Baryons 2025

Jeju, South Korea

13 November, 2025

Effective field theory for radiative corrections to charged-current processes: neutron decay, V_{ud}, and gA. Hadronic uncertainty in neutral currents

O.T., (2023)

Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., Phys.Rev.D (2023)

Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T., Phys.Rev.D (2025)

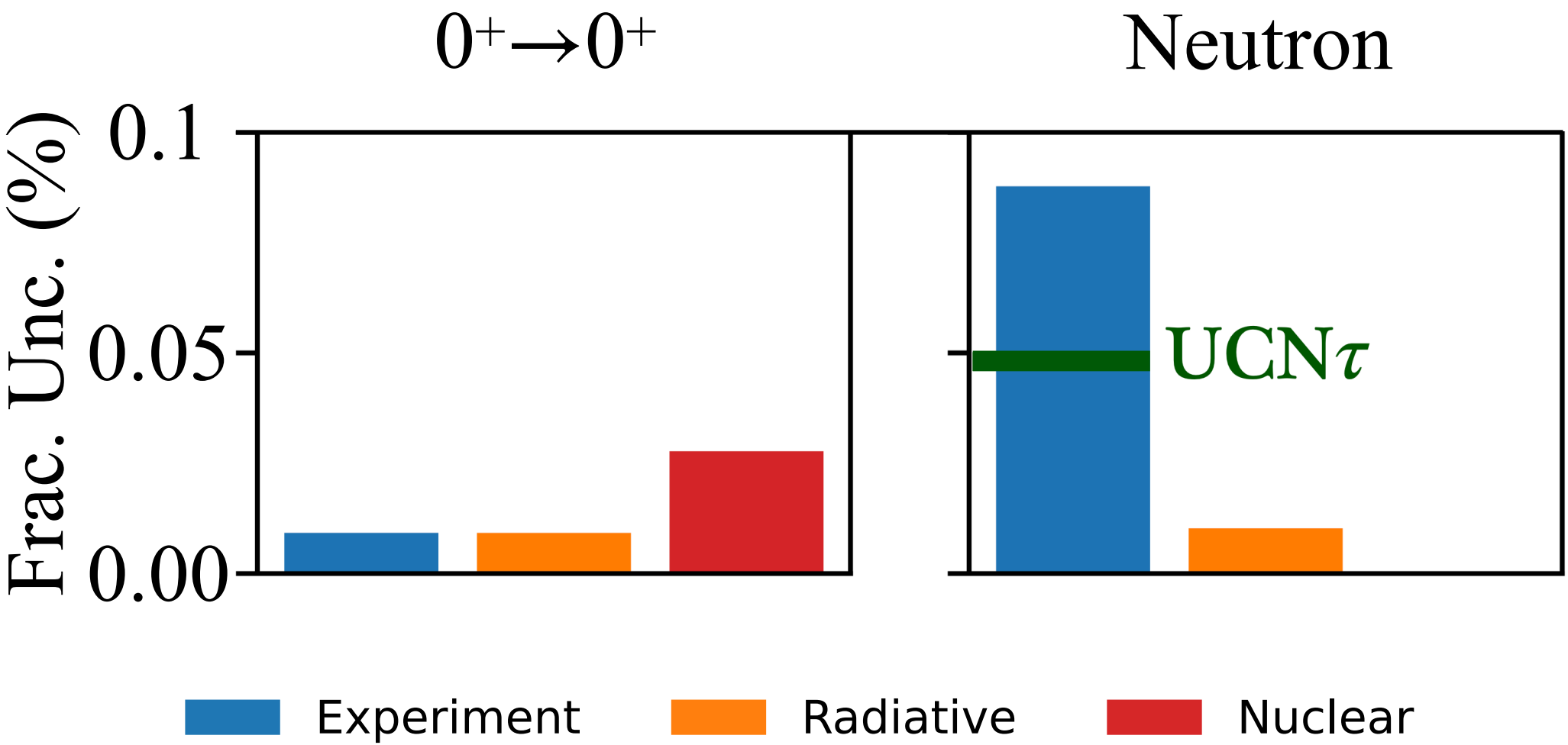
O.T., arXiv (2025)

Oleksandr (Sasha) Tomalak

Neutron decay and Vud

O.T., Few-Body Syst. (2023)
Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T.,
Phys.Rev.D (2023)

