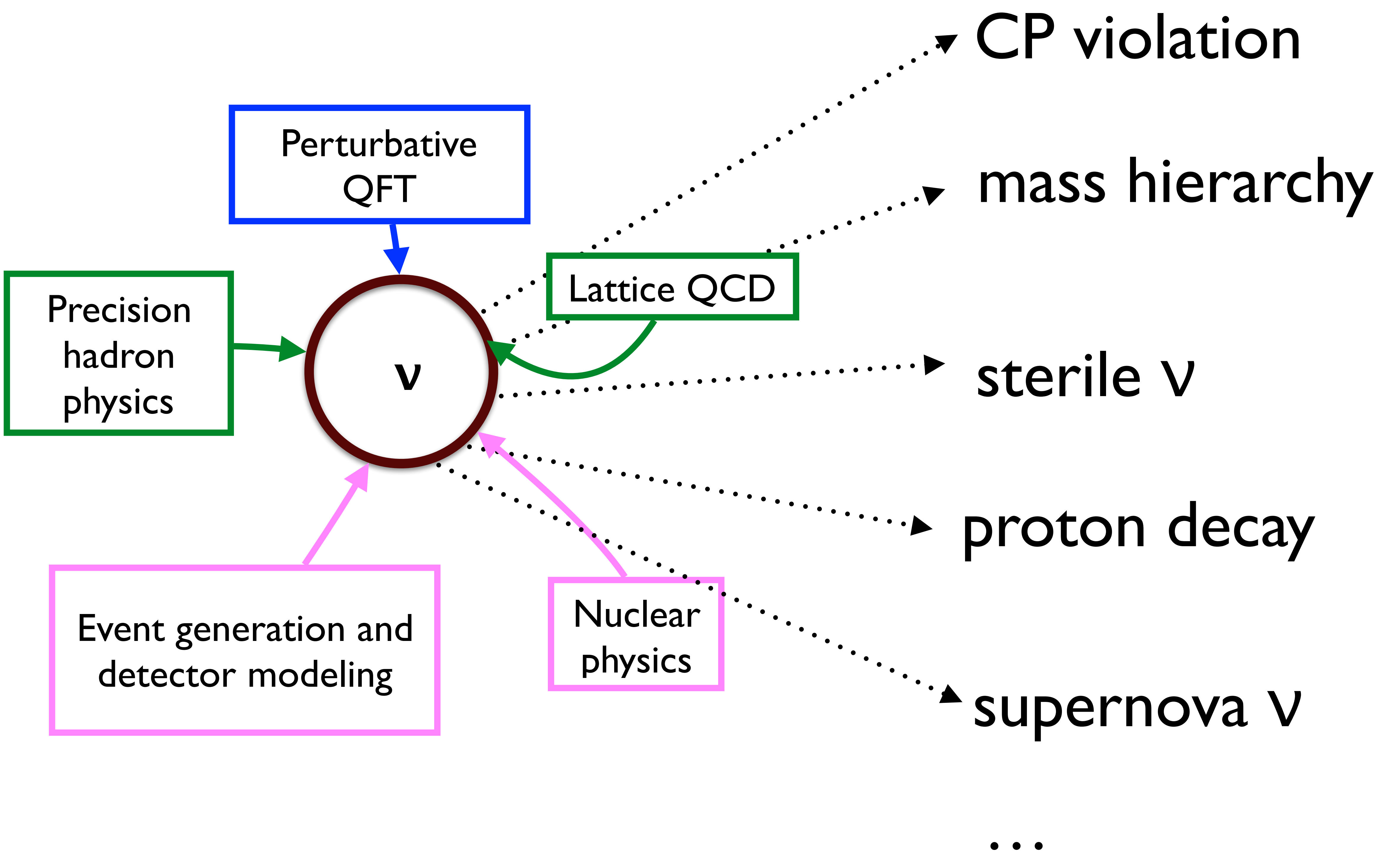
QCD and neutrino-nucleus cross sections

RICHARD HILL

TRIUMF & Perimeter Institute & U. Chicago

Fermilab grassroots discussion
15 March 2016

QCD in many regimes critical to extracting fundamental physics in the neutrino sector



Neutrino-nucleus grassroots points for discussion

1) HEP should take ownership

- critical for assessing sensitivity and establishing discovery
- HEP tools are critical (QCD analysis, radiative corrections, lattice, …)
- broader context of intensity frontier searches and measurements

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2) Connections with nuclear theory and generator/modeling

- connection goes both ways

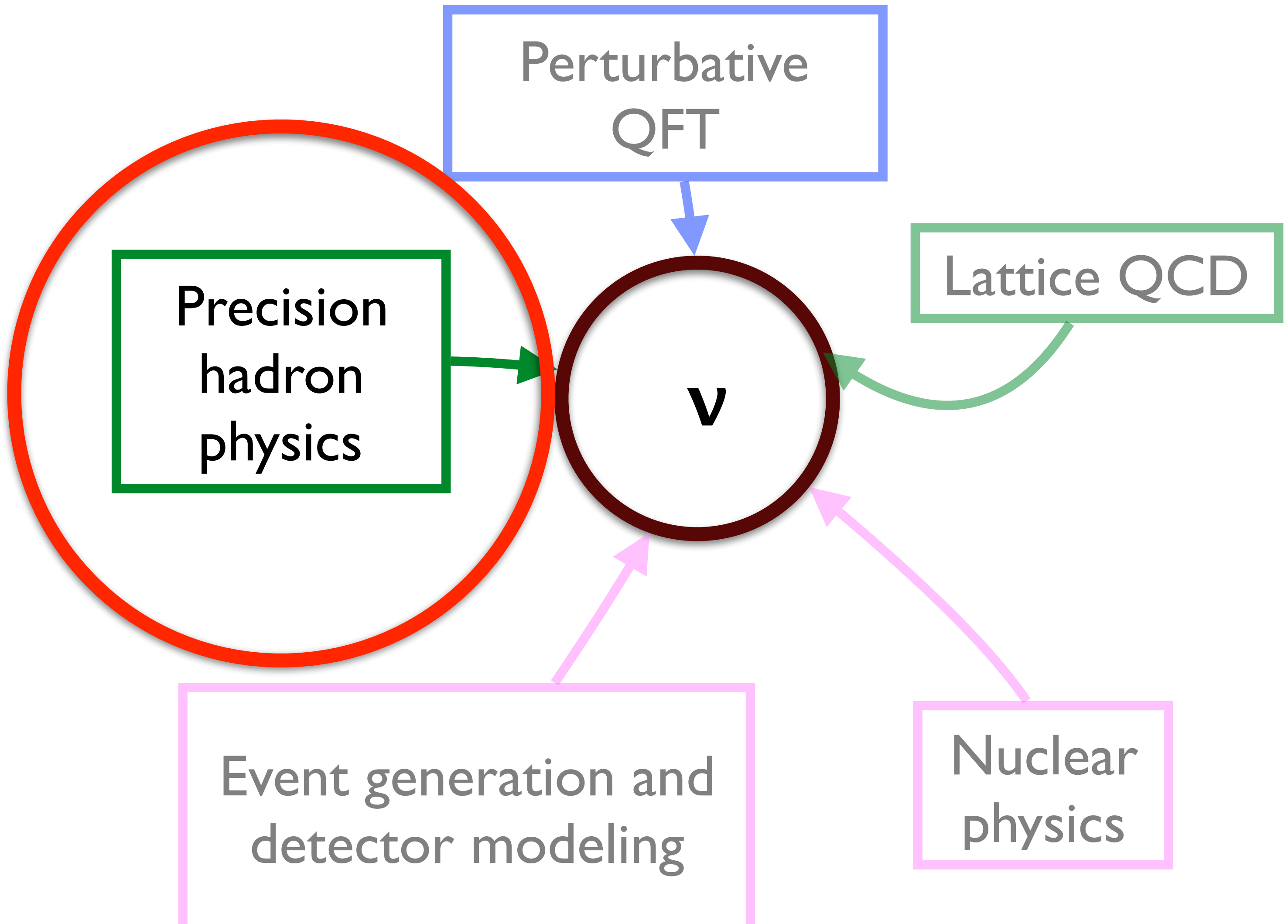
- two paradigms

  1) determine elementary (NN, NΔ, NNπ,…) amplitudes (elementary targets, lattice, …) then constrain nuclear models from data

  2) determine elementary amplitudes (elementary targets, lattice, …) then compute nuclear effects "ab initio"

