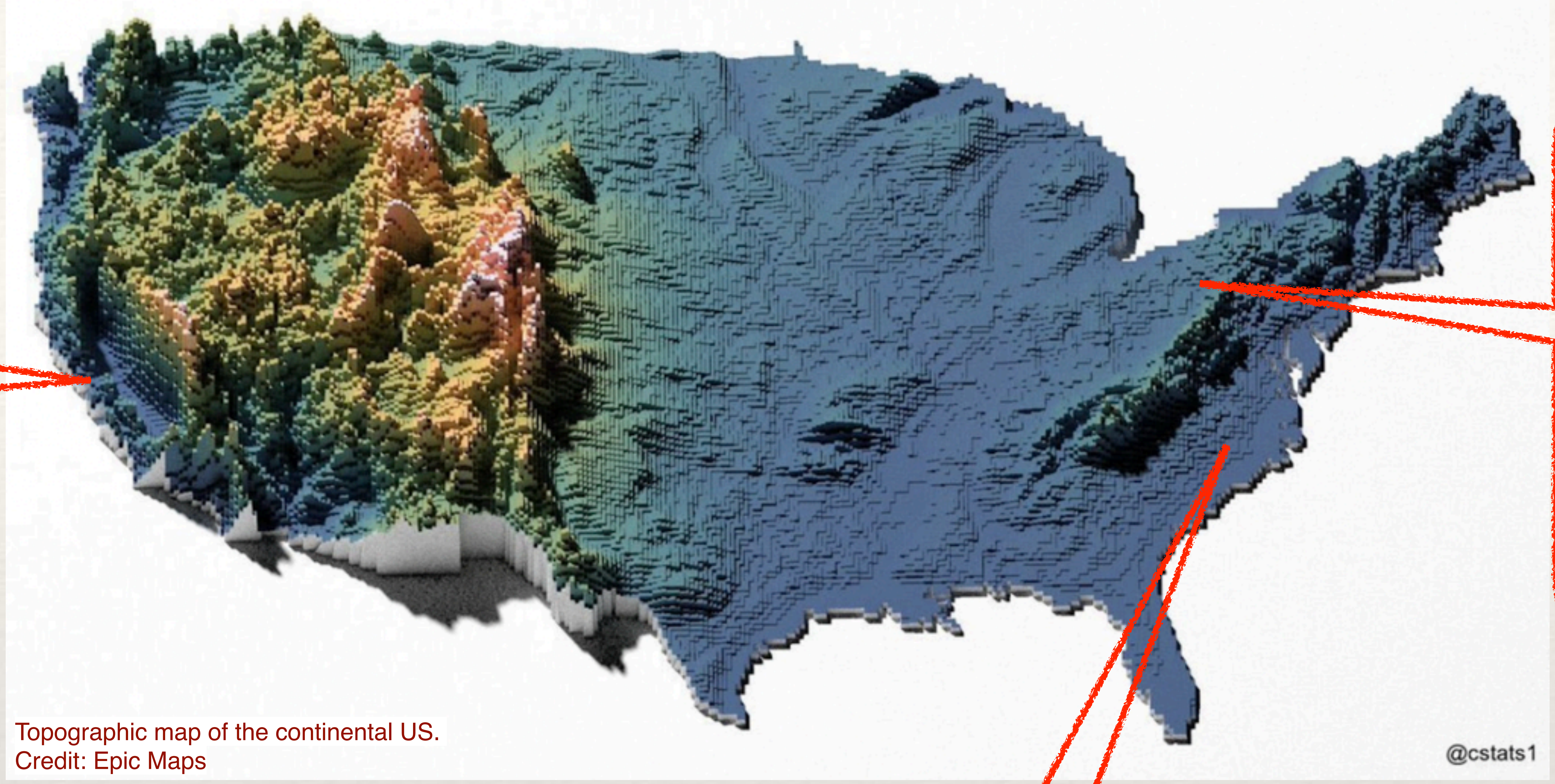
Nuclear Theory for New Physics
Progress with lattice QCD

Topical Collaboration Meeting @ DOE
2 May, 2024

André Walker-Loud

BERKELEY LAB

Lattice QCD subgroup



Topographic map of the continental US.
Credit: Epic Maps

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2023 DOE SCGSR @ LBNL
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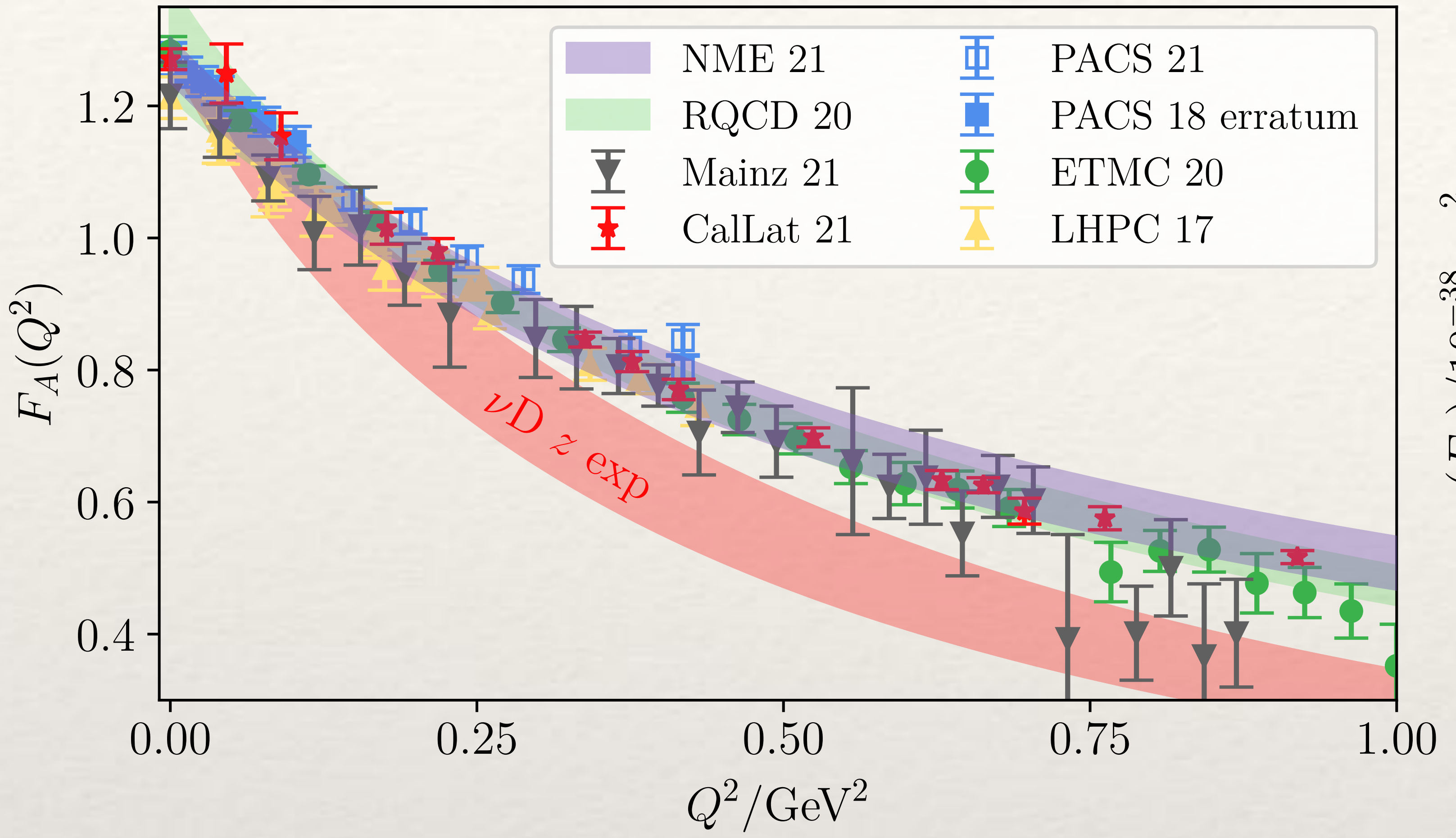
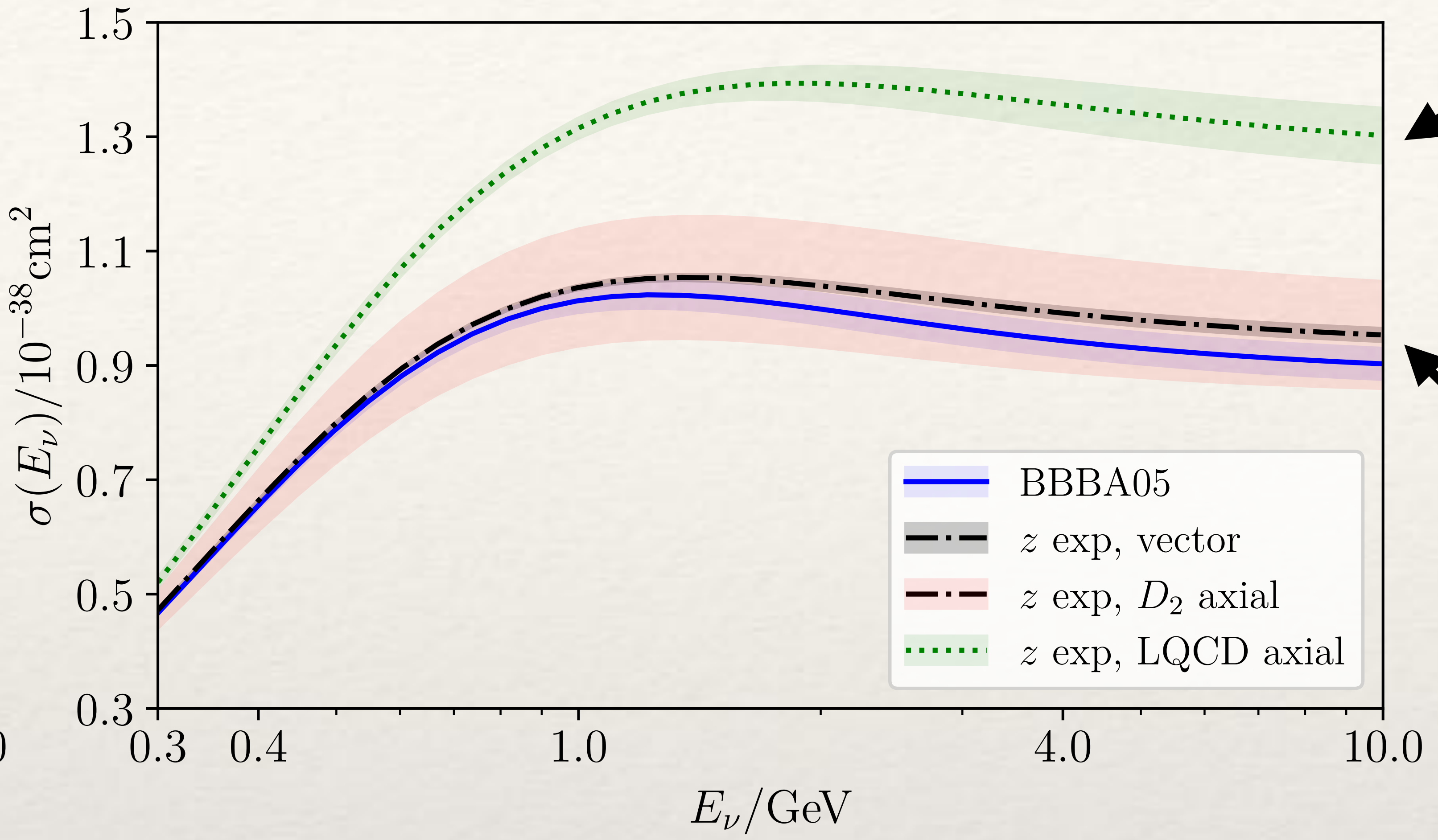
2024-2025: applying for DOE SCGSR @ LBNL

