Experimental Neutrino Cross Sections

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York/Fermilab

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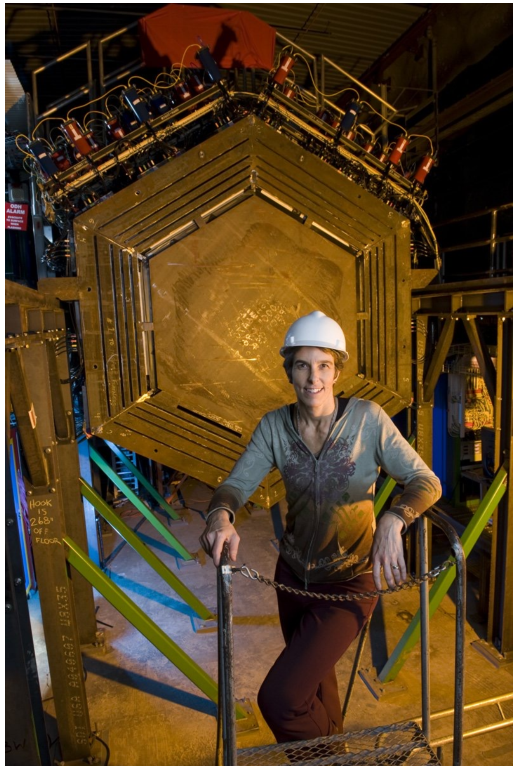
International Neutrino Summer School

Who am I?

- This is the start of my fifth year as a prof at York U., with a joint appointment with Fermilab.
- Before that, I worked 20 years as a Scientist at Fermilab
- Before that, I was a postdoc for U of Rochester, also doing a neutrino experiment at Fermilab
- Before that, I was a grad student at U of Chicago, working on a Kaon Experiment at Fermilab
- Have seen different aspects of particle physics:
  - Graduate thesis looking for CP-violation in rare Kaon decays
  - Spent postdoc years studying weak interactions with high energy (~100GeV) neutrinos
  - Started working on neutrino oscillations (~GeV neutrinos)
    - Initially worked on neutrino beam designed for MINOS
    - Started worrying about neutrino interactions-enter MINERvA!
    - Collaborator on T2K & DUNE



Haven't we heard enough about cross sections?

- Noemi Rocco: 2 lectures on Theory of neutrino interactions
- Stephen Dolan: 2 lectures on Neutrino Interactions and Generators
- Sowjanya Gollapinni: "Neutrino Interactions are Complex"

- Yours Truly: 2 lectures on "Experimental Neutrino Cross Sections"
    1. How to make a cross section measurement
    2. Tricks of the Trade: how to use your own data to make a reliable cross section measurement

Quick soapbox

- There is a lot that goes into cross section measurements
- Papers don't always have enough space to describe those details
- These lectures are meant to explain how to measure a cross section
- Even if you don't measure one yourself, I hope to give you tools to know what a detailed cross section publication *should* be talking about
- Morals of this story:
  - Every measurement has backgrounds
  - No detector is perfect
  - No cross section model is perfect
  - But there are ways to ensure your cross section measurement is valid anyway!

https://www.theguardian.com/science/blog/2014/jun/27/women-scientists-soapboxes-london-south-bank-soapbox-science

Top ten reasons to measure cross sections

1. To understand the weak interaction
2. To understand the structure of the nucleus
3. There is lots of non-perturbative QCD here, it is not something that is calculable from first principles, need data
4. To improve precision in neutrino oscillation experiments
5. You can’t find Beyond the Standard Model Physics until you account for the standard model neutrino interactions!
6. You need to predict the backgrounds to your dark matter experiment
7. You get to be involved with all the parts of an analysis
8. Your measurement may get used by lots of other experiments

Reason 9: it makes an awesome thesis topic!

- Even if you ARE on an oscillation experiment, there’s some chance your thesis will be a neutrino cross section measurement
- NOvA: https://novaexperiment.fnal.gov/theses/
  - 13 out of 63 Doctoral Theses were on cross sections
- T2K: https://t2k.org/docs/thesis
  - 57 out of 138 PhD+Masters theses have been on cross sections!

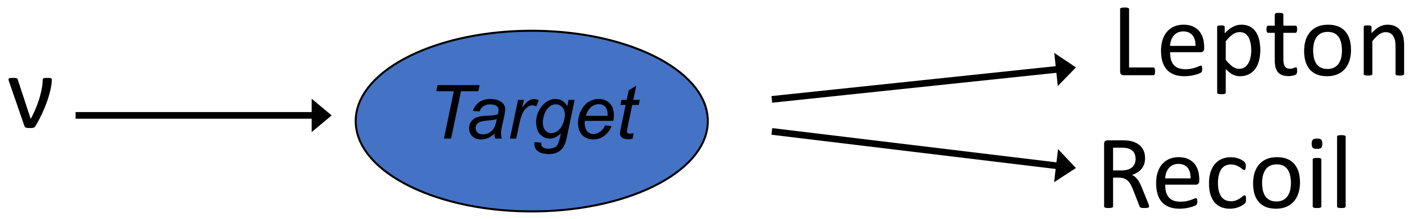
As of August 12, 2023

	Dates	Source	Primary Energy (GeV)	P [kW]	M [kt]	L [km]	E [GeV]
K2K	1999 - 2004	KEK PS	12	5.2	22.5	250	0.9
T2K	2010 - present	JPARC	30	515	22.5	295	0.6
T2HK	2027	JPARC	30	[500,1 300]	188	295	0.6
MINOS	2005 - 2012	Fermilab Main Injector	120	240	5.4	735	3.6
MINOS+	2013 - 2016	Fermilab Main Injector	120	700	5.4	735	6.2
NOvA	2014- present	Fermilab Main Injector	120	400 - 960	14	810	1.8
DUNE	>2030	Fermilab Main Injector	120	1000 - 2400	40	1350	2.2
CNGS / OPERA	2008 - 2012	CERN PS	400	512	1.25	730	1.25

From Mark Messier, INSS23

Reason 10: to learn more about neutrinos

- *Quick wakeup question: what can we learn about neutrinos WITHOUT seeing them interact?*
- Creation of that final state may require energy to be transferred from the neutrino



  - In charged-current reactions, where the final state lepton is charged, this lepton has mass
  - The recoil may be a higher mass object than the initial state, or it may be in an excited state

K. McFarland, INSS 2013

Thresholds and processes

Process	Considerations	Threshold (typical)
$\nu N \rightarrow \nu N$ (elastic)	Target nucleus is often free (recoil is very small)	None ("CEνNS")
$\nu_e n \rightarrow e^- p$	In some nuclei (mostly metastable ones), this reaction is exothermic if proton not ejected	None for free neutron and some others.
$\nu e \rightarrow \nu e$ (elastic)	Most targets have atomic electrons	~ 10eV – 100 keV
anti-$\nu_e p \rightarrow e^- n$	$m_n > m_p$ & m_e. Typically more to make recoil from stable nucleus.	1.8 MeV (free p). More for nuclei.
$\nu_\ell n \rightarrow \ell^- p$ (quasielastic)	Final state nucleon is ejected from nucleus. Massive lepton	~ 10s MeV for ν_e +~100 MeV for ν_μ
$\nu_\ell N \rightarrow \ell^- X$ (inelastic)	Must create additional hadrons. Massive lepton.	~ 200 MeV for ν_e +~100 MeV for ν_μ

- Energy of neutrinos determines available reactions, and therefore experimental technique

K. McFarland, INSS 2013

Thresholds and processes

Process	Considerations	Lecturer at INSS 2023
$\nu N \rightarrow \nu N$ (elastic)	Target nucleus is often free (recoil is very small) Sometimes called "CEνENs"	Josh Spitz (COHERENT source) Bill Louis (CEνENs background)
$\nu_e n \rightarrow e^- p$	In some nuclei (mostly metastable ones), this reaction is exothermic if proton not ejected	Jelena Maricic (solar ν's) Irene Tambora (SuperNovae)
$\nu e \rightarrow \nu e$ (elastic)	Most targets have atomic electrons	Jelena Maricic (solar ν's)
anti-$\nu_e p \rightarrow e^- n$	$m_n > m_p$ & m_e. Typically more to make recoil from stable nucleus.	Jelena Maricic (reactor ν's)
$\nu_\ell n \rightarrow \ell^- p$ (quasielastic)	Final state nucleon is ejected from nucleus. Massive lepton	Jelena Maricic (solar ν's), Ed K Mark Messier (accelerator ν's)
$\nu_\ell N \rightarrow \ell^- X$ (inelastic)	Must create additional hadrons. Massive lepton.	Mark Messier (accelerator ν's) Irene Tambora (Astrophysics)

- Energy of neutrinos determines available reactions, and therefore experimental technique

K. McFarland, INSS 2013

Why measure cross sections if you have a near detector?