- critical to have realistic assessment of error bars from all sources

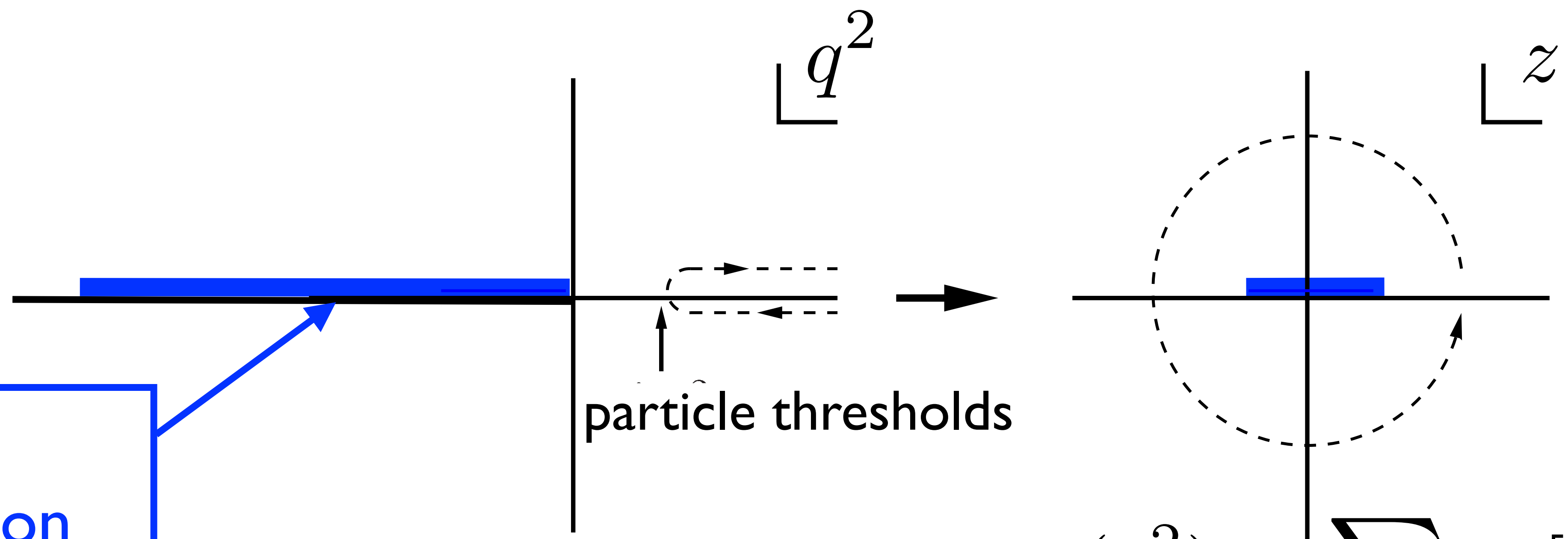
example 1: CCQE and the nucleon axial form factor



Every neutrino-nucleus cross section prediction relies on nucleon-level amplitudes constrained by deuterium experiments of the 1970's, 80's, fit to simple models. What is the actual uncertainty?

HEP toolbox is being applied to precision lepton-nucleon scattering

Underlying QCD tells us that Taylor expansion in appropriate variable is rapidly convergent



experimental kinematic region

$$F(q^2) = \sum_k a_k [z(q^2)]^k$$

coefficients in rapidly convergent expansion encode nonperturbative QCD

Systematically improvable, quantifiable uncertainties

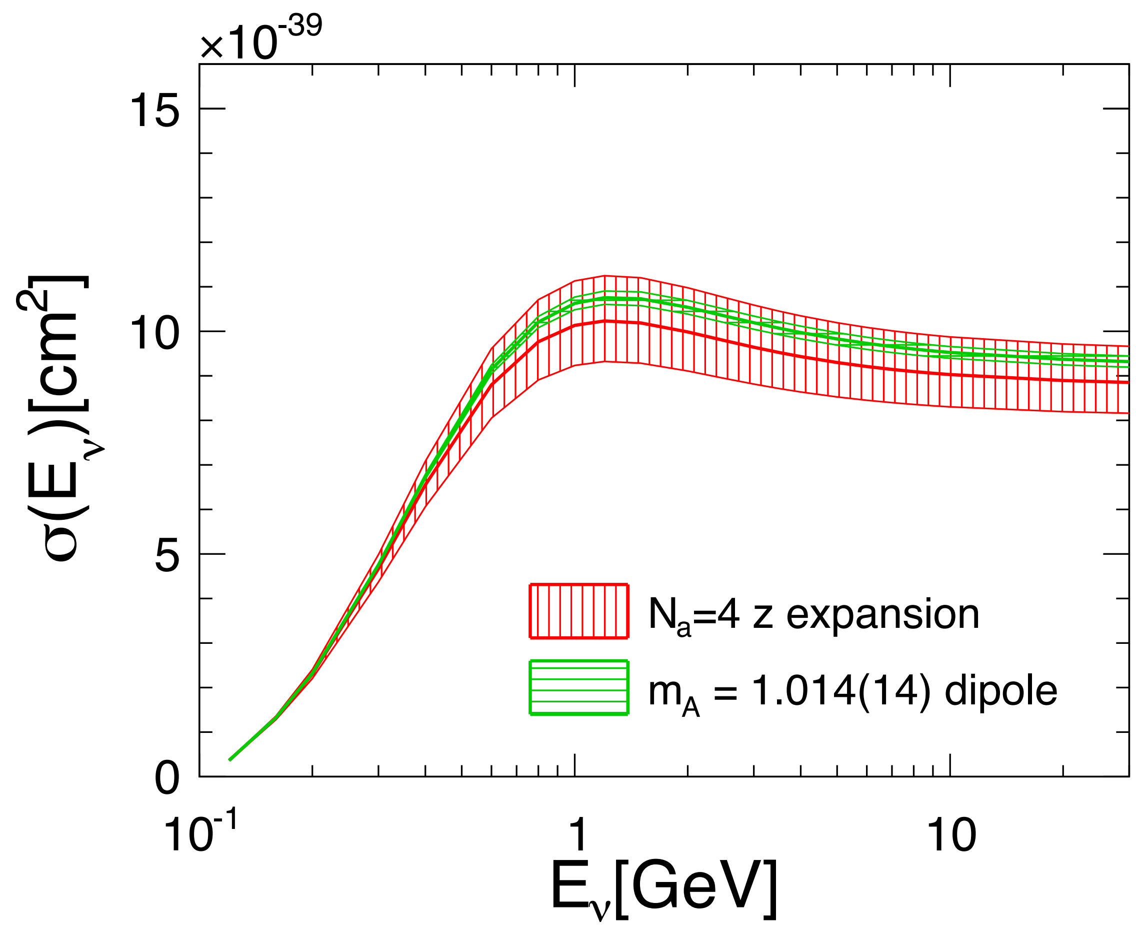
- F_A with complete error budget: *[Meyer, Betancourt, Gran, Hill, 1603.03048]*

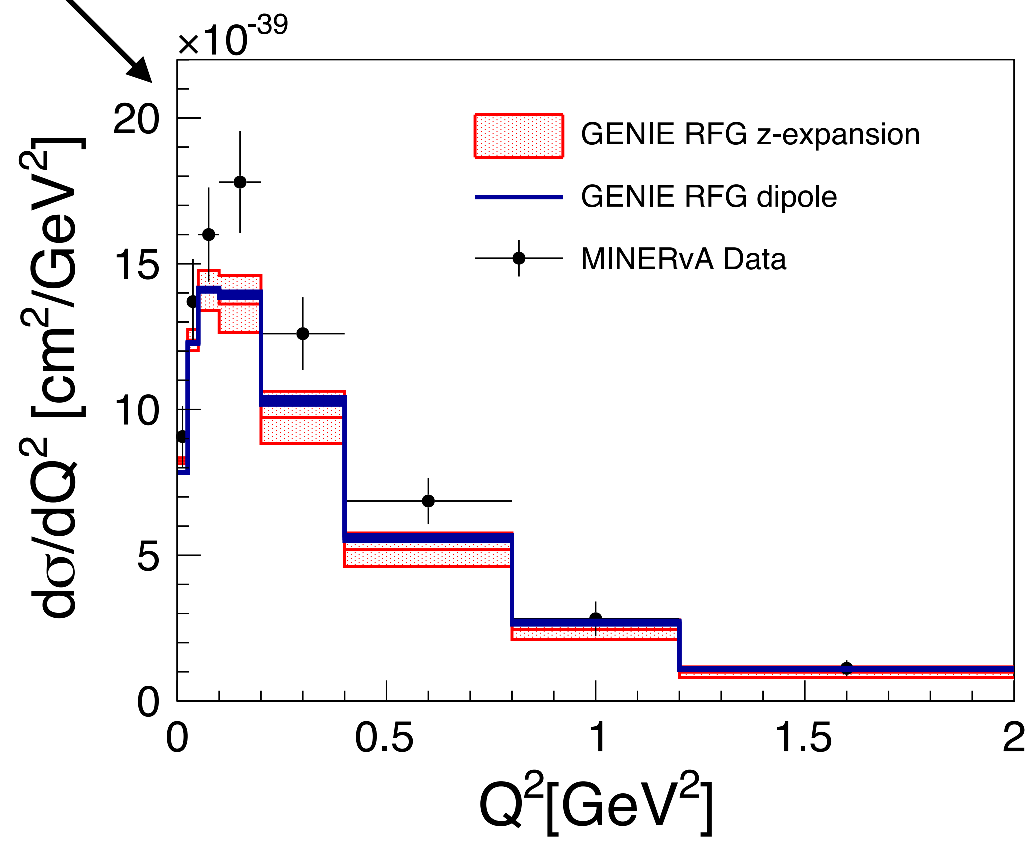
$$[a_1, a_2, a_3, a_4] = [2.30(13), -0.6(1.0), -3.8(2.5), 2.3(2.7)]$$

$$C_{ij} = \begin{pmatrix} 1 & 0.350 & -0.678 & 0.611 \\ 0.350 & 1 & -0.898 & 0.367 \\ -0.678 & -0.898 & 1 & -0.685 \\ 0.611 & 0.367 & -0.685 & 1 \end{pmatrix}$$

...

