Effective theories for accelerator neutrino cross sections

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28th Rencontres de Blois

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Overview

- introduction: importance of accelerator neutrino cross sections ($E_\nu \sim$ GeV)

- deuteron constraints on the elementary signal process $\sigma(\nu_\ell n \to \ell^- p)$

  1603.03048, with A. Meyer, M. Betancourt and R. Gran and related work with B. Bhattacharya and G. Paz

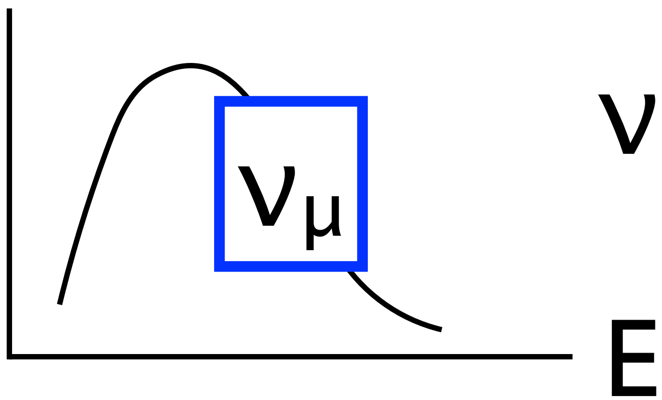
- new formalism for radiative corrections impacting $\sigma(\nu_e n \to e^- p)/\sigma(\nu_\mu n \to \mu^- p)$

  1605.02613, and related work with J. Arrington, G. Lee

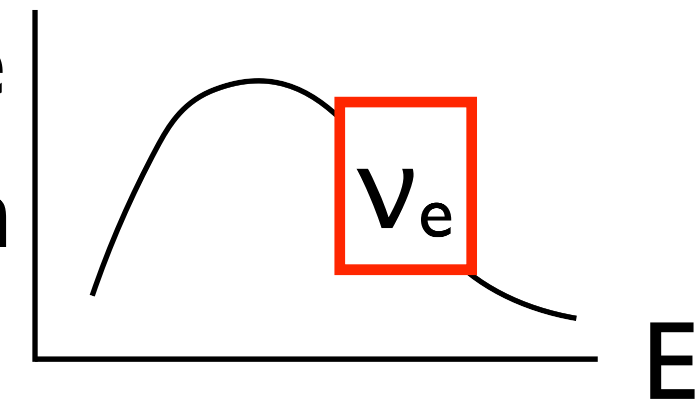
- summary

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

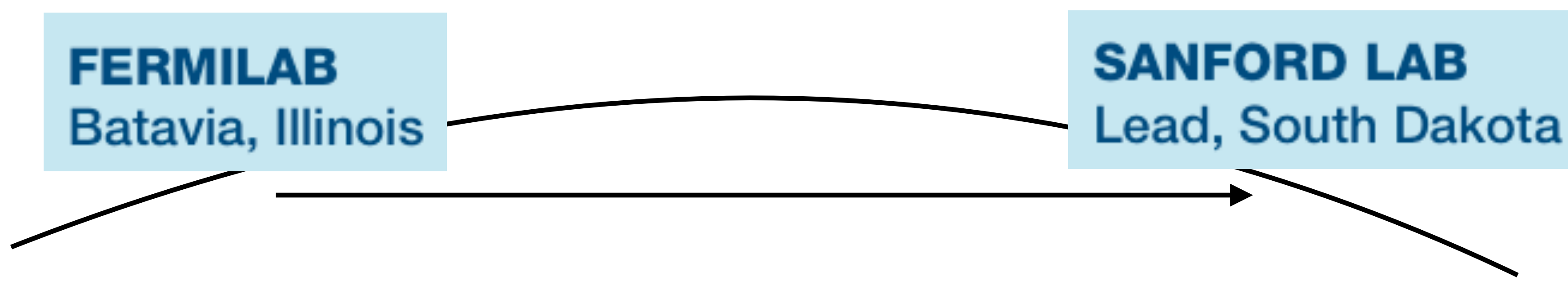
ν_μ flux



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

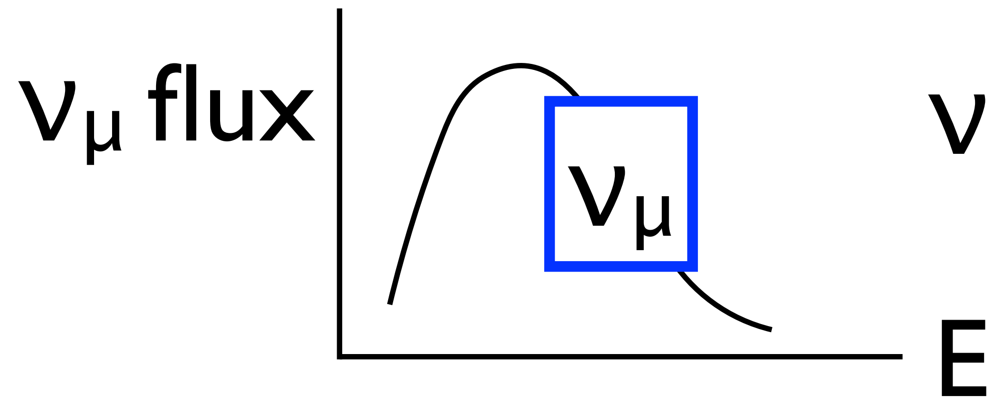


E.g. DUNE



Cross section translates observed event rate to ν_e appearance prob.

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



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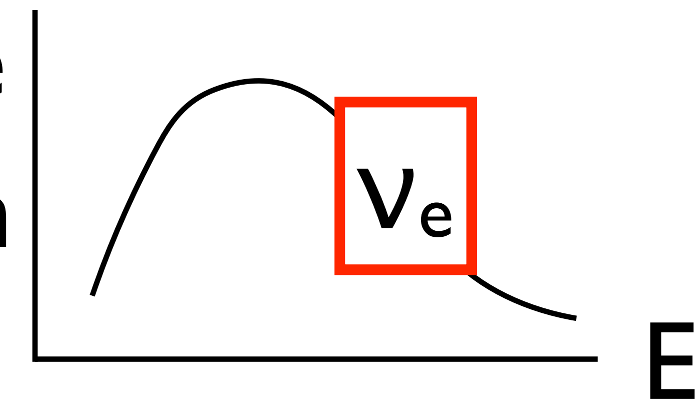

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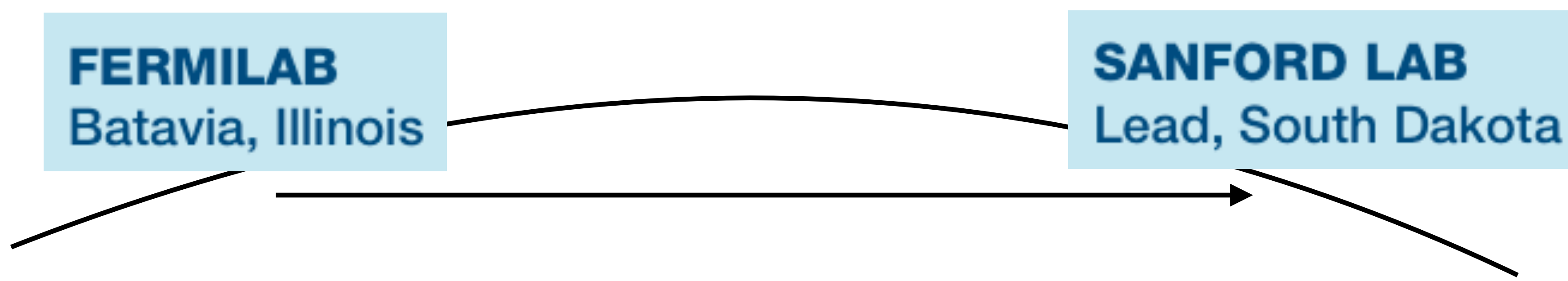

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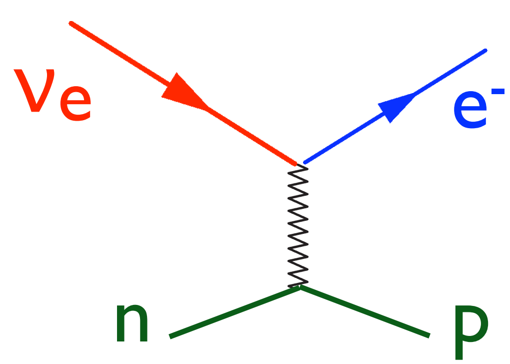
Basic signal process: charged current quasi elastic scattering

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



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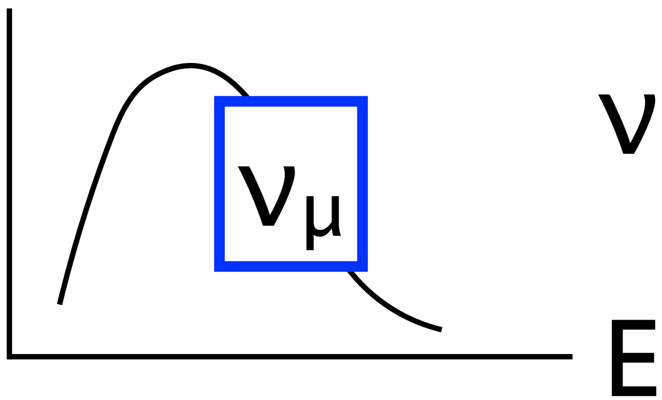

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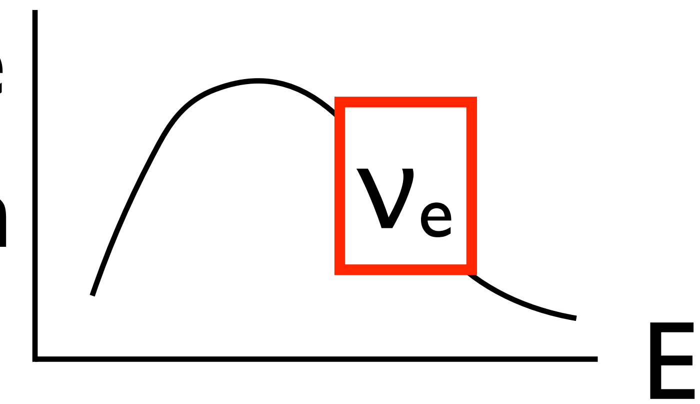

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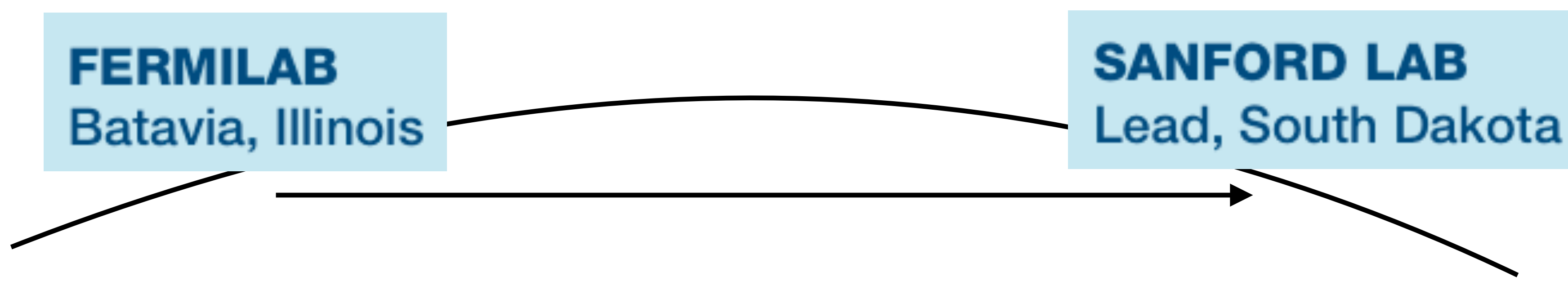

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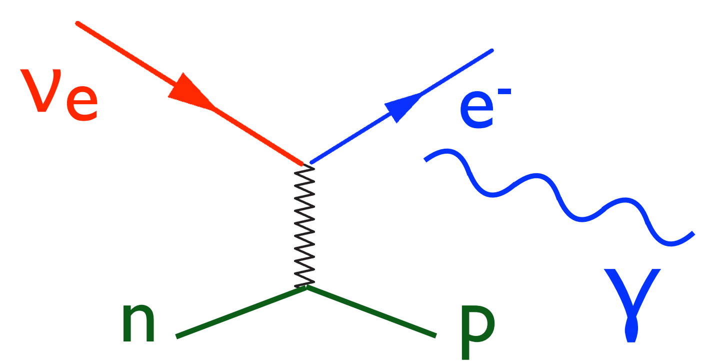
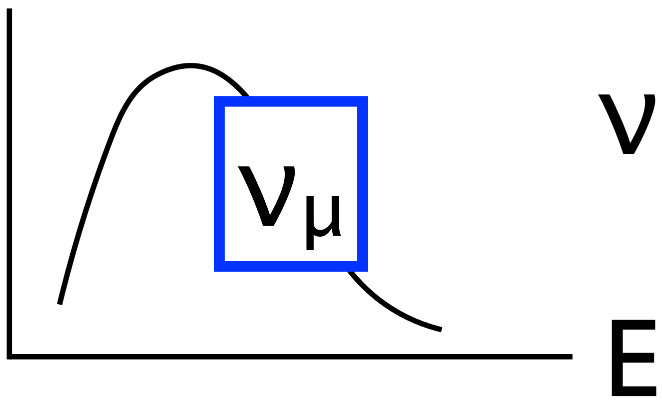


radiative corrections

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

ν_μ flux



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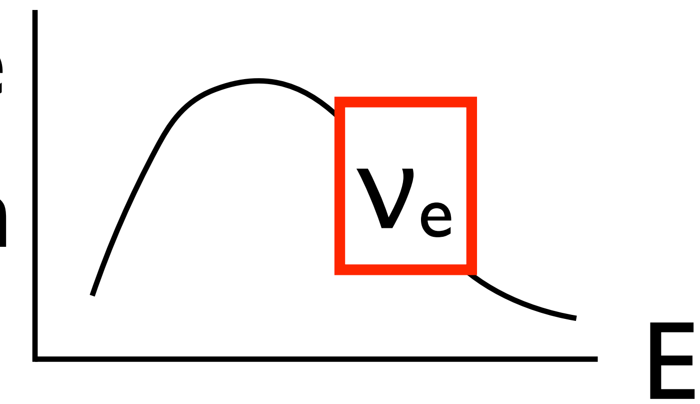

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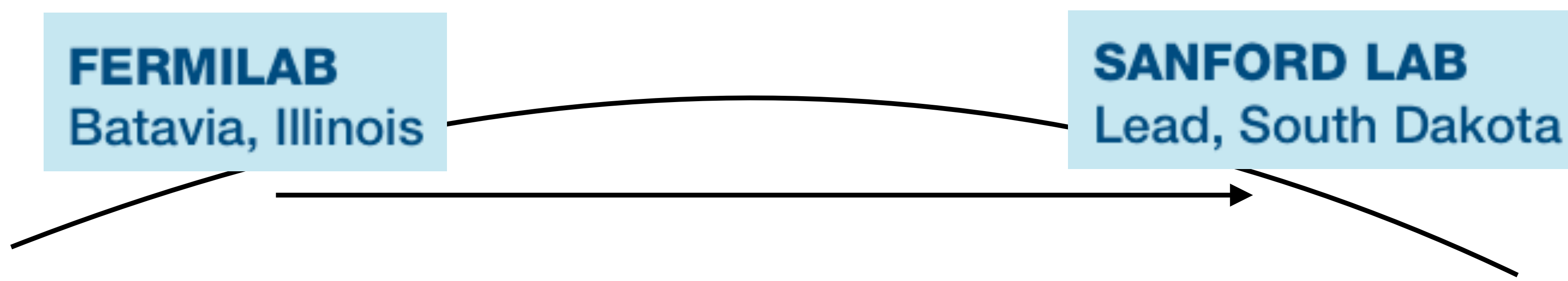

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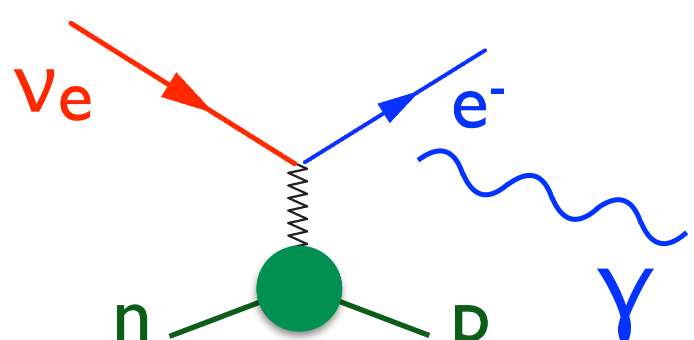

radiative corrections

hadronic amplitudes

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

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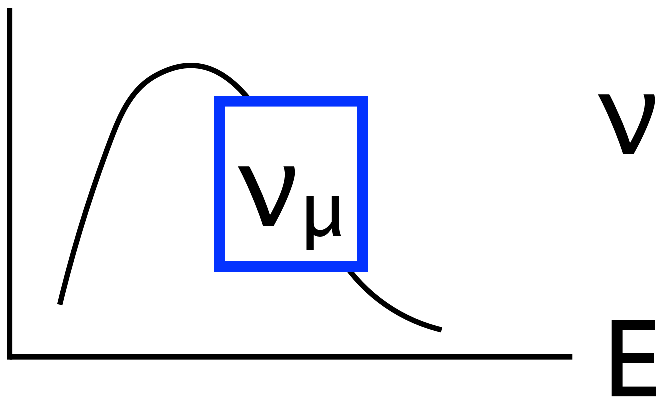

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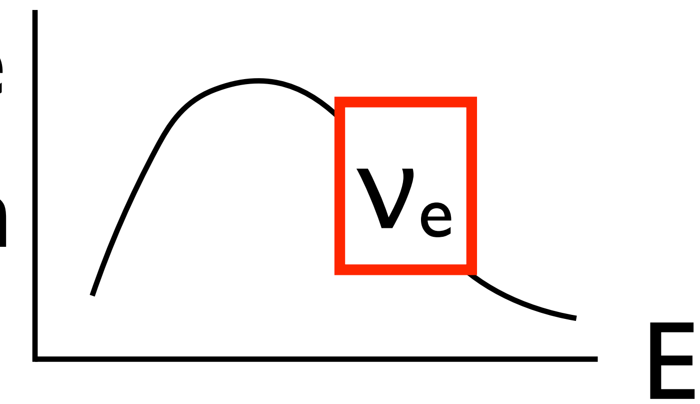

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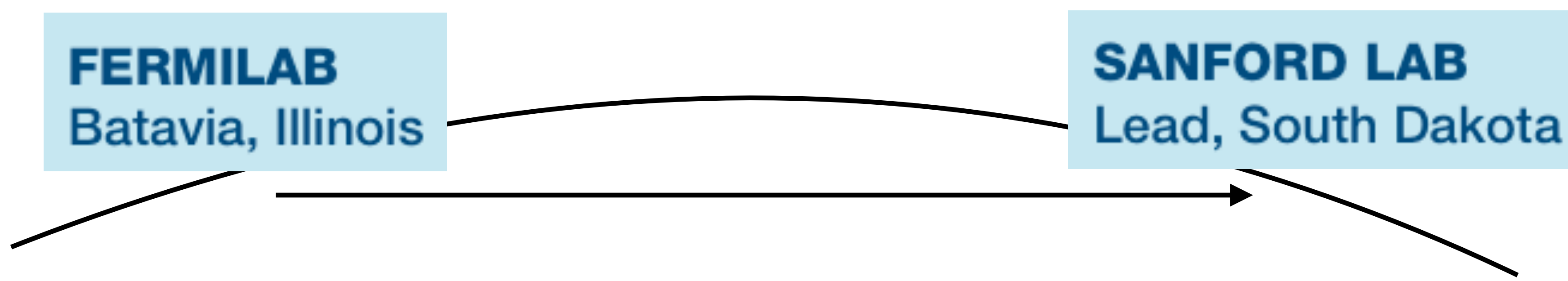

