Charm Physics from the ETM Collaboration

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ETM Collaboration

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ETM Collaboration : lattice QCD

- Cyprus (Nicosia)
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- France (CEA, Clermont Ferrand, Grenoble, Orsay)
  B. Blossier, Ph. Boucaud, M. Brinet, J. Carbonell, P. Guichon, P.A. Harraud, V. Morénas, M. Papinutto, O. Pène, K. Petrov
- Germany (Berlin, Bonn, Frankfurt, Hamburg, Münster, Zeuthen)
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- Netherlands (Groningen)
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  K. Cichy
- Spain (Barcelona, Huelva, Madrid, Sevilla, Valencia)
  N. Carrasco, F. De Soto, V. Giménez, G. Herdoíza, F. Mescia, J. Rodríguez Quintero
- Switzerland (Bern)
  A. Deuzeman, U. Wenger
- United Kingdom (Cambridge, Liverpool)
  Z. Liu, C. Michael

Charm Physics through Lattice QCD

Study QCD in a non-perturbative way

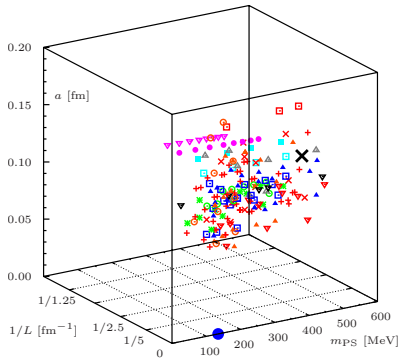
- QCD Parameters : α_S, $\Lambda_{\rm QCD}$, quark masses : m_c
- Hadronic Properties :
  - Spectrum : D-meson, charmonium, charmed baryons
  - Structure
- Constrain Effective Theories :
  - Heavy Quark Effective Theory (HQET) , NRQCD
  - Chiral Perturbation Theory (χPT)
- Constraints on the Standard Model : flavour physics
  - CKM , charm decays
  - New Physics : precision in the non-perturbative determinations of hadronic matrix elements
  - Control of systematic uncertainties in lattice QCD results

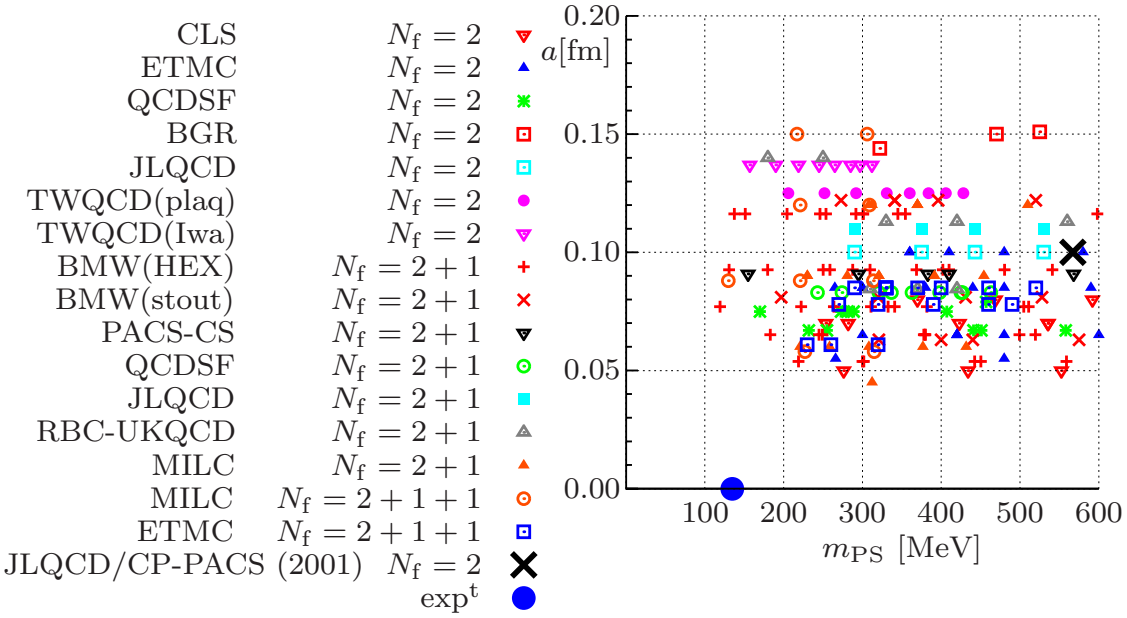
precision in lattice QCD results

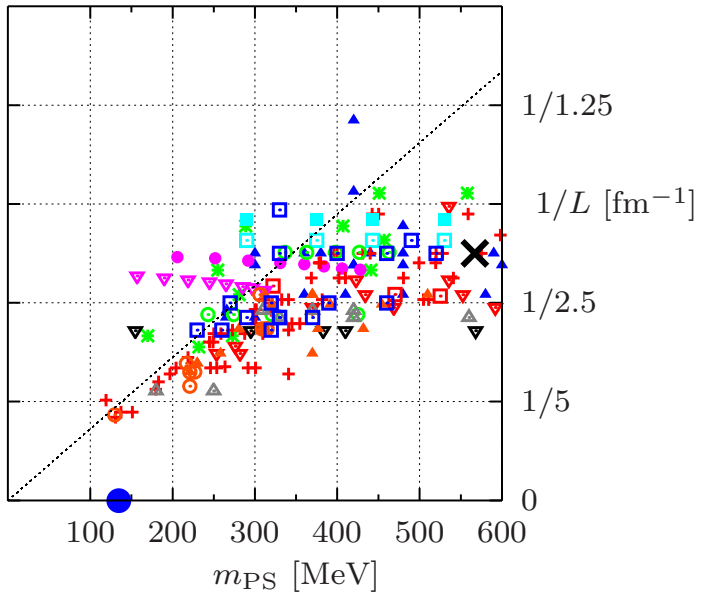
- control of systematic uncertainties
  - number of dynamical flavours (u,d,s,c,...quarks) $N_f = 0;\ 2;\ 2+1;\ 2+1+1$
  - cutoff effects: lattice spacing a — $O(a)$ improvement, continuum limit
    broken symmetries at $a \neq 0$
    $m_q \ll 1/a$
  - range of quarks masses : simulation/physics — applicability of χPT, HQET
  - Finite Size Effects (FSE): lattice size L — $m_{PS} L \gg 1$
  - renormalisation — non-perturbative
- statistical errors
  - improvement in algorithms
  - autocorrelations
  - machines

dynamical simulations : parameter landscape

- number of flavours : N_f
- lattice spacing : a
- lattice size : L
- pion masses : m_{PS}







Caveat in plots : no information on systematic effects (cut-off effects, FSE, scale setting, ...), m_s, m_c, ...