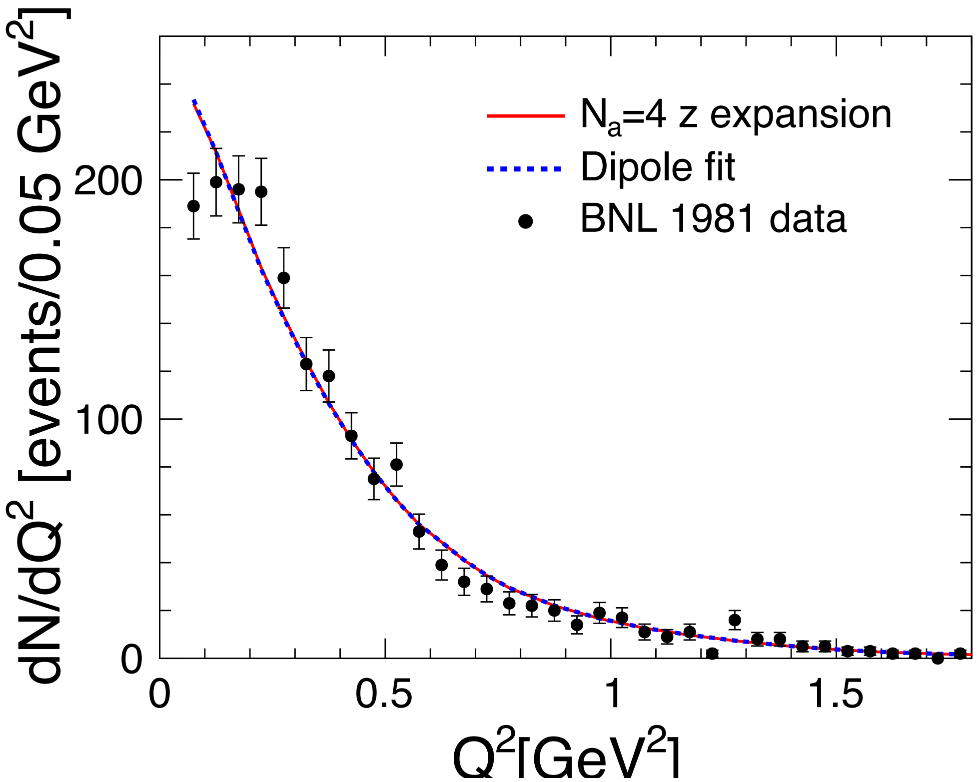
$$r_A^2 = 0.46(22)\ \mathrm{fm}^2$$

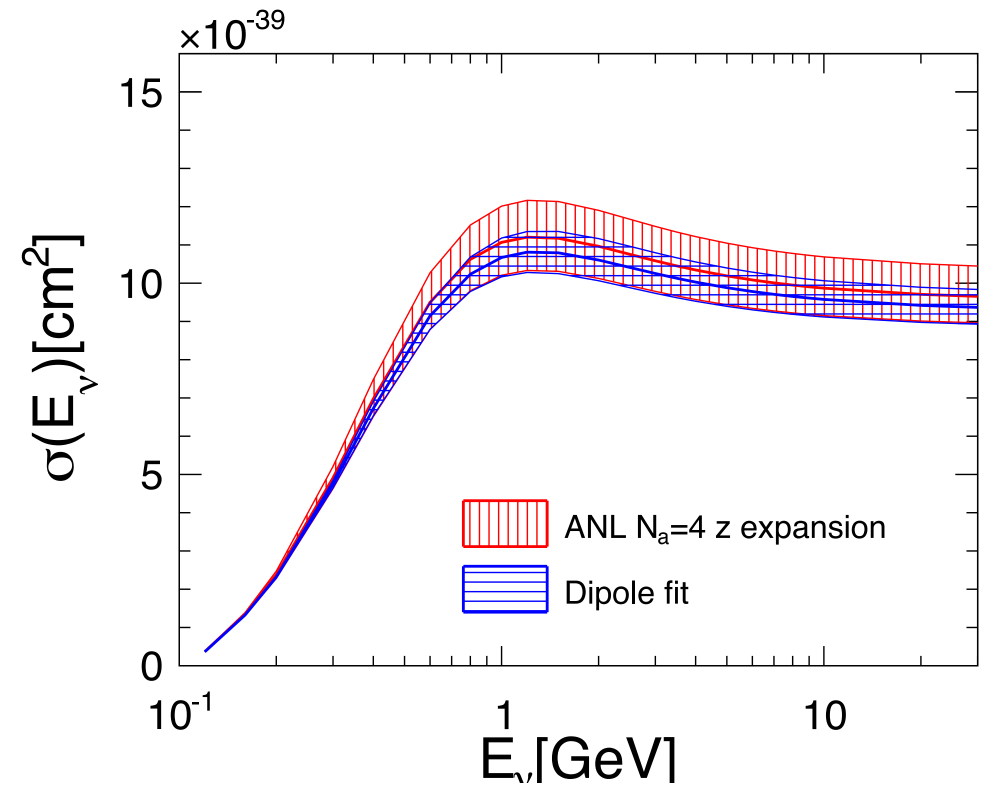


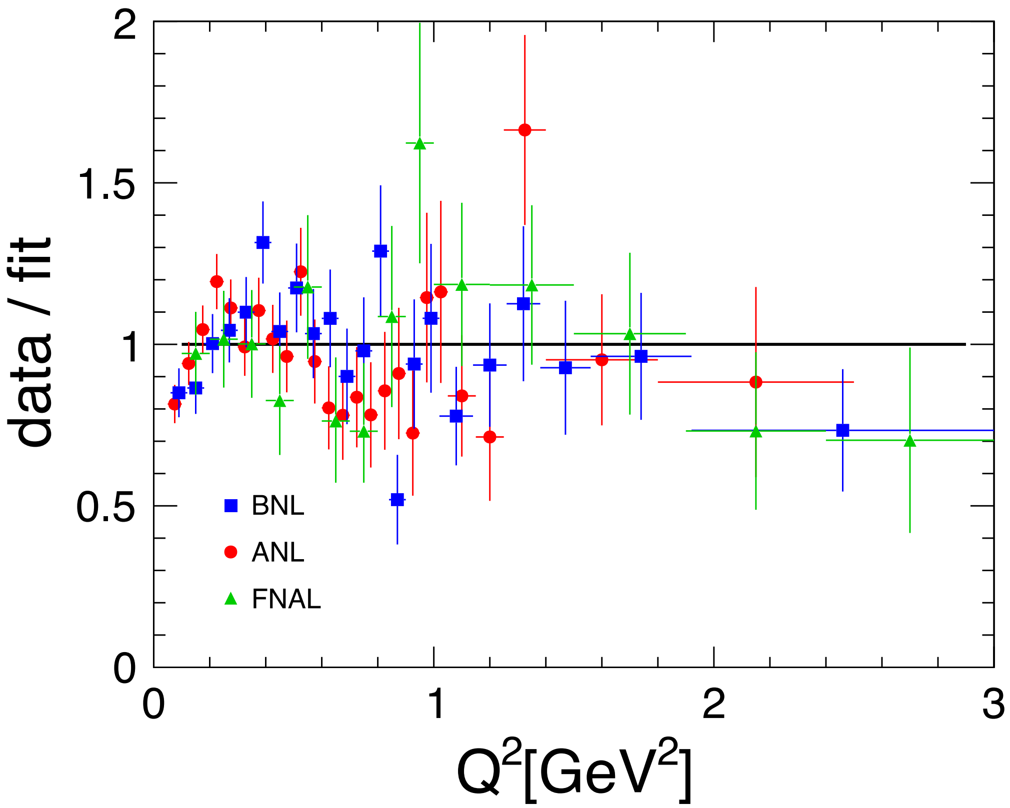


New module for z expansion and reweighting in GENIE event generator

A. Meyer

