Progress in the improved lattice calculation of direct CP-violation in the Standard Model

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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

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

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

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

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

(δ_I are strong scattering phase shifts.)

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

Lattice Calculation

- First calculation performed using 216 configurations of $32^3 \times 64$ Mobius DWF ensemble (L_s=12) with physical pions m_π=143.1(2.0) MeV.

- Iwasaki+DSDR gauge action (β=1.75) ⇨ coarse lattice spacing a^{-1}=1.378(7) GeV but large, 4.6fm box - vital for controlling FV effects.

- Use G-parity boundary conditions (GPBC) in 3 directions to match ππ and kaon energies, ensuring physical interaction without multi-state fits.

- Use Trinity-style all-to-all propagators : 900 exact low-modes (Lanczos) and stochastic approximation to high mode component.

  - ➢ Allows usage of "physical" sources - specifically 1s hydrogen wavefunction with radius 2 - to minimize overlap with vacuum

  - ➢ Maximal sampling of source/sink and operator locations.

- Operators non-perturbatively renormalized using RI-SMOM scheme and matched to MSbar via 1-loop PT.

- Basis includes:

  - ➢ 7 independent dim-6 four-quark operators Q_1'-Q_7'

  - ➢ All relevant dim-3 and dim-4 operators.

  - ➢ The single two-quark dim-6 operator G_1, which mixes at O(α). [NEW]

- Neglecting two other dim-6 operators that mix at O(α^2).

- Neglecting dim-5 chirality-breaking operators that come with coefficient of quark mass and thus expected to be small.

Results for ε'

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

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

$$= 1.38(5.15)(4.43) \times 10^{-4}, \quad \text{(this work)}$$
$$16.6(2.3) \times 10^{-4} \quad \text{(experiment)}$$

- 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!

- Error is dominated by that on A_0.

Our main focuses are therefore to:

- Increase statistics on A_0 calculation, enabling improved precision and better systematic error estimation.

- Reduce dominant systematic errors, particularly NPR and finite lattice spacing.

Statistics increase

- Aim for 4x increase in # of measurements from original 216 by the end of year.

Configuration generation

- Achieve goal by generating multiple independent streams originating from widely separated configurations of original ensemble.

- On 512-nodes of BG/Q using the highly-tuned CPS/BFM/Bagel libraries we could formerly generate 1 trajectory every 7.7 hours.

- Time is large due to 2x from GPBC Dirac op being explicitly 2-flavor, plus additional slowdown caused by necessity to use RHMC to take root of light-quark $M^{\dagger}M$ determinant to obtain 2f action.

- We have implemented and improved TWQCD's "exact one-flavor action", a formulation of DWF that reproduces 1f determinant (2f with GPBC) without rooting. [Y-C Chen, T-W Chiu, arXiv:1403.1683]   [D.J. Murphy arXiv:1611.00298]

- Achieved 4.2x speed-up of 32^3 evolution by combining EOFA with mixed-precision CG and multiple Hasenbusch splittings now possible due to decreased linalg overheads $\Rightarrow$ 1.8 hours per trajectory on 512-nodes BG/Q!

[cf. D.Murphy's talk, Tuesday]

- Autocorrelation length $\lesssim 4$ MD time units, choose 4 as separation between indep. configs.