ν-N cross section

Meyer, Walker-Loud, Wilkinson
Ann. Rev. Nucl. Part. Sci. 72 (2022)





This discrepancy impacts the ability to interpret neutrino oscillation parameters

Some of this uncertainty comes from nucleon electromagnetic form factors

- Lattice QCD determination of $F_A(Q^2)$ is inconsistent with older phenomenological extraction
- results in 30% increase in ν-N cross section
- New MINERνA measurement of νN with hydrocarbon lies between LQCD and νD — Nature 614 (2023)

ν-N cross section

Meyer, Walker-Loud, Wilkinson
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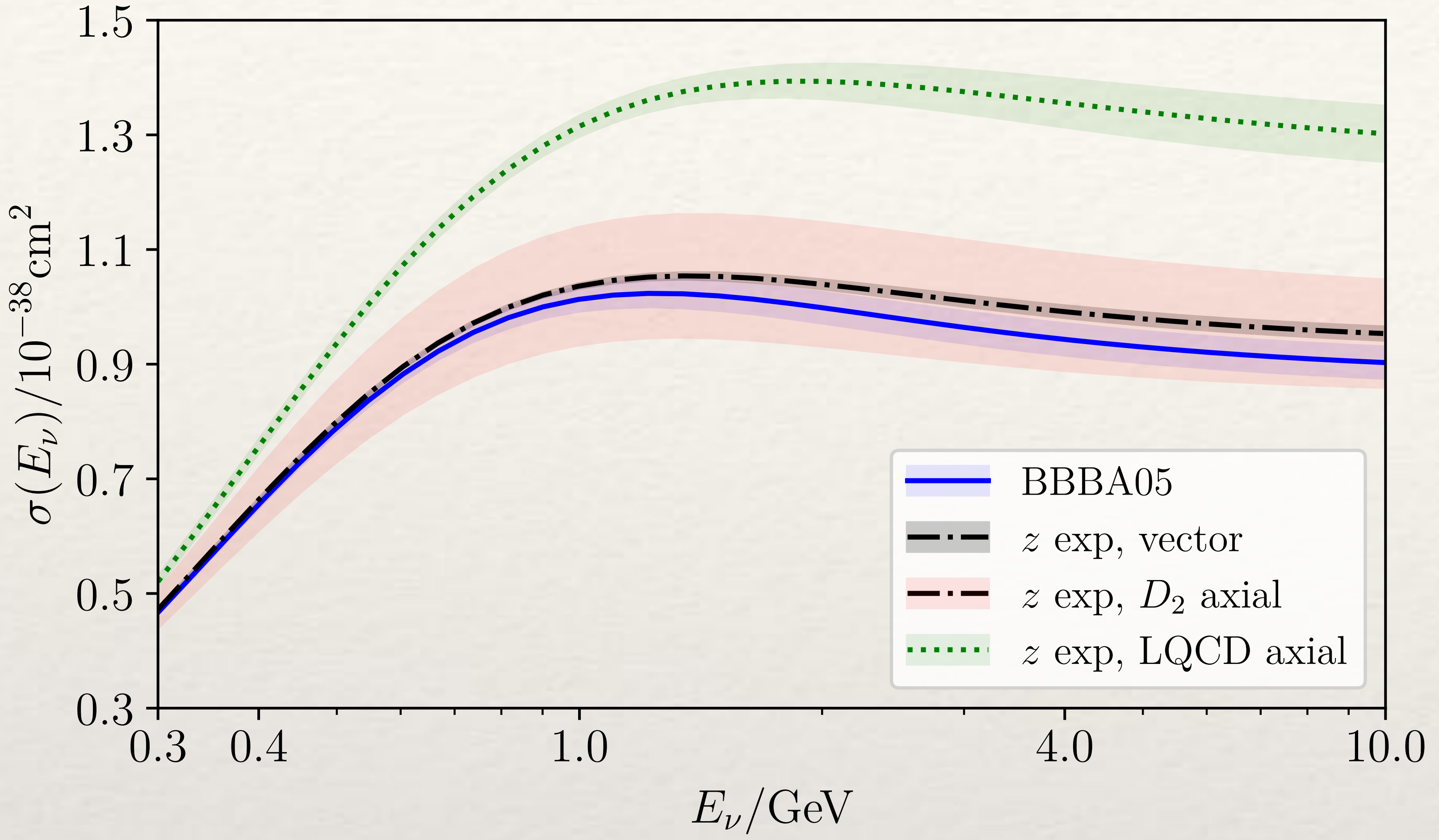
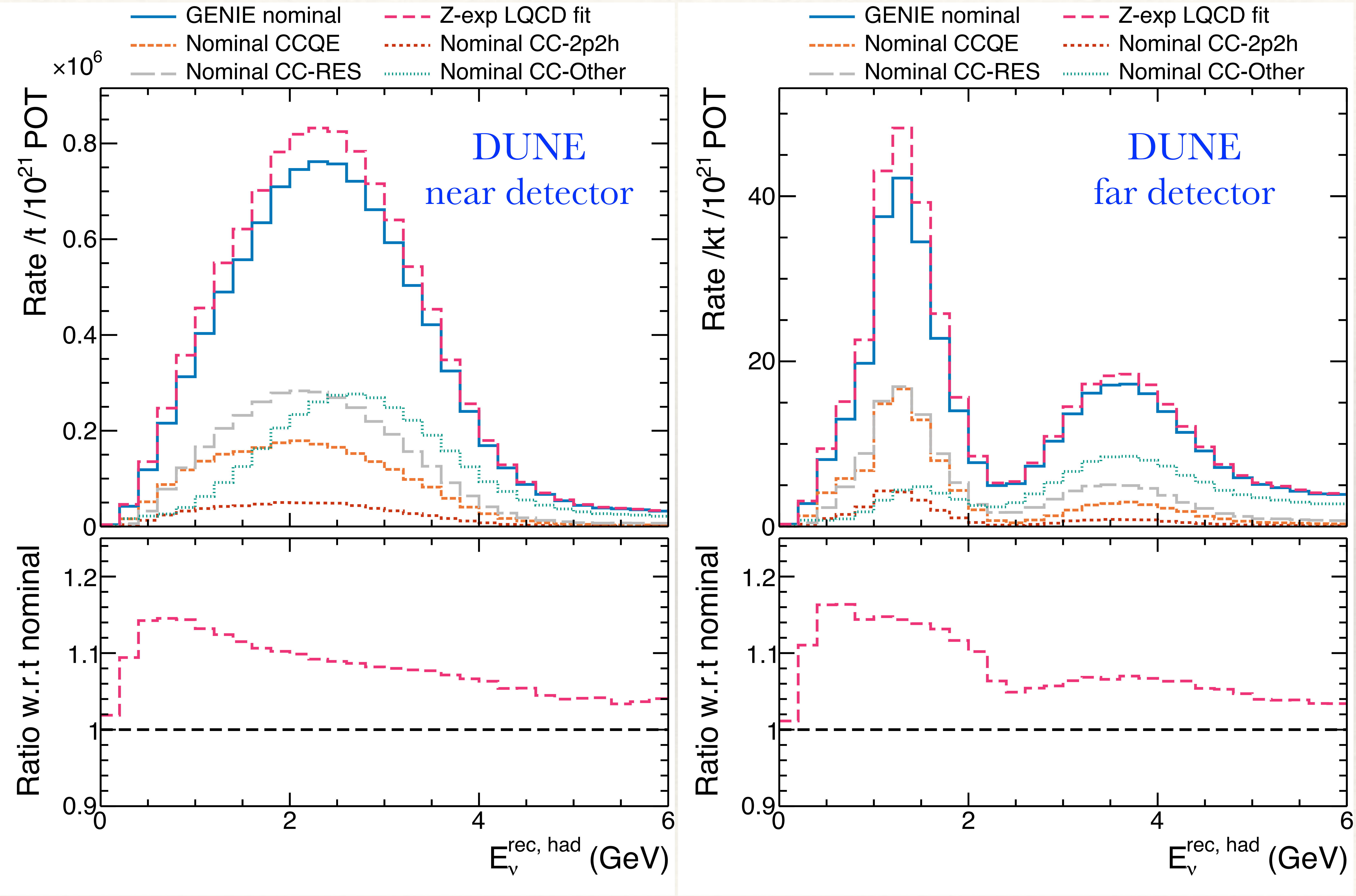


