Lattice Measurement of the Delta I=1/2 Contribution to Standard Model Direct CP-Violation in $K \to \pi\pi$ Decays at Physical Kinematics: Part II

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Outline

1. Motivation
2. Method
   - Weak matrix elements.
   - Decay amplitude.
3. Current results.
   - $\pi\pi$ phase shift.
   - $K \to \pi\pi(I = 0)$ weak matrix elements, decay amplitude A_0.
4. Conclusion

Motivation

- First ab initio calculation of direct CP-violation (in $K \to \pi\pi$).

  current experiment result: $Re(\epsilon'/\epsilon) = 1.65(26) \times 10^{-3}$

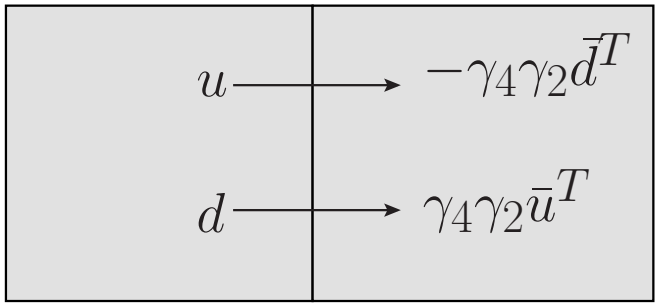
$$\epsilon' = \frac{ie^{i(\delta_2-\delta_0)}}{\sqrt{2}} \frac{ReA_2}{ReA_0} [\frac{ImA_2}{ReA_2} - \frac{ImA_0}{ReA_0}] \tag{1}$$

  current lattice result: Only has $Re(A_2)$ and $Im(A_2)$, both with $< 10\%$ error. (mainly from stat and Wilson coefficients)

  Once we obtain A_0 with $\approx 20\%$ error, could compare ϵ' with experiments.

Weak matrix elements $\langle \pi\pi | Q_i | K \rangle$

- G-parity Boundary introduces even larger numbers of contractions.



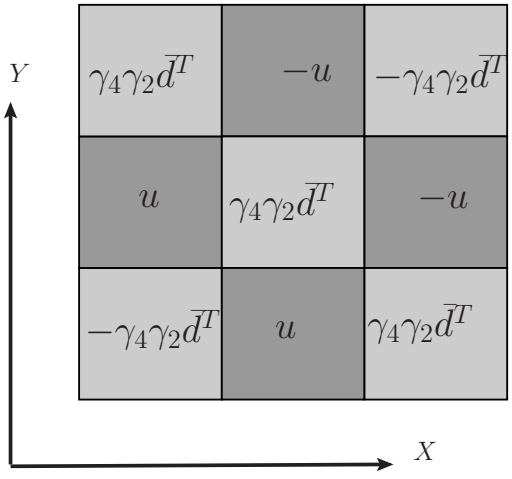
$$\langle \pi\pi \rangle = \bar{u}\gamma_5 d \quad \bar{d}\gamma_5 u + \bar{u}\gamma_5 d \quad \bar{d}\gamma_5 u$$

Not like single pion, the 10 matrix elements $\langle \pi\pi | Q_i | K \rangle$ each contains 256 possible contractions. One has to figure out the linear combination:

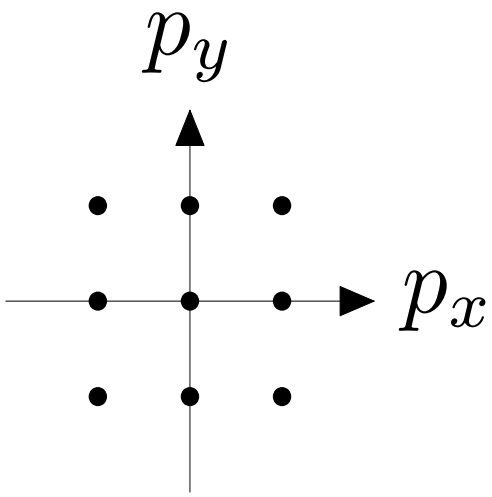
$$\langle \pi\pi | Q_i | K \rangle = \sum_{j=1}^{256} c_{ij} [Contraction_j]$$