- "2-detector strategy": two detectors, identical technology, target nucleus, detector acceptance, just compare near and far spectra!

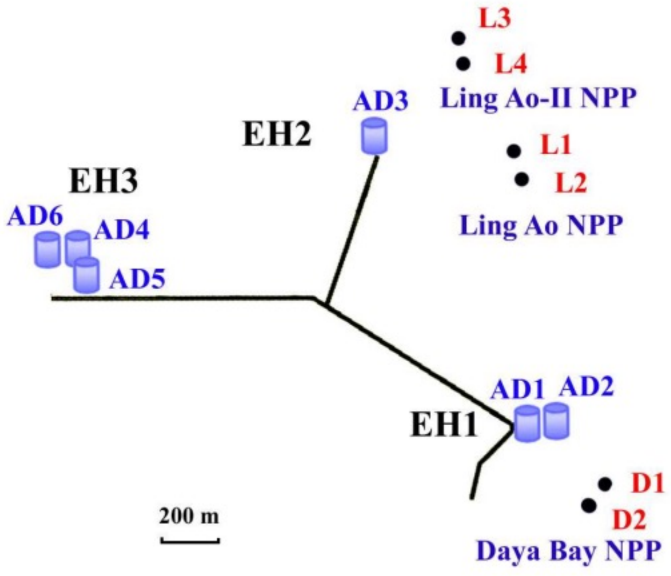
Observation of electron-antineutrino disappearance at Daya Bay #32

Daya Bay Collaboration • F.P. An (Beijing, Inst. High Energy Phys.) et al. (Mar, 2012)

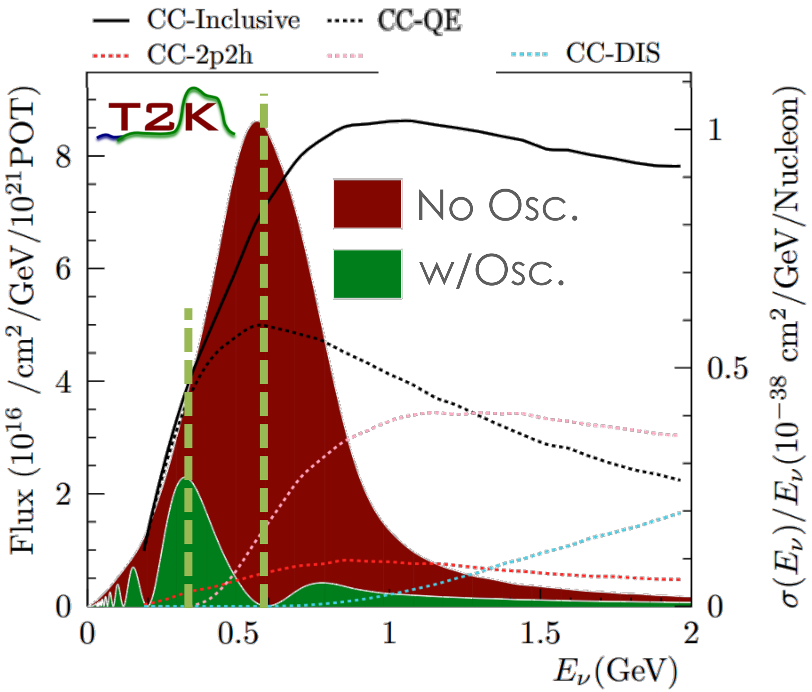
Published in: *Phys.Rev.Lett.* 108 (2012) 171803 • e-Print: 1203.1669 [hep-ex]

pdf links DOI cite claim reference search 2,8

- Daya Bay reactor experiment:
  3 near detectors, 3 far detectors
- Turned on their near detectors first!
- Published their first reactor measurement of θ_{13} in March 2012
  - After only 55 live time days of the far detectors
- Classic example of identical detectors near and far, to measure small $\bar{\nu}_e$ disappearance probability



Event rates to oscillation parameters



- Near / far ratios don't fully cancel systematics:
  - Dramatic change in E_ν distribution due to oscillations
  - ν_μ at ND vs ν_e at FD (for appearance)
  - Different ND/FD design, acceptance

S. Dolan, INSS 23

At the near detector

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

Interaction cross section

Neutrino flux

Detector effects

At the far detector

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

Oscillation probability

How to measure a Cross Section

- You've seen this expression before:

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

- (I added the "M" for detector mass)
- More generally, consider an observable *x* that describes the interaction

$$\mathrm{N}(x_{true}) = \int \frac{d\sigma(E_\nu, x_{true})}{dx_{true}} \Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M dx_{true}$$

- And no detector is perfect, so what we really measure is as a function of "$\mathrm{N}(x_{measured})$" , so there's an additional step

Quick word about units

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

- What are the units of the different components?
  - N: number of events, unitless
  - σ: cross section, area per target (for neutrinos, usually x10^{-38} cm^2)
  - Φ: flux, Neutrinos per unit area (for near detector location, cm^{-2})
    - example: NOvA reports*: 87ν_μ/cm^2/10^{10} POT or for 10^{20} POT, 10^{12} ν/cm^2
  - ε: efficiency, unitless
  - M: ”mass” must be “number of targets” : recall this is 6.023x10^{23} if your detector weighed 1 gram

*Phys.Rev.D 107 (2023) 11, 112008

How to measure a cross section

- From the equation: $\mathrm{N}(x_{true}) = \frac{d\sigma(E_\nu, x_{true})}{dx_{true}} \Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M$

$$\mathrm{N}(x_{measured}) = \int U(x_{measured}, x_{true}) \frac{d\sigma(E_\nu, x_{true})}{dx_{true}} \times \Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M \, dx_{true}$$

U written this way is a "smearing" step that translates from the true quantity to a reconstructed quantity

Solving for ${}^{d\sigma}/_{dx}$

$$\frac{d\sigma(E_\nu, x_{true})}{dx_{true}} = \frac{\mathrm{N}(x_{measured})\, U^{-1}(x_{measured}, x_{true})}{\Phi_\nu(E_\nu)\epsilon(x_{true}, E_\nu)M}$$

- And in real life, there are backgrounds: not every event you select is going to be the signal process you are looking for!
- Integrate over the entire flux to find:

$$\frac{d\sigma(x_{true})}{dx_{true}} = \frac{(\mathrm{N}(x_{measured}) - B)U^{-1}(x_{measured}, x_{true})}{\int \Phi_\nu\, \epsilon(x_{true})M\Delta x_{true}}$$

Measuring Cross Sections: Simplify notation

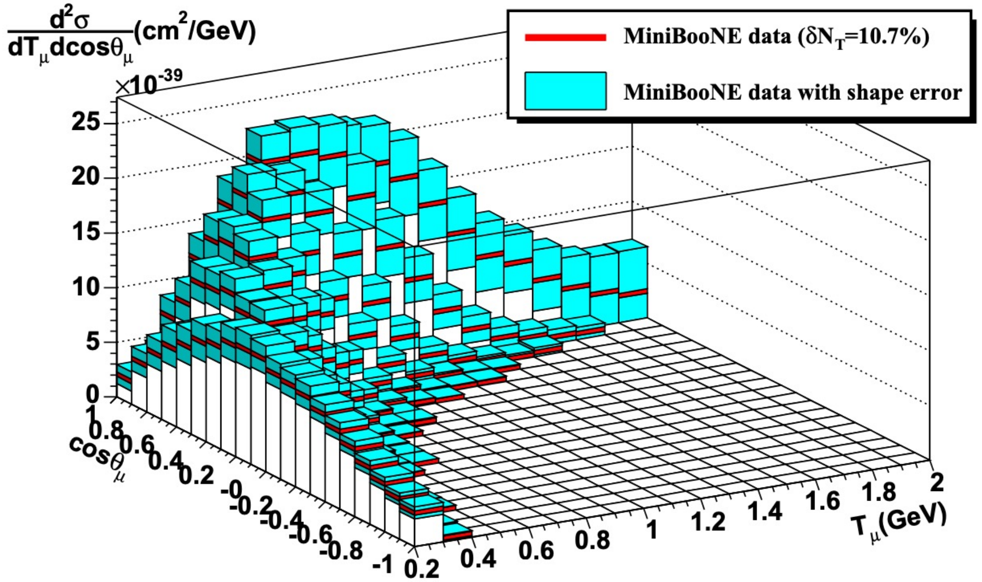
- Remove subscript from true variables, but t=bin of x_{true}, m=measured
- We'll write phi but it really means "integrating over the flux"
- Switch from U^{-1} to U again just for simplicity, sometimes called "unfolding"

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

- Deconstruct this piece by piece, from the easiest to the most complicated:

Will discuss 1-dimensional cross sections but..

