Overview of theoretical neutrino physics & relevant synergies between NP & HEP

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UKentucky and Fermilab

PAC preparatory meeting
Fermilab

10 November, 2017

"We ask the PAC to comment on progress and plans towards improving the understanding and modeling on nuclear physics effects, particularly those effects that are of relevance to the future neutrino oscillation program."

I will discuss several efforts that are underway. Most are based at Fermilab or have significant Fermilab involvement.

Overview

1) Neutrino interaction physics

2) Fermilab Theory Experiment Working Group

3) NUSTEC

4) Elementary amplitudes

5) Radiative corrections at the intensity frontier

6) Community building

1. Neutrino interaction physics

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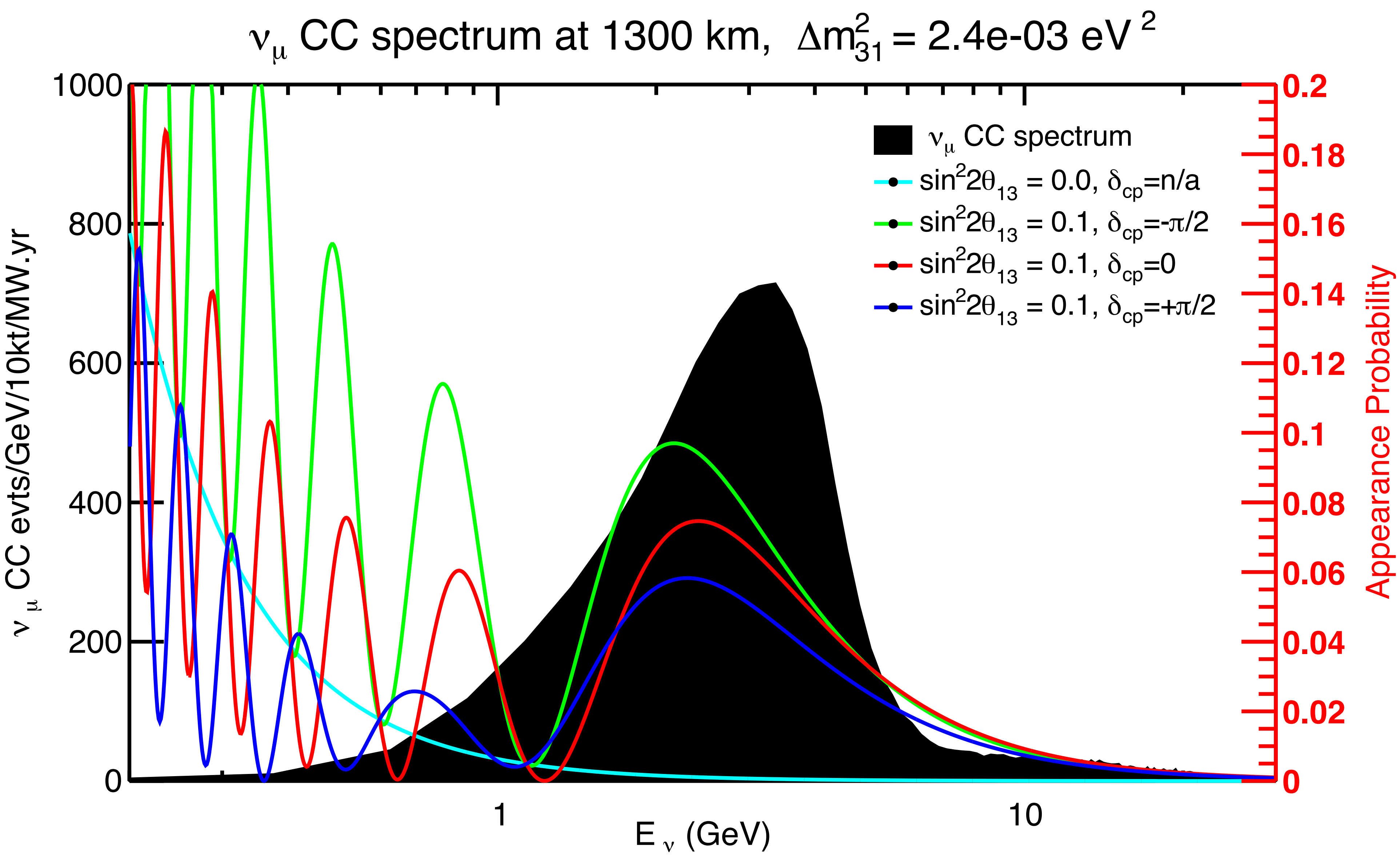
long baseline neutrino oscillation experiment is **simple** in **conception**:



LBNE, 1307.7335

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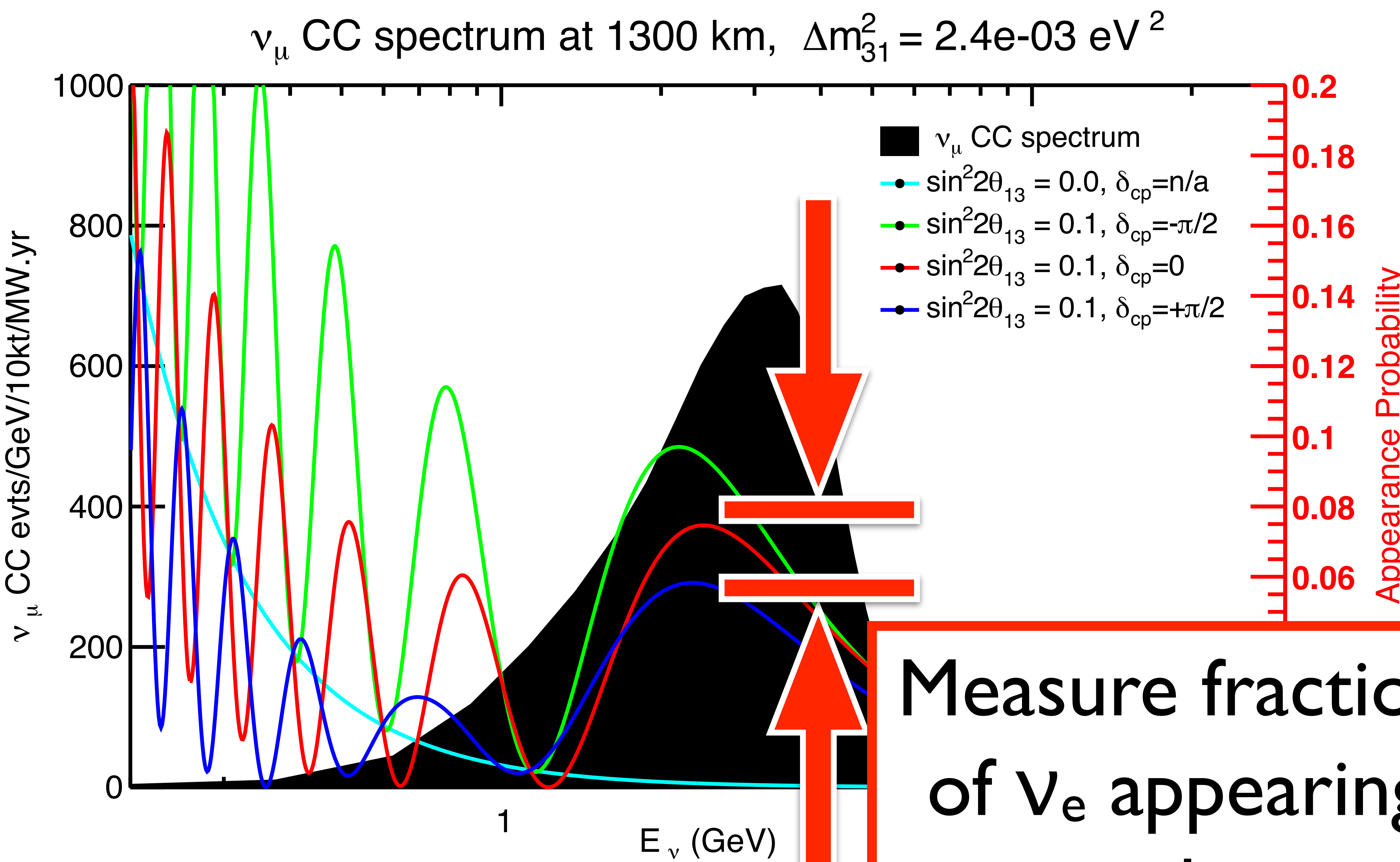

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Measure fraction of ν_e appearing in ν_μ beam

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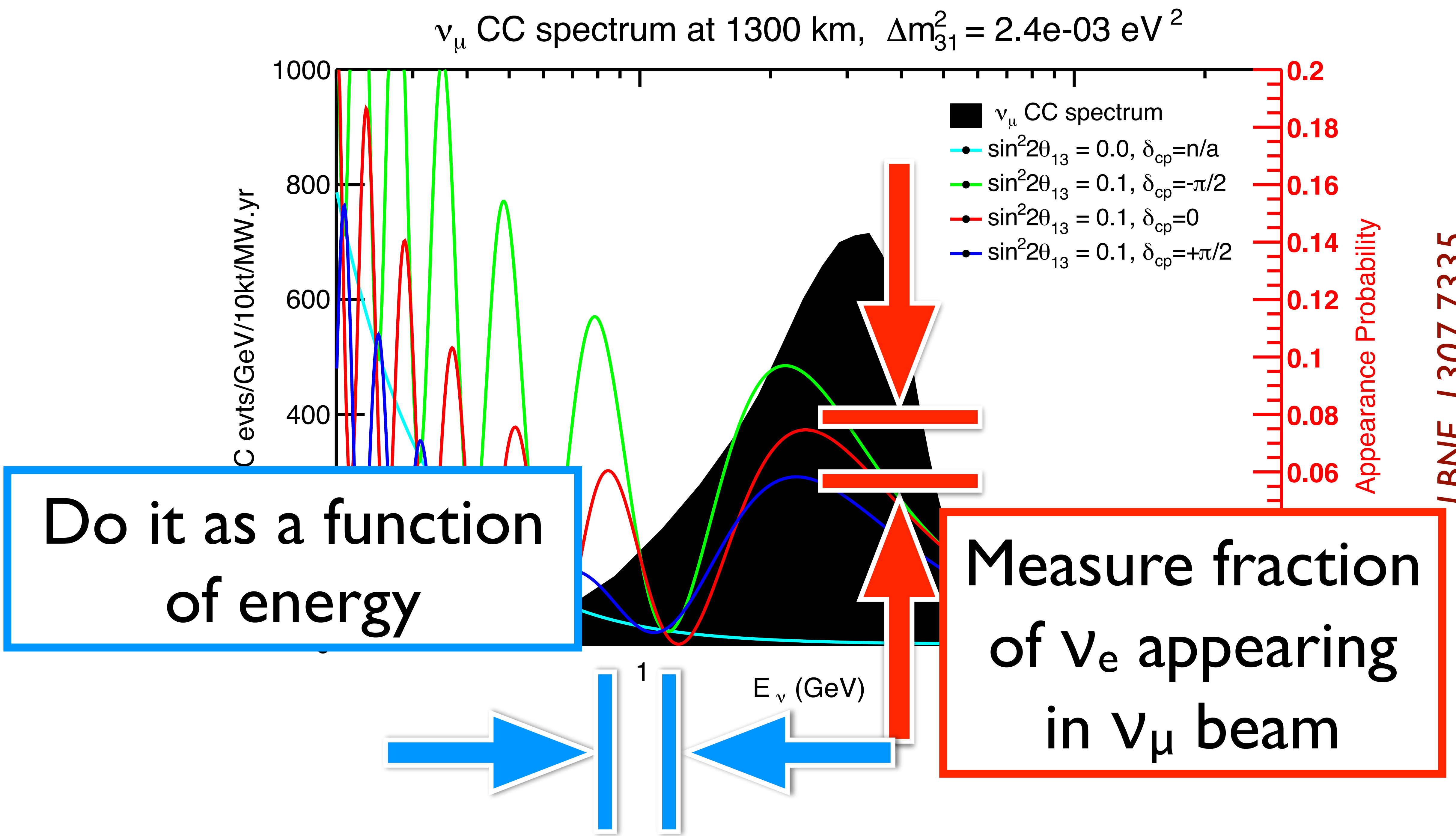


