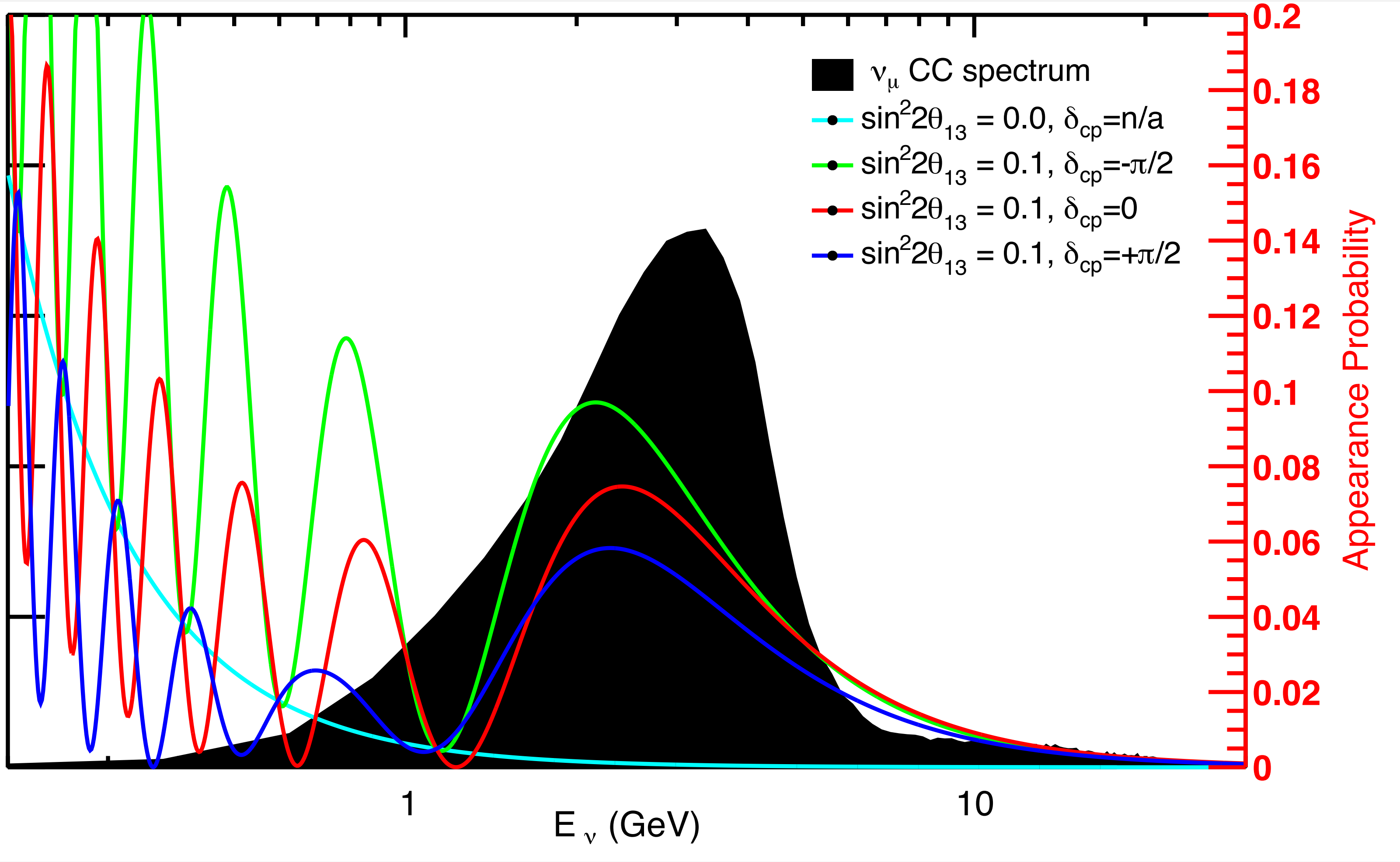
Elementary amplitudes from and for neutrino interactions

RICHARD HILL, U. Kentucky and Fermilab

PONDD, 3 December 2018

ν_e appearance from a ν_μ beam

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



but **difficult in practice:** rely on theory to determine cross sections: e.g. $\sigma(\nu_e)/\sigma(\nu_\mu)$ to a precision of 1%

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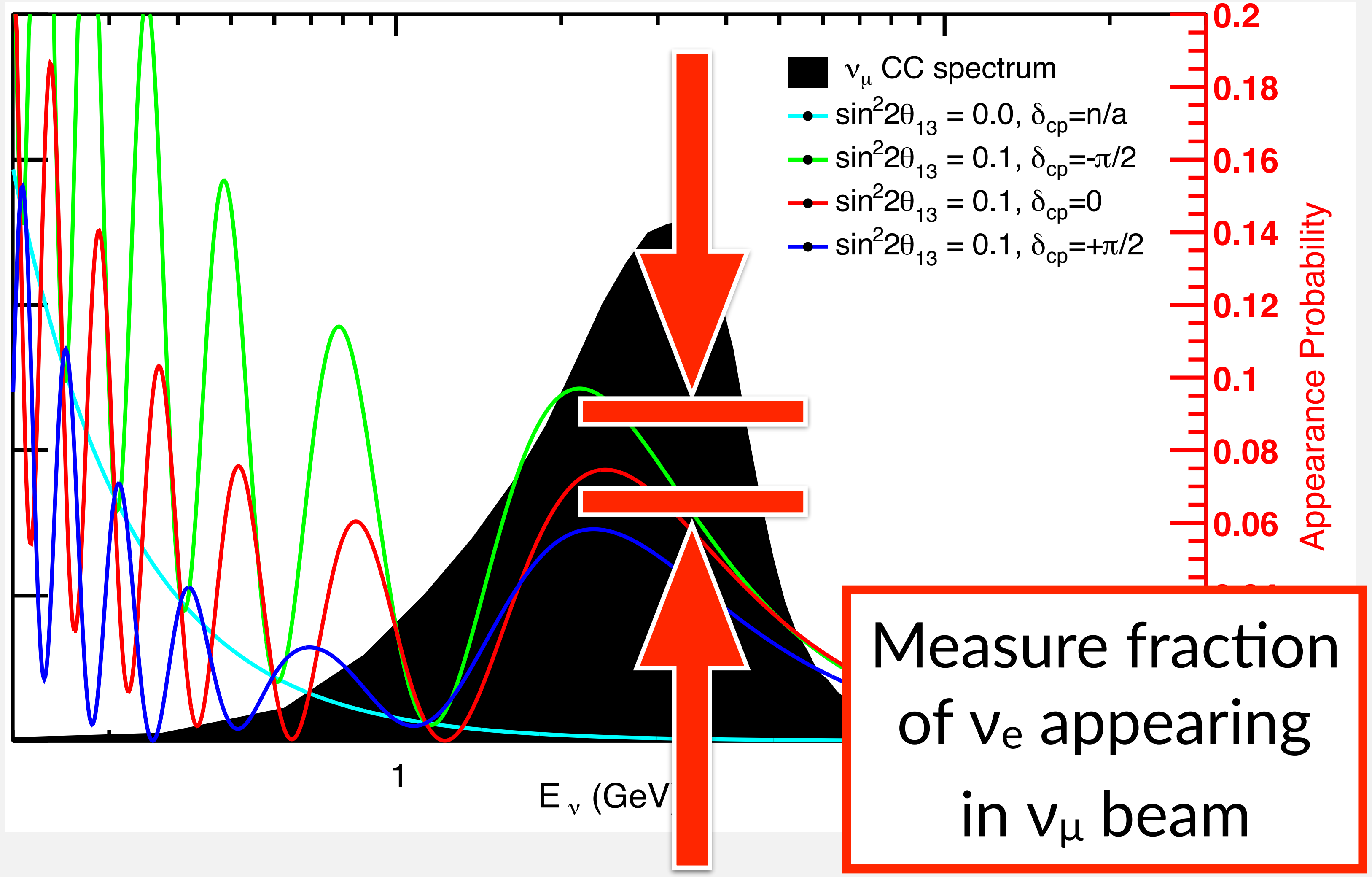

Measure fraction of ν_e appearing in ν_μ beam

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ν_e appearance from a ν_μ beam

