Pion and Kaon form factors using twisted-mass fermions

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Abstract

We present a calculation of the connected contributions to the pion and kaon scalar, vector and tensor form factors. We use an ensemble of $N_f = 2+1+1$ maximally twisted mass fermions with clover improvement, with a pion mass of 260 MeV, and a kaon mass of 530 MeV. The lattice spacing of the ensemble is 0.093 fm and the lattice has a spatial extent of 3 fm. We analyze several values of the source-sink time separation to eliminate excited-states effects. The scalar and tensor form factors are converted to the $\overline{\text{MS}}$ scheme at a scale of 2 GeV. We also address the effect of SU(3) flavor symmetry breaking.

Motivation

- Form factors (FFs) give access to properties describing hadron structure
  - Scalar FFs: exploration of interplay between EHM mechanism and Higgs boson interaction
  - Vector FFs: electromagnetic properties
  - Tensor FFs: useful for beyond the Standard model studies
- An important QCD property is spontaneous chiral symmetry breaking (SCSB)
  - QCD Lagrangian would have full chiral symmetry
  - Would give rise to massless Goldstone bosons (i.e. pions and kaons)
  - Mass difference of pion and kaon: interplay between QCD dynamics and quark-mass effect
- Limited experimental data
  - Pion less studied then the nucleon. Kaon structure is very limitedly studied

Lattice Setup

- Ensemble of N_f = 2 + 1 + 1 twisted mass fermions

Parameters							
Ensemble	β	a [fm]	volume $L^3 \times T$	N_f	m_π [MeV]	Lm_π	L [fm]
cA211.32	1.726	0.093	$32^3 \times 64$	u,d,s,c	260	4	3.0

- Each matrix element decomposes to one form factor (spin-0 mesons) with a normalization $C = 1/\sqrt{4E(p)E(p')}$ and $E(p) = \sqrt{m^2+p^2}$:

$$\langle p'|\mathcal{O}_S|p\rangle = C\, F_S^{M,q},\ \ \langle p'|\mathcal{O}_V^{\mu}|p\rangle = -2i\, C\, P^{\mu}\, F_V^{M,q},\ \ \langle p'|\mathcal{O}_T^{\mu\nu}|p\rangle = i\, C\, \frac{(P^{\mu}\Delta^{\nu} - P^{\nu}\Delta^{\mu})}{m_M} F_T^{M,q}$$

