Standard Model Prediction for Direct CP-violation in K-decays, and Long-Distance Contributions to Kaonic Amplitudes

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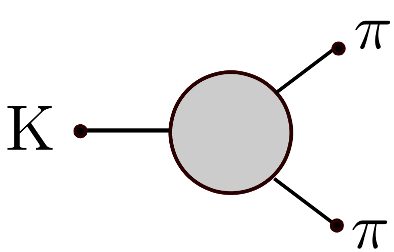
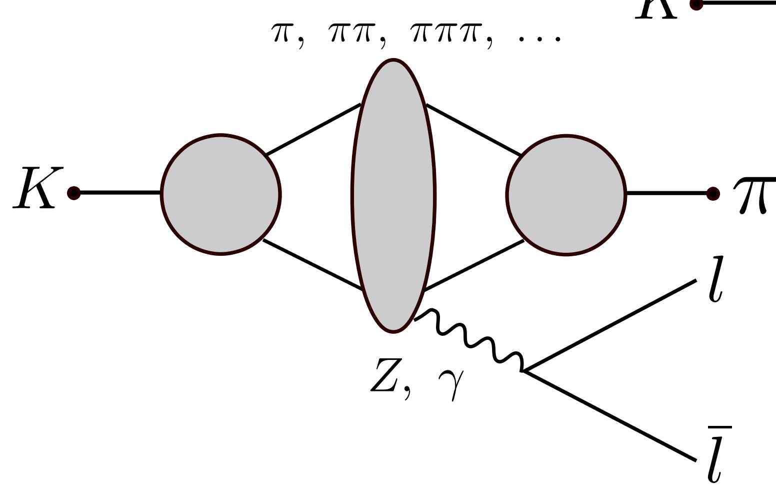
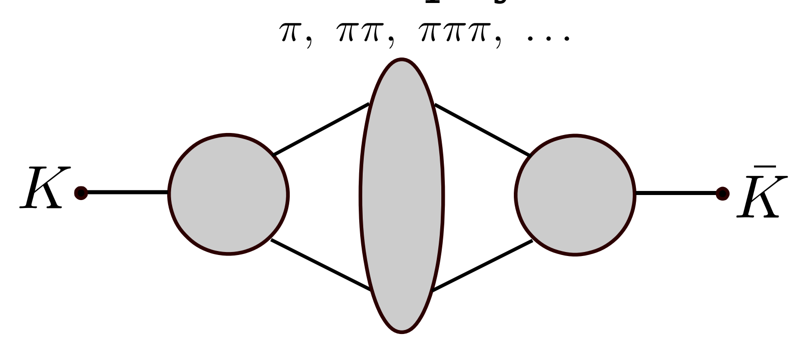
Introduction

- Lattice QCD directly simulates low-energy hadronic interactions on supercomputers.
- Only known *ab initio**, systematically improvable*** technique for studying non-perturbative QCD.
- The simulations have now reached levels of precision with which it can make a significant impact on the search for BSM physics.
- In particular, with recent advances in theoretical and computational techniques, we are now able to directly compute matrix elements involving multi-particle states.
- In this talk we focus upon lattice calculations of kaonic matrix elements relating to quantities that are sensitive to BSM physics:







$K \to \pi\pi$ and ε'/ε

Motivation for studying K→ππ Decays

- Likely explanation for matter/antimatter asymmetry in Universe, baryogenesis, requires violation of CP.
- Amount of CPV in Standard Model appears too low to describe measured M/AM asymmetry: tantalizing hint of new physics.
- Direct CPV first observed in late 90s at CERN (NA31/NA48) and Fermilab (KTeV) in $K^0 \to \pi\pi$:

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}.$$

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \frac{1}{6}\left(1 - \left|\frac{\eta_{00}}{\eta_{\pm}}\right|^2\right) = 16.6(2.3) \times 10^{-4} \quad \text{(experiment)}$$

measure of direct CPV

measure of indirect CPV

- In terms of isospin states: $\Delta I=3/2$ decay to I=2 final state, amplitude A_2
  $\Delta I=1/2$ decay to I=0 final state, amplitude A_0

$$\omega = \mathrm{Re}A_2/\mathrm{Re}A_0$$

$$A(K^0 \to \pi^+\pi^-) = \sqrt{\frac{2}{3}}A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}}A_2 e^{i\delta_2}\,,$$

$$A(K^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}}A_0 e^{i\delta_0} - 2\sqrt{\frac{1}{3}}A_2 e^{i\delta_2}\,.$$

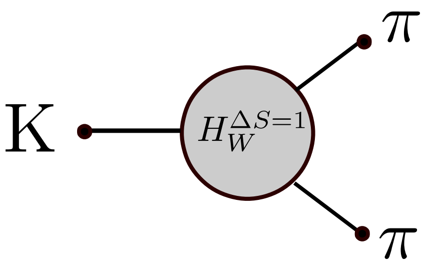
$$\Rightarrow \quad \epsilon' = \frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}}\left(\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right)$$

(δ_I are strong scattering phase shifts.)

