Continuum Light Hadronic Observables from 2+1 flavor DWF QCD

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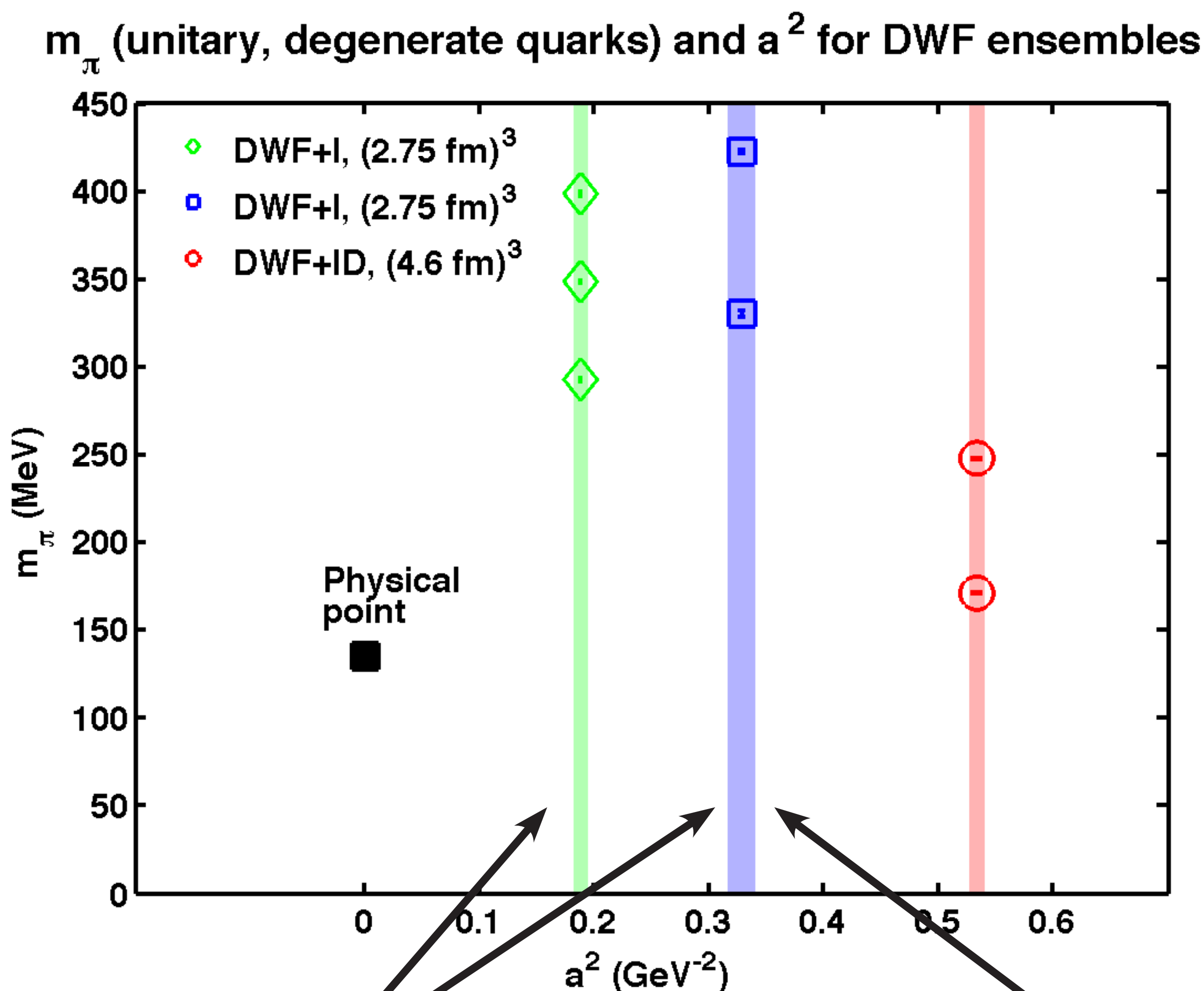
Recent RBC/UKQCD 2+1 flavor DWF ensembles



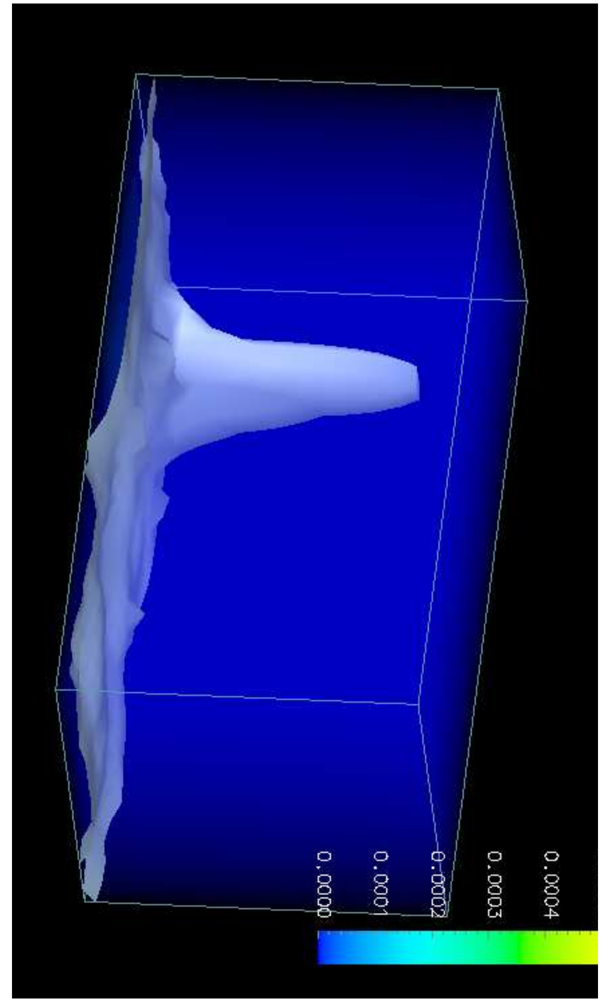
2010 analysis
Phys.Rev. D83 (2011) 074508
Phys.Rev. D84 (2011) 014503

