Challenges in Neutrino-Nucleus Scattering*

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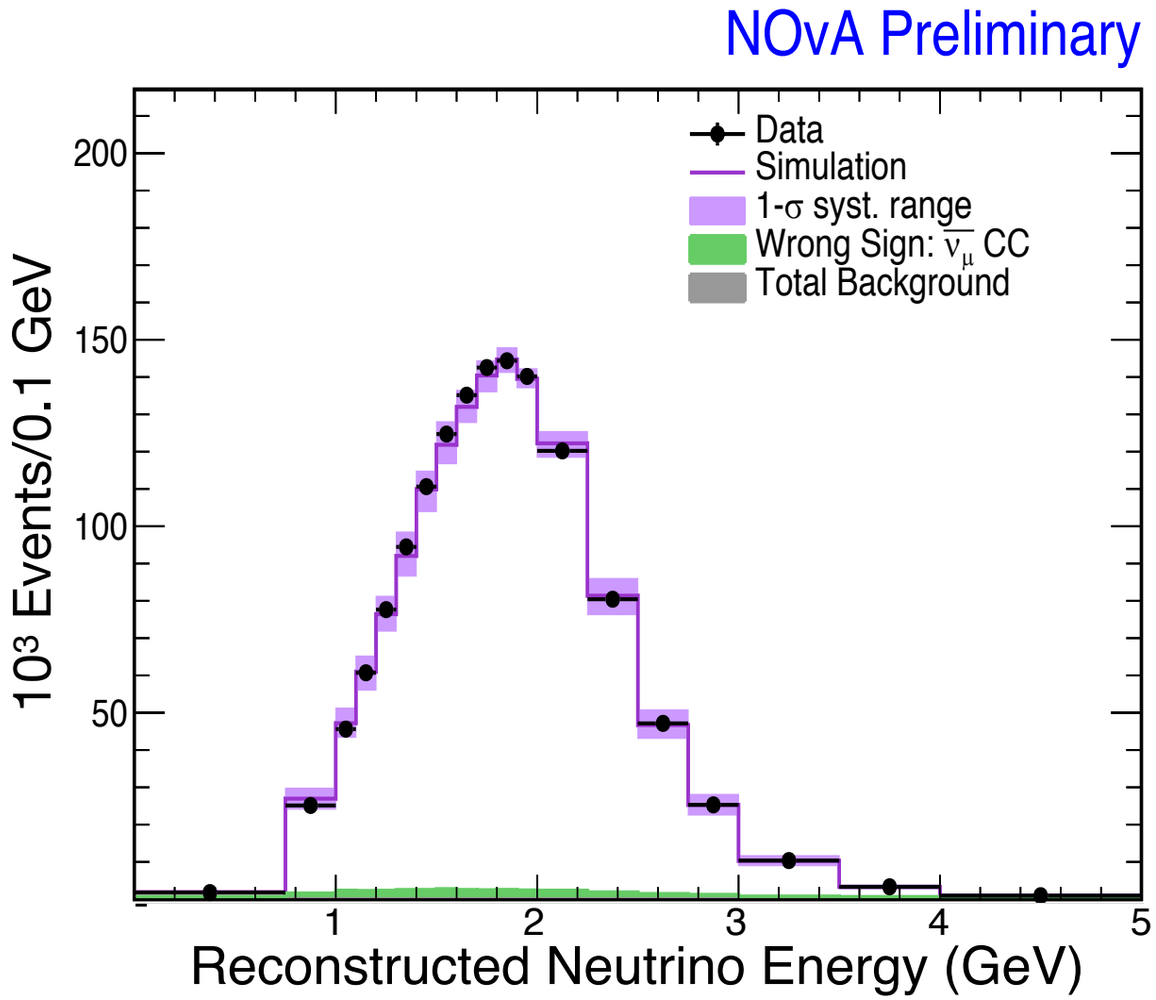
Fermilab & IAS TU München

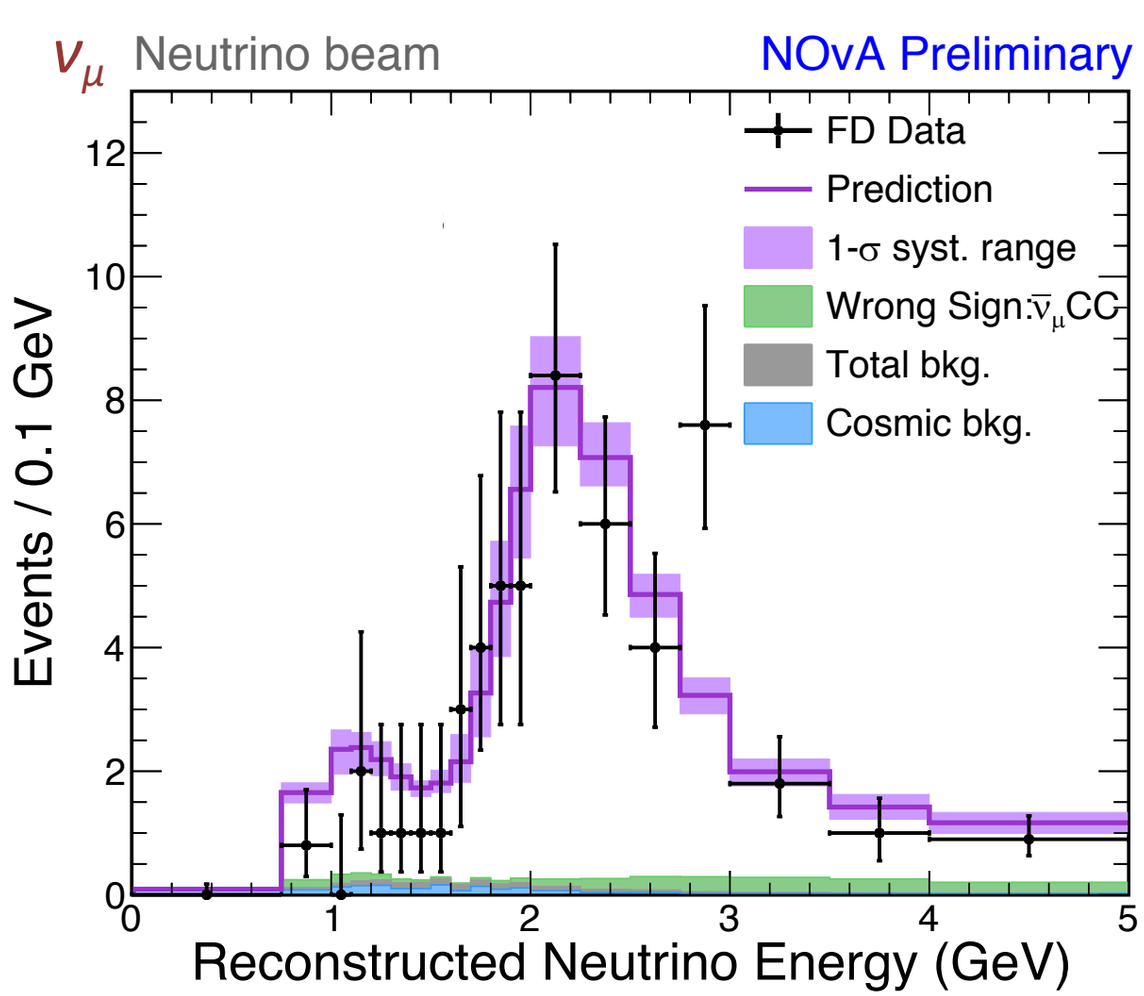
Lattice 2018 | Michigan State University
July 27, 2018

*esp. those connected to lattice QCD

Neutrino Oscillations

- Suppose you have a neutrino beam and two enormous vats of neutrons, one nearby and the other far away:





Alex Himmel, Wine & Cheese Seminar, June 15 @ Fermilab

Neutrino Oscillations

- The “disappearance” can be explained as an interference effect, if the muon couples to more than one (*i.e.*, three) mass eigenstates.

- Simplest extension of Standard Model has neutrino Yukawa couplings:

$$\mathscr{L} = \cdots + \sum_{j,i=1}^{3} y^{(e)}_{ji} \bar{E}_j \tilde{\Phi}^\dagger L_i + \sum_{a=1}^{n_N} \sum_{i=1}^{3} y^{(\nu)}_{ai} \bar{N}_a \Phi^\dagger L_i + \sum_{a=1}^{n_N} m_a \bar{N}_a C N_a + \cdots$$

  where the N_a fields (right-handed neutrinos) are gauge singlets.

- The last term (“Majorana mass term”) violates (global) lepton number but but imposing global symmetries is unappealing.

- Other fields: E_i = lepton singlet; Φ = Higgs doublet; L_i = lepton doublet.

Pontecorvo–Maki–Nakagawa–Sakata Matrix

- The PMNS matrix is to neutrino & lepton-flavor physics as the Cabibbo-Kobayashi-Maskawa (CKM) matrix is to quark-flavor physics:

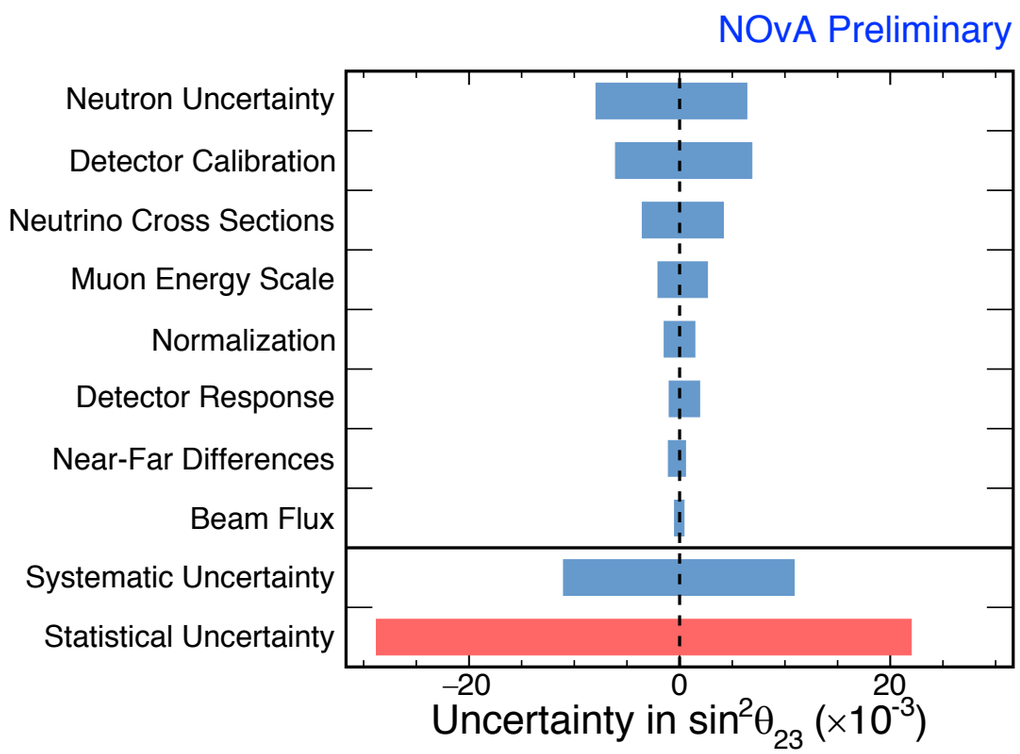
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = [U]_{\ell j}$$

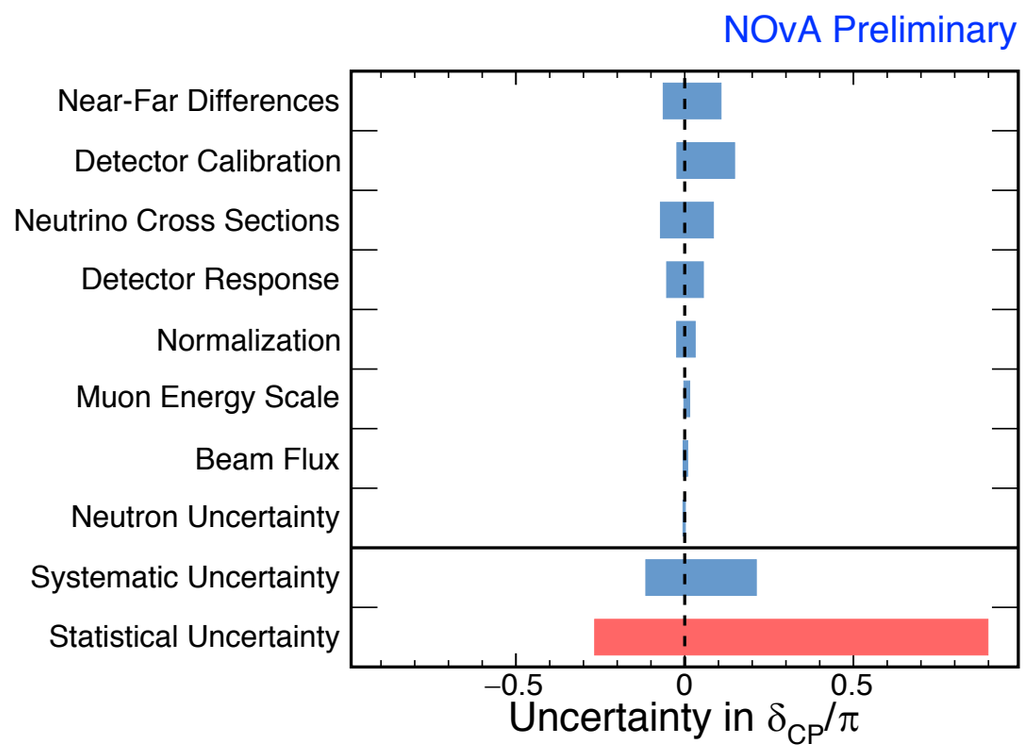
where $\ell \in \{e, \mu, \tau\}$ labels flavor and $j \in \{1, 2, 3\}$ labels mass eigenstate.

