Current Physics Projects by JLQCD

Jun Noaki

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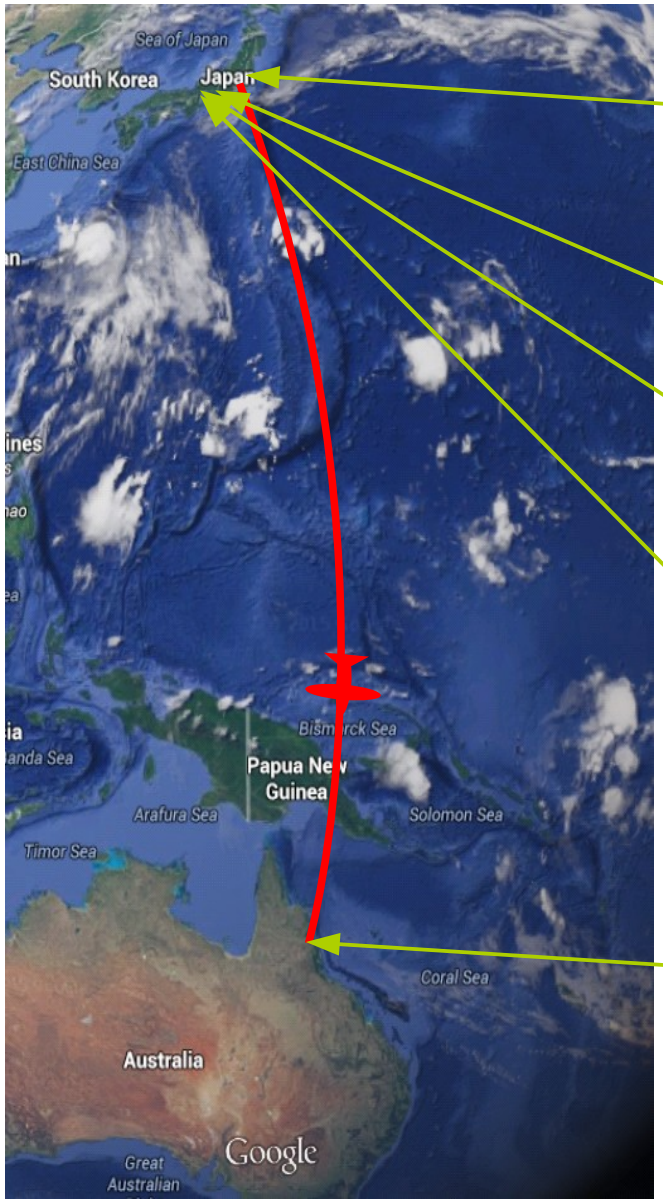
for JLQCD Collaboration

Lattice Hadron Physics V, Cairns July 20—24, 2015

Geography



JLQCD members (as of Jul. 2015)

Tsukuba (KEK) :
G. Cossu, B. Fahy, S. Hashimoto, T. Kaneko, K. Nakayama, J. Noaki, M. Tomii, Y-G. Cho (TITEC), N. Yamanaka (RIKEN)

Kyoto (YITP): S. Aoki

Osaka Univ.: H. Fukaya, T. Onogi, T. Suzuki, A. Tomiya

Kobe: LATTICE2015 venue

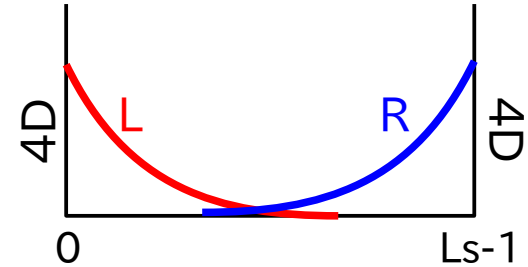
JST = GMT +9

Cairns GMT +10

Flavor physics w/ GW fermions

- NP search by high luminosity frontier experiments
  - heavy flavor (B,D) decays
  - theoretical studies at high-precision → lattice QCD
- Matrix elements (decay consts.,form factors etc) by N_f = 2+1 lattice QCD
  - good chiral symmetry → (Möbius) DW fermions RBC Collab., 1998-
    - control of chiral extrapolation
    - suppression of operator mixing
  - continuum extrapolation in the fine (a < 0.1 fm) region
    - accommodate relativistic heavy quarks
  - light sea quarks (m_π= 500, 400, 300 MeV and lighter)
  - lattice volume satisfying $m_\pi L$ > 4
  - rather multipurpose configs

(Möbuis) Domain-Wall fermions



- Defined in 5D lattice (V x L_s) to separate L/R modes

  Kaplan 1992; Shamir 1994; Borici 1997; Chiu 1998; Brower et al. 2001

  - 5D → 4D effective op ≈ Ginsparg-Wilson op

$$D^{(4)}_{DW}(m) = \left[\mathcal{P}^{-1} D^{(5)}_{DW}(m=1)^{-1} D^{(5)}_{DW}(m)\mathcal{P}\right]_{11}$$

$\mathcal{P}$: 5D projection

$$(L_s \to \infty) \to \frac{1+m}{2} + \frac{1-m}{2}\gamma_5 \cdot \mathrm{sign}\left(\gamma_5 \frac{bD_W(-M)}{2+cD_W(-M)}\right)$$