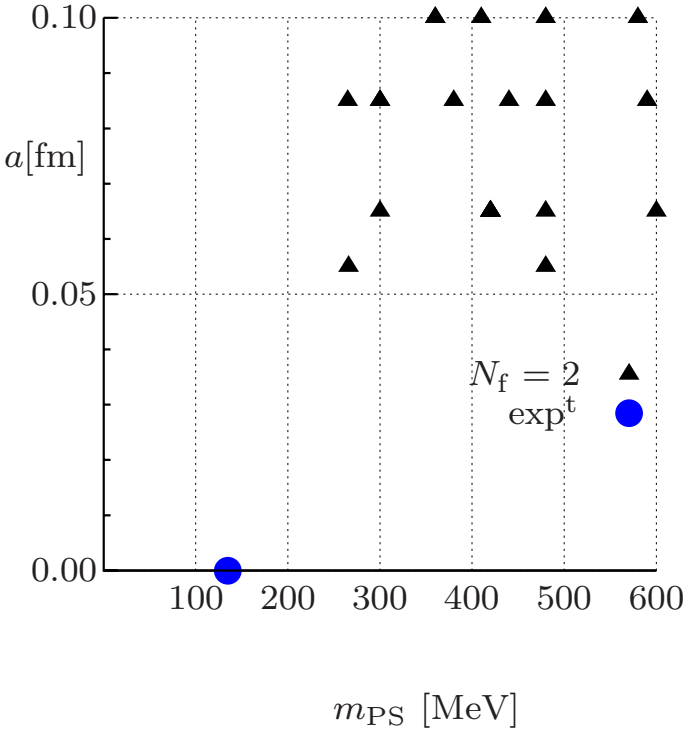
$N_f = 2$

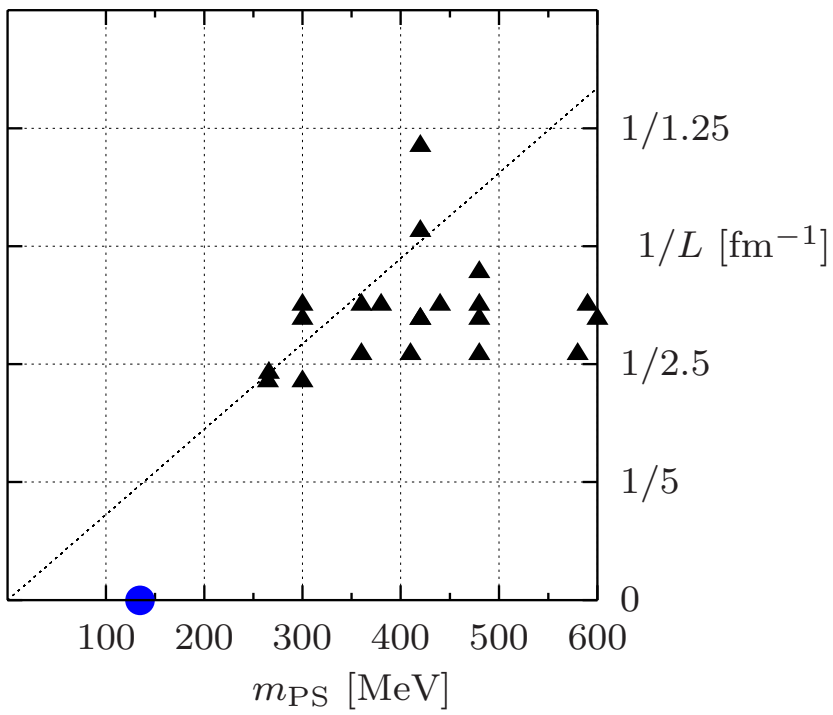
u, d sea quarks

$N_f = 2$ ETMC ensembles

- Wilson twisted-mass fermions
- Gauge action : tree-level Symanzik

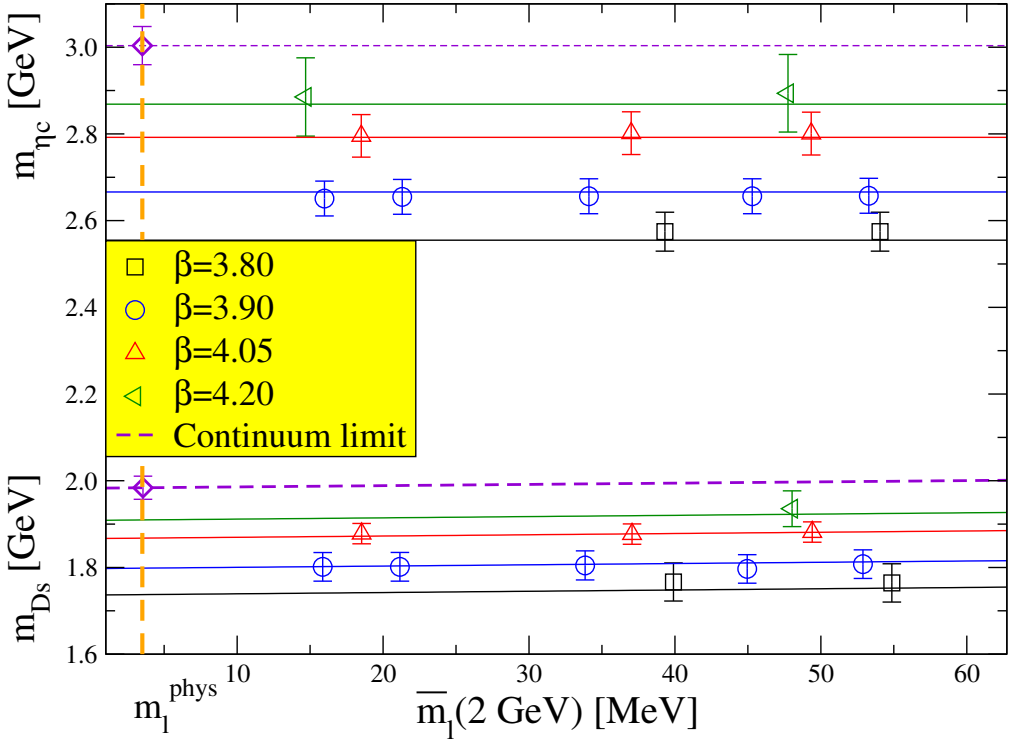
- $a = \{0.054,\ 0.067,\ 0.085,\ 0.098\}$ fm
- $m_{PS} \in \{270,\ 600\}$ MeV
- $L \in \{1.7,\ 2.8\}$ fm , $m_{PS}L \gtrsim 3.5$





$N_f = 2 : \; m_c$

$a \; = \; \{0.054, \; 0.067, \; 0.085, \; 0.098\}$ fm from $f_\pi^{(\exp)}$

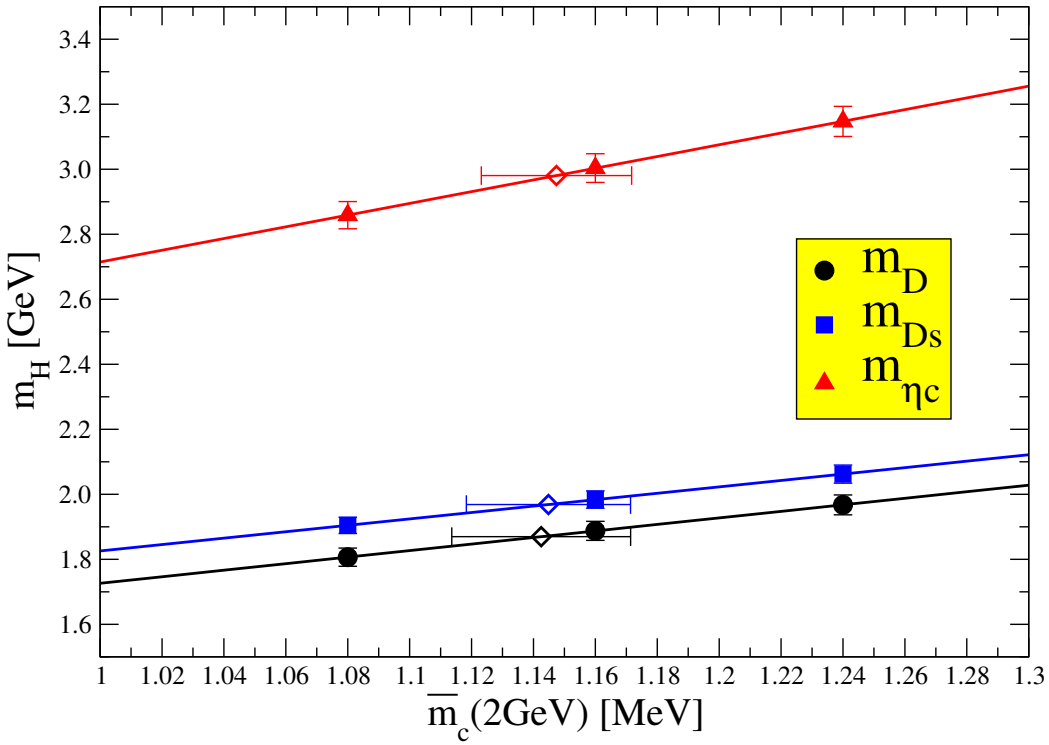


light-quark mass and lattice spacing dependence [ETMC, 2010]

- Non-perturbative renormalisation of m_q

$N_f = 2 : \; m_c$

$a = \{0.054,\ 0.067,\ 0.085,\ 0.098\}$ fm from $f_\pi^{(\mathrm{exp})}$



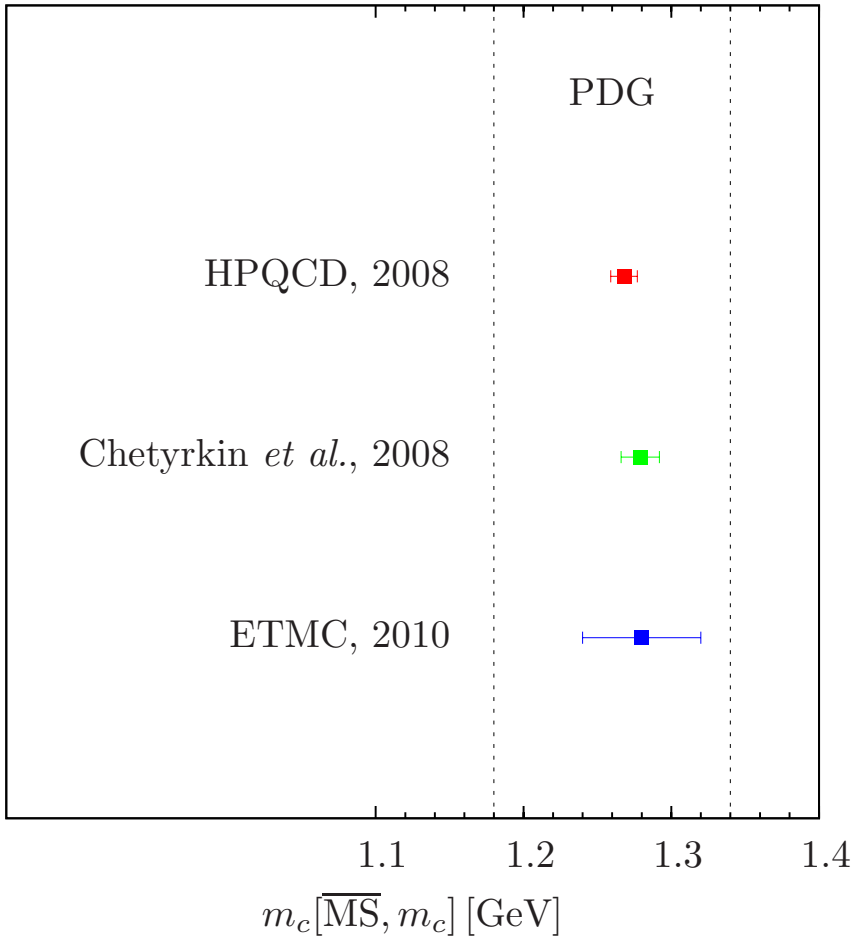
heavy-quark mass dependence [ETMC, 2010]