2008 analysis
Phys.Rev. D78 (2008) 114509

Current analysis uses all 3 ensembles

Improving Domain Wall Fermions via DSDR

- When underlying gauge field changes topology, the DWF modes can extend farther in the fifth dimension
- This gives a non-perturbative contribution to residual chiral symmetry breaking
- Becomes problematic at strong coupling
- Add ratio of determinants of twisted Wilson fermions to suppress these gauge field dislocations
- Tune to minimize residual mass while still preserving toplogical ergodicity



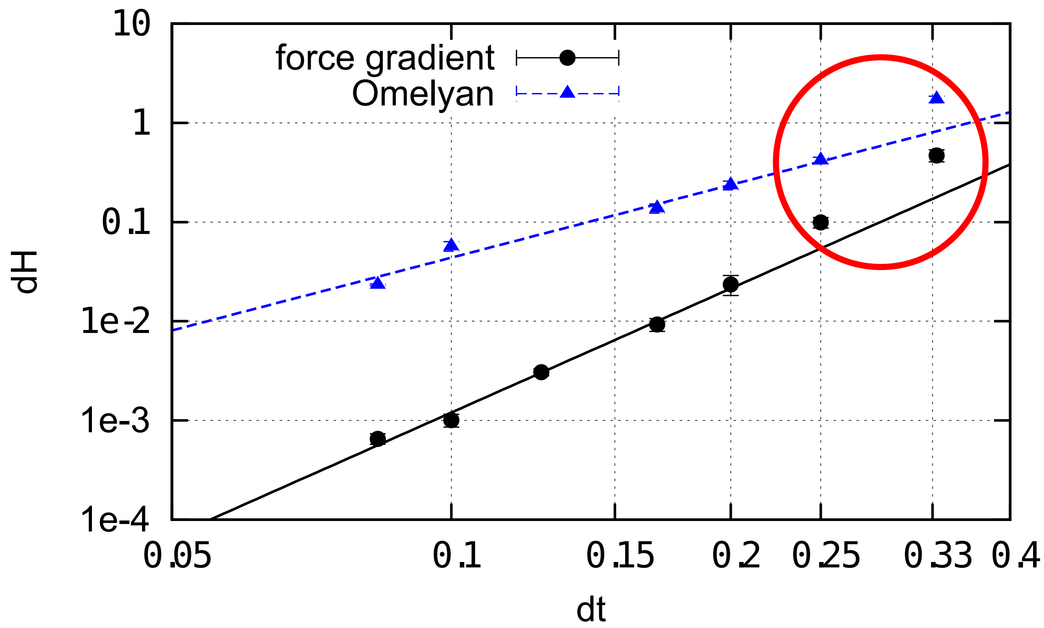
$$\frac{\det\left[D_W(-M+i\varepsilon_f\gamma^5)^\dagger D_W(-M+i\varepsilon_f\gamma^5)\right]}{\det\left[D_W(-M+i\varepsilon_b\gamma^5)^\dagger D_W(-M+i\varepsilon_b\gamma^5)\right]} = \prod_i \frac{\lambda_i^2+\varepsilon_f^2}{\lambda_i^2+\varepsilon_b^2}$$