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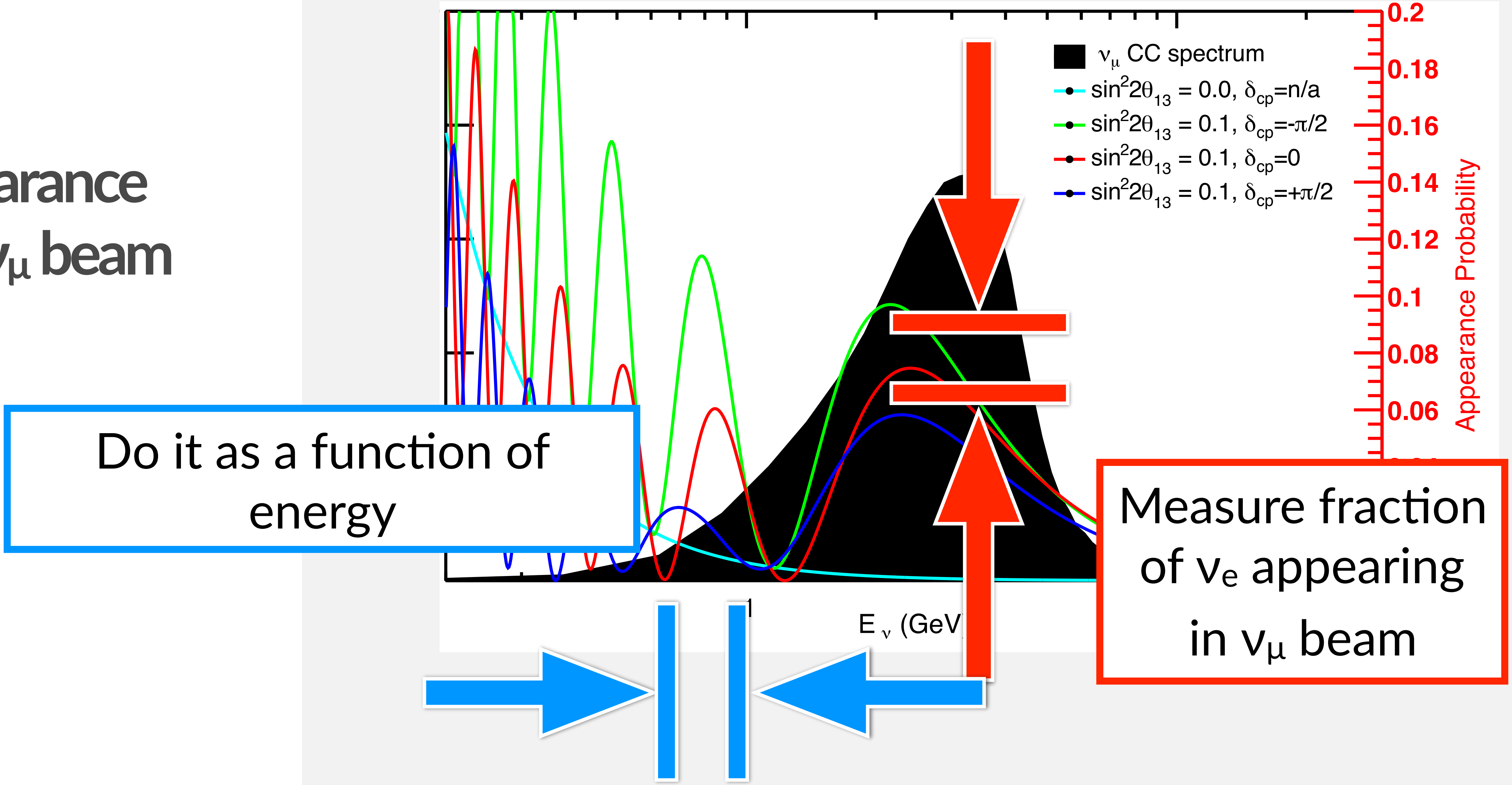


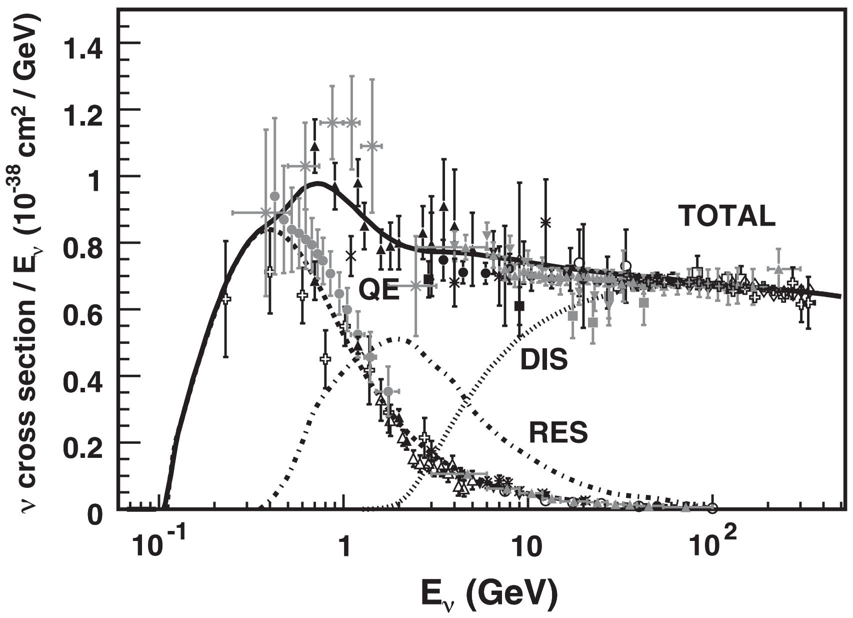
Do it as a function of energy

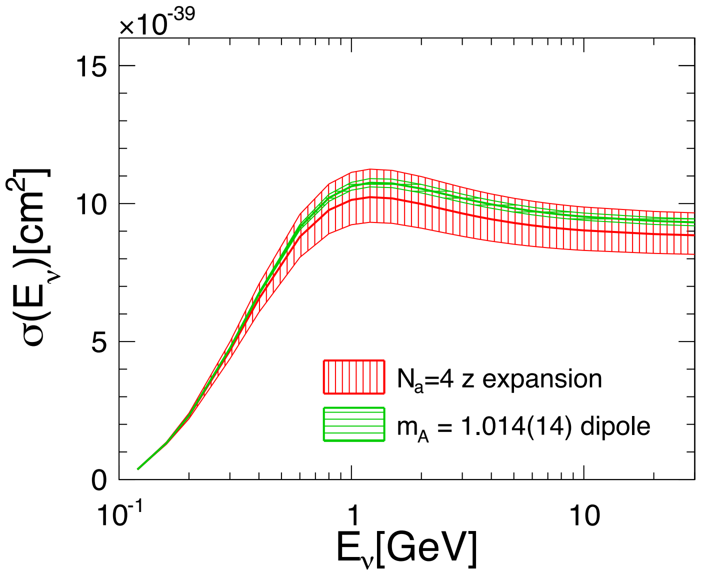
Measure fraction of ν_e appearing in ν_μ beam

but **difficult in practice:** rely on theory to determine cross sections: e.g. $\sigma(\nu_e)/\sigma(\nu_\mu)$ to a precision of 1%

Important questions in the 3 flavor paradigm

- **limits on achievable precision due to neutrino interaction uncertainties**





$$\sigma_{\nu n\to\mu p}(E_\nu = 1\,\mathrm{GeV}) = 10.1(0.9)\times 10^{-39}\,\mathrm{cm}^2$$

$$\sigma_{\nu n\to\mu p}(E_\nu = 3\,\mathrm{GeV}) = 9.6(0.9)\times 10^{-39}\,\mathrm{cm}^2$$

current knowledge of nucleon level CCQE cross section based on ~3.5k events

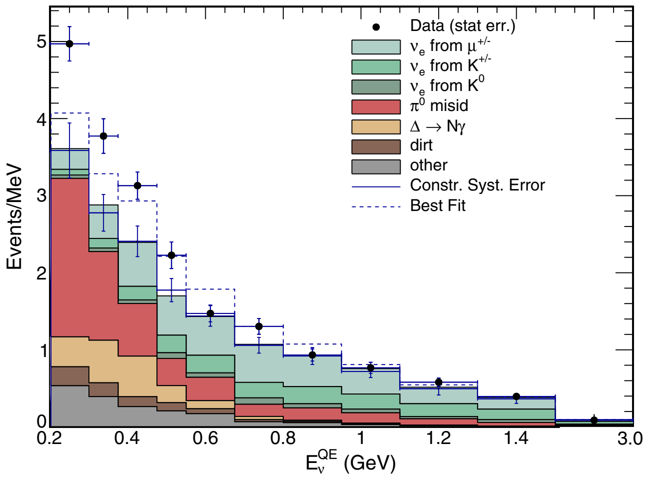
$$\delta\sigma_{\mathrm{CCQE}} \lesssim 5\,\% \implies \sim 7k \text{ CCQE events}$$

$$\delta\sigma_{\mathrm{CCQE}} \lesssim 1\,\% \implies \sim 170k \text{ CCQE events}$$