- But there are plenty of reasons to try to measure cross sections in more than just one dimension!
- 2-D example from MiniBooNE: 3-D example from MINERvA:



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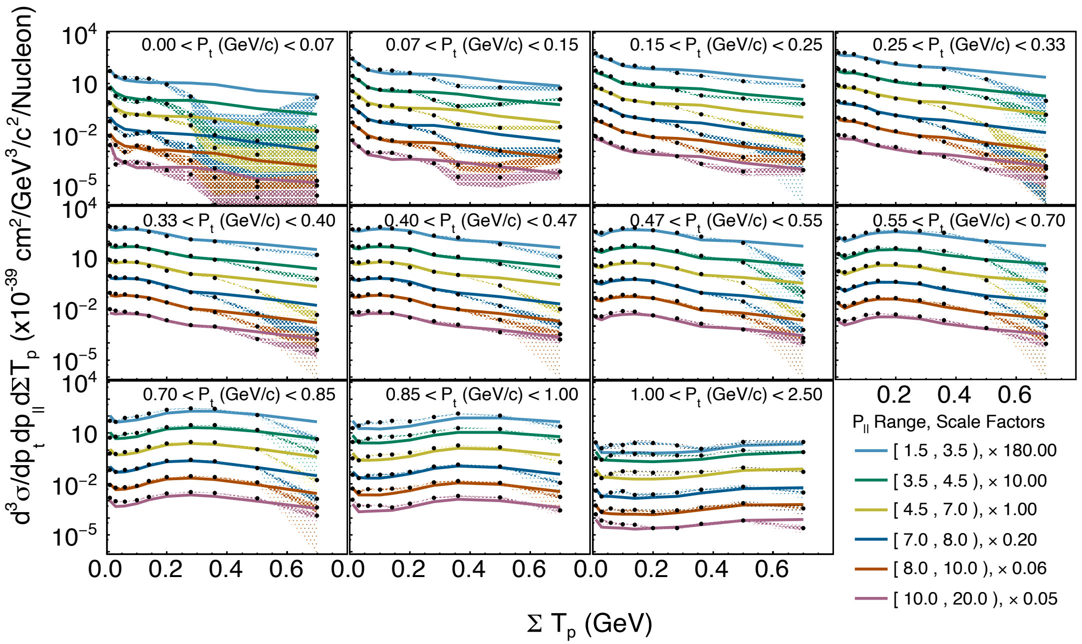


Phys.Rev.Lett. 129 (2022) 2, 021803

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(N(x_m) - B(x_m))\,U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

- $N(x_m)$: This is the number of events in your data after you've made all the cuts in your analysis to remove all the events that aren't the process you are trying to measure

- This is either the easiest (N) or the most complicated to explain (x_m)

- What's the process you are looking for?
  - If it's a charged current event: need a final state lepton (muon or electron)
  - After that it's more complicated

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

- M: ”Mass” [nucleons] Sounds easy, right?
- Cross sections are usually reported “per nucleon” so…

- BUT, it depends on what cross section you are trying to measure: are you trying to measure something “per nucleon”?

- What if you are measuring something that (in principle) only happens on neutrons? (i.e. $\nu_\mu + n \rightarrow \mu^- + p$)
- What if you are measuring something that (in principle) only happens on protons? (i.e. $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$)

Full Disclosure on calculating "M"

- For Liquid Argon detector, it's very pure so you can be sure the nucleus that is struck is Ar
- For Water, at least at SK or HK those detectors are very pure H_2O
- But scintillator-based detectors may not always be all CH or CH2:
  for example NOvA:

Element	Mass [kg]	Nucleon Count	Mass Fraction
H	3814.5	2.28×10^{30}	0.108
C	23650	1.41×10^{31}	0.667
O	1050	6.30×10^{29}	0.030
Cl	5690	3.40×10^{30}	0.161
Ti	1140	6.81×10^{29}	0.032
Other	95	5.7×10^{28}	0.003

- *Phys.Rev.D* 107 (2023) 11, 112008

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

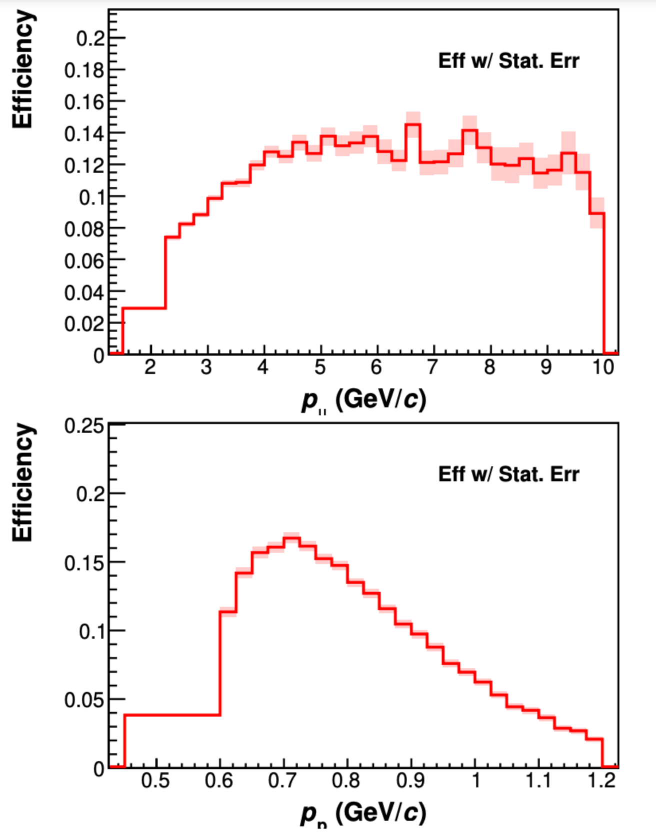
- Φ_ν: Flux [neutrinos/cm^2]
- Usually the cross section is reported assuming you've integrated over all neutrino energies: so Φ really means
- $\Phi_\nu = \frac{\int dE_\nu \Phi_\nu(E_\nu)}{\int dE_\nu}$
- For the rare cases where neutrino energy is measurable

Total Cross Section:

$$\sigma(E_\nu) = \frac{(\mathrm{N}(E_\nu) - B(E_\nu))\, U_{mt}}{\Phi_\nu(E_\nu)\epsilon(E_\nu) M}$$

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(N(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

- $\epsilon(x_t)$: Efficiency [unitless]
- The fraction of signal events that you retain after making all the analysis cuts to remove your backgrounds
- In truth, this efficiency may depend not only on x_t but also on neutrino energy, and remember you're integrating over the flux
- $\epsilon(x_t) = \frac{\int \epsilon(x_t, E_\nu)\Phi_\nu dE_\nu}{\int \Phi_\nu dE_\nu}$



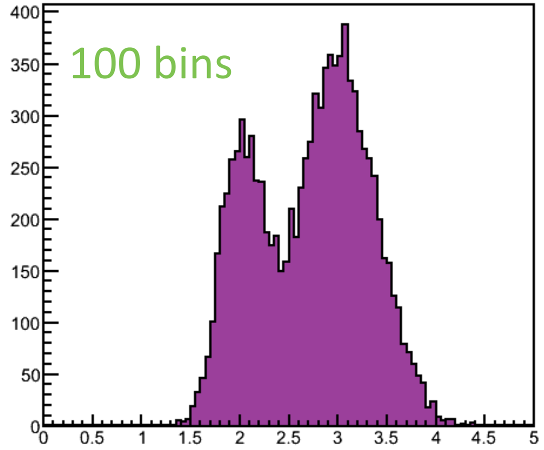
MINERvA Phys. Rev. D. 101 092001, TKI analysis

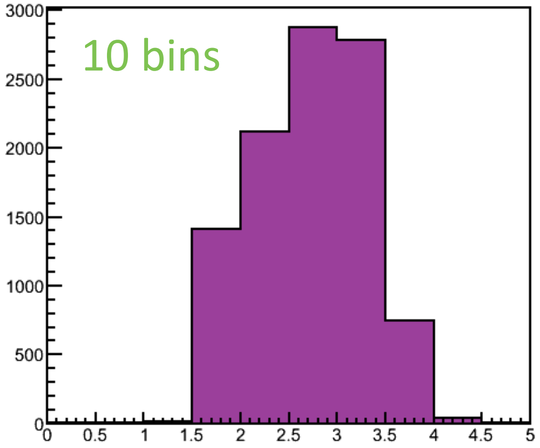
Except for the case of the Total Cross Section:

$$\sigma(E_\nu) = \frac{(N(E_\nu) - B(E_\nu))\, U_{mt}}{\Phi_\nu(E_\nu)\epsilon(E_\nu) M}$$

$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x) M \Delta x}$$

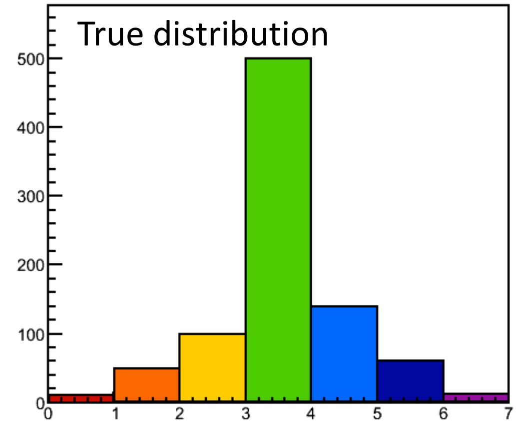
- Δx: Bin width [units of whatever x is]
- How wide should this bin width be?
- The more bins you have, easier to distinguish features of the distribution
- The more bins you have, the worse the statistics are in each bin
- BUT…Depends on your resolution: if you can't measure something to better than δ , you shouldn't pick bins that are δ/10!