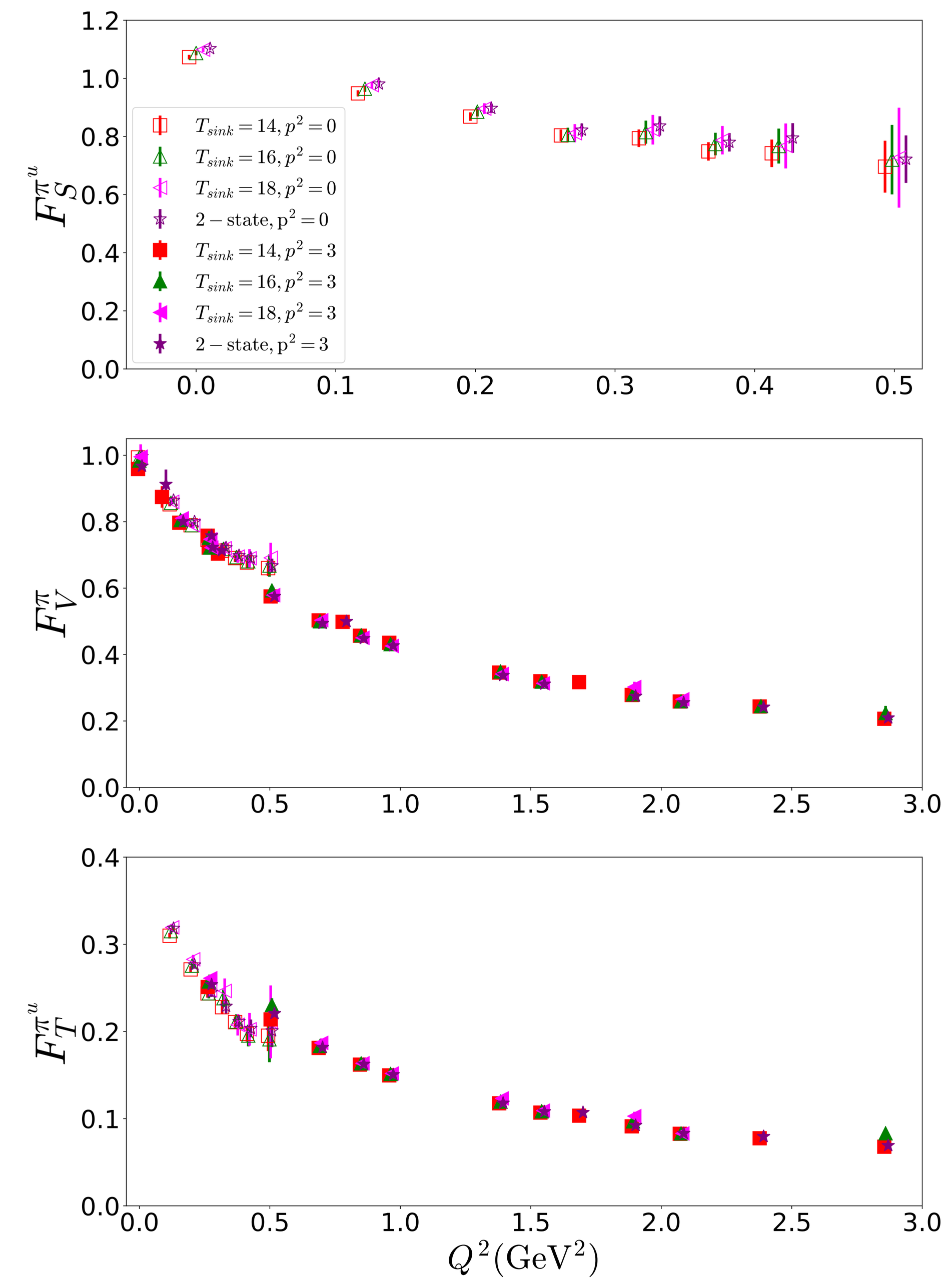
- We explore both rest and boosted frame ($p = 2\pi\mathbf{n}'/L$) for a wide range of Q^2

Statistics					
$\mathbf{n}'$	t_s/a	N_{confs}	N_{src}	$N_{p'}$	Total statistics
(0,0,0)	12, 14, 16, 18, 20, 24	122	16	1	1,952
(±1,±1,±1)	12	122	16	8	15,616
(±1,±1,±1)	14, 16, 18	122	72	8	70,272

- Study of excited-states effects: **plateau fit** (1.12-2.23 fm) and **2-state fit**