λ_i are eigenvalues of the Hermitian Wilson operator

- DSDR = Dislocation Suppressing Determinant Ratio

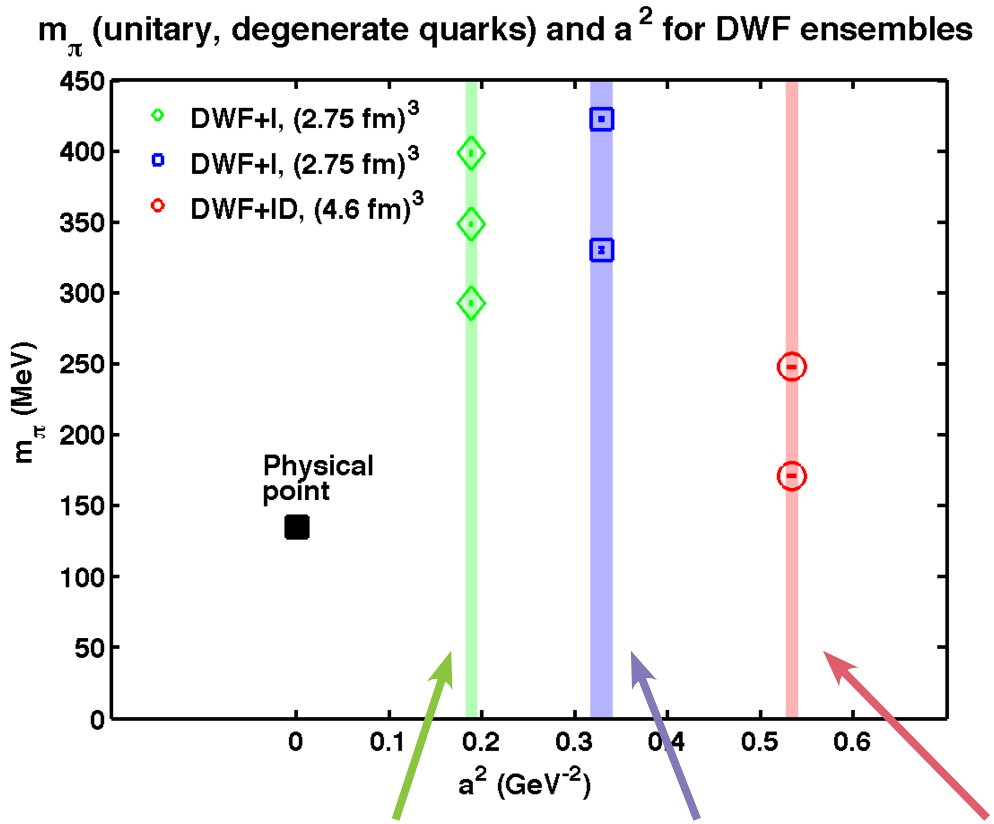
Force Gradient Integrator (FGI)

- Proposed by Clark and Kennedy. Implemented (and simplified) in CPS by Hantao Yin
- For $16^3 \times 32 \times 16$ volumes, no speed-up compared to $O(\delta\tau^2)$ Omelyan



- For larger volumes, where δH grows with volume, force gradient may be helpful
- Tests on $48^3 \times 64 \times 16$ with 220 Mev pions using FGI and retuning Hasenbush masses, 184 minutes/accepted configuration went down to 108 minutes/accepted configuration.
- For DWF+ID ensembles analyzed here, lattice is $32^3 \times 64 \times 32$. For $m = 0.001$, FGI used with 5 intermediate Hasenbusch preconditioning masses, all at top integration level.

m_{res}, Input Masses, Reweighting Range for Strange Quark

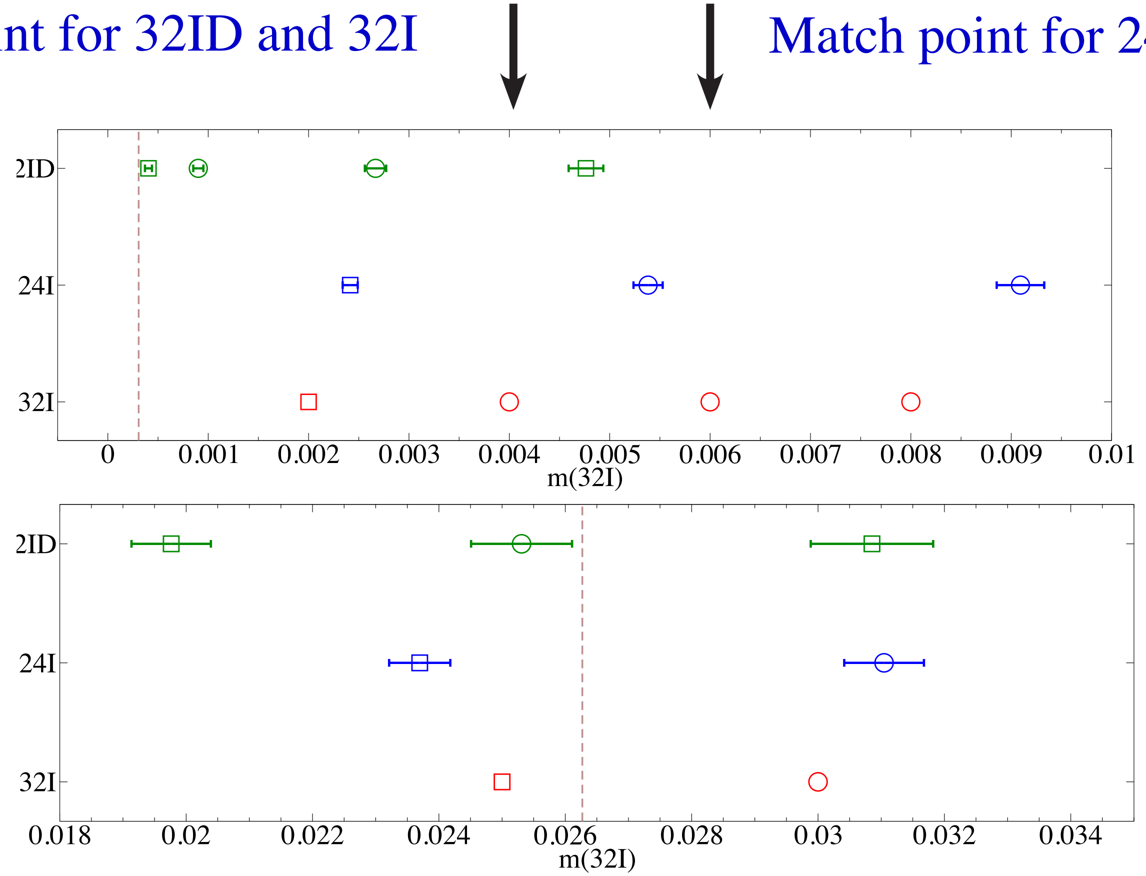


am_{res}	0.000666(8)	0.00308(6)	0.001842(7)
L_s	16	16	32
lightest input dynamical quark mass (am_l)	0.004	0.005	0.001
input dynamical heavy quark mass	0.03	0.04	0.045
am_s - am_{res} (from fits)	0.0263(9)	0.0336(13)	0.0467(6)

