Neutrino experiments and lattice QCD

Gabriel N. Perdue (Fermilab)

Lattice QCD All Hand's Meeting

April 20, 2018

Introduction

- Goal: try to talk about things a lattice QCD practitioner would find interesting w.r.t. neutrino experiments. So, focus on aspects of the physics modeling, and explain how a few oscillation experiments experience these effects by examining their detector technologies at a high level.
  - Disclaimer: I'm not a member of any of these collaborations - please do not regard my comments as official statements on the experiments, etc.

$$\mathcal{M}_{\nu_\mu n\to\mu p}(p,p') = \langle\mu(p')|\,(V_\mu - A_\mu)\,|\nu(p)\rangle\langle p(q)|\,(V_\mu - A_\mu)\,|n(0)\rangle$$

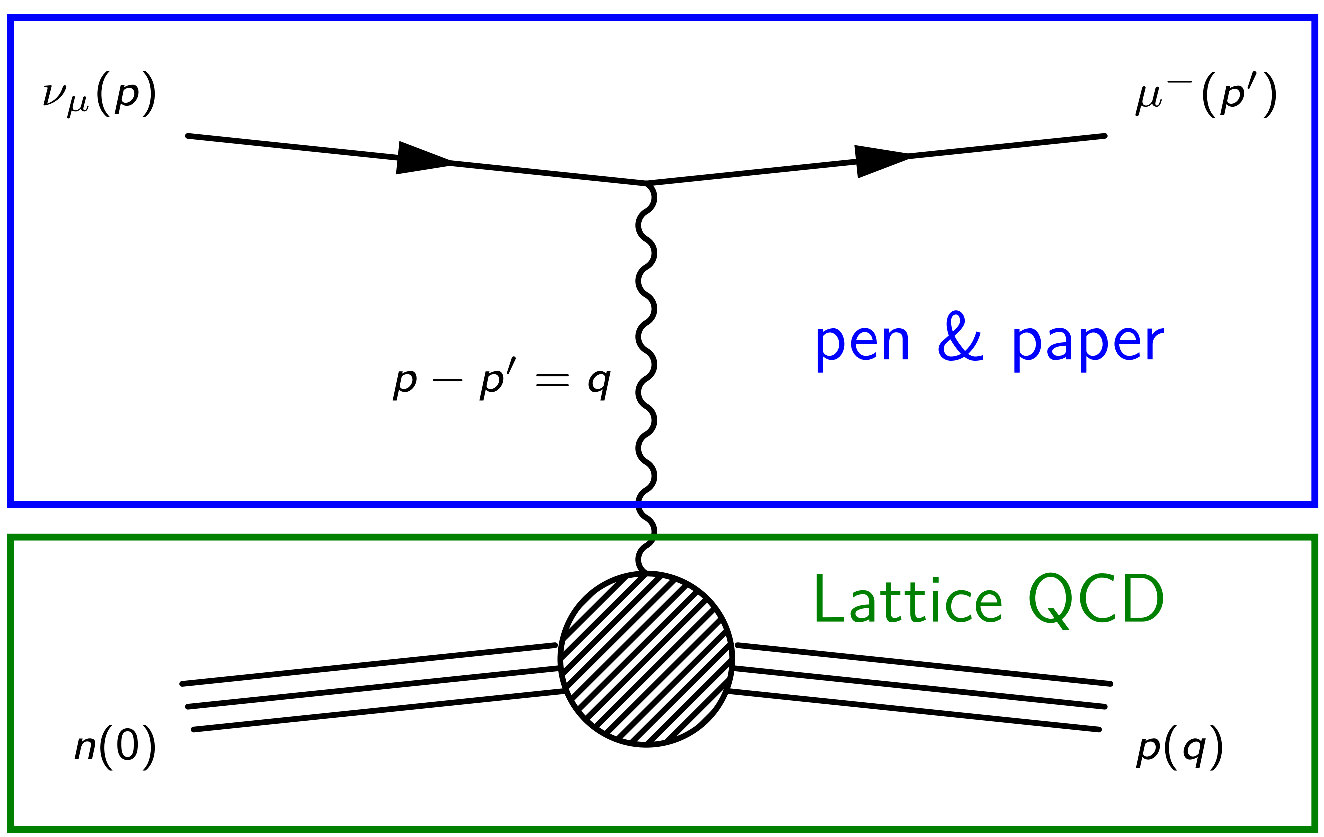
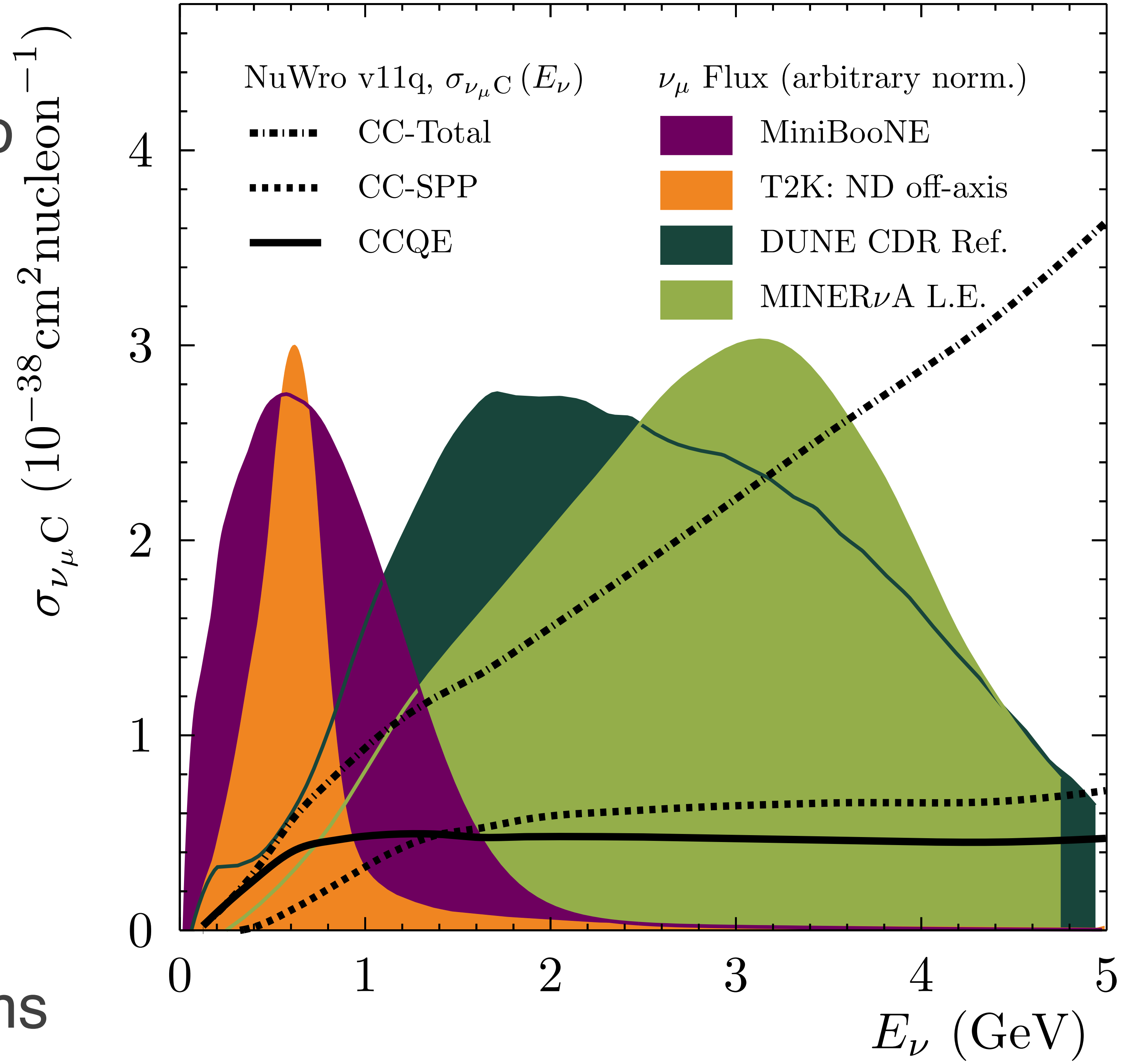


Figure by A. Meyer

Outline

- Brief **motivation** from a neutrino oscillation physics perspective
- How do neutrino experiments **model neutrino-nucleus interactions**?
  - MC Event Generators
    - Focus on GENIE due to author affiliations...
  - What are the major outstanding problems?
- What do neutrino experiments actually **measure**?
- How are we sensitive to problems with the interaction physics modeling?



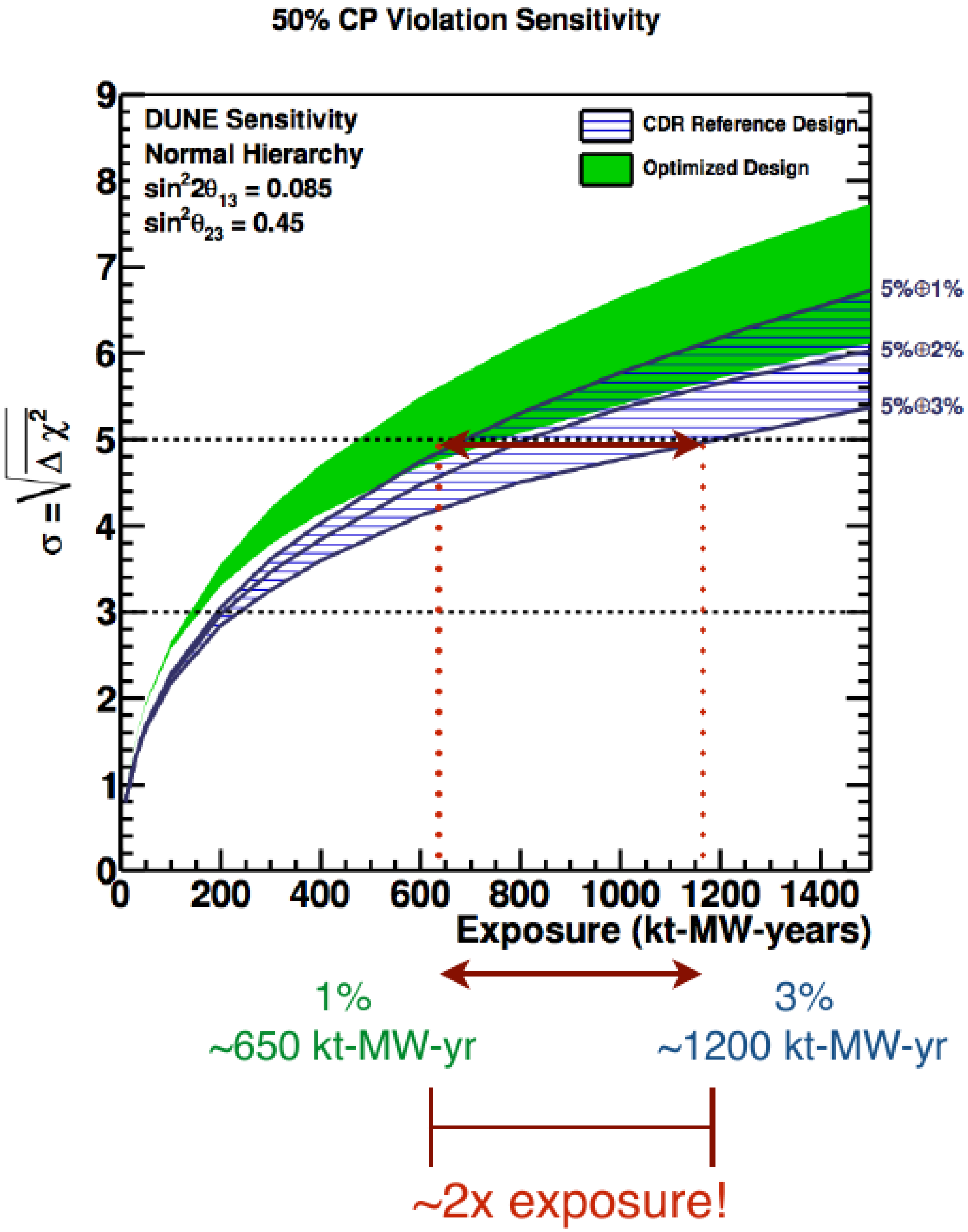
M. Betancourt et al, "Comparisons and challenges of modern neutrino scattering experiments (TENSIONS2016 report)", *in preparation*

A very brief motivation

- U. Mosel, NuInt 2017: **DUNE is "an impossible" experiment**:
  - Flux not fully specified,
  - Beamline is over 1,000 km, diameter is over 1 km at Far Detector,
  - Cross sections are tiny (10^{-11} mb) and plagued by numerous theory and experimental uncertainties,
  - Somehow we need to extract evidence of physics beyond the Standard Model!
- **Control of cross section systematics is a critical piece** - requires a multi-pronged effort involving theorists, experimenters, and and Monté Carlo authors all **working together**.
  - **No single measurement or calculation will solve it all!**

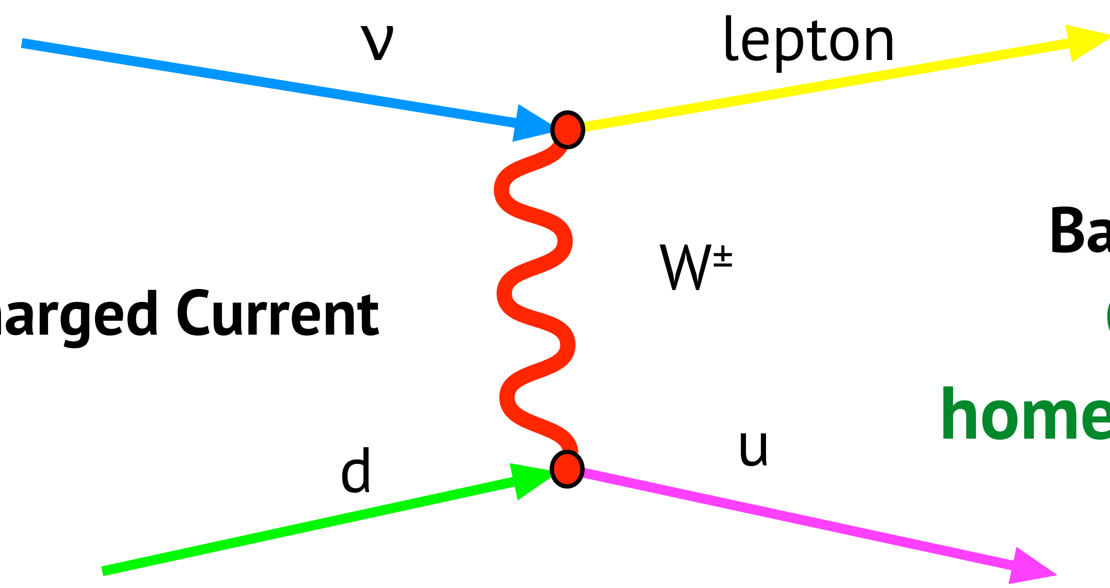
We have ~10 years to get everything under control!

DUNE CDR, arXiv:1512.06148

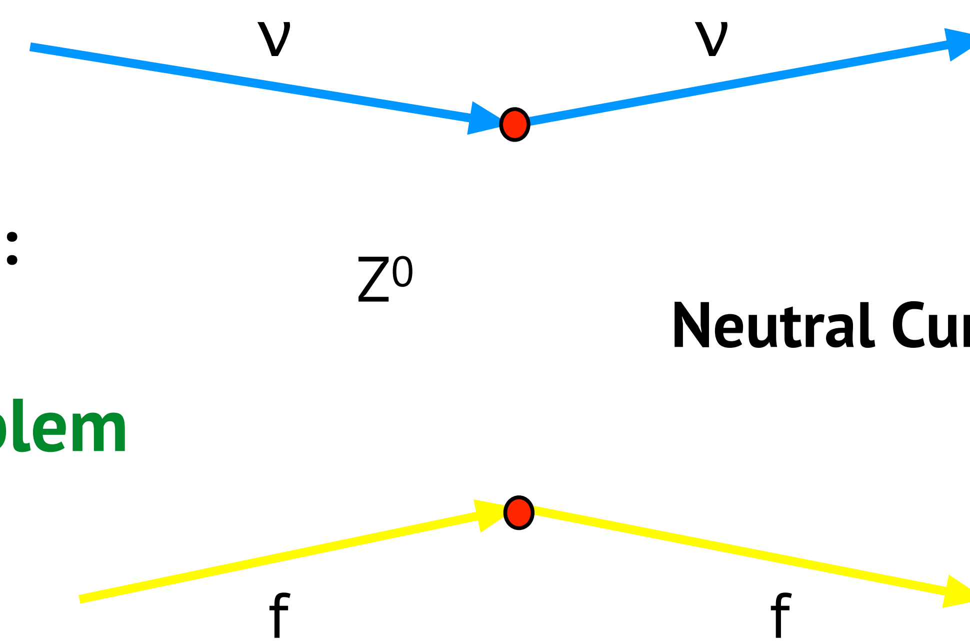


Framing the issue

Charged Current



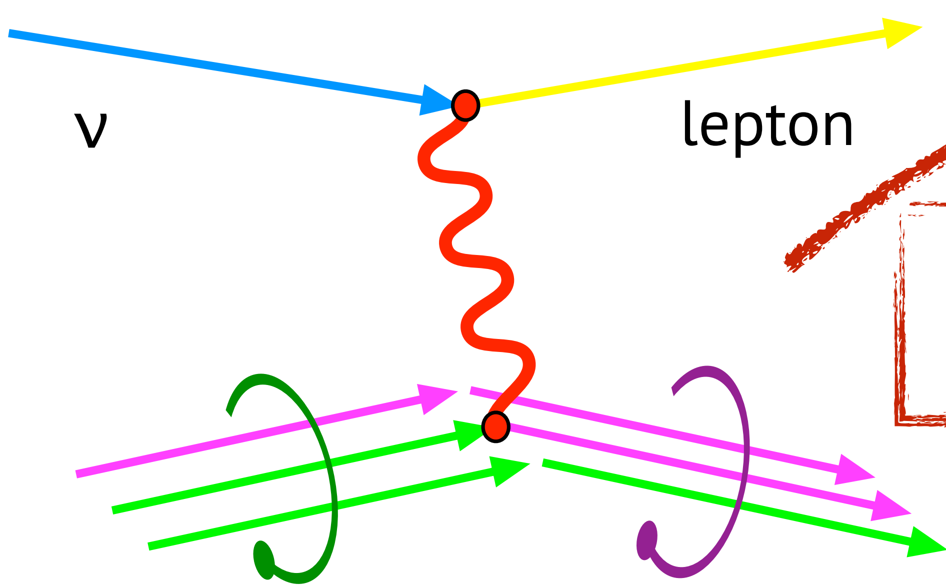
Bare fermions:
Graduate homework problem



Neutral Current

?

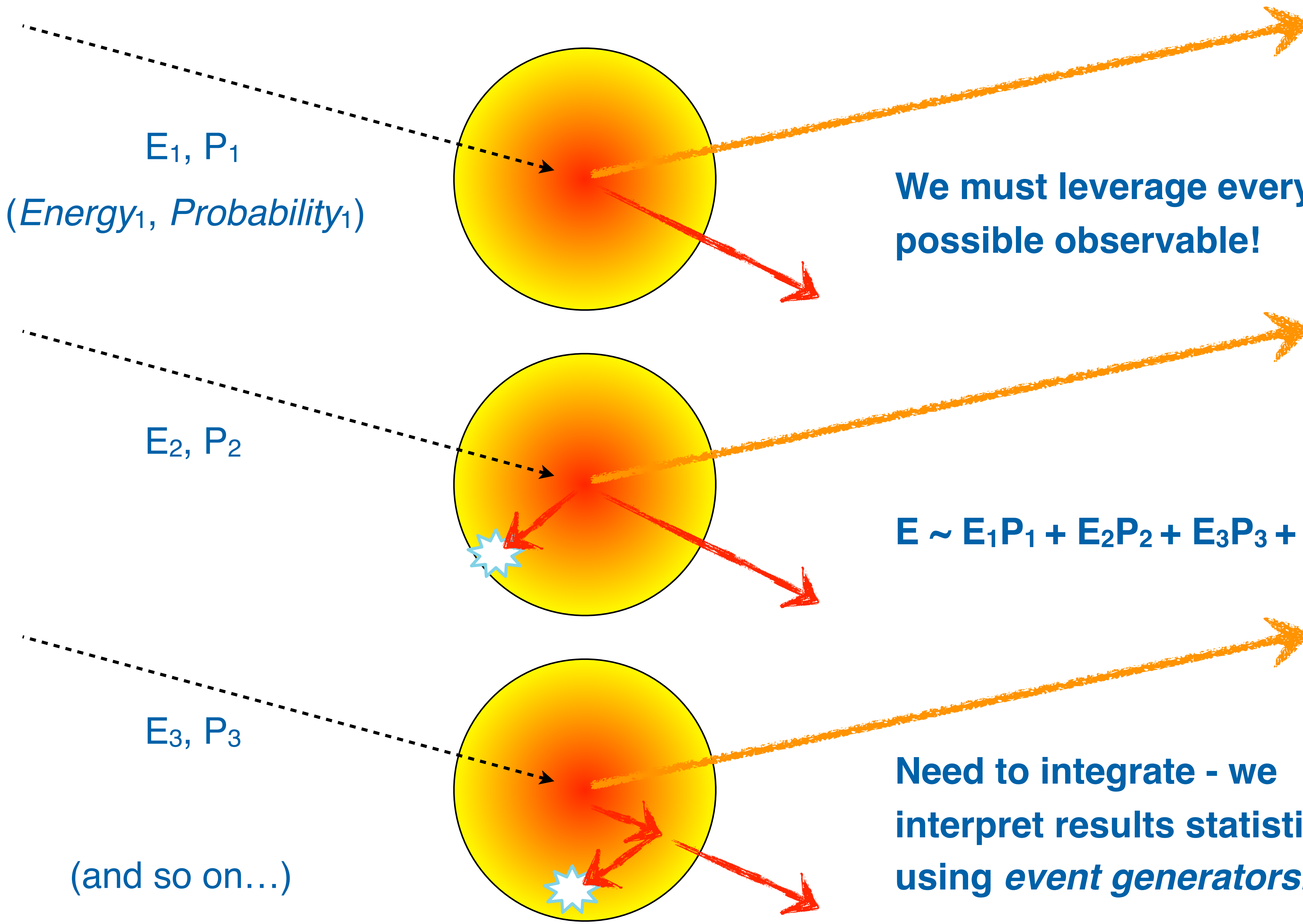
Free Nucleon:
Parameterize
w/ Form Factors…



Nucleus:
What is the initial state?
What escapes the nucleus?

