Leptonic decays of pions and kaons in lattice QCD+QED

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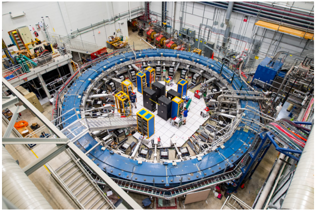
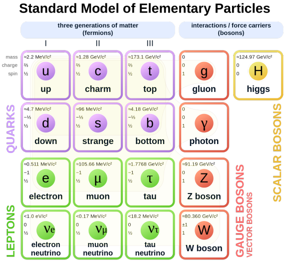


Experiment

=



Theory prediction

+ ?

Unknown

Indirectly search for new particles with precision calculations

⟶ If real tension found, search for new particles in direct detection

⟶ Interested in low energies: Non-perturbative effects from QCD!

- Lattice QCD: Non-perturbative ab initio method
- Euclidean, discretised, finite-volume spacetime to calculate

$$\langle \mathcal{O} \rangle = \frac{\int DU\, e^{-S[U]}\, \mathcal{O}[U]}{\int DU\, e^{-S[U]}}$$

- Monte Carlo simulations: Computationally demanding
- Statistical and systematic uncertainties
- Finite lattice spacing, a
- Finite-volume effects
- ...

Physics: $L \to \infty$, $a \to 0$, ...

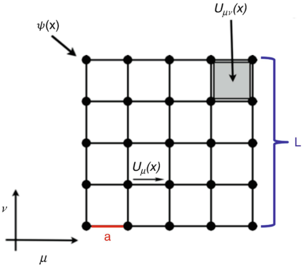


Figure from Ratti et al., 2021

Flavour physics sector

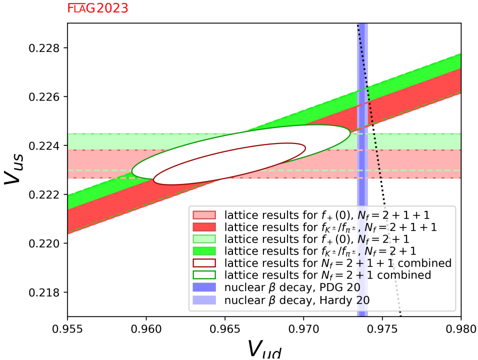
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Fundamental parameters of the Standard Model: Essential

A. Complex phase: Matter-antimatter asymmetry of the Universe

B. Search for new physics by testing unitarity:

$$1 \stackrel{\text{SM}}{=} |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$$



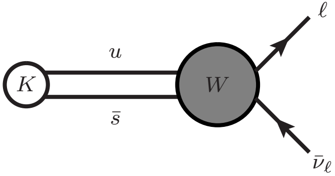
- Determine $|V_{ud}|$ and $|V_{us}|$
- Tensions with unitarity?
- 1.7–5.6 σ
- Depends on the input!
- Need to better control theory/exp. uncertainties

- Precision goal: (Sub-)% level
- Isospin-breaking effects crucial:

$$\text{QED:}\ \alpha \neq 0$$
$$\text{QCD:}\ m_u \neq m_d$$

- Consider diagonal $|V_{us}|/|V_{ud}|$: Leptonic decays

- Access $|V_{us}|/|V_{ud}|$ from leptonic kaon/pion decays



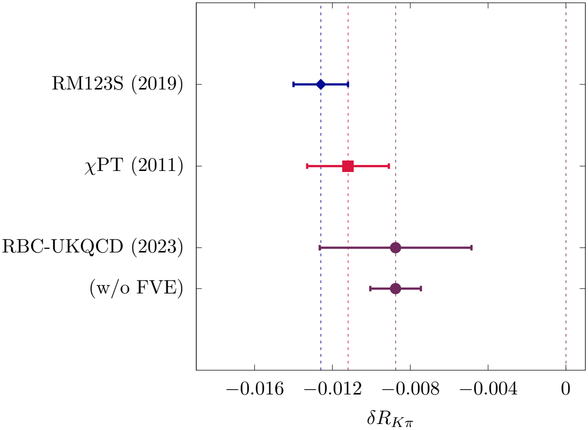
$$\underbrace{\Gamma\left(K^- \to \mu^- \nu_\mu\right)}_{\text{Exp.}} \propto |V_{us}|^2 \underbrace{\frac{\left(m_K^2 - m_\mu^2\right)^2}{m_K^3}}_{\text{Exp.}} \underbrace{f_K^2\left(1+\delta R_K\right)}_{\text{Theory}}$$