Important questions beyond the 3 flavor paradigm

- **short baseline anomalies**

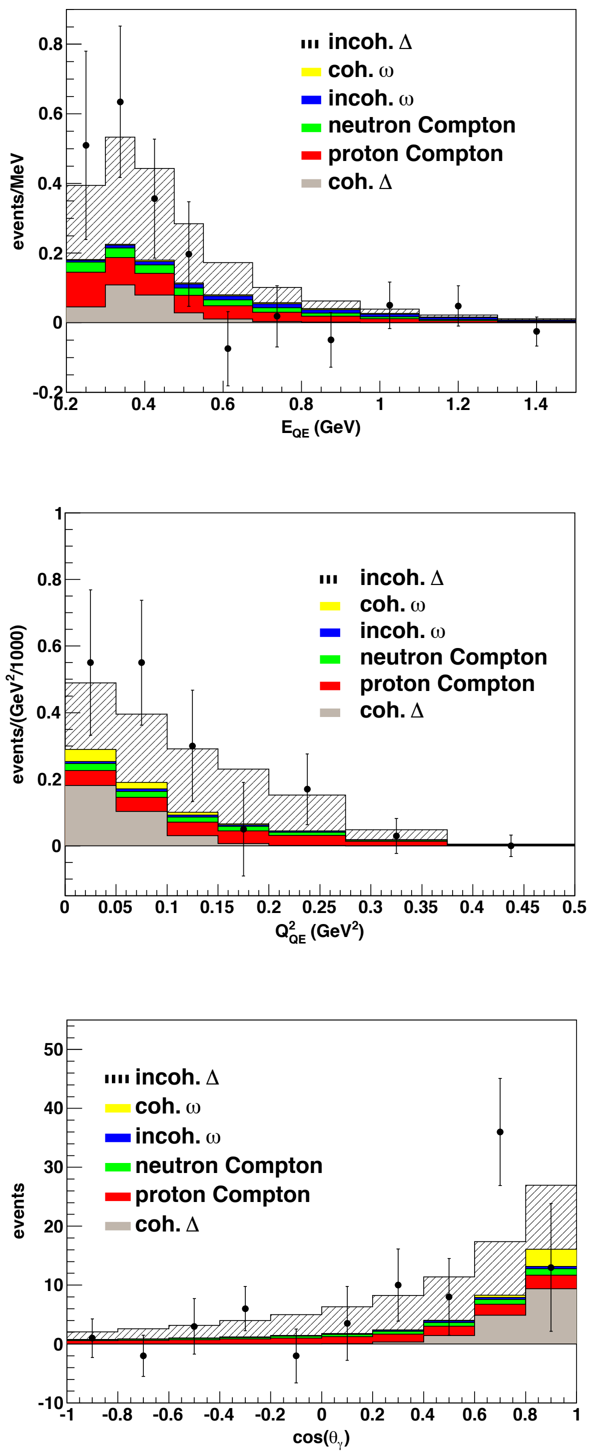
SM backgrounds to MiniBooNE excess



MiniBooNE PRL 121, 221801 (2018)

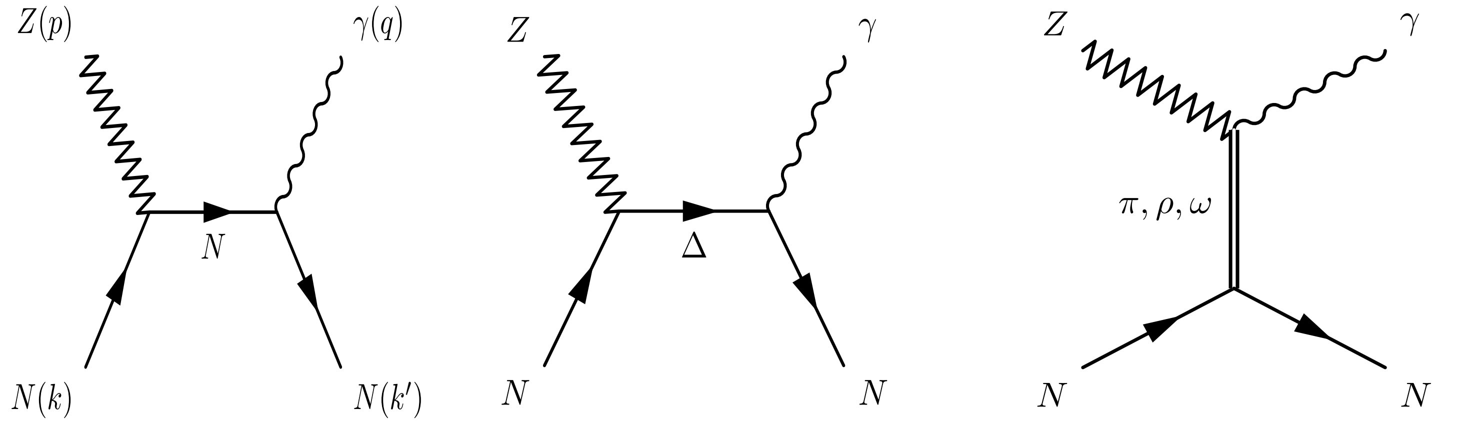
In the MiniBooNE detector, CC signal degenerate with NC single photon background

kinematic shape of the excess looks similar to single photon background



RJH, PRD 84, 017501 (2011)

this background is estimated using a resonance insertion approach



At the nucleon level, 12 invariant amplitudes depending on 3 kinematic invariants
(cf. CCQE: 1 poorly known amplitude F_A depending on 1 invariant Q^2)

Background looks like signal, is hard to calculate, and has never been measured. (!)

Nucleon level needed to validate MiniBooNE pion-based estimate, and to relate MiniBooNE/MicroBooNE

$$\delta\sigma_{1\gamma} \lesssim 100\,\% \implies \mathcal{O}(1k) \text{ CCQE events}$$

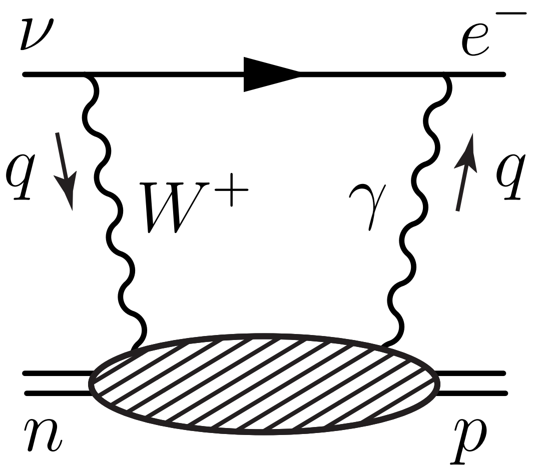
$$\delta\sigma_{1\gamma} \lesssim 10\,\% \implies \mathcal{O}(100k) \text{ CCQE events}$$

(based on counting statistics, $\sigma_{1\gamma} \sim O(10^{-3})\, \sigma_{CCQE}$)

Important questions beyond neutrinos

- **BSM signals and constraints beyond neutrinos**

V_{ud} and CKM unitarity

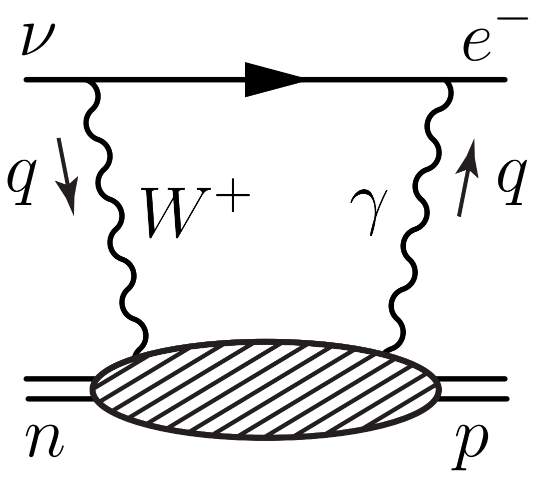


A key radiative correction to neutron and nuclear beta decay is sensitive to nucleon structure