V_{ud} determinations

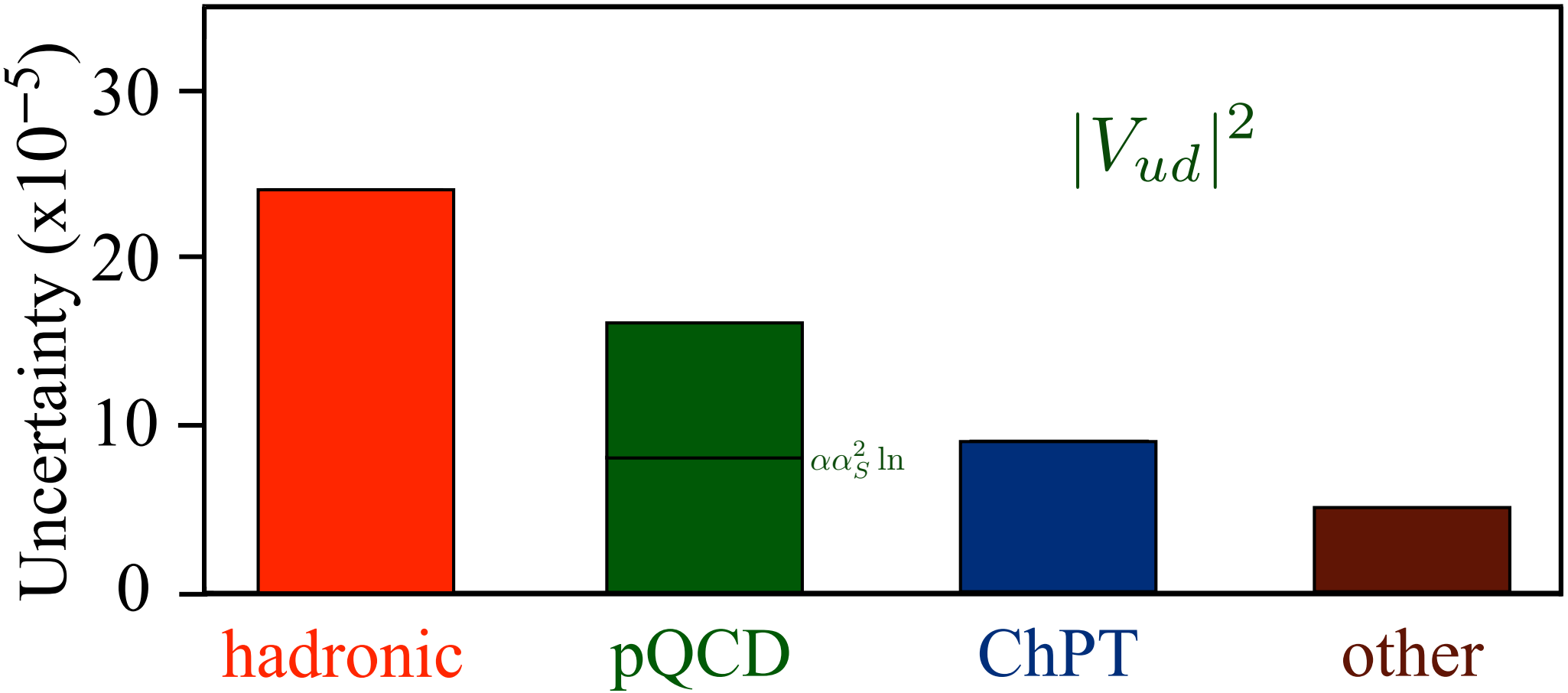


2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) white paper

- neutron decay becomes competitive with $0^+ \to 0^+$

Our work

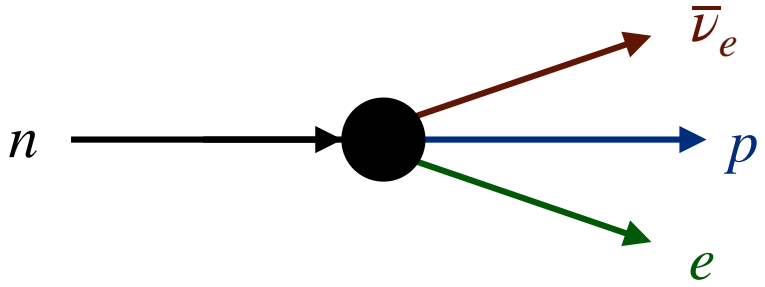
- detailed error budget and perturbative corrections

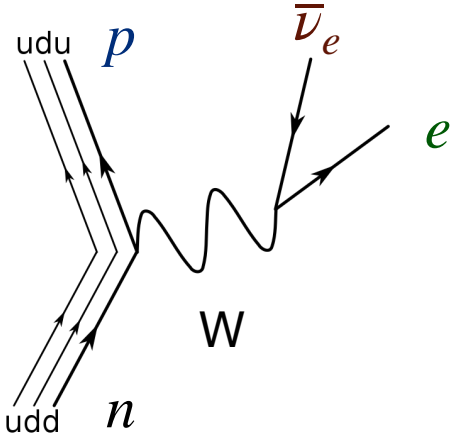


- shift of central value by ~1 error of radiative corrections
- quantification of perturbative/nonperturbative uncertainties

New EFT approach

- neutron is heavier than proton by 1.3 MeV and can decay
- neutron lifetime is around 15 mins





New EFT approach

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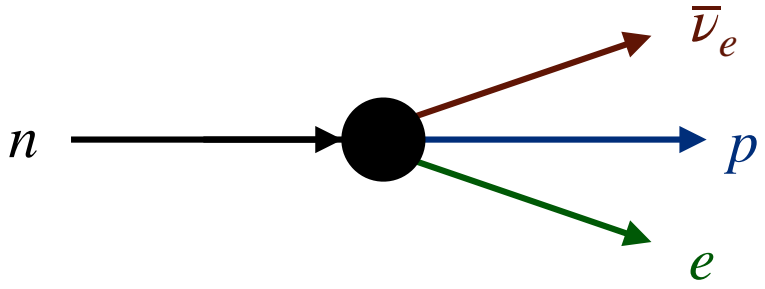
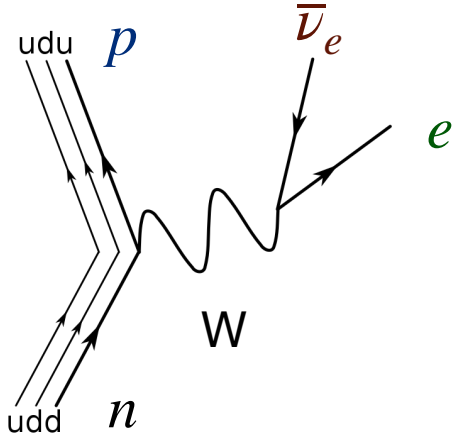