long baseline neutrino oscillation experiment is **difficult** in **practice**:

simple picture is complicated by

- ν_e versus ν_μ cross section differences

  need theory for $\sigma_{\nu e}/\sigma_{\nu\mu}$, at ~% precision of measurement

and also

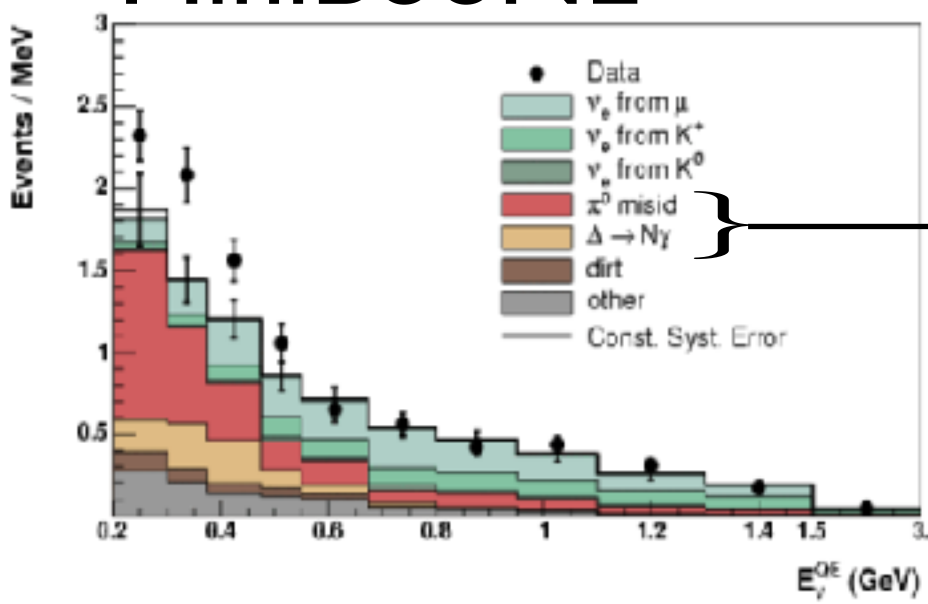
- intrinsic ν_e component of beam
- degeneracy of uncertainty in detector response and neutrino interaction cross sections
- imperfect energy reconstruction

aided by near detector but

- beam divergence and oscillation (near flux≠far flux)

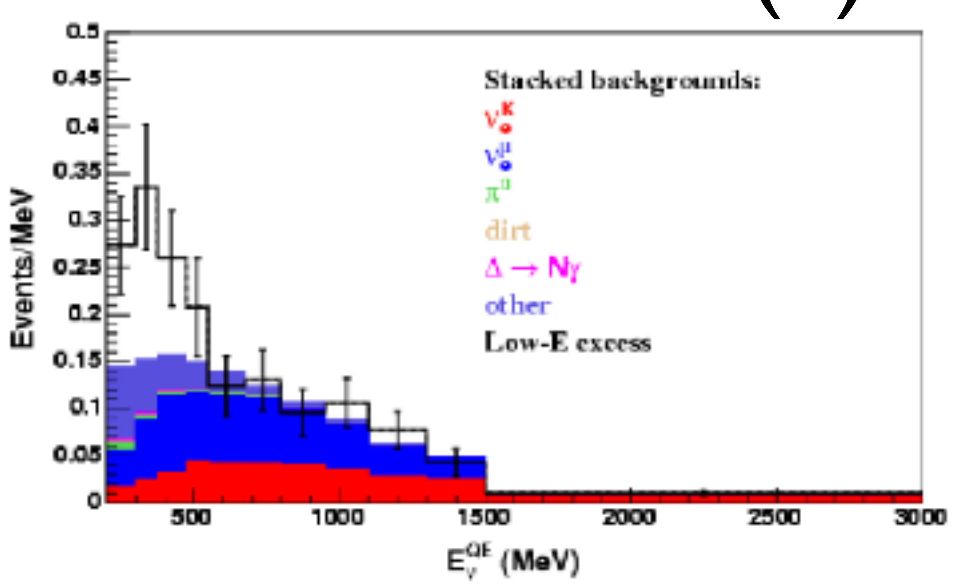
  need theory for $\sigma_{\nu\mu}$, at a precision depending on the experimental capabilities short baseline oscillation searches: important to constrain and measure backgrounds