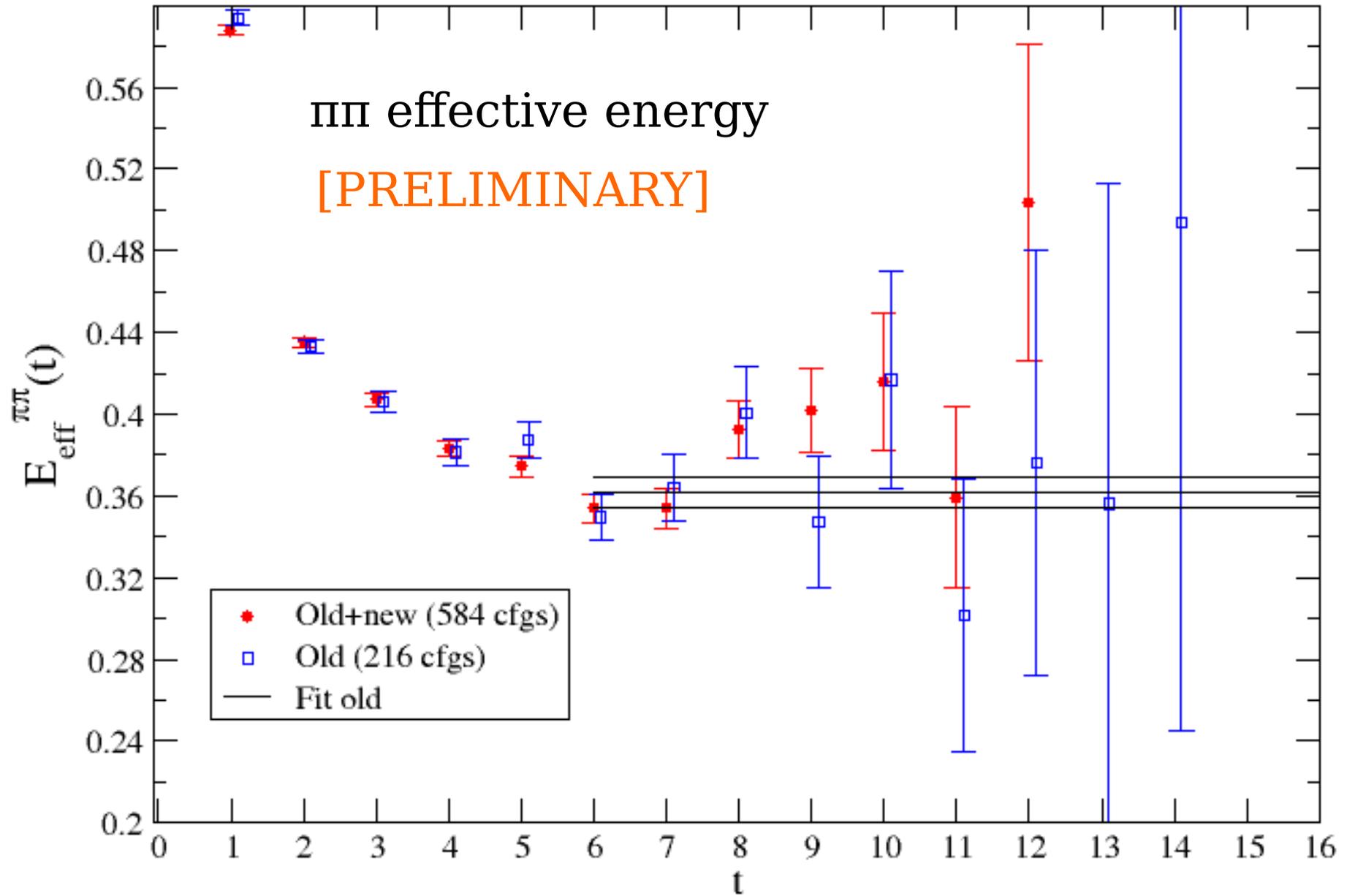- Allow 20 trajectories (~5x autocorrelation length) to ensure streams independent from origin configuration.

