DOE Topical Collaborations: New Theory Opportunities

NSD Staff Meeting, Feb. 7

André Walker-Loud

Department of Energy Announces $11.24 Million for Research on Topical Collaborations in Nuclear Theory

Annoucement Number: *DE-FOA-0002643* *List Posted:* *12/7/2022*

- Every ~5 years, DOE NP competes these Topical Collaborations (TC)
  - 2011, 2016, 2023
- Bring together groups of 10-20 co-investigators to work on focussed nuclear theory topics in support of DOE NP Mission
- Each TC supports 1 - 3 faculty bridge positions as well as postdocs and students

DOE TC 2023: 5 Collaborations - LBNL involved in all

ExoHad

Raúl Briceño

Develop pathway to study Exotic Hadron Spectroscopy

HEFTY

Ramona Vogt

Heavy Flavor Particles - production and diffusion through QGP

NTNP

Wick Haxton
André Walker-Loud

Nuclear Theory for New Physics - precision low-energy tests of the Standard Model

QGT

Feng Yuan

Drive our understanding and discovery in the quark and gluon tomography of hadrons

SURGE

Xin-Nian Wang

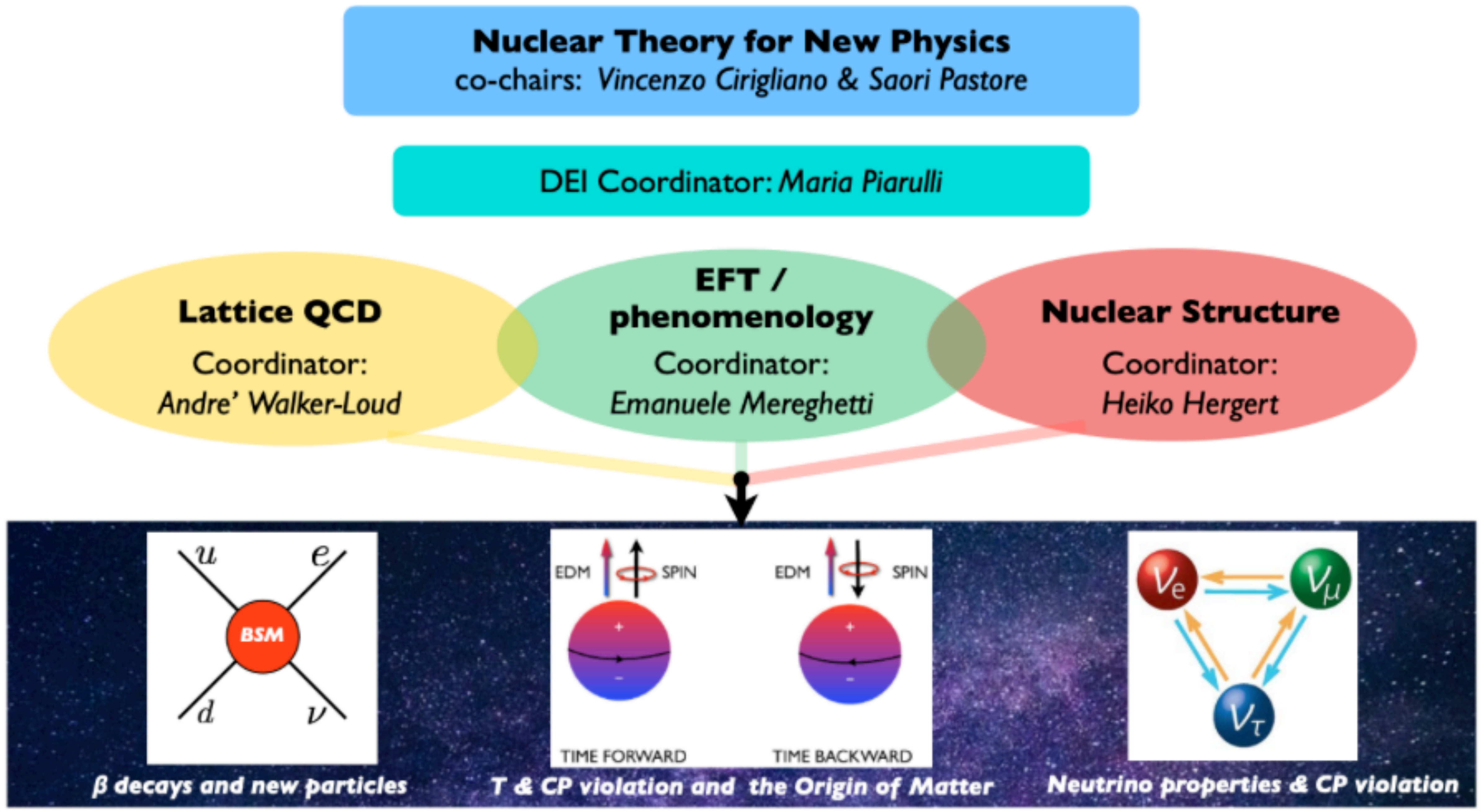
Explore the gluon saturation regime of QCD

NTNP Home science people meetings Code of Conduct

https://a51.lbl.gov/~ntnp/TC/

Nuclear Theory for New Physics

- About Us
- Commitment to Diversity
- Funding Acknowledgement



About Us

The mission of the Topical Collaboration on Nuclear Theory for New Physics (NTNP) is to address outstanding theoretical questions related to the "targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model" (2015 NSAC Long Range Plan). NTNP researchers will focus on three main topics: (i) precision calculations of β decays of neutron and nuclei, which probe possible new physics in the weak charged current at levels inaccessible by high-energy colliders; (ii) calculations of Electric Dipole Moments (EDMs) of neutral diamagnetic atoms, which provide a unique window into the breaking of CP (Charge-Parity) symmetry and the origin of the matter-antimatter asymmetry in the universe; and (iii) precise calculations of neutrino-nucleus scattering processes, a key ingredient entering the measurement of CP-violation in neutrino oscillations at long-baseline experiments. The NTNP collaboration will provide robust predictions for these processes, with controlled theoretical uncertainties, which is a prerequisite to turn experimental measurements into discovery tools.

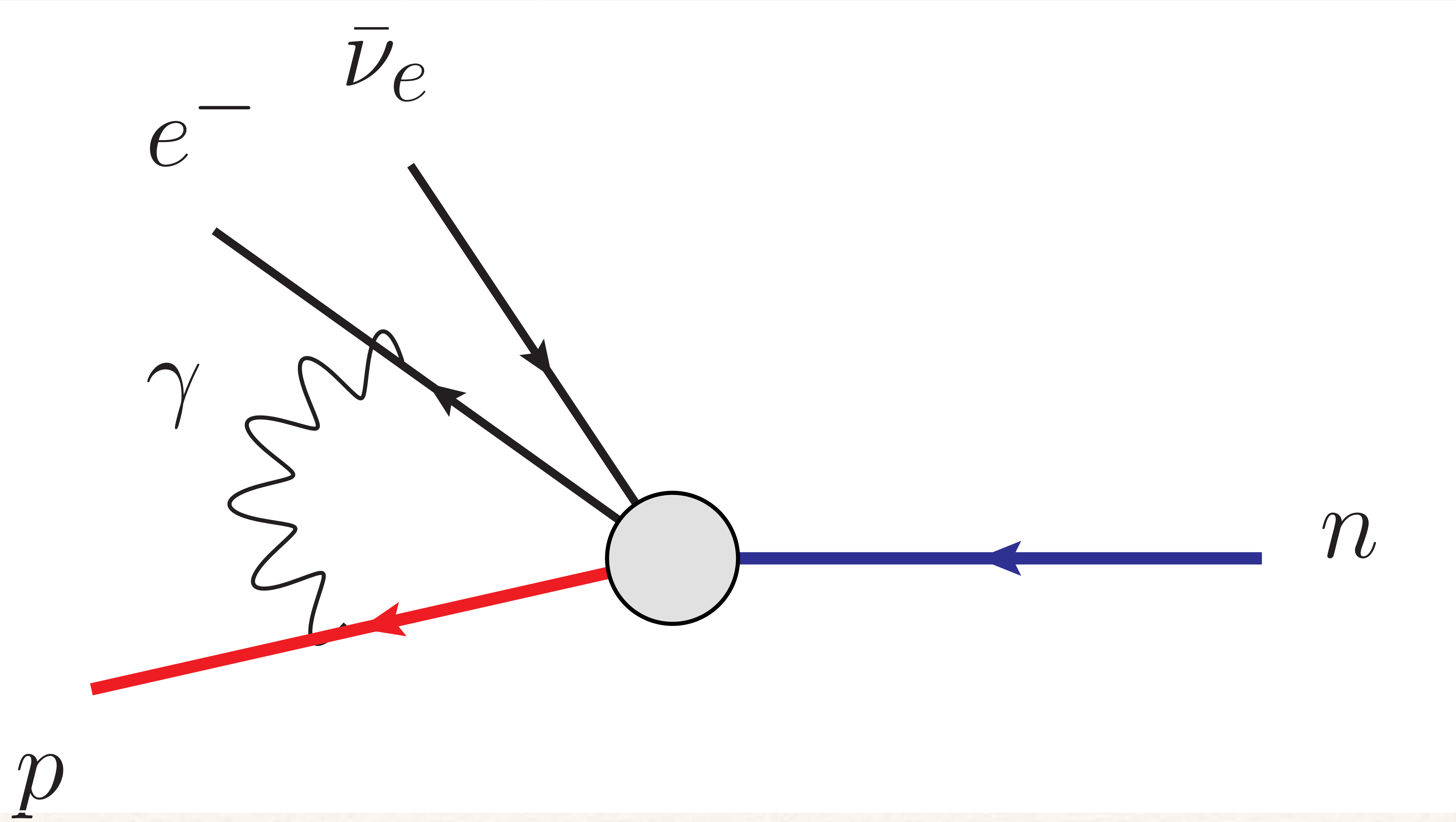
- Three main research areas
  - β-decay
  - Electric Dipole Moments
  - ν-A scattering for ν properties

- Three main research tools
  - Lattice QCD
  - Effective Field Theory / Phenomenology
  - Many-body nuclear theory

NTNP: β-decay

- β-decay is one of the most promising methods of testing the Standard Model
  - β-decay experiments are how we know the *weak*-interactions are V-A (left handed)
  - Precise measurements are used to search for small corrections to V-A structure
  - β-decay is used to determine elements of the quark mixing matrix (CKM)

