Neutrino cross sections at accelerator energies

comments on radiative corrections and lessons from electron-proton scattering

RICHARD HILL

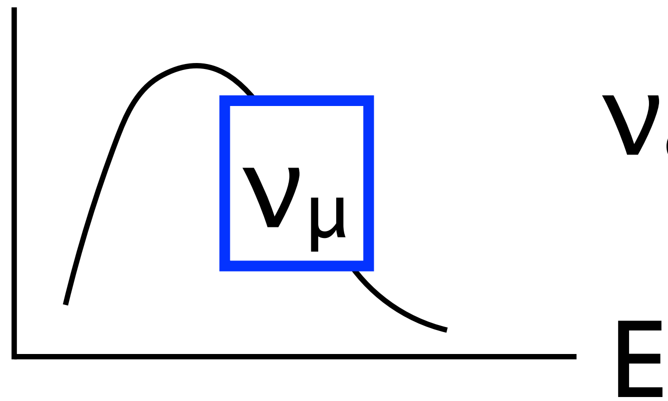
University of Chicago

Fermilab neutrino workshop

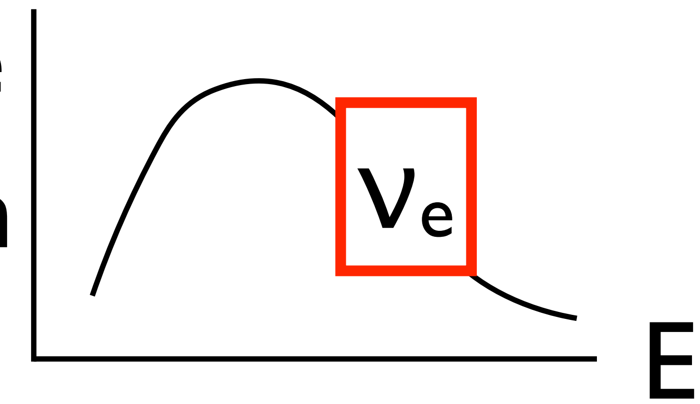
24 June 2015

probability of $\nu_\mu \to \nu_e$ ⇒ fundamental neutrino properties

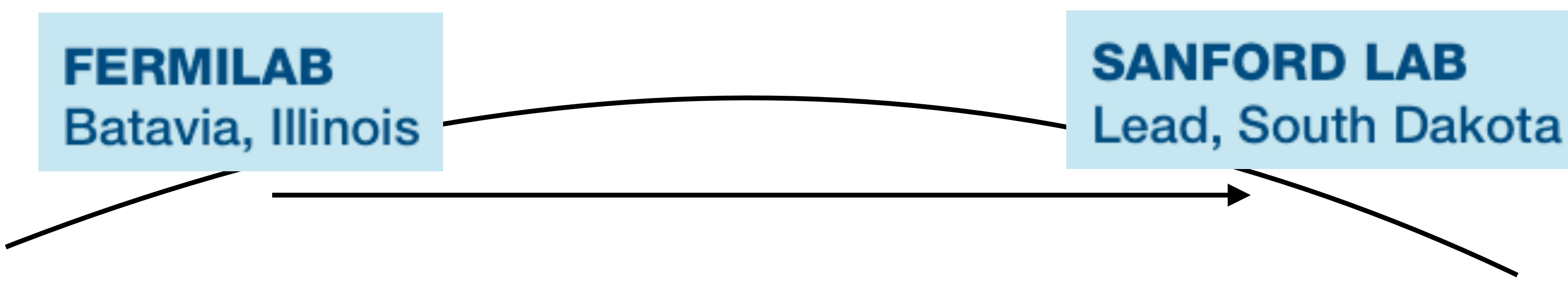
ν_μ flux



$$\nu_e \text{ flux} = \frac{\nu_e \text{ event rate}}{\text{cross section}}$$



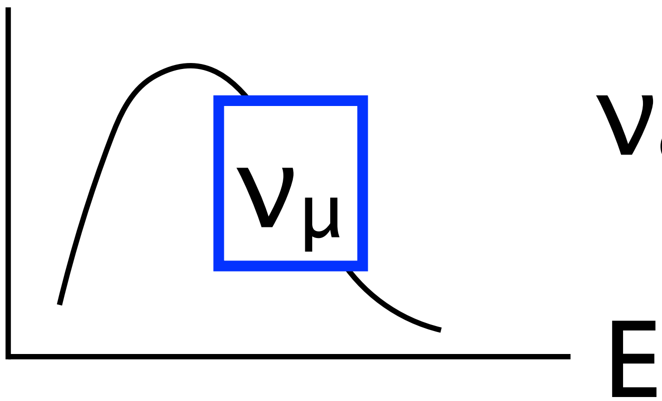
E.g. DUNE



Cross section translates observed event rate to ν_e appearance prob.

probability of $\nu_\mu \rightarrow \nu_e$ $\Rightarrow$ fundamental neutrino properties

ν_μ flux



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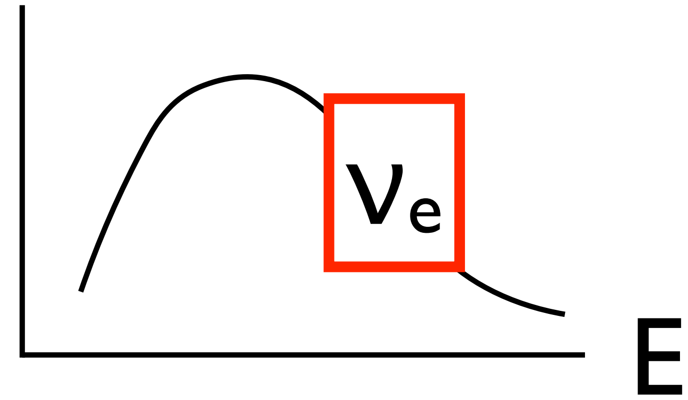

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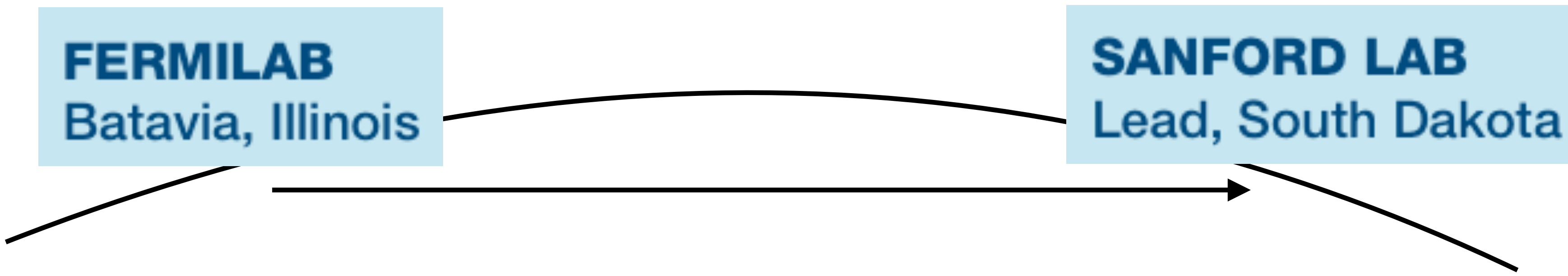
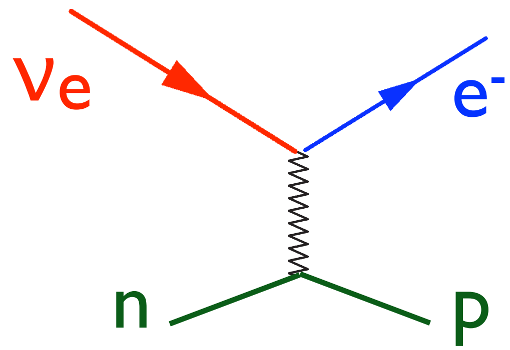


Cross section translates observed event rate to ν_e appearance prob.

Basic signal process: charged current quasi elastic scattering

(large event sample, "reconstructible" neutrino energy, theoretically "clean")



probability of $\nu_\mu \to \nu_e$ ⇒ fundamental neutrino properties

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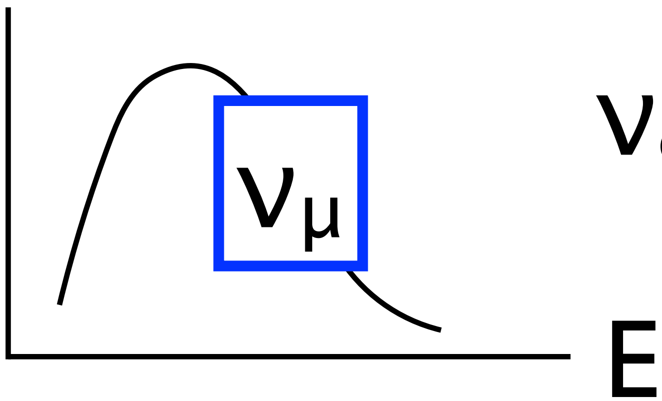

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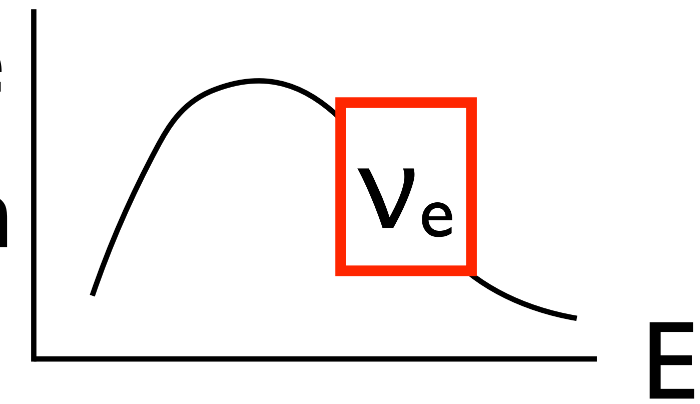

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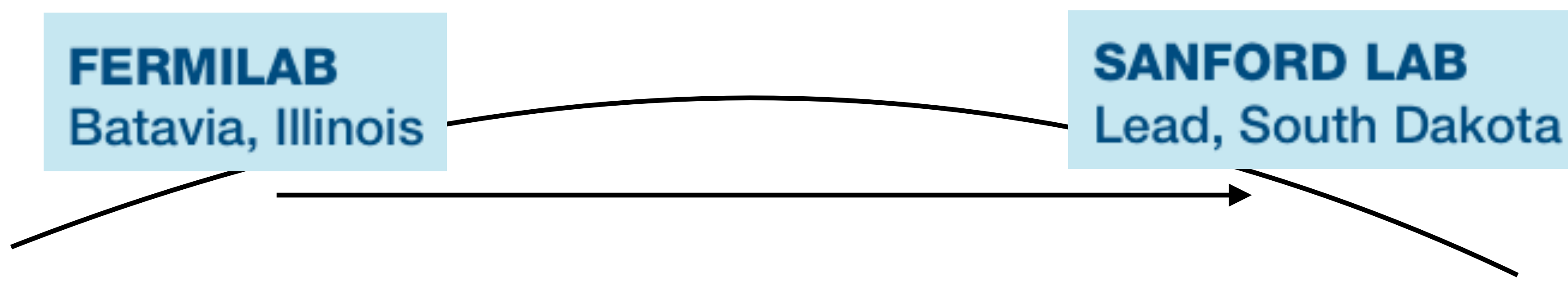

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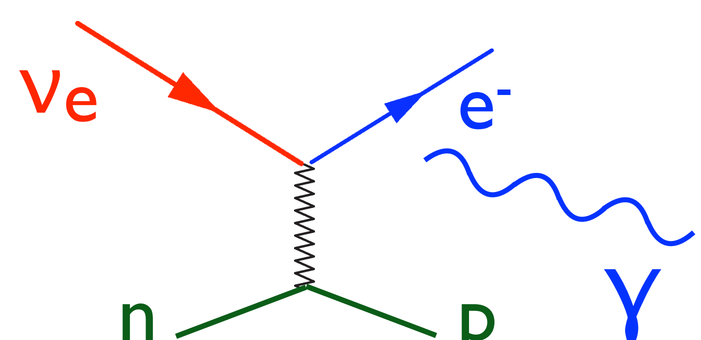
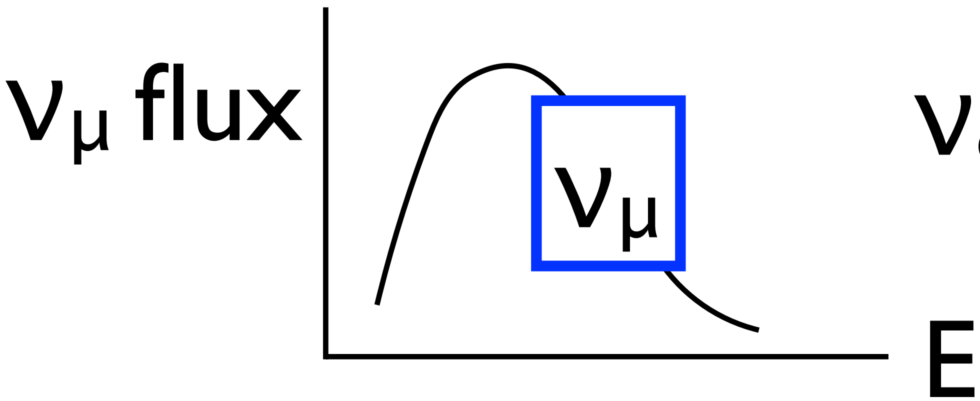


radiative corrections

probability of $\nu_\mu \to \nu_e$ $\Rightarrow$ fundamental neutrino properties



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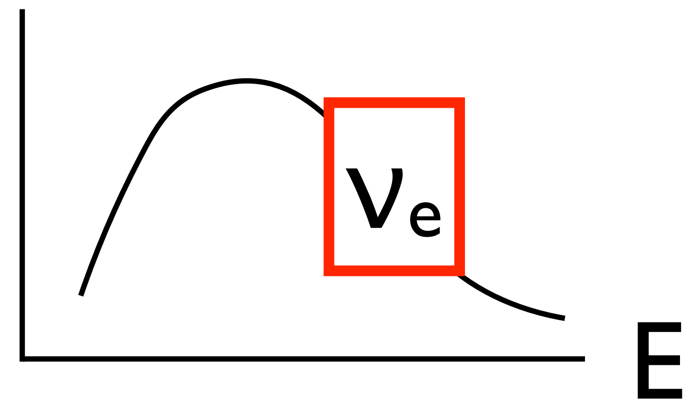

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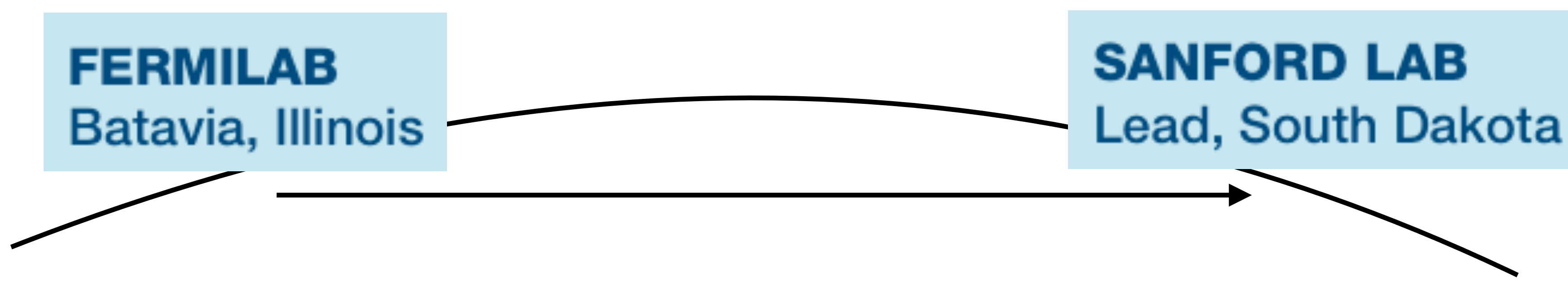

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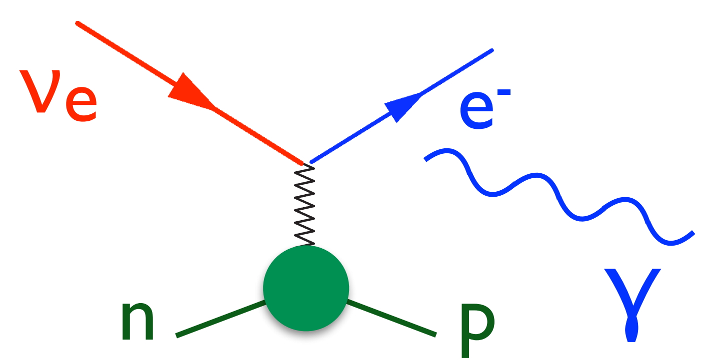
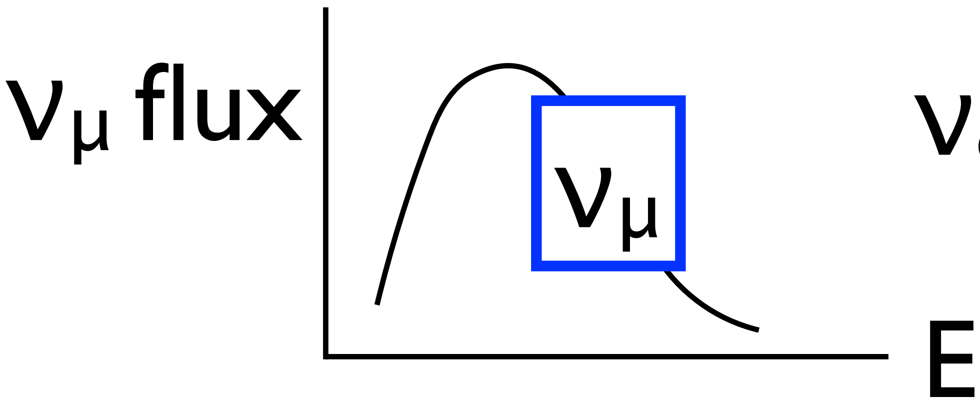


radiative corrections

hadronic amplitudes

probability of $\nu_\mu \to \nu_e$ ⇒ fundamental neutrino properties



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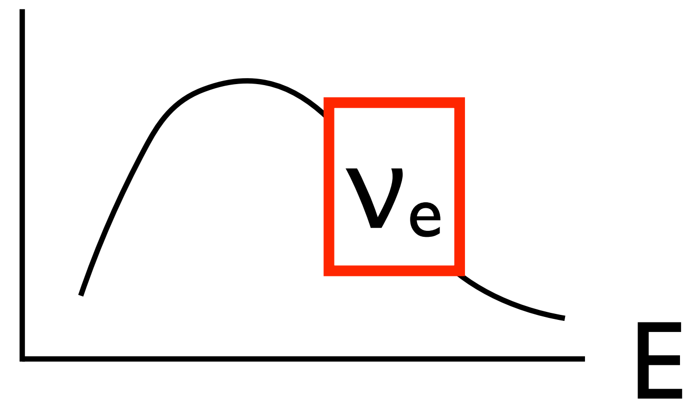