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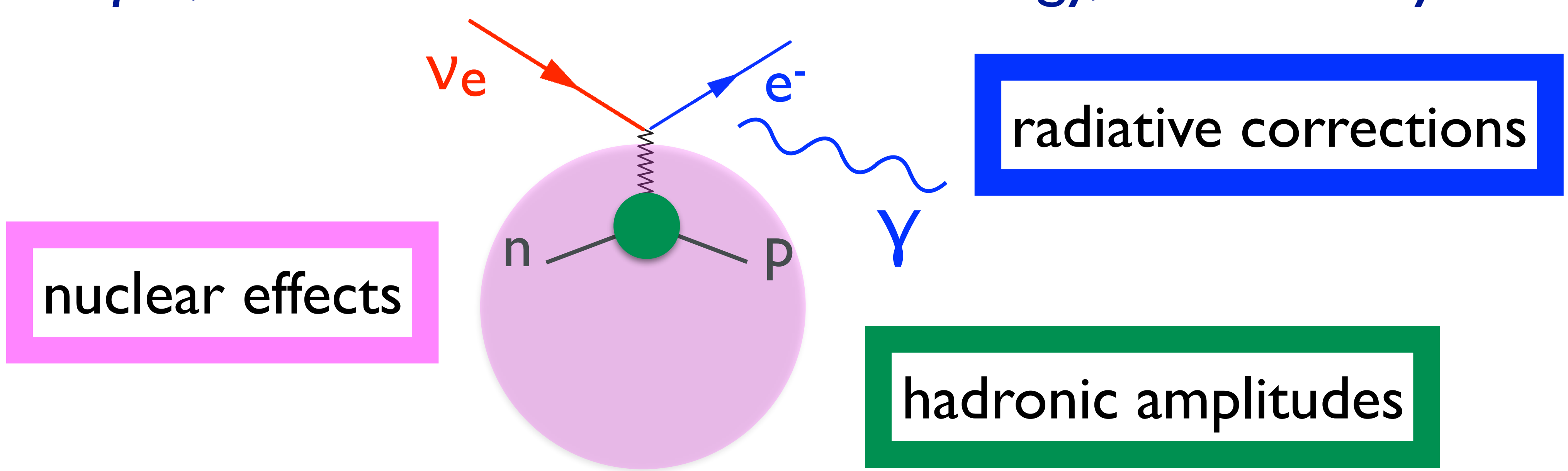
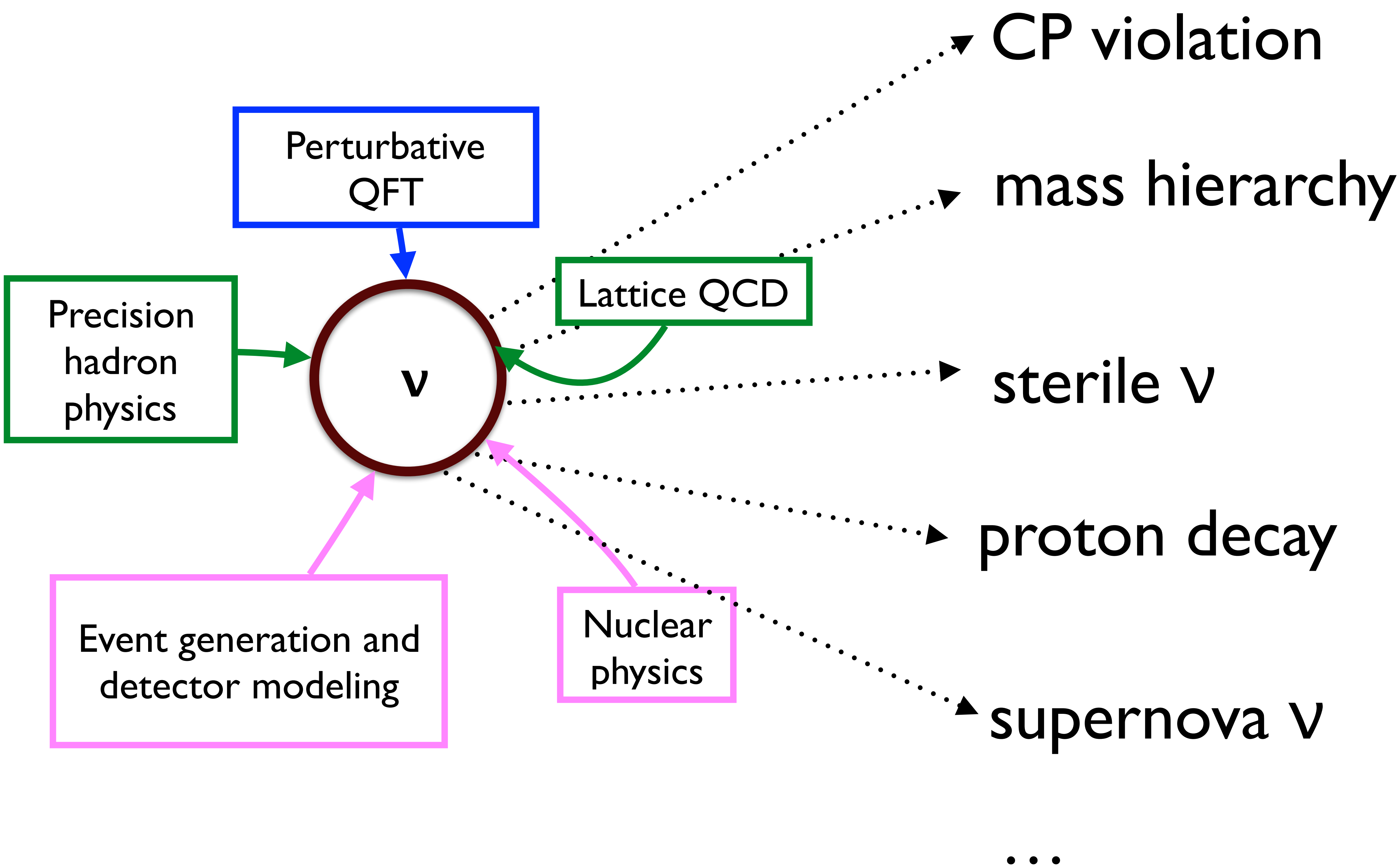
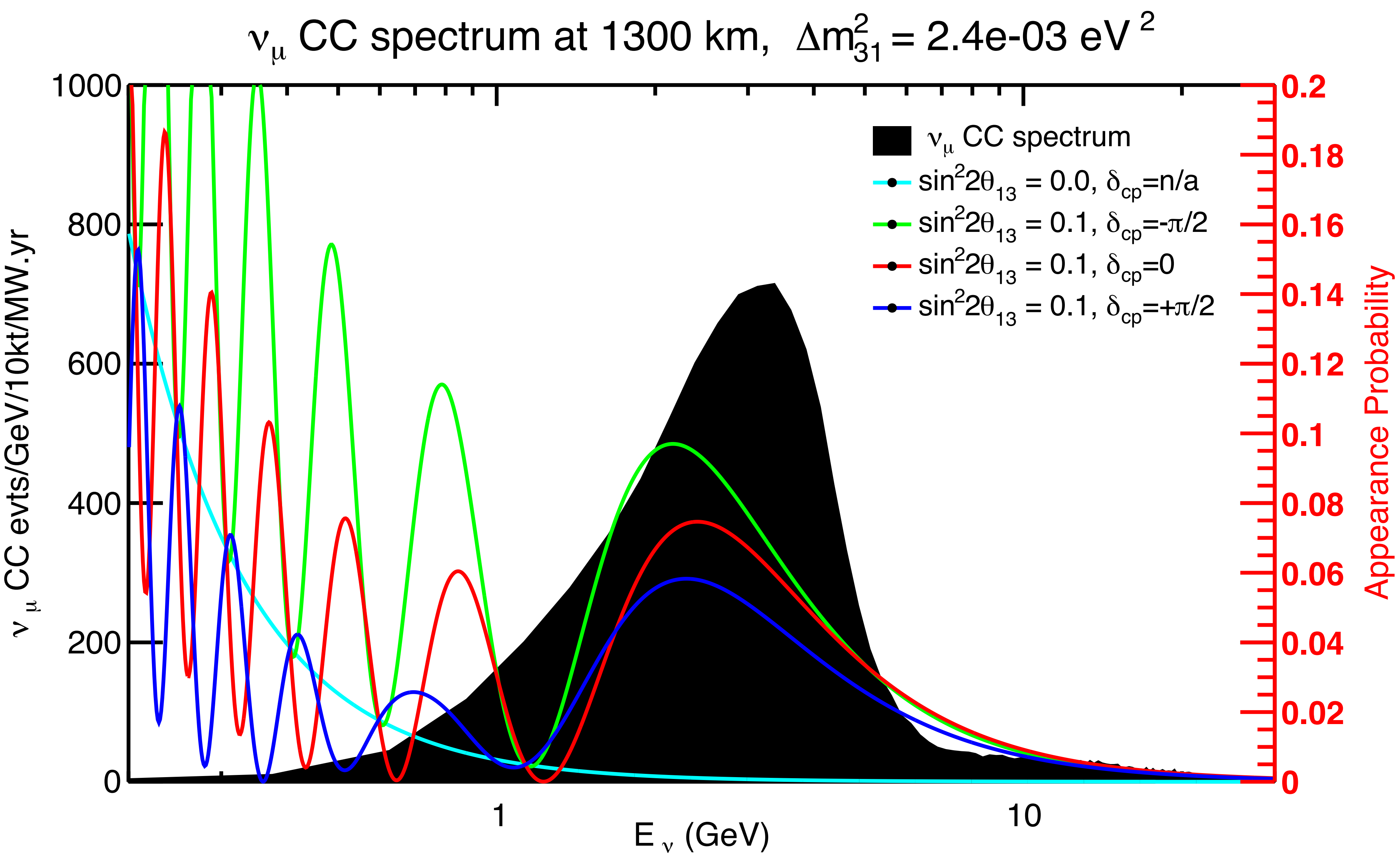
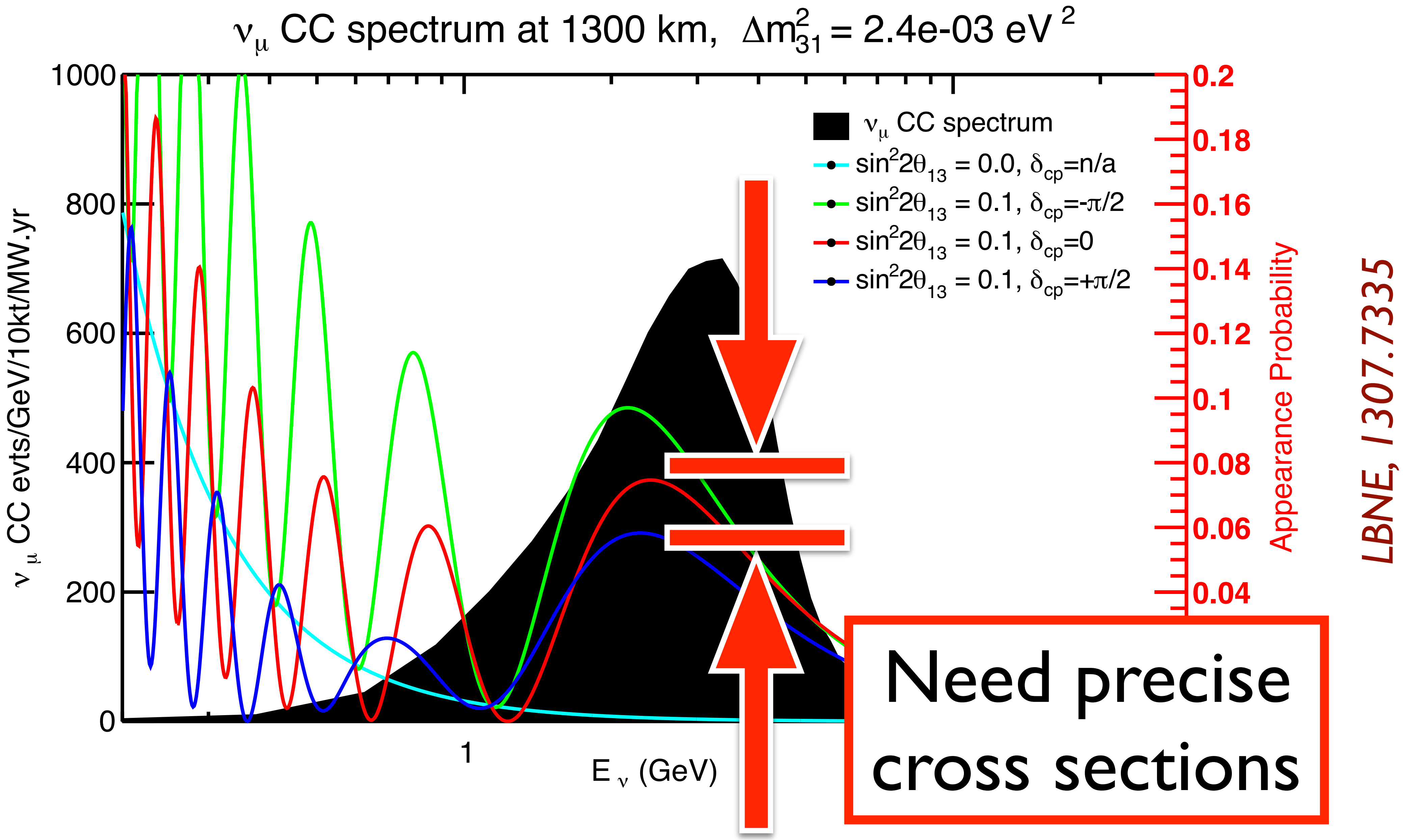


QCD in many regimes critical to extracting fundamental physics in the neutrino sector





LBNE, 1307.7335


ν_μ CC spectrum at 1300 km, $\Delta m^2_{31} = 2.4e\text{-}03\ eV^2$
ν_μ CC evts/GeV/10kt/MW.yr
1000
800
600
400
200
0
1
E_ν (GeV)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
Appearance Probability
ν_μ CC spectrum
$\sin^2 2\theta_{13}$ = 0.0, δ_{cp}=n/a
$\sin^2 2\theta_{13}$ = 0.1, δ_{cp}=-π/2
$\sin^2 2\theta_{13}$ = 0.1, δ_{cp}=0
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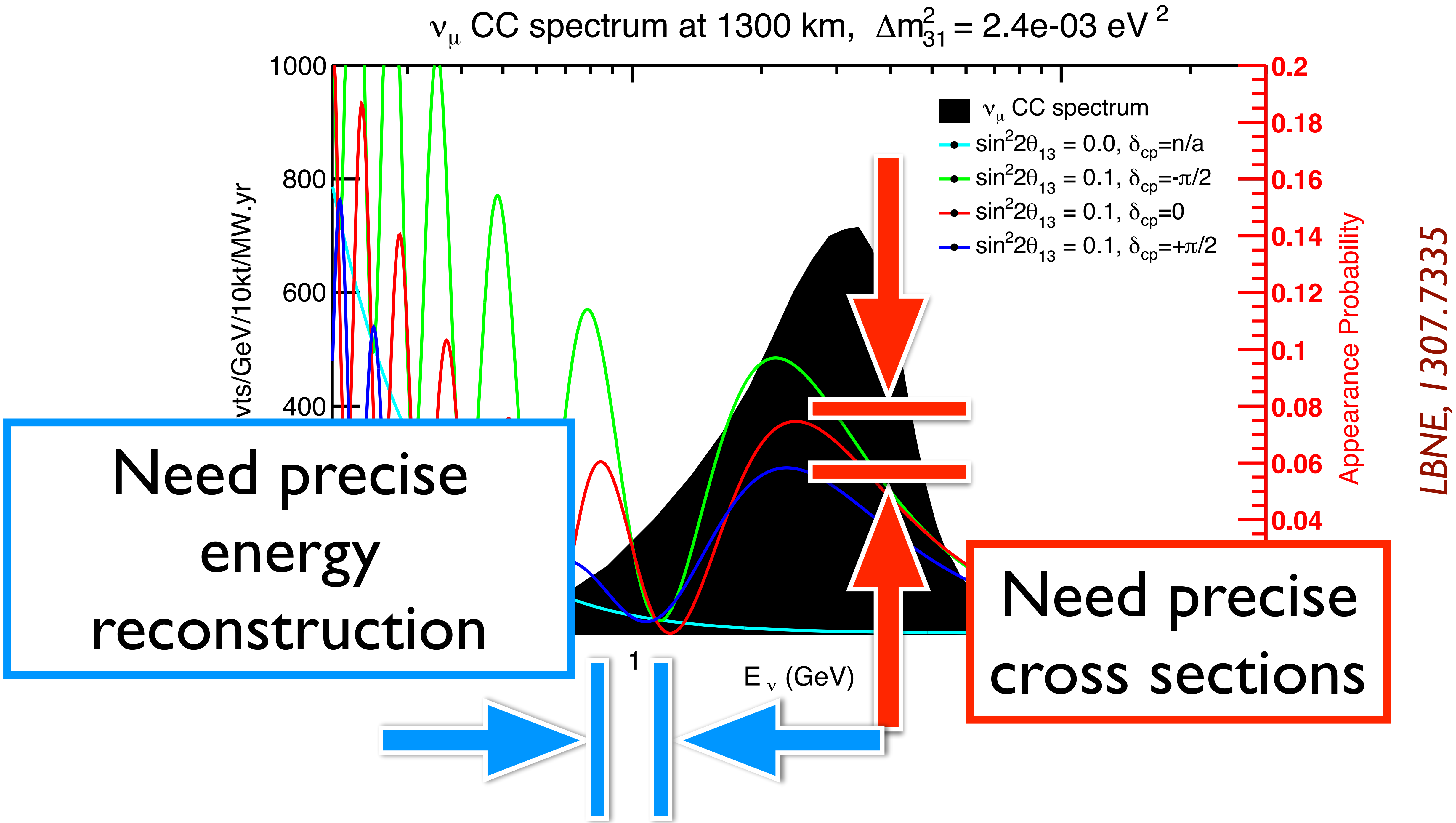
LBNE, 1307.7335
Need precise cross sections



ν_μ CC spectrum at 1300 km, Δm^2_{31} = 2.4e-03 eV ^{2}
1000
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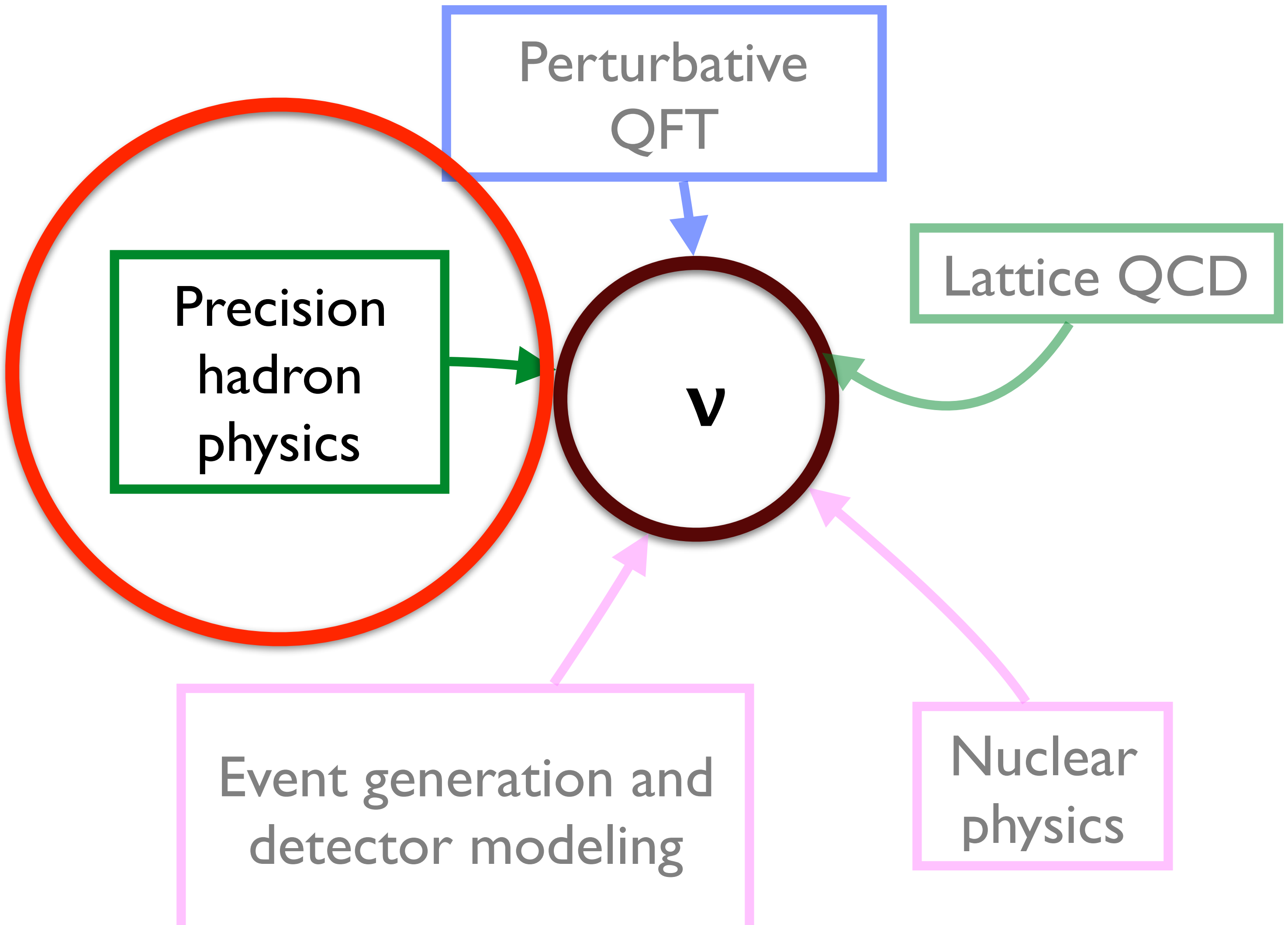
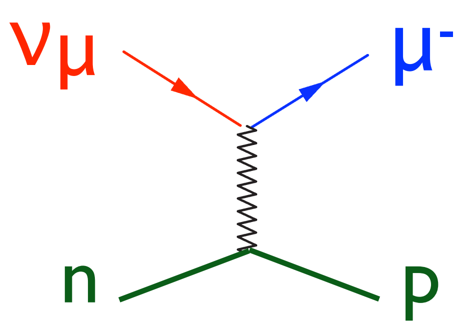
Appearance Probability
LBNE, 1307.7335
1
E_ν (GeV)
Need precise energy reconstruction
Need precise cross sections



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

Start with the basic process



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

poorly known axial-vector form factor

A common ansatz for F_A has been employed for the last ~40 years:

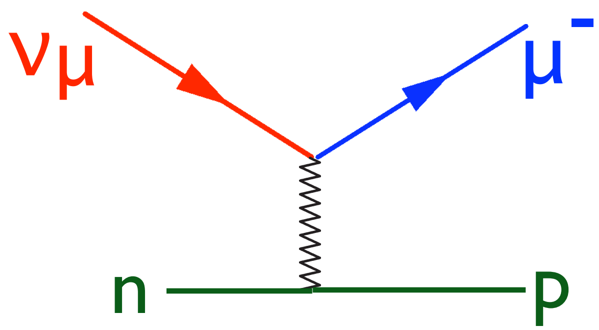
$$F_A^{\rm dipole}(q^2) = F_A(0)\left(1 - \frac{q^2}{m_A^2}\right)^{-2}$$

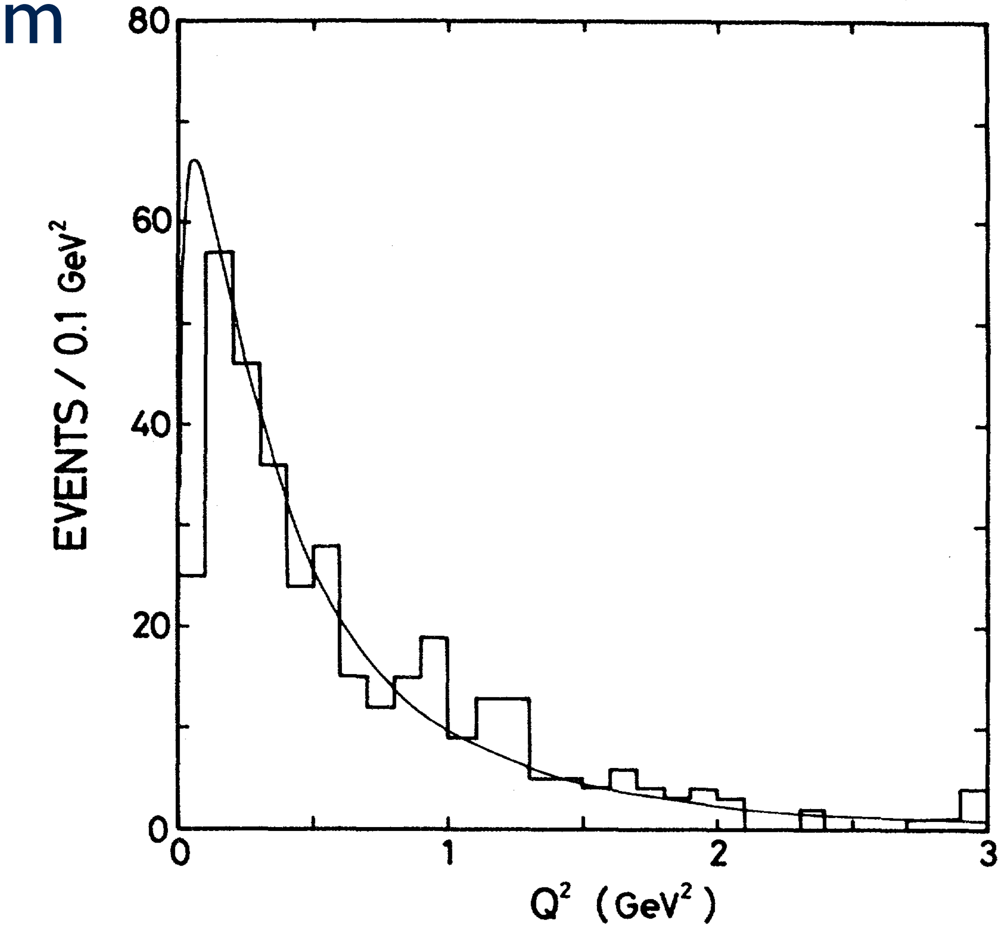
Inconsistent with QCD.

