# Advancing Physics with Neutrino Cross Sections and a Diverse Workforce

Mateus F. Carneiro

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Outline

Why are Neutrino Cross Sections important?

What’s so hard about it?

Where are we now?

Where are we going?

Who gets to do it?

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## Why are Neutrino Cross Sections important?

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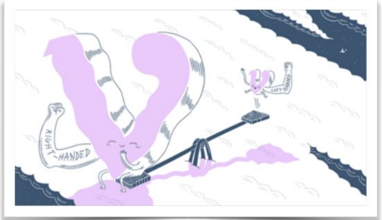
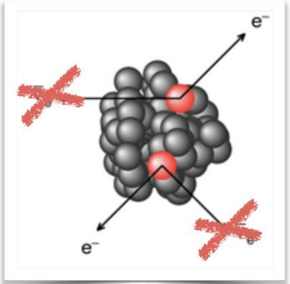
# Neutrino Physics outstanding questions (guided by neutrino experiments)

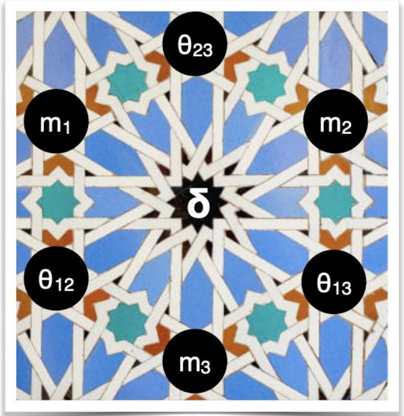


The mechanism of neutrino masses
The nature of neutrinos
The unification of all forces
The matter-antimatter asymmetry
Neutrinos as a portal to new physics
CP violation in the leptonic sector
The absolute masses of neutrinos
Neutrino mixings: patterns and symmetries
Existence of extra neutrino species
The nature of dark matter
CP violation in strong interactions
The existence of dark sectors

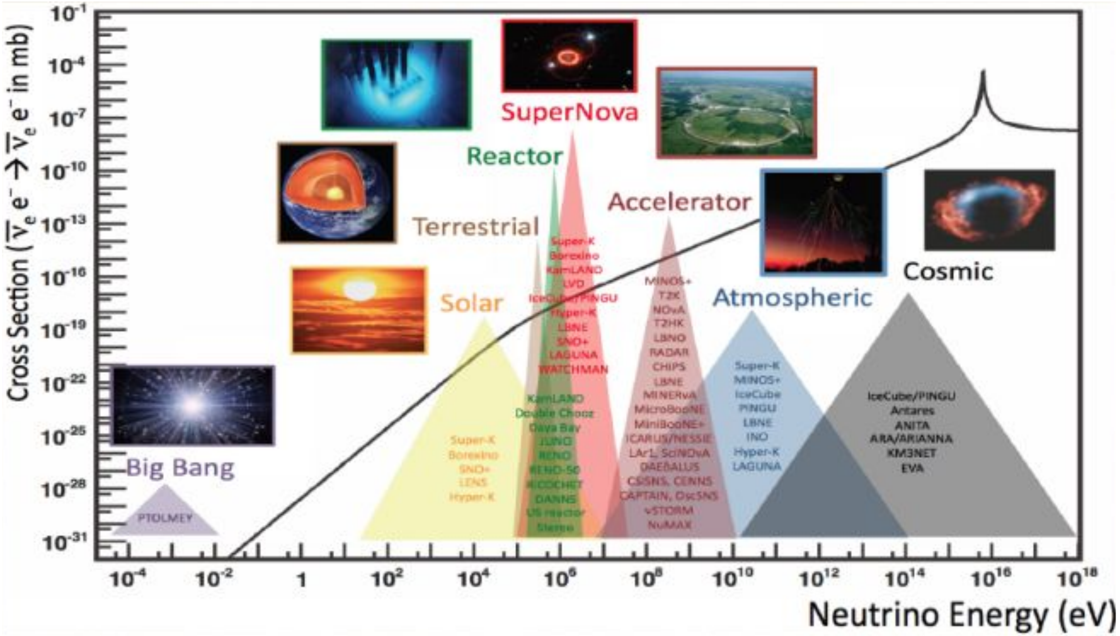
...

**Where does the standard model break?**



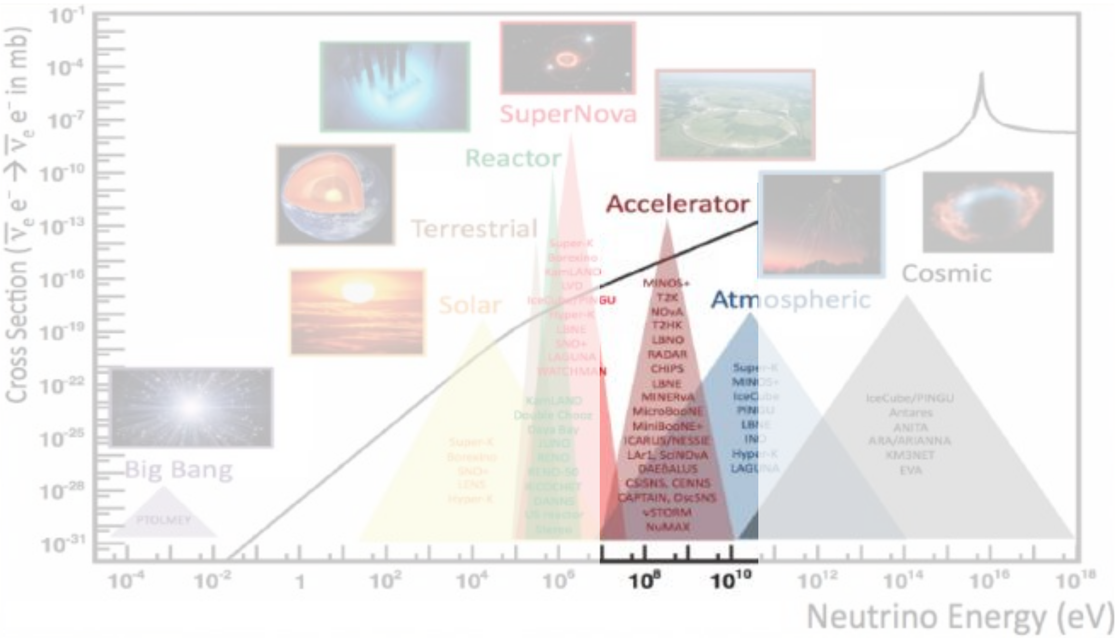



# Neutrinos have numerous sources covering a great range of energies. Knowledge of neutrino-nucleus scattering cross sections is crucial to the global neutrino physics program




J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012), via Snowmass Neutrino WG Summary

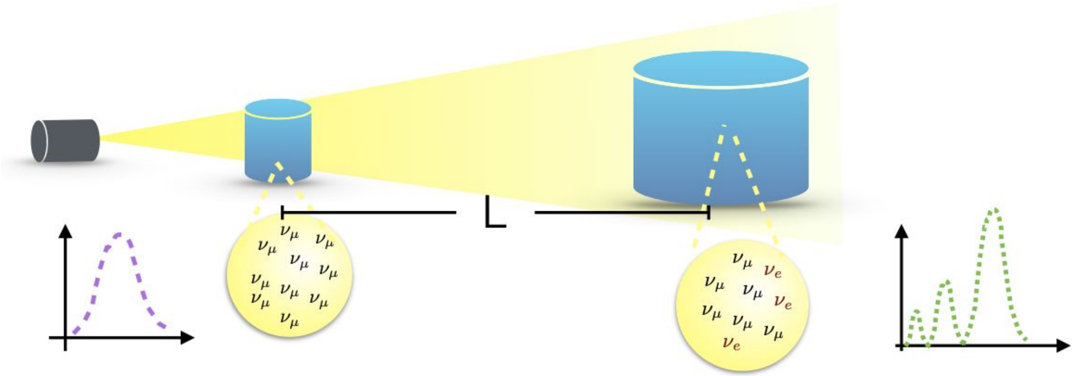
# I will focus **accelerator based experiments** which are the main focus of the US Particle Physics program




J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012), via Snowmass Neutrino WG Summary

# How do we find osc parameters?

1. Measure the rate of neutrino events in the Near Detector by reconstructing topology and energy
2. use a **nuclear model** to infer the neutrino interaction energy
3. use geometry differences (and oscillation hypothesis) to predict the Far Detector flux
4. Measure the rate of neutrino events in the Far Detector using the **nuclear model** and the estimated flux to reconstruct topology and energy
5. compare mc and data and test your hypothesis




$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$
$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

$$P(\nu_\mu \to \nu_x) \sim \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$

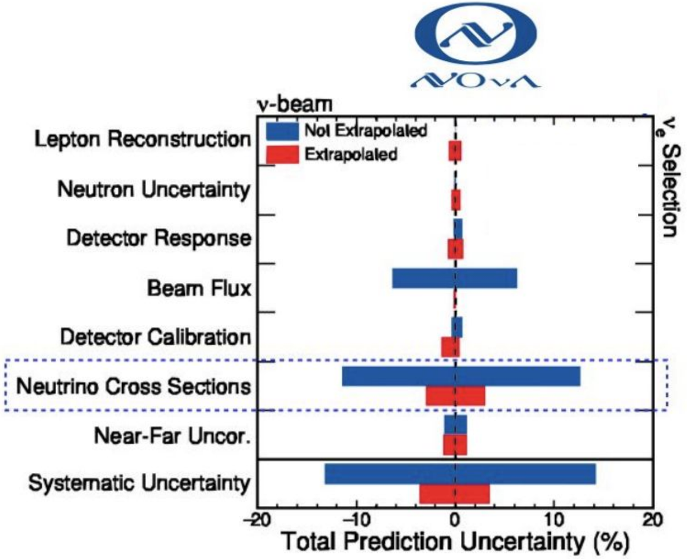
# How do we find osc parameters?

Current oscillation experiments report **large systematics uncertainties** associated with neutrino-nucleus interaction models

Beyond that, nuclear models uncertainties **hinder CP violation search**

T2K

| Error source | $\nu_e$ FHC | $\bar{\nu}_e$ RHC | $\nu_e / \bar{\nu}_e$ FHC/RHC |
|---|---|---|---|
| Flux and (ND unconstrained) | 15.1 | 12.2 | 1.2 |
| cross section (ND constrained) | 3.2 | 3.1 | 2.7 |
| SK detector | 2.8 | 3.8 | 1.5 |
| SK FSI + SI + PN | 3.0 | 2.3 | 1.6 |
| Nucleon removal energy | 7.1 | 3.7 | 3.6 |
| $\sigma(\nu_e)/\sigma(\bar{\nu}_e)$ | 2.6 | 1.5 | 3.0 |
| NC1$\gamma$ | 1.1 | 2.6 | 1.5 |
| NC other | 0.2 | 0.3 | 0.2 |
| $\sin^2\theta_{23}$ and $\Delta m^2_{21}$ | 0.5 | 0.3 | 2.0 |
| $\sin^2\theta_{13}$ PDG2018 | 2.6 | 2.4 | 1.1 |
| All systematics | 8.8 | 7.1 | 6.0 |




T2K, Phys. Rev. D 103, 112008 (2021)

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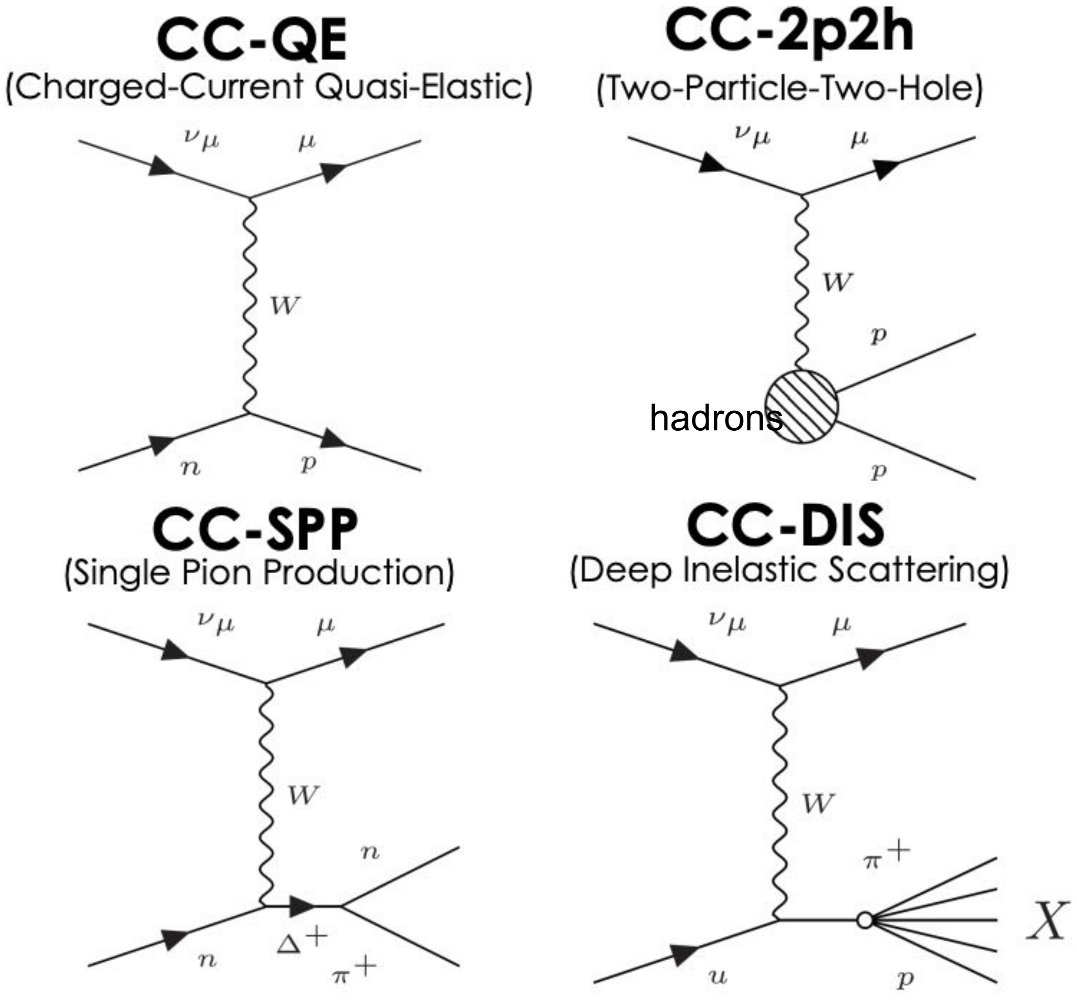
Who gets to do it?

# Neutrino Nucleon Interactions

**Initial State Interactions**

Neutrinos can interact in a variety of channels:

- **Quasi-Elastic**
- **Resonance**
- **Single Pion Production**
- **Deep Inelastic Scattering**



# Neutrino Nucleon Interactions

**Initial State Interactions**

Neutrinos can interact in a variety of channels:

- **Quasi-Elastic**
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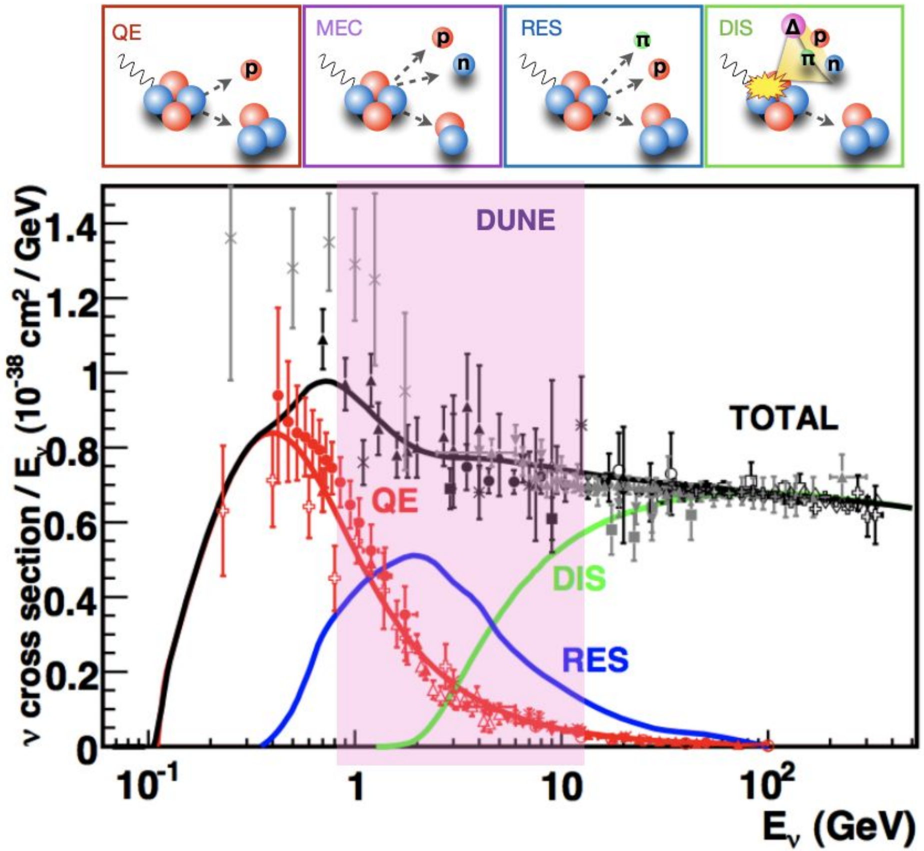
- **Deep Inelastic Scattering**

and the interaction channel cross section depends on the neutrino energy

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



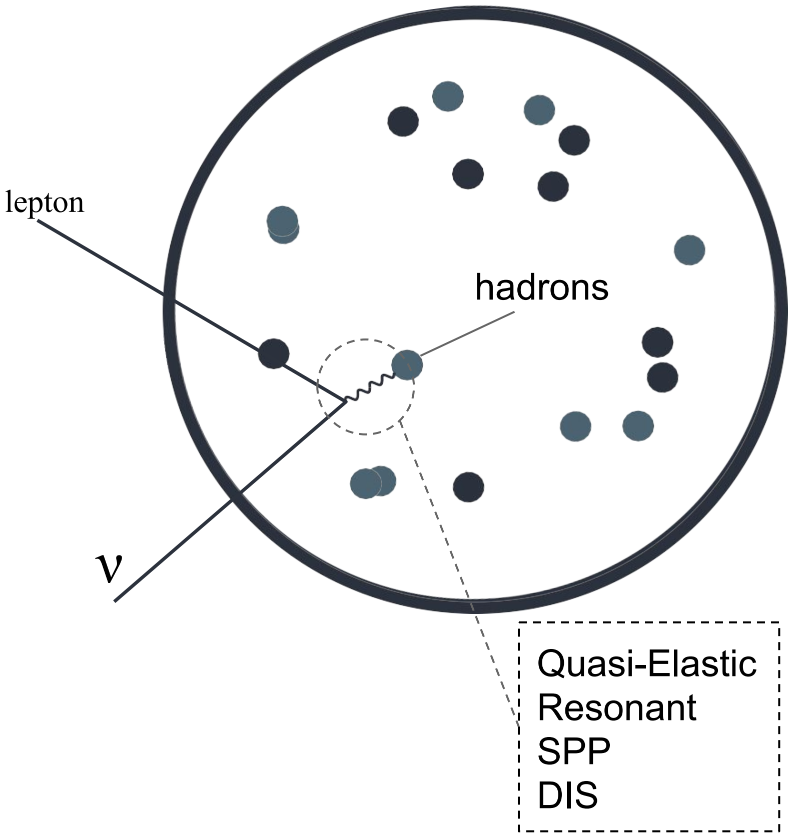
# Neutrino Nucleus Interactions

**Initial State Interactions**

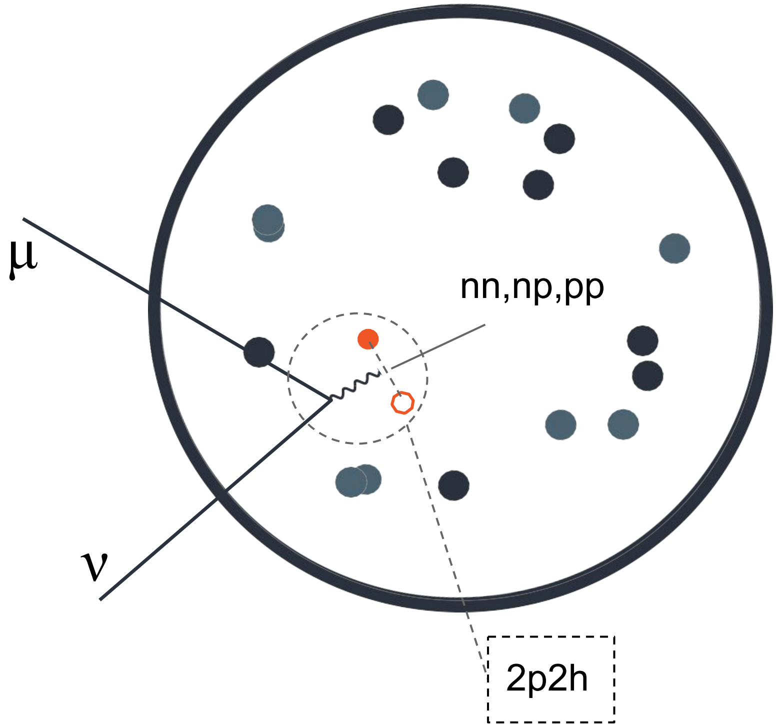
Neutrinos can interact in a variety of channels:

- **Quasi-Elastic**
- **Resonance**
- **Single Pion Production**
- **Deep Inelastic Scattering**

Once we consider the interaction inside the nucleus we became dependent from **nuclear models**



# The Nucleus!




**Initial State Interactions**

Neutrinos can interact in a variety of channels:

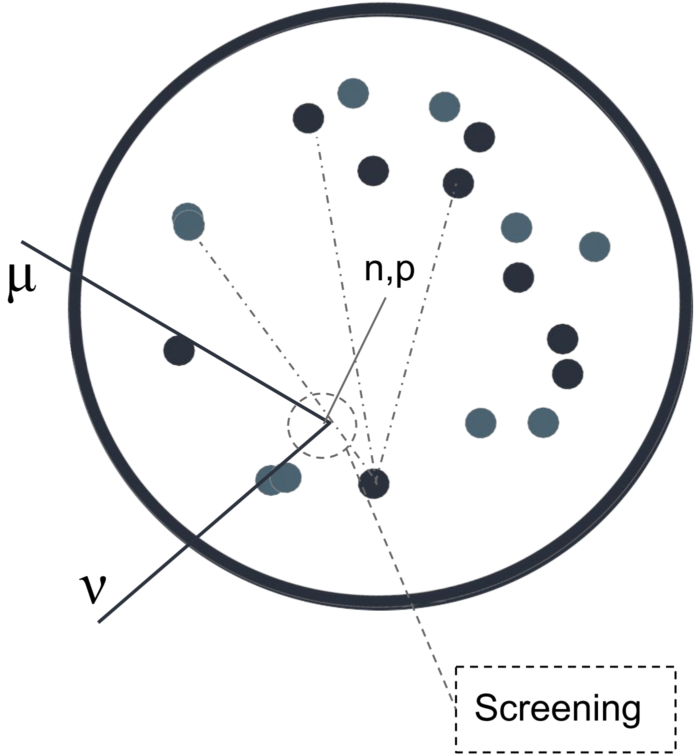
- Quasi-Elastic
- Resonance
- Single Pion Production
- Deep Inelastic Scattering
- **Multi-nucleon interactions (2p2h, RPA, …)**

# The Nucleus!

**Initial State Interactions**

Neutrinos can interact in a variety of channels:

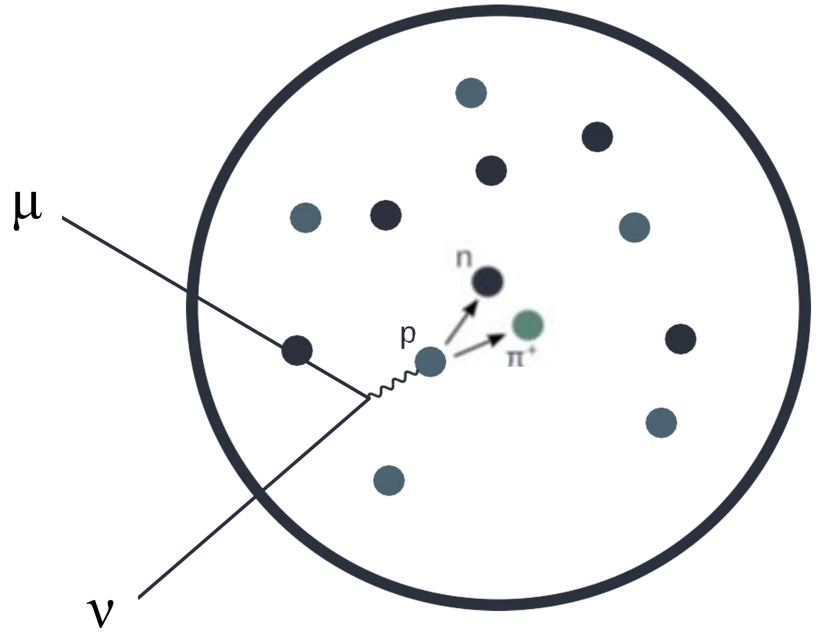
- Quasi-Elastic
- Resonance
- Single Pion Production
- Deep Inelastic Scattering
- Multi-nucleon interactions (2p2h, RPA, ...)
- **Screening**



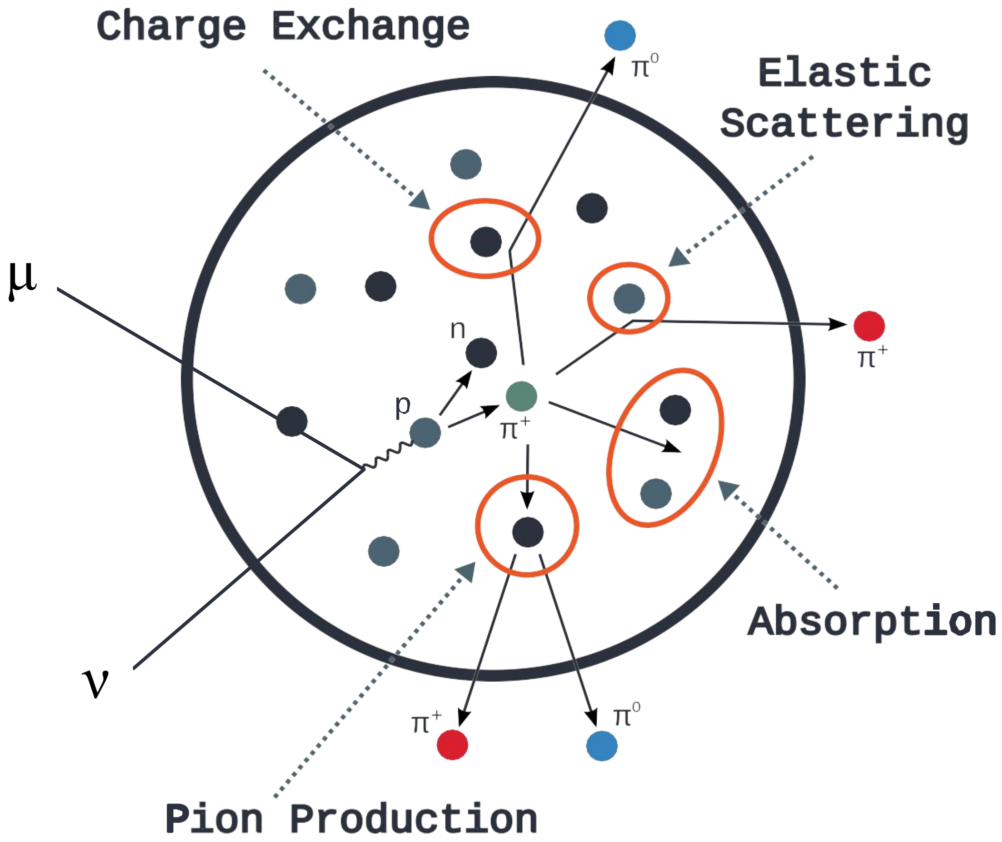
# The Nucleus!

**Final State Interactions (FSI)**

The products of the Initial interaction undergo different process before leaving the nucleus



# The Nucleus!



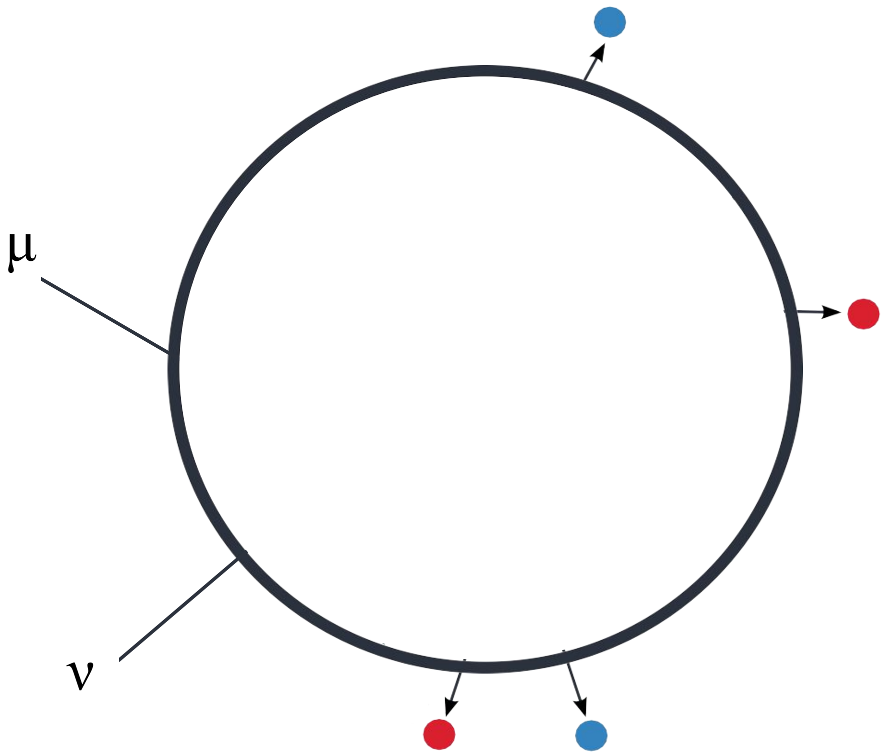

**Final State Interactions (FSI)**

the strong-interaction physics in play alters:
**- final state particle compositions and kinematics**
**- determination of the incident neutrino energy, and**
**- neutrino versus antineutrino scattering**

# The Nucleus!

### The Final State

What is actually seen in the detector **cannot be classified in terms of the Initial Interactions**

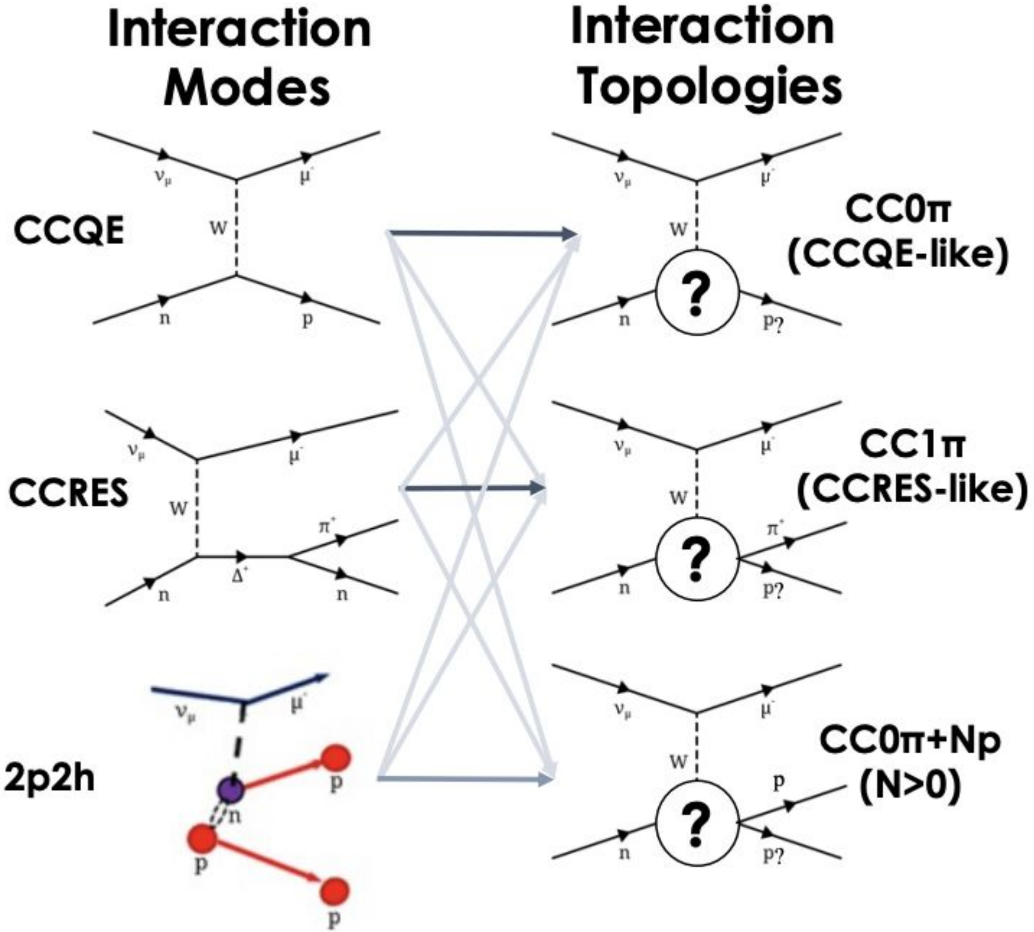


# The Nucleus!

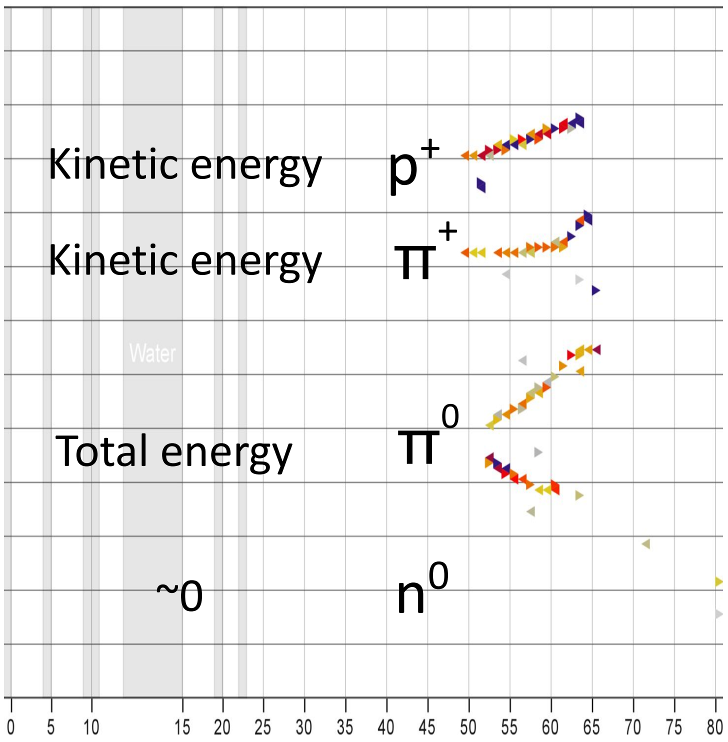
**The Final State**

FSI can make different interaction modes give the same final state topology

What is actually seen in the detector **cannot be classified in terms of the Initial Interactions**



# The Flux and Neutrino Energy




Neutrino experiments must determine the neutrino energy from kinematic information from CC neutrino interactions.

This must account for:
- **unobserved energy deposition**,
- **particles below the threshold**,
- **passive material and escaping neutral particles**

In practice assumptions about these effects are **based on the nuclear model**

With the current limited understanding of neutrino-nucleus interactions, the neutrino energy scale cannot achieve the goal accuracy in experiments like DUNE.

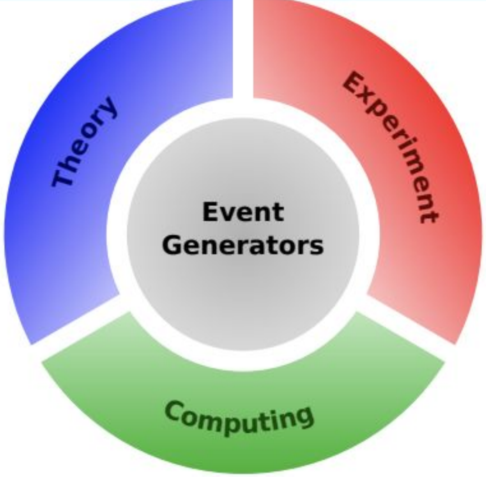
What's so hard about it?

# Neutrino Event Generators

The propagation of hadrons through the nuclear medium is crucial in the neutrino data analysis.

Neutrino interaction generators typically involve a number of unknown model parameters that must be tuned to experimental data while maintaining the integrity of the physics model

Developing and maintaining event generators requires tight collaboration between theory, experiment, and computing science



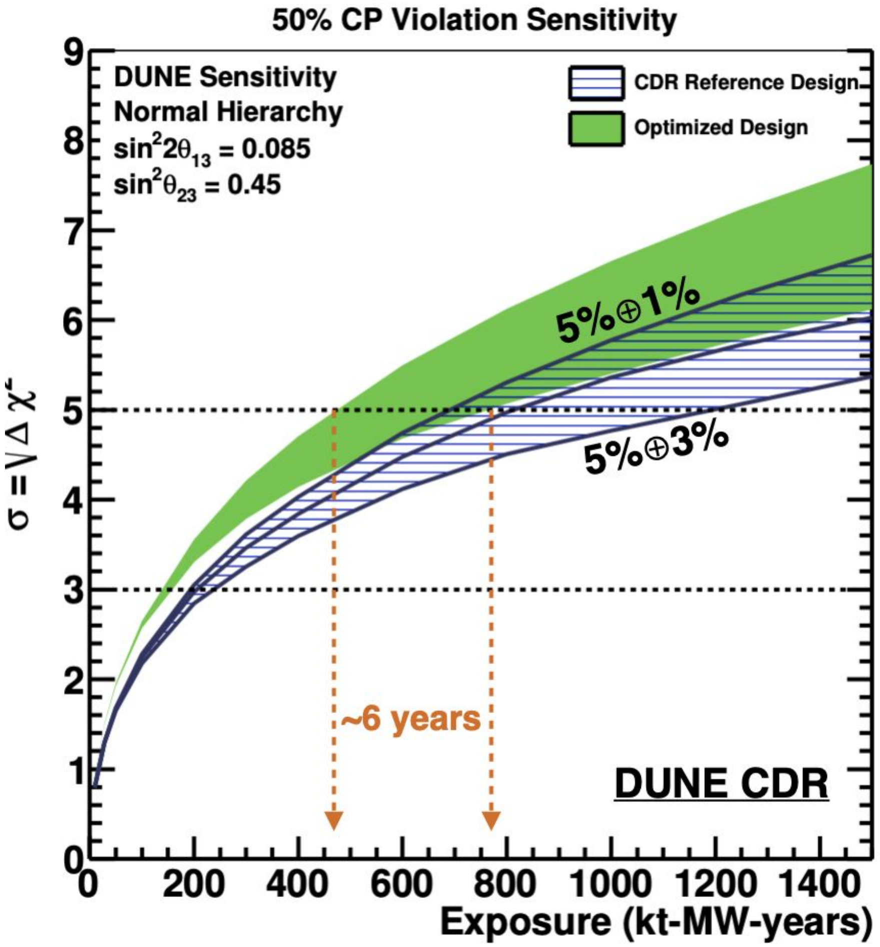
# We need to be ready for DUNE and Hyper-K!

We want precision neutrino oscillation measurements and **reducing systematics uncertainties is critical**

This includes neutrino **interaction cross sections**

Oscillation experiments **rely on neutrino-nucleus interaction models** in neutrino event generators.