- Lattice QCD determination of $F_A(Q^2)$ is inconsistent with older phenomenological extraction
- results in 30% increase in ν-N cross section
- Energy dependent change



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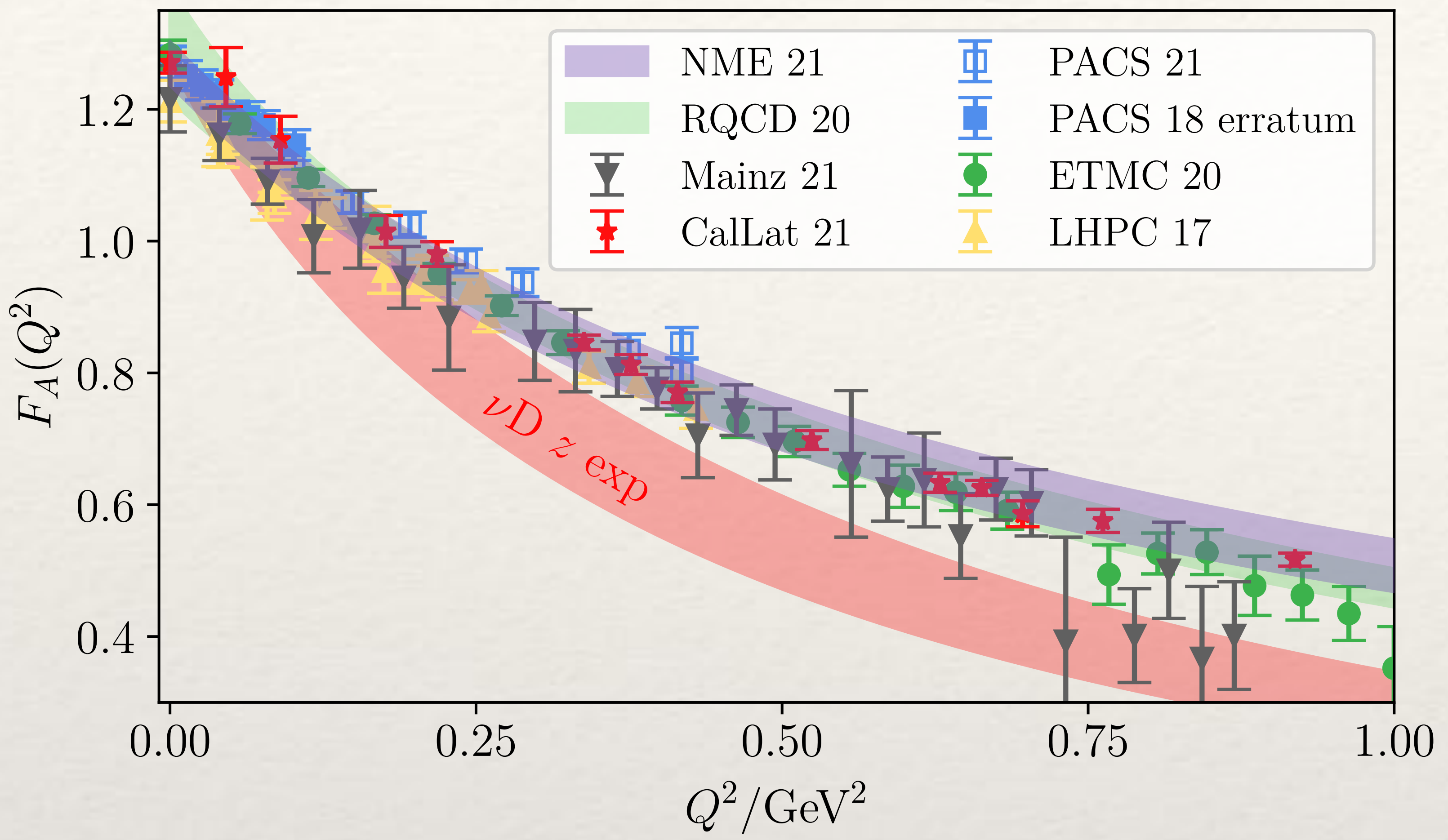
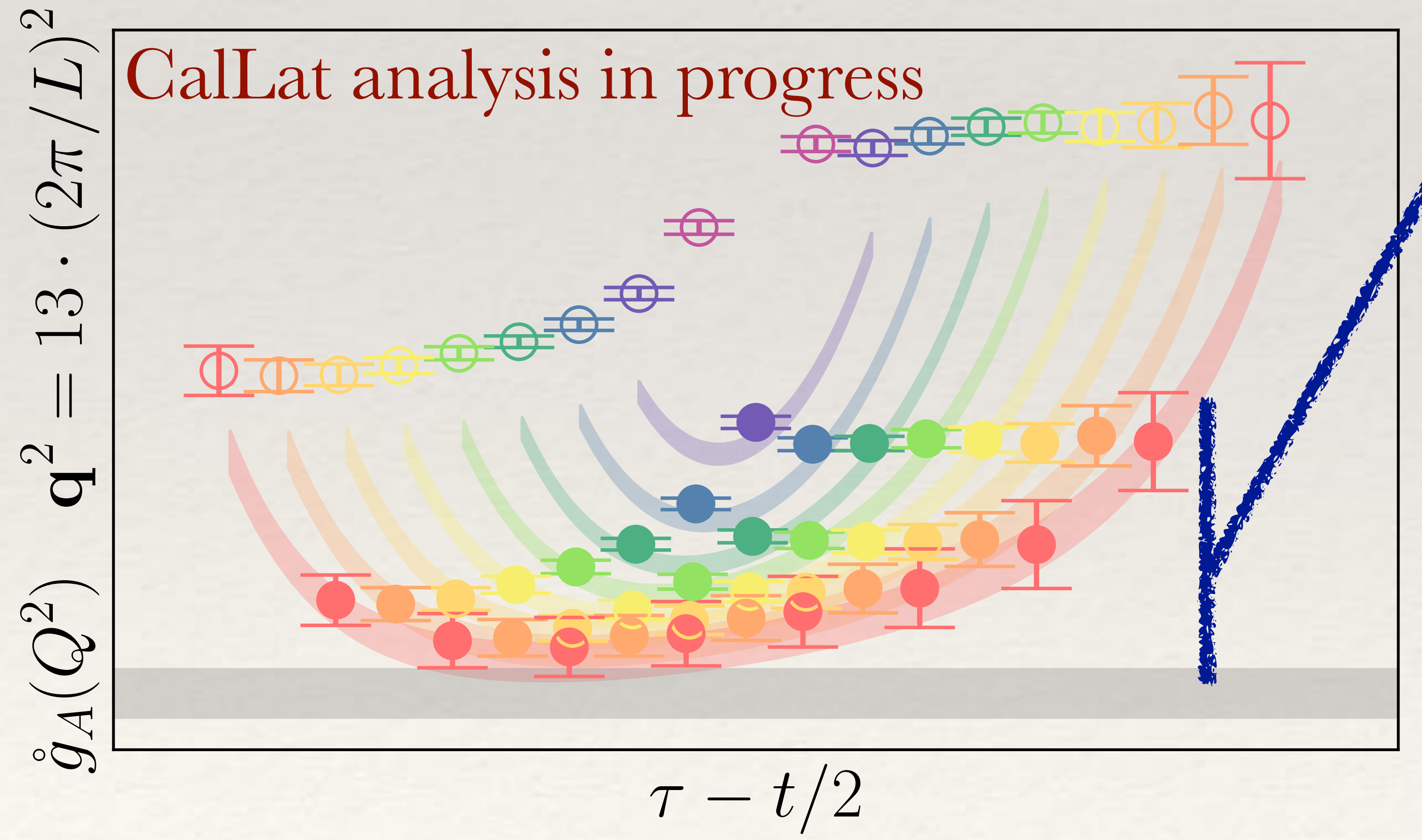




- **What is required to finalize the lattice QCD results?**
- All lattice calculations are performed with the same strategy
  - use different $t_{\mathrm{sink}} - t_{\mathrm{source}}$ separation to understand and model excited state contamination

$$\langle N(t_{\mathrm{sink}}, \mathbf{p}_f = 0) | j^A_\mu(\tau, \mathbf{q}) | N(t_{\mathrm{source}}, \mathbf{p}_i = -\mathbf{q}) \rangle$$

  - No calculations are/can be performed with large enough $t_{\mathrm{sink}} - t_{\mathrm{source}}$ to ignore excited state contamination
- **We need a new strategy that has a different dependence on excited states**
- We are developing such a technique: it that will enable momentum-space creation operators