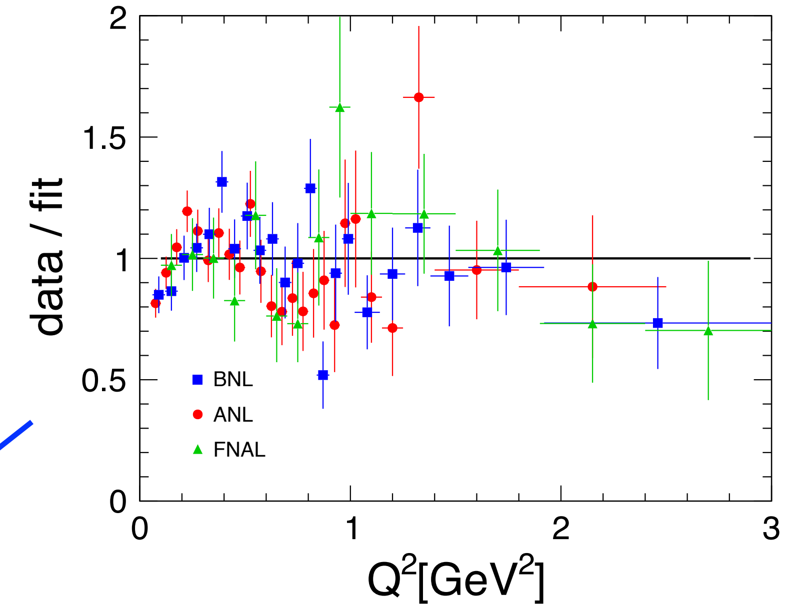




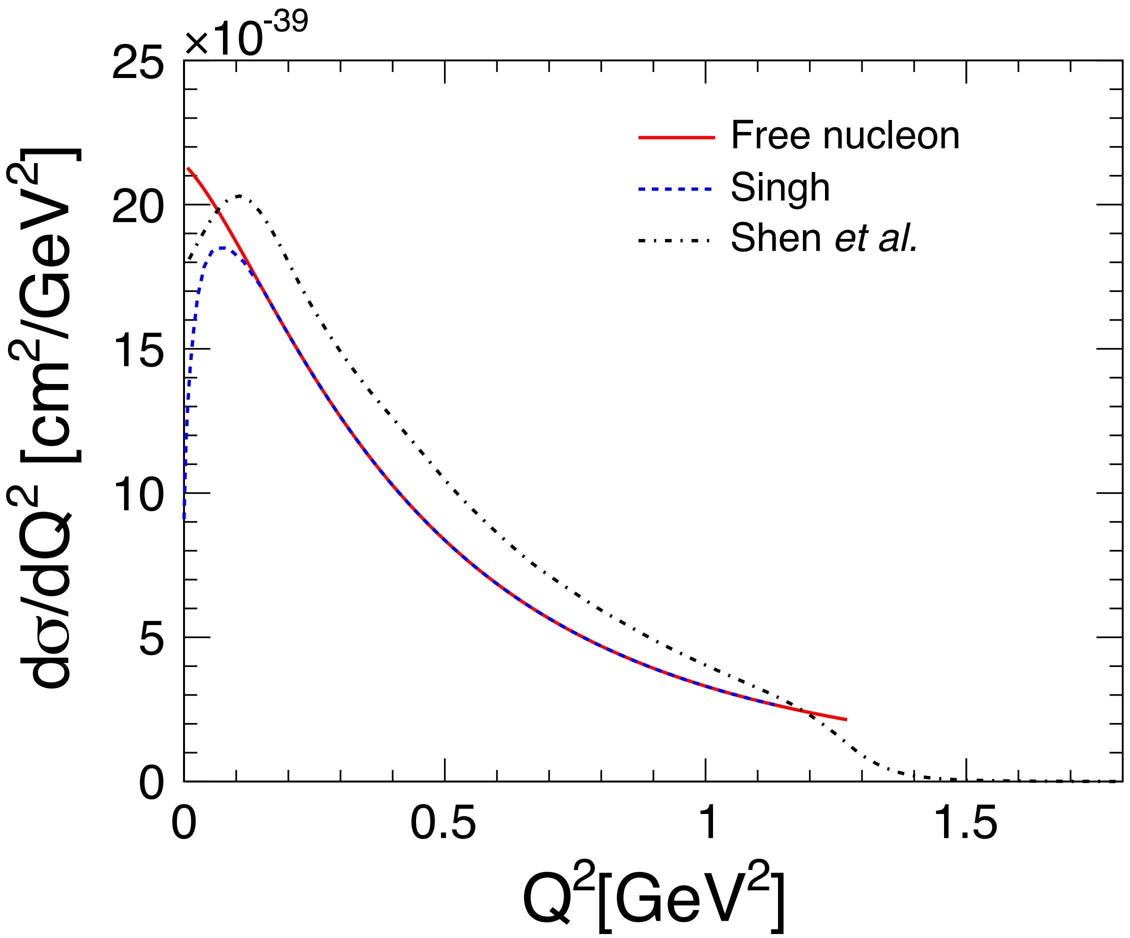


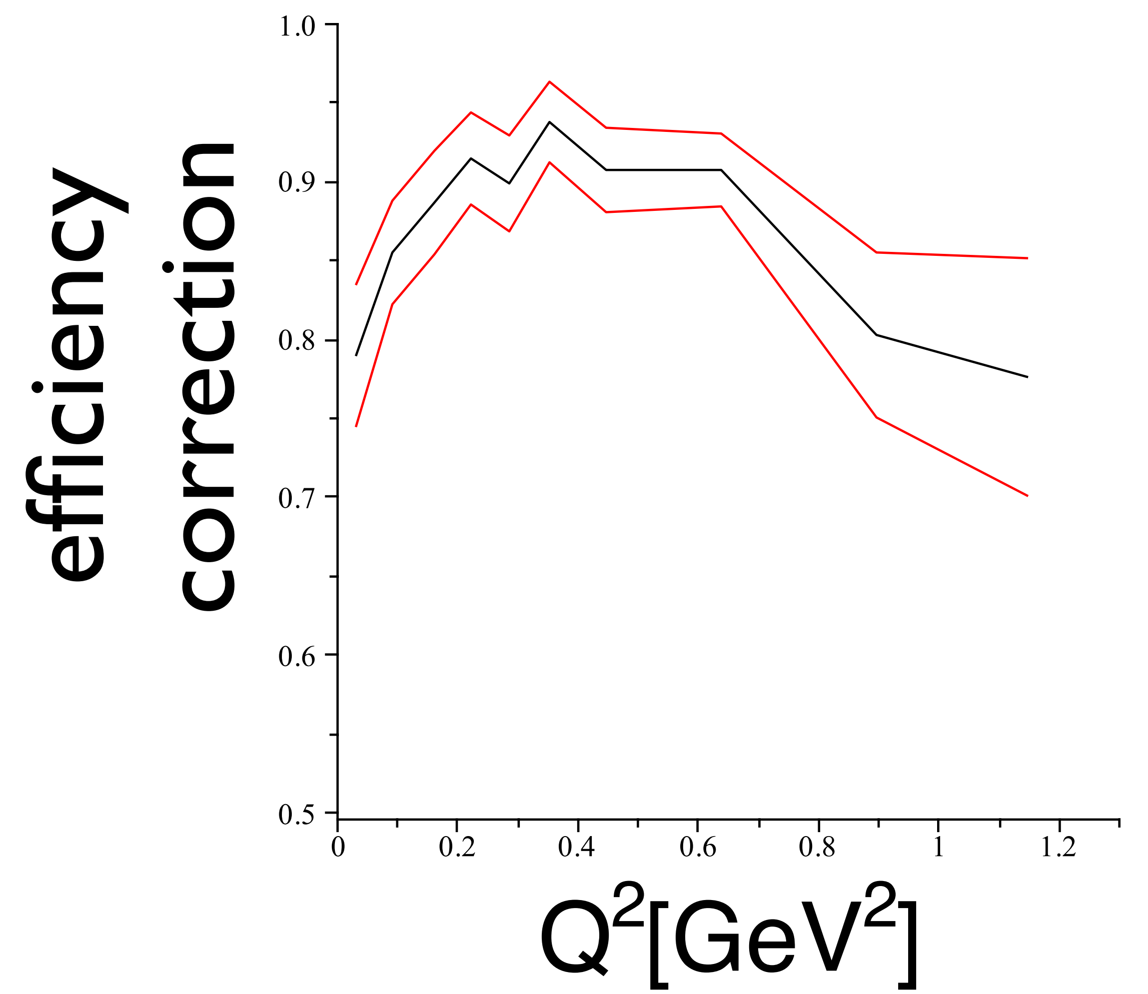
- previous extractions biased by unjustified dipole ansatz
- QCD analysis uncovers an underestimated systematic