- four-fermion interaction between leptons and heavy nucleons

$$\mathcal{L}_{\text{eff}} = -\sqrt{2}\mathrm{G_F} V_{ud} \bar{e}\gamma_\mu \mathrm{P_L} \nu_e \cdot \overline{N}\left(g_V v^\mu - 2 g_A S^\mu\right)\tau^+ N$$

Standard Model -> LEFT -> HBχPT -> $\not\pi$EFT

- systematic approach to determine low-energy coupling constants

Low-energy description

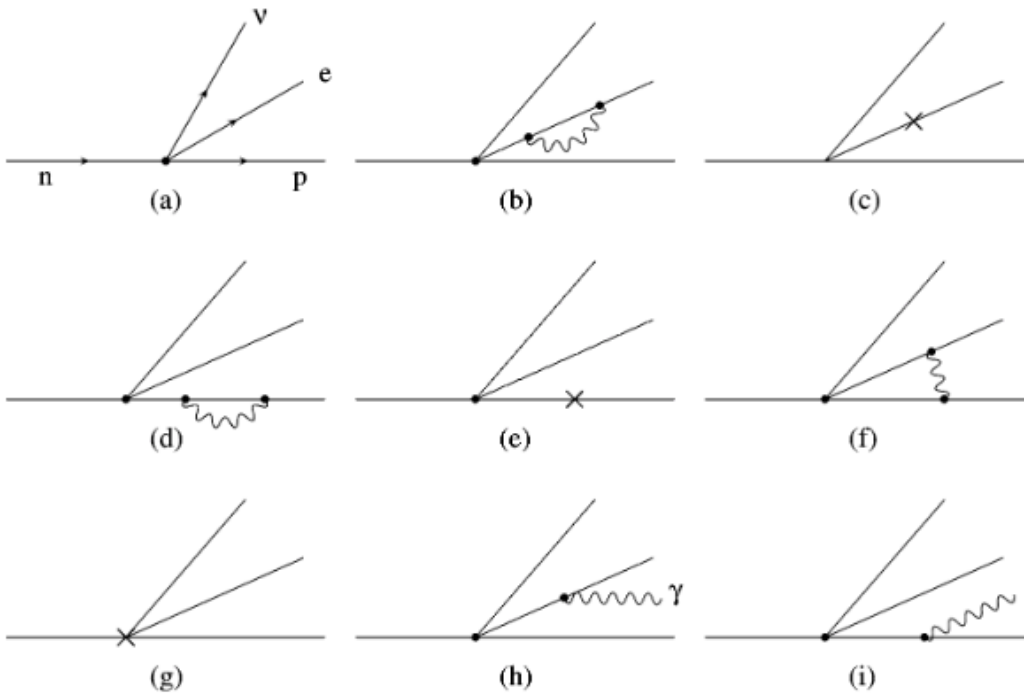
- four-fermion interaction between leptons and heavy nucleons

$$\mathcal{L}_{\text{eff}} = -\sqrt{2}\mathrm{G_F}V_{ud}\bar{e}\gamma_\mu \mathrm{P_L}\nu_e \cdot \overline{N}\left(g_V v^\mu - 2g_A S^\mu\right)\tau^+ N + \mathrm{O}\left(\frac{m_e}{M_p}, \alpha, \alpha\frac{m_\pi}{M_p}, \alpha\frac{m_e}{m_\pi}\right)$$

for uncertainty $m_e \sim M_p - M_n$

A. Sirlin, Phys. Rev. (1967)

- radiative corrections formulated in modern EFT language



vector and axial-vector counterterms (diagrams c, e, g)

data

Standard Model

S. Ando et al., Phys. Lett. B (2004)

- two coupling constants predict all observables

Effective field theory for β decay

M_Z

full content of Standard Model (SM)

integrate out top, Z, W, h

O.T., R. J Hill, Phys. Lett. B 805, 3, 135466 (2020)