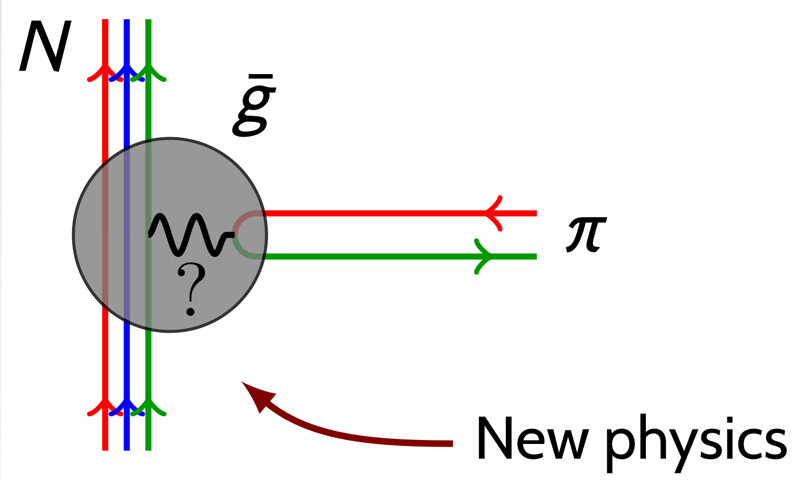
- With current limits, our understanding of β-decay must be controlled with a precision of $O(10^{-4})$
  - The main challenge is understanding electromagnetic (QED) corrections often denoted *radiative* or *radiative QED* corrections
  - The challenge is that neutrons and protons are composite states of quarks and gluons, the degrees of freedom of QCD, which is a strongly coupled theory

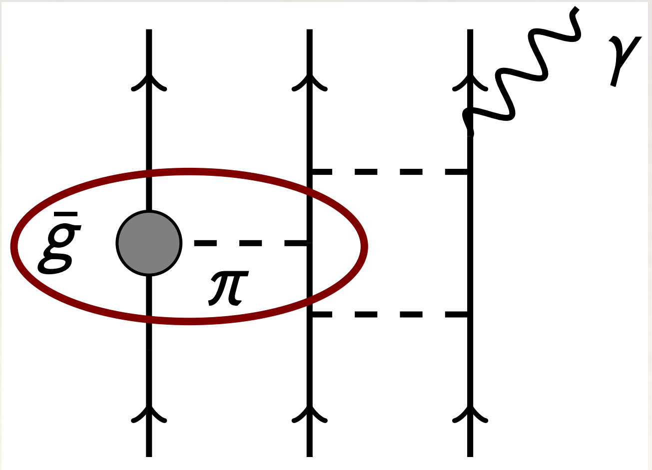


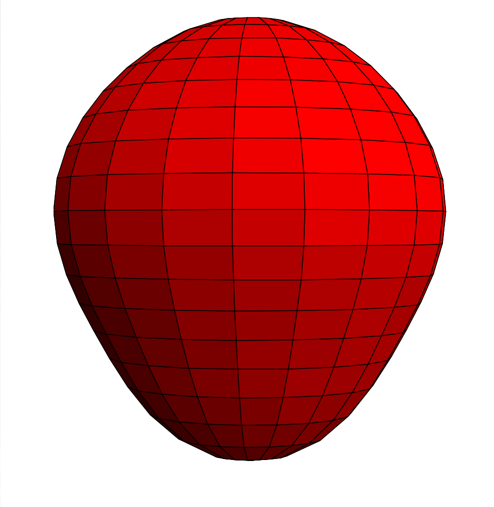
NTNP: Electric Dipole Moments (EDMs)

- There is an excess of matter over anti-matter in the universe of O(1e^{-9})
  - We believe this excess matter can be explained with
    - Baryon-number violation
    - CP violation (breaking particle/anti-particle symmetry and parity)
    - Out of equilibrium dynamics in the early universe
  - The known CP violation in the Standard Model is orders-of-magnitude too small to explain the observed asymmetry

- CP violation will give rise to permanent EDMs in fermions (quarks and electrons)
  - A quark EDM will manifest as a neutron and proton (and nuclear) EDM
  - Connecting BSM quark-EDMs to nucleon and nuclear EDMs requires
    - Lattice QCD
    - Many-body nuclear methods





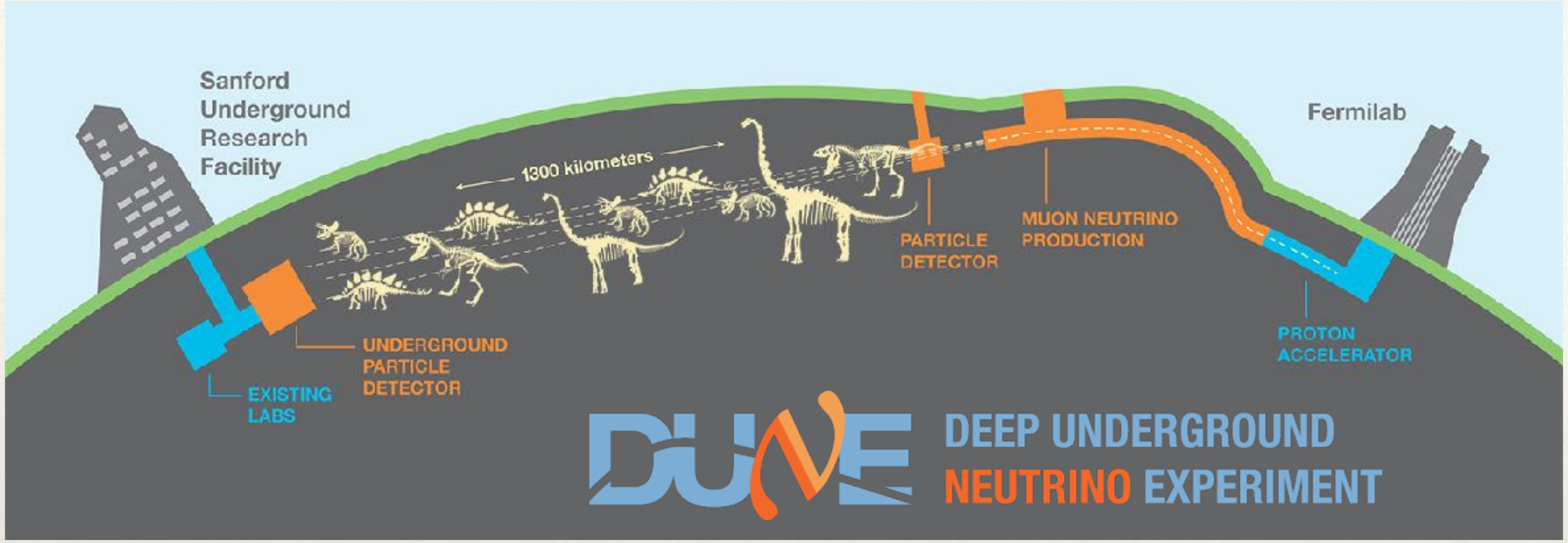


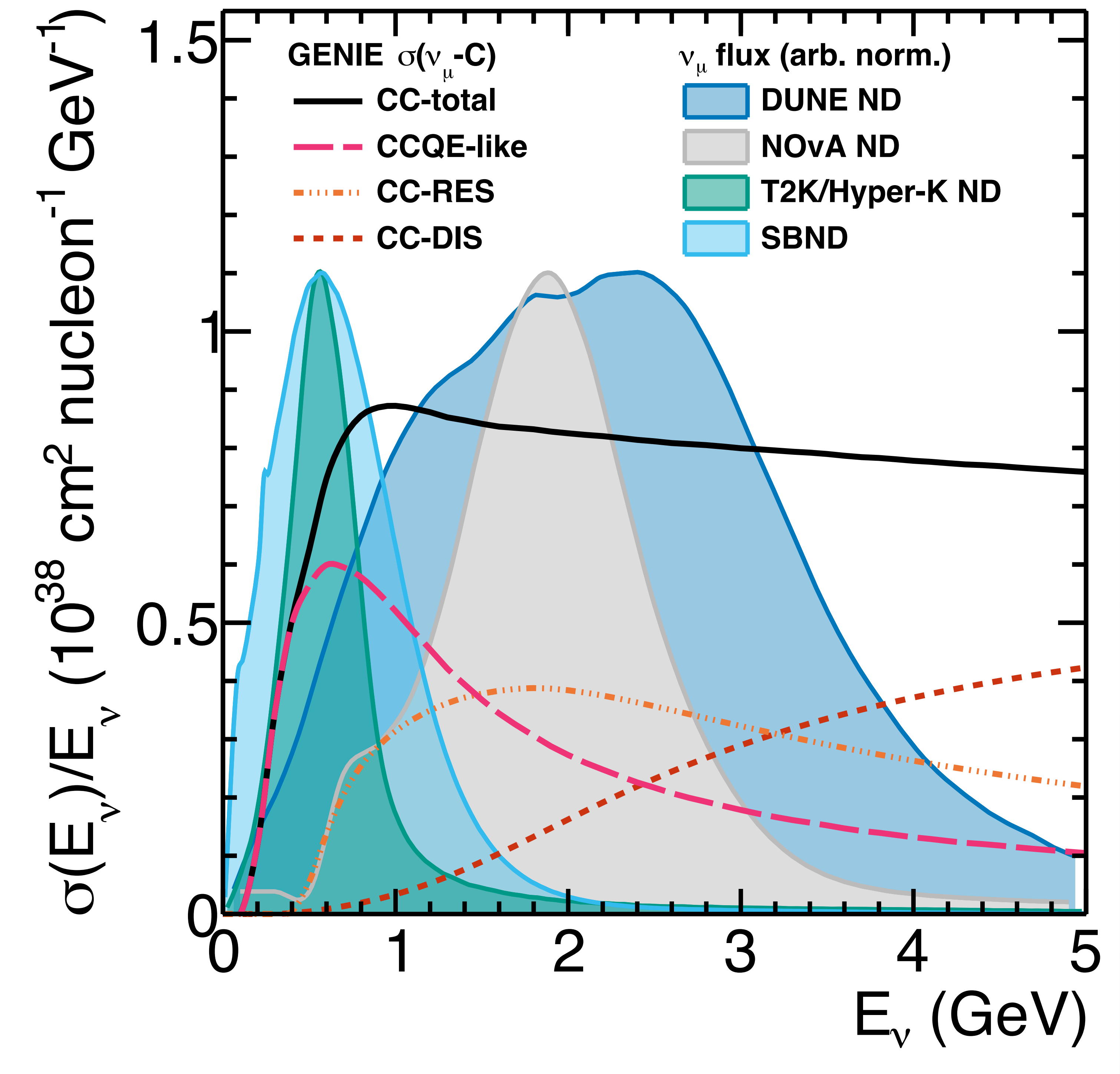
Deformed density

eg. ^{225}Ra

possible 10^4 enhancement of EDM

NTNP: ν-A scattering and neutrino properties





Unoscillated flux from different ν-A mechanisms

- Major experimental effort to measure ν properties with ν-A scattering
  - Need improved understanding of ν-N cross section
  - Need improved understanding of N-to-Δ transitions (N-to-Nπ etc.)
  - Need improved understanding of 2- (and 3- ?) body corrections
  - Need to propagate all this information into event generators