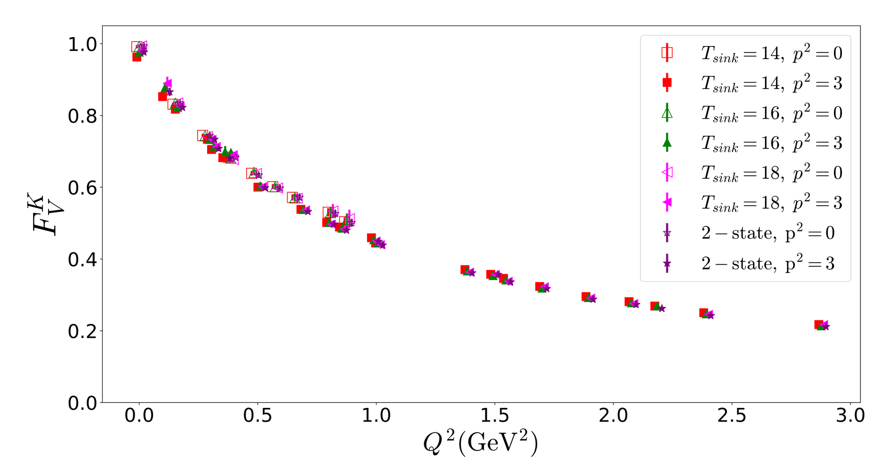
Results

Pion

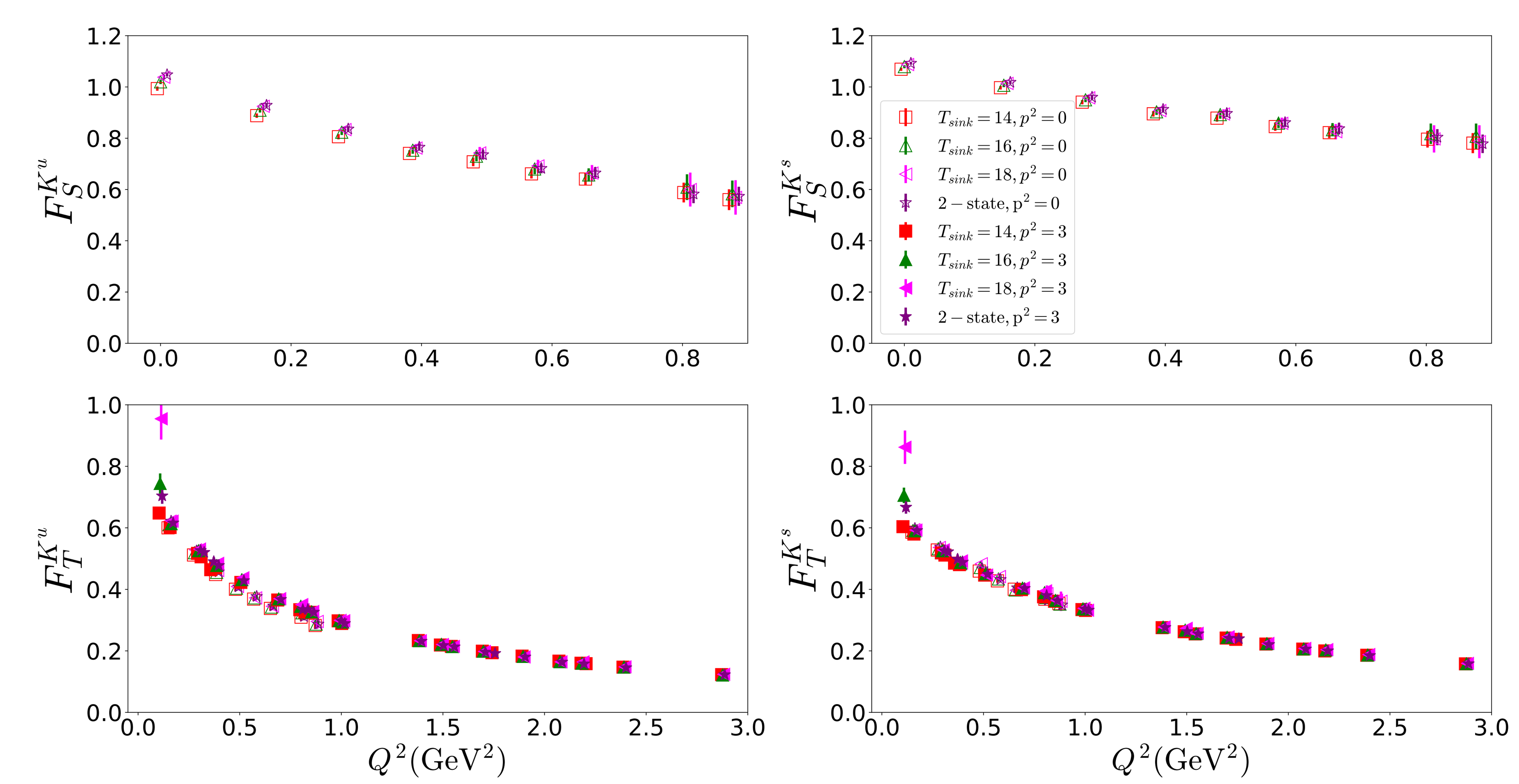


- Rest frame: signal up to 0.5 GeV^2 ($|Q_{\text{max}}|/m_\pi \sim 2.5$)
- Boosted frame: signal up to 3 GeV^2 ($|Q_{\text{max}}|/E_0 \sim 2$)
- FFs in rest and boosted frame compatible
- Scalar FF only in rest frame (increased gauge noise)
- Tensor FF suppressed by quark mass (chirality flip on a quark line)
- Excited states contamination:
  – suppressed for $t_s \geq 1.3$ fm in vector FF
  – scalar and tensor FFs suffer from severe excited states ($t_s \geq 1.7$ fm)
- 2-state fit employed for final results