theory systematic



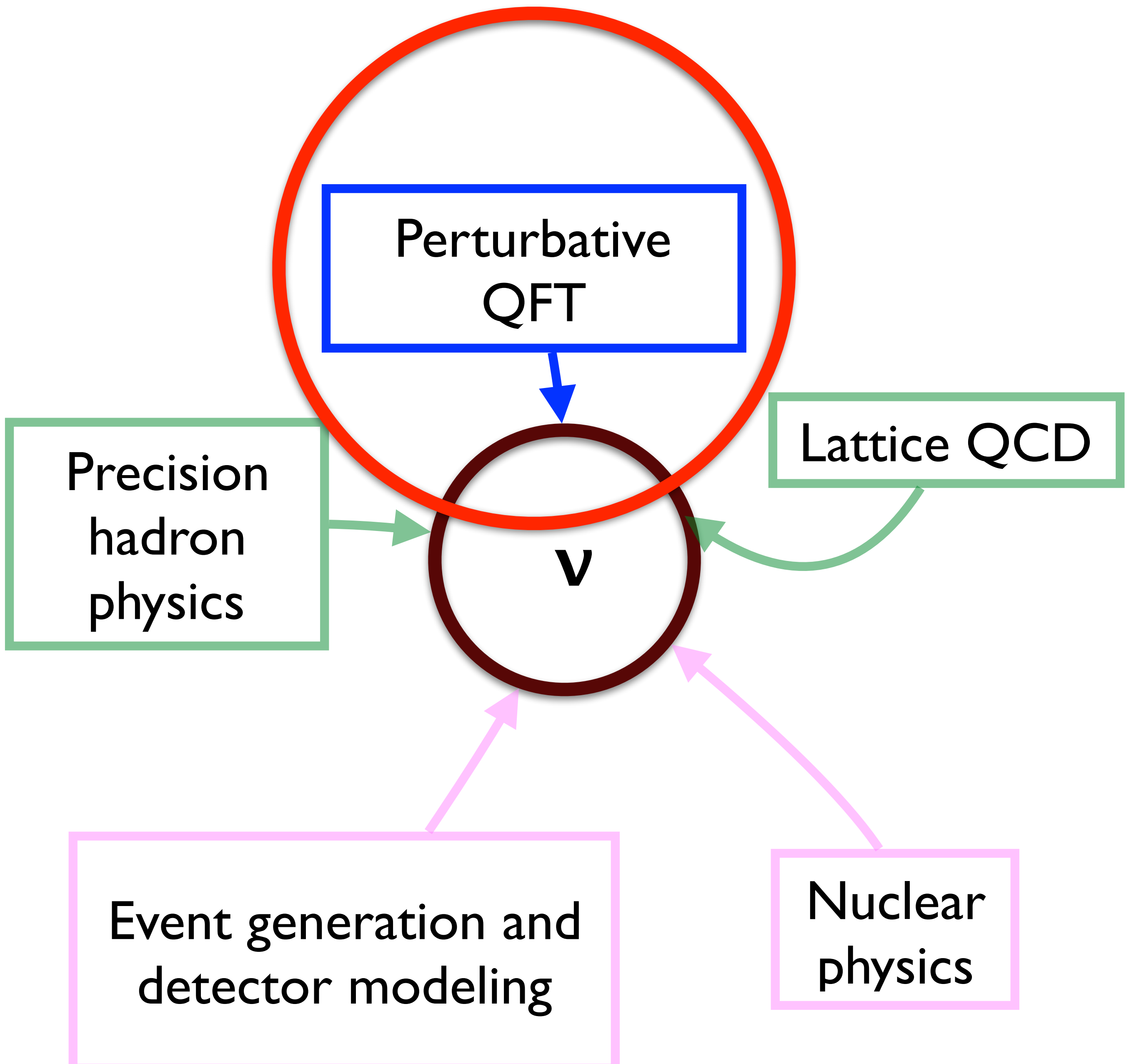
expt. systematic





- nuclear predictions on larger nuclei cannot be better than these inputs

<u>example 2:</u> ν_e/ν_μ cross sections and radiative corrections



Electromagnetic radiative corrections, especially for electron, are large and detector-dependent. Consider analogous e-p scattering process.

Some facts about the Rydberg constant puzzle (a.k.a. proton radius puzzle)

1) It has generated a lot of attention and controversy

2) The *most* mundane resolution necessitates:

- 5σ shift in fundamental Rydberg constant
- discarding or revising decades of results in e-p scattering and hydrogen spectroscopy

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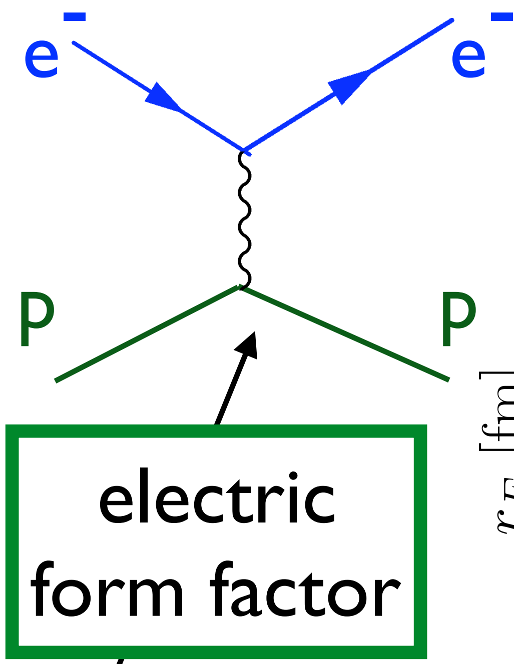
This *is* HEP's problem:

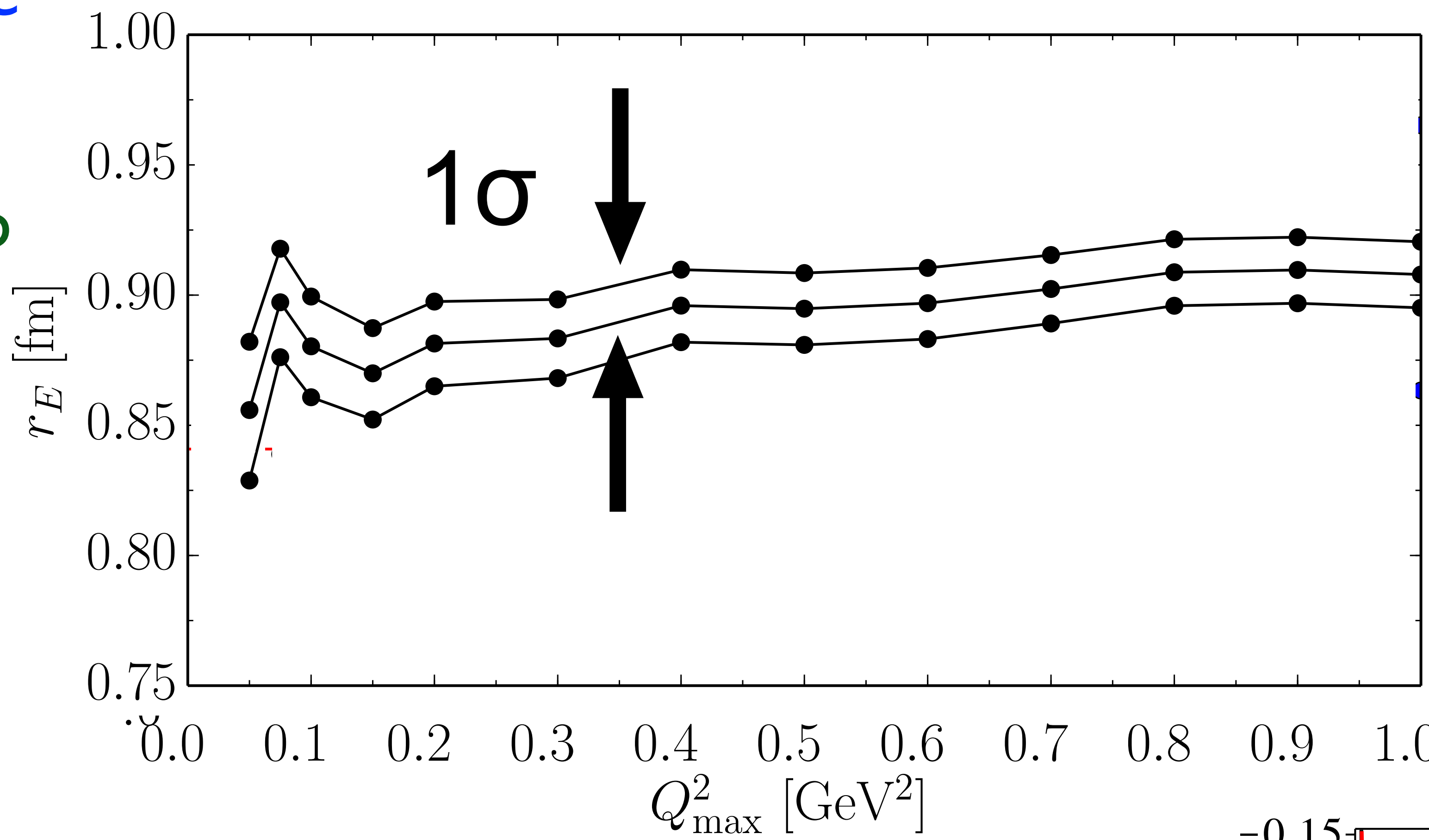
"The good news is that it's not my problem"

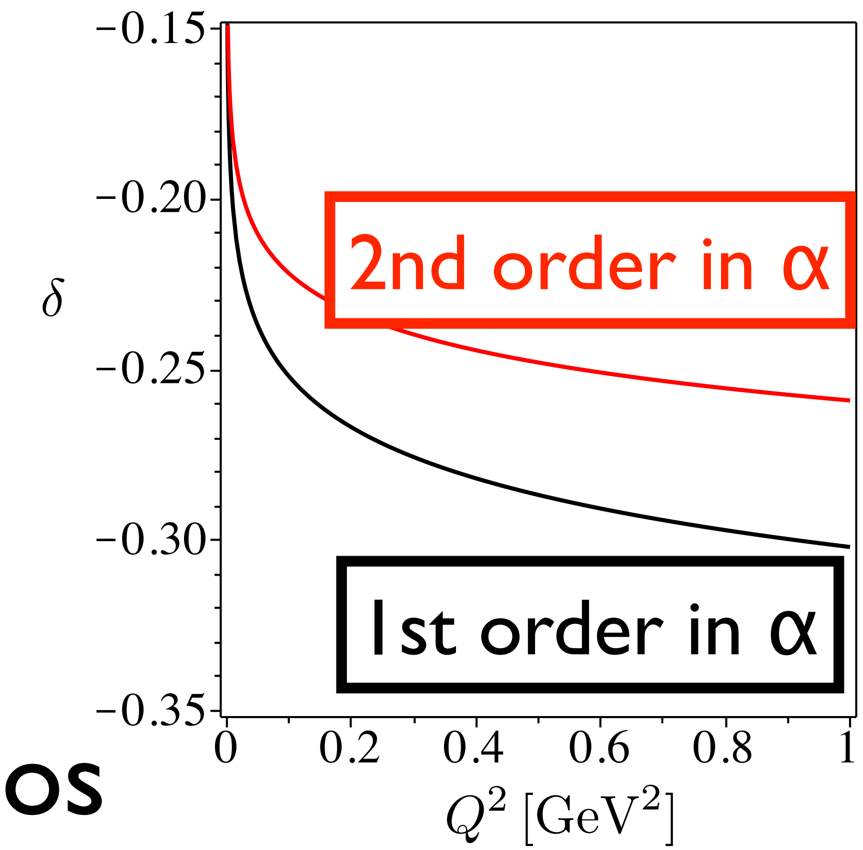
3) Systematic effects in electron-proton scattering impact neutrino-nucleus scattering, *at a level large compared to DUNE precision requirements*