NTNP: β-decay

NTNP: β-decay

- The generic β-decay rate is given by

$$\Gamma_k = \left(G_F^{(\mu)}\right)^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

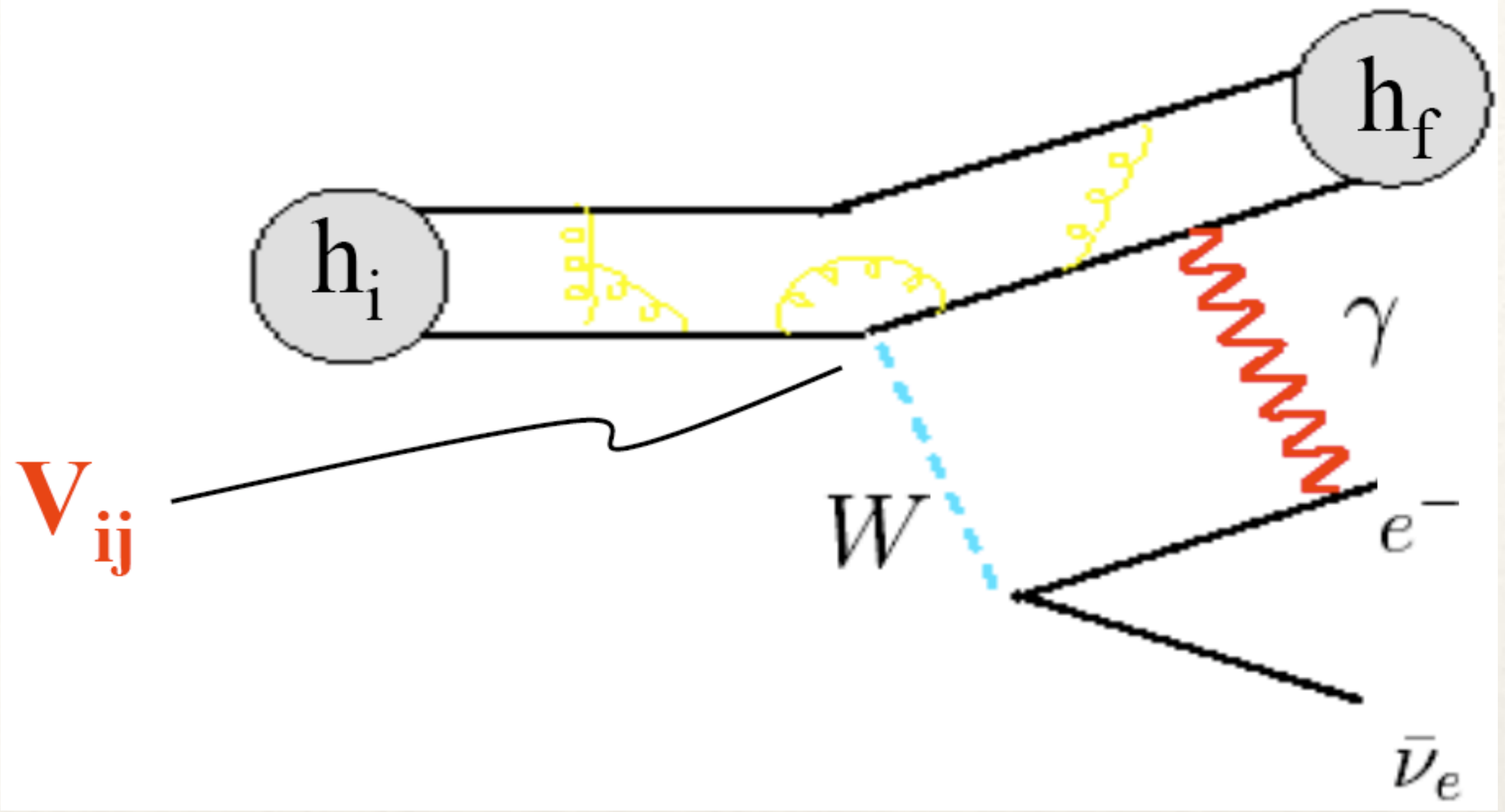
Fermi's decay constant measured with μ-decay

Quark mixing matrix elements

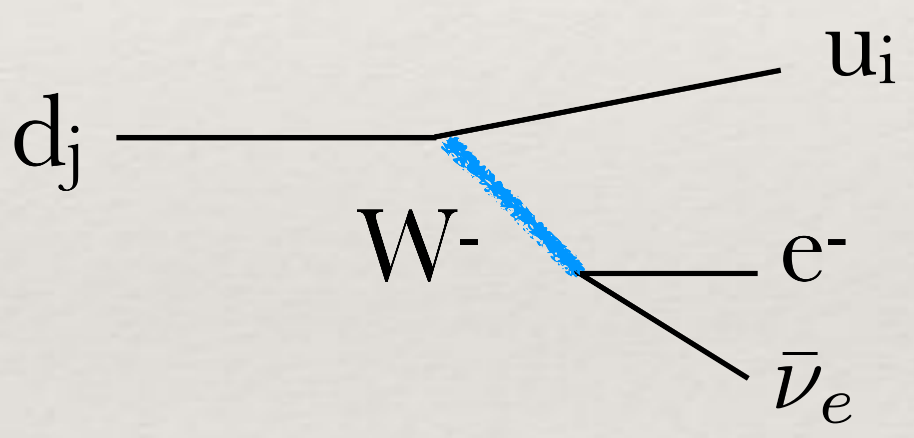
non-perturbative hadronic matrix elements

radiative corrections

phase space kinematic factor



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{weak} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{QCD}$$



V_{CKM} = Cabibbo-Kobayashi-Maskawa matrix

V_{CKM} is a unitary matrix

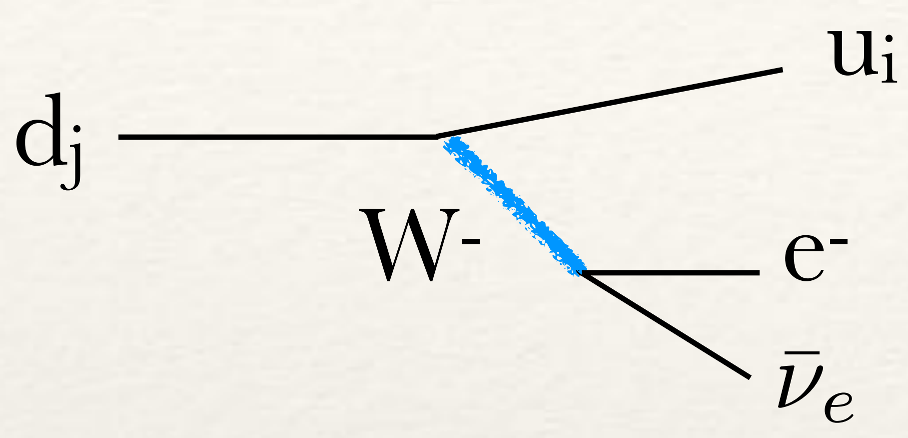
no new physics: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

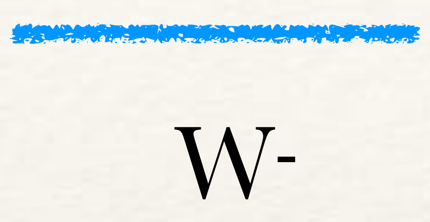
$$|V_{ub}|^2 \ll |V_{us}|^2 \ll |V_{ud}|^2$$

- If $|V_{ud}|^2 + |V_{us}|^2 \neq 1$, this is a low-energy sign of new, beyond the Standard Model (BSM) physics
- To determine V_{ud}, V_{us} from experimental measurements, we require precise predictions of
  - $M_{\rm had}$
  - δ_{RC}

NTNP: β-decay - possible new physics

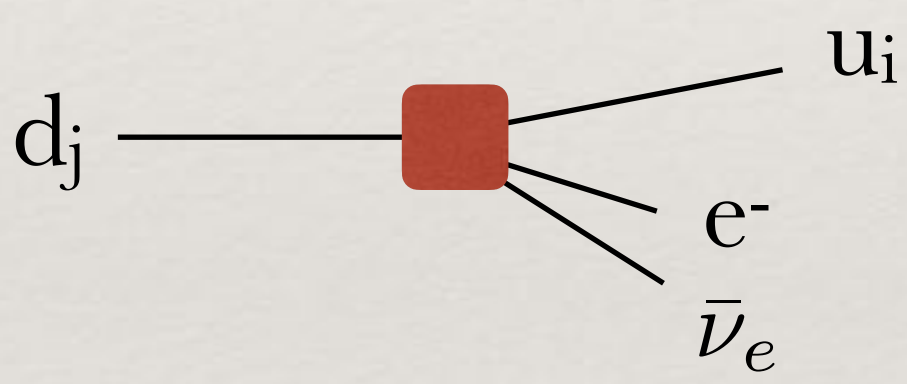
- What would new (heavy) physics look like?





$$= \frac{i}{q^2 - M_W^2} = \frac{-i}{M_W^2} \frac{1}{1 - \frac{q^2}{M_W^2}} \simeq \frac{-i}{M_W^2} \left[1 + \frac{q^2}{M_W^2} + \cdots \right]$$

- At very low energy (small q^2), the W-propagator looks like a point-interaction leading to Fermi's theory of weak interactions



- If the BSM physics is heavy - it will also look like a point-interaction
  - It can give rise to corrections that appear like V-A Dirac structure, or different