??

The Basic Problem: we must interpret with *models*



We must leverage every possible observable!

$\mathbf{E \sim E_1P_1 + E_2P_2 + E_3P_3 + \ldots}$

Need to integrate - we interpret results statistically using *event generators.*

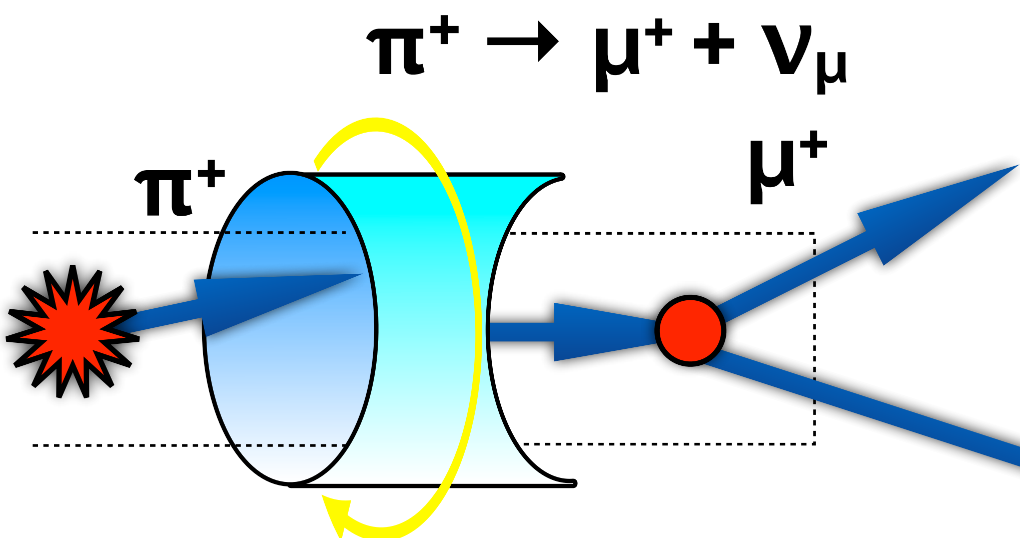
Neutrino MC Event Generators

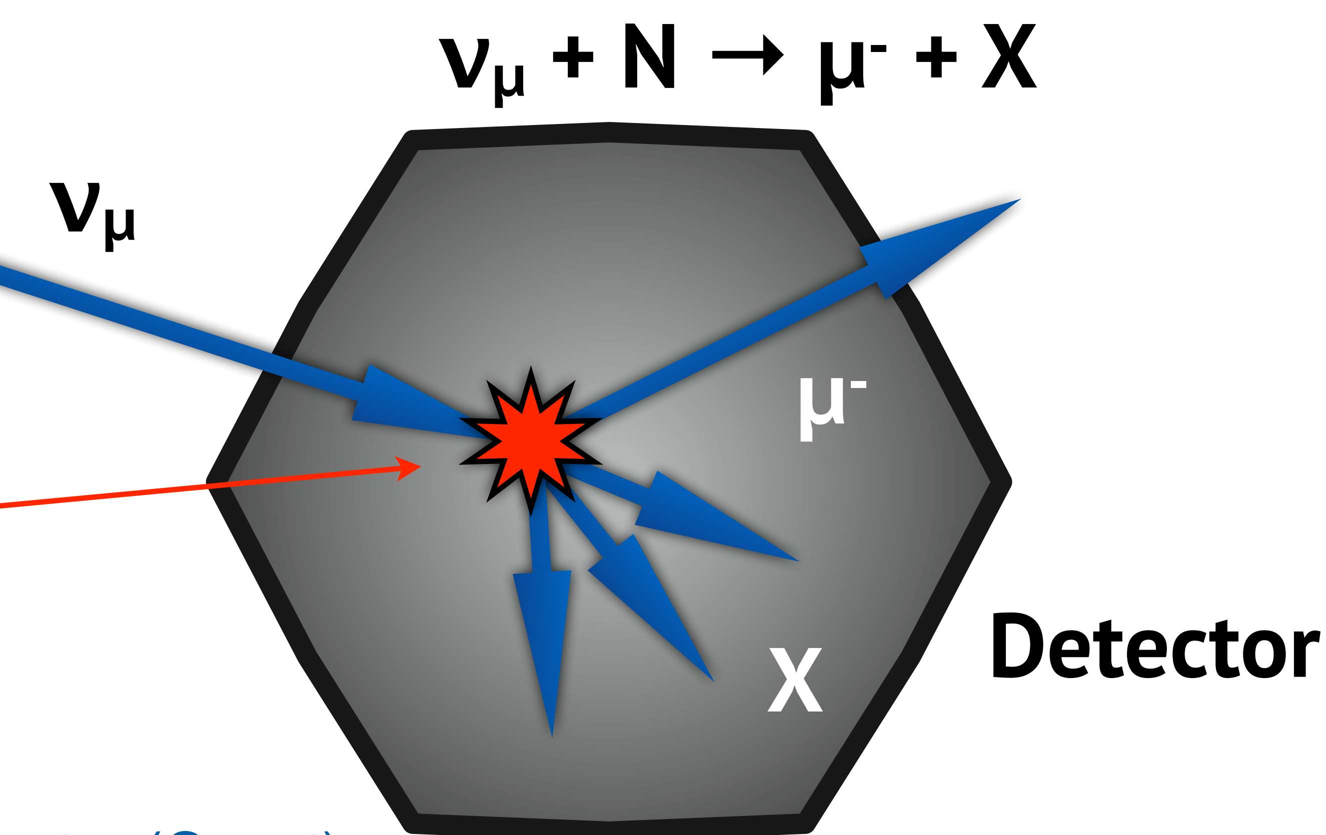
- The generator must simulate all the types and momenta of every particle that appears in the final state.
- Some generators (MadGraph, Pythia, etc.) are computation aids for theorists, but most neutrino event generators are not (GiBUU is somewhat different).
- This is because we lack a theoretical framework that is both *complete* and *consistent*.
- The ideal input theory would be internally consistent and provide fully-differential cross sections in the kinematics of *every* final state particle over all reaction mechanisms, energies, and targets.
  - But the experiments must go on! So we must *stitch together* an ensemble that is consistent with all the data.

Neutrino Simulations: A Three-Part Software Stack

Beamline (FLUKA/Geant)
+ Produces a flux prediction
+ Hadron production, focusing, etc.

Geant 4
(won't say much about Geant here...)





GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

Event Generator (GENIE)
+ Interaction Physics
+ Nuclear medium

NuWro Wroclaw Neutrino Event Generator

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NEUT

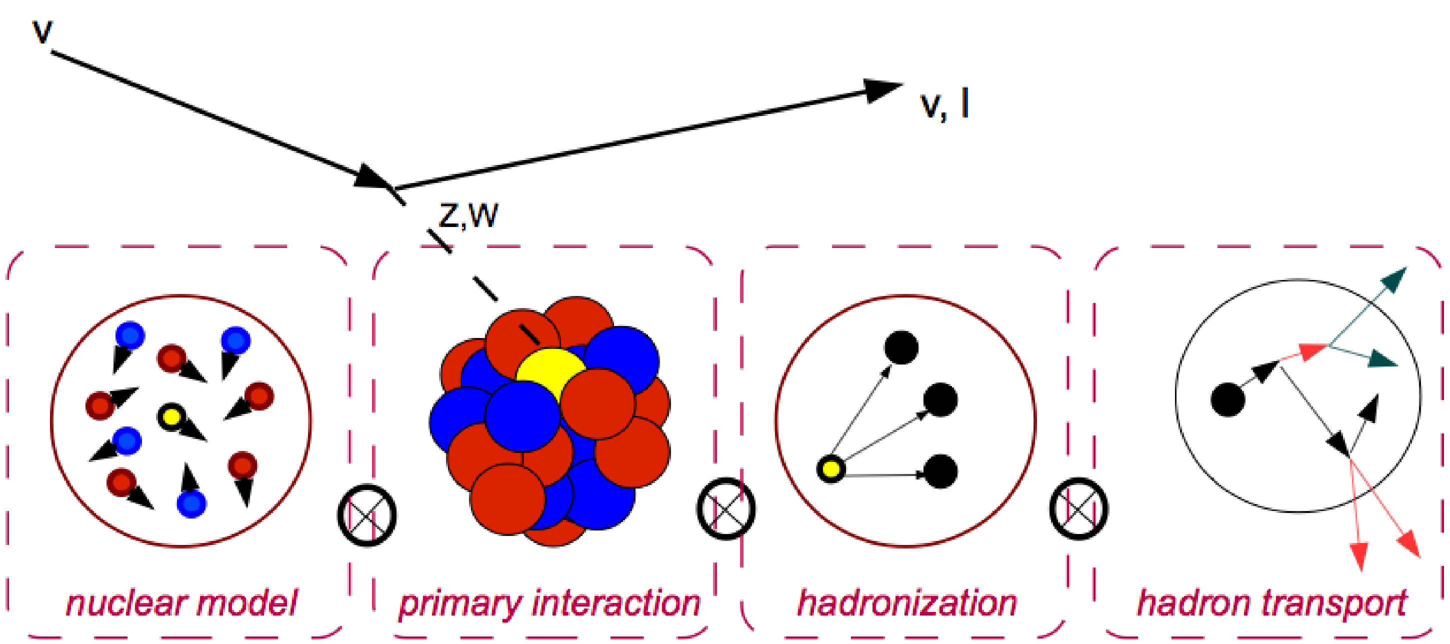
Detector (Geant)
+ Final state radiation traversing matter

Geant 4
(won't say much about Geant here...)

Philosophy

http://www.genie-mc.org

- The kernel of GENIE's physics model is a *free nucleon* model, with corrections to account for bound state effects and final state particle propagation.
- Exclusive states are added together with no interference terms (generally) to build a global inclusive model. Two-body currents are tacked on as another piece of the cross section (so they are not exactly free nucleons, etc.).
  - We are working on new models that blend one and two-body currents together with an interference term. These calculations often have their own, "built-in" ground state model that is, in general, different from the usual GENIE ground state and other calculations.
- Supposing we solve the interference terms problem, can this philosophy hold up?



C.Andreopoulos et al
The GENIE Neutrino Monte Carlo Generator
Published in
Nucl.Instrum.Meth.A614 (2010) 87-104

Pieces (Usually)

- Vertex selection
  - Simple nuclear density model
- Initial state nuclear model
  - Removal energy and momentum
    - RFG with Bodek-Ritchie tails.
    - New: Local Fermi Gas
    - New: Effective Spectral Function
    - Almost there: "Benhar" spectral function
    - Just started: Correlated Fermi Gas (MIT)

GROUND STATE

- Hard scattering process
  - Differential cross section formula to get event kinematics (x, y, Q2, W, t, etc.)
- Lepton kinematics
- Hadronic system

INITIAL STATE

  - Propagation/transport (default is an "effective cascade")
    - Fast and re-weightable

FINAL STATE

Pieces (Usually)

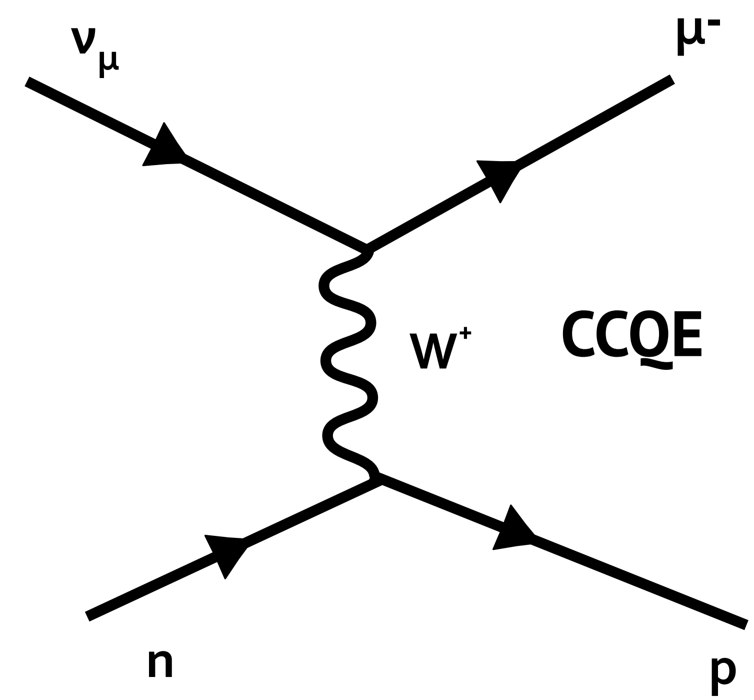
- Decays before and after propagation
- Remnant decay
  - Just started caring about this, really...
  - Current model is very simple
    - Working on adopting other codes (Geant4, INCL++, possibly GiBUU) to handle clustering, de-excitation, evaporation
    - May be a bridge to more sophisticated transport codes

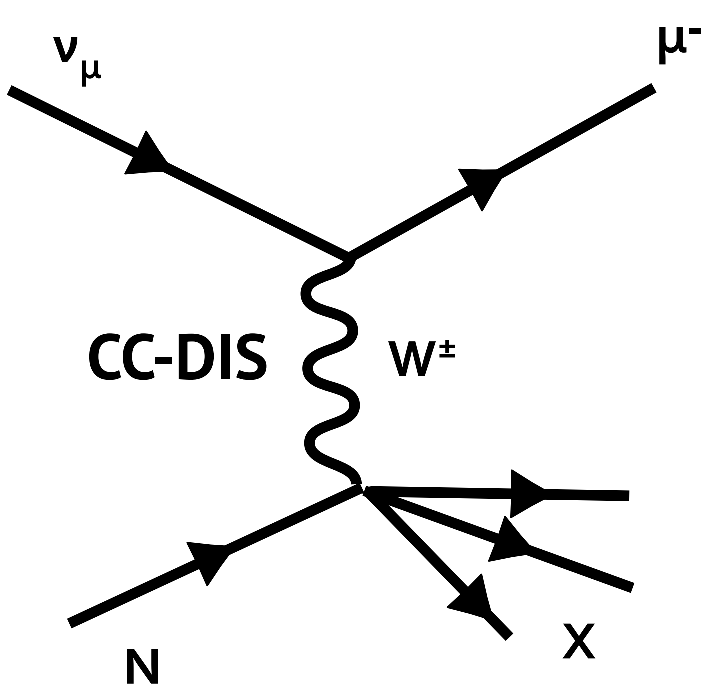
REMNANT STATE

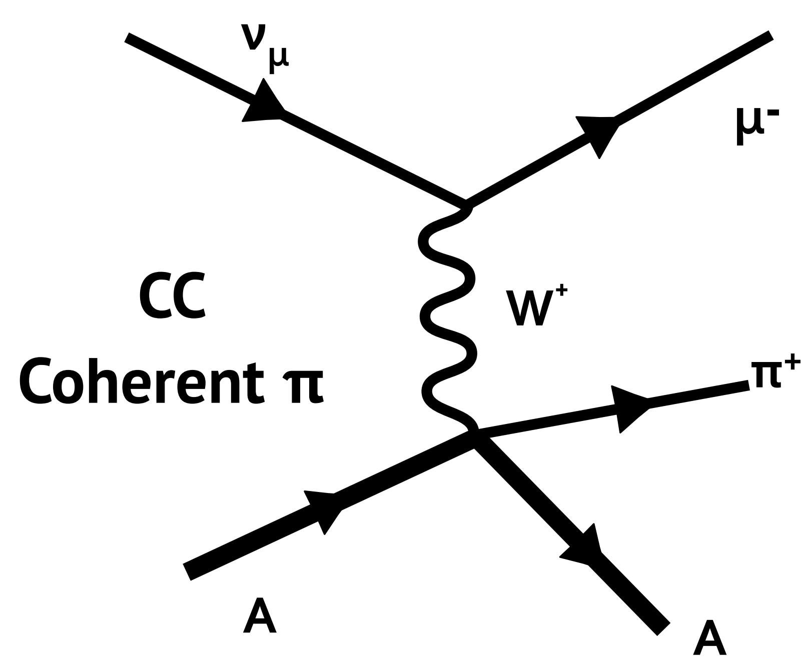
- Sometimes models can't work this way - e.g., it really is better physics to include draws from the ground state nuclear model in the accept-reject loop for determining kinematics. But this slows the code down a lot and so we must think about when to apply that paradigm.
- Also, some calculations are integrated over very specific ground state models and we cannot factorize them.

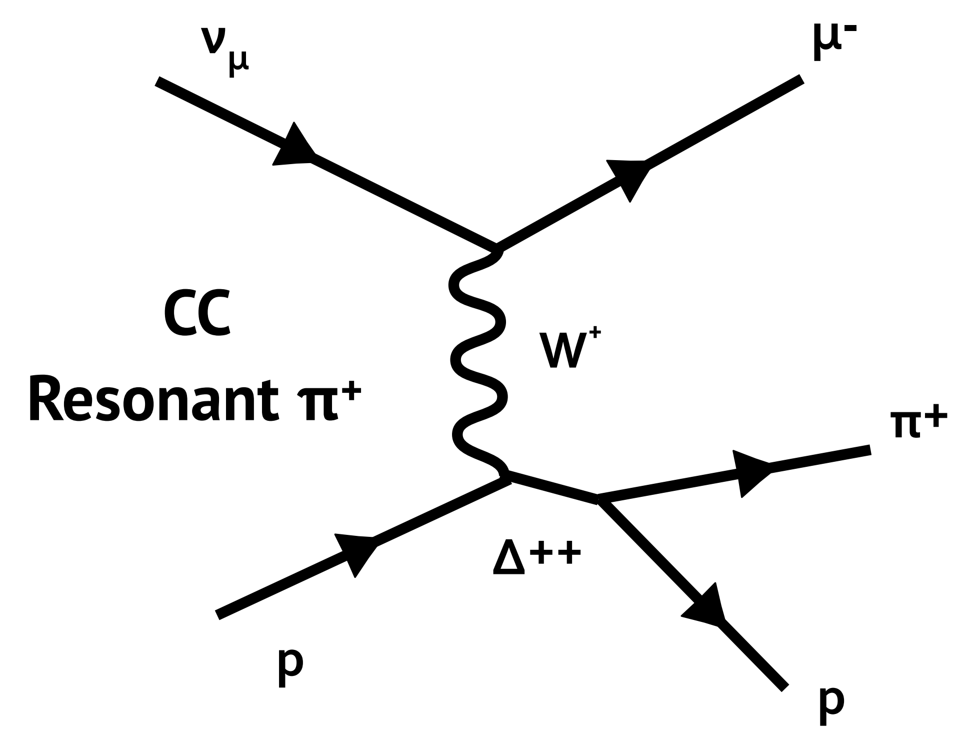
Reaction Channel Menagerie: A Glossary

- Charged current: exchange a W boson; neutral current: exchange a Z (not shown) - no charged lepton in the final state for NC.
  - CCQE : Charged-Current Quasi-Elastic
  - CC $\pi^{\pm}$, π^0
    - Coherent (no break-up) & Resonance Production
  - Deep Inelastic Scattering (DIS - scatter on a parton)
- **Our descriptive language is something of a historical accident**. These terms are really only proper when discussing scattering on **free nucleons**.
  - When scattering on nuclei, final state interactions (FSI) mix up the particles leaving the nucleus, making this sort of assignment impossible.
  - Modern language prefers specification by visible particles in the final state.









