

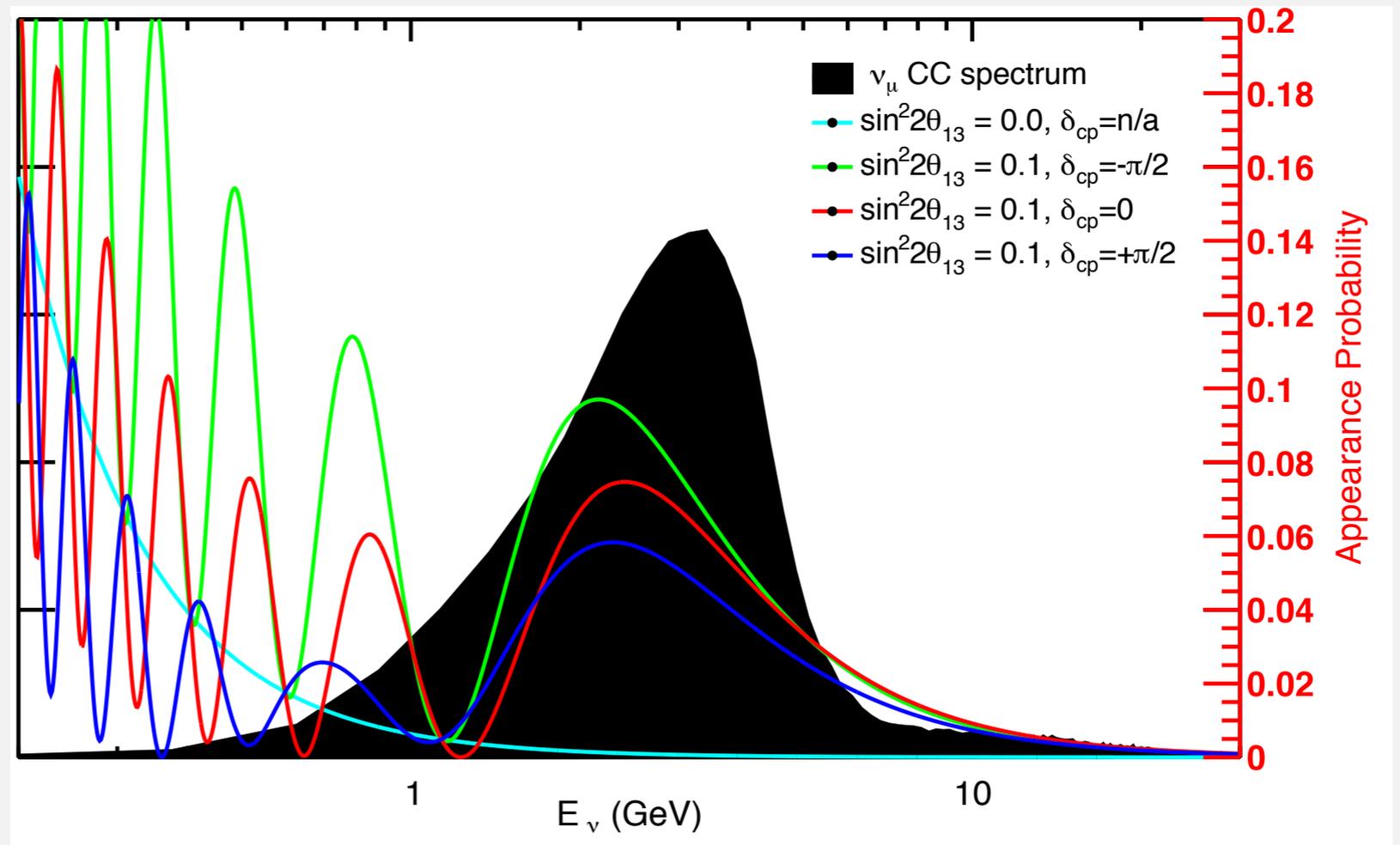
# Elementary amplitudes from and for neutrino interactions

RICHARD HILL, U. Kentucky and Fermilab

**PONDD, 3 December 2018**

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

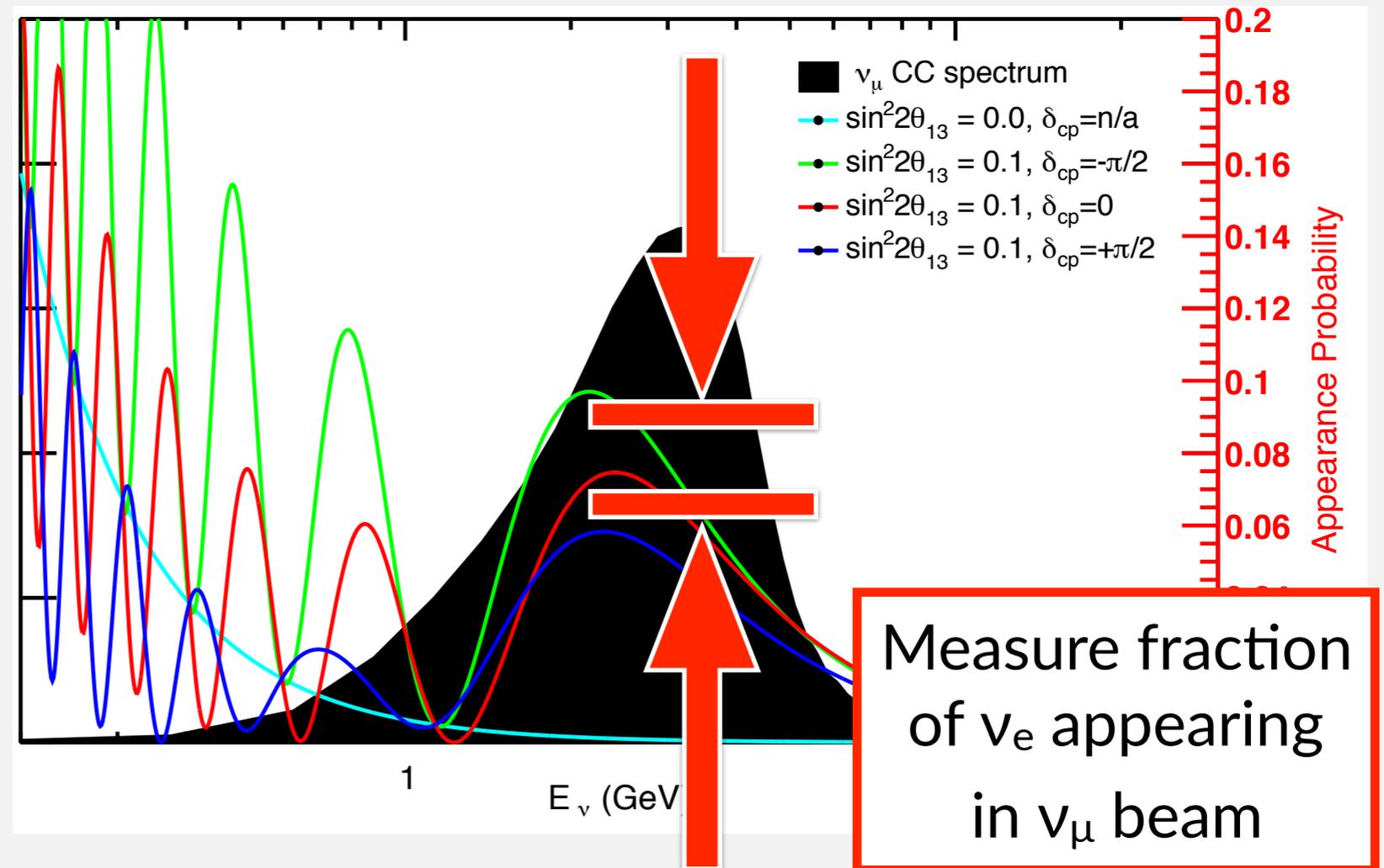
$\nu_e$  appearance  
from a  $\nu_\mu$  beam