- Small size of ε' makes it particularly sensitive to new direct-CPV introduced by most BSM models.

Overview of calculation

- Hadronic energy scale << M_W – use weak effective theory.
- K→ππ decays require single insertion of ΔS=1 Hamiltonian:



10 effective four-quark operators

$$H_W^{\Delta S=1} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} \sum_{j=1}^{10} [z_j(\mu) + \tau y_j(\mu)] Q_j$$

perturbative Wilson coeffs.

$$\tau = -\frac{V_{ts}^* V_{td}}{V_{us}^* V_{ud}} = 0.0014606 + 0.00060408i$$

Imaginary part solely responsible for CPV
(everything else is pure-real)

LL finite-volume correction

renormalization
matrix (mixing)

$$A^I = F \frac{G_F}{\sqrt{2}} V_{ud} V_{us} \sum_{i=1}^{10} \sum_{j=1}^{7} \left[\left(z_i(\mu) + \tau y_i(\mu) \right) Z_{ij}^{\mathrm{lat} \to \overline{\mathrm{MS}}} M_j^{I,\,\mathrm{lat}} \right]$$

$M_j^{I,lat} = \langle (\pi\pi)_I | Q_j | K \rangle$ (lattice)

- Operators must be renormalized into same scheme as Wilson coeffs: Use RI-(S)MOM NPR and perturbatively match to MSbar at high scale.

Key challenges of lattice calculation

- Primary challenge is to assure physical kinematics. Signal dominated by amplitude with 2 stationary pions in final state.

$$2m_\pi \approx 260 \text{ MeV} \ll m_K \approx 500 \text{ MeV}$$

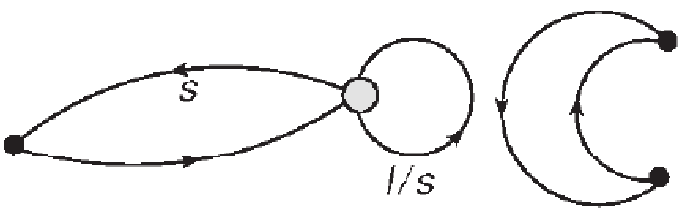
Solution: Remove stationary pion state from system by manipulating lattice spatial boundary conditions.

  - Antiperiodic BCs on down-quark for A_2
  - G-parity BCs on both quarks for A_0

$$p_\pi = 0 \rightarrow \pi/L$$

tune L to match E_K and $E_{\pi\pi}$

- For A_0 serious noise issue due to "disconnected diagrams"



type4

Solution: Use "all-to-all" propagators to tune source to minimize overlap with vacuum and maximize sampling for every configuration.

Summary of RBC/UKQCD calculations

[Phys.Rev. D91 (2015) no.7, 074502]

- A_2 computed on RBC/UKQCD 64^3x128 and 48^3x96 2+1f Mobius DWF ensembles with the Iwasaki gauge action.
- a^{-1}= 2.36 GeV and 1.73 GeV resp - continuum limit taken.
- 10% and 12% total errors on Re(A_2) and Im(A_2) resp.
- Statistical errors sub-percent, dominant systematic errors due to truncation of PT series in computation of renormalization and Wilson coefficients.

[Phys.Rev.Lett. 115 (2015) 21, 212001]

- A_0 computed on 32^3x64 Mobius DWF ensemble with Iwasaki+DSDR gauge action. G-parity BCs in 3 directions to give physical kinematics.
- Single, coarse lattice with a^{-1}= 1.38 GeV but large physical volume to control FV errors.
- 21% and 65% stat errors on Re(A_0) and Im(A_0) due to disconn. diagrams and, for Im(A_0) a strong cancellation between Q_4 and Q_6.
- Dominant, 15% systematic error is due again to PT truncation errors exacerbated by low renormalization scale 1.53 GeV.