Recent reanalysis of this correction implies > 4σ violation of CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9983(4)$$

Seng, Gorchtein, Patel, Ramsey-Musolf, 1807.10197



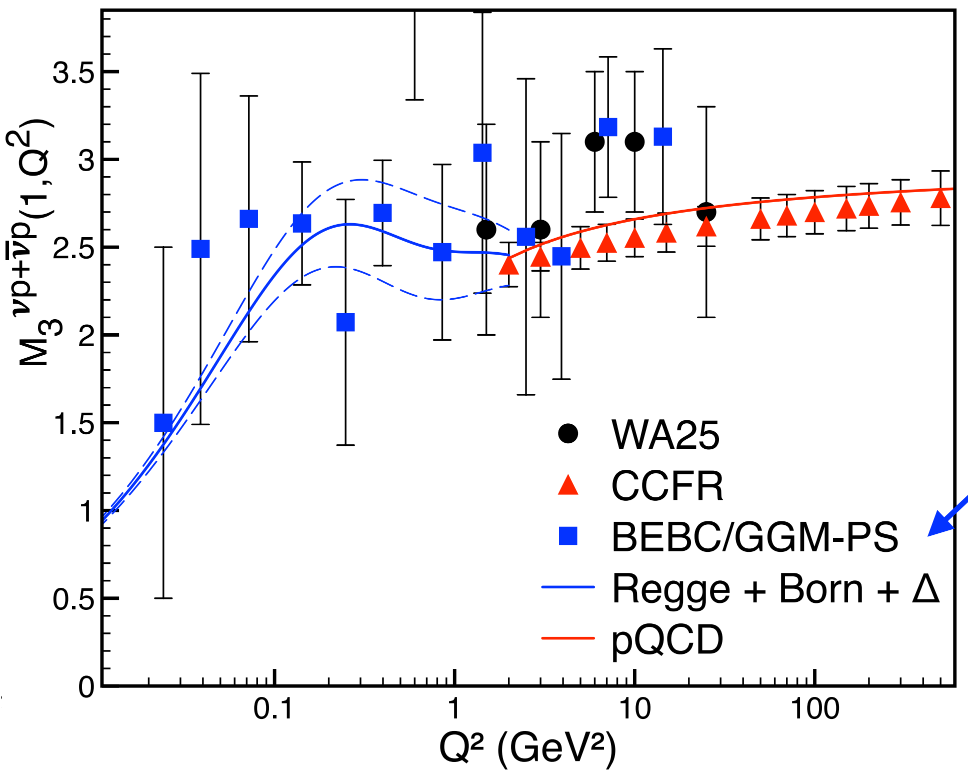
Inaccessible to electron scattering, but related (via isospin) to forward neutrino scattering and (via dispersion relation) to neutrino-nucleon cross sections

Available data is limited by statistics and impacted by nuclear effects

Moment of inelastic structure function

box correction related to integral of this function, needed to 1% precision

$$\Box^{VA}_{\gamma W} = \frac{3\alpha}{2\pi}\int_0^\infty \frac{dQ^2}{Q^2}\frac{M_W^2}{M_W^2+Q^2}M_3^{(0)}(1,Q^2).$$



~3k events

relevant sample on nucleon target:

$\sim \mathcal{O}(10-100k)$ events

Important questions beyond neutrinos

- **precision measurements**

r_A puzzle

[

Aside: can we phrase the neutrino-nucleus scattering problem in standard form?

1) identify a finite set of physical quantities that determine the problem

2) constrain these numbers by any and all means

3) propagate uncertainties to interesting quantities, like fundamental neutrino parameters

We’re still trying to arrive at this standard form. Regardless, r_A is likely to be in the final set.

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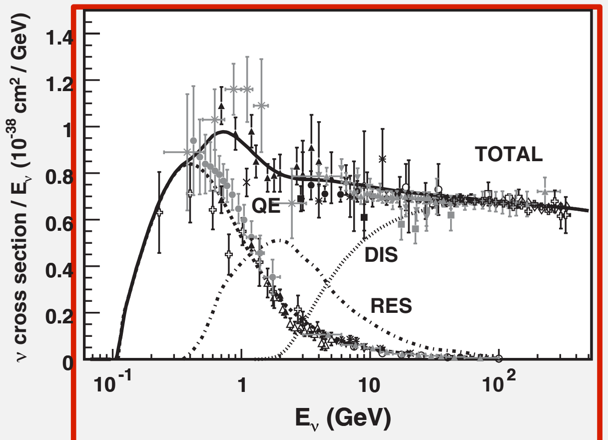
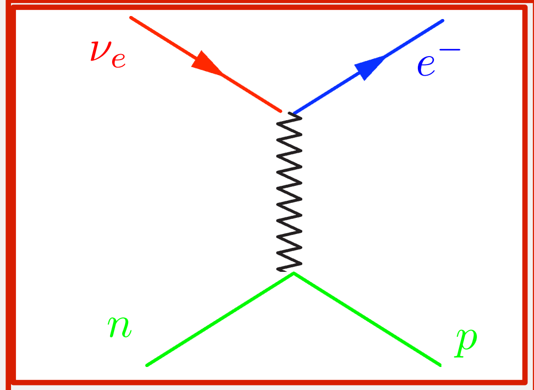
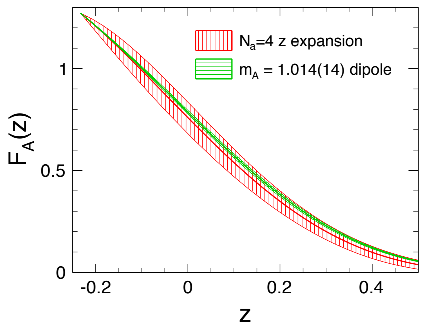
A critical number: the nucleon axial radius



quasi elastic (QE) dominance

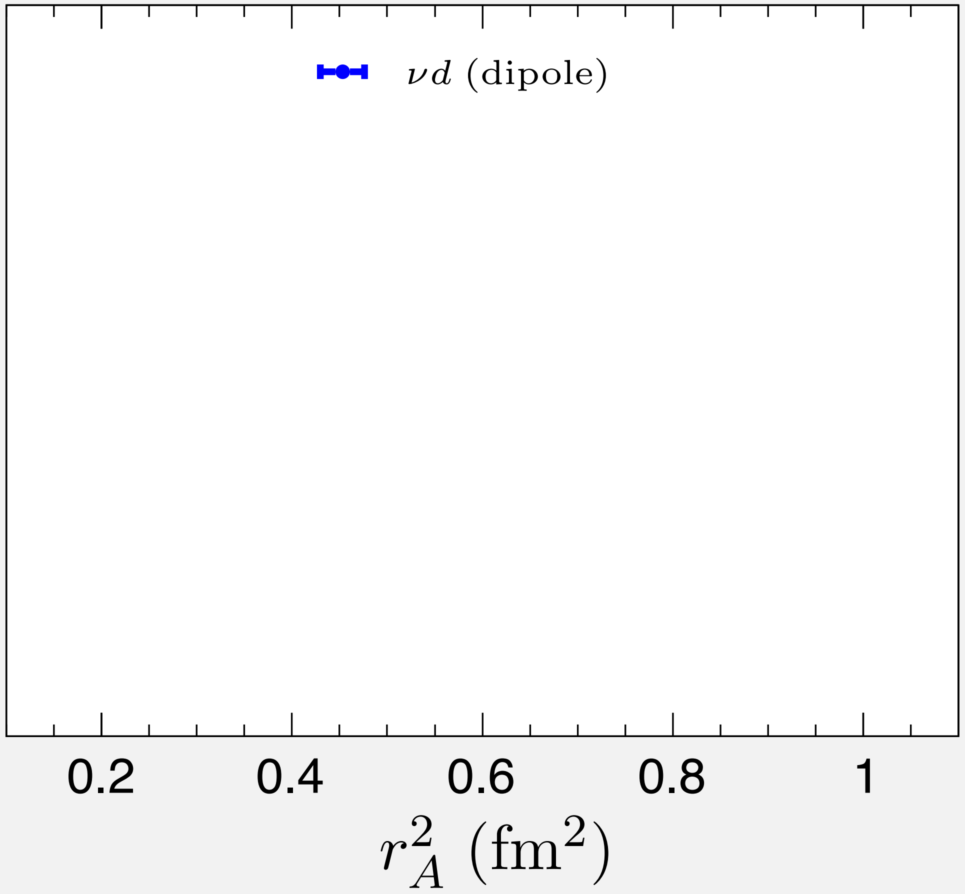


nucleon form factors for QE process



linear dependence of form factors on kinematics

What do we know about this critical number?