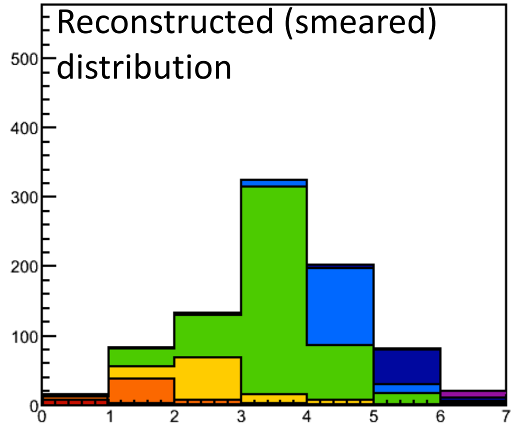




$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

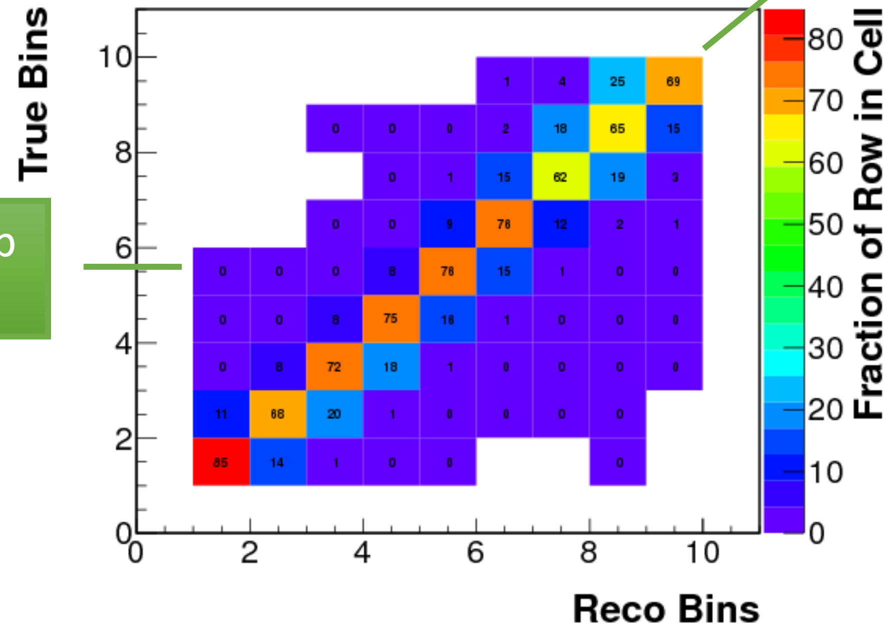
- U_{mt}: This is the "unsmearing matrix" that takes you from the measured variable to the true variable
- We want to know, if an event is observed in bin m, what bin did it really happen in?
- In other words, what's the probability that an event observed in bin m (measured) actually occurred in bin t (true)?
- We can use our Monte Carlo to form a migration matrix indicating what fraction of events generated in each true bin α were observed in each reconstructed bin j
- If the detector has good resolution, the matrix should be close to diagonal





$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

Each row adds up to 100%



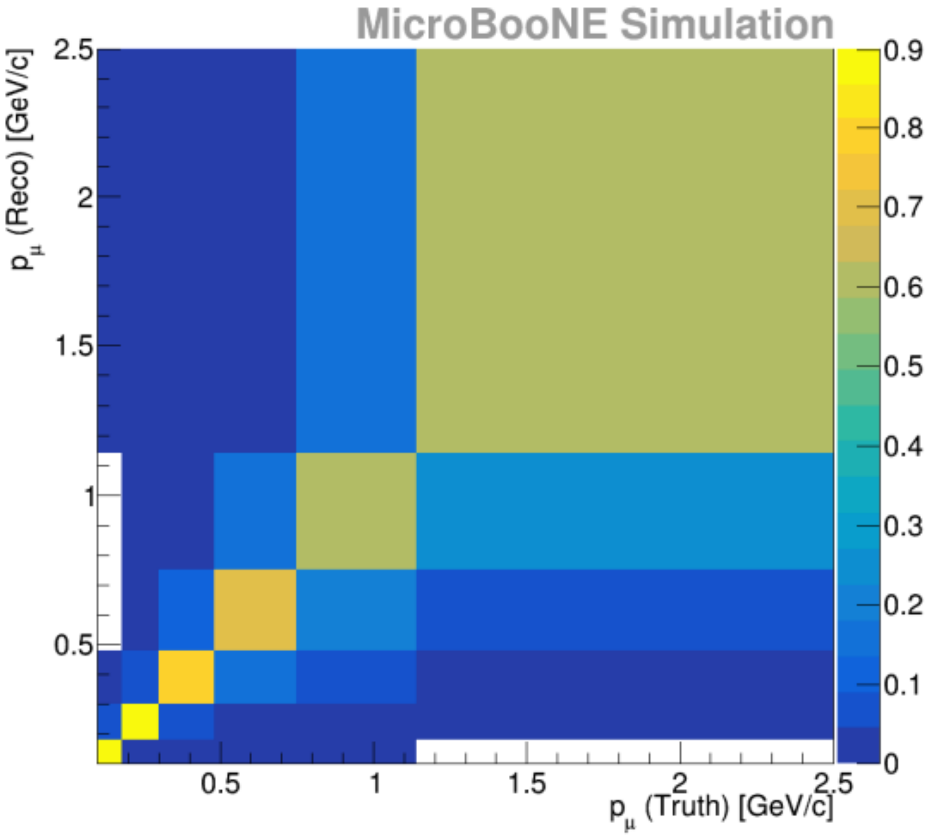
Diagonal corresponds to events reconstructed in the right bin

“Migration Matrix”

- To get the unsmearing matrix U_{tm}, you have to invert the migration matrix
- …in theory. In practice, it often gives poor results and we often need to use a more sophisticated method

Other migration matrices:

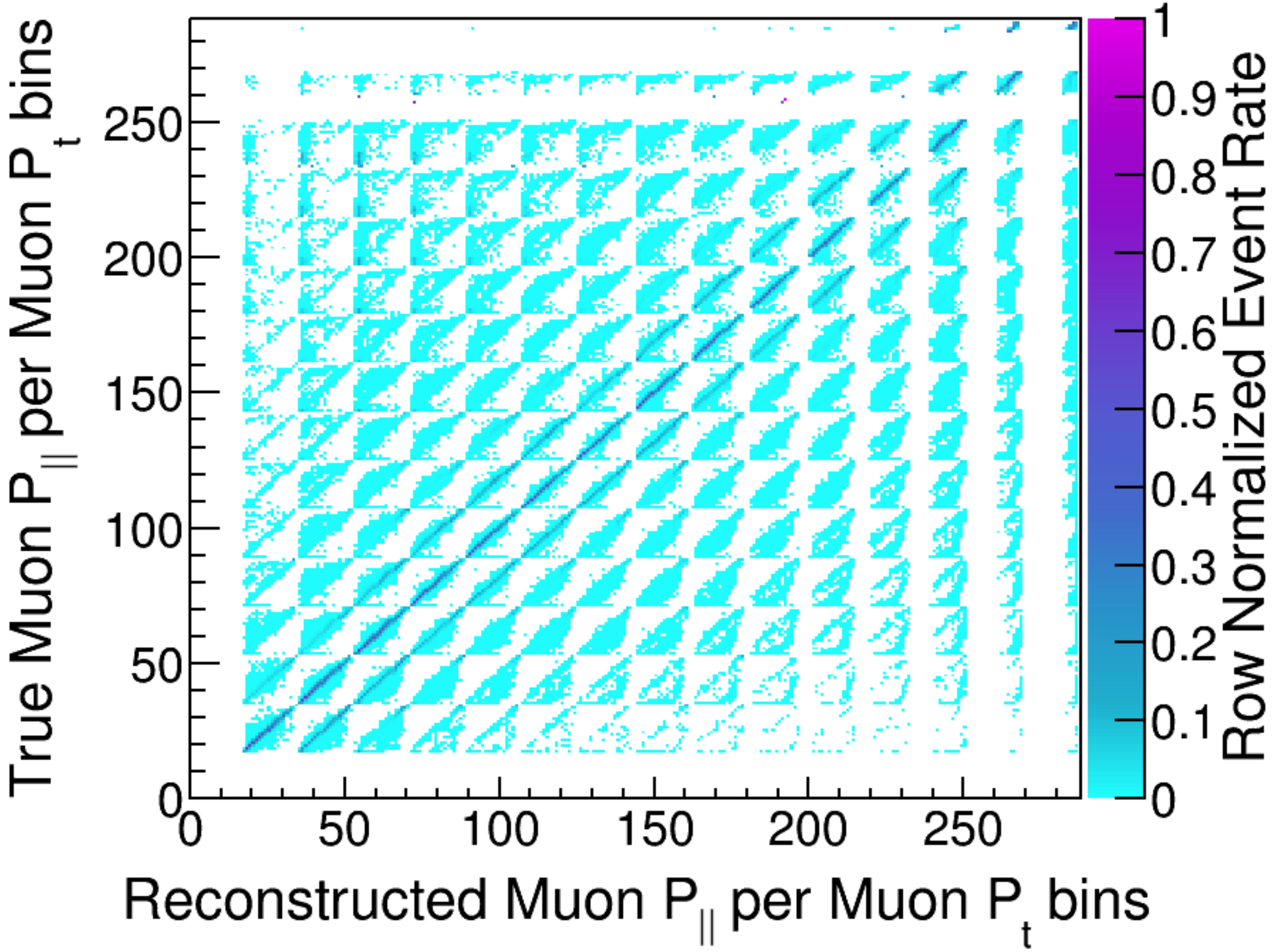
- MicroBooNE: muon momentum measured by range in liquid argon
- Note: experiments may not all publish these migration matrices or even call them by that name
- But any differential cross section measurement needs to take detector resolution into account