W. Dekens, P. Stoffer, JHEP 07, 107 (2019)

m_b

m_τ

integrate out GeV particles

m_c

α_s becomes too strong going to lower energies

this talk

hadron physics

m_π

dynamical pions

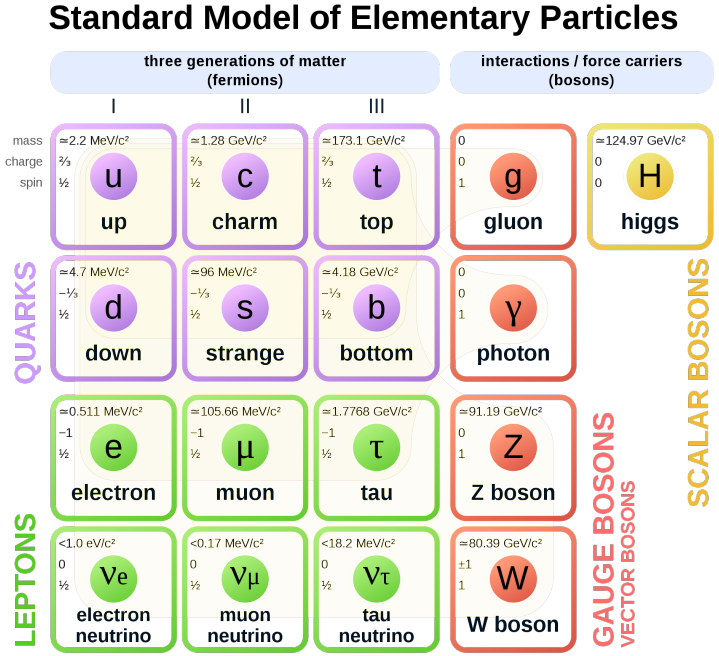
Vincenzo Cirigliano, Jordy de Vries, Leendert Hayen, Emanuele Mereghetti, and Andre Walker-Loud, Phys. Rev. Lett. (2022)

photons, neutrinos, electrons, external nucleons

m_e

S. Ando et al., Phys. Lett. B (2004)

- coupling constants from SM + small QED corrections



HBχPT to $\not\pi$EFT matching

- purely leptonic counterterm

$$\mathcal{L}_{\text{lept}}^{\text{CT}} = e^2 X_6 \bar{e} \left(i\partial_\mu + eA_\mu\right) \gamma^\mu e$$

- $\not\pi$EFT counterterms from χPT couplings in baryon sector

$$g_V = C_\beta^r \left(1 + e^2 \left[-\frac{X_6}{2} + 2\left(V_1 + V_2 + V_3 + V_4\right) - g_9\right]\right)$$

EW + electromagnetic

- vector-vector and vector-axial-vector products of quark currents

- LECs in terms of correlation functions

One-loop result

- clear illustration of leading logarithms

$$g_{\mathrm{V}}\left(\mu_\chi\right) = 1 - \frac{\alpha}{2\pi}\left[\frac{5}{8} + \frac{3}{4}\ln\frac{\mu_\chi^2}{\mu_0^2} + \ln\frac{\mu_0^2}{M_Z^2}\right]$$
$$- e^2 \int \frac{i\mathrm{d}^4 q}{(2\pi)^4}\frac{\nu^2+Q^2}{Q^4}\left[\frac{\mathrm{T}_3(\nu,Q^2)}{2\nu} - \frac{2}{3}\frac{1}{Q^2+\mu_0^2}\right]$$

- same Regge and resonance inputs as in traditional approach

- updates in elastic; DIS is part of running in LEFT

- agreement with current algebra evaluation

Effect of running

M_Z $\quad \mathcal{L}_{\rm LEFT} \sim G_F V_{ud} C^r_\beta(a,\mu)\, \bar{e}_L \gamma_\rho \nu_{eL}\, \bar{u}_L \gamma^\rho d_L$

- renormalization group equations

$$\mu \frac{\mathrm{d}C^r_\beta(a,\mu)}{\mathrm{d}\mu} = \left(\gamma_0 \frac{\alpha}{\pi} + \gamma_1 \left(\frac{\alpha}{\pi}\right)^2 + \gamma_{se} \frac{\alpha}{\pi} \frac{\alpha_s}{4\pi}\right) C^r_\beta(a,\mu)$$

m_b

$$\mu \frac{\mathrm{d}g_V(\mu)}{\mathrm{d}\mu} = \left(\tilde{\gamma}_0 \frac{\alpha}{\pi} + \tilde{\gamma}_1 \left(\frac{\alpha}{\pi}\right)^2\right) g_V(\mu)$$

m_τ

m_c

- resummed result with leading $\alpha\alpha_s$ corrections

matching scale

$$g_V(\mu_\chi = m_e) - 1 = (2.499 \pm 0.012)\,\%$$

m_π

- one-loop result without $\alpha\alpha_s$ contributions

$$g_V^{1-\mathrm{loop}}(\mu_\chi = m_e) - 1 = (2.430 \pm 0.012)\,\%$$

m_e

- cancellation of various contributions -> 0.07 % effect

V_{ud} from neutron decay

- λ from electron spin correlation measurements

$$|V_{ud}|^2 \tau_n \left(1+3\lambda^2\right)\left(1+\Delta_{\rm TOT}\right) = 5283.321(5)\ {\rm s}$$

$$\Delta_{\rm TOT}^{\rm EFT} = 7.761(27)\% \qquad \text{vs} \qquad \Delta_{\rm TOT} = 7.735(27)\% \qquad \lambda = \frac{g_A}{g_V}$$

- extraction with PDG lifetime and λ

$$V_{ud}^{\rm n,\ PDG} = 0.97430(2)_{\Delta_f}(13)_{\Delta_R}(82)_{\lambda}(28)_{\tau_n}[88]_{\rm total}$$

- extraction with UCNτ lifetime and PERKEO-III λ

$$V_{ud}^{\rm n,\ best} = 0.97402(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\rm total}$$