Weak matrix elements $\langle \pi\pi | Q_i | K \rangle$

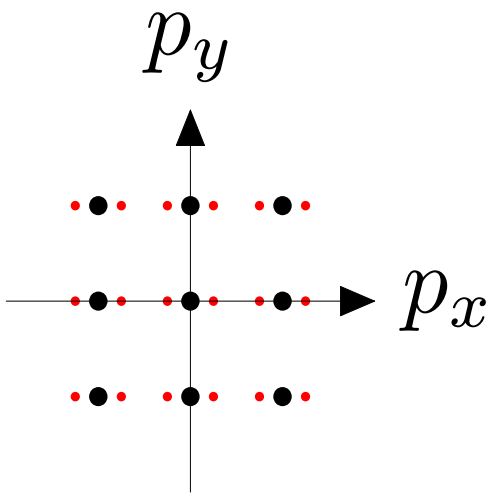
- G-parity boundary introduces subtlety in momentum directions.



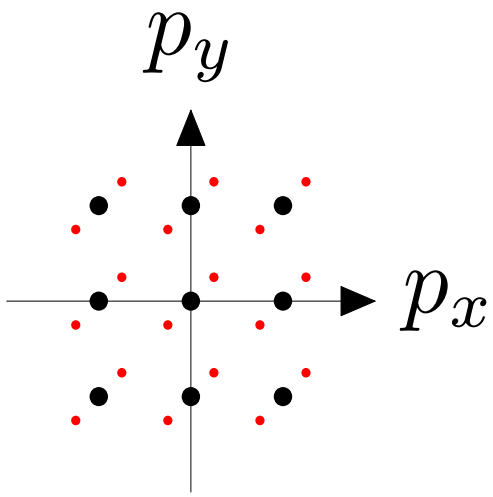
Under G-parity boundary condition, the degrees of freedom doubles in momentum space. Allowed quark momentum are in 'diagonal' direction.



No G-parity twist



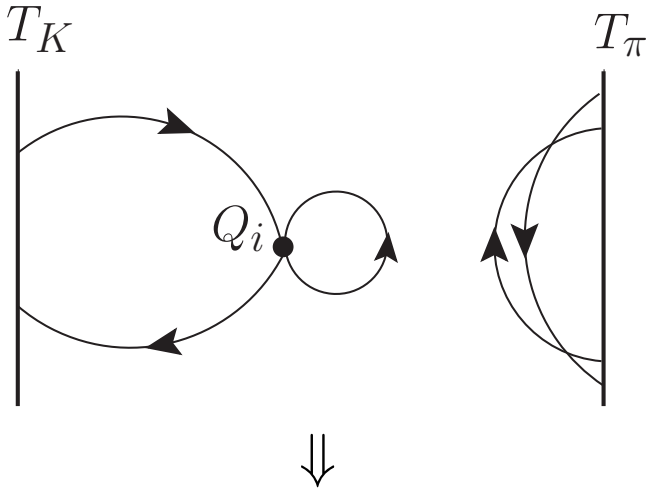
1 G-parity twist



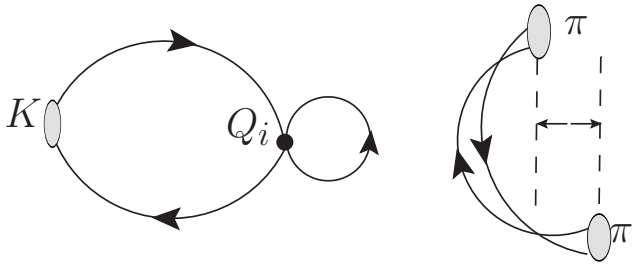
2 G-parity twists

Weak matrix elements $\langle \pi\pi | Q_i | K \rangle$

- Reducing errors from 'disconnected' diagrams.