- Combine experiment and theory (lattice)

$$\frac{|V_{us}|^2}{|V_{ud}|^2} = \frac{\text{Kaon exp.}}{\text{Pion exp.}} \times \frac{f_K^2}{f_\pi^2}\left(1+\delta R_K - \delta R_\pi\right)$$

- Isospin-breaking corrections in $\delta R_K - \delta R_\pi$: % level precision

[RM123S 2019; Di Carlo, Hansen, NHT, Portelli 2022; RBC/UKQCD(NHT) 2023]



RBC-UKQCD(NHT):
$\delta R_{K\pi} = -0.0086(39)$

total	(39)
total (w/o FVE)	(13)
statistical	(3)
FVE	(37)
fit	(11)
QED quenching	(5)
discretisation	(5)

χPT : $\delta R_{K\pi} = -0.0112(21)$

RM123S 19: $\delta R_{K\pi} = -0.0126(14)$

Issue: QED finite-volume effects not sufficiently understood

Simulate at different volumes: Analytical knowledge important

- Correct data with $Y(L)$: $\delta R_P = \delta R_P(L) - Y(L)$

$$Y(L) = \underbrace{Y_0 + Y_{\log}\log(m_P L) + \frac{Y_1}{m_P L}}_{\text{[RM123/S 16]}} \quad \underbrace{+\frac{Y_2}{(m_P L)^2} + \frac{Y_3}{(m_P L)^3}}_{\text{[Di Carlo, Hansen, NHT, Portelli 22/23]}} \quad + \ldots$$

- Structure dependent: $1/L^2 + 1/L^3$

$$Y_3 = \frac{32\pi^2 m_P}{f_P(1-r_\ell^4)}\left\{c_0(\mathbf{v}_\ell)\left[F_V^P - F_A^P + 2m_P^2 r_\ell^2 F_A^{P\,\prime}\right] + c_0\,\mathcal{C}_\ell\right\}$$

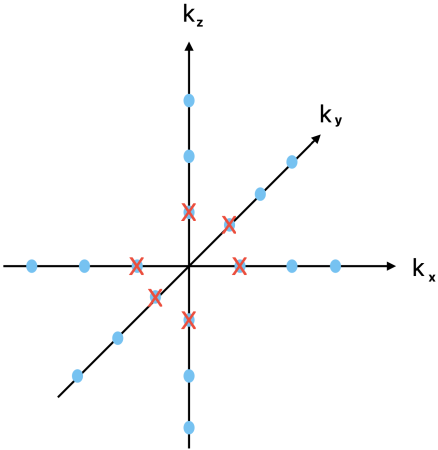
- F_V^P, F_A^P, $F_A^{P\,\prime}$ Lattice [RM-123/S 20/22/23, RBC/UKQCD 23], ChPT [Bijnens et al. 92]
- Cannot determine structure dependent $\mathcal{C}_\ell$: Drove uncertainty
- Known finite-volume coefficients $c_j(\mathbf{v}_\ell)$ at every order
- $\mathrm{QED_r}$: A new finite-volume QED $\overline{c}_0 = 0$ [Di Carlo, Hansen, NHT, Portelli In Prep.]

- FV momentum $\mathbf{k} = \frac{2\pi \mathbf{n}}{L}$
- Play with action [Davoudi et al. 19]

$$D_{\mu\nu}(k) = \delta_{\mu\nu} \frac{1 + w_{|\mathbf{n}|^2}}{k^2}$$

- Why OK? Only care about IV
- $\mathrm{QED_r}$ $w_{|\mathbf{n}|^2} = \delta_{|\mathbf{n}|,1}/6$

$$\bar{c}_0 = \underbrace{c_0}_{=-1} + \sum_{|\mathbf{n}|} w_{|\mathbf{n}|^2} = 0$$



$$Y_3 = \frac{32\pi^2 \, m_P \, \bar{c}_0(\mathbf{v}_\ell)}{f_P(1 - r_\ell^4)} \left[F_V^P - F_A^P + 2 m_P^2 r_\ell^2 \, F_A^{P\,\prime} \right]$$

Conclusions and outlook

- Searching for/constraining new physics with precision calculations
- Need to understand tensions: CKM matrix unitarity
- Leptonic decays: Solved bottleneck, $\mathrm{QED_r}$
- New RBC-UKQCD calculation with $\mathrm{QED_r}$
- Address volume and sub-leading uncertainties: Edinburgh & CERN
- $\mathrm{QED_r}$: General: Beta decays, Matter-antimatter asymmetry
- Relevant for ESS fundamental physics programme See talks tomorrow