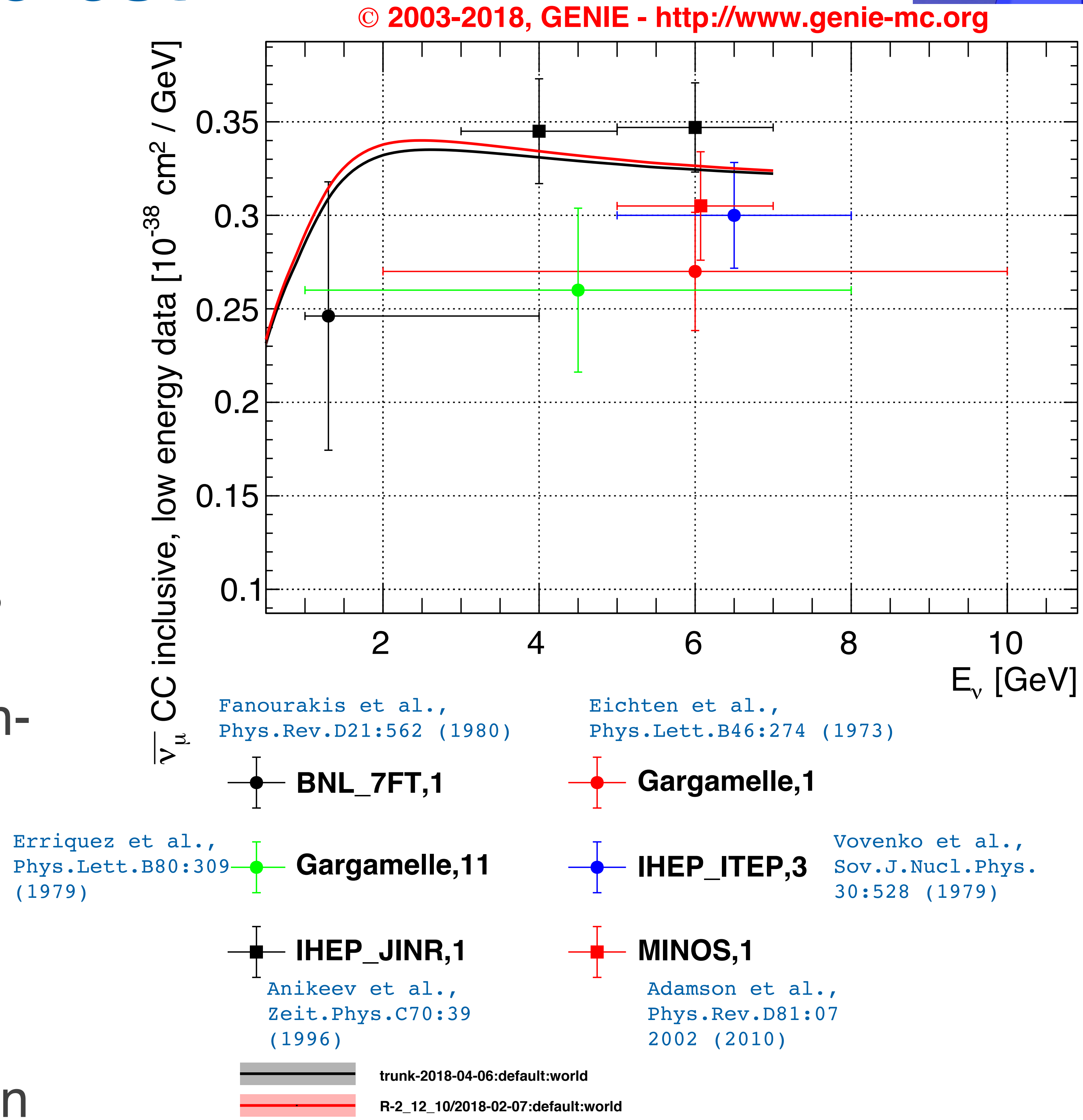
GENIE Cross Section Models

(mostly for reference)

- GENIE has a large collection of physics models - combined to create global models.
  - Many are fairly **primitive**, but for the most part they are **fast, re-weightable, and not awfully wrong**. In some corners of phase space, GENIE disagrees with data by as much as 50% but across many distributions it is within ~5%.
- The default nuclear model is the relativistic Fermi gas with Bodek and Ritchie high-momentum tails. GENIE also implements the Effective Spectral Function, and the Local Fermi Gas.
- The quasielastic process defaults to Llewellyn-Smith, but we also have the Nieves et al model. We offer dipole and z-expansion axial form factors.
- Excitation of nucleon resonances (decaying by meson emission) and coherent pion production are both described by models by Rein and Sehgal, but we offer a number of alternatives (Berger and Sehgal, different form factor models, etc.).
  - We also offer a diffractive pion production model (Rein).
- Models for neutrino-electron scattering and inverse muon decay are included and mostly complete (additional radiative corrections required for neutrino-electron scattering).
- We offer (non-default) a custom built and the Valencia 2p2h models.
- Bodek and Yang (2003) is used for nonresonant inelastic scattering.
- Other interesting exclusive states (QEL hyperon production, single Kaon production, etc.) are optional (making them default would lead to double counting in the hadronization model).

Missing effects of interest...

- Electron and muon final states differ only in lepton mass - no other corrections are applied. (Same form factors, etc.)
- There are essentially no radiative corrections.
- Our resonant pion production model is not complete and does not account for interference terms with other single pion production modes. We also do not model non-resonant pion production well (essentially use our DIS model).
- Neutrino-nucleon (especially antineutrino-nucleon) cross sections are not well known and will be VERY difficult to measure in the future.

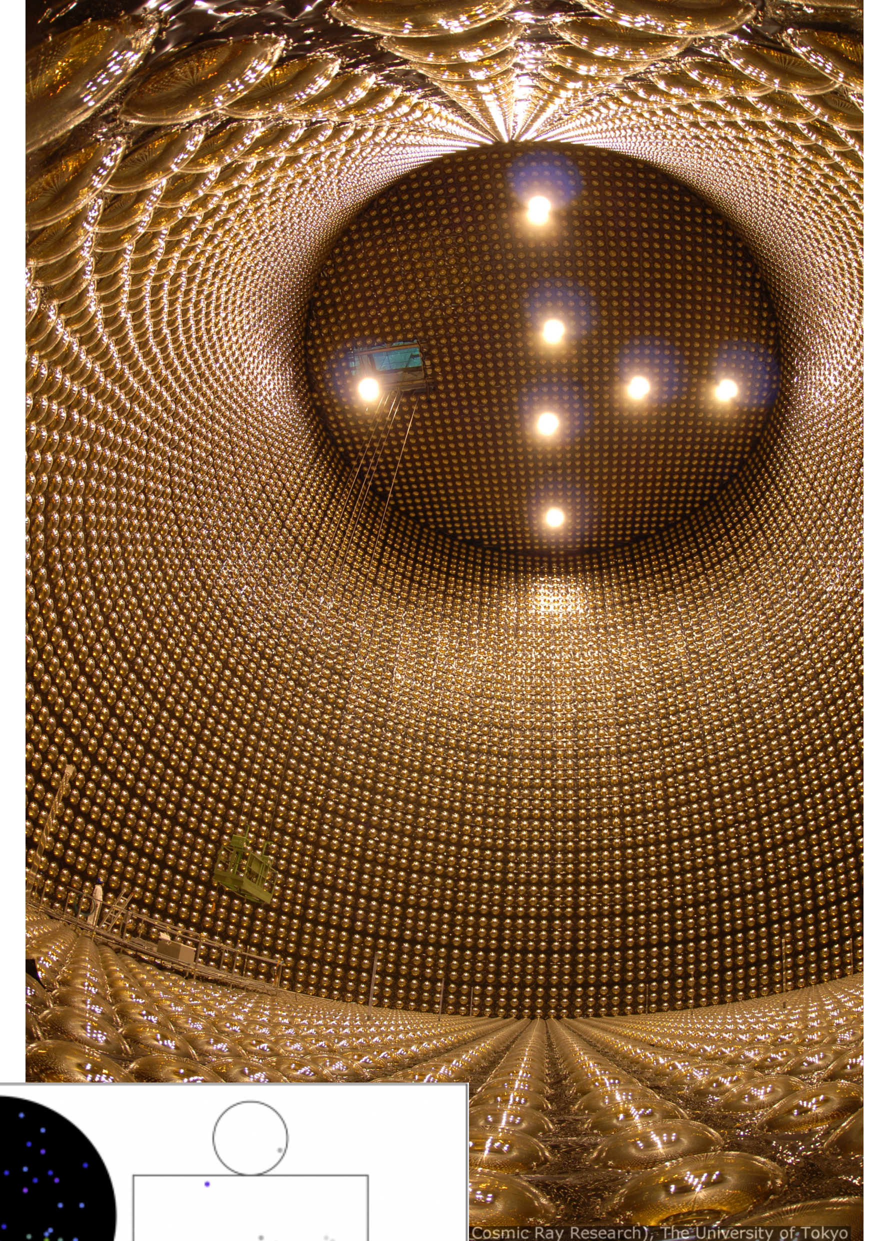


What do we measure?

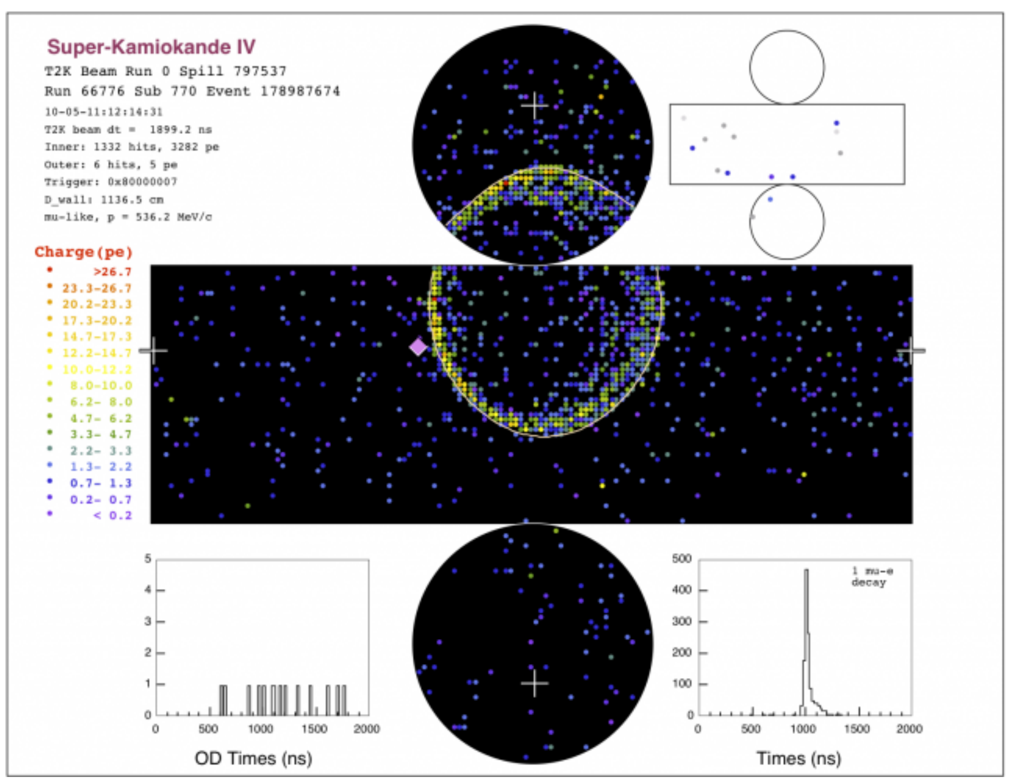
- Sliding scale across detector technologies - ranging from a "limited" picture (water Cherenkov) all the way through hyper-fine details (liquid Argon).
  - No implication of a hierarchy here - there are lots of pros and cons for each - the right choice is a function of beam energy, funds available, and physics goals.
- Reasonably universal themes:
  - **The neutrino energy is unknown!** And fluxes are constrained to the 5-10% level based on external data. Oscillation experiments can leverage their Near Detector to reduce this uncertainty, but residuals remain due to varying beam spectra at Near and Far sites.
  - **Leptons are fairly well-measured** (when correctly identified).
  - **The hadronic system is partially, or even largely, invisible.**
    - It is often possible to veto on exotic baryons or the presence of mesons, etc.
    - It is often possible to reconstruct a significant fraction of the hadronic system.
      - Low energy nucleons are problematic.
      - Neutrons are often invisible (they will sometimes kick out protons when the detector contains hydrogen, and they will capture on Gadolinium, etc.).
      - De-excitation and evaporation of the remnant nucleus is generally not observed, although this is changing in liquid Argon.

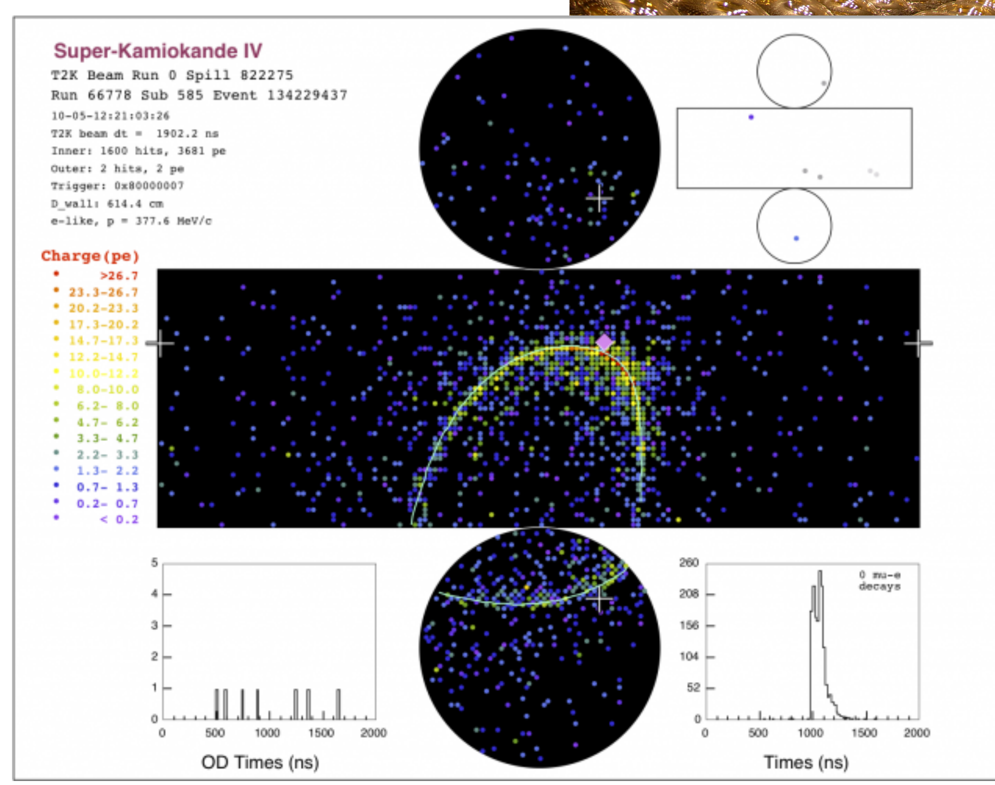
T2K FD

- Far detector Superkamiokande: 50 kiloton water Cherenkov detector.
  - Good lepton flavor identification,
  - Good pion veto,
  - Hadronic recoil is difficult to measure - heavy nucleons are generally below threshold,
  - No magnetic field,
  - Target nucleus is Oxygen (Water).