Lee, Arrington, Hill, 1505.01489



$$\frac{dF_E}{dq^2} \propto r_E^2$$





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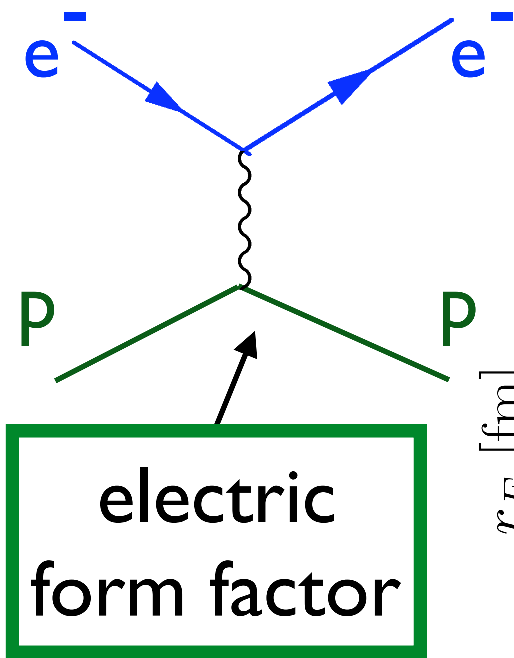
- radiative corrections important (being revisited)
- similar corrections impact ν_e/ν_μ ratios



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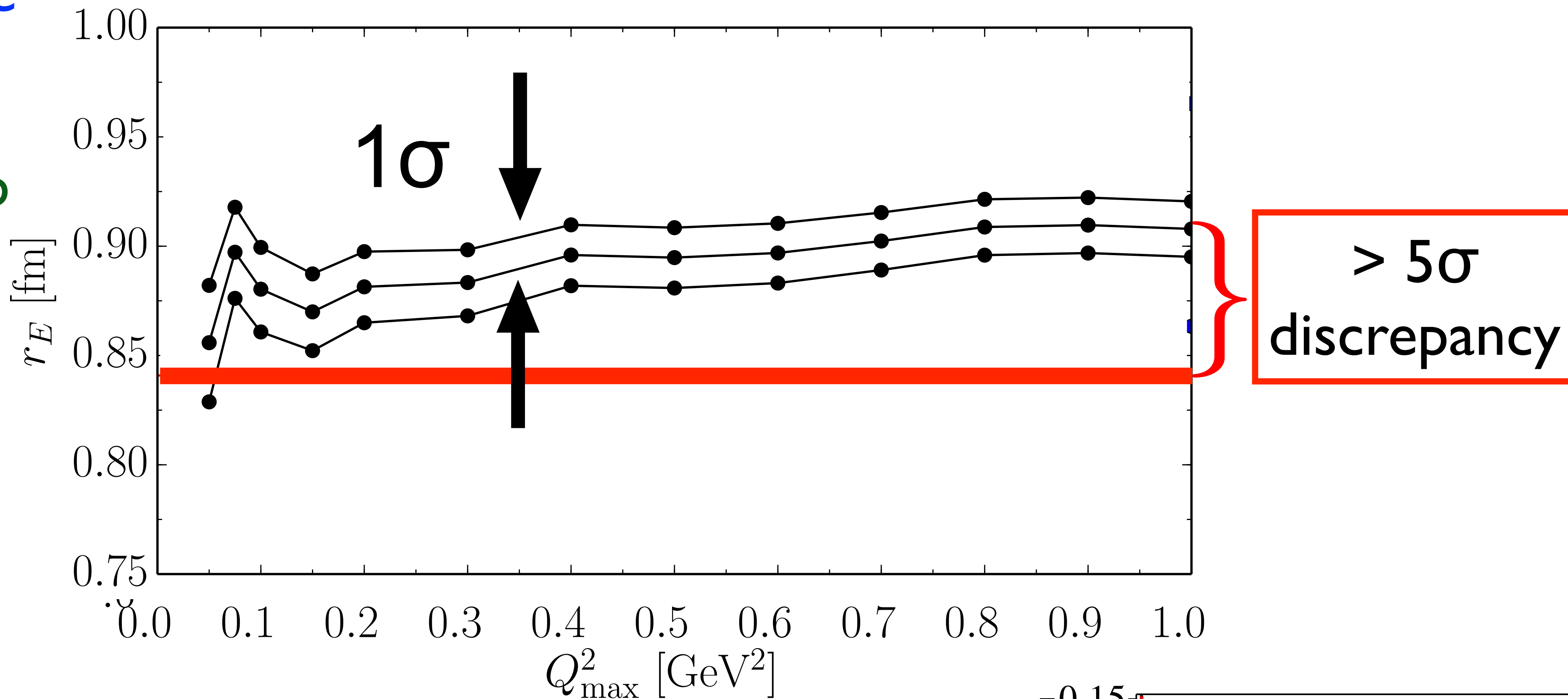

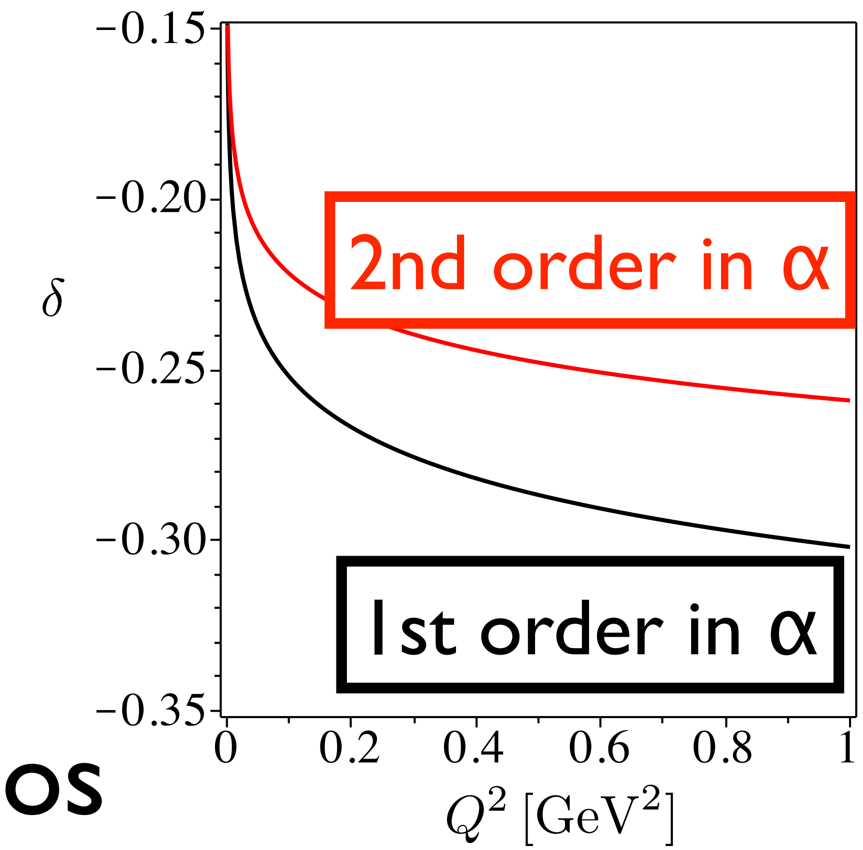

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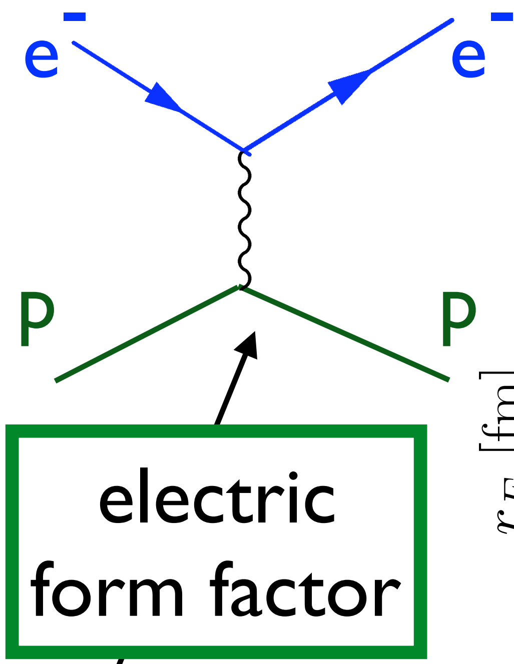