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

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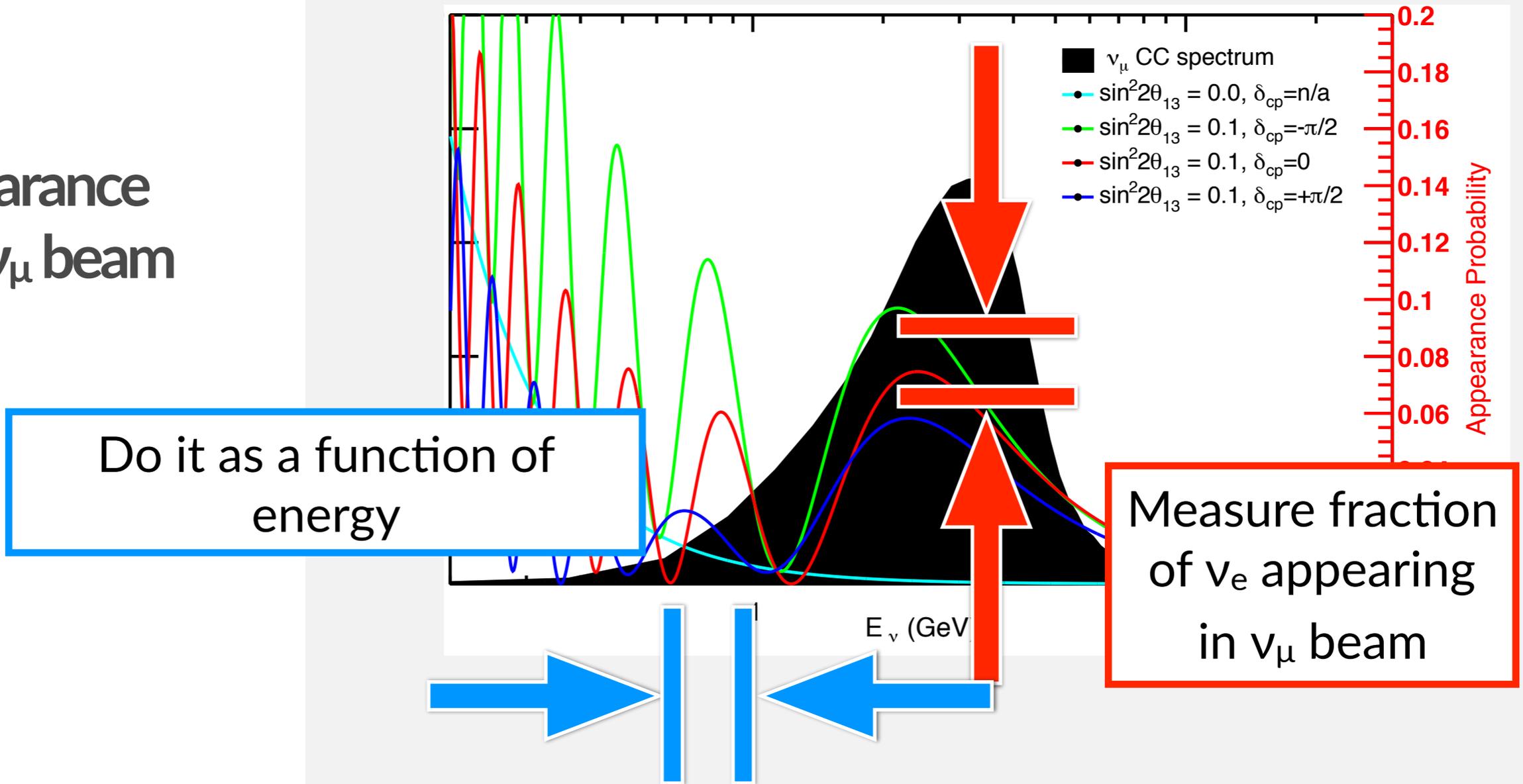
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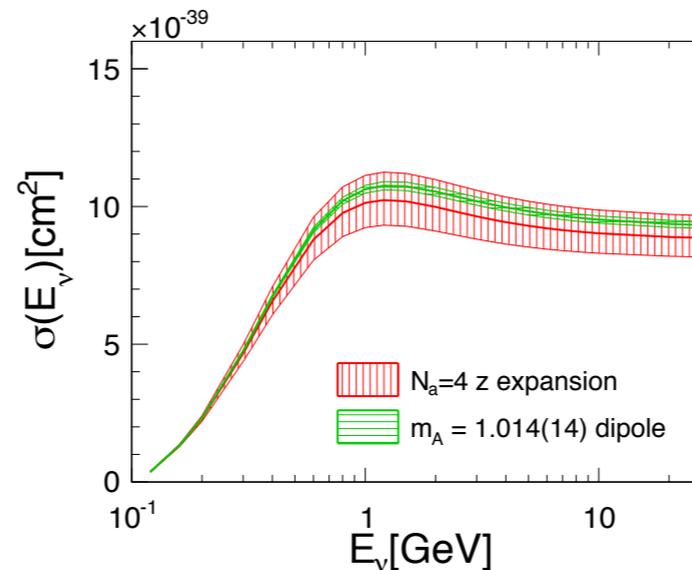
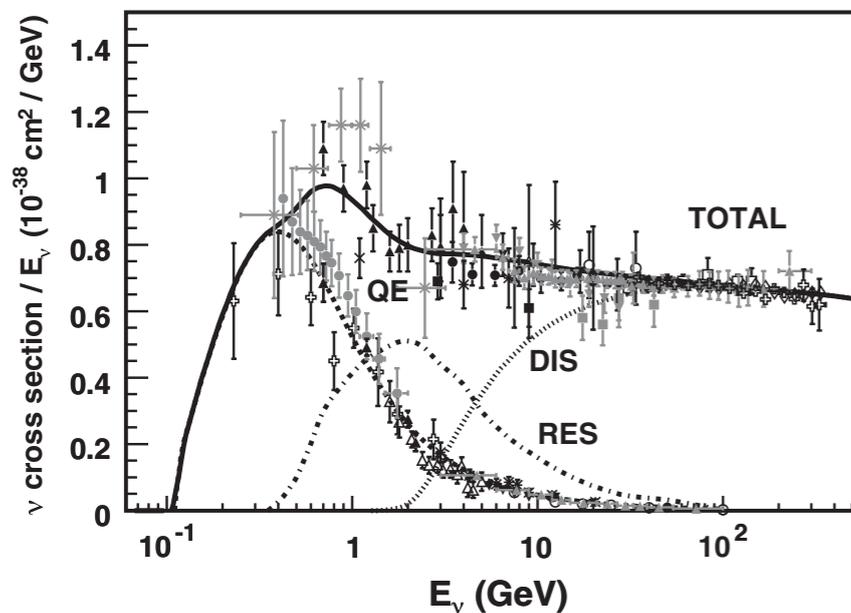
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but **difficult in practice**: rely on theory to determine cross sections: e.g.  $\sigma(\nu_e)/\sigma(\nu_\mu)$  to a precision of 1%

