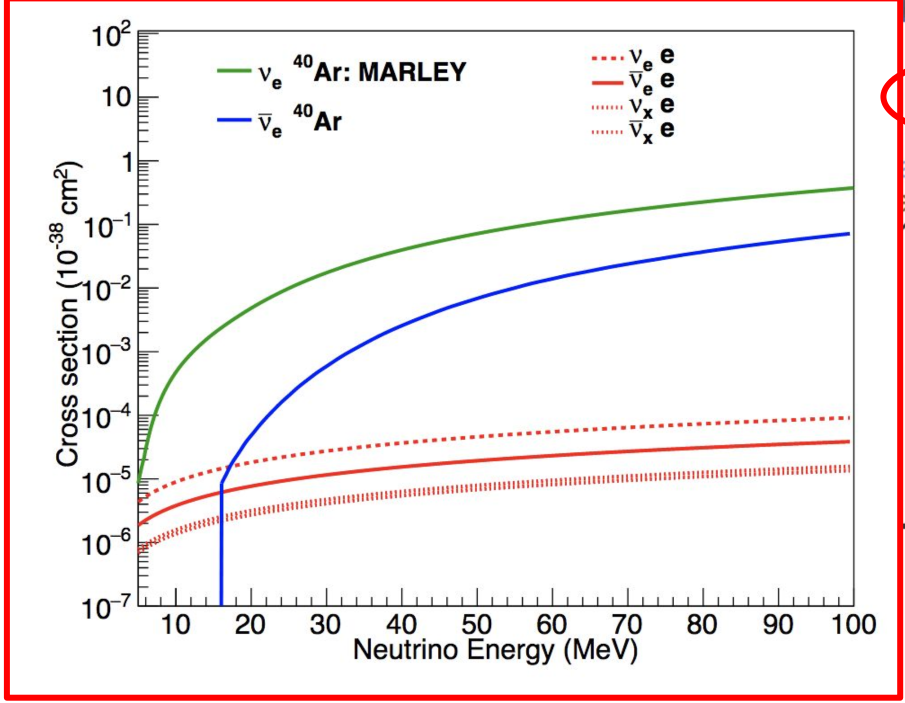


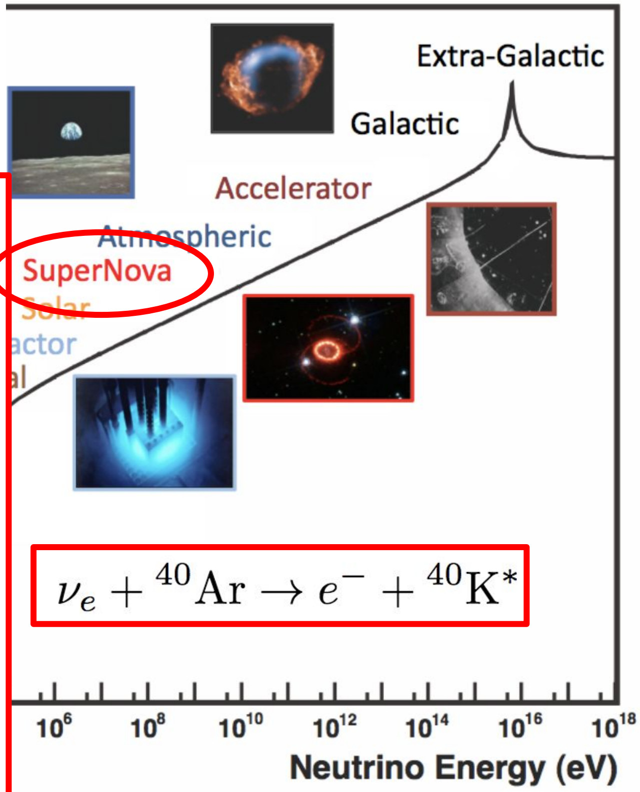
Science, Vol 357, 6356, pp. 1123-1126

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

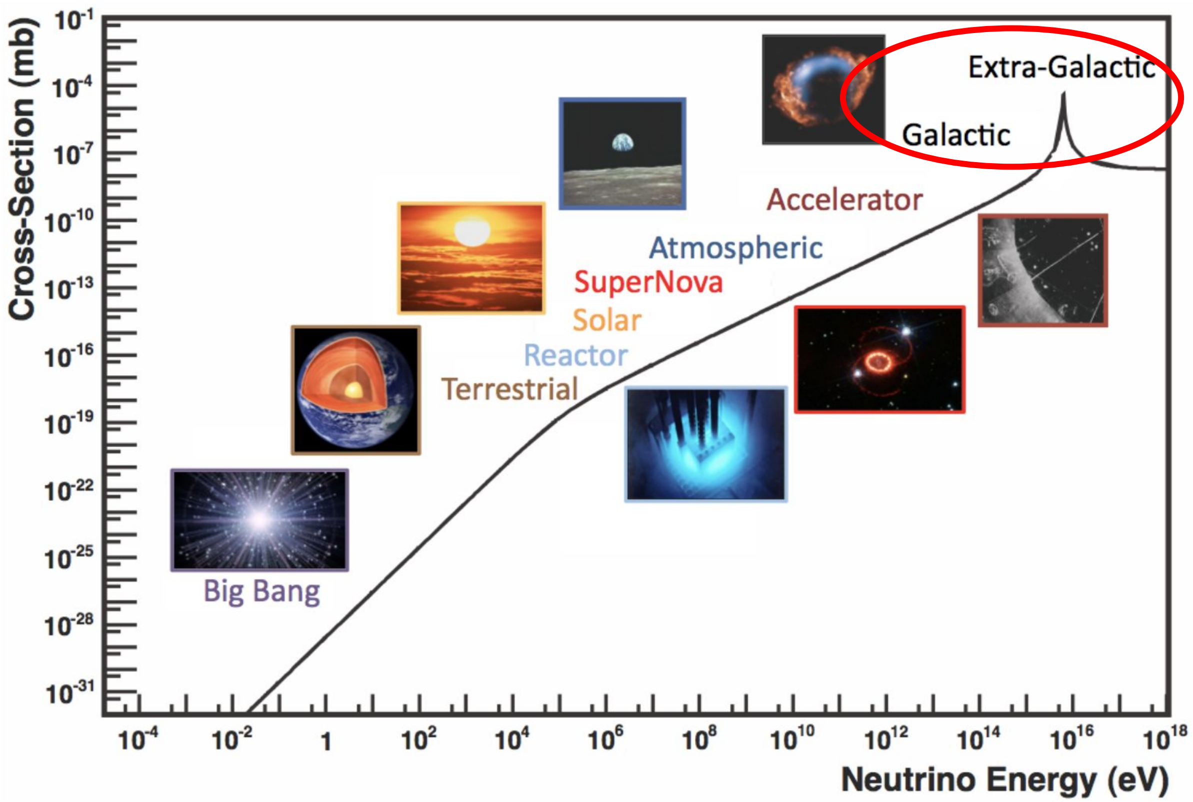




$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

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

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

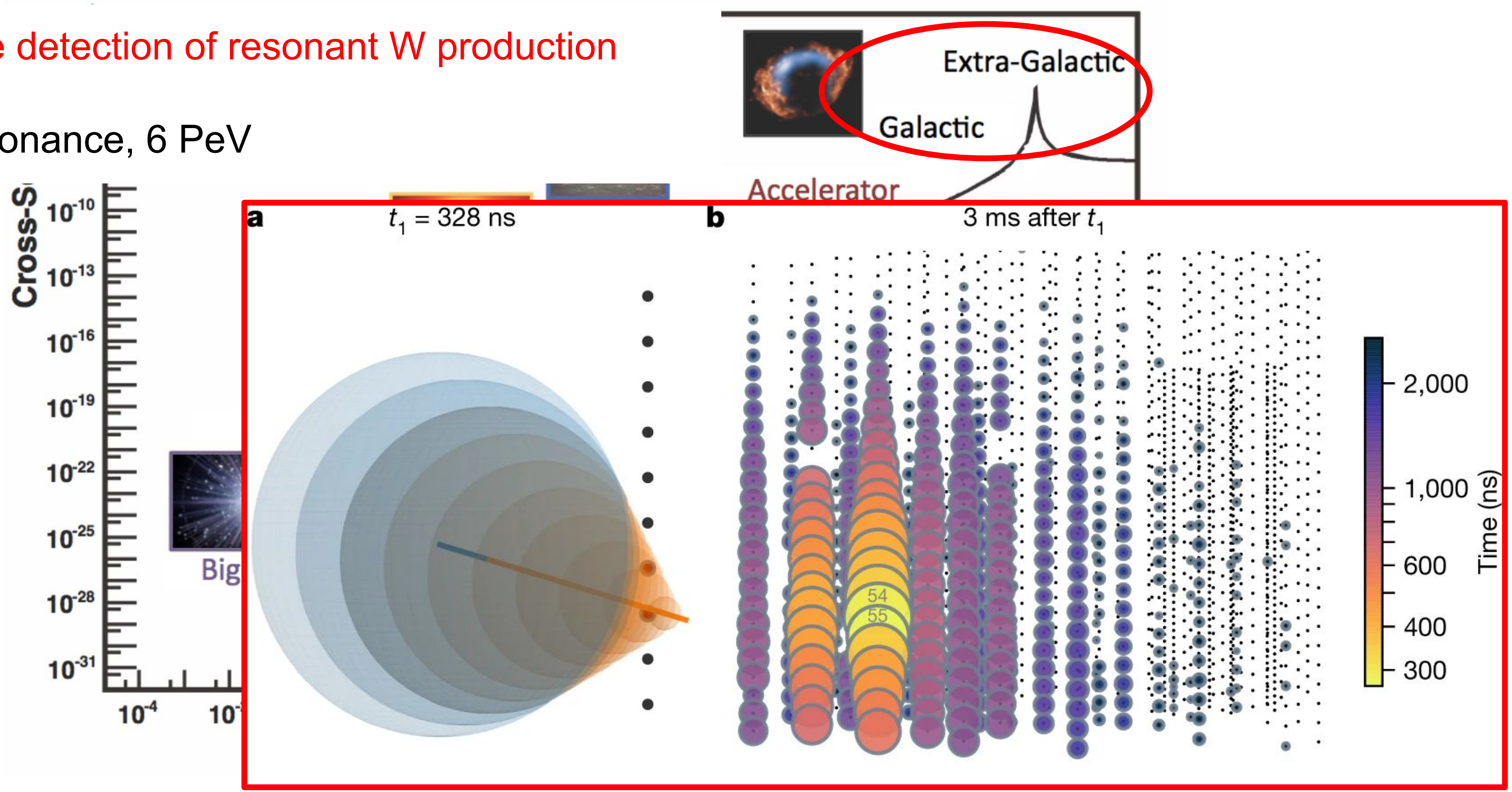


The scale of neutrino interactions: high energy,~20 GeV-1EeV

Example: IceCube detection of resonant W production

- Glashow resonance, 6 PeV

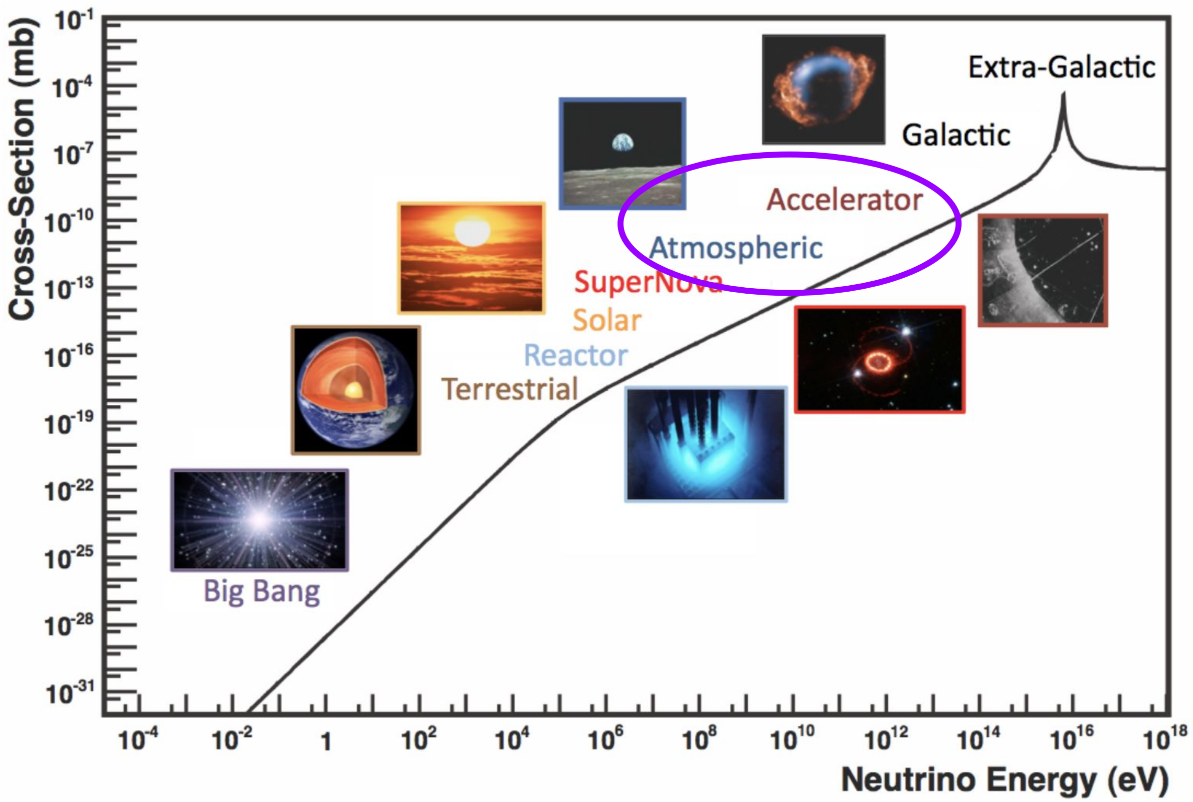
Rev. Mod. Phys. 84, 1307 (2012)