http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/index-e.html



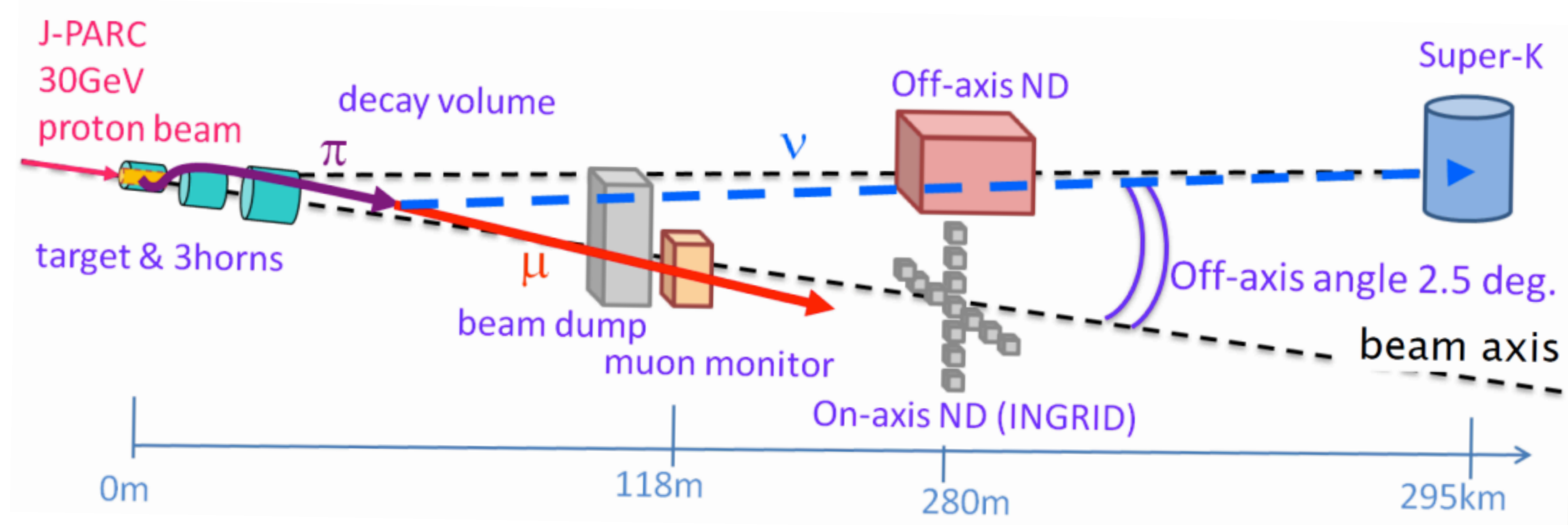


mu-like (left): sharp ring

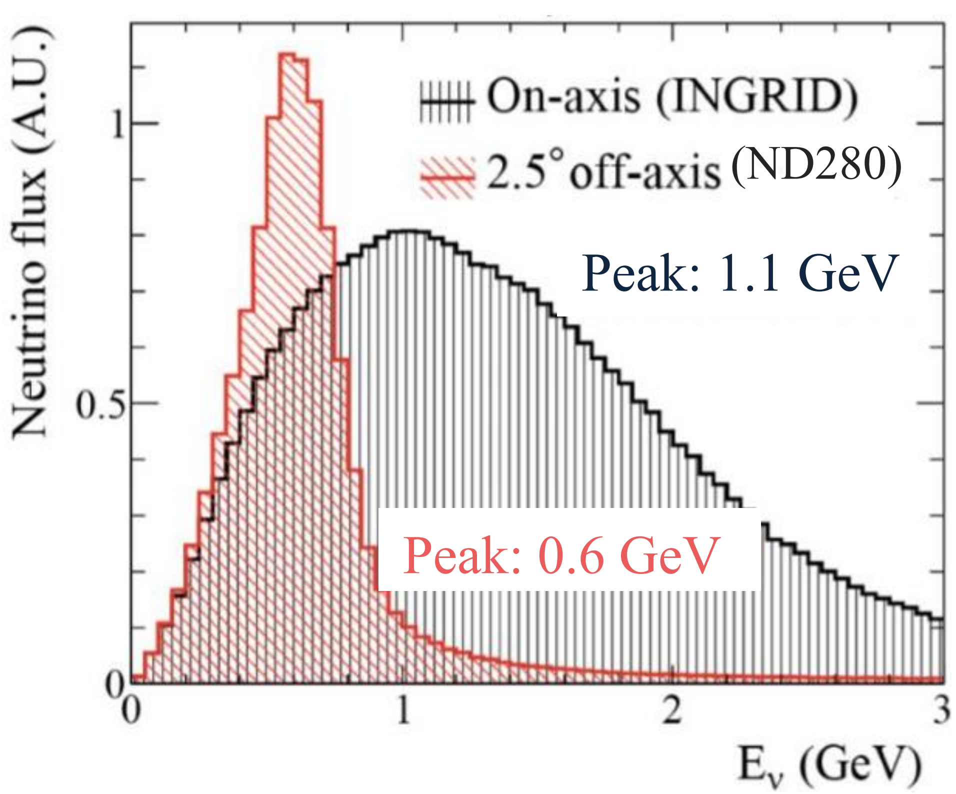
e-like (right): fuzzy ring

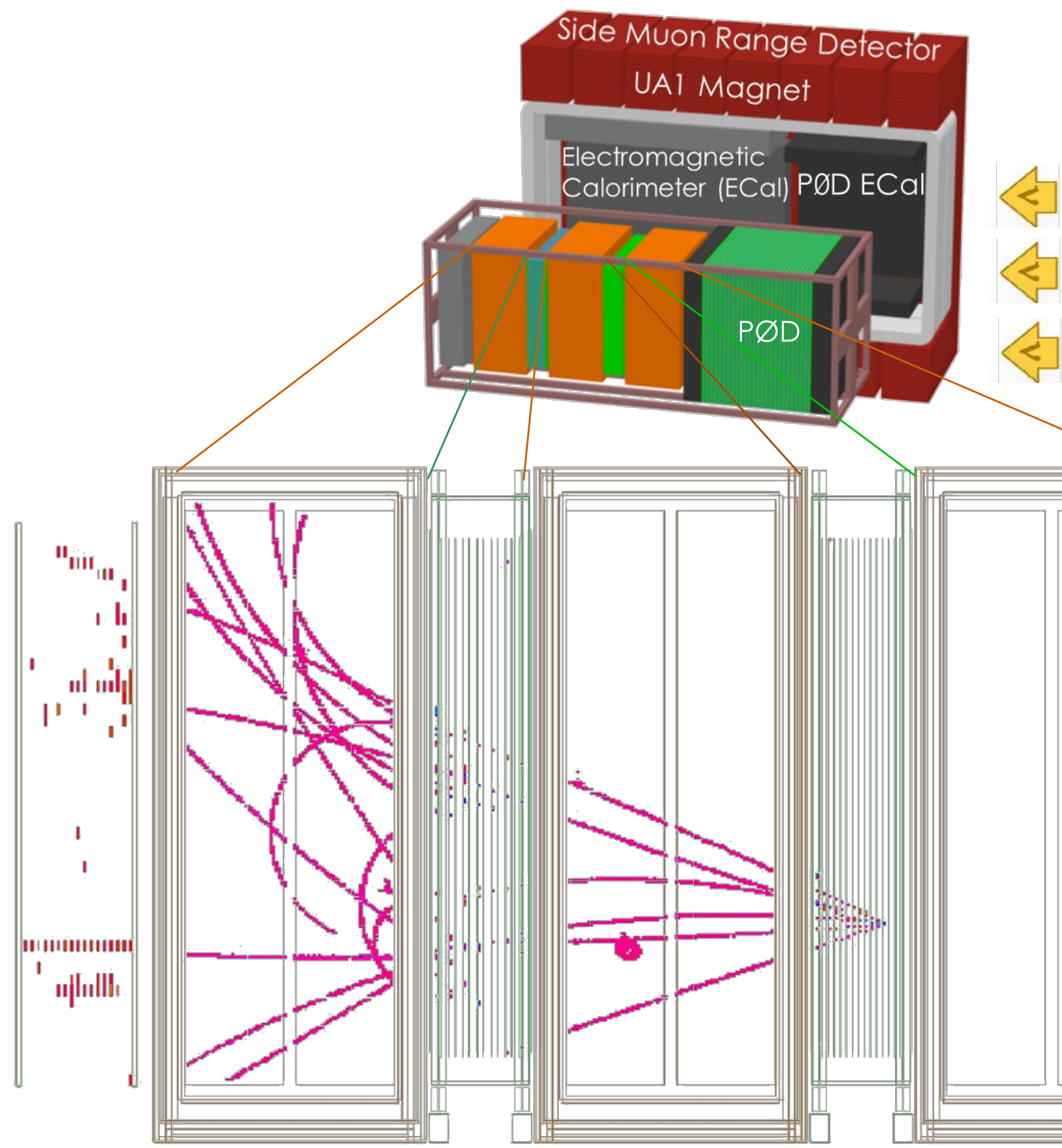
http://t2k-experiment.org/photo/super-kamiokande/

T2K ND



- High granularity, **magnetized** near detector complex for comprehensive cross section program on Carbon, Oxygen.
  - "**P0D**" contains water layers, scintillator, and absorbers.
  - **TPC** and **segmented scintillator** modules.





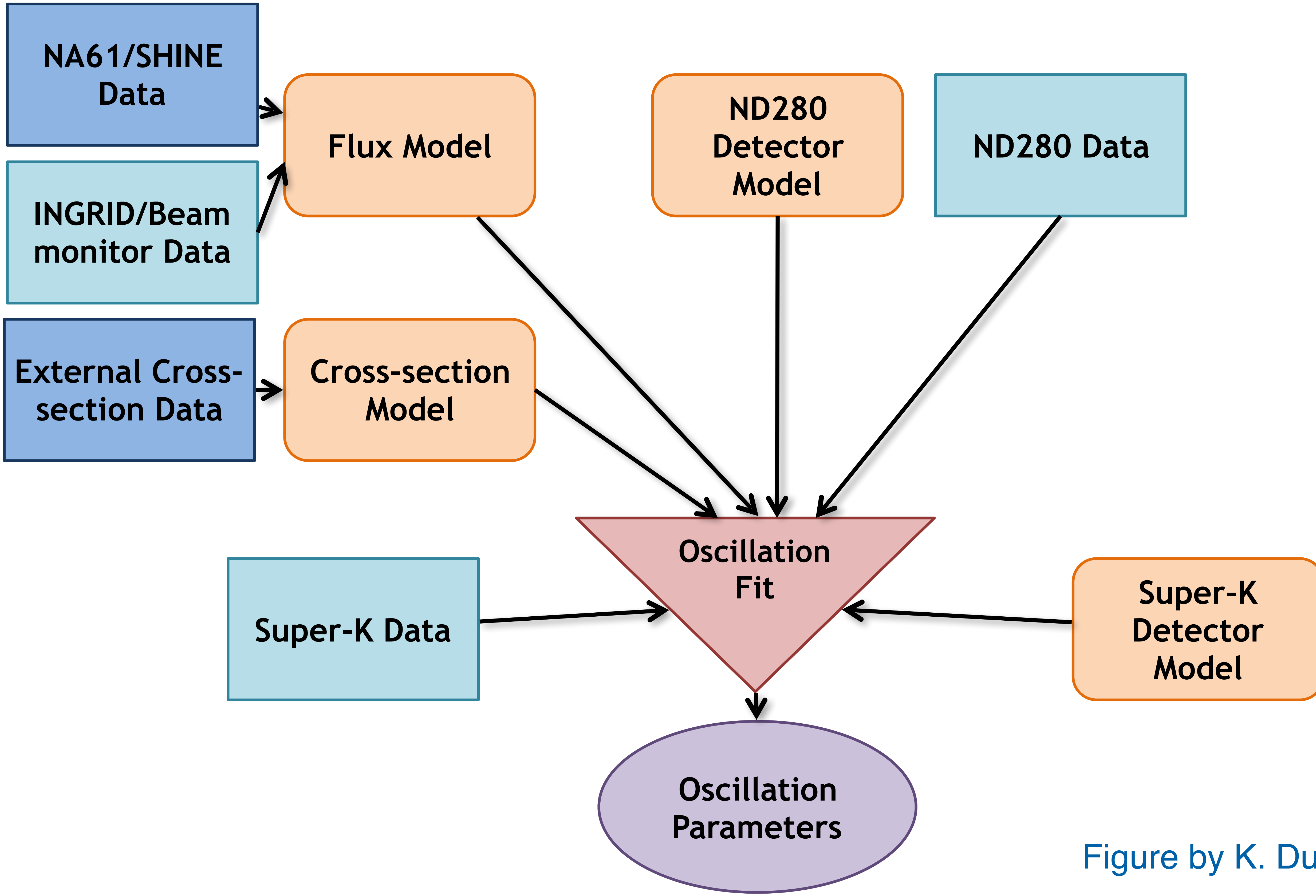


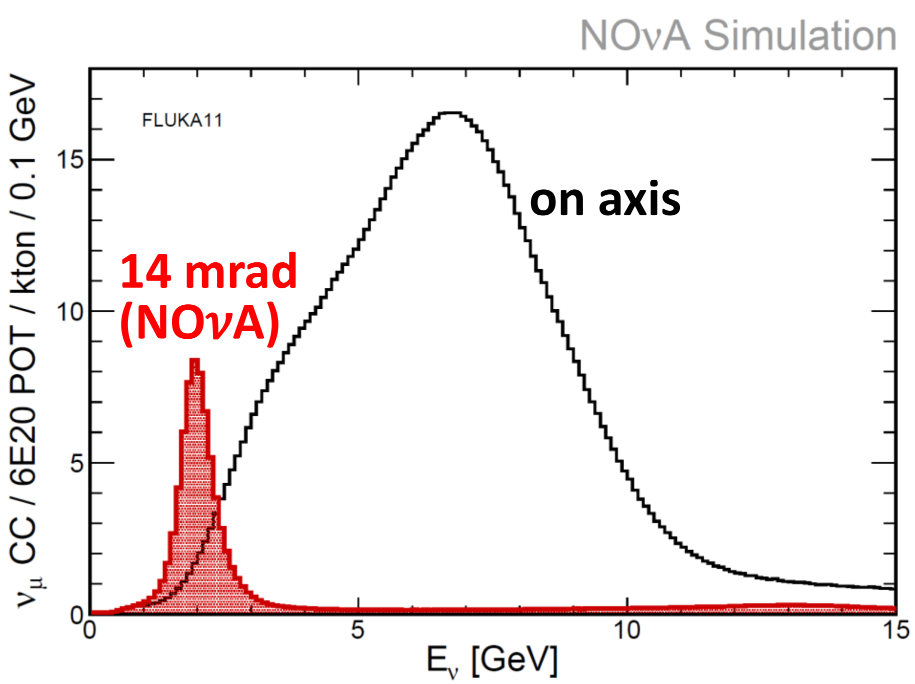
Figure by K. Duffy

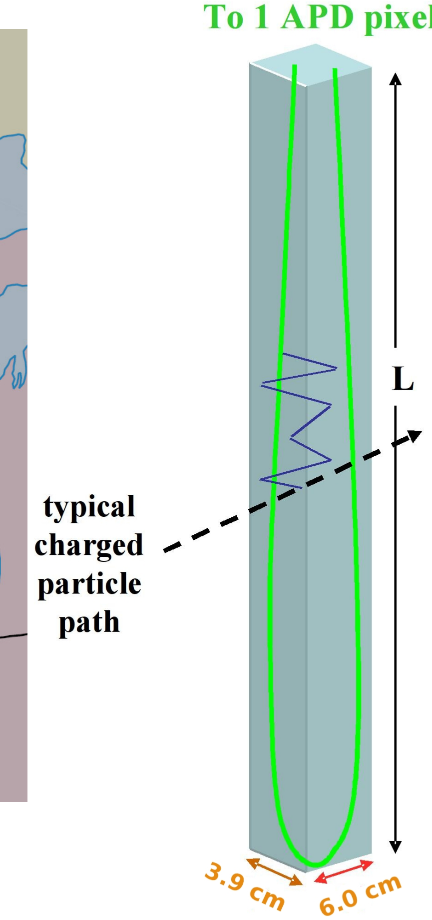
T2K and Lattice QCD

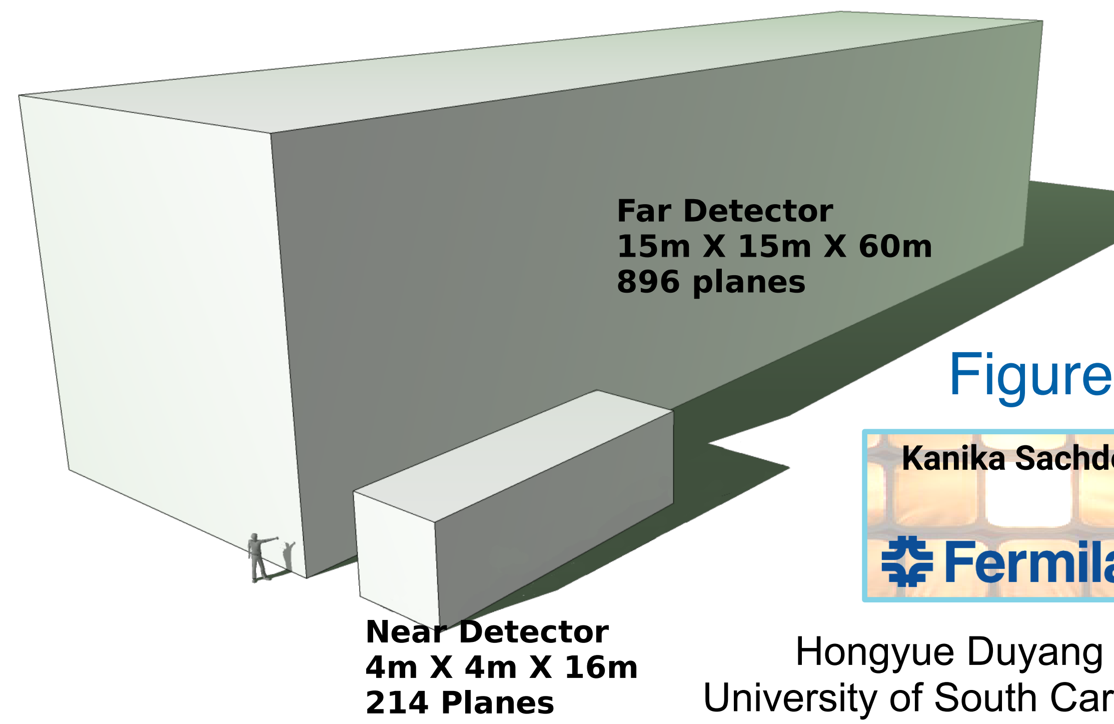
- Because T2K uses **different target nuclei at their near and far detectors** (for the most part; the near detector does contain water targets that they have begun to fold into the analysis), they need to build a detailed model of neutrino-nucleus interactions and constrain it with their near detector data.
  - Of course, the near and far detectors also have different acceptances and measure different details about the final state, etc.
- **Quasi-elastic scattering is a dominant reaction mechanism** at their energies, and their far detector does not measure recoil protons.
- **Neutrino energy reconstruction uses lepton kinematics** under the assumption of two-body scattering (one-body currents). This technique works even when there are two-body currents as long as the simulation models the distribution of those events. But even for one-body currents they benefit from tighter controls on the nucleon cross section.
- This means they are **avid consumers of improved nucleon-level cross section modeling**.

NOvA
@novaexperiment

- NOvA (NuMI Off-axis ν_e Appearance) is a neutrino oscillation experiment
  - Baseline of 810 km
  - NuMI, beam of mostly ν_μ
  - 14 mrad off-axis from the beam
  - Two functionally identical detectors
- Oscillation channels accessible to NOvA:
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_e(\bar{\nu}_e)$ (appearance)
  - $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_\mu(\bar{\nu}_\mu)$ (disappearance)





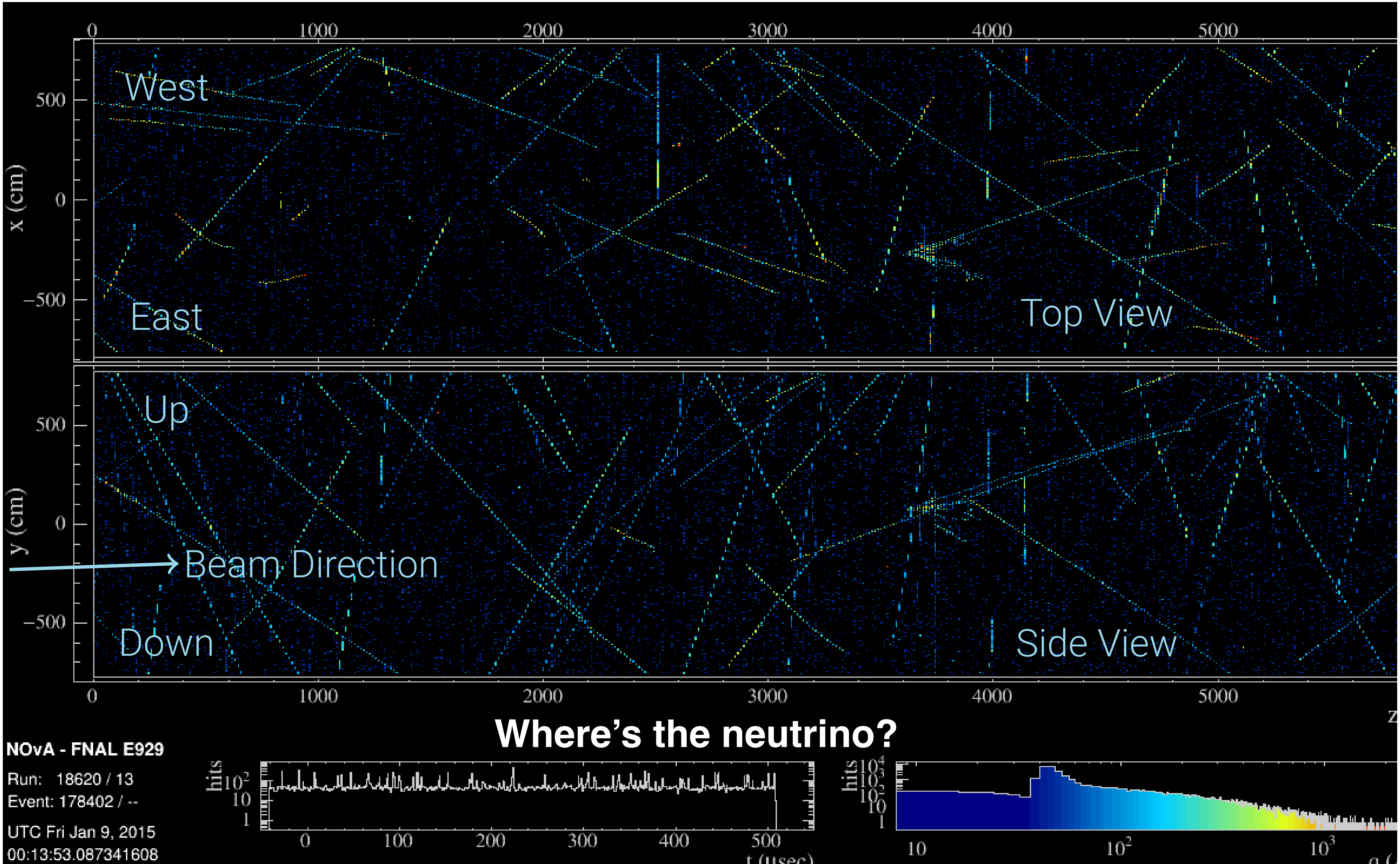


Figures:
Kanika Sachdev
Fermilab

Hongyue Duyang
University of South Carolina

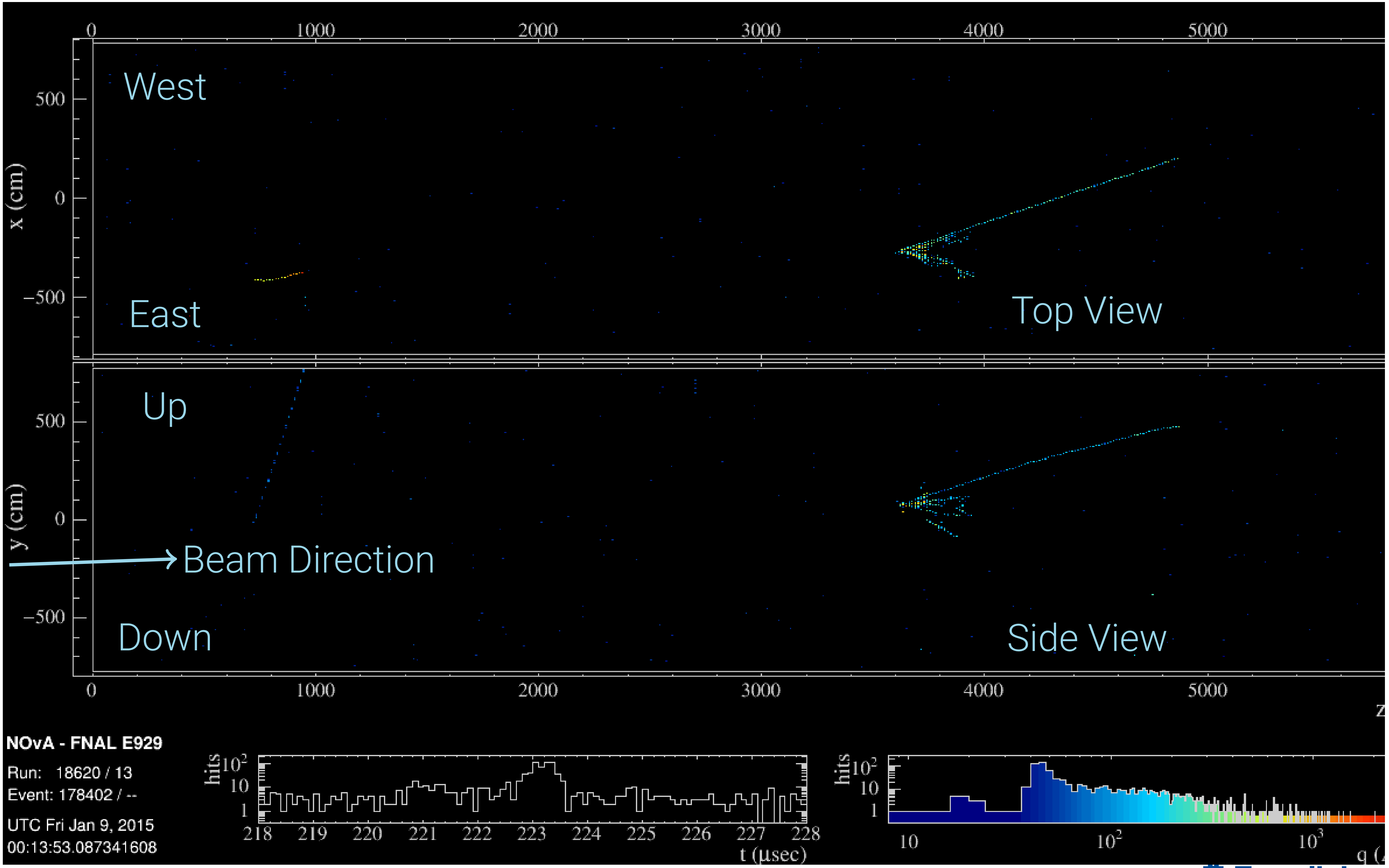
Far Detector (FD)	Near Detector (ND)
14 kt, $\gtrsim$ 344,000 channels	0.3 kt, $\gtrsim$ 20,000 channels
On surface	100 m below surface
810 km from source	1 km from the NuMI

500 microsecond readout "gate": Detector on the surface.