Typically quoted uncertainties are (too) small (e.g. compared to proton charge form factor)

$$\frac{1}{F_A(0)}\frac{dF_A}{dq^2}\bigg|_{q^2=0} \equiv \frac{1}{6}r_A^2 \qquad r_A = 0.674(9)\ \mathrm{fm}$$

Best source of almost-free neutrons: deuterium





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

Deuterium bubble chamber data

- small(-ish) nuclear effects
- small(-ish) experimental uncertainties
- small statistics, ~3000 events in world data

also:

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

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

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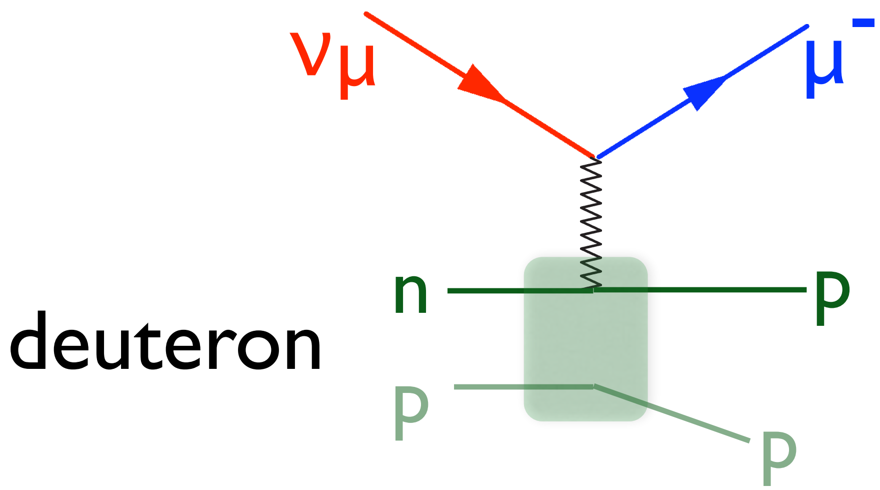

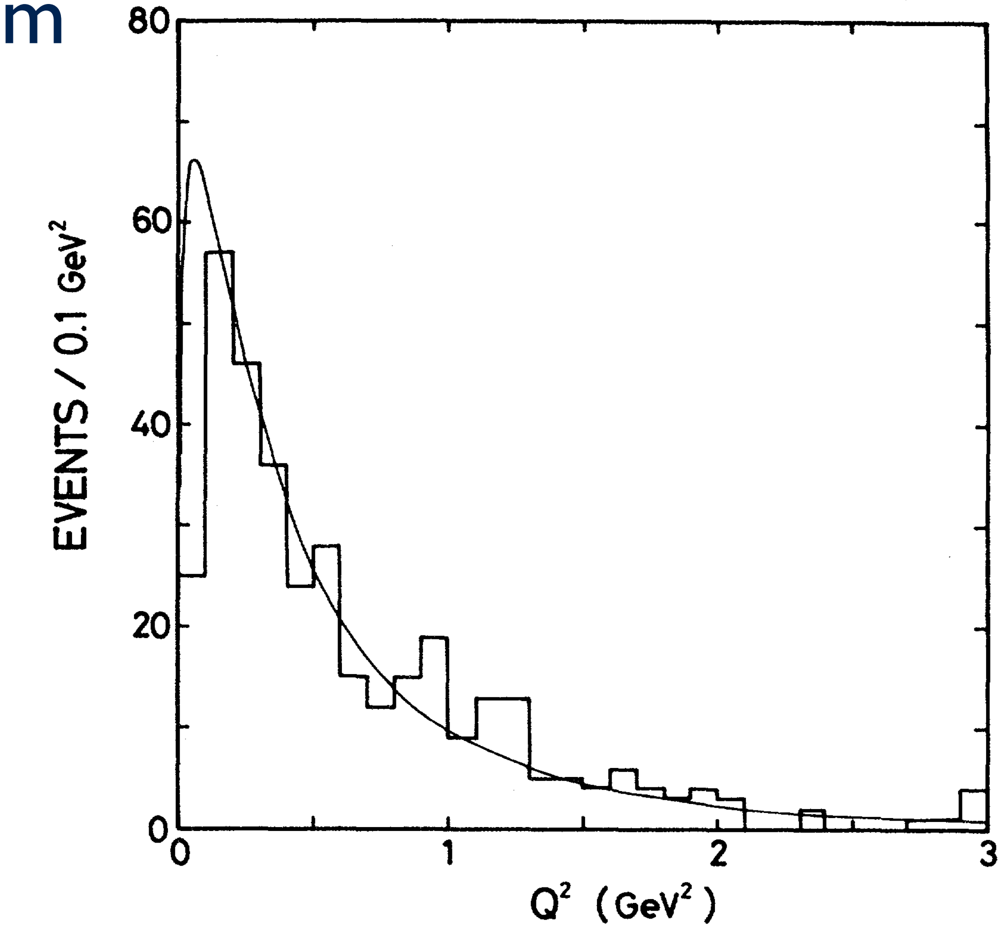

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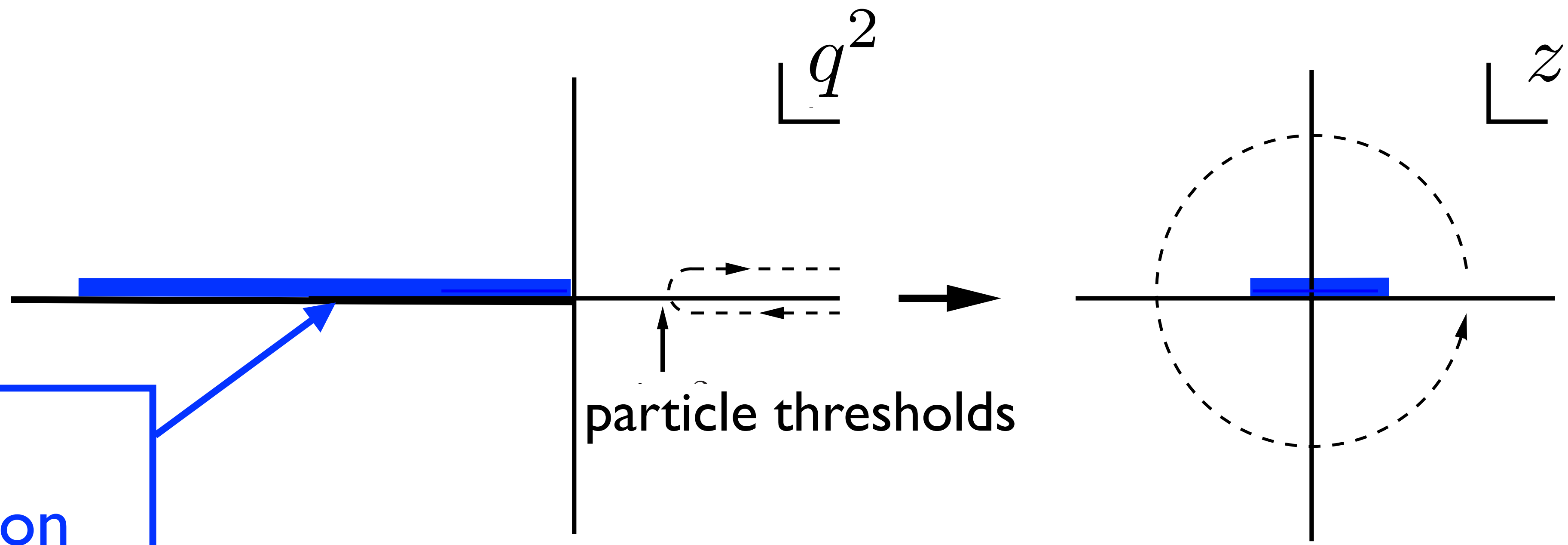
HEP toolbox is being applied to precision lepton-nucleon scattering

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



experimental kinematic region

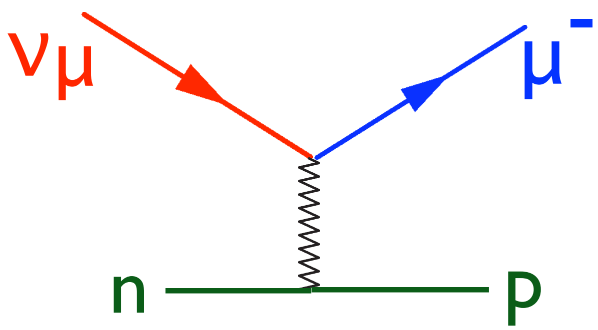
$$F_A(q^2) = \sum_k a_k [z(q^2)]^k$$

$$z(q^2, t_{\rm cut}, t_0) = \frac{\sqrt{t_{\rm cut} - q^2} - \sqrt{t_{\rm cut} - t_0}}{\sqrt{t_{\rm cut} - q^2} + \sqrt{t_{\rm cut} - t_0}}$$

coefficients in rapidly convergent expansion encode nonperturbative QCD

Systematically improvable, quantifiable uncertainties

Adapt these tools for neutrino - hadron scattering



$\nu_\mu + n \rightarrow \mu^- + p$,
$0 < Q^2 < 3\ \mathrm{GeV}^2$

$|z|<0.35$

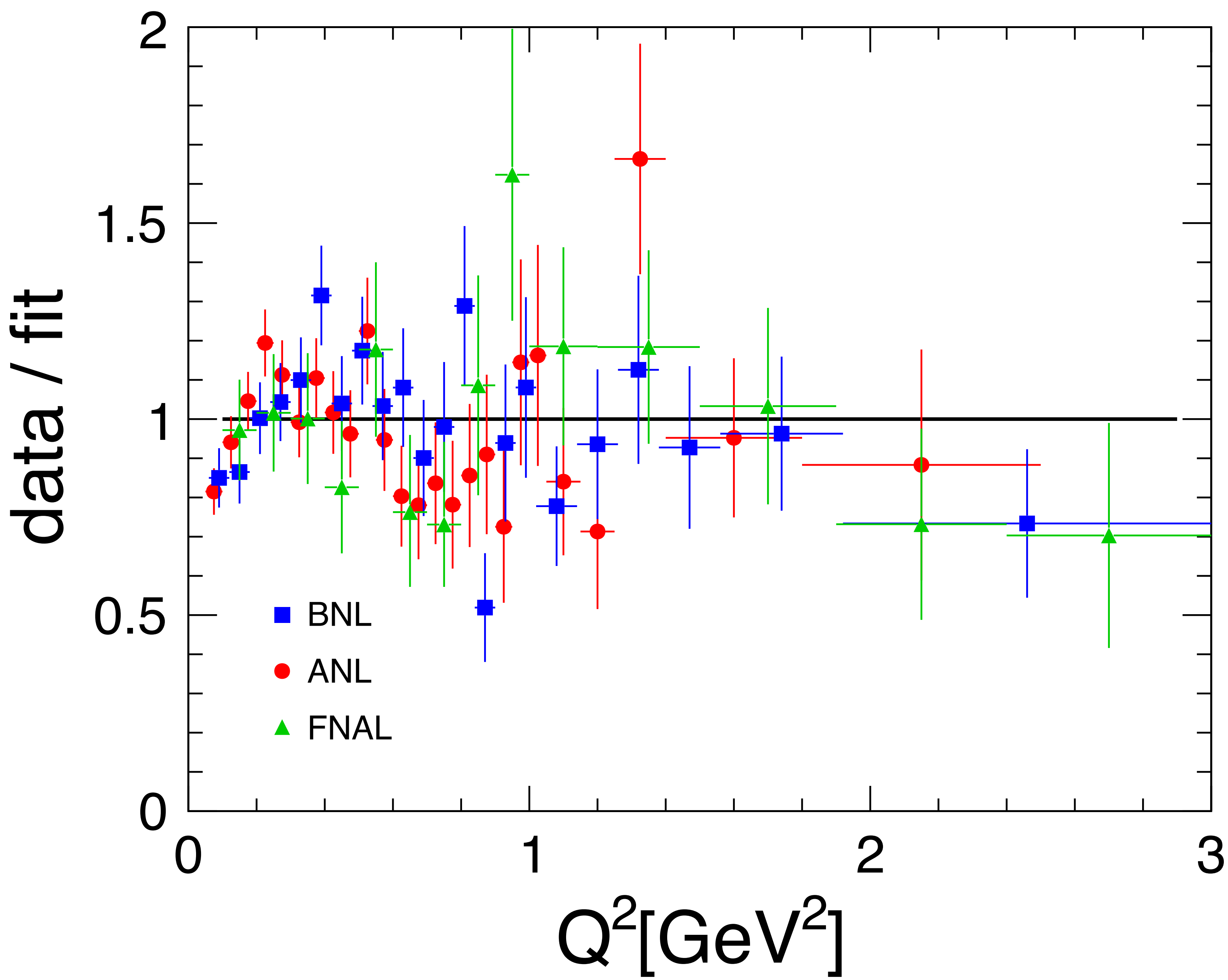
- Event-level data from the deuterium experiments has been lost
- Ab initio flux estimates have poorly constrained systematics.
    - Use published distributions in neutrino energy to determine flux:

$$\Phi(E_\nu)dE_\nu = \frac{1}{\sigma(E_\nu, F_A)}\frac{dN}{dE_\nu}dE_\nu$$

    - Fit to published Q^2 distributions to determine F_A

- Reproduced results of original publications under same assumptions
- Replaced dipole F_A with model-independent z expansion

Data are in tension with any F_A described by QCD

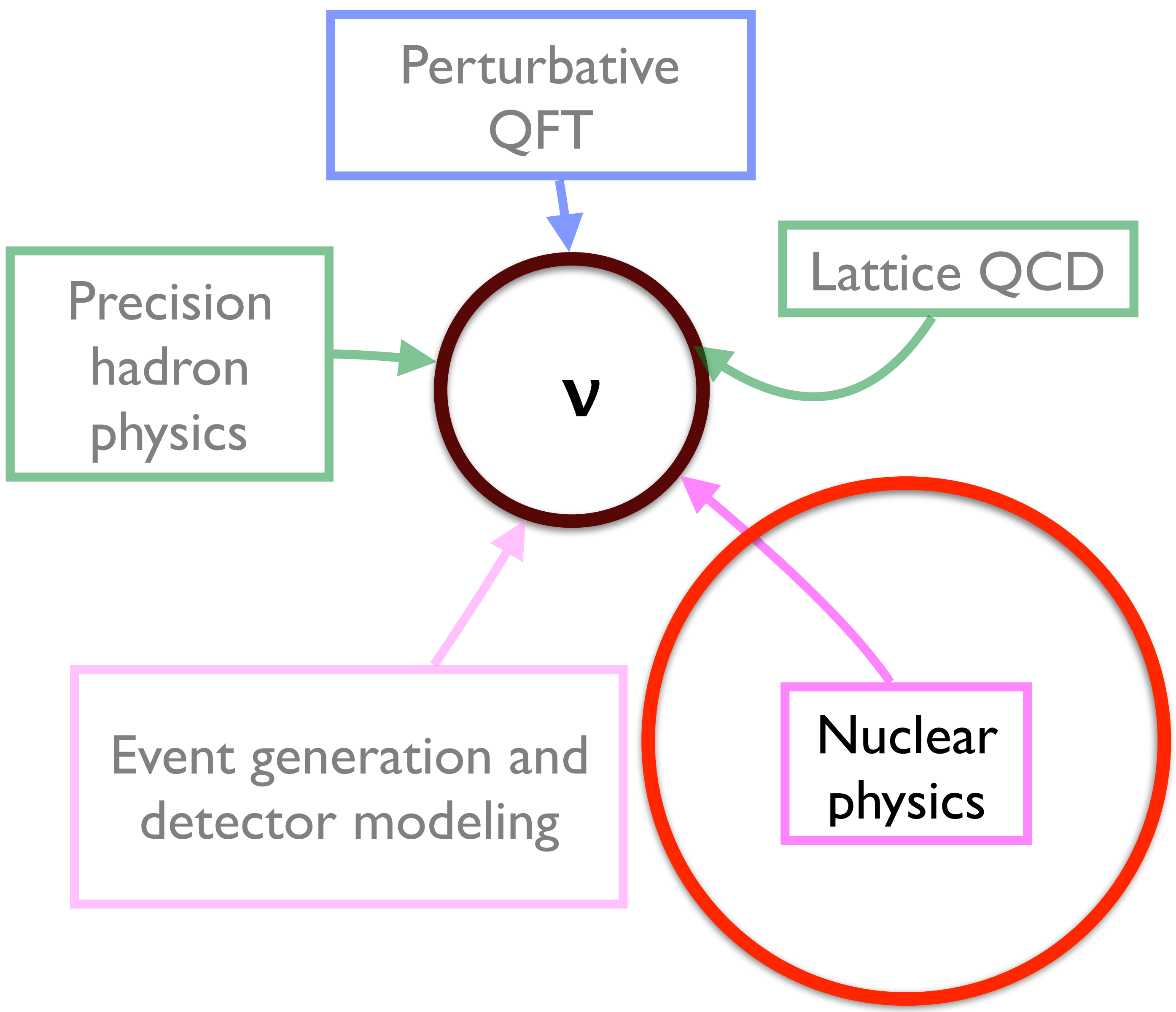


$$\chi^2 = 30 \ (16\,\text{points, BNL})$$

$$\chi^2 = 32 \ (19\,\text{points, ANL})$$

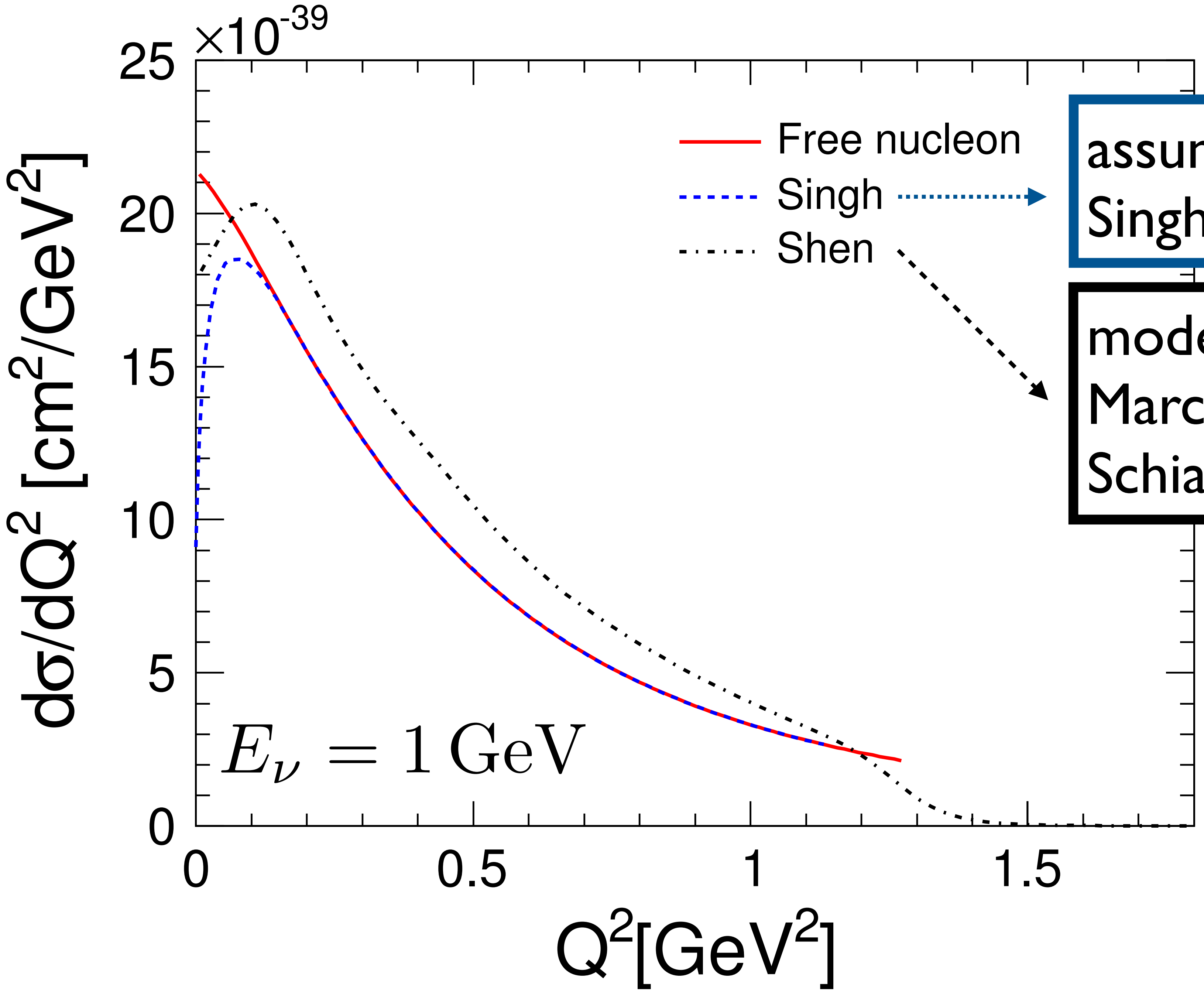
Possible correlated effect between datasets, including deficit at small Q^2