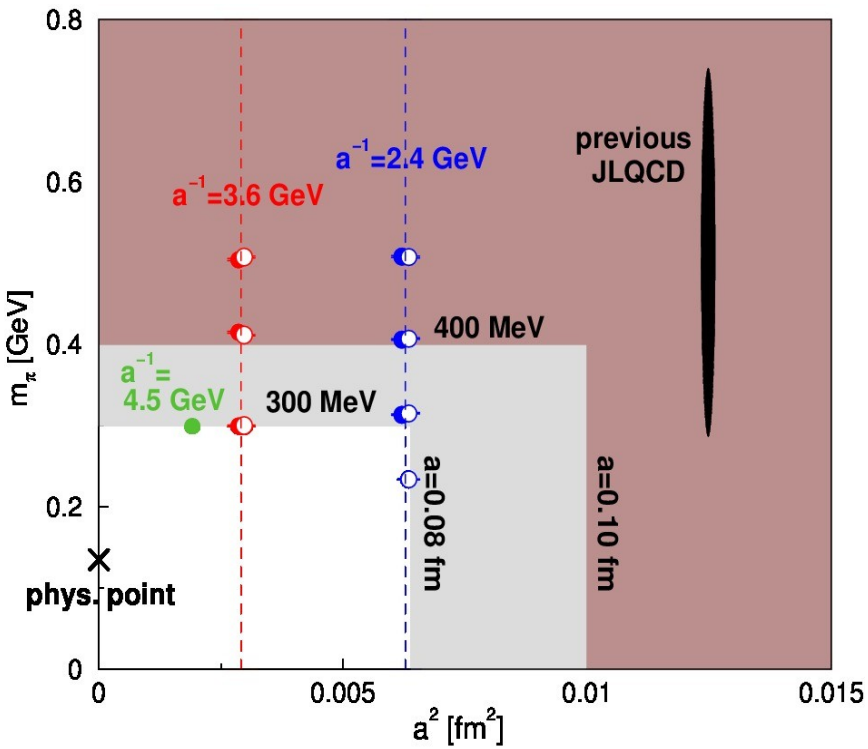
M, b, c : tunable parameter

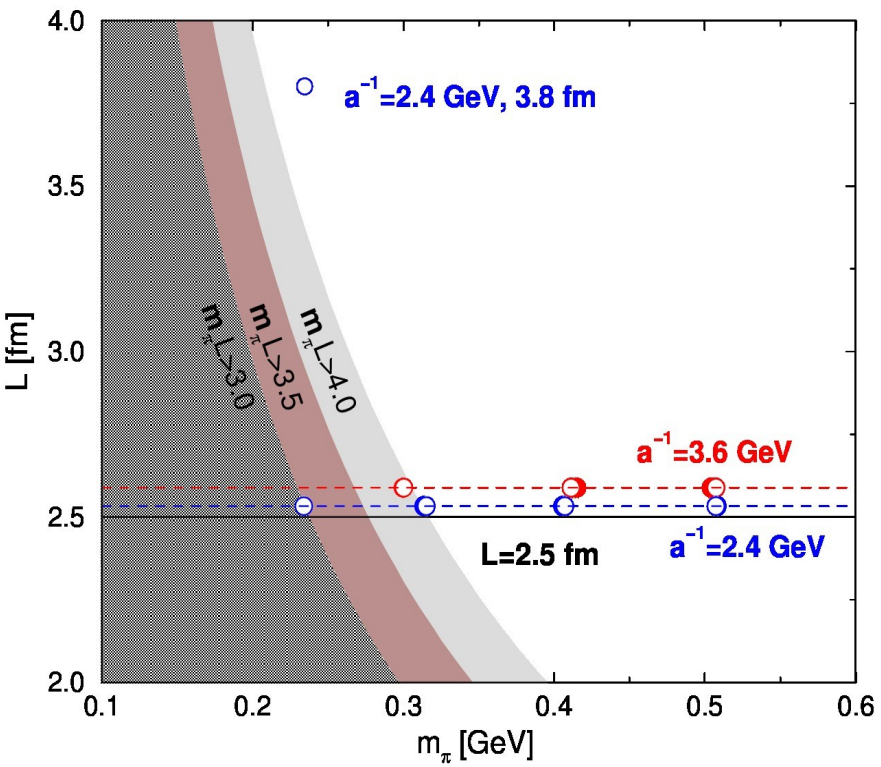
- In our simulation
  - set M = 1.0, b = 2, c = 1
  - stout link smearing: smaller residual mass, faster inversion JLQCD 2013
  - good chiral properties with modest size of L_s
    - violation of GW relation (residual mass) is measured

$m_{\rm res} \sim m_{\rm ud}$ x 0.1 at a^{-1} = 2.4 GeV / $m_{\rm ud}$ x 0.02 at a^{-1} = 3.6 GeV

Design of the numerical simulation

- Config generations have been finished





- three lattice spacings with physical size fixed to $\sim$ 2.5 fm
- $m_\pi L > 4$ even for lightest pion
- Extrapolate the data to phys. point.

Plan of this talk

- Introduction
- Generation of config.
  - HMC + basic measurements
- Lattice2015 summary + discussion
  - especially on hadron physics
  - chiral extrapolations
- Conclusions

Generation of config

HMC

- Action = Symanzik gauge + Möbius Domain-Wall (N_f = 2+1)
  - tree-level Symanzik action
  - 3-level stout smearing
- standard RHMC with Omelyan integrator
- performance @BG/Q : 30 GFlops/node (HMC), 45 GFlops/node (meas)

thanks to P. Boyle !

Hitachi SR16k M1, 57TFlops peak

IBM BG/Q, 1.2PFlops peak

IROIRO++

powered by BAGLE^{TM}

Gauge ensembles

- β = 4.17, 32^3 x64 x12 a^{-1} ~2.4 GeV

m_{ud}	m_π[MeV]	MD time
m_s=0.030		
0.007	310	10,000
0.012	410	10,000
0.019	510	10,000
m_s=0.040		
0.0035	230	10,000
0.007	320	10,000
0.012	410	10,000
0.019	510	10,000
m_s=0.040, 48^3x96		
0.0035	240	10,000

- β = 4.35, 48^3 x96 x8 a^{-1} ~3.6 GeV

* 1 traj. = 2 MD time

m_{ud}	m_π[MeV]	MD time*
m_s=0.018		
0.0042	300	10,000
0.0080	410	10,000
0.0120	500	10,000
m_s=0.025		
0.0042	300	10,000
0.0080	410	10,000
0.0120	510	10,000

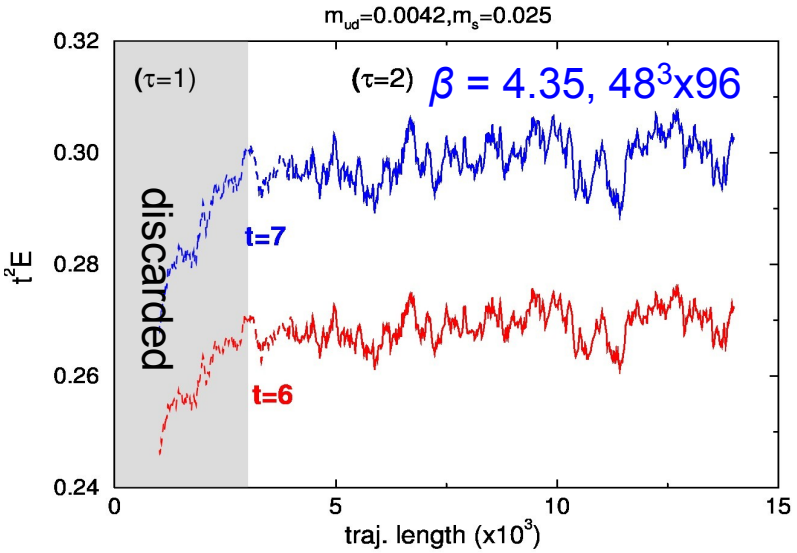
- β = 4.47, 64^3 x128 x8 a^{-1} ~4.5 GeV