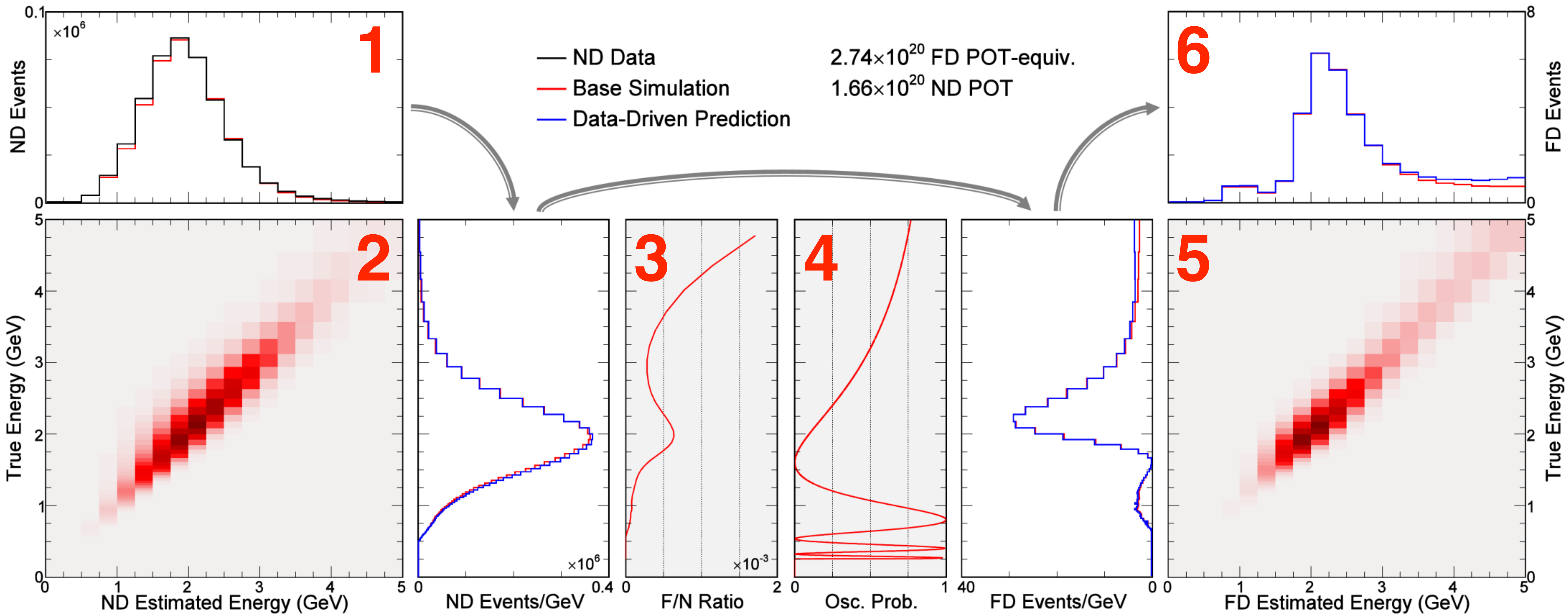


Where's the neutrino?

Apply a timing cut (still significant cosmic background)



Near-to-Far Extrapolation



1. ND Data E_ν Spectrum
2. ND Reco. → True E_ν
3. FD / ND Event Ratio in True E_ν Bins
4. $P(\nu_x \rightarrow \nu_y)$
5. FD True → Reco. E_ν
6. FD Oscillated Prediction

Figure by A. Mislivec

Fermilab

NOvA and Lattice QCD

- NOvA's **energy reconstruction is calorimetric,** so they are more sensitive to the way energy is shared between hadrons in the final state and less sensitive to effects that change lepton energy and angle.
  - Fraction of energy in neutrons,
  - Few high energy nucleons vs many low energy nucleons,
  - Charged to neutral pion ratios, etc.
- NOvA is at a higher energy than T2K, so quasielastics form a lower fraction of their total event budget, but it is still a very **large fraction of their mix of events**.
- QE and QE-like events tend to have better energy resolution in NOvA, so their weighted impact on the oscillation analysis is high.
- **Pion production is extremely important** for NOvA!

PHYSICAL REVIEW D **90,** 112017 (2014)

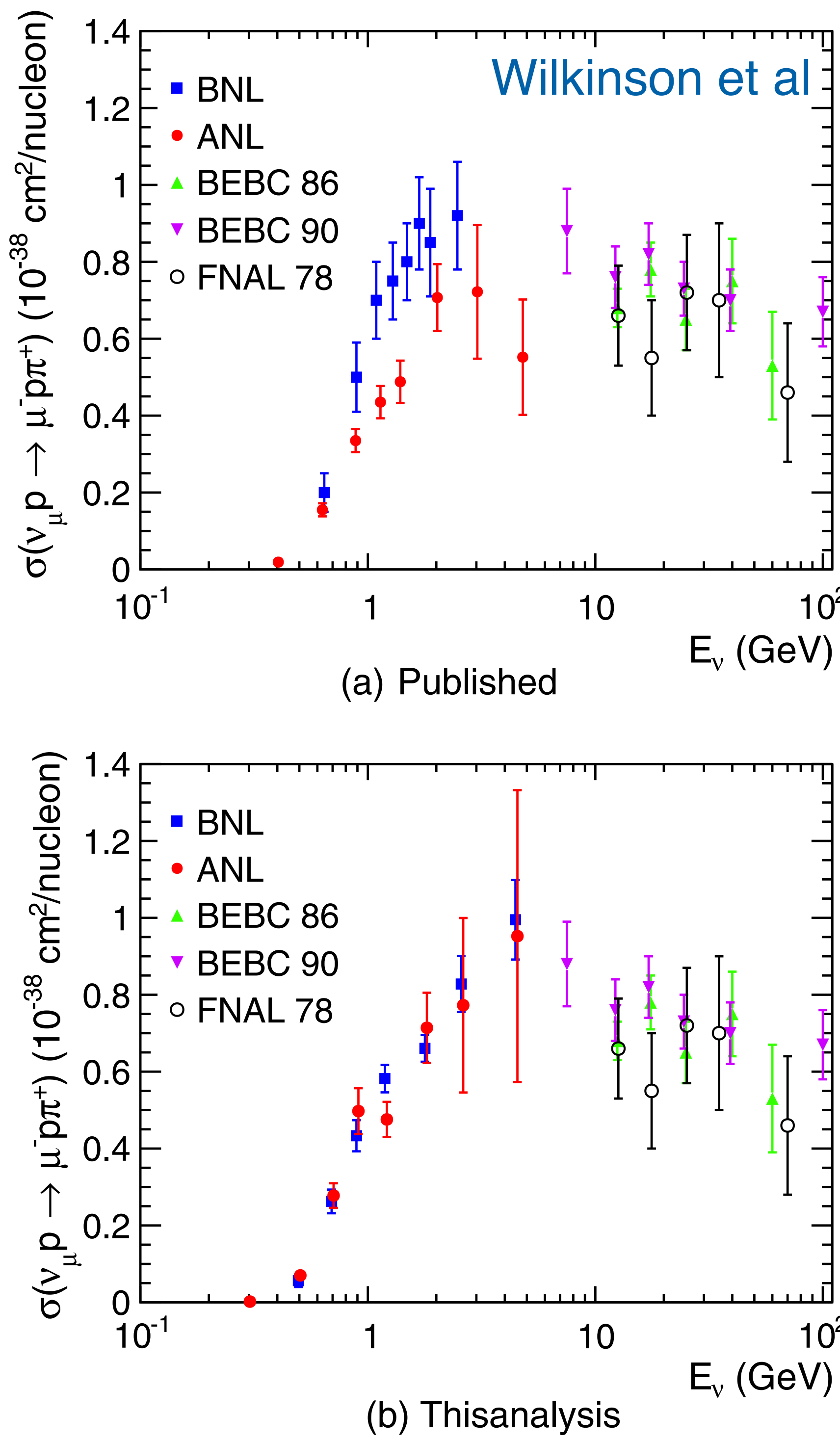
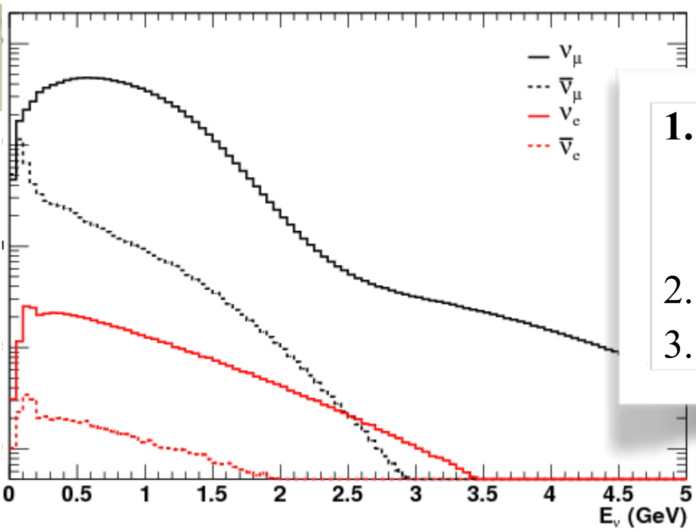


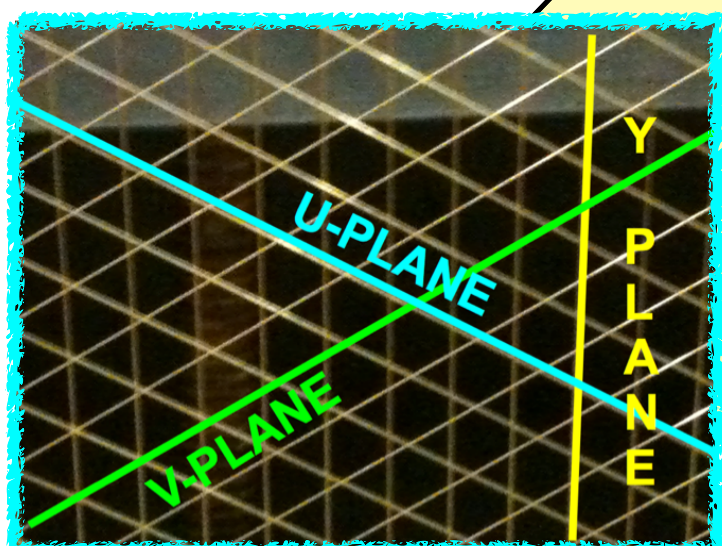
FIG. 8 (color online). The published and extracted ANL and BNL data are compared with other measurements of $\nu_\mu p \to \mu^- p \pi^+$ on hydrogen or deuterium targets [26–28]. Note that the ANL and BNL data have no invariant mass cut, whereas the other data sets have an invariant mass cut of $W \leq 2$ GeV.

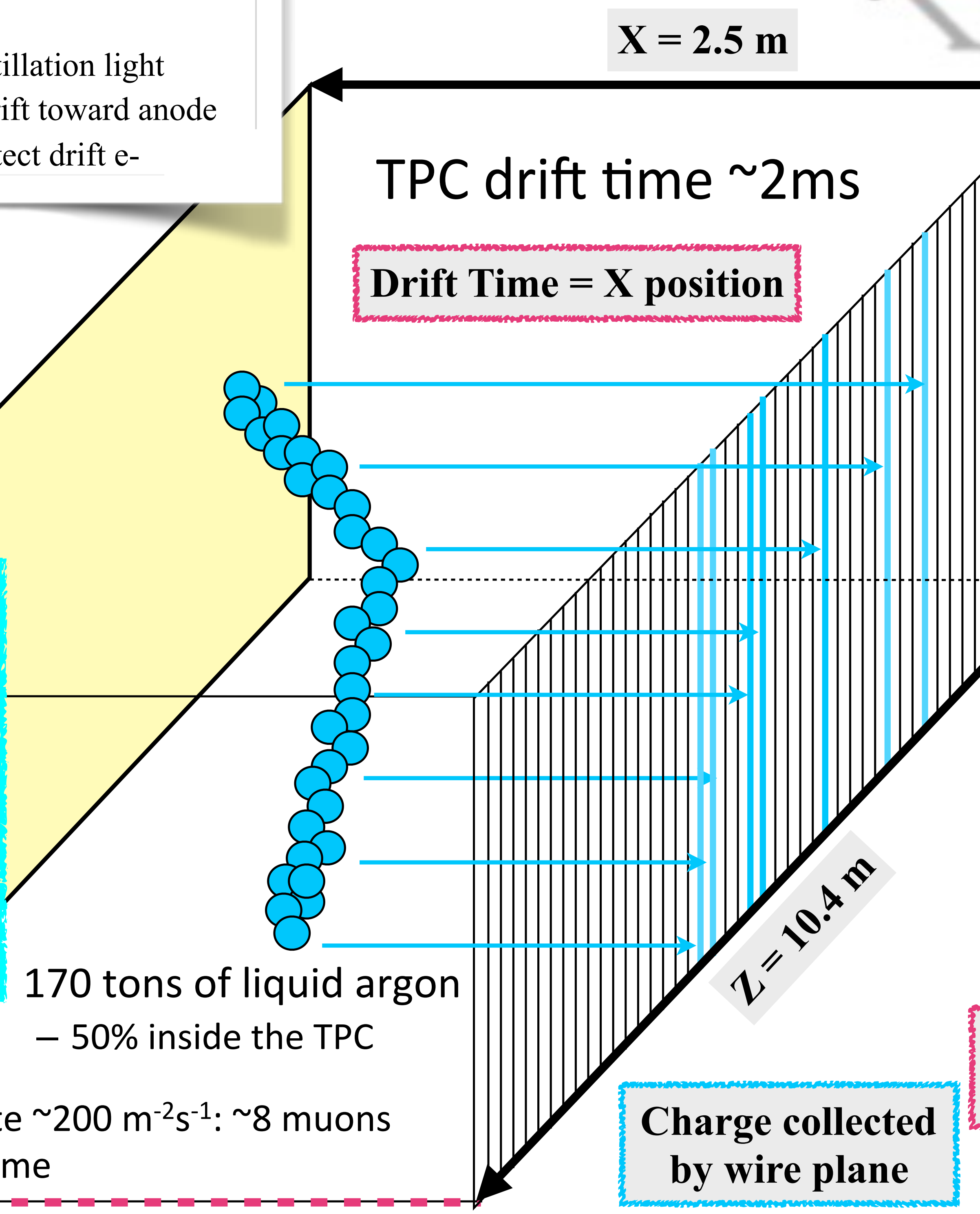


1. **Charged particles interact in Ar**
   - Ionize argon
   - Produce scintillation light
2. Ionization e- drift toward anode
3. Wire planes detect drift e-

µBooNE LArTPC

Three Wire Planes





170 tons of liquid argon
– 50% inside the TPC

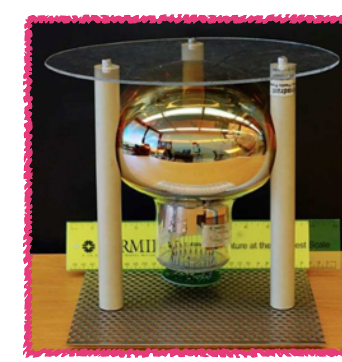
cosmic rate ~200 $m^{-2}s^{-1}$: ~8 muons per drift time

Cathode @ 70 kV (plate)

Electric Field ~270 V/cm

Anode (wire plane)