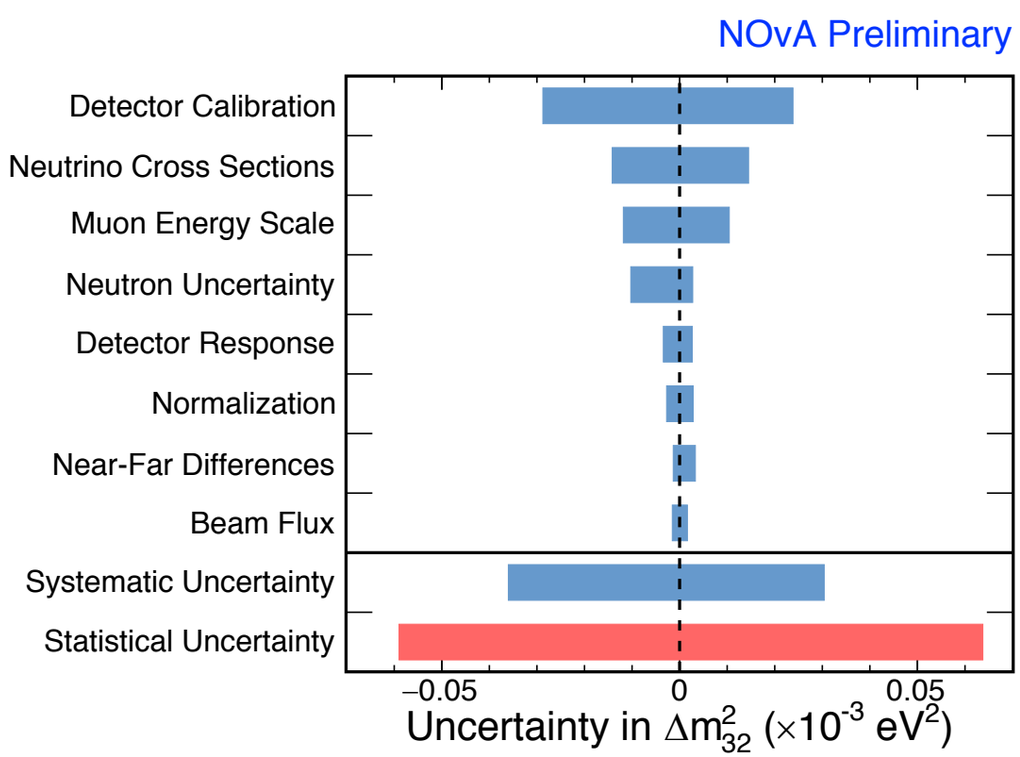
- Like CKM, PMNS has three mixing angles, θ_{lj}, & a CP-violating phase, δ.

- With Majorana mass terms, two fewer field phases absorbed into fields, so two more CP-violating phases, α_i, $i \in \{1, 2\}$, are physical ← $0\nu\beta\beta$.

Systematic Uncertainties



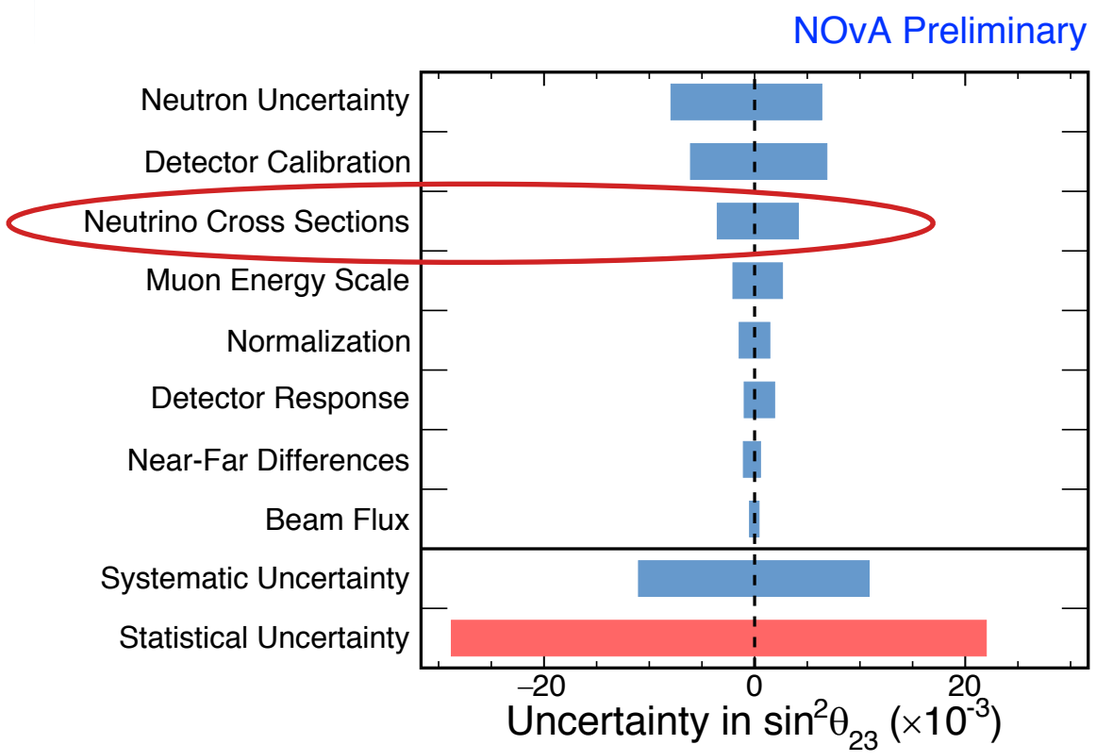


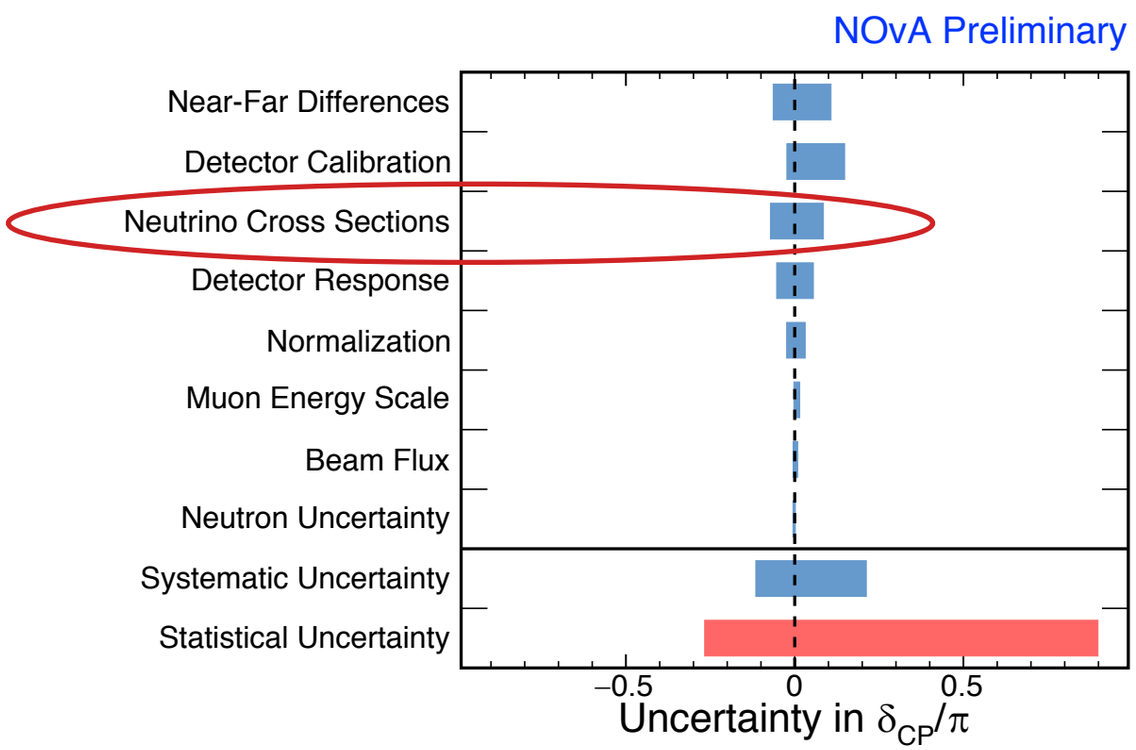


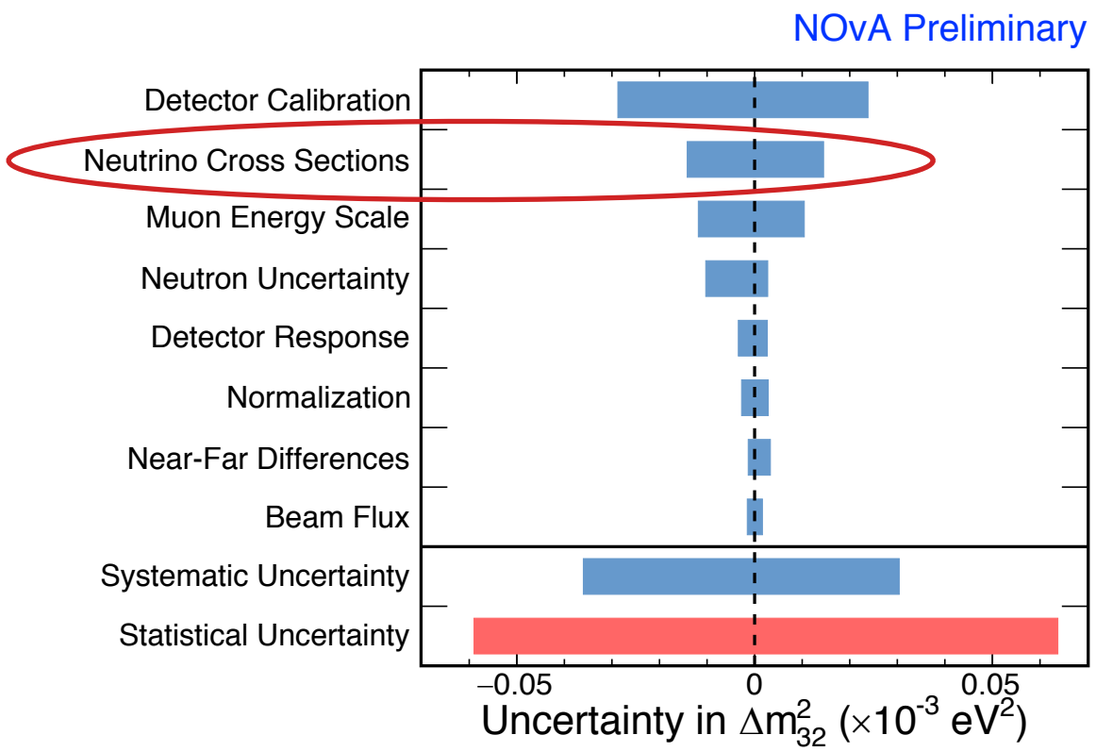
Most important systematics:

- Detector Calibration
  - Will be improved by the 2019 test beam program
- Neutrino cross sections
  - Particularly nuclear effects (RPA, MEC)
- Muon energy scale
- Neutron uncertainty – **new** with $\bar{\nu}$'s

Systematic Uncertainties







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Looking Forward

- Statistical errors will be reduced via much larger exposure.
- Dominant systematic uncertainty will soon be that from νA cross section:
  - other large ones connected to statistics, test beam, and/or cross section itself.

