Study of the $\Lambda \to p\ell\bar{\nu}_\ell$ semi-leptonic decay in LQCD

The Cyprus Institute

University of Cyprus
Department of Physics

by Simone Bacchio and **Andreas Konstantinou**

Overview

- First-principles computation of $\Lambda \to p$ semi-leptonic **form factors** from lattice QCD at the **physical point**.
- Independent $|V_{us}|$ extraction.
- Process: $s \to u$ via virtual W.

Physical Insights

- Scale separation: $m_W \gg \Lambda_{QCD}$ → W acts **instantaneously**
- **Dominance: tree level** is sufficient.
- EW/QED **radiative effects are** small but relevant at (sub-)percent and are **neglected** here.
- Decay amplitude = **leptonic** current (perturbative) × **hadronic** matrix element (LQCD) (see Eq. 1).
- The decay rate is given by Eq. 2

$$\Gamma = \frac{1}{2m_\Lambda}\int \frac{d^3\vec{p}_p}{(2\pi)^3 2E_p}\frac{d^3\vec{p}_\ell}{(2\pi)^3 2E_\ell}\frac{d^3\vec{p}_\nu}{(2\pi)^3 2E_\nu}\times \quad (2)$$
$$(2\pi)^4\delta^{(4)}(p_\Lambda - p_p - p_\ell - p_\nu)\,|\mathcal{M}|^2.$$

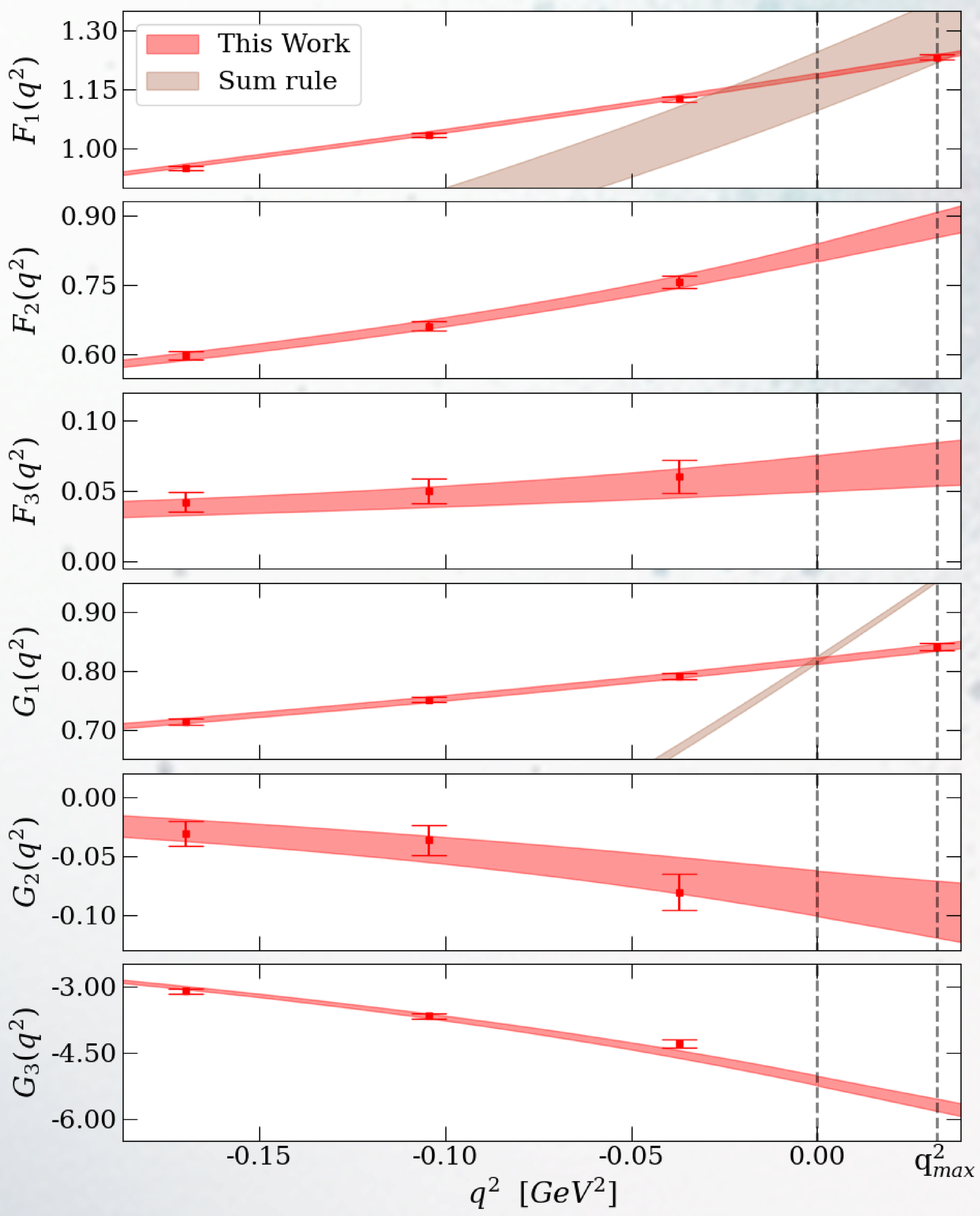


Fig 1. Momentum transfer dependence of the Weinberg form factors.