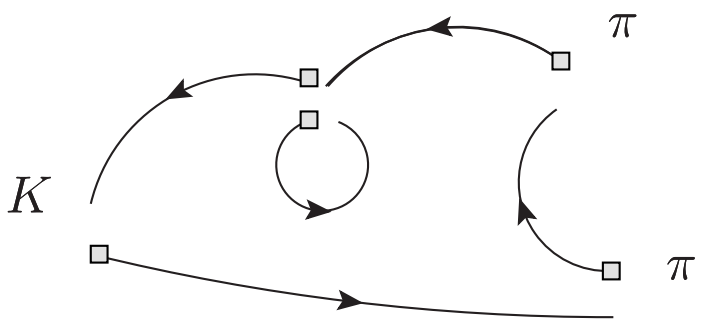
Since the $\pi\pi(I=0)$ state couples with vacuum, the amplitude doesn't decay as separation increases, small fluctuation could result in huge error.



In order to reduce the $\pi\pi(I=0)$ to vacuum coupling, we chose to use the localized meson source, and separate the two pions in time direction.

Weak matrix elements $\langle \pi\pi | Q_i | K \rangle$

- Using localized source (all-to-all propagators).



Shaded boxes are where the random sources have been used.

$$\sum_{\vec{x}_{op}} Tr\{\gamma_\mu(1-\gamma_5)L(\vec{x}_{op}, t_{op}; t_\pi)\gamma_5 L_w(t_\pi; t_{\pi'})\gamma_5 L_w(t_{\pi'}; t_K)\gamma_5$$
$$S(t_K; \vec{x}_{op}, t_{op})\} \cdot Tr\{\gamma^\mu(1-\gamma_5)L(\vec{x}_{op}, t_{op}; \vec{x}_{op}, t_{op})\}$$

$$= \sum_{\vec{x}_{op}} \{{w'}^{m\,\dagger}_{x_{op}} \gamma_\mu(1-\gamma_5) v^i_{x_{op}}\} \cdot \{{w^j_{x_{op}}}^{\dagger} \gamma^\mu(1-\gamma_5) v^j_{x_{op}}\} \cdot \pi^{ik}_{t_\pi} \pi^{kl}_{t'_\pi} K^{lm}_{t_K}$$

The complexity is $(Mode\ Number)^2 \times (Volume) \times (T\ size) \times 144$
Mode number for light quark is 2436, volume is $32^3 \times 64$, T is 64.

From $M_i = \langle \pi\pi | Q_i | K \rangle$ to decay amplitude

Bare M_i on Lattice	
$\Downarrow$	Finite volume correction[1]
M_i in infinite volume	
$\Downarrow$	Lat$\rightarrow$RI/SMOM matching at 1.52GeV[2]
M_i in RI/SMOM scheme	
$\Downarrow$	RI/SMOM$\rightarrow$ $\overline{MS}$ matching at 1.52GeV[3]
M_i in $\overline{MS}$ scheme	
$\Downarrow$	times $\overline{MS}$ Wilson coefficients at 1.52GeV[4]
Decay amplitude A_0	

[1] Laurent Lellouch et al. HEP-LAT/0003023;
[2] C.Sturm et al. ARXIV:0901.2599
[3] Christoph Lehner et al. ARXIV:1104.4948;
[4] Buchalla et al. HEP-PH/9512380;