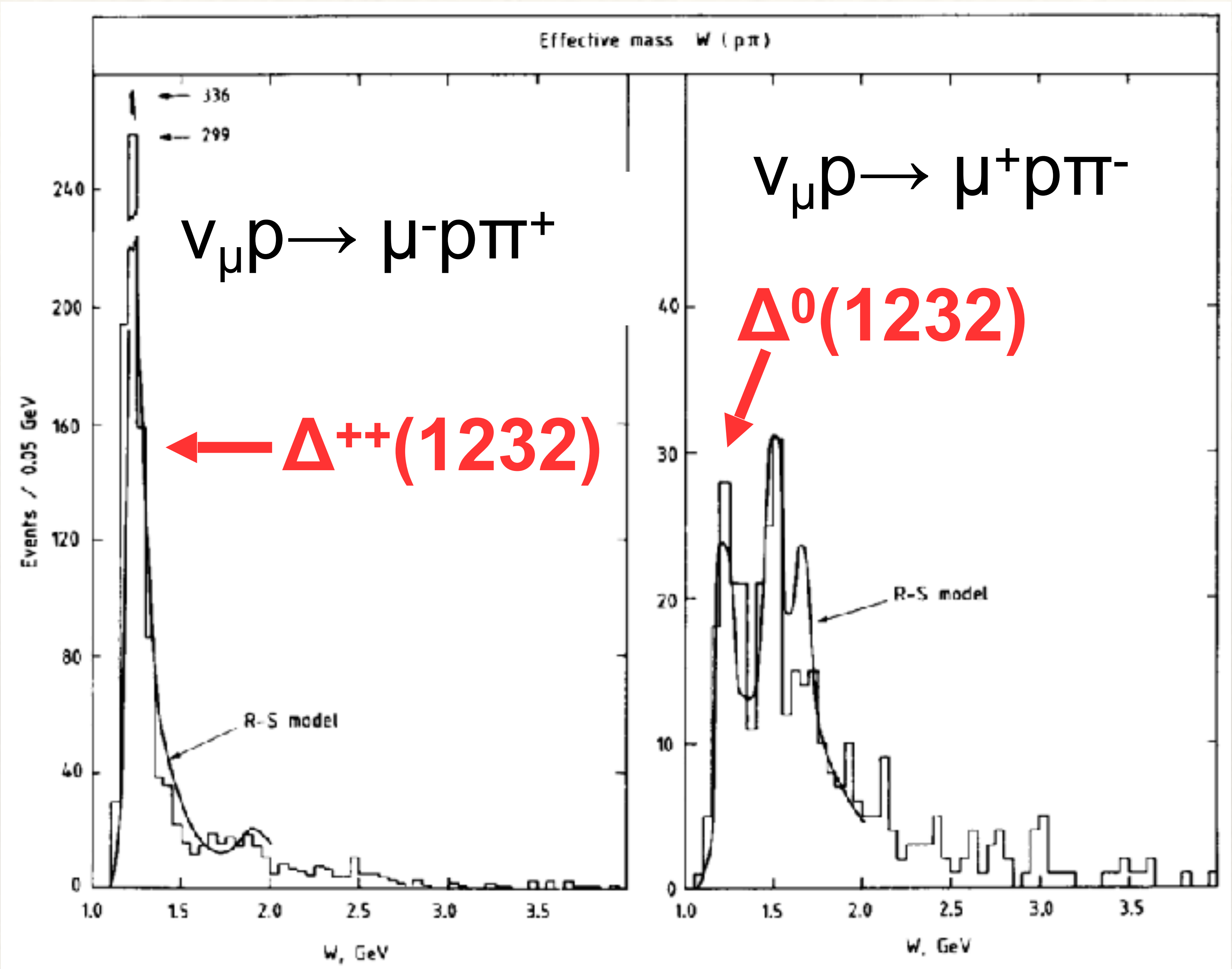
$$\langle N(t_{\mathrm{sink}}, \mathbf{p}_f) | j^A_\mu(\tau, \mathbf{q} = \mathbf{p_f} - \mathbf{p_i}) | N(t_{\mathrm{source}}, \mathbf{p}_i) \rangle$$

- This technique will also allow $\langle \Delta | j_\mu | N \rangle, \ \langle N\pi | j_\mu | N \rangle, \ \langle NN | j_\mu | NN \rangle$

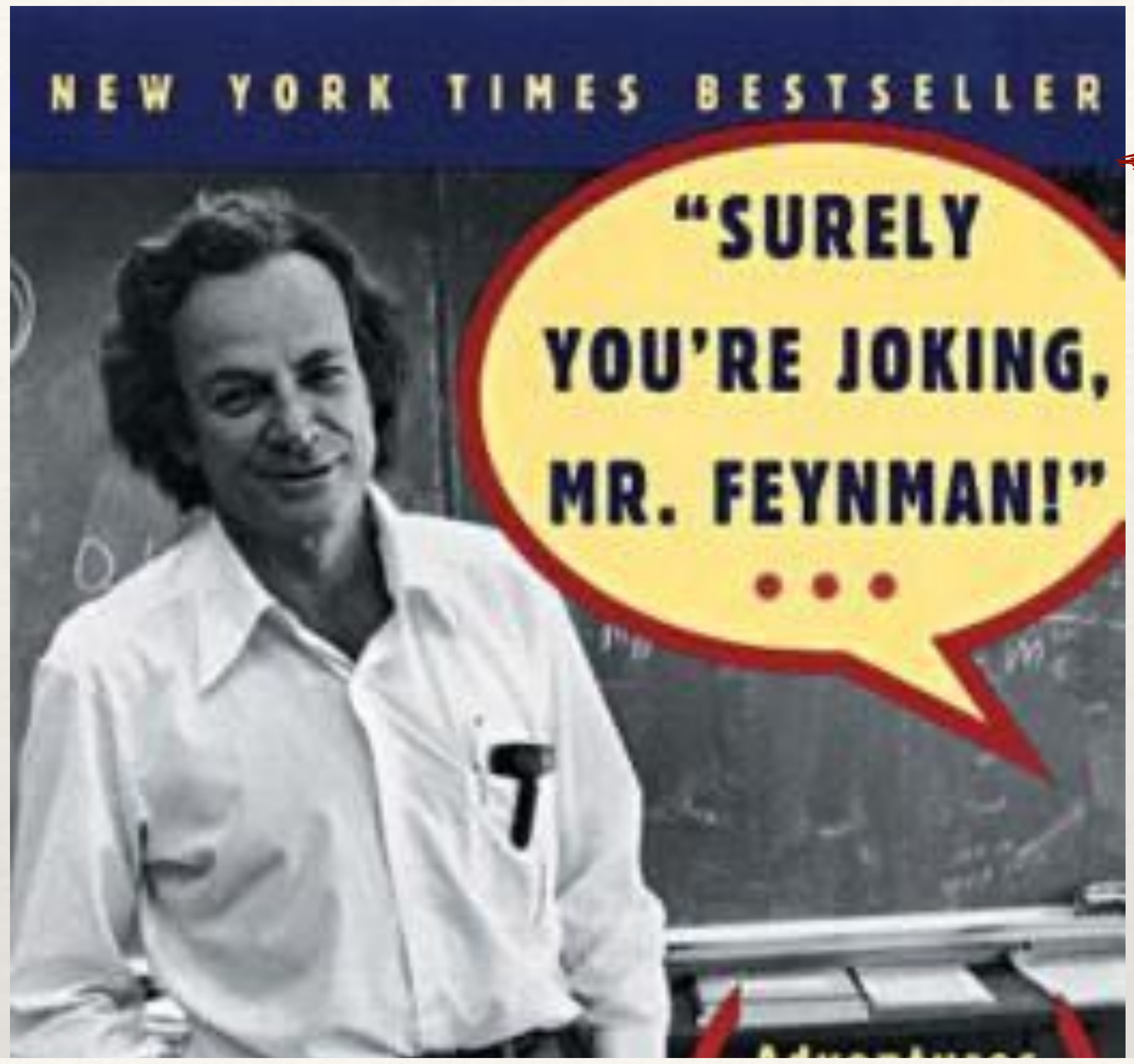
ν-N cross section — Future directions

State of the Field

Nucl. Phys. B264 221 (1986)



$$W^2 = (\Sigma E)^2 - |\Sigma \mathbf{p}|^2$$



Indeed not!

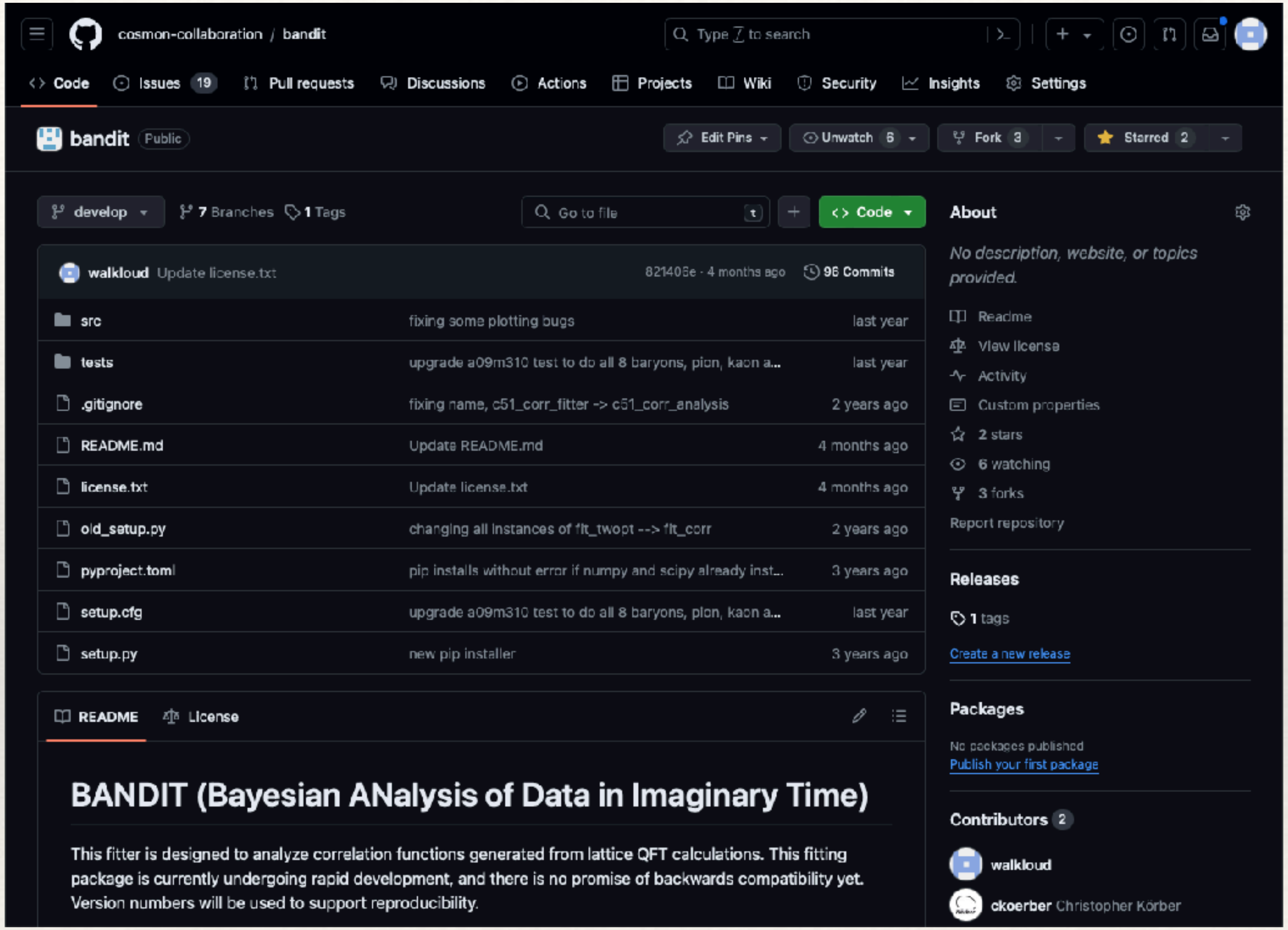
Our pion production model uses a description of resonance production that is "naive and obviously wrong in its simplicity" [Feynman, Kislinger, Ravndal PRD3 (1971)]