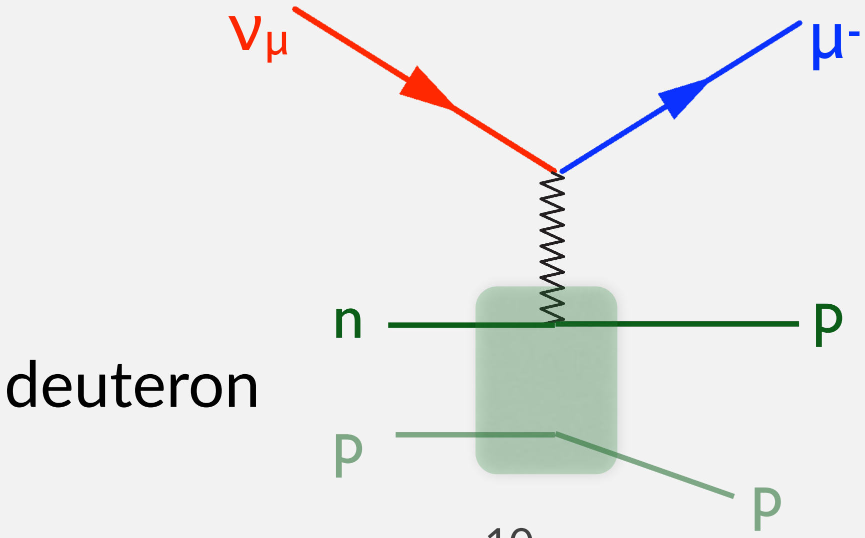
BNL 1981

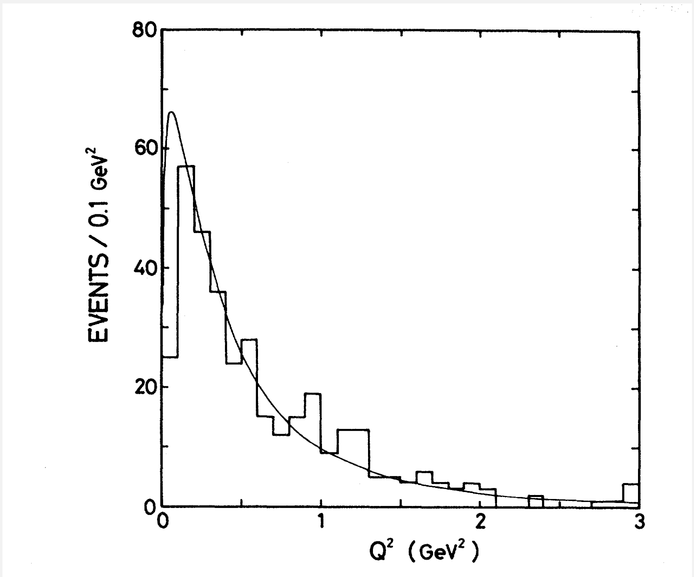
ANL 1982

Fermilab 1983

The number seemed uncontroversial for decades:

extracted from deuterium bubble chamber data





Kitigaki et al. PRD 28, 436 (1983)

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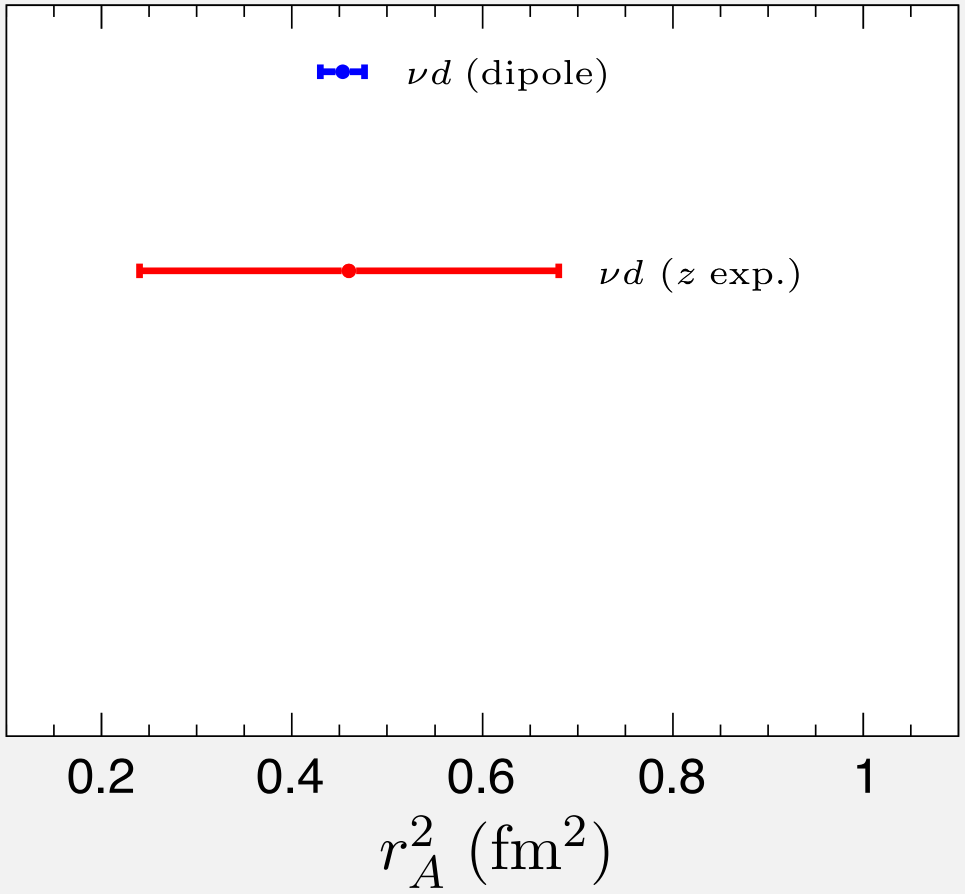


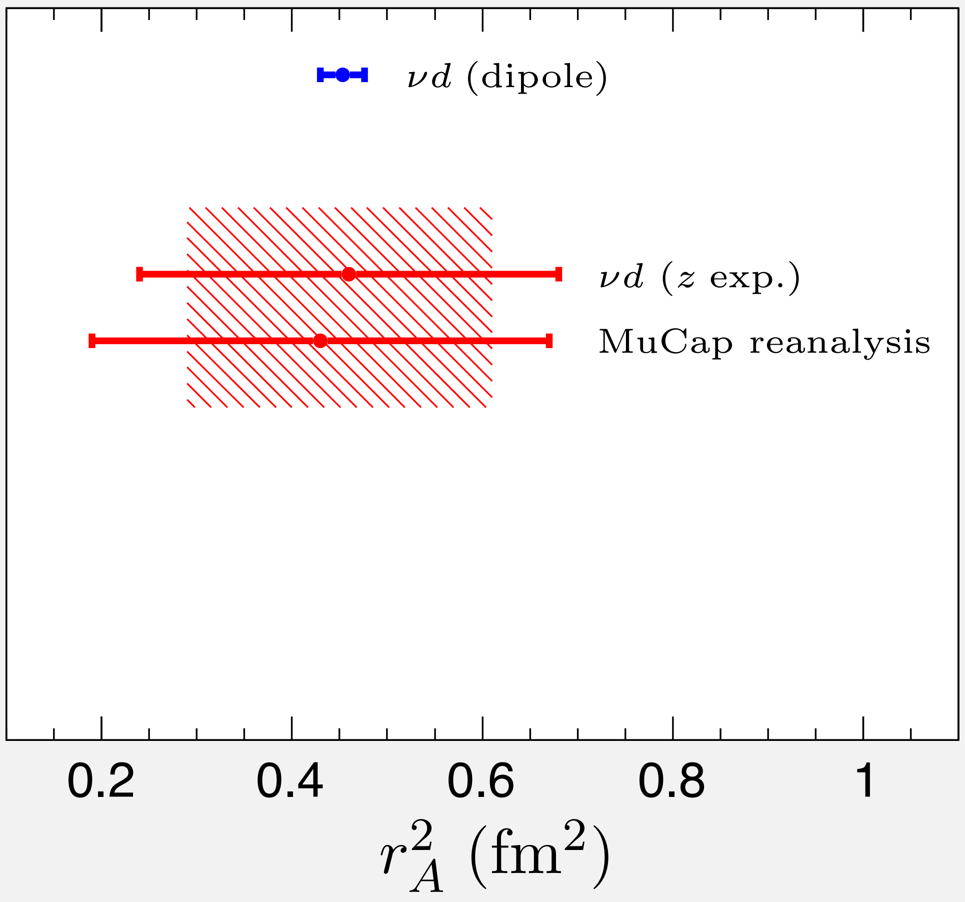
In fact the extraction relied on a hidden model assumption, and the true uncertainty is an order of magnitude larger