Nature 591, 220–224 (2021)

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

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



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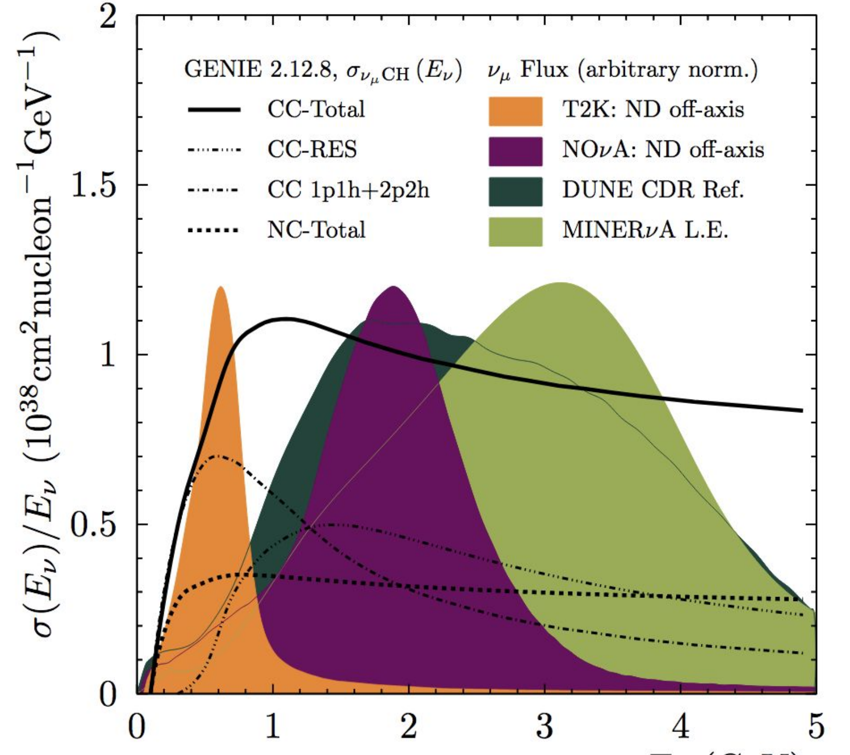
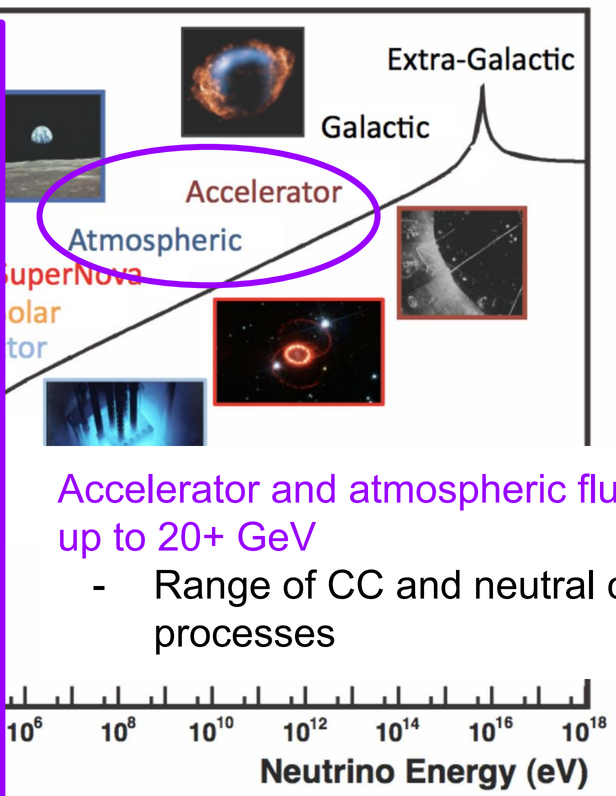


Ann.Rev.Nucl.Part.Sci. 68 (2018)



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

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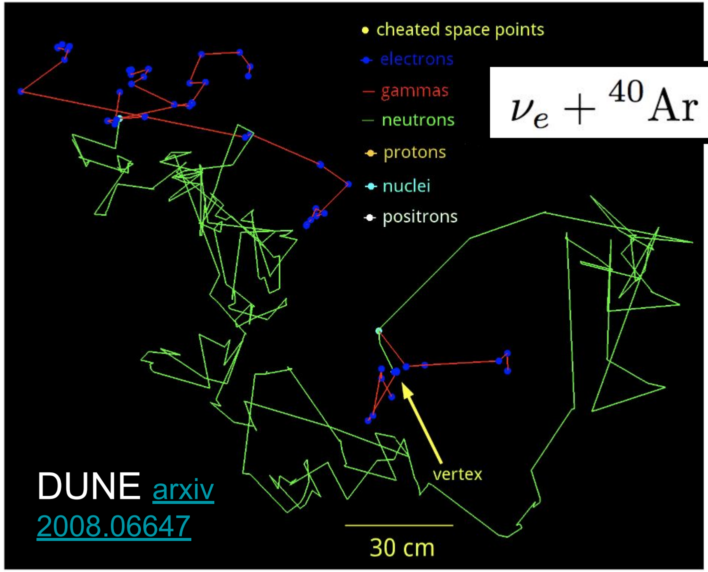


DUNE arxiv 2008.06647

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

Interesting physics

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

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

Needed Information:
- Semi inclusive predictions of SNB cross section

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

Why are neutrino interactions important?

Energy regime

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

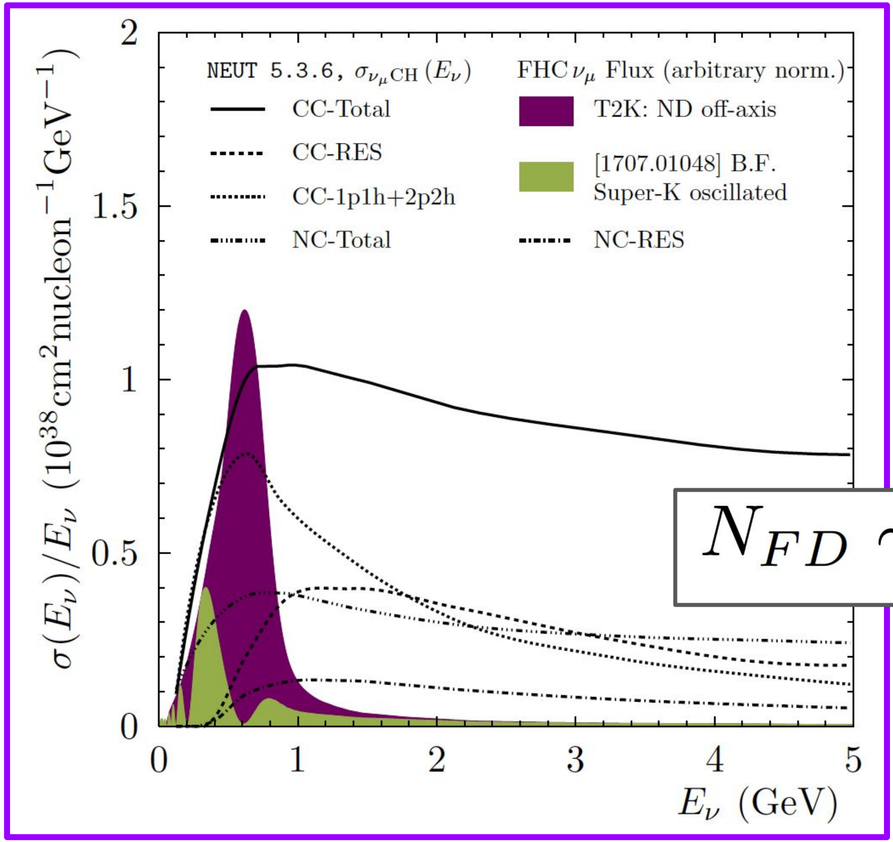
Interesting physics

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 processes

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

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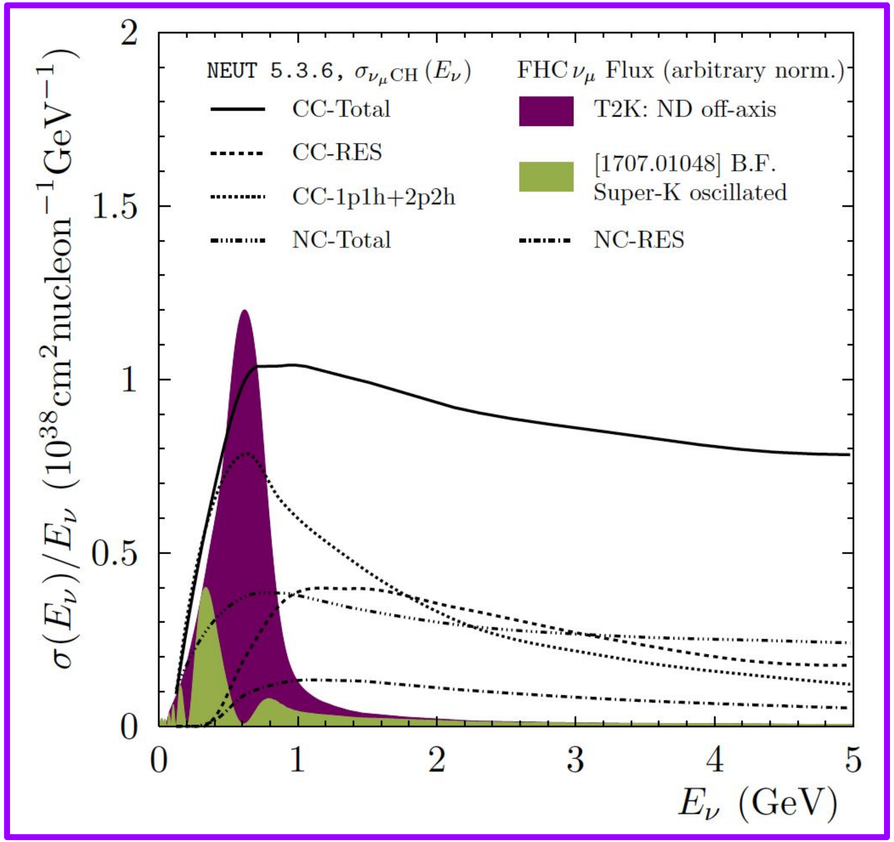

Example: Tokai-to-Kamioka (T2K) experiment

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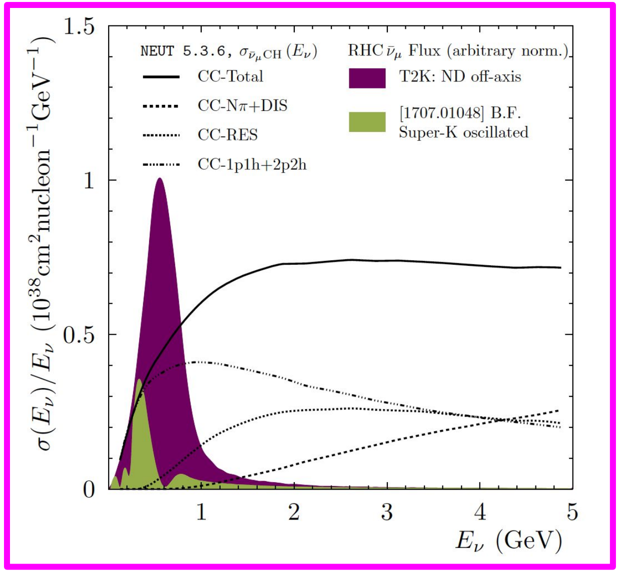