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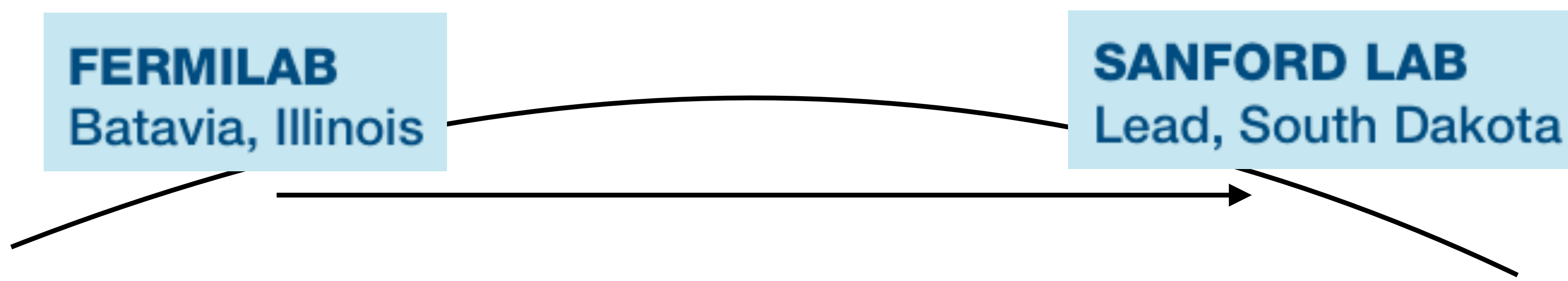

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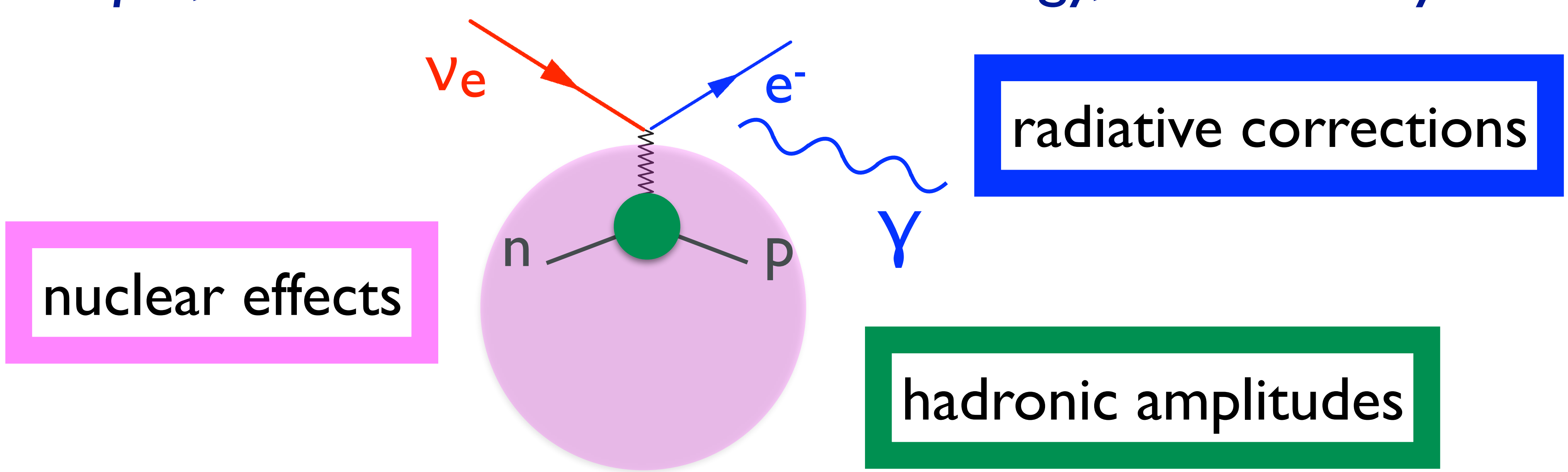
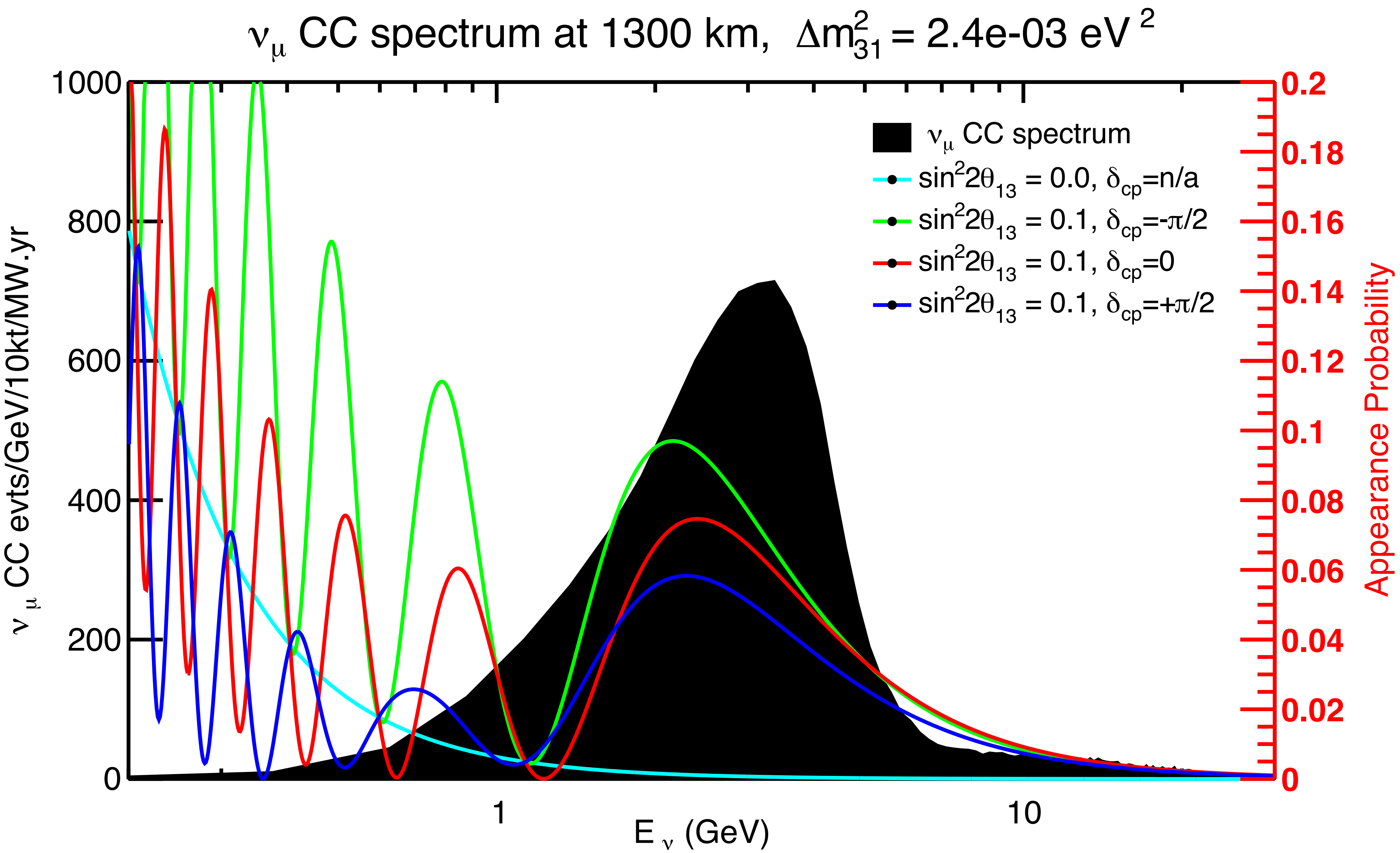
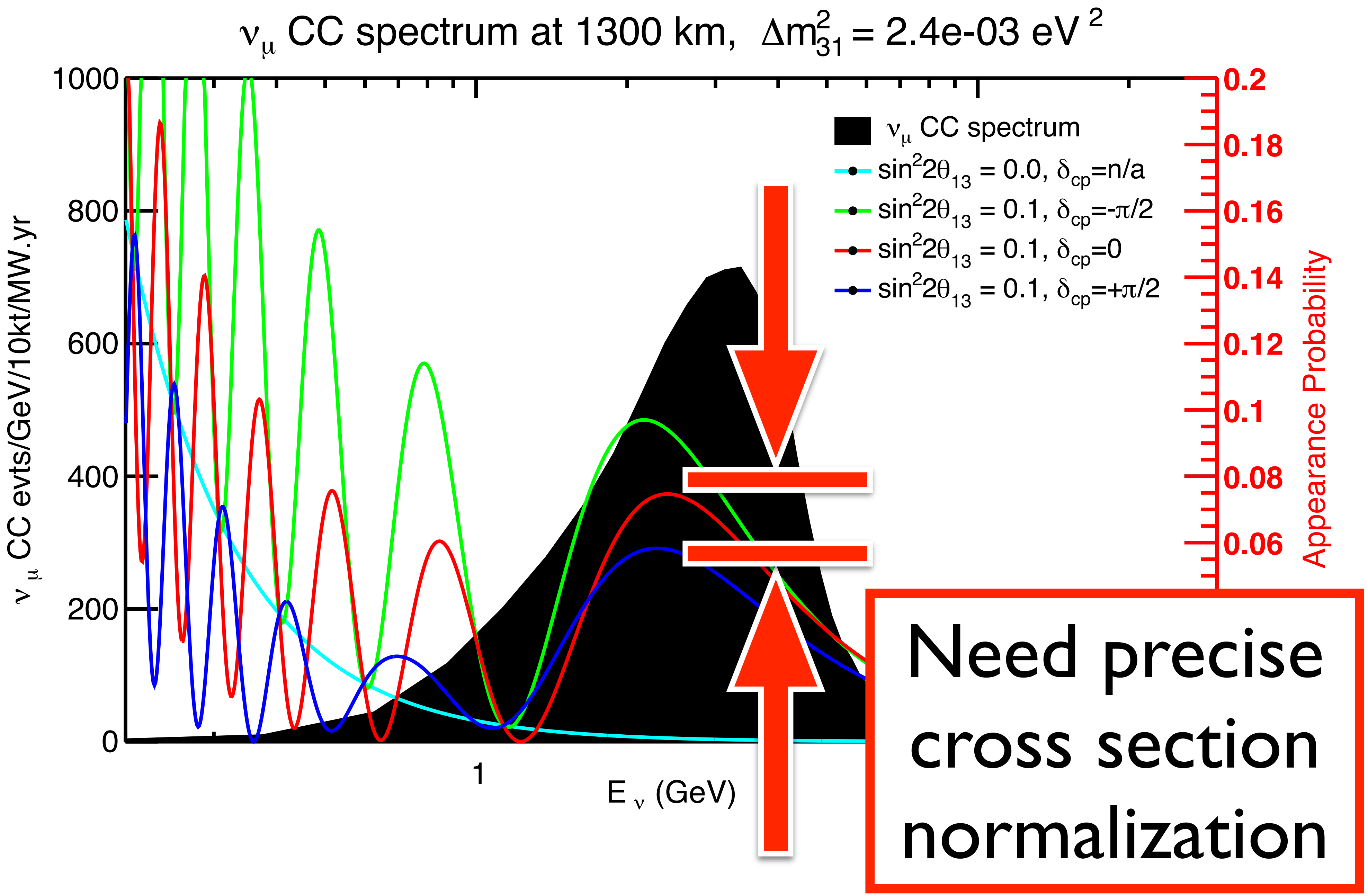




LBNE, 1307.7335

cf. Coloma, Huber et al., 1307.1243, 1311.4506; Lalakulich and Mosel, 1311.7288



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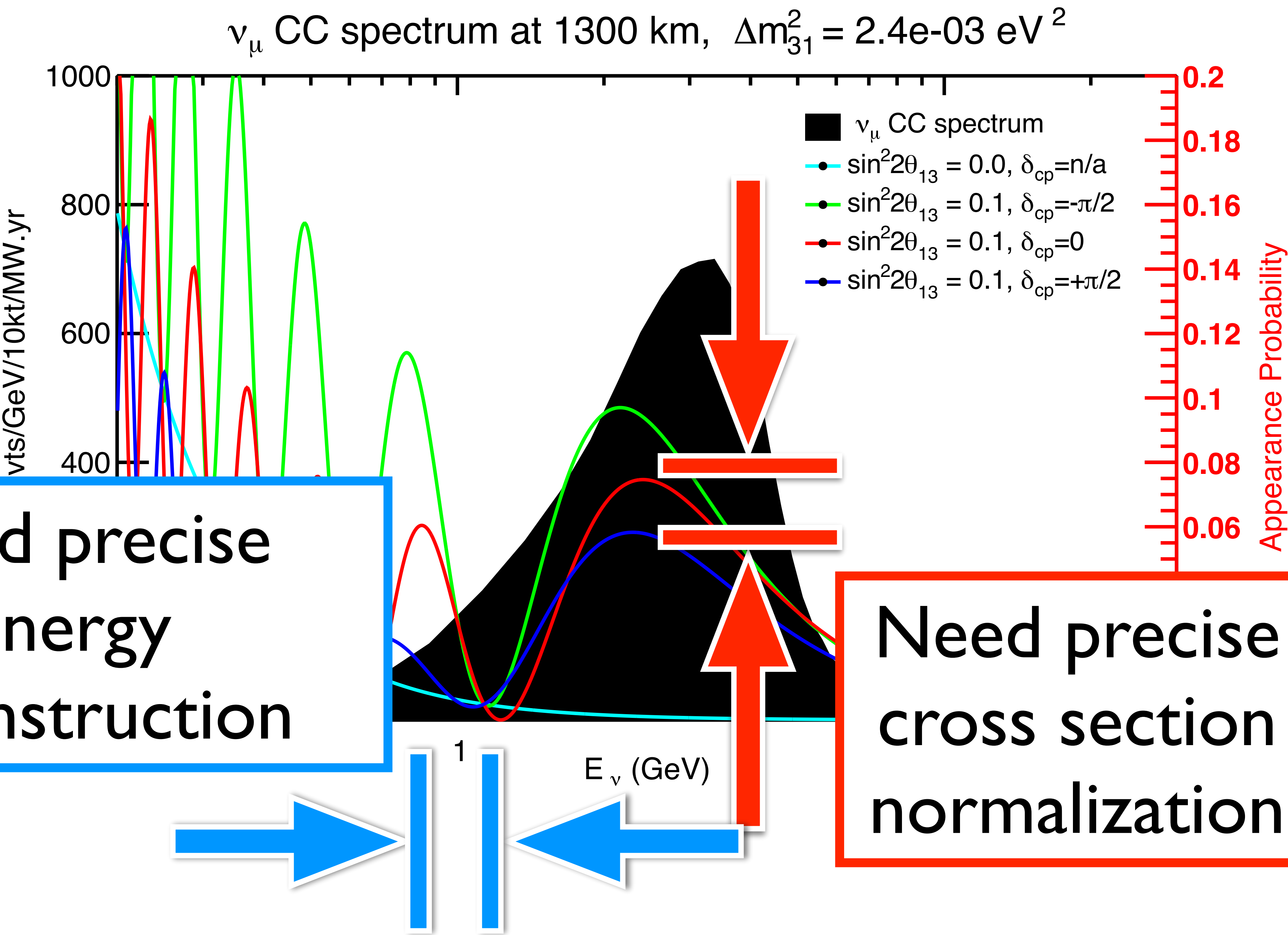