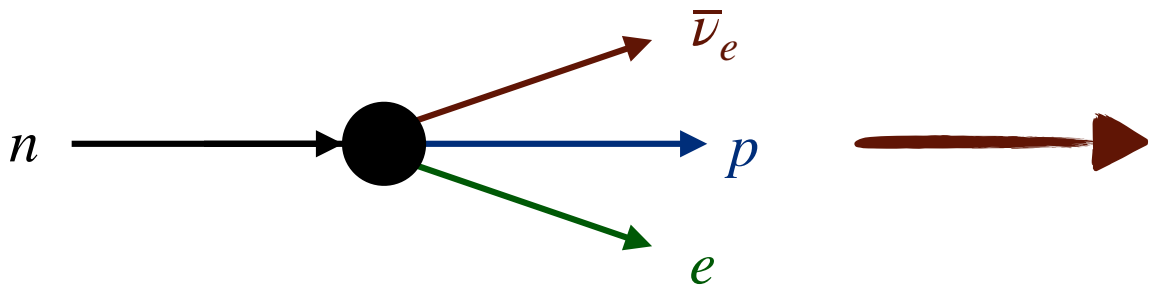
- in agreement with superallowed β decays, similar error

$$|V_{ud}^{0^+\to 0^+}| = 0.97373(31)$$

Hardy and Towner (2020)

- clean neutron lifetime extraction vs superallowed β decays

Conclusions



radiative corrections
in EFT framework
+ scheme-dependence

- radiative corrections in effective field theory approach

Standard Model -> LEFT -> HBχPT -> πEFT

- electroweak large logs and Coulomb enhancement

- next-to-leading logarithms and resummation

- updated extraction of V_{ud}

Axial-vector coupling constant

Vincenzo Cirigliano, Wouter Dekens, Emanuele Mereghetti, and O.T.,
Phys.Rev.D (2025)

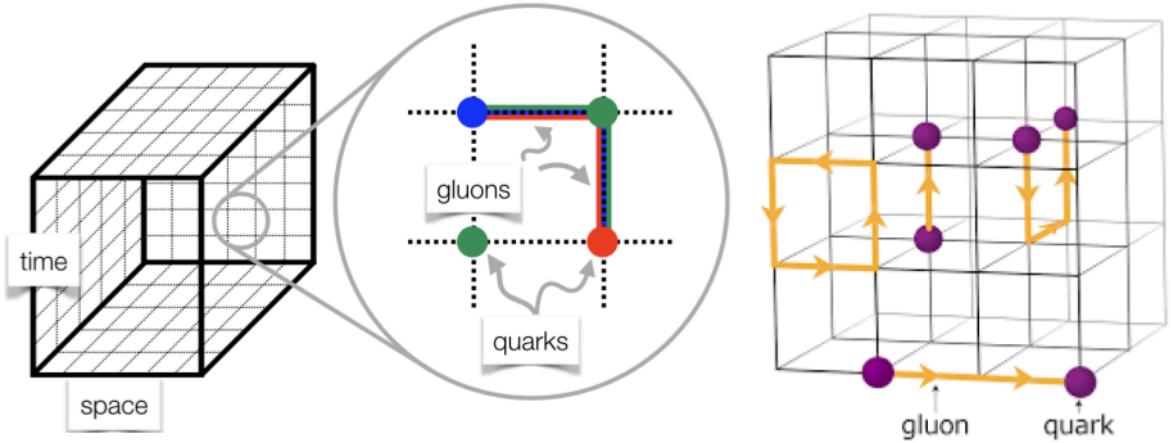
Axial-vector coupling constant

- per-mille level measurements of the ratio $\lambda = \frac{g_A}{g_V}$

- can we predict the axial-vector coupling constant from theory?

$$\Gamma^\mu = < p|\overline{u}\,(\gamma^\mu - \gamma^\mu\gamma_5)\,u|n >$$

- lattice QCD is appropriate tool: %-level precision for gA



- QED is not included in these calculations

- need framework to interpret QCD calculations of gA

HBχPT to $\not\pi$EFT matching

- purely leptonic counterterm

$$\mathcal{L}_{\rm lept}^{\rm CT} = e^2 X_6 \bar{e} \left(i\partial_\mu + eA_\mu\right) \gamma^\mu e$$

- $\not\pi$EFT counterterms from χPT couplings in baryon sector

$$g_A = g_A^{(0)} C_\beta^r \left(1 + e^2 \left[\underbrace{-\frac{X_6}{2} + 2\left(A_1 + A_2 + A_3 + A_4\right) + \frac{g_{11}+g_{12}}{4g_A^{(0)}}}_{\text{2pt}} + \frac{e^2}{g_A^{(0)}} \left(\underbrace{g_1 + g_2 + g_{13} + \frac{g_{11}-g_{12}}{4}}_{\text{3pt}} \right) \right] \right)$$

- 2pt and 3pt correlation functions = EW + electromagnetic

- LECs in terms of correlation functions

2pt contributions

- IR: no dependence on photon and pion masses, κ
- UV: construct OPE-subtracted object
- independent of μ_0

$$\left(-\frac{X_6^r}{2}+2\left(V_1^r+V_2^r\right)-g_9\right)(\mu_\chi,\mu)=\frac{1}{(4\pi)^2}\frac{3}{2}\left(1-\ln\frac{\mu_\chi^2}{\mu^2}\right)$$

$$\left(-\frac{X_6^r}{2}+2\left(A_1^r+A_2^r\right)+\frac{g_{11}^r+g_{12}^r}{4g_A^{(0)}}\right)(\mu_\chi,\mu)=\frac{1}{(4\pi)^2}\frac{3}{2}\left(1-\ln\frac{\mu_\chi^2}{\mu^2}\right)$$

$$2\left(V_3^r+V_4^r\right)(a,\mu)=\frac{1}{(4\pi)^2}\left[\frac{1}{2}\ln\frac{\mu^2}{\mu_0^2}+\frac{3-8a}{12}\right]+\int\frac{i\mathrm{d}^4q}{(2\pi)^4}\frac{\bar{t}_{VA,0}\left(q,v,\mu_0\right)}{q^2}$$

$$2\left(A_3^r+A_4^r\right)(a,\mu)=\frac{1}{(4\pi)^2}\left[\frac{1}{2}\ln\frac{\mu^2}{\mu_0^2}+\frac{3-8a}{12}\right]+\int\frac{i\mathrm{d}^4q}{(2\pi)^4}\frac{\bar{t}_{VV,0}\left(q,v,\mu_0\right)}{q^2}$$