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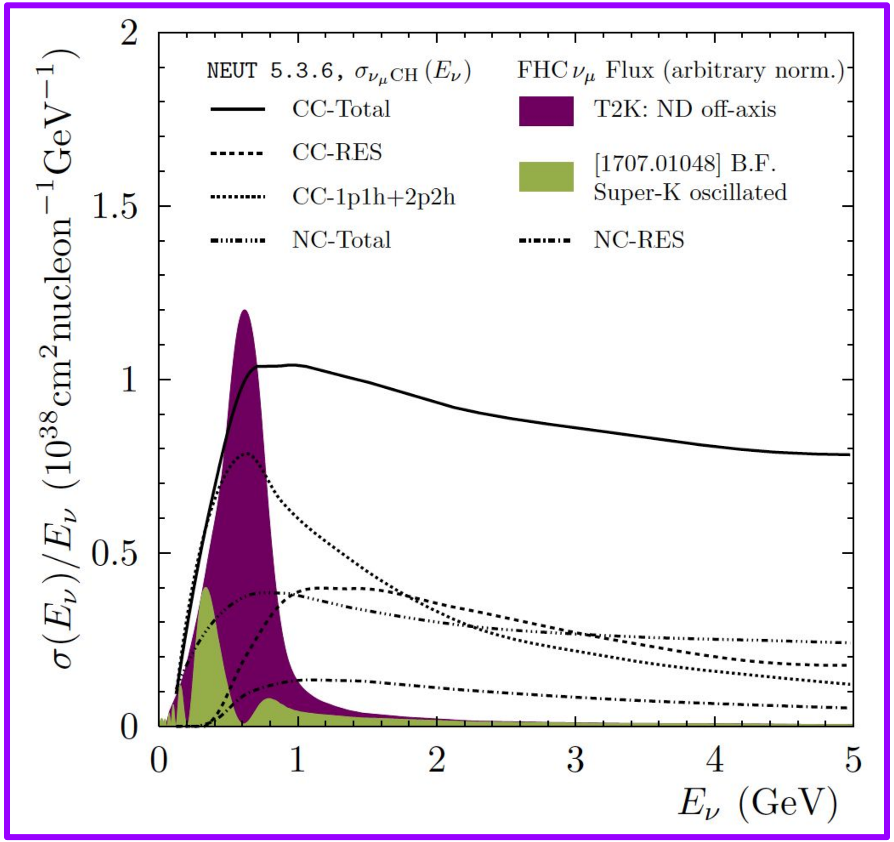
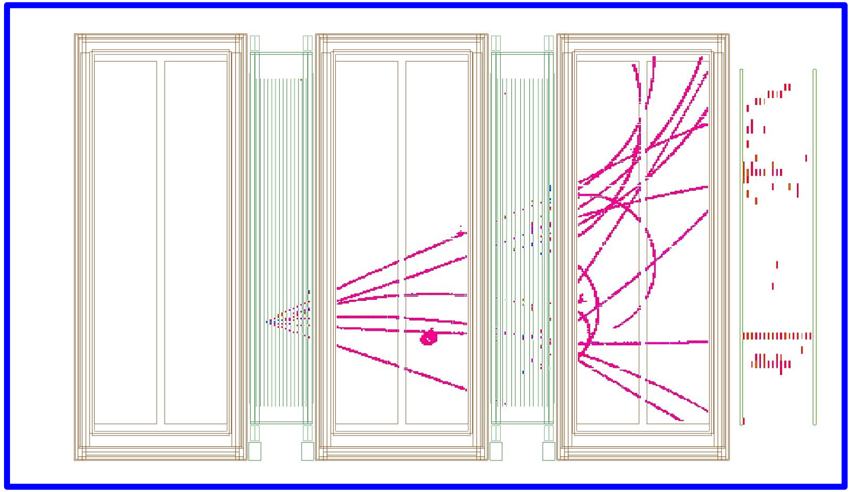


Example: Tokai-to-Kamioka (T2K) experiment

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

$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \rightarrow \nu_e)$$

Near detectors (ND) are essential to test completeness of, and improve estimates of shared sources of systematic uncertainty:

(Anti) neutrino flux (Φ)

(Anti) neutrino interaction cross section (σ)

Detection efficiency (ϵ)

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Near detectors (ND) are essential to test completeness of, and improve estimates of shared sources of systematic uncertainty:

- Current program: NOvA ND, T2K ND (new upgrade - arxiv 1901.03750)
- Future program: DUNE ND, Hyper-Kamiokande ND

(Anti) neutrino flux ($\mathbf{\Phi}$)

Interaction cross section ($\boldsymbol{\sigma}$)

Detection efficiency (ϵ)

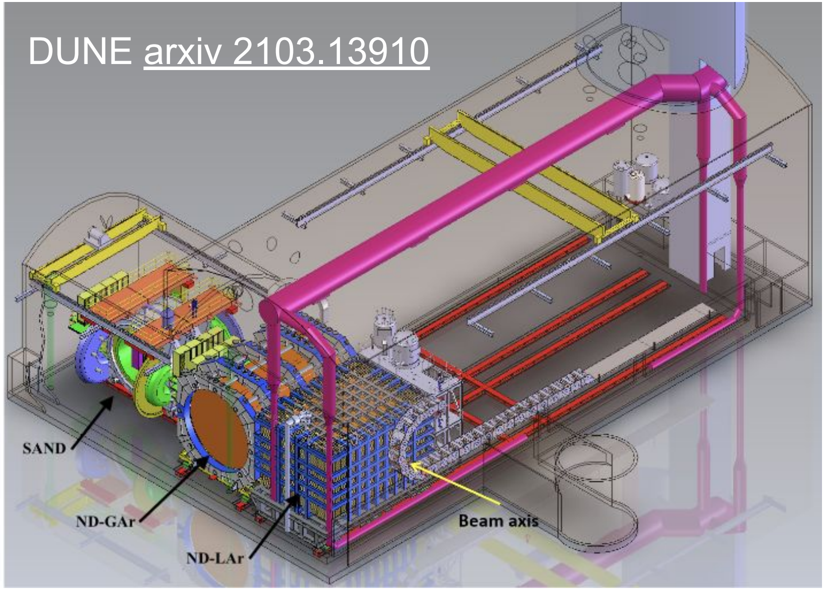
Role of “near detector” in oscillation experiments

$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

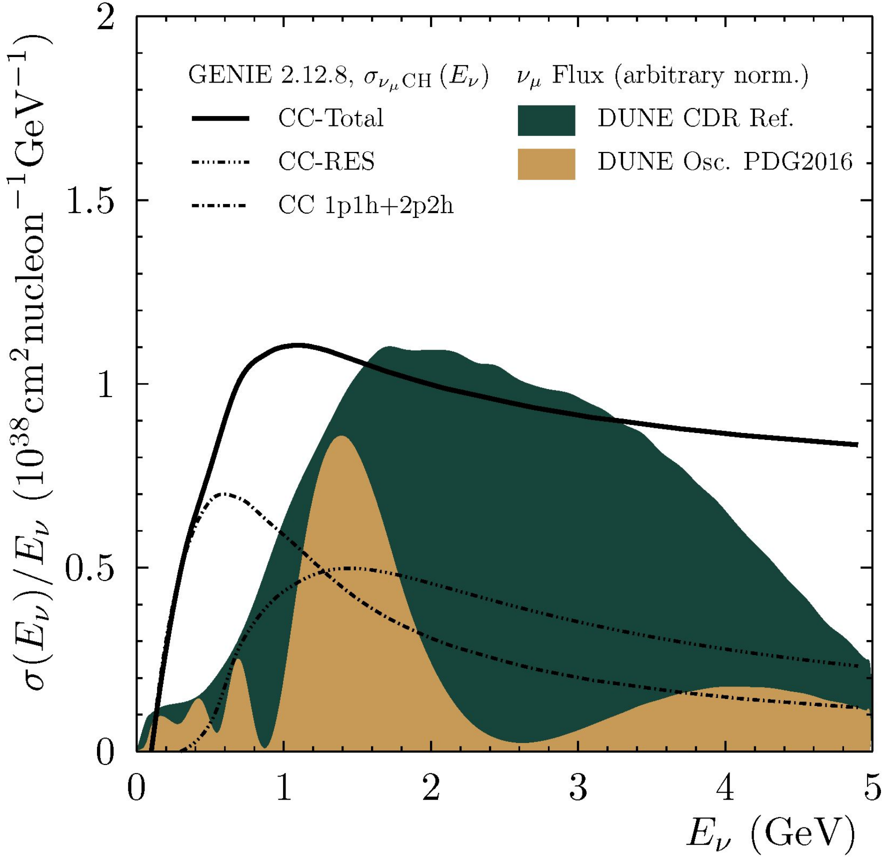
$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Example: DUNE Near Detector “suite”

- Liquid Argon (ND-LAr)
- Gaseous detector (ND-GAr)
- Beam monitoring (SAND)

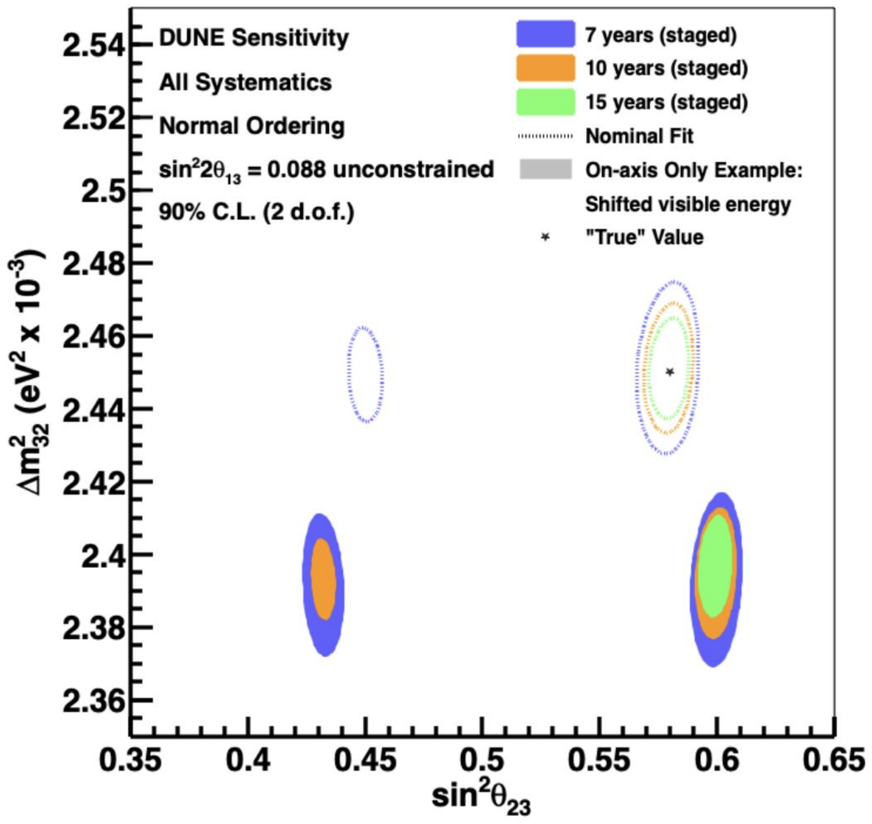


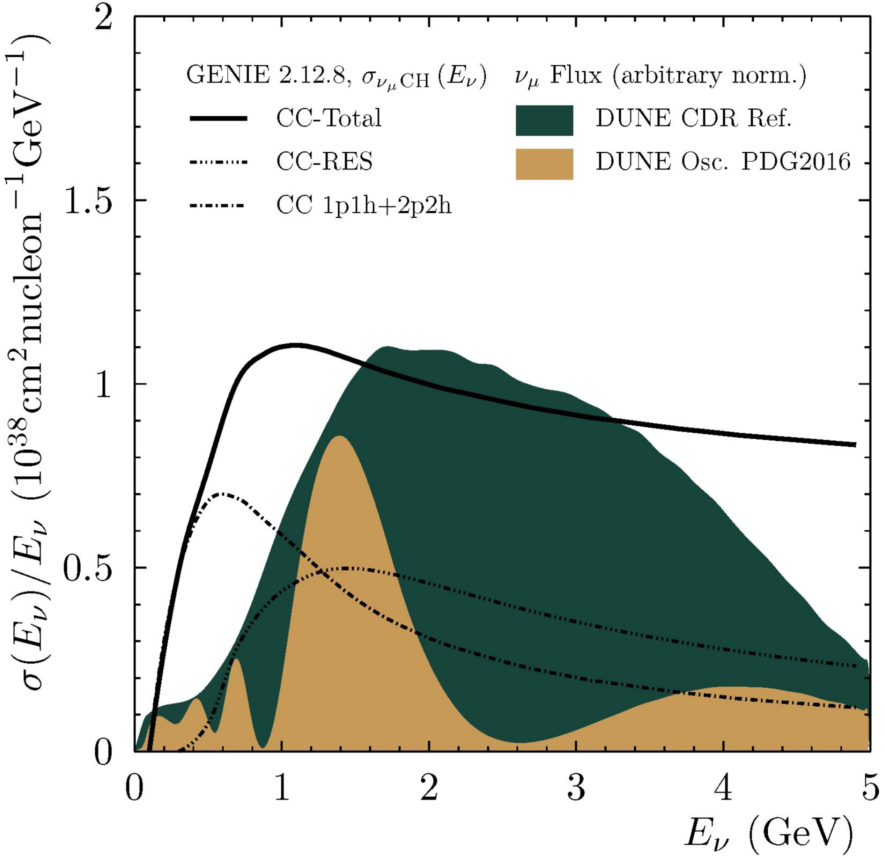
New capabilities to meet challenges: example from DUNE