* 1 traj. = 4 MD time

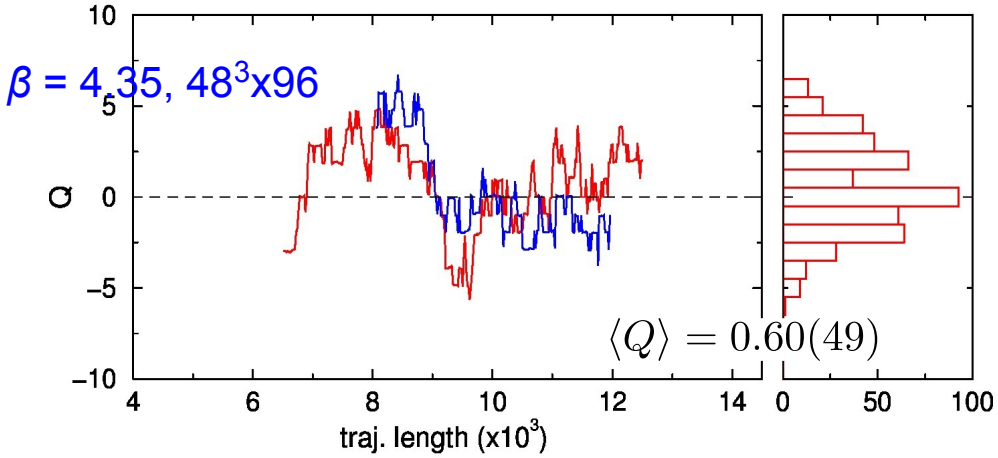
m_{ud}	m_π[MeV]	MD time*
m_s=0.015		
0.0030	240	10,000

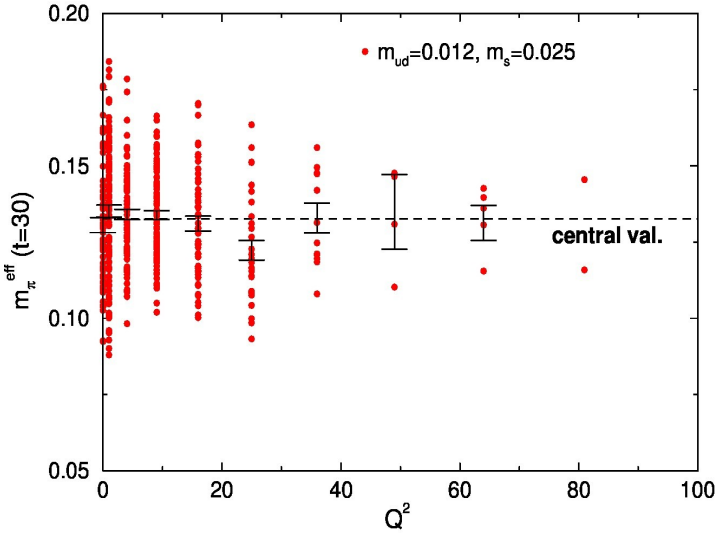
Basic studies through YM grad. flow

- history of $t^2\langle E\rangle$ (around t_0) Lüscher, 2010
  - sensitive only global (IR) structures
  - useful to monitor the thermalization or auto-correlation JLQCD 2013
  - traj. length $\tau = 2$ (β = 4.35) and 4 ($\beta = 4.47$)



- topology changing $Q = \frac{1}{32\pi^2}\sum \mathrm{tr} F_{\mu\nu}\tilde{F}_{\mu\nu}$
  - finer → less frequent, but reasonable sampling observed





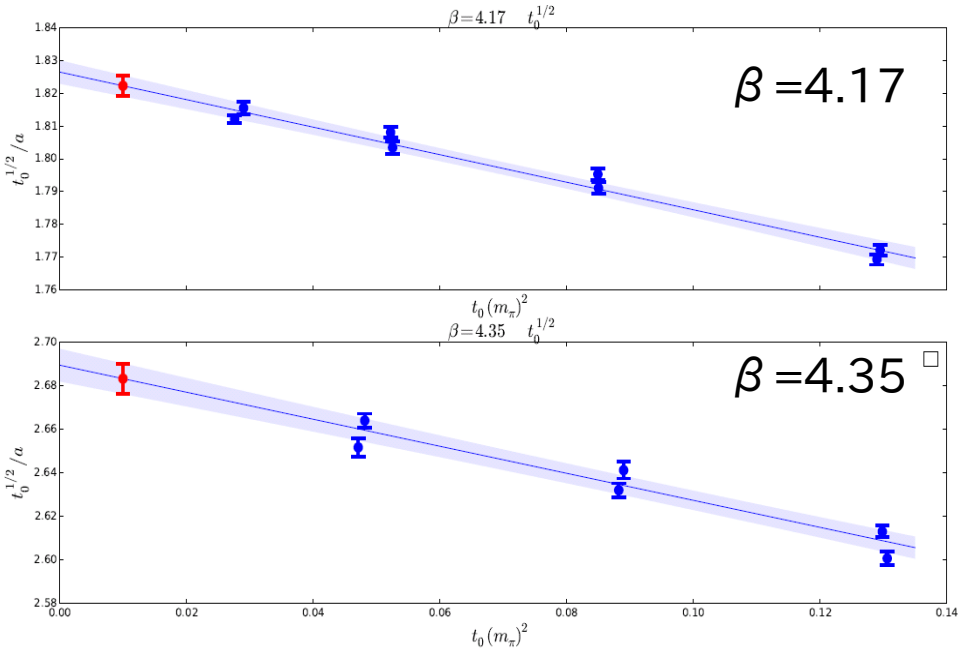
  - no significant correlation between Q and m_π

Scale setting

- mass dependence of t_0/a^2

$$t^2\langle E\rangle|_{t=t_0} = 0.3, \quad \sqrt{t_0^{\rm phys}} = 0.1465 \text{ fm}$$