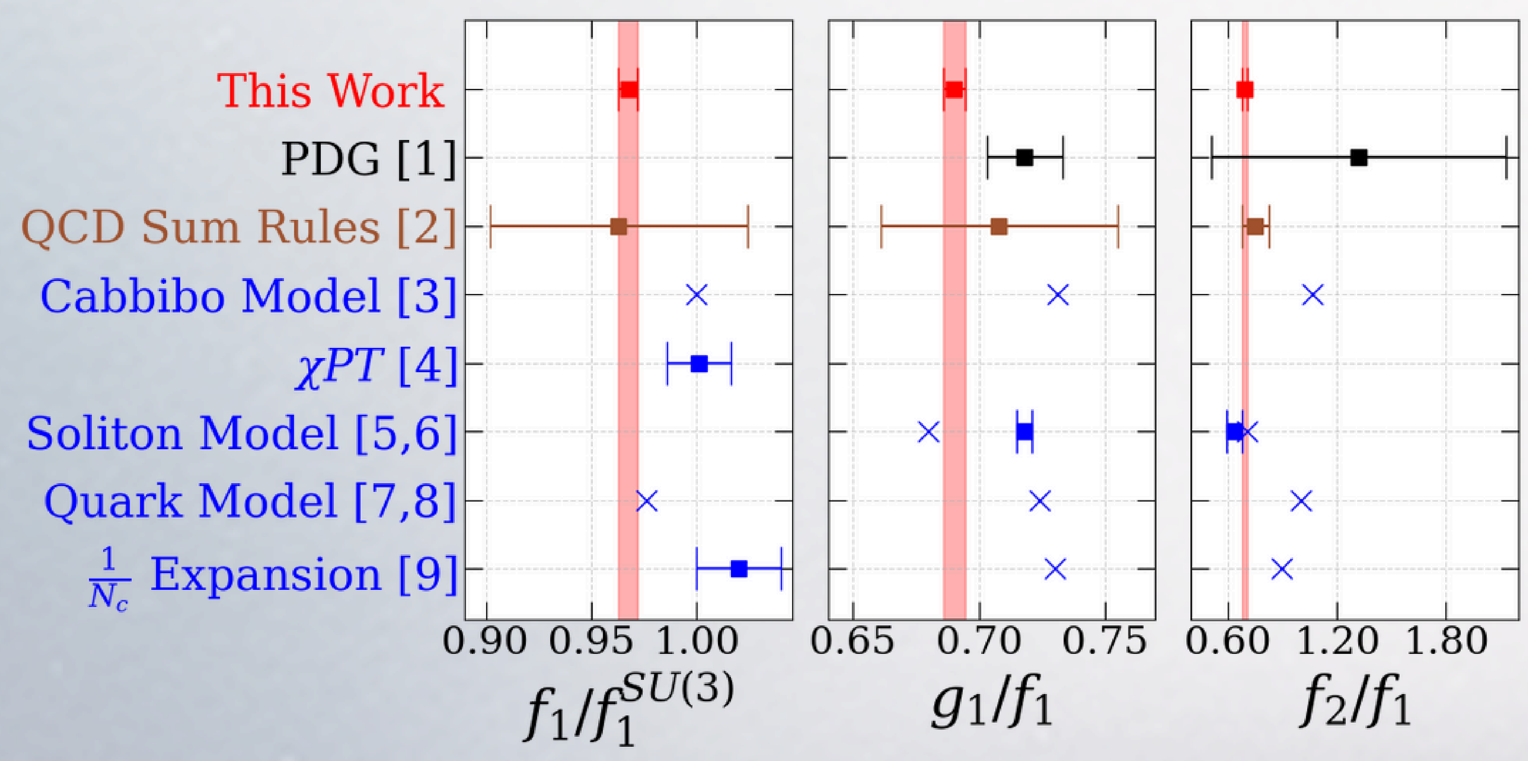
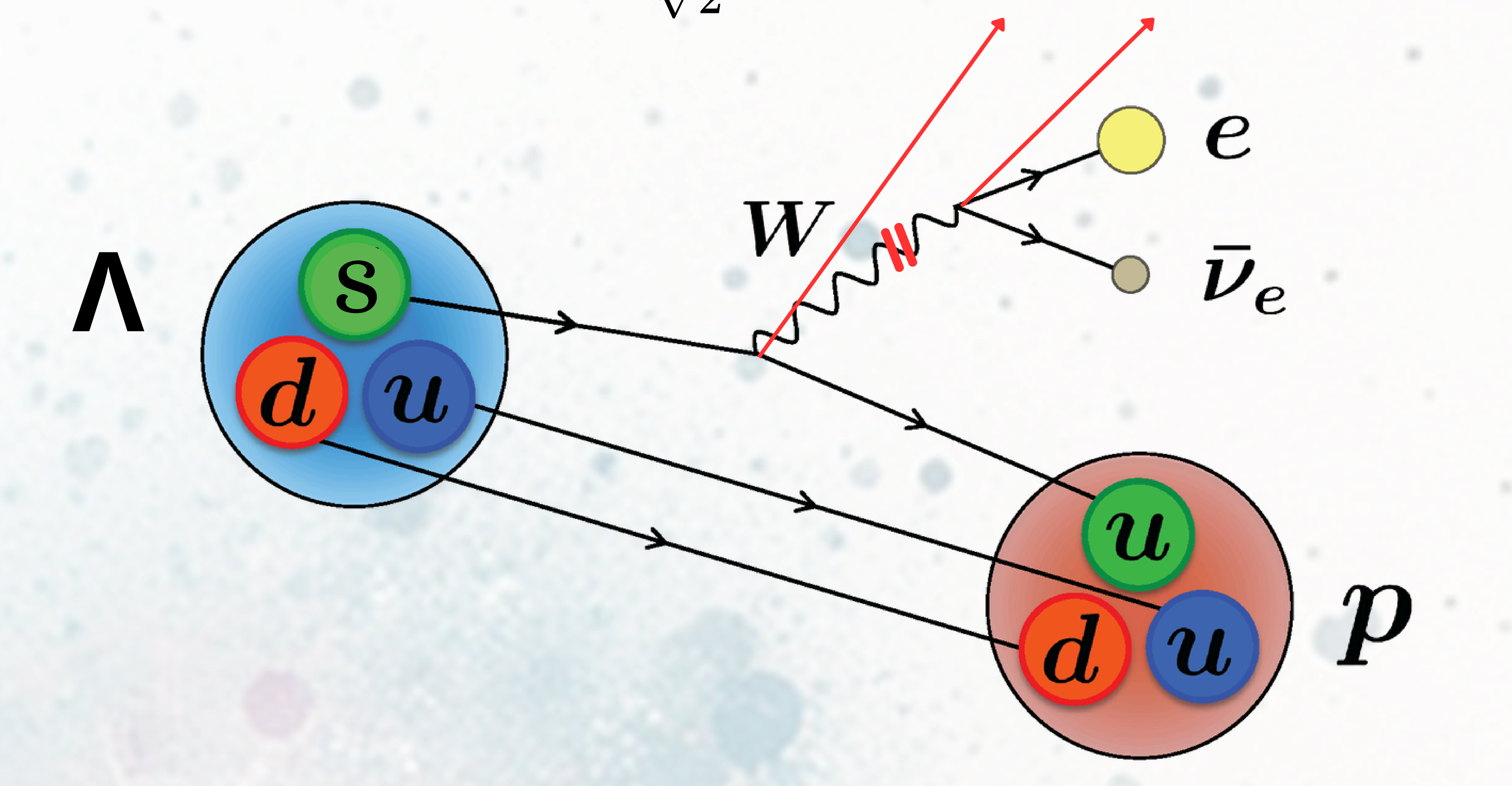