- Taxpayers are eager to find out about CP and to test the three-family paradigm!

T2K

NOvA

µBooNE

HYPER HK

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

- 10^9 for LBNF/DUNE

Oscillation Probabilities

- Probability of a charged lepton of flavor α to be emitted from the source with a neutrino of mass m_j and energy E, which converts at the detector to a charged lepton of flavor β:

$$P_{\alpha\beta} = \sum_{j,k} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \, e^{\pm i \Delta m^2_{jk} L/2E}$$

  with upper (lower) sign for ν ($\bar{\nu}$); ultrarelativistic neutrino $p \approx E - m^2/2E$.

- The key to the measurement is the neutrino energy, which cannot be measured.

- It must be reconstructed from energy-momentum four-vectors of final-state particles.

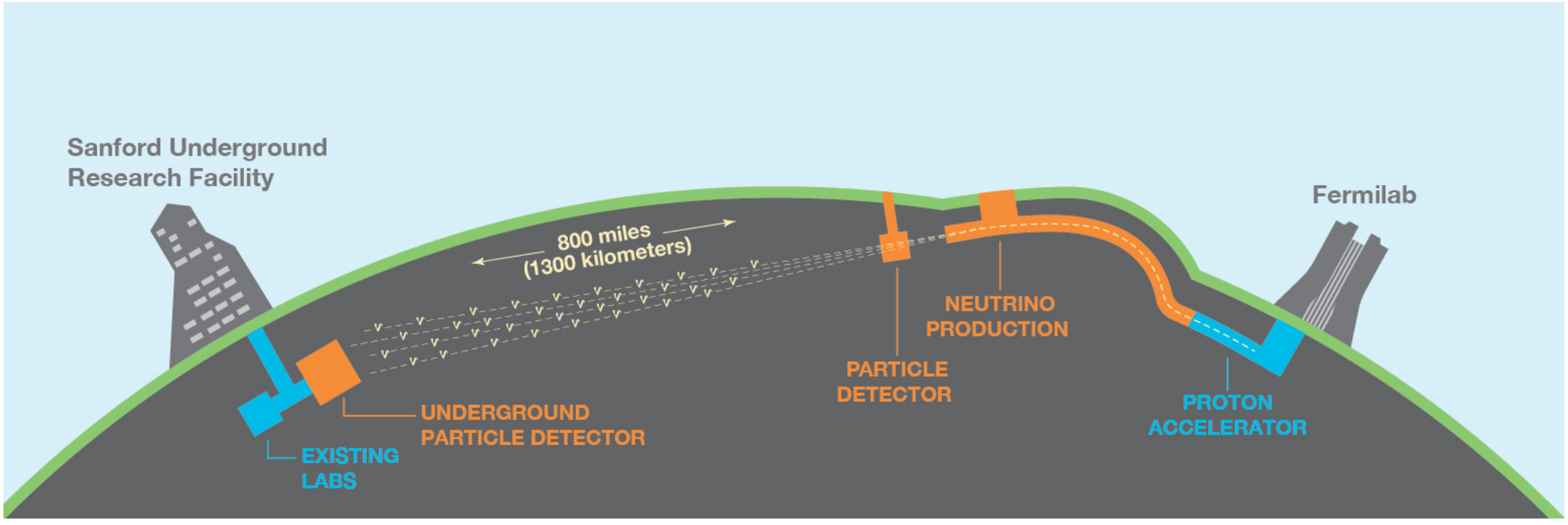
- What incident energy E could turn a nucleus into the final state?

- Oscillation experiments make a(n) (anti)neutrino beam and aim it at nuclei such as ^{12}C, ^{16}O, ^{40}Ar.

- A nucleus can be thought of as a collection of nucleons.

- “A riddle, wrapped in a mystery, inside an enigma” —

  - a flavor change, wrapped in a nucleon, inside a nucleus.



Nuclear Structure

- A huge challenge:
  - nuclear theorists use a unified formalism describes many things and can be systematically improved—
    - many-body theory, with interactions that are tuned to data or—
      - can be cast as a chiral effective theory (nucleons in a pion cloud);
      - not QCD, although sometimes called “*ab initio*”.
- Full error budgets are yet to come and may be impossible.
- Measure “data over here” to constrain nuclear model; then trust validated models “over there” where oscillation parameters are determined.

Hadronic Physics—νN Scattering

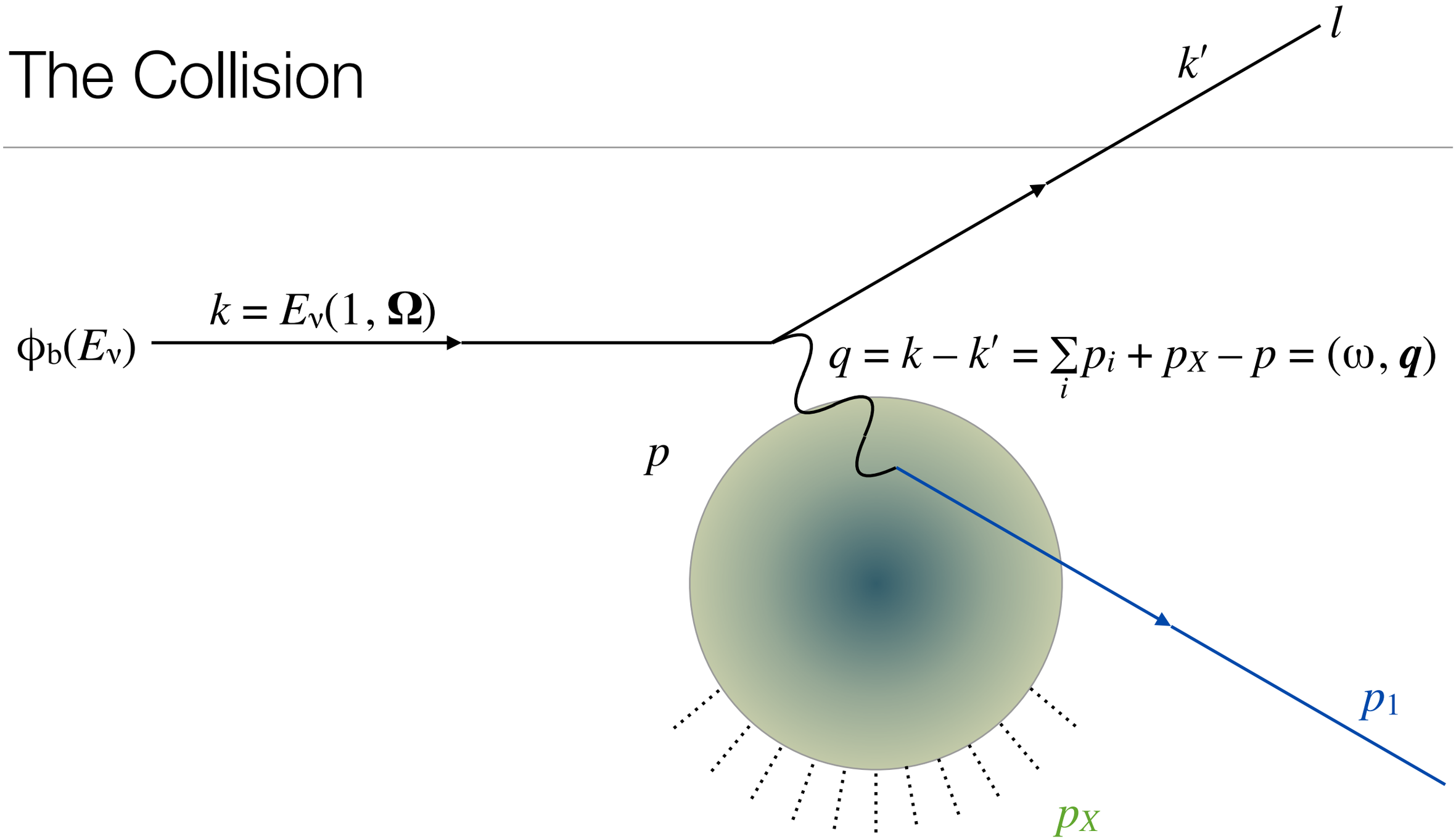
- Hard, but easy compared to nuclear theory.
- Avoid trap: nuclear model with nucleonic ingredients inconsistent with QCD:
  - even if tuned up “here” such a thing would be scary “over there”.
- Therefore, aim to get scattering amplitudes from first principles.
- Two approaches:
  - $\bar{\nu} p$ or νd scattering experiments in the Tokai, NuMI, or LBNF beam;
  - lattice QCD with error budgets as comprehensive as those for CKM.

Outline

- Introduction
- My view of the problem
- A little nuclear theory (of initial state)
- Thoughts on target calculations
- Outlook
- (not a review talk 👈 Green, Friday, 9:30)