Need precise energy reconstruction

Need precise cross section normalization

LBNE, 1307.7335
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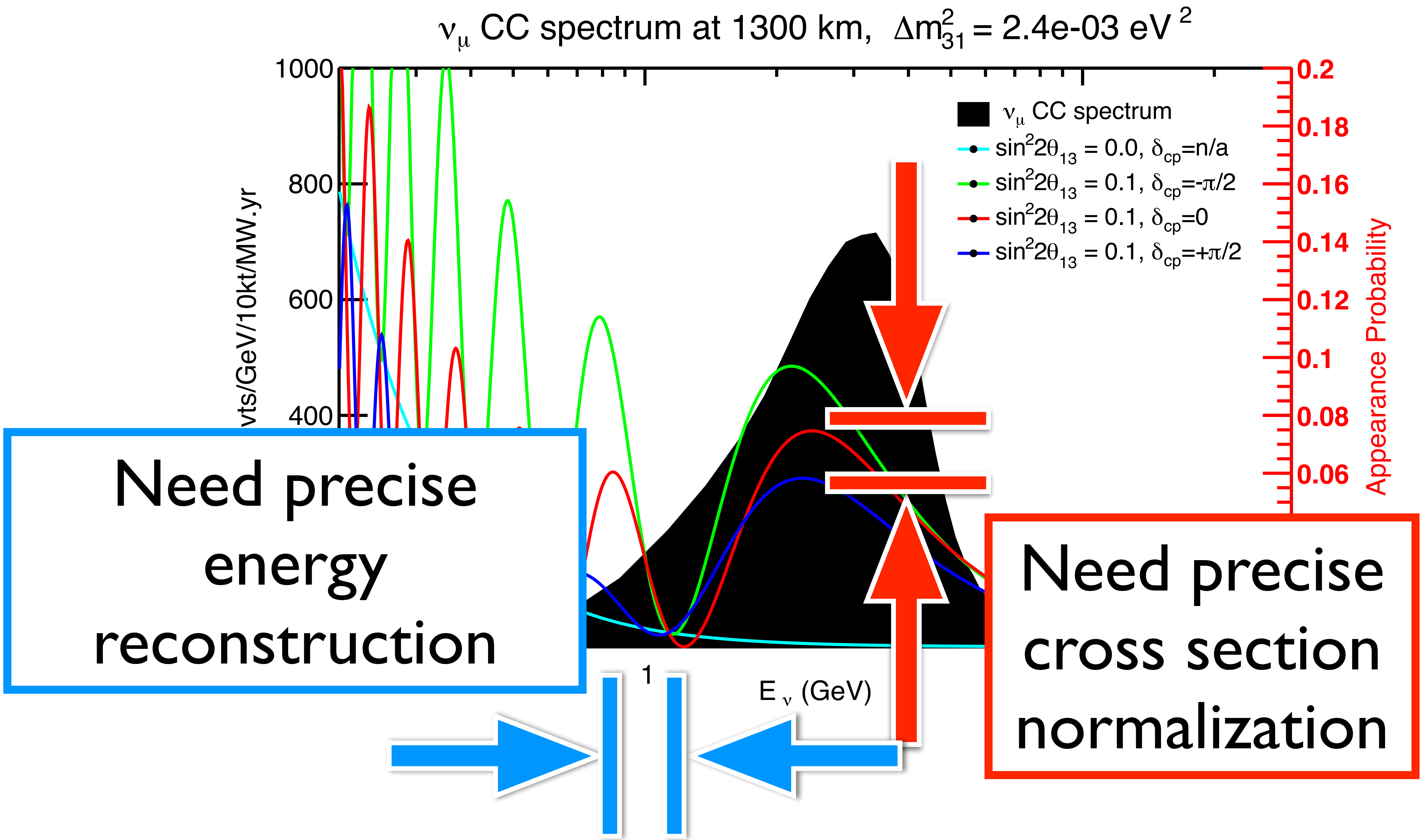

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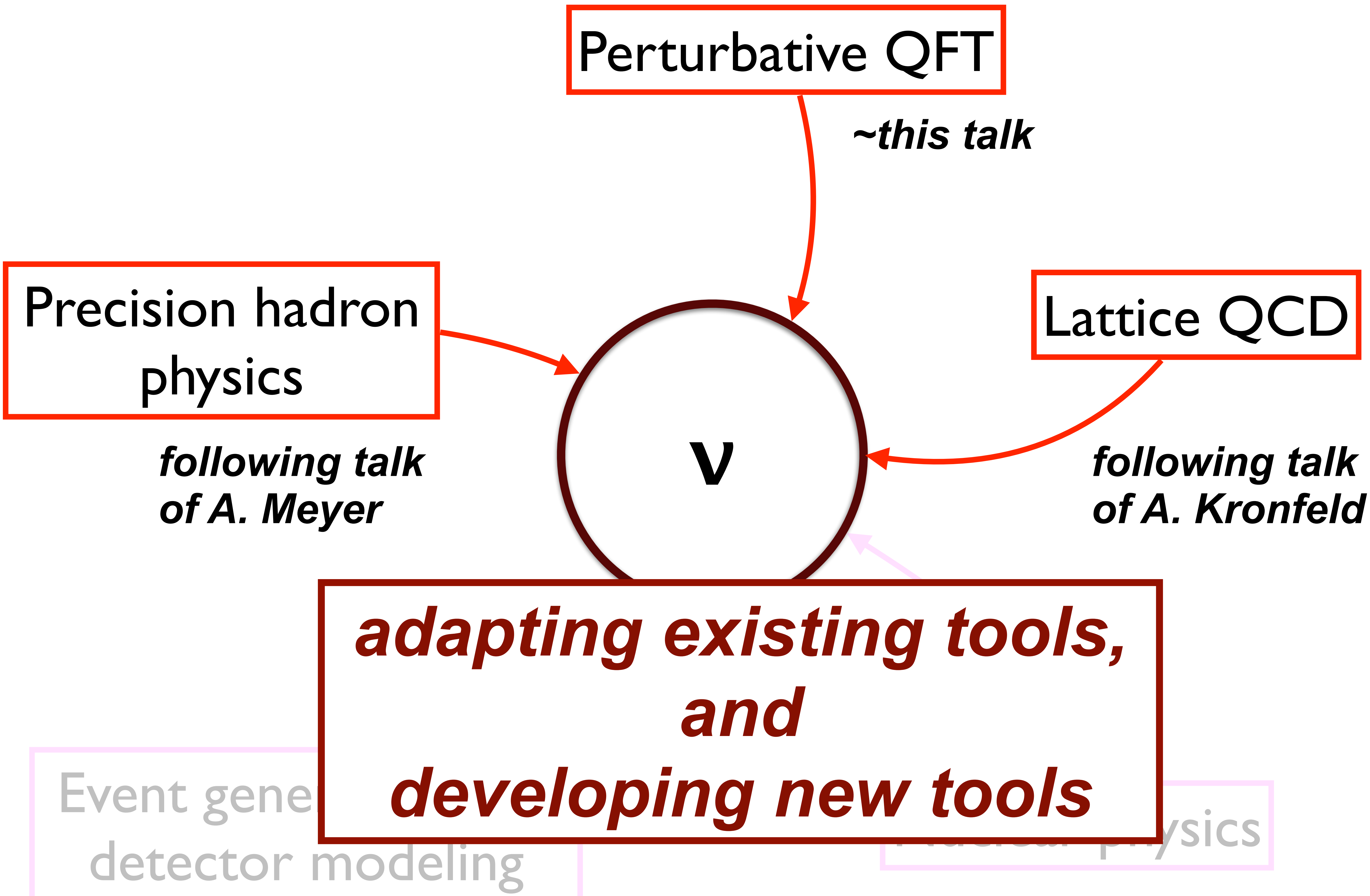
Many related activities and applications, over a wide energy range:

- **sterile neutrino searches**
- **reactor, supernova, astrophysical, solar, cosmological ν's**
- **proton decay, …**

Focus here on ~GeV ν cross sections for oscillation experiments

HEP Theory is…



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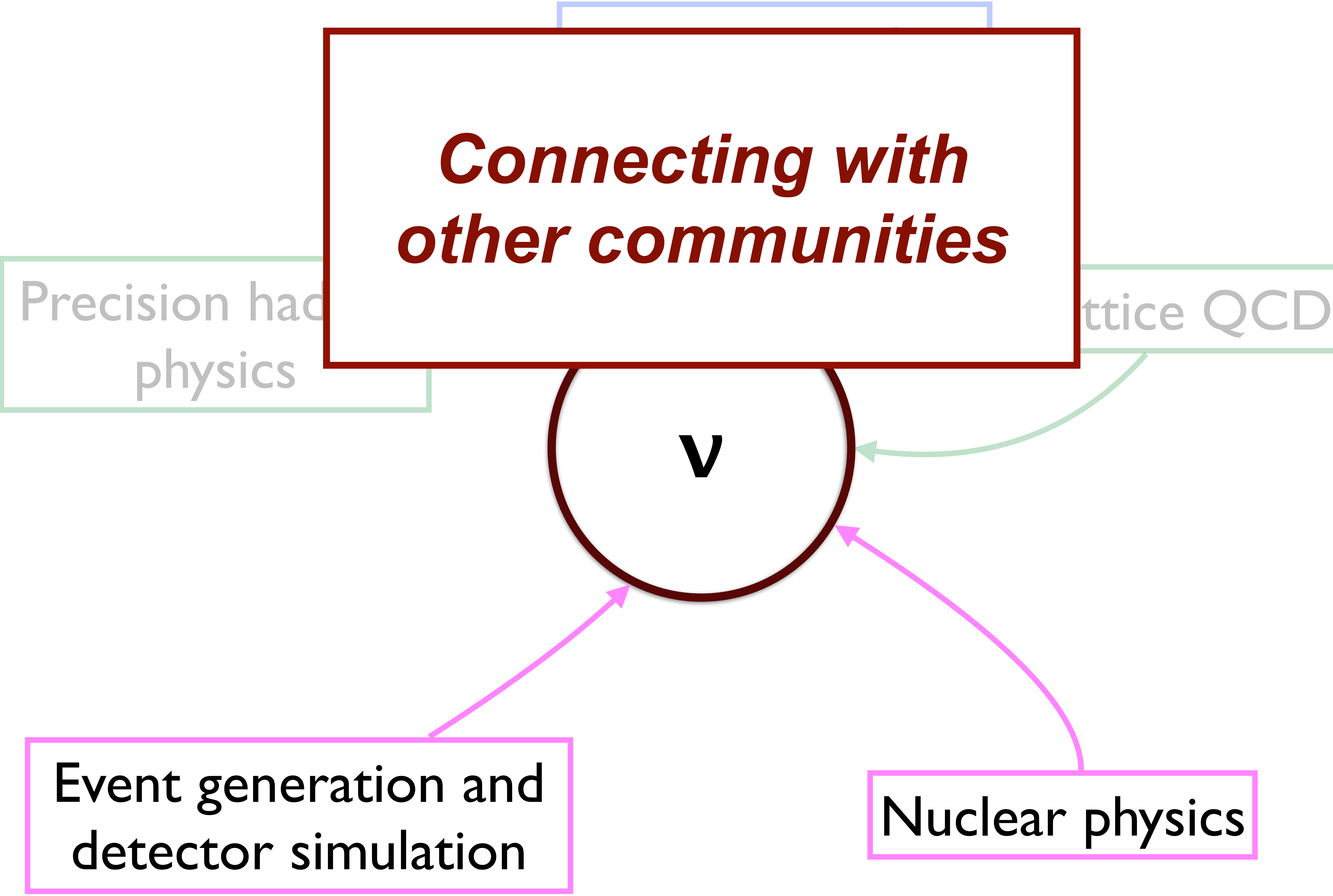


A few words about radiative corrections in neutrino scattering

- effective field theory and mass scales

- electromagnetic radiative corrections

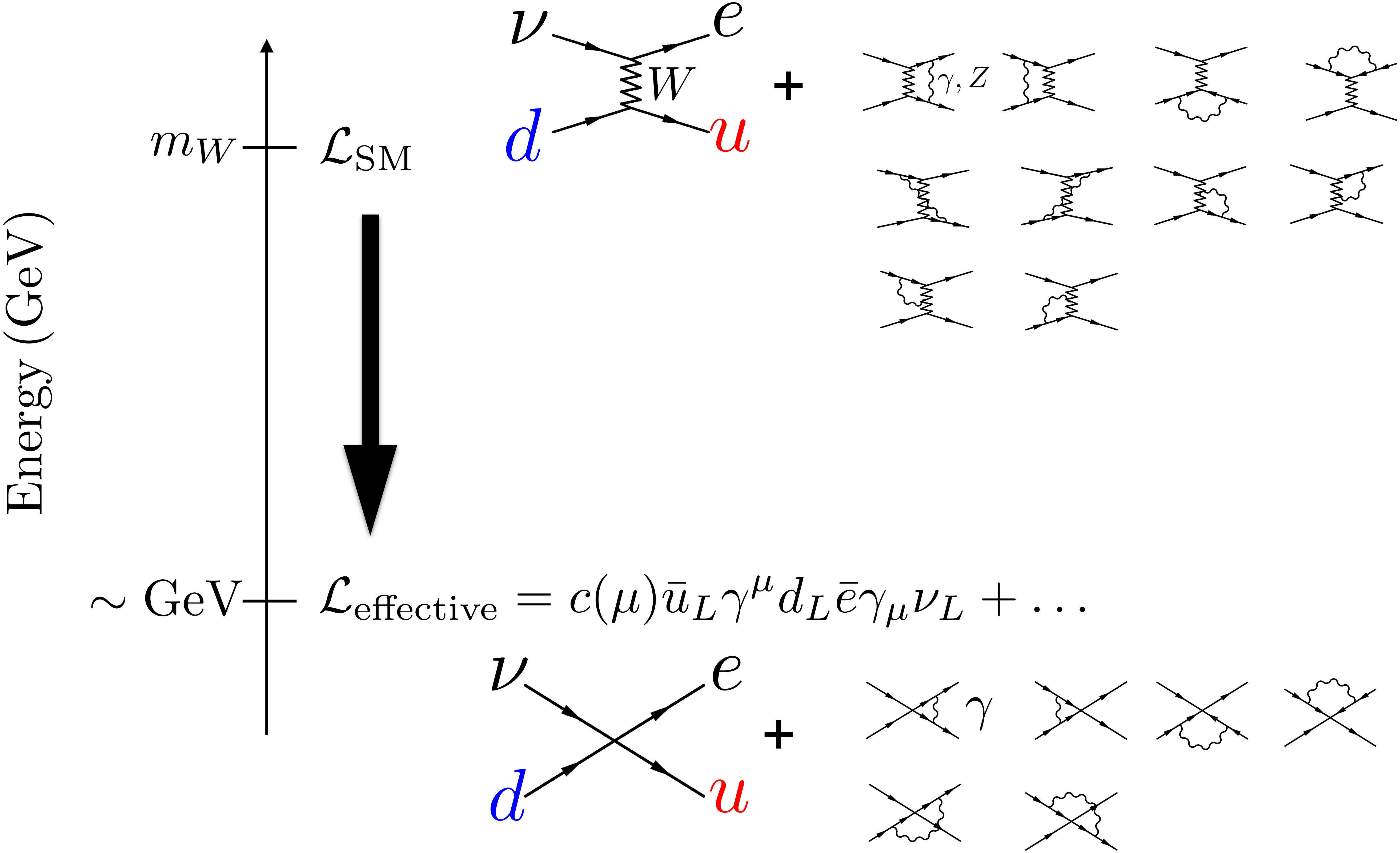
Then a look at electron-proton scattering

why? *- vector form factor inputs for neutrino observables*

- proving ground for theory

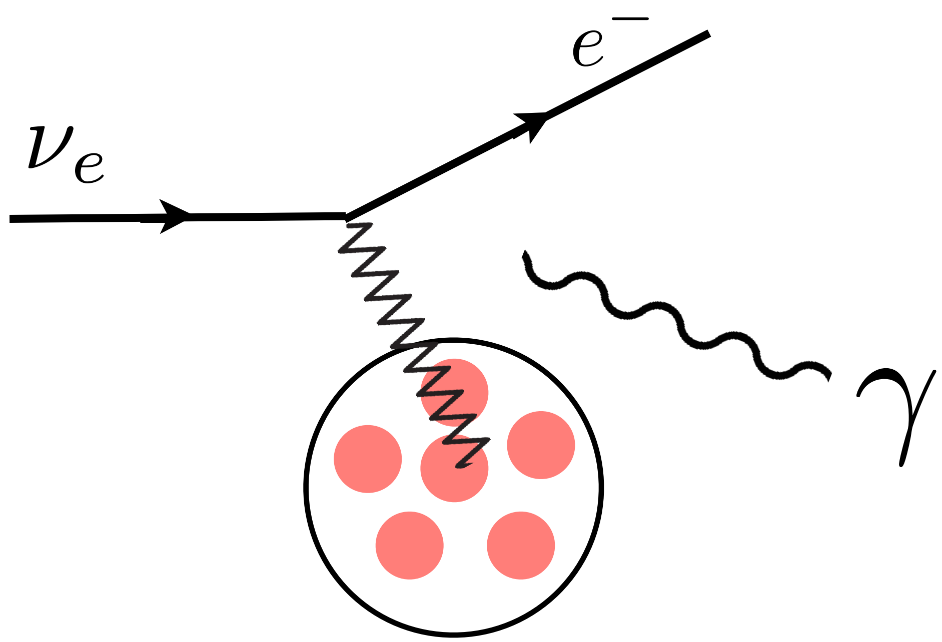
(- important in its own right: Rydberg constant puzzle)

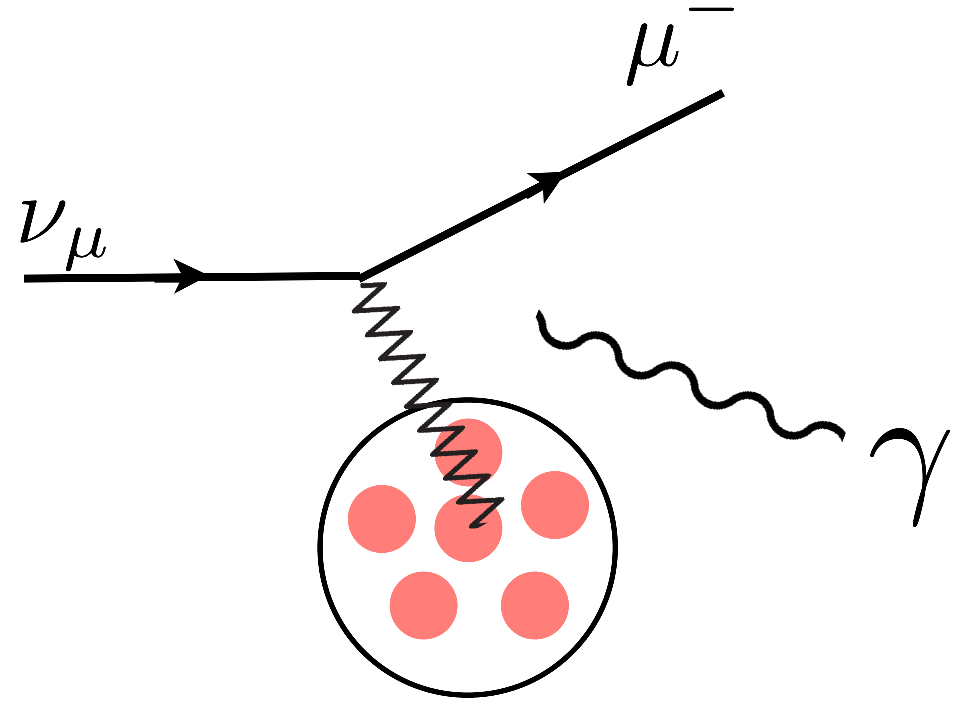
- effective field theory and mass scales