New capabilities to meet challenges: example from DUNE

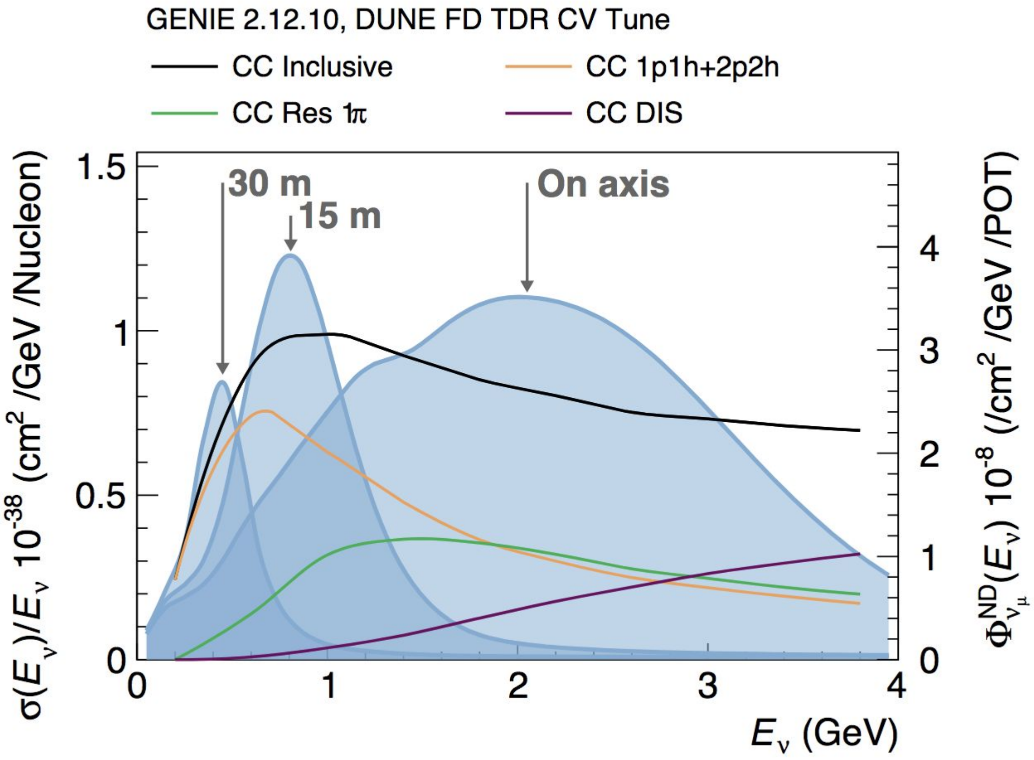
DUNE Physics TDR arxiv. 2002.03005





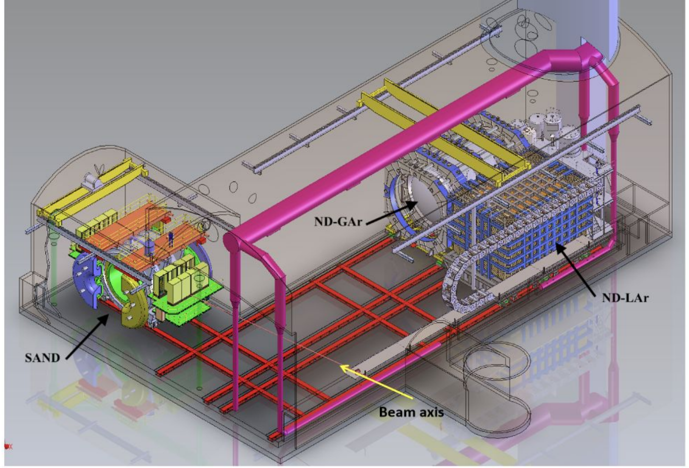
Possibility of bias in key oscillation parameters with 'conventional' ND

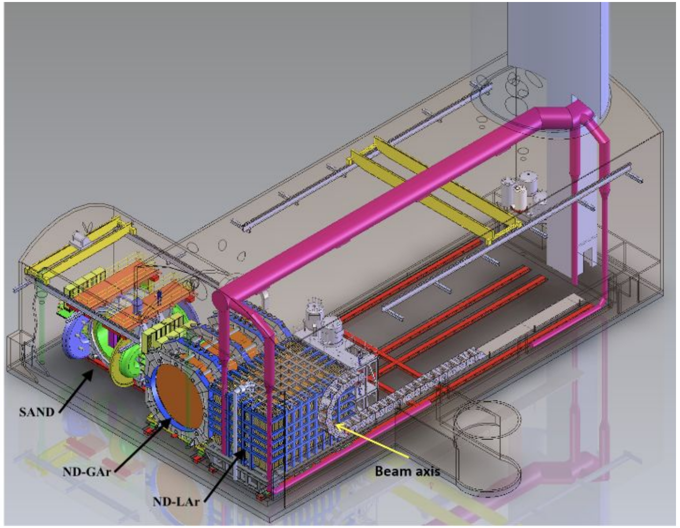
New approach: DUNE PRISM



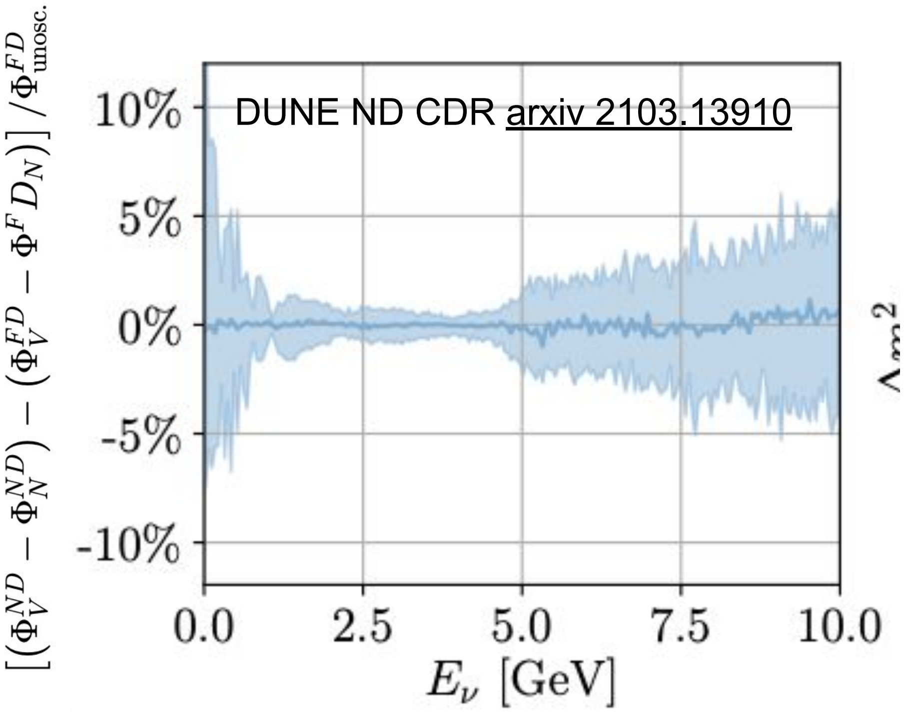
Place detectors at different positions relative to beam to measure different energy spectra

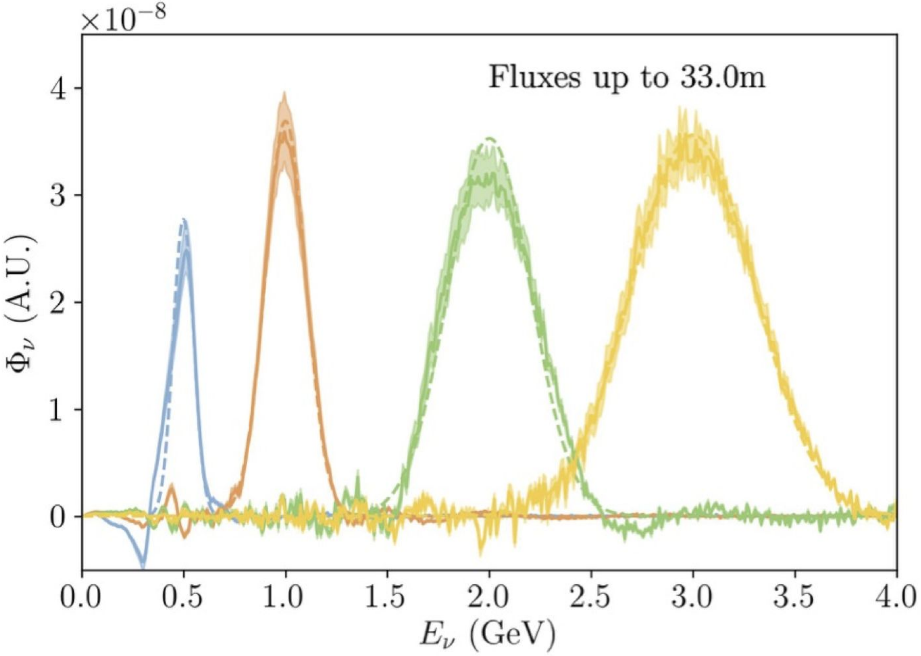
DUNE arxiv 2103.13910





DUNE PRISM provides robustness against mismodelling





Novel nuclear physics studies, exotics physics reach - *theory, NP collaboration*

ND-GAr, SAND also have unique cross section measurement opportunities

The role of external experiments

Nuclear Theory

HEP Theory

Electron Scattering

Pion Scattering

Neutrino scattering: hydrogen/deuterium

Neutrino scattering: Nuclear targets

Refine, revisit and test models

$$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

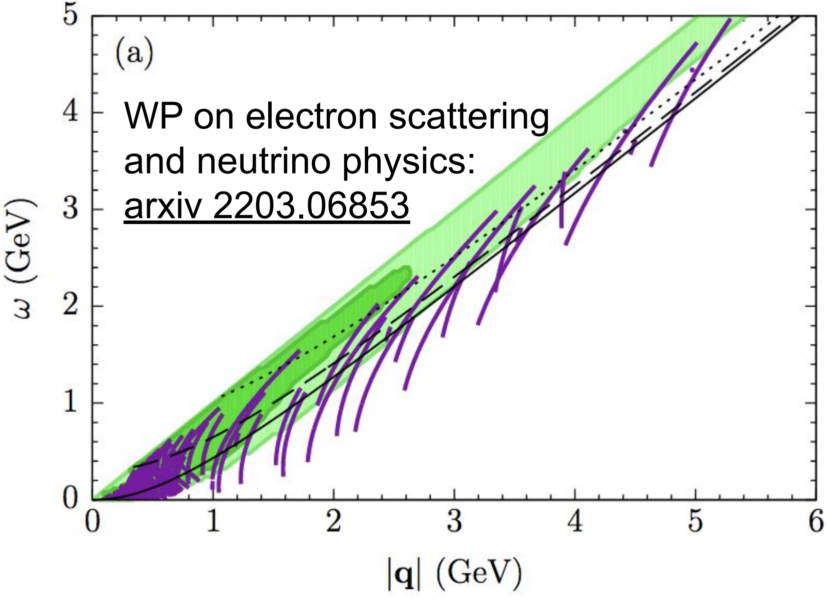
$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Inputs from theory, external and in-situ data

Theory, external experiments are crucial to determine parameterization, uncertainties.