MiniBooNE

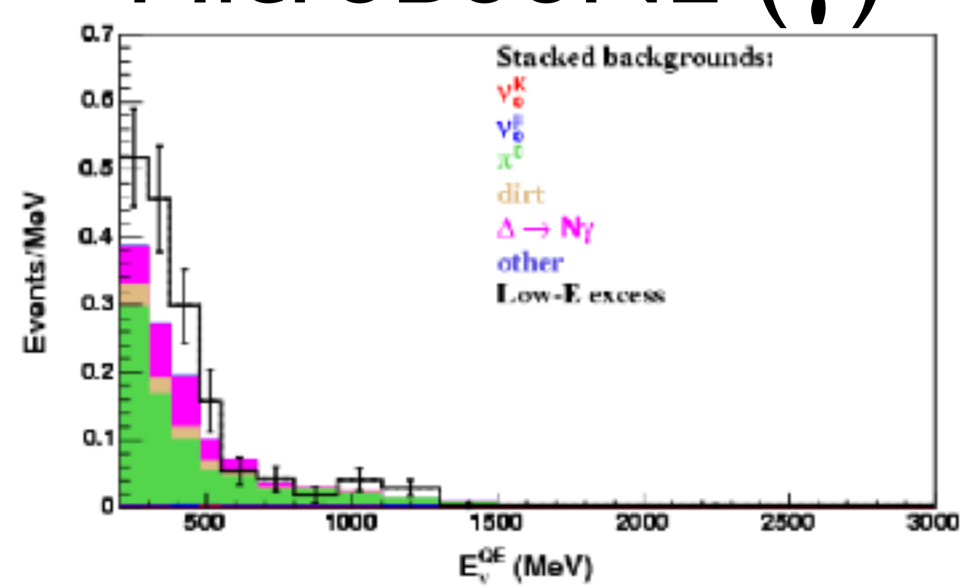


γ background vs. e^- signal

MicroBooNE (e)



MicroBooNE (γ)



current paradigm:

constrain neutrino interactions by

- determining nucleon level amplitudes
- parameterizing/measuring/calculating nuclear modifications

folk paradigms:

constrain neutrino interactions by

- starting at the quark level
- computing nuclear response

"perfect theory"

constrain neutrino interactions by

- starting directly at the nuclear level
- parameterizing and measuring every cross section

"perfect expt."

2. Fermilab Theory Experiment Working Group

Group of people representing theory, experiment and event generators. Concentrated at Fermilab, concentrating on neutrino-nucleus interactions

M. Betancourt, S. Brice, J. Campbell, M. Carena, P. Coloma, A. Furmanski, W. Giele, D. Harris, R. Hill, **A. Kronfeld**, S. Mrenna, J. Morfin, M. Muether, J. Paley, S. Parke, G. Perdue, S. Prestel, A. Schukraft, R. Van De Water, D. Wackeroth, G. Zeller, **...**

fermilab listserv NEUTRINO-THEO-EXPE

meet ~monthly to discuss progress and new ideas

Working group: **who's** involved

• working people includes Fermilab staff, distinguished scholars, NPC fellows, and Intensity Frontier Fellows (IFFs)

• three IFFs coming next year: S. Dytman (GENIE development), S. Pastore (nuclear ab initio), H. Haider (DIS, theory/generator interface)

• involvement of Neutrino Physics Center, Fermilab and several other institutions

Working group: **what's** involved

focus topics:

- interfacing theory and generators (GENIE)
  lattice QCD; nuclear models; software interfaces from QCD collider physicists
- radiative corrections and nue/numu cross section differences
  ν - e scattering; signal definitions including radiation; structure-dependent corrections
- modeling (deep, shallow) inelastic scattering
- interplay of neutrino interactions and phenomenology
- ...

→ subgroups to work on each topic

3. NUSTEC

Collaboration promoting and coordinating efforts between theorists/experimentalists/generator builders

NUSTEC: **who's** involved

broad, international, membership

Theorists

- **Luis Alvarez Ruso (co-spokesperson, IFIC, Valencia, Spain)**
- Mohammad Sajjad Athar (Aligarh Muslim University, Aligarh, India)
- Maria Barbaro (University of Turin, Turin, Italy)
- Omar Benhar (Sapienza University of Rome, Rome, Italy)
- Richard Hill (University of Kentucky and Fermilab, USA)
- Patrick Huber (Center for neutrino physics, Virginia Tech, Blacksburg, VA, US
- Natalie Jachowicz (Ghent University, Ghent, Belgium)
- Andreas Kronfeld (Fermilab, IL, USA)
- Marco Martini (IRFU Saclay, Saclay, France)
- Toru Sato (Osaka, University, Osaka, Japan)
- Rocco Schiavilla (Old Dominion University and Jefferson Lab, Norfolk, VA, US
- Jan Sobczyk (nuWro representative, University of Wroclaw, Wroclaw, Poland)