•*MicroBooNE Phys.Rev.D* 102 (2020) 11, 112013

Two-dimensional Migration Matrix

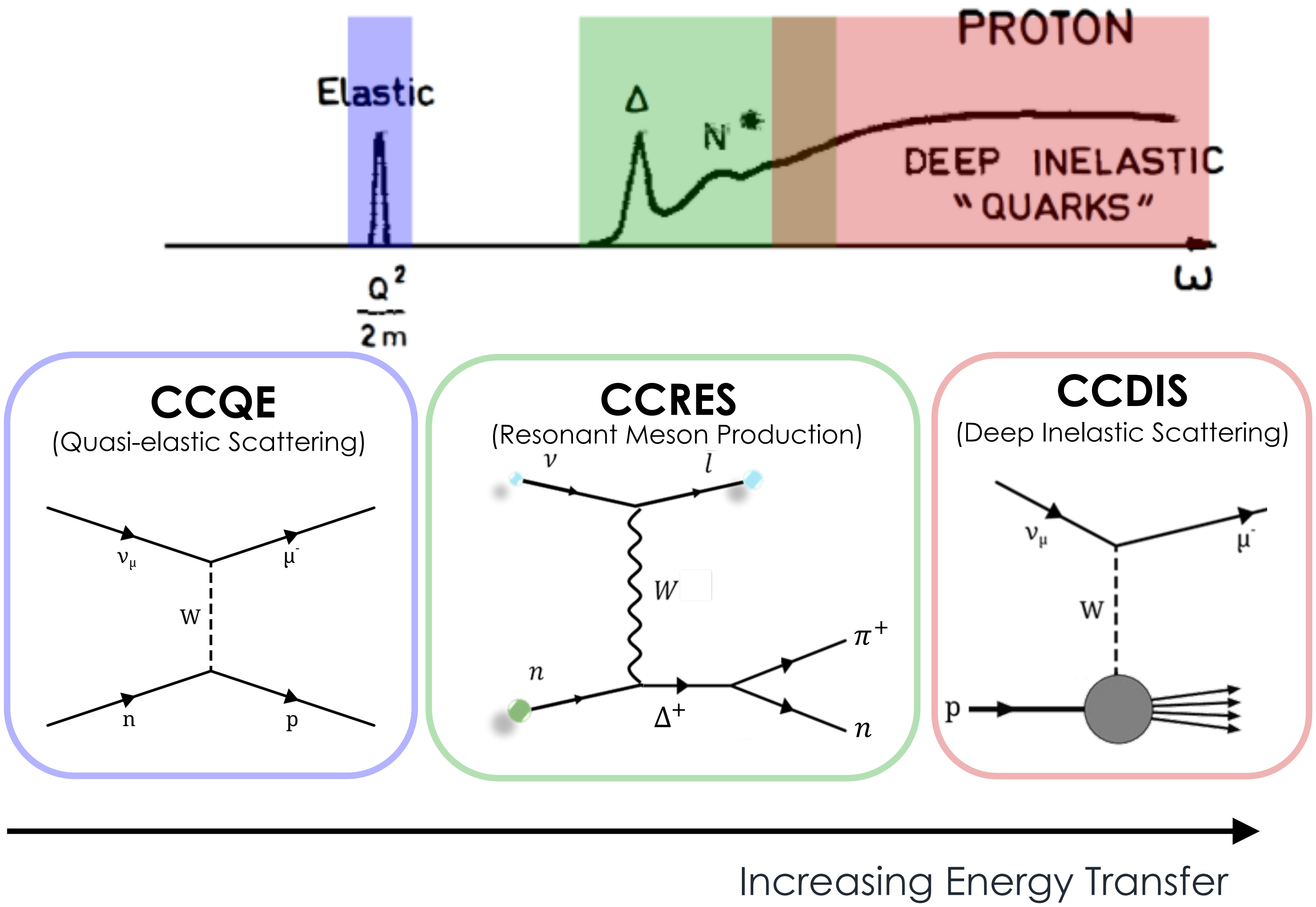
- Each bin in one dimension gets its own migration matrix
- Ref: A.Filkins, MINERvA W&C talk, 2/28/2020
- Only the 1-d matrices are shown inpublication *Phys.Rev.D* 101 (2020) 11, 112007



$$\frac{d\sigma(x_t)}{dx_t} = \frac{(\mathrm{N}(x_m) - B(x_m))\, U_{mt}}{\Phi_\nu \epsilon(x_t) M \Delta x}$$

- $B(x_m)$: These are the backgrounds that are still in the event sample even after you make all your cuts.
- $\mathrm{B}(x_m) = M \sum {U^{mt}}^{-1} \frac{d\sigma_B(E_\nu, x_{true})}{dx_{true}} \Phi_\nu(E_\nu)\epsilon_B(x_{true}, E_\nu)$
- You could predict what this background is from your simulation, but that prediction may have a large uncertainty!
  - Background Process Cross Section uncertainties (have to sum over all processes!)
  - Flux uncertainties (have to Sum over all fluxes!)
  - Have to smear back: is that smearing matrix the same for all backgrounds?

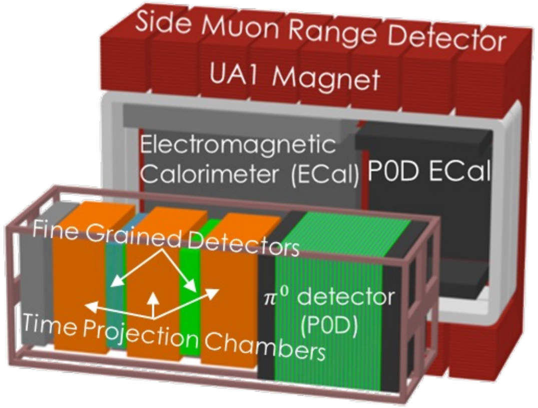
Neutrino nucleon scattering



One person's signal is another person's background!