Need **better model** and high precision data



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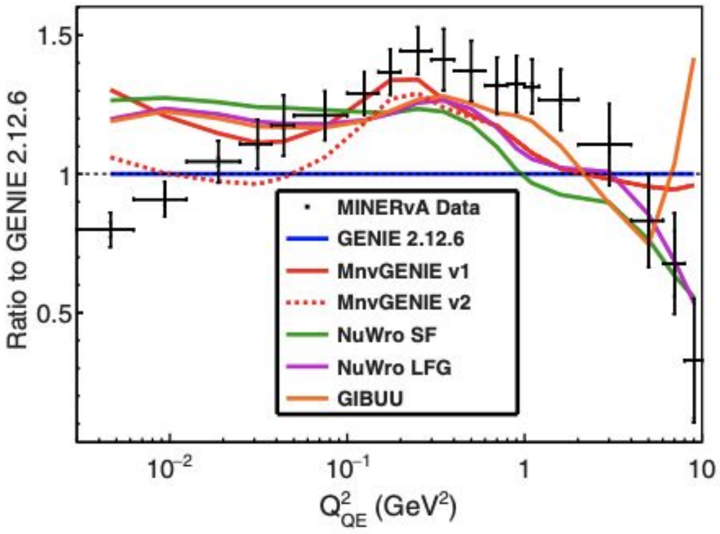
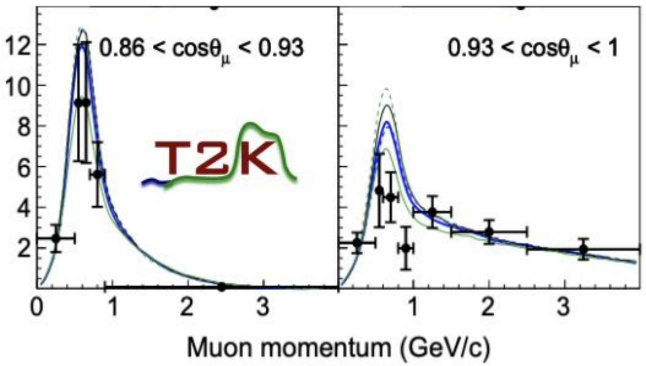
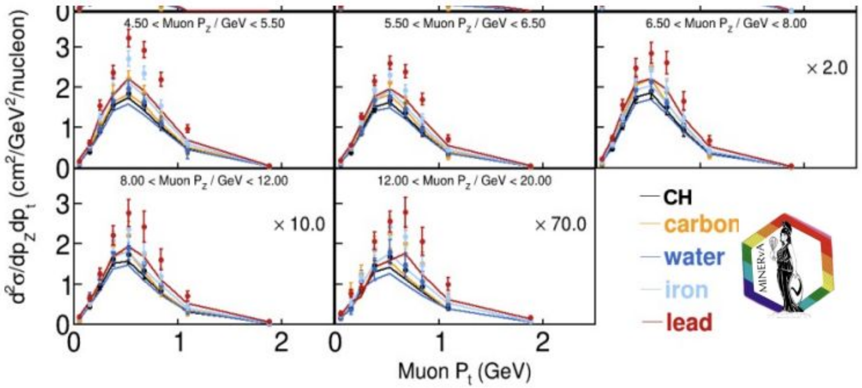
# Current experimental status

Neutrino interaction cross section are hard to model

Our current generator predictions are **all ruled out** by existing measurements

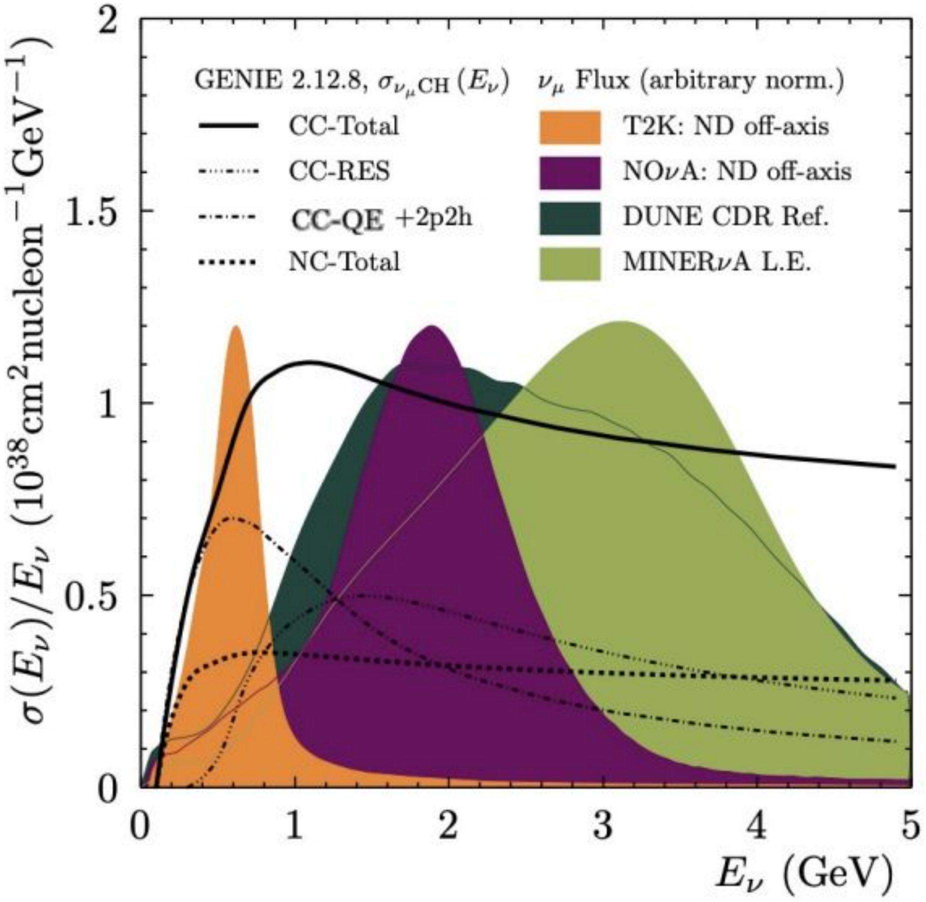


# Current experimental status

Different experiments cover different ranges of energy and different measurements complement each other using different technologies and materials



# Current experimental status

[Snowmass Neutrino Frontier: Neutrino Interaction Cross Sections (NF06) Topical Group Report]

| Experiment | Flavor | $\nu_\mu$ Flux Peak (GeV) | Target | Detection |
|---|---|---|---|---|
| T2K | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$ | 0.6,0.8,1 | CH, $H_2O$, Fe | Tracking |
| NOvA | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\ \bar{\nu}_e$ | 2 | $CH_2$ | Tracking+Calorimetry |
| DUNE | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$ | PRISM: 0.5-3 | H,C,Ar | Tracking+Calorimetry |
| HK IWCD | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$ | PRISM: 0.4-1 | $H_2O$ | Cherenkov |
| MicroBooNE | $\nu_\mu,\nu_e$ | 0.3,0.8 | Ar | Tracking+Calorimetry |
| SBND | $\nu_\mu,\nu_e$ | 0.8 (PRISM: 0.6-0.8) | Ar | Tracking+Calorimetry |
| ICARUS | $\nu_\mu,\nu_e$ | 0.3,0.8 | Ar | Tracking+Calorimetry |
| MINERvA | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$ | 3.5,6 | He, C, CH, $H_2O$, Fe, Pb | Tracking+Calorimetry |
| ANNIE | $\nu_\mu,\bar{\nu}_\mu$ | 0.6 | CH, $H_2O$ | Cherenkov |
| NINJA | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e,$ | 1 | CH, $H_2O$, Fe | Emulsion |
| FPF | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e,$ $\nu_\tau,\ \bar{\nu}_\tau$ | 700 GeV | W, Ar | Emulsion, Tracking+Calorimetry |
| nuSTORM | $\nu_\mu,\bar{\nu}_\mu,\nu_e,\bar{\nu}_e$ | PRISM: 0.8-3 | CH,$H_2O$,Ar,TBD | Tracking+Calorimetry (TBD) |

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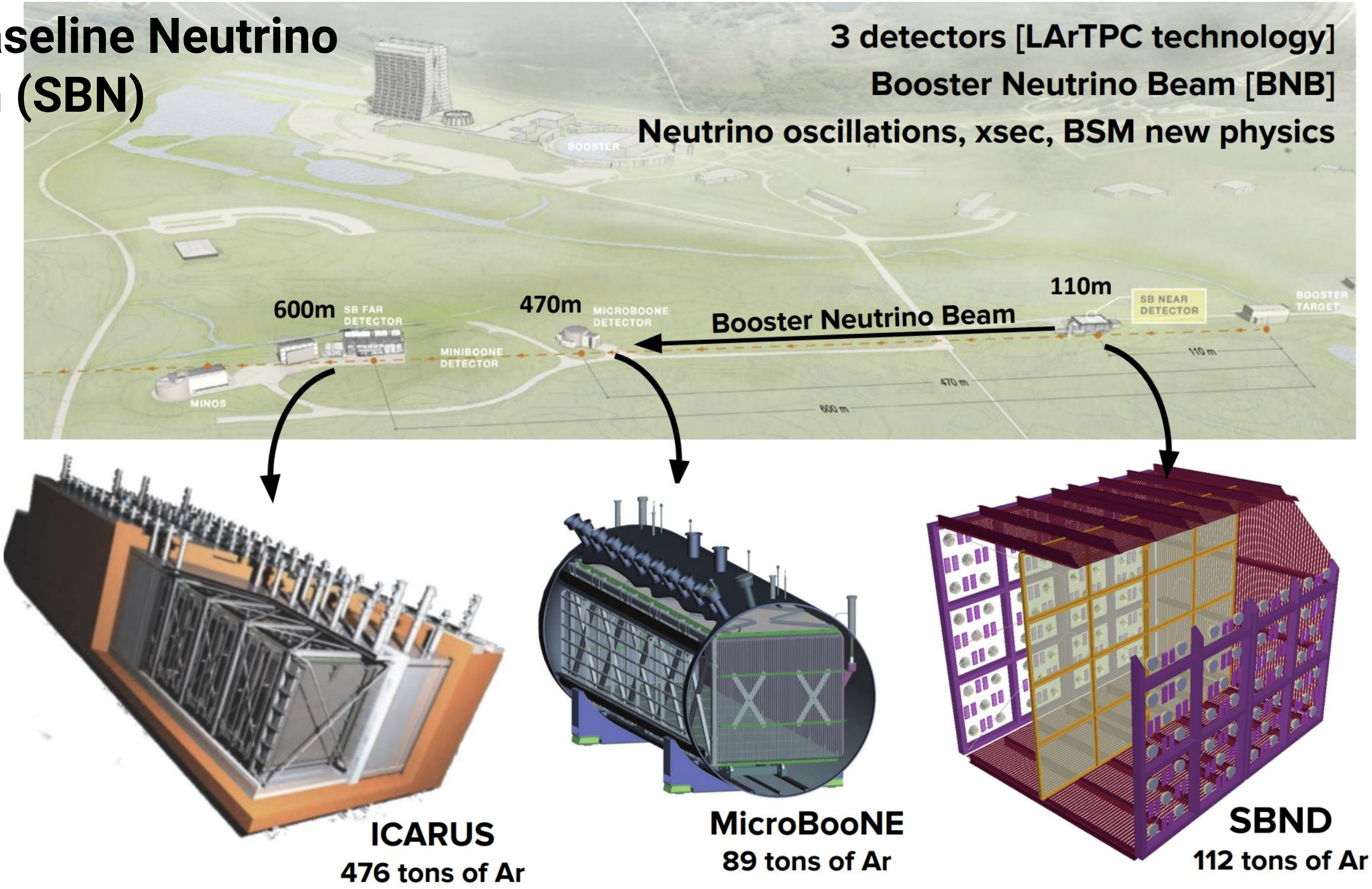
# Short Baseline Neutrino Program (SBN)

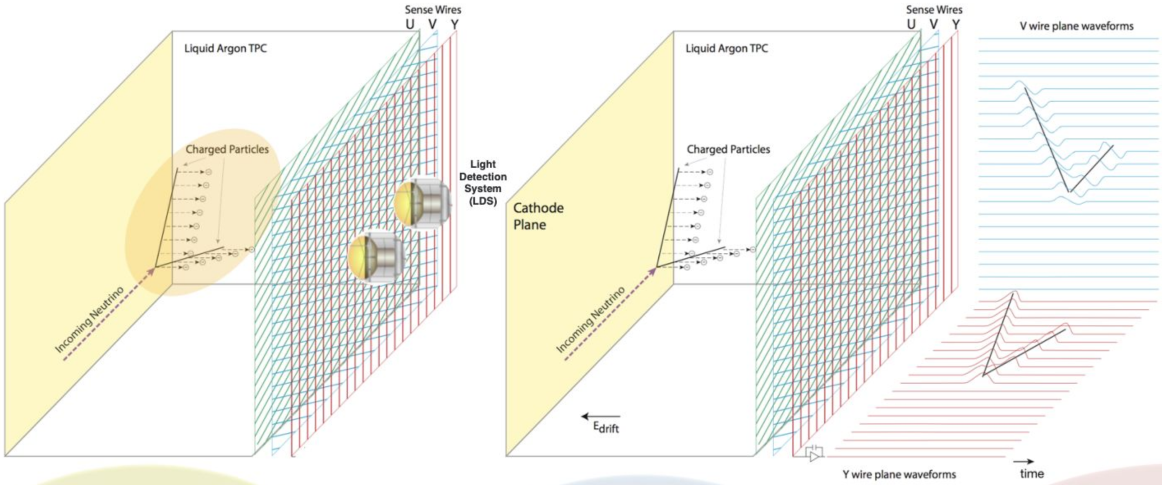


# Liquid Argon Time Projection Chamber (LArTPC)

3D reconstruction with mm resolution

Excellent particle identification with dE/dx information

Low energy thresholds, subMeV to GeV




Charged particles in LAr produce free ionization electrons and scintillation light

*m.i.p. at 500 V/cm: ~ 60,000 e/cm*
*~ 50,000 photons/cm*

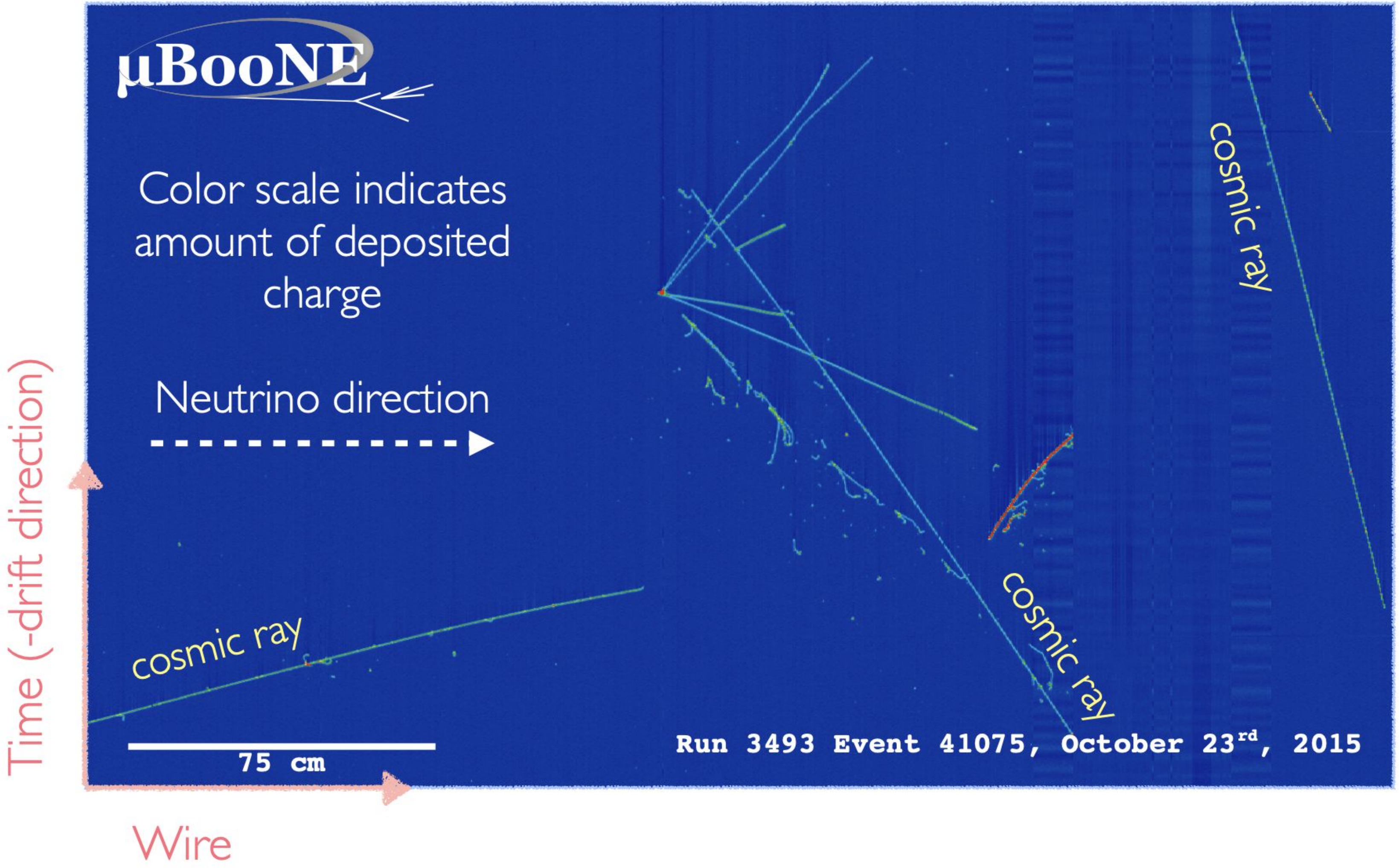
VUV photons propagate and are shifted into VIS photons

Ionization charge drifts in a uniform electric field towards the readout wire-planes

*Electron drift time ~ ms*

Scintillation light fast signals from LDSs give event timing

Digitized signals from the wires are collected [*time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge*]



μBooNE
Color scale indicates amount of deposited charge
Neutrino direction
cosmic ray
cosmic ray
cosmic ray
Time (-drift direction)
Wire
75 cm
Run 3493 Event 41075, October 23rd, 2015

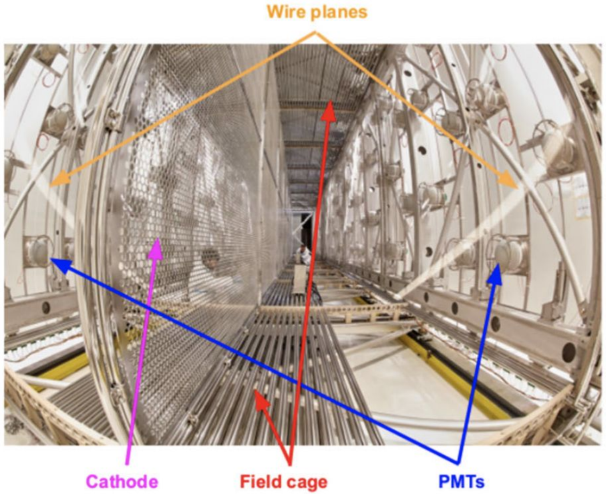
# SBN-ICARUS (Far Detector)

ICARUS was originally deployed in Gran Sasso and exposed to the LGNS beam before moving to CERN to be refurbished for its run at Fermilab

Four TPCs split between **two cryostats**, **470 tons of active LAr,** observed by **360 8" PMTs**, **54000 wires**, a **cosmic ray tagger system**, and a **3m concrete overburden** to reduce soft cosmic backgrounds

Data taking started fall 2020, with stable noise & electron lifetime (>3ms), physics run started June 2022!

## TPC and PMTs




## Cosmic Taggers

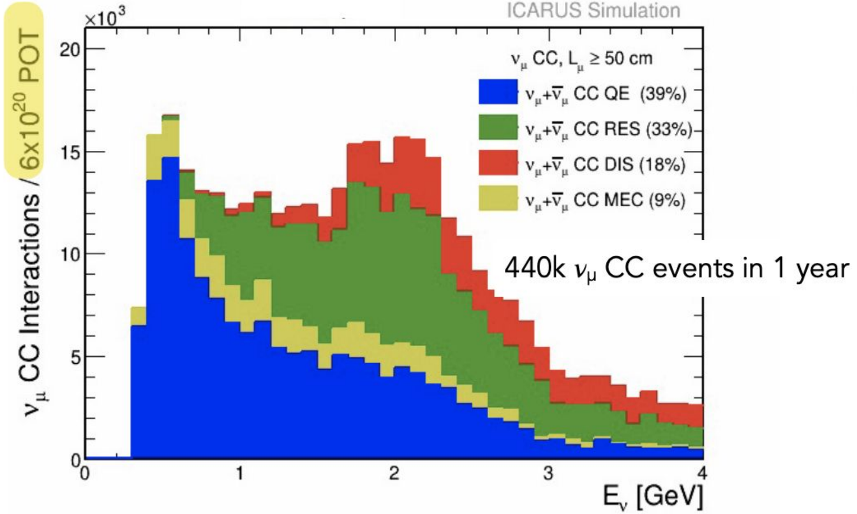
## 3 m Overburden

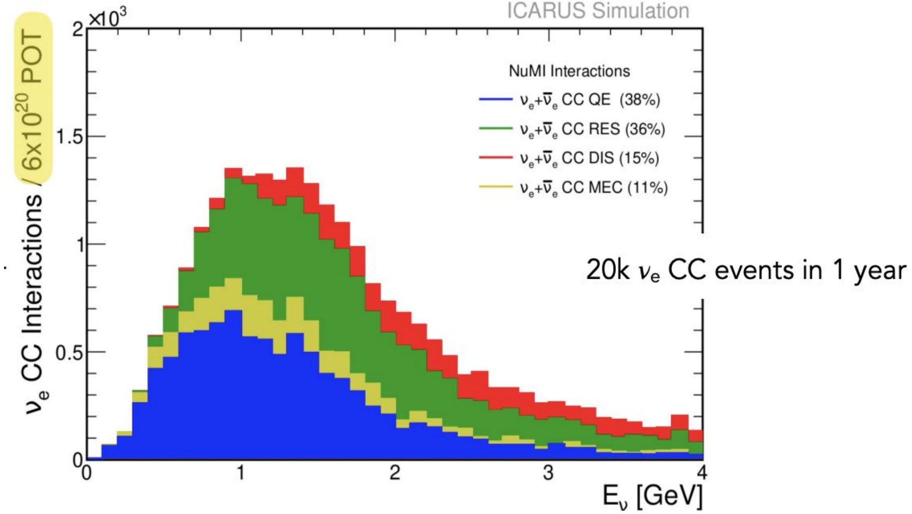
# SBN-ICARUS (Far Detector)

ICARUS is also exposed to the offaxis (6º) NuMI neutrino beam

NuMI has higher proton energy (120 GeV) contributing to an extra range to be explored with high statistics for neutrino interaction studies

We are currently developing tools for cross section extraction and starting systematics evaluations while strategizing our first cross section measurements!