Revisit systematics:
- experimental acceptance/efficiency correction
- theoretical deuteron correction



To validate nuclear models for ^{12}C, ^{16}O, ^{40}Ar, … , should first master ^{2}H (work remains - new experimental data would be very valuable)

- theoretical systematic: deuteron correction



assumed in existing world averages: Singh, NPB 36, 419 (1972).

modern potential model: Shen, Marcucci, Carlson, Gandolfi, Schiavilla (1205.4337)

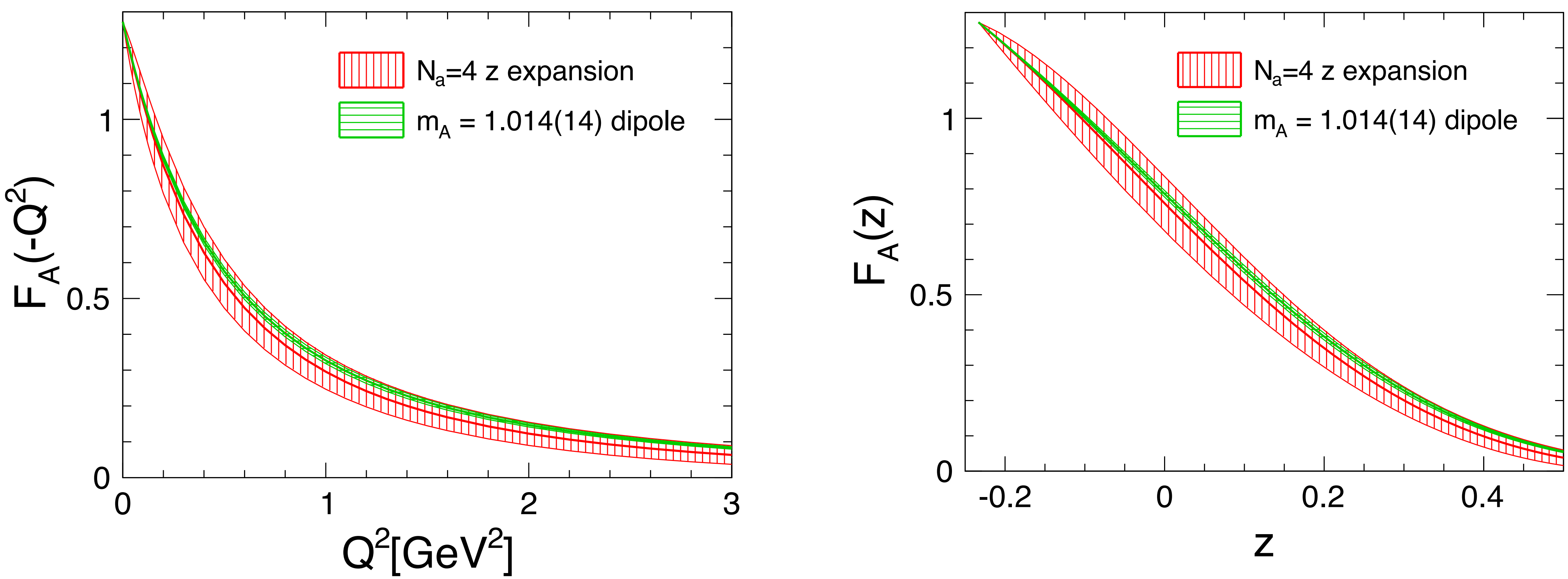
- An open problem to quantify uncertainty, especially at larger energy

- F_A with complete error budget, correlations:

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

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

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



Derived observables: 1) axial radius

$$\frac{1}{F_A(0)} \frac{dF_A}{dq^2}\bigg|_{q^2=0} \equiv \frac{1}{6} r_A^2$$

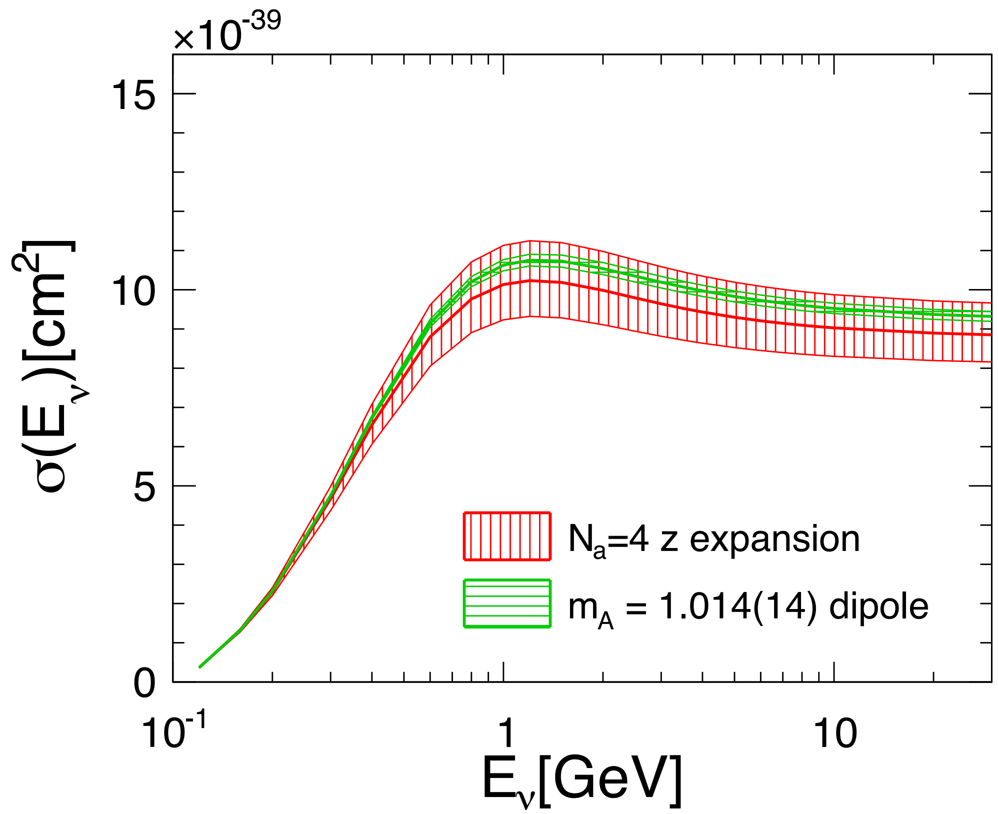
$$r_A^2 = 0.46(22)\,\mathrm{fm}^2$$

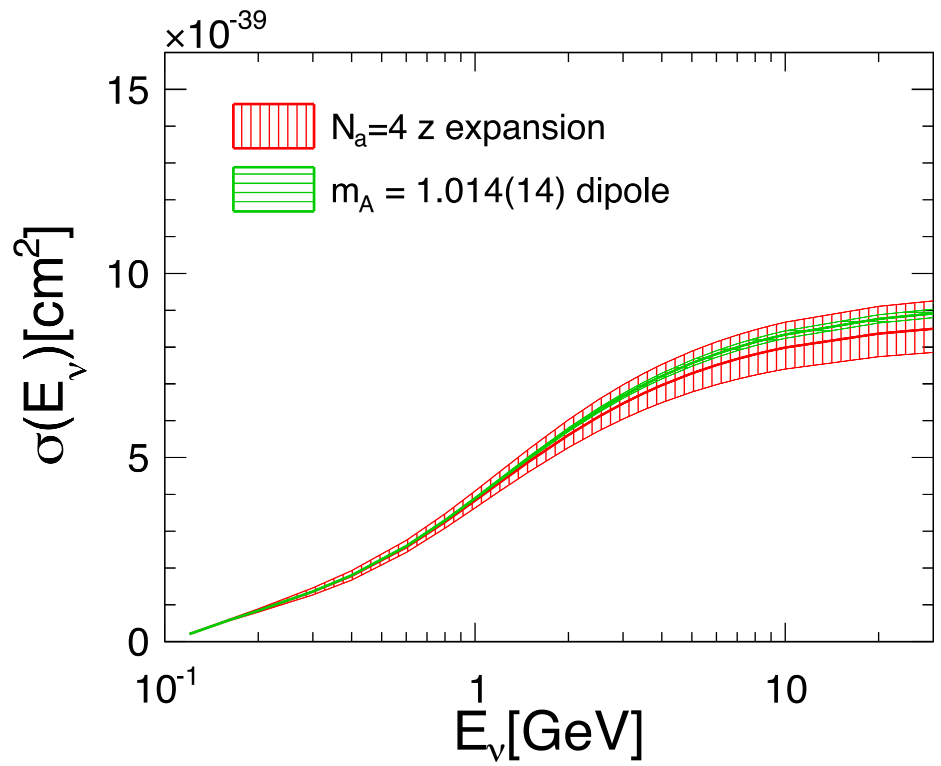
- a basic parameter of nucleon structure

- order of magnitude larger uncertainty compared to dipole fits

- impacts comparison to other data, e.g. pion electroproduction, muon capture

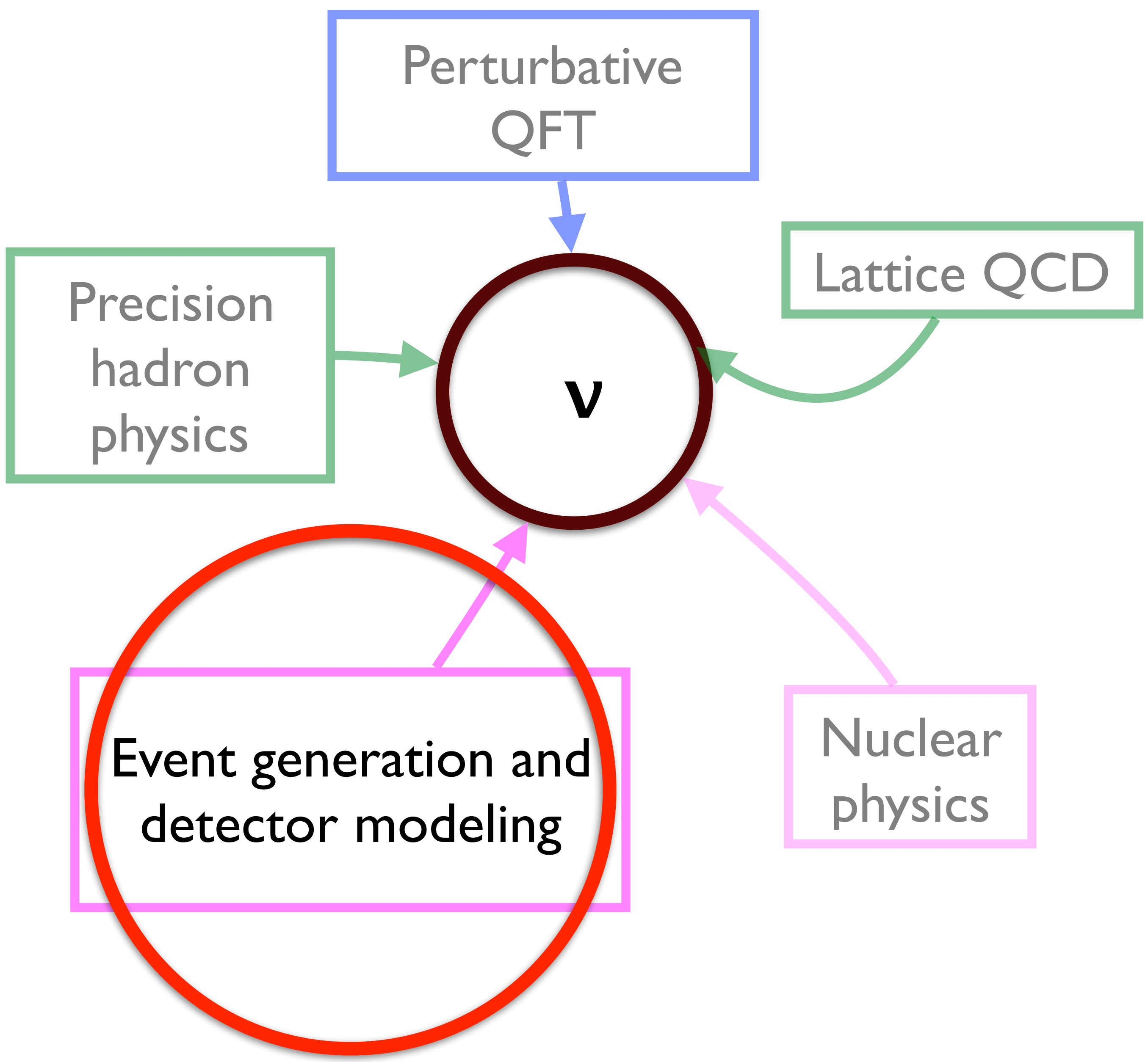
Derived observables: 2) neutrino-nucleon quasi elastic cross sections





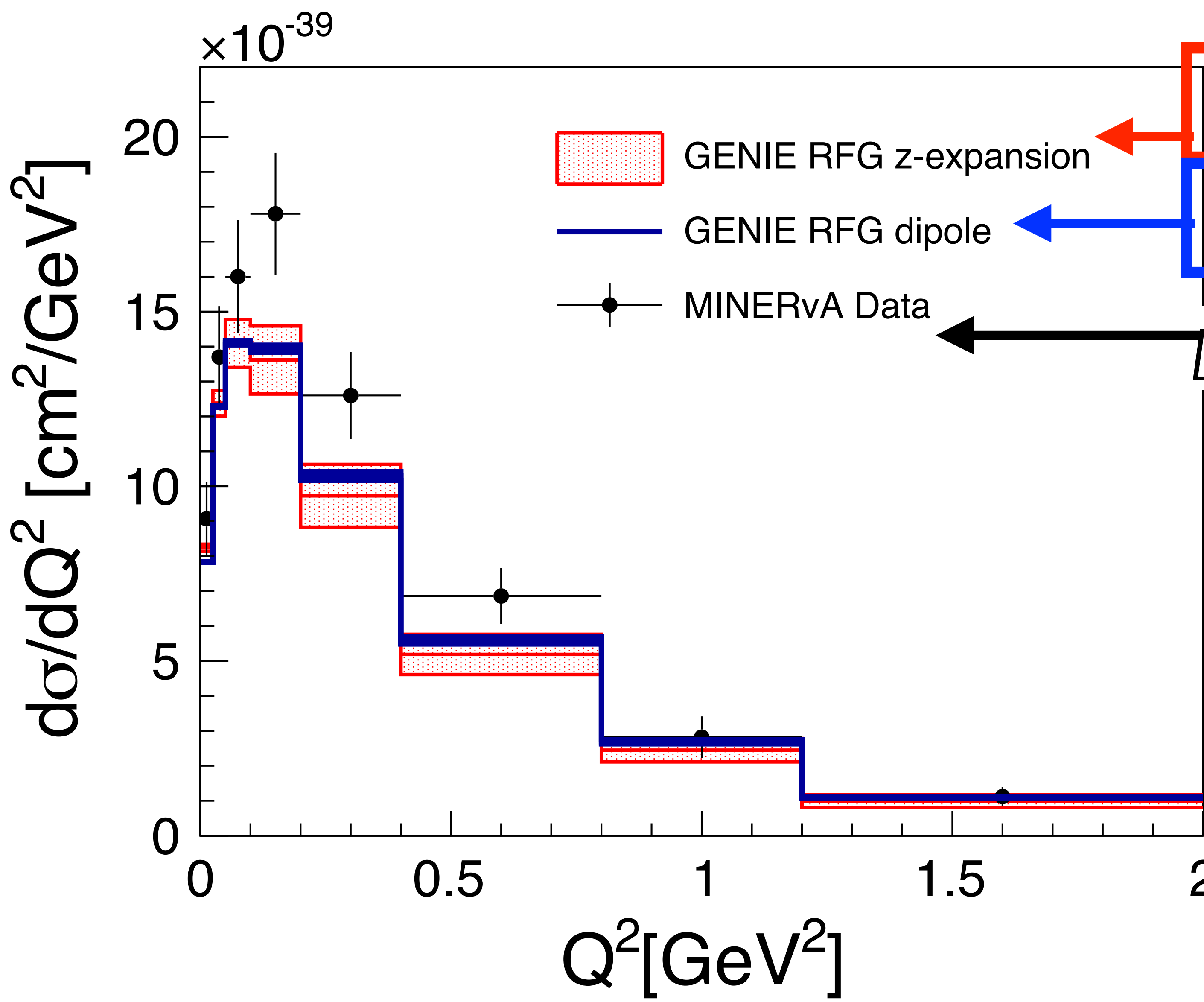
$$\sigma_{\nu n \to \mu p}(E_\nu = 1\,\mathrm{GeV}) = 10.1(0.9) \times 10^{-39}\,\mathrm{cm}^2$$ (~ T2K)

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



The model independent z expansion has been implemented in GENIE event generator for input to nuclear models

Derived observables: 3) neutrino-nucleus quasi elastic cross sections



z expansion constrained by deuterium

"world average dipole"

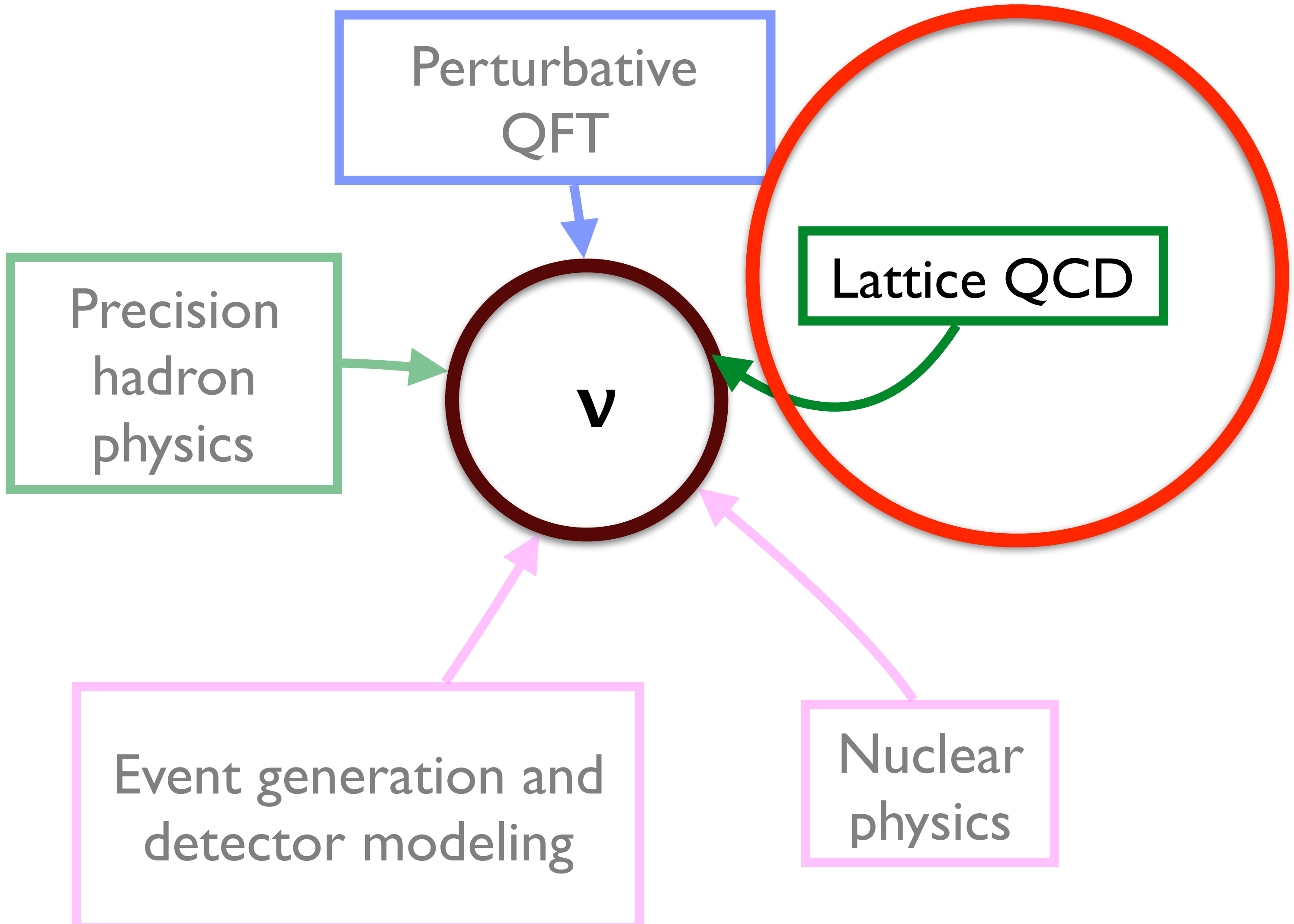
[Minerva PRL 111, 022502 (2013)] with 2015 updated flux