- Non-perturbative renormalisation of m_q

$\rightsquigarrow \; m_c[\overline{\mathrm{MS}}, \mu = m_c] = 1.28(4)$ GeV $\qquad m_c/m_s = 12.0(2)$

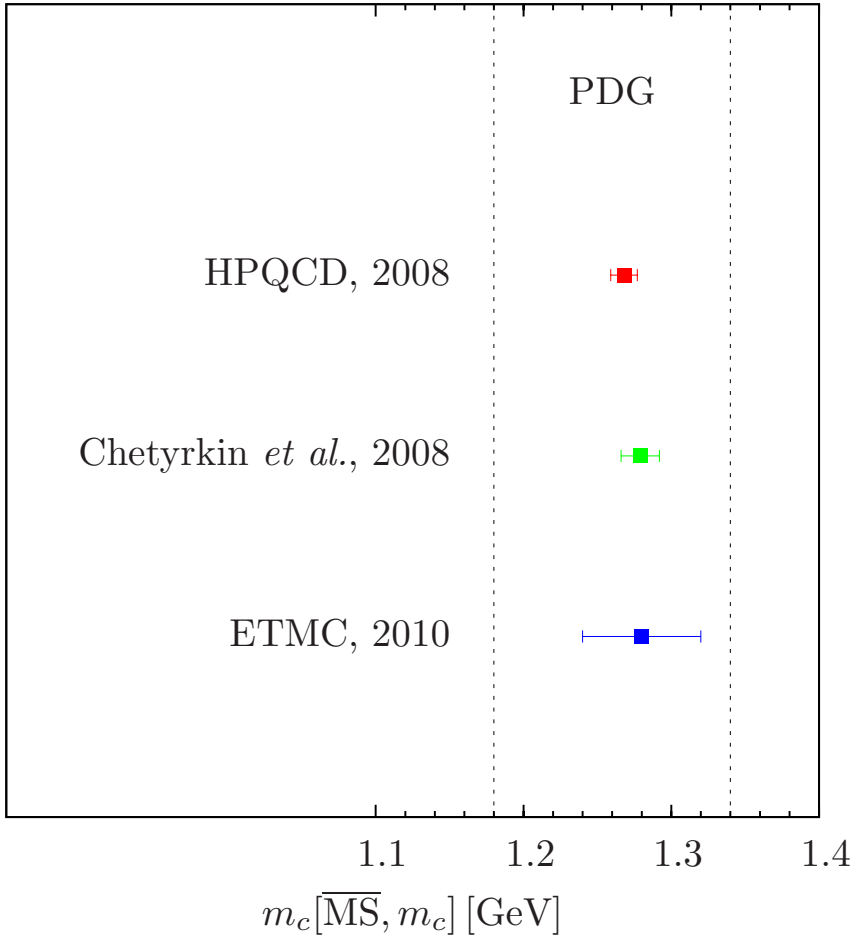
m_c

non exhaustive comparison of recent results



m_c

non exhaustive comparison of recent results

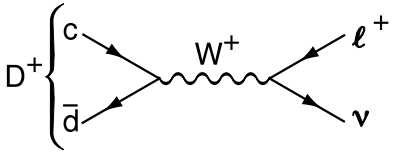


ETMC ongoing : determination of m_c from charm current correlators

[ETMC, Petschlies et al., LAT2011]

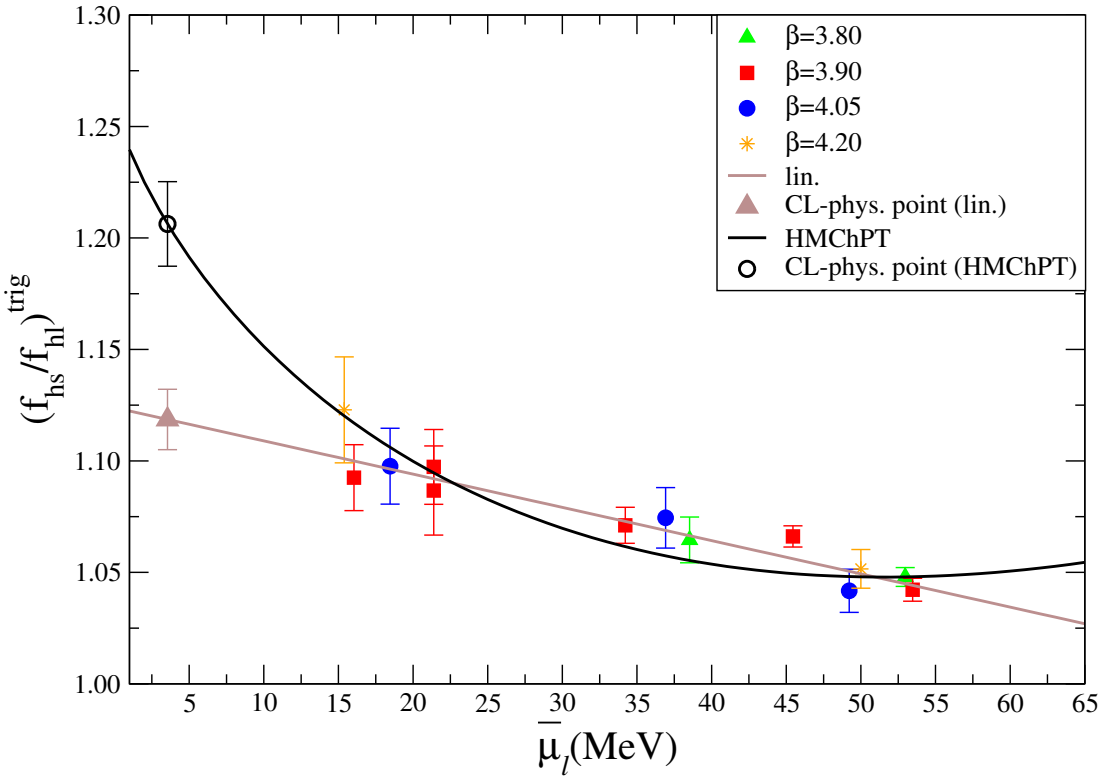
$N_f = 2$: f_D and f_{D_s}

$$\Gamma(D_s \to \ell\nu) \propto |V_{cs}|^2 \, f_{D_s}^2 \qquad \text{with} \qquad f_{D_s} p_\mu = \langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s(p)\rangle$$



$a = \{0.054,\ 0.067,\ 0.085,\ 0.098\}$ fm

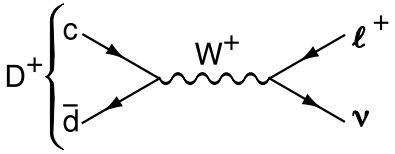
light-quark mass dependence : f_{D_s}/f_D vs. m_ℓ