NTNP: β-decay - determining V_{ij}

V_{ud}

$\pi^\pm \to \pi^0 e \bar{\nu}_e$

theoretically clean
experimentally noisy

nuclear $0^+ \to 0^+$

theoretically messy
experimentally clean

$n \to p e \bar{\nu}_e$

theoretically clean-ish
experimentally clean-ish

V_{us}

$K \to \pi \mu \bar{\nu}_\mu$

theoretically clean
experimentally clean

$\frac{V_{us}}{V_{ud}}$

$\frac{K \to \mu \bar{\nu}_\mu}{\pi \to \mu \bar{\nu}_\mu}$

$$\frac{\partial_\mu \langle 0 | j_A^\mu | K \rangle = \sqrt{2} F_K m_K^2}{\partial_\mu \langle 0 | j_A^\mu | \pi \rangle = \sqrt{2} F_\pi m_\pi^2}$$

theoretically clean
experimentally clean

NTNP: β-decay - determining V_{ij}

V_{ud}

$\pi^{\pm} \to \pi^0 e \bar{\nu}_e$

theoretically clean
experimentally noisy

nuclear $0^+ \to 0^+$

theoretically messy
experimentally clean

$n \to p e \bar{\nu}_e$

theoretically clean-ish
experimentally clean-ish

V_{us}

$K \to \pi \mu \bar{\nu}_\mu$

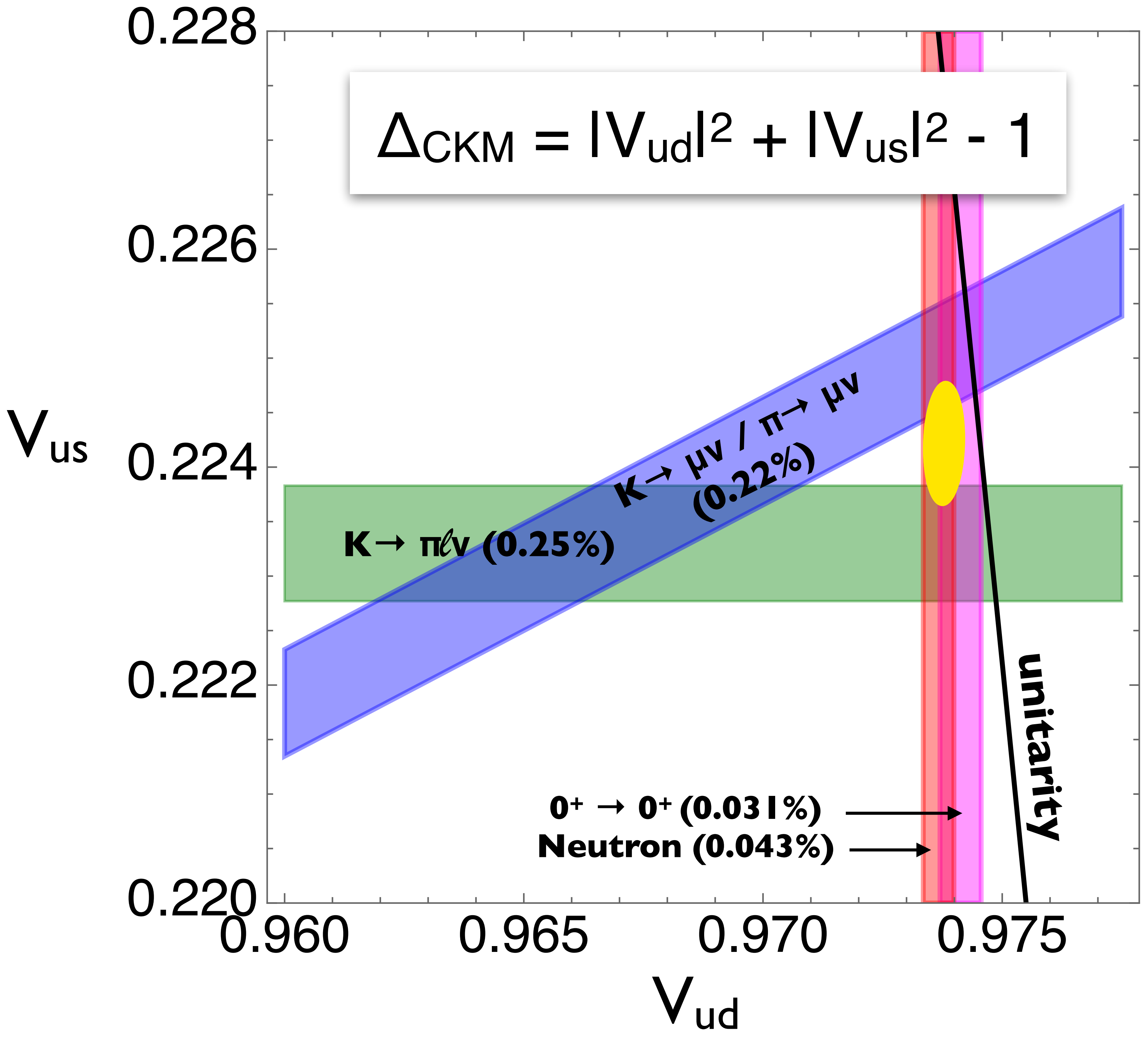
theoretically clean
experimentally clean

$\frac{V_{us}}{V_{ud}}$

$$\frac{K \to \mu \bar{\nu}_\mu}{\pi \to \mu \bar{\nu}_\mu} \qquad \frac{\partial_\mu \langle 0 | j_A^\mu | K \rangle = \sqrt{2} F_K m_K^2}{\partial_\mu \langle 0 | j_A^\mu | \pi \rangle = \sqrt{2} F_\pi m_\pi^2}$$

theoretically clean
experimentally clean

V.Cirigliano, A.Crivellin, M.Hoferichter, M.Moulson
2208.11707



- ❑ there is tension with unitarity
- ❑ there is tension between results

$$\Delta_{\rm CKM} = |V_{ud}|^2 - |V_{us}|^2 - 1$$
$$= -1.48(53) \times 10^{-3}$$

NTNP: β-decay - determining V_{ud}

- The present ~3σ tension is driven in large part from the determination of V_{ud} from super-allowed nuclear β-decay

nuclear $0^+ \to 0^+$

theoretically messy
experimentally clean

$$|V_{ud}|^2 = \frac{2984.432(3)s}{ft\left(1+\Delta_R^V+\delta_R'+\delta_{NS}-\delta_C\right)}$$

universal radiative QED corrections to vector current matrix element

nuclear long-distance radiative corrections

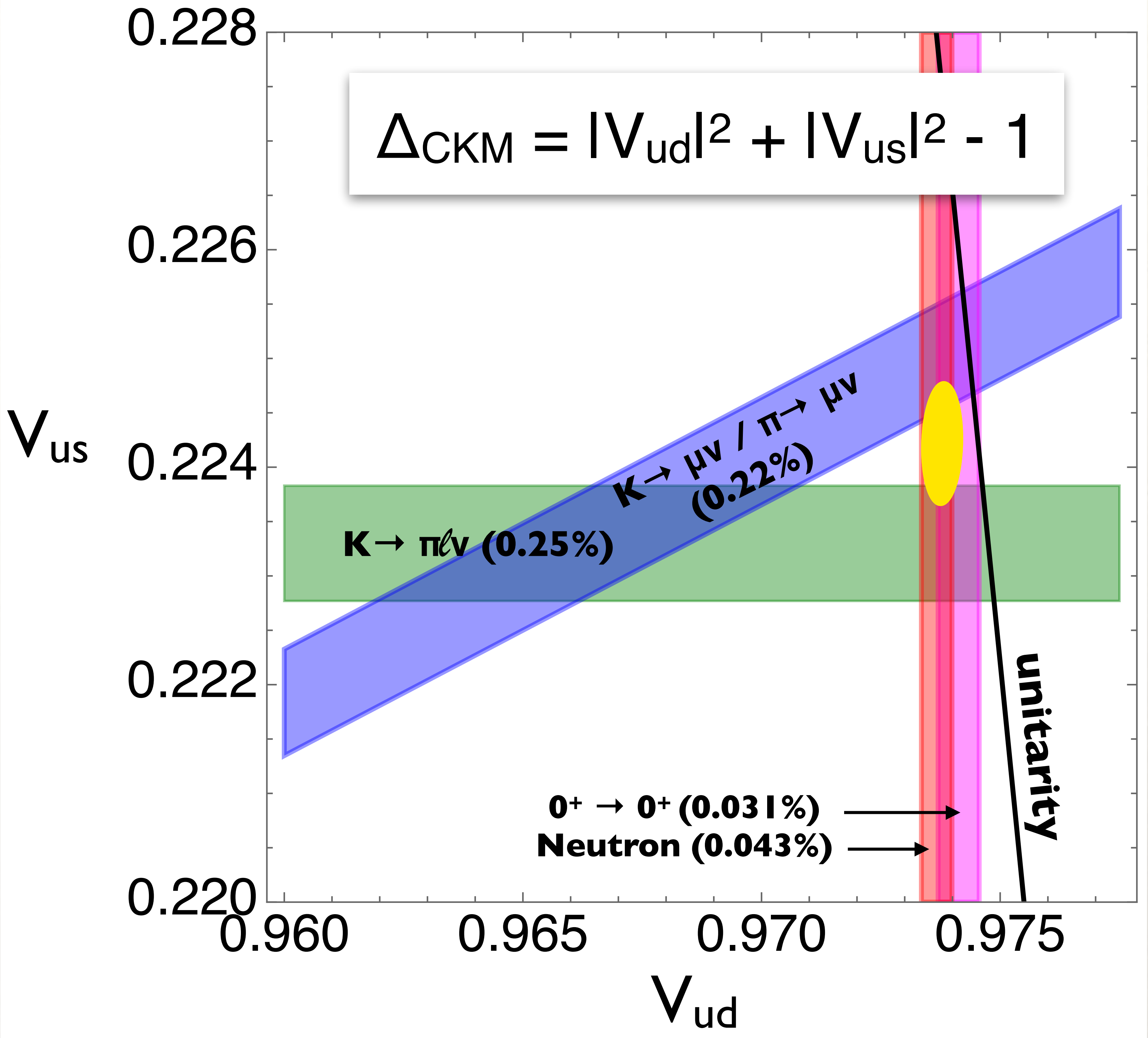
nuclear short-distance radiative corrections

nuclear Coulomb correction

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\text{exp}}(13)_{\Delta_V^R}(27)_{\text{NS}}[32]_{\text{total}}$$