New module for z expansion and reweighting in GENIE event generator

A. Meyer

- errors have different kinematic dependence than dialing m_A in dipole ansatz

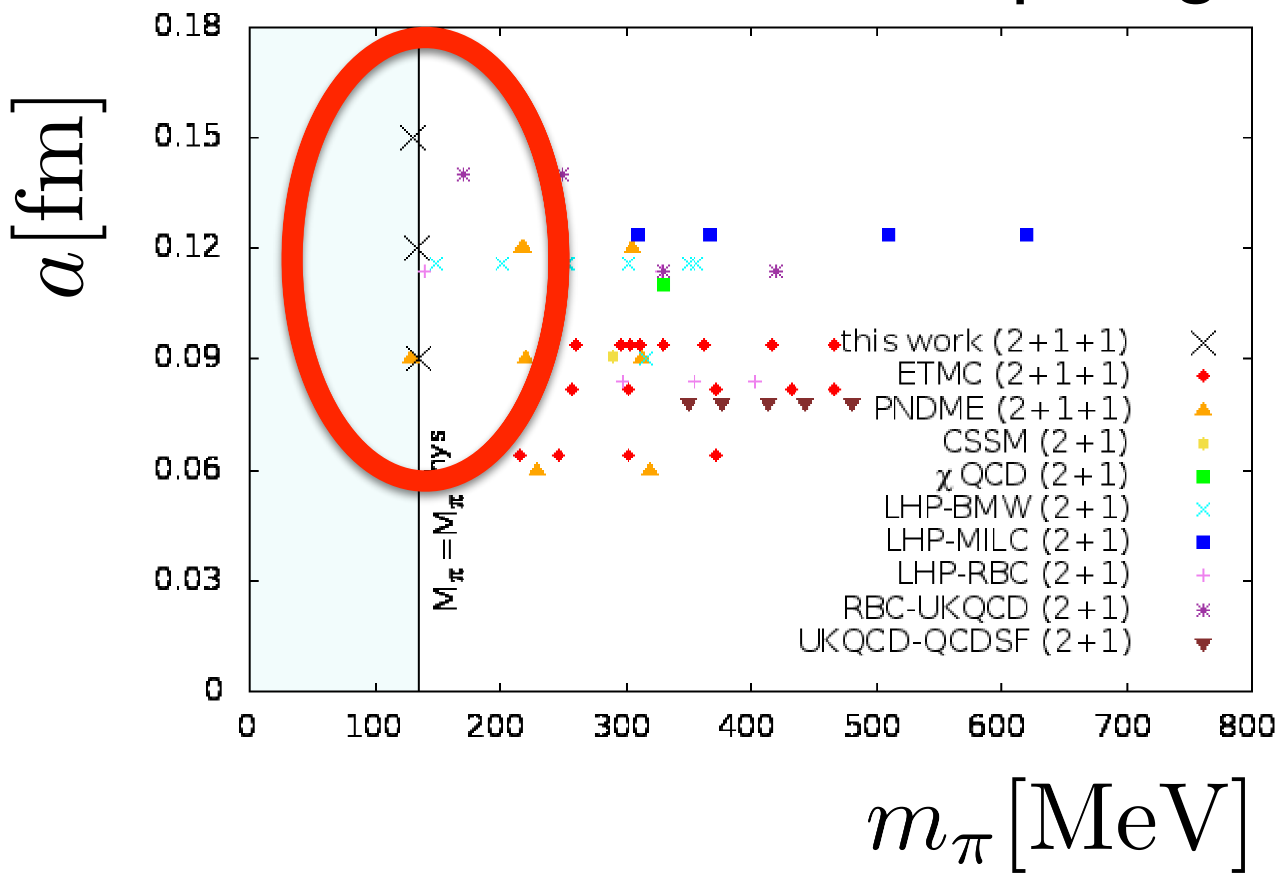
- z expansion (with correlations, reweighting) coded in GENIE, can be readily implemented with nuclear models



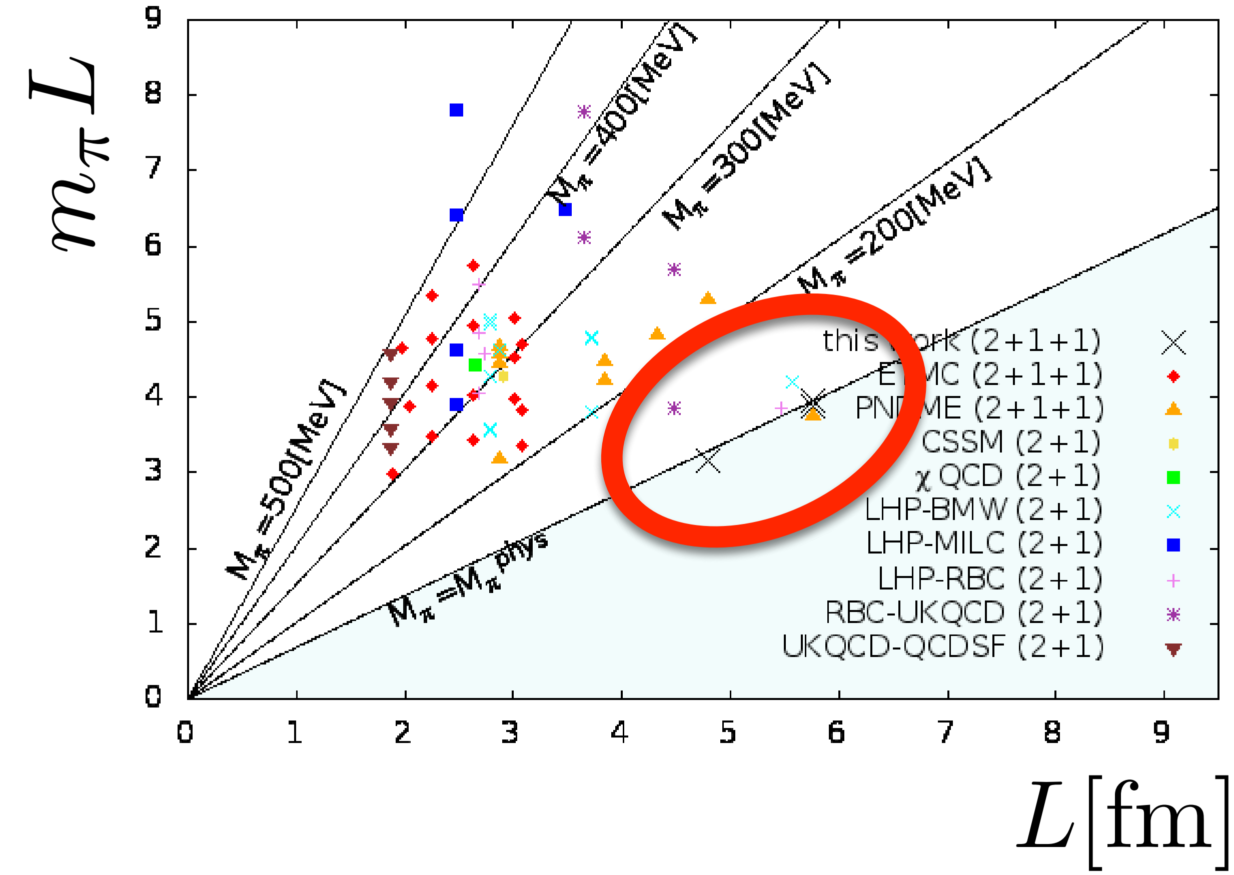
Practical obstacles to modern neutrino experiments with elementary (hydrogen or deuterium) target. Lattice QCD is poised to contribute.

A. Meyer, A. Kronfeld, RJH with Fermilab Lattice and MILC collaborations

Pion mass vs. lattice spacing



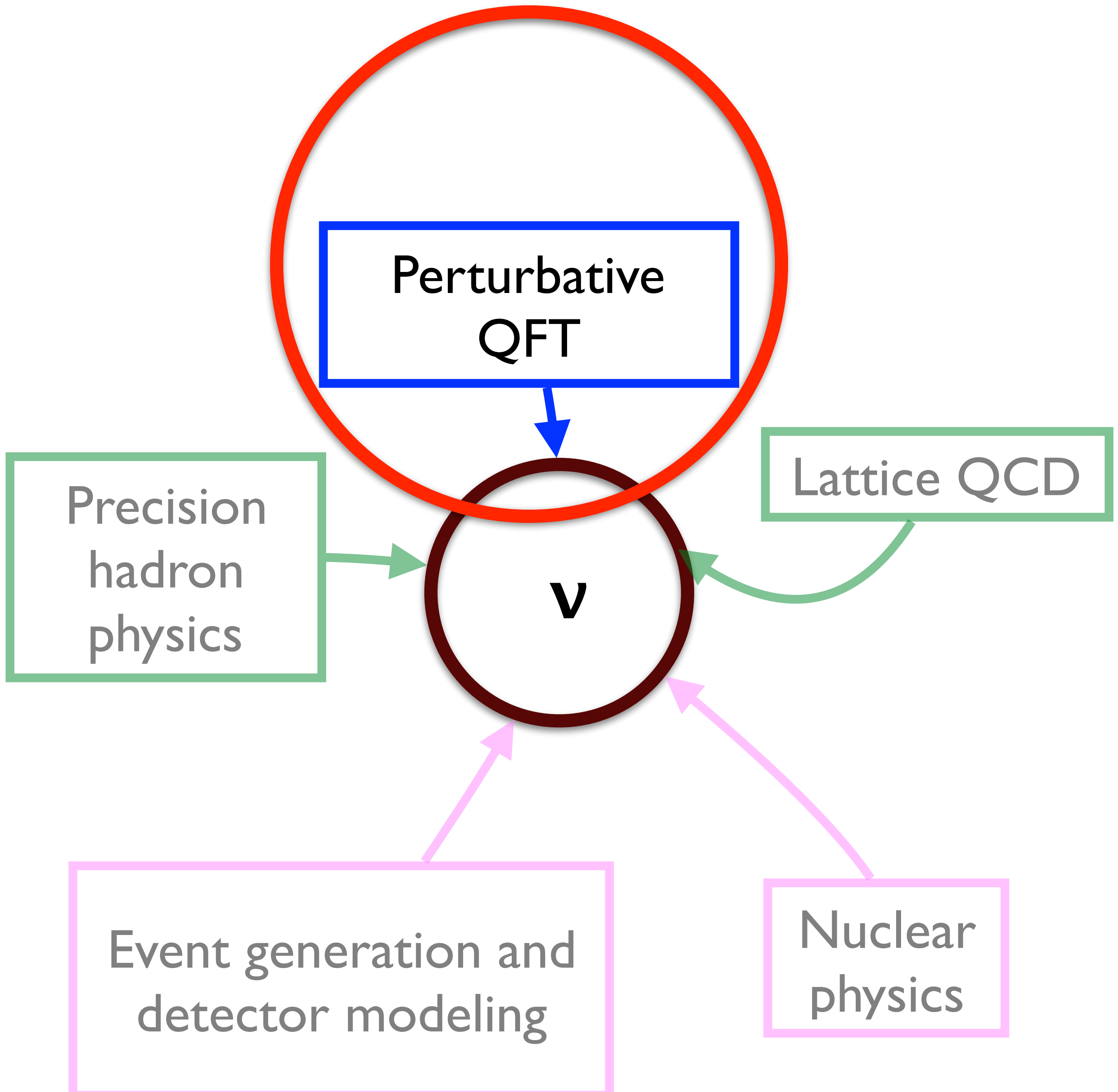
Lattice Extent vs. Pion Mass



Big lattices, multiple spacings, physical quark masses

<u>Other targets</u>: neutral currents; resonance couplings and form factors; pion final states

<u>Advantages</u>: independent of detector-dependent radiative corrections and nuclear effects (and for lattice QCD: no underground safety hazard)



QED radiative corrections impact, e.g., ν_e appearance signal. Validate with electron-proton scattering. (Actually, progress in radiative corrections required here also.)

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

1) It has generated a lot of attention and controversy

The New York Times

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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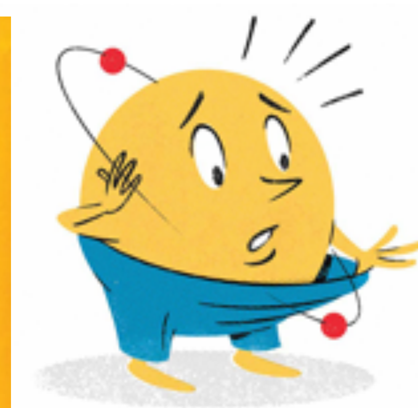

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This problem has broad ownership, e.g.:

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

What is the proton charge radius?

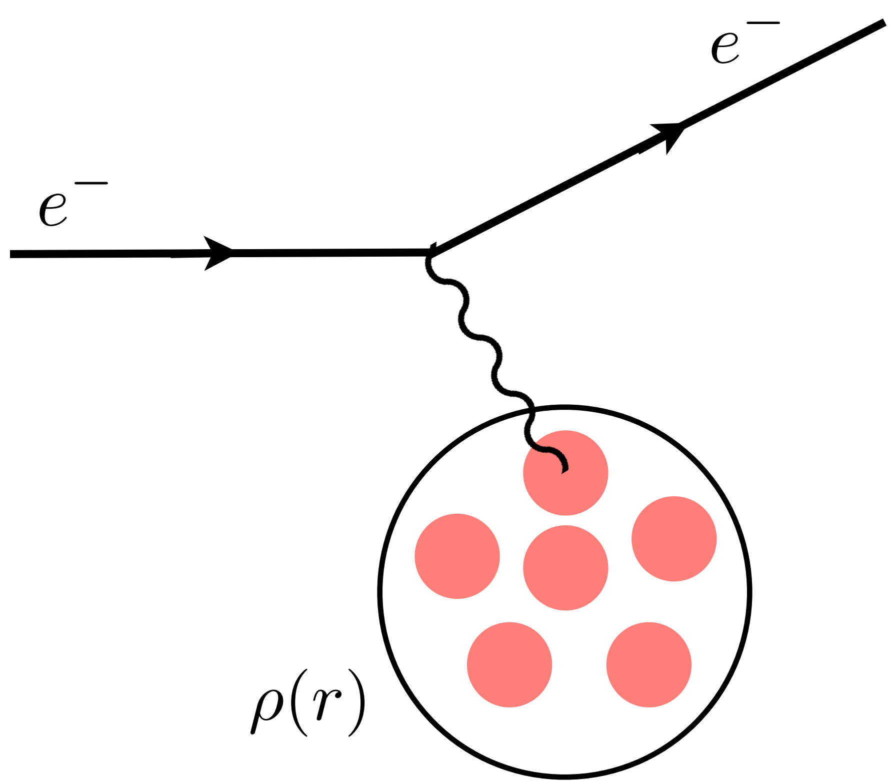
recall scattering from extended classical charge distribution:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{pointlike}} |F(q^2)|^2$$

$$F(q^2) = \int d^3r \, e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \rho(\boldsymbol{r})$$

$$= \int d^3r \left[1 + i\boldsymbol{q}\cdot\boldsymbol{r} - \frac{1}{2}(\boldsymbol{q}\cdot\boldsymbol{r})^2 + \dots\right]\rho(r)$$

$$= 1 - \frac{1}{6}\langle r^2\rangle \boldsymbol{q}^2 + \dots$$



for the relativistic, QM, case, *define* radius as slope of form factor

$$r_E^2 \equiv 6 \frac{d}{dq^2} G_E(q^2)\Big|_{q^2=0}$$

$$\langle J^\mu \rangle = \gamma^\mu F_1 + \frac{i}{2m_p}\sigma^{\mu\nu} q_\nu F_2$$

$$G_E = F_1 + \frac{q^2}{4m_p^2} F_2 \qquad G_M = F_1 + F_2$$

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

Disentangle 2 unknowns, R_∞ and r_E, using well-measured 1S-2S hydrogen transition *and*

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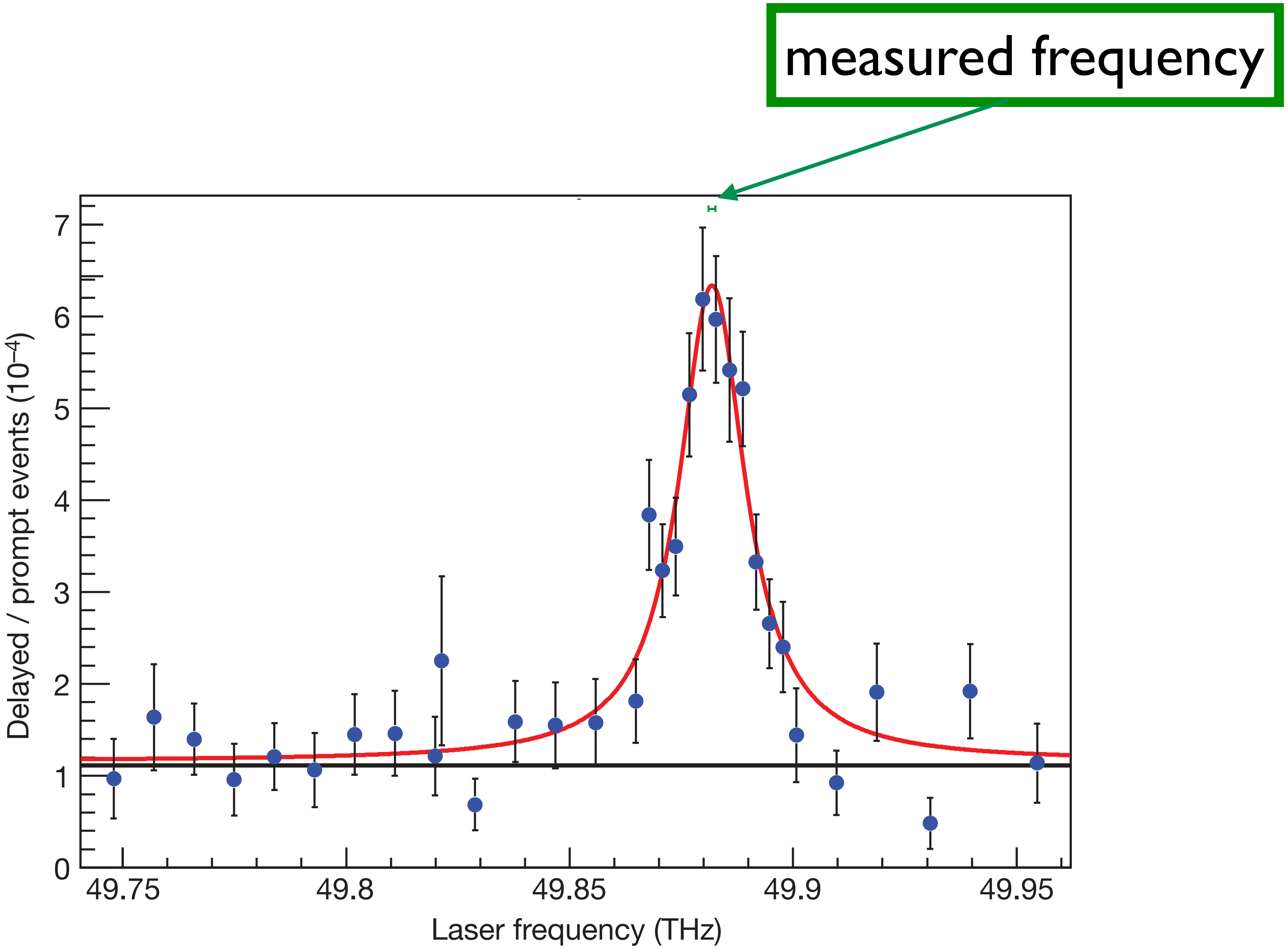
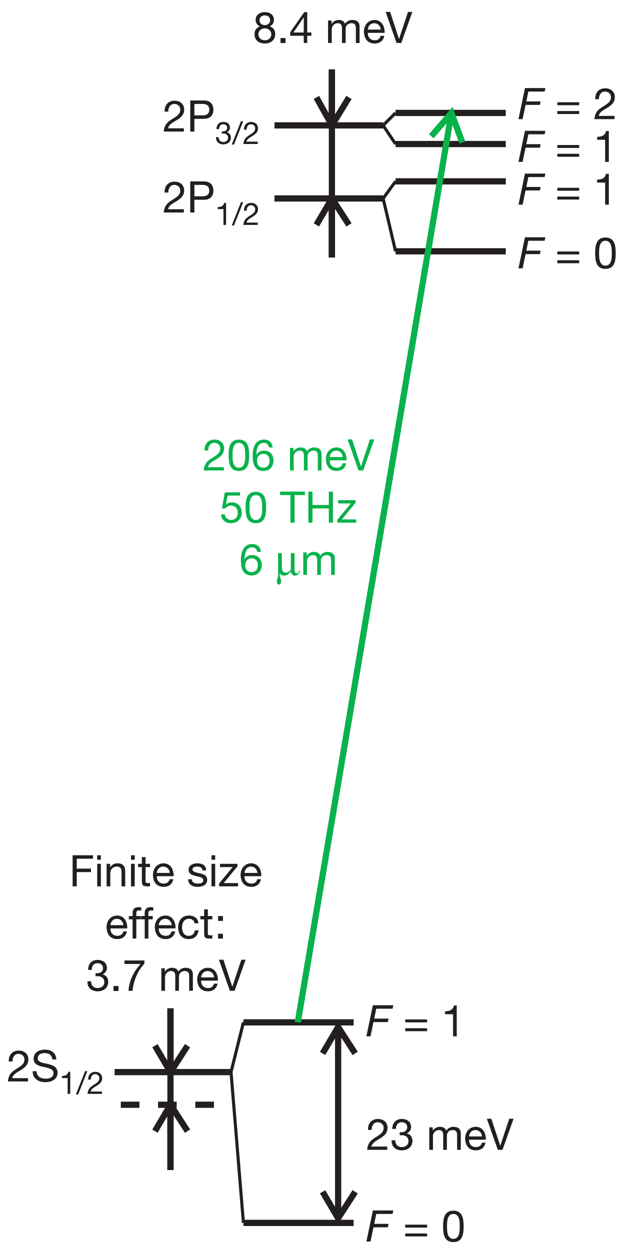
5σ discrepancy in Rydberg constant from (1+2) versus (3)

muonic hydrogen Lamb shift measurement

Pohl et al., Nature 466, 213 (2010)