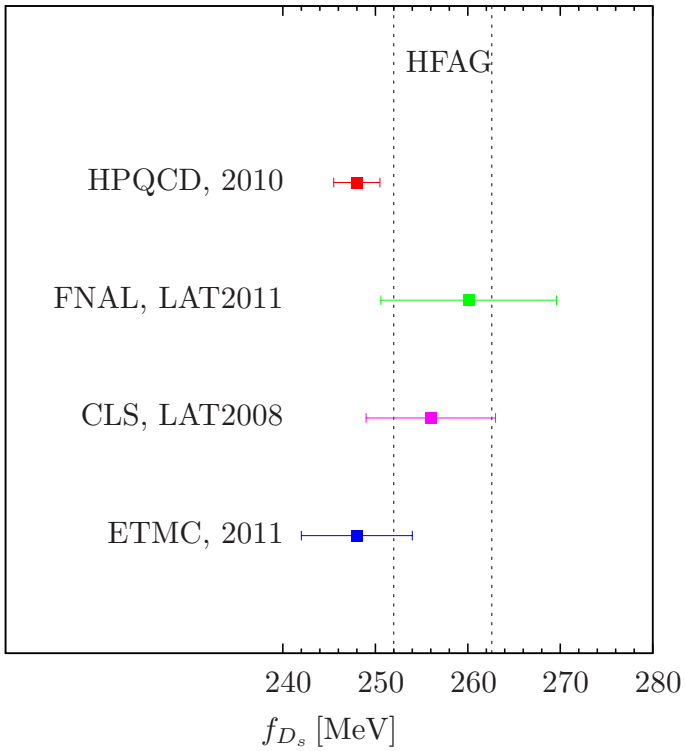


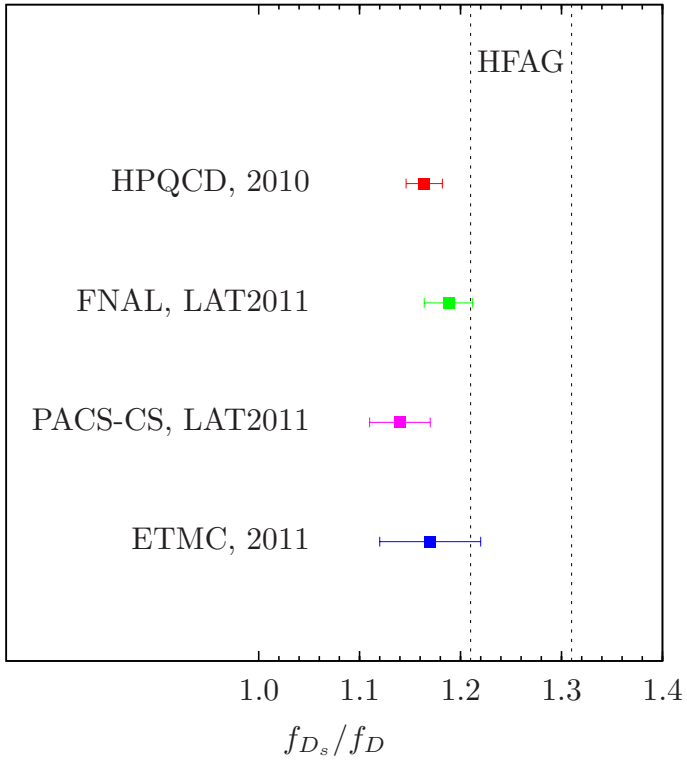
[ETMC, 2011]

f_D and f_{D_s} : comparison

$\Gamma(D_s \to \ell\nu) \propto |V_{cs}|^2 \, f_{D_s}^2$ with $f_{D_s} p_\mu = \langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s(p)\rangle$







$f_D = 212(8)$ MeV $f_{D_s} = 248(6)$ MeV $f_{D_s}/f_D = 1.17(5)$

$f_K/f_\pi = 1.21(2)$ $f_{B_s}/f_B = 1.19(5)$

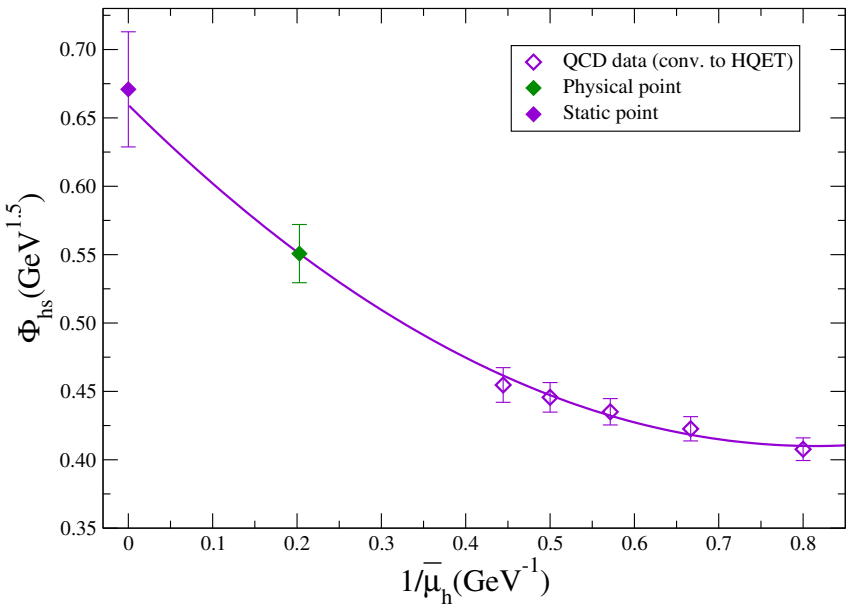
$f_\pi = 130.4$ MeV $f_K = 158(2)$ MeV $f_D = 195(12)$ MeV

$N_f = 2: \; B \to \ell\nu$

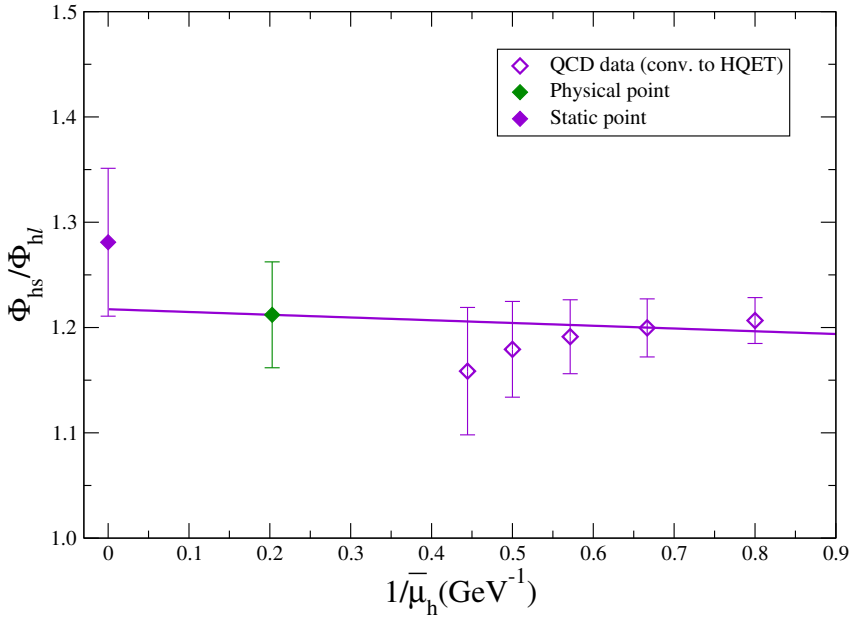
f_B : unitarity triangle $\rightsquigarrow$ tension between $\mathcal{B}(\mathcal{B}^+ \to \tau^+\nu_\tau)$, $|V_{ub}|$ and $\sin(2\beta)$

f_{B_s}

$f_{B_s} \times \sqrt{M_{B_s}}$



$(f_{B_s} \times \sqrt{M_{B_s}}) \,/\, (f_B \times \sqrt{M_B})$

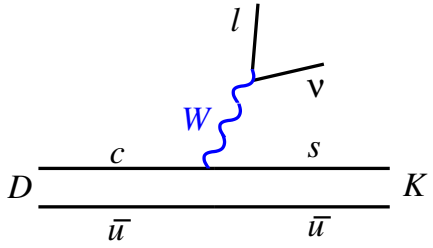


[ETMC, 2011]

$f_B = 195(12)$ MeV $\qquad f_{B_s} = 232(10)$ MeV $\qquad f_{B_s}/f_B = 1.19(5)$

$m_b[\overline{\mathrm{MS}}, \mu = m_b] = 4.29(14)$ GeV

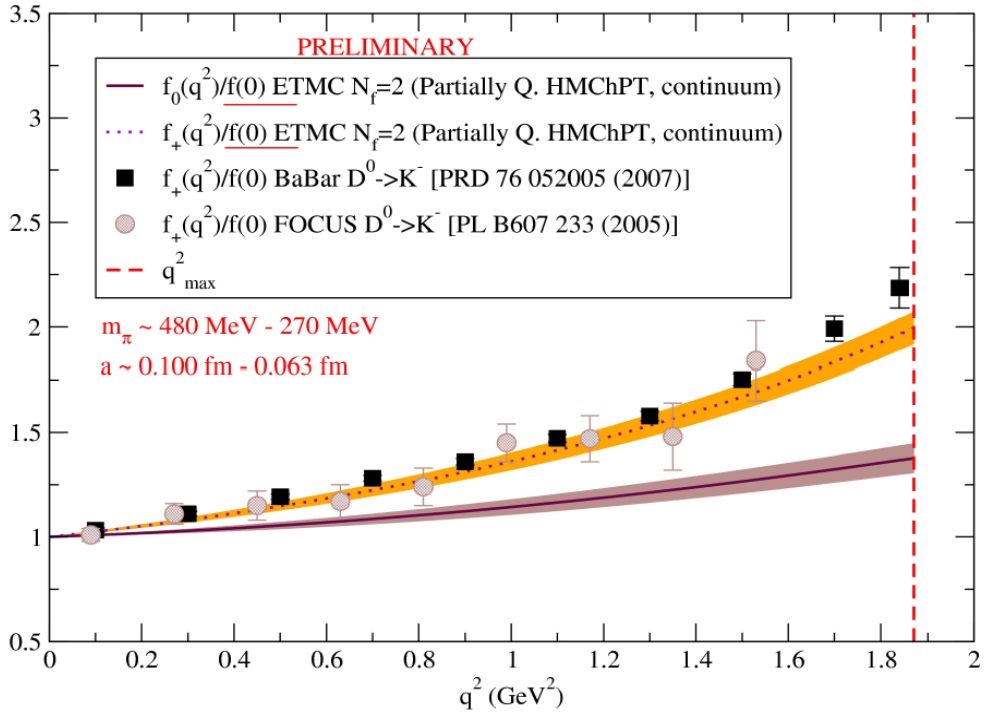
$N_f = 2$: semileptonic $D \to K$



$$\frac{d\Gamma}{dq^2}(D_s \to K\ell\nu_\ell) \propto |V_{cs}|^2 \, f_+(q^2)^2$$

$$\langle K(k)|\bar{q}\gamma_\mu c|D(p)\rangle = \left(p_\mu + k_\mu - q_\mu \frac{m_D^2 - m_K^2}{q^2}\right) f_+(q^2) + q_\mu \frac{m_D^2 - m_K^2}{q^2} f_0(q^2)$$