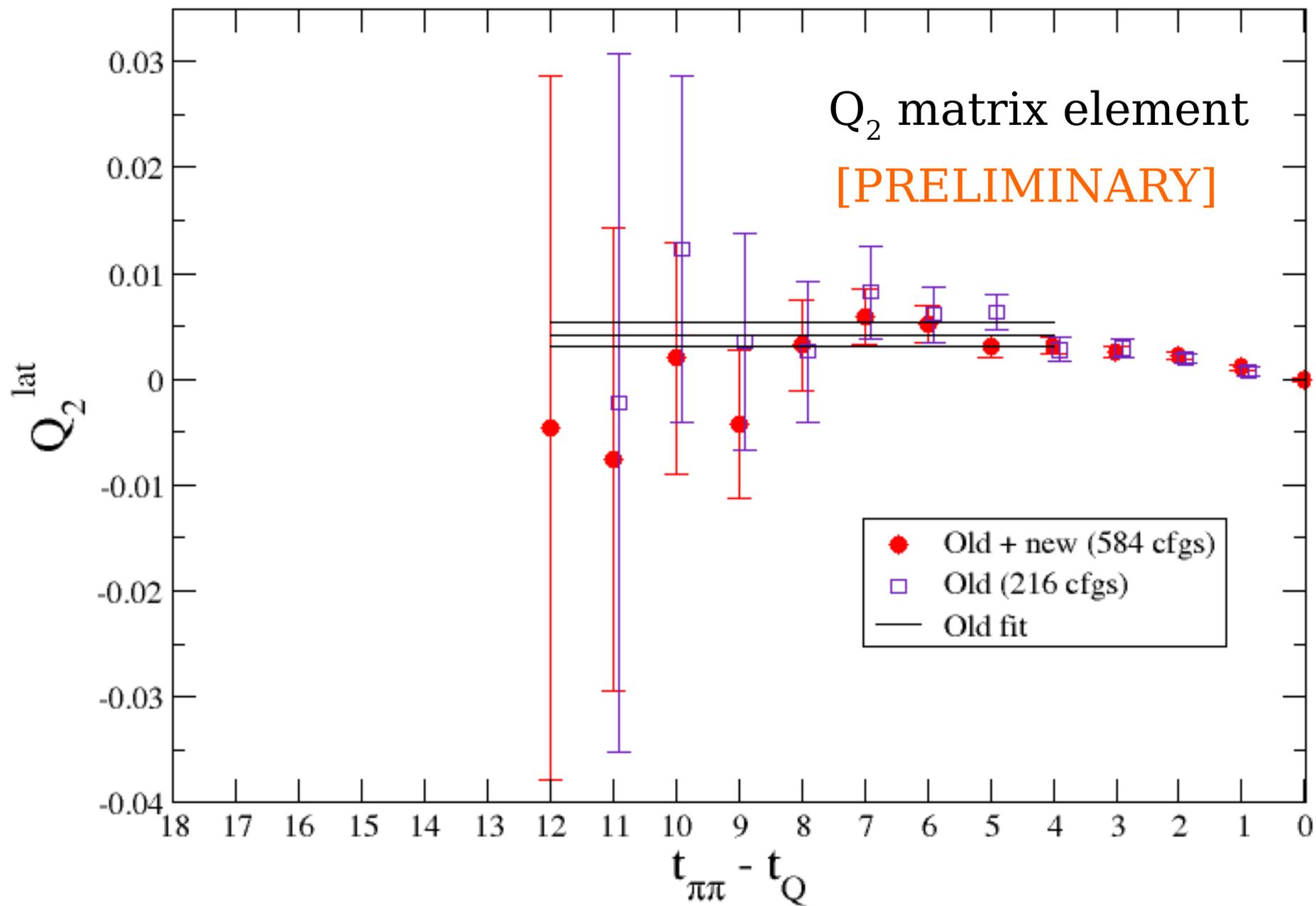| Source	Determinant computation	Trajectories	Independent configs.
Blue Waters	RHMC	116+69+37+32	24+12+4+3
KEKSC	RHMC	441	105
BNL	RHMC	854	208
DiRAC	RHMC	309	72
KEKSC	EOFA	557+344	134+81
BNL	EOFA	871	212
Mira	EOFA	157	34
			889 total