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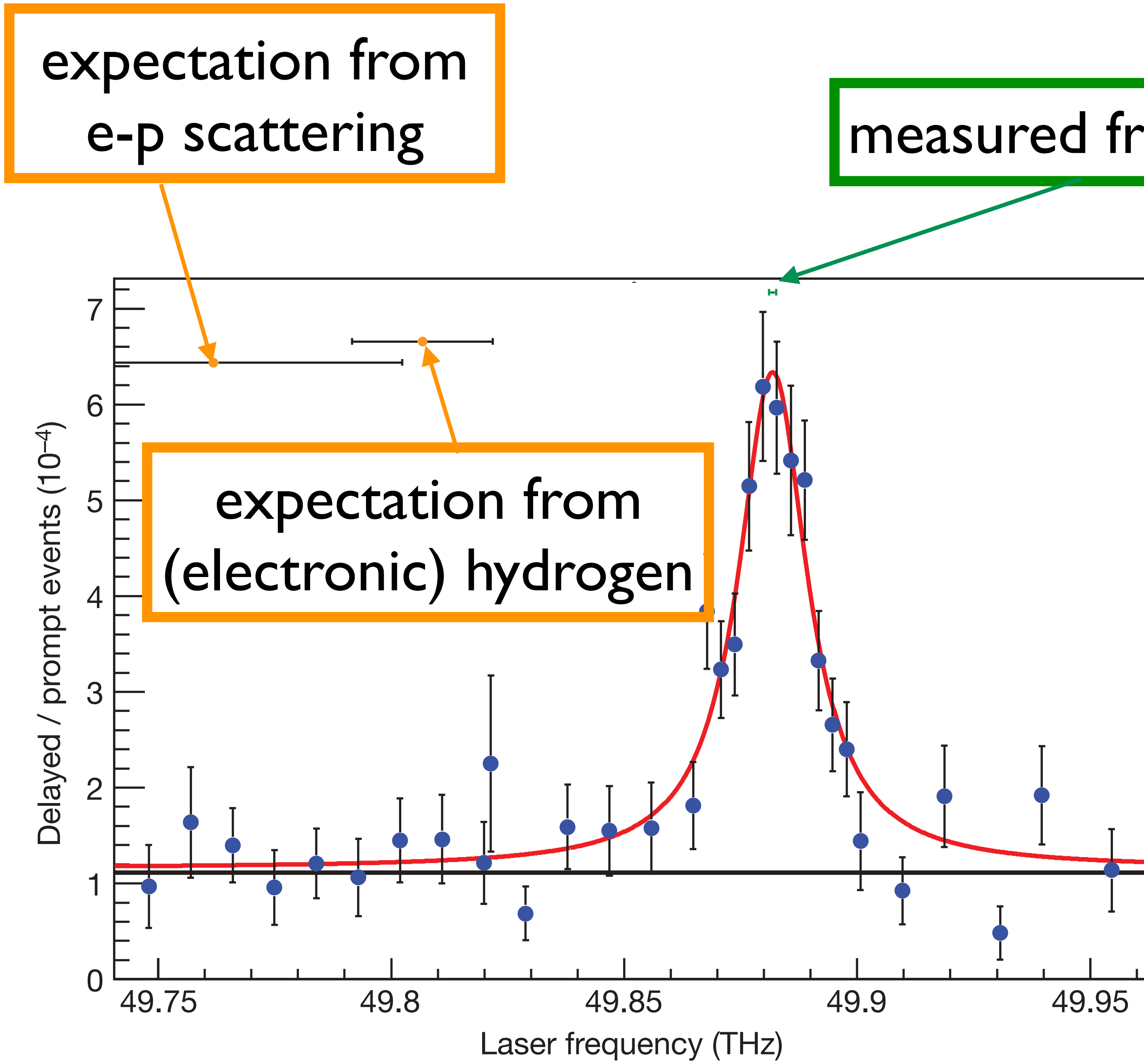
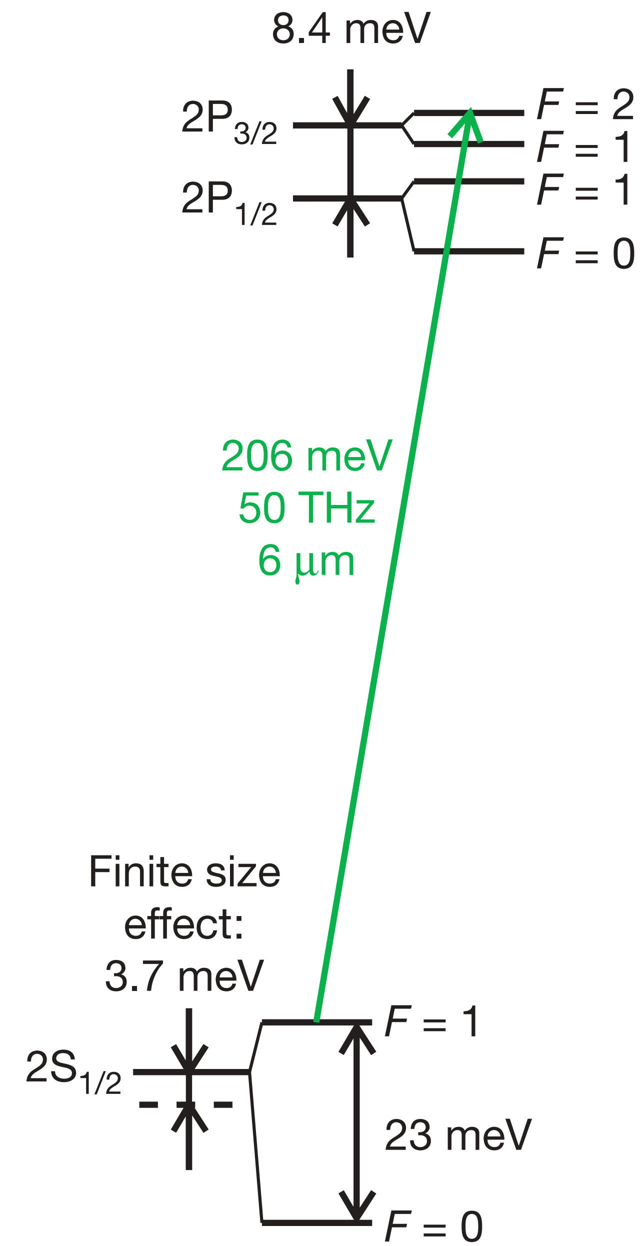
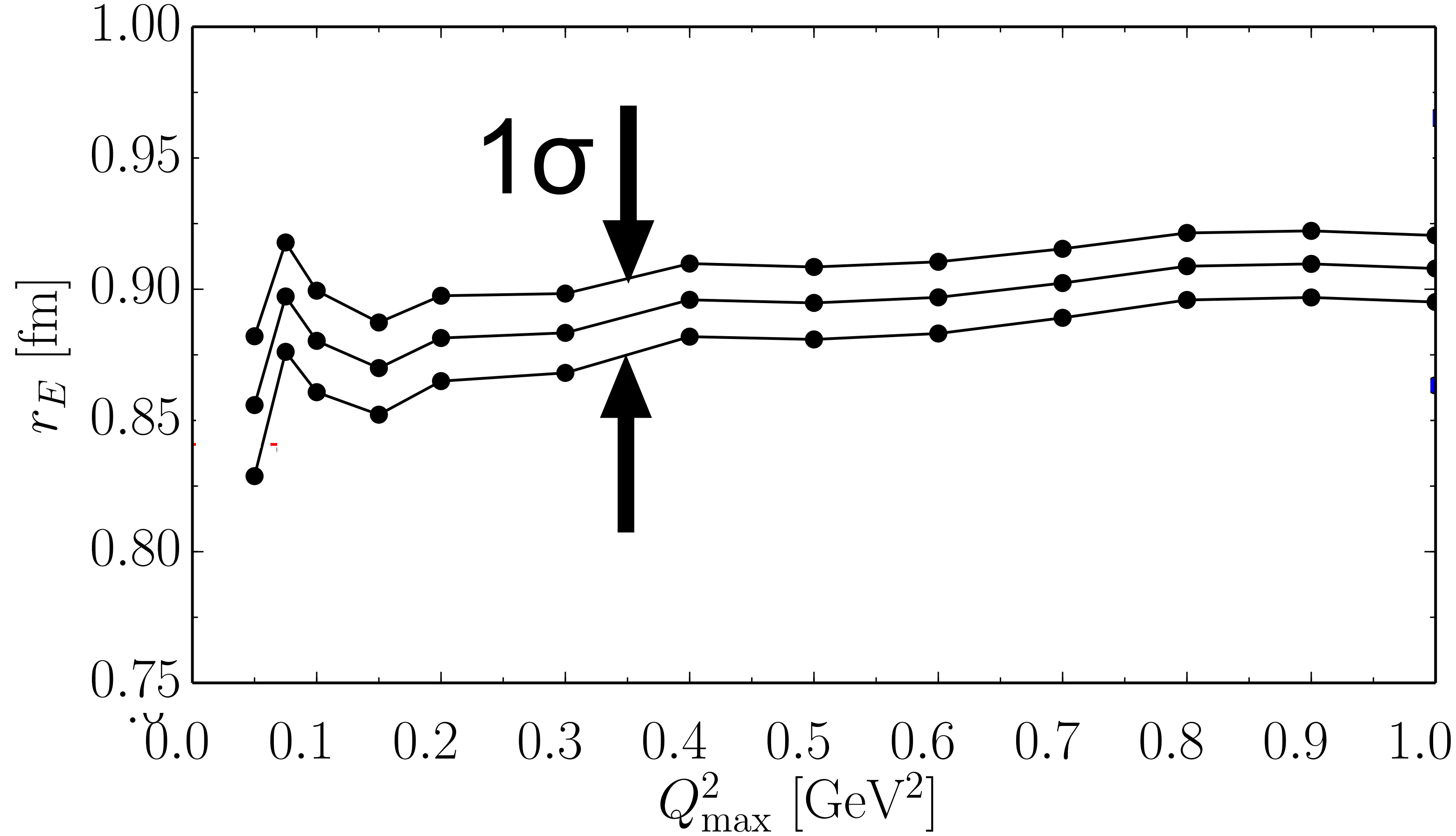




Tension between radius extracted from different Q^2 ranges



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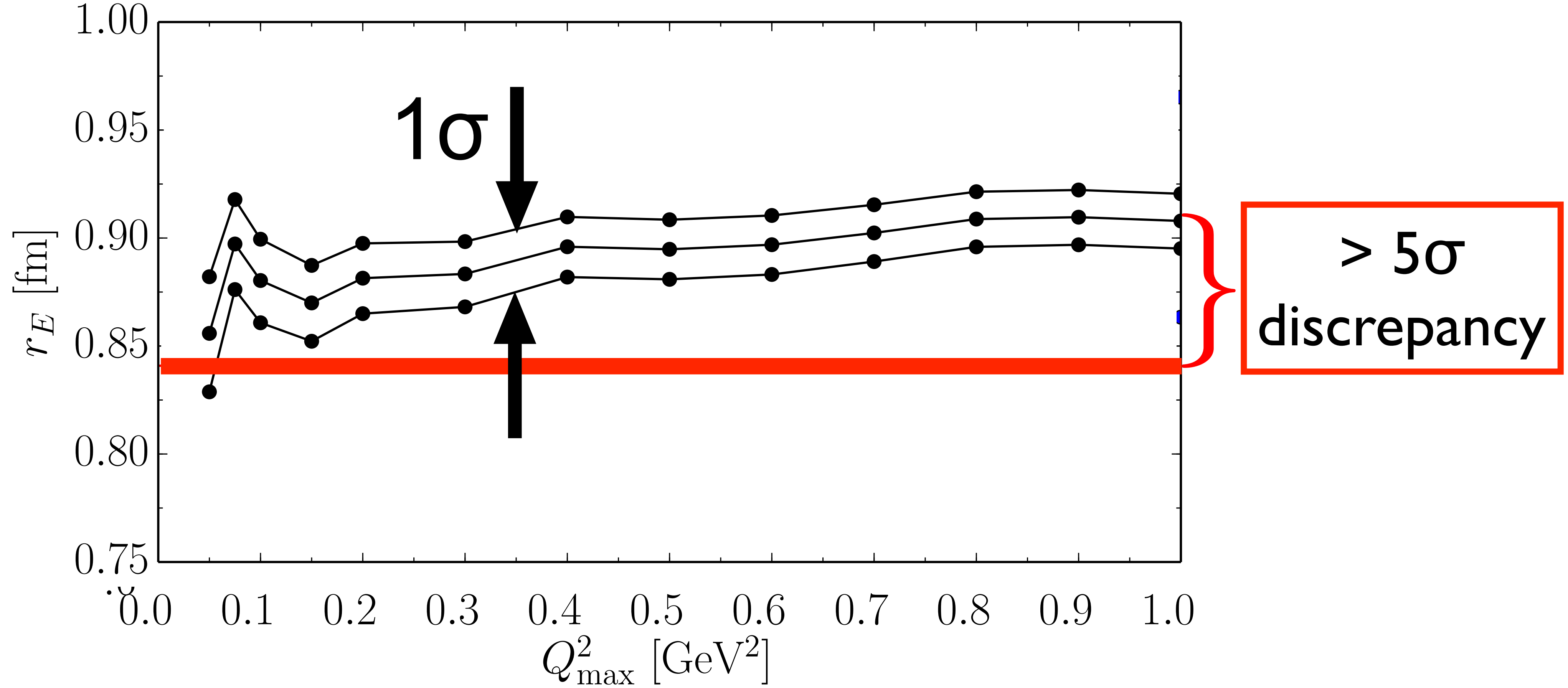

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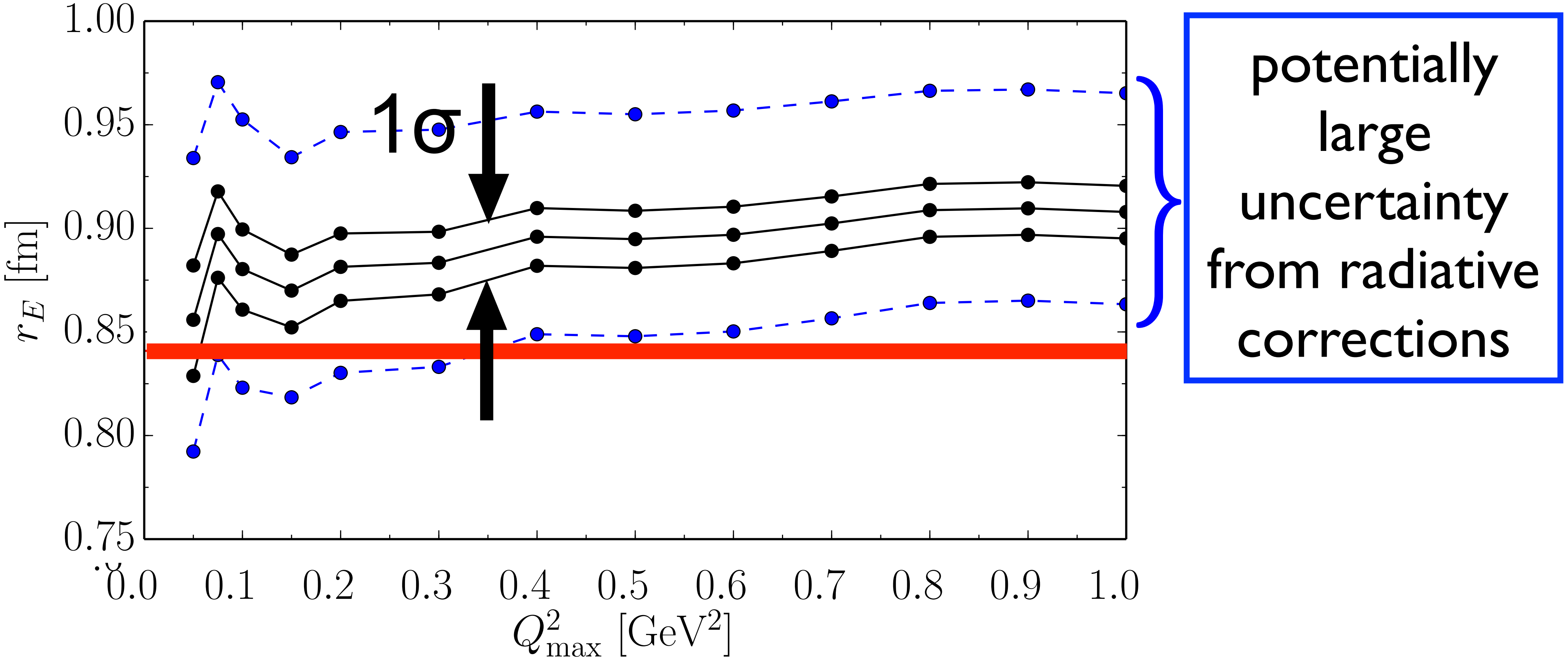

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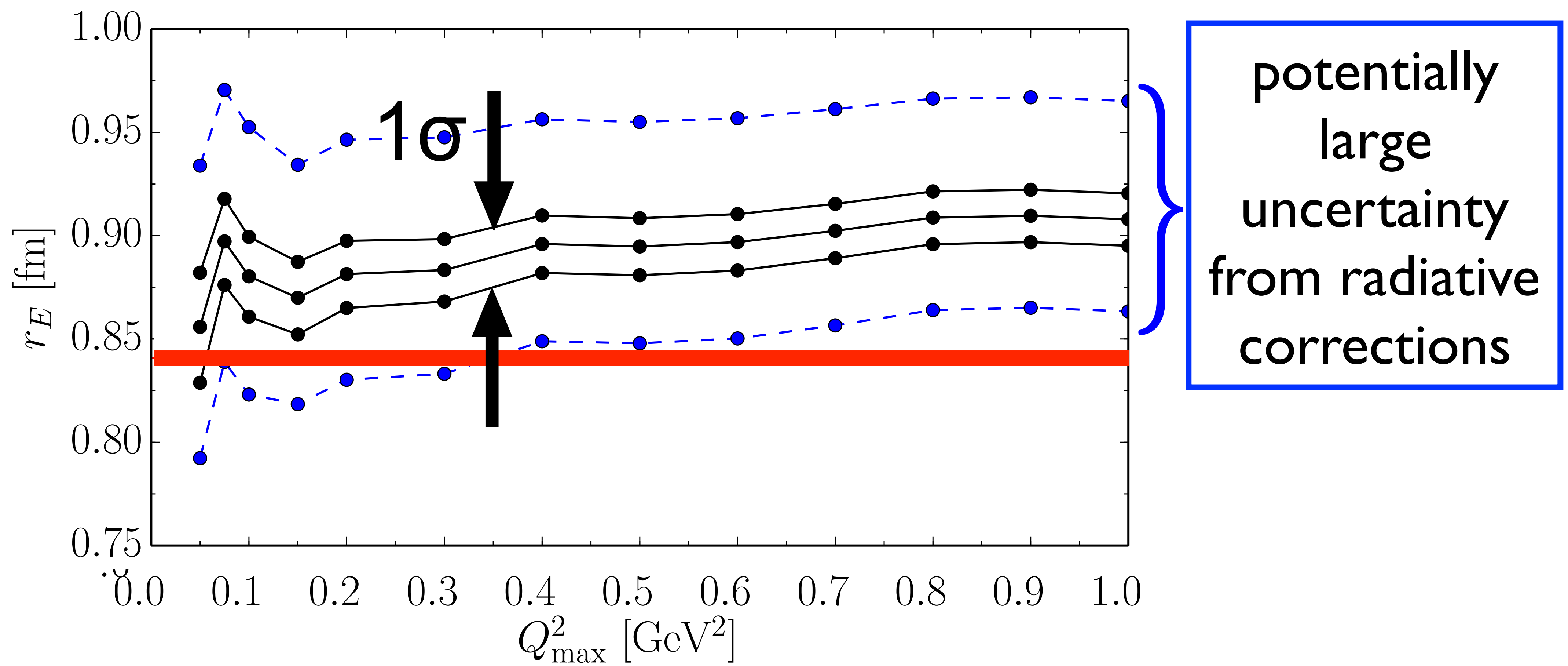