Lüscher 2010; BMW 2012



- $\beta = 4.17$:non-significant FV effect
- sizable strange mass dependence
- combined linear-fit of all data

$$\frac{t_0}{a^2} = \frac{t_0^{\rm phys}}{a^2}\left[1 + c_\pi\left(t_0 m_\pi^2 - (t_0 m_\pi^2)^{\rm phys}\right) + c_s\left(t_0(2m_K^2 - m_\pi^2) - (t_0(2m_K^2 - m_\pi^2))^{\rm phys}\right)\right]$$

- NLO ChPT : small higher order effect Bär-Golterman, 2013

- Result (statistical error only):

β	4.17	4.35	4.47
a^{-1}[GeV]	2.453(4)	3.609(9)	4.496(9)

LATTICE2015 summary + discussion

LATTICE2015 presentations

- Hadron physics
  - Charmonium current-current correlators K. Nakayama
  - OPE study of coord. space correlators M. Tomii
  - Eta' -mass by topological analysis H. Fukaya
  - light(-heavy) meson spectrum B. Fahy
  - D-meson semileptonic decays T. Suzuki
  - g_A & g_T (on previous confs) N. Yamanaka
  - light meson EM form factors (on previous confs) T. Kaneko
- Finite temperature
  - restoration of $U(1)_A$ symmetry at Nf=2 G. Cossu + A. Tomiya
- etc
  - Stochastic approach to the spectral density S.Hashimoto

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Charm correlators (K. Nakayama)

- charm J_5-J_5 correls on the lattice ↔ continuum VP funcs

Chetyrkin et al. 2006; Boughezal et al. 2006

$$\sum_t t^n G(t) \qquad \frac{1}{n!}\left(-\frac{\partial}{\partial q^2}\right)^n q^2\Pi(q^2)$$

⇨ quantum effect $\quad R_n^{\rm latt} \leftrightarrow R_n^{\rm cont}$

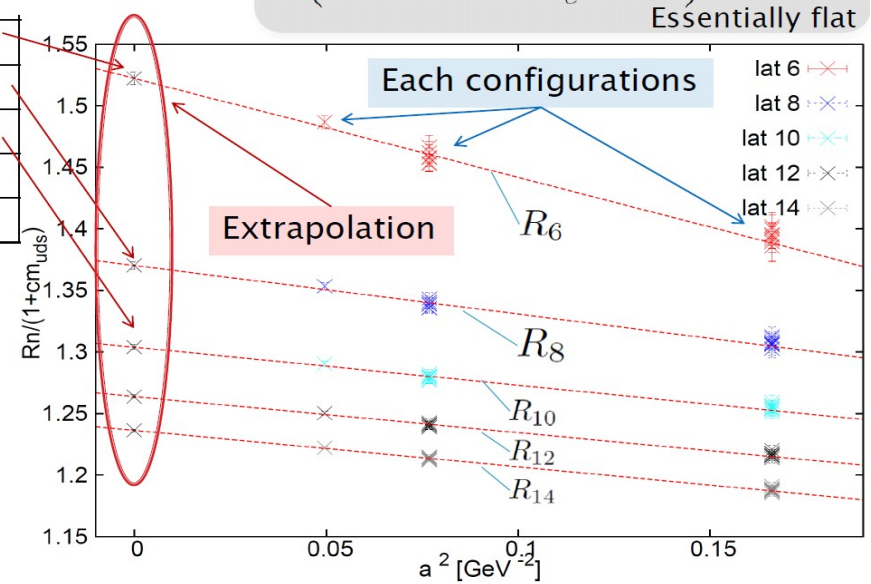
HPQCD 2008,2015; ETMC 2010

- t-window : $\Lambda_{\rm QCD}$ « π/t « π/a
- n-dependence
- chiral limit
- continuum limit

$$R_n(a) = R_n(0)\left(1+c_1(am_c)^2\right)\times\left(1+f_1\frac{m_u+m_d+m_s}{m_c}\right).$$

Essentially flat

R_6	1.526(9)
R_8	1.373(5)
R_{10}	1.305(4)
R_{12}	1.265(2)
R_{14}	1.237(1)



- charm mass & α_S

χ^2 fitting.

$$m_c(\mu) = \frac{m_{\eta_c}^{\rm exp}}{2}\frac{R_n^{\rm cont}}{R_n^{\rm latt}} \qquad \frac{R_n^{\rm latt}}{R_{n+2}^{\rm latt}} = \frac{R_n^{\rm cont}(\alpha_S^{\overline{\rm MS}},\mu/m_c)}{R_{n+2}^{\rm cont}(\alpha_S^{\overline{\rm MS}},\mu/m_c)} \longrightarrow \alpha_S^{\overline{\rm MS}}(\mu)$$

result: $m_c(3\ {\rm GeV}) = 0.9901(81)\ {\rm GeV}, \quad \alpha_S^{\overline{\rm MS}}(3\ {\rm GeV}) = 0.2526(77)$

OPE study in coord. space (M. Tomii)

- Lattice correlator and its improvement

$$\Pi_\Gamma^{\rm latt}(x) \equiv \langle \mathcal{O}_\Gamma(x)\mathcal{O}_\Gamma(0)^\dagger\rangle \to \Pi_\Gamma^{\rm latt}(x) - \left(\Pi_\Gamma^{\rm latt,free}(x) - \Pi_\Gamma^{\rm cont,free}(x)\right)$$