Fysikaktuellt

- Fysikersamfundet magazine
- https://www.fysikersamfundet.se/fysikaktuellt/
- 4 volumes per year
- Contains articles, book reviews etc.
- If you have an idea about particle physics article: Email

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Backup slides

The RBC & UKQCD collaborations

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Masaaki Tomii
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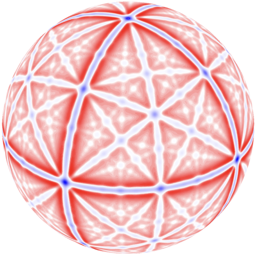
- Let us look at angular dependence in $\bar{c}_0(\mathbf{v})$ for $|\mathbf{v}| = 0.999$ ($\approx D_s \to \mu\nu$ decay)



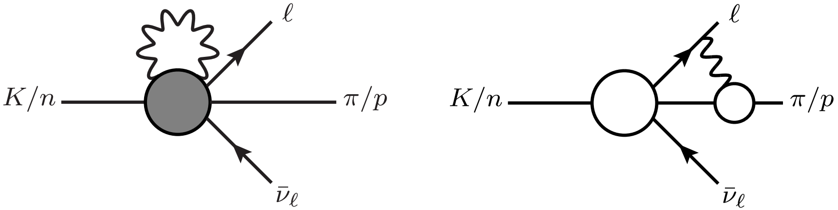
$\max \bar{c}_0(\mathbf{v}) \approx 9000$

$\min \bar{c}_0(\mathbf{v}) \approx -800$

Figure from Di Carlo, Lattice 2023

- Divergences but there are magic angles: $\bar{c}_0(\mathbf{v}_{\text{magic}}) = 0$
- Angular average: $\int d\Omega\, \bar{c}_0(\mathbf{v}) \propto \bar{c}_0 = 0$ [Davoudi, Harrison, Jüttner, Portelli, Savage 2019]
- Requires many velocities
- Magic velocity seems a reasonable way forward

- What about $|V_{us}|$ and $|V_{ud}|$ from beta decays?



Kaon ($|V_{us}|$) or neutron ($|V_{ud}|$)   The difficult part...

- Similar decays but spin and mass scales different
- Computational difficulties
- Effective field theory and lattice complementary [Gorchtein et al., 2023]
- Fundamentally difficult due to electromagnetic scattering
- Scattering essential for also studying matter asymmetry

Neutron beta decays at ESS

Figure from ESS

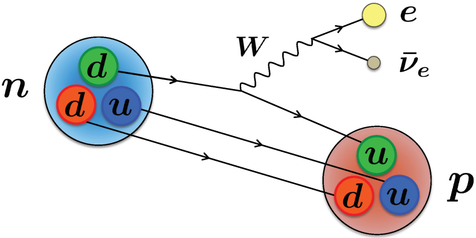


Figure from Fornal 2023

Rich neutron program at ESS also for fundamental physics

$\longrightarrow$ CKM matrix, matter asymmetry, dark matter, ...

[Abele et al., 2022]

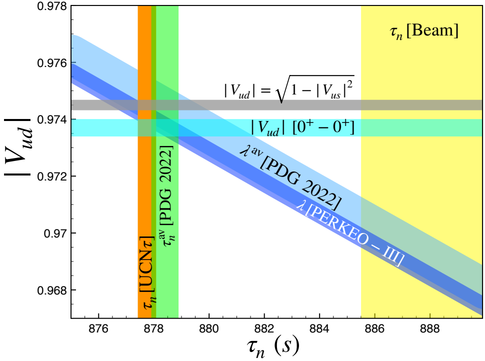


Figure from [Gorchtein et al., 2023]

Current tension: Neutron lifetime τ_n

$$|V_{ud}|^2 \propto \frac{1}{\tau_n (1+\lambda^2)(1+\Delta)}$$

Δ extracted from theory: Isospin-breaking corrections

ESS can measure τ_n

Figure references

- ⋆ Uppsala skyline by Michael Tompsett. https://wallism.com/si/product/4qGKEaMWdkeR
- ⋆ Fermilab: https://vms.fnal.gov/gallery/view?id=41
- ⋆ ESS: https://europeanspallationsource.se/ess-mandate
- ⋆ Fornal 2023: https://www.mdpi.com/2218-1997/9/10/449