Bhattacharya, RJH, Paz 2011

Meyer, Betancourt, Gran, RJH 2016

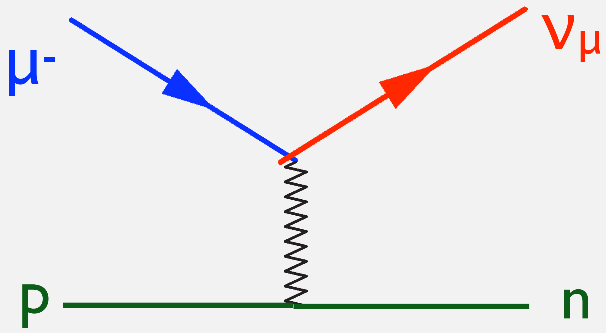
Introduces a ≳10% uncertainty in every neutrino-nucleus cross section. A wrench in the works for oscillation experiments.

What do we know about this critical number?



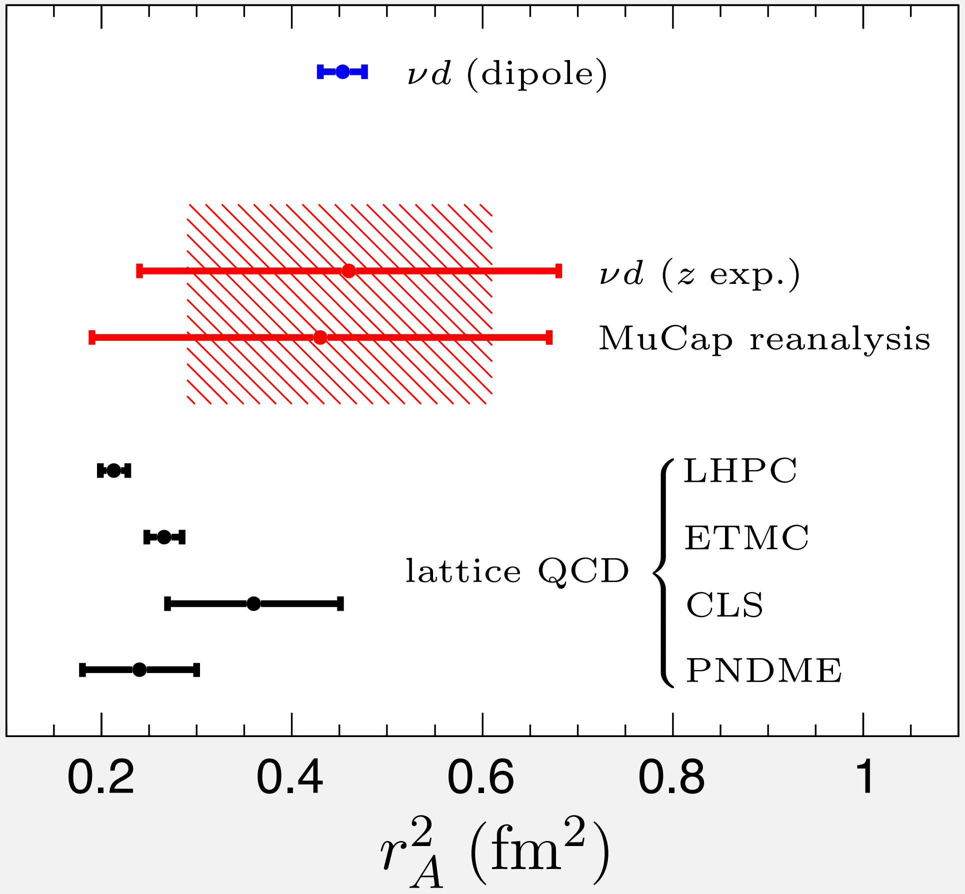
Look at the process in reverse: muon capture from ground state of muonic hydrogen

Improved theory analysis and existing data: already competitive with world ν-d data. Significant improvements possible



RJH, Kammel, Marciano, Sirlin 2017

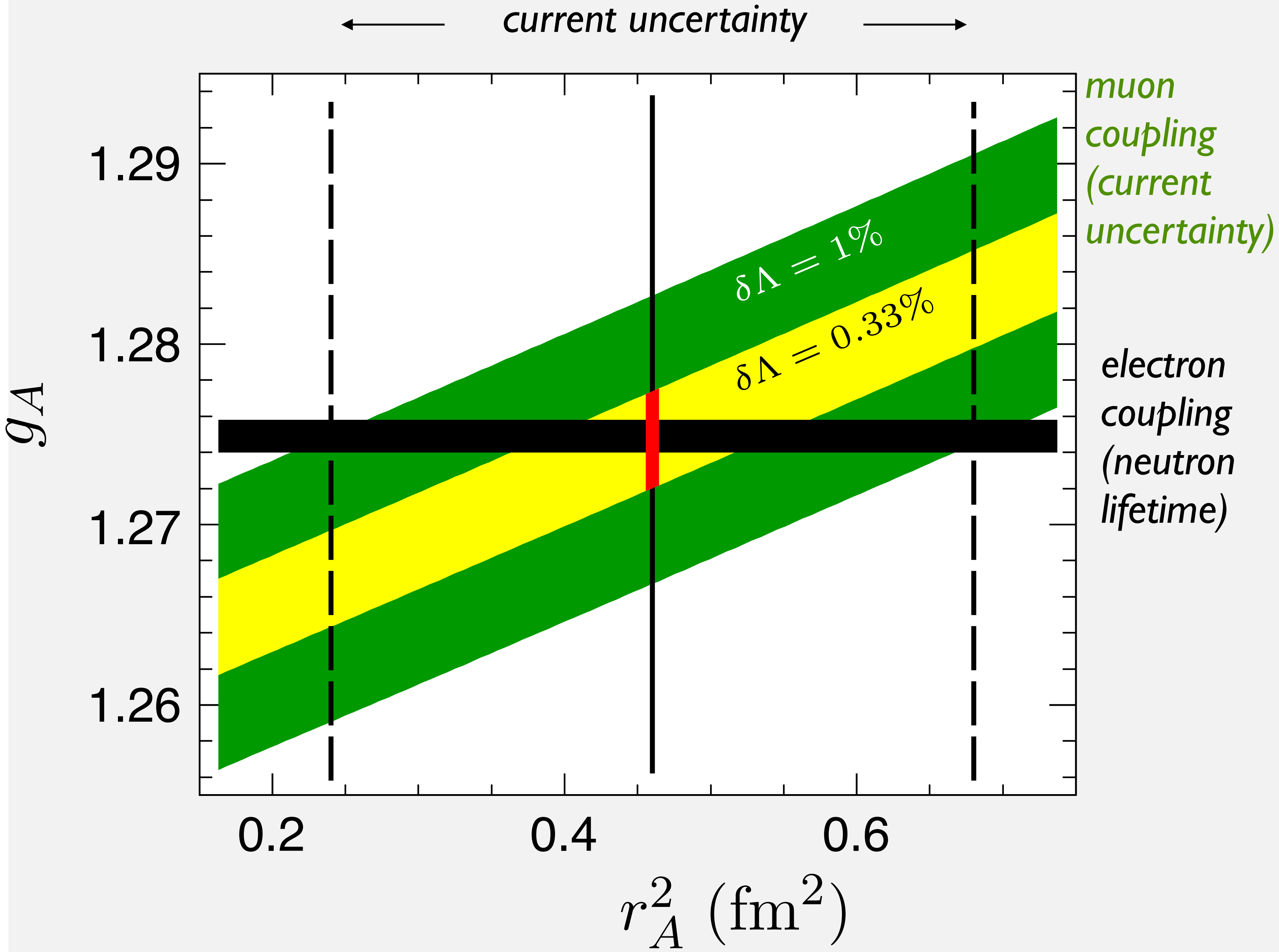
What do we know about this critical number?