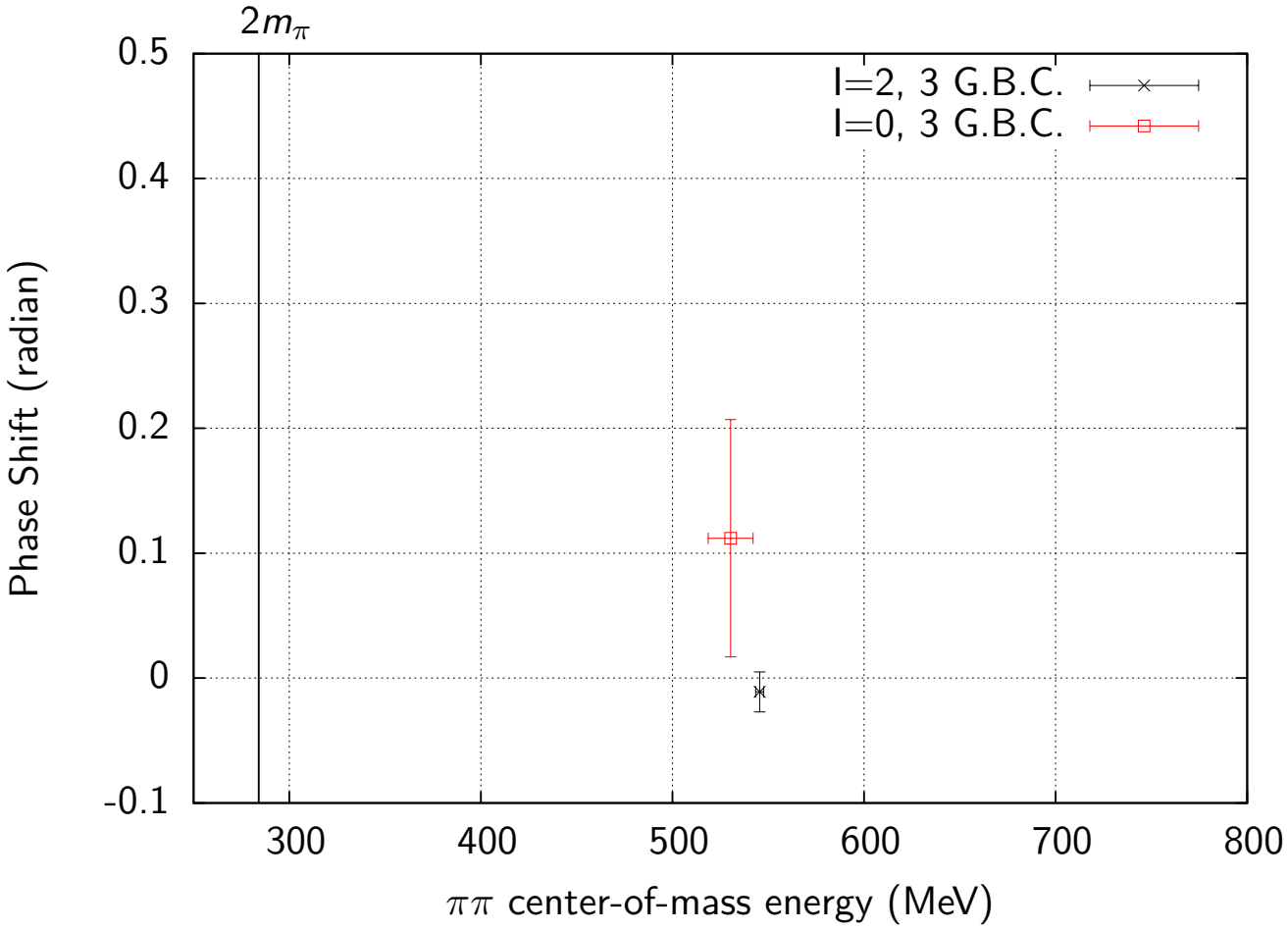
Lattice setup and measurement time

- Used $32^3 \times 64$ lattice, DWF+IDSDR action, $a^{-1} \approx 1.38 GeV$, $(4.6 fm)^3$ box, physical pion and kaon. With G-parity boundary in X,Y,Z directions.
- Measurement time on IBM BG/Q 512-node machine:

	time	flops
Generating eigenmodes	3.6h	22 Gflops/Node
Quark propagator (CG)	7.5h	38 Gflops/Node
Meson field contraction	5h	∼20 Gflops/Node
Total	∼17h	