Experimentalists

- Sara Bolognesi (CEA-IRFU, Saclay, France)
- Steve Brice (Fermilab, IL, USA)
- Raquel Castillo Fernández (Fermilab, IL, USA)
- Dan Cherdack (Colorado State University, Fort Collins, CO, USA)
- Steve Dytman (University of Pittsburgh, Pittsburgh, PA, USA)
- Andy Furmanski (University of Manchester, UK)
- Yoshinari Hayato (NEUT representative, ICRR, Univ. Tokyo, Japan)
- Teppei Katori (Queen Mary University of London, UK)
- Kendall Mahn (Michigan State University, East Lansing, MI, USA)
- Camillo Mariani (Center for neutrino physics, Virginia Tech, Blacksburg, VA, USA)
- **Jorge G. Morfin (co-spokesperson, Fermilab, IL, USA)**
- Ornella Palamara (Fermilab, IL, USA)
- Jon Paley (Fermilab, IL, USA)
- Roberto Petti (University of South Carolina, Columbia, SC, USA)
- Gabe Perdue (GENIE representative, Fermilab, IL, USA)
- Federico Sanchez (IFAE, Autonomous University of Barcelona, Barcelona, Spain)
- Sam Zeller (Fermilab, IL, USA)

NUSTEC: **what's** involved

- workshops

  - NuInt conference series (~every 18 months).

  - smaller topic-specific workshops

    - NuInt17, June 25-30 2015, University of Toronto, Canada
    - NuInt15, Nov. 16-21 2015, Osaka University, Osaka, Japan
    - NuInt14, May 9-24 2014, Selsdon PArk Hotel, Surrey, UK
    - NuInt12, Oct. 22-27 2012, CBPF, Rio De Janeiro, Brazil
    - NuInt11, Mar. 7-11 2011, Dehradun, India
    - NuInt09, May 18-22 2009, Sitges, Spain
    - NuInt07, May 3-June 3 2007, Fermilab, USA
    - NuInt05, Sep. 26-29 2005, Okayama university, Okayama, Japan
    - NuInt04, Mar. 17-21 2004, Gran Sasso, Italy
    - NuInt02, Dec. 12-15 2002, UC Irvine, Irvine, USA
    - NuInt01, Dec. 13-16 2001, KEK, Japan

- school

  - theorists/experimentalists +/- few years from Ph.D.

    - 2017, NuSTEC school, November 7-15, Fermilab, USA
    - 2015, NuSTEC School, November 8-14, Okayama University, Japan
    - 2014, NuSTEC School, October 20-30, Fermilab, USA
    - 2014, NuSTEC MC School, May 14-16, Liverpool, UK

- white paper

  - "Status and Challenges of Neutrino-Nucleus Scattering" arXiv:1706.03621

- future goals also include direct support of generators, global fits

4. Elementary amplitude workshop

"Elementary amplitudes for the neutrino scattering program"

INT, Seattle
June 2018 (TBC)

w/ M. Betancourt (FNAL), S. Pastore (LANL)

part of a larger INT program organized by S. Bacca (Mainz/TRIUMF), RJH, D. Phillips (Ohio), S. Pastore (LANL)

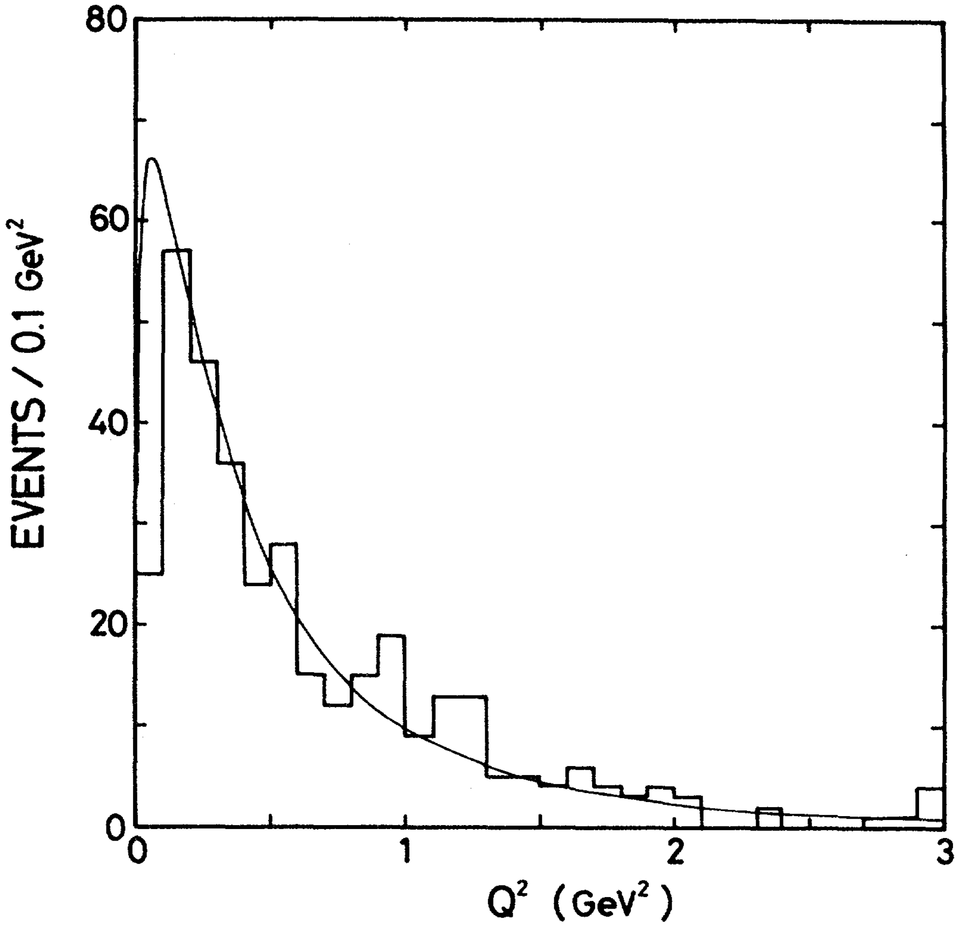
- may be a NUSTEC workshop
- may present work from Theory-Expt WG