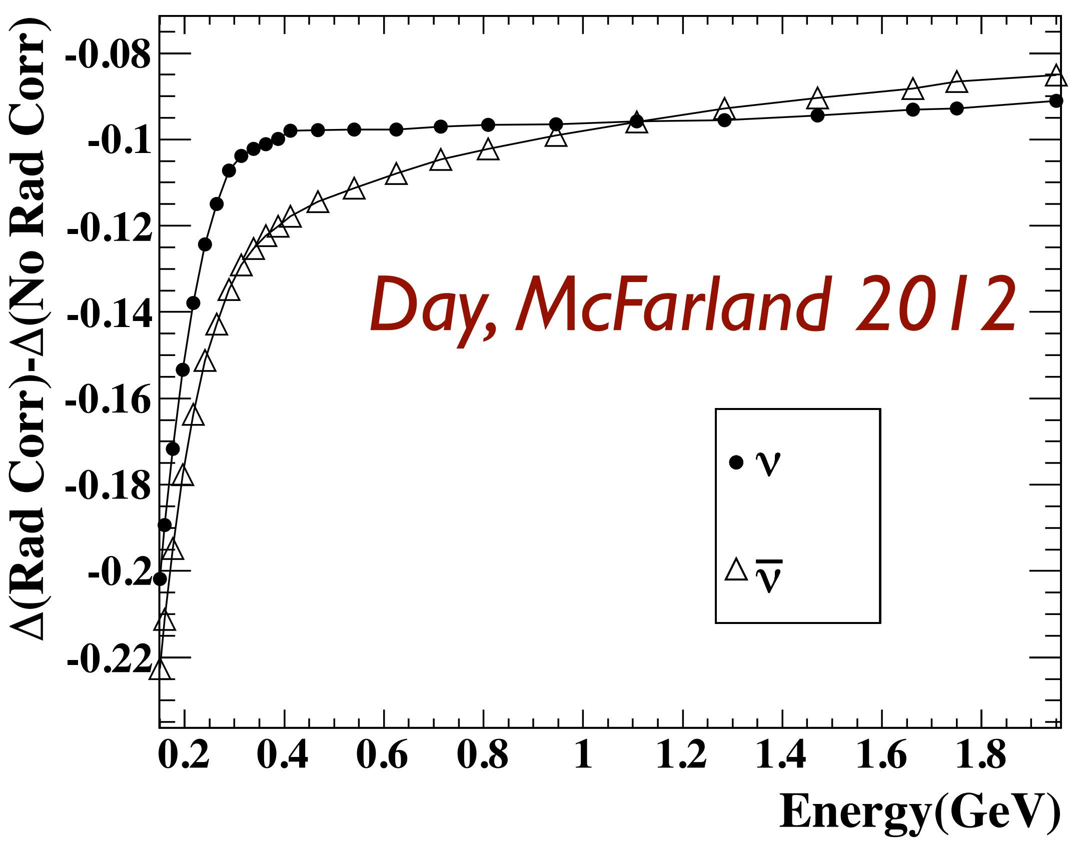
$$\mathcal{L}_{\mathrm{effective}} = c(\mu)\bar{u}_L\gamma^\mu d_L \bar{e}\gamma_\mu \nu_L + \ldots$$

- electromagnetic radiative corrections and neutrino cross sections





- important effects, e.g. comparison of ν_e, ν_μ



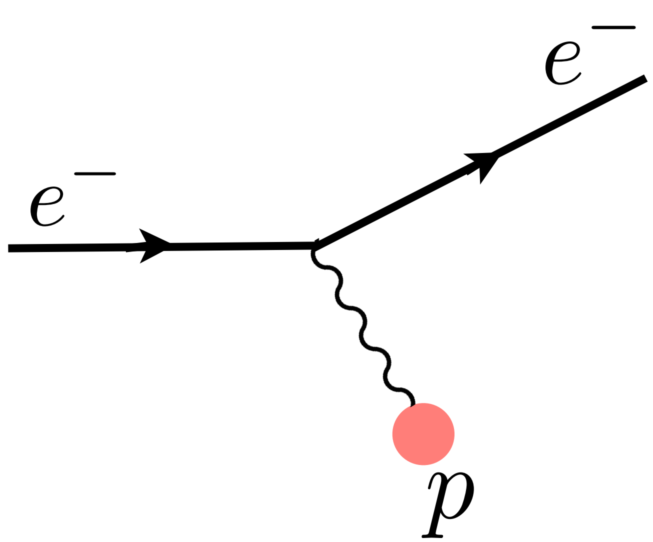
- must be defined/calculated/ implemented in generators, compatible with detector acceptance, selections, etc.

- all important issues appear in e-p scattering where there is much data, controlled flux and nuclear corrections

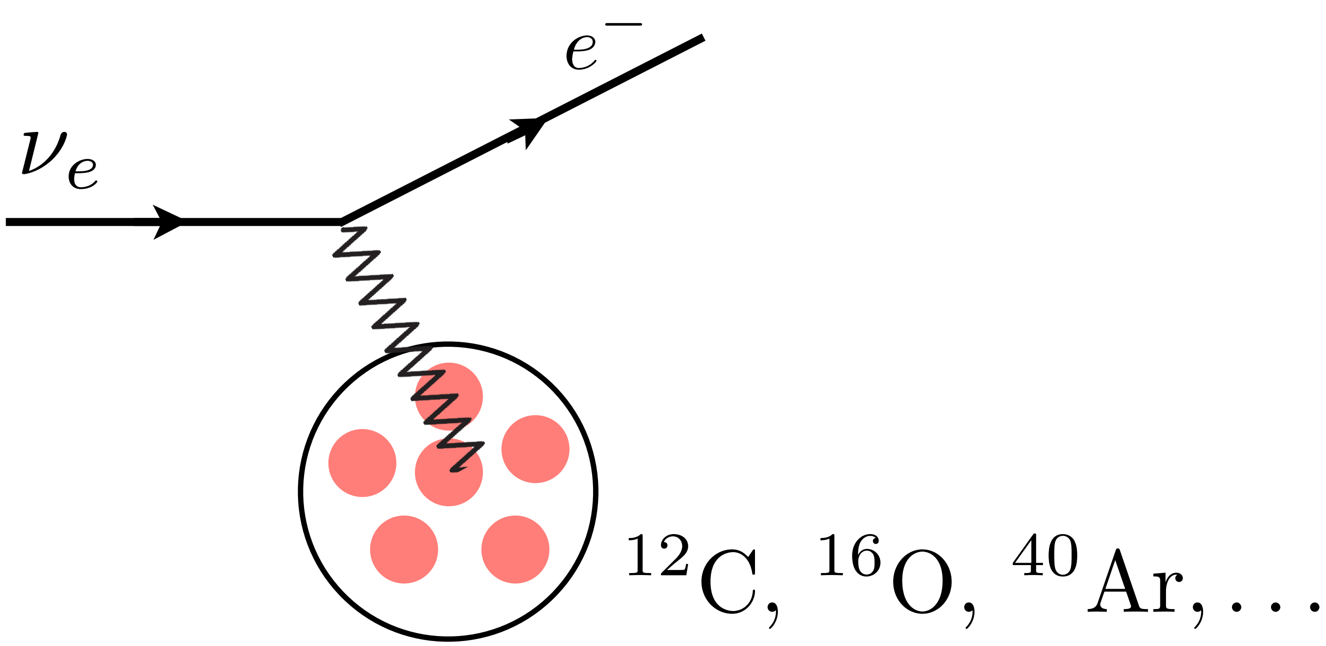
Regardless of the existence of the "proton radius puzzle":

- serious issues to confront in the precision era of lepton-nucleon scattering data
- addressing these issues will be critical to discovery potential of the accelerator neutrino program

e-p scattering



signal process at DUNE, HyperK, NOvA, T2K, ...



Solving the simpler e-p problem prerequisite to more challenging neutrino processes

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
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This *is* HEP's (and everyone'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 precision requirements for oscillation measurements*

Recall hydrogen spectrum:

$$E_n \sim \frac{R_\infty}{n^2} + \frac{r_E^2}{n^3}$$

$$hcR_\infty = \frac{m_e c^2 \alpha^2}{2} \approx 13.6\,\mathrm{eV}$$

proton charge radius

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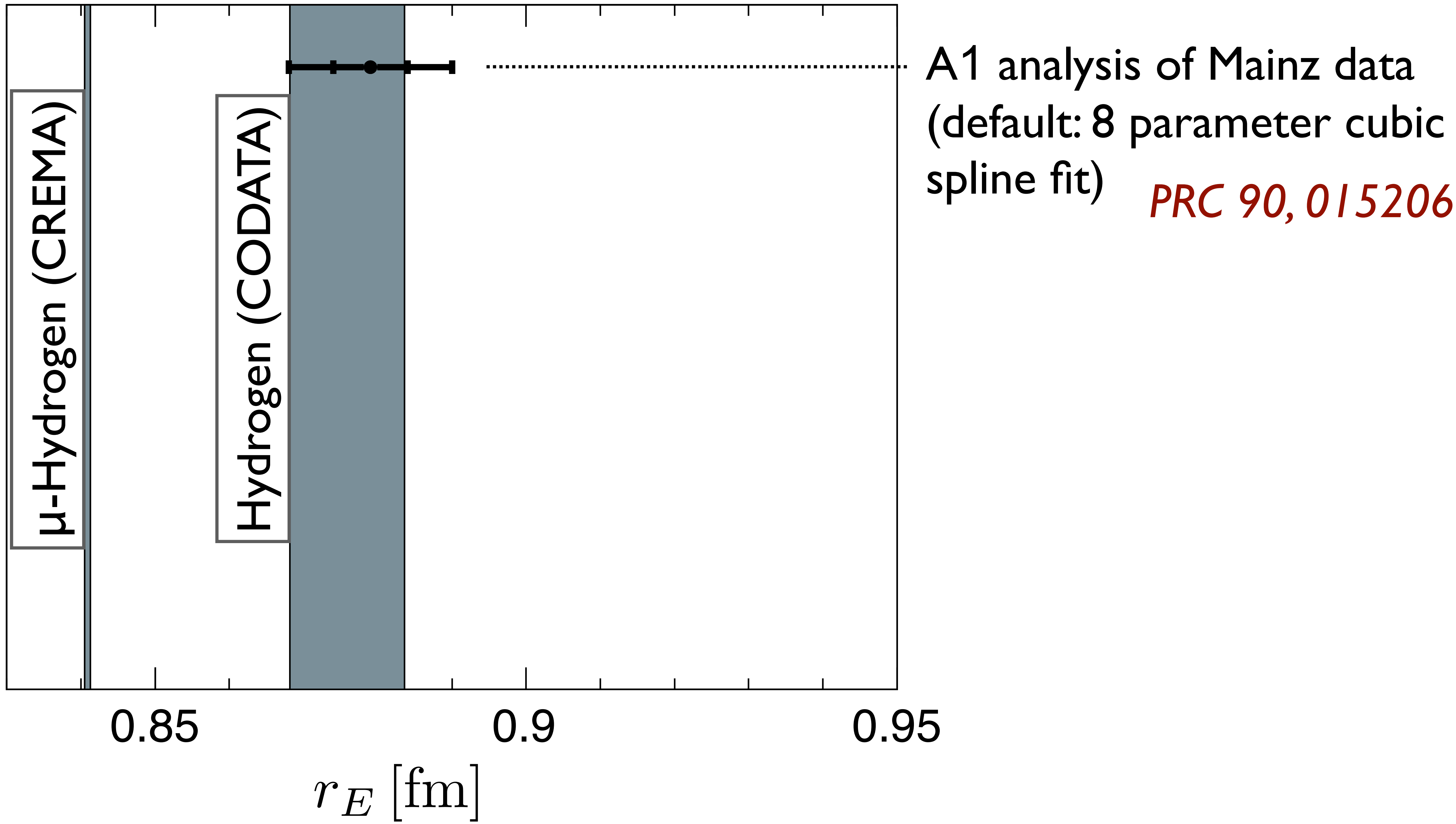
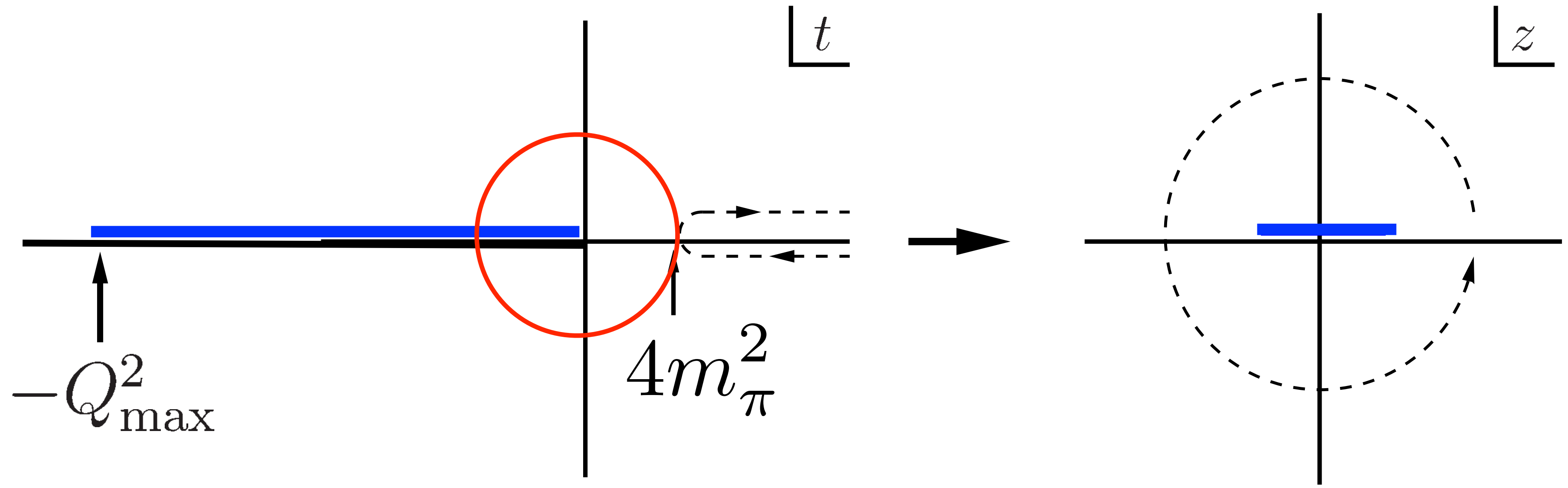
5σ discrepancy in Rydberg constant from (1+2) versus (3)



<u>this talk</u>: new analysis of proton charge and magnetic radii from electron scattering data

1505.01489, with Gabriel Lee, John Arrington

Unfortunately, for the proton form factors, a simple Taylor expansion has finite (small) radius of convergence

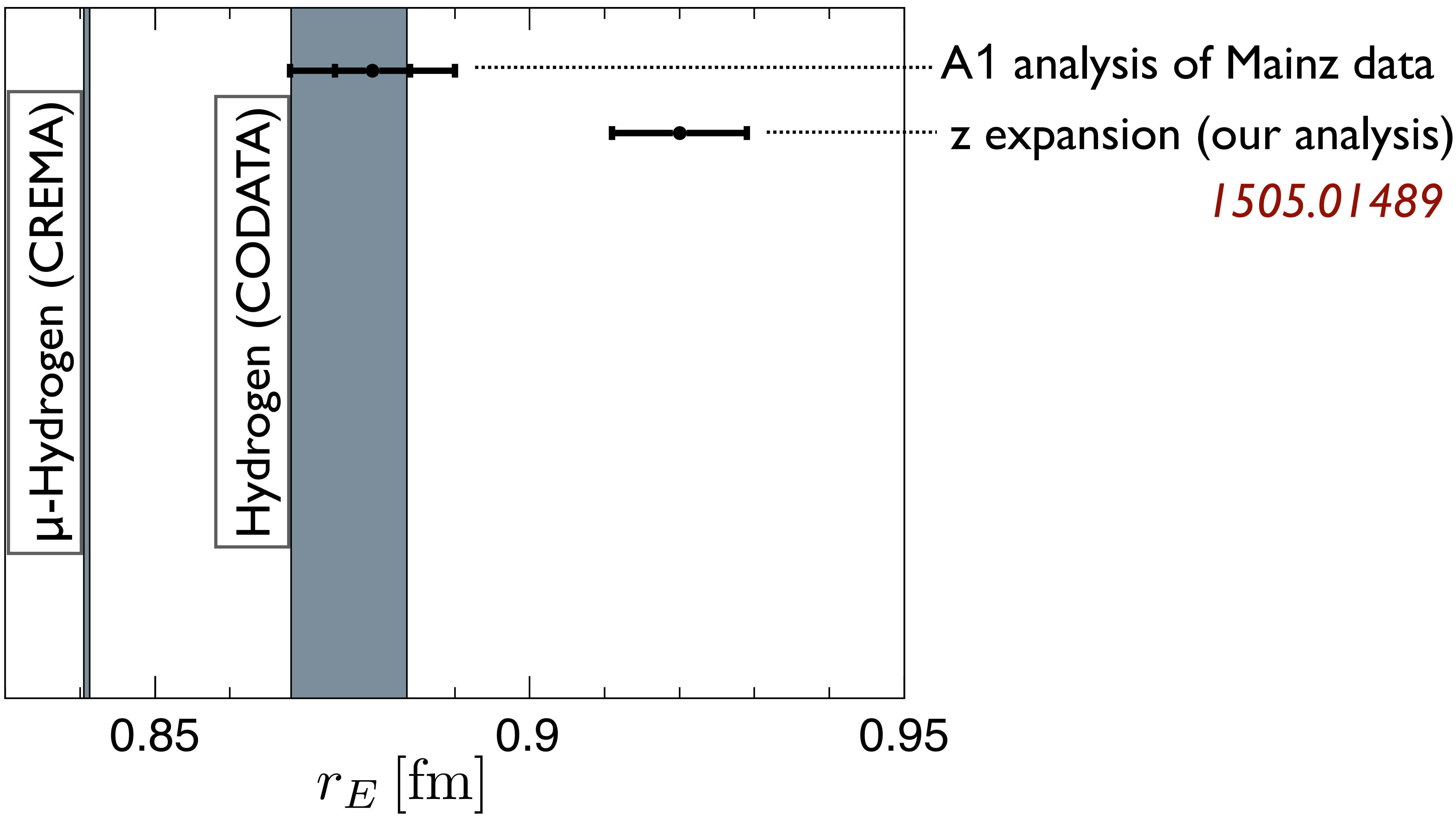


Fortunately, the analytic structure of amplitudes allows us to resum by change of variables into expansion covering the entire physical region