Checking Scaling at Unphysical Masses

Match point for 32ID and 32I

Match point for 24I and 32I



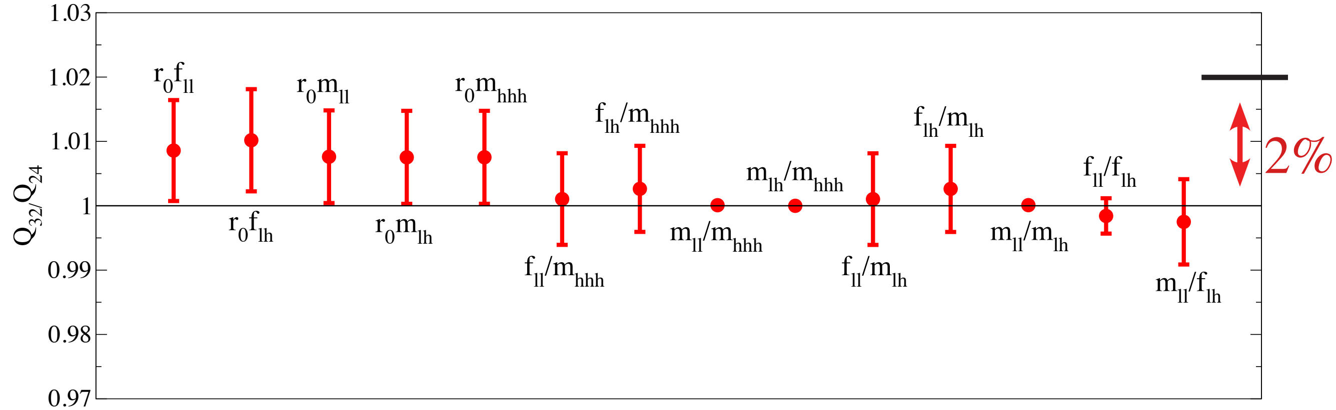
- Total light and strange quark masses, using bare quark normalization for 32 DWF+I
- Can check scaling at unphysical quark masses by interpolating/extrapolating data to masses where m_{ll}/m_{hhh} and m_{lh}/m_{hhh} are identical on different ensembles.

Scaling at unphysical light quark mass

Compare

- DWF+I: 1/a = 2.28 GeV
- DWF+I: 1/a = 1.73 GeV

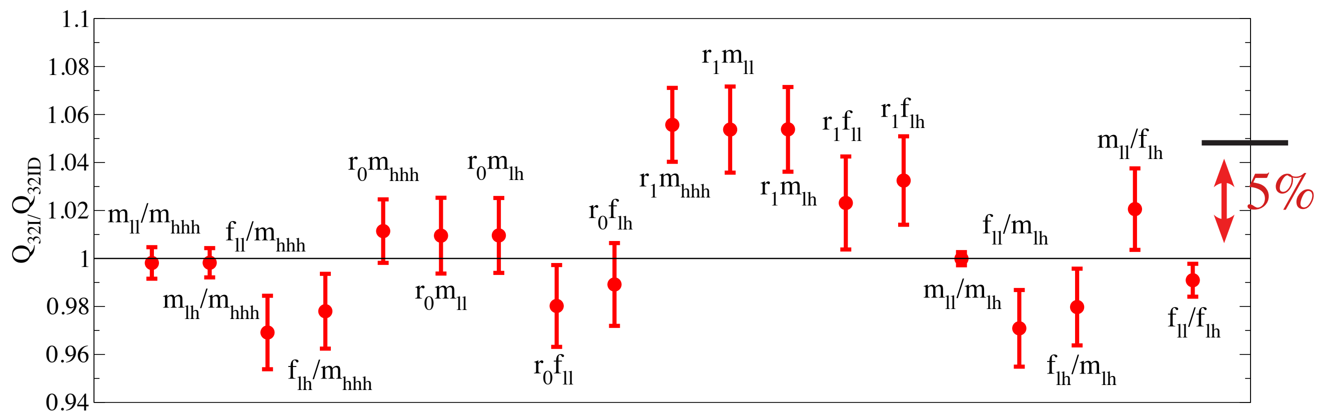
(Phys. Rev. D83 (2011) 074508)



Compare

- DWF+I: 1/a = 2.28 GeV
- DWF+ID: 1/a = 1.37 GeV

(RBC/UKQCD to appear)



See few percent scaling errors from $1/a = 1.73$ GeV $\rightarrow \infty$, with larger $O(5\%)$ errors from 1/a = 1.37 GeV