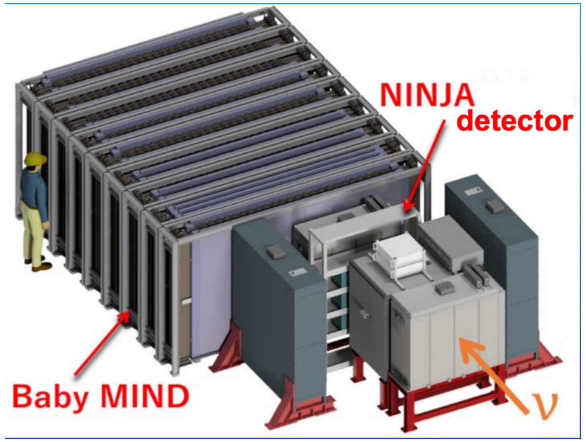
Graphics from S. Dolan, INSS 2023

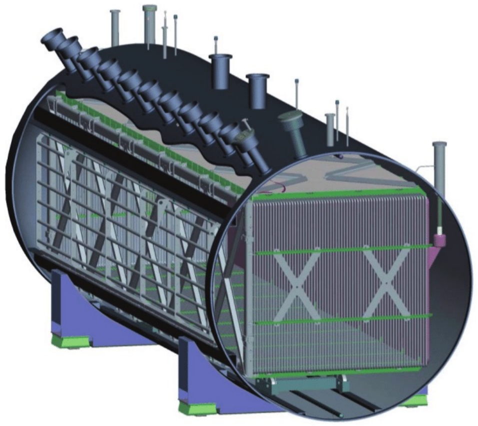
Experiments current releasing results (in 0.5-20GeV region)



T2K Near Detector: CH, H_2O

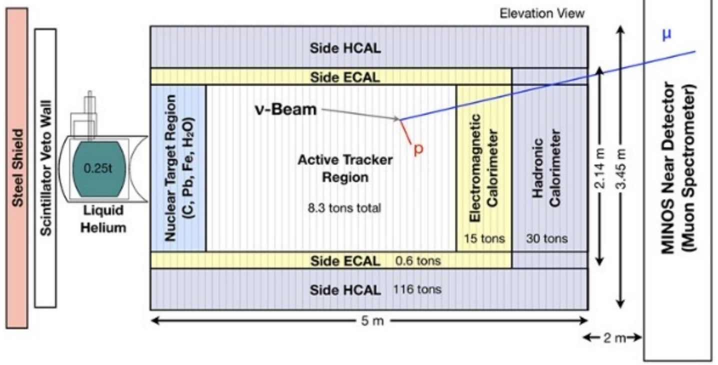
NINJA: CH, H_2O, Fe

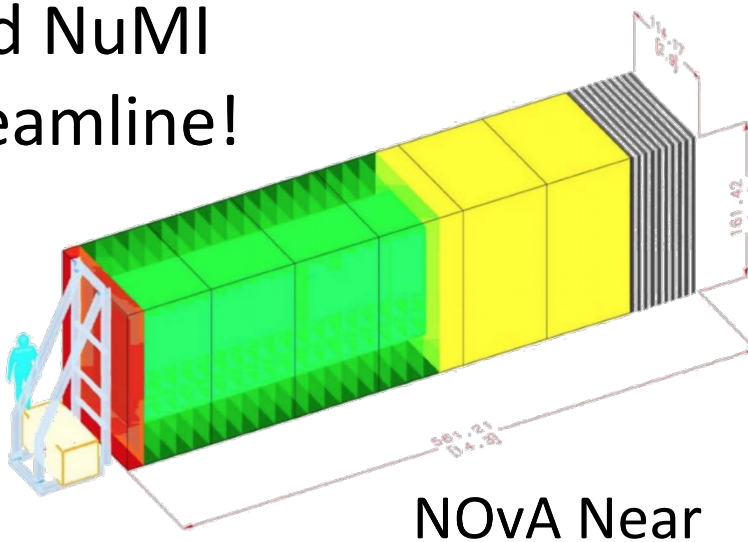




MicroBooNE: Liquid Argon TPC Booster and NuMI (off axis) beamline!

MINERvA: He, CH, C, H_2O, Fe, Pb





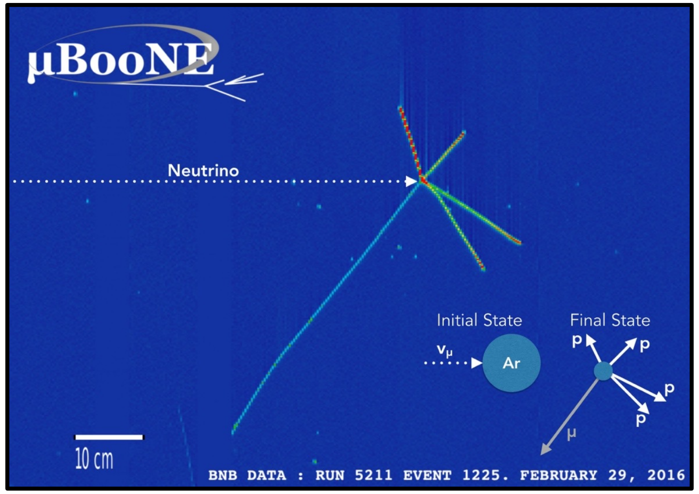
NOvA Near Detector: CH

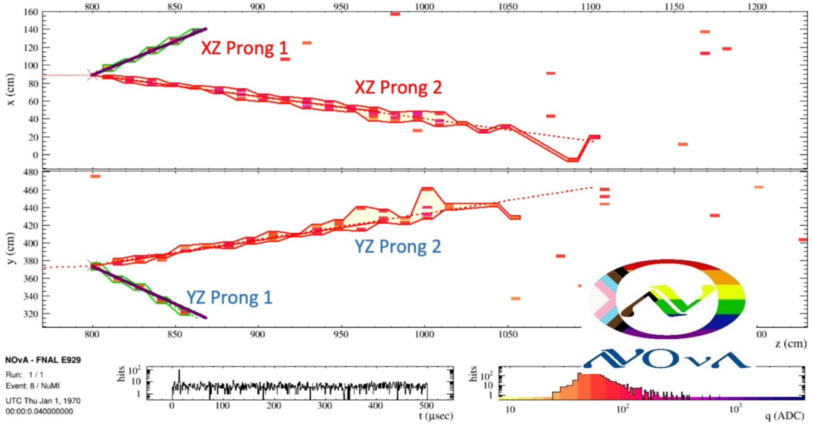
Fermilab YORK UNIVERSITÉ UNIVERSITY

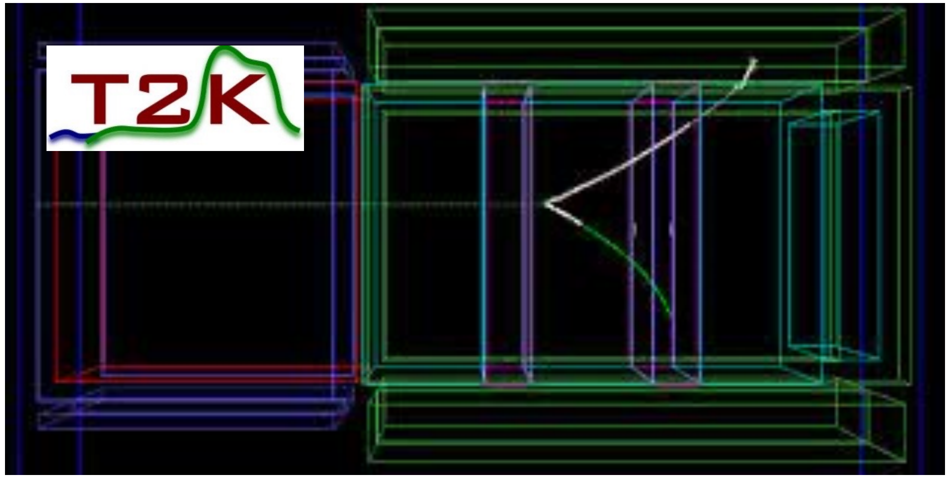
Modern Cross Section Experiments

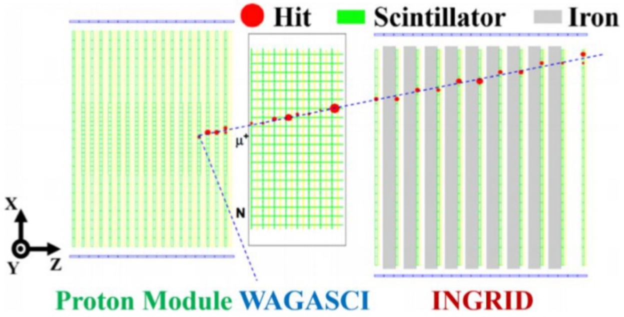
Experiment	Beam Energy	Target Nucleus	B field?	Granularity	Status
COHERENT	25MeV, broad	CsI, Ar, ….	No	various	Data-taking
MINERvA	3.5GeV and 6GeV, broad band	He, CH, C, H_2O, Fe, Pb	For muons only	1.6cm x3.3 cm triangles (scint)	Last data: 2019 Still analyzing
T2K (Wagasci)	600MeV	CH, H_2O	Yes!	~few cm triangles + Gas TPC	Data-taking in 2023
NOvA	2GeV	CH	No	4cmx6cm (scint)	Data-taking in 2023
NINJA	700MeV	Pb, H_2O	For muons only	Emulsion!	
MicroBooNE	600MeV (BNB) and 2GeV (NuMI)	Ar	No	3mm wire pitch	Data-taking ended in 2022 Still analyzing
ICARUS			No	3mm wire pitch	Data-taking in 2023
SBND	600MeV (BNB)		No	3mm wire pitch	Data-taking soon!