Elementary amplitudes workshop: **motivation**

- neutrino nucleus cross sections rely on nucleon-level inputs

- critical inputs rely on 70's era bubble chamber data: pioneering but not designed to underpin today's neutrino program

- e.g. neutrino-neutron CCQE: about 3K events in world data



Fermilab 15-foot deuterium bubble chamber, PRD 28, 436 (1983)

ANL 12-foot deuterium bubble chamber, PRD 26, 537 (1982)

BNL 7-foot deuterium bubble chamber, PRD23, 2499 (1981)

Elementary amplitudes workshop: **topics**

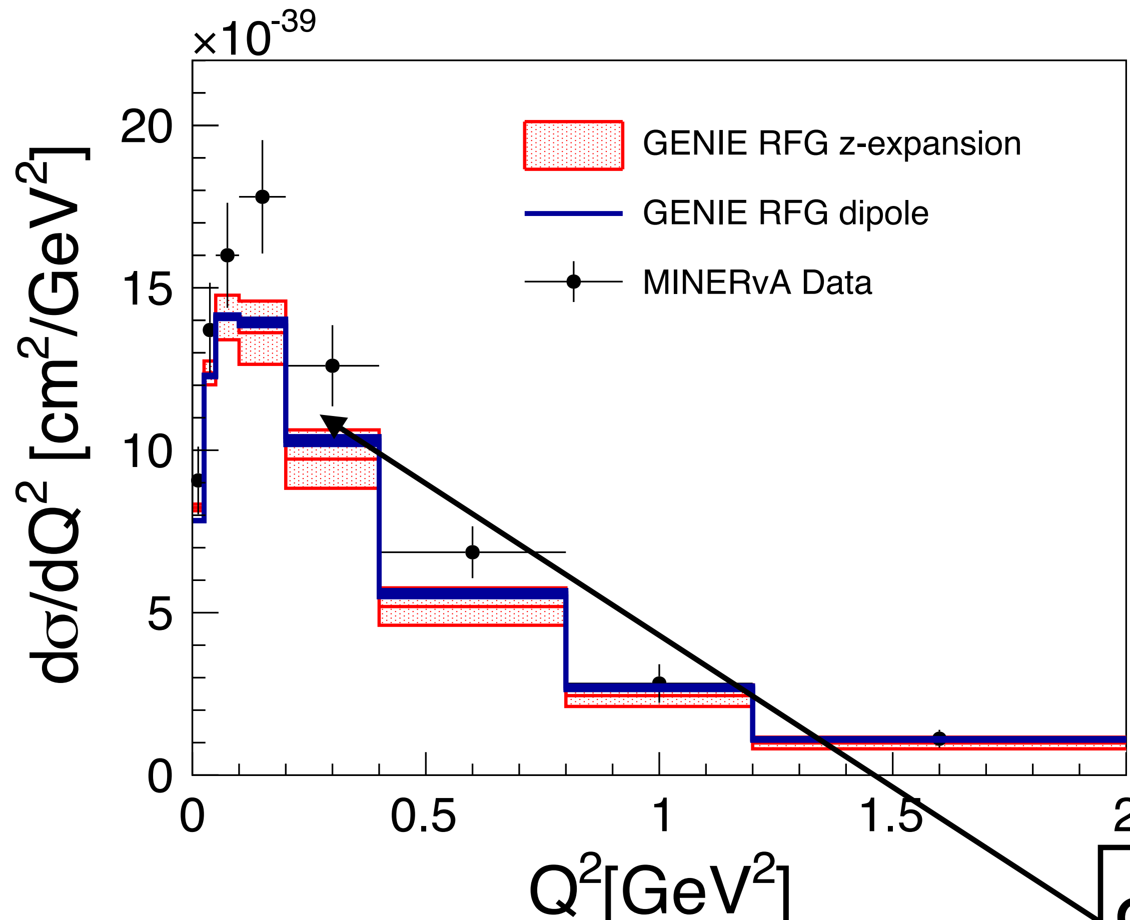
1) the quantitative impact of better constraints on the elementary amplitudes

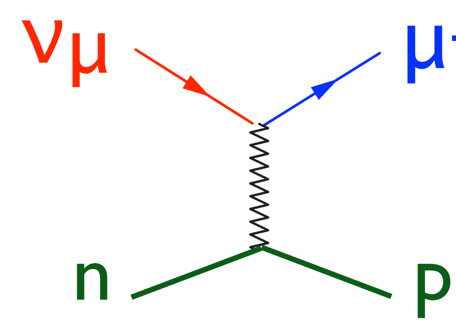
2) the scientific impact of a new hydrogen or deuterium target experiment

3) the optimal design and technical feasibility of a new hydrogen or deuterium target experiment;