- Iterative process takes time
- Multiple communities benefit and are important to success: theory and experiment, HEP and NP

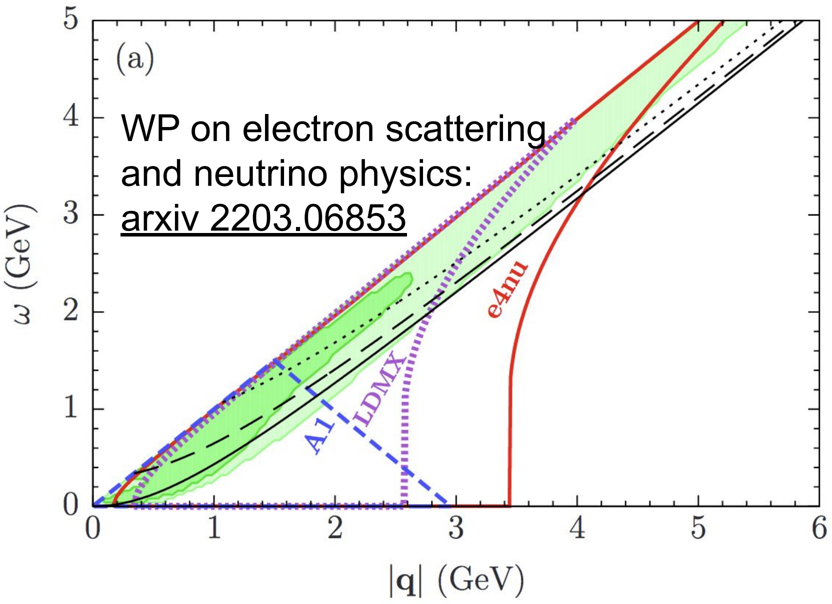
External experiments example: electron scattering



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 example: electron scattering



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')

Electron scattering provides vector cross section - complementary to ND

- 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 underway

External experiments: neutrinos on nuclei

Experiment	Flavor	ν_μ Flux Peak (GeV)	Target
T2K	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	0.6,0.8,1	CH,H_2O, Fe
NOvA	ν_μ,$\overline{\nu}_\mu$,ν_e, $\overline{\nu}_e$	2	CH_2
DUNE	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	PRISM: 0.5-3	H,C,Ar
HK IWCD	ν_μ,$\overline{\nu}_\mu$,ν_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	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$	3.5,6	He, C, CH, H_2O, Fe, Pb
ANNIE	ν_μ,$\overline{\nu}_\mu$	0.6	CH,H_2O
NINJA	ν_μ,$\overline{\nu}_\mu$	1	H_2O, Fe
FPF	ν_μ,$\overline{\nu}_\mu$,ν_e,$\overline{\nu}_e$, ν_τ, $\overline{\nu}_\tau$	700 GeV	W, Ar
nuSTORM	ν_μ,$\overline{\nu}_\mu$,ν_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 - WP arxiv 2203.06853

- Form factor from PVES improves reach of CEvNS programs
- Theory important here in application

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

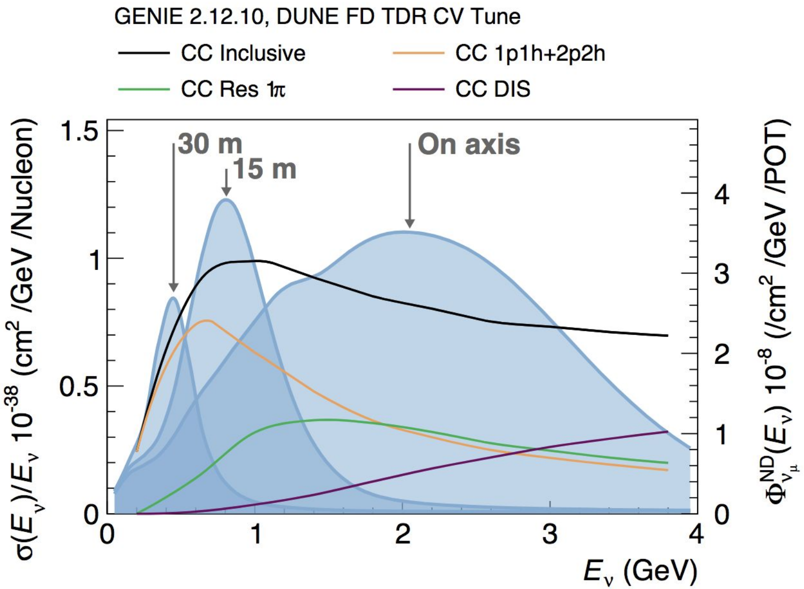
A robust understanding of neutrino interactions is important to answer many of the open questions we face today

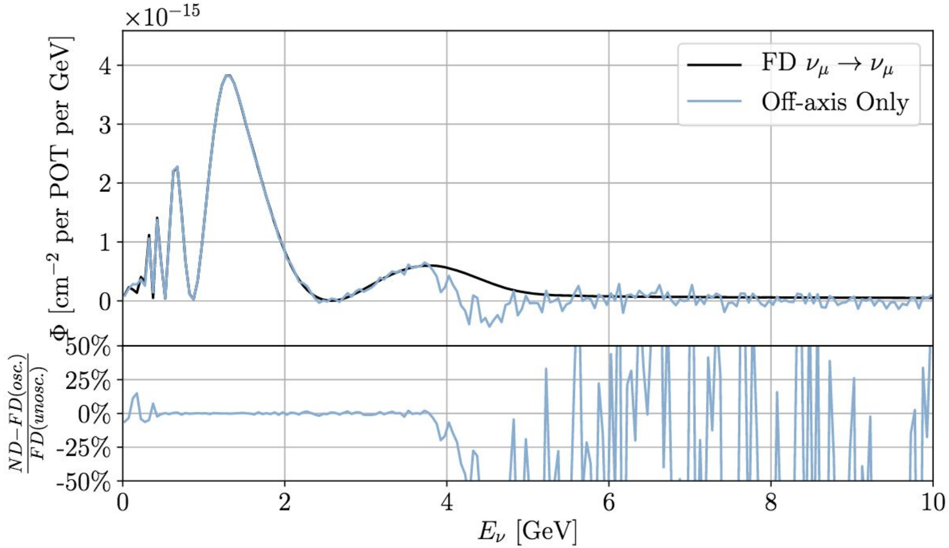
There are multiple efforts planned or underway, to inform theory and simulation:

- 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

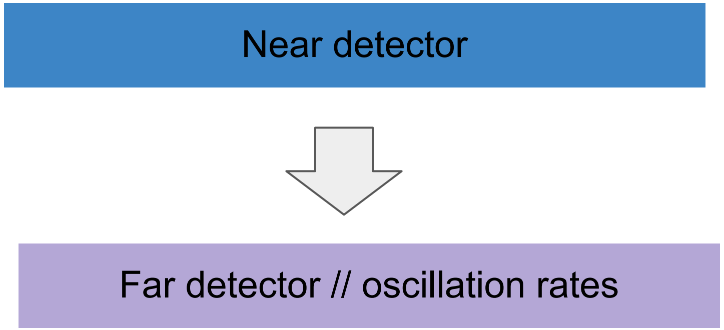
New approach: PRISM





Combine spectra for an oscillation-matched flux

Current plans of oscillation experiments



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/

NuSTORM

MINERvA
minerva.fnal.gov/

Parting gifts of data preservation, ultimate measurements

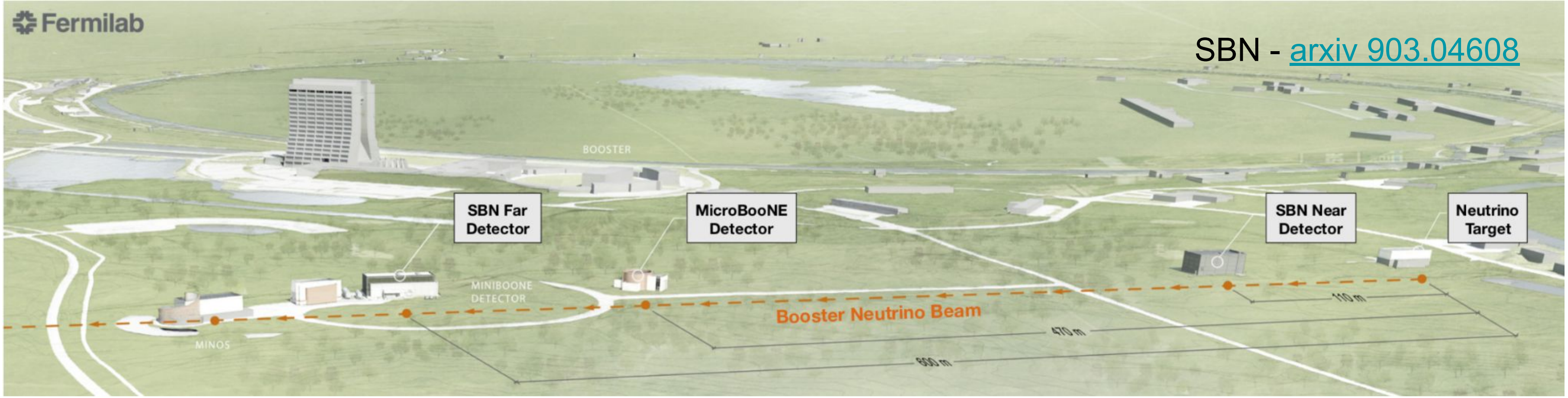
ANNIE

annie.fnal.gov/

NINJA

Recent: Phys. Rev. D 102, 072006

External experiments: Short Baseline Neutrino Program

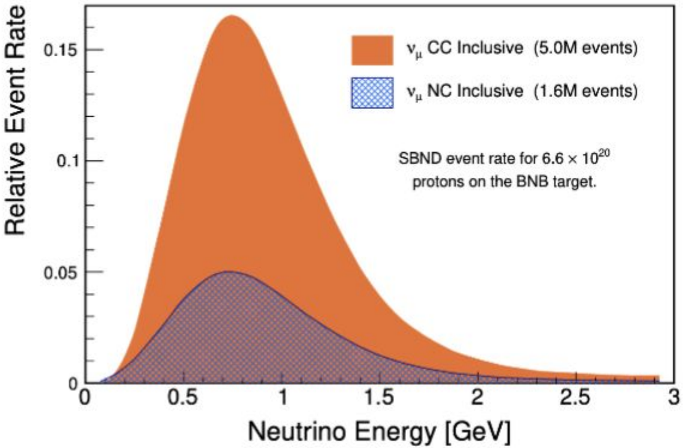


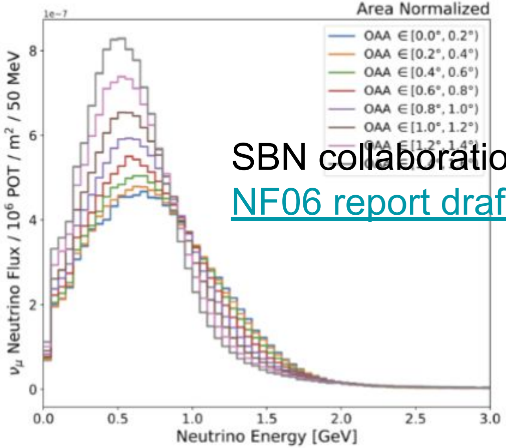
SBN - [arxiv 903.04608]

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

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

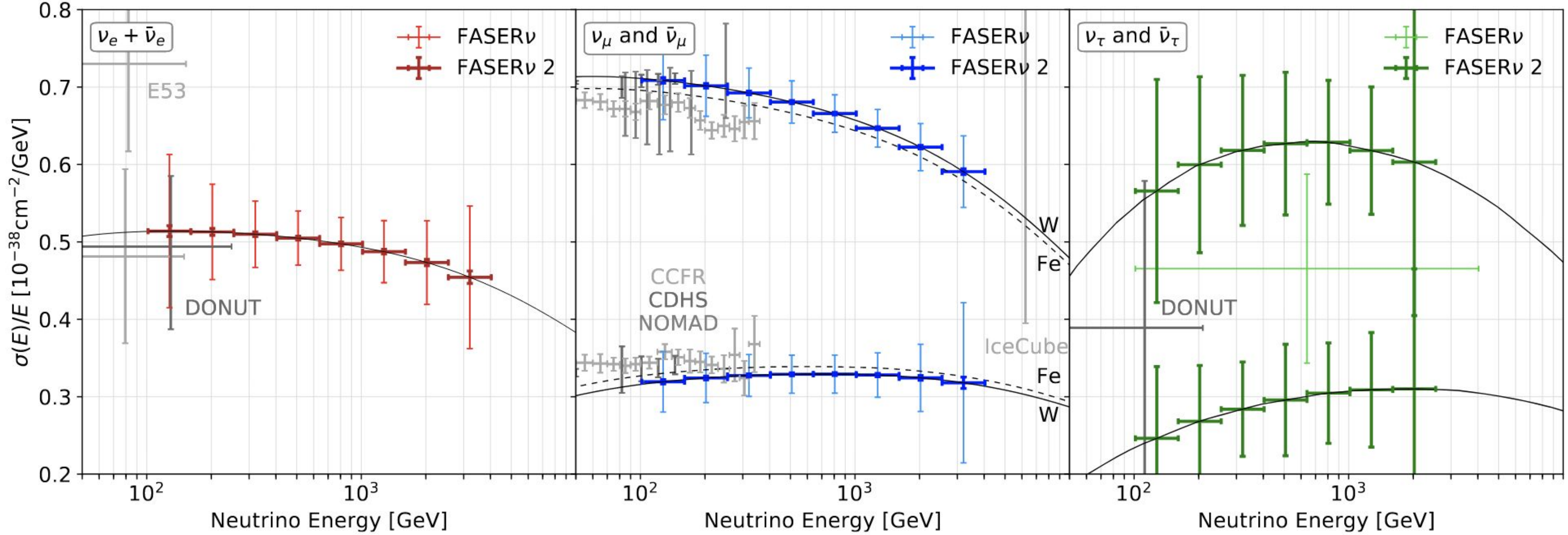
ICARUS: Extra feature: enhanced ν_e cross section capability from NuMI beam

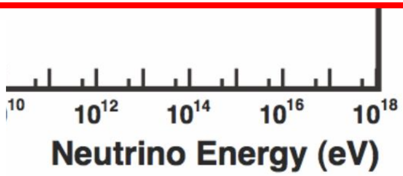




SBN collaboration, [NF06 report draft]