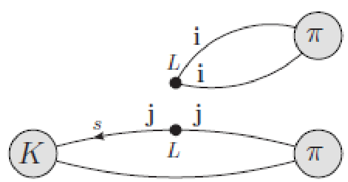
ΔI=1/2 rule

- In experiment kaons approx 450x (!) more likely to decay into I=0 pi-pi states than I=2.

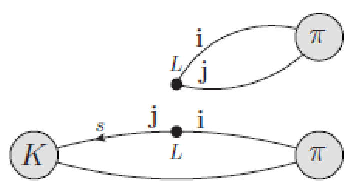
$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \simeq 22.5$$ (the ΔI=1/2 rule)

- Perturbative running to charm scale accounts for about a factor of 2. Is the remaining 10x non-perturbative or New Physics?
- The answer is **low-energy *QCD*!** RBC/UKQCD [arXiv:1212.1474, arXiv:1502.00263]

Strong cancellation between the two dominant contractions



Contraction ①.

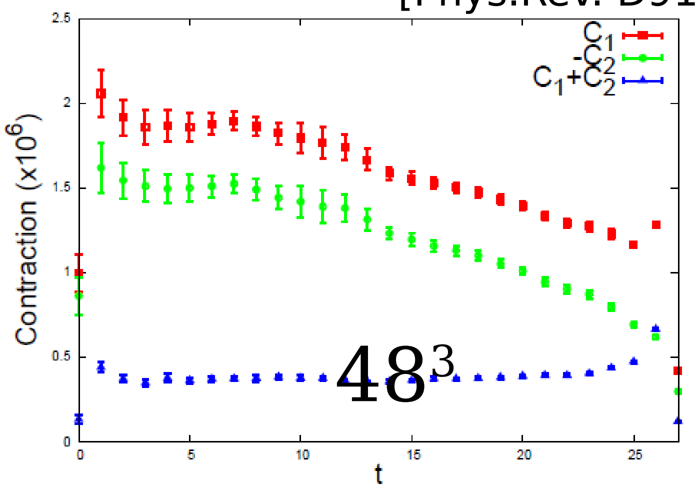


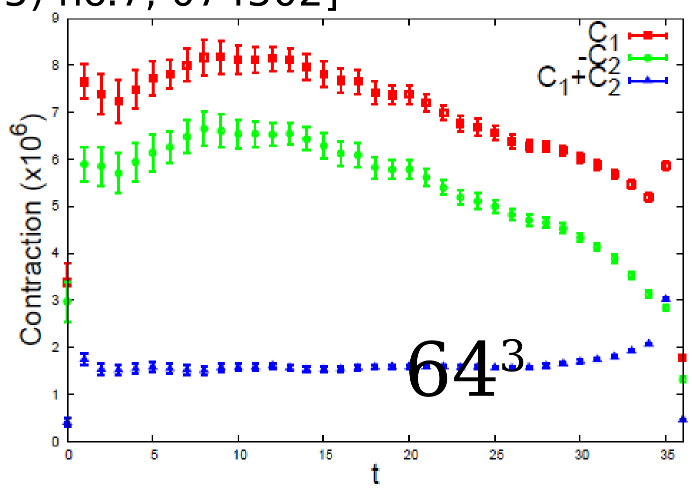
Contraction ②.

$$\mathrm{Re}(A_2) \sim ① + ②$$

find $② \approx -0.7①$ heavily suppressing Re(A_2).

[Phys.Rev. D91 (2015) no.7, 074502]





Pure-lattice calculation

$$\frac{\mathrm{Re}(A_0)}{\mathrm{Re}(A_2)} = 31.1(11.2)$$

[Re(A_0) agrees with expt.]

Results for ε' [Phys.Rev.Lett. 115 (2015) 21, 212001]

- Re(A_0) and Re(A_2) from expt.
- Lattice values for Im(A_0), Im(A_2) and the phase shifts,

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}\mathrm{A}_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

$$= \boxed{\begin{array}{ll} 1.38(5.15)(4.43)\times 10^{-4}, & \text{(this work)} \\ 16.6(2.3)\times 10^{-4} & \text{(experiment)} \end{array}}$$

- Total error on Re(ε'/ε) is ~3x the experimental error.
- Find reasonable consistency with Standard Model (at 2.1σ level).
- Tantalizing hint of discrepancy strong motivation for continued study!

Outlook

- Error is dominated by those on A_0.
- Main priority is to increase statistics on A_0 calculation, enabling improved precision and better sys. error estimation. Aim for 4x increase in stats within ~1 yr.
- Reduce dominant NPR (15%) and Wilson coefficient (12%) systematic error arising from perturbative MSbar matching by increasing renormalization scale. Currently close to completion.
- On longer timescale:
  - Add second lattice spacing and perform continuum limit.
  - Include dynamical charm rather than relying on PT.
  - Investigate (expected %-level) EM and isospin corrections.