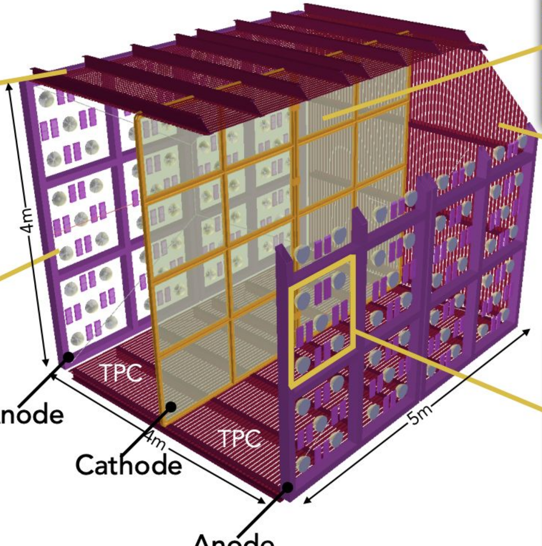
# SBN-SBND (Near Detector)

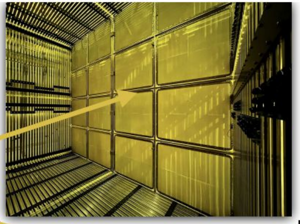
Detector assembly finished spring 2023

Comissioning starting this summer

TPC Cold electronics

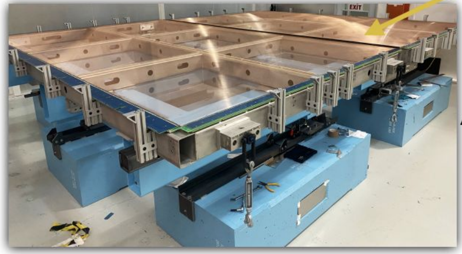
Two Time Projection Chambers
**Total dimension**: 4m x 4m x 5m



**Cathode** covered with TPB coated reflectors

**Field Cage**



**Wire Plane** - 3 readout planes, ~11000 wires

**Photo Detection System**: 120 PMTs, 192 X-Arapucas

Novel photon detection system. Testing components will be used in DUNE

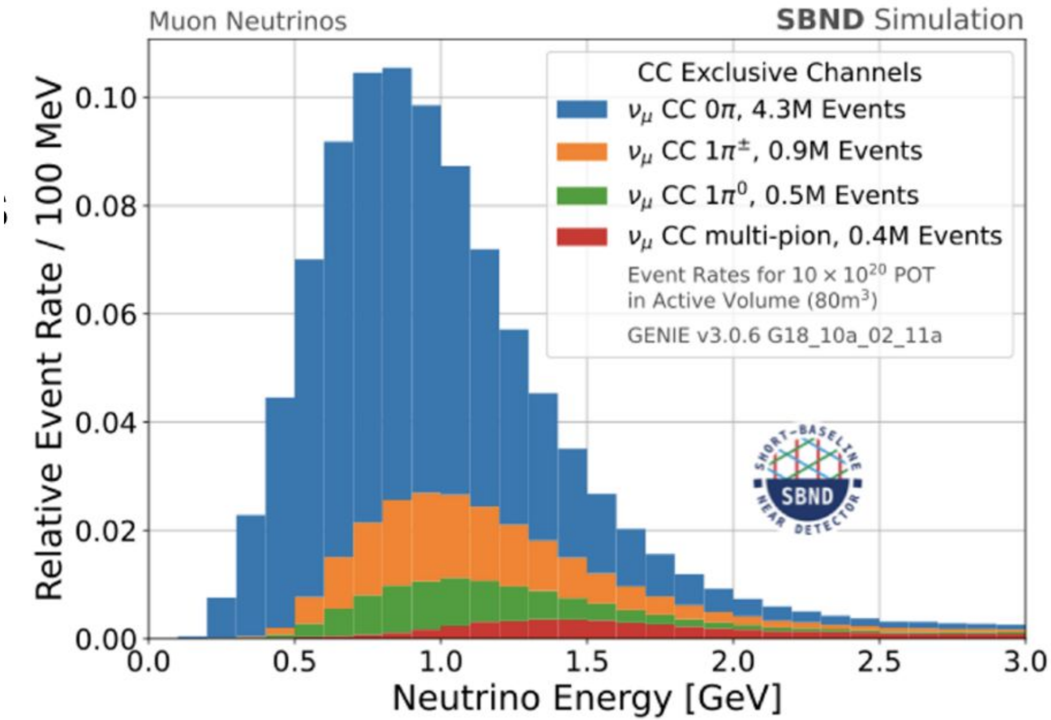
# SBN-SBND (Near Detector)

SBND sits very close (110m) to the BNB target providing a high rate of neutrino interactions

SBND will compile neutrino data with unprecedented high event rate and will enable a generational advance in the study of neutrino-Ar in the GeV energy range.

Up to 7000 $\nu$ events/per day in SBND!

We work with ICARUS collaborators under the SBN program, the developed cross section extraction tools will be available for SBND!

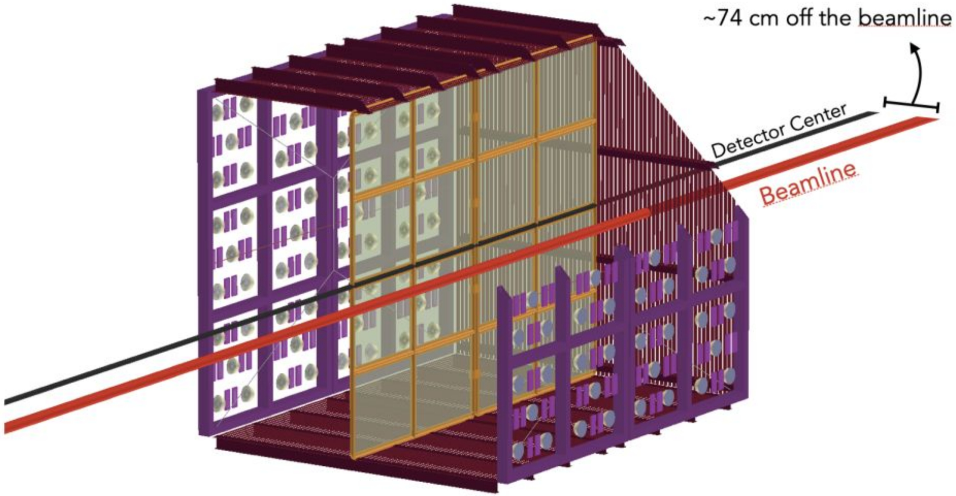


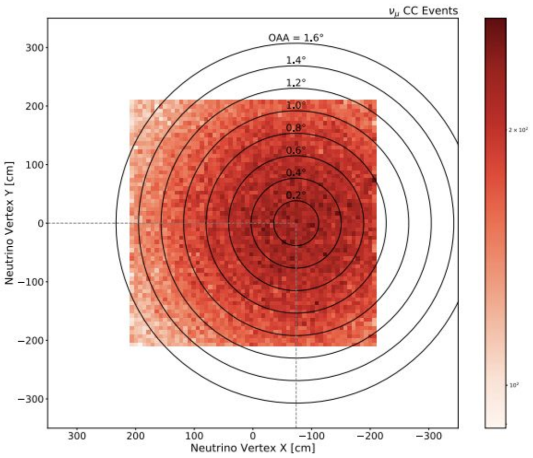
# SBN-SBND (Near Detector)

The high statistics allow for a plethora of new techniques like SBND-PRISM

The detector sees a different flux based on the position within the detector

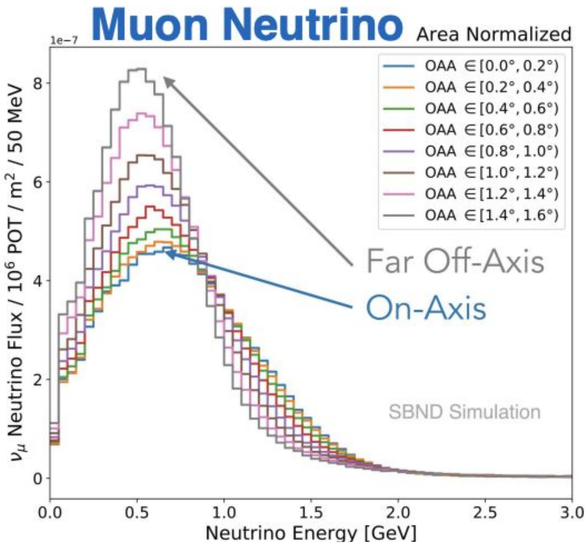
PRISM concept can exploit better understand ve and vμ of cross-section differences



Where are we going?

# SBN-SBND (Near Detector)

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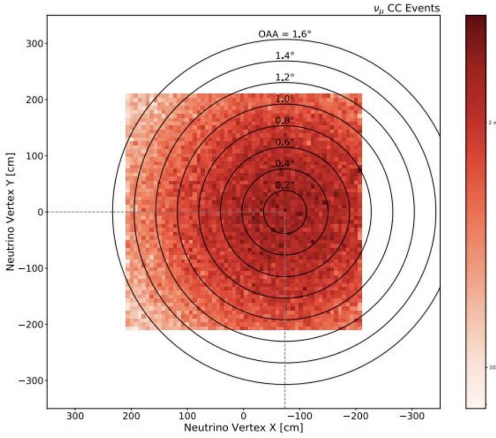
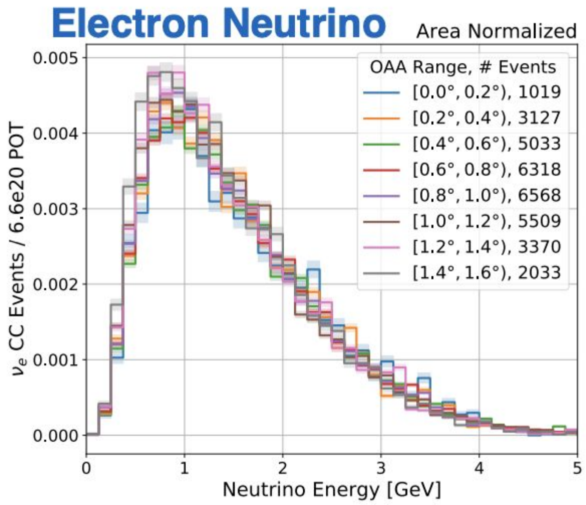
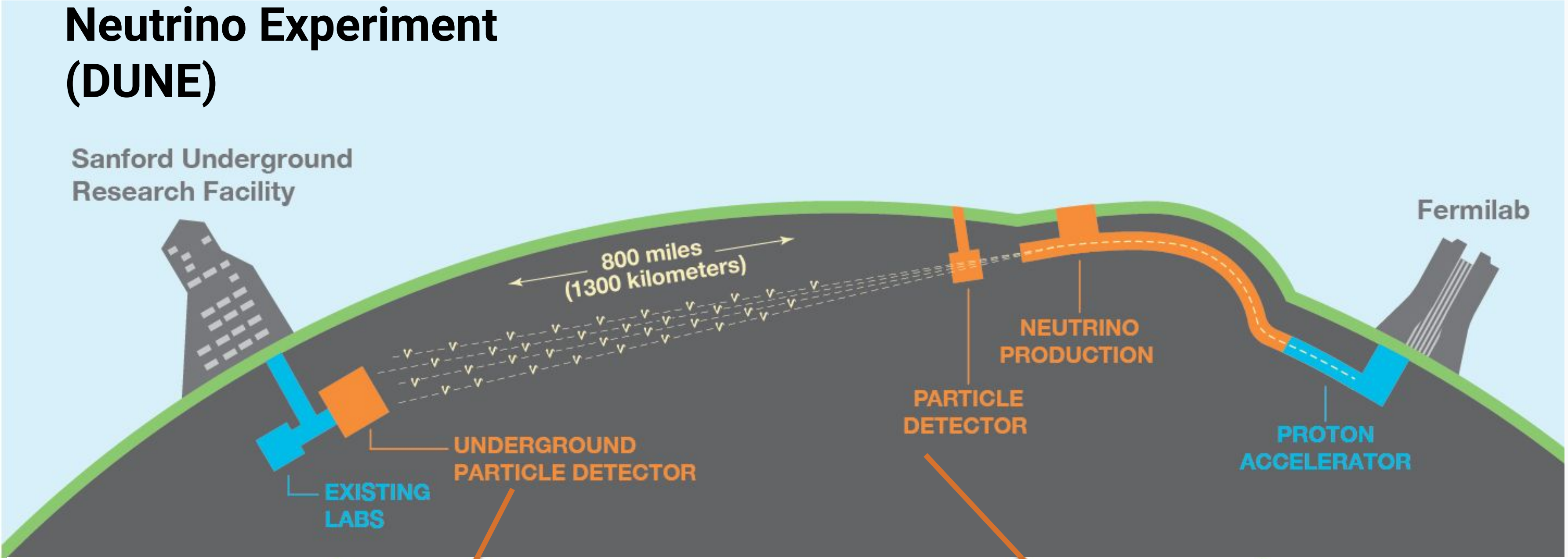


# Deep Underground Neutrino Experiment (DUNE)




**Far Site**

- *1300km from the proton source*
- *very large LAr TPCs (each 17 ktons)*
- *underground in South Dakota*

**Near Site**

- *550m from proton source*
- *on-site at Fermilab*
- *both stationary & moveable detectors*

# DUNE - Far Detector

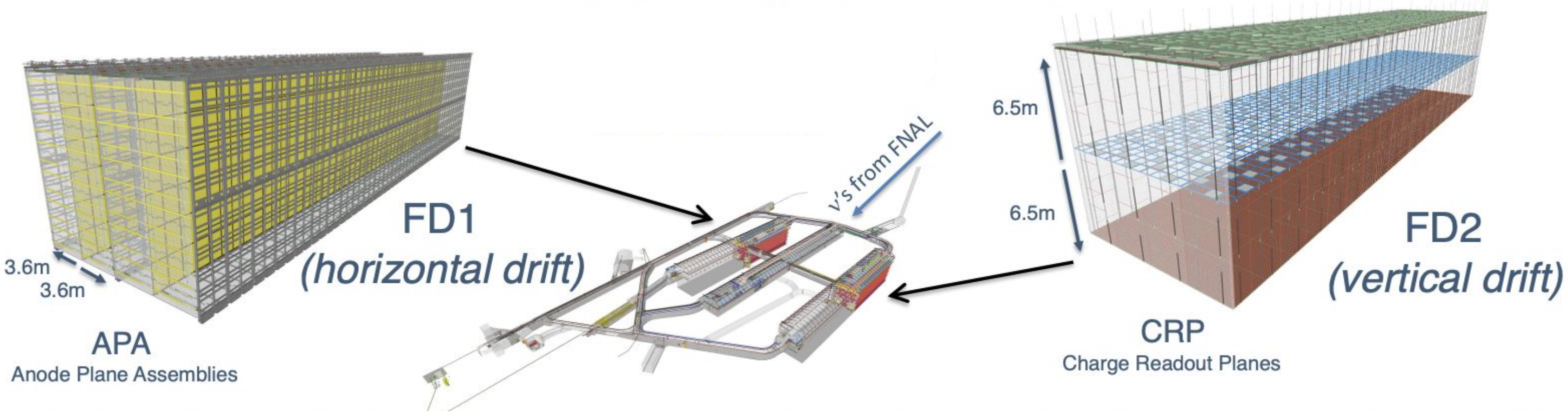
DUNE installation and operation is split in 2 phases

Phase 1 will include caverns for 4 detector modules in South Dakota and 2 far detector modules, each 17 kton of LAr, the largest LAr TPCs ever constructed

Far Detector 1: horizontal drift
Far Detector 2: vertical drift

Order of magnitude more mass than has been deployed up to now from all LAr TPCs

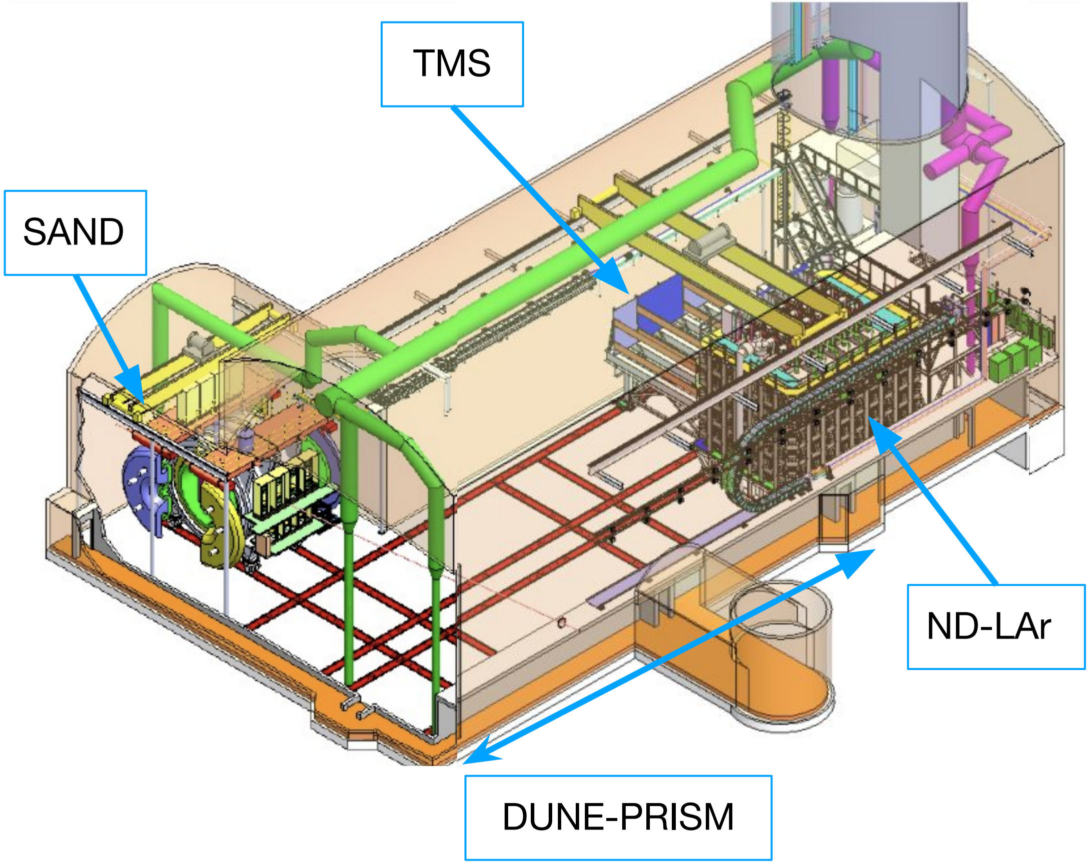
Cryostat installation starts in 2024!



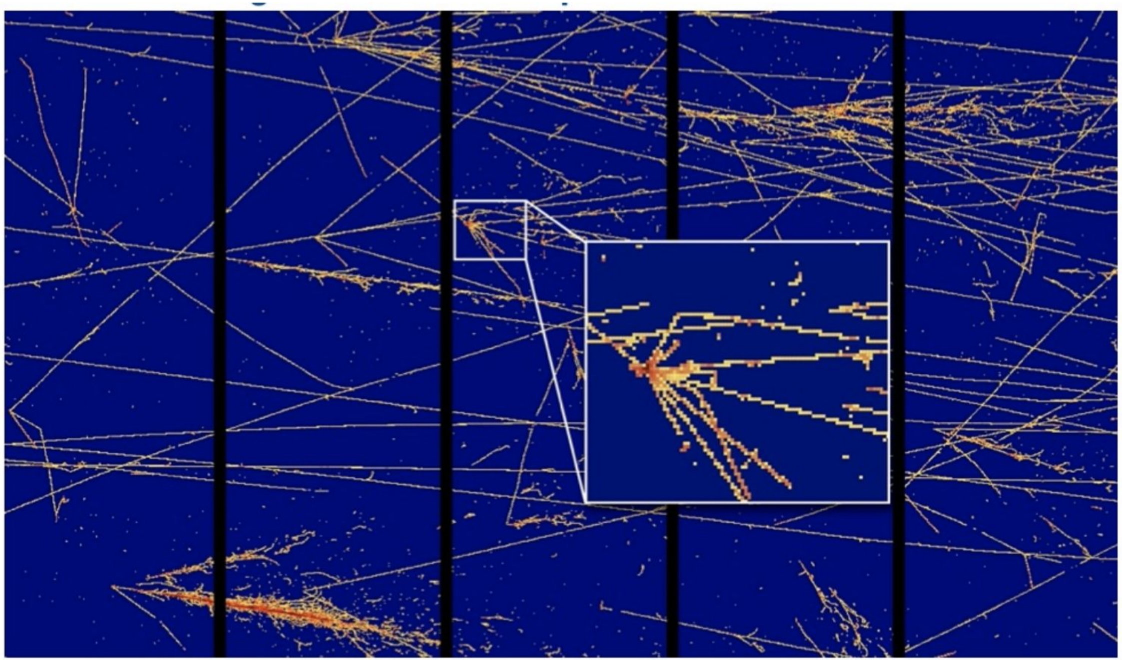
# DUNE - Near Detector

Phase 1 Detector
- Moveable DUNE-PRISM: Move up to 28.5 m off-axis:
  ND-LAr: 7 x 5 array of modular 1x1x3 m3 LArTPCs with pixel readout with low-mass window
  TMS: Magnetized steel range stack for measuring muon momentum/sign from CC interactions in ND-LAr

- SAND: On-axis magnetized beam spectrum monitor with STT, GRAIN, ECAL



# DUNE ND - nu interaction physics



ND must measure the flux, ν-Ar cross sections, and LAr TPC detector response

ND-LAr is as similar as possible to FD; differences (modularity, pixelization) are to cope with high event rate & pile-up

It is critical to measure how neutrinos interact, and what we see in LArTPC

After long studies we decided on a base model for our neutrino interaction generator and our systematics studies just started!