4) constraints on the elementary amplitudes from other methods

- impact of nucleon-level uncertainties



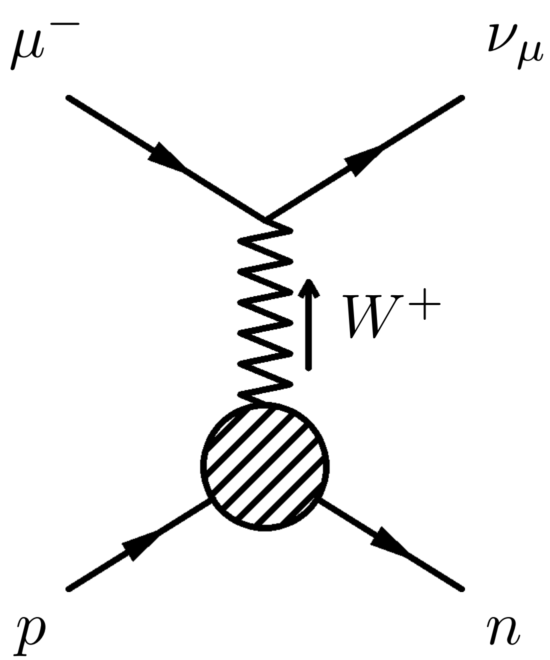


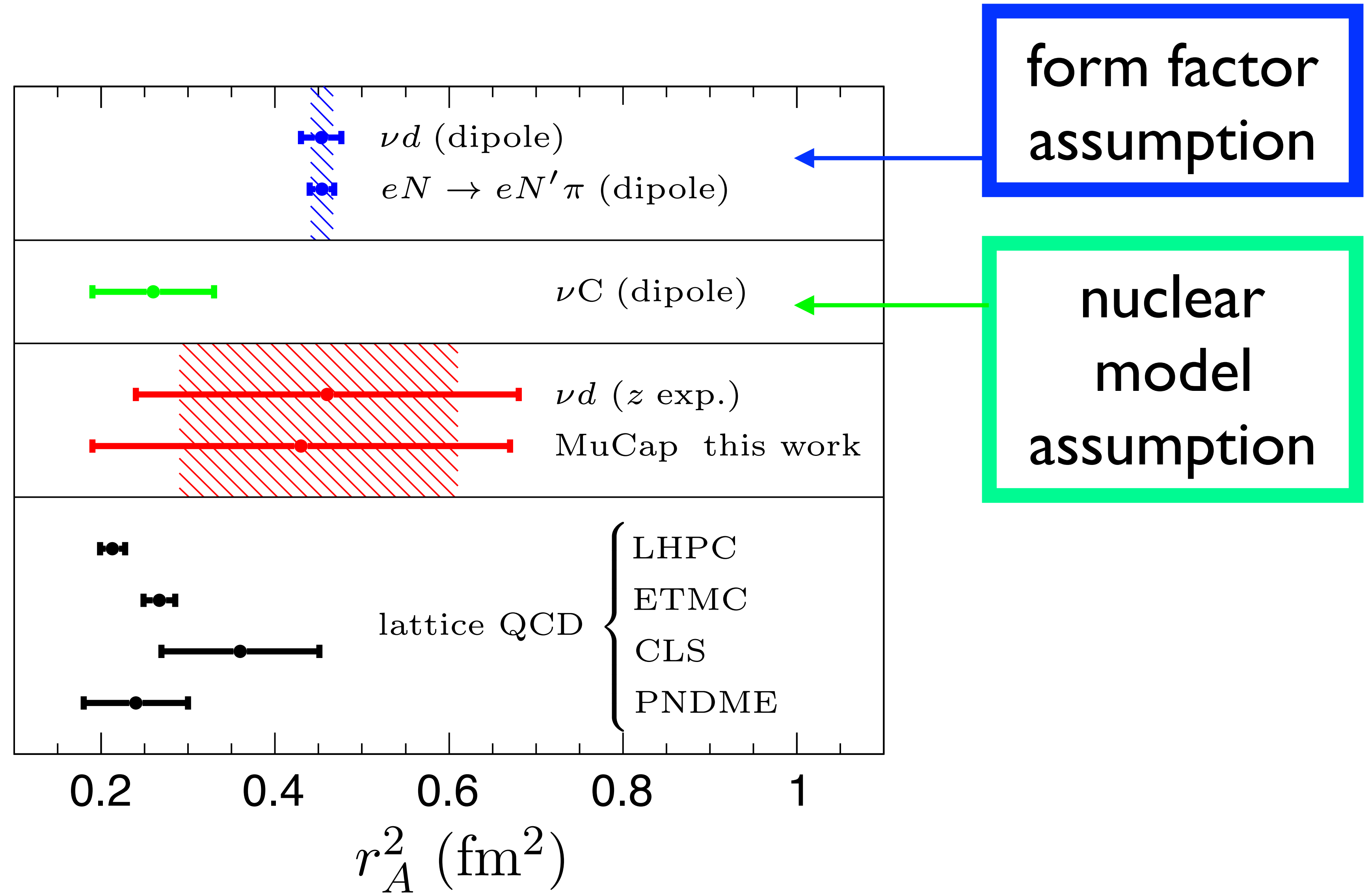
$$\sigma(\nu n \to \mu p) = |\cdots F_A(q^2) \cdots|^2$$

poorly known axial form factor

discrepancy: nucleon effects or nuclear effects ?