Lattice QCD is also embarking on an ambitious, long-range program to answer this challenge

~5σ discrepancy between blue point and black points

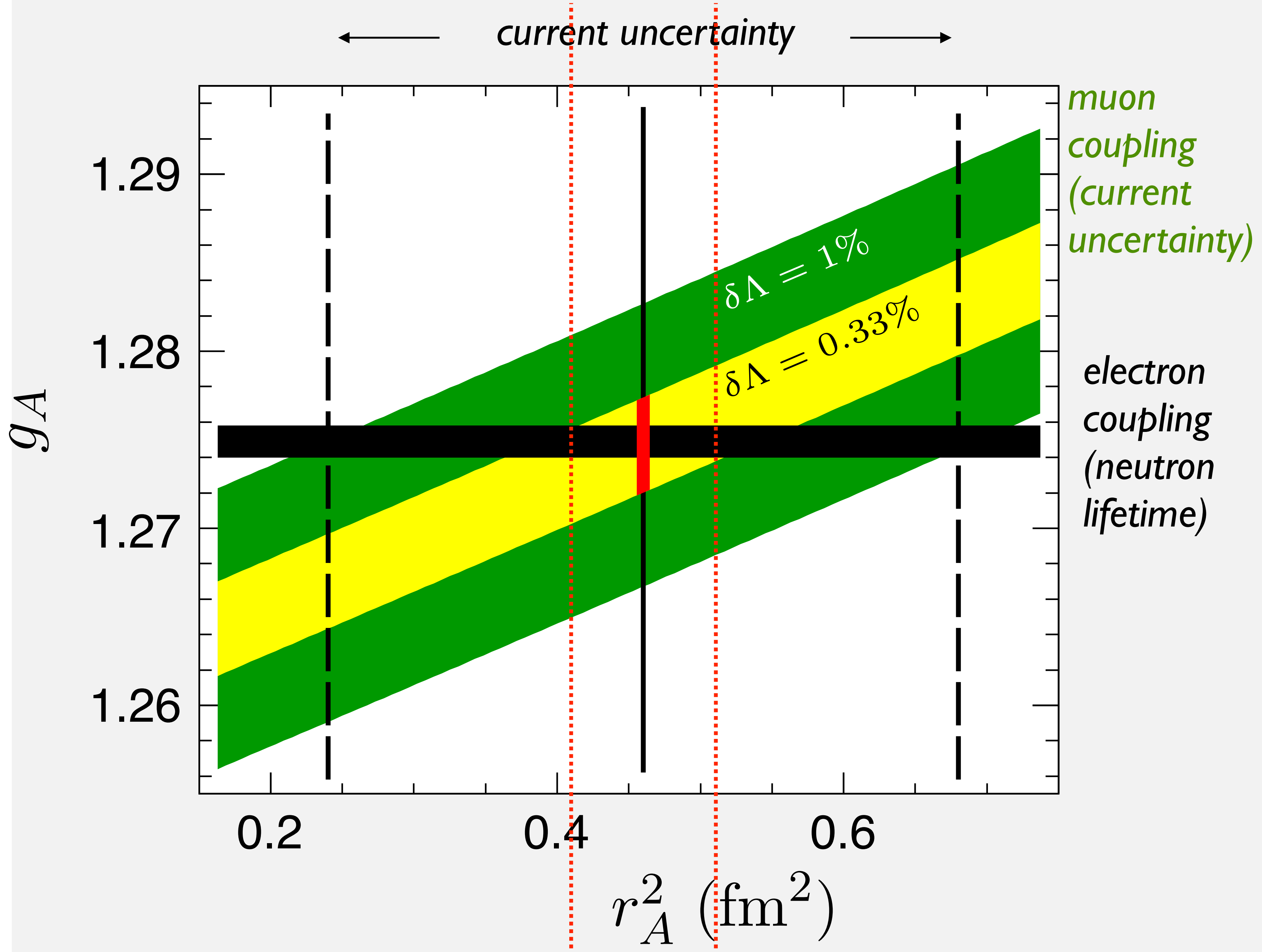
Complementarity between r_A constraints from different processes



r_A from neutrino data, and/or lattice QCD ⇒ muon capture provides a stringent test of muon versus electron universality

$$\text{current}: \ \delta(r_A^2) = 50\,\%$$

Complementarity between r$_A$ constraints from different processes



r$_A$ from neutrino data, and/or lattice QCD ⇒ muon capture provides a stringent test of muon versus electron universality

$$\text{current}: \ \delta(r_A^2) = 50\,\%$$

$$\text{e.g.} \ \ \delta(r_A^2) = 10\,\% \ \Longrightarrow \sim 30k \ \text{CCQE events}$$

a smattering of topics needing more precise elementary amplitude input:
(certainly not exhaustive)

- nucleon level CCQE cross section $\delta\sigma_{\text{CCQE}} \lesssim 5\,\% \implies \sim 7k$ CCQE events
  $\delta\sigma_{\text{CCQE}} \lesssim 1\,\% \implies \sim 170k$ CCQE events

- MiniBooNE excess $\delta\sigma_{1\gamma} \lesssim 100\,\% \implies \mathcal{O}(1k)$ CCQE events
  $\delta\sigma_{1\gamma} \lesssim 10\,\% \implies \mathcal{O}(100k)$ CCQE events

- neutron beta decay and CKM unitarity $\delta\,\square = 1\,\% \implies \sim \mathcal{O}(10 - 100k)$ events

- r_A for muon capture and mu-e universality $\delta(r_A^2) = 10\,\% \implies \sim 30k$ CCQE events

- …

Workshop in summer 2018 at Seattle INT featured a focused discussion on the question of elementary amplitudes

http://www.int.washington.edu/PROGRAMS/18-2a/18-2a_workshop.html

organizers M. Betancourt, RJH, S. Pastore

A report is in progress, not restricted to workshop participants (rjh@fnal.gov)

The following is a selective summary of the workshop discussion.

(In what follows, parenthetical talk references refer to other talks at the INT link above. There are many relevant talks here at PONDD, I will not attempt to list them all.)

- definition of elementary amplitude
  - F_A (too narrow)
  - S matrix elements at the nucleon level: $\nu N \to \ell N$, $eN \to eN$, $N \to N\pi$, $N \to X$, $NN \to NN$, etc.
  - inputs to nuclear modeling
  - the initio of ab initio
  - any physical quantity that lattice QCD can measure involving one or a few nucleons
  - any physical quantity that can be measured in an elementary target (H or D) scattering experiment

- the questions

  (1) what do we know?

  (2) what do we need to know?

  (3) how can we come to know it?

All questions are difficult, but after normalization, (1)=(3)=easy, (2)=hard

discussion and report on elementary amplitudes

- motivations
  - well defined quantities
  - important component of the error budget
  - necessary to inform and discriminate nuclear models
  - important, fruitful, interesting intersections (lattice, e-p, muonic atoms, …)

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Probably not enough, but serious attempts to quantify

(talks of Meyer, Morfin, Ruso, Sato, Wilkinson)

- challenges from low statistics and limited data preservation
- open questions on deuteron corrections

- the questions

  (1) what do we know?

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New elementary target data (Bross, Kammel)

- underground safety raises the bar for making the physics case
- what can be achieved by subtraction methods using compound targets?

Precision lattice QCD (talks of Kronfeld, Lin, Shanahan)

- F_A within sight
- complementary to scattering data

Electron and positron beams (Crawford, Nakamura), muonic atoms (Kammel), …

Many elements of the physics case (question 2) are common between these paths. Practitioners have strategic interest in helping make this physics case.

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(1) what do we know?

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Three levels (at least) of answer

(i) regardless of nuclear model, nucleon-level data tests critical elements of oscillation analyses (e.g. disentangling differences in ν_μ/ν_e from radiative corrections and detector response) (McFarland)

(ii) propagate elementary input errors through a/the default nuclear model and oscillation analysis. Need those errors to be smaller than the desired precision on fundamental neutrino parameters.