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

Bounded parameter space that contains the true form factor

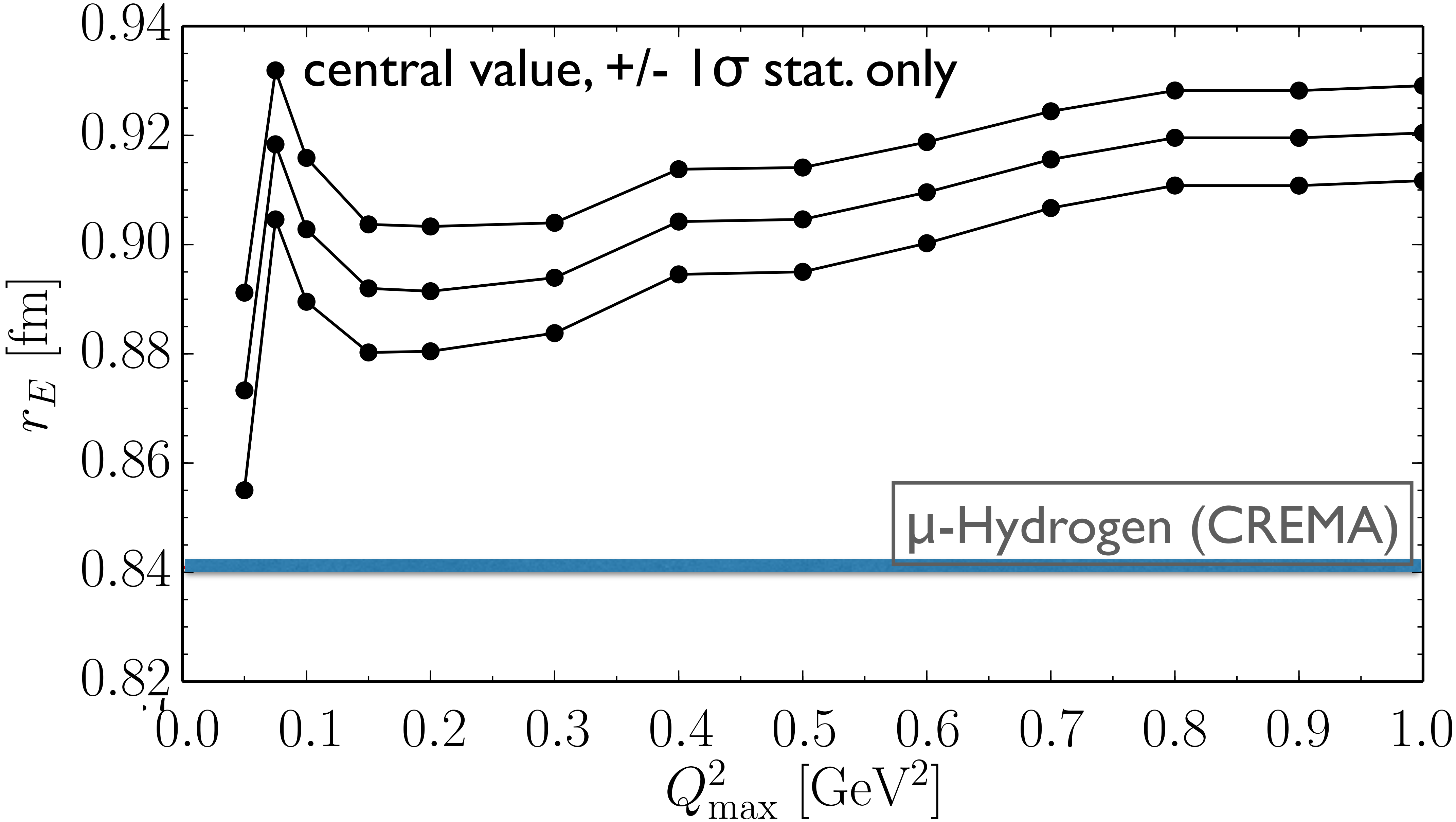
Fit for undetermined order unity coefficients a_k



Require form factors to lie within QCD-constrained class of curves: *larger (7σ) discrepancy with μ-Hydrogen !*

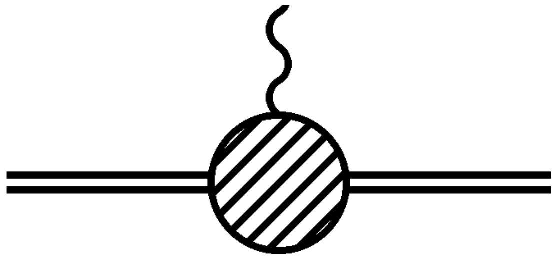
Besides 7σ discrepancy with μH, now 3σ tension with H, 3σ with A1 analysis of same dataset.

Also: tension between fit to entire dataset and fit to data subsets

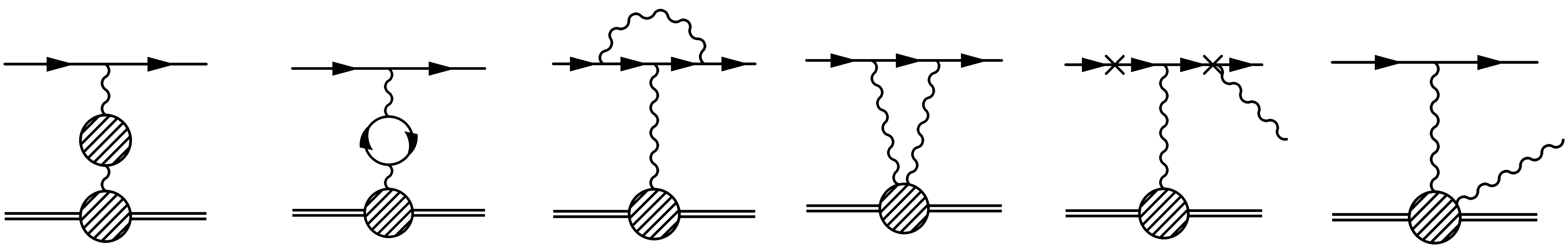


⇒ Form factor shape is important

In order to isolate the proton vertex defining form factors and radius

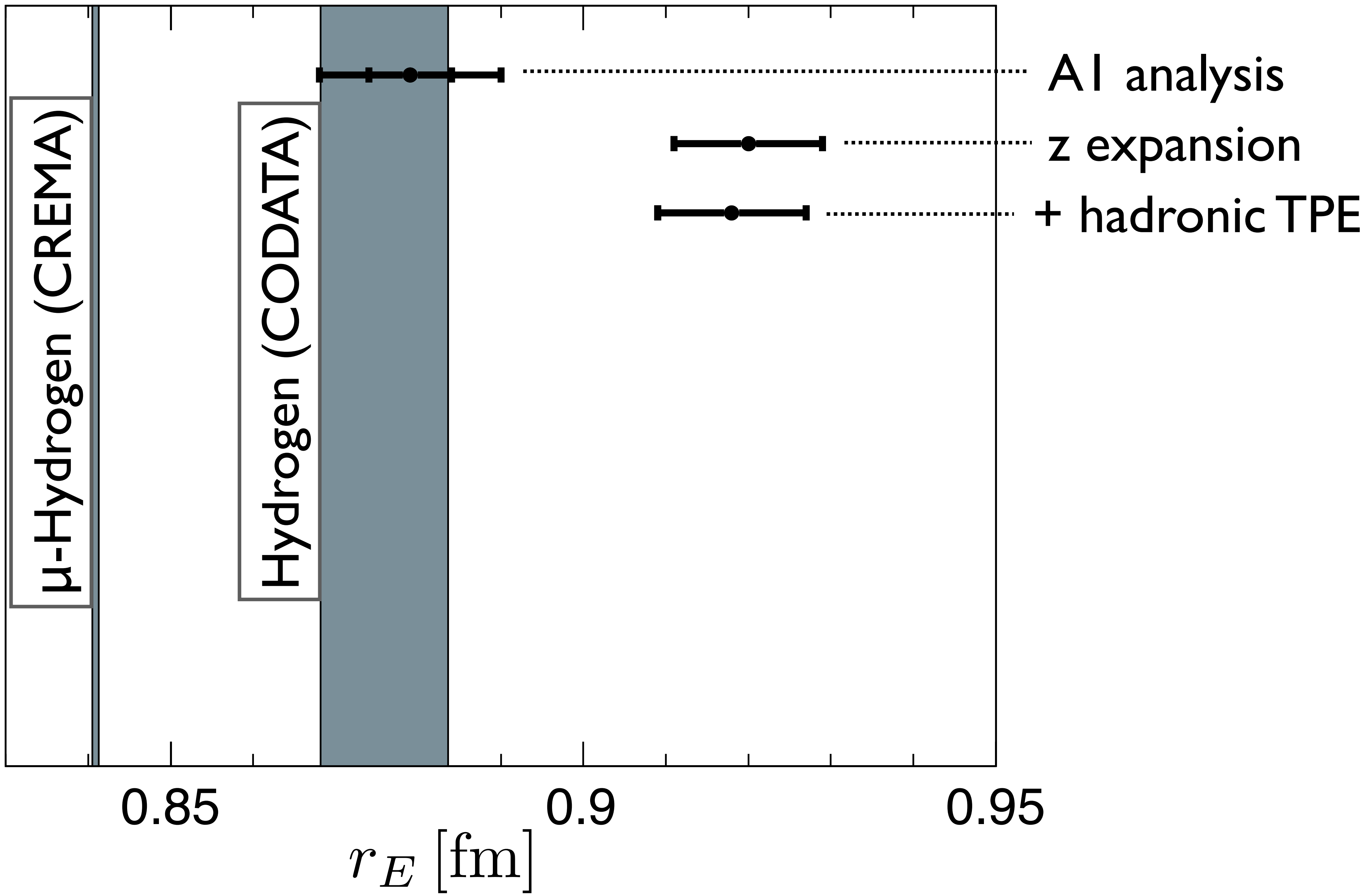


must subtract off radiative corrections that are part of the experimental measurement:



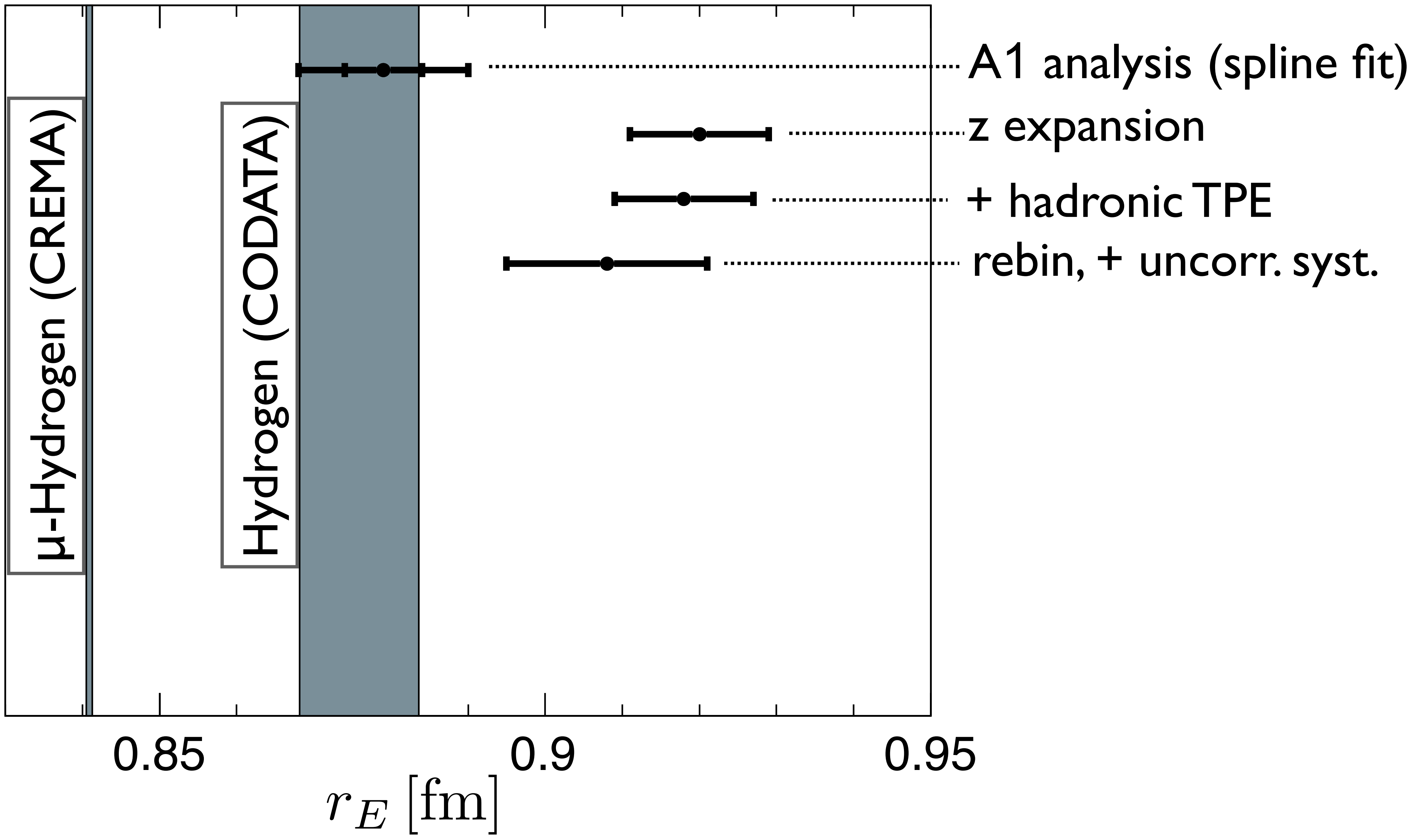
(Through one-loop order, some residual uncertainty from two-photon exchange)