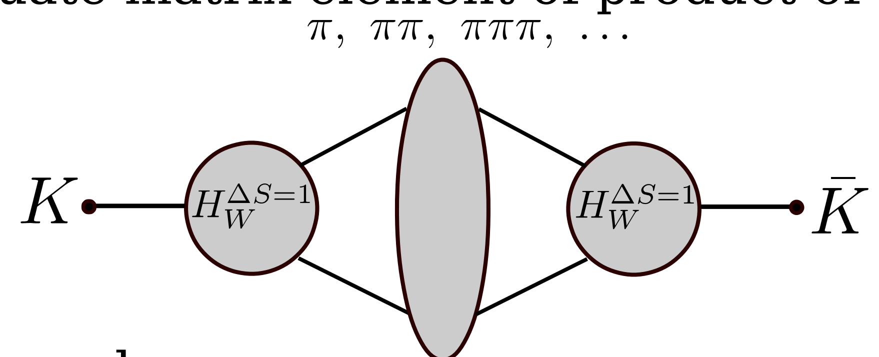
K_L-K_S mass difference

Introduction

- Neglecting small CP-violation effects, mixing of neutral kaons induced by 2nd order weak processes gives rise to mass difference between CP eigenstates $K_1 \sim K_L$ and $K_2 \sim K_S$

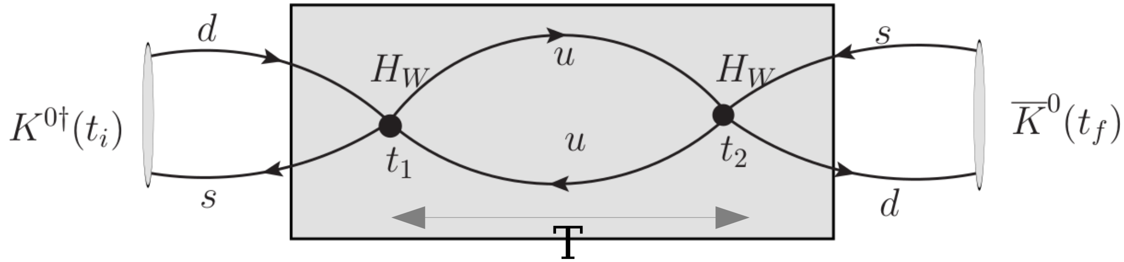
$$\Delta M_K = 2 \sum_n \frac{\langle \overline{K}^0 | H_W | n \rangle \langle n | H_W | K^0 \rangle}{M_K - E_n}$$

- Arises due to FCNC and therefore highly suppressed in SM due to GIM mechanism: $\Delta m_K = 3.483(6) \times 10^{-12}$ MeV small and highly sensitive to new BSM FCNC.
- PT calc using weak EFT with $\Delta S=2$ eff. Hamiltonian (charm integrated out) dominated by $p \sim m_c$: poor PT convergence at charm scale → ~36% PT sys error.
- PT calc neglects long-distance effects arising when 2 weak operators separated by distance $\sim 1/\Lambda_{QCD}$.
- Use lattice to evaluate matrix element of product of $H_W^{\Delta S=1, \text{ eff}}$ directly:



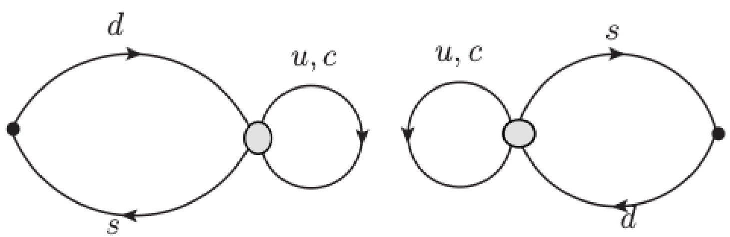
including charm quark.