# Important questions in the 3 flavor paradigm

- limits on achievable precision due to neutrino interaction uncertainties



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

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

current knowledge of nucleon level CCQE cross section based on  $\sim 3.5k$  events

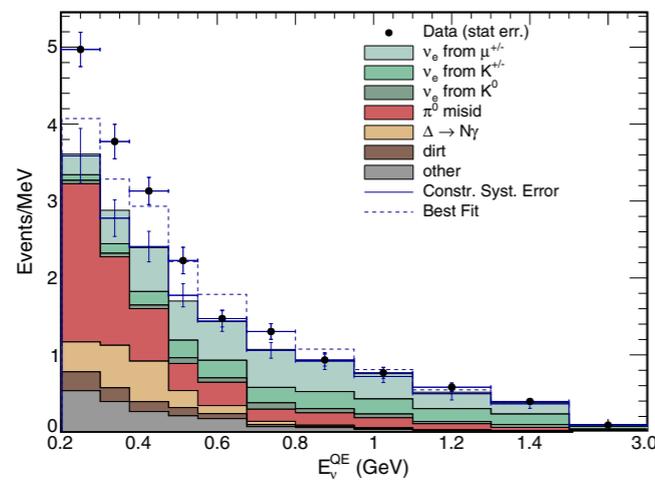
$$\delta\sigma_{\text{CCQE}} \lesssim 5\% \implies \sim 7k \text{ CCQE events}$$

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

# Important questions beyond the 3 flavor paradigm

- **short baseline anomalies**

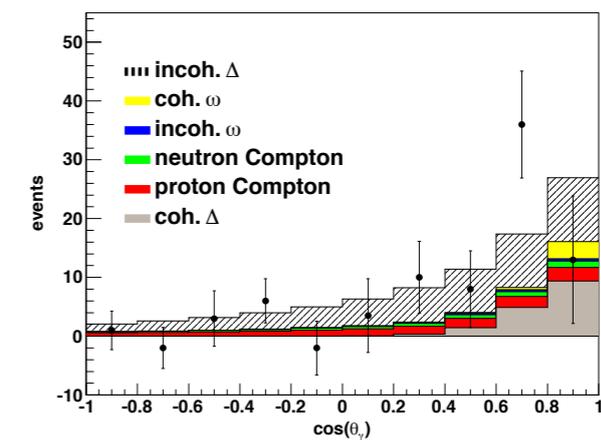
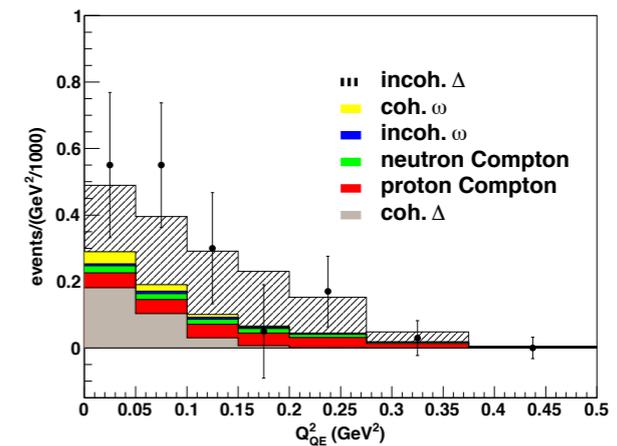
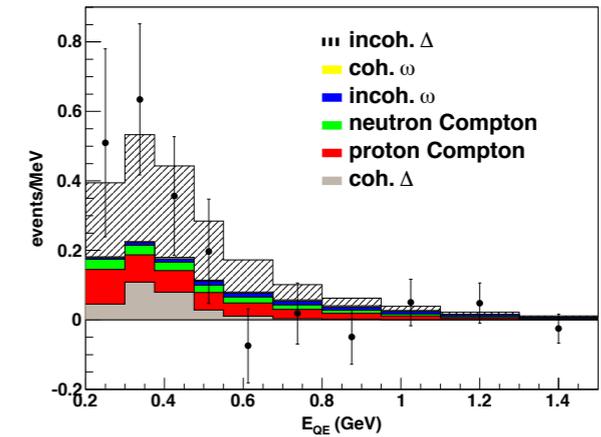
SM backgrounds to MiniBooNE excess



*MiniBooNE PRL 121, 221801 (2018)*

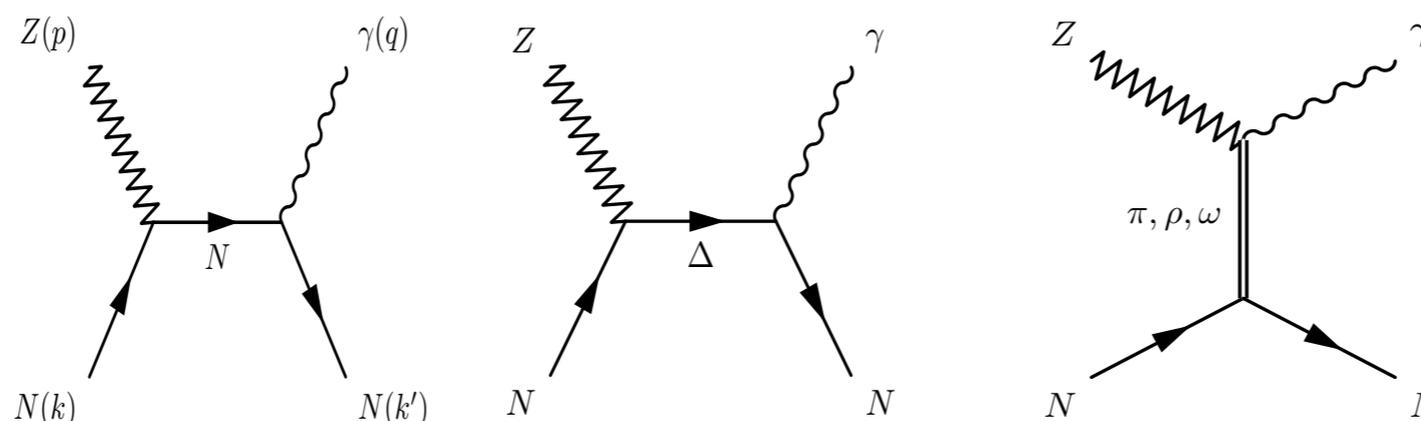
In the MiniBooNE detector, CC signal degenerate with NC single photon background