Better one-loop radiative corrections…



Return later to log-enhanced higher-order effects

Improved treatment of uncorrelated systematics…



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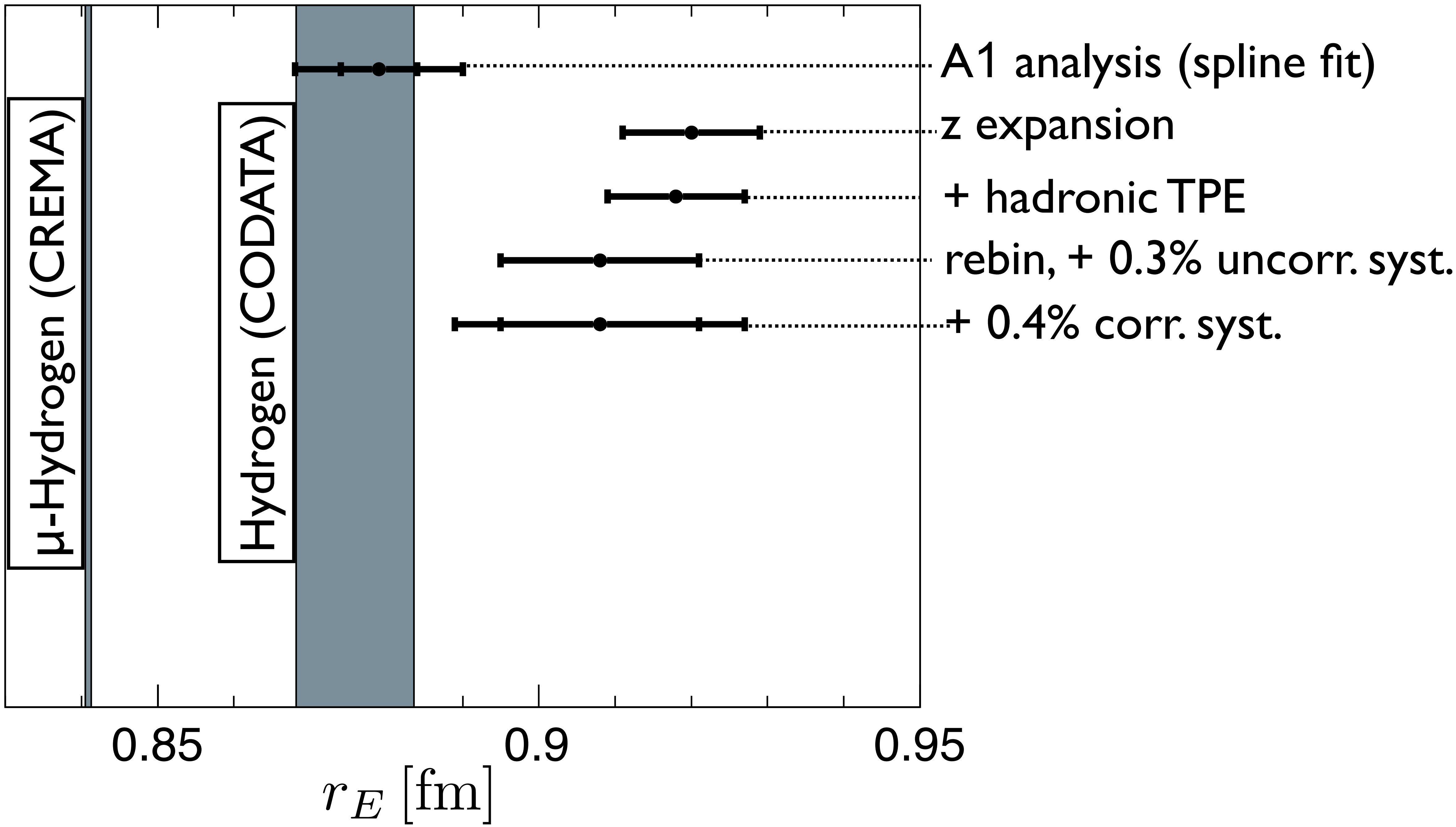
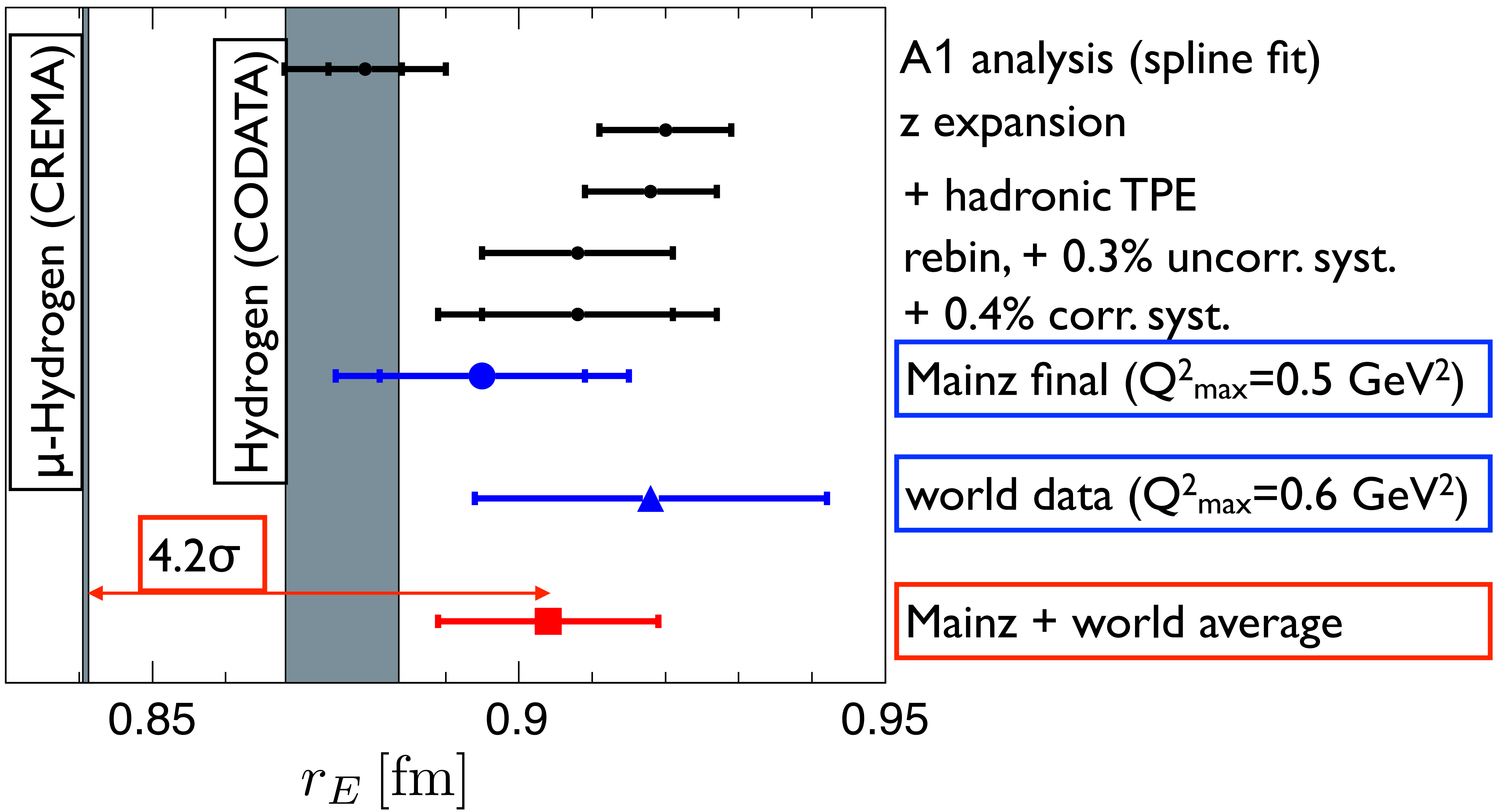


Final results for proton charge radius



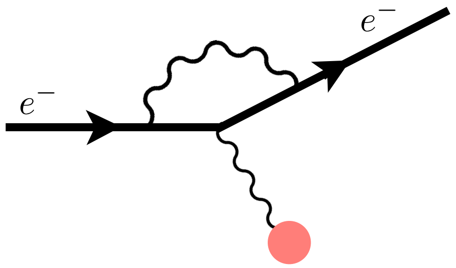
r_E^{Mainz} = 0.895(14)(14)

r_E^{world} = 0.918(24)

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

Large logarithms spoil QED perturbation theory when $Q^2 \sim$??

$$|F(q^2)|^2 \to |F(q^2)|^2 \left(1 - \frac{\alpha}{\pi} \log^2 \frac{Q^2}{m_e^2} + \dots \right)$$



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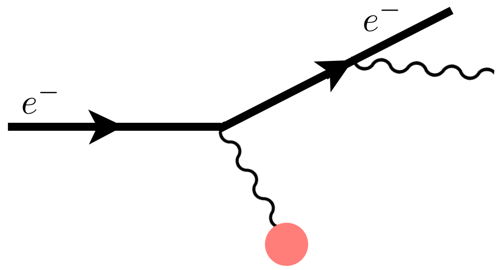
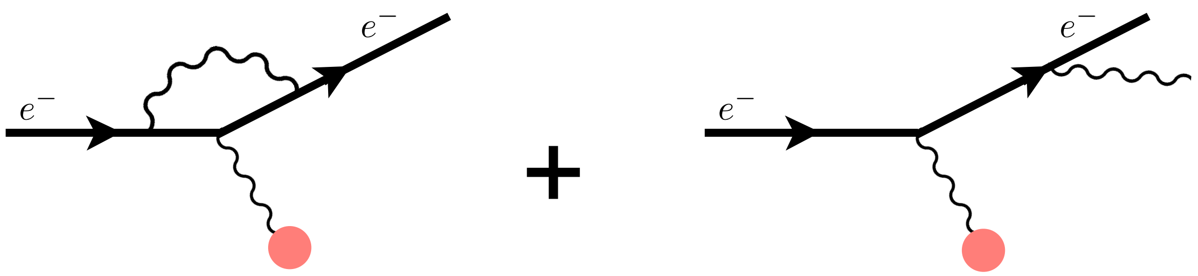


Large logarithms spoil QED perturbation theory when $Q^2 \sim$ GeV^2

$$|F(q^2)|^2 \to |F(q^2)|^2 \left(1 - \underbrace{\frac{\alpha}{\pi} \log^2 \frac{Q^2}{m_e^2}}_{} + \dots \right)$$

≈ 0.5 at $Q^2 \sim$ GeV^2



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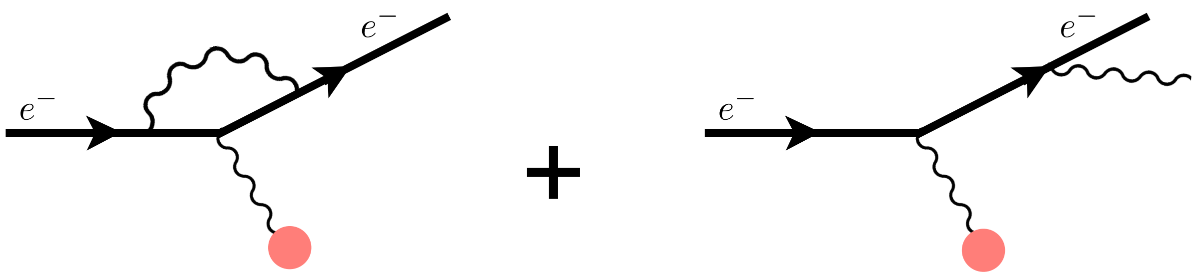


A standard ansatz sums leading logarithms by exponentiating 1st order:

$$|F(q^2)|^2 \left(1 - \frac{\alpha}{\pi} \log \frac{Q^2}{m_e^2} \log \frac{E^2}{(\Delta E)^2} + \dots \right) \to |F(q^2)|^2 \exp \left[-\frac{\alpha}{\pi} \log \frac{Q^2}{m_e^2} \log \frac{E^2}{(\Delta E)^2} \right]$$

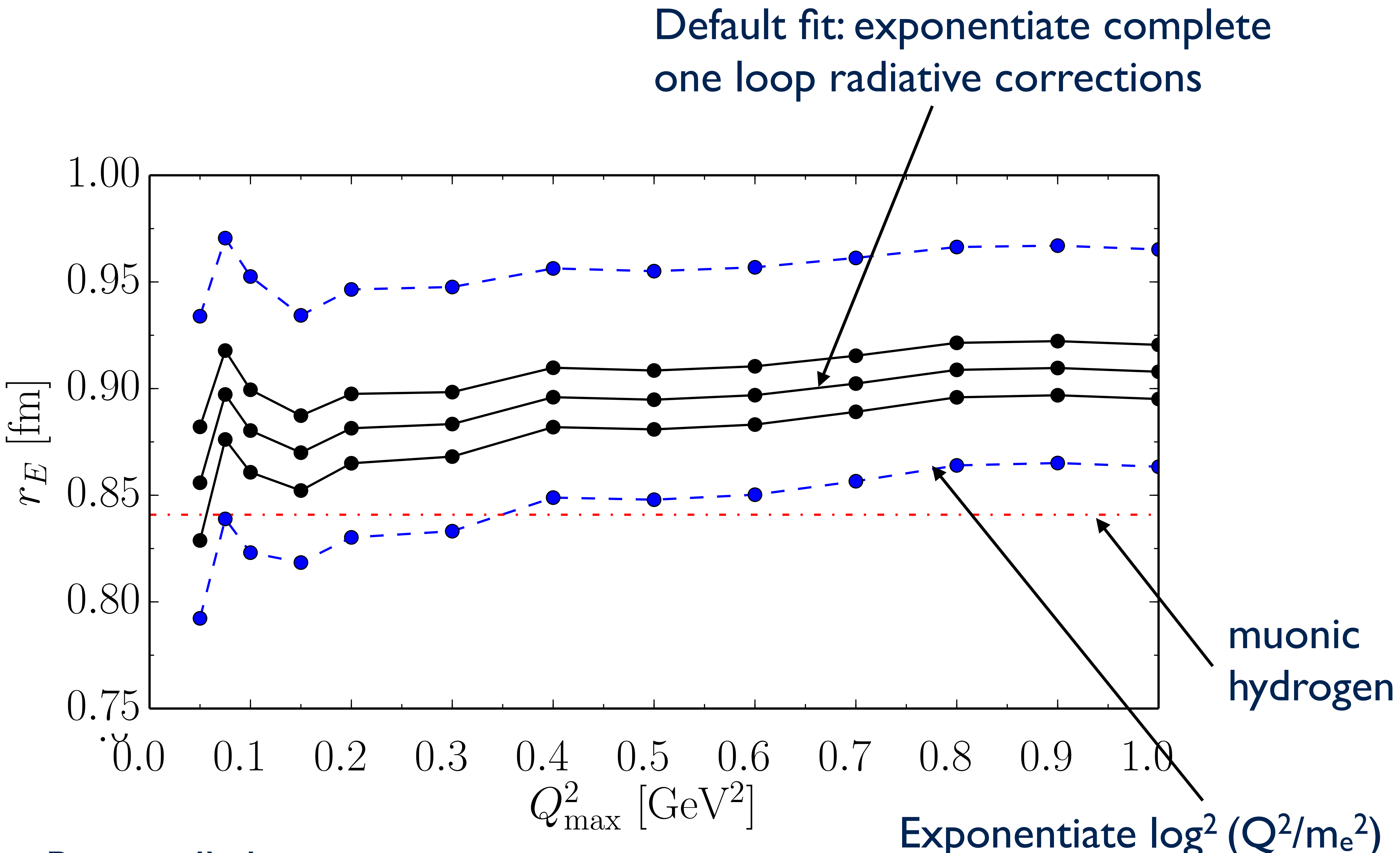
Yennie, Frautschi, Suura, 1961

Captures leading logarithms when

$$Q \sim E \,, \quad \Delta E \sim m_e$$

As consistency check, should find the same result for resumming:

$$\log^2 \frac{Q^2}{m_e^2} \qquad \text{vs.} \qquad \log \frac{Q^2}{m_e^2} \log \frac{E^2}{(\Delta E)^2}$$

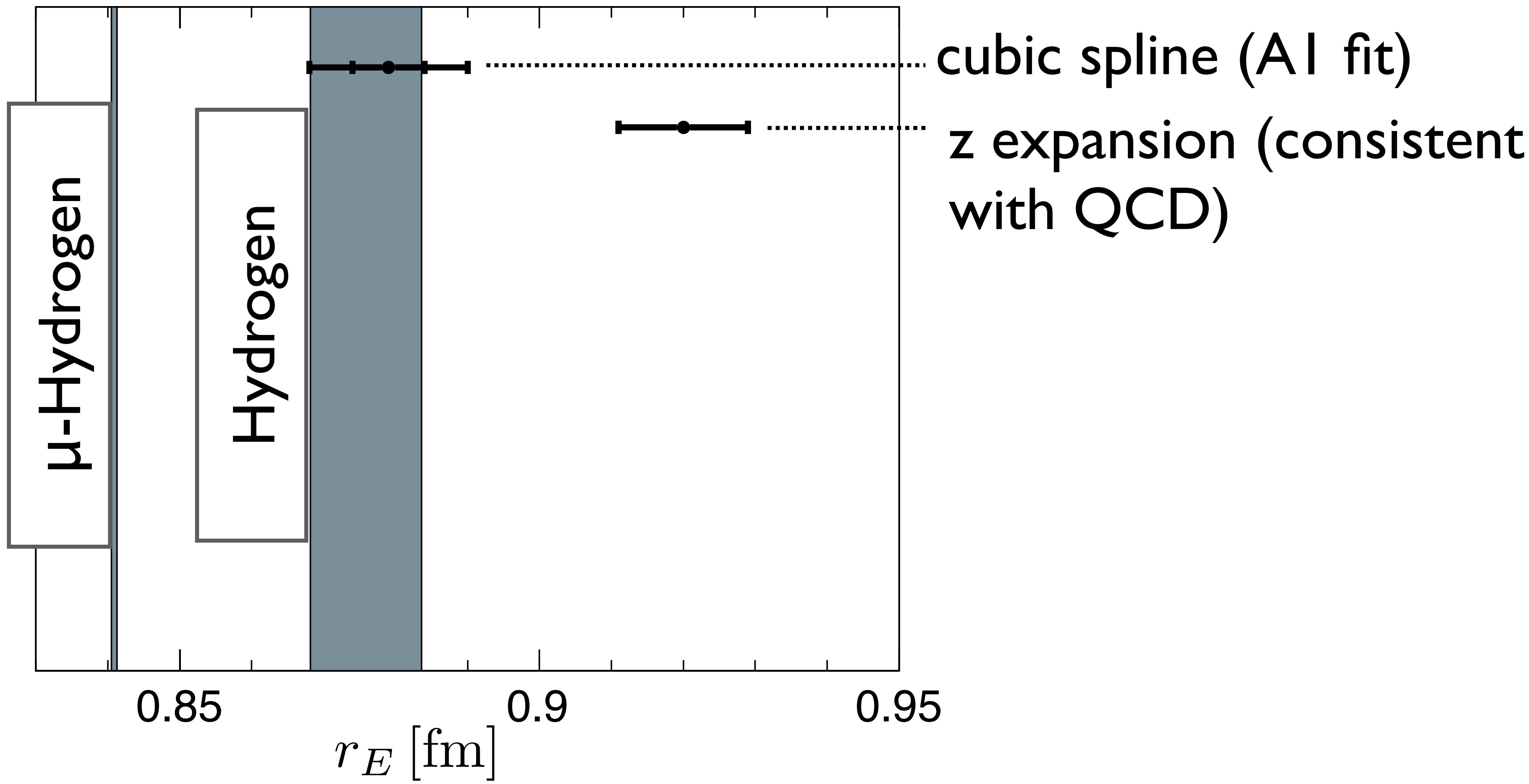


Potentially large corrections.

More detailed analysis of subleading radiative corrections required and in progress. Have presented results using ("state of the art") standard radiative correction models.