Charge collected by wire plane

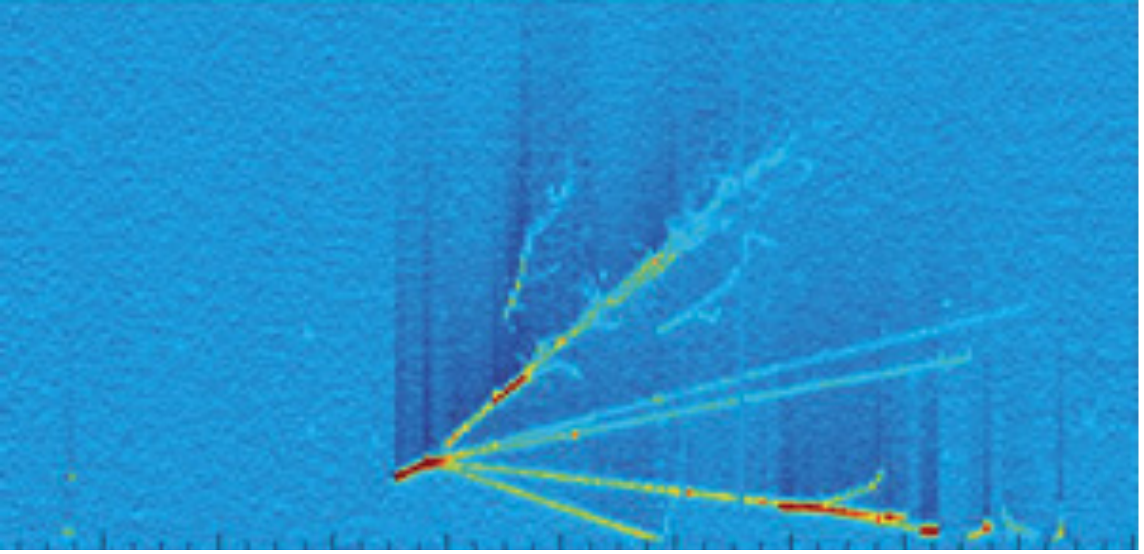


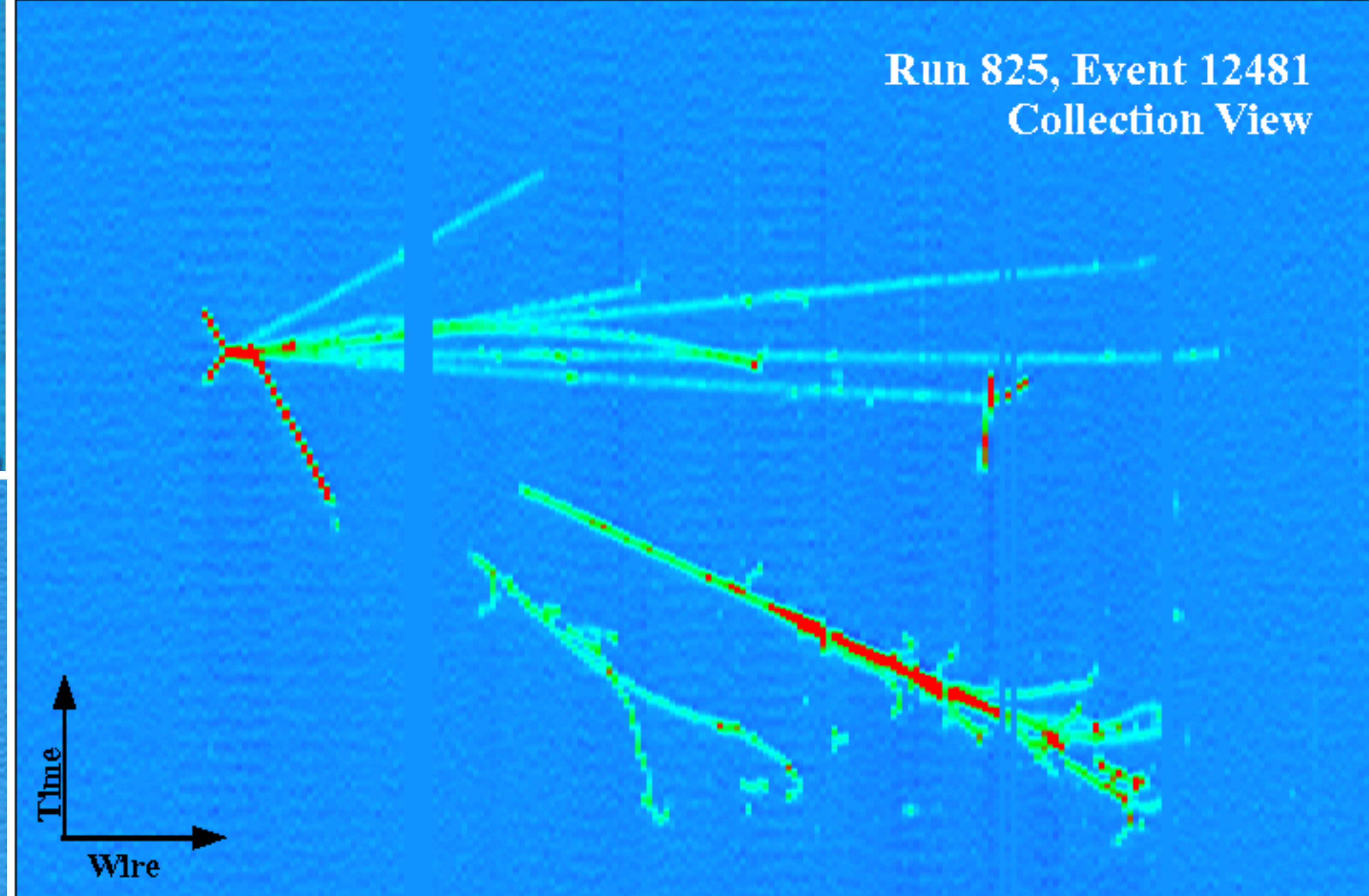
Scintillation Light detected by PMTs

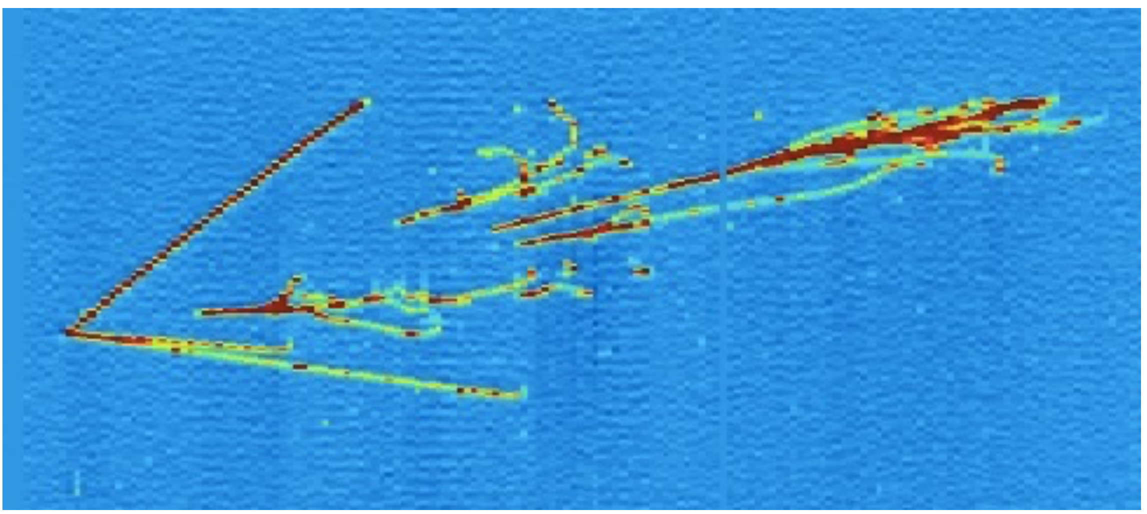
32 eight-inch PMTs for scintillation light (fast)

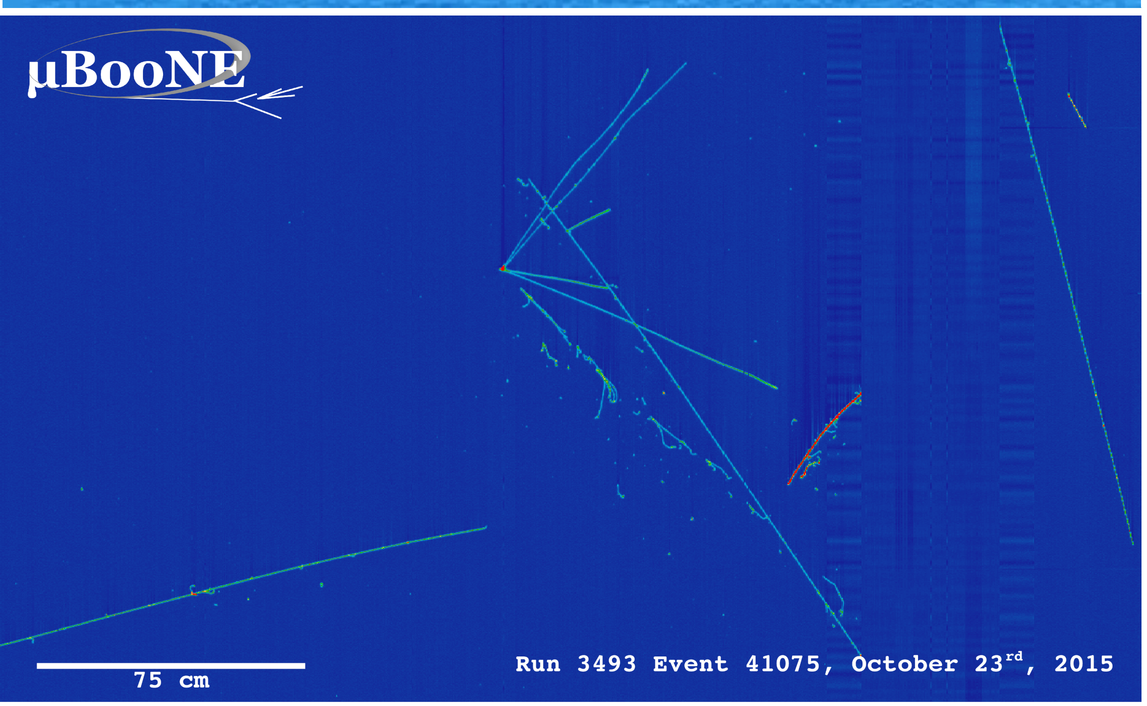
Figures: Kazuhiro Terao, SLAC & Andy Furmanski, Manchester

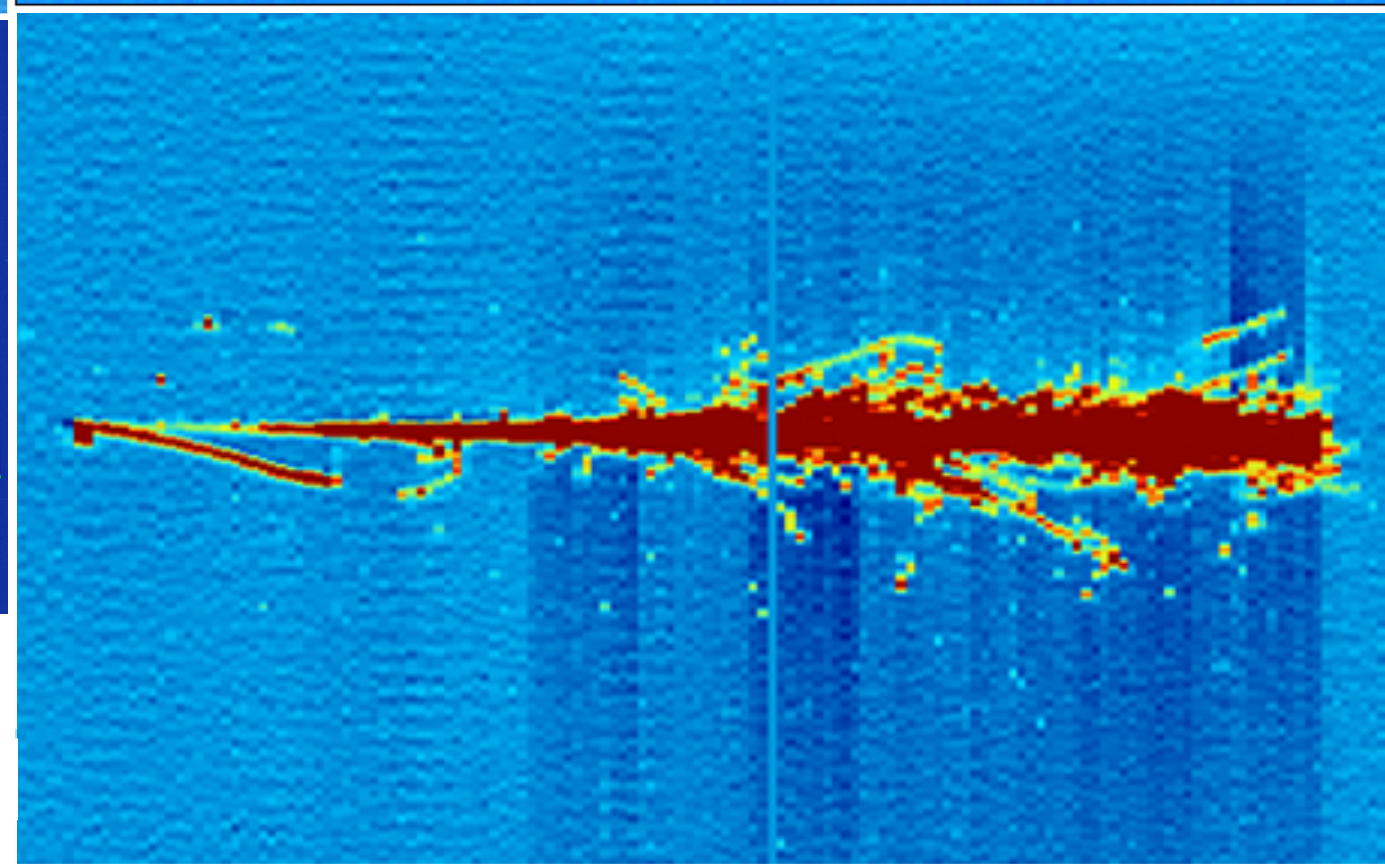
R. Acciarri et al 2017 *JINST* **12** P02017 **@Microboone**











(These are mostly ArgoNeut images)

Rampant speculation! - MicroBooNE and Lattice QCD

- We're eagerly awaiting results from MicroBooNE (but patiently waiting - they only started taking data recently).
- Like T2K, MicroBooNE should see the majority of its events as quasielastics, but like NOvA, their energy reconstruction will be calorimetric.
- Convincing evidence of a sterile neutrino will require excellent theoretical controls across the board.

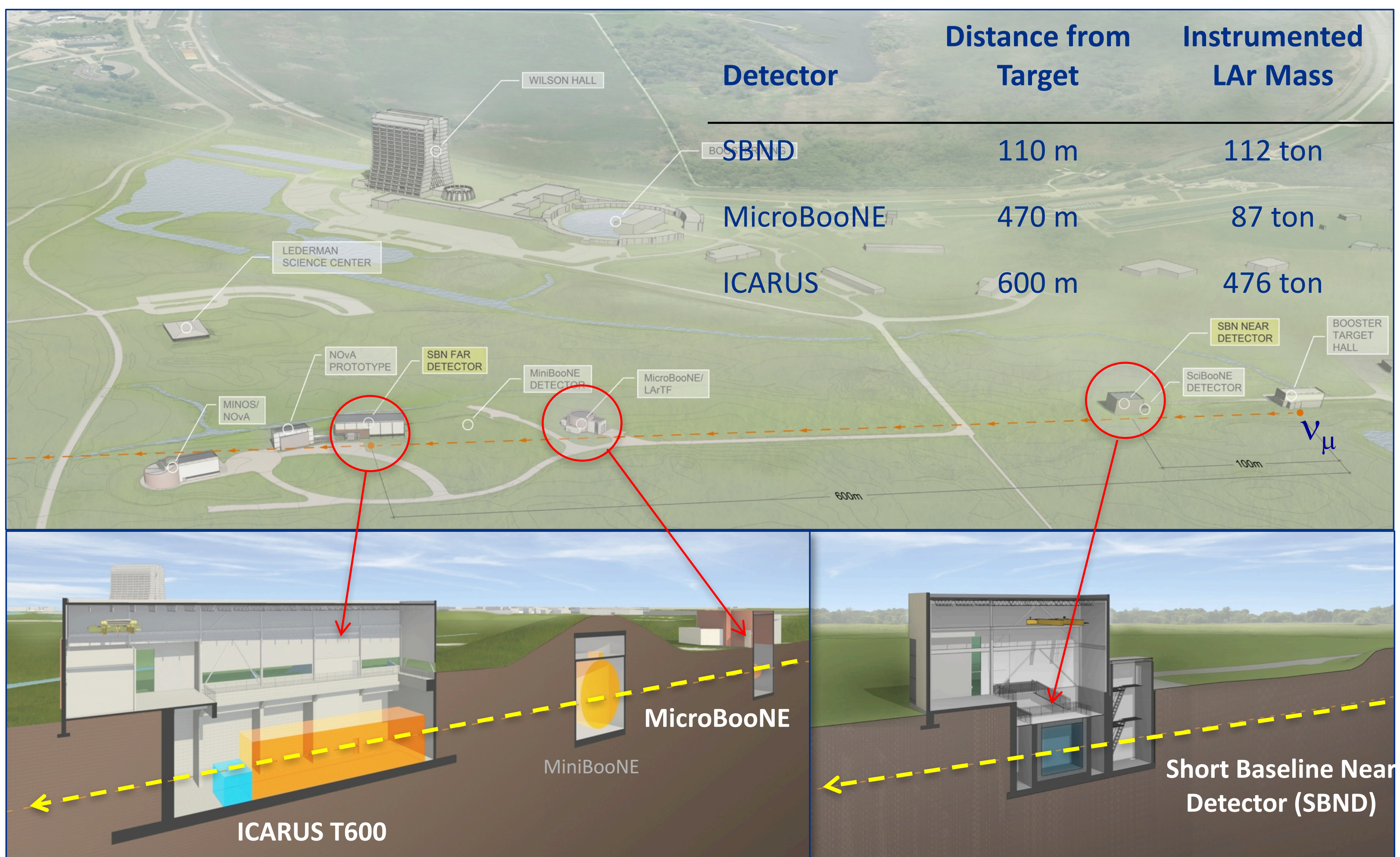
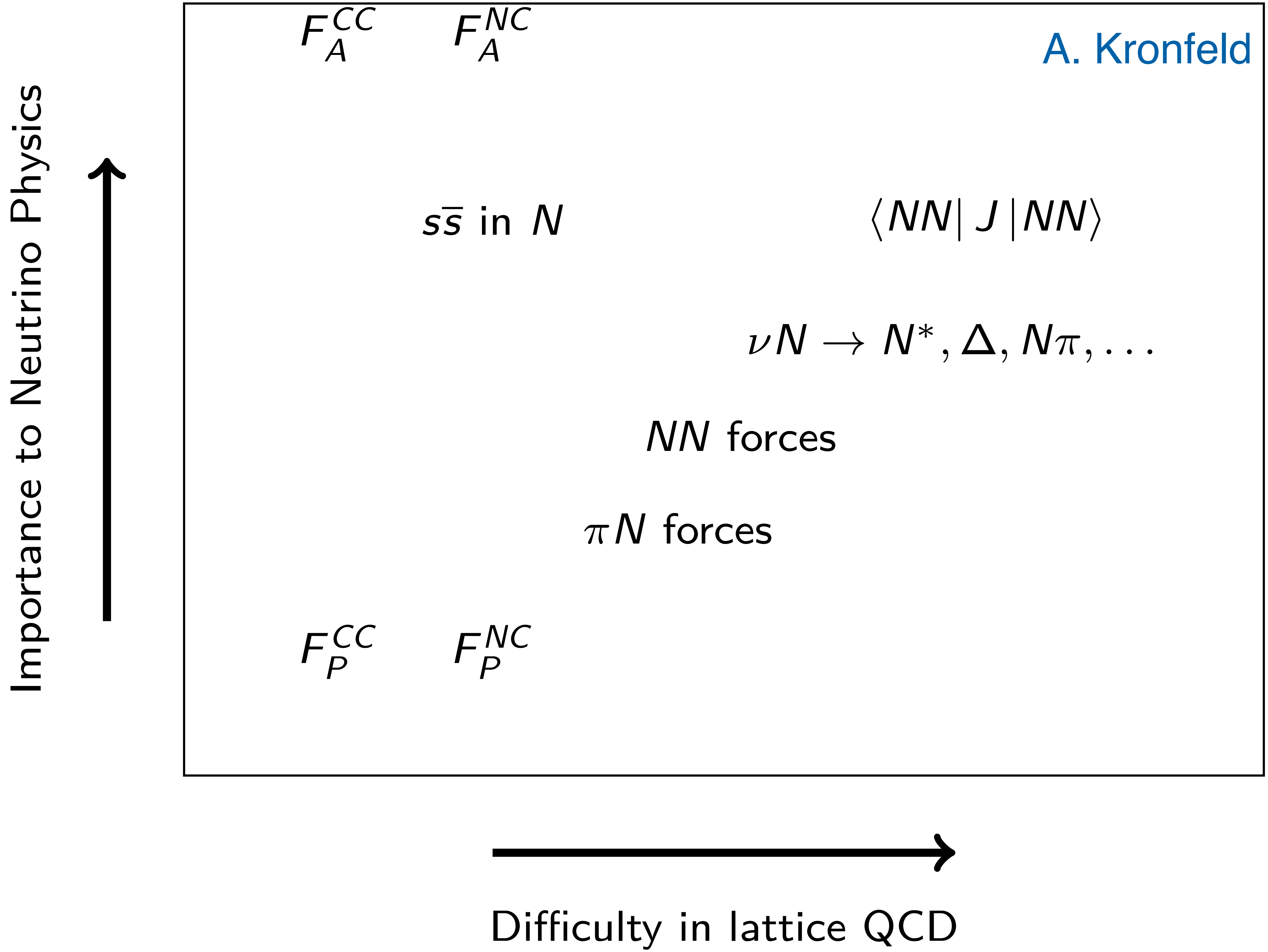


Figure by M. Kirby

Fermilab

Lattice QCD and neutrino experiments...



Conclusions

- A running theme in all three of the experiments highlighted today is that quasielastic events are a very large portion of their total cross section (and they are dominant at T2K and MicroBooNE).
- Pion production is crucial for today's program and that importance will only grow at DUNE, etc.
- Nucleon-level uncertainties are extremely important and neutrino-nucleon data will be extremely hard to come by!

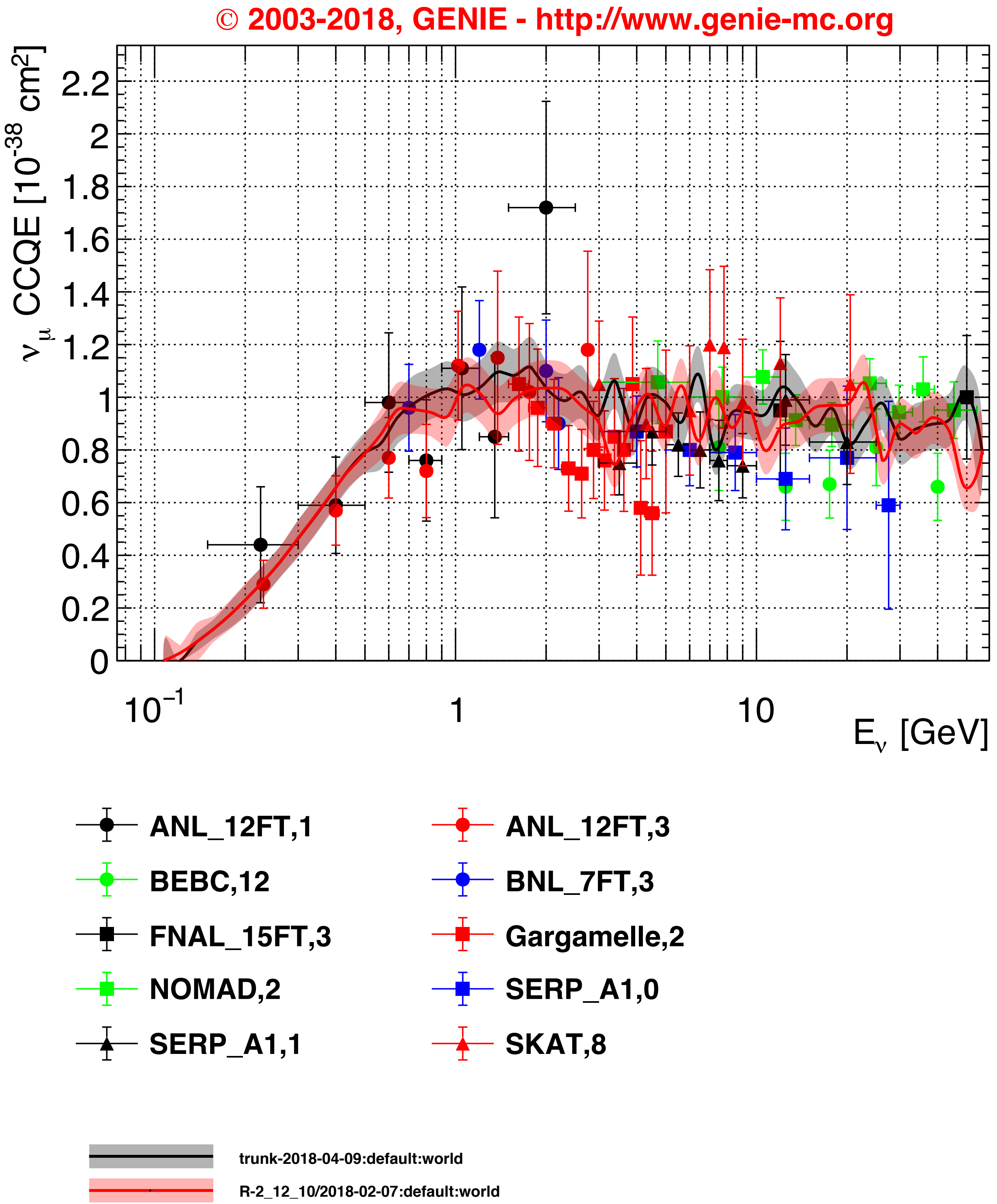
The major challenges for this reaction channel are: (QE)

- improvement of our knowledge of the axial part of the nucleon–nucleon transition matrix elements via
  1. a new high-statistics hydrogen and/or deuterium cross section experiment; or
  2. lattice-QCD calculations of the nucleon form factors at the same level of quality and precision as for meson form factors used in quark-flavor physics;

L. Alvarez-Ruso et al. / Progress in Particle and Nuclear Physics 100 (2018) 1–68

You'll hear more about this in the next talk!