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

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

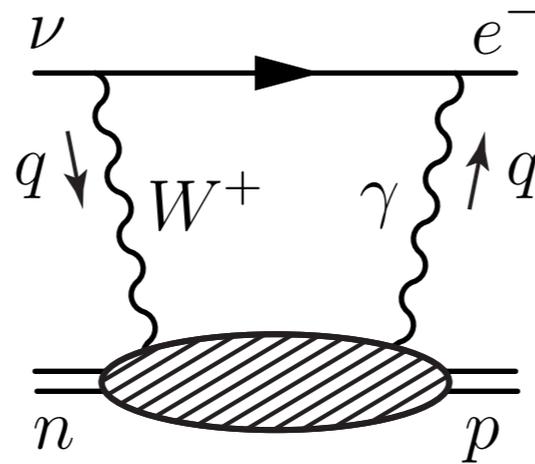
$$\delta\sigma_{1\gamma} \lesssim 10\% \implies \mathcal{O}(100k) \text{ CCQE events}$$

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

# Important questions beyond neutrinos

- **BSM signals and constraints beyond neutrinos**

$V_{ud}$  and CKM unitarity

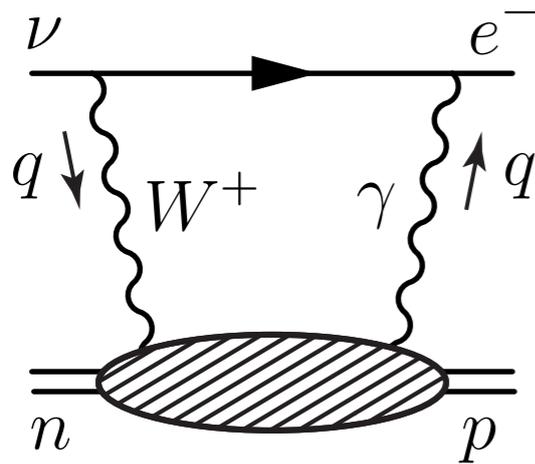


A key radiative correction to neutron and nuclear beta decay is sensitive to nucleon structure

Recent reanalysis of this correction implies  $> 4\sigma$  violation of CKM unitarity

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

*Seng, Gorchtein, Patel, Ramsey-Musolf, 1807.10197*



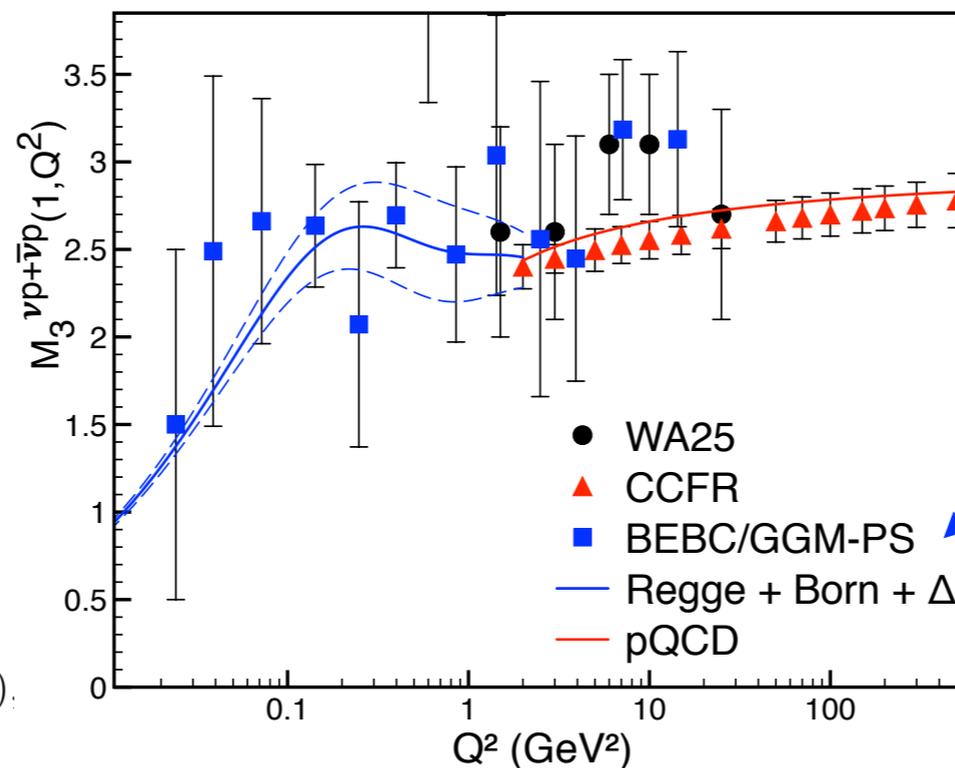
Inaccessible to electron scattering, but related (via isospin) to forward neutrino scattering and (via dispersion relation) to neutrino-nucleon cross sections

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*

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



~3k events

relevant sample on nucleon target:

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

# Important questions beyond neutrinos

- **precision measurements**

$r_A$  puzzle

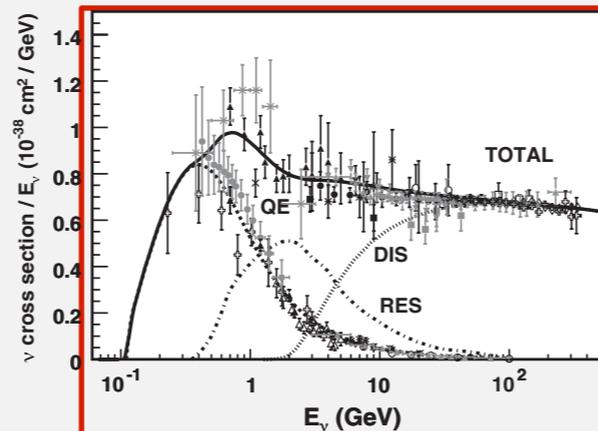
[ Aside: can we phrase the neutrino-nucleus scattering problem in standard form?

- 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

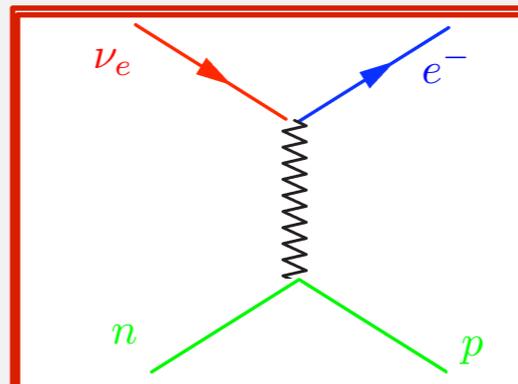
We're still trying to arrive at this standard form. Regardless,  $r_A$  is likely to be in the final set.