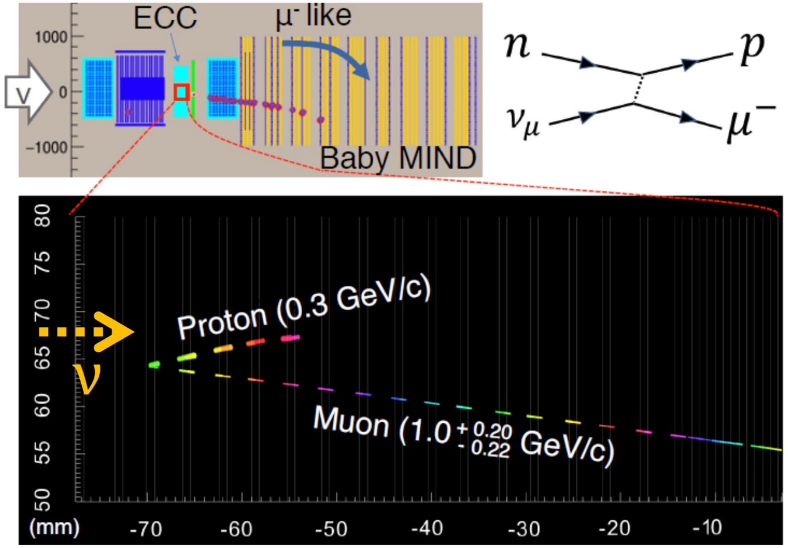
Neutrino Events at Some Experiments

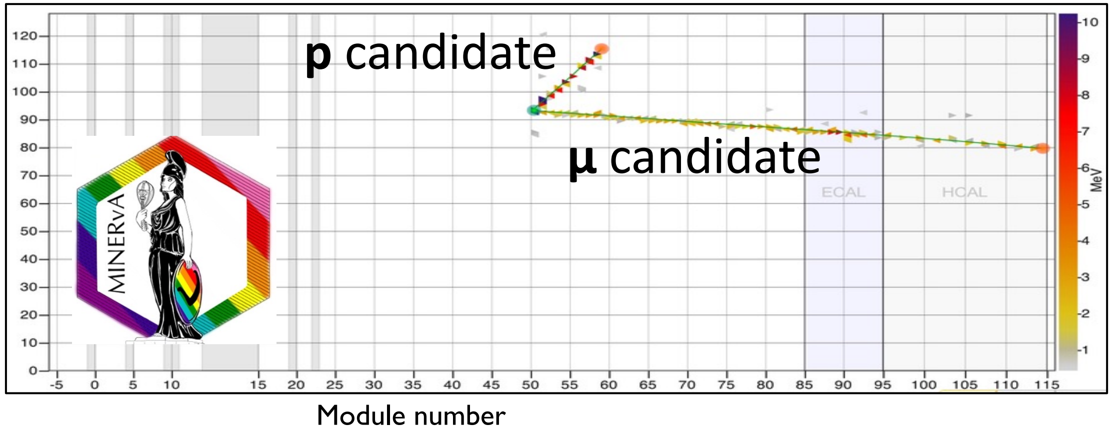






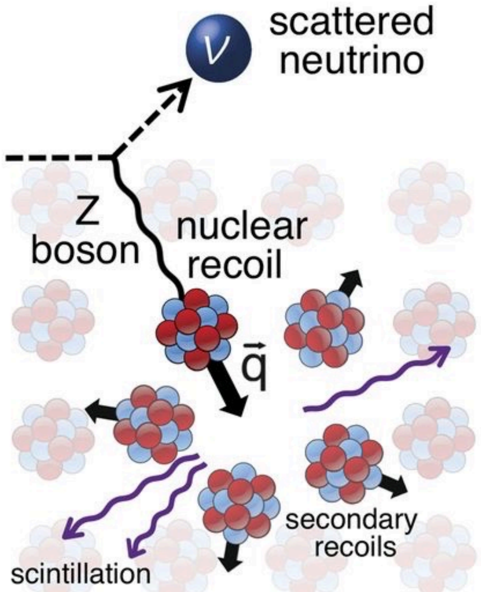


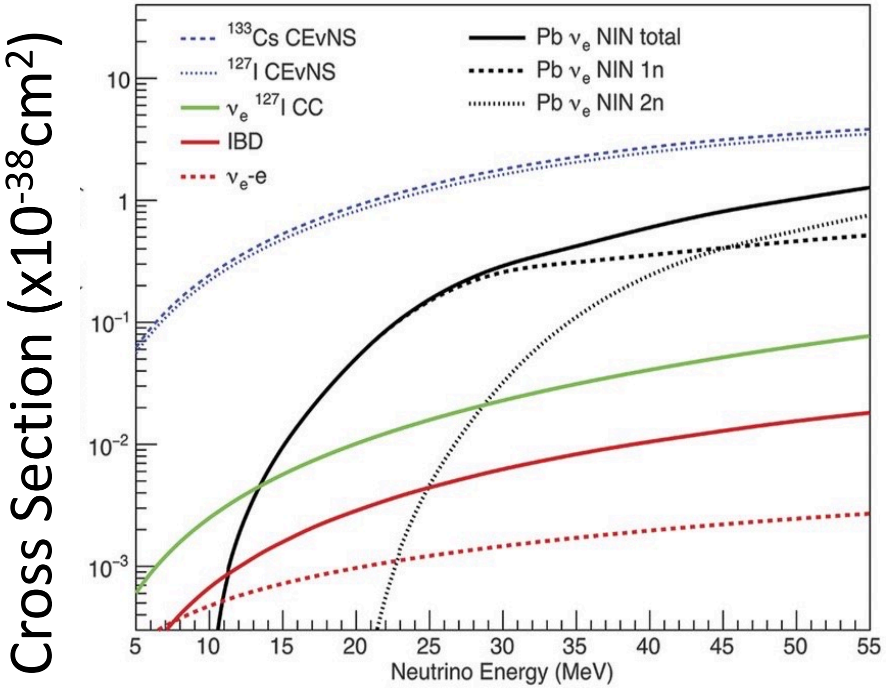




Observables in a 20MeV ν Experiment?

- Coherent Elastic Neutral Current Scattering
- This IS a cross section that is predicted by the Standard Model
- DeBroglie wavelength for 50MeV ν: $\lambda = \frac{hc}{E} = \frac{1200 eV \cdot fm}{50 MeV} \simeq 25 fm$
- Challenge: have to be sensitive to keV energies, and be shielded from backgrounds
- On the bright side, sαN² so cross section is larger than other processes





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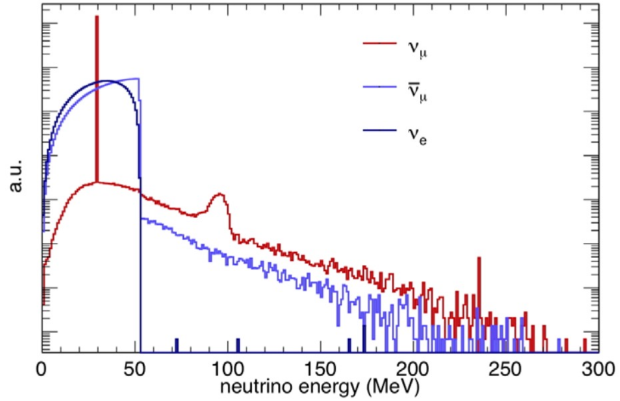
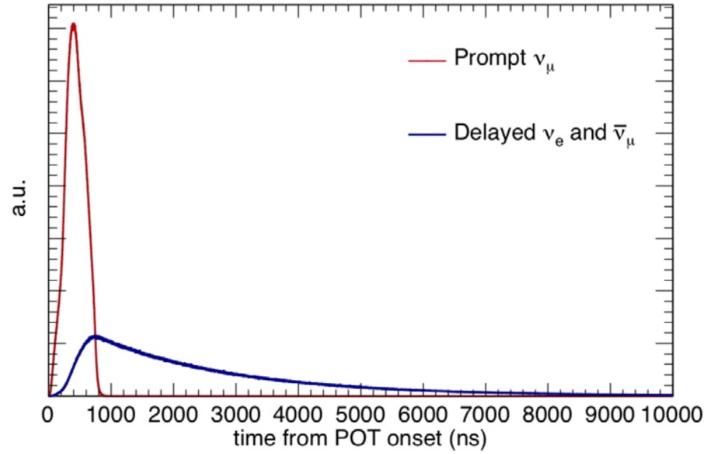
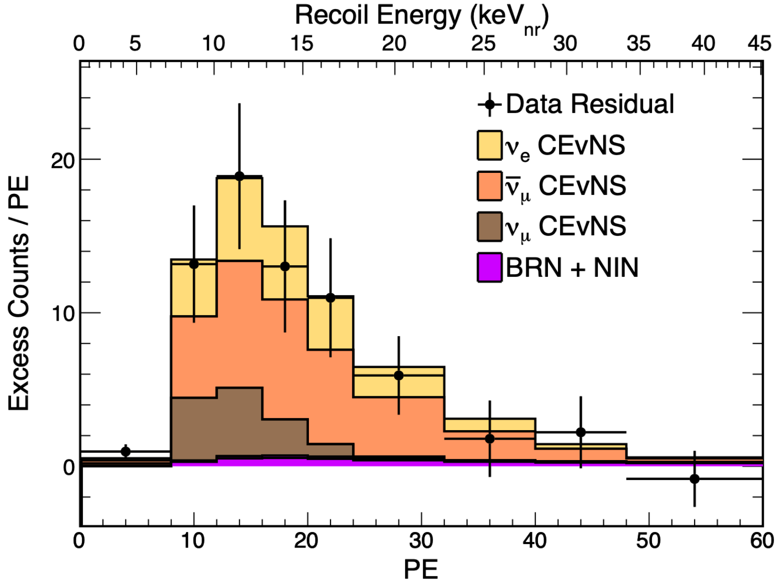
COHERENT Cross Section