Fig 2. Comparison of ratios of coupling constants.

$$\mathcal{M}(\Lambda \to pe^-\bar{\nu}_e) = \frac{G_F}{\sqrt{2}}V_{us}\langle\Lambda|W_\mu|p\rangle L^\mu \quad (1)$$



Lattice QCD

- Physical quark masses.
- a ~ 0.08 fm, L ~ 5 fm, and m_π ~135 MeV.

Hadronic matrix elements

- Vector: F_1, F_2, F_3; Axial: G_1, G_2, G_3.
- These fully encode QCD dynamics (see Eq. 3).

$$\langle\Lambda|W_\mu|p\rangle = \bar{u}_p\left[\gamma_\mu\left(F_1(q^2) - G_1(q^2)\gamma_5\right) - i\sigma_{\mu\nu}q^\nu\frac{F_2(q^2) - G_2(q^2)\gamma_5}{m_\Lambda} + q_\mu\frac{F_3(q^2) - G_3(q^2)\gamma_5}{m_\Lambda}\right]u_\Lambda \quad (3)$$

Results

- Form factor dependence to momentum transfer, q^2 (see Fig. 1).
- Form factor ratios at $q^2 = 0$; consistent with experiment (see Fig. 2).
- Use of the experimental electron-channel decay rate; obtain $|V_{us}|$, and check first-row CKM unitarity (see Fig. 3).
- Suggesting that the decay rate (Eq. 2) must be integrated non-perturbatively (NLO deviates by 4%).