Hardy-Towner PRC 2020
Seng et al. 1812.03352
Gorchtein 1812.04229

V.Cirigliano, A.Crivellin, M.Hoferichter, M.Moulson
2208.11707



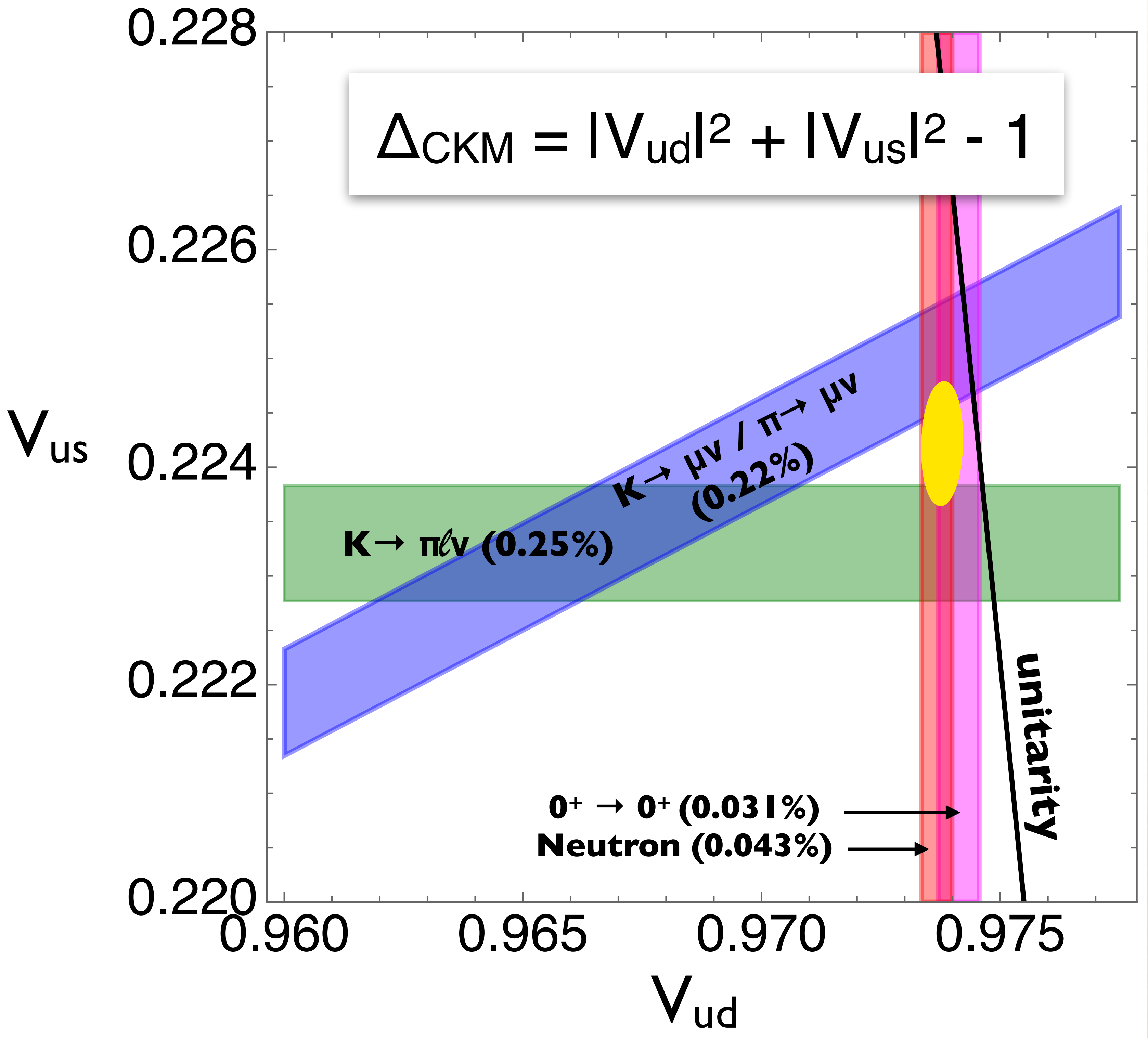
NTNP: β-decay - determining V_{ud}

- Nuclear super-allowed $0^+ \to 0^+$ decays

$$|V_{ud}|^2 = \frac{2984.432(3)s}{ft\,(1+\Delta_R^V+\delta'_R+\delta_{NS}-\delta_C)}$$

$$V_{ud}^{0^+\to 0^+} = 0.97367(11)_{\rm exp}(13)_{\Delta_V^R}(27)_{\rm NS}[32]_{\rm total}$$

V.Cirigliano, A.Crivellin, M.Hoferichter, M.Moulson
2208.11707



- Compare with neutron decay

V.Cirigliano, A.Crivellin, M.Hoferichter, M.Moulson - 2208.11707

$$|V_{ud}|^2\tau_n\,(1+3\lambda^2)\,(1+\Delta_R) = 5099.3(3)s \qquad \lambda = \frac{g_A}{g_V}$$

neutron lifetime   nucleon axial charge

$$V_{ud}^{n,\rm PDG} = 0.97441(3)_f(13)_{\Delta_R}(82)_\lambda(28)_{\tau_n}[88]_{\rm total}$$

$$V_{ud}^{n,\rm best} = 0.97413(3)_f(13)_{\Delta_R}(35)_\lambda(20)_{\tau_n}[43]_{\rm total}$$

λ PERKEO III - Maerkish et al. 1812.04666

τ_n UCNτ - Gonzalez et al. 2106.10375

The neutron decay precision is becoming competitive with what can be achieved with the super-allowed nuclear decays

NTNP: neutron β-decay - opportunity

- The importance of neutron decays for obtaining a more (the most?) precise determination of V_{ud} places increased scrutiny on our ability to control the radiative QED corrections, Δ_R

$$|V_{ud}|^2 \tau_n \left(1 + 3\lambda^2\right) \left(1 + \Delta_R\right) = 5099.3(3) s$$

neutron lifetime   nucleon axial charge

- We believe we know how to compute Δ_R, but it is required with a precision of 10^{-4}

- The dispersion theory methods that are used to determine Δ_R are well established (Cauchy contour integral of experimental data)
  - however, recently, it was uncovered that they missed an O(2%) correction to g_A
    (Δ_R can be thought of as a correction to g_V)
    Cirigliano, de Vries, Hayen, Mereghetti, Walker-Loud, Phys.Rev.Lett. 129 (2022) 2202.10439

- Could there be corrections to Δ_R that are missed by the dispersive methods relevant at the 10^{-4} level?

- The only viable method to cross check the determination of Δ_R is with lattice QCD + QED calculations
  - Lattice QCD offers a fully non-perturbative method to compute such corrections