Parameters in DWF+I and DWF+ID Global Fits

- Simultaneous fit to m_π^2, m_K^2, f_π, f_K, and m_Ω, with m_π, m_K and m_Ω chosen to be quantities without $O(a^2)$ corrections
- 18 Parameters in SU(2) chiral expansion:
  - m_π^2 and f_π: 8 parameters – 2 LO, 4 NLO, $2O(a^2)$
  - m_K^2 and f_K: 6 parameters – 2 LO, 4 NLO, $2O(a^2)$
  - m_Ω: 1 LO, 1 NLO
- Fits also determine
  - 3 lattice spacings
  - 2 ratios of light quark mass renormalization factors
  - 2 ratios of strange quark mass renormalization factors
  - m_s
- Only use SU(2) ChPT to NLO
- Also do analytic fits to compare with ChPT and to help estimate chiral extrapolation errors

Global Fits to Multiple Ensembles

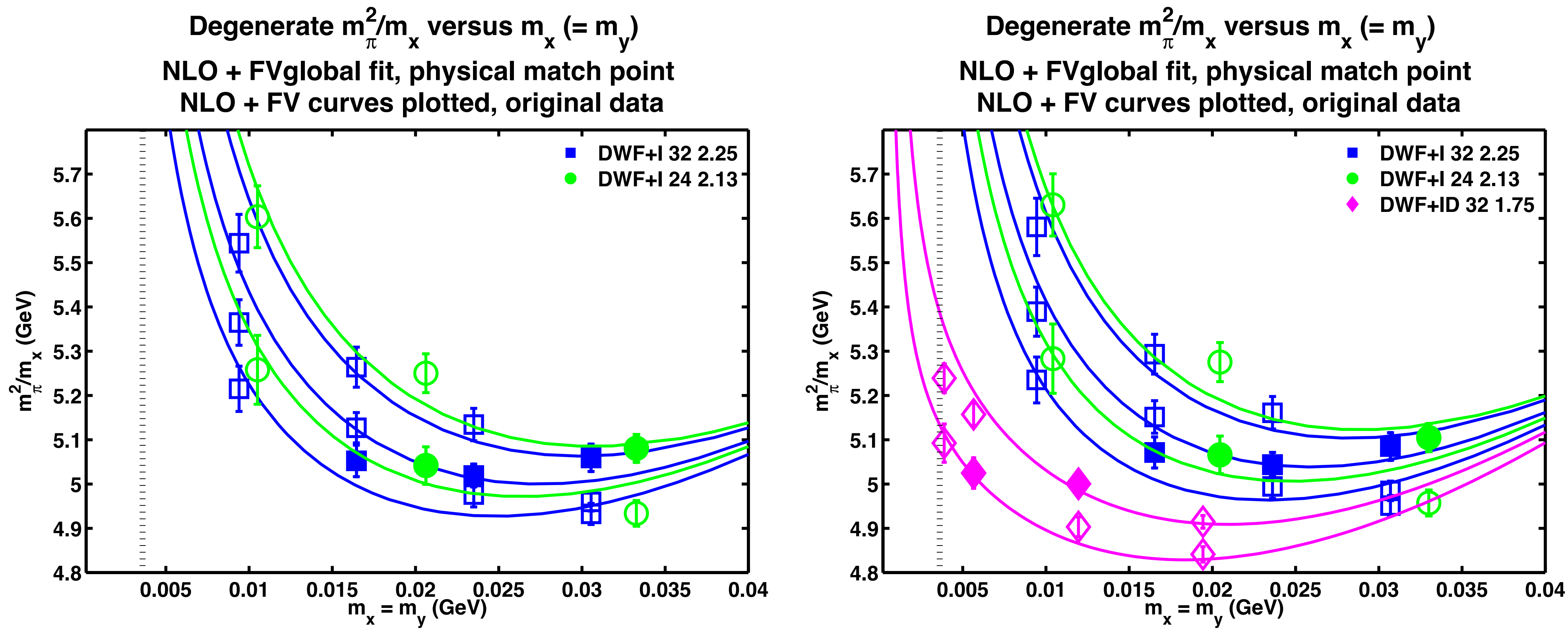
- Fit m_π^2, f_π, m_K^2, f_K and m_Ω to an expansion in powers of a^2 and m_l, including SU(2) logs where appropriate. Examples are

$$m_{ll}^2 = \chi_l \left[1 + \boxed{c_B a^2}\right] + \chi_l \cdot \left\{ \frac{16}{f^2}\Big((2L_8^{(2)} - L_5^{(2)}) + 2(2L_6^{(2)} - L_4^{(2)})\Big)\chi_l + \frac{1}{16\pi^2 f^2}\chi_l \log\frac{\chi_l}{\Lambda_\chi^2} \right\}$$

$$f_{ll} = f\left[1 + \boxed{c_f a^2}\right] + f \cdot \left\{ \frac{8}{f^2}(2L_4^{(2)} + L_5^{(2)})\chi_l - \frac{\chi_l}{8\pi^2 f^2}\log\frac{\chi_l}{\Lambda_\chi^2} \right\}.$$