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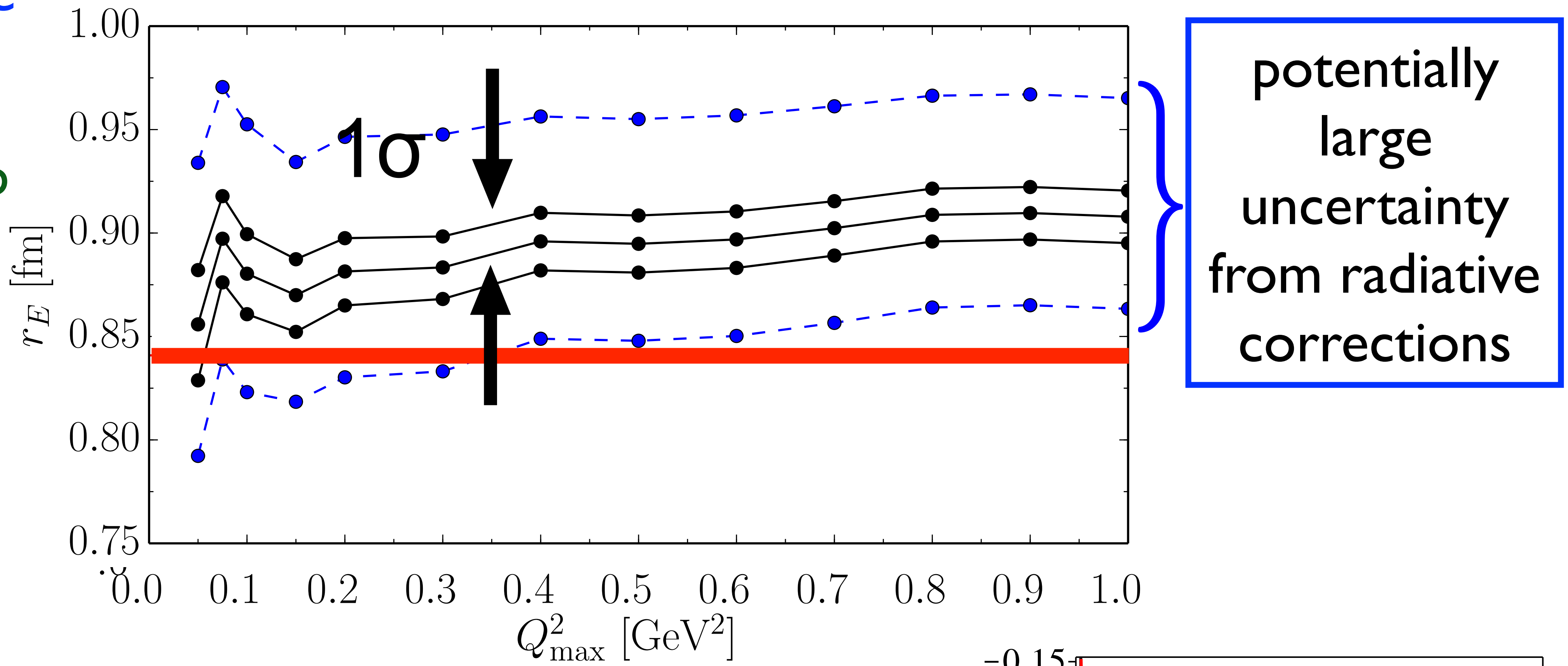

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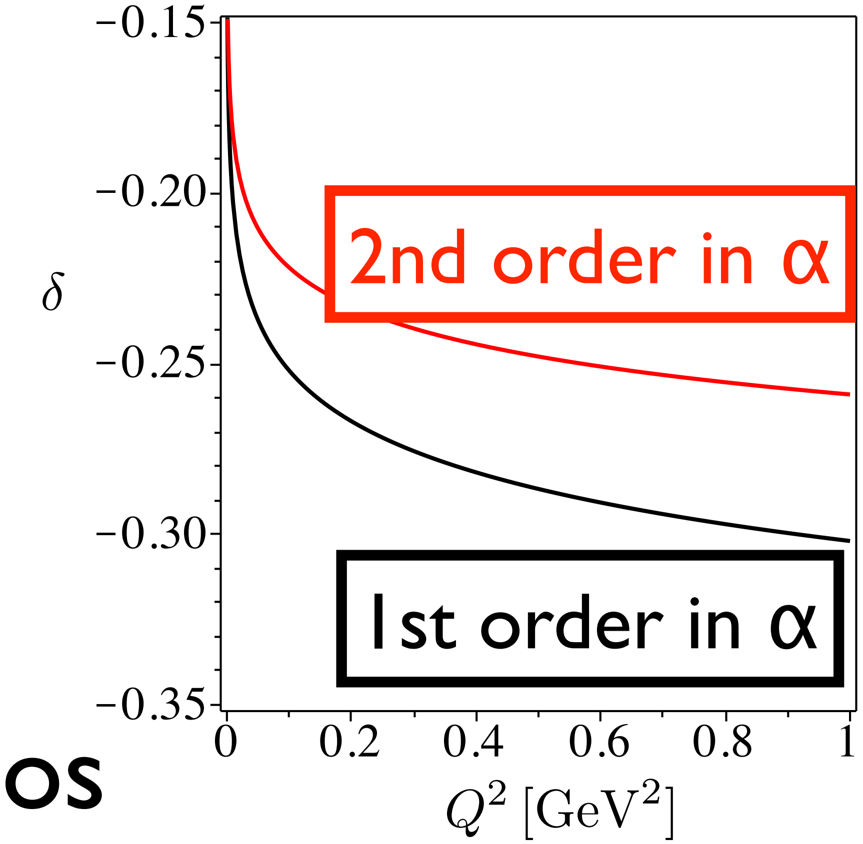

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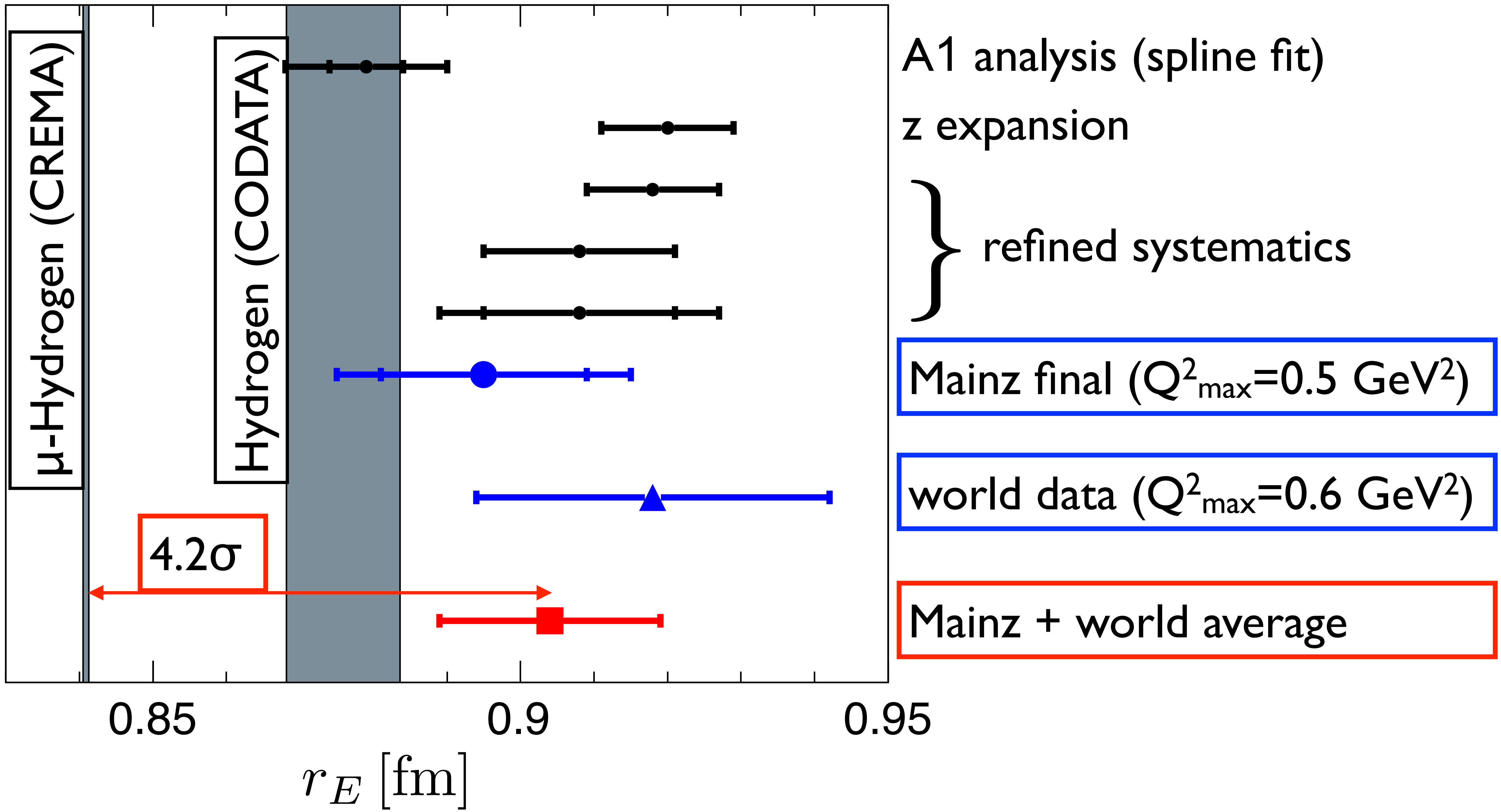
experimental landscape: electron-proton scattering