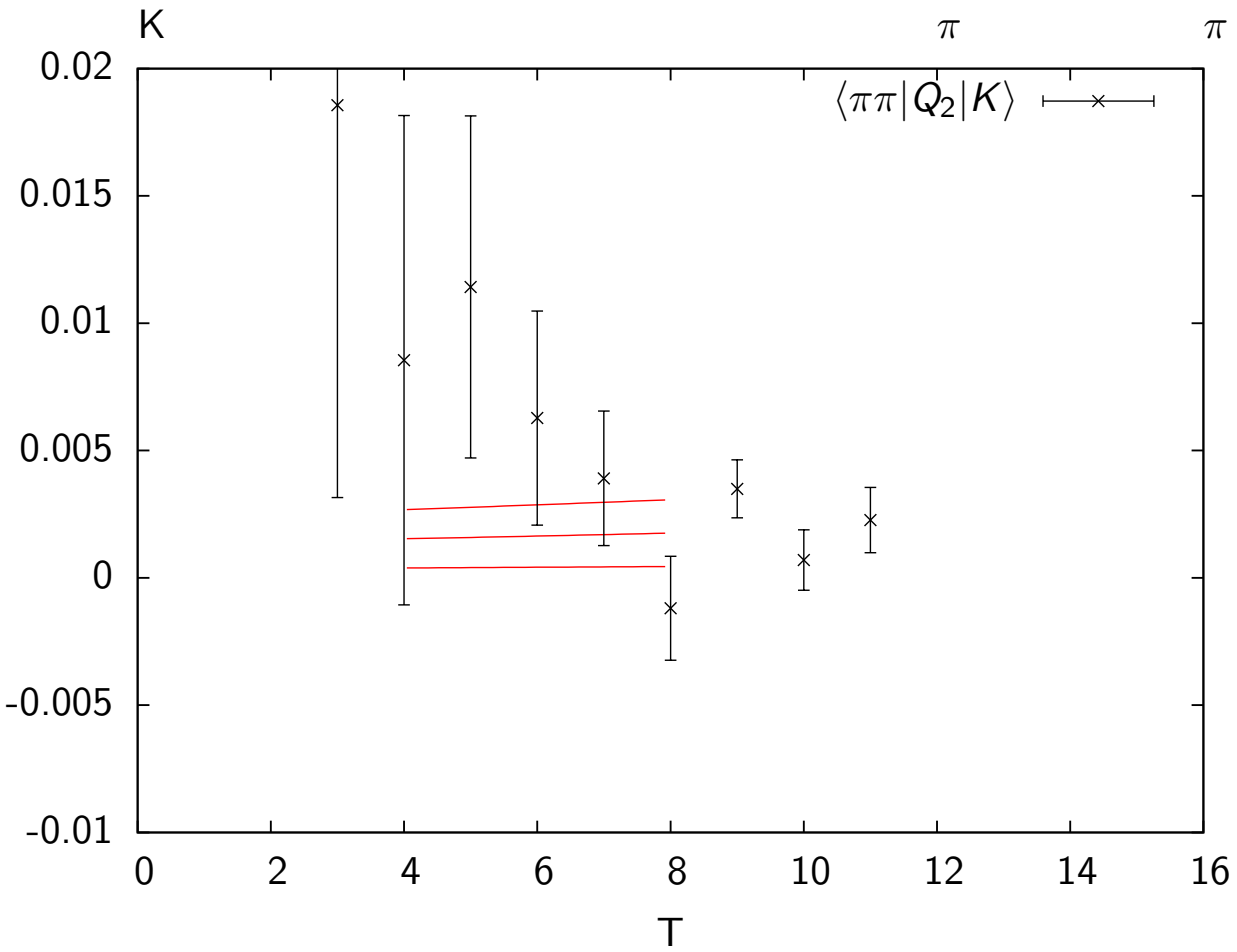
Result: Meson spectrum

	E_π	$\sqrt{E_\pi^2 - p_\pi^2}$	m_K	$E_{\pi\pi(I=0)}$
Lat	0.19834(67)	0.1021(12)	0.35490(32)	0.3888(86)
MeV	273.71(92)	140.9(17)	489.76(44)	537(12)