 ]

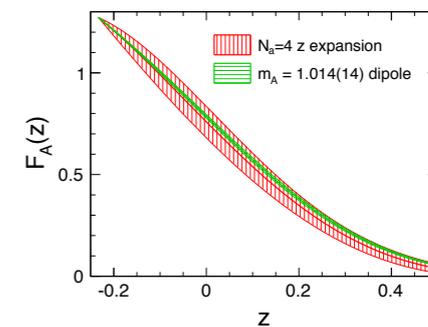
# A critical number: the nucleon axial radius



quasi elastic (QE)  
dominance

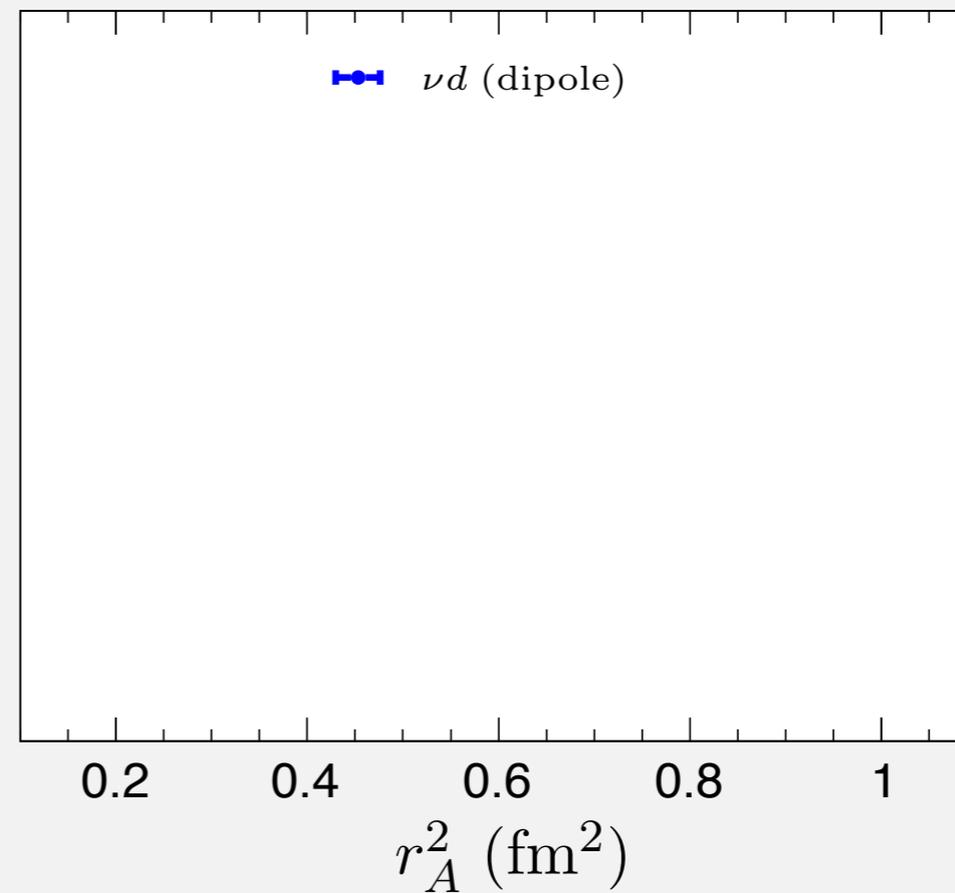


nucleon form  
factors for QE  
process



linear dependence  
of form factors on  
kinematics

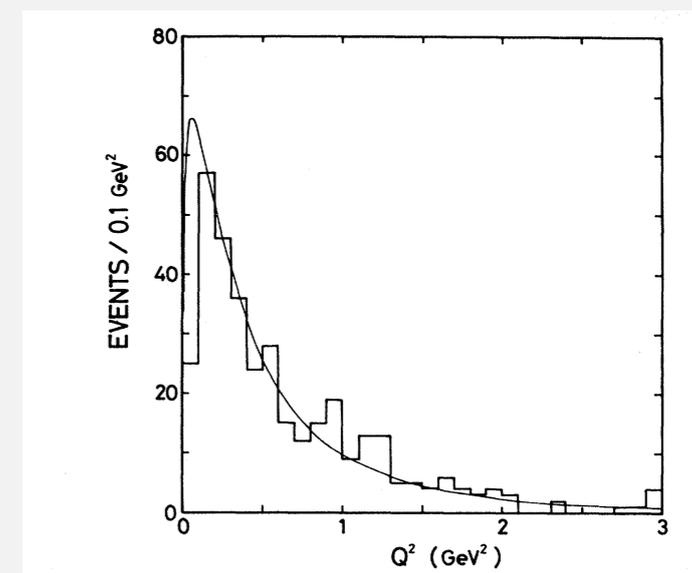
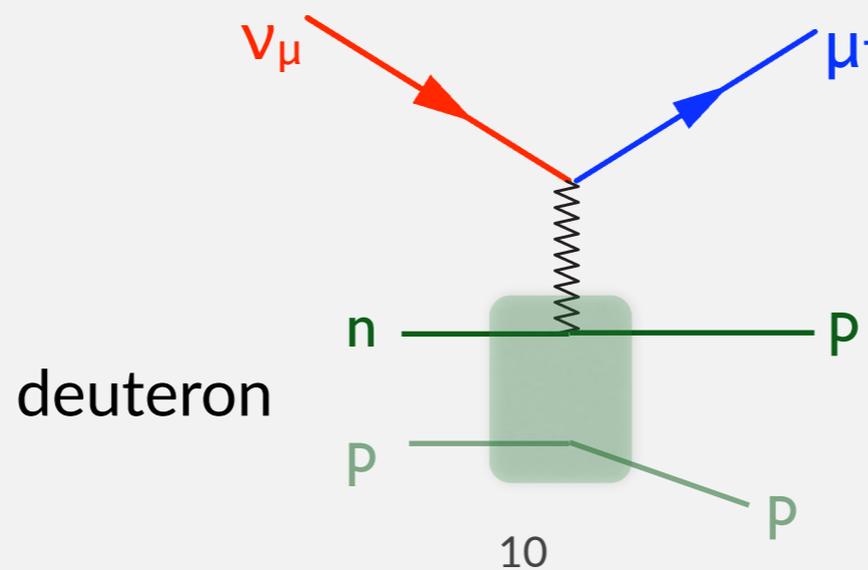
What do we know about this critical number?



BNL 1981  
ANL 1982  
Fermilab 1983

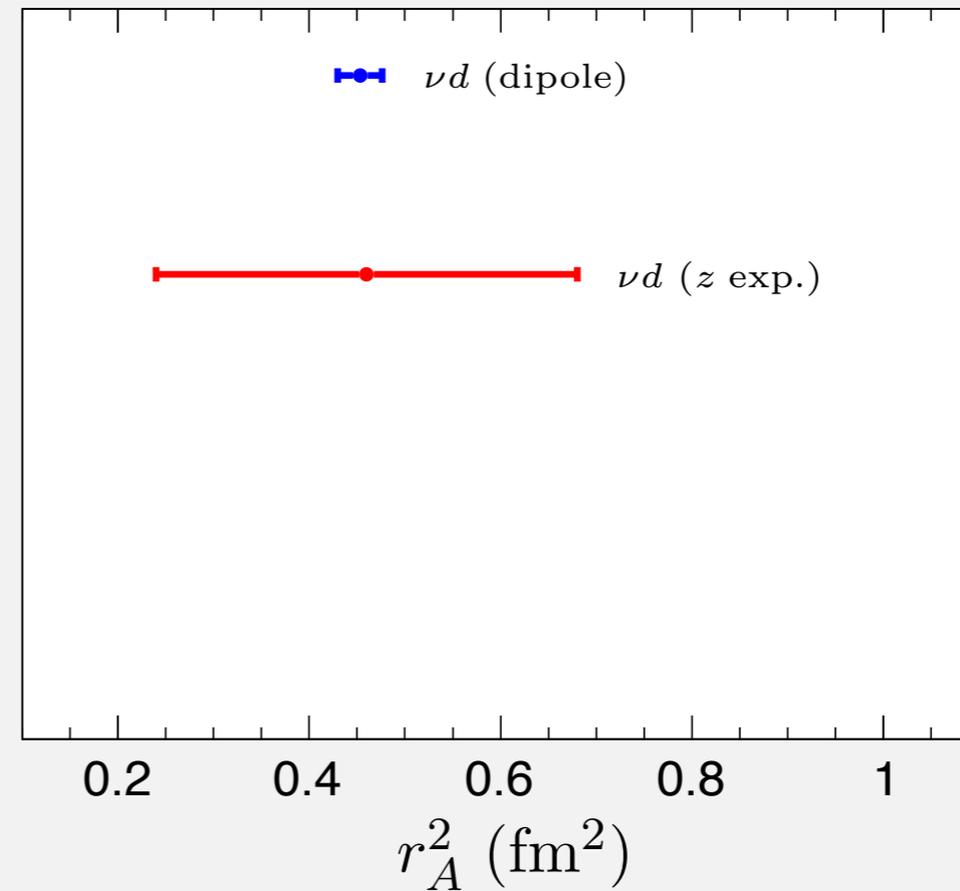
The number seemed uncontroversial for decades:

*extracted from deuterium bubble chamber data*



*Kitigaki et al. PRD 28, 436 (1983)*

## What do we know about this critical number?



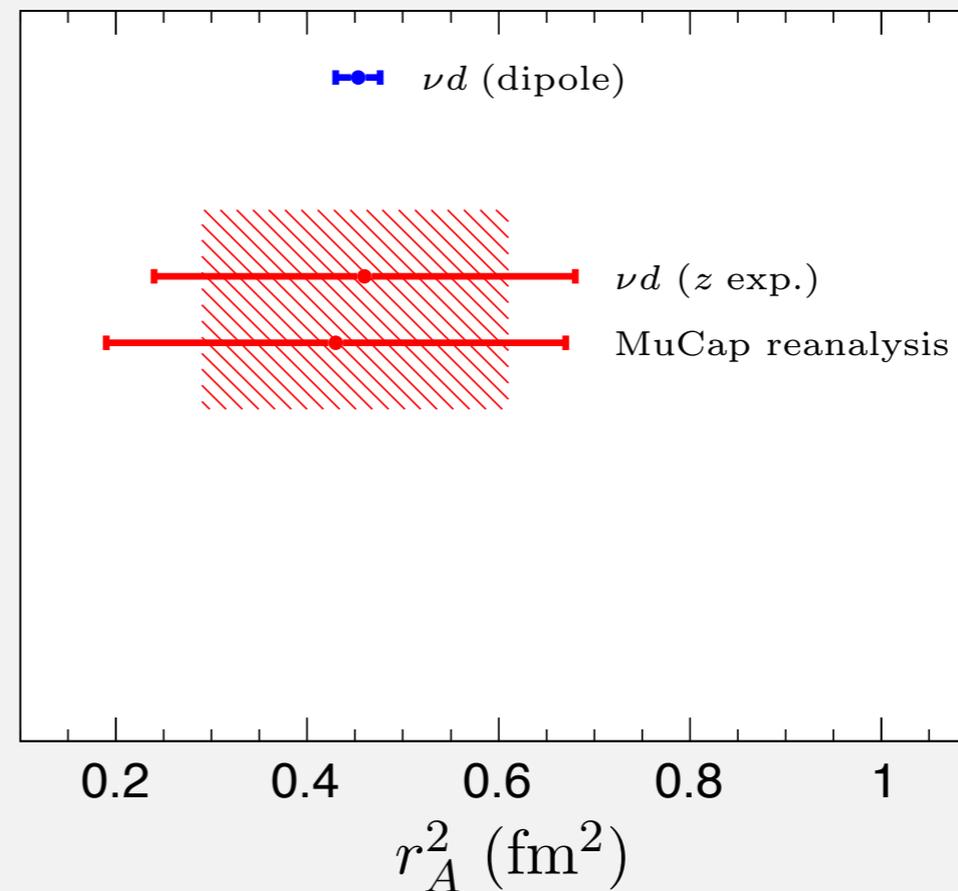
In fact the extraction relied on a hidden model assumption, and the true uncertainty is an order of magnitude larger

*Bhattacharya, RJH, Paz 2011*

*Meyer, Betancourt, Gran, RJH 2016*

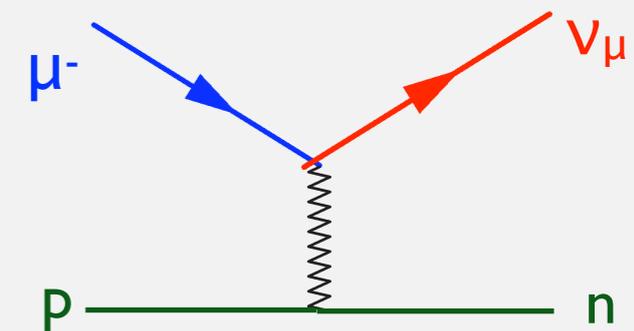
*Introduces a  $\approx 10\%$  uncertainty in every neutrino-nucleus cross section. A wrench in the works for oscillation experiments.*

## What do we know about this critical number?



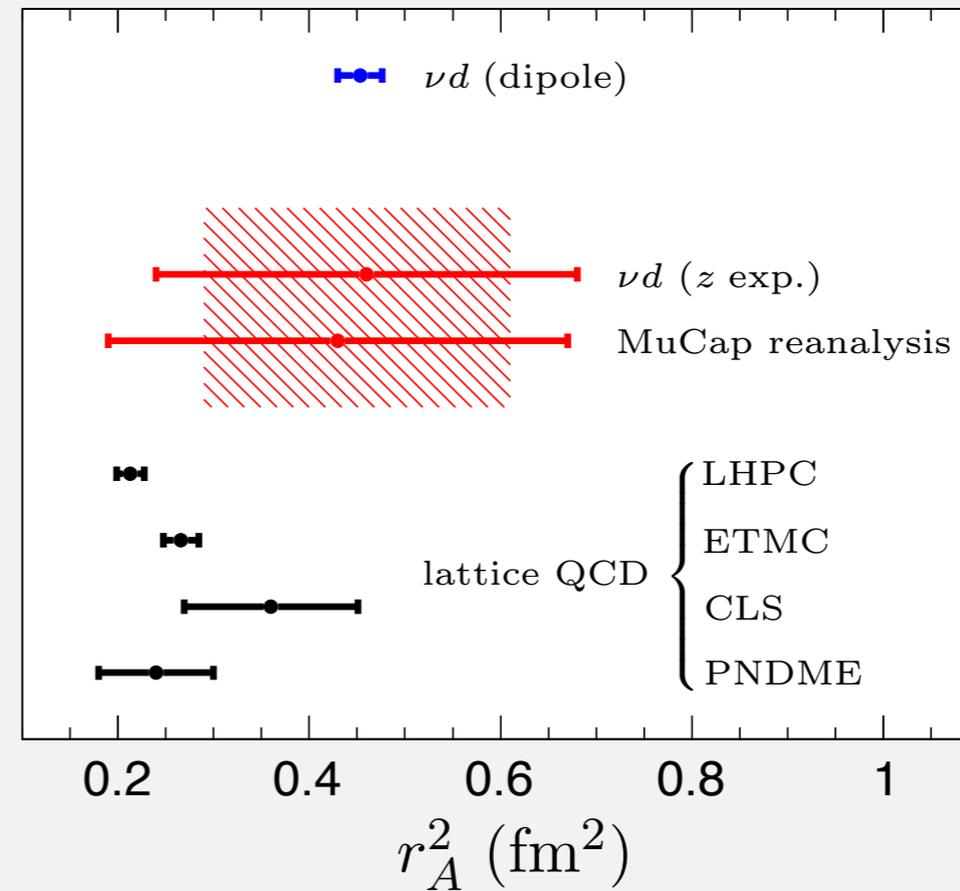
*Look at the process in reverse: muon capture from ground state of muonic hydrogen*