G. Lee, J. Arrington, RJH, 2015

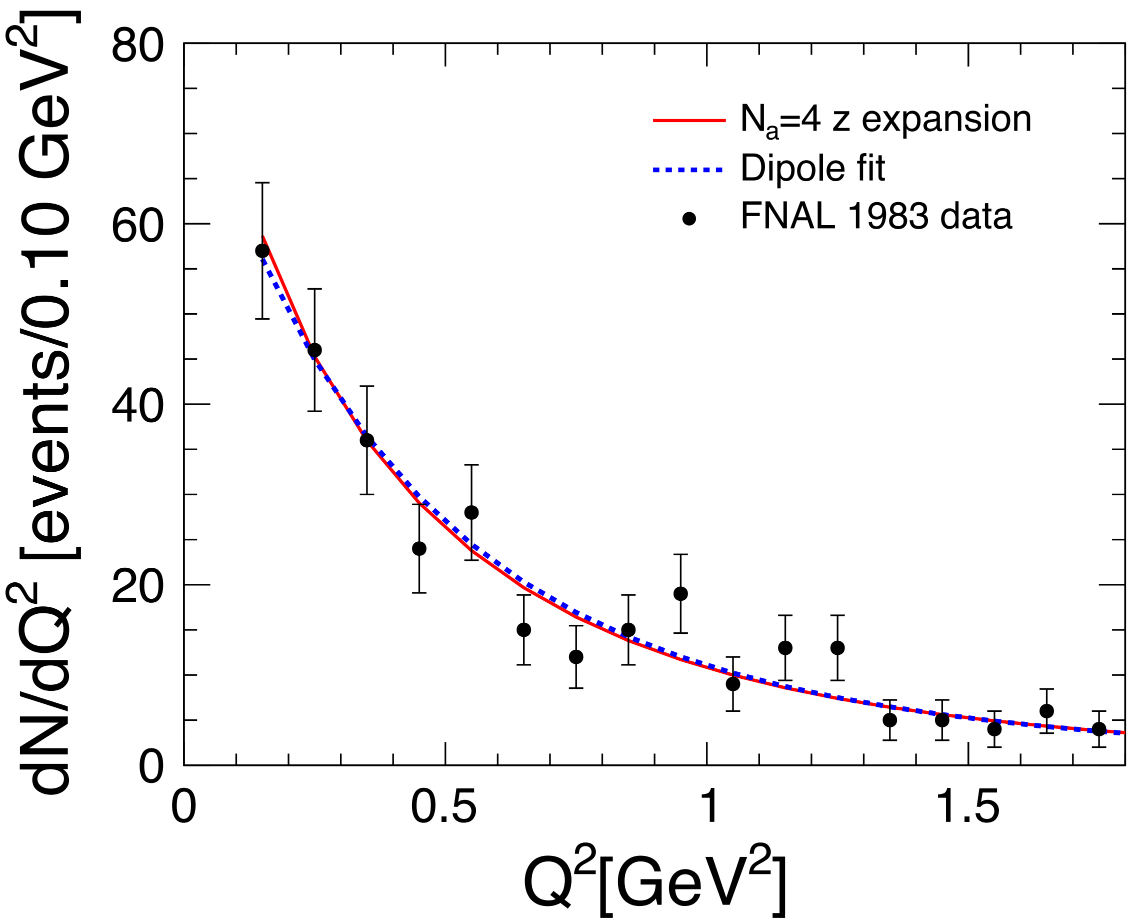


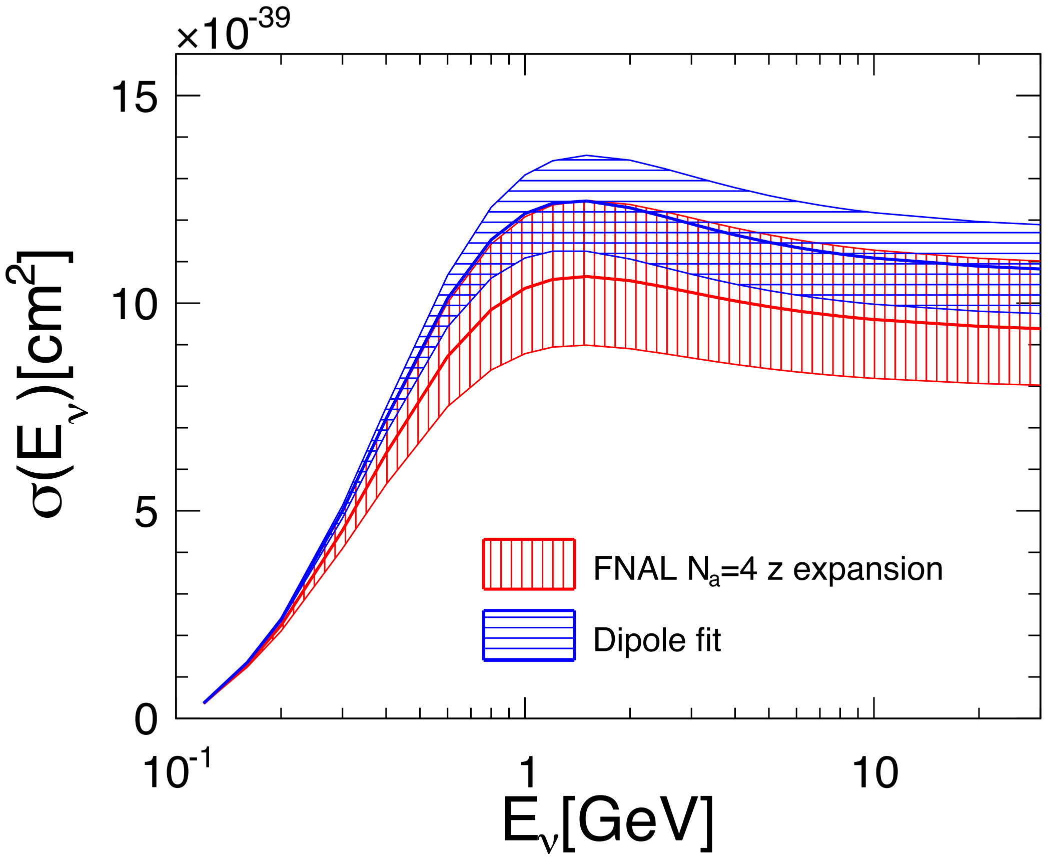
r_E^{Mainz} = 0.895(14)(14) fm

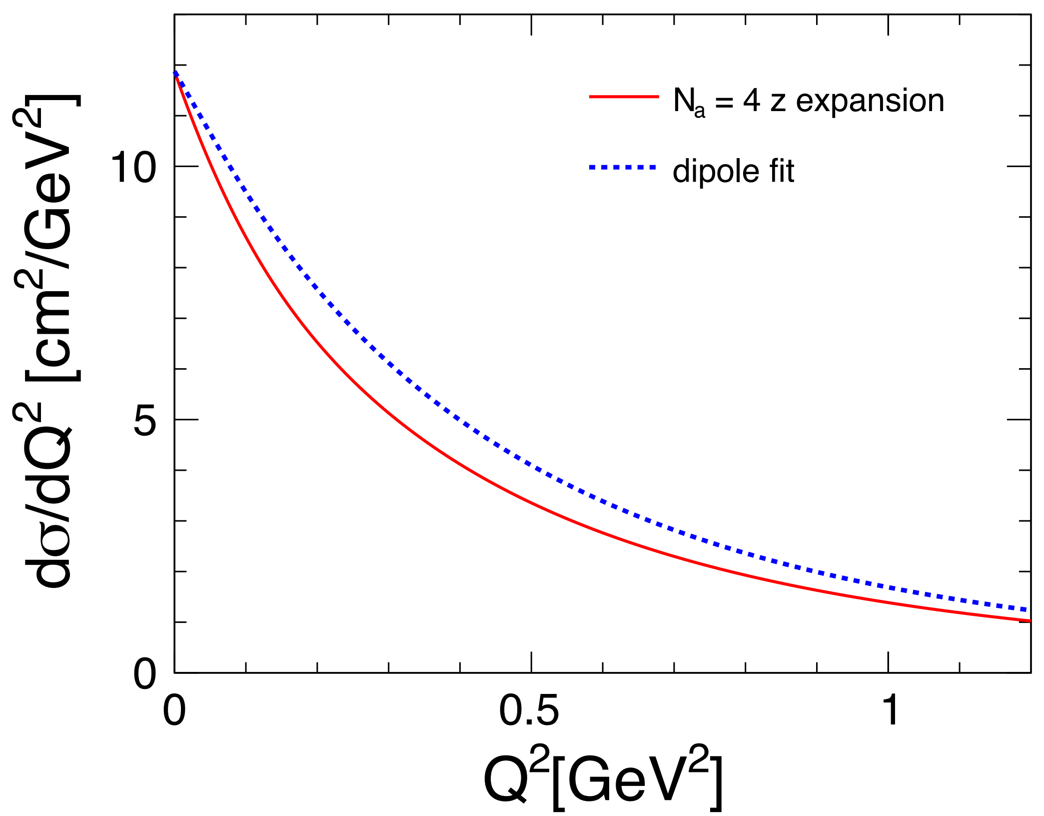
r_E^{world} = 0.918(24) fm

simple average: $r_E^{avg.}$ = 0.904(15) fm

Dipole and z expansion yield different F_A







(recall floating normalization and self-consistent flux: different F_A can yield similar dN/dQ^2 in fit range)

Cross sections key to discoveries in the neutrino sector

Particle theory has a critical role to play

- precision hadron physics: *model-independent amplitudes, error bars*
- radiative corrections: *critical for control over ν_e/ν_μ ratios*
- lattice QCD: *completely different systematics vs. elementary targets*

Important connections: other intensity frontier initiatives

- radiative corrections: *neutrinos, g-2, proton radius puzzle, CKM, …*
- lattice QCD & baryons: *neutrinos, DM, proton radius puzzle, nEDM, …*
- interplay of nucleon amplitudes and nuclear effects: *energy reconstruction in ν-N scattering; atmospheric bkgd. to proton decay, next generation WIMP searches, neutrinoless double beta decay, …*