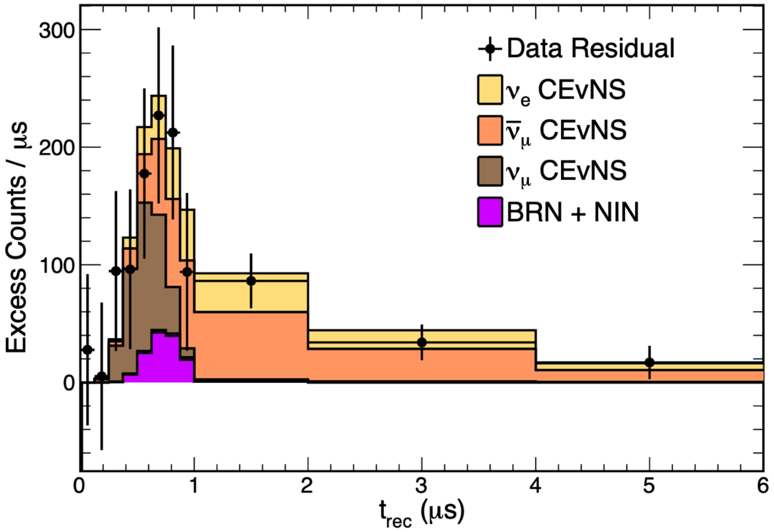
	Events (uncertainty)
Data	306 ± 20
Prediction	341 ± 11(theory) ± 42(experiment)

- Backgrounds are mostly from beam off events
- Easy to measure those, since timing of beam is known
- No cross section reported in first paper, probably because result agrees with SM prediction
- Second result: Cross Section: $(165 \pm 30) \times 10^{-40}\,\mathrm{cm}^2$





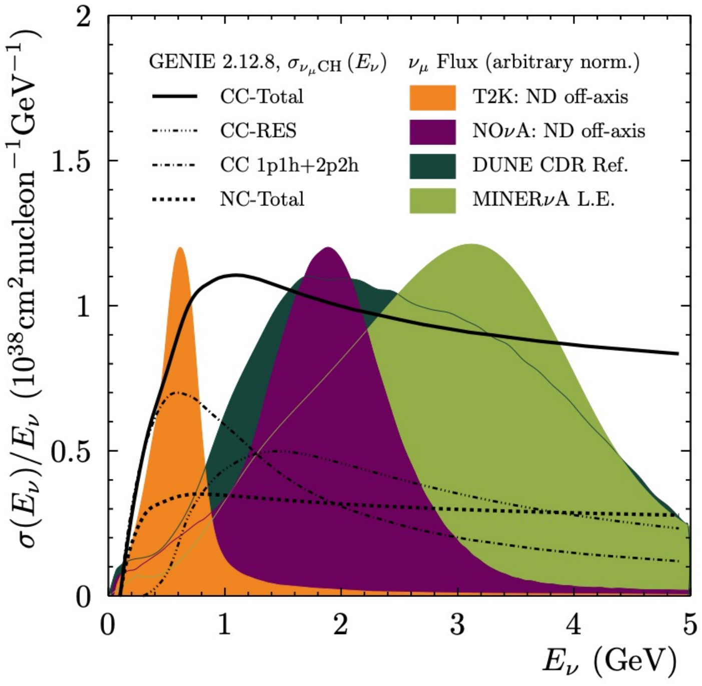




Graphics from *Science* 357 (2017) 6356, 1123-1126 and Phys.Rev.Lett. 126 (2021) 1, 012002

Neutrino Observables: what *could* x_m be?

- You have a neutrino beam made by an accelerator:
  - What do you know before the neutrino interacts?
    - Neutrino Direction (within a mrad, roughly)
    - Flux Energy distribution
    - Flavour and helicity composition
  - What could you measure after the neutrino interacts?
    - Final state lepton if it's a Charged current event
      - Direction
      - Momentum
      - Charge (to determine ν helicity)



Plot courtesy L. Pickering

Phys. Rev. D 94, 013012 (2016)

Observables in the era of 100GeV Neutrino Experiments…

- Events were dominated by high energy hadronic showers, and we didn't worry so much about the about the neutron content of the final states
- We measured E_{had}, E_{μ}, θ_{μ} on Steel-Scintillator calorimeters to get to… $E_{\nu} = E_{had} + E_{\mu}$

Bjorken x and y

$$x = \frac{Q^2}{2M\nu} = \frac{Q^2}{2ME_{\nu}y}$$

$$y = E_{had}/E_{\nu}$$

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

- Call this the "careless youth" stage

Photo courtesy FNAL, Reidar Hahn Aug. 1996

Cross Sections in era of Oscillation Experiments

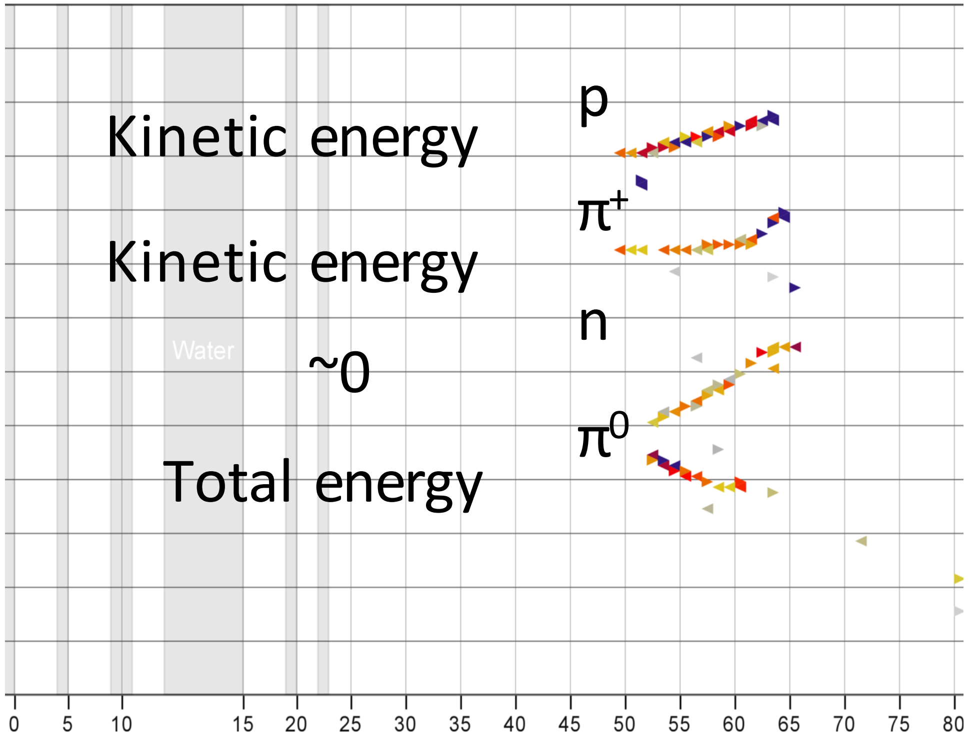
- Because of the size of the mass squared splittings, and the accelerators we have on hand, most cross section publications today are far away from the two extremes of 100GeV and 20MeV

- Need to understand scattering on scale of deBroglie wavelengths that are on order of

$$\frac{hc}{E} = \frac{1200eV \cdot fm}{500 - 5000MeV} \simeq 0.25 \ - \ 2.5fm$$

Why is measuring Hadron Energy Difficult?

- What could you measure about final state hadronic system
  - Do you track charged particles so you can measure their total kinetic energy?
  - Can you distinguish between p, π^+, π^+, π^0
  - What about neutrons, do you see those?



Example from MINERvA at right,
3.3cm plastic granularity
Similar in spirit to ~3cm wire pitch Liquid Argon (but different density, Z)

Figure courtesy P. Rodrigues

Phys. Rev. D 94, 013012 (2016)