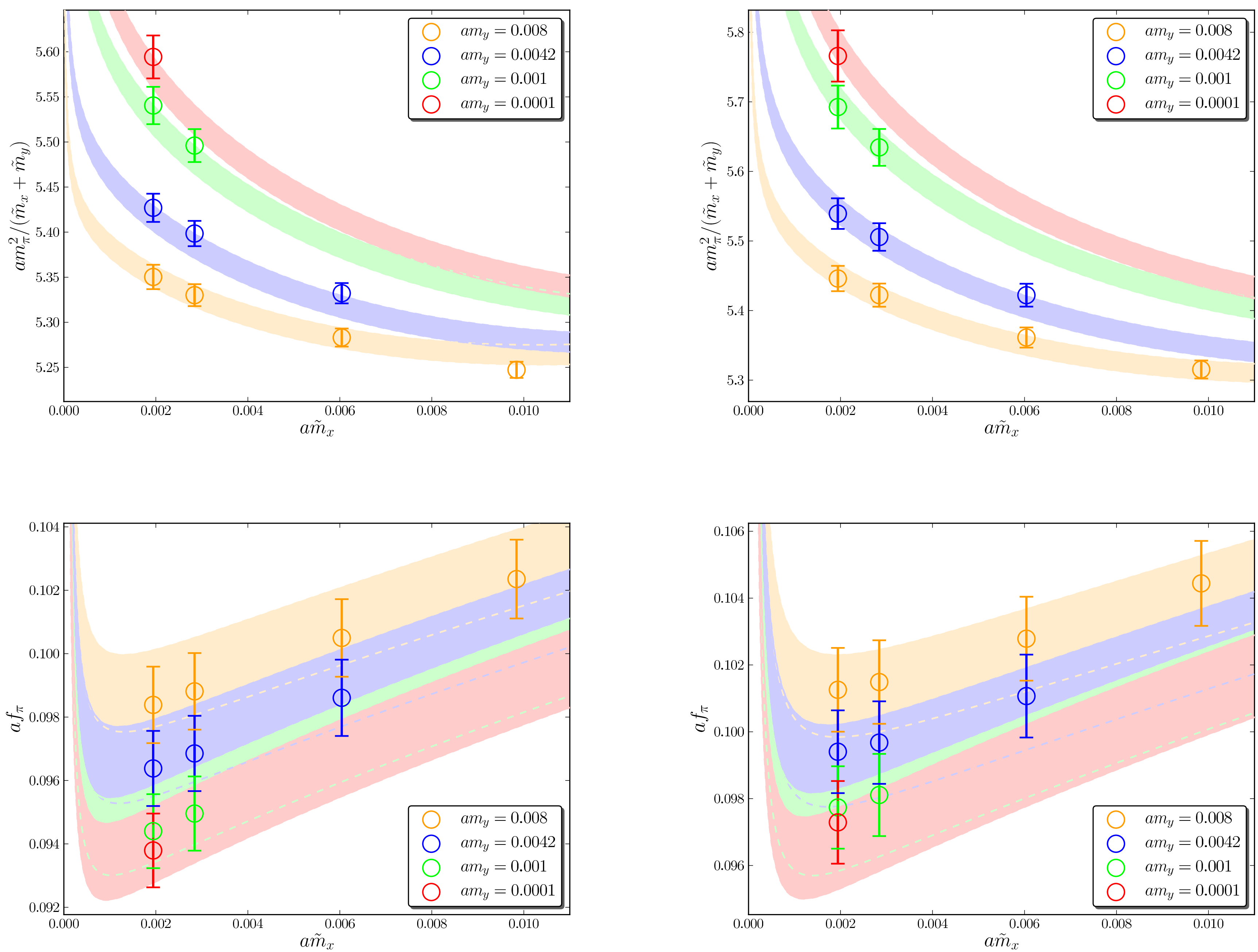
- Note different $O(a^2)$ coefficients used for DWF+I and DWF+ID
- Fit all partially quenched data, including SU(2) ChPT finite volume corrections in fit
- Reweight data from simulation m_h to self-consistently determined m_s (Jung)
- Interpolate valence propagators to self-consistently determined m_s
- Use m_π m_K and m_Ω set scale.

m_π^2/m_f versus m_f



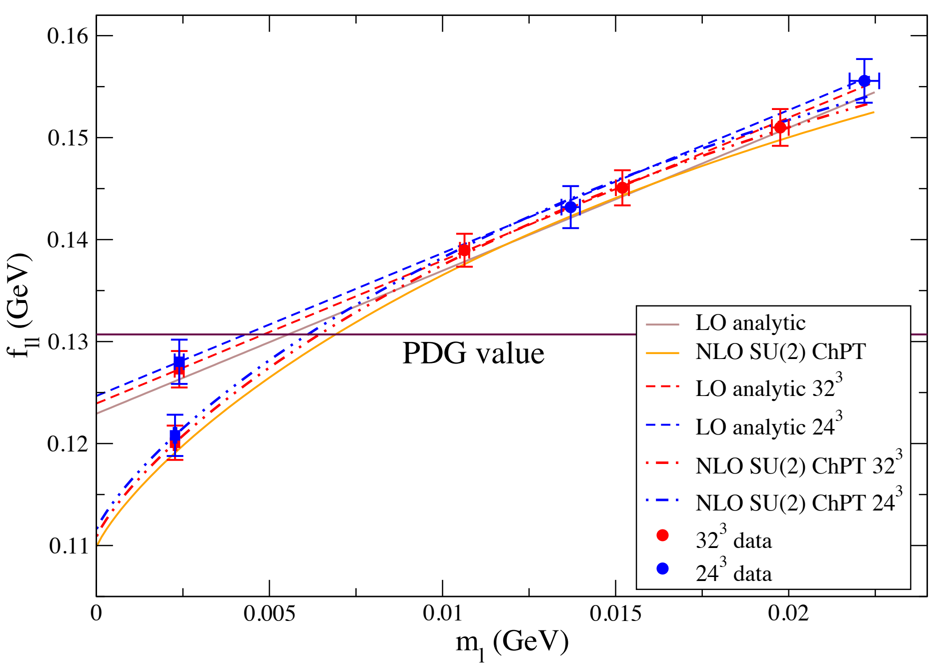
- Early fits from partial DWF+ID dataset
- Data consistent with chiral logarithms