- complementary processes





from RJH, Kammel, Marciano, Sirlin 1708.08462

lattice average: see also Yao, Alvarez-Ruso, Vicente-Vacas 1708.08776 [r_A^2=0.26(4) fm^2]

5. Radiative corrections workshop

"Radiative corrections at the intensity frontier"

Perimeter Institute
June 12-14, 2017

organizers J. Campbell (Fermilab), P. Coloma (Fermilab), RJH, M. Pospelov (Perimeter), S. Prestel (Fermilab), D. Wackeroth (Buffalo)

- follow-up meeting planned at Fermilab, 2018

Radiative corrections workshop: **key topics**

1) radiative corrections and neutrinos

2) electron-nucleon scattering

3) muonic atoms

4) flavor transitions and precision measurements

6. Community considerations

building a thriving neutrino interaction effort

- find interesting, well-defined and solvable problems
- avoid zero sum games
- experiments: precisely define their needs/capabilities
- ok to parameterize and measure, but must avoid implicit bias
- core part of HEP mission shouldn't be (simply) outsourced
- identify as part of a larger intellectual effort (intensity frontier/precision science/…)
- think new/big/different (large scale lattice QCD; quantum computers for nuclear physics; …?)

backup

notes on complementarity:

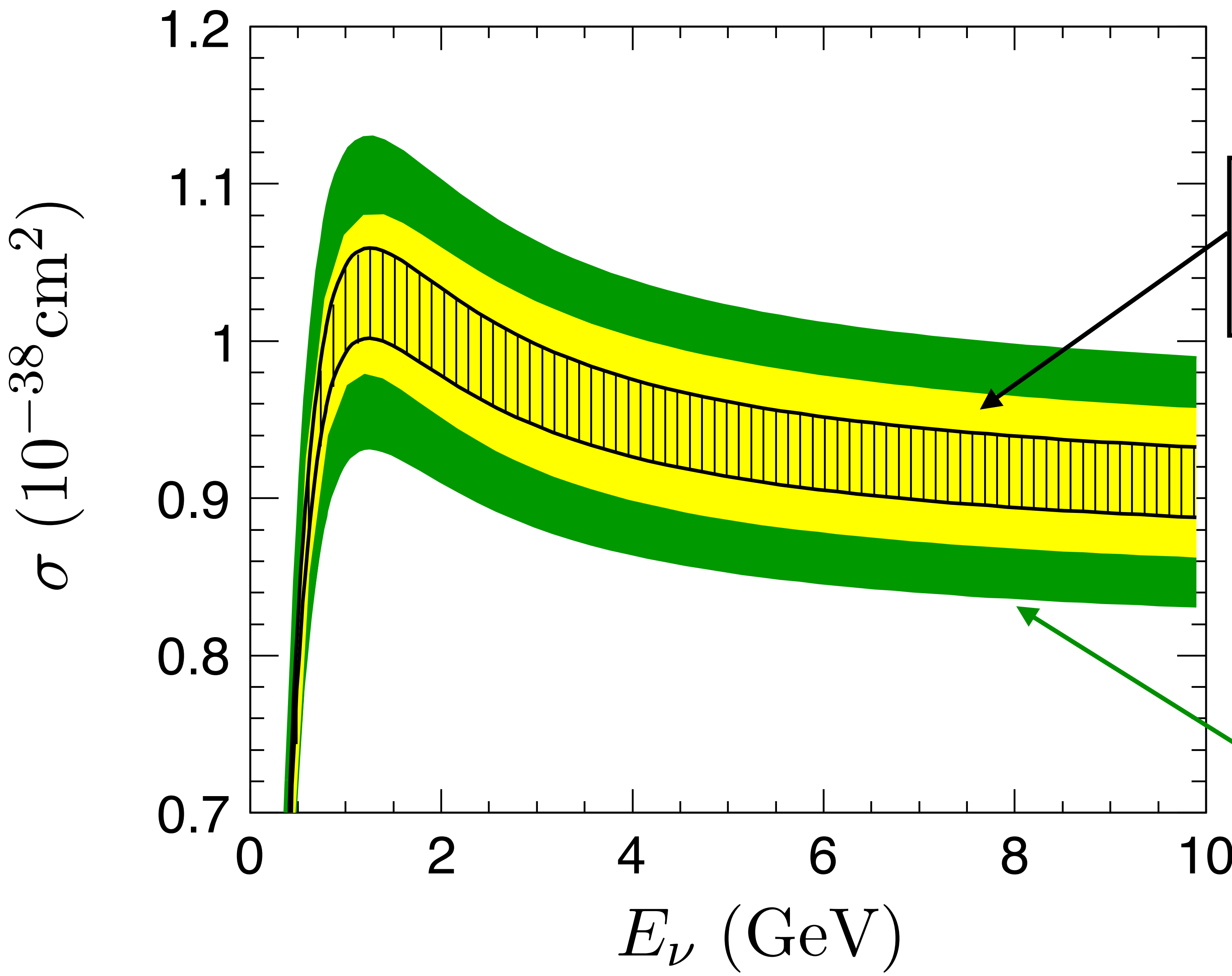
- beyond neutrino oscillations, many related applications relying on quantitative nucleon structure:
  - fundamental constants (probable 7 sigma shift in Rydberg)
  - sigma terms and WIMP-DM direct detection
  - g_A and BBN
  - …

- QED is "easy". But QED + nucleon structure is "hard"

- entering a precision realm where percent level corrections to nucleon structure need to be calculated, not just estimated in any paradigm:

- near detector has access to primarily ν_μ neutrinos
- ν_e appearance signal is directly impacted by ν_μ/ν_e cross section differences
  - kinematics (muon mass)
  - radiative corrections (QED and EW)
  - 2nd class currents (G parity violation)
  - signal definition (which photons are included)

muon capture constraints on neutrino cross sections



with radius constraint: (hatched: external radius error δr_A^2=20%)

existing error (no external radius constraint)