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



*RJH, Kammel, Marciano, Sirlin 2017*

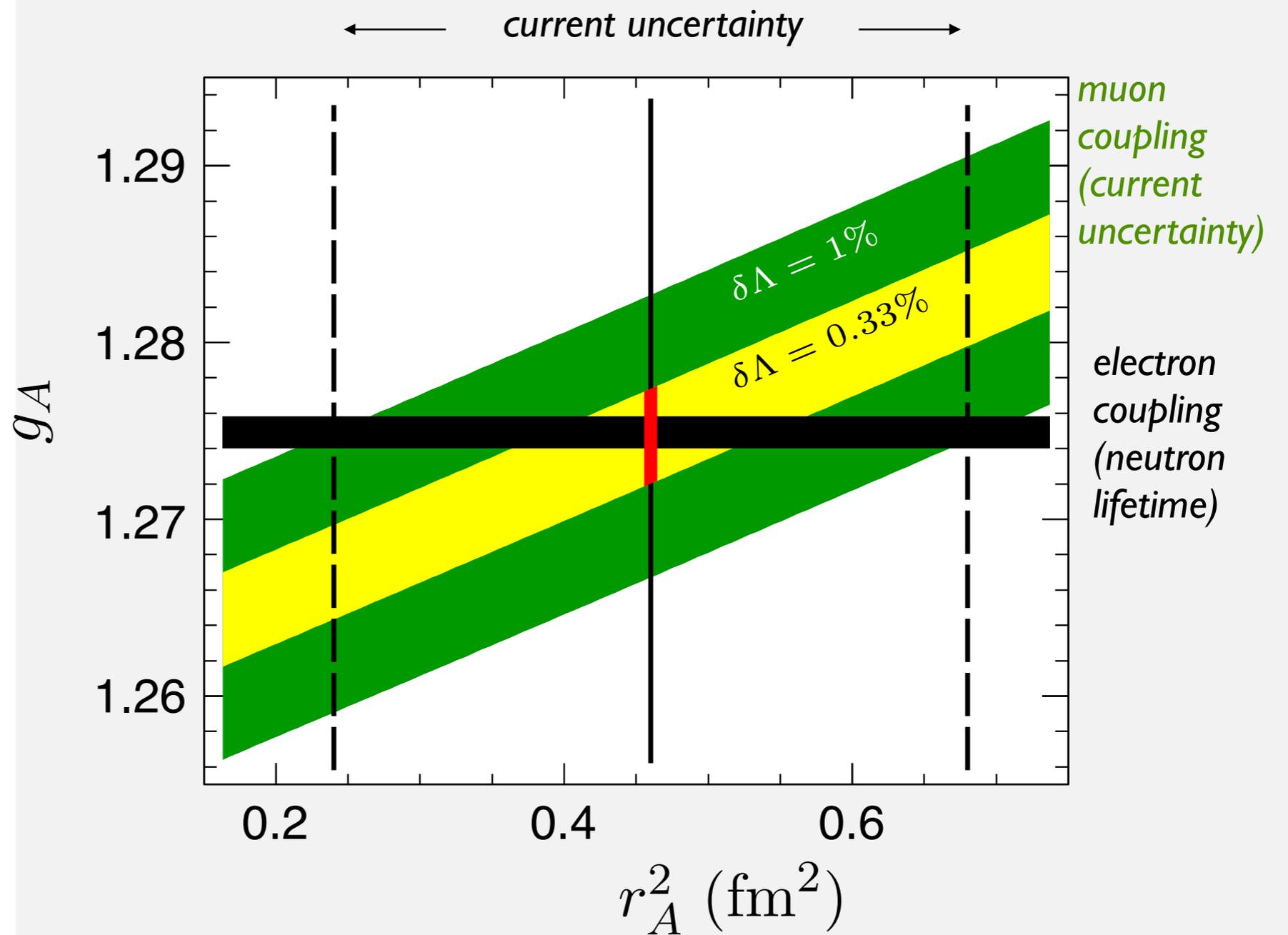
What do we know about this critical number?



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

$\sim 5\sigma$  discrepancy between blue point and black points

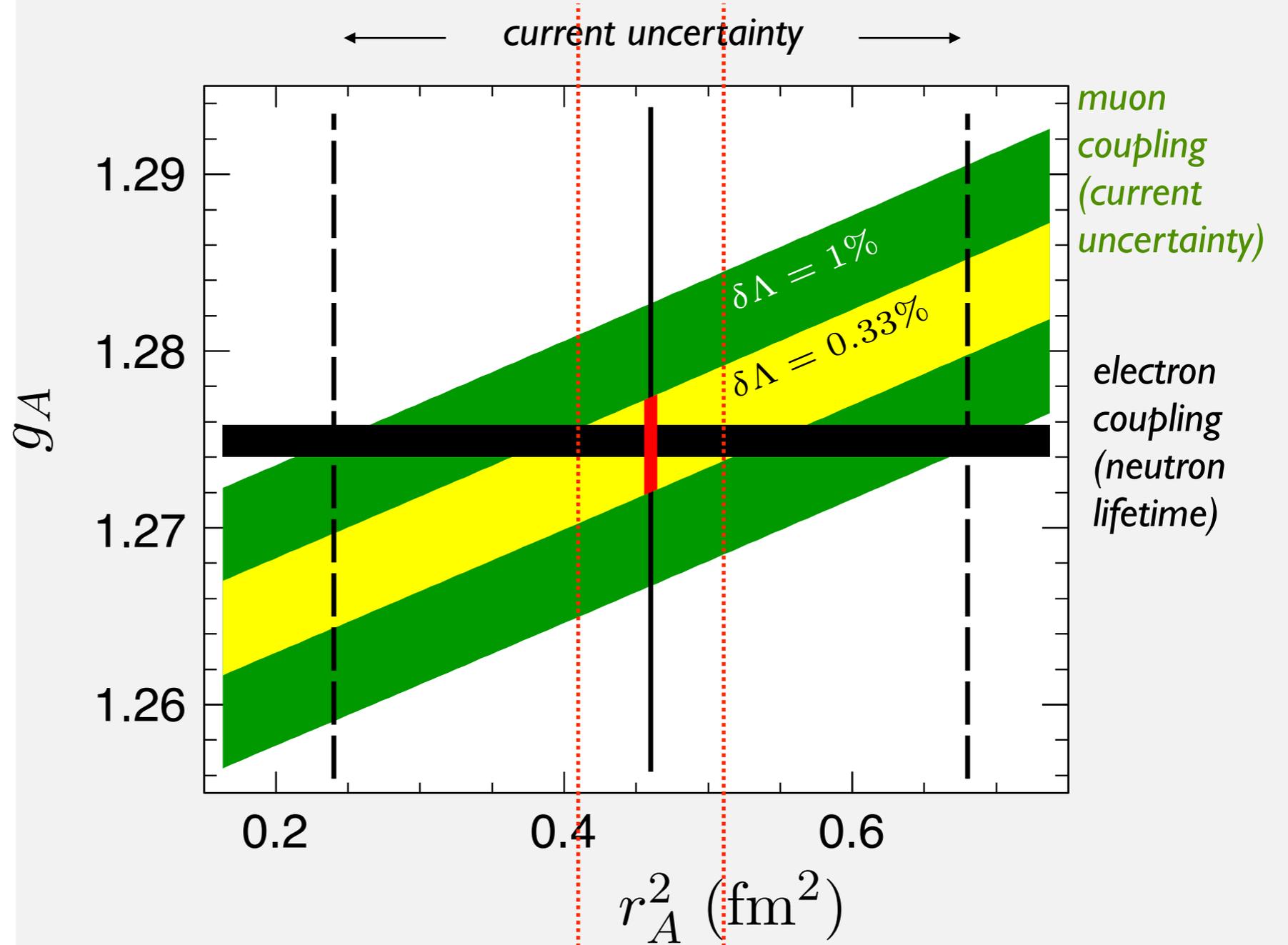
**Complementarity  
between  $r_A$   
constraints from  
different processes**