$m_\pi{}^2/m_f$ versus m_f

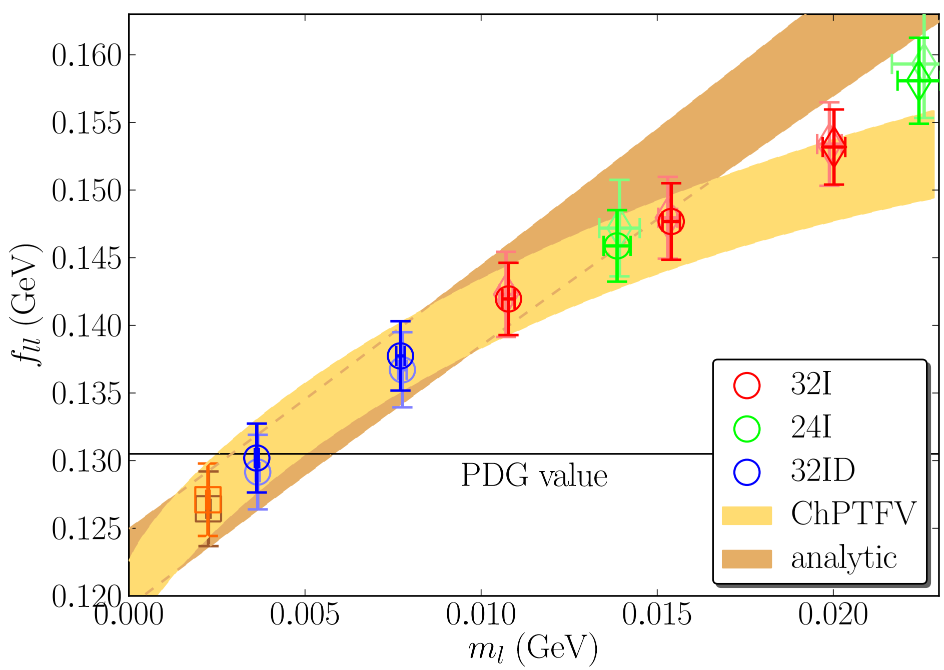


Chiral Extrapolation for f_π

- DWF+ID ensemble gives results for much smaller quark masses.
- Can drop pion masses above 350 MeV for ChPT and still do fits.
- Can drop pion masses above 260 MeV for analytic fits and still do them.
- ChPT and analytic agree if pion masses below 260 MeV are used.
- f_π now much closer to physical value than with 2010 analysis