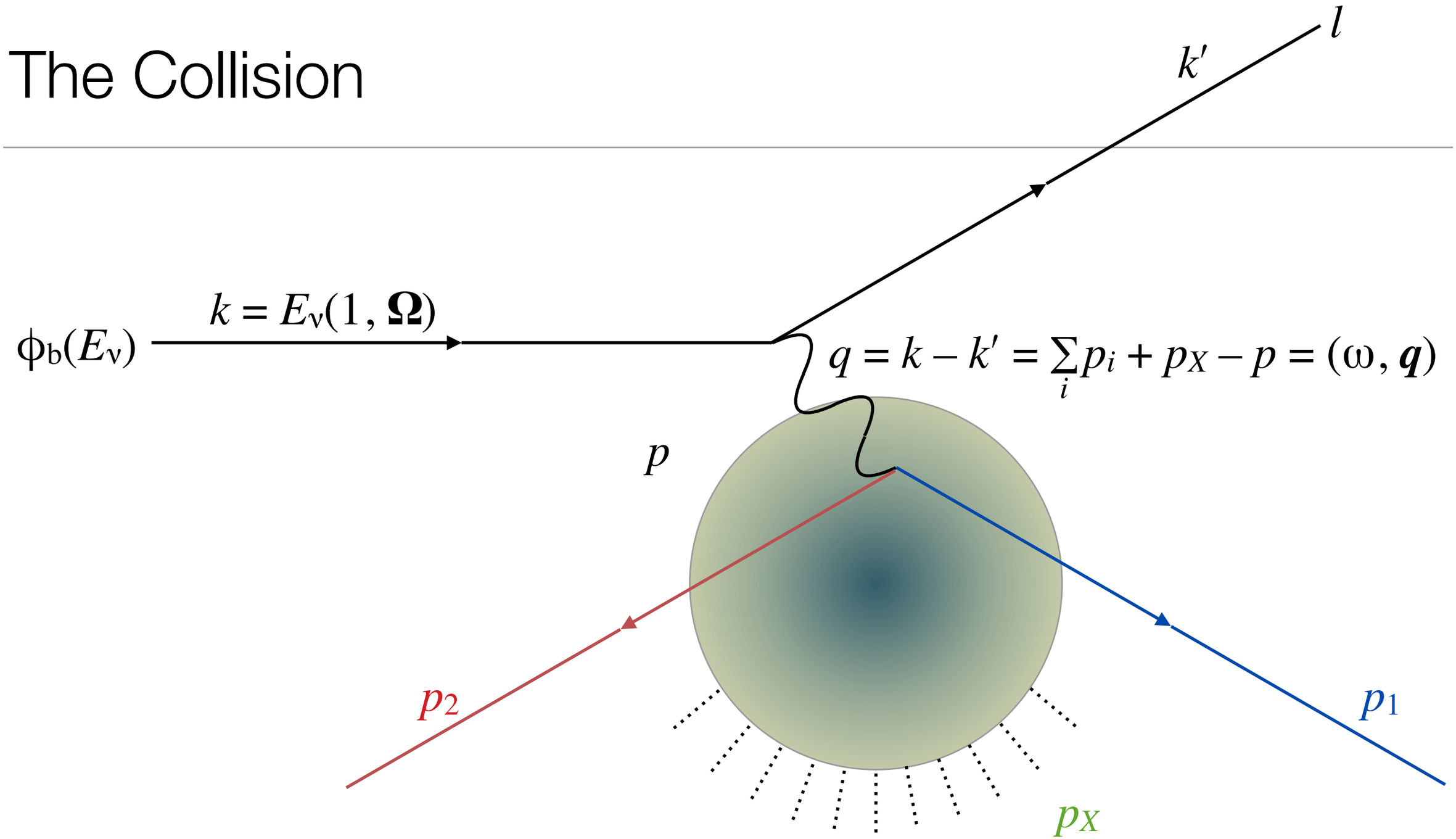
νA Scattering

The Collision



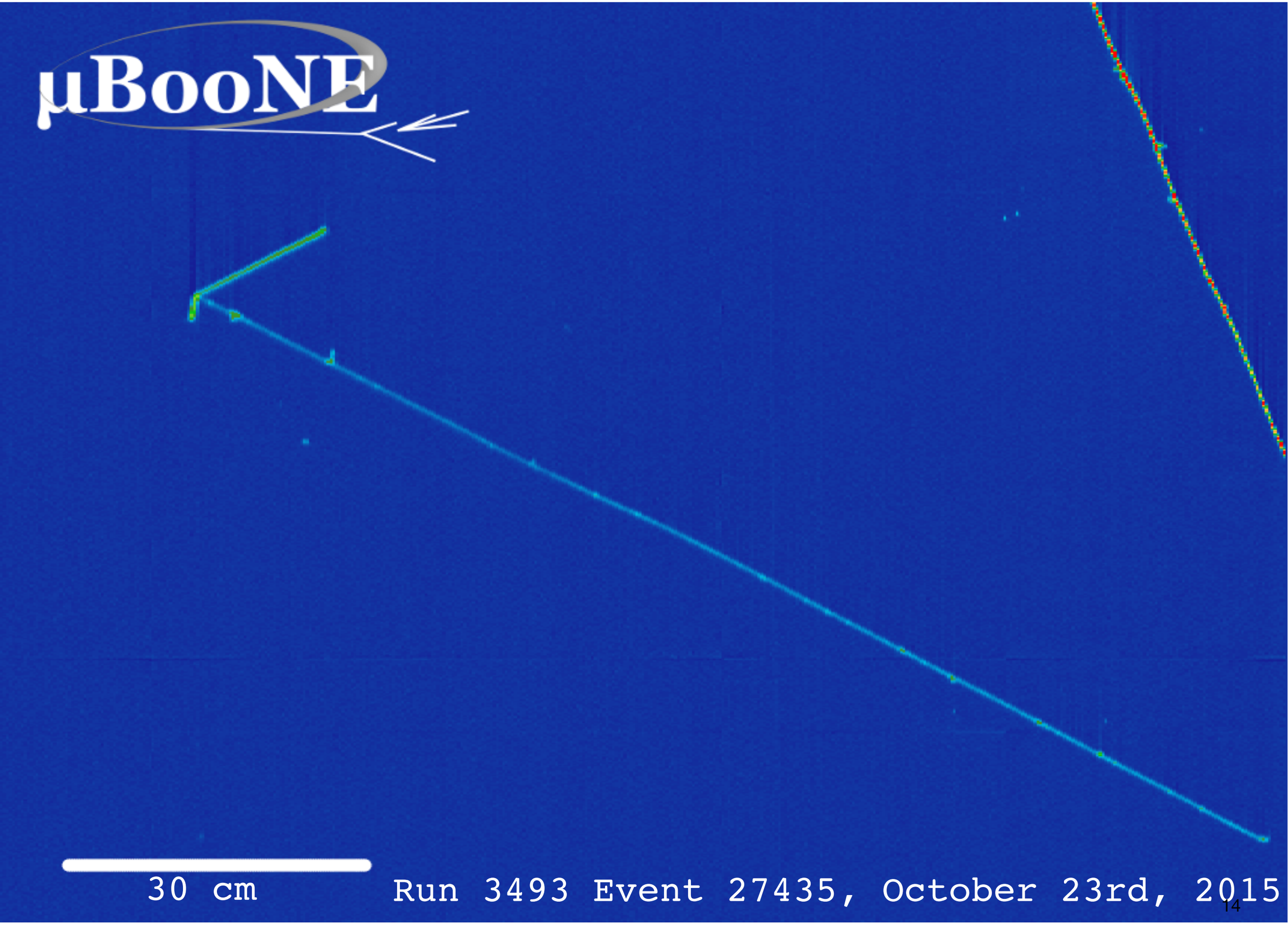
Useful discussion of kinematics by Donnelly

The Collision



knock out 2nd nucleon:
sign of “2p2h”

Useful discussion of kinematics by Donnelly


μBooNE
30 cm
Run 3493 Event 27435, October 23rd, 2015

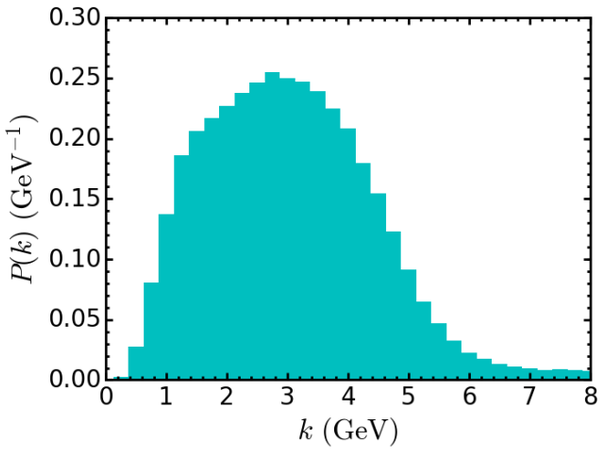
Statement of the Problem I

- Neutrino-nucleus (A) scattering: $\nu_{\mathrm{b}} A \to \mu^{-} X_p$, where X_p can be A, an excitation of A, $A'p$, $A'p\pi$, …, smithereens. Similarly for $\bar{\nu}_{\mathrm{b}} A \to \mu^{+} X_n$.

- Measure 4-momentum of muon, probably of proton, maybe of a few more charged particles; just consider muon:

$$\frac{d\sigma[P_{\mathrm{b}}]}{dE_\mu d\cos\theta} = \int \frac{d\sigma(E_\nu)}{dE_\mu d\cos\theta} P_{\mathrm{b}}(E_\nu)\, dE_\nu$$

muon energy & direction



DUNE flux as a probability density.

- Cross section proportional to lepton & hadron tensors:

$$d\sigma(E_\nu) \propto L^{\mu\nu} W_{\mu\nu}$$

$$W_{\mu\nu} \propto \sum_{X_p} \left\langle A \middle| \hat{J}_\nu^\dagger \middle| X_p \right\rangle \left\langle X_p \middle| \hat{J}_\mu \middle| A \right\rangle$$

- The hadronic tensor depends on the four-vectors q^μ and $p^\nu = M_T v^\nu$ (lab frame is (essentially) nucleus rest frame; use v to make invariant):

$$W^{\mu\nu}(q,p) = W_1(q^2, q\cdot v)e^{\mu\nu} + W_2(q^2, q\cdot v)d^{\mu\nu} + W_3(q^2, q\cdot v)c^{\mu\nu}$$

$$e^{\mu\nu} = g^{\mu\nu} - q^\mu q^\nu/q^2, \quad c^{\mu\nu} = i\varepsilon^{\mu\nu\rho\sigma} v_\rho q_\sigma,$$
$$d^{\mu\nu} = (v^\mu q^\nu + v^\nu q^\mu)/q\cdot v - v^\mu v^\nu q^2/(q\cdot v)^2 - g^{\mu\nu}$$

- HEP calls the W_i "structure functions" (especially when $A = N$); while NP calls them "nuclear responses" (especially when $A \neq N$).

- HEP (Bjorken) writes $\nu = q\cdot v$; NP denotes this "energy transfer" ω.

- Everyone writes $Q^2 = -q^2 > 0$.

- NP sometimes writes q^2 for 3-momentum aka $|\boldsymbol{q}|^2$.

Energy Scales

- Thermal, molecular motion: $k_{\mathrm{B}}T = 7.5\ \mathrm{meV},\ 16/A\ \mathrm{meV};$
- Energy transfer $\omega = E_\nu - E_l$: $200\ \mathrm{MeV} < \omega < E_\nu - m_l;$
- Beam energy E_ν: $1\ \mathrm{GeV} < E_\nu < 5\ \mathrm{GeV}$ (DUNE);
- Binding energy (per nucleon): $8.6\ \mathrm{MeV}$ (^{40}Ar);
- Pion mass: $140\ \mathrm{MeV};$
- Fermi motion of nucleons: $250\ \mathrm{MeV};$
- Nuclear mass: $0.94A\ \mathrm{GeV},\ A \in \{1, 2, 12, 16, 40\}.$

Statement of the Problem II

- So we have to know the W_i reliably—for me this means a curve plus an (empirical) error band.

- The energies cover a range in which both nuclear and nucleonic effects are important:

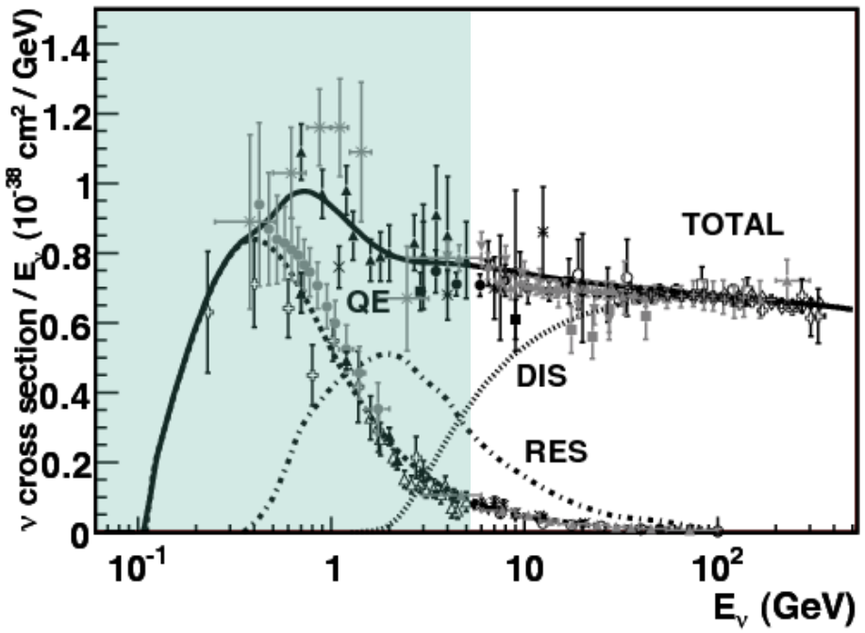
  - quasielastic—scatter off “whole nucleon”;

  - resonance—enough energy for Δ, N^*, $N\pi$;

  - shallow inelastic scattering—many pions, but not enough for OPE;

  - deep inelastic scattering—but Q^2 not huge in oscillation experiments.

Formaggio & Zeller, arXiv:1305.7513



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  nuclear and nucle
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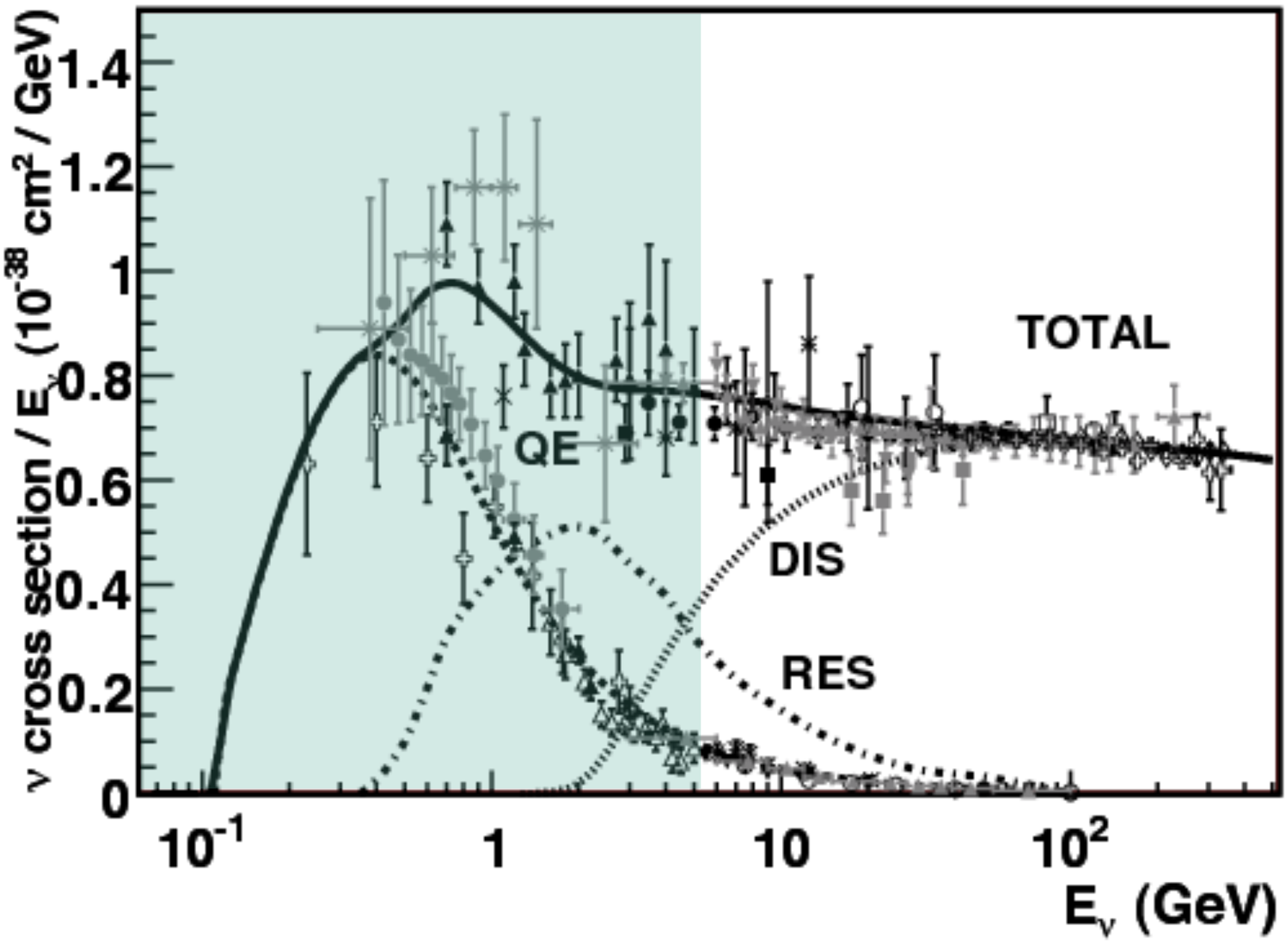