significant discretization error

  - OPE ↔ $\Pi_\Gamma^{\rm latt}$(x) ↔ perturbation

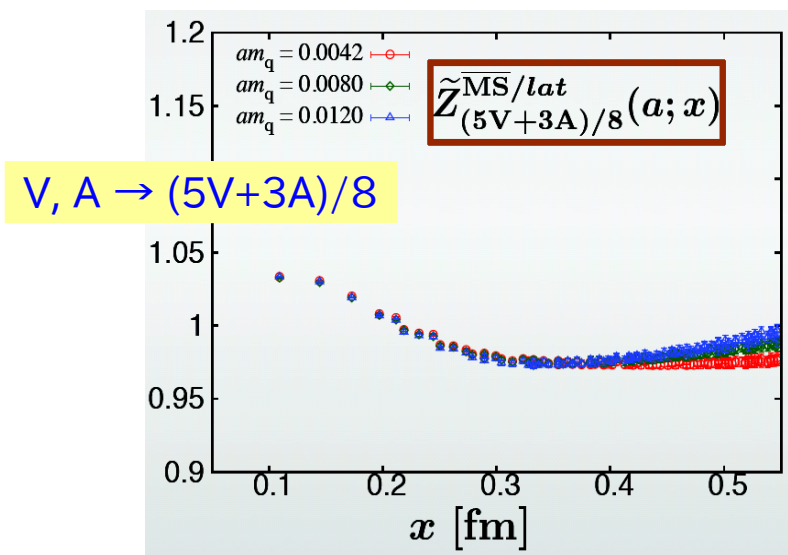
- NPR

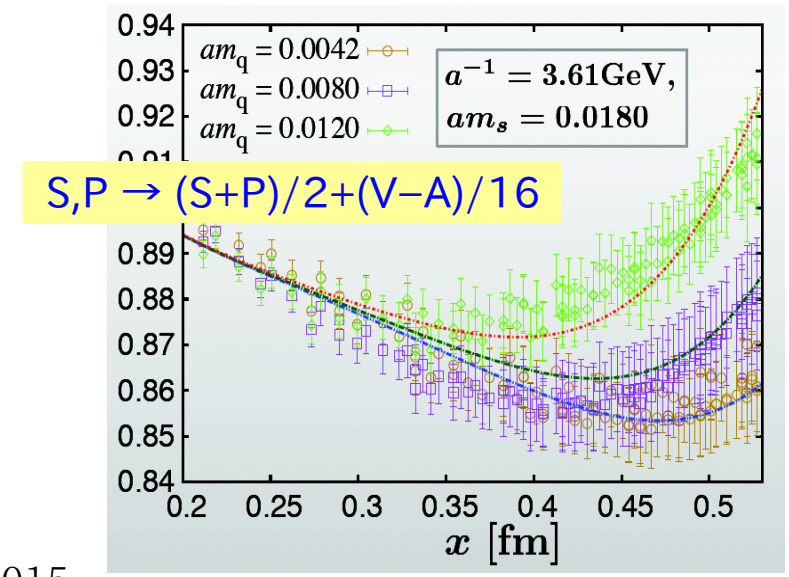
$$Z_\Gamma^{\overline{\rm MS}}(\mu) = \sqrt{\Pi_\Gamma^{\overline{\rm MS},\rm cont}(\mu;x)/\Pi_\Gamma^{\rm latt}(x)}$$

Martinelli et al, 1997; Gimenez et al, 2004; Cichy et al, 2012

  - gauge invariant, $\Pi_\Gamma^{\rm latt}$(x) available to 4-loop level
  - OPE tells best modification $O_\Gamma \to O_{\Gamma'}$ to simplify x-dependence → extract Z's

$$Z_{\Gamma'}^{\overline{\rm MS}}(x;a) = Z_\Gamma^{\overline{\rm MS}}(a) + c_{-2}(a/x)^2 + c_4 x^4 + (c_6 + c_6' m_q^2)x^6$$





η' by YM-gradient flow (H. Fukaya)

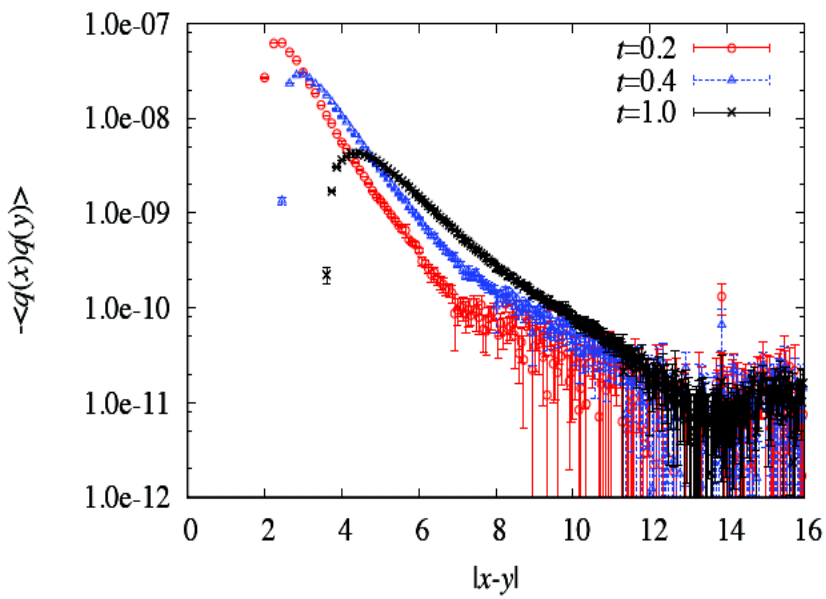
- Use of gluonic operator after the flow
  Chowdhury et al. 2014

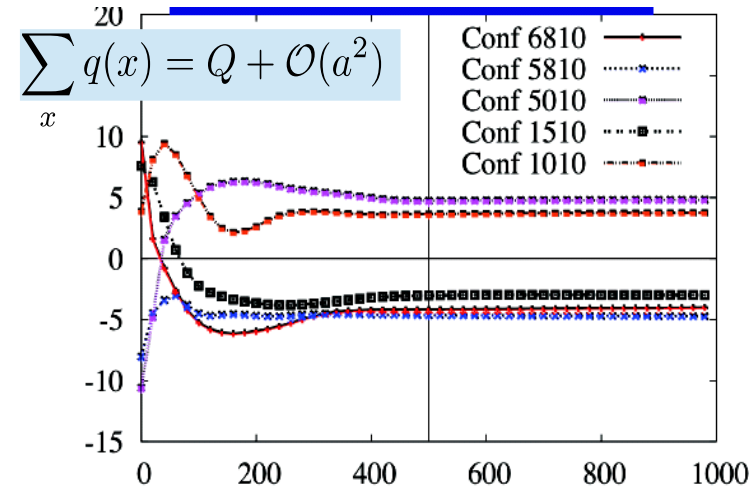
$$\eta'(x) \to q(x) \equiv \frac{1}{32\pi^2}\mathrm{Tr}\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}$$