Conclusion

- We have presented the first lattice QCD calculation of the vector and axial-vector form factors governing the semi-leptonic decay $\Lambda \to p$.
- Our results for the form factor couplings are consistent with theoretical expectations, phenomenological models, and available experimental data.
- Our determination of $|V_{us}|$ is consistent with CKM unitarity, albeit with a larger uncertainty than other determinations that show a notable tension.

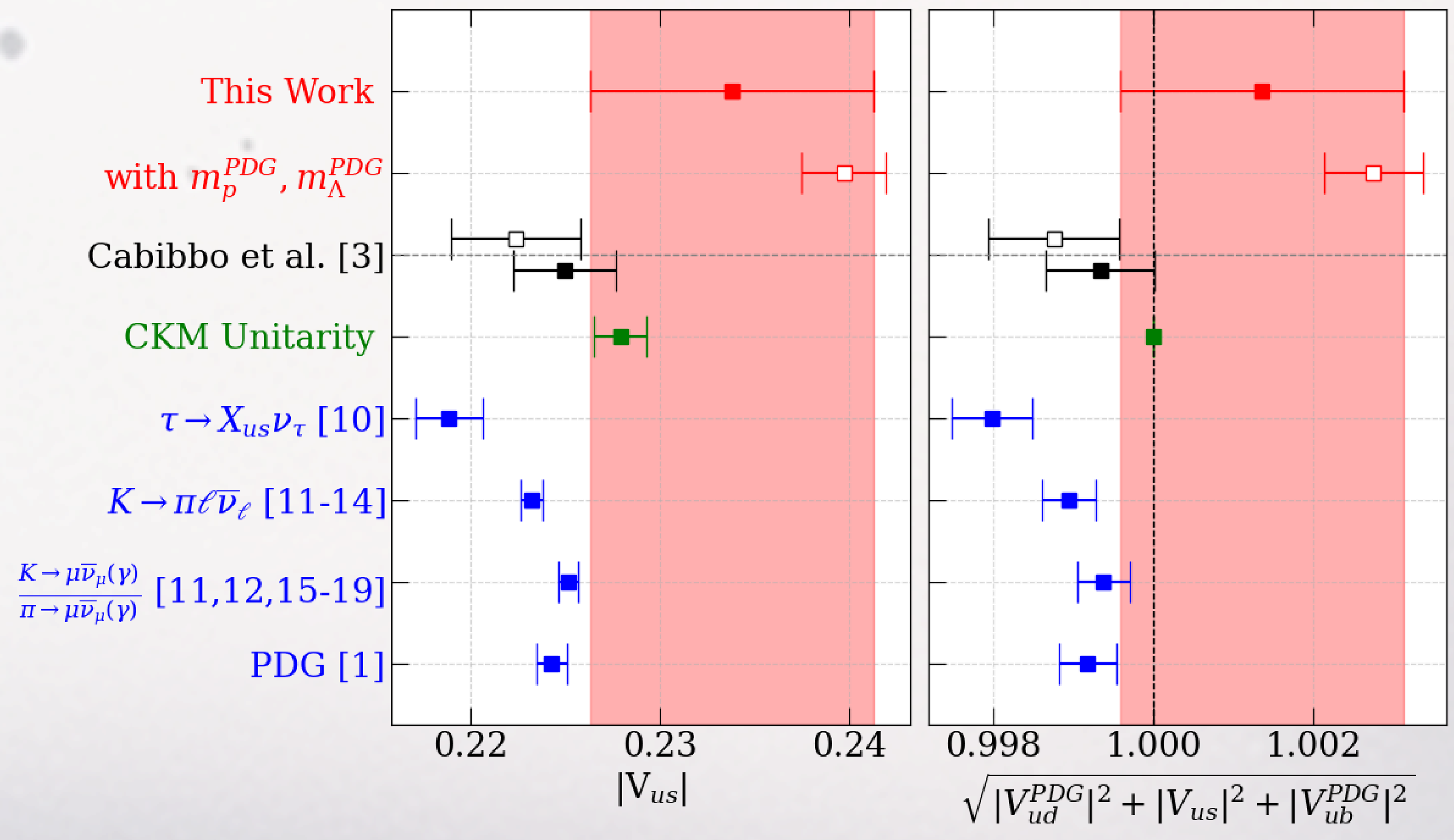


Fig 3. $|V_{us}|$ and the resulting CKM unitarity relation.

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