Kaon



- Similar conclusions for kaon, but signal up to 0.8 GeV^2 in rest frame
- Excited states effects negligible for $Q^2 > 0.2$ GeV^2.
- 2-state fit used for final results



Radii

- Parameterizing the form factors allows extraction of the radius
- 1-parameter or 2-parameter fit for scalar and vector
- $F_T(0)$ not determined from lattice data (vanishing kinematic factor)
- Fits on rest and boosted frame combined

$$F^{\Gamma}(Q^2) = \frac{F^{\Gamma}(0)}{1+\frac{Q^2}{M_\Gamma^2}}, \qquad \langle r^2\rangle^{\Gamma} = -\frac{6}{F^{\Gamma}(0)}\frac{\partial F^{\Gamma}(Q^2)}{\partial Q^2}\bigg|_{Q^2=0} = \frac{6}{M_\Gamma^2}.$$

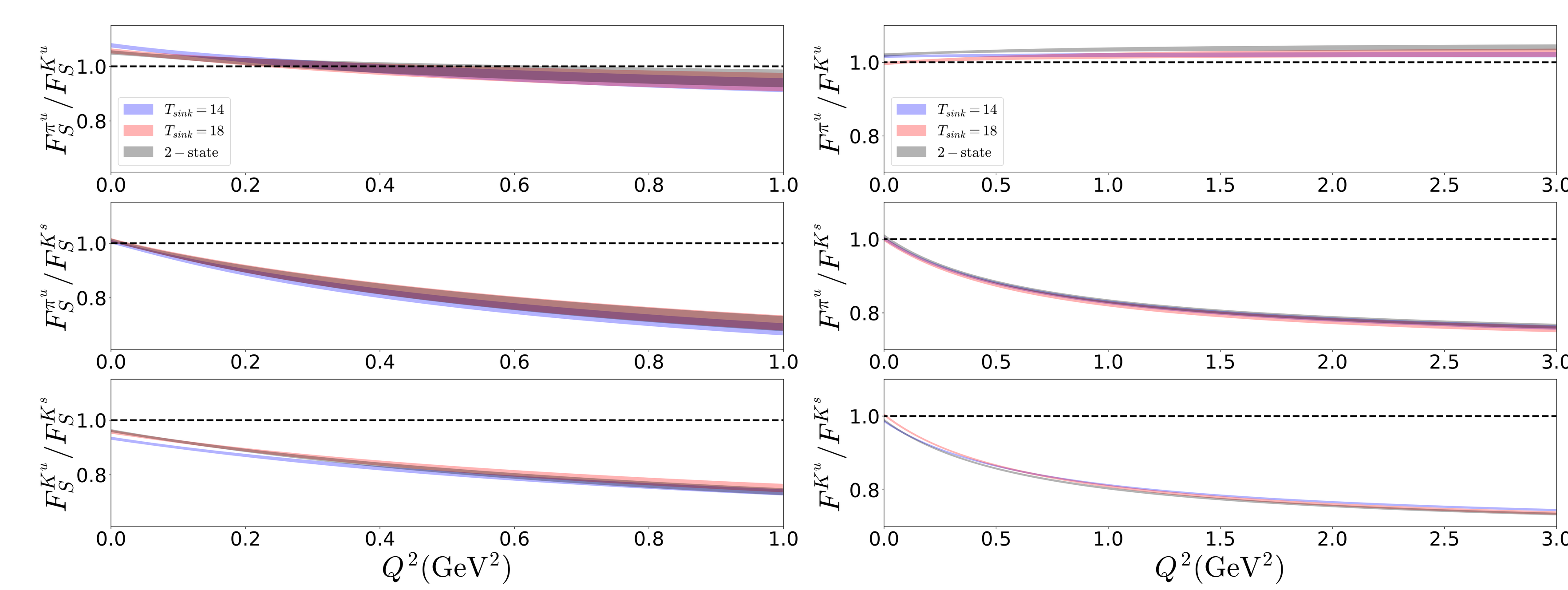
Preliminary

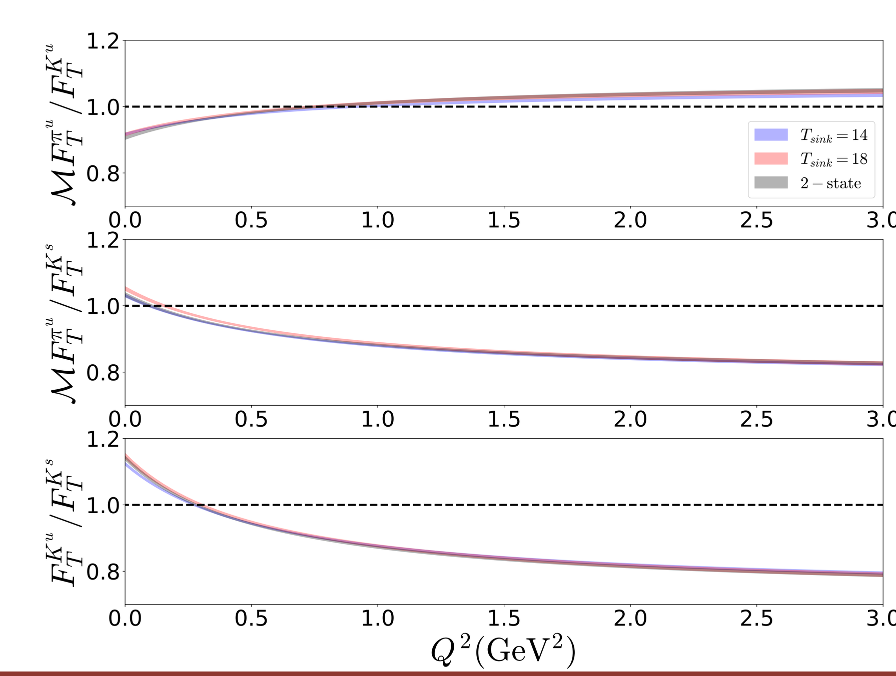
$\langle r^2\rangle^{\pi^u}_{S,1}$ (fm^2)	$\langle r^2\rangle^{\pi^u}_{S,2}$ (fm^2)	$\langle r^2\rangle^{\pi^u}_{V,1}$ (fm^2)	$\langle r^2\rangle^{\pi^u}_{V,2}$ (fm^2)	$\langle r^2\rangle^{\pi^u}_{T,2}$ (fm^2)