- scheme dependence through a

- similar expressions for 2pt contributions to gV and gA
- same non-perturbative inputs as in γW-box diagram

Electroweak coupling constants

- unexplored isospin structure from LEFT side of matching

$$\varepsilon^{abc}\tau^c_{ij}S^{\rho}_{\sigma\sigma'} < N\left(k,\sigma',j\right)|T\left[\overline{q}\gamma^{\mu}\tau^b q(x)\,\overline{q}\gamma^{\nu}\gamma_5\tau^a q(0)\right]|N\left(k,\sigma,j\right) >$$

- LEFT contains unexplored 2pt correlation function

Ward identities

radiative corrections to gA

2pt + 3pt contributions

gauge-independent pieces

pseudoscalar-vector-vector

EW+electromagnetic

gauge-dependent terms

axial-vector-vector-vector

Ward identities

- equivalence of 2 representations:

$$b_\rho b_\lambda \int \frac{i\mathrm{d}^4q}{(2\pi)^4} \frac{g_{\mu\nu}\left(\bar{t}^{\mu\nu\lambda\rho}_{AVV}(q,v)+\bar{t}^{\mu\nu\lambda\rho}_{AVV,0}(q,v)\right)}{q^2-\lambda_\gamma^2} + \frac{g_A^{(0)}}{2m_N}\int \frac{\mathrm{d}^4q}{(2\pi)^4} \frac{g_{\mu\nu}\left(\tau^{\mu\nu}_{VV}(q,v)+\tau^{\mu\nu}_{VV,0}(q,v)\right)}{q^2} + \frac{1}{2}\frac{g_A^{(0)}}{(4\pi)^2}$$

$$= \overline{m} b_\rho b_\lambda \frac{\partial}{\partial r_\lambda}\left(\int \frac{i\mathrm{d}^4q}{(2\pi)^4} \frac{g_{\mu\nu}\left(t^{\mu\nu\rho}_{PVV}(r,q,v)+t^{\mu\nu\rho}_{PVV,0}(r,q,v)\right)}{q^2-\lambda_\gamma^2}\right)\Bigg|_{r_\lambda=0} + g_A^{(0)}\int \frac{i\mathrm{d}^4q}{(2\pi)^4}\frac{\bar{t}_{VA}(q,v)}{q^2}$$

- Ward identities provide new sum rules

NLO HBChPT Lagrangian

- leading-order Lagrangian:

$$\mathcal{L}_\pi^{p^2} + \mathcal{L}_\pi^{e^2} + \mathcal{L}_{\pi N}^{p} = \frac{F_\pi^2}{4}\langle u_\mu u^\mu \rangle + e^2 Z_\pi F_\pi^4 \langle \mathcal{Q}_L \mathcal{Q}_R \rangle + \overline{N}_v i v\cdot\nabla N_v + g_A^{(0)} \overline{N}_v S\cdot u N_v$$

- to account for $\frac{m_\pi}{\Lambda_\chi}\frac{\alpha}{\pi}$ corrections, include recoil and NLO

$$\mathcal{L}_{\pi N}^{p^2} + \mathcal{L}_{\pi N}^{e^2} = \overline{N}_v \Bigg[\frac{(v\cdot\nabla)^2 - \nabla^2}{2m_N} - \frac{i g_A^{(0)}}{2m_N}\{S\cdot\nabla, v\cdot u\} + c_1\langle\chi_+\rangle + \left(c_2 - \frac{\left(g_A^{(0)}\right)^2}{8m_N}\right)(v\cdot u)^2 + c_3 u\cdot u$$

$$+ \left(c_4 + \frac{1}{4m_N}\right)[S^\mu, S^\nu]\, u_\mu u_\nu + c_5\tilde{\chi}_+ - \frac{i\,[S^\mu, S^\nu]}{4m_N}\left((1+\kappa_1) f_{\mu\nu}^+ + \frac{1}{2}(\kappa_0 - \kappa_1)\langle f_{\mu\nu}^+\rangle\right)\Bigg] N_v$$