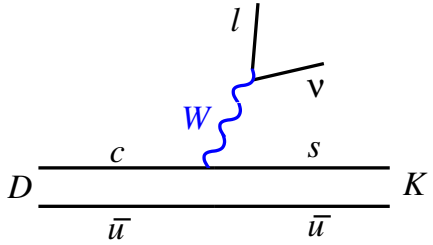
momentum transfer dependence of $f_+(q^2)/f_+(0)$



$a = \{0.067,\ 0.085,\ 0.098\}$ fm

[ETMC, S. Di Vita et al., LAT2010]

$N_f = 2$: semileptonic $D \to K$



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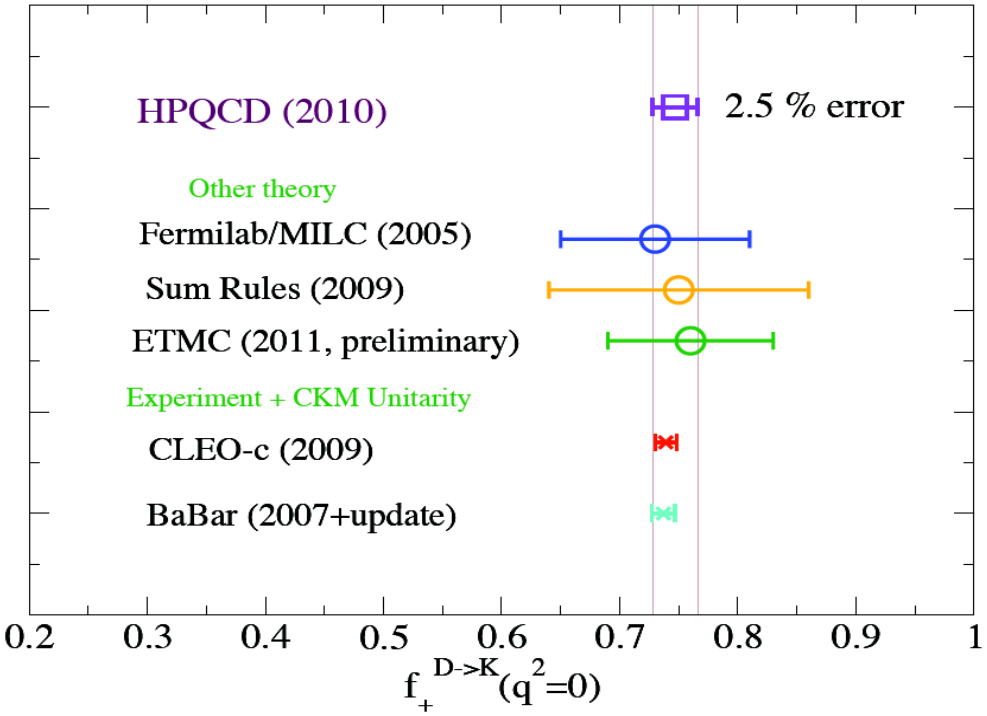
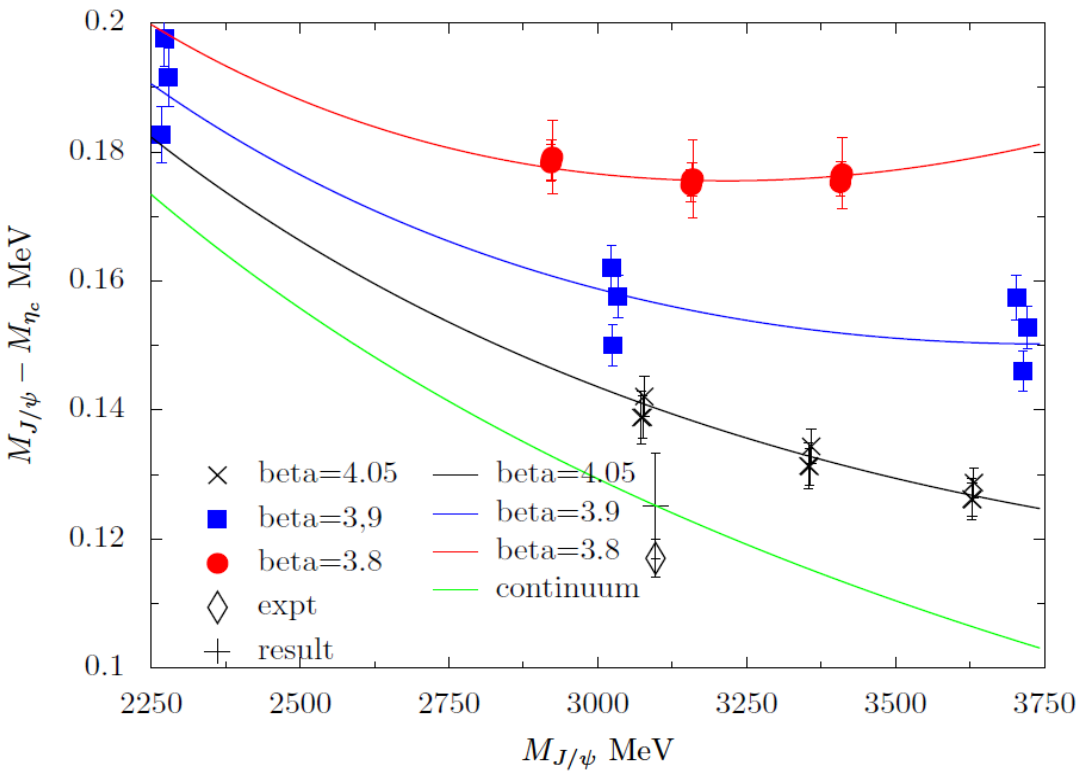


[Na et al., LAT2011]

ETMC results for $D \to \pi$ are also available [ETMC, S. Di Vita et al., LAT2010]

$N_f = 2$: hyperfine splitting

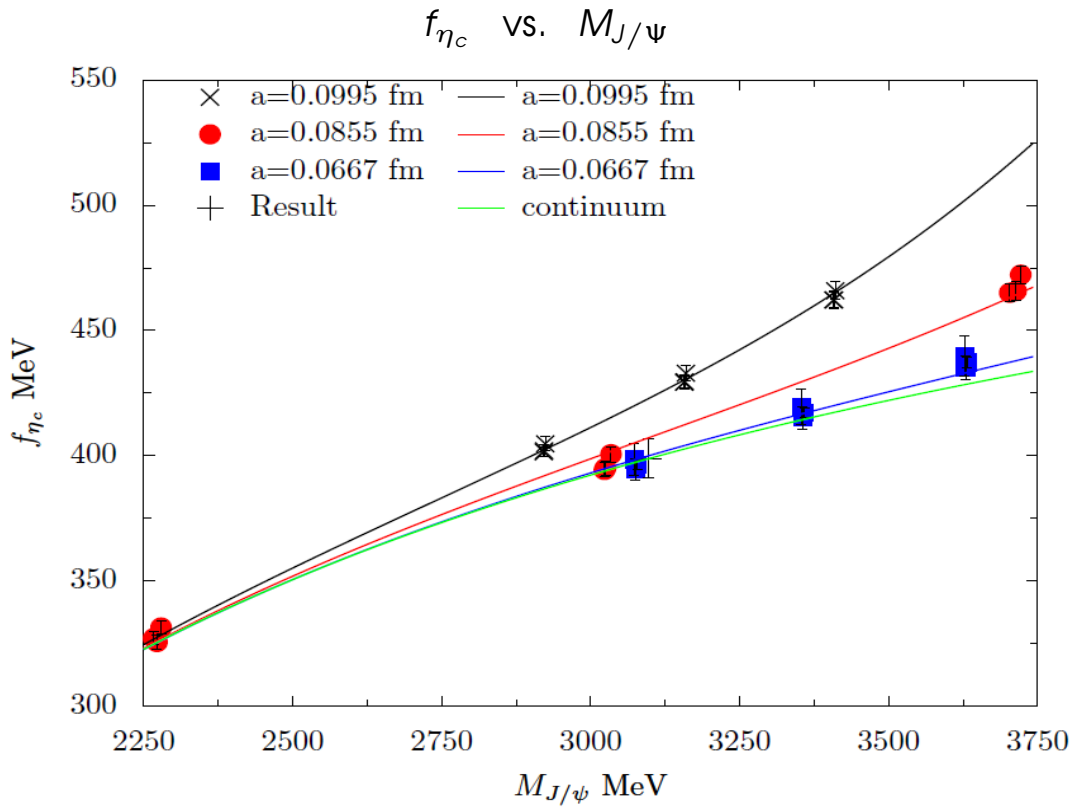
$M_{J/\Phi} - M_{\eta_c}$ vs. $M_{J/\psi}$