0.258(28)	0.258(28)	0.3105(47)	0.3276(54)	0.3533(97)

$\langle r^2\rangle^{K^u}_{S,2}$ (fm^2)	$\langle r^2\rangle^{K^s}_{S,2}$ (fm^2)	$\langle r^2\rangle^{K}_{V,2}$ (fm^2)	$\langle r^2\rangle^{K^u}_{T,2}$ (fm^2)	$\langle r^2\rangle^{K^s}_{T,2}$ (fm^2)
0.196(26)	0.0518(85)	0.2932(47)	0.4217(48)	0.2670(32)

- Results for scalar and vector radius lower than PDG value ($\langle r^2\rangle^{\pi} = 0.434(4)$ fm^2, $\langle r^2\rangle^{K} = 0.314(25)$ fm^2) due to significant pion mass dependence
- Results agree with other lattice data at similar m_π (JLQCD, arXiv:0810.2590)

SU(3) Flavor Symmetry Breaking





- Results from parameterization on 2-state fit (Q^2 different in π and K)
- Tensor FF includes the ratio of the meson masses: $\mathcal{M} \equiv m_K/m_\pi$
- Up-quark contribution in pion and kaon similar in all FFs
- Up-quark contribution in kaon about 80% of strange quark as Q^2 increases

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