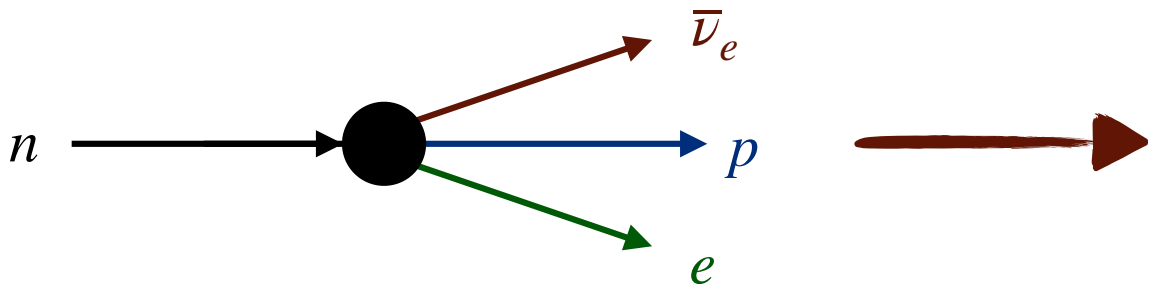
$$+ e^2 F_\pi^2\, \overline{N}_v \left(f_1\langle \tilde{\mathcal{Q}}_+^2 - \mathcal{Q}_-^2\rangle + f_2 \tilde{\mathcal{Q}}_+\langle\mathcal{Q}_+\rangle + f_3\langle\tilde{\mathcal{Q}}_+^2 + \mathcal{Q}_-^2\rangle + f_4\langle\mathcal{Q}_+\rangle^2 + f_5\mathcal{Q}_-\langle\mathcal{Q}_+\rangle\right) N_v$$

- apply spurion technique with various derivatives

- all LECs are expressed as 1pt and 2pt correlation functions

- new way to calculate all NLO HBChPT LECs

Conclusions



radiative corrections
in EFT framework
+ scheme-dependence

- radiative corrections in effective field theory approach

Standard Model -> LEFT -> HBχPT -> πEFT

- framework to precisely determine gA: 2 alternative ways

- future: evaluation of 2pt and 3pt correlation functions

- framework to determine all NLO HBChPT LECs

Hadronic uncertainty in low-energy neutral-current process

O.T., arXiv (2025)

(anti)neutrino-electron scattering with beam energy < 1 TeV

CEvNS with beam energy < 100 MeV

Light-quark contribution

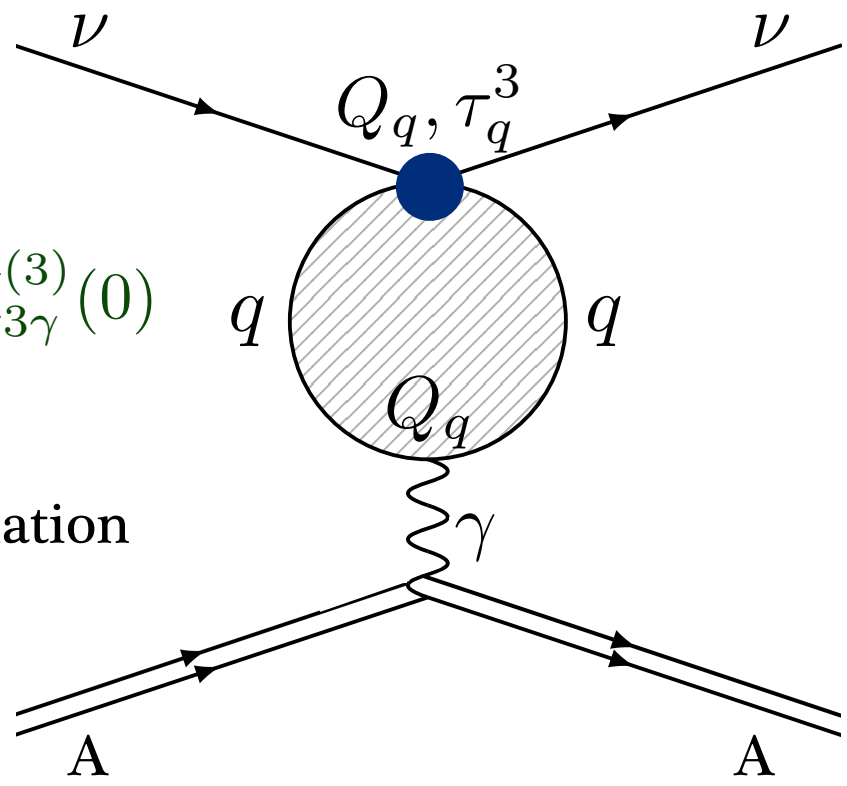
- description in terms of quarks is invalid

$$Q^2 \ll \Lambda^2_{\rm QCD}$$

O.T. and Richard J Hill, Phys Lett B (2020)

- light quarks

$$\delta^{\rm QCD} = 4\Pi^{(3)}_{\gamma\gamma}(0)\sin^2\theta_{\rm W} - 2\Pi^{(3)}_{3\gamma}(0)$$



- SU(3) chiral symmetry approximation

- flavor independent

O.T., Pedro Machado, Vishvas Pandey, and Ryan Plestid, JHEP (2021)

- non-perturbative light-quark contribution: error at low energy

Light-quark contribution

- charge-charge $\Pi_{\gamma\gamma}$ and charge-isospin $\Pi_{3\gamma}$ correlators:

$$\left(q^\mu q^\nu - q^2 g^{\mu\nu}\right)\Pi_{\gamma\gamma}\left(q^2\right) = 4i\pi^2 \int \mathrm{d}^d x e^{iq\cdot x}\langle 0|T\left[J^\mu_\gamma\left(x\right)J^\nu_\gamma\left(0\right)\right]|0\rangle$$