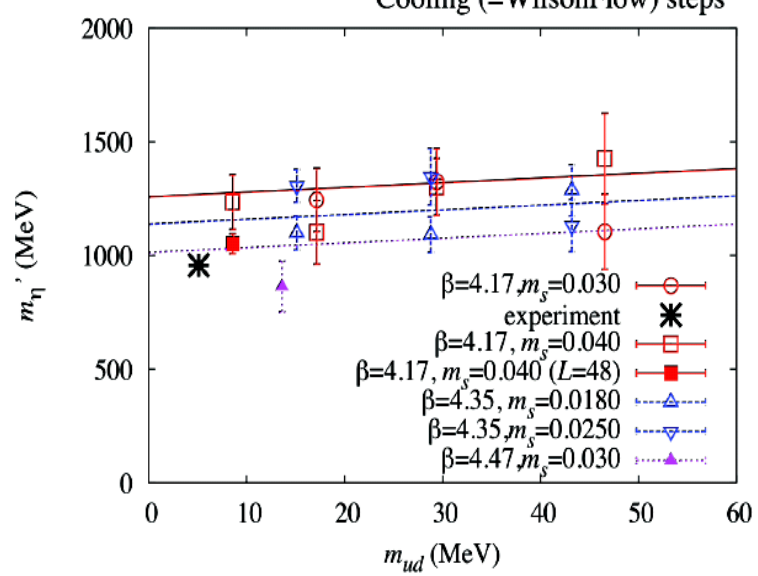
$$\langle q(x)q(y)\rangle = \frac{A}{|x-y|}K_1(m_{\eta'}|x-y|)$$

much cheaper than hadronic calc.

- consider $\sqrt{8t} \ll |x-y| = \mathcal{O}(m_{\eta'}^{-1})$
  - We chose t < 0.008 fm^2, |x-y| > 0.7 fm





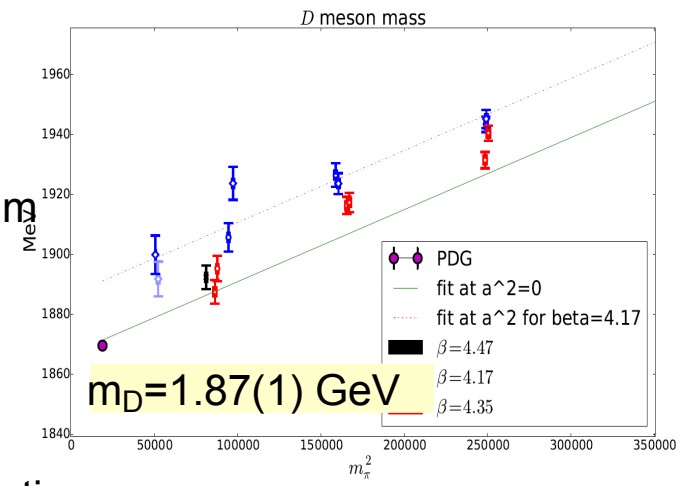


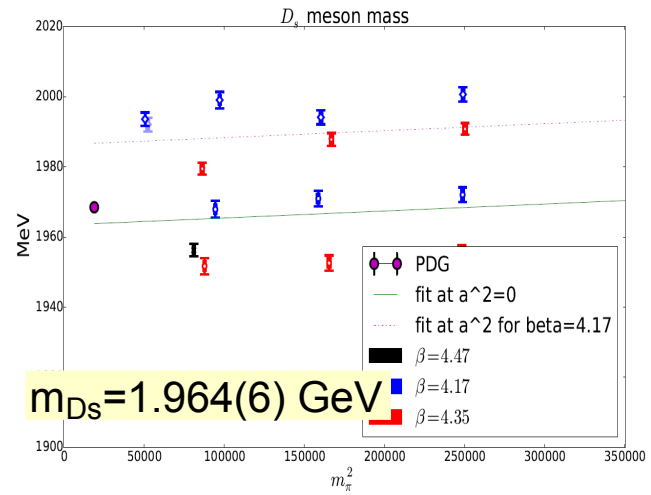
mild { a, V, $m_{\rm sea}$ } dependence

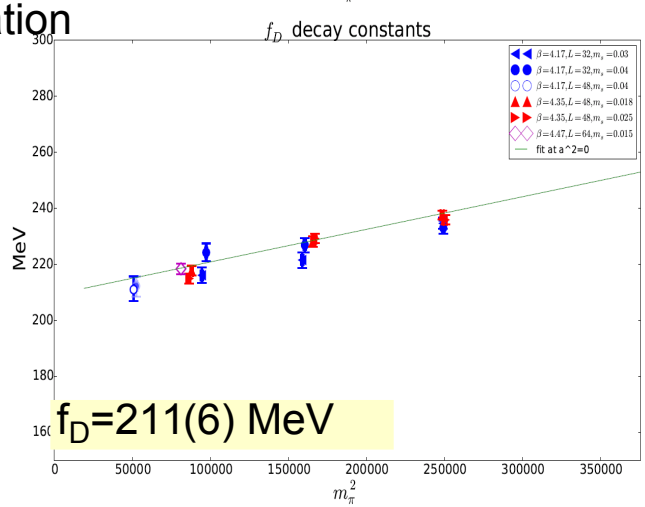
→ $m_{\eta'}$= 1.03(11) GeV by linear fit

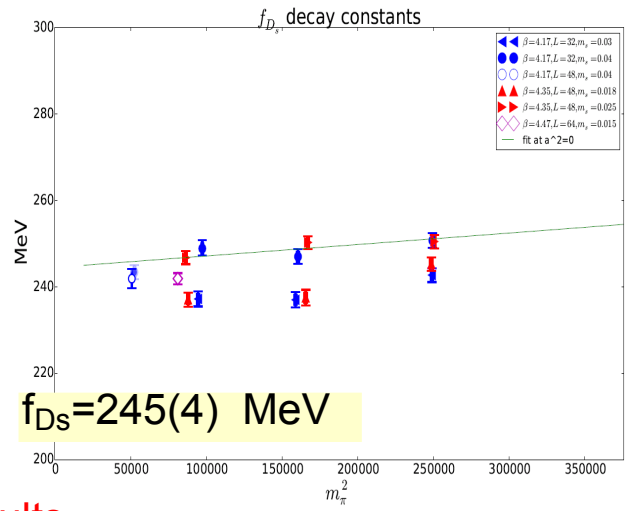
Meson spectrum (B. Fahy)

- charmed observables
  - DW charm mass tuned by spin-averaged charmonium
  - gaussian smeared source
  - decay constant by PCAC relation
  - combined linear fit to extract the physical value → preliminary results