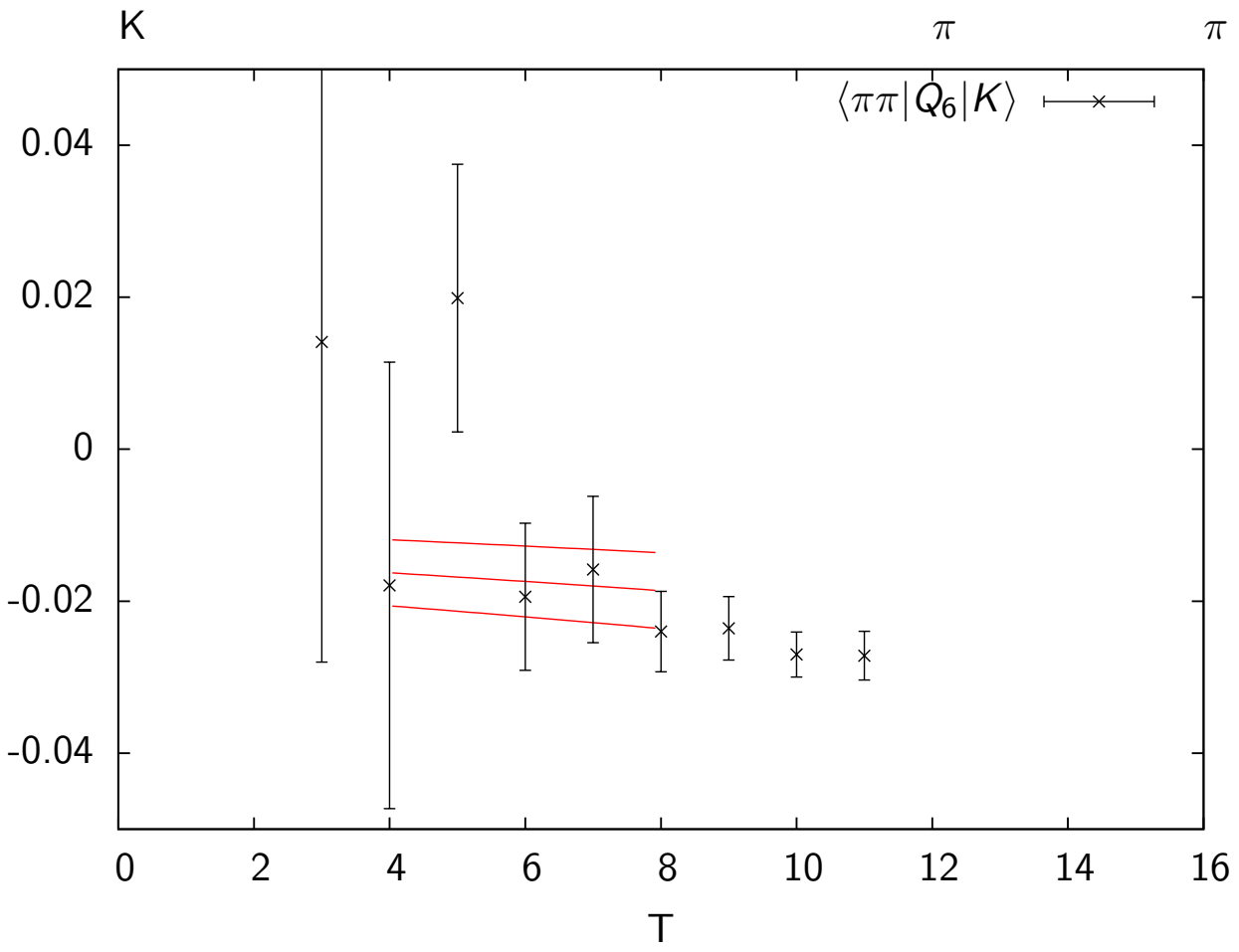
Result: Weak matrix elements and decay amplitude

$\langle \pi\pi | Q_2 | K \rangle = (1.30 \pm 0.96) \times 10^{-3}$, using 50 configurations, fitting from 4 to 8:



Result: Weak matrix elements and decay amplitude

$\langle \pi\pi | Q_6 | K \rangle = (-1.35 \pm 0.37) \times 10^{-2}$, using 50 configurations, fitting from 4 to 8:



Conclusion

- $K \to \pi\pi(I = 0)$ decay amplitude is underway, with physical π, K, and physical kinematics. Estimate 100 more measurements in order to get 50% error for A_0. The measurement will take a few months.
- Future work:
  - estimate lattice artefacts / do the same computation on a finer lattice.
  - Match at higher scale in $\overline{MS}$ scheme / use dynamic charm quark.

Thank you!