# Snowmass

Snowmass is a community planning exercise organized by the Division of Particles and Fields (DPF) of the American Physical Society (APS), aiming to produce a scientific vision of the group goals for the next decade.

It was organized into ten working groups, or “Frontiers" which comprise a broad array of ground-breaking research topics and the underlying technology and infrastructure to execute them

Each Frontier was divided in Topical Groups

Snowmass 2021 Frontiers:

**Accelerator (AF)**
**Community Engagement (CEF)**
**Computational (CompF)**
**Cosmic (CF)**
**Energy (EF)**
**Instrumentation (IF)**
**Neutrinos (NF)**
**Rare Processes and Precision Measurements (RPF)**
**Theory (TF)**
**Underground Facilities and Infrastructure (UF)**

# Snowmass - Neutrino Frontier

Neutrino Oscillations

Experimental Neutrino Anomalies

Neutrinos Beyond the Standard Model

Neutrinos from Natural Sources

Neutrino Properties

Neutrino Interaction Cross Sections

Neutrino Applications

Artificial Neutrino Sources

Neutrino Detectors

Theory of Neutrino Physics

Snowmass 2021 Frontiers:

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# Snowmass - Neutrino Frontier (some) Recommendations

The community understands the need for support to neutrino theory and DUNE

**NF Recommendations Distilled from Community Input**

Support for **neutrino theory**

Completion of ***full scope* of DUNE** recommended by the last P5

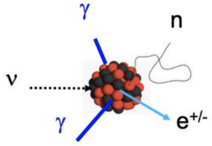
Support of **R&D for DUNE Phase II**

From: Overview of Neutrino Frontier by Kate Scholberg at the P5 Town Hall @Fermilab & Argonne

# Snowmass - Neutrino Frontier (some) Recommendations

Cross Section measurements are recognized by the neutrino community as a crucial part of the neutrino physics program as a whole!

And a final note: understanding of **neutrino interactions with matter** is very important, and connects to ~everything ... especially critical for oscillation physics




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

Astrophysics: supernova bursts, solar models

Tests of neutrino mixing model

| Experiment | Source | Target |
| --- | --- | --- |
| COHERENT | $\pi$DAR | Na, Ar, Ge, CsI, |
| Coherent CAPTAIN Mills | $\pi$DAR | Ar |
| JSNS$^2$ | $\pi$DAR | |
| ESS | $\pi$DAR | |
| 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 |

Many experimental & theory efforts over many orders of magnitude of neutrino energy

Short baseline Neutrino Program:
**MicroBooNE, SBND, ICARUS**
sbn.fnal.gov/

**ANNIE**
annie
annie.fnal.gov/

**NuSTORM**

**MINERvA**
minerva.fnal.gov/

**NINJA**
NINJA
Recent: Phys. Rev. D 102, 072006

Kendall Mahn

From: Overview of Neutrino Frontier by Kate Scholberg at the P5 Town Hall @Fermilab & Argonne

Outline

Why are Neutrino Cross Sections important?

What's so hard about it?

Where are we now?

Where are we going?

**Who gets to do it?**

Outline

Why are Neutrino Cross Sections important?

What's so hard about it?

Where are we now?

Where are we going?

**Who gets to do it*?**

***Nuclear & Particle Physics in the US**

# Snowmass - Neutrino Frontier (some) Recommendations

The community also understands the need for Diversity, Equity, Inclusion (DEI) efforts

## NF Recommendations Distilled from Community Input

**Leadership in HEP-wide strategic plan for DEI and community engagement**

- Neutrinos have connections to practically all other sectors of particle physics as well as many adjacent disciplines, offering neutrino physicists the opportunity to be community leaders in issues of diversity, equity and inclusion (DEI). These opportunities must be embraced. **The Neutrino Frontier has a special responsibility to contribute to leadership for a cohesive, HEP-wide strategic plan for DEI and community engagement.**

From: Overview of Neutrino Frontier by Kate Scholberg at the P5 Town Hall @Fermilab & Argonne

# Snowmass - Community Engagement Frontier

CEF explored how the U.S. HEP community can be more representative of and responsive to all of its members and can engage with society as a whole

Snowmass 2021 Frontiers:

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# Snowmass - Community Engagement Frontier

Applications and Industry

Career Pipeline and Development

Diversity, Equity, and Inclusion

Physics Education

Public Education and Outreach

Public Policy and Government Engagement

Environmental and Societal Impacts

Snowmass 2021 Frontiers:

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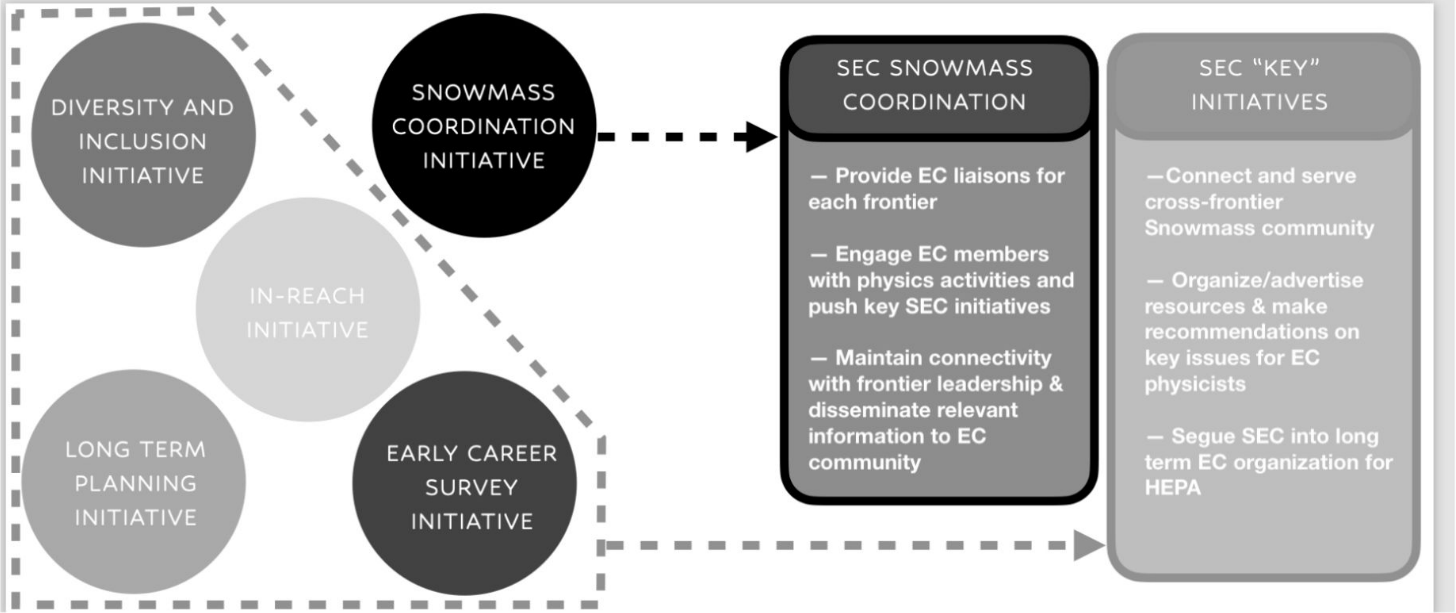
Who gets to do it?

# Snowmass Early Career (SEC)

Snowmass covers a time range of planning that often surpass the timescale of a single career, consideration of the next generation of physicists is crucial.

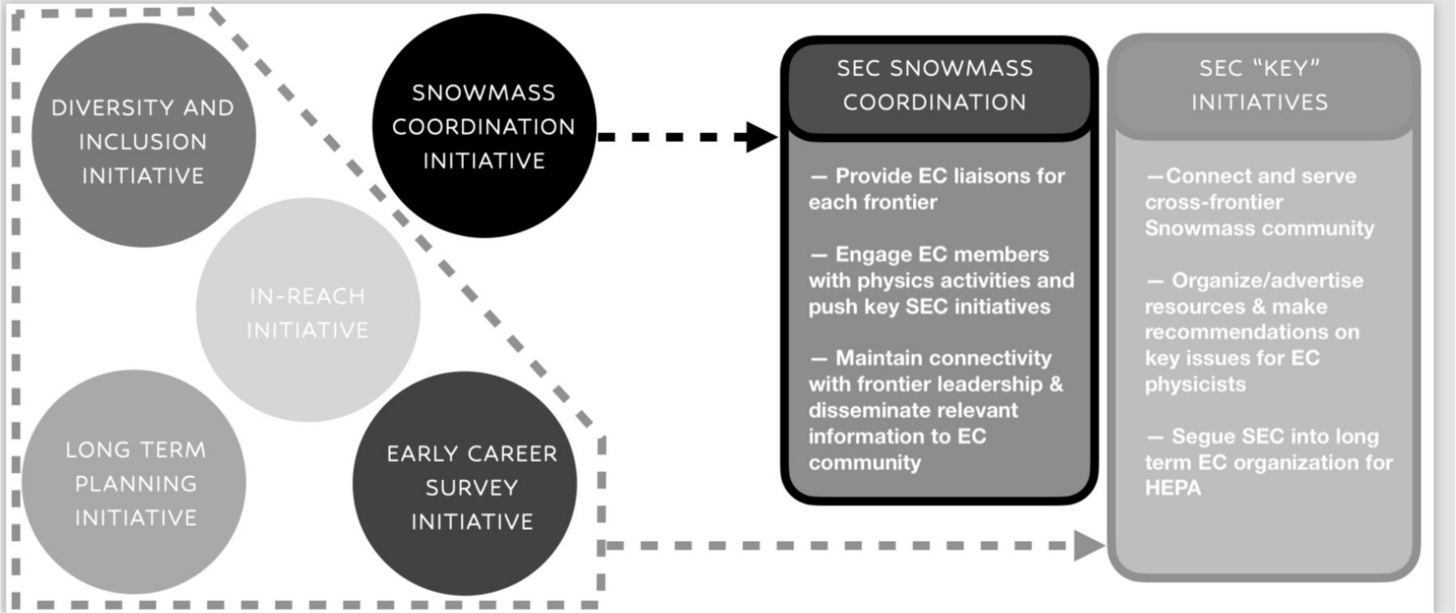
The 2021 Snowmass Early Career (SEC) organization aimed to unite this group, with the purpose of both educating the newest generation of physicists while informing the senior generation of their interests and opinions.



# Snowmass Early Career (SEC)

Community Engagement Frontier, SEC liaison
CEF - Public Education and outreach topical group, SEC liaison
CEF - Public Policy & Government Engagement topical group, SEC liaison

SEC Survey Initiative coordinator
SEC Diversity and Inclusion Initiative coordinator

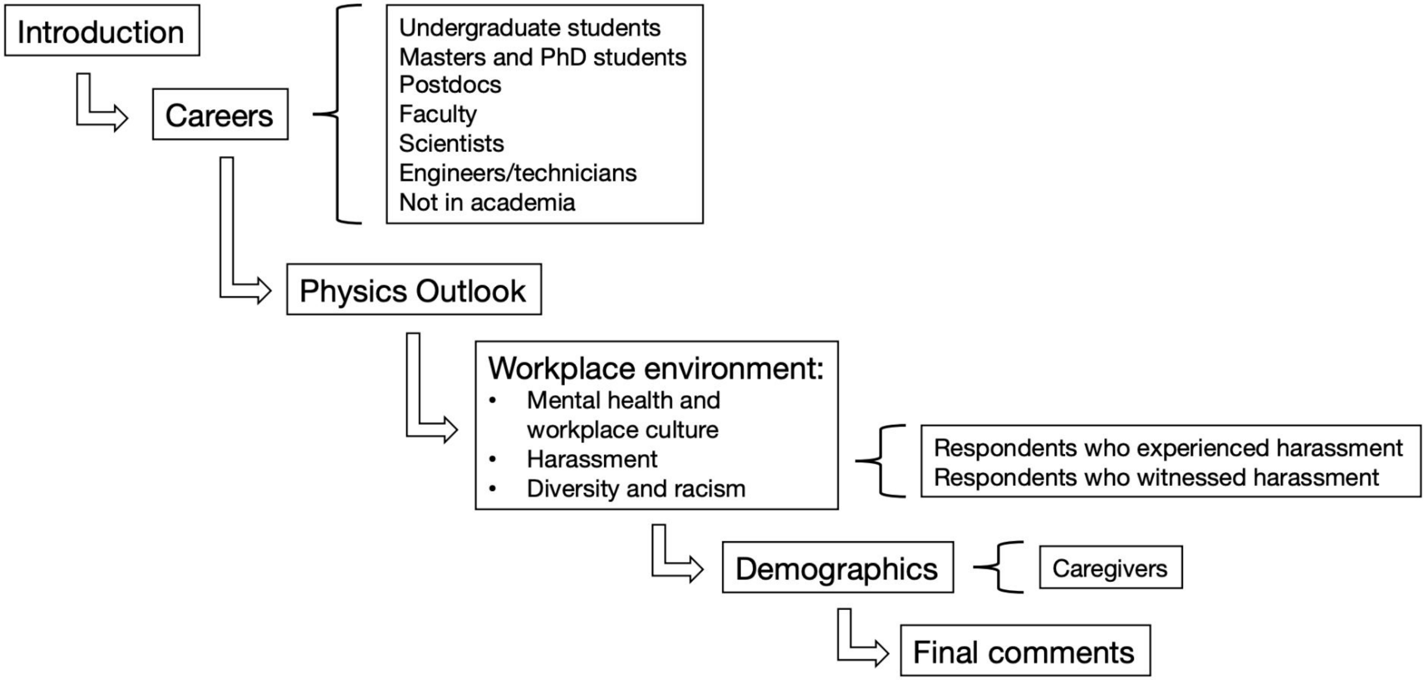


Who gets to do it?

# SEC Survey Initiative

The SEC Survey aims to be a comprehensive assessment of the state of the high-energy particle and astrophysics (HEPA) field

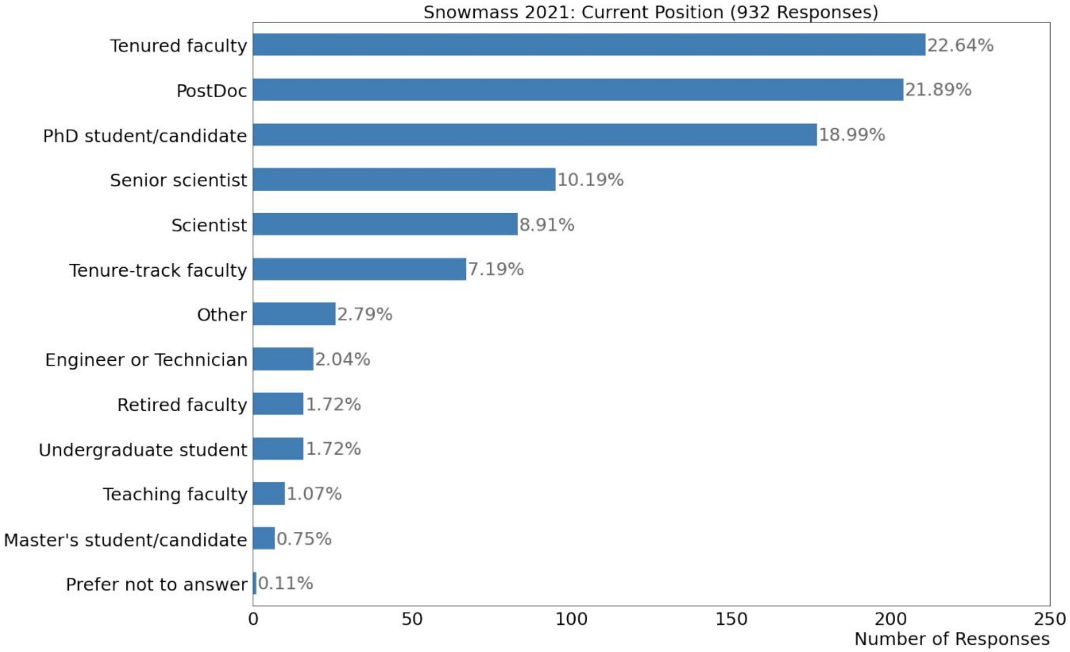
We developed an inclusive survey of the community to gather demographic, career, physics outlook, and workplace culture data on a large segment of the Snowmass community.



# SEC Survey Initiative
# Career stage

Engagement from ~1500 participants with the survey (not all answered every question)

Roughly distributed between respondents are tenured faculty members (22.6%), followed by postdocs (21.9%) and PhD students or candidates (19%)

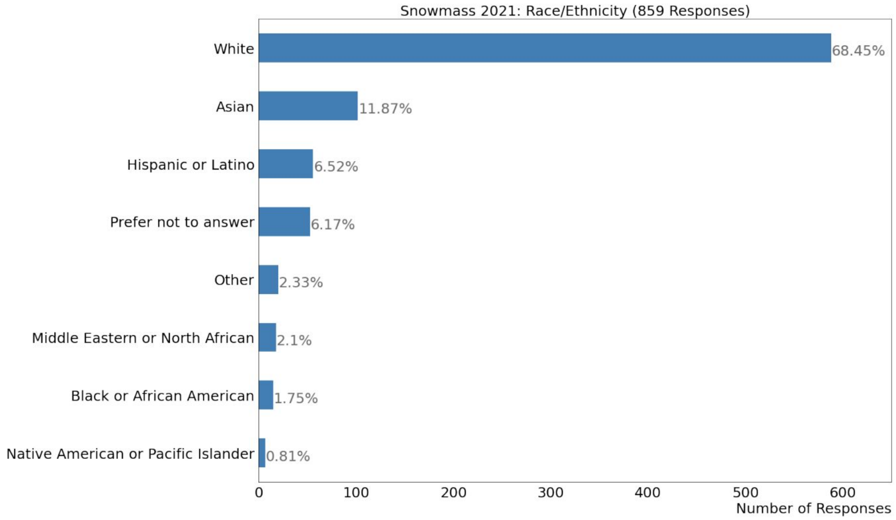


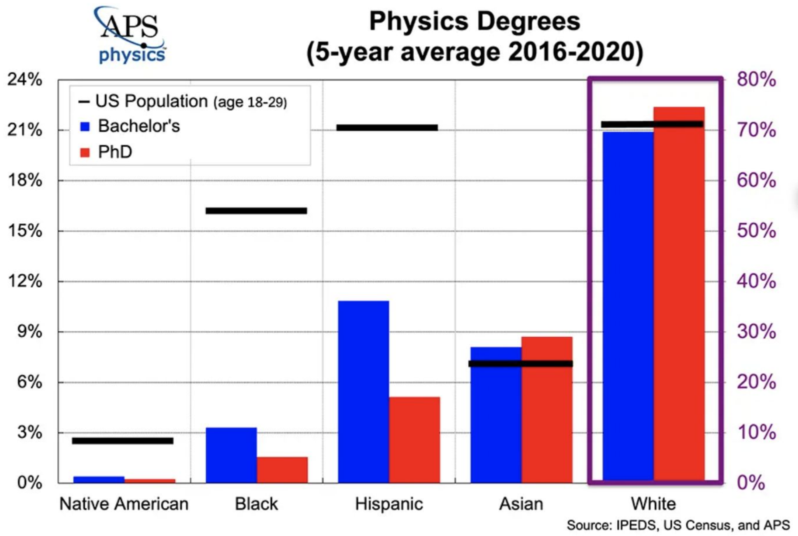
# SEC Survey Initiative Race/Ethnicity

The distribution of race/ethnicity of the SEC Survey is comparable to APS national data of physics degrees by race/ethnicity (2016-2020)

We seem to have better representation from the 'Hispanic or Latin' which is likely an effect of international collaborations with Latin America.

Our survey responses had ~10% of visa holders that work in the US.