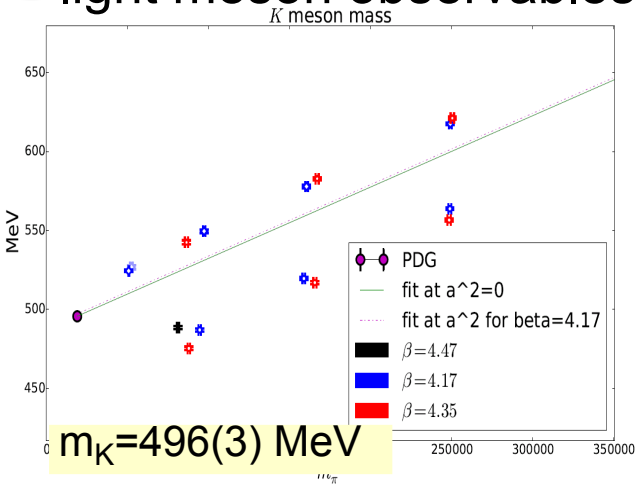


$$\mathcal{O}^{\rm latt}(m_\pi^2, m_s, a^2) = \mathcal{O}^{\rm phys} + C_\pi(m_\pi^2 - m_\pi^{2\ \rm phys}) + C_s(\hat{m}_s - \hat{m}_s^{\rm phys}) + C_a a^2$$

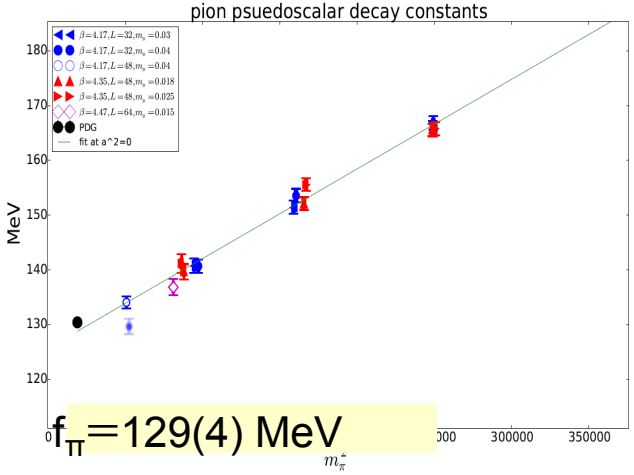
$$\hat{m}_s \equiv 2m_K^2 - m_\pi^2$$

Meson spectrum contd.

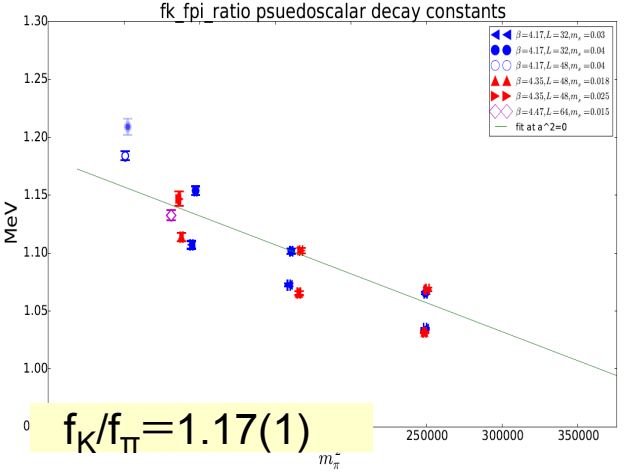
- light meson observables



m_K=496(3) MeV



f_π=129(4) MeV



f_K/f_π=1.17(1)

- naïve linear fit works! What about chiral log and LECs ?
- eg. NLO SU(2) ChPT with expansion param $\xi_\pi \equiv \left(\frac{m_\pi}{4\pi f_\pi}\right)^2$ JLQCD 2008

$$m_\pi^2/m_{ud} = 2B(1+\xi_\pi \ln \xi_\pi/\Lambda_R) + A_m \xi_\pi + C_{m_\pi} a^2$$

$$f_\pi = f(1-2\xi_\pi \ln \xi_\pi/\Lambda_R) + A_f \xi_\pi + C_{f_\pi} a^2$$

$$\Lambda_R \equiv \left(\frac{\Lambda_\chi}{4\pi f_0}\right)^2, \quad F_{1,2} \text{ and } G_{1,2} \text{ are known funcs}$$

$$m_K^2/m_s = B^{(K)}\left(1+\frac{1}{2}\frac{A_m}{2B}+\frac{A_f+fF_1(m_s)}{f^{(K)}}+G_1(m_s)\right)+C_{m_K}a^2$$

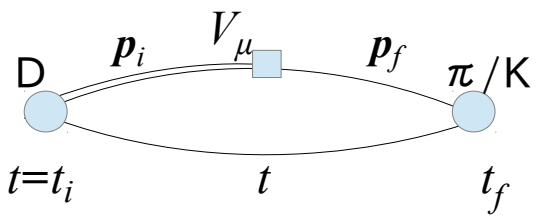
$$f_K = f^{(K)}\left(1-\frac{3}{4}\xi_\pi \ln \xi_\pi/\Lambda_R + F_2(m_s)\xi_\pi\right) + \left(\frac{1}{2}\left(\frac{f^{(K)}}{f}+1\right)A_f + f^{(K)}F_2(m_s) + fG_2(m_s)\right)\xi_\pi + C_{f_K}a^2$$

$$(B^{(K)}, f^{(K)}, A_m, A_f) \to (L_4, L_5, L_6, L_8)$$

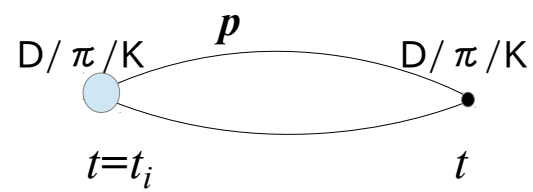
does not describe the data → needs more study

D-meson semileptonic decays (T. Suzuki)

- Determination of CKM matrix elements $\frac{d\Gamma(D\to\pi)}{dq^2} \propto |V_{cd}|^2 |f_+^{D\to\pi}(q^2)|^2$
- Correlators with momentum insertion
  - gaussian smeared source/sink, tuned meson separation



$\rightarrow C_{3pt}(p_i, p_f)$



$\rightarrow C_{2pt}(p)$

    - remove time dependence by picking up plateau
  - observables as a func of momenta
    - matrix elements on the lattice