Pion-induced radiative corrections to neutron beta-decay

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

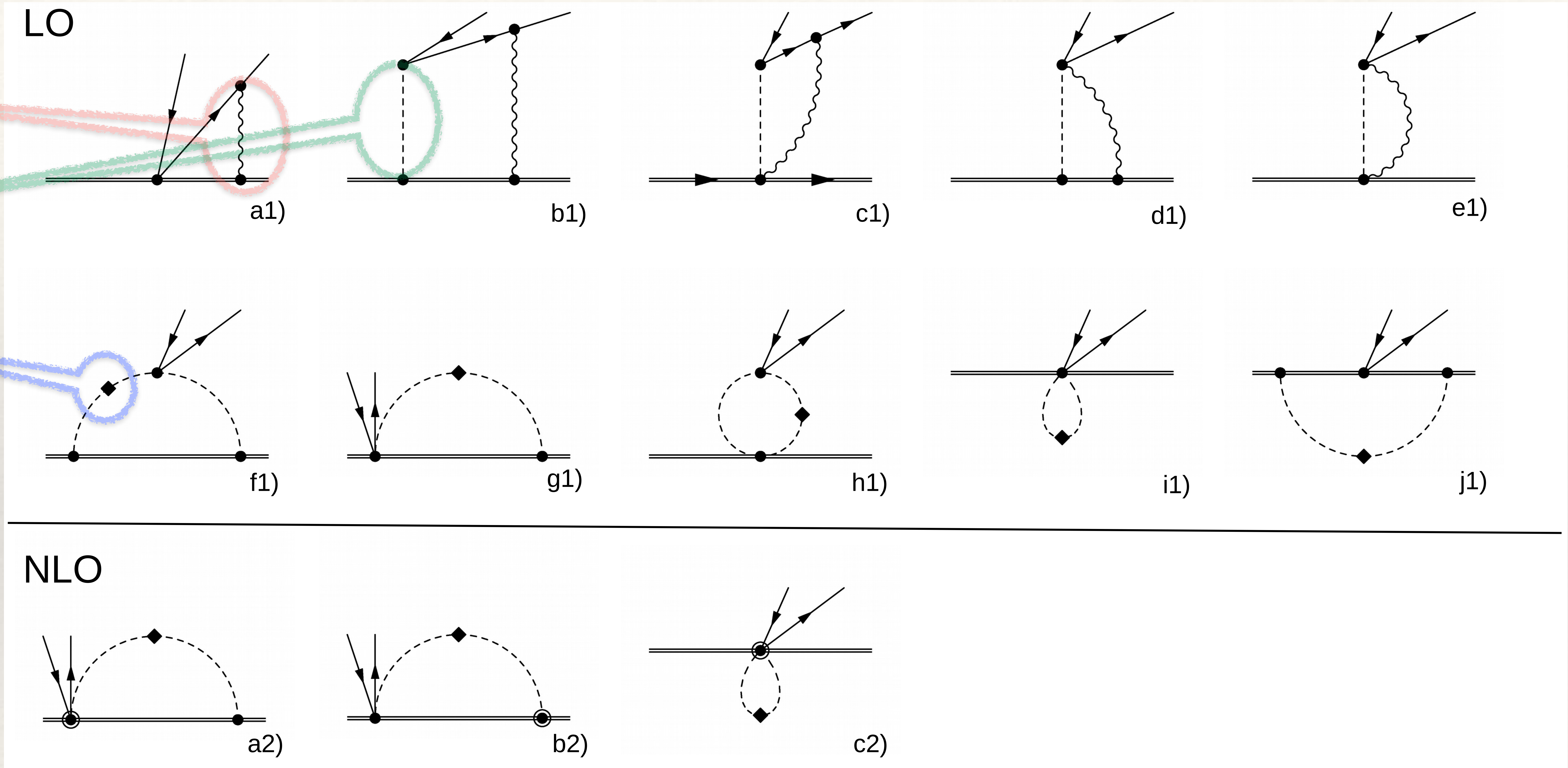
- Sub-set of O(50) diagrams

photons

pions

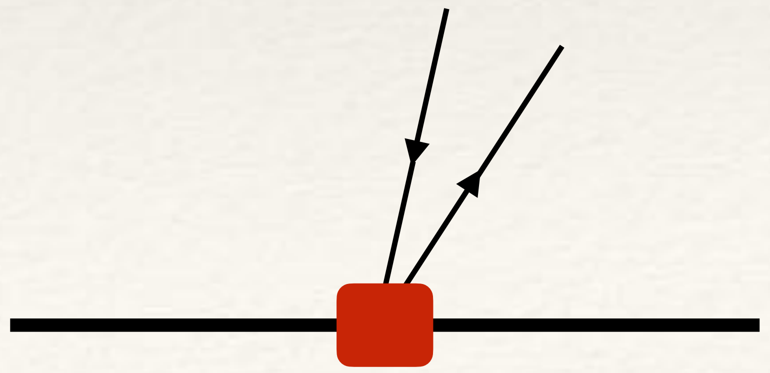
pion electromagnetic mass splitting

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



nucleon "structure" corrections from the pion-cloud of the nucleon

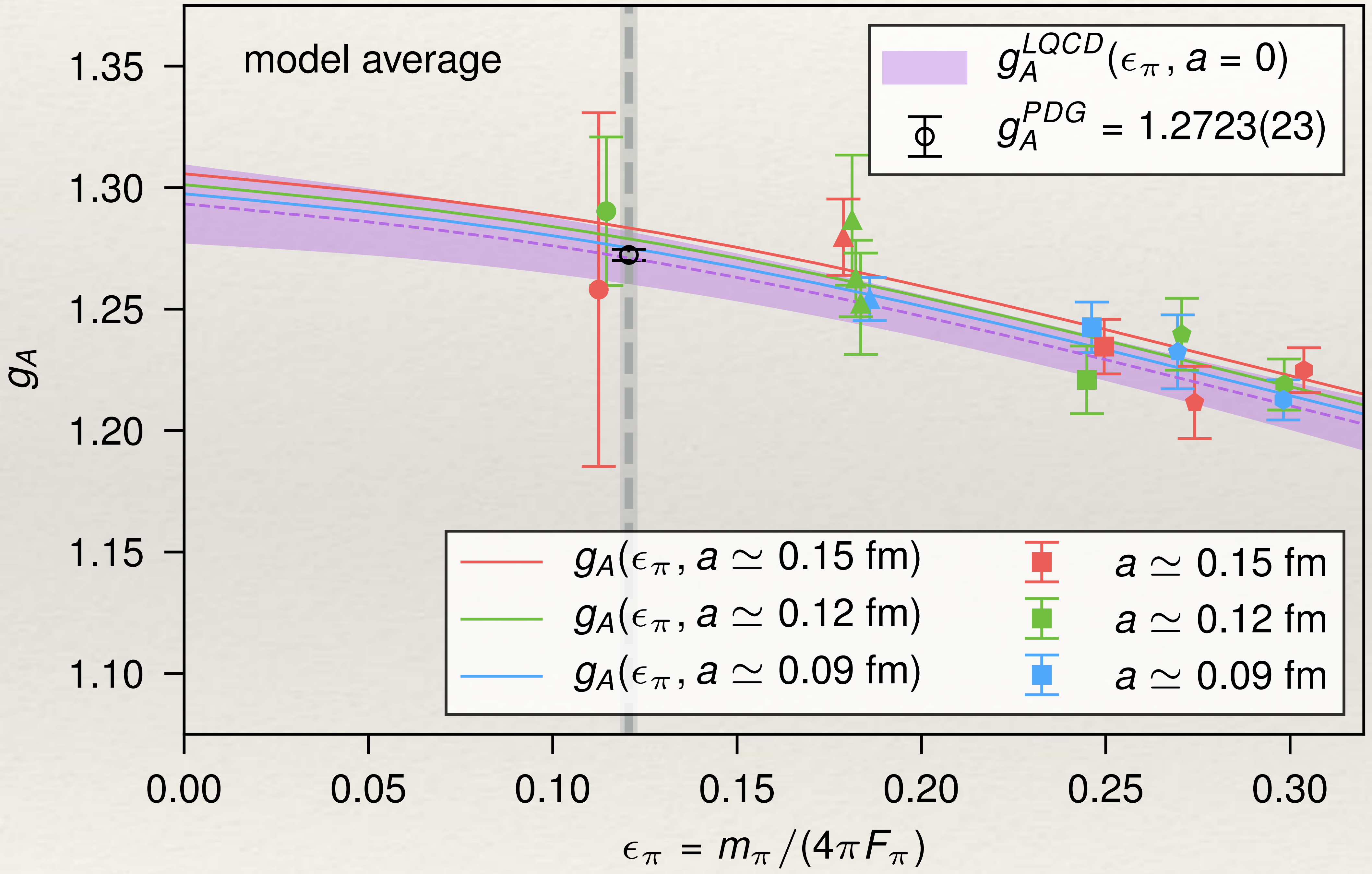
there are unknown short-distance nucleon corrections that must be determined for a complete answer — need lattice QCD!



NTNP: neutron β-decay - LQCD+QED challenges

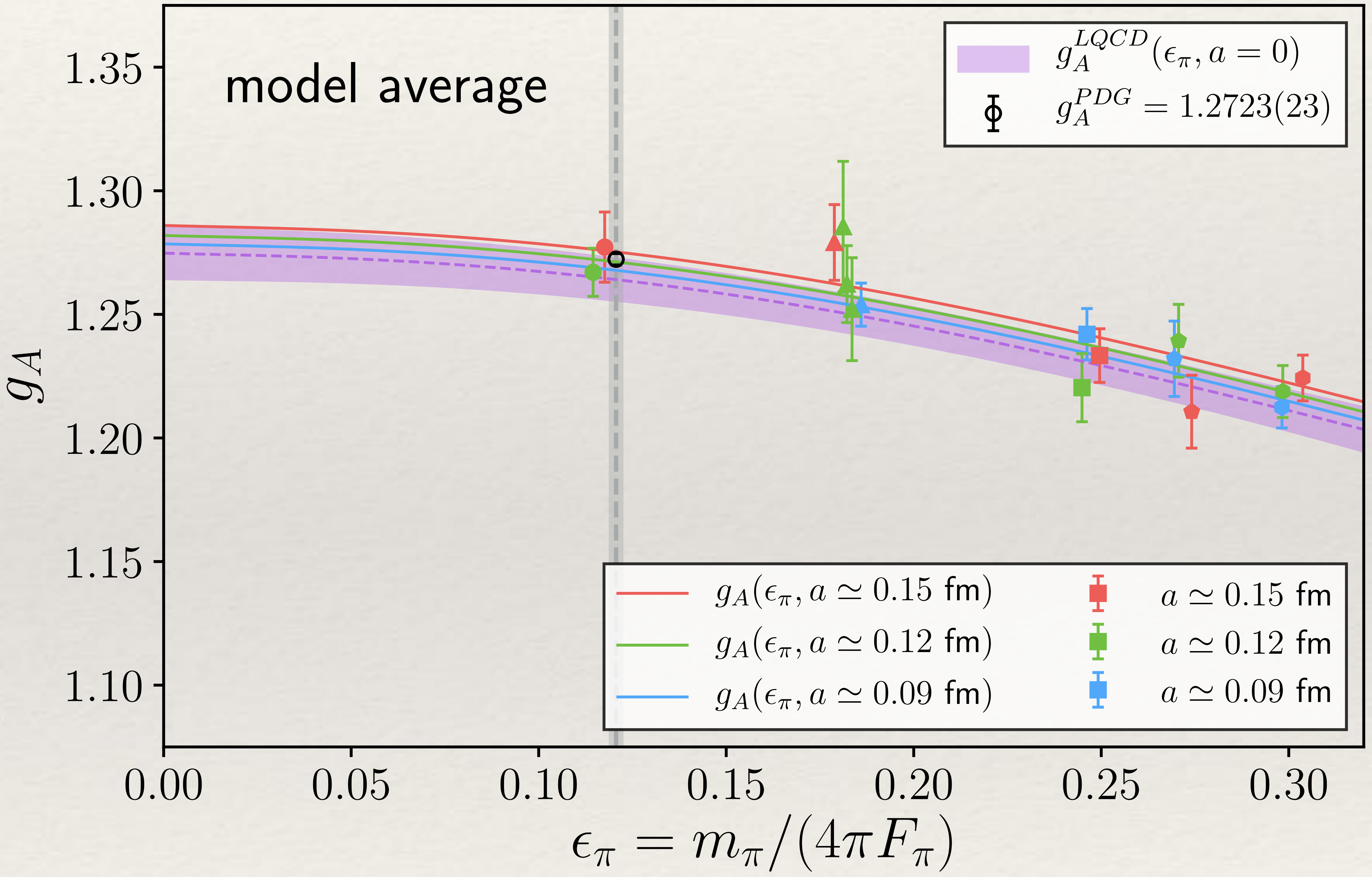
- Lattice QCD calculations are challenging - but we have demonstrated the ability to control g_A at the sub-percent level

Nature 558 (2018) no. 7708, 91-94
Chang et al. [arXiv:1805.12130]



Sierra Early Science
1912.08321

PRELIMINARY

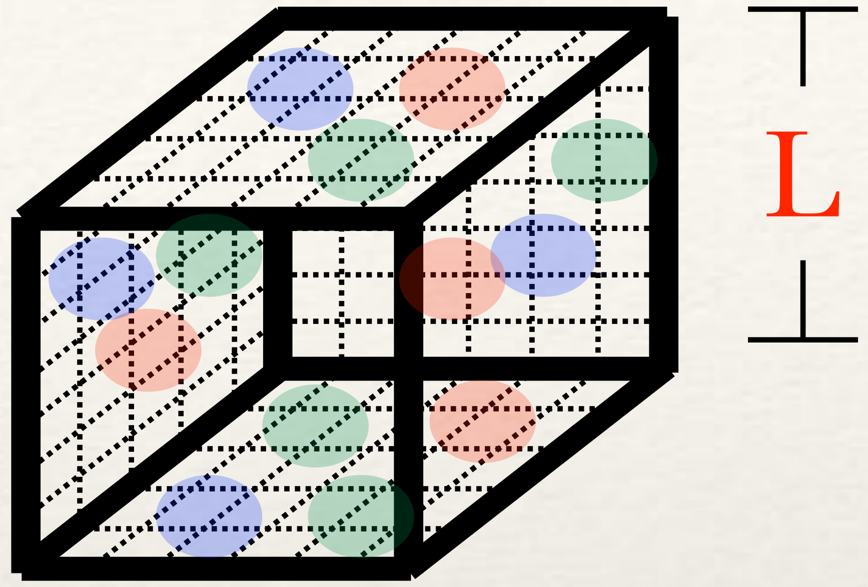


$g_A = 1.2711(125) \rightarrow 1.2641(93)$ [0.74%]

NTNP: neutron β-decay - LQCD+QED challenges

- Lattice QCD calculations are challenging - but we have demonstrated the ability to control g_A at the sub-percent level

- Adding QED to lattice QCD presents new challenges
  - how to squeeze photons in an $L \sim 3 \times 10^{-15}$m box?
  - how to add electrons in the same small box?