Key challenges of lattice calculation



$$\mathscr{A} = N_K^2 e^{-M_K(t_f-t_i)} \boxed{\sum_n \frac{\langle \overline{K}^0 | H_W | n \rangle \langle n | H_W | K^0 \rangle}{M_K - E_n}} \left(-T - \frac{1}{M_K - E_n} + \frac{e^{(M_K-E_n)T}}{M_K - E_n} \right)$$

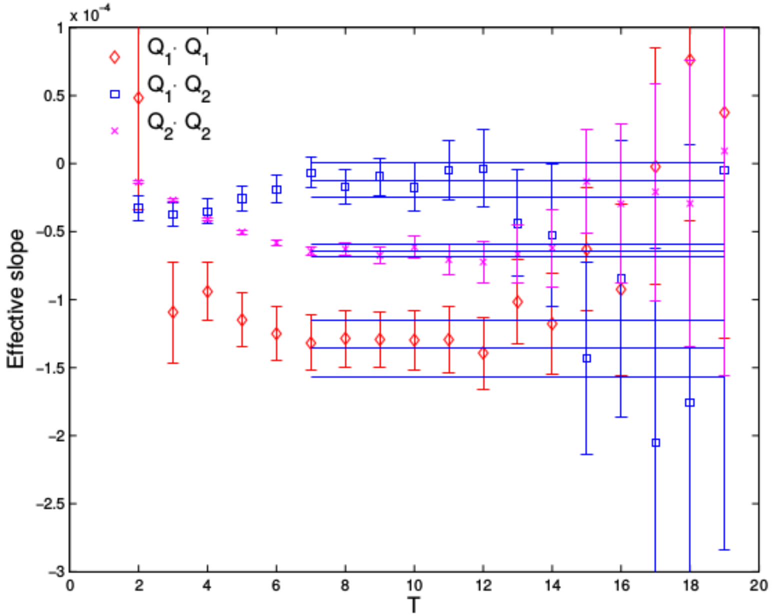
- Vary integration window T to extract desired matrix element.
- Require explicit subtraction of exponentially-growing term when $E_n < m_K$
- Disconnected diagrams make the calculation noisy. Requires large statistics.



- Divergence when operators approach removed by GIM – requires (valence) charm on lattice. Need fine lattice to control discretization errors.
- Finite-volume corrections due to multi-particle intermediate states may be large, requiring explicit Lellouch-Luscher correction.

Calculation status [Phys.Rev.Lett. 113 (2014) 112003]

- Most recent calculation on one 24^3x64 DWF+I lattice with a^{-1}=1.73 GeV.
- Unphysically heavy pions (330 MeV) - no multi-particle intermediate states.
- Unphysically light charm (949 MeV) for controlled discretization error on this somewhat coarse lattice.
- Large statistics (800 configs) with maximal use of each configuration give good signal for disconnected diagrams.



- Disconnected diagram contribution large, appears to violate OZI “rule”.
- Results in good agreement with expt:

lattice

$$\Delta M_K = 3.19(41)(96) \times 10^{-12}\ \mathrm{MeV}$$

experiment

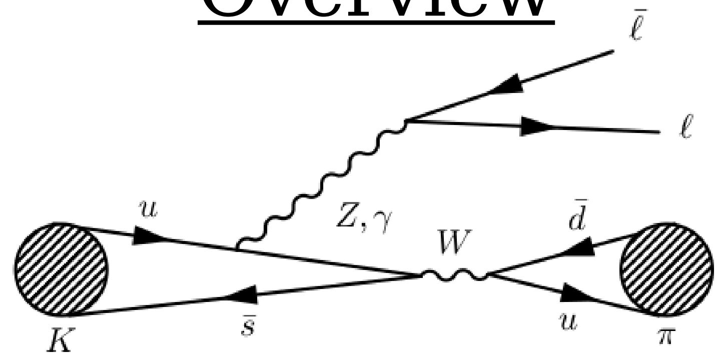
$$3.483(6) \times 10^{-12}\ \mathrm{MeV}$$

- Dominant error expected to be charm disc. effects ~ 30%. Need finer lattices.

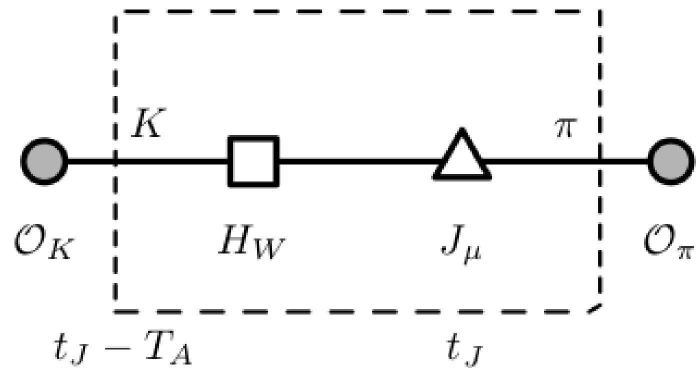
Rare kaon decays $K \to \pi l\bar{l}$

Overview

[arXiv:1507.03094]