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

current :  $\delta(r_A^2) = 50\%$

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current :  $\delta(r_A^2) = 50\%$

e.g.  $\delta(r_A^2) = 10\% \Rightarrow \sim 30k$  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](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](mailto: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:  $\nu N \rightarrow \ell N$ ,  $eN \rightarrow eN$ ,  $N \rightarrow N\pi$ ,  $N \rightarrow X$ ,  $NN \rightarrow NN$ , 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

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(2) what do we need to 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.*

- the questions

(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  $v_\mu/v_e$  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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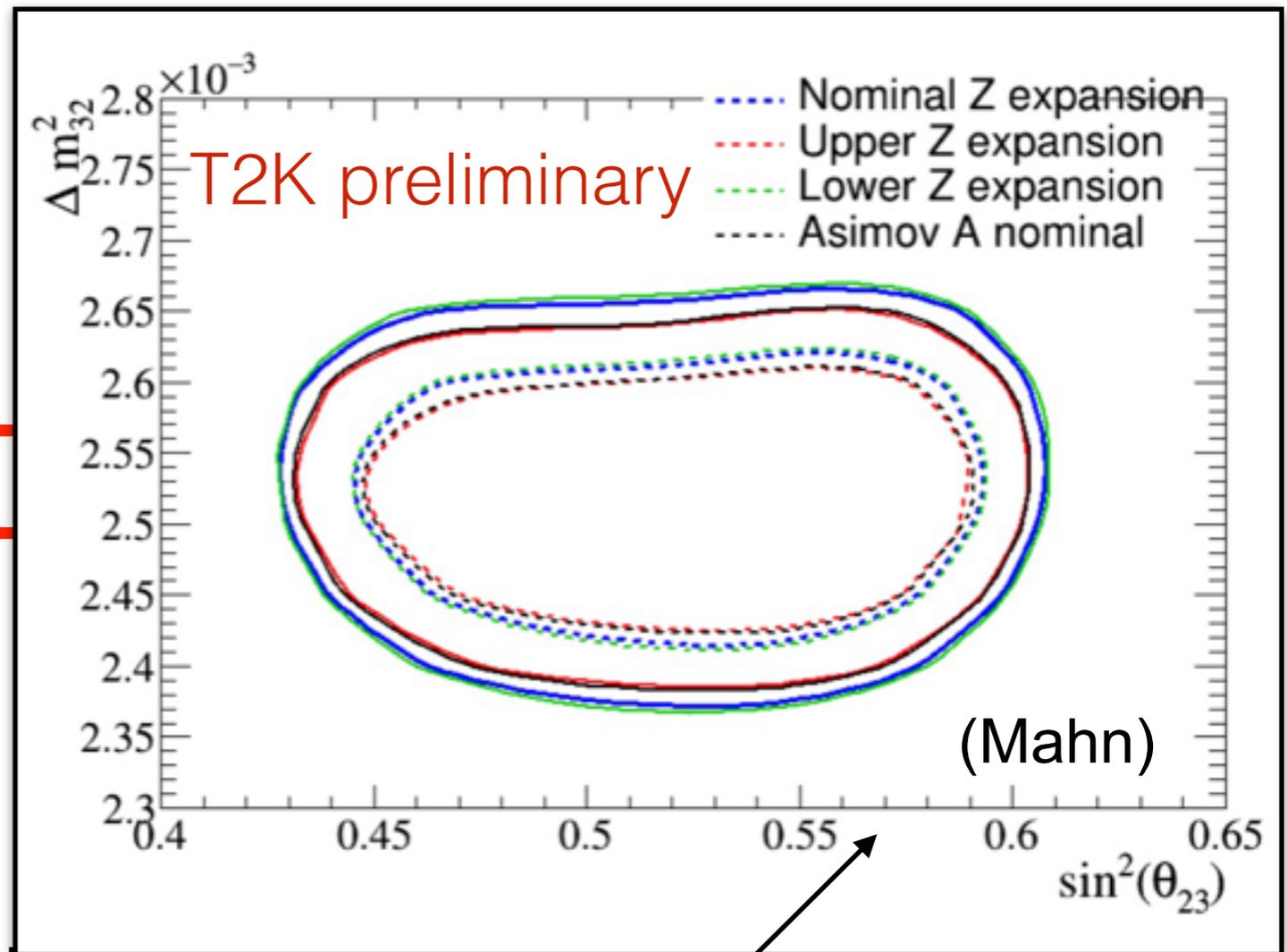
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Three levels (at least) of answer

(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.

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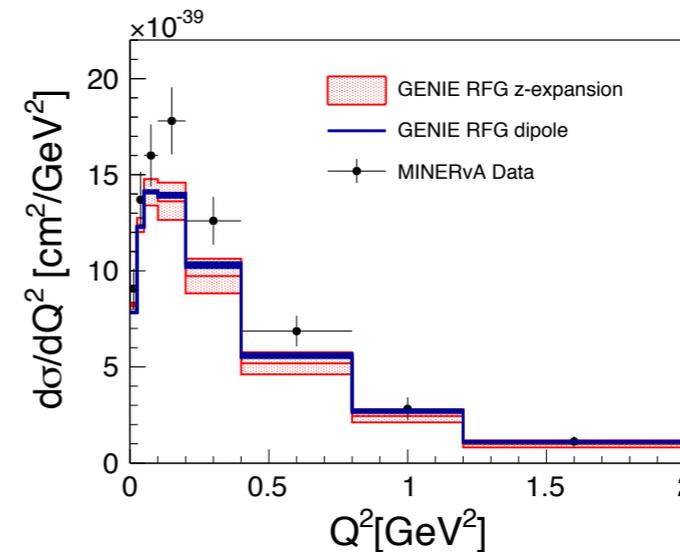
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### z Expansion in GENIE

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  
⇒ need to improve  $F_A$  determination to make headway on nuclear effects



(Meyer)

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

- 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!**