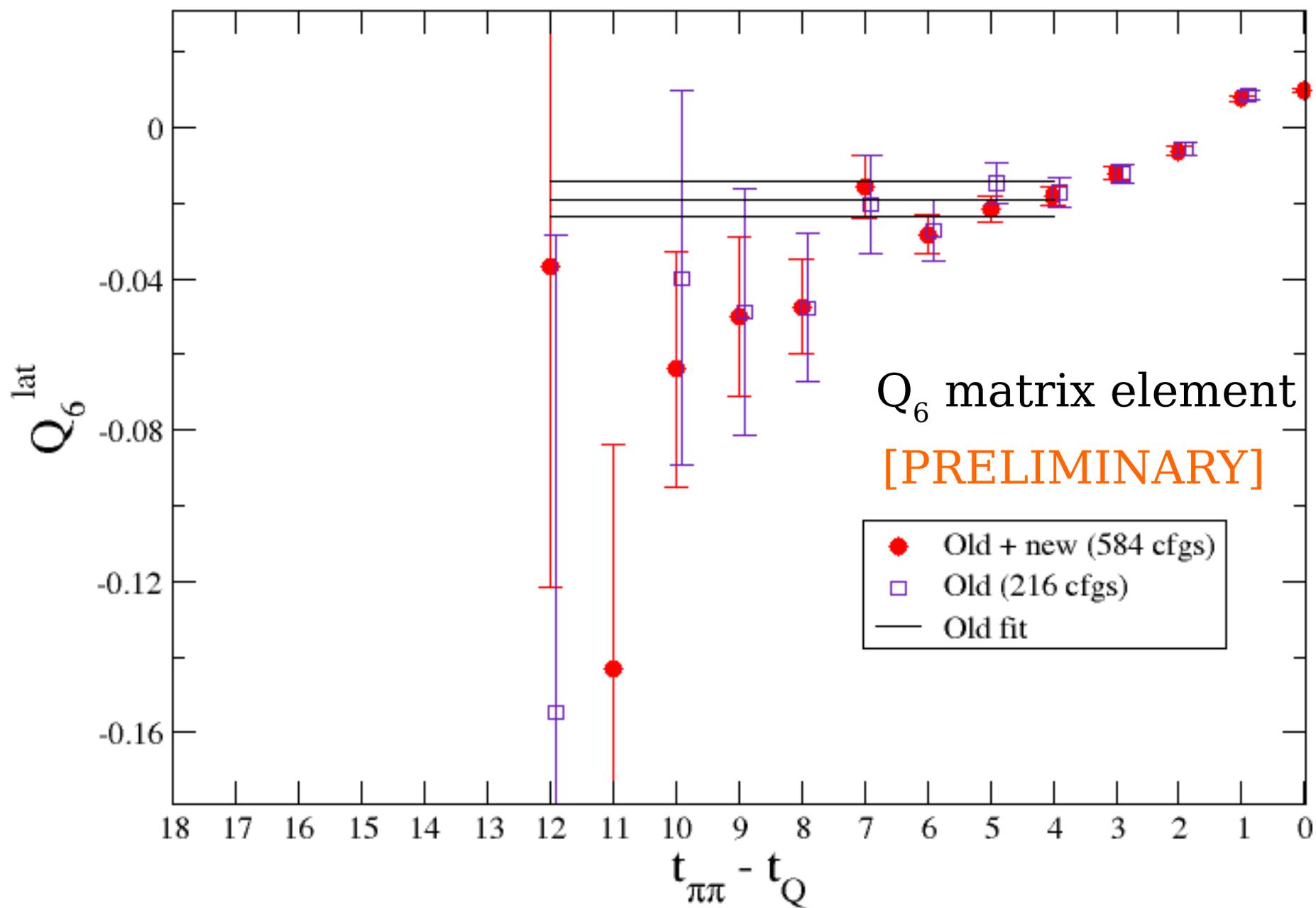- Very close to achieving goal of 4x increase (surpassed if include original data).

Measurements

- Since publication we have completely re-implemented and substantially improved performance of CPS measurement code.

- Can run with BFM/Bagel for optimal BG/Q performance and now also with Grid for high performance on modern SIMD machines (Intel KNL [AVX512], Cray XC40 [AVX2]) for Lanczos and CG.

- Contraction code performance improvements include:

  ➢ SIMD lattice decomposition of A2A vectors, particularly important for AVX512.
  ➢ Hand-coded AVX512 assembly kernel for "meson field" contraction, achieving 400+ Gflops/node on KNL.
  ➢ Optimized work distribution over nodes and threads of matrix operations, hook-ins for performant matrix algebra libraries (MKL, ATLAS).
  ➢ Optimized parallel FFT.
  ➢ Flexible structure allowing easy adaptation to memory constraints (v. important for BG/Q).
  ➢ Large programme of general optimization.

- Measurements being performed on
  Cori II (Intel KNL + Cray Aries "Dragonfly" network),
  Cori I (Cray XC40 + Aries),
  BNL SDCC (Intel KNL + dual-rail Omnipath)
  IBM BG/Q

- 352 new measurements produced thus far! (06/07)

Q_2 matrix element

[PRELIMINARY]

Q_6 matrix element

[PRELIMINARY]

Old + new (584 cfgs)
Old (216 cfgs)
Old fit

Systematic error improvements

Description	Error	Description	Error
Finite lattice spacing	12%	Finite volume	7%
Wilson coefficients	12%	Excited states	$\leq 5\%$
Parametric errors	5%	Operator renormalization	15%
Unphysical kinematics	$\leq 3\%$	Lellouch-Lüscher factor	11%
Total (added in quadrature)			27%

[RBC&UKQCD PRL 115 (2015) 21, 212001]

NPR+Wilson Coefficients

- NPR error large due to use of 1-loop PT to match to MSbar at low, 1.53 GeV renormalization scale.