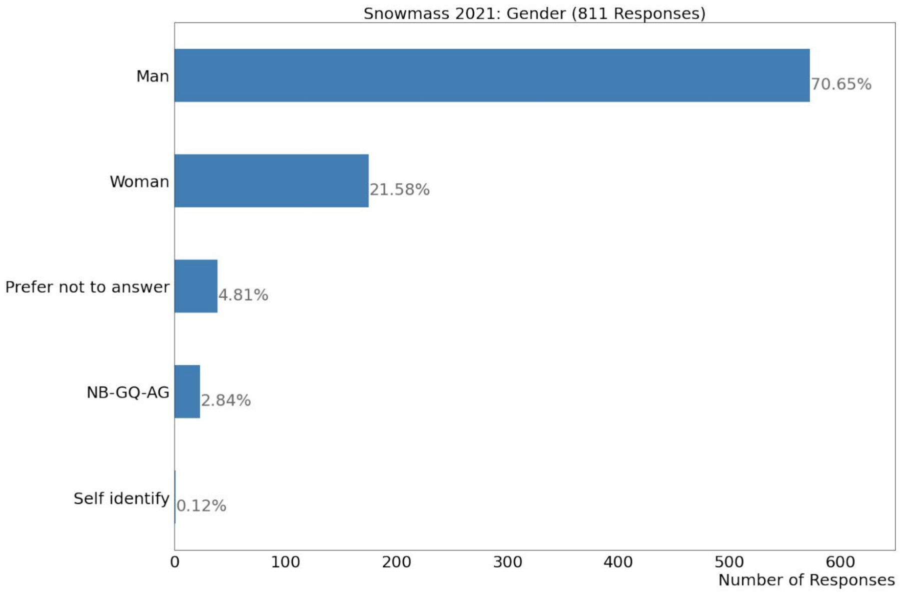


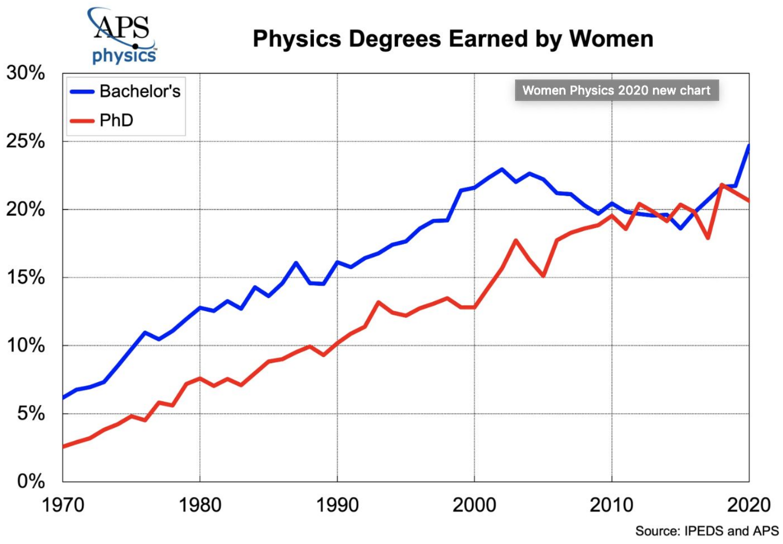



# SEC Survey Initiative Gender

The distribution of gender of the SEC Survey is comparable to APS national data of physics degrees by women

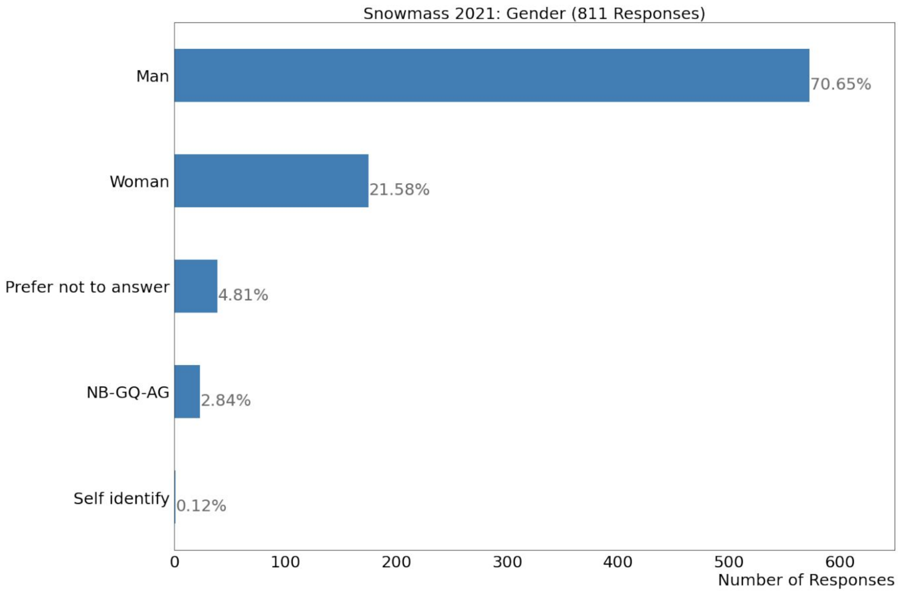
Again, we seen to be tracking in the HEP field a similar gap to what is seen in the demographics of physics degrees earned

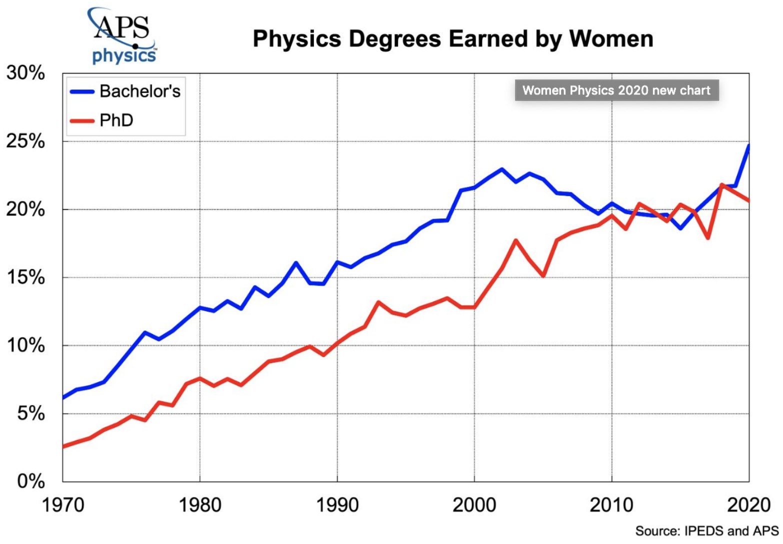


# SEC Survey Initiative Gender

The typical profile of the 2021 survey respondents is a North American, white, straight man, between 30 and 40 years old, married, with a tenured faculty or Postdoc position. This observation corroborates with several other reports in the literature that demonstrates the low number of women and underrepresented minorities in Physics, which is reflected in the HEP community



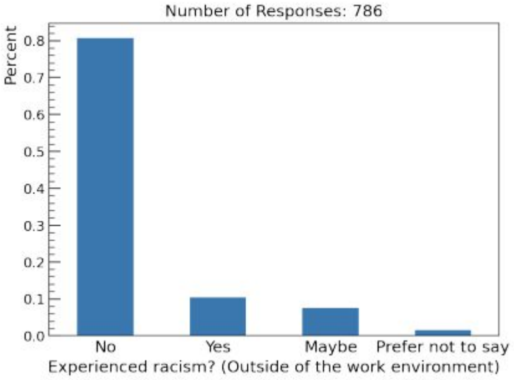



# SEC Survey Initiative Racism

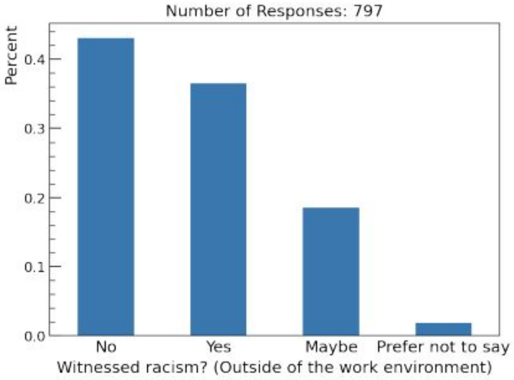
When asked about racism in, and out, of the work environment most respondents said they did not experience racism either outside (~ 81%) or inside (~ 86%) their work environment

However, this percentage dropped to ~ 43% and ~ 60% for witnessed racism outside and inside their work environment, respectively

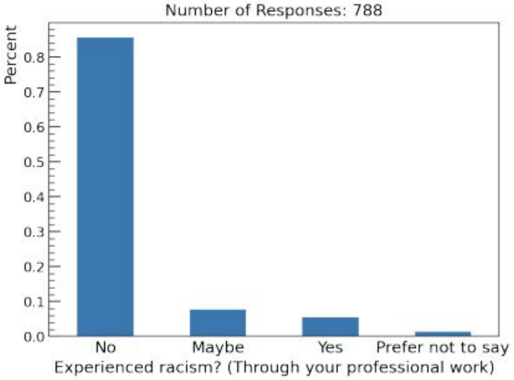
According to comments respondents feel like they like mechanisms to deal with witnessed and experienced racism or harassment



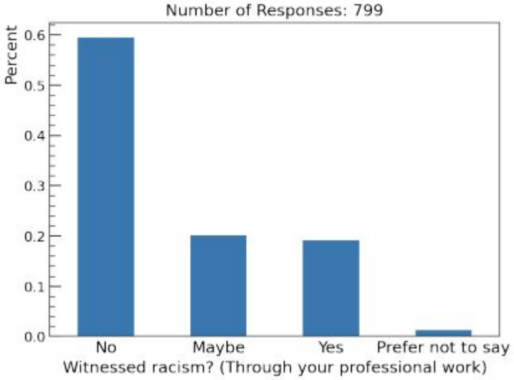

(a) Experience of racism outside the work environment.




(b) Witness of racism outside the work environment.




(c) Experience of racism in the work environment.




(d) Witness of racism in the work environment.

**Who gets to do it?**

# SEC Survey Initiative
# Racism

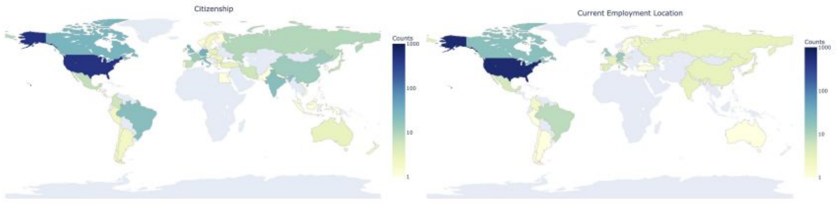
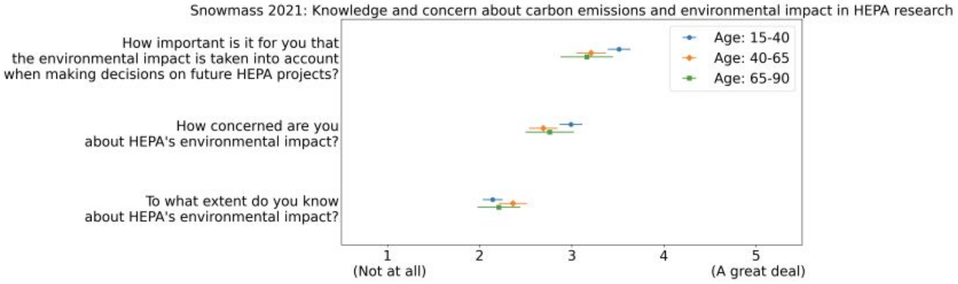
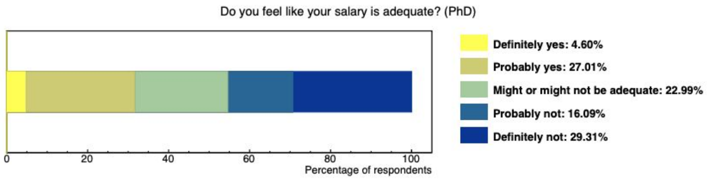


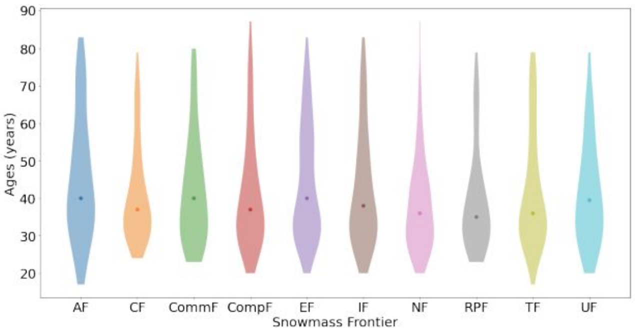

Figure 8: Citizenship and employment location of the respondents.

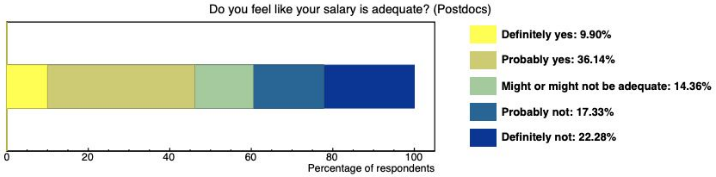
...and much, much more!

There's tons of interesting data (including physics), please read the report if you are interested (and you should be)



# CEF recommendations for DEI (and what we are already doing)

From Kétévi A. Assamagan (BNL), CE Frontier convener, presentation at the P5 Panel @BNL

## The 11 canons of Community Engagement

1. Climate within
2. Work-life balance
3. Accessibility
4. Education, Career Pipeline & Retention
5. Policies & Government Engagement
6. Outreach
7. Environmental & Societal Engagements
8. International Engagements
9. Technology Transfers
10. Individual Participation
11. Implementation & Progress Monitoring

Who gets to do it?

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Improve strategic planning procedures, science workplace norms and culture, ethics and code of conduct guidelines and procedures to encourage adherence to and address violations thereof

We need partnership with scholars, professionals, and other experts in several disciplines, including but not limited to anti-racism, critical race theory, and social science.

Improving the climate also consists of implementing practices and programs for participation in HEP by non-R1 institutions

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Improving the climate also consists of implementing practices and programs for participation in HEP by non-R1 institutions


Climate within
Accessibility
Outreach
Environmental
International

- Collaborations in HEP have been creating Community Agreements to address this, are professionals part of the conversation?

- recent initiatives from DOE to improve non-R1 institutions participation:
    - Reaching a New Energy Sciences Workforce (RENEW)
    - Funding for Accelerated, Inclusive Research (FAIR)

I worked with NPP in the submission of 3 different projects in the last months that included: funding for research and education structure at MSIs, grants for students maintain research work through a year period, training for scientists at the lab on working with URM and capability for students to attend international conferences

# CEF recommendations for DEI (and what we are already doing)

From Kétévi A. Assamagan (BNL), CE Frontier convener, presentation at the P5 Panel @BNL

A diverse pool of candidates cannot be expected at the tertiary or higher levels of HEP engagement if efforts were not made as far back as the K-12 and university undergraduate levels, to nurture the pipeline.

It's necessary to create effective programs to support pupils, teachers and students in their local communities, to develop and maintain interests in physics.

Educational institutes should develop or expand programs to prepare students with the skills needed for HEP and related applications.

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Educational institutes should develop or expand programs to prepare students with the skills needed for HEP and related applications.

BNL and NPP have programs for undergraduates and high schoolers, we can improve our reach to K-12

In 2021 I worked with the New York Academy of Sciences (NYAS) in a project teaching 8 graders concepts of particle physics. Funding for structure is needed but a lot of material is already available.

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It's necessary to create effective programs to support pupils, teachers and students in their local communities, to develop and maintain interests in physics.

Educational institutes should develop or expand programs to prepare students with the skills needed for HEP and related applications.

In an institutional level BNL and NPP have been making efforts to approach MSIs, especially HBCUs.

In April I was part of a cohort visiting the North Carolina Agricultural & Technical State University to have conversations with group leaders, staff, chairs, faculty, and students, towards building a relationship and create a career pipeline.

Who gets to do it?

# CEF recommendations for DEI (and what we are already doing)

From Kétévi A. Assamagan (BNL), CE Frontier convener, presentation at the P5 Panel @BNL

We should provide resources to sustain and grow the annual HEP Congressional advocacy efforts

HEP groups should coordinate efforts in order to extend advocacy to the federal executive branch, state and local governments
.

HEP groups should improve concerted efforts toward international advocacy
to facilitate the reach of HEP and, in particular, to support HEP communities of developing countries.

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HEP groups should improve concerted efforts toward international advocacy to facilitate the reach of HEP and, in particular, to support HEP communities of developing countries.

I participated in congressional/senate advocacy efforts and trips since 2015 and our message is often well received across the political spectrum

But we need to have uncomfortable conversations within the community. What are we doing while the queer community is attacked through public policies?

Who gets to do it?

# CEF recommendations for DEI (and what we are already doing)

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Funding agencies, universities and research institutes should encourage staff to spend appropriate time on outreach, DEI and climate improvement efforts. Which should be included favorably in staff evaluation, career progressions and grant evaluations.

The HEP community should take a foundational approach to successful outreach by building lasting relationships with target communities. Successful outreach programs cannot be transactional with the target communities.

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The HEP community should take a foundational approach to successful outreach by building lasting relationships with target communities. Successful outreach programs cannot be transactional with the target communities.

The community seems to agree that taking part in communication should be part of the definition of a scientist job. How can we bring this to funding agencies?

Through my career I took many opportunities in engaging in public communication, but also took opportunities to be trained. We cannot expect everyone to know how to communicate their science to every public.

Who gets to do it?

# CEF recommendations for DEI (and what we are already doing)

From Kétévi A. Assamagan (BNL), CE Frontier convener, presentation at the P5 Panel @BNL

These goals and suggestions for improvement will be beneficial to the individual HEP researchers in establishing a climate of inclusivity, diversity and equity that fosters scientific excellence.

Prrogress in these goals will improve the socioeconomic, societal and environmental impacts of HEP. In so doing, HEP as a whole will benefit from societal advocacy.

It is important for the HEP communities to encourage more participation in community engagement.

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10. **Individual Participation**
11. Implementation & Progress Monitoring

Participation in the CEF was smaller than expected for a Frontier that englobes the whole community.

The SEC survey shows people don't feel supported (by their colleagues or intitution) to participate. We need to change that culture.

# CEF recommendations for DEI (and what we are already doing)

From Kétévi A. Assamagan (BNL), CE Frontier convener, presentation at the P5 Panel @BNL

Many institutions have been making efforts in community engagement; what is lacking is a coherent approach where best practices are shared and encouraged.

The HEP community should create the framework where a coherent approach towards improving the climate can flourish.

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5. Policies &…
6. …ch
7. Environmental & Societal Engagements
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9. Technology Transfers
10. Individual Participation
11. **Implementation & Progress Monitoring**

DOE recently implemented the request for Promoting Inclusive and Equitable Research (PIER) plan in every project submission

I helped the effort in projects submitted at NPP this year, but we need to follow up and make sure the plans are being followed

## Closing remarks

Particle Physics, specifically Neutrino Physics, have a huge role to play in the future of the US science program

Neutrino Cross Sections are a crucial part of it, we need more precision, more ideas, and new techniques

A diverse workforce is needed, recognizing it's a problem is a step, but not enough

There are clear steps ahead given to us by the work of lots of people. It's our responsibility to contribute to a better future.

# Thank you!

Outline

Why are Neutrino Cross Sections important?

What's so hard about it?

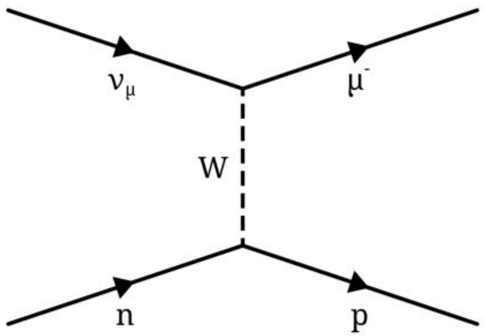
Where are we now?

Where are we going?

Who gets to do it?

**Backups**

- Even the most simple "CCQE" interaction is hard to describe as the target in an extended object




$$M \sim \frac{g_W^2}{8}\frac{1}{M_W^2}[\bar{u}_\mu \gamma_\mu (1-\gamma_5) u_\nu][\bar{u}_p (\dots) u_n]$$

$$J_H^\beta = \bar{u}_p \left[ f_{1V}\gamma^\beta + i\frac{\xi f_{2V}}{2M}\sigma^{\beta\delta}q_\delta + \frac{f_{3V}}{M}q^\beta + f_A\gamma^\beta\gamma_5 + \frac{f_p}{M}q^\beta\gamma_5 + \frac{f_{3A}}{M}\left(P_p^\beta + P_n^\beta\right)\gamma_5 \right] u_n$$

$$M = (M_p + M_n)/2 \qquad q = p_\nu - p_\mu = P_p - P_n \qquad \xi = \mu_p - \mu_n \qquad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

- The $f$ factors are the "form factors" (read "fudge factors")
- Many of these can be extracted from electron scattering experiments
- $f_A$ is the axial form factor, here we don't have much data to help us!
  - Usually we take a dipole form but recent lattice QCD calculations suggest this might not be a good idea Ann. Rev. Nucl. Part Vol. 72:205-232

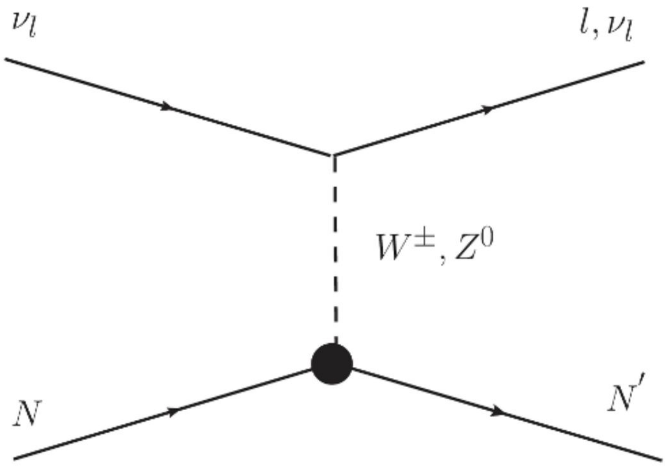
# The Charged Current Quasi-Elastic (CCQE) scattering

**CCQE dominate at energies in the few GeV range,** a common energy range for neutrino beams

.