Nuclear Theory

Nuclear Hamiltonian

- The A nucleons in a nucleus are described by the Hamiltonian:

nucleon kinetic energy;
nucleon mass M_N

two-body potentials;
e.g., Argonne v_{18}

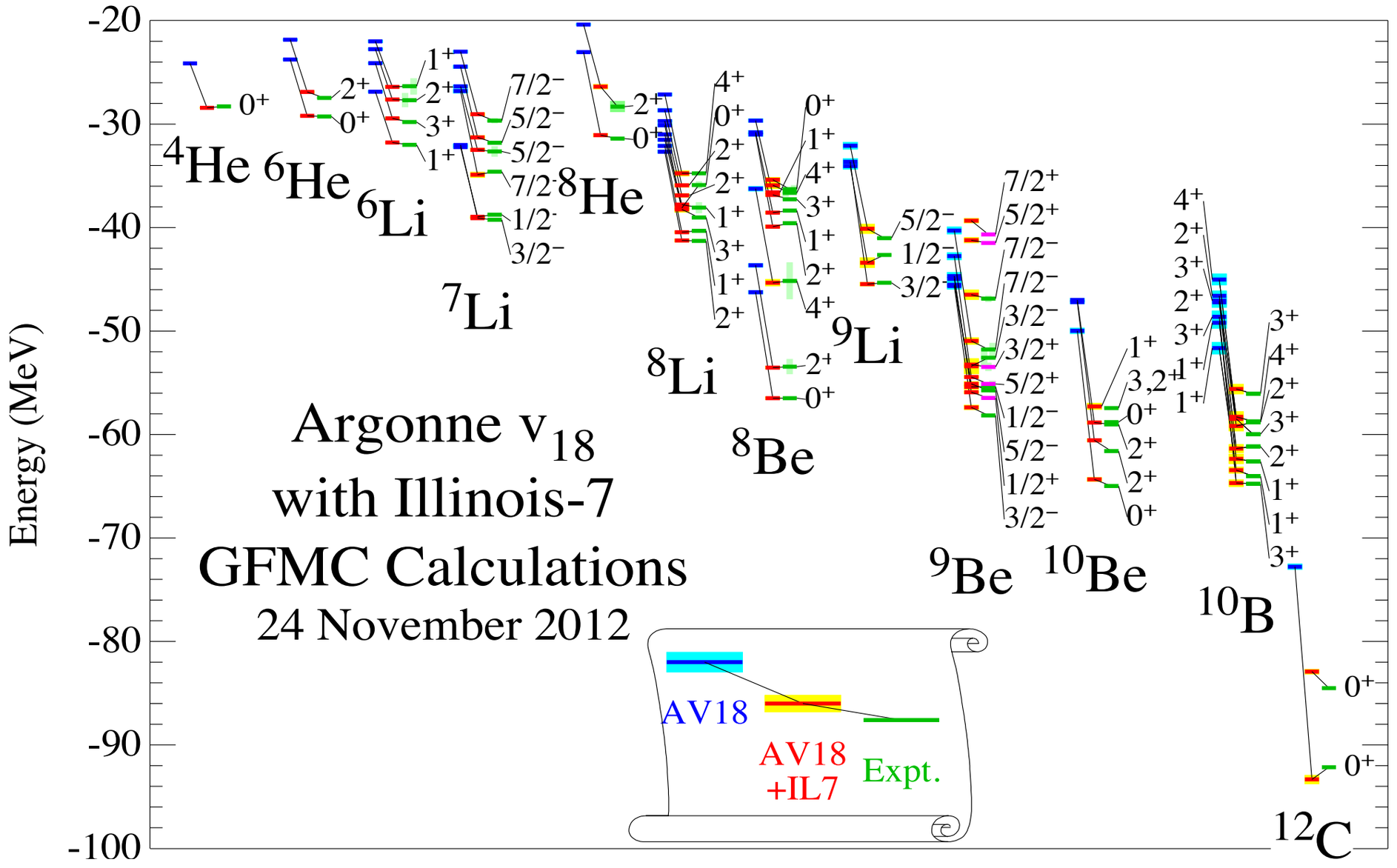
$$H = -\frac{1}{2M_N}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

three-body potentials;
e.g., Illinois 7

- Fit to scattering data.
- Reproduced by πN EFT [Mereghetti].
- Could also be extracted from lattice QCD.

Big Success

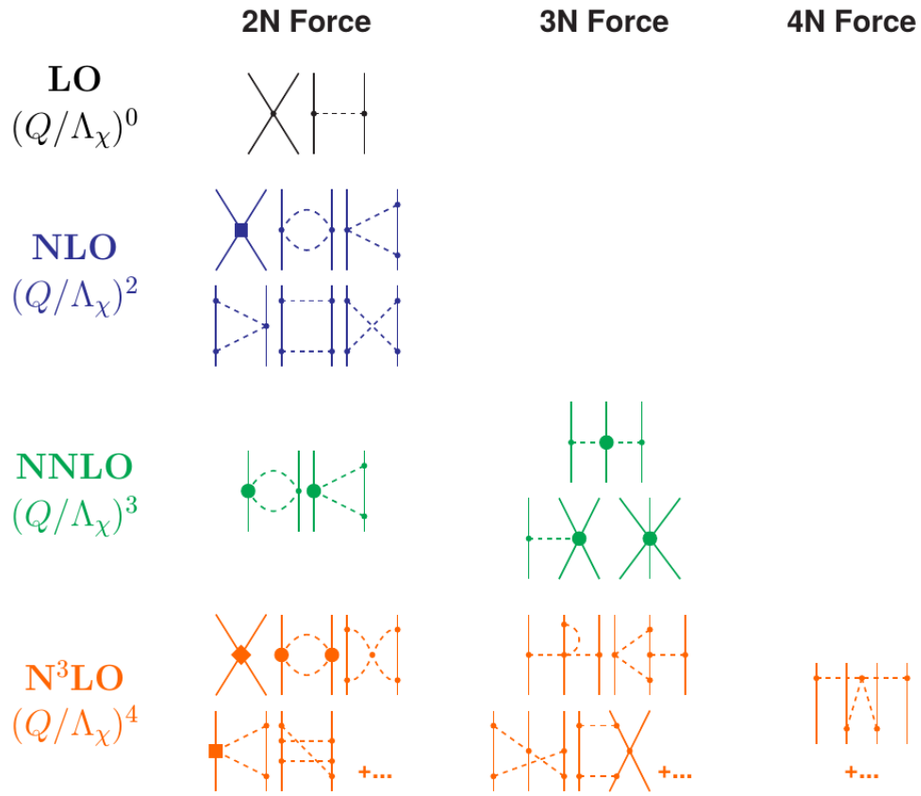
- Compute level splittings in nuclei up to ^{12}C:



Mereghetti, Monday, 10:00

time-ordered PT,
Weinberg (1997)

Nuclear EFT(s)



from D. R. Entem and R. Machleidt, ‘17 ★

see also:

P. Reinert, H. Krebs, E. Epelbaum, ‘18

M. Piarulli *et al*, ‘16

M. Piarulli *et al*, ‘14

A. Nogga, R. Timmermans, B. van Kolck, ‘05

D. Kaplan, M. Savage, M. Wise, ‘96

- LECs are fit to data in 2- and 3-nucleon systems
- and predict light-nuclear observables

Neutrino-Nucleus Interaction

- The A nucleons interact with the neutrino via an electroweak current:

"one-body" currents;
aka form factors

"two-body" current;
i.e., ff of $\langle NN|J^\mu|NN\rangle$

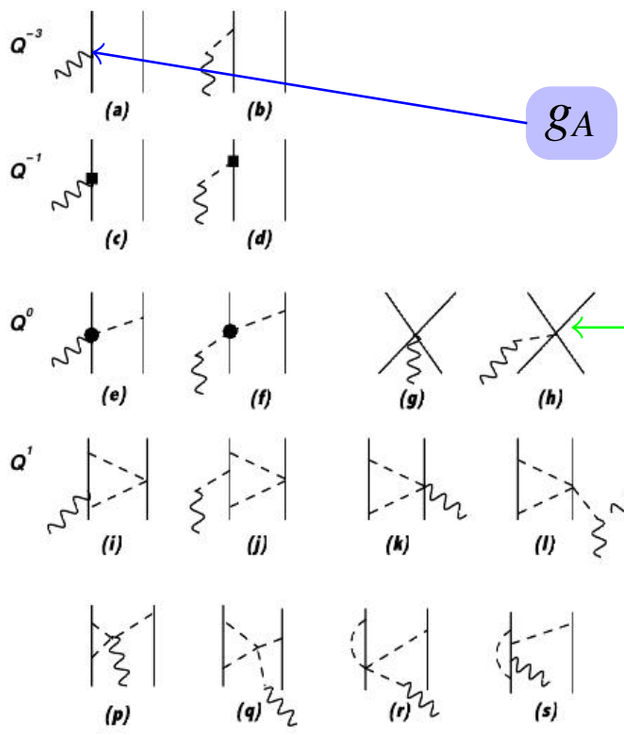
$$J^\mu = \sum_i j_i^\mu + \sum_{i<j} j_{ij}^\mu$$

- Extract one-body currents from $\bar{\nu}p$ or νd scattering, or—
  - computed with lattice QCD.
- Two-body currents can be described by meson-exchange in πN EFT.

Mereghetti, Monday, 10:00

time-ordered PT

External currents in chiral EFT



Axial current: $\bar{q}\tau^{+}\gamma^{\mu}\gamma_5 q$

g_A

two-nucleon currents

from A. Baroni *et al*, '16 ★

- similar expansions for external currents

  e.g. vector, axial, scalar, pseudoscalar, tensor

- for SM operators, LECs can be fit to data
- for BSM operators, need LQCD!

Return of the Hadron Tensor

- Recall

$$d\sigma(E_\nu) \propto L^{\mu\nu} W_{\mu\nu}$$

$$W_{\mu\nu} \propto \sum_{X_p} \left\langle A \middle| \hat{J}^\dagger_\nu \middle| X_p \right\rangle \left\langle X_p \middle| \hat{J}_\mu \middle| A \right\rangle$$

- Approximate (quasielastic region):

$$\langle X\, p(\boldsymbol{p}'_1)|\hat{J}^\mu|A\rangle \approx \sum_{n=1}^{A-Z} \langle X\, p|\hat{a}_{\boldsymbol{p}'_1}\, j^\mu(q)\hat{a}_{\boldsymbol{p}_n}|A\rangle,$$

$$\langle p(\boldsymbol{q}+\boldsymbol{p})|\hat{a}_{\boldsymbol{q}+\boldsymbol{p}_n}\, j^\mu(q)\hat{a}_{\boldsymbol{p}}|n(\boldsymbol{p})\rangle = \langle p(\boldsymbol{q}+\boldsymbol{p})|\bar{u}\boldsymbol{\gamma}^\mu(\boldsymbol{\gamma}^5)d|n(\boldsymbol{p})\rangle$$

- Perhaps at higher energies $\langle A|\hat{J}^\mu \hat{J}^\nu|A\rangle \leftrightarrow \langle n|\bar{d}\boldsymbol{\gamma}^\mu(\boldsymbol{\gamma}^5)u\,\bar{u}\boldsymbol{\gamma}^\nu(\boldsymbol{\gamma}^5)d|n\rangle$.