"I trust some bright motivated physicists will fix this soon"

- ❑ Current models are unsatisfactory:
  - ❑ Simplistic description of neutrino-nucleon interaction
  - ❑ Unsophisticated description of the nucleus
- ❑ Heavy reliance on old data (experiments shut down)
- ❑ ~10% uncertainties on effective parameters at best
  - ❑ insufficient for precision goals of DUNE (C. Wilkinson, private communication)

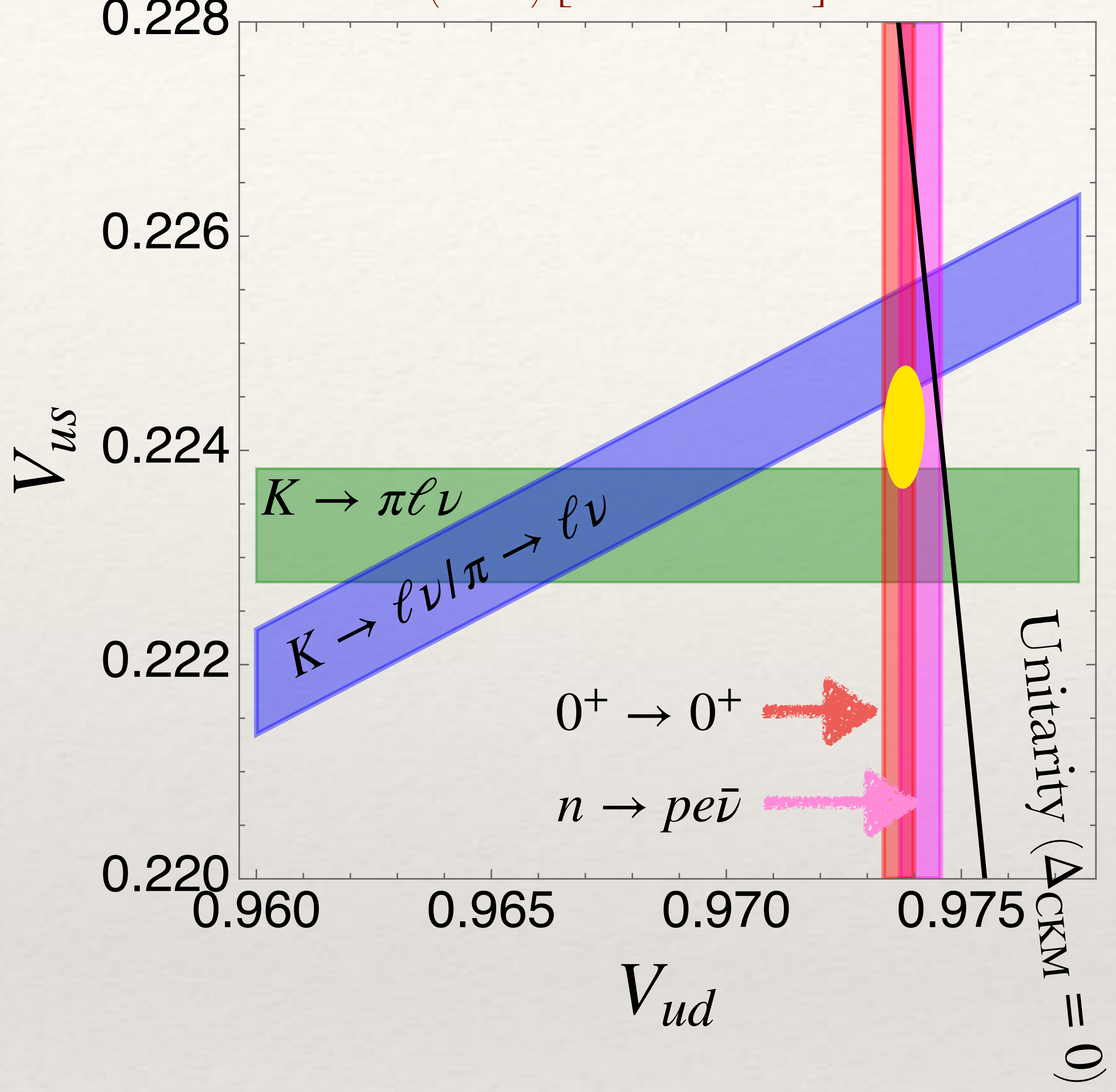
ν-N cross section — Synergy

- We realize that some of the analysis needed for Quantum-Monte-Carlo is very similar to lattice QCD
- I have been developing sophisticated data analysis package for lattice QCD BANDIT
- Saori and I are collaborating to see if the lattice QCD analysis code can be helpful for analyzing the QMC results



Precision β decays

Cirigliano, Crivellin, Hoferichter, Moulson
PLB 838 (2023) [2208.117707]



$$\Delta_{\mathrm{CKM}} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$
$$= -0.00176(56)$$

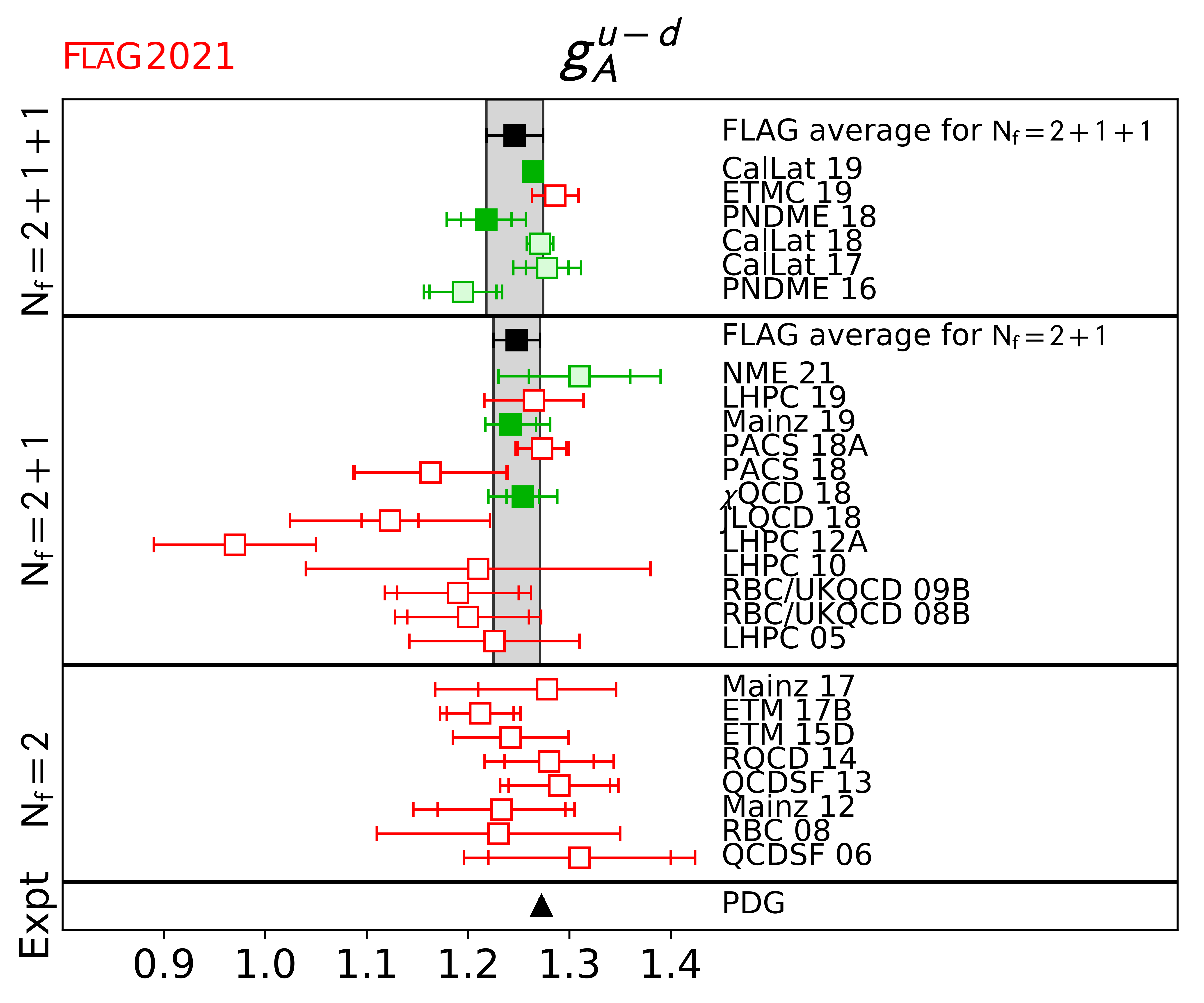
$$\Gamma_n = \frac{G_F^2 |V_{ud}|^2 m_e^5}{2\pi^3}(1+3\lambda^2)\cdot f_0 \cdot (1+\Delta_f)\cdot(1+\Delta_R), \qquad \lambda = g_A/g_V$$

phase space corrections
radiative QED corrections

- LQCD can help determine radiative QED corrections,
  - nucleon: Δ_R^V
  - NN: nuclear structure corrections, δ_{NS}

- Comparing LQCD calculations of g_A^{LQCD} to experimentally measured $\lambda^{exp} = g_A^{exp}/g_V^{exp}$ constrains BSM right-handed currents (corrections to V-A)