(Ashkenazi, Castillo, Himmel, Mahn, Ruterbories)

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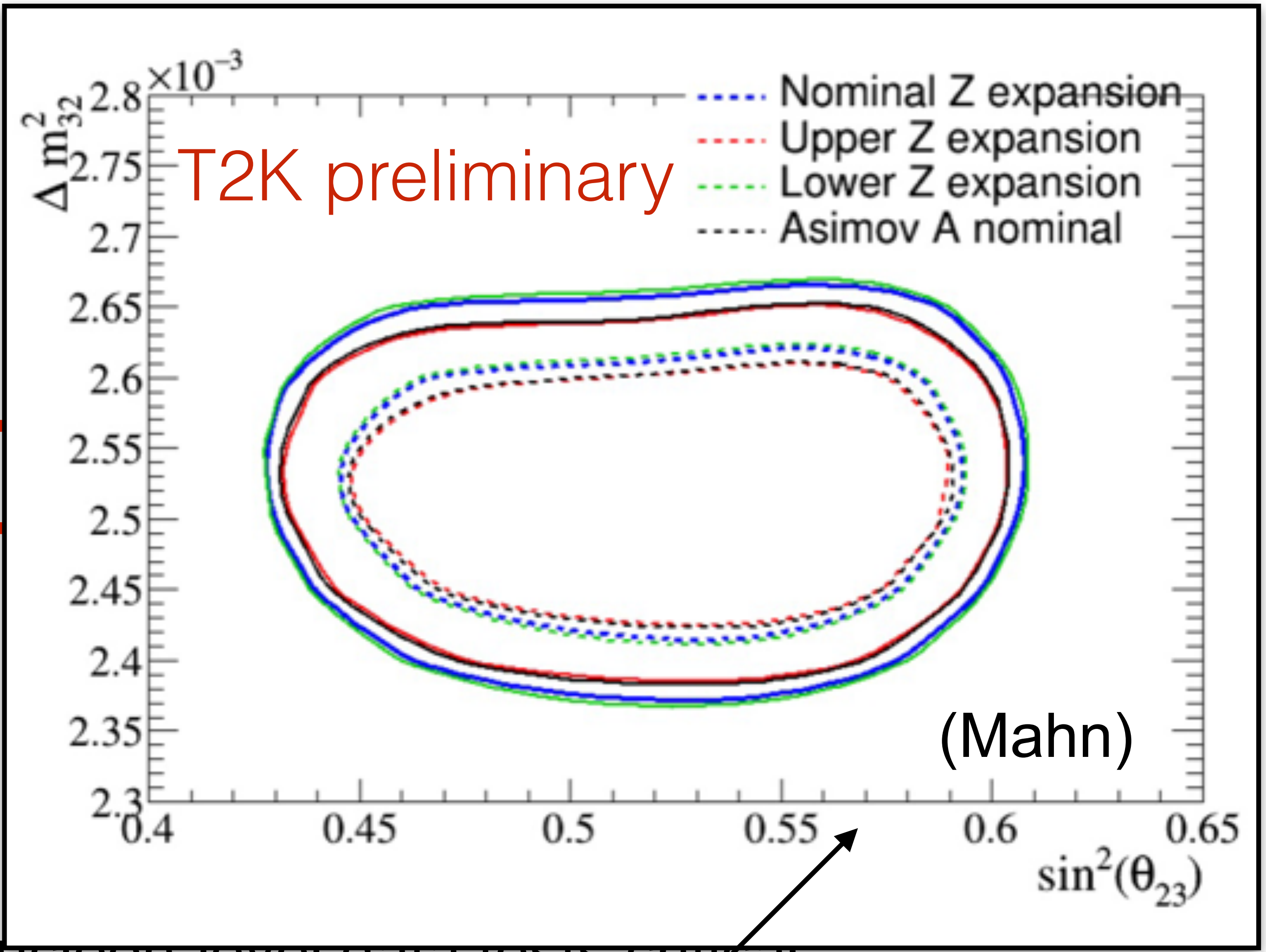

(Mahn)

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Three levels (at least) of answer

(iii) the whole shebang

A complete and quantitative answer requires a complete and quantitative nuclear model.

- need to break the circle: improving nuclear models requires better knowledge of the nucleon level amplitudes.

- the questions

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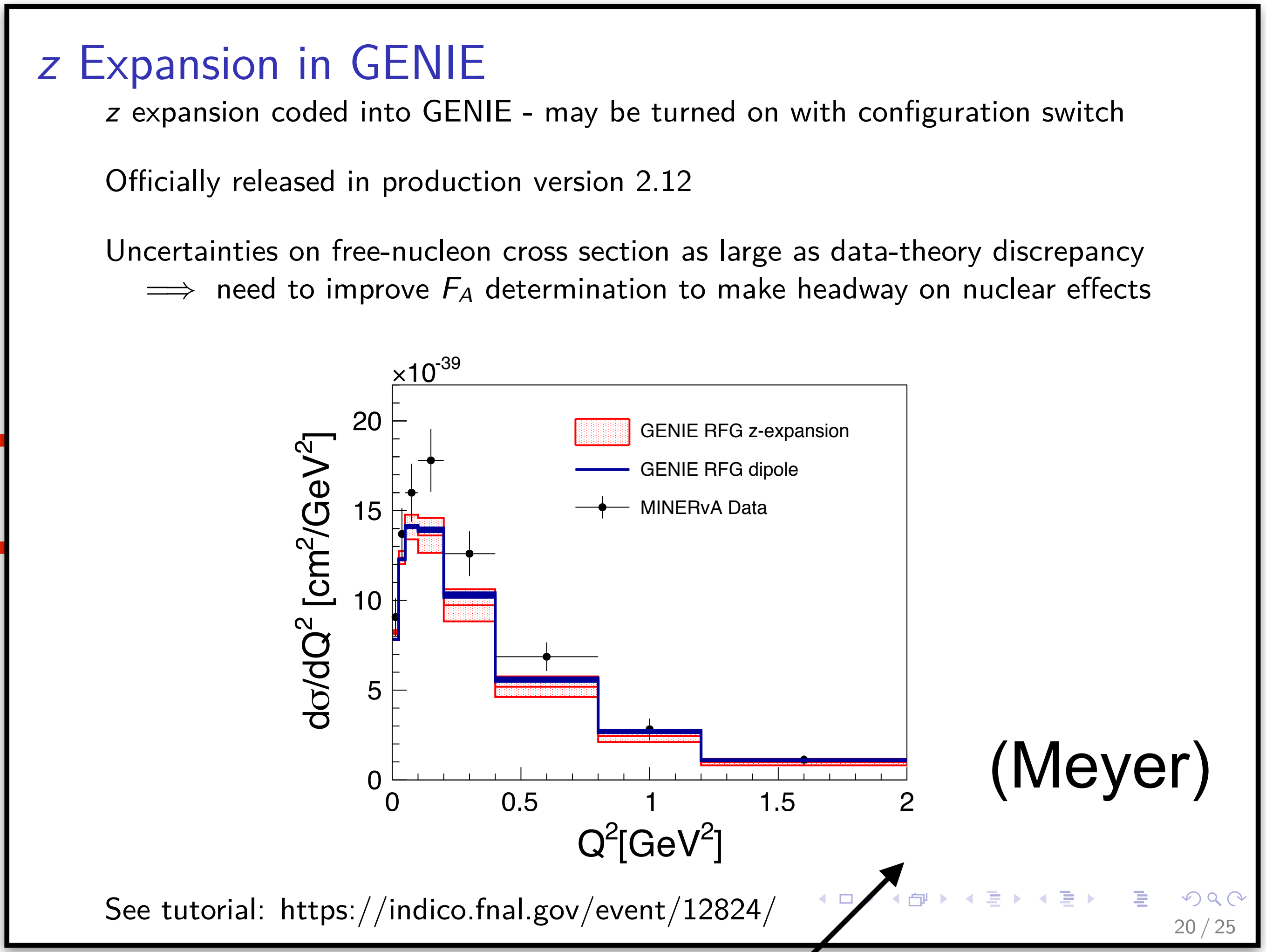

z Expansion in GENIE

z expansion coded into GENIE - may be turned on with configuration switch

Officially released in production version 2.12

Uncertainties on free-nucleon cross section as large as data-theory discrepancy
$\Longrightarrow$ need to improve F_A determination to make headway on nuclear effects

See tutorial: https://indico.fnal.gov/event/12824/

(Meyer)

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- closing thoughts

  - our knowledge of elementary amplitudes is rudimentary

  - our ignorance impacts neutrino and non-neutrino processes, long and short baseline, SM measurements and BSM searches, quasielastic and inelastic scattering

  - difficult but important measurements are obvious targets at future neutrino facilities

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THANKS!