Liang, Monday, 4:50

Priority vs Difficulty

$f_+^{K\to\pi}$ $f_+^{B\to\pi}$ F_A^{CC} F_A^{NC}

importance to neutrino oscillations
(my evolving vague impression)

$\langle NN|J|NN\rangle$ Baroni, Thurs., 10:30

$\langle d|J^\mu|d\rangle$

$s\bar{s}$ in N

$\nu N \to N', \Delta, N\pi, \ldots$

NN forces

πN forces

F_P^{CC} F_P^{NC}

difficulty in lattice QCD (let's discuss)

Lattice-QCD Calculations

Form Factors

- Hadronic matrix elements of the weak currents are decomposed into Lorentz covariant forms, multiplied by form factors:

$$\langle p(\boldsymbol{p})|\mathcal{V}^{\mu}_{\bar{u}d}|n(\boldsymbol{k})\rangle = \bar{u}_p(\boldsymbol{p})\gamma^{\mu}u_n(\boldsymbol{k})\,F_1(q^2) + \frac{q_\nu}{2M_N}\bar{u}_p(\boldsymbol{p})i\sigma^{\mu\nu}u_n(\boldsymbol{k})\,F_2(q^2),$$

$$\langle p(\boldsymbol{p})|\mathcal{A}^{\mu}_{\bar{u}d}|n(\boldsymbol{k})\rangle = \bar{u}_p(\boldsymbol{p})\gamma^{\mu}_{\perp}\gamma^5 u_n(\boldsymbol{k})\,F_A(q^2) + \frac{2M_N q^{\mu}}{q^2}\bar{u}_p(\boldsymbol{p})\gamma^5 u_n(\boldsymbol{k})\,F_P(q^2),$$

$$q^{\mu} = k^{\mu} - p^{\mu}$$

- The q^2 dependence is constrained by unitarity and analyticity:
  - essential to retain this feature when combining discrete box-momenta to obtain a curve.

A Word on Parametrizations

- When data are poor (large uncertainties, limited q^2 range), any functional form will do, as long as the shape is not aggressively stupid.

- Nucleon form factors of employ "dipole Ansatz":

$$f(t) = \frac{g_A}{\left(1 - t/M_A^2\right)^2}$$

- Instead use properties of field theory: analyticity, unitarity, ….

- For example, the "z expansion", Padé approximants (dispersion relation is Stieltjes), ….

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not QCD

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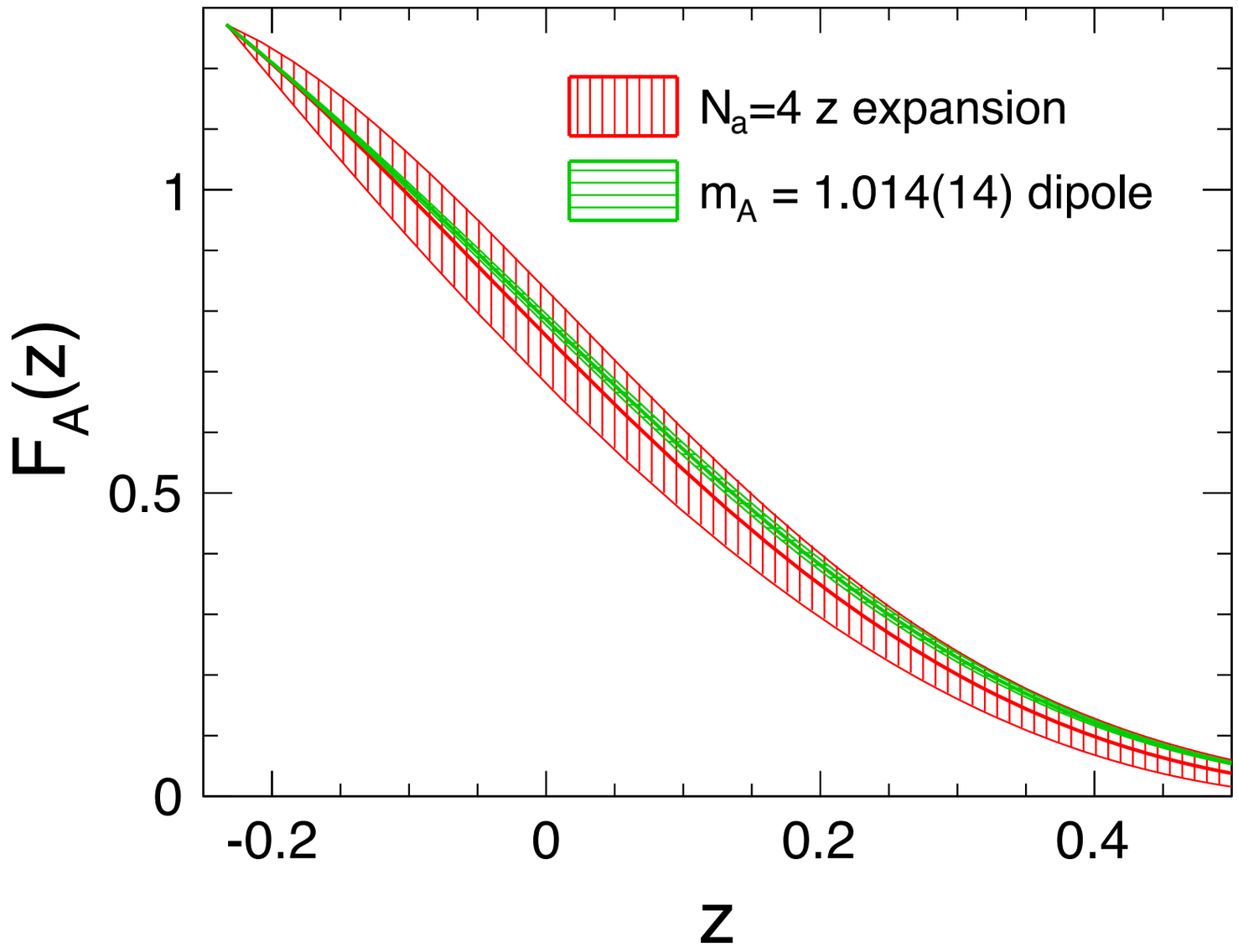
Axial Form Factor from Deuterium

- Meyer, Betancourt, Gran, Hill [arXiv:1603.03048]:



$$z = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

$$f\left(t(z)\right) \propto \sum_n a_n z^n$$

dipole underestimates uncertainty!

Axial Form Factor from Lattice QCD

- Gupta, Jang, Lin, Yoon, Bhattacharya (PNDME) [arXiv:1705.06834]:

- $a \neq 0$ slope smaller than deuterium & other data.

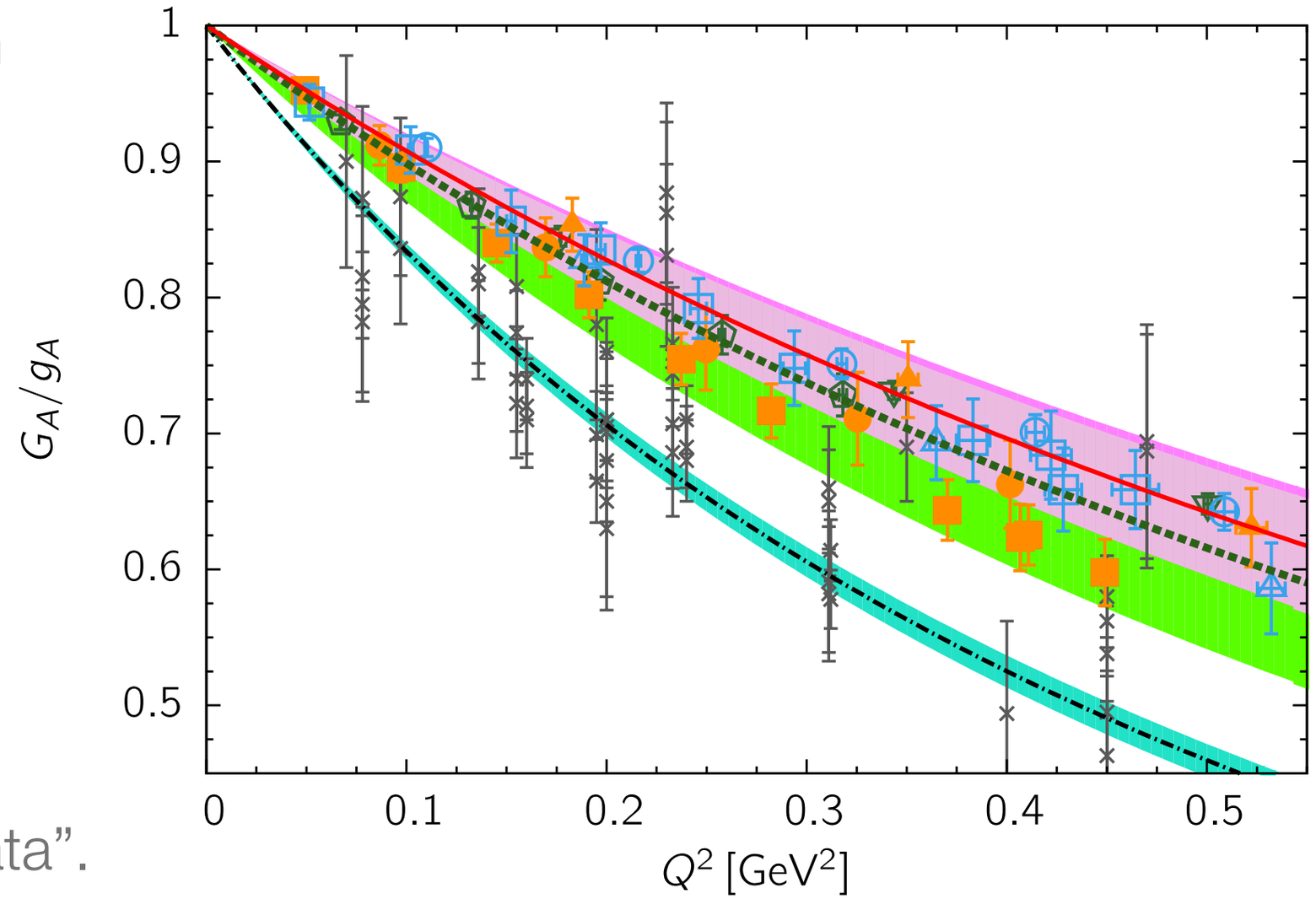
- Even continuum limit:

  $r_A = 0.46(6)$ fm

  vs Meyer *et al.*:

  $r_A = 0.68(16)$ fm

- *Caveat emptor* expt "data".