Status of lattice QCD results for g_A – 2021



- Now many groups obtaining values of g_A fully extrapolated to the physical point (green)
  - physical pion mass
  - continuum
  - infinite volume

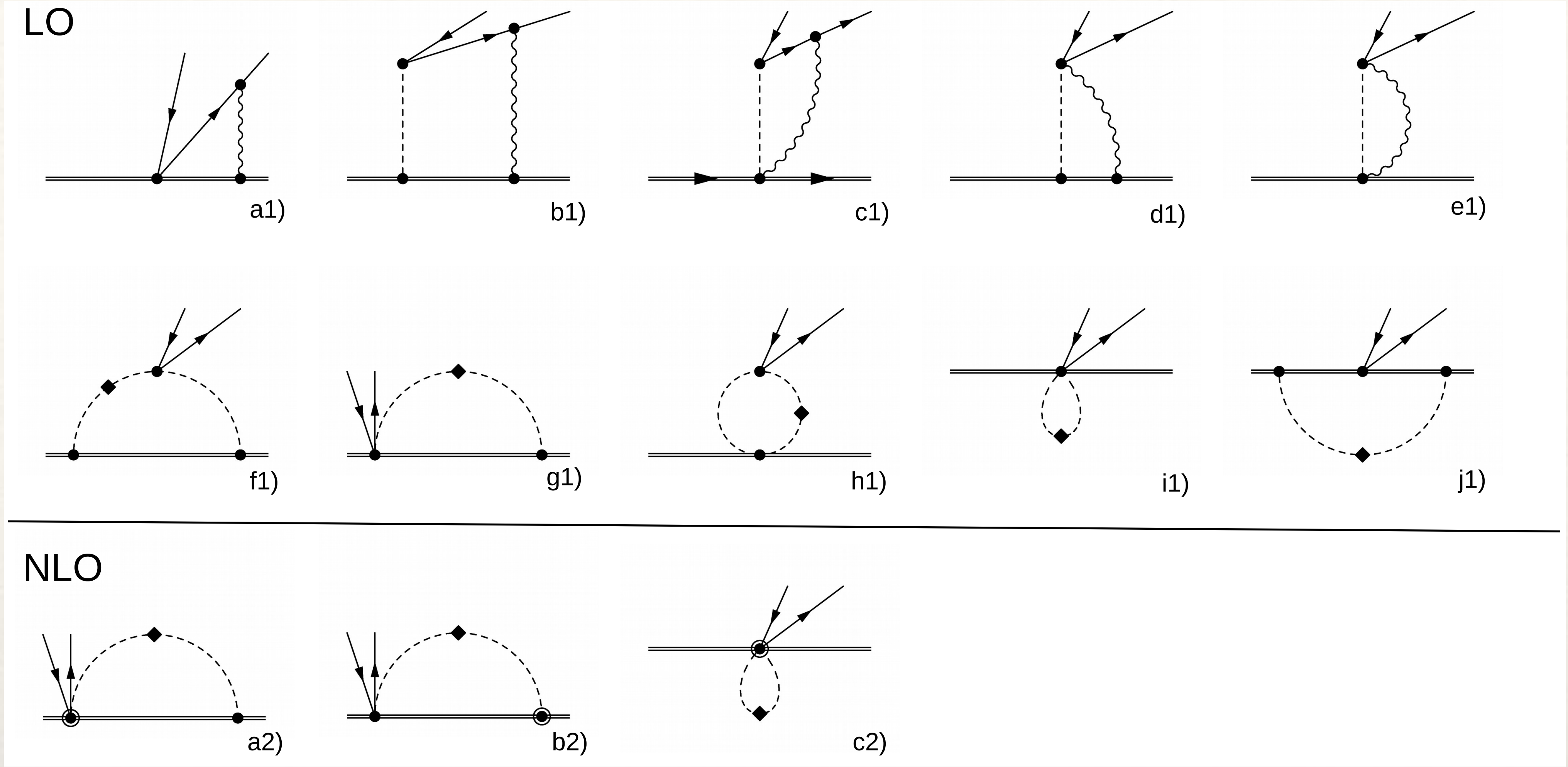
- CalLat results
  - CalLat 18: $g_A = 1.271(13)$ 1%
  - CalLat 19: $g_A = 1.2642(93)$ 0.74%
  - CalLat 24?: ~0.5%

- Experiment:
  - $|g_A^{PDG}| = 1.2754(13)$
  - $|g_A^{PERKEO-III}| = 1.27641(46)$

Pion-induced radiative corrections to neutron beta-decay

Cirigliano, de Vries, Hayen, Mereghetti & Walker-Loud, PRL 129 (2022) [2202.10439]

- Sub-set of O(50) diagrams



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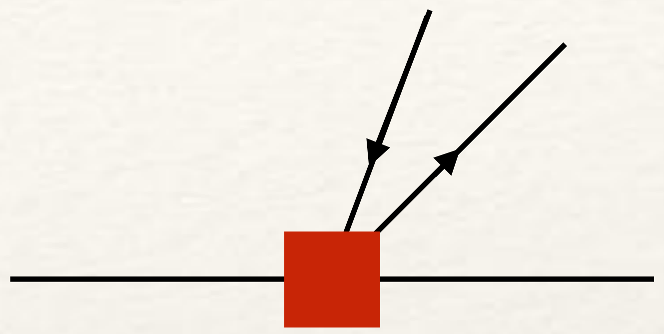

$\hat{C}_A(\mu)$

Low-Energy-Constants (LECs)

$$g_A^{\mathrm{SM}} = g_A^{\mathrm{QCD}} + \delta_{\mathrm{RC}}^{(\lambda)}(\alpha_{fs}, \hat{C}_A(\mu), \ldots)$$

$\hat{C}_A(\mu)$ - completely unknown	estimate by varying μ (NDA)
other LECs (c_3, c_4)	estimate from literature

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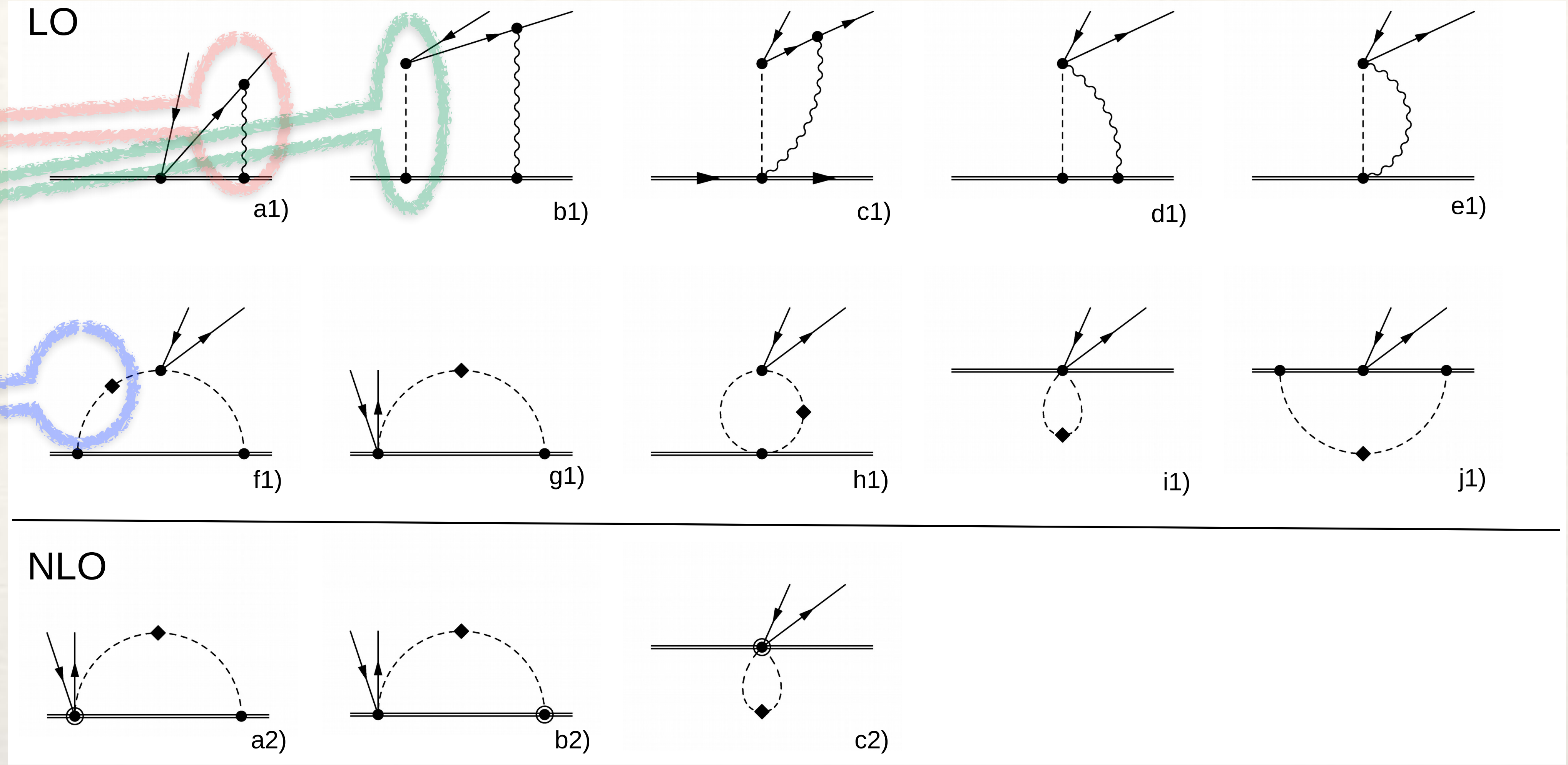
photons

pions

pion electromagnetic mass splitting

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = 2e^2 F_\pi^2 Z_\pi$$



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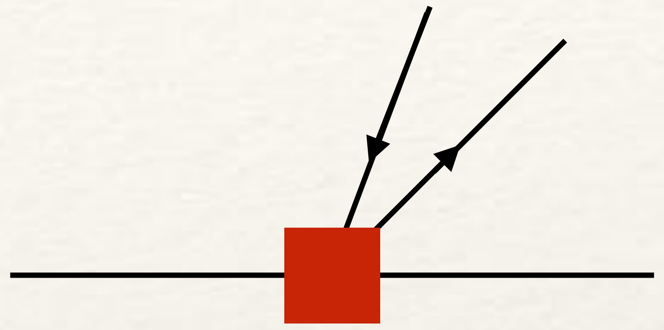