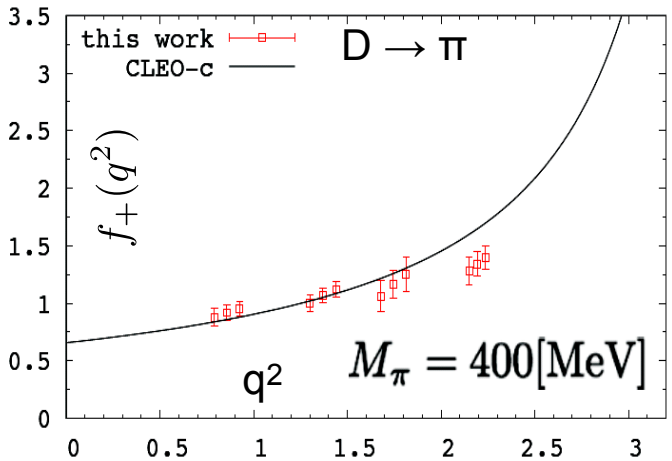
$$\langle \pi(\mathbf{p}_f)|V_\mu^{\rm latt}|D(\mathbf{p}_i)\rangle = 2\sqrt{E_D E_\pi}\sqrt{\frac{C^\mu_{3pt}(\mathbf{p}_i,\mathbf{p}_f)^2}{C^D_{2pt}(\mathbf{p}_i)C^\pi_{2pt}(\mathbf{p}_f)}}$$

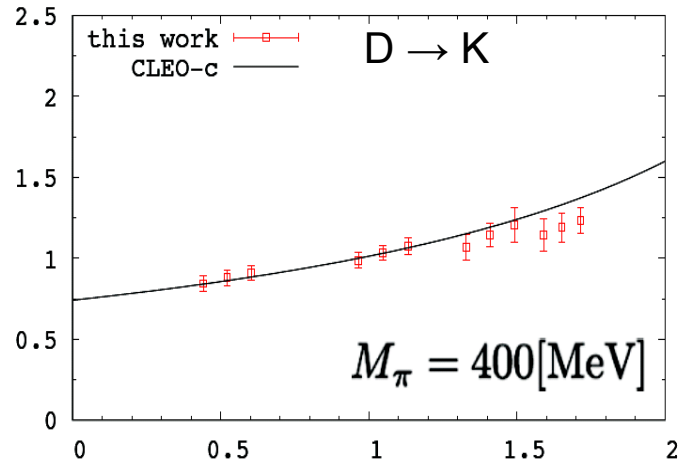
    - form factor ($V_\mu = Z_V V_\mu^{\rm latt}$, $q^2 = (p_i - p_f)^2$)

$$f_+^{D\to\pi}(q^2) = \frac{(E_D - E_\pi)\langle \pi(\mathbf{p}_f)|V_k|D(\mathbf{p}_i)\rangle (p_D - p_\pi)_k \langle \pi(\mathbf{p}_f)|V_0|D(\mathbf{p}_i)\rangle}{2(E_D p_\pi^k - E_\pi p_D^k)}$$

D-meson semileptonic decays contd.

- Performance test (β = 4.17): compare the q-dependence with CLEO-c



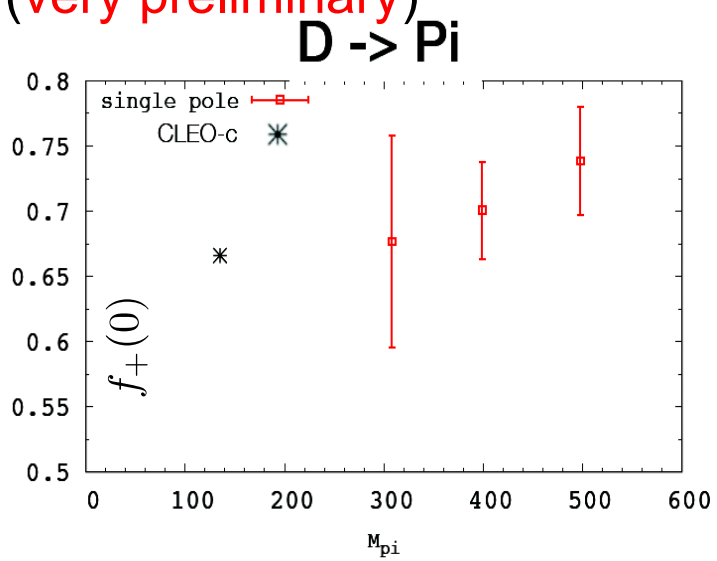


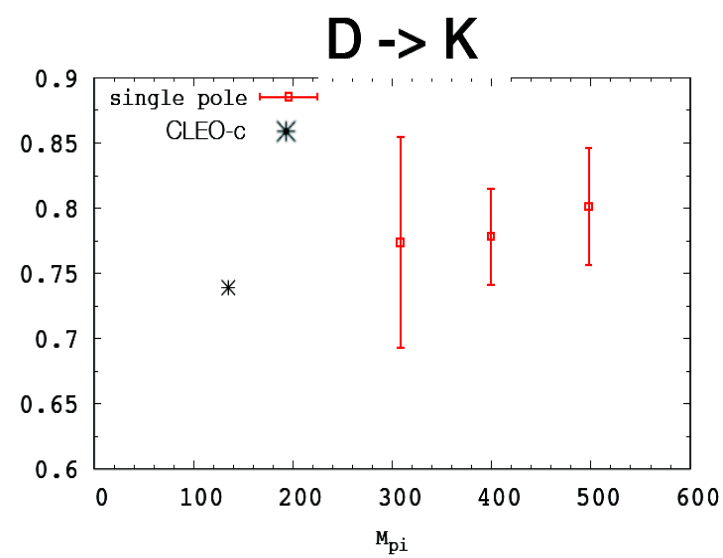
- Extrapolation to q=0 (very preliminary)

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/m_V^2} \cdot P(q^2)$$

best fit with P(q²)=1

More statistics coming





Conclusions

- N_f = 2+1 simulation with Möbius Domain-Wall fermions
  - precise control of systematics with chiral symm. / discretization / finite volume
  - heavy quarks in the same framework as light quarks
  - 10,000 MD-times generated at a^{-1} = 2.4, 3.6, 4.5 GeV
  - basic study and scale setting by YM gradient flow
- Physics
  - ongoing projects including η' -mass / charm-current / OPE study / D-meson semileptonic / spectrum + chiral property
  - semileptonic decay: more statistics / data points / operators
  - chiral property: consistency with previous works? determine LECs.
  - next plans (more phenomenology-driven)
    - baryon (hyperon)-semileptonic decays
    - B-meson decay constants