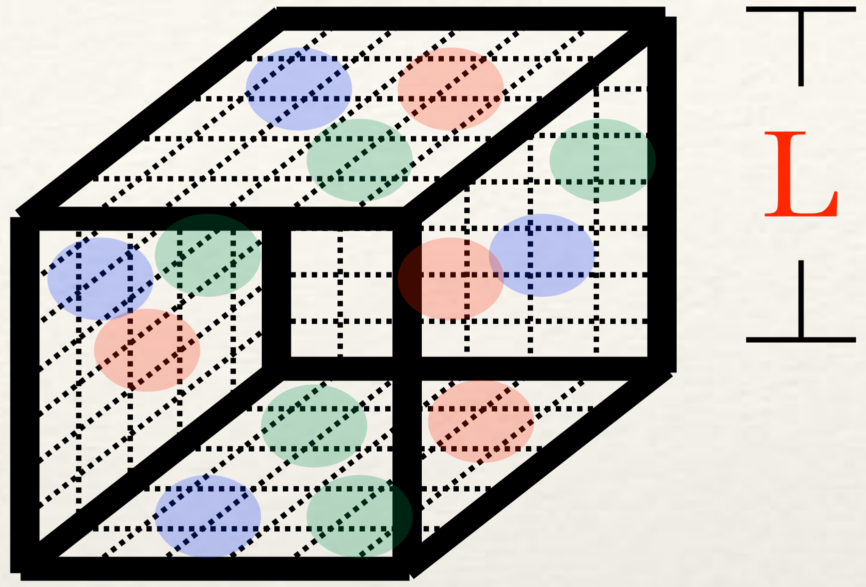


- We can begin by computing QED corrections to g_A

- and build upon this to compute the full $n \rightarrow pe\nu$ amplitude
  - The goal is not to control the full calculation at 10^{-4} precision but to control the correlated correction at $10^{-4} / \alpha_{fs} \sim 10^{-2}$ level

NTNP: neutron β-decay - LQCD+QED challenges

- Lattice QCD calculations are challenging - but we have demonstrated the ability to control g_A at the sub-percent level



- Adding QED to lattice QCD presents new challenges
  - how to squeeze photons in an $L \sim 3 \times 10^{-15}$m box?
  - how to add electrons in the same small box?

- We can begin by computing QED corrections to g_A

- and build upon this to compute the full $n \rightarrow pe\nu$ amplitude
  - The goal is not to control the full calculation at 10^{-4} precision but to control the correlated correction at $10^{-4} / \alpha_{fs} \sim 10^{-2}$ level

Zack Hall
UNC Chapel Hill
DOE SCGSR @ LBNL

Visiting me this year to begin work on this interesting problem

Thank You

QED corrections to neutron β-decay

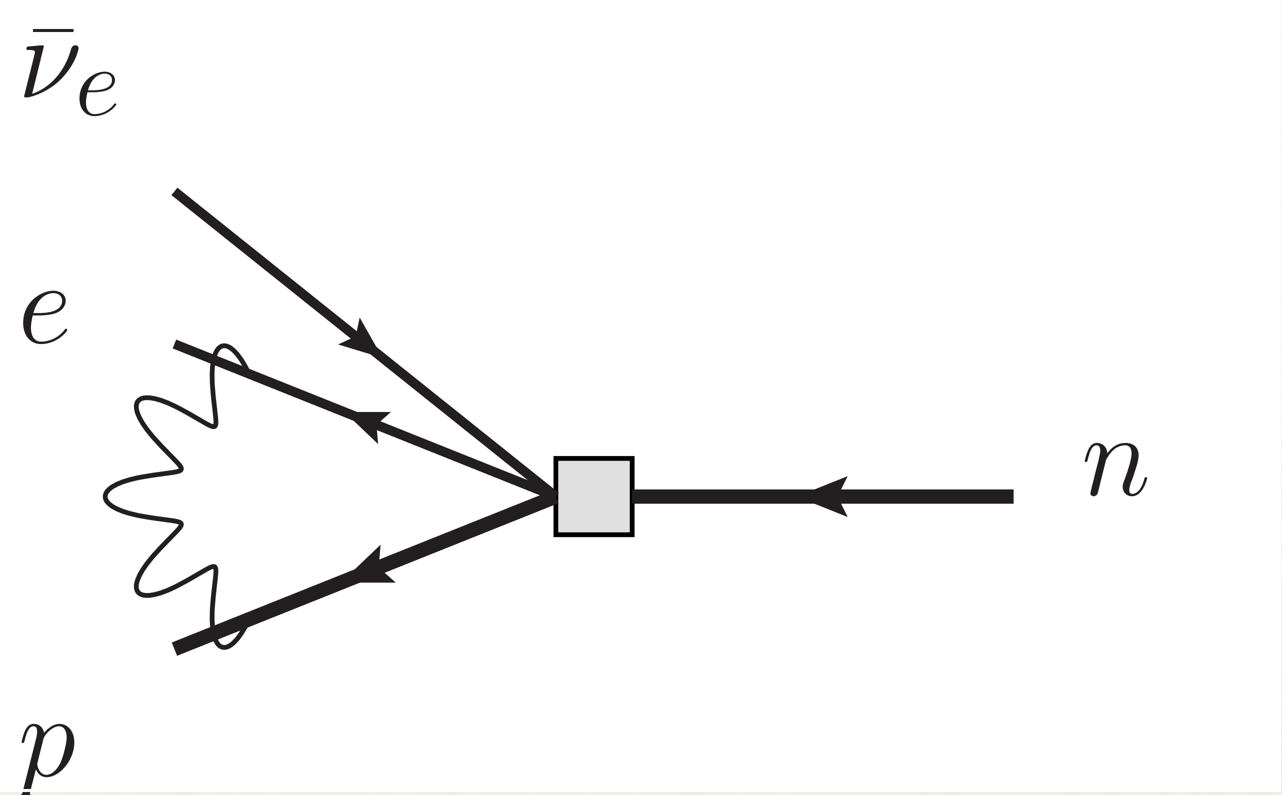
- Recent work uncovered an O(2%) QED correction to g_A, (previously estimated at 0.2%)
  Cirigliano, de Vries, Hayen, Mereghetti, Walker-Loud, PRL 129 (2022)

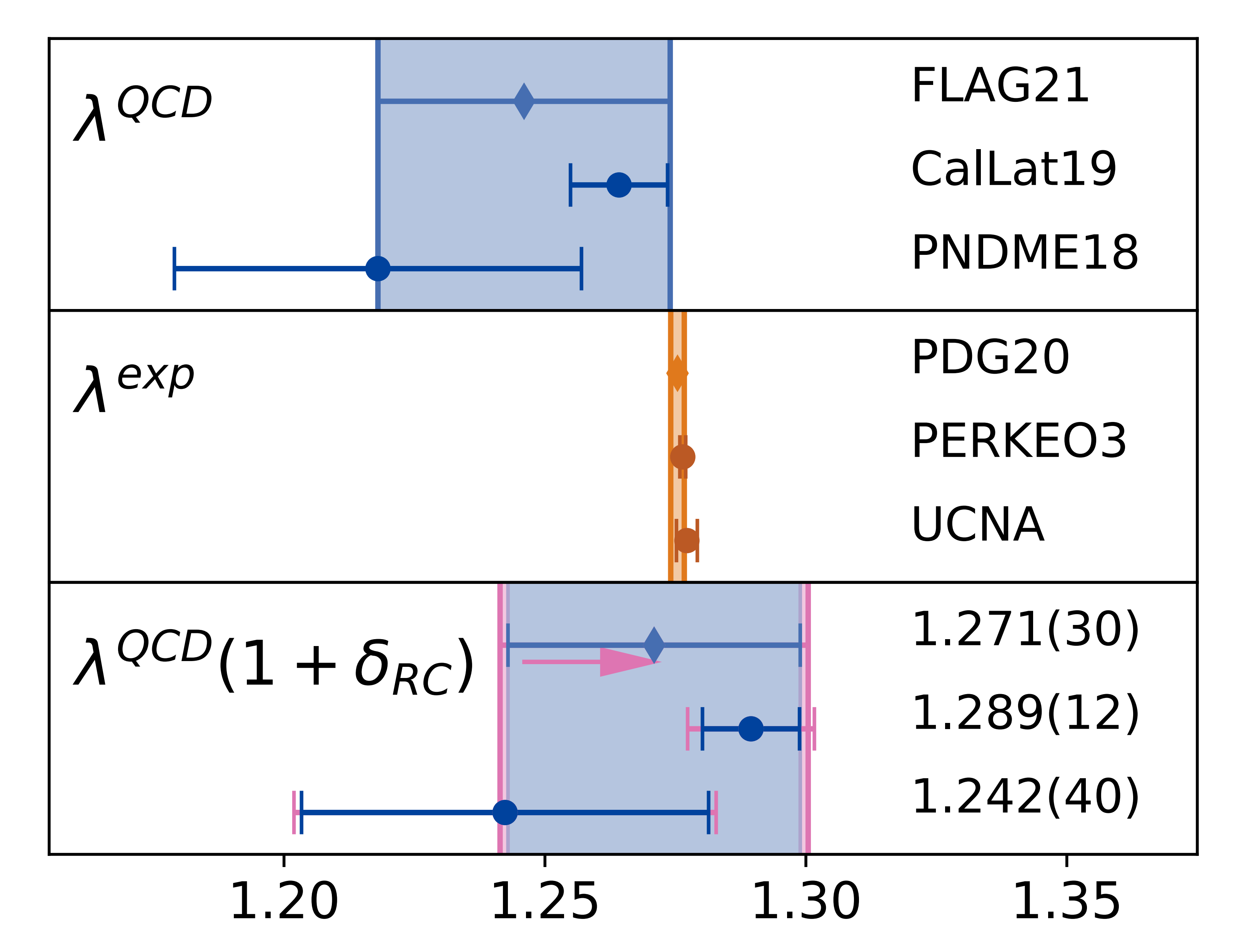
- Limiting factor comparing experiment and LQCD to constrain BSM right-handed currents

- LQCD + QED can be used to determine this correction

- Given that this term was missed with other theory methods, and QED corrections need to be controlled at 10^{-4} level, could there be other hadronic corrections important for gV and therefore a determination of V_{ud}?