Back-up



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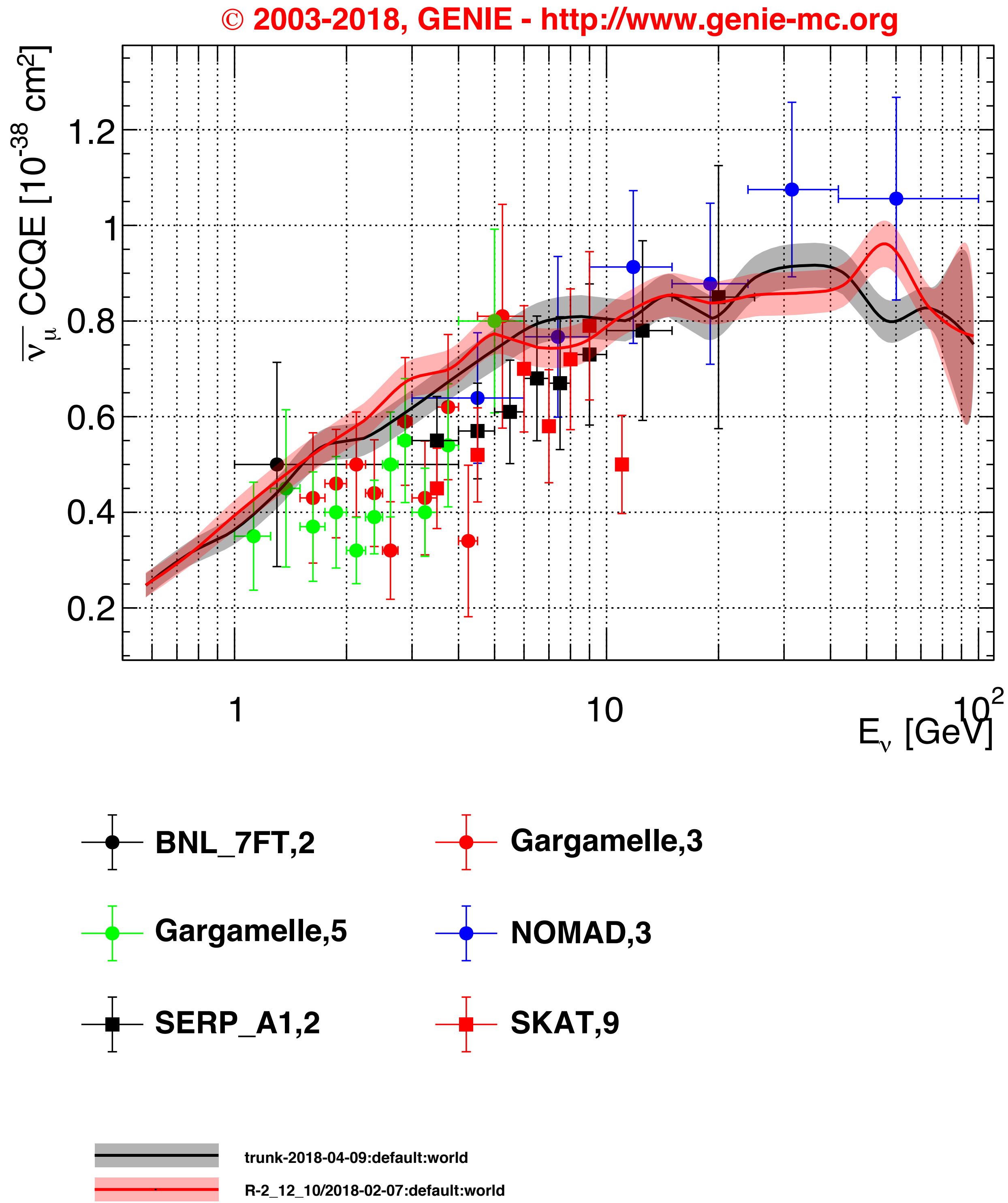
ν_μ CCQE [10^{-38} cm^2]
E_ν [GeV]
ANL_12FT,1
ANL_12FT,3
BEBC,12
BNL_7FT,3
FNAL_15FT,3
Gargamelle,2
NOMAD,2
SERP_A1,0
SERP_A1,1
SKAT,8
trunk-2018-04-09:default:world
R-2_12_10/2018-02-07:default:world



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$\overline{\nu}_\mu$ CCQE [10^{-38} cm^2]
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BNL_7FT,2
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NOMAD,3
SERP_A1,2
SKAT,9
trunk-2018-04-09:default:world
R-2_12_10/2018-02-07:default:world

Experiments

We do not measure the probability directly - we measure a *rate:*

$$R(E_{\text{vis}}) = N \int dE \Phi_\alpha(E) \sigma_\beta(E, E_{\text{vis}}) \epsilon_\beta(E) P(\nu_\alpha \to \nu_\beta, E)$$

- N = overall normalization (e.g., mass)
- Φ_α = flux of ν_α
- σ_β = cross section for ν_β
- ε_β = detection efficiency for ε_β
- NOTE: $\sigma_\beta \varepsilon_\beta$ always appear together. Define:

$$\tilde{\sigma}_\beta = \sigma_\beta \epsilon_\beta$$

Slide inspired by P. Huber, NuInt2017

Problem & Solution

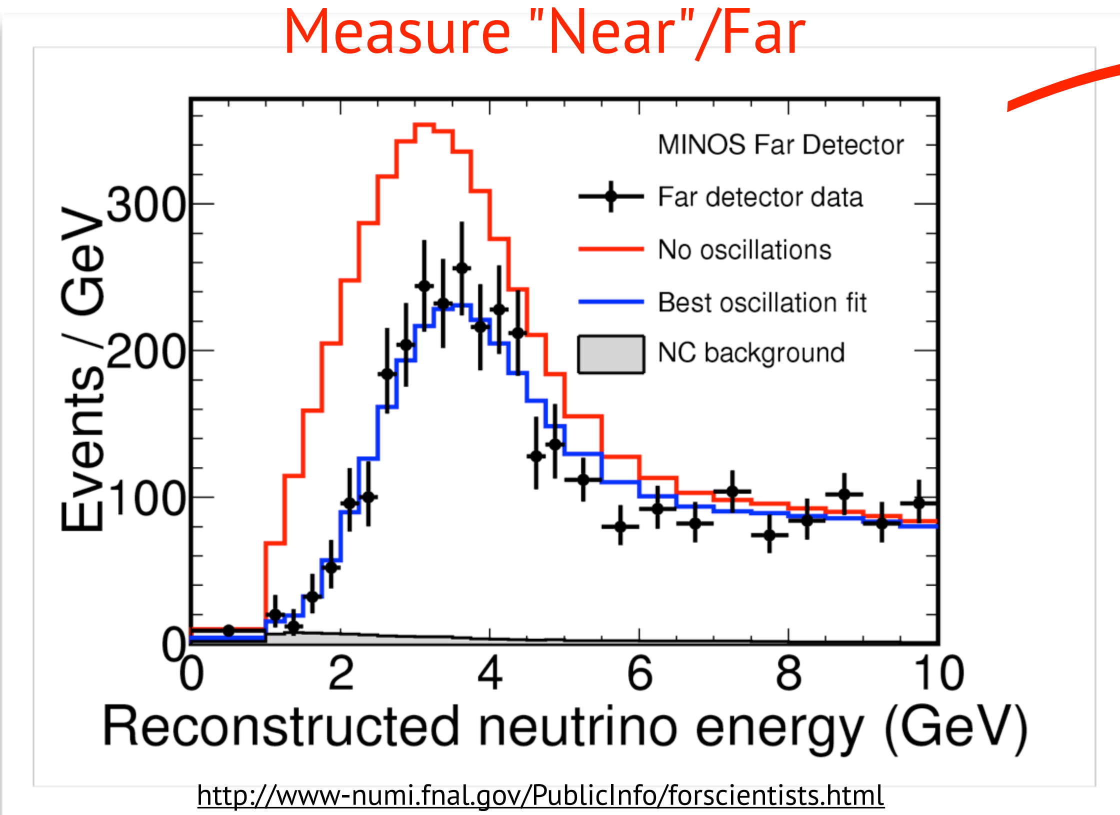
- How do we know the components of the integral?
- How can we even determine the ratios for flavor and helicity combinations?
- Even if we know the cross sections from theory, we don't know efficiency ratios.
- But, we can measure ratios if we use two detectors!

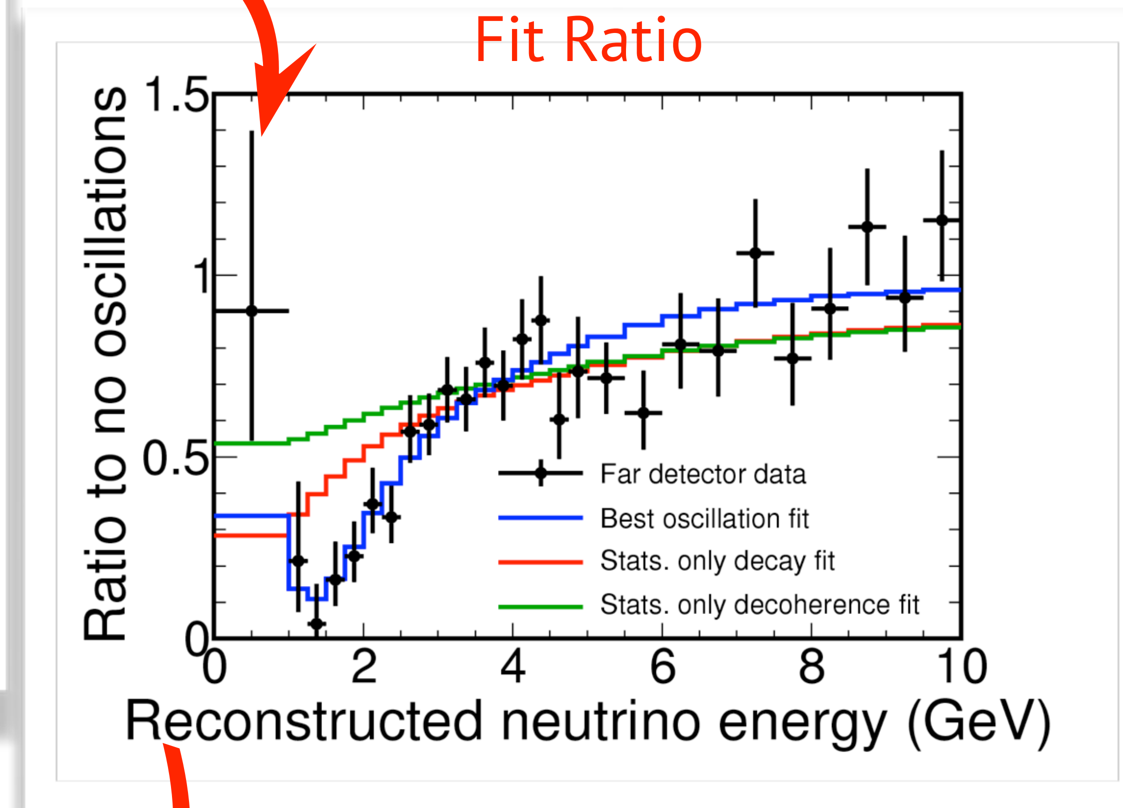
$$\frac{R_{\alpha\to\alpha}(\text{Far})L^2}{R_{\alpha\to\alpha}(\text{Near})} = \frac{N_{\text{far}}\Phi_\alpha\tilde{\sigma}_\alpha P(\nu_\alpha \to \nu_\alpha)}{N_{\text{near}}\Phi_\alpha\tilde{\sigma}_\alpha}$$

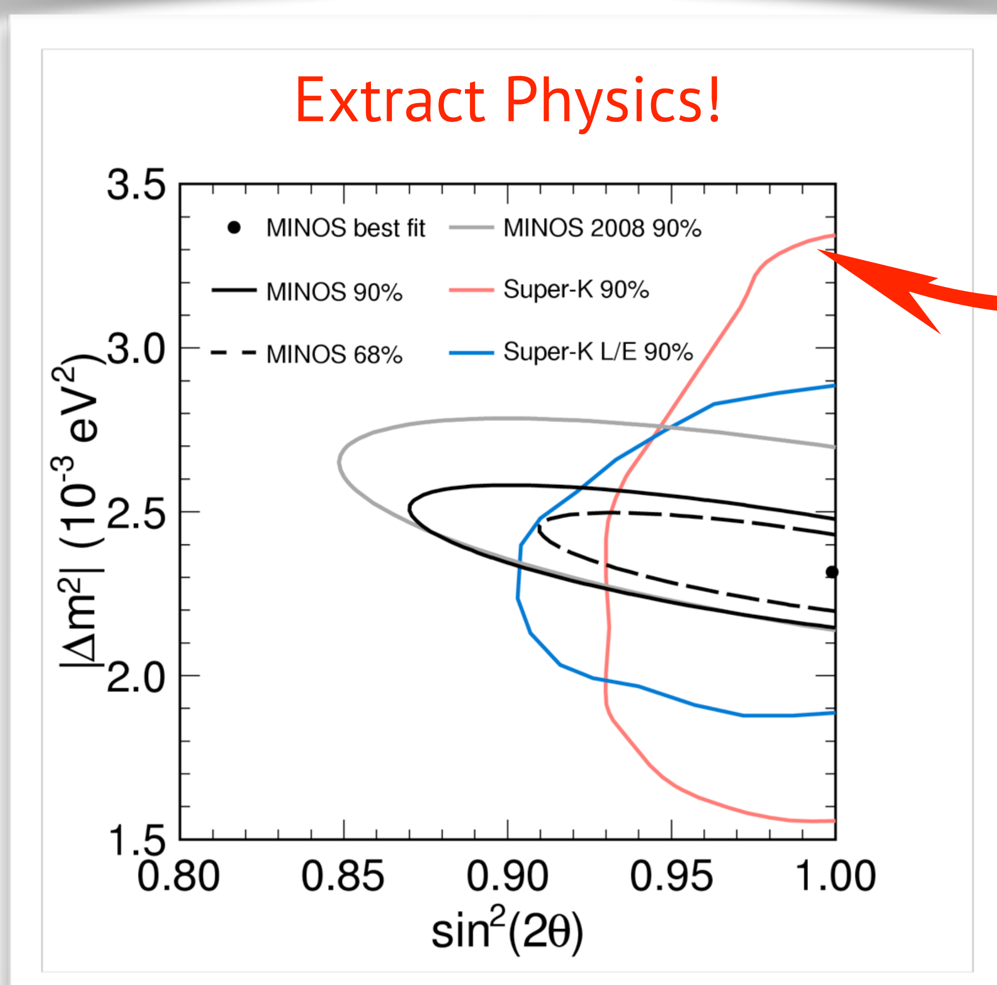
$$\frac{R_{\alpha\to\alpha}(\text{Far})L^2}{R_{\alpha\to\alpha}(\text{Near})} = \frac{N_{\text{far}}}{N_{\text{near}}} P(\nu_\alpha \to \nu_\alpha)$$

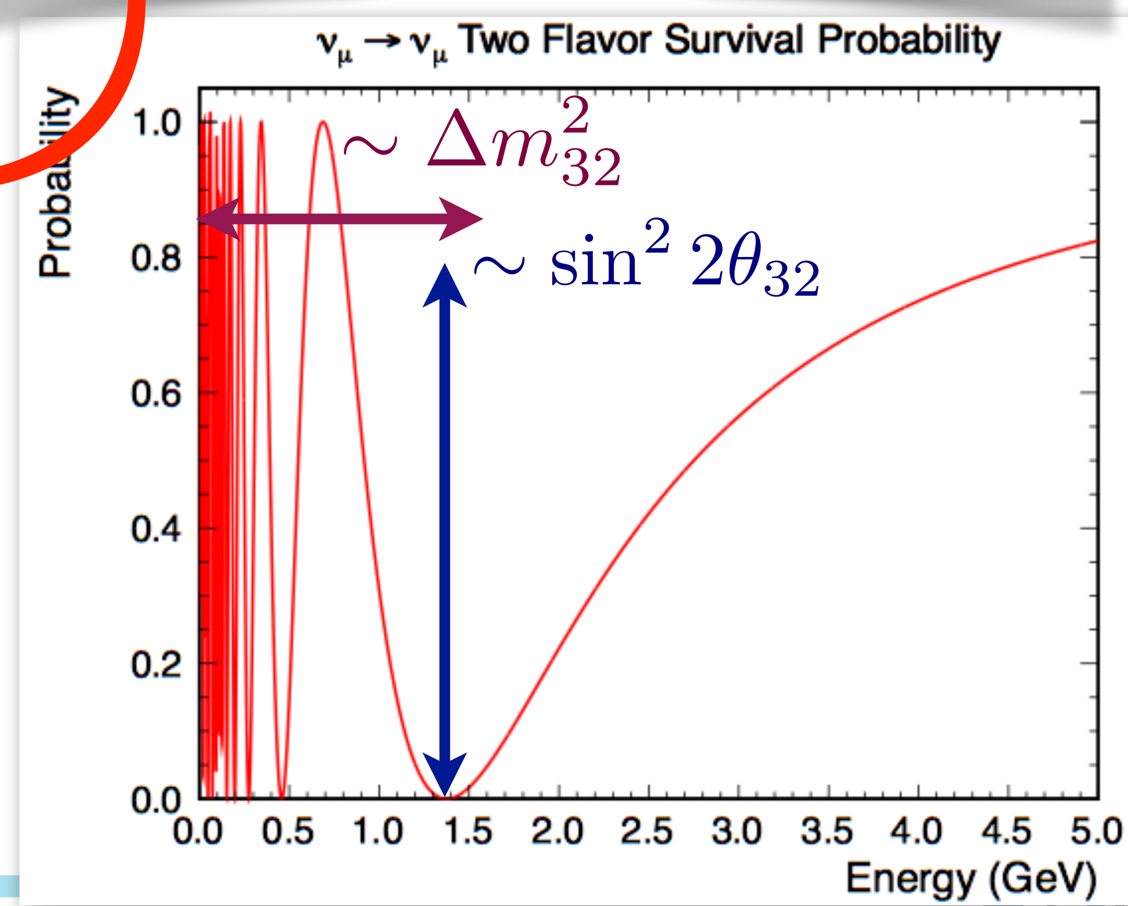
Slide inspired by P. Huber, NuInt2017

$$P\left(\nu_\mu \rightarrow \nu_\mu\right) = 1 - \sin^2 2\theta_{32} \sin^2\left[1.27\Delta m^2_{32}\left(L/E\right)\right]$$









But, another (harder) problem!