- Additional FCNC processes "rare kaon decays": $K^+ \to \pi^+ l^+ l^-$, $K_S \to \pi^0 l^+ l^-$
- Amplitude is long-distance dominated: Compute $K \to \pi\gamma^*$ on lattice.
- Lattice approach very similar to Δm_K but with EM-current insertion:

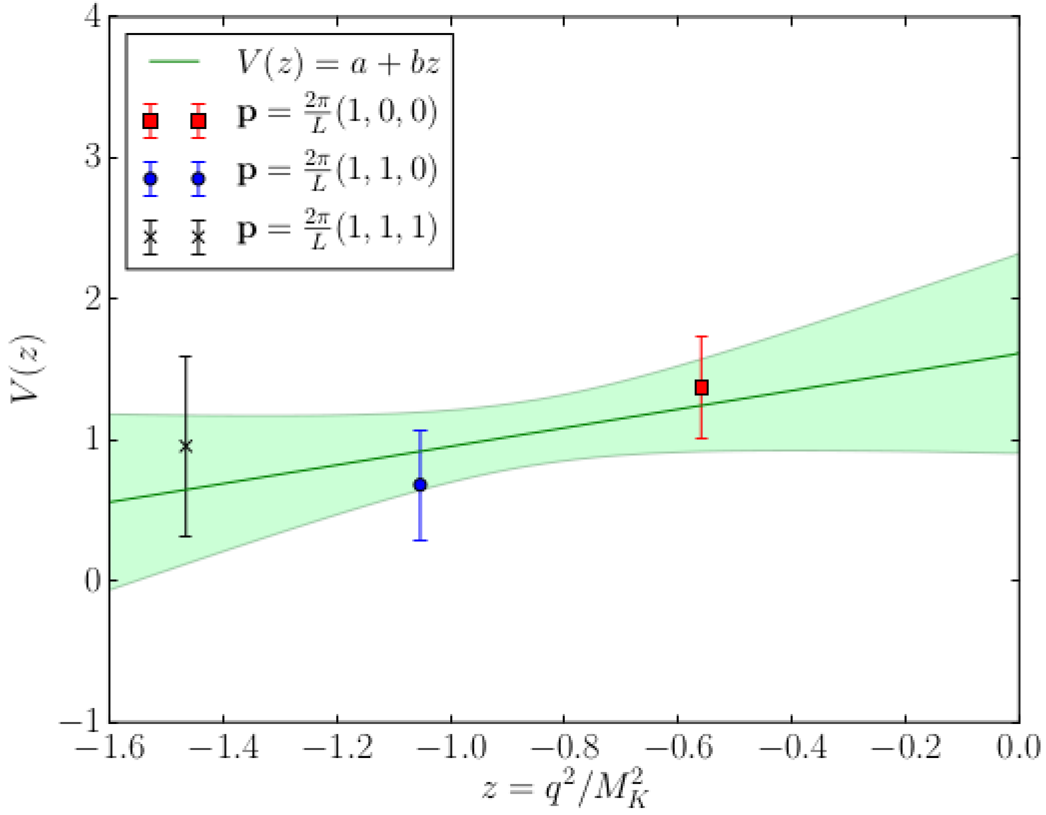


Momentum applied to pion to study dependence

- Unphysical initial calculation presently underway on 24^3x64 ensemble with 430 MeV pions, 620 MeV kaons and m_c~ 533 MeV.
- Multiple pion momenta allow extraction of form factor.

- Preliminary results from Lattice 2016 talk by A.Lawson (July 28th):

$$A_\mu\left(q^2\right) \equiv G_F \frac{V(z)}{(4\pi)^2}\left(q^2 (k+p)_\mu - \left(M_K^2 - M_\pi^2\right) q_\mu\right), \qquad z = q^2/M_K$$