$a = \{0.067,\ 0.085,\ 0.098\}$ fm PRELIMINARY [ETMC, C. McNeile et al., LAT2008]

$N_f = 2$: η_c decay constant

$$\langle 0|\bar{c}\gamma_\mu\gamma_5 c|\eta_c\rangle = m_{\eta_c} f_{\eta_c} p_\mu$$



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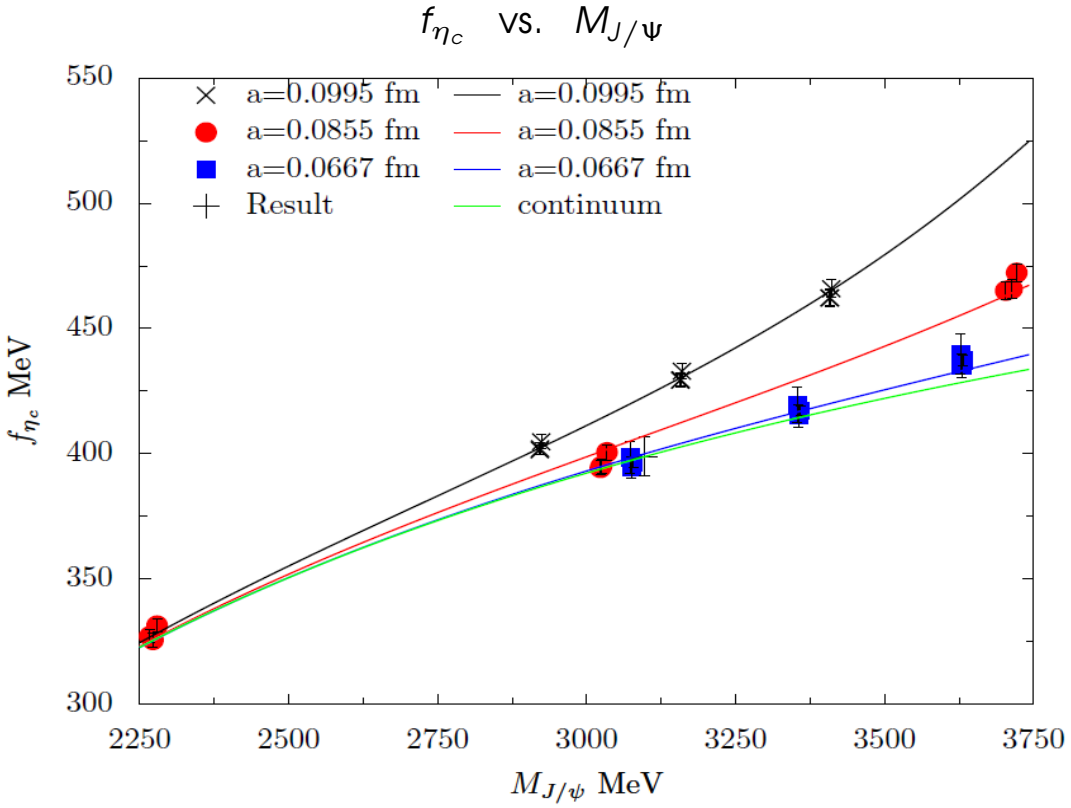


Recent study by [CLQCD, 2011] : $\langle h_f|J_\mu^{(\mathrm{e.m.})}|h_i\rangle$

η_c and χ_{c0} form factors

radiative decays: $J/\Psi \to \gamma\eta_c$, $\chi_{c0} \to \gamma J/\Psi$, $h_c \to \gamma\eta_c$

$N_f = 2 + 1 + 1$

u, d, c, s sea quarks

$N_f = 2 + 1 + 1$

u, d, s, c dynamical quarks with $m_u = m_d < m_s < m_c$

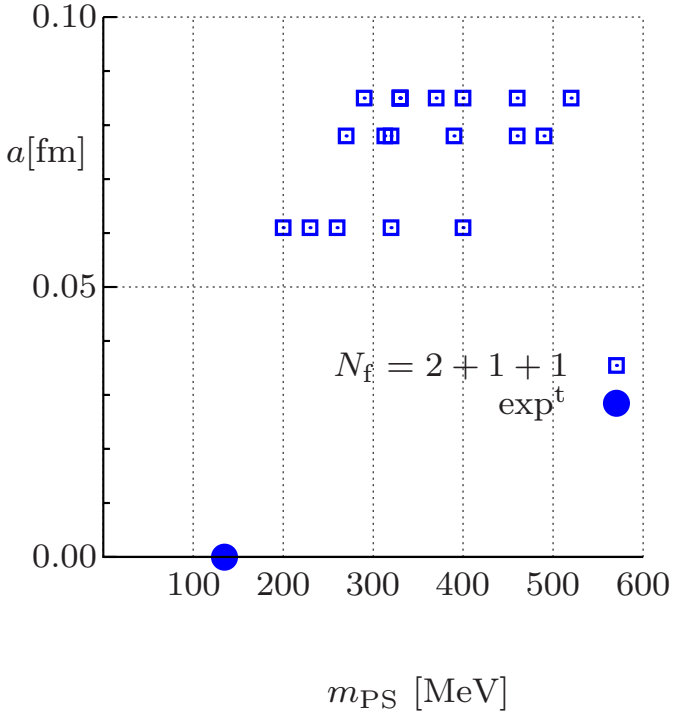
Motivations for including the dynamical charm?

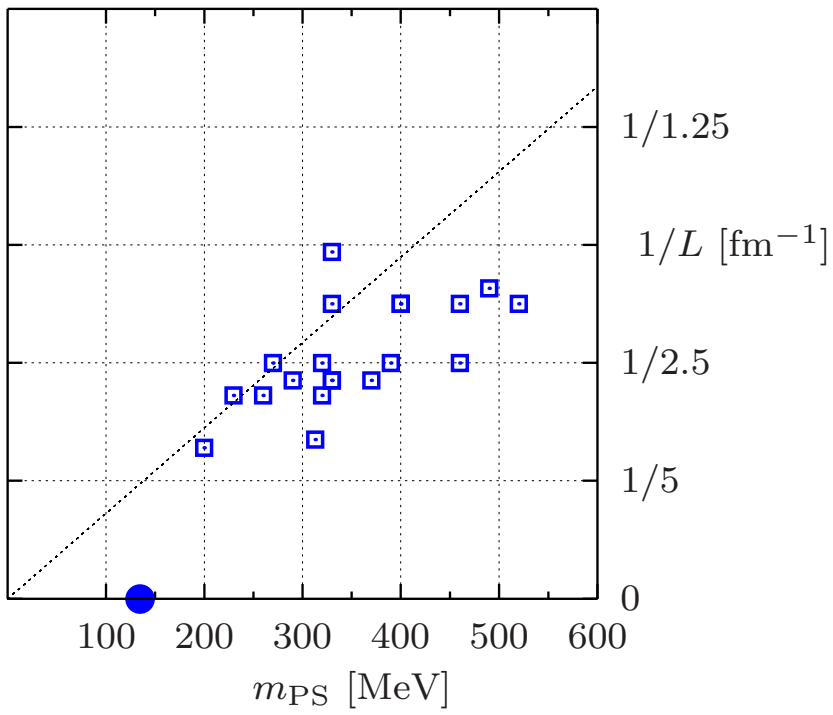
- expected effect $O(1/m_c^2)$ and $O(\alpha_S(m_c))$
- a dynamical quark is active at energy scales $E > m_q$
- running of renormalised quantities with $N_f = 4$
- matching to $\overline{\mathrm{MS}}$ with $N_f = 4$ at $\mu > m_c$
- explore physical effects dynamical c on hadronic masses and matrix elements
- remove so far uncontrolled systematic effect of the dynamical charm : relevant with increasing precision in lattice computations

$N_f = 2+1+1$ ETMC ensembles

- $a = \{0.06,\ 0.08,\ 0.09\}$ fm
- $L = \{1.9,\ 3.9\}$ fm , $m_{PS}L \gtrsim 3.5$
- $m_\pi \in \{200,\ 520\}$ MeV