- The above equations were for a disappearance measurement. For appearance measurements:

$$\frac{R_{\alpha\to\beta}(\text{Far})L^2}{R_{\alpha\to\beta}(\text{Near})} = \frac{N_{\text{far}}\Phi_\alpha\tilde{\sigma}_\beta P(\nu_\alpha \to \nu_\beta)}{N_{\text{near}}\Phi_\alpha\tilde{\sigma}_\alpha}$$

$$\frac{R_{\alpha\to\beta}(\text{Far})L^2}{R_{\alpha\to\beta}(\text{Near})} = \frac{N_{\text{far}}}{N_{\text{near}}}\frac{\tilde{\sigma}_\beta}{\tilde{\sigma}_\alpha}P(\nu_\alpha \to \nu_\beta)$$

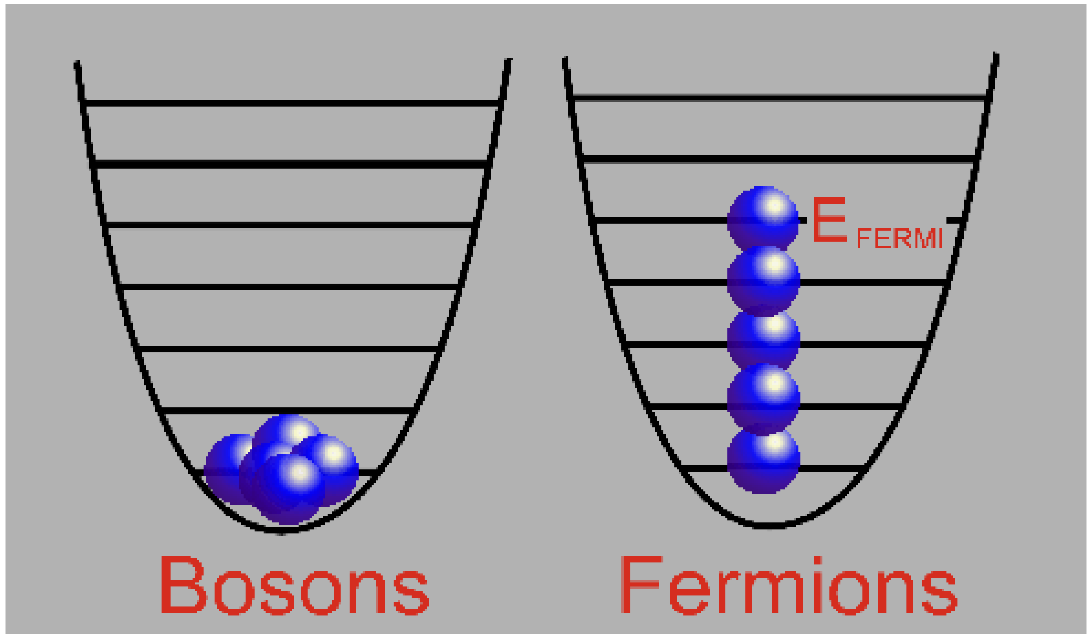
- It is even worse than that, because the efficiencies and the cross sections will both change for antineutrinos.

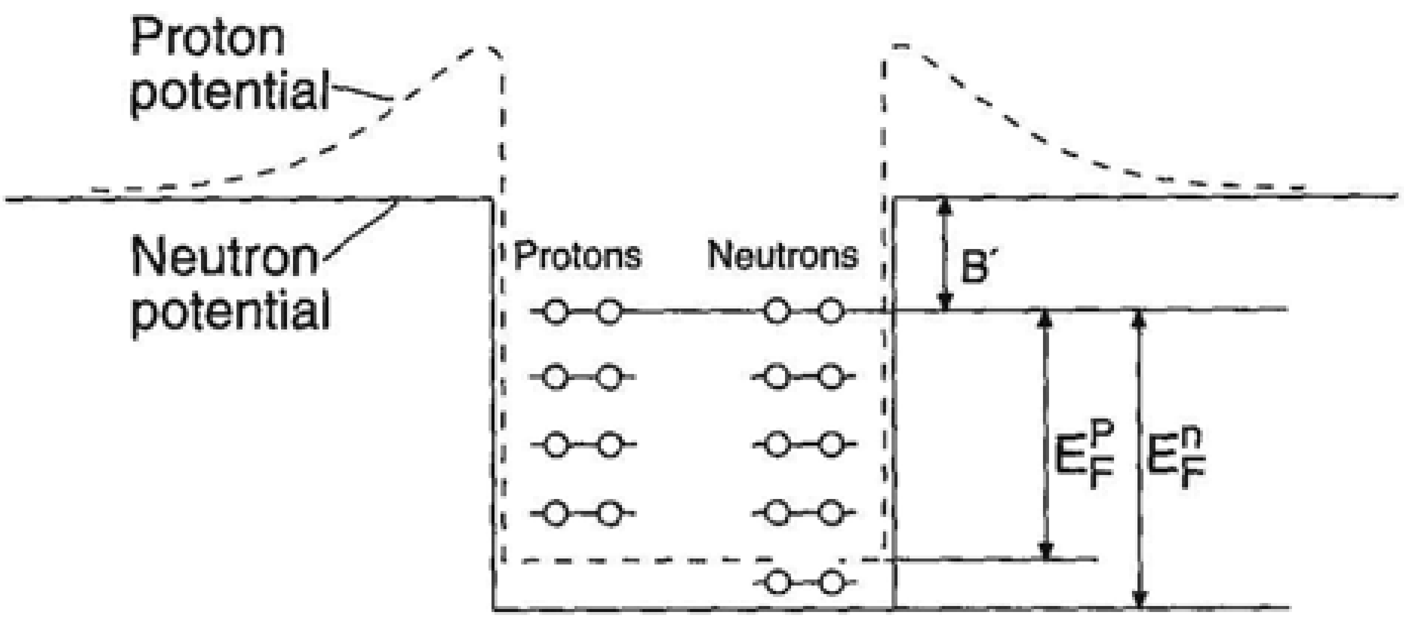
Slide inspired by P. Huber, NuInt2017

But wait - because our beams aren't pure, we're saved, right?

- The oscillated flux is different for a given species, so energy-dependent effects never really cancel.
- You need independent, external measurements to constrain your cross section model. Using internal measurements only introduces a degree of circularity.
- If you are truly able to build identical near and far detectors, projecting your near detector measurement to the far detector to compute an expected spectrum is a powerful technique. But...
  - It is hard to build identical near and far detectors!
  - If nothing else, you typically want your far detector to be much, much larger than your near detector. Even assuming perfect calibration this has important consequences for the **acceptance** in both detectors.
  - Scaling the same technology in the same way is also challenging. Typically technologies that scale well for both small and large detectors involve making granularity sacrifices in the near detector.

Nucleon not at rest: Fermi Gas Model





B. Povh et al, *Particles and Nuclei*, Springer 2002

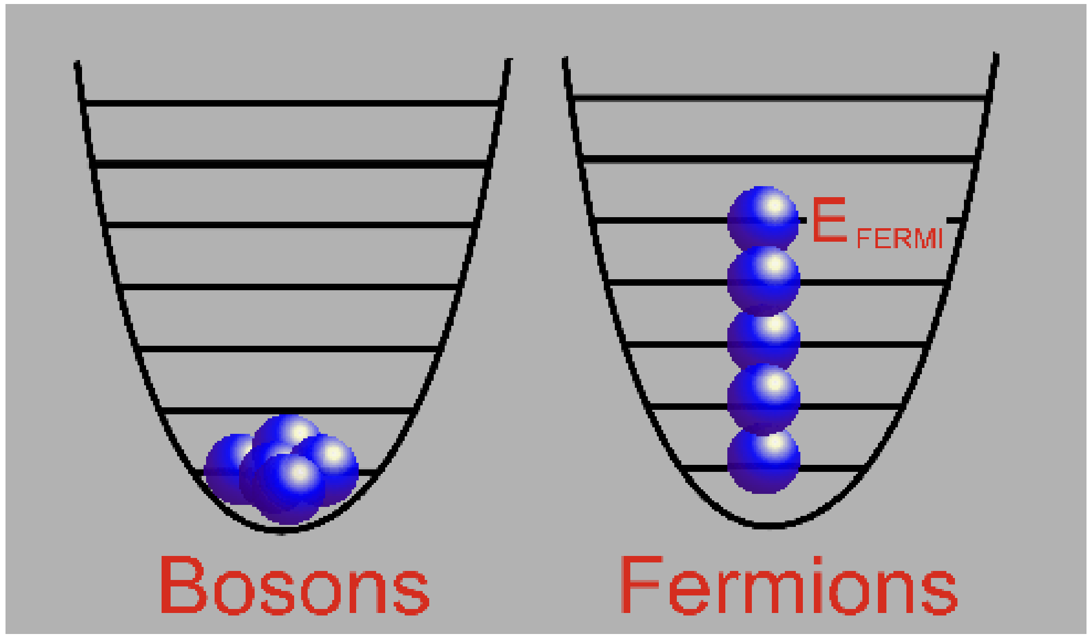
^{12}C	E_B = 25 MeV	p_F = 220 MeV/c

- **Impulse approximation:** scatter off independent single nucleons summed (incoherently) over the nucleus.
- In the FGM, all the nucleons are non-interacting and all states are filled up to k_F.
- The IA becomes problematic when the momentum transfer is *smaller* than ~300 MeV (think about the de Broglie wavelength and remember 1 fm = 1/200 MeV).

It is nice to see this problem getting high-level attention.

Smith and Moniz, 1972, Nucl. Phys. B43, 605

Nucleon not at rest: Fermi Gas Model



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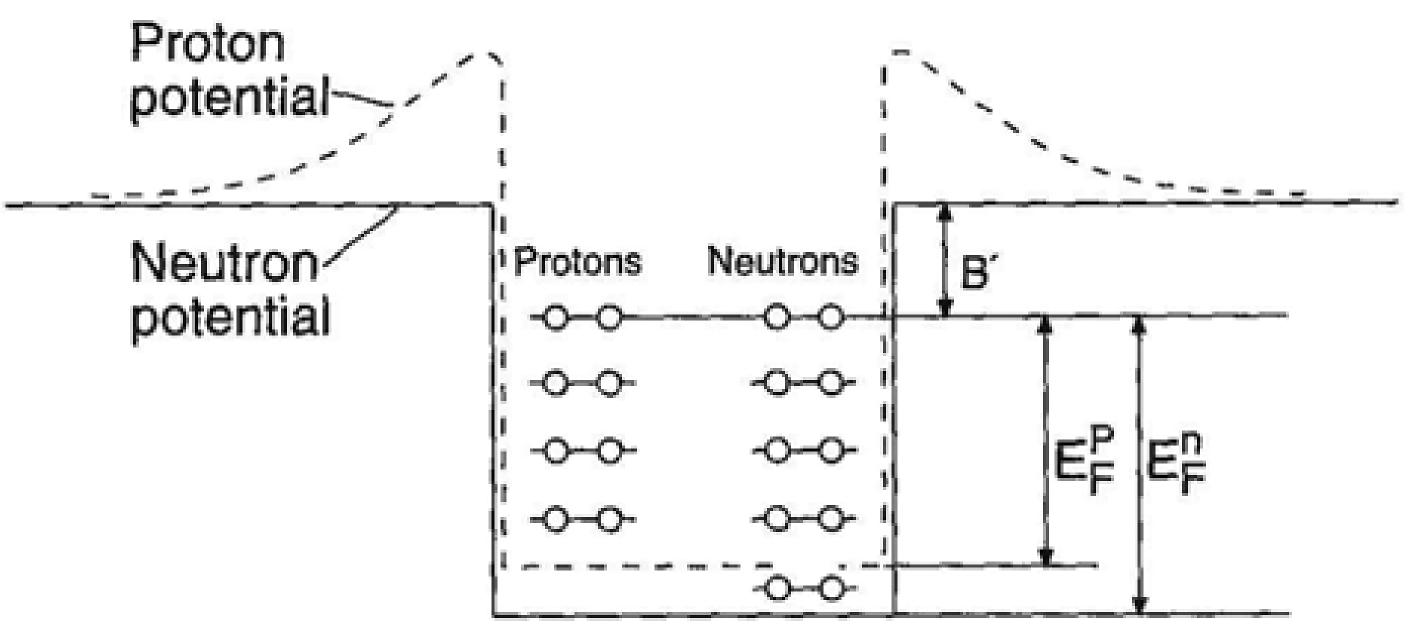

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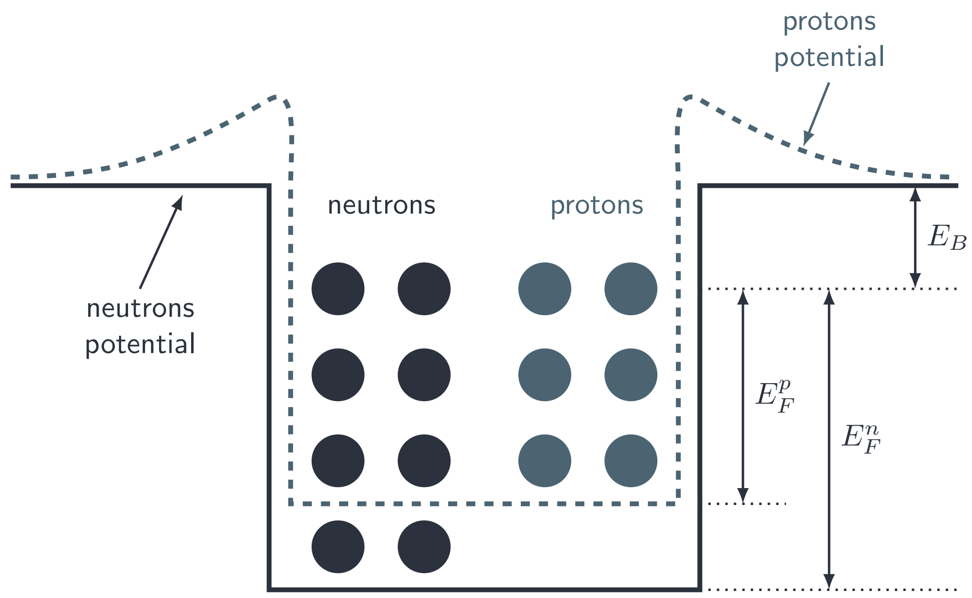
Nucleons move freely within the nuclear volume in constant binding potential.



Global Fermi Gas

$$p_F = \frac{\hbar}{r_0}\left(\frac{9\pi N}{4A}\right)^{1/3}$$

Local Fermi Gas

$$p_F(r) = \hbar\left(3\pi^2\rho(r)\frac{N}{A}\right)^{1/3}$$

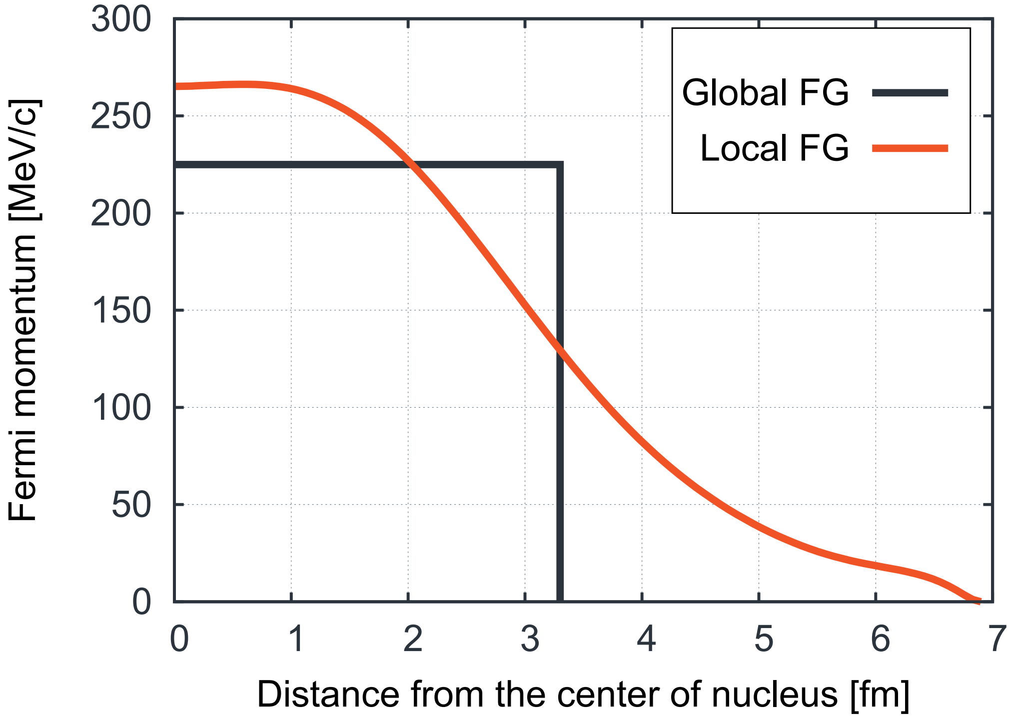


Figure by T. Golan

QE Cross Section

ν Cross Section: $$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A\left(Q^2\right) \pm B\left(Q^2\right)\frac{s-u}{M^2} + C\left(Q^2\right)\frac{(s-u)^2}{M^4}\right]$$

- Early formalism by Llewellyn Smith.
- Vector and Axial-Vector Components.
  - Vector piece can be lifted from ("easier") electron scattering data.
  - We have to measure the Axial piece.
- Q^2 is the 4-momentum transfer ($-q^2$).
- s and u are Mandelstam variables.
- The lepton vertex is known; the nucleon structure is parameterized with 2 vector (F_1, F_2) and 1 axial-vector (F_A) form factors.
  - Form factors are $f(Q^2)$ and encoded in A, B, and C.

C. H. Llewellyn Smith, Phys. Rept. 3 261 (1972).

Form Factors

$$A \simeq \frac{t}{M^2}\left(|f_{1V}|^2 - |f_A|^2\right) + \frac{t^2}{4M^2}\left(|f_{1V}|^2 + \xi^2|f_{2V}|^2 + |f_A|^2 + 4\xi\mathrm{Re}\left(f_{1V}f_{2V}^*\right)\right) + \frac{t^3\xi^2}{16M^6}|f_{2V}|^2$$

$$B \simeq \frac{1}{M^2}\left(\mathrm{Re}\left(f_{1V}f_A^*\right) + \xi\mathrm{Re}\left(f_{2V}f_A^*\right)\right)t$$

$$C = \frac{1}{4}\left(|f_{1V}|^2 + |f_A|^2 - \frac{\xi^2|f_{2V}|^2}{4M^2}t\right)$$

$$f_A\left(q^2\right) = \frac{f_A(0)}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

f_A is the axial-vector form factor. We must *measure* this in ν-scattering. The dipole has been dominant, but that is changing...

The ***form factors*** (f) contain parameterized information about the target (general shape of the form factors comes from symmetry arguments).

Not calculable from first principles, instead we measure them experimentally.

*See e.g. PRD 84, 7, 073006 (2011)

Lattice QCD and neutrino-nucleus scattering

- **New neutrino-nucleon data will be hard to come by**, making lattice contributions potentially critical.
- We have **started to phase out the dipole form factor in favor of the model-independent z-expansion** (lattice program ongoing to compute the elements of the z-expansion):

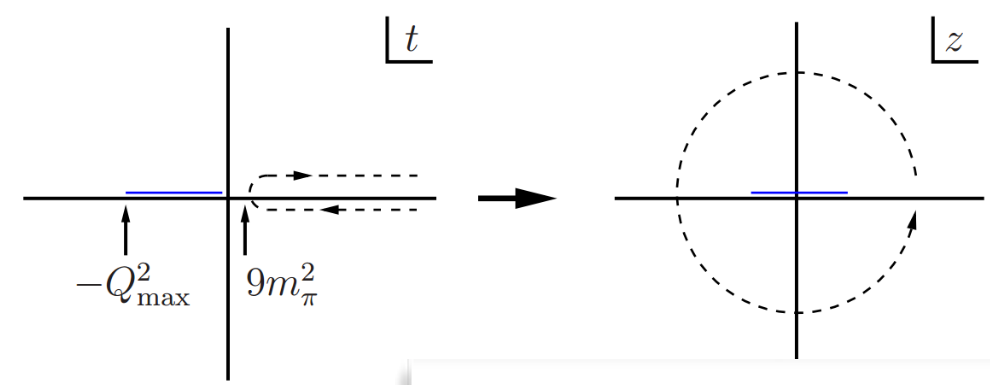
z-expansion: conformal mapping taking kinematically allowed region ($t = -Q^2$) to $|z| < 1$.

PHYSICAL REVIEW D **84,** 073006 (2011)

Model-independent determination of the axial mass parameter in quasielastic neutrino-nucleon scattering

Bhubanjyoti Bhattacharya, Richard J. Hill, and Gil Paz

$$z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}} \qquad F_A(z) = \sum_{n=0}^{\infty} a_n z^n \qquad t_c = 9m_\pi^2$$



$$F_A^{\mathrm{dipole}}(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{m_A^2}\right)^2}$$

(Llewellyn-Smith, 1972)

[Phys.Rept.3 (1972),261]

Aaron S. Meyer (asmeyer2012@uchicago.edu)

University of Chicago/Fermilab

Radiative Corrections at the Intensity Frontier of Particle Physics