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



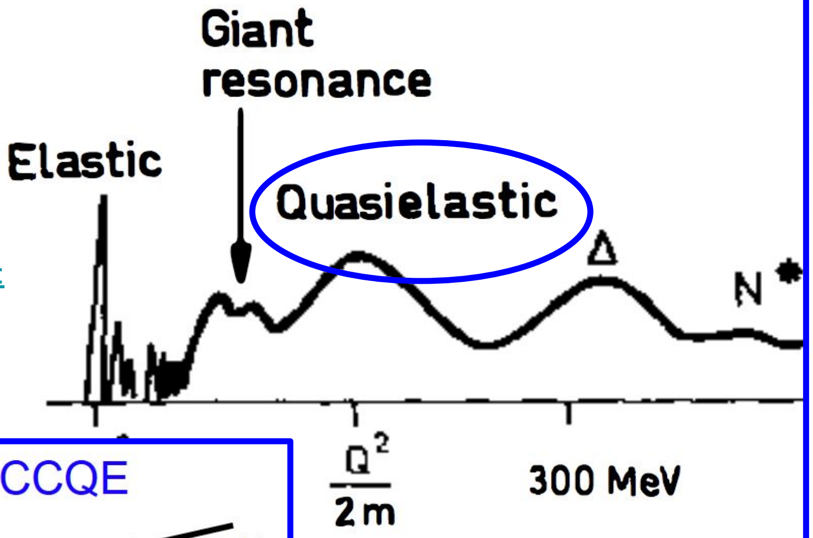


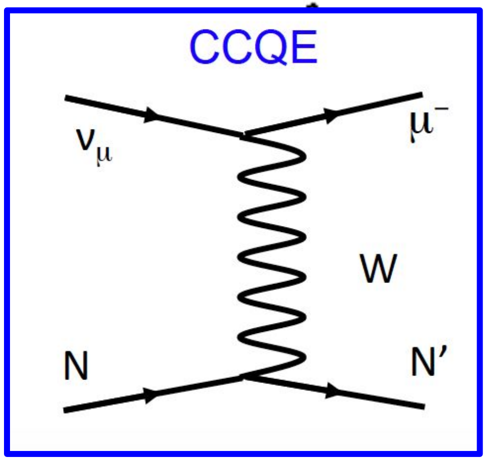
Example: Forward Physics Facility cross section measurements at LHC measurements of deep inelastic scattering (DIS)

- White Paper (WP): arxiv 2109.10905.pdf

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

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

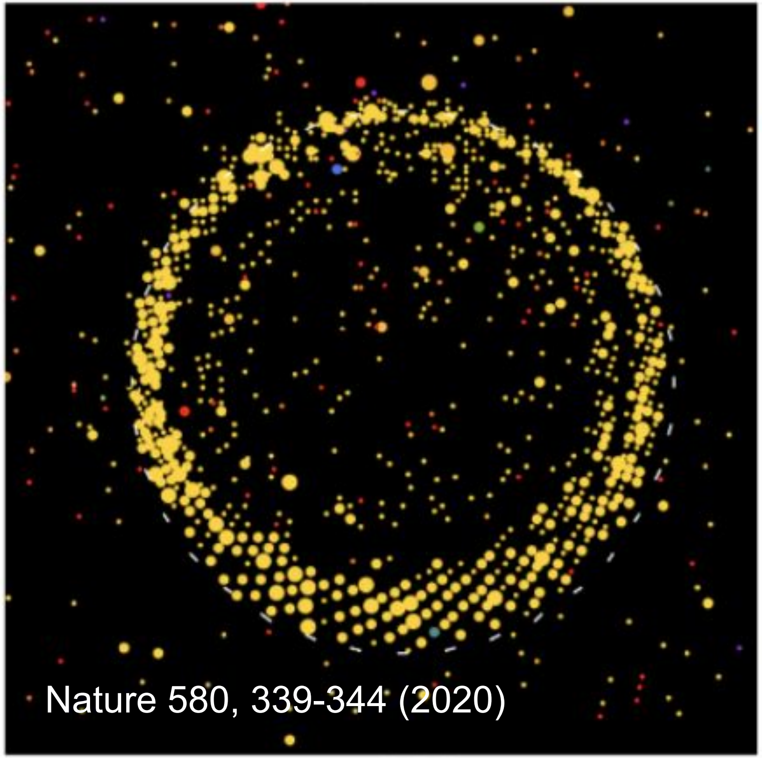




Charged current quasielas

Observables:

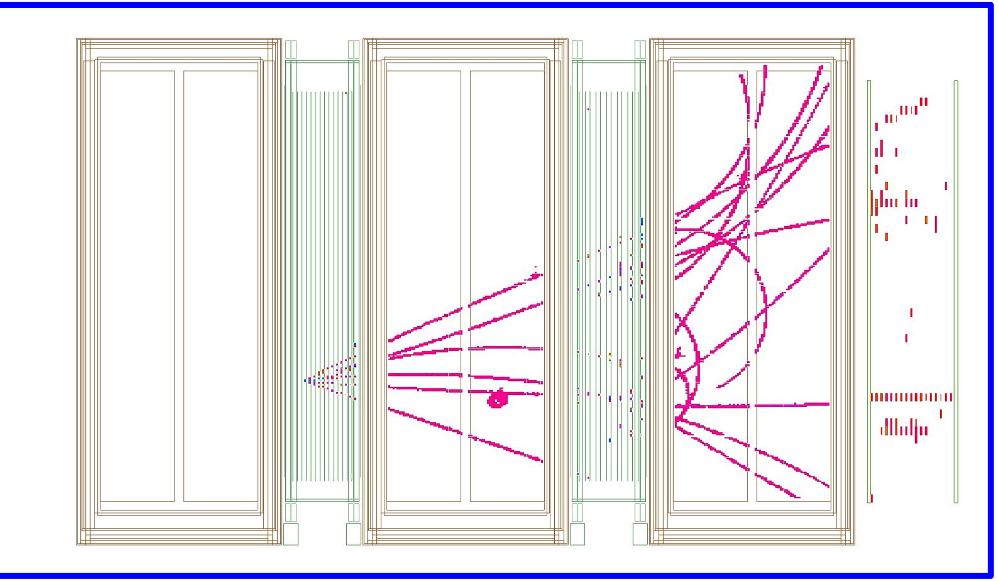
- lepton in final state, antineutrino (+)
- Outgoing proton (ne



Nature 580, 339-344 (2020)

ν_μ-like

Why exclusive?



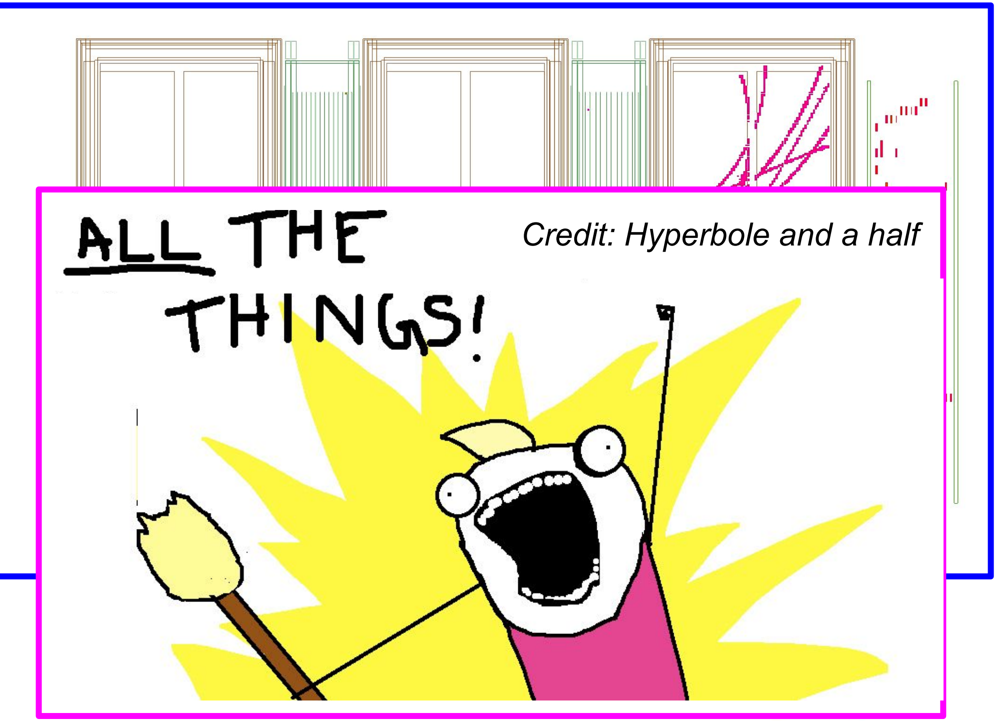
Example of a multiparticle shower,
T2K ND280 detector

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

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

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…)

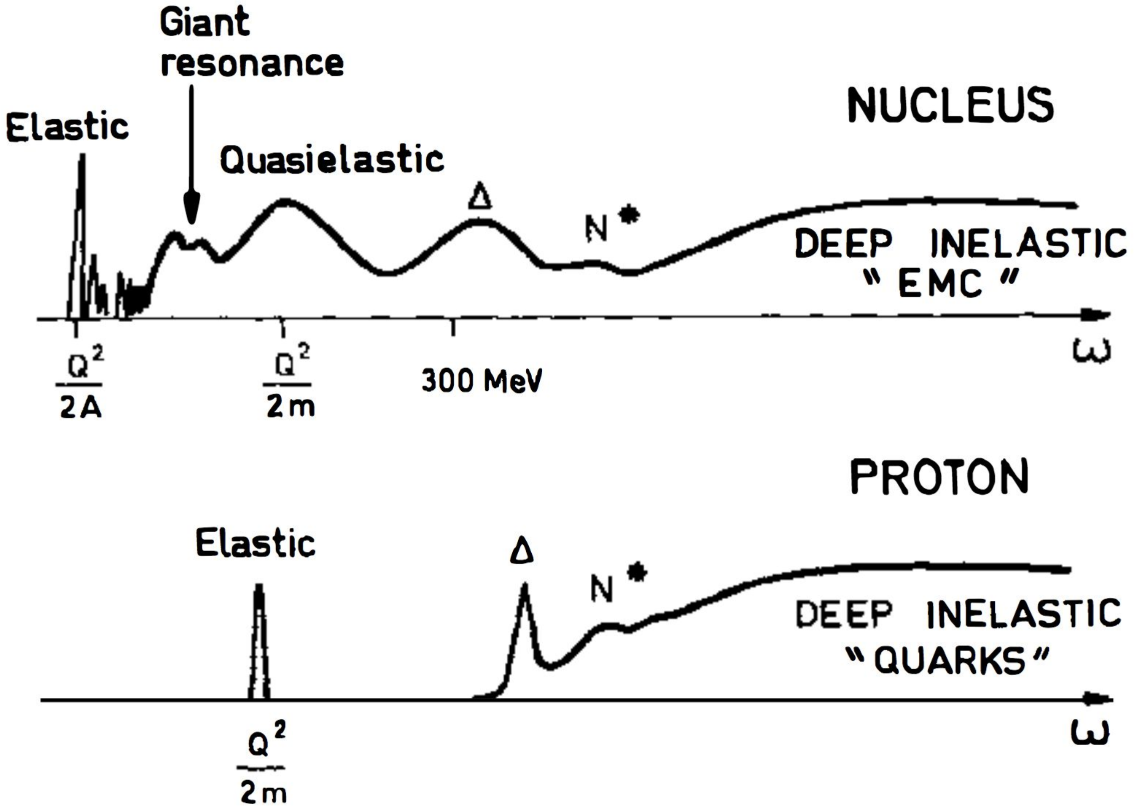
$$N_{FD}^{\alpha\rightarrow\beta}(E_{reco}) = \sum_i \phi_\alpha(E_{true}) \times \sigma_\beta^i(E_{true}) \times P_{\alpha\beta}(E_{true}) \times \epsilon_\beta(E_{true}) \times R_i(E_{true}; E_{reco})$$

External experiments: neutrino scattering on H/D

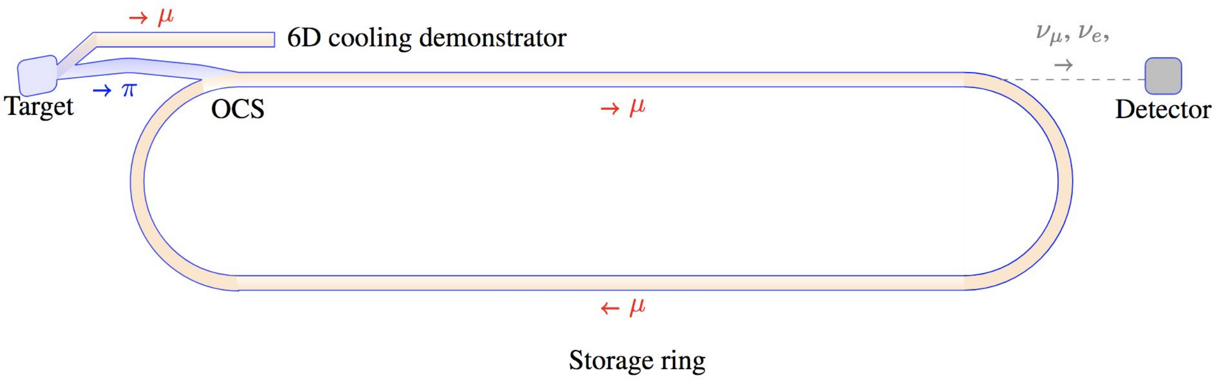
Resolve current discrepancies in nuclear data with improved, complementary H, D measurements