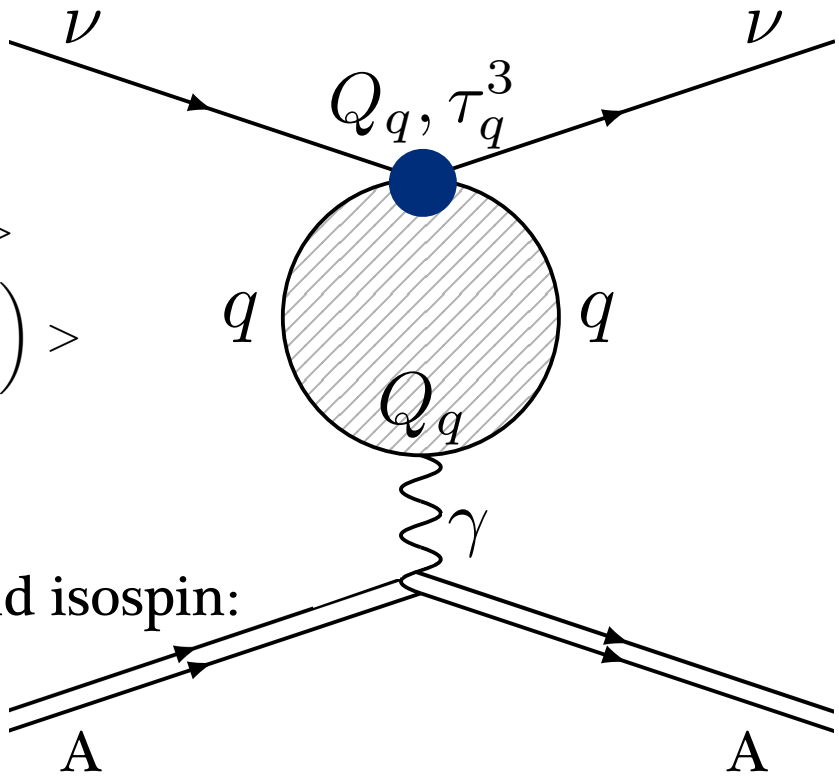
$$\left(q^\mu q^\nu - q^2 g^{\mu\nu}\right)\Pi_{3\gamma}\left(q^2\right) = 4i\pi^2 \int \mathrm{d}^d x e^{iq\cdot x}\langle 0|T\left[J^\mu_3\left(x\right)J^\nu_\gamma\left(0\right)\right]|0\rangle$$

- spurion technique in ChPT

$$J_\gamma \sim < \left(u^\dagger\partial_\mu u - u\partial_\mu u^\dagger\right)\left(uQu^\dagger - u^\dagger Q u\right) >$$

$$J_3 \sim < \left(u^\dagger\partial_\mu u - u\partial_\mu u^\dagger\right)\left(u\frac{\tau^3}{2}u^\dagger - u^\dagger\frac{\tau^3}{2}u\right) >$$

chiral field u



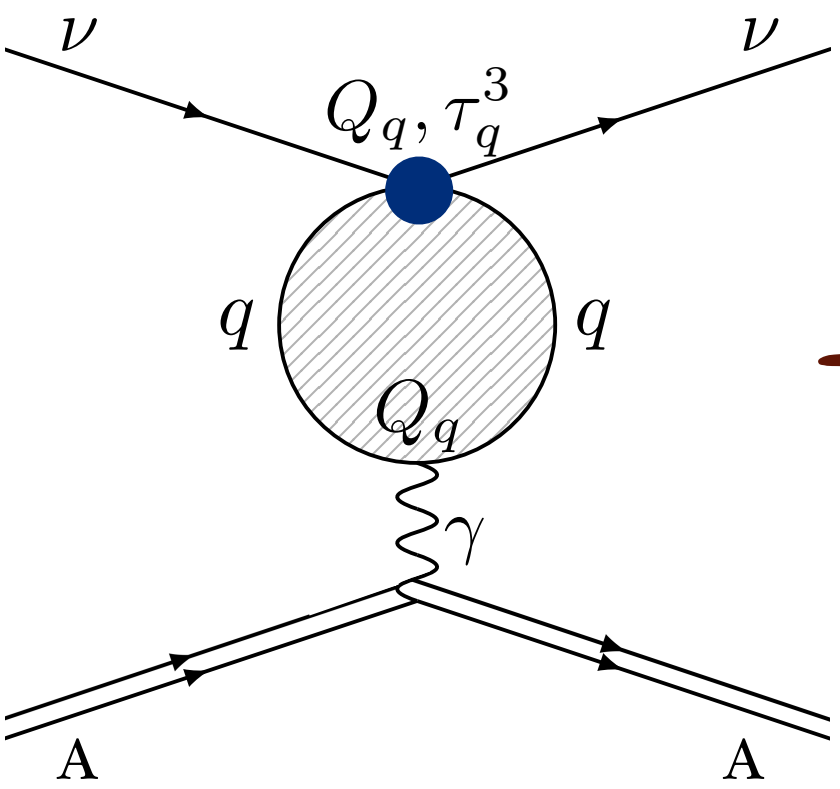
- SU(2) relation between charge and isospin:

$$Q = \frac{1}{2} + \frac{\tau^3}{2}$$

O.T., arXiv (2025)

- exact relation within validity of ChPT: $\Pi_{\gamma\gamma} = \Pi_{3\gamma}$

Conclusions



first ChPT analysis

of charge-isospin correlator

neutral currents

reduction of uncertainty

by a factor ~35

Thanks for your attention !!!