- Previously reported NPR error 12% → 8% (preliminary) by increasing scale to 2.29 GeV using step-scaling procedure. [CK, Lattice 2016]

- Inclusion of G_1 operator which mixes with Q_i, effects demonstrated to be percent-scale as expected. [G. McGlynn arxiv:1605.08807] [CK, Lattice 2016]

- Do not expect significant improvement in Wilson coeffs. error as dominated by use of PT to cross the charm threshold (1.29 GeV).

- Working on circumventing this by computing 3→4 flavor matching non-perturbatively.
  [M. Tomii @ Columbia]

- Requires $\mu \ll m_c$. At these low energies, MOM-scheme NPR severely hampered by increased mixing with tower of gauge-noninvariant operators.

- Circumvent using position-space NPR which does not require gauge fixing.

Finite lattice-spacing errors

- Currently have results only on single lattice with coarse lattice spacing $a^{-1}=1.38(1)$ GeV.

- Finite-lattice spacing errors estimated by comparing A_2 results on near-identical (non-Gparity) lattice to our continuum results.

- Fine lattice spacing repeat of A_0 calculation unfeasible with current gen. hardware. Instead consider a **coarser** lattice.

- For other applications we have generated an ensemble with the following parameters (without Gparity) that is an ideal candidate:

  [cf. R. Mawhinney's talk, Tuesday]

  - $24^3 \times 64$ Ls=24 Mobius DWF + IDSDR ensemble

  - $\beta = 1.633 \Rightarrow a^{-1} \sim 1.0$ GeV

  - 4.7fm box almost identical to size of 32^3 lattice : GPBC in 3 dirs (may need slight tuning in β).

  - Physical pion mass ~ 140 MeV

- Strong evidence from large number of observables and ensembles that DSDR action scales extremely well - observed scaling errors O(2%) for f_π, w_0 etc on 1 GeV ensemble.

- Will begin tuning a corresponding ensemble with G-parity BCs shortly.

Resolving the pi-pi puzzle

- Our result for I=0 pi-pi scattering phase shift $\delta_0=23.8(4.9)(1.2)^{\circ}$ lower than the value of $38.3(1.3)^{\circ}$ obtained by combining expt. data with Roy Equations

  [RBC&UKQCD PRL 115 (2015) 21, 212001] [G.Colangelo, priv. comm.]

- Matching pheno. requires $E_{\pi\pi} \sim 470$ MeV vs. our 498(11) MeV.

- Possibility of nearby excited state unresolvable from ground-state pi-pi. (The presence of such a pair of states would also be inconsistent with pheno.)

- To address and to improve fitting in general, have expanded measurement programme, introducing new operators that also couple to I=0 pi-pi:

  - Added scalar bilinear (σ-meson) operator. In continuum σ is resonant state of the I=0 pi-pi system. In finite-volume is a stable state that mixes with pi-pi.

  - σ-σ, σ-ππ matrix elements with a number of operator choices soon to be included in fits.

  - Alongside 1s hydrogen-wavefunction pion source smearing, have added 2s form. Alternative coupling to radial excited states of pion and sigma.

- Combining these new handles on the pi-pi state and modern multi-operator methods such as GEVP will allow us to obtain the finite-volume spectrum in more detail.

  [T. Wang @ Columbia]

Related projects on the horizon:

- Performing calculation taking advantage of modern multi-operator techniques to fit excited-state ππ contributions directly, without G-parity BCs.

  [Blum, Hoying @ UConn]

- Laying the groundwork for non-perturbatively computing the effects of isospin breaking and electromagnetism.

  [cf. N. Christ's talk, earlier today]

- Study of complete, non-perturbative calculation of Wilson coefficients

  [cf. M. Bruno, Friday 17:30]

Conclusions and outlook

- Substantial progress made towards 4x increase in statistics combining large-scale running with algorithmic and computational improvements.

- A number of complementary projects intending to reduce systematic errors and/or support this work:

  - Many new pi-pi operators to improve energy and phase-shift determination and resolve apparent discrepancy with phenomenological result.

  - Step-scaling from 1.53 GeV to 2.29 GeV decreases renormalization systematic by ~35%. Considering taking this further.

  - Inclusion of G_1 operator in NPR.

  - Attempt calculation of 3f → 4f matching using position-space NPR.

  - Second lattice spacing with coarser, a^{-1}=1 GeV to enable continuum limit.

  - Independent calculation using periodic BCs and high-statistics alongside modern multi-operator methods.

  - Investigation into future determination of EM and isospin-breaking effects.

- We aim to publish new results by the end of 2017.

Thank you