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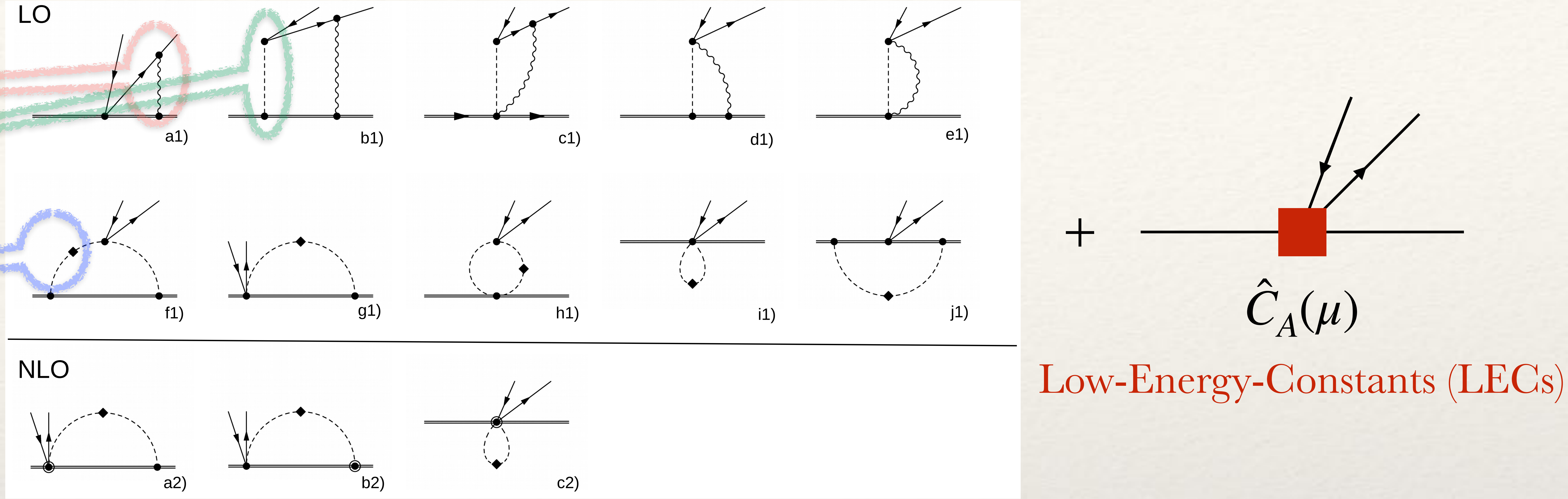

$$\delta_{\rm RC}^{(\lambda)} \in \{1.4,\ 2.6\} \cdot 10^{-2}$$

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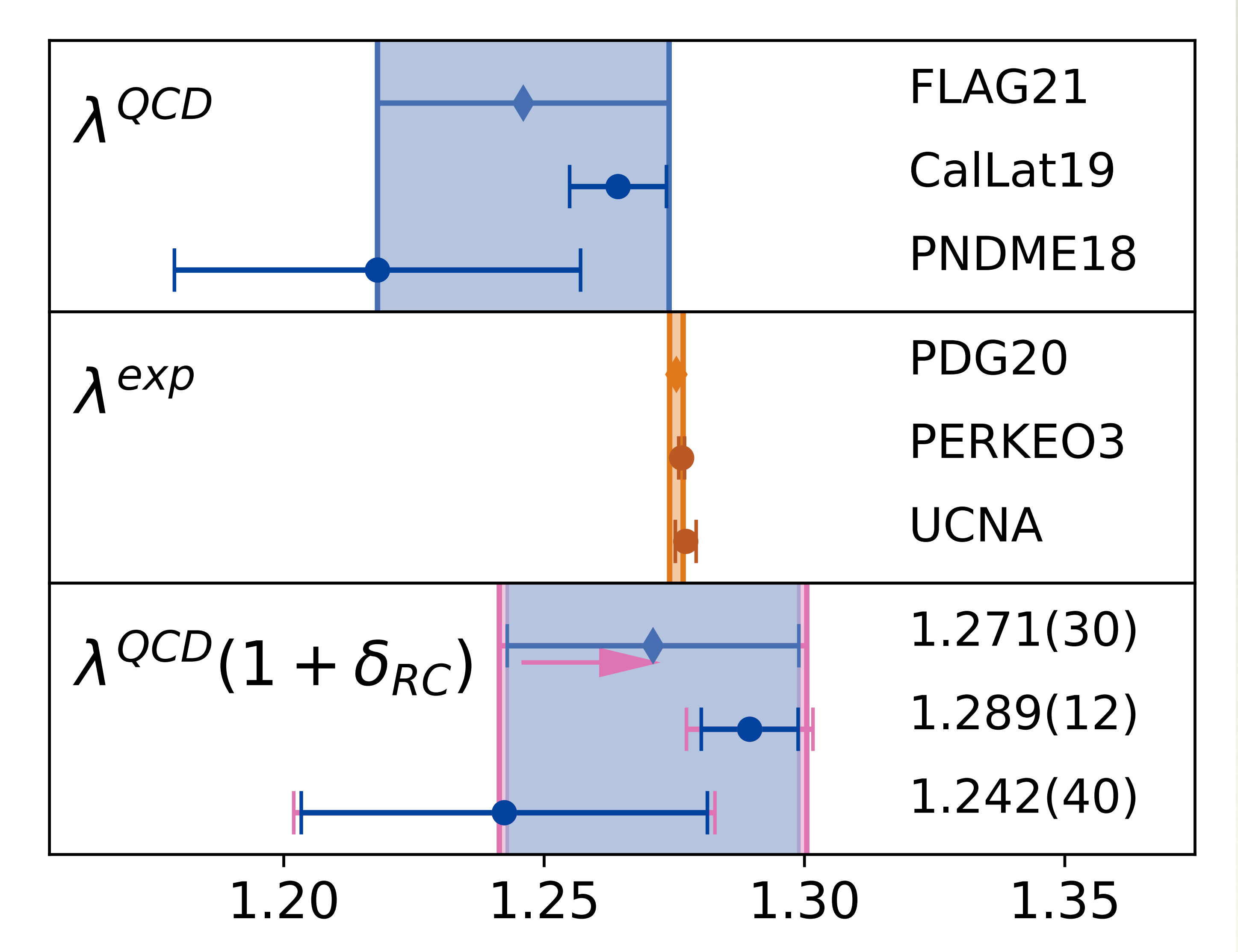
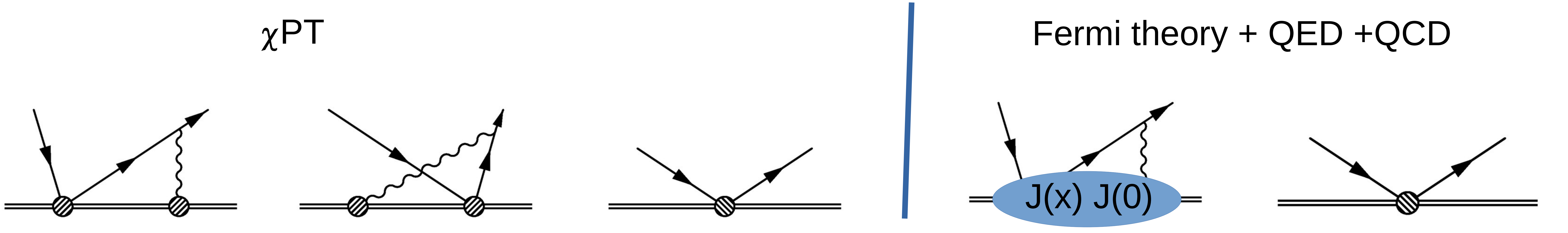


Precision β decays: Electroweak Box

from Emanuele's slides

V. Cirigliano, W. Dekens, EM, O. Tomalak, PRD 108 (2023) 5, 053003



$$g_V(\mu_\chi) = \overline{C}^r_\beta(\mu)\left[1 + \overline{\Box}^V_{\rm Had}(\mu_0) - \frac{\alpha(\mu_\chi)}{2\pi}\left(\frac{5}{8} + \frac{3}{4}\ln\frac{\mu_\chi^2}{\mu_0^2} + \left(1-\frac{\alpha_s}{4\pi}\right)\ln\frac{\mu_0^2}{\mu^2}\right)\right]$$

$$\overline{\Box}^V_{\rm Had}(\mu_0) = -e^2\int \frac{i d^4q}{(2\pi)^4}\frac{\nu^2+Q^2}{Q^4}\left[\frac{T_3(\nu,Q^2)}{2m_N\nu} - \frac{2}{3}\frac{1}{Q^2+\mu_0^2}\left(1-\frac{\alpha_s(\mu_0^2)}{\pi}\right)\right]$$

$$\Gamma_n = \frac{G_F^2|V_{ud}|^2 m_e^5}{2\pi^3}(1+3\lambda^2)\cdot f_0\cdot(1+\Delta_f)\cdot(1+\Delta_R), \qquad \lambda = g_A/g_V$$

- Feng, Gorchtein, Jin, Ma, Seng, PRL 124 (2020)
  Seng, Feng, Gorchtein, Jin, PRD 101 (2020)
  $\Delta_V^R = 0.02477(24)$ [0.02467(22) – previous dispersion result]

- Yoo, Bhattacharya, Gupta, Mondal, Yoon, PRD 108 (2023)
  Ma, Feng, Gorchtein, Jin, Liu, Seng, Wang, Zhang [2308.16755],
  $\Delta_V^R = 0.02439(19)$

Precision β decays

- Given the $\approx 3\sigma$ tension in first-row CKM unitarity constraints, and the prospect to improve the precision in the relevant β-decays, it is important to have alternative and complimentary strategies to determine the QED corrections

- We are incorporating QED corrections to LQCD
  - QED_M: use a photon mass to regulate IR behavior (thanks for ERCAP 2024! and previous ALCC)

- We are investigating how to build up QED corrections to full $n \to pe\bar{\nu}$ amplitude
  - QED corrections to spectrum
  - QED corrections to g_A
  - Precise calculation of g_A^{QCD}
  - neutron decay amplitude?