Vector Form Factor from Lattice QCD

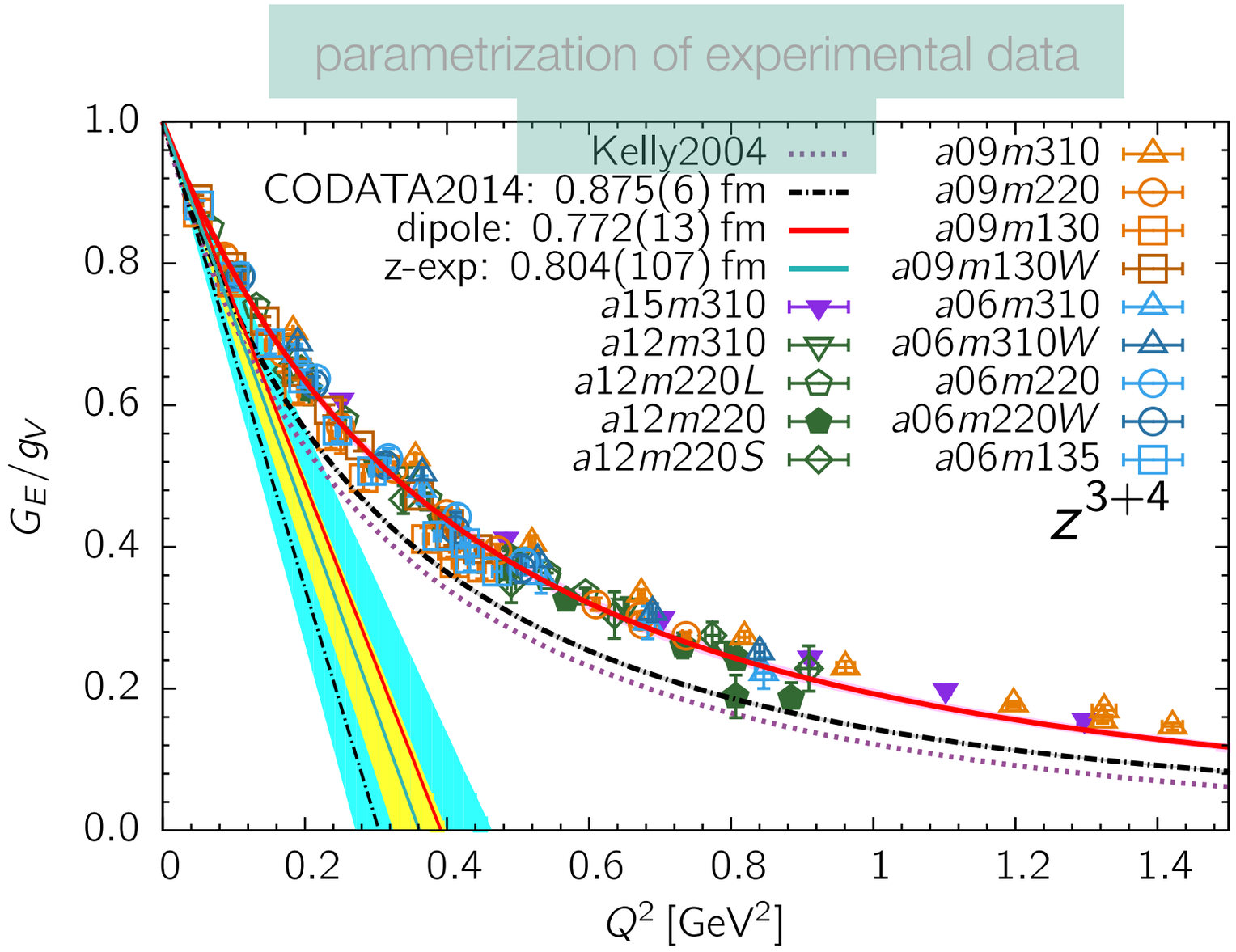
- Jang, Thursday, 9:50 AM.
- lattice QCD too high?
- Even continuum limit:

$r_E = 0.80(11)$ fm,

vs CODATA:

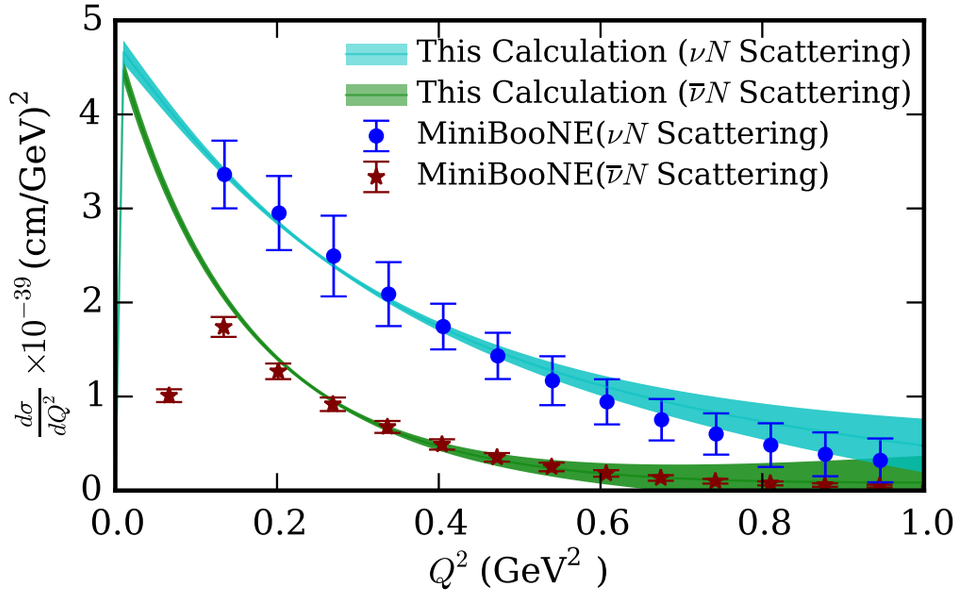
$r_E = 0.875(6)$ fm.

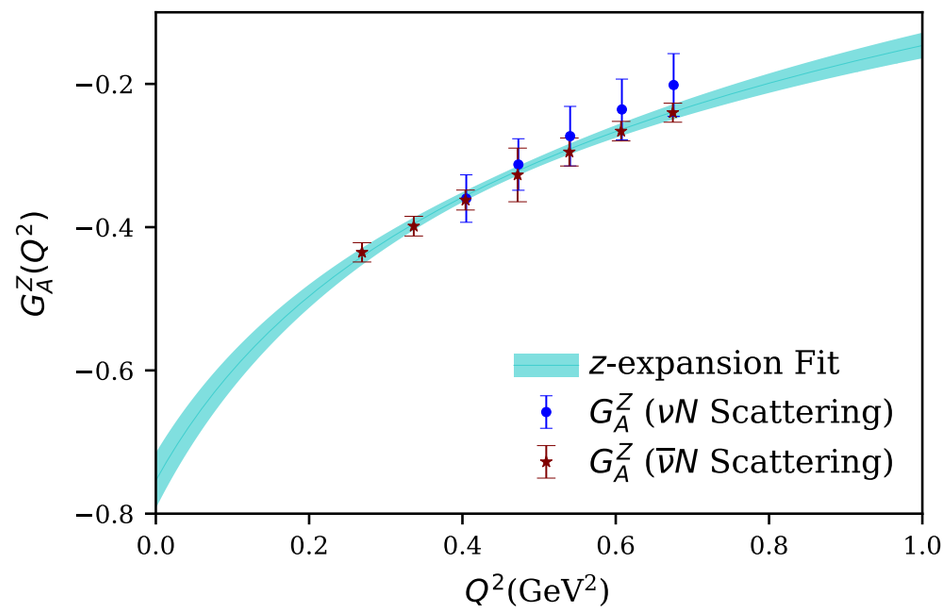
- $G_E = F_1 - Q^2 F_2/M^2$.



Neutrino Phenomenology

- Pragmatic inputs:
  - vector form factors from ep scattering (z parametrization) [Ye *et al.*, arXiv:1707.09063];
  - $s\bar{s}$ form factor from lattice QCD [χQCD, arXiv:1705.05849];
  - extract GA(Q2(z)) from MiniBooNE;
  - compare with BNL E734.
- Richards, Thursday, 12:20 PM.





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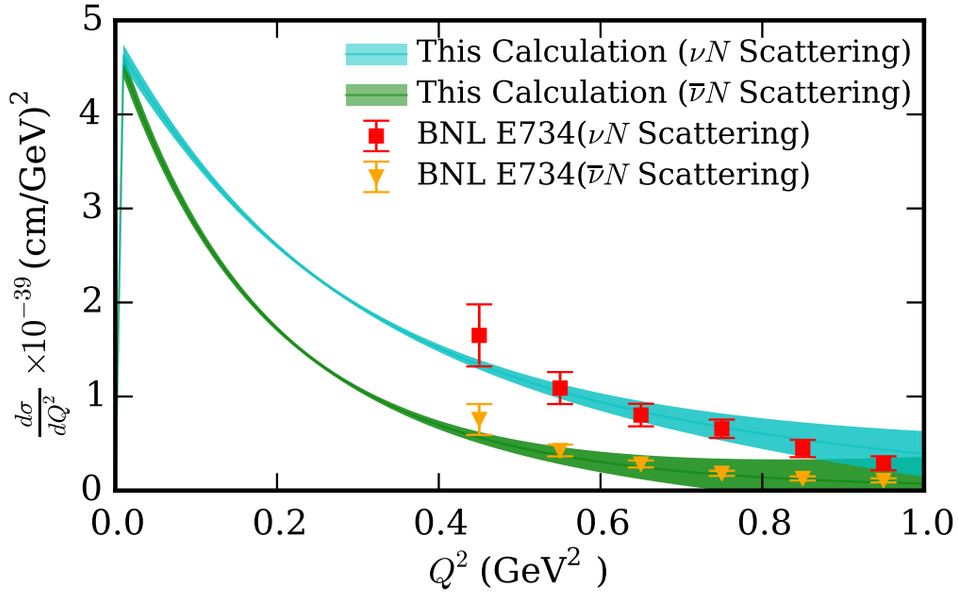
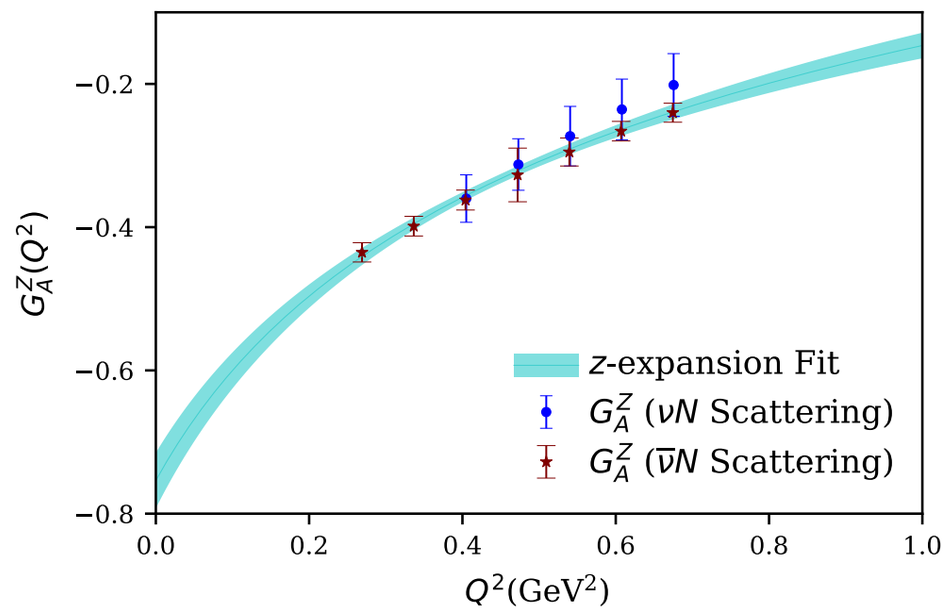
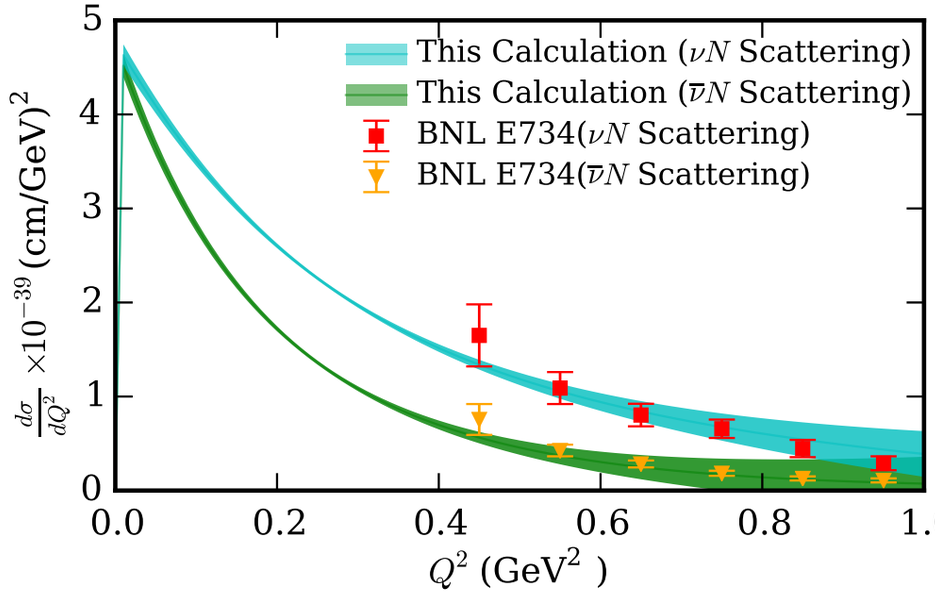
- Richards, Thursday, 12:20 PM.