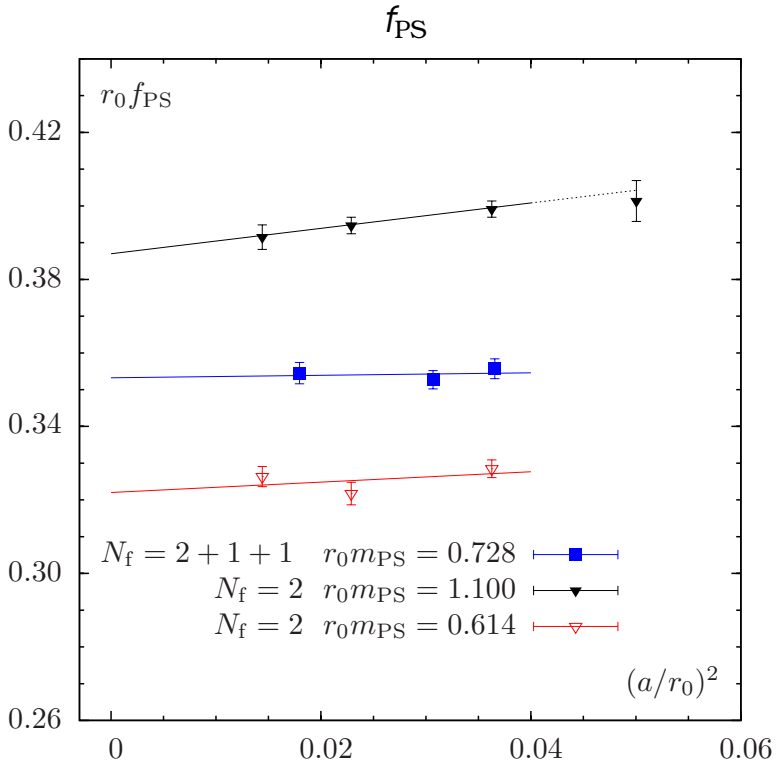
- m_s and m_c from $2m_K^2 - m_\pi^2$, m_D around physical values

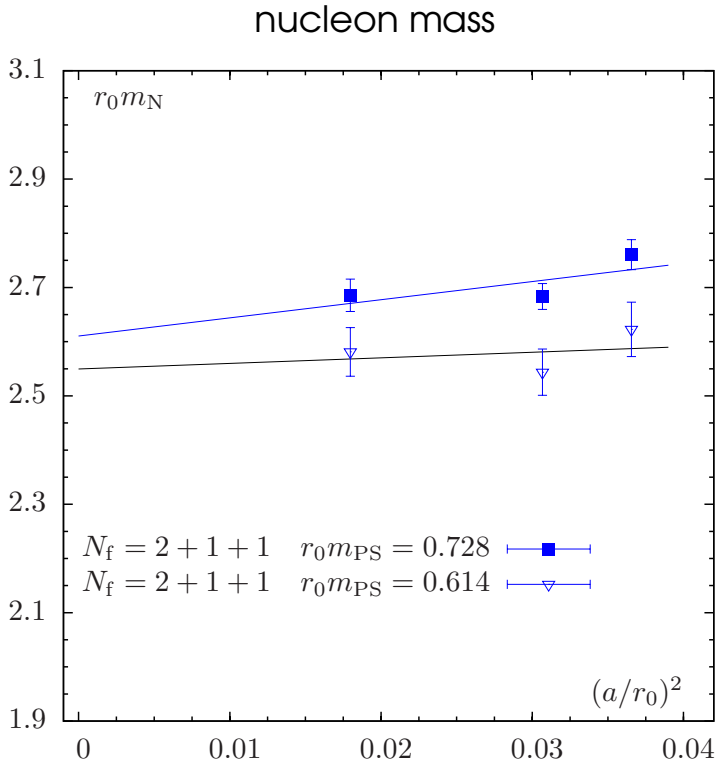




continuum limit scaling of f_{PS} and m_N

$N_f = 2+1+1 \quad a = 0.06,\ 0.08,\ 0.09$ fm



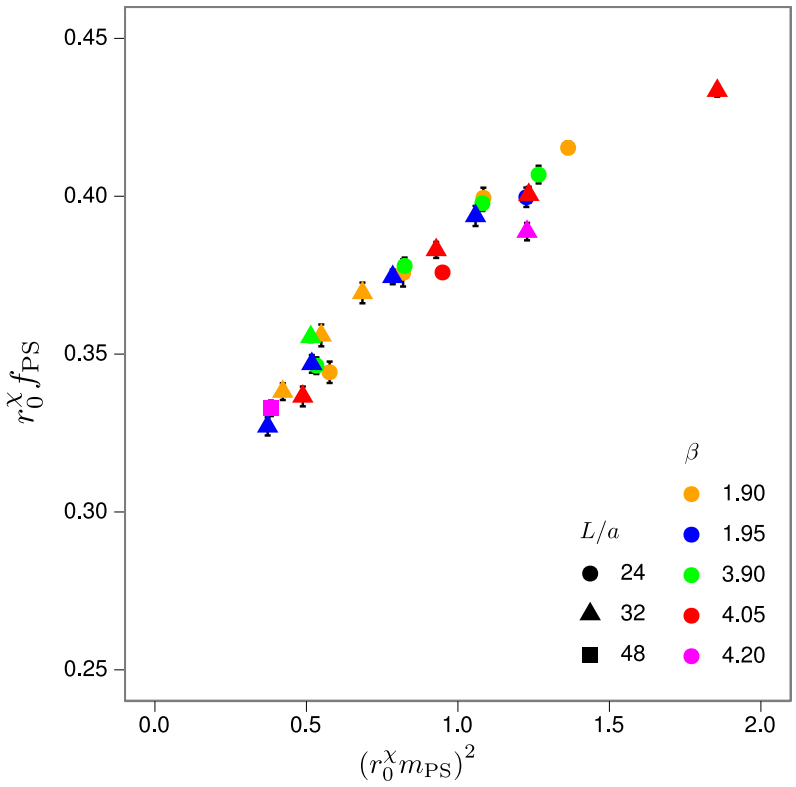


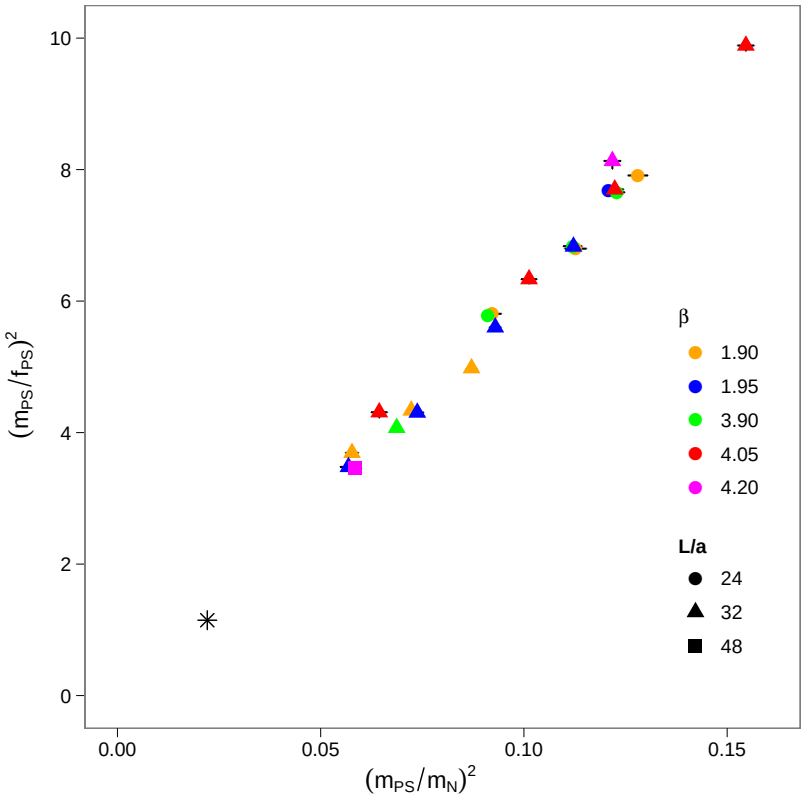
no signs of large $O(a^2)$ consistent with analyses by [MILC (2010), ALPHA (2011)]