Lessons for neutrino scattering

1) form factor shape assumptions matter



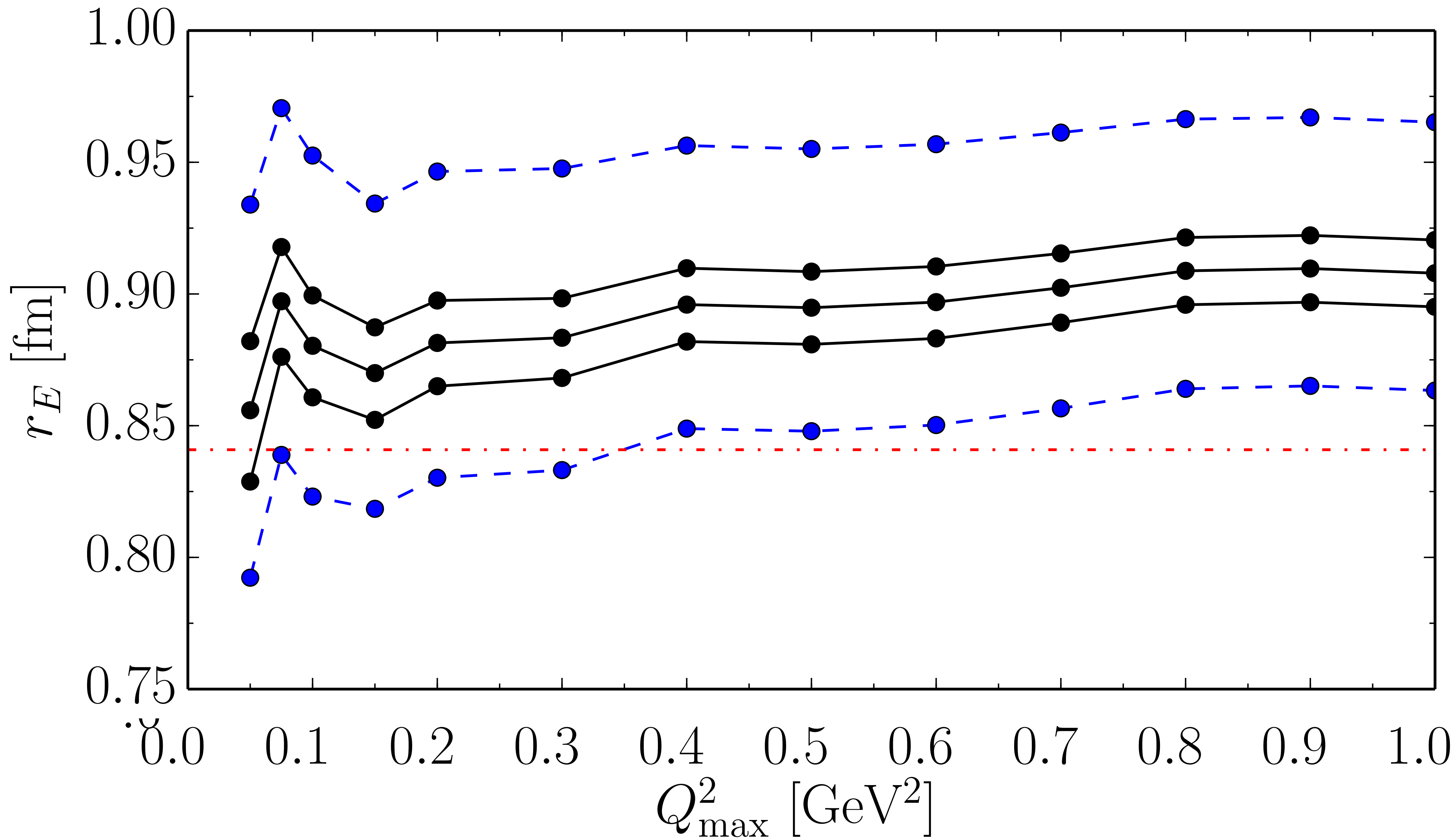
Determinations of r_E differ by as much as 8%.

World average r_A quoted with uncertainty ≲ 2%

very likely an underestimate relying on assumed dipole shape (cf. A. Meyer's talk)

Lessons for neutrino scattering

2) radiative corrections matter



The order at issue in e-p scattering is the same order that appears (and is presently ignored) in ν-N scattering

Summary

Particle theory toolbox is being applied to neutrino cross sections

A systematic framework is being constructed to map elementary-target/lattice data through to oscillation observables

Demonstrated with electron-proton scattering

Both form factor shape and radiative corrections are important, and require refined treatment

Similar techniques may be applied to elementary-target neutrino data

- Limited statistics from bubble chamber data *(see A. Meyer)*
- First principles calculations from lattice QCD *(see A. Kronfeld)*

<u>Comments and points for discussion</u>

- Important to quantify the impact of elementary target + nuclear + radiative correction + other uncertainty on oscillation observables

  (what is the impact of X ? In many cases, easy to see that corrections are "large", but quantification needed in order to focus effort)

- It is a collaborative effort. Not just HEP. Not just nuclear. (definitions may be unhelpful)

- There are interesting, timely, theory problems directly impacting neutrino cross sections.   Precision lattice baryon matrix elements. SCET for exclusive lepton/nucleon processes (+ BSM, + nuclear + …)

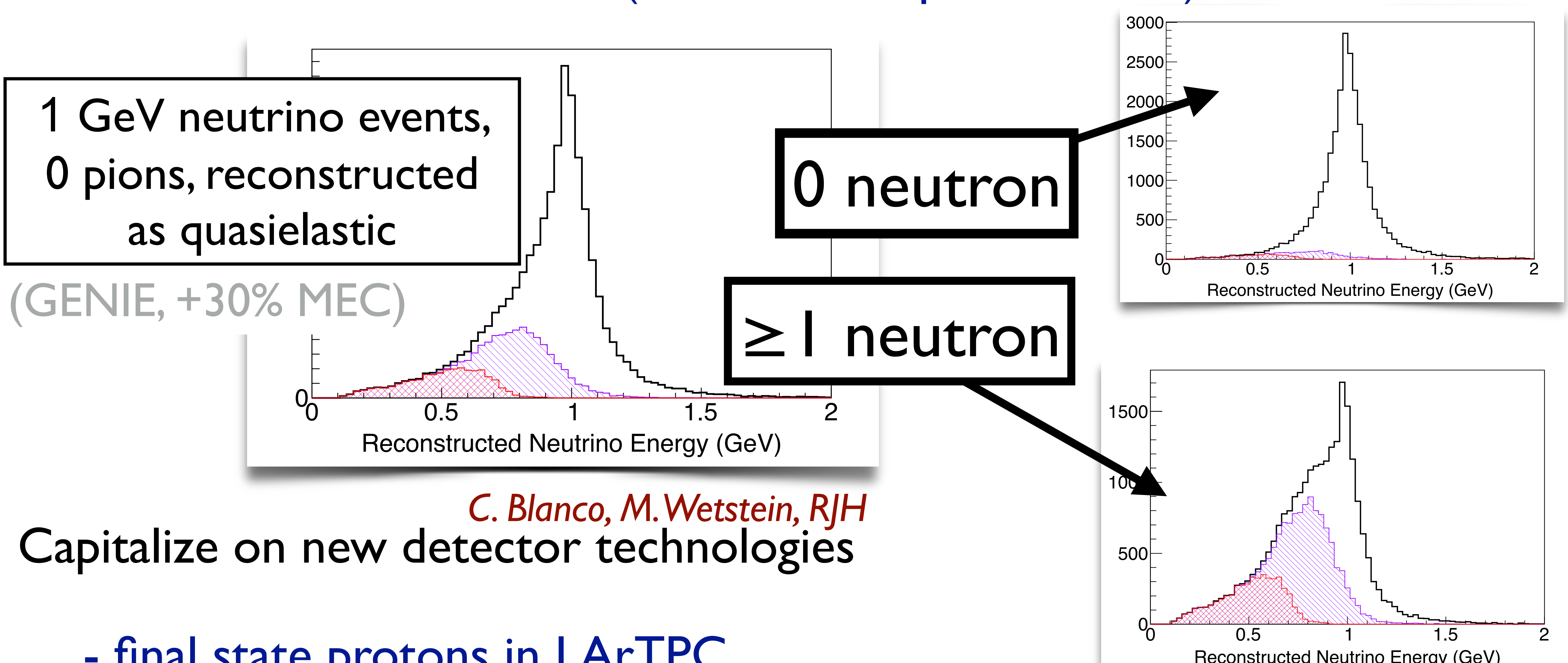
exciting theory! | *exciting applications!* | *exciting opportunities!*

back up

Nuclear effects and energy reconstruction biases

cf. colliders: define event classes to isolate underlying parton mechanisms (vector boson fusion, gluon fusion,…)

for neutrinos: define event classes with (in)sensitivity to underlying nucleon-level mechanisms (multinucleon processes,…)

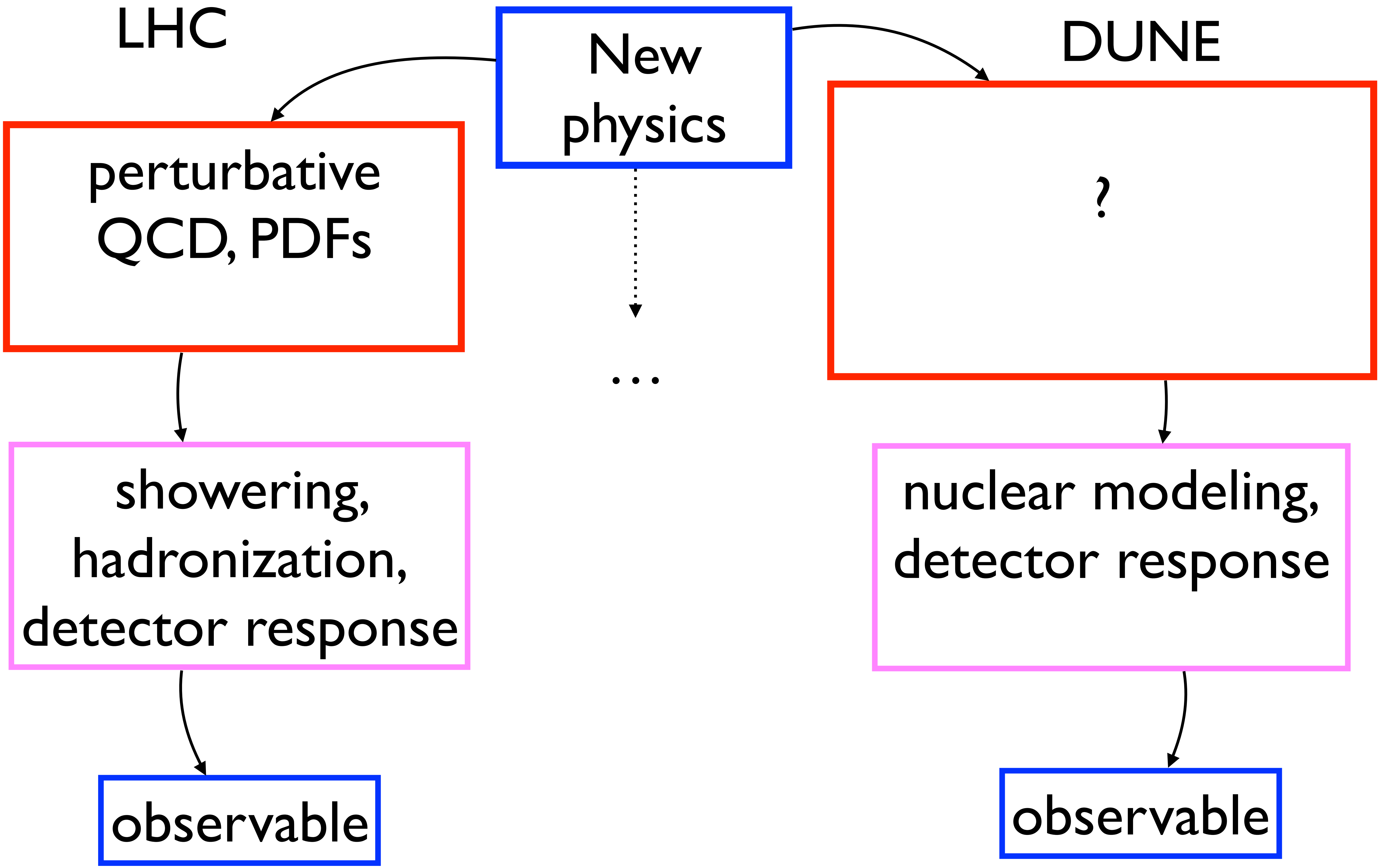


C. Blanco, M. Wetstein, RJH

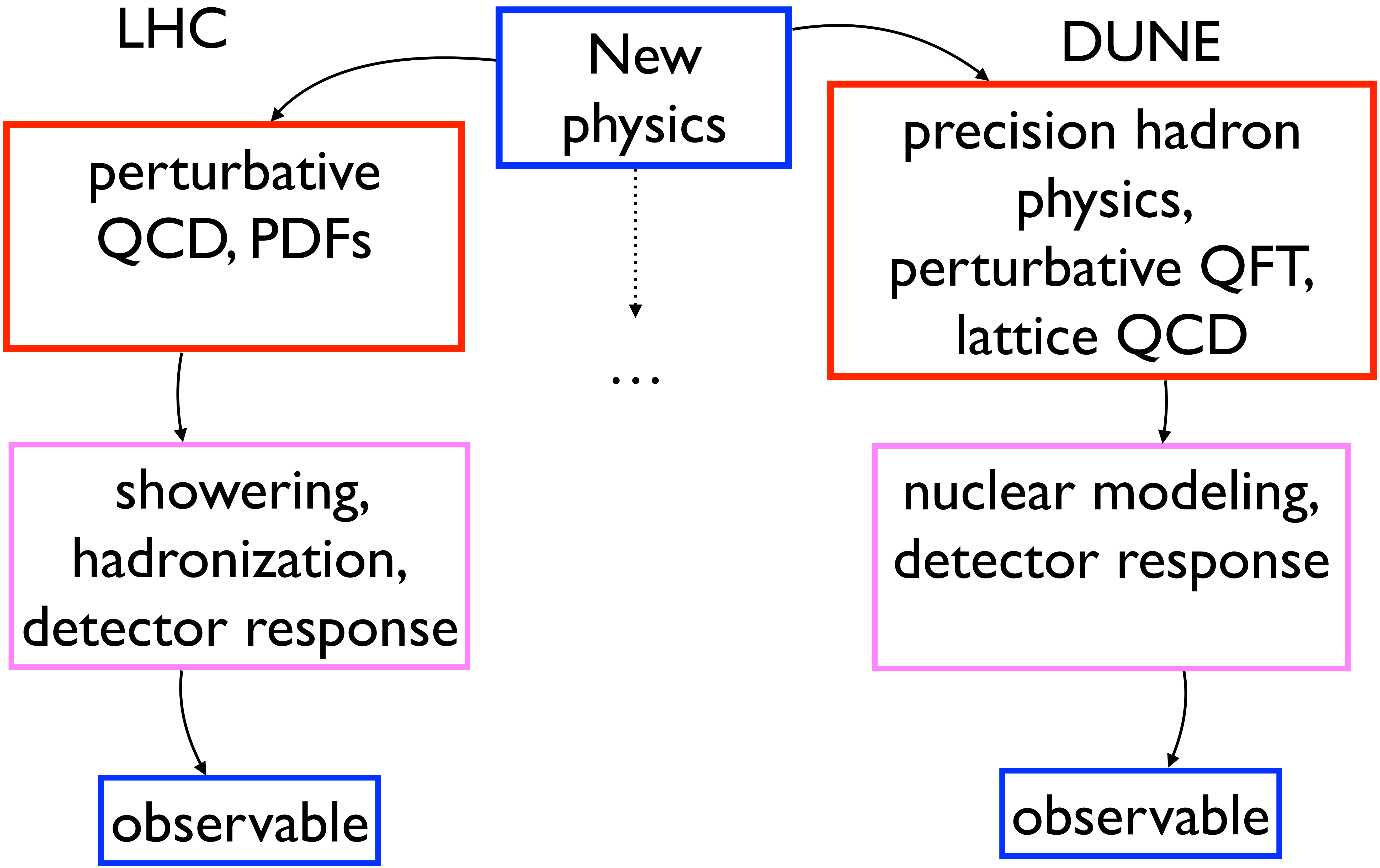
Capitalize on new detector technologies

- final state protons in LArTPC
- final state neutrons (WC: ANNIE, LAr: CAPTAIN)

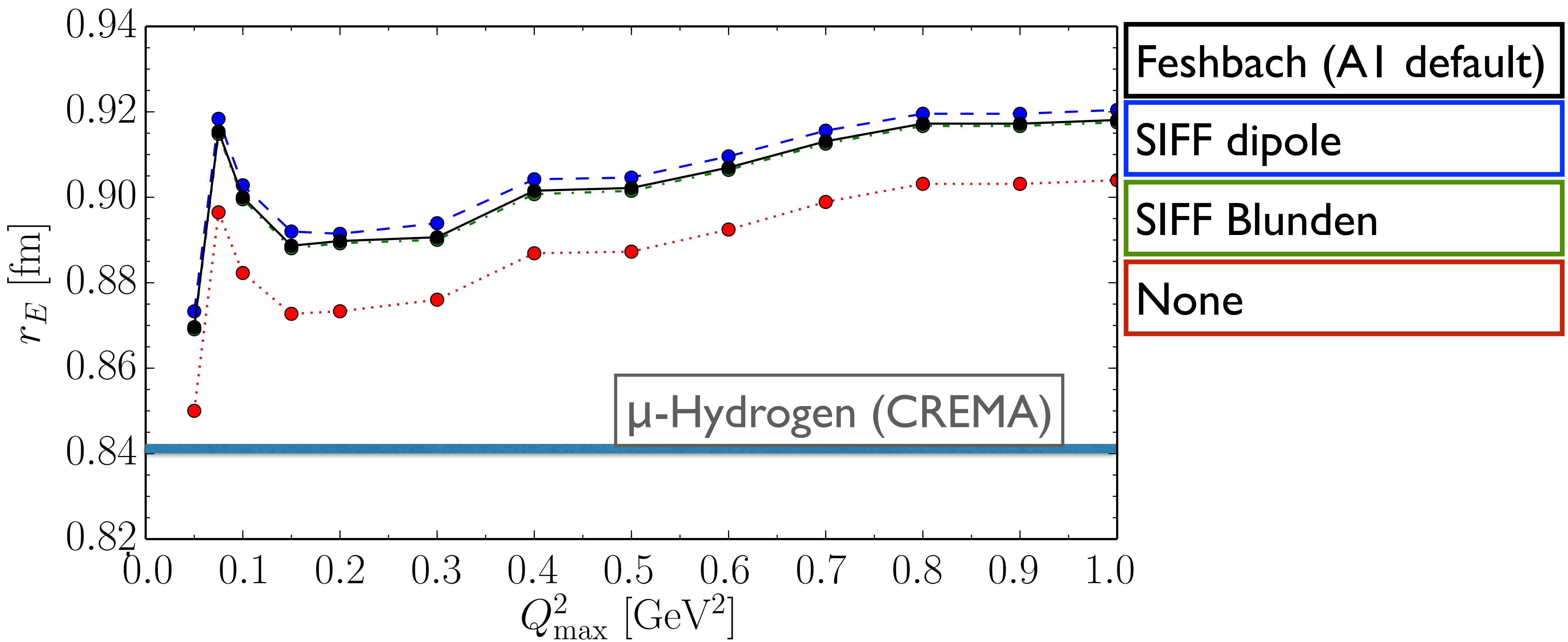
Q: What is HEP theory doing about this problem?