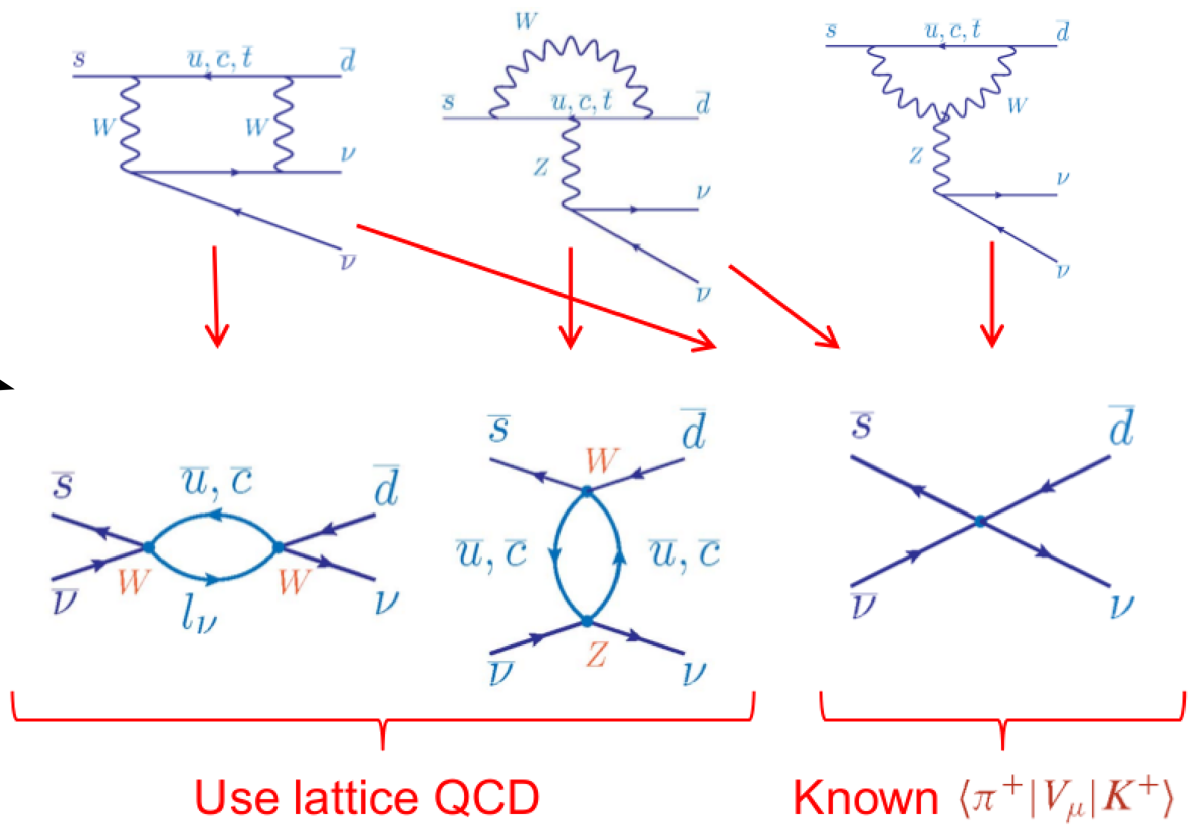


- Future steps are physical pion and kaon masses.
- No statistically significant charm mass dependence observed – is going to physical charm necessary?

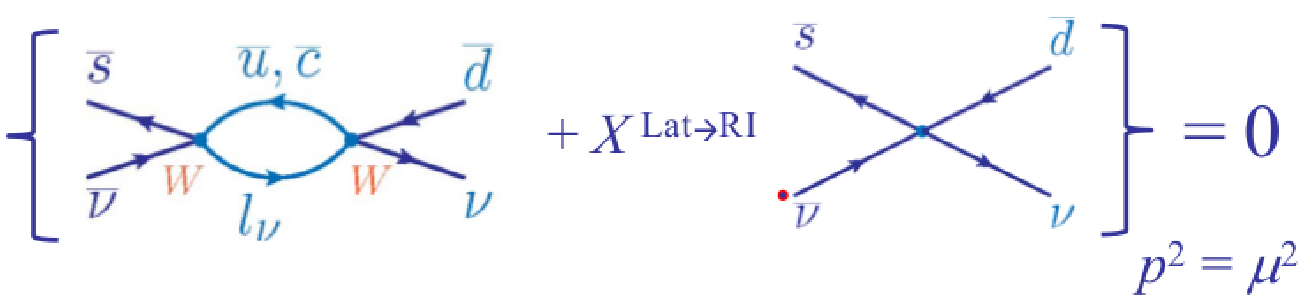
Rare kaon decays $K \to \pi\nu\bar{\nu}$

- Another FCNC thus far not particularly well experimentally measured.
- NA62 expt expected to provide ~10% error on 2-3 yr timescale.
- Short-distance dominated but expect ~5% LD effect: Lattice!
- Again 2x operator insertions:

Effective operators representing both W and Z required

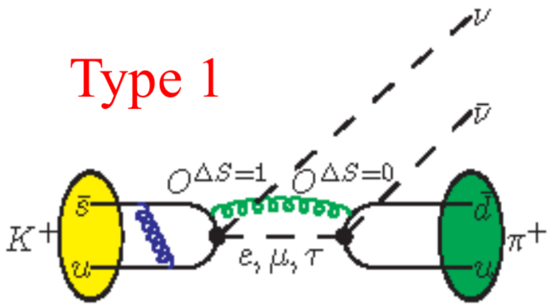


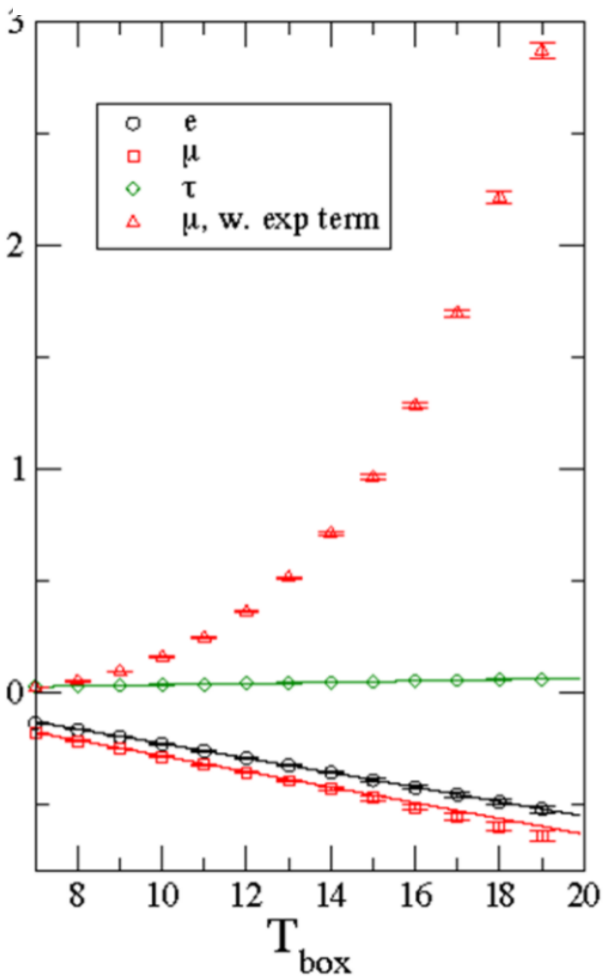
- Short-distance divergence requires NPR “matching” to point operator.



- Exploratory calculation on 16^3x32 a^{-1}=1.73 GeV ensemble complete.
- Unphysical masses similar to previous slides.
- Preliminary results presented by N. Christ at Lattice 2016 (July 28th):

Type 1





- Unphysical kinematics but demonstration of technique:

$$P_C = P_C^{\mathrm{SD}} + \delta P_{cu}$$

total charm contrib.

short-distance part from PT: 0.365(12)

bilocal contrib.

PT $\delta P_{\mathrm{cu}} = 0.040(20)$ [Isodori et al hep-ph/0503107]

$$\Delta P_{cu}(\overline{\mathrm{MS}},\ 2\ \mathrm{GeV}) = -0.007(2) \begin{pmatrix} +7 \\ -11 \end{pmatrix}_{\mathrm{RI}} \begin{pmatrix} +5 \\ -21 \end{pmatrix}_{\overline{\mathrm{MS}}}$$

$$WW:\ -0.032(1)\ +\ Z:\ 0.025(1)$$

- Strong cancellation of WW and Z contribs.
- Wait to observe if situation stays true for more physical kinematics (underway).

Conclusions

- Lattice techniques now sufficiently advanced to significantly impact search for BSM physics.
- RBC & UKQCD collaboration are leading the way in computing experimentally relevant kaonic amplitudes.
- Complete, physical calculation of ε'/ε performed with hint of tension with experiment.
- Lattice calculation demonstrates $\Delta I=1/2$ rule arises due to non-perturbative suppression of $\mathrm{Re}(A_2)$.
- Matrix elements with 2 operator insertions now possible with controlled systematics, particularly finite-volume errors.
- Early results for FCNC suppressed Δm_K and $K \to \pi l \bar{l}$.
- $K \to \pi \nu \bar{\nu}$ long-distance contributions computable by similar technique. Preliminary calculation complete.

We hope that these results will spur the experimental community to improve their determinations, particularly for ε'/ε.