It is a **two-body process** and the incoming neutrino direction is known, a reasonable approximation of the neutrino energy can be calculated using only the **outgoing lepton kinematics**.

CCQE is the **preferred signal** process for neutrino oscillation experiments.




$$\nu_l + n \rightarrow l^- + p$$

$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

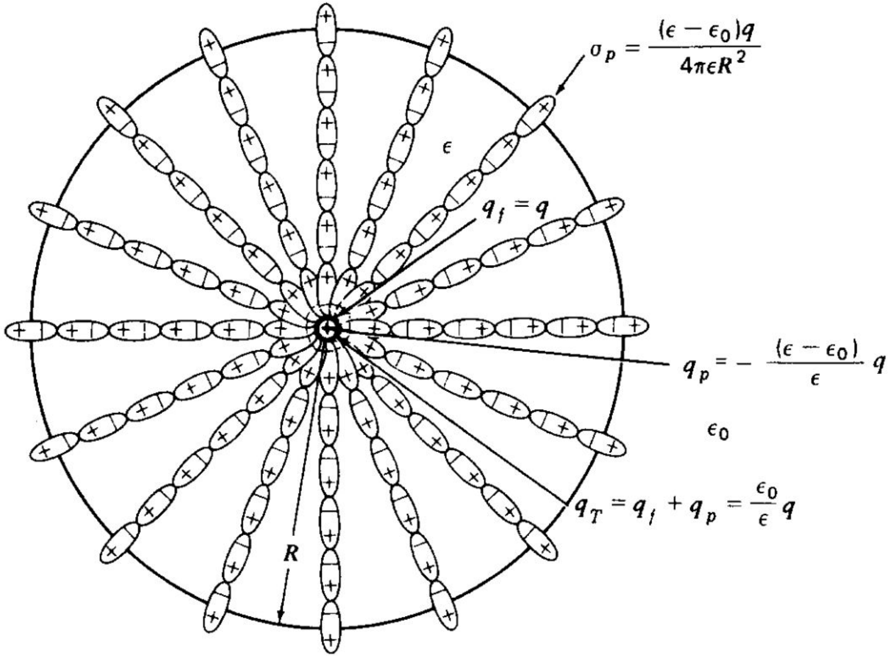
$$Q_{QE}^2 = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

# Screening effect

As we learn in classical E&M, Polarization of a dielectric medium “screens” and reduces the field outside

The quantum “RPA-type” calculation for electron gas or nuclear matter gives long-range (whole medium) nucleon-nucleon correlation.

Net effect: at low energy transfer, nucleon is screened; for QE reaction, looks like only 60% of a nucleon

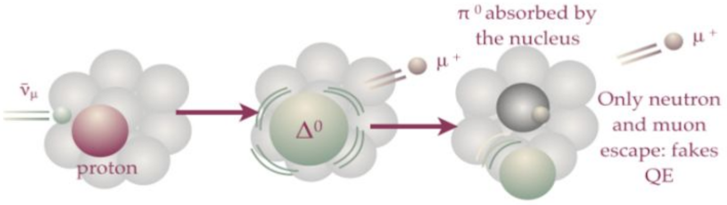


# Why CCQE-like?

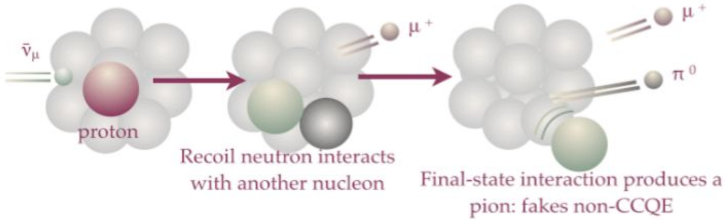
CCQE-like (or CC0π) is a signal definition based on the final state topology:

- **1 positive Muon**
- **Any number of nucleons**
- **No pions**

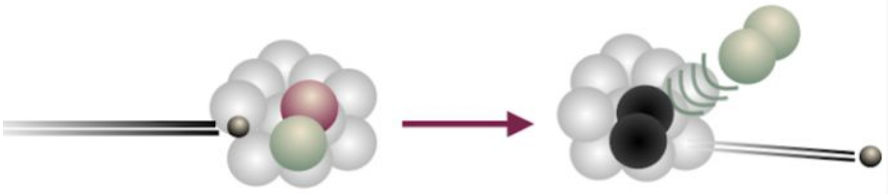
- Resonant event where pion is absorbed?
  **CCQE-like!**




- CCQE event with FSI produced pion?
  **Not** CCQE-like

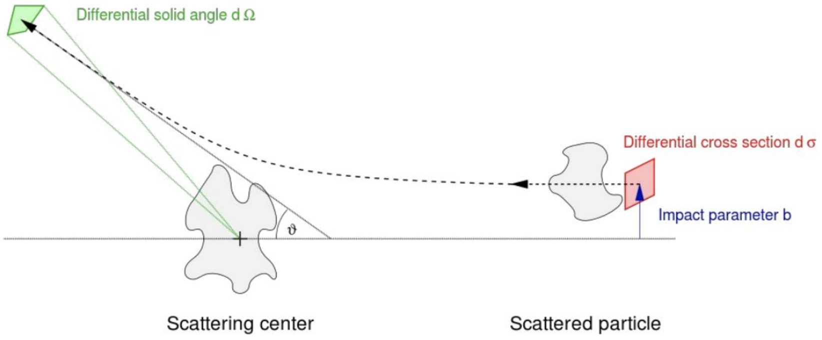



- 2p2h interaction with Muon and nucleons in the final state?
  **CCQE-like!**



# What is a Cross Section?

- Measure of probability of interaction occurring
- Given in units of area
  - Analogy to cross sectional area of a hard sphere scattering target
- Tells us about (weak) charge field




## How do we turn counts in a detector into a cross section?

$$N = \int \sigma(E)\phi(E)T\,\epsilon(E)\,dE$$ ← Total number of events (assuming no bkgds)

$$N_i = \int \sigma_i(E)\phi(E)T\,\epsilon_i(E)\,dE$$ ← Events in some final state kinematic region

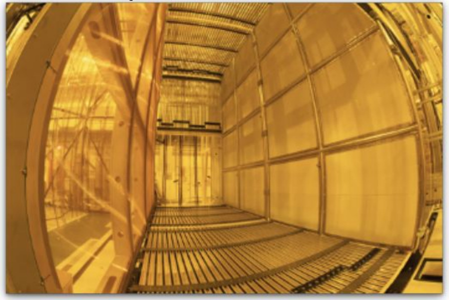
$$N_i = T<\sigma_i><\epsilon_i>\int \phi(E)\,dE$$ ← Use energy averaged xsec and eff

$$N_i = T<\sigma_i><\epsilon_i>\Phi$$ ← $\Phi$ is the integrated flux

$$<\sigma_i> = \frac{N_i}{T\Phi<\epsilon_i>}$$ ← Solve for the energy averaged xsec

# SBN in Numbers

A **large, International team** to produce the SBN physics!

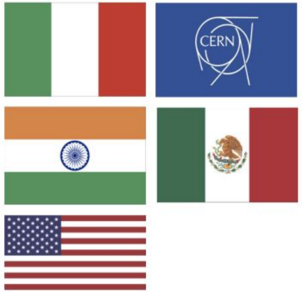


**178 Total Collaborators**

**150 Scientific Collaborators**
**(faculty/scientists, postdocs, PhD students)**

**25 Institutions**

12 INFN Sections (Italy)
CERN
1 Indian Laboratory
1 Mexico University
7 US Universities, 3 National Laboratories




**253 Total Collaborators**

**206 Scientific Collaborators**
**(faculty/scientists, postdocs, PhD students)**

**39 Institutions**

5 Brazilian Universities
CERN
1 Spanish University, 1 National Laboratory
1 Swiss University
7 UK Universities, 1 National Laboratory
18 US Universities, 4 National Laboratories

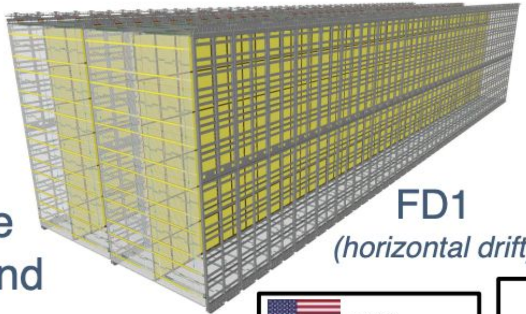

<u>**P5-2014 - Recommendation 15**</u>: Select and perform in the short term a set of small-scale **short-baseline experiments** that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use **liquid argon to advance the technology and build the international community for LBNF [DUNE] at Fermilab.**

# Far Detector Partners (Phase I)

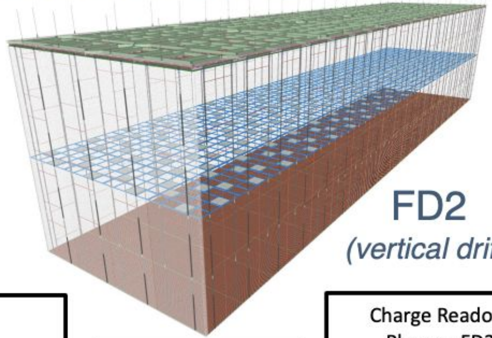
*(Mary Bishai's talk)*

- Multiple international partners have invested significant resources in the DUNE FDs

- ~50/50 share U.S./non-U.S (M&S)
- our partners are preparing to send detectors and components
- we are on schedule and getting ready to build these detectors!



FD1 *(horizontal drift)*



FD2 *(vertical drift)*

High Voltage FD1, FD2

Anode Plane Assemblies - FD1

TPC Electronics FD1, FD2-B

Photon Detection FD1, FD2

Data Acquisition FD1, FD2

Charge Readout Planes - FD2

CALCI FD1, FD2

Electronics FD2-T

Brookhaven National Laboratory

BERKELEY LAB

Argonne NATIONAL LABORATORY

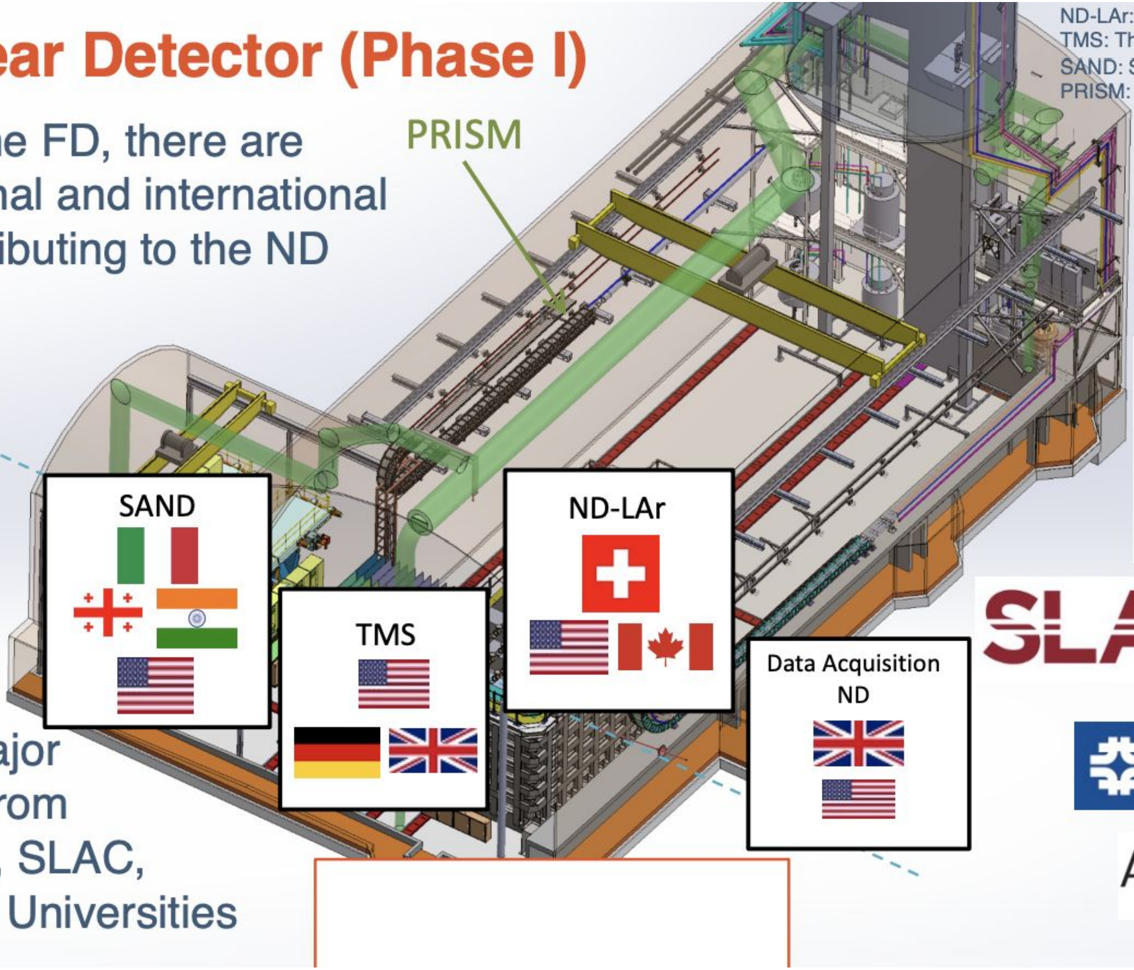
Fermilab

Los Alamos NATIONAL LABORATORY

+ many Universities

# DUNE Near Detector (Phase I)

- Just as with the FD, there are multiple national and international partners contributing to the ND
- Our partners have been building prototypes & sending detector components
- In the U.S., major contributions from LBNL (pixels!), SLAC, ANL, FNAL, & Universities




ND-LAr: liquid argon TPC near detector
TMS: The Muon Spectrometer
SAND: System for On-Axis ν Detection
PRISM: off-axis movement system

BERKELEY LAB
SLAC NATIONAL ACCELERATOR LABORATORY
Fermilab
Argonne NATIONAL LABORATORY

# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\varepsilon_i}$$

# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\varepsilon_i}$$

$N_j^{data}$ is the measured distribution of selected CCQE-like event in bin $j$ of reconstructed $Q^2_{QE}$.

# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\varepsilon_i}$$

$N_j^{bg}$ is an estimate of the distribution of background events present in the selected sample in bin $j$ of reconstructed $Q^2_{QE}$.

# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\varepsilon_i}$$

$U_{ij}$ is a matrix that describes the migration from the true $Q^2_{QE}$ bin $j$ to the reconstructed $Q^2_{QE}$ bin $i$, due to finite resolution and relistic biases of the reconstruction.

# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\boxed{\varepsilon_i}}$$

$\varepsilon_i$ is the efficiency for reconstructing and selecting signal events as a function of the true variable.

# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\boxed{\Phi_\nu} \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\varepsilon_i}$$

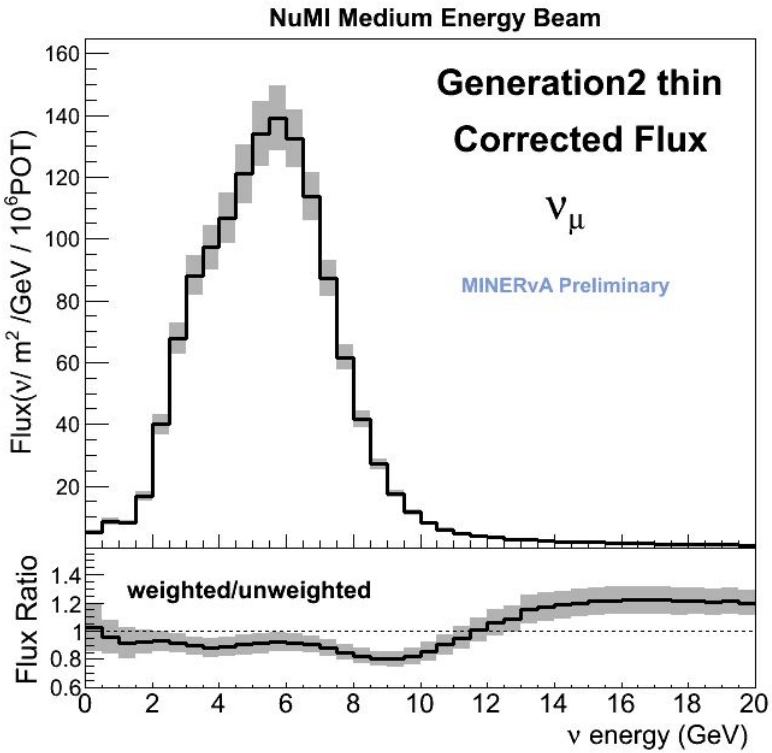
$\Phi_\nu = \int \phi(E_\nu) dE_\nu$ is the total neutrino flux over the region which contributes to the event sample.

# Integrated Flux

Hadron production and detailed beamline geometry is simulated using **GEANT4**

Corrects GEANT4 predicted hadron production using **world hadron production data**

**Thin target (NA49)** dataset used for constraining hadron production in target



# Calculating a Xsection

$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times \boxed{T_n}} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N_j^{data} - N_j^{bg}]}{\varepsilon_i}$$

$T_n$ is the total number of neutron targets in the considered fiducial volume.

# Calculating a Xsection

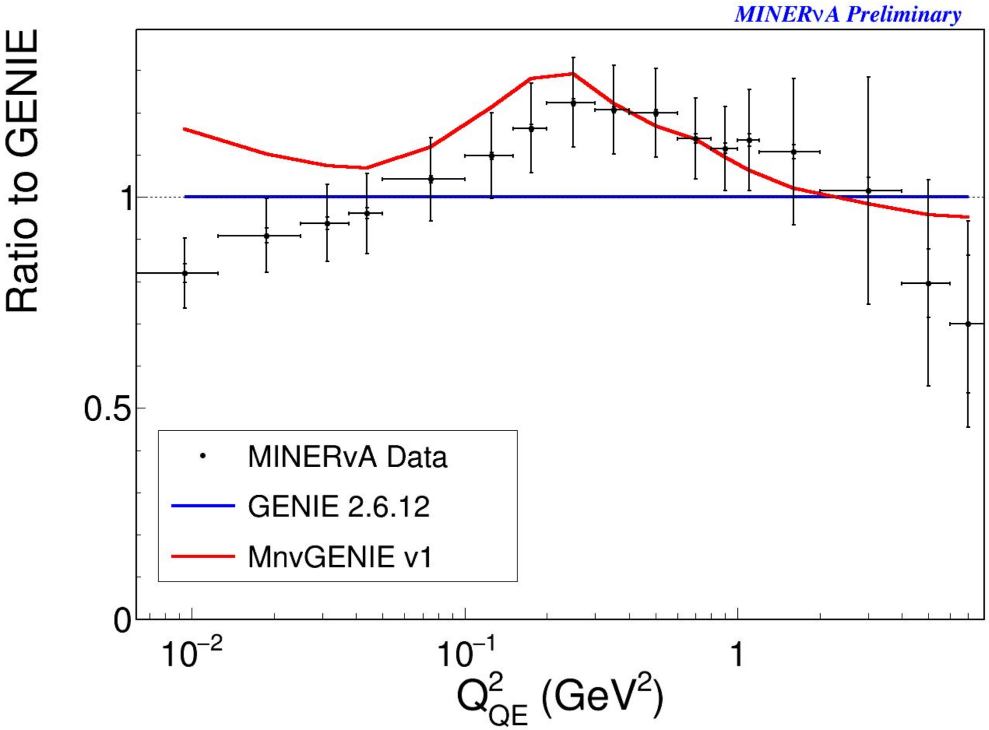
$$\left(\frac{d\sigma}{dQ^2_{QE}}\right)_i = \frac{1}{\Phi_\nu \times T_n} \times \frac{1}{(\Delta Q^2_{QE})_i} \frac{\sum_j U_{ij}[N^{data}_j - N^{bg}_j]}{\varepsilon_i}$$

$(\Delta Q^2_{QE})_i$ is width of the $i$th $Q^2_{QE}$ bin.