• potentially large impact of QED radiative corrections on proton radius puzzle

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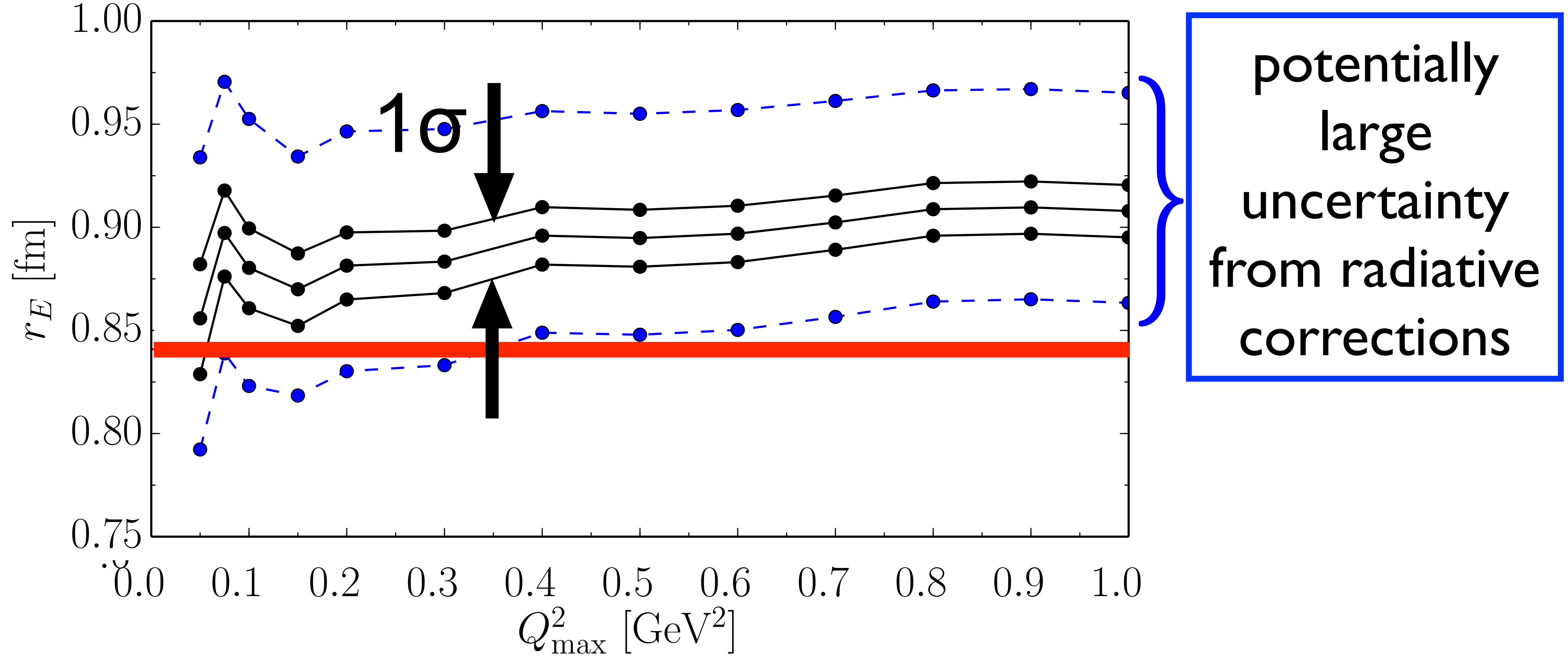

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• soft-collinear effective theory developed to systematically compute/resum large logarithms *details: 1605.02613*

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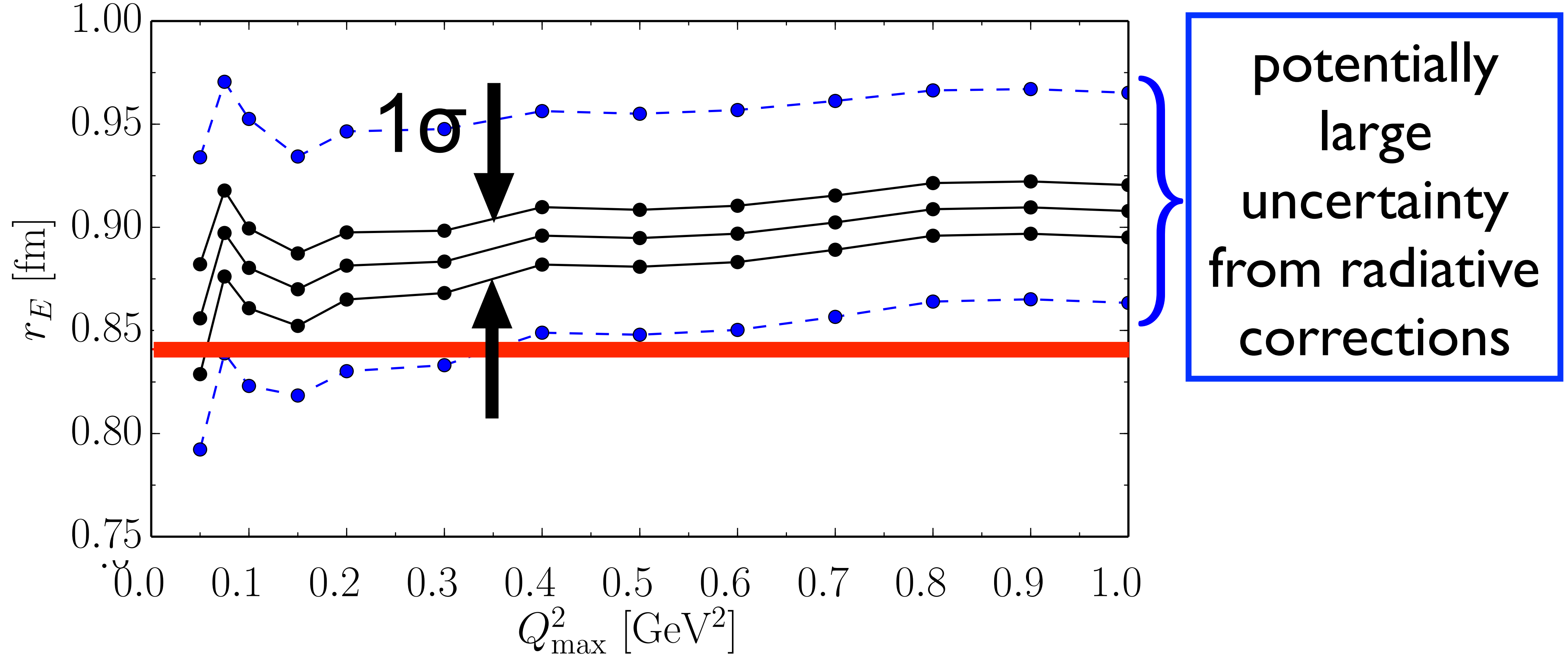


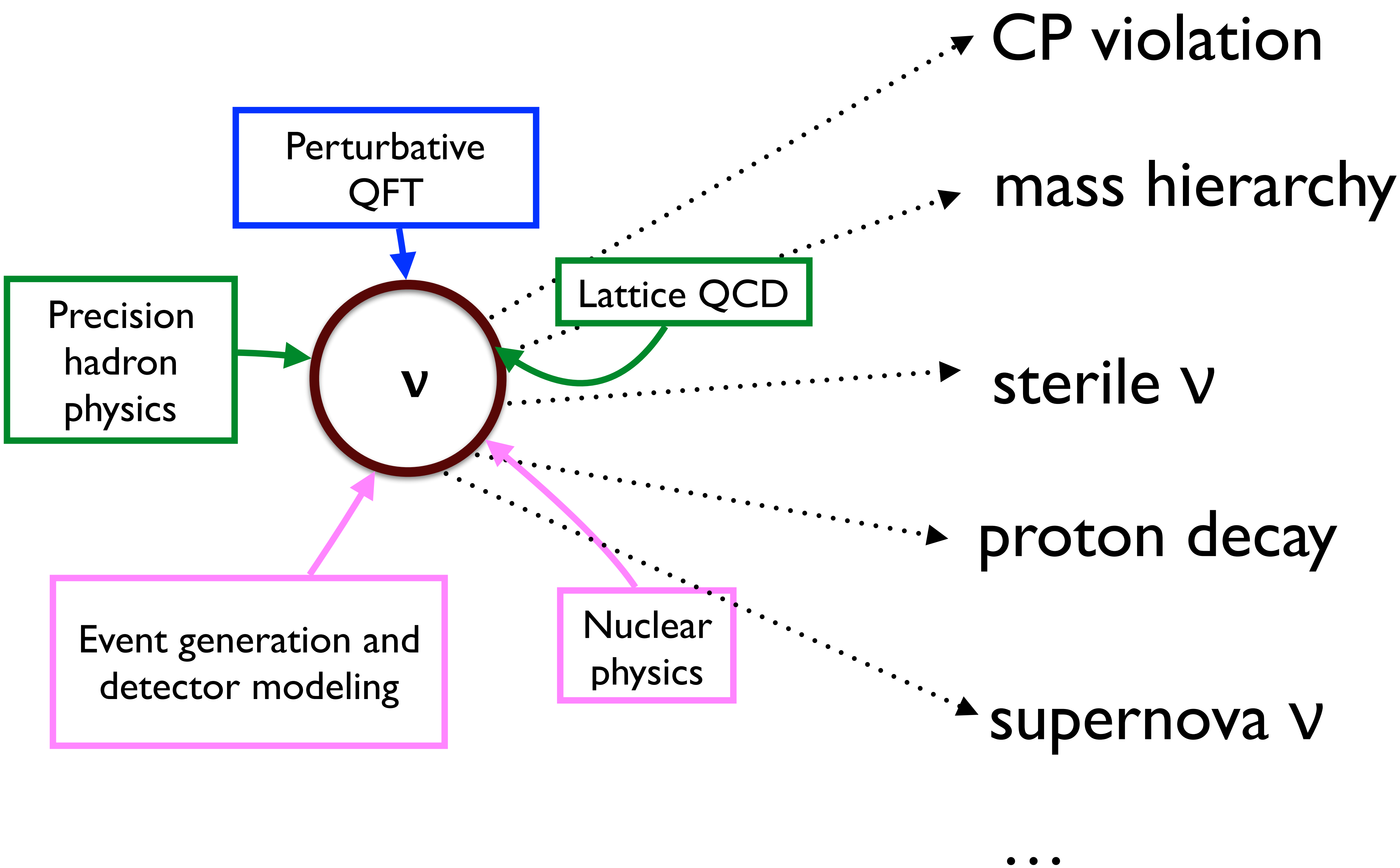
- potentially large impact of QED radiative corrections on proton radius puzzle

- soft-collinear effective theory developed to systematically compute/resum large logarithms *details: 1605.02613*

- same formalism applies to neutrino processes, impacting ν_e/ν_μ cross section ratios, critical for long baseline oscillation program

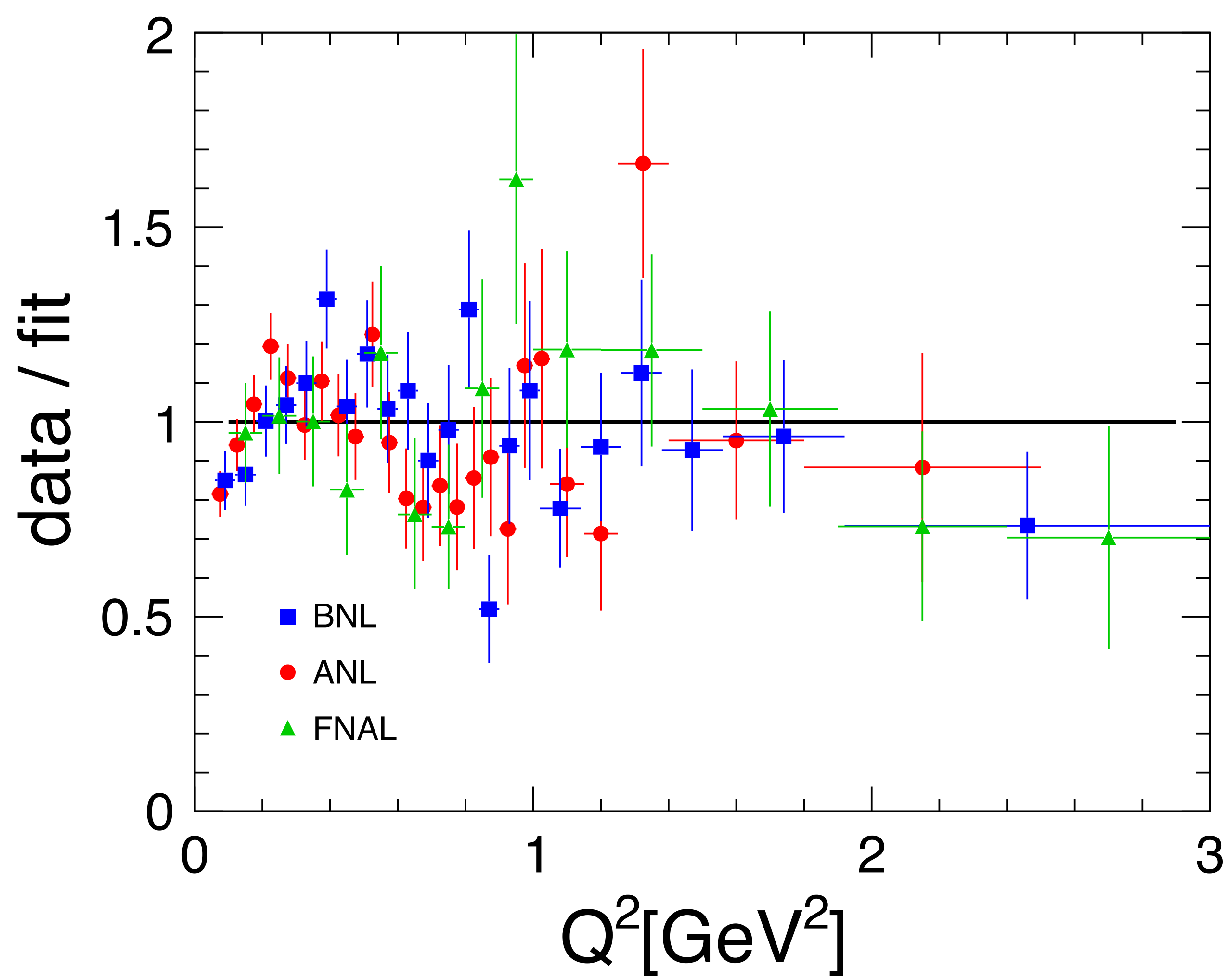
Summary

- progress in neutrino cross sections critical for probing new physics of the neutrino sector
- z expansion + lattice QCD: *model independent analysis of elementary signal process* $\sigma(\nu_\ell\, n \to \ell^- p)$
- soft-collinear effective theory: *radiative corrections to* $\sigma(\nu_e\, n \to e^- p)/\sigma(\nu_\mu\, n \to \mu^- p)$
- active field, modern theory techniques: *soft-collinear effective theory, lattice gauge theory, ab initio nuclear responses*
- many unavoidable connections with other intensity/cosmic/energy frontier problems


Perturbative QFT
Precision hadron physics
ν
Lattice QCD
Event generation and detector modeling
Nuclear physics
CP violation
mass hierarchy
sterile ν
proton decay
supernova ν
...

backup

see: 1603.03048



In final determination :

- joint fit to all data (ANL, BNL, FNAL)

- include correlated efficiency correction (for each dataset)

- include additional uncorrelated error to achieve X^2/d.o.f. = 1 ($\delta N/N \approx 10\%$)

- experimental acceptance/efficiency correction

see: 1603.03048

allow for correlated variation: η=0 ± 1

$$\frac{dN}{e(Q^2)} \to \frac{dN}{e(Q^2)+de(Q^2)} = \frac{dN}{e(Q^2)}\left(1+\eta_e\frac{de(Q^2)}{e(Q^2)}\right)^{-1}$$

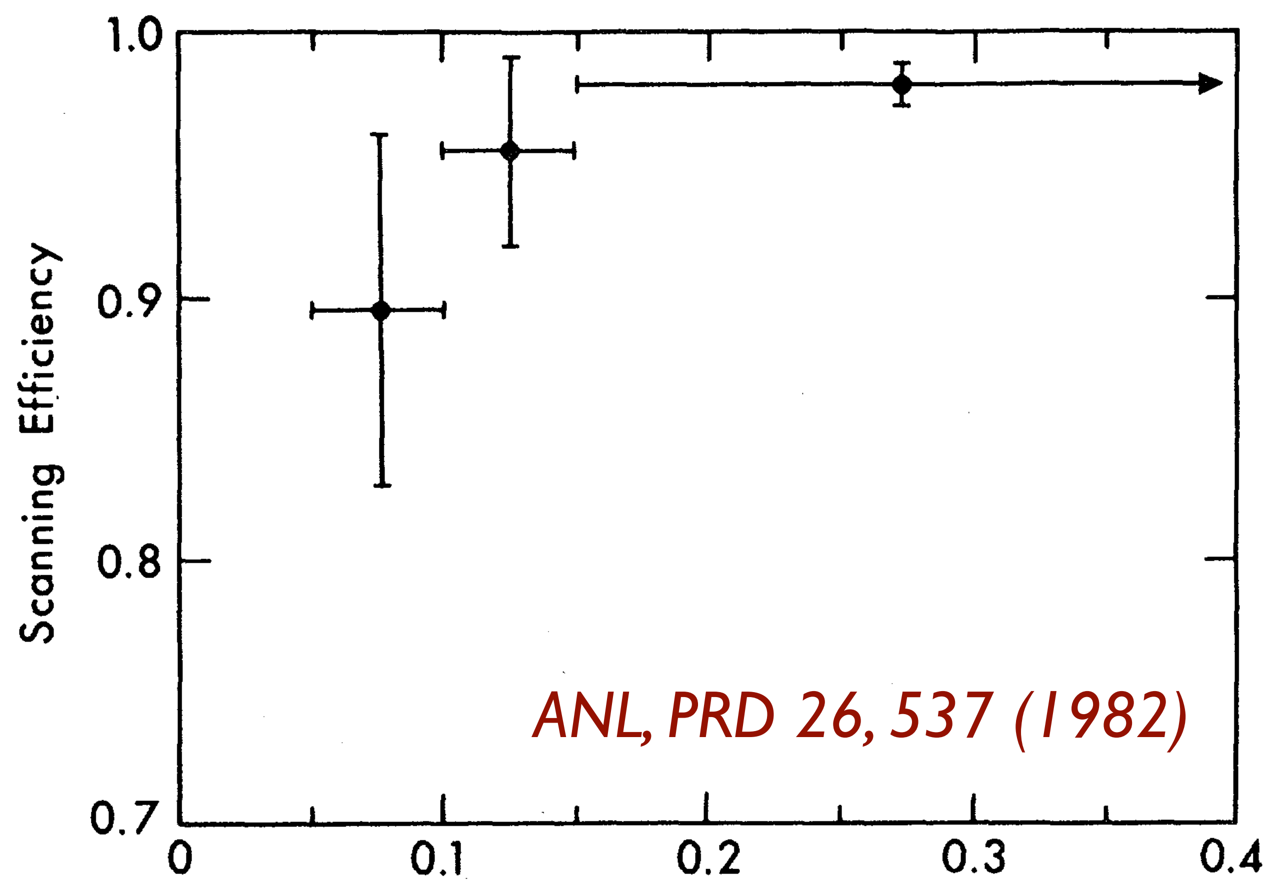
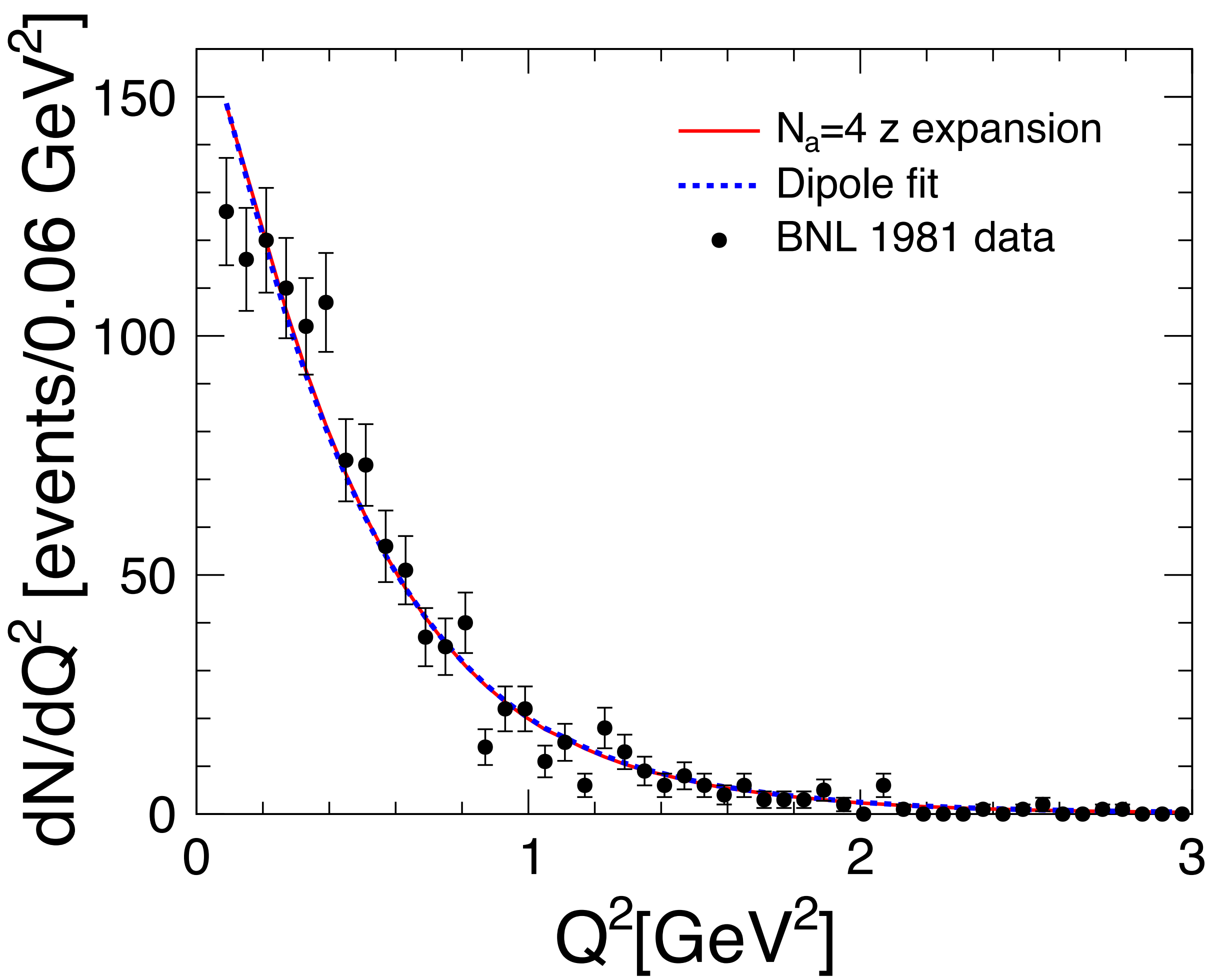
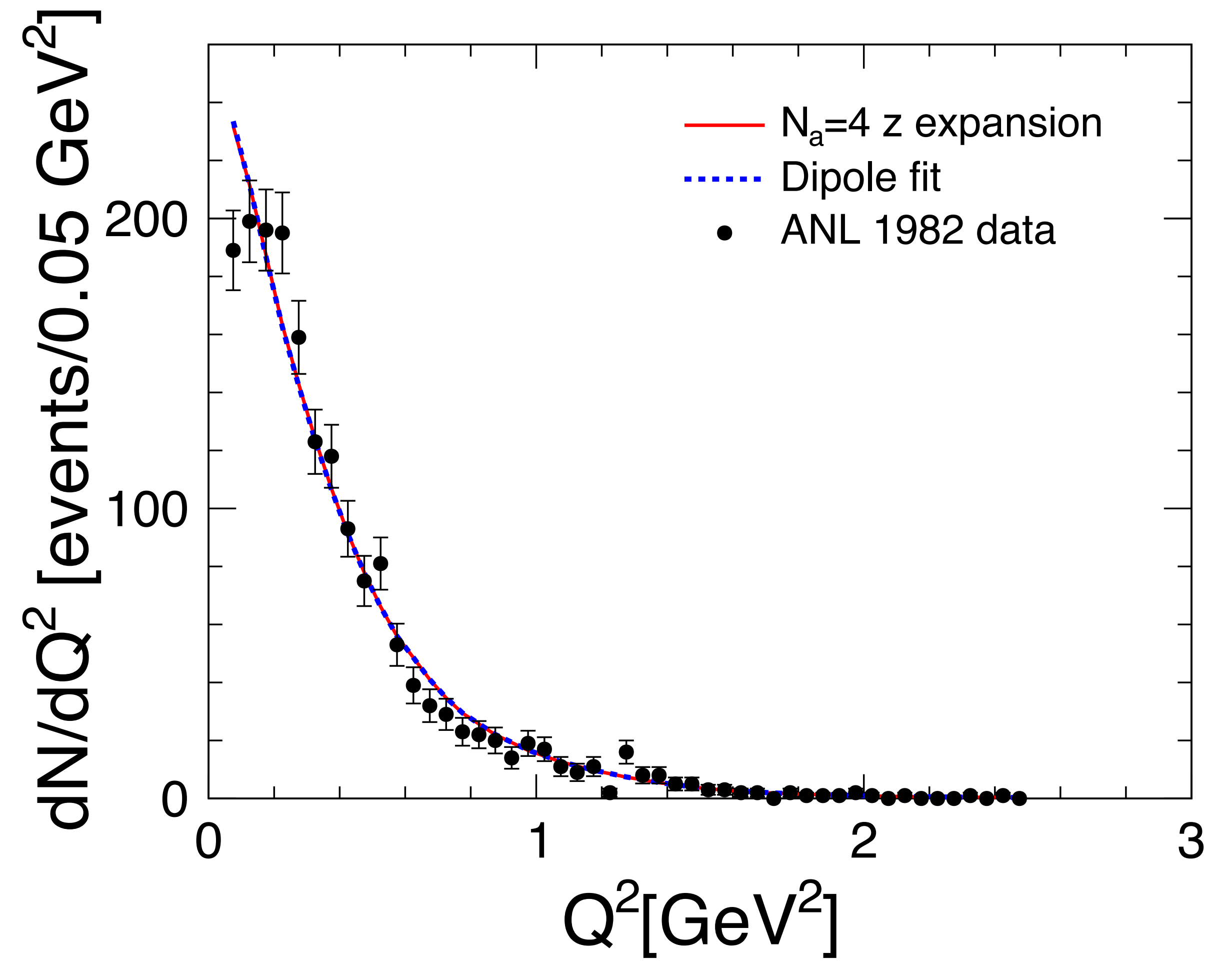