Q: What is HEP theory doing about this problem?



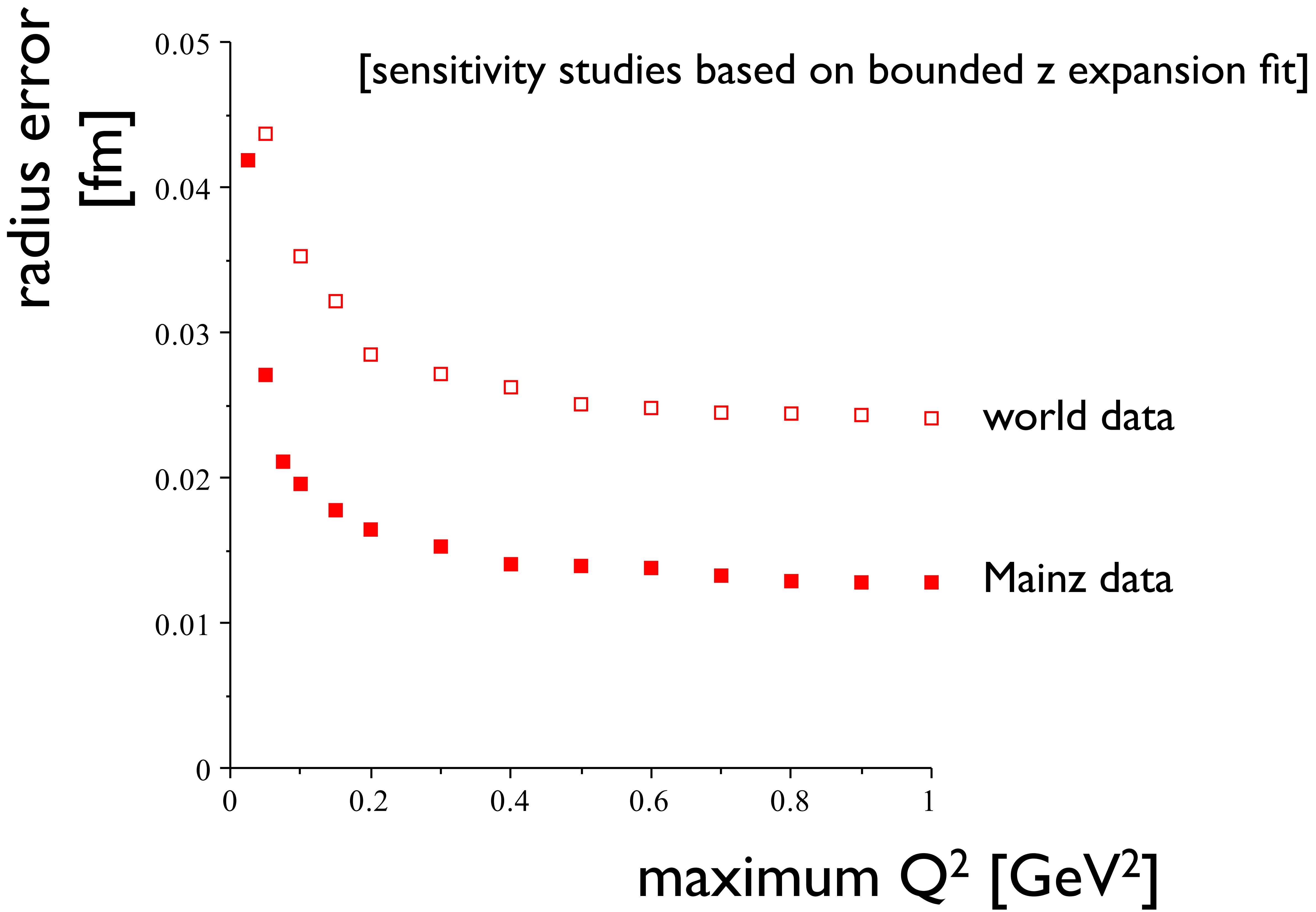
Consider a range of one-loop Two-Photon Exchange (TPE) corrections



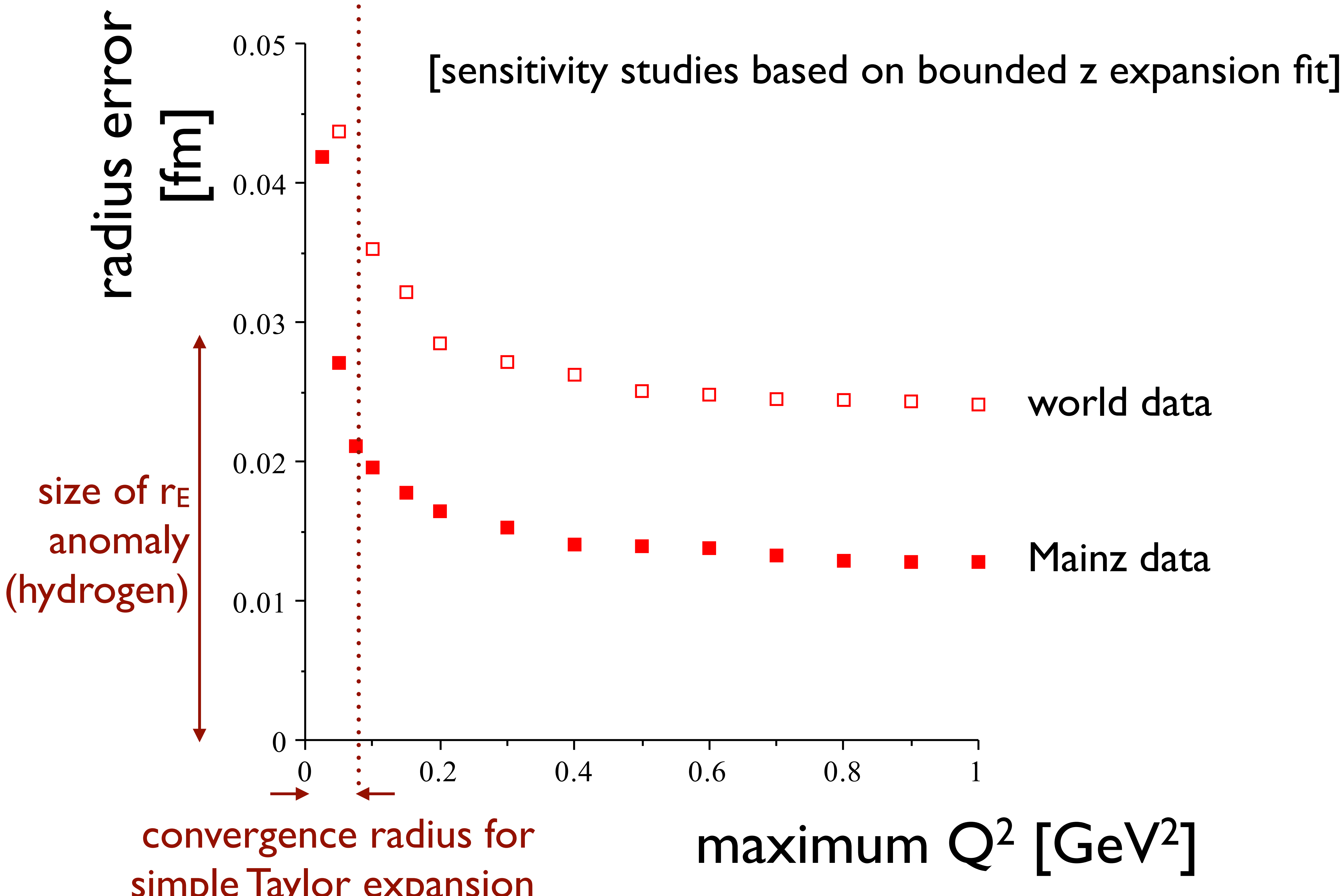
Model dependence in TPE, but appears small for r_E

Take Blunden et al. hadronic model as default *PRC 72, 034612*

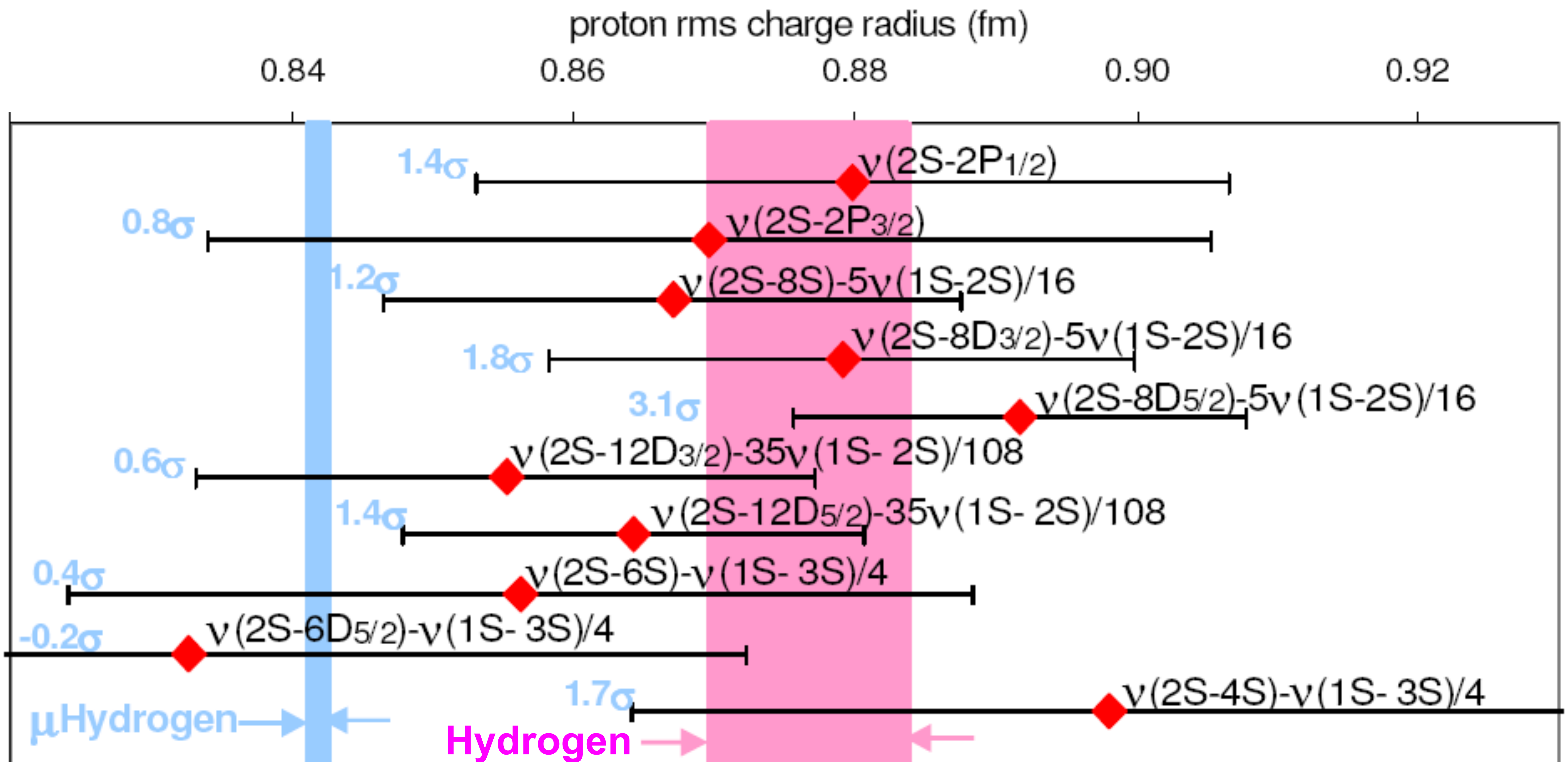
Radius defined as slope. Requires data over finite Q^2 range



Radius defined as slope. Requires data over finite Q^2 range



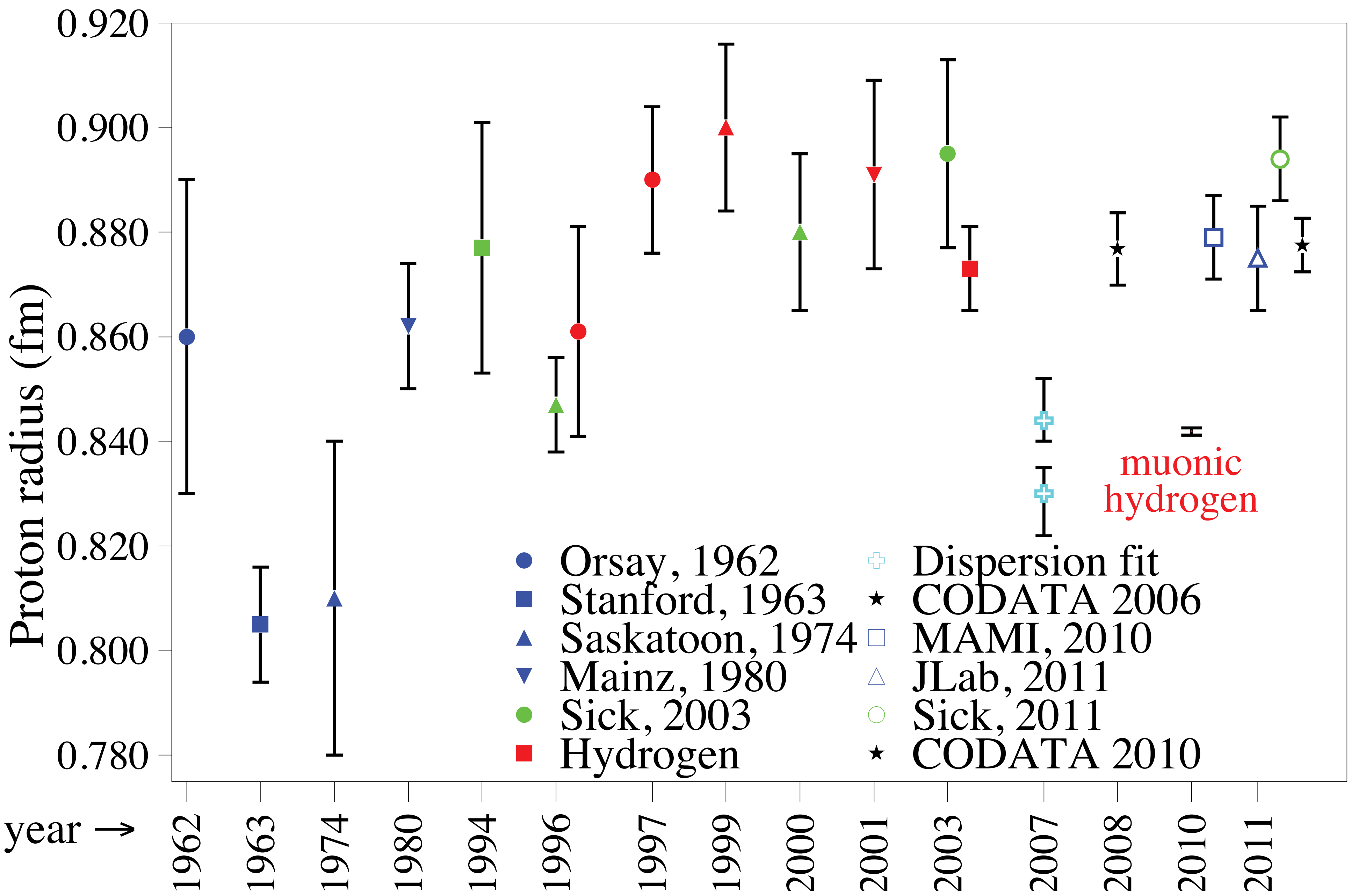
Experimental landscape: hydrogen



plot courtesy E. Hessels, proton radius workshop 2014

- no straightforward systematic explanation identified, but ~5σ deviation results from summing many ~2σ effects

Experimental landscape: historical e-p extractions



From Pohl et al., Ann.Rev.Nucl.Part.Sci. 63, 175