# Cross Section Results
# 1D Q2

After efficiency correction we extract the 1D cross section for Q2QE

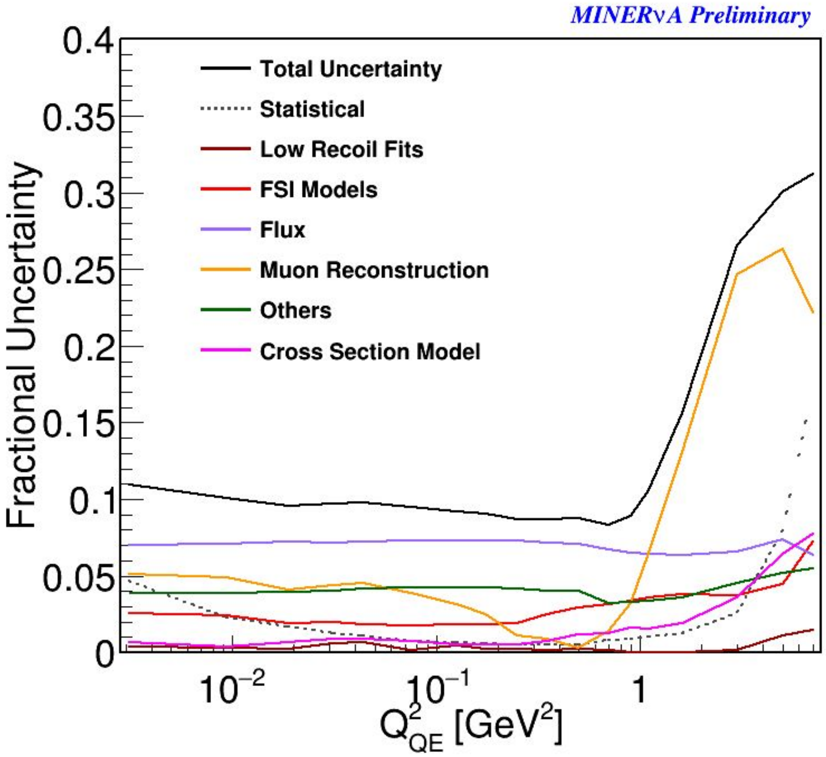
Comparison
Data / MnvGENIE v1 / GENIE 2.12.6



# Cross Section Results
# 1D Q2 Systematics

Fractional Uncertainty in the 1D $Q^2_{QE}$ cross section

Dominated by the flux and muon reconstruction

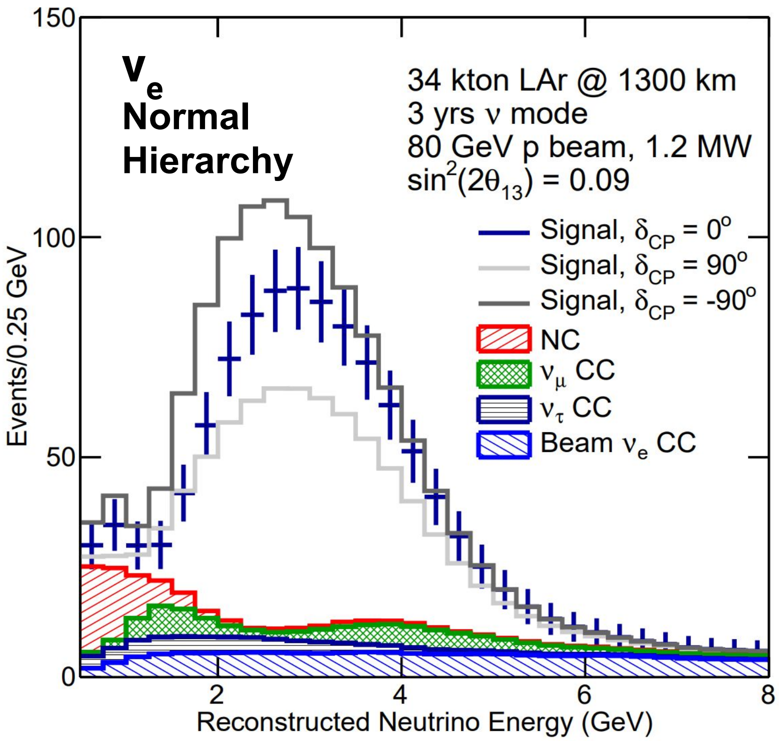


# We need to be ready for DUNE and Hyper-K!

DUNE will study the CP phase and mass hierarchy by measuring $\nu_\mu \rightarrow \nu e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions

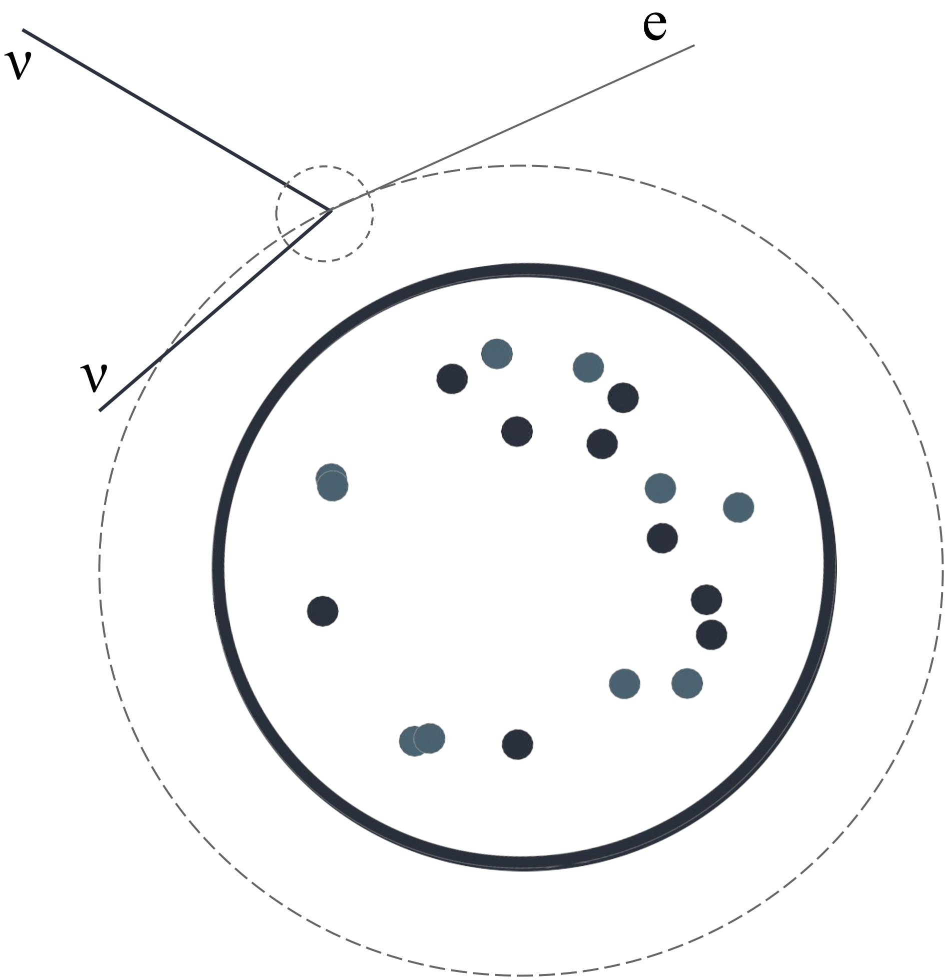
The energy spectrum of $\nu_e$'s and $\bar{\nu}_e$'s at the far detector is subtly different for different values of CP violation and substantially different for the two mass hierarchies

LBNE Collaboration
arXiv:1307.7335




*also, we keep using $\nu_\mu$ physics for $\nu_e$ events

# The Nucleus!



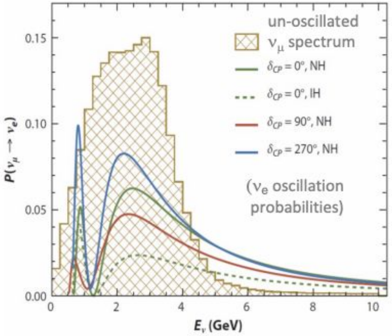

**Initial State Interactions**

Neutrinos can interact in a variety of channels:

- Quasi-Elastic
- Resonance
- Deep Inelastic Scattering
- **Neutrino - electron elastic scattering**

# Beam Physics with the Far Detectors

- DUNE is unique in that we can unambiguously distinguish the MO, CPV and do not require inputs from other experiments.



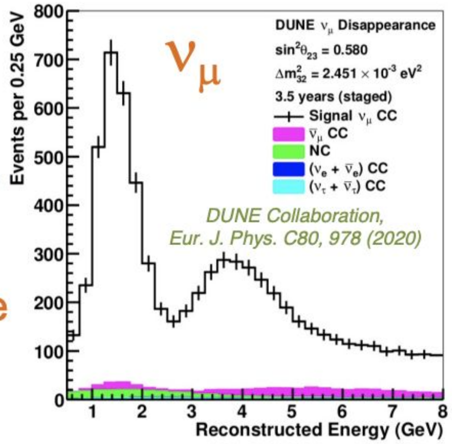

- Phase II is critical!

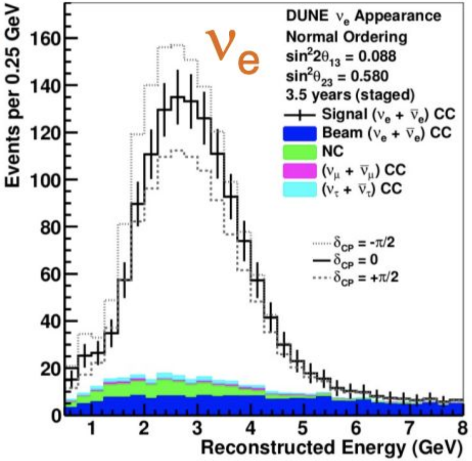
*(Chris Marshall's talk)*

disappearance

$\nu_\mu \to \nu_e$

appearance



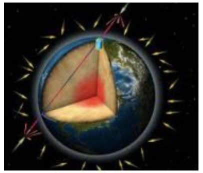

- When beam turns on, the DUNE far detectors will collect ~150 oscillated $\nu_e$ events in the first year alone. This is larger than each of the current NOvA, T2K $\nu_e$ data sets. We immediately hit the ground running.

  - *assuming a beam ramp-up to 1.2 MW, 2 FDs, normal ordering, $\delta_{CP}$=0*
  - *expected range is 70-180 $\nu_e$ events in FHC, depends on true MO, CP*

# Non-Beam Physics with the Far Detectors (Phase I)

- DUNE science begins as soon as far detectors turn on (2028). *(Chris Marshall's talk)*
- DUNE will collect large samples of $\nu$'s from the earth's atmosphere, sun, and from a Galactic core-collapse supernovae. Plus will look for BSM physics & nucleon decay. Information coming from DUNE is very different. Important comparisons with JUNO, Hyper-K possible. Gets even better with Phase II!

## Atmospheric neutrinos

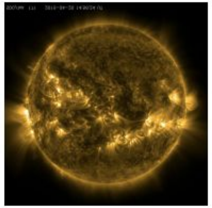


- *While not as sensitive, are also a tool for studying $\nu$ oscillations to compare with beam $\nu$'s*
- *Important theory work showing new types of analyses possible because of LAr TPC in DUNE*

*C. Ternes, S. Gariazzo, R. Hajjar, O. Mena, M. Sorel, M. Tortola, PRD 100, 093004 (2019)*

*K. Kelly, P. Machado, I. Martinez-Soler, S. Parke, Y. Perez-Gonzalez, PRL 123, 081801 (2019)*

*K. Kelly, P. Machado, I. Martinez-Soler, Y. Perez-Gonzalez, JHEP 05, 187 (2022)*



## Solar neutrinos

- *will measure $^8B$ and the yet un-observed hep solar $\nu$ flux in Phase 1*
- *With ability to measure solar $\nu$'s, will be able to measure all of the $\nu$ mixing parameters in a single experiment*

## Supernova neutrinos

- *unique sensitivity to $\nu_e$ due to LAr*
- *will immediately be a part of SNEWS*

General Motivation

# We need to be ready for DUNE and Hyper-K!

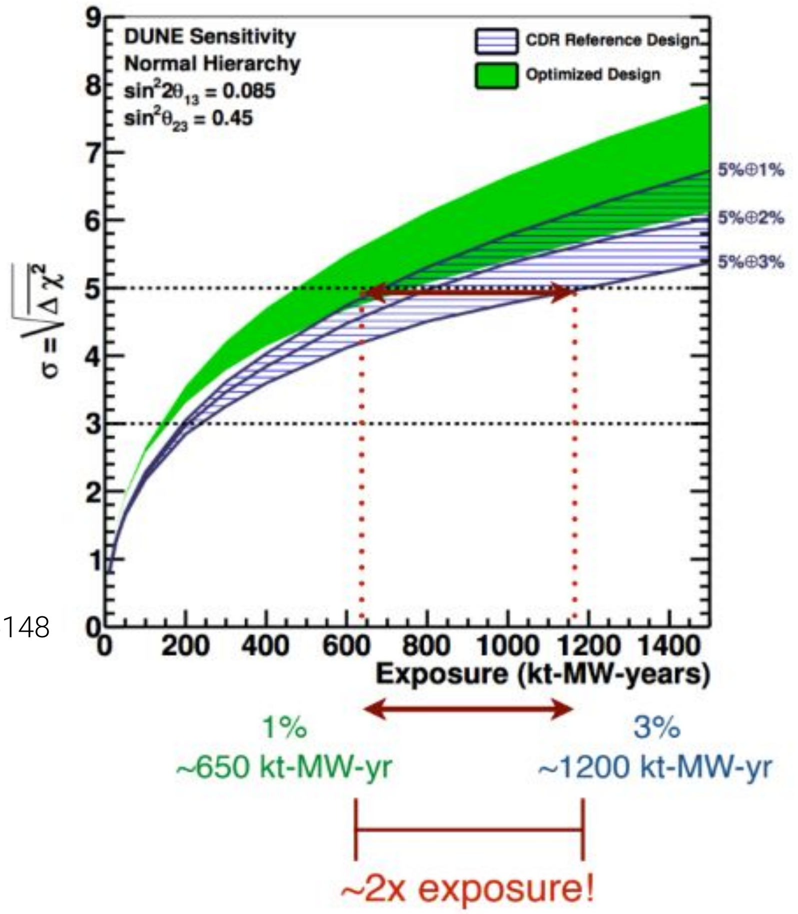
We want precision neutrino oscillation measurements and **reducing systematics uncertainties is critical**

This includes neutrino **interaction cross sections**

Oscillation experiments **rely on neutrino-nucleus interaction models** in neutrino event generators.

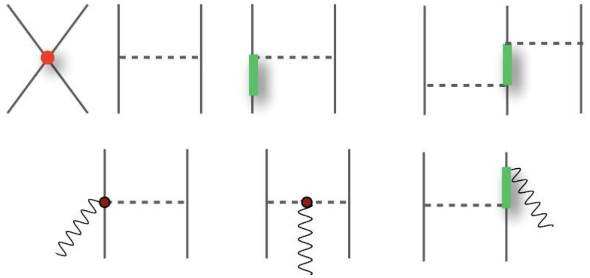
Need **better model** and high precision data

DUNE CDR, arXiv:1512.06148



# A more fundamental approach

## Effective Hamiltonians and consistent currents

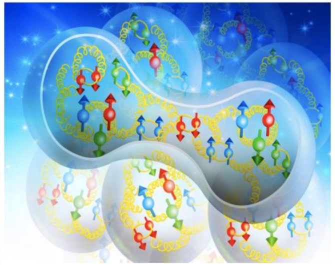


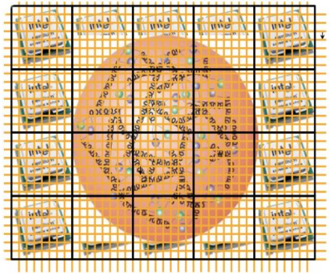
## Accurate nuclear many-body methods


$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

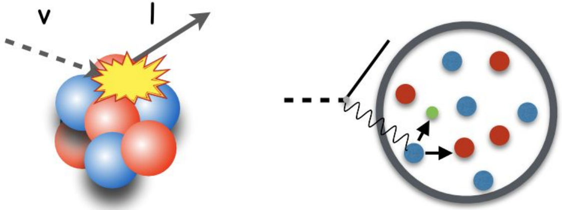
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

## Quantum Chromodynamcs



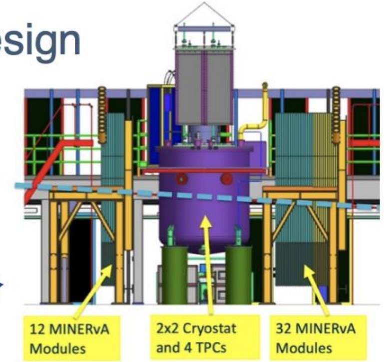


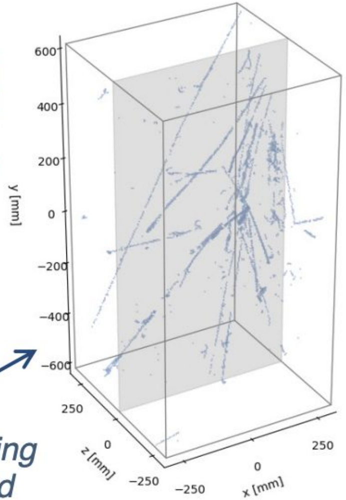
## Neutrino-nucleus interactions



# DUNE Near Detector Status (Phase I)

- We are also building prototypes of the near detector
    - *2x2 Demonstrator in NuMI beam at Fermilab*
    - *Full Scale Demonstrator (FSD) of ND-LAr*
- Important to test pixelated, modular design
- Like with the protoDUNEs, we will be getting physics out of ND prototypes
- ND-LAr 2x2 Demonstrator is being installed in the NuMI beam
    - *this will be the first ν data from DUNE*




*fully instrumented 20% scale ND-LAr module operating at U Bern, Switzerland*

- Also, KLOE magnet is currently being disassembled in Frascati for shipment to Fermilab for SAND

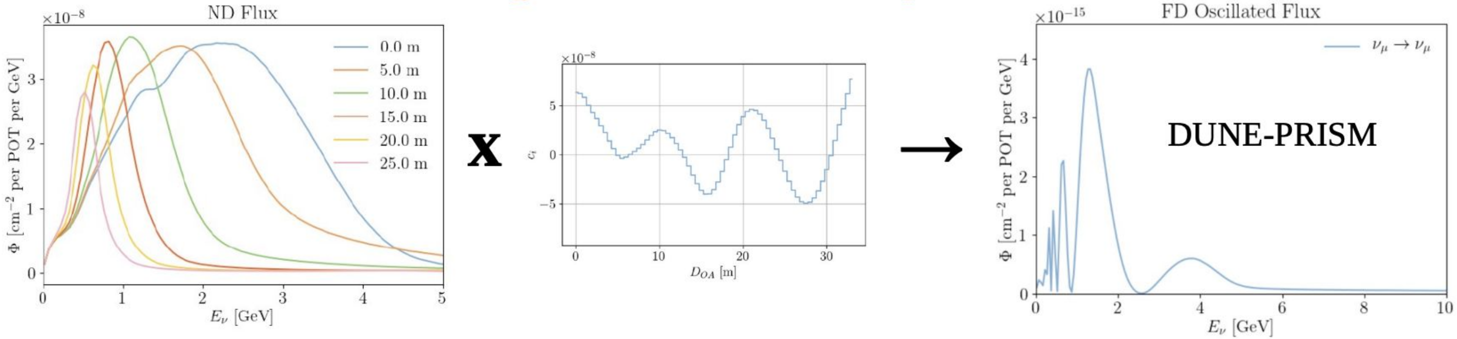
INFN National Institute for Nuclear Physics

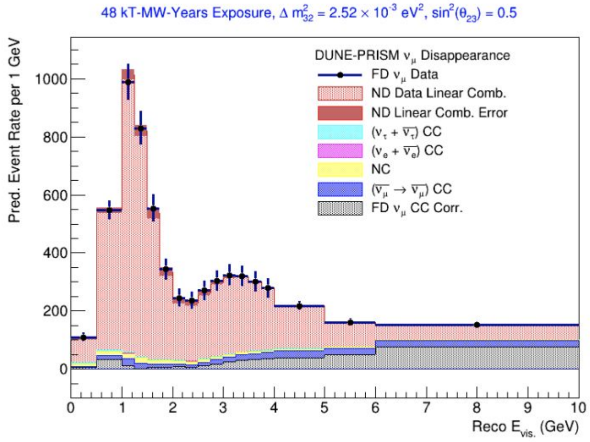
LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN

BERKELEY LAB

SLAC

# PRISM plays a critical role in enabling DUNE's precision




- FD flux ≠ ND flux → uncertainties in energy dependence of flux, cross sections
- ND flux changes with angle → take ND data in different fluxes → build linear combination to match FD *oscillated* spectra
- For LBL: robust analysis approach with very minimal dependence on interaction modeling
- Also extends dark matter sensitivity