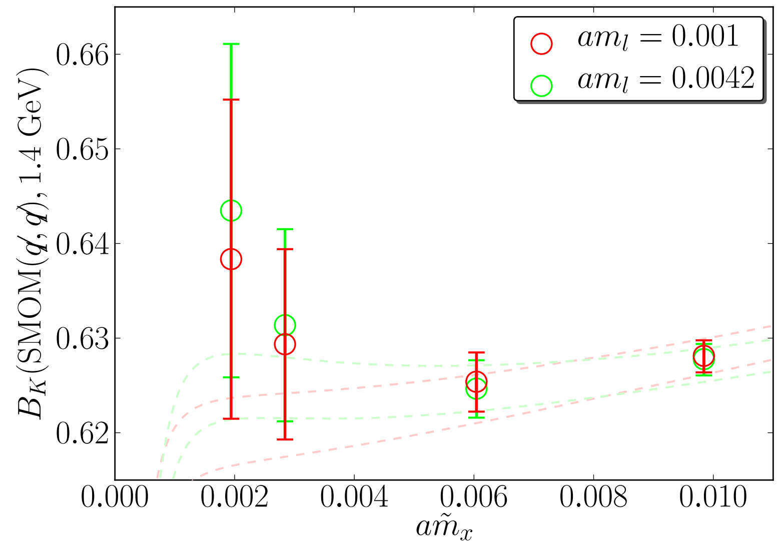
2010 analysis

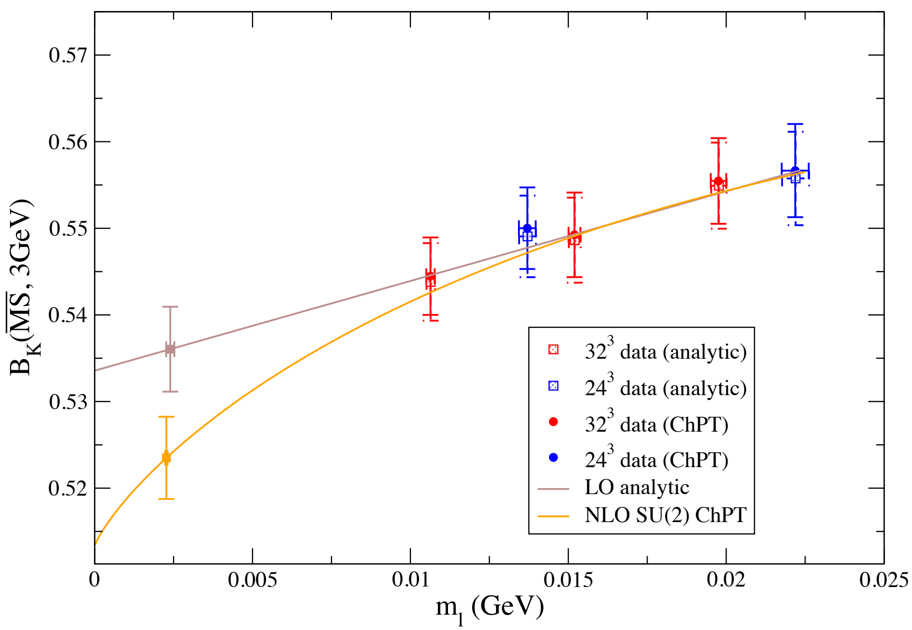


Current analysis

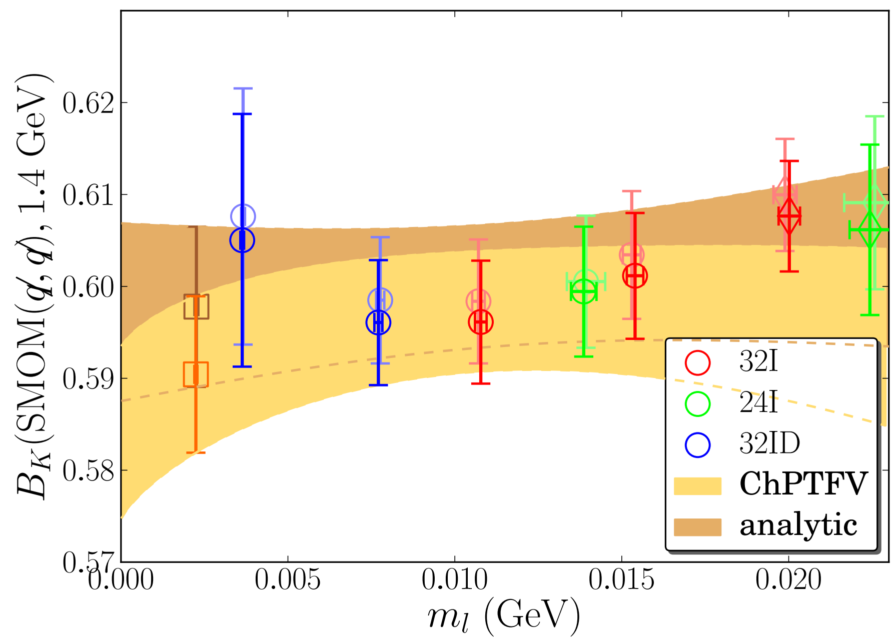
Chiral Extrapolation for B_K

- DWF+ID data rise slightly for light quarks
- Factor of 0.906(3) between normalization in graphs of 2010 and current analysis





2010 analysis



Current analysis

Some physical results

DWF+I (2010 Analysis)	DWF+I and DWF+ID
$f_\pi^{\text{continuum}} = 124(2)(5)\,\text{MeV}$ $f_K^{\text{continuum}} = 149(2)(4)\,\text{MeV}$ $(f_K/f_\pi)^{\text{continuum}} = 1.204(7)(25)\,,$	$f_\pi = 127.1(2.7)(0.7)(2.5)$ MeV, $f_K = 152.4(3.0)(0.1)(1.5)$ MeV, $f_K/f_\pi = 1.1991(116)(69)(116)\,.$
$m_{ud}^{\overline{\text{MS}}}(2\,\text{GeV}) = (3.59 \pm 0.21)\,\text{MeV}$ $m_s^{\overline{\text{MS}}}(2\,\text{GeV}) = (96.2 \pm 2.7)\,\text{MeV}$ $\dfrac{m_s}{m_{ud}} = 26.8(0.8)_{\text{stat}}(1.1)_{\text{sys}}.$	$m_{u/d}(\overline{\text{MS}}, 3\text{ GeV}) = 3.05(8)(6)(1)(4)\,\text{MeV}$ $m_s(\overline{\text{MS}}, 3\text{ GeV}) = 83.6(1.7)(0.7)(0.4)(1.0)\,\text{MeV}$ $\dfrac{m_s}{m_{u/d}} = 27.36(39)(30)(22)(0)$
$\hat{m}_{ud} = 9.34(34)(31)(16)(21)\,\text{MeV},$ $\hat{m}_s = 250.2(3.9)(0.5)(0.3)(5.5)\,\text{MeV}\,.$	$\hat{m}_{ud} = 8.77(23)(17)(3)(12)\,\text{MeV},$ $\hat{m}_s = 240.5(4.9)(2.0)(1.2)(2.9)\,\text{MeV},$
$B_K(\overline{\text{MS}}, 3\ \text{GeV}) = 0.529(5)(15)(2)(11)$	$B_K(\overline{\text{MS}}, 3\ \text{GeV}) = 0.535(8)(7)(3)(11)$ (stat, chiral, finite V, pert. theory)

RBC/UKQCD 2+1 flavor DWF ensembles