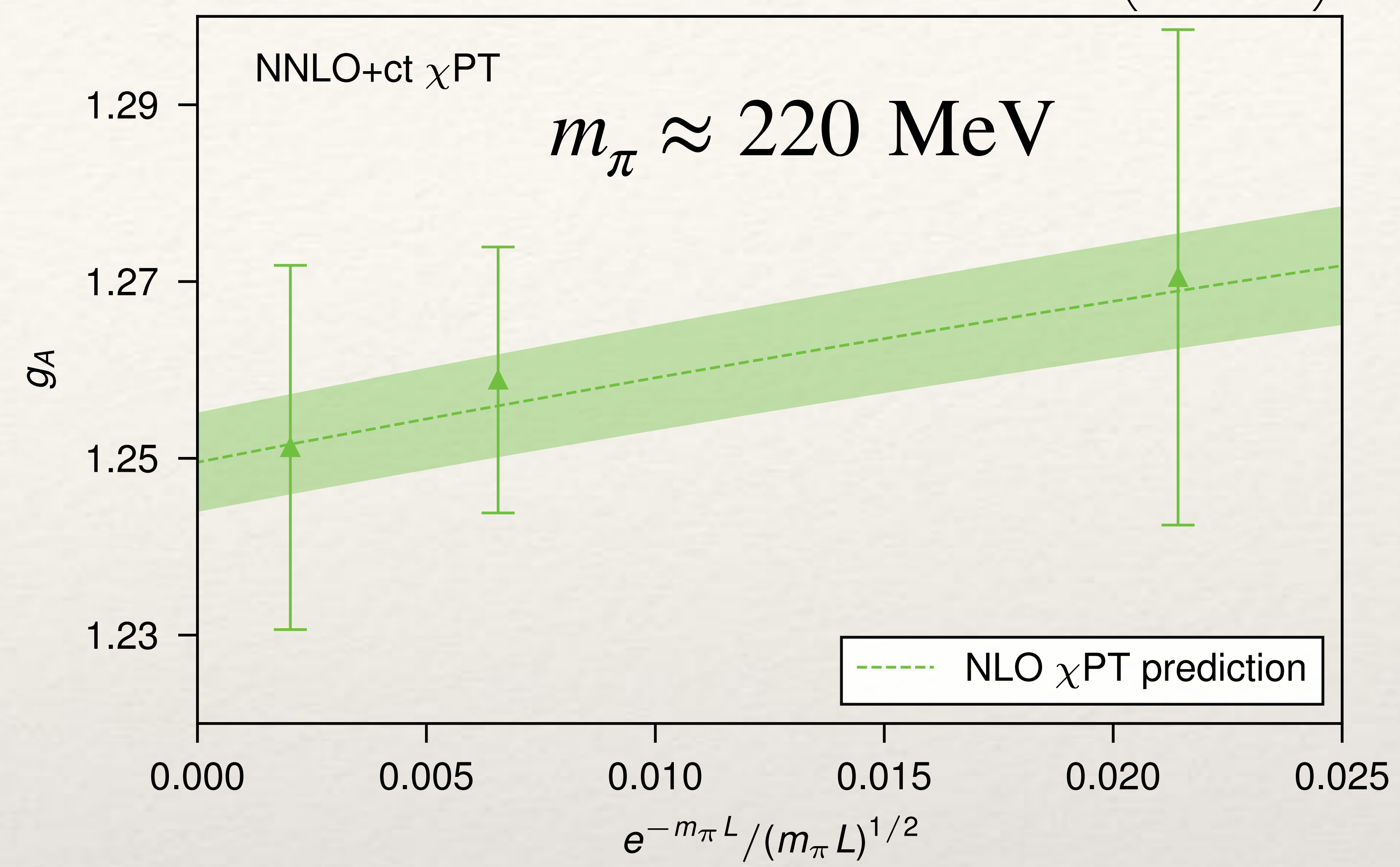
Precision β decays

- Non-monotonic finite-volume (FV) corrections to g_A
  - led by Zack Hall (grad student at UNC)

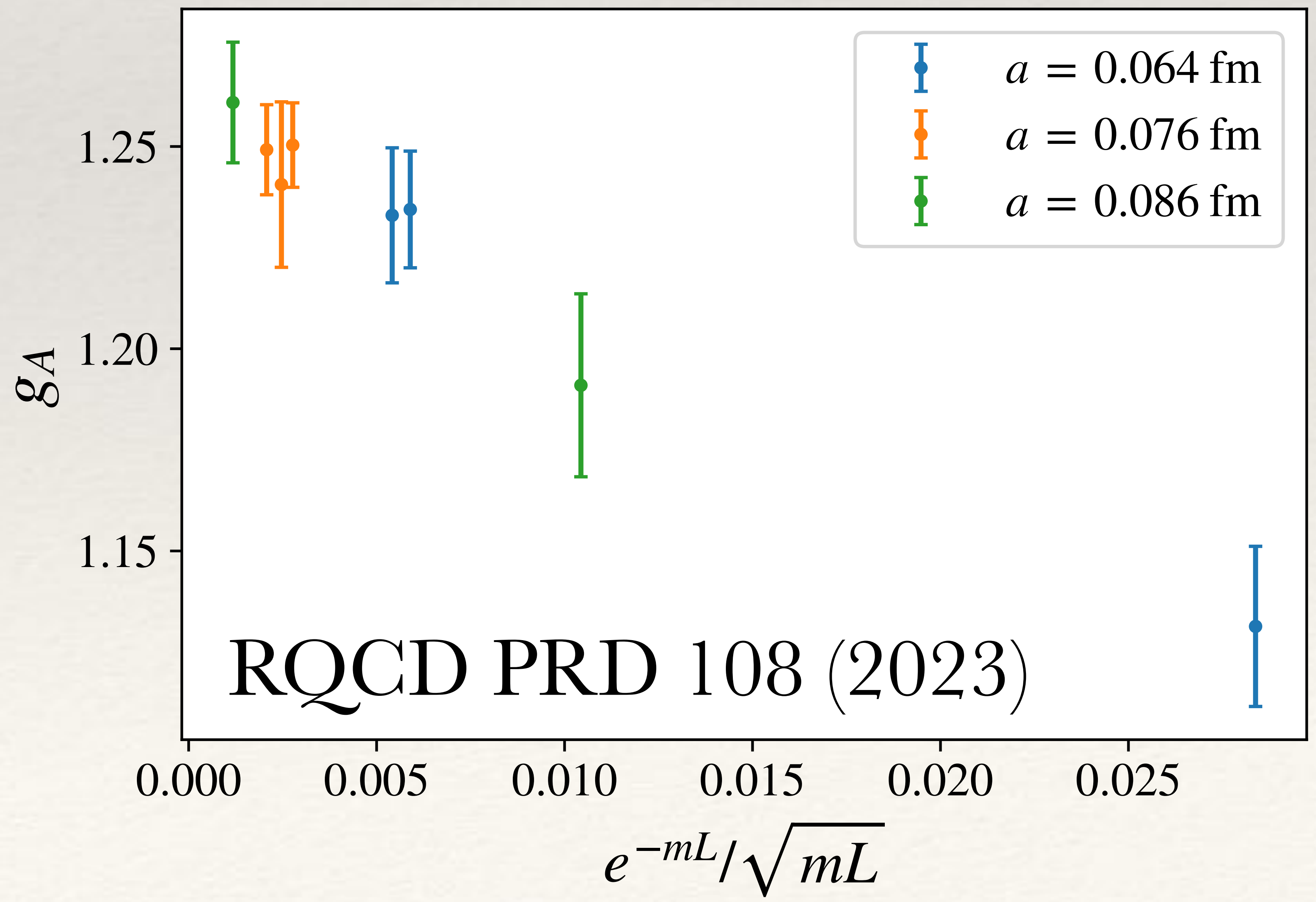
$$L \quad g_A(L) = g_A + c_2 \frac{m_\pi^2}{(4\pi F_\pi)^2} \frac{e^{-m_\pi L}}{\sqrt{m_\pi L}} + c_3 \frac{m_\pi^3}{(4\pi F_\pi)^3} \frac{e^{-m_\pi L}}{m_\pi L} + \cdots$$

- All groups (except CalLat) only use leading FV correction (c_2 term) and leave c_2 a free parameter (instead of χPT prediction)
- This gives the "wrong" sign for FV correction at lighter pion mass
- **At what level of precision will this strategy make a statistically significant error?**
- This project is also synergistic — Emanuele Mereghetti derived the full NNLO FV corrections in χPT
  - EFT colleagues are deriving formula for QED corrections to g_A
  - Two-nucleon matrix elements that are needed
  - …

CalLat Nature 558 (2018)



$m_\pi = 280 - 290$ MeV



Summary

- NTNP Topical Collaboration is creating a synergistic effort between sub-disciplines in Nuclear Theory to help search for new physics in low-energy precision tests of the Standard Model
- Lattice QCD provides essential input for each area (and receives guidance from EFT/Pheno)
  - Precision β-decay
    - LQCD+QED: compute key matrix elements to determine structure functions and/or unknown LECs
    - LQCD+QED: perform non-perturbative calculation of radiative QED corrections
  - Permanent Electric Dipole Moments
    - LQCD: compute CP-odd pion-nucleon couplings $\longrightarrow$ many-body calculations of nuclear EDMs
  - Neutrino-Nucleus scattering
    - Determine $\nu - N$ cross section from QCD: $F_A(Q^2), F_1(Q^2), F_2(Q^2)$
    - Determine $N \to \Delta, N \to N\pi$ transition amplitudes as well as $\langle NN|J_\mu|NN\rangle$ matrix elements


Thank You!
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