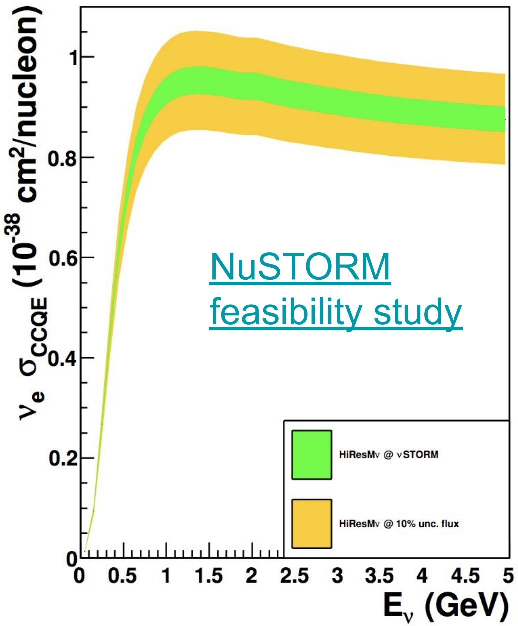
WP on opportunities for new measurements - arxiv 2203.11298

- 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

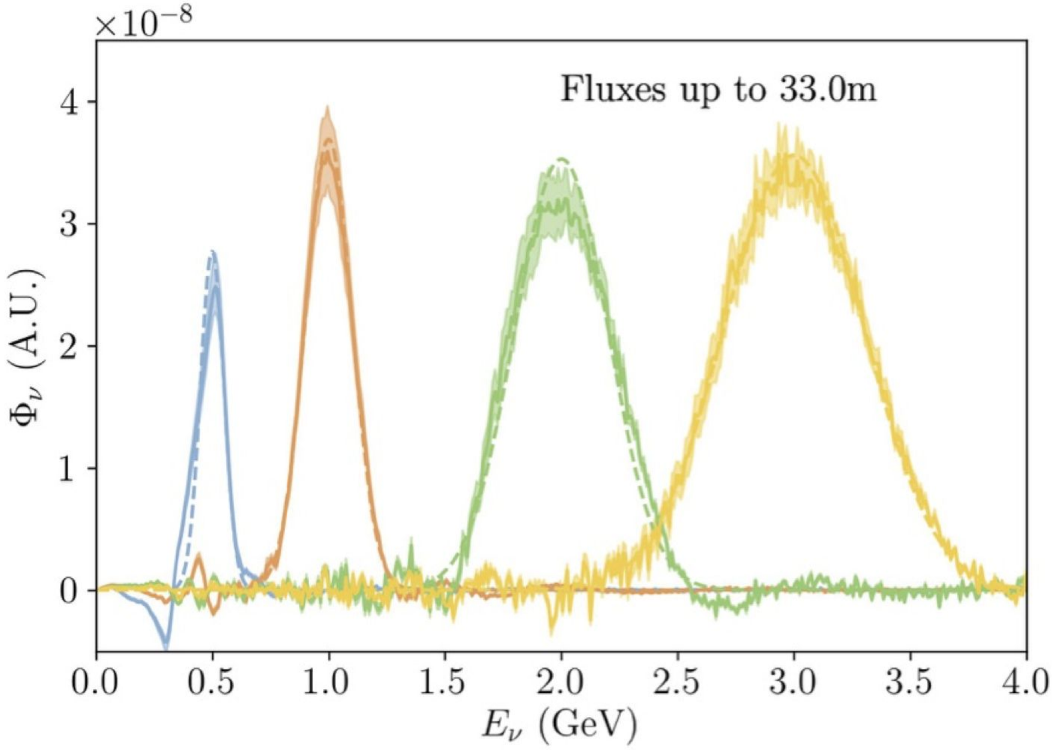
CPV measurements depend on electron neutrino-antineutrino asymmetry

WP: arxiv 2203.07545

Another view of the necessity of precision modelling

From: DUNE ND CDR:

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



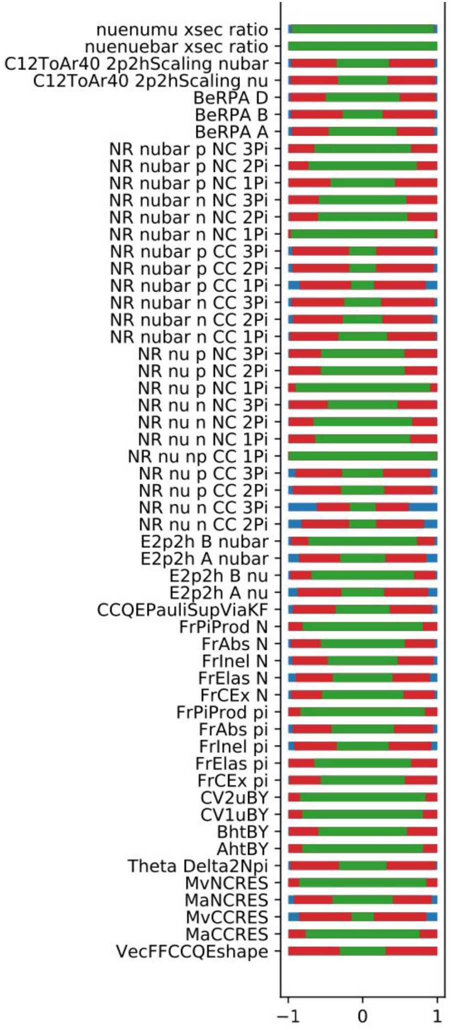
What we learn at the ND: parameter constraints

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)



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*

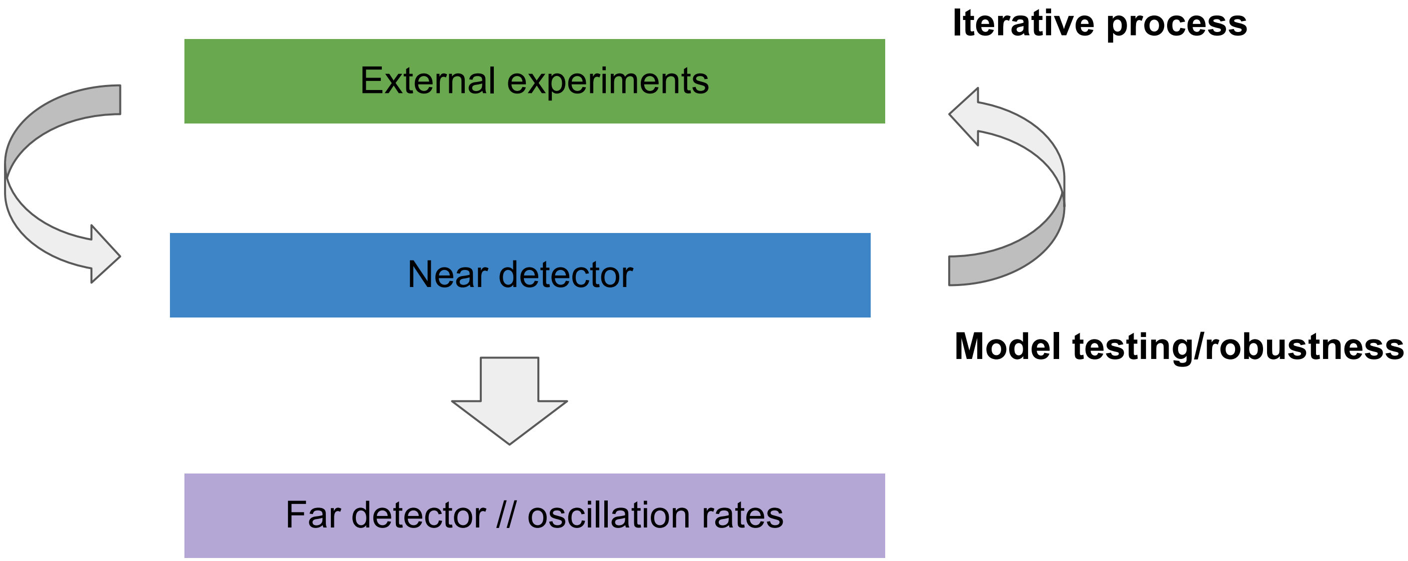
We know next to nothing in transition region, which is also where the power of PRISM decreases

- *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

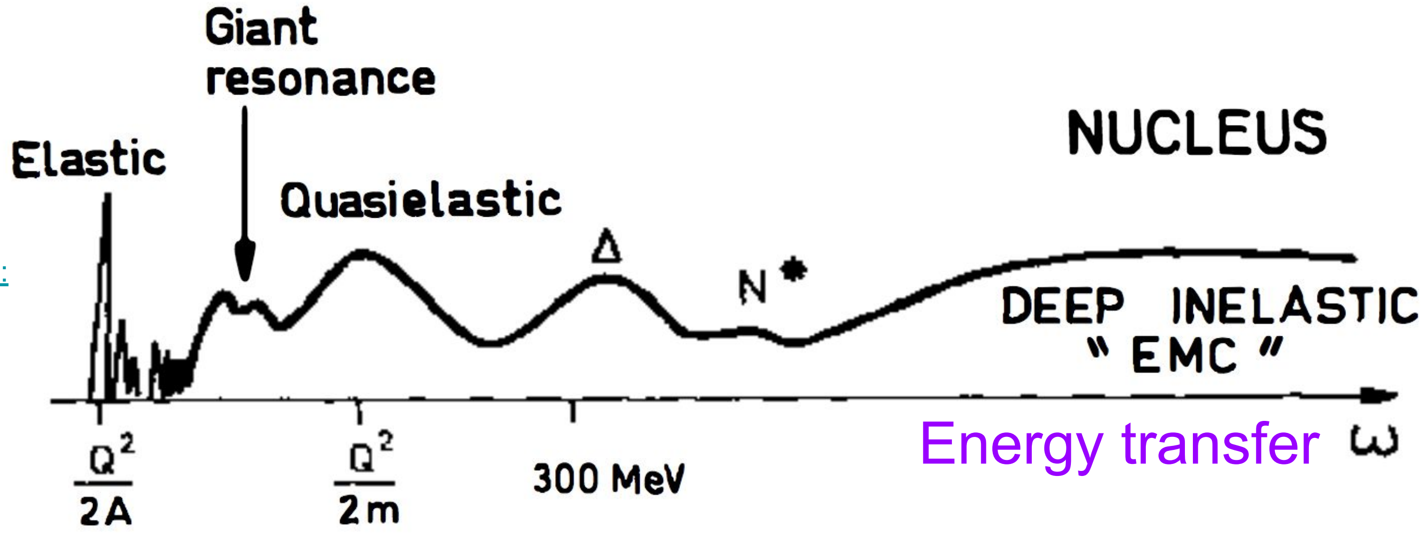


External experiments are important; determine parameterization, uncertainties.

- 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



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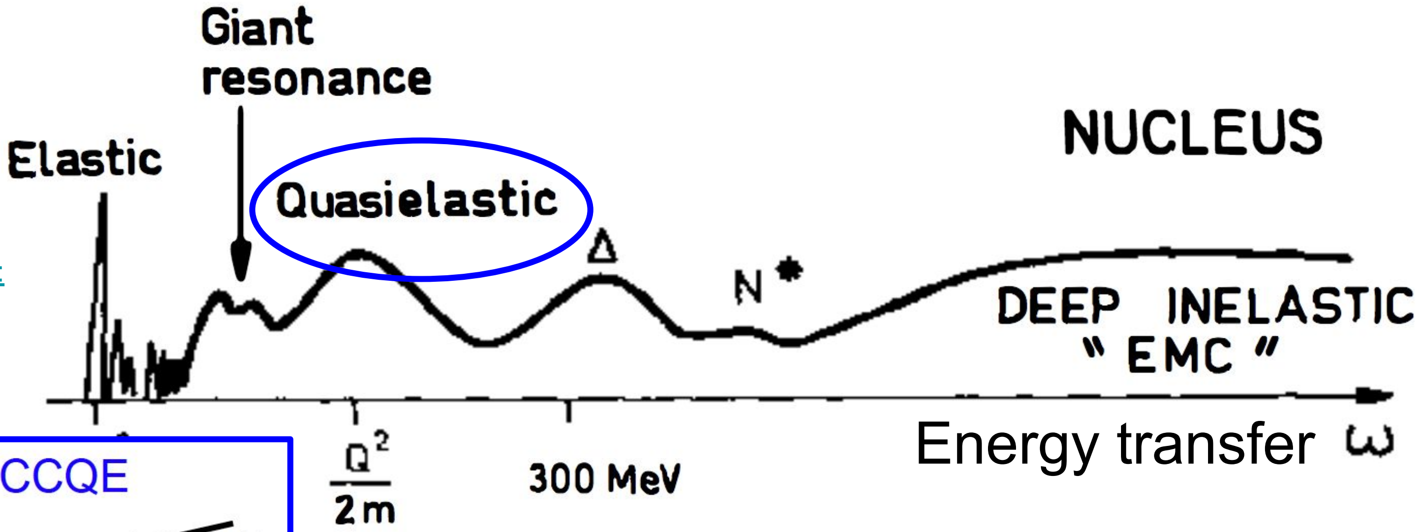
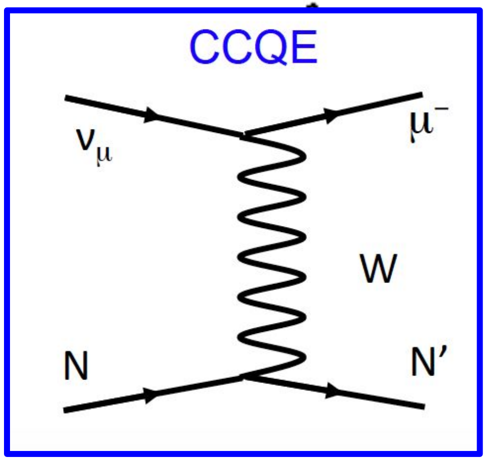