FIG. 1. Scanning efficiency as a function of momentum transfer squared.

data prefer η≠0 (ANL: η=-1.9, BNL: η=-1), but no significant improvement in fit quality

see: 1603.03048

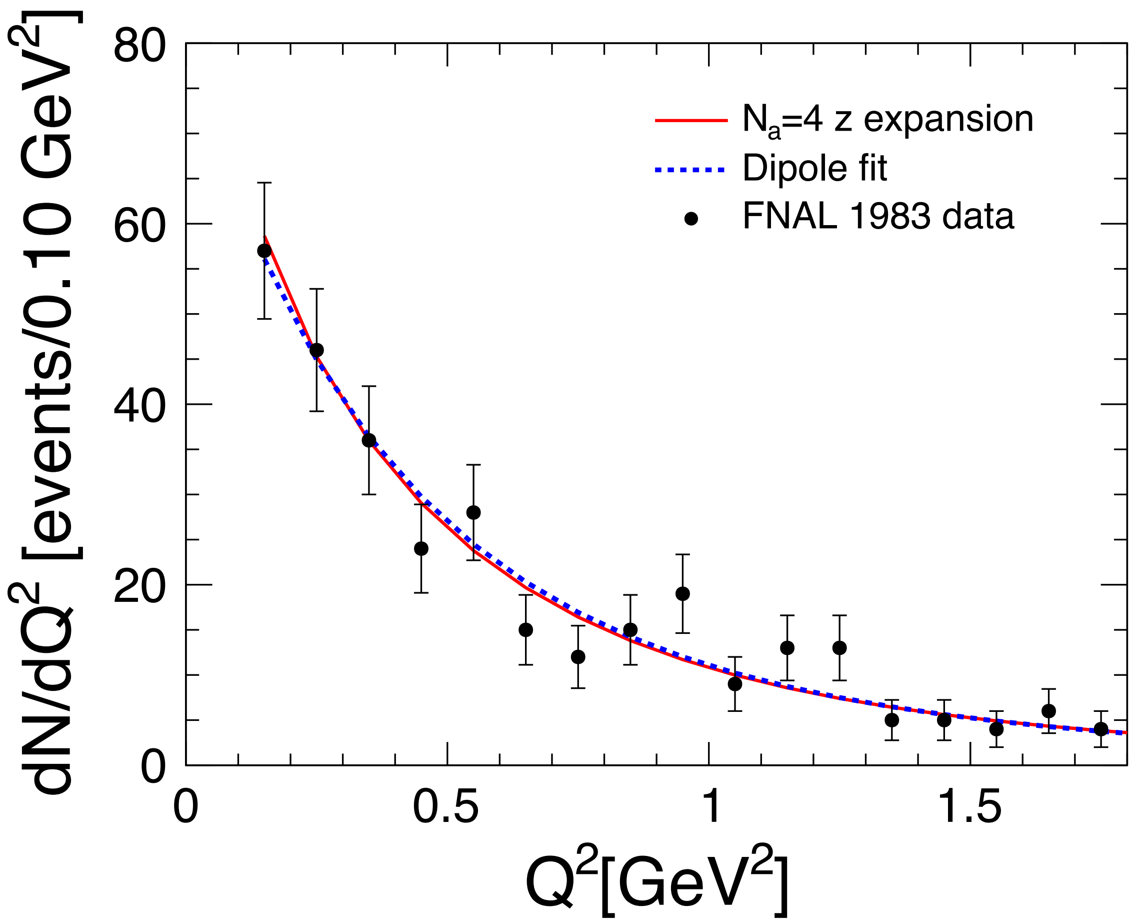


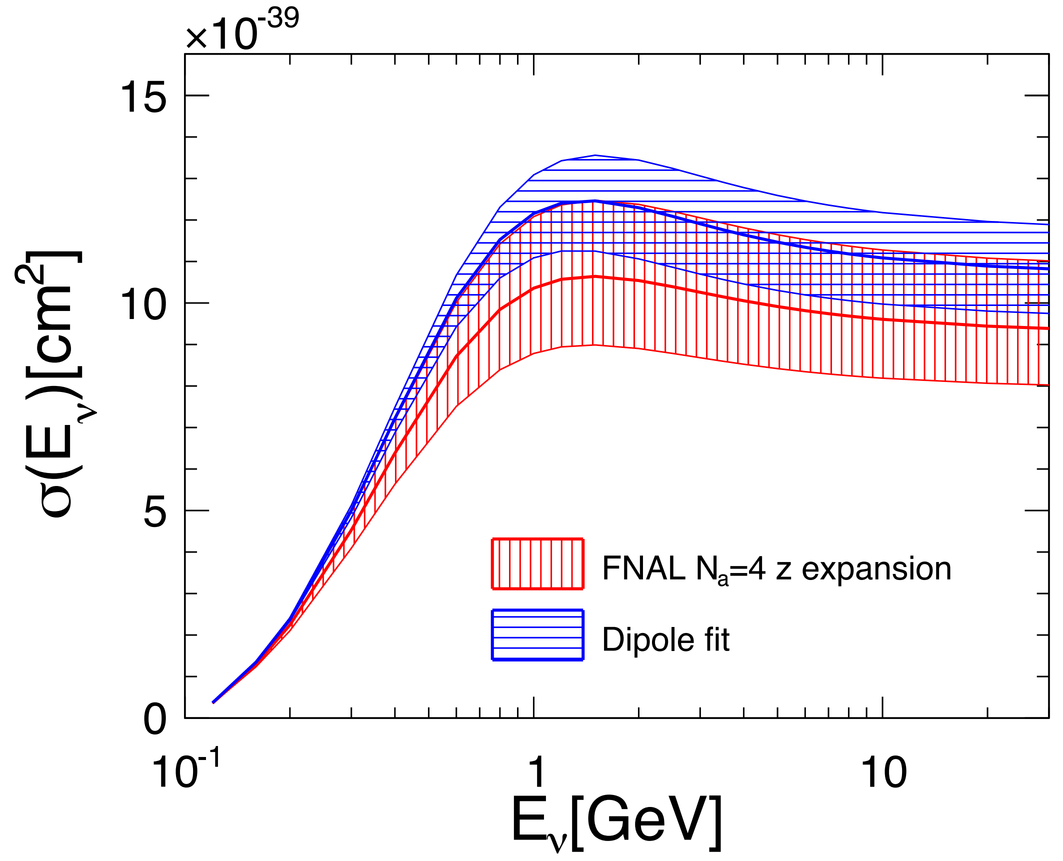


- Poor fit quality, symptom of underestimated systematic errors

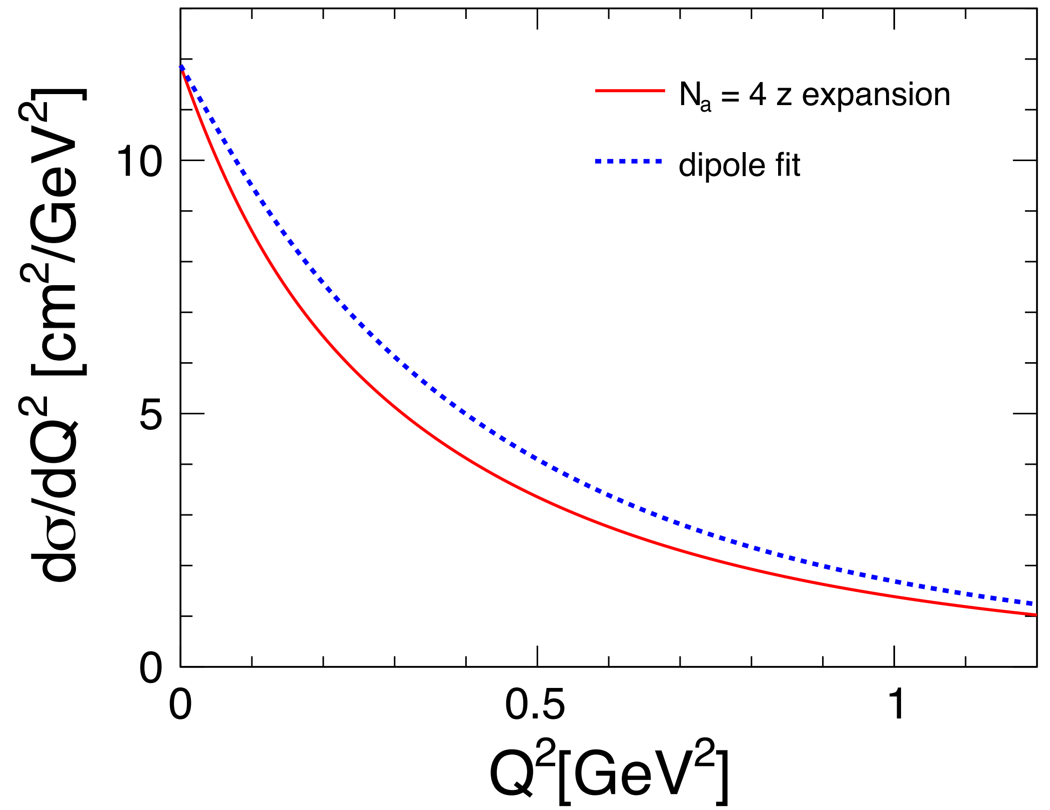
Dipole and z expansion yield different F_A

see: *1603.03048*





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



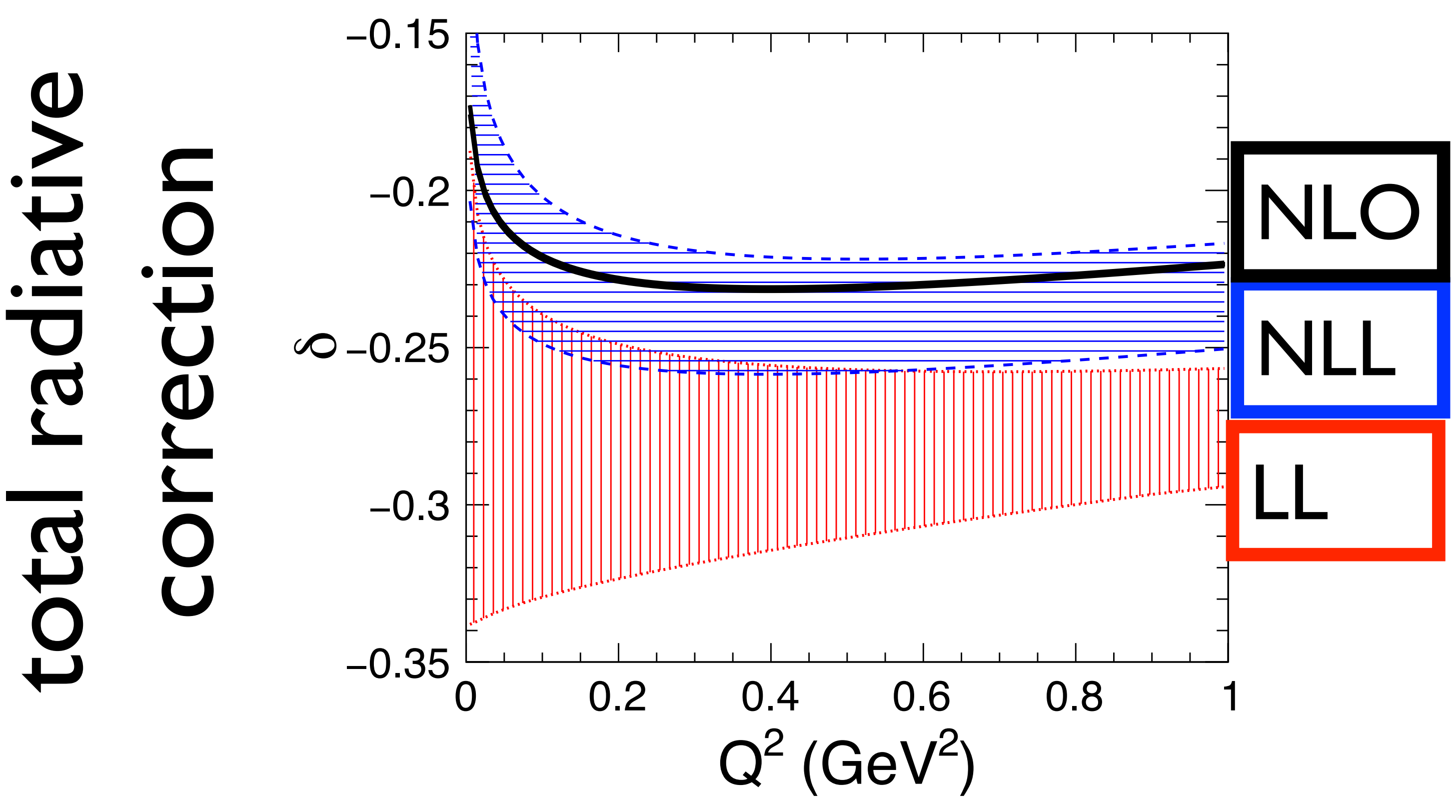
see: 1605.02613

$$d\sigma = H(M) \times \underbrace{\frac{H(\mu)}{H(M)} \times J(\mu) \times S(\mu)}_{\text{total radiative correction}}$$

numerically: $\alpha L^2 = \alpha \log^2 \frac{Q^2}{m^2} \sim 1 \quad \Rightarrow \quad \alpha L \sim \alpha^{\frac{1}{2}}$, etc.

electron energy: $E = 1\,\mathrm{GeV}$

electron energy loss cut: $\Delta E = 5\,\mathrm{MeV}$



correct through:

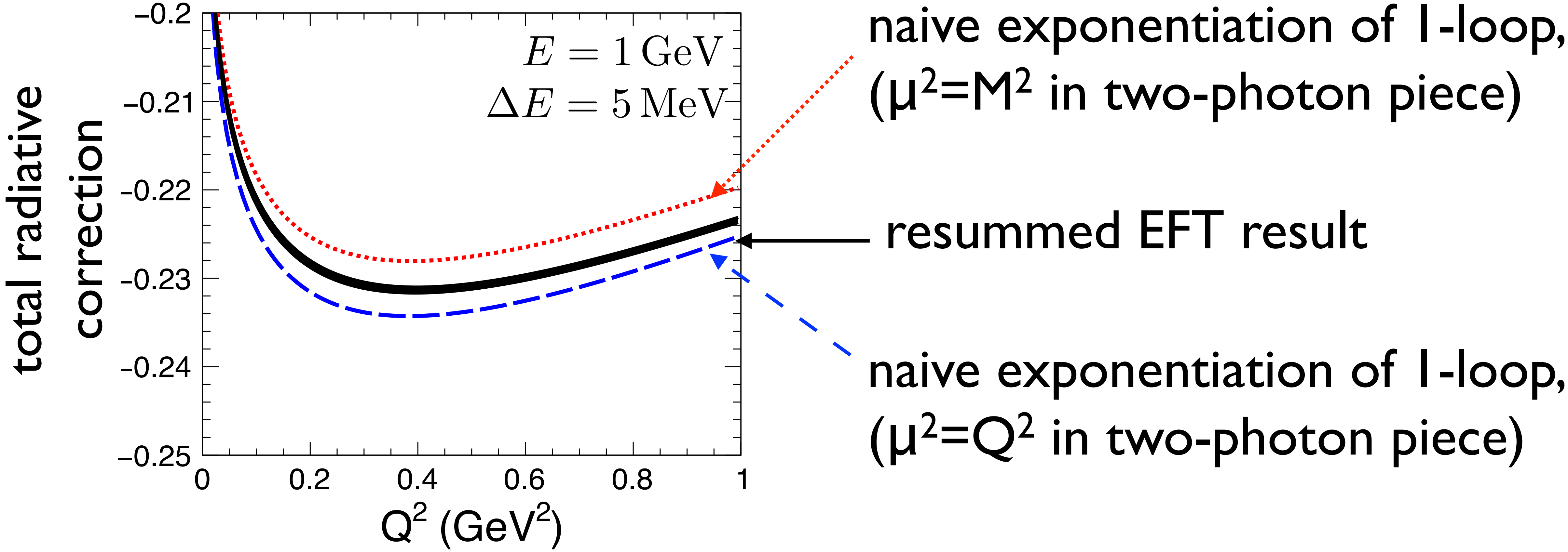
NLO: $\mathcal{O}(\alpha)$

NLL: $\mathcal{O}(\alpha^{\frac{1}{2}})$

LL: $\mathcal{O}(1)$

see: 1605.02613

Comparison to previous implementations of radiative corrections, e.g. in A1 collaboration analysis of electron-proton scattering data



- discrepancies at 0.5-1% compared to currently applied radiative correction models (cf. 0.2-0.5% systematic error budget of A1)

- conflicting implicit scheme choices for 1PE and 2PE

- complete analysis: account for floating normalizations, correlated shape variations when fitting together with backgrounds

Broader context: Sudakov logs ubiquitous, appear whenever kinematic invariants large compared to particle masses. Poor convergence, or even breakdown of fixed order perturbation theory

- massive boson production at proton collider $\alpha_s \log^2 \frac{m_Z^2}{q_T^2}$ $q_T \sim \text{GeV}$

- dark matter annihilation $\alpha_2 \log^2 \frac{M_{\text{DM}}^2}{m_W^2}$ $M_{\text{DM}} \sim \text{TeV}$

- Lepton-nucleon scattering $\alpha \log^2 \frac{Q^2}{m_e^2}$ $Q \sim \text{GeV}$

Effective theories differ in detail. For lepton-nucleon scattering: explicit lepton mass, bremsstrahlung energy cut, nuclear recoil and charge corrections