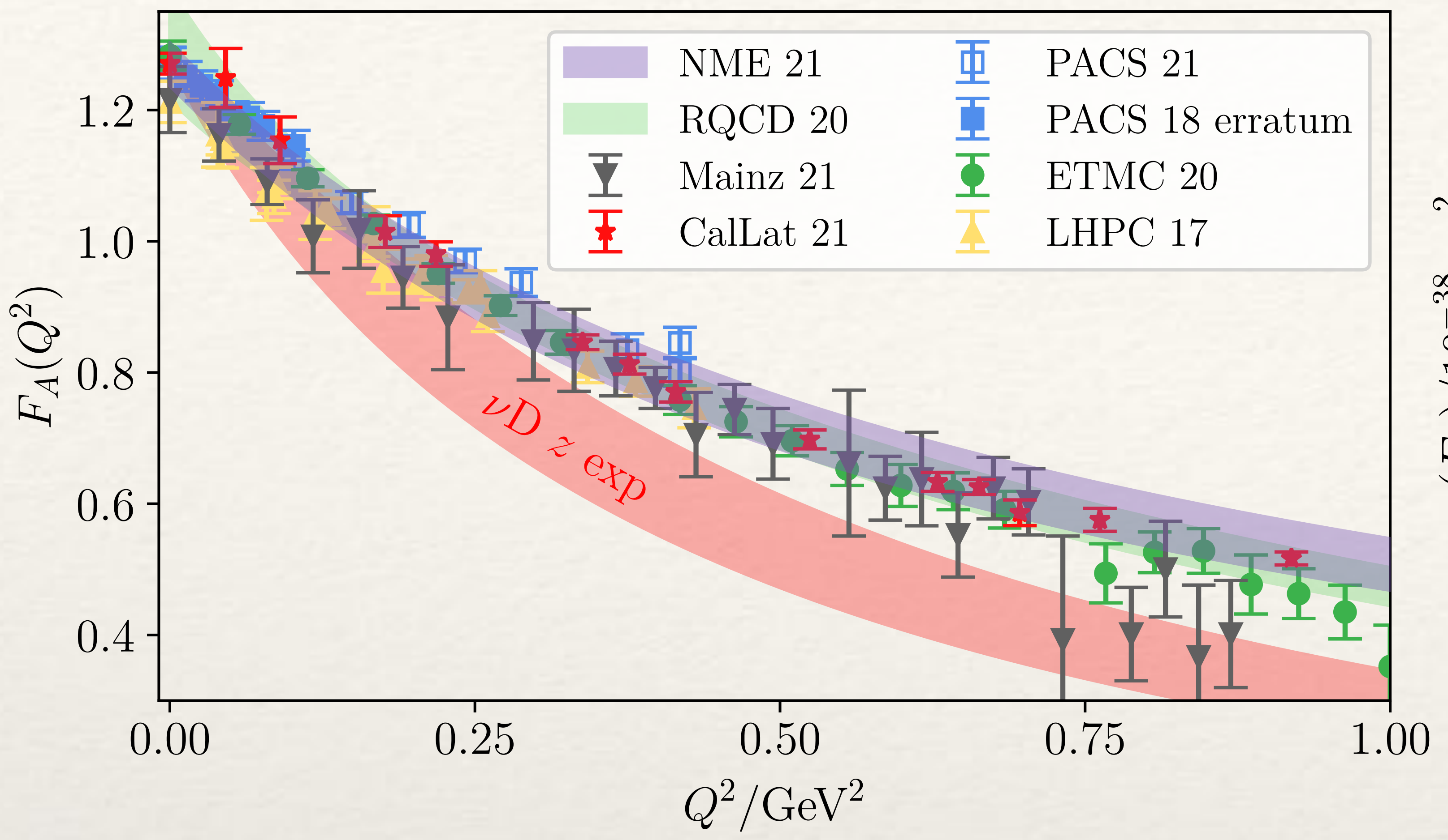
- We need a fully non-perturbative LQCD+QED calculation of neutron β-decay to validate the more recent dispersive determinations (or uncover larger corrections)

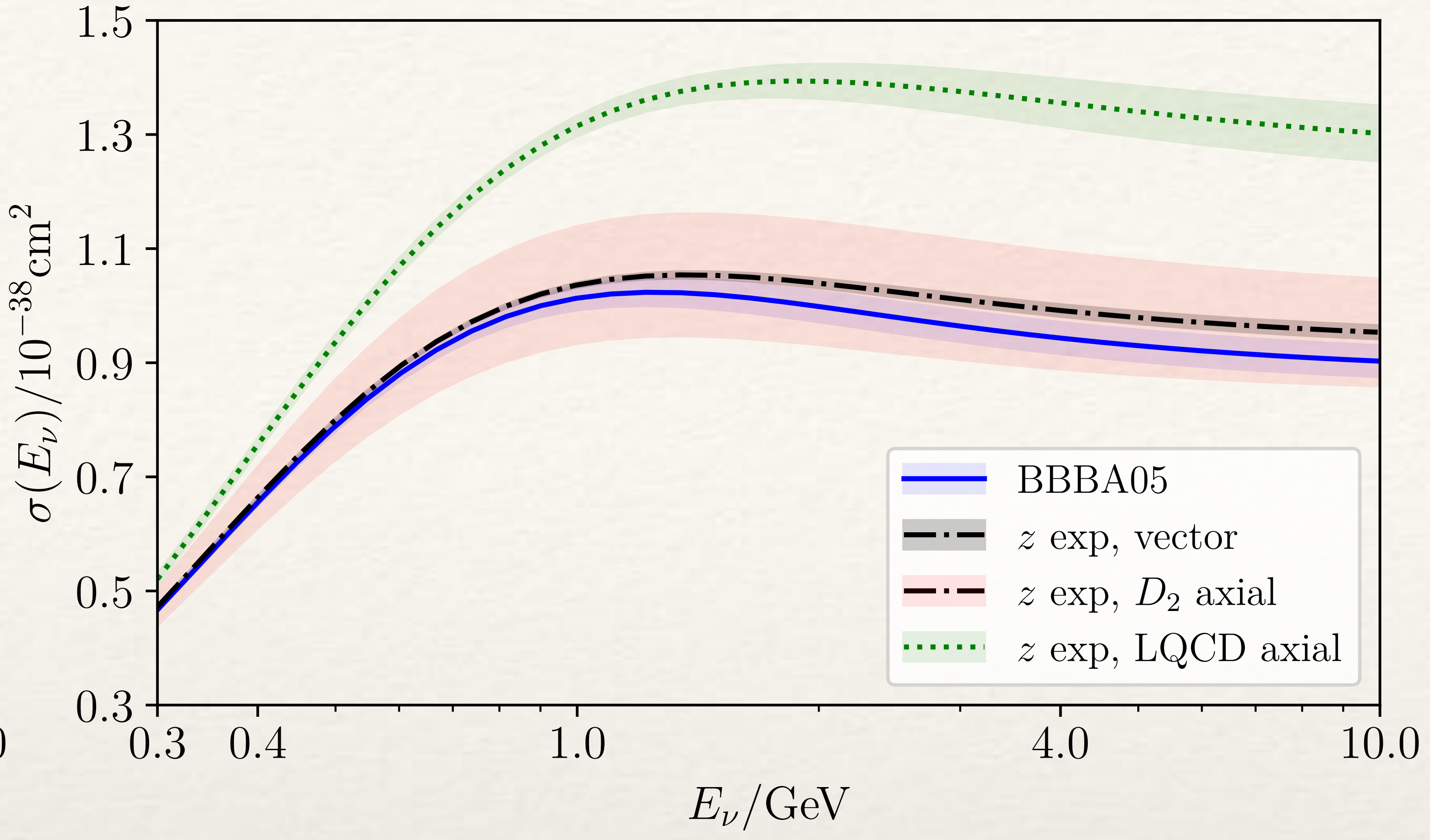


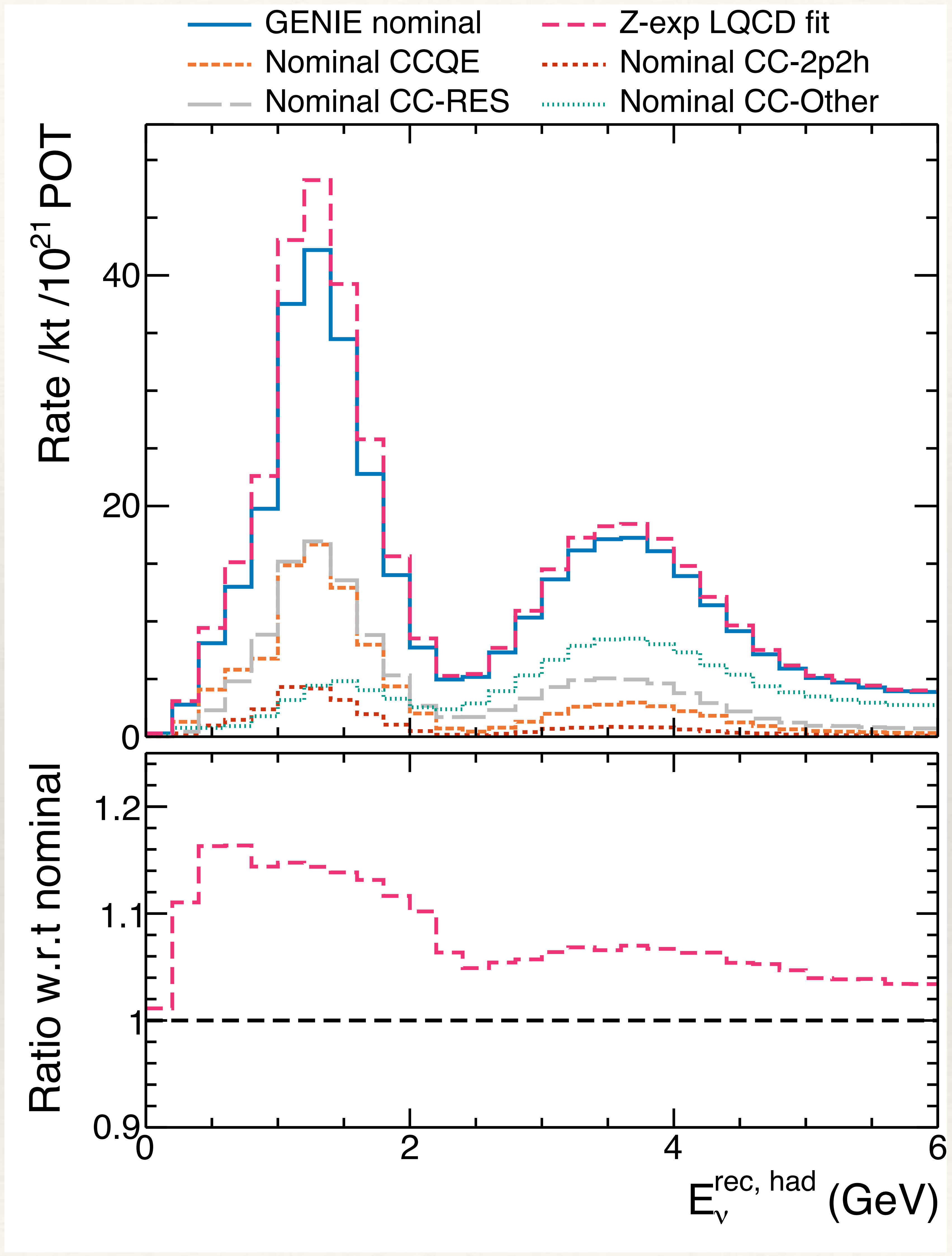


ν-N cross section

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







- 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 in DUNE near/far detector
- Use novel method (stochastic Laplacian Heaviside) to
  - solidify LQCD determination
  - Explore inelastic N-to-Δ transitions - next most important contribution to ν-A