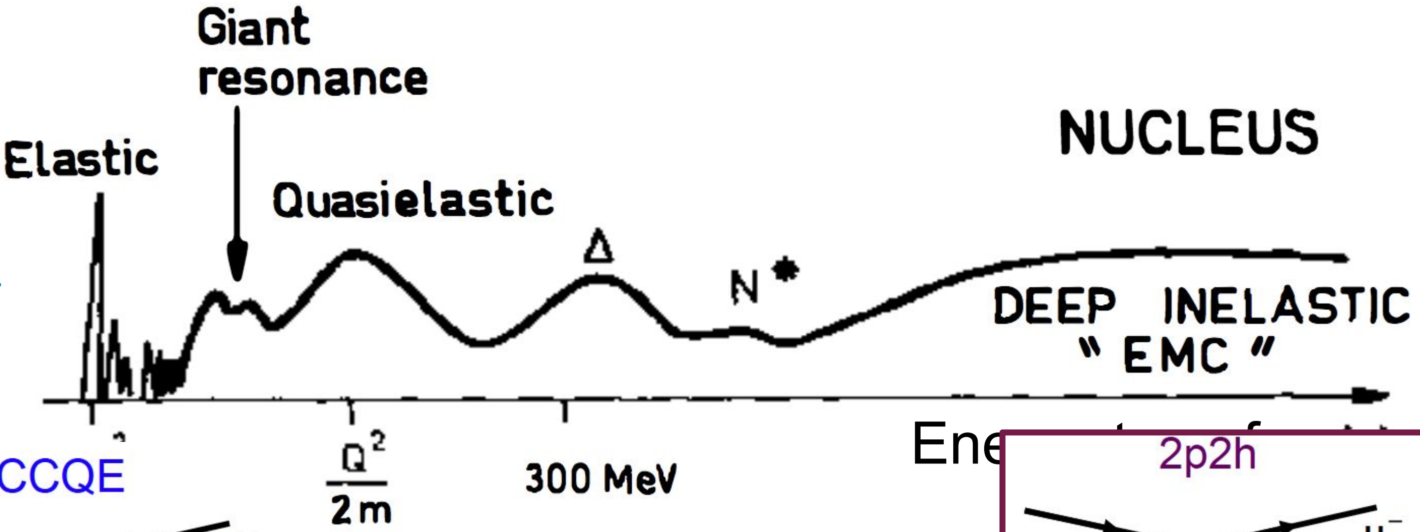
Charged current quasielastic scattering

Observables:

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

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

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



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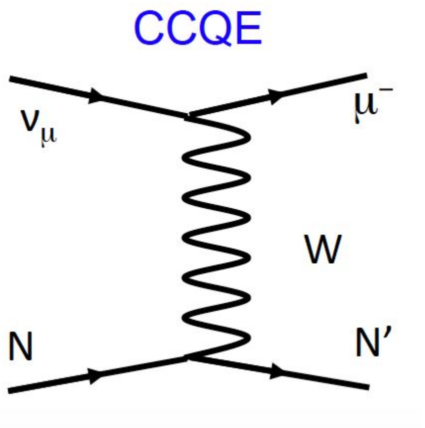
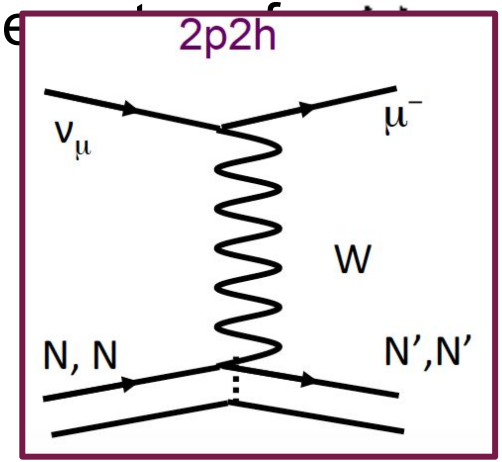


Multinucleon scattering

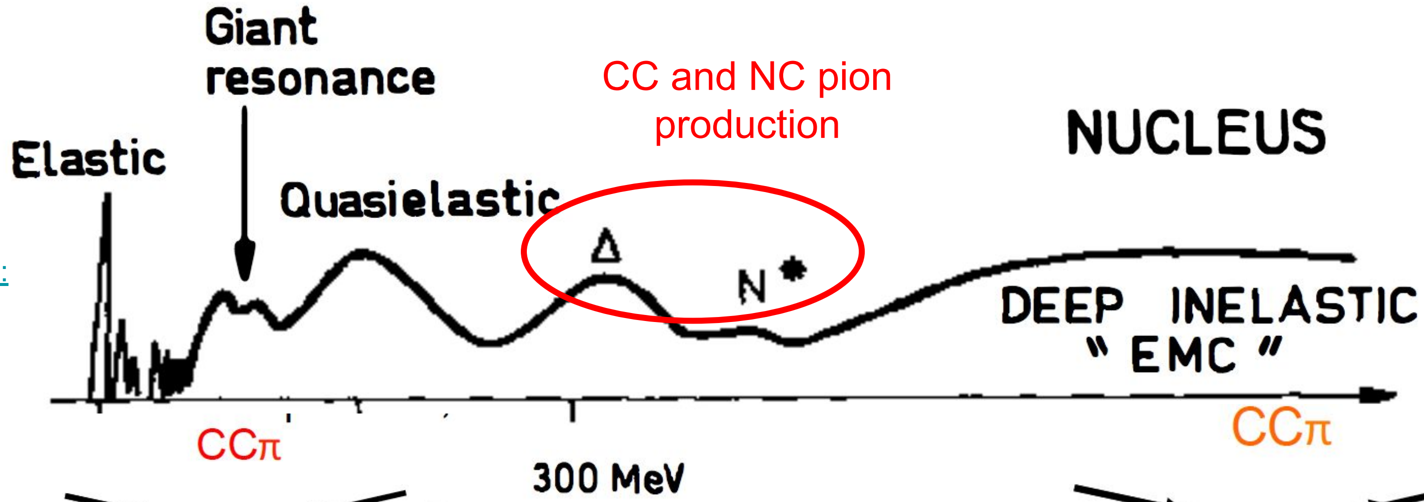
Similar observables:

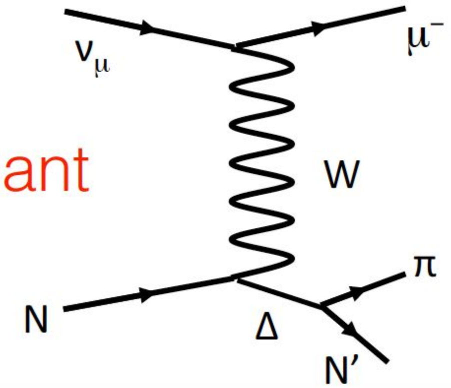
- lepton in final state
- Outgoing protons (neutrons)

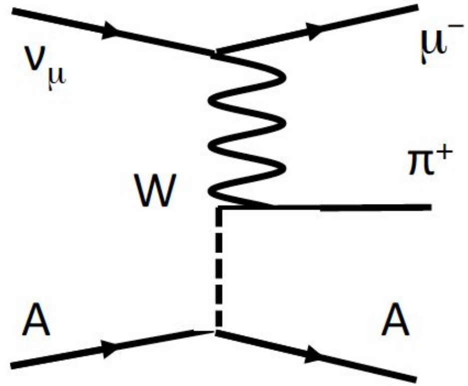


The scale of neutrino interactions: intermediate, ~0.1-20 GeV

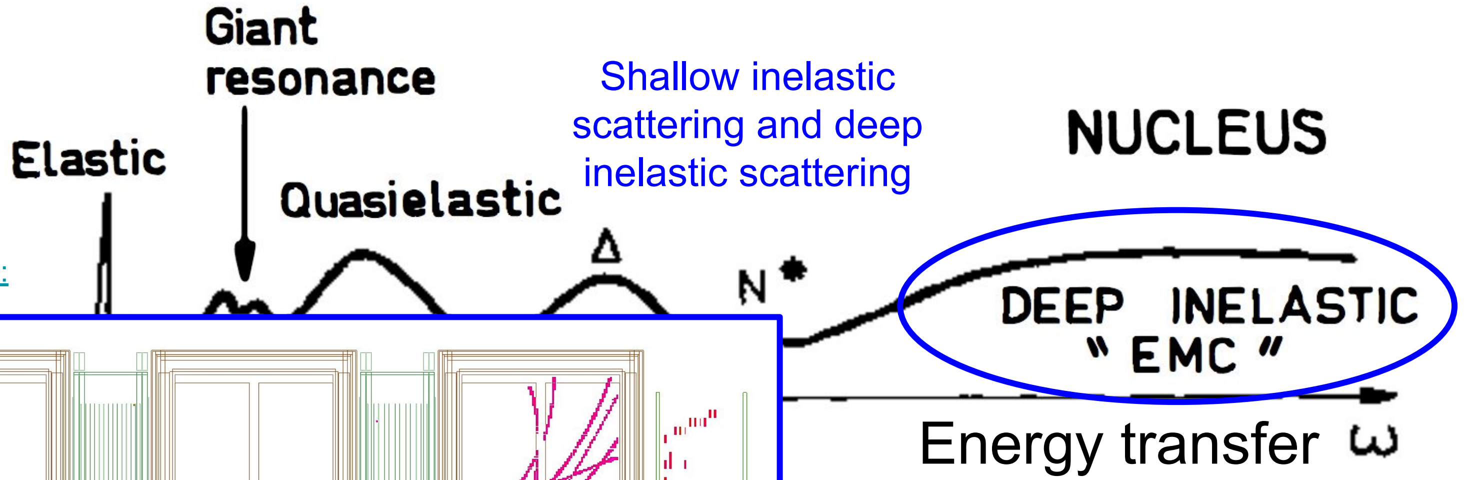
Ann. Rev. Nucl. Part.Sci.1987.37: 133-76





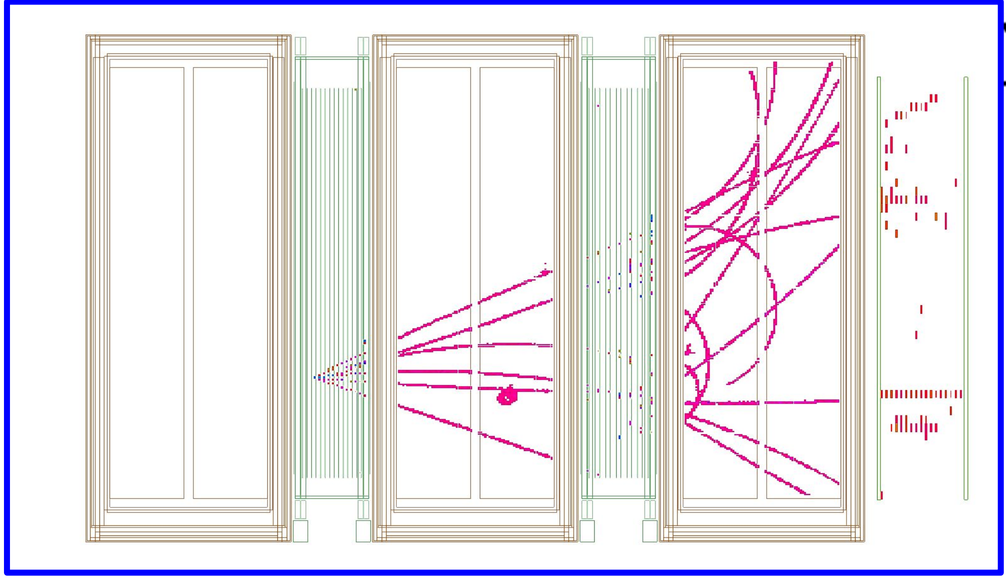


The scale of neutrino interactions: intermediate, ~0.1-20 GeV



Shallow inelastic scattering and deep inelastic scattering

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



Example of a multiparticle shower, T2K ND280 detector

External experiments: neutrinos on nuclei

Short baseline Neutrino Program:
MicroBooNE, SBND, ICARUS

sbn.fnal.gov/

NuSTORM

MINERvA
minerva.fnal.gov/

ANNIE

annie.fnal.gov/

NINJA

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