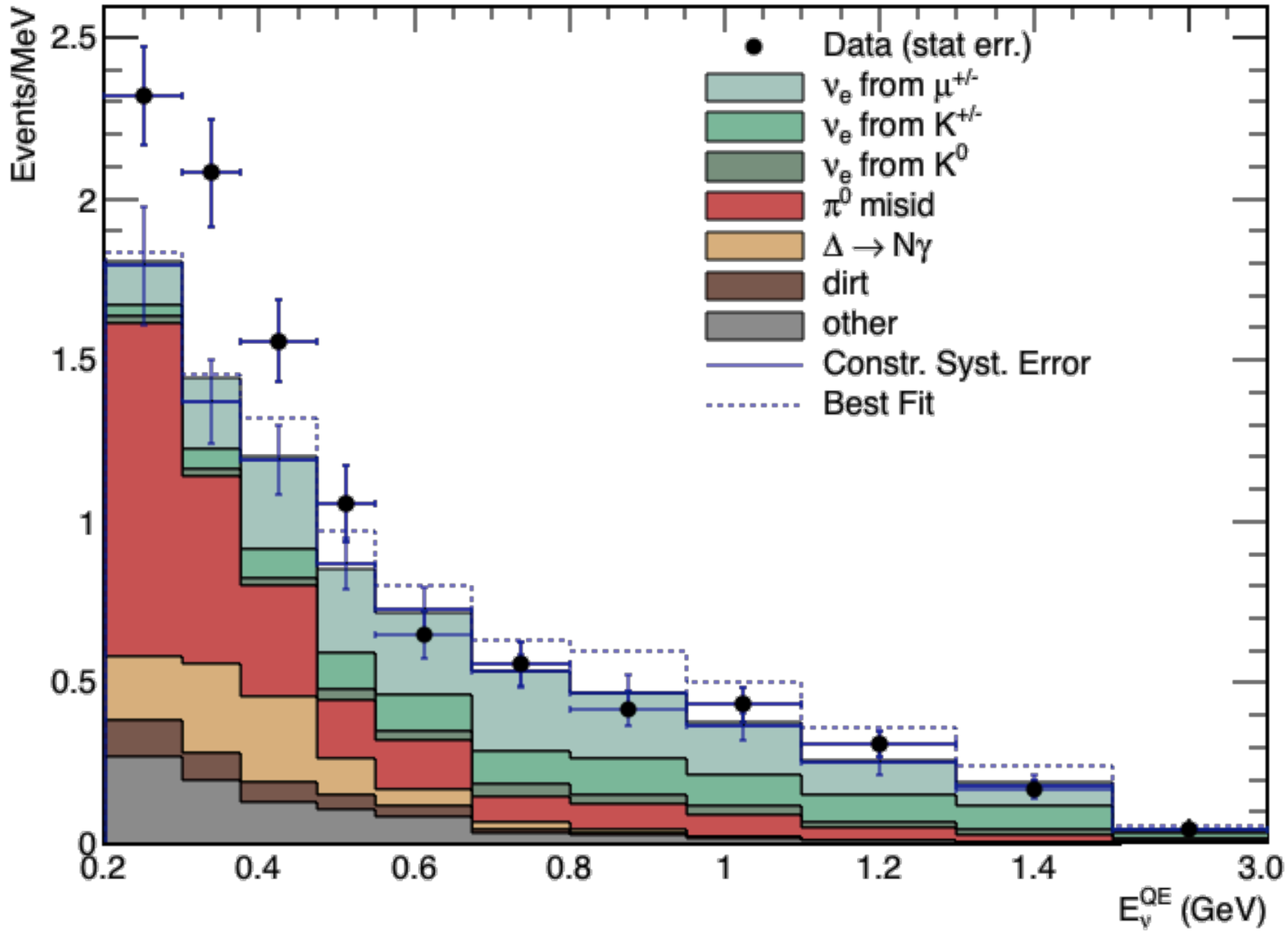
Neutrino Phenomenology

- Pragmatic inputs:
  - vector form factors from ep scattering (z parametrization) [Ye *et al.*, arXiv:1707.09063];
  - $s\bar{s}$ form factor from lattice QCD [χQCD, arXiv:1705.05849];
  - extract GA(Q2(z)) from MiniBooNE;
  - compare with BNL E734.
- Richards, Thursday, 12:20 PM.



MiniBooNE Excess

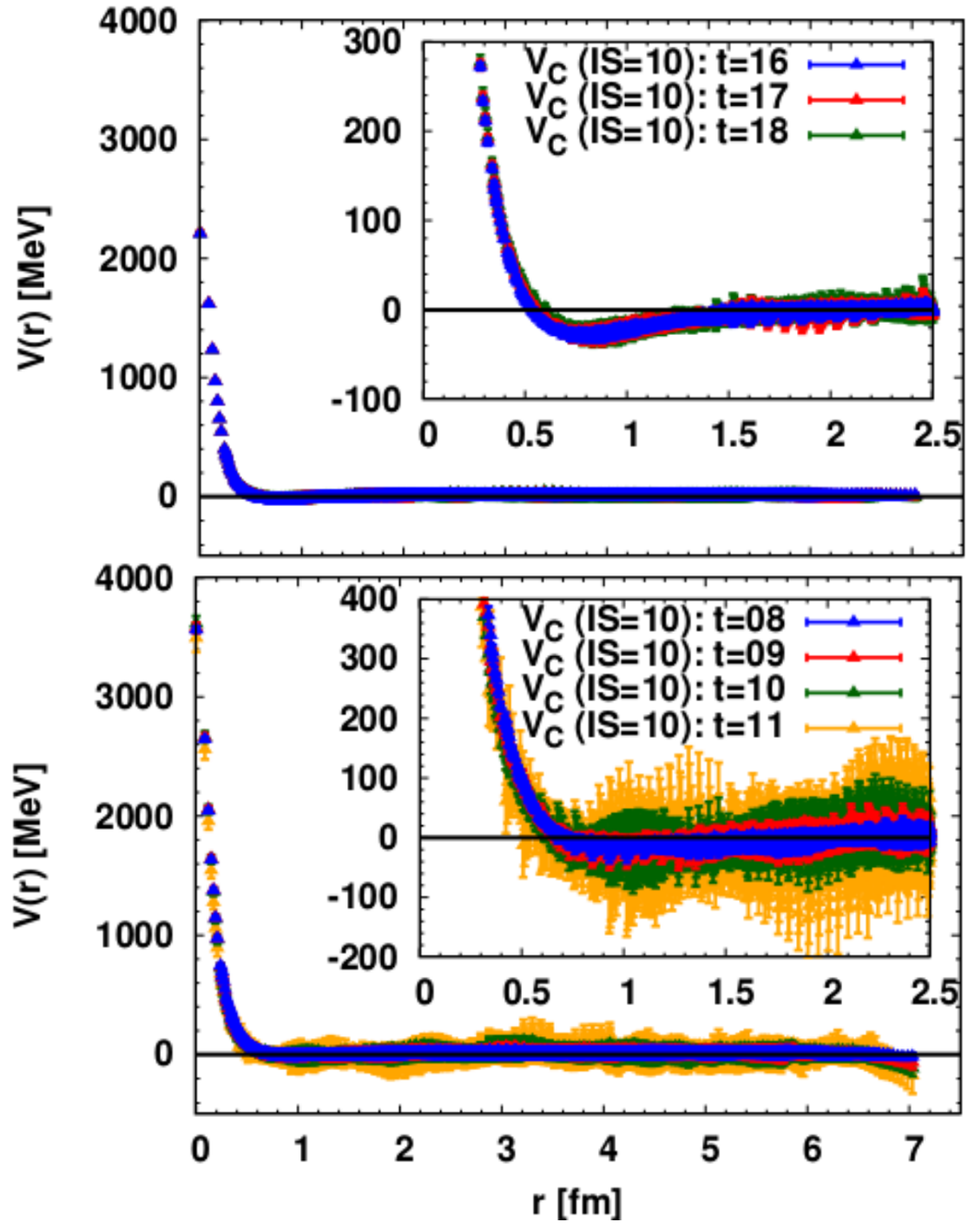
- What do lattice-QCD form factors say about this?



- Aguilar-Arevalo *et al.* [arXiv:1805.12028].

Nucleon Forces

- HALQCD Collab computes baryon-baryon potentials in lattice QCD [nucl-th/0611096, arXiv:1711.01952].
- Implicitly assumes smoothness.
- $\Xi\Xi$ (top); NN (bottom).
- Hard-core repulsion obvious.
- Attraction between 0.5 fm and 1.0 fm (almost) visible.
- Doi, Friday, 5:50 PM.



Outlook

Particle Physics Questions

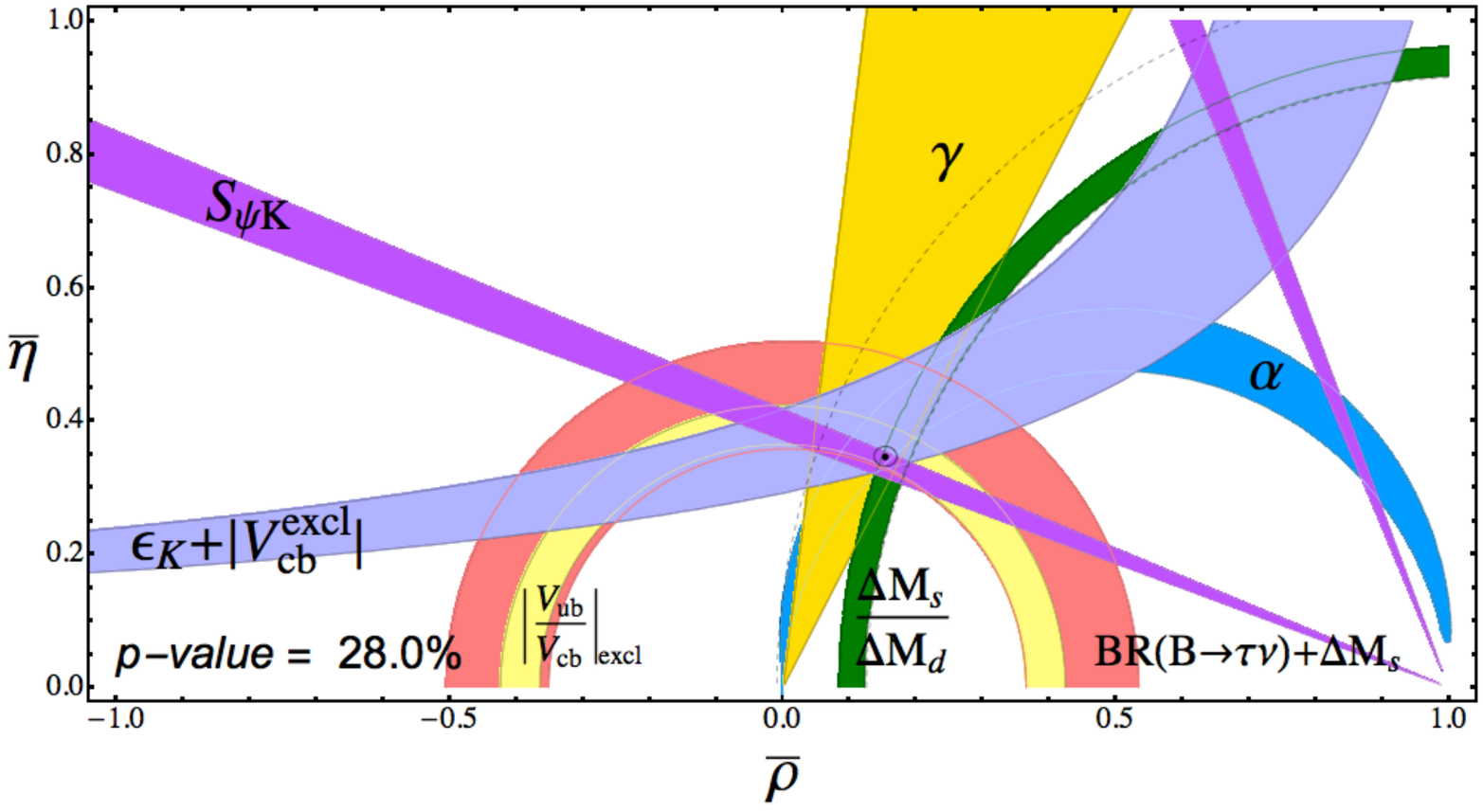
- Mediator in direct dark matter detection (if detected)?
- Mediator of lepton flavor violation? If detected, it won't be neutrinos!
- How many sterile neutrinos are there (within reach)?
- Do leptons violate CP?
- What values do the neutrino masses take?
- What values do the PMNS matrix elements take?
- What, if any, is the relation of PMNS to CKM?

Lattice QCD Input

- Nucleon matrix elements: we know how to obtain them from QCD.
- Nucleus matrix elements (small ones, to test EFT). Detmold, Tues, 2:40
- Controlled uncertainties:
  - don’t introduce non-QCD assumptions;
  - put together full error budgets.

CKM vs PMNS

- Decades of conversation and collaboration among experimenters and QCD theorists led to



- We need to do this in the lepton sector! — André de Gouvêa

Thank you!