$N_f = 2+1+1$: f_π , m_N

$N_f = 2+1+1$ and comparison to $N_f = 2$

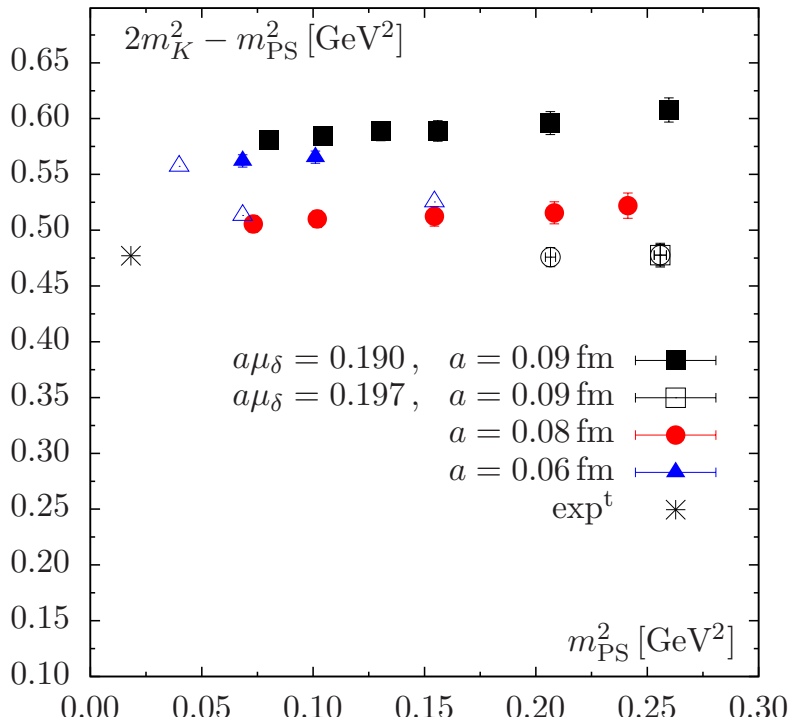
$a = 0.08,\ 0.09\,\mathrm{fm}$

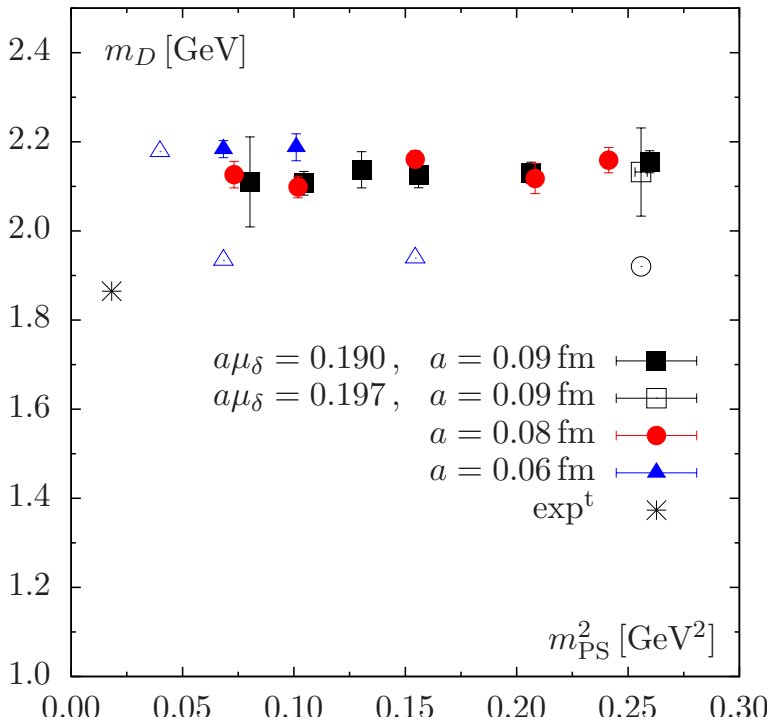




$N_f = 2+1+1$: tuning m_s and m_c

$a = 0.06,\ 0.08,\ 0.09$ fm





Conclusions

$N_f = 2$: heavy-quark physics

- determinations of m_c ,m_b
- f_D, f_{D_s}, f_B, f_{B_s}
- $D \to K$ and $D \to \pi$ semileptonic form factors
- charmonium : hyperfine splitting, decay constants
- charmed baryons

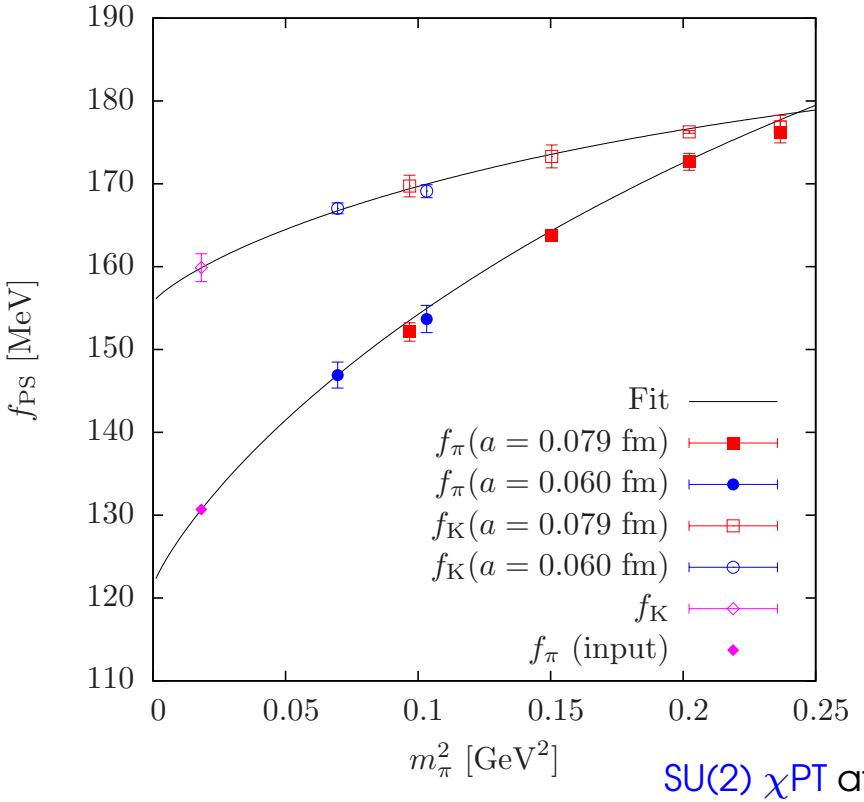
$N_f = 2+1+1$: dynamical charm quarks

- no clear signs of large cut-off effects from dynamical charm in light-quark observables
- ongoing : charm physics, charmonium spectrum, η' mass, nucleon matrix elements, $\langle N|\bar{s}s|N\rangle$ ...

$N_f = 2+1+1$: mixed action f_K

$a = 0.060,\ 0.079$ fm

f_K and f_π

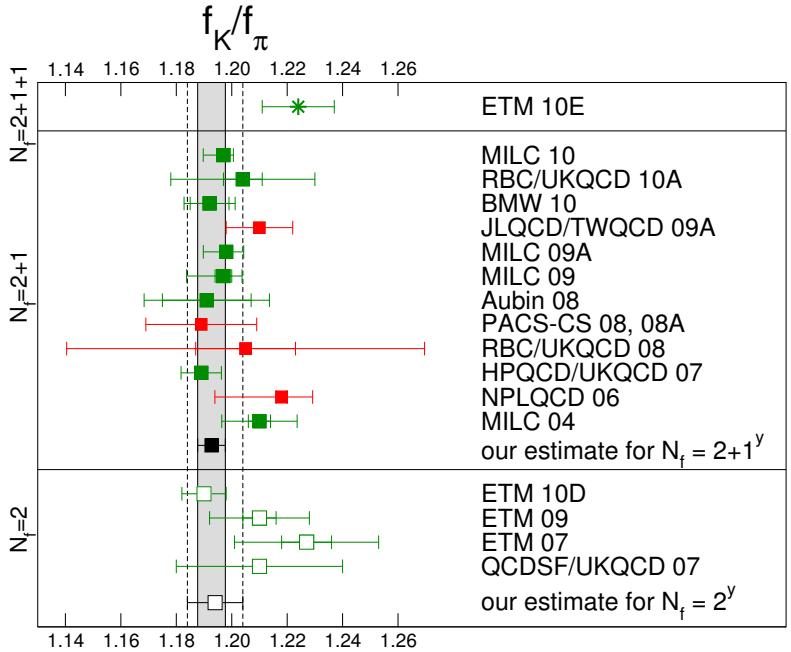


SU(2) χPT at NLO with analytic NNLO

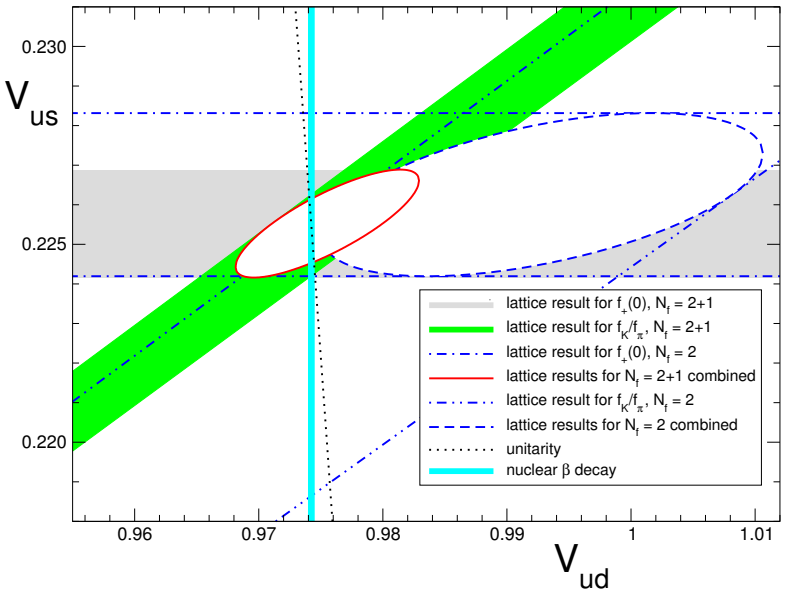
only π dof in the expansion $\rightsquigarrow$ $O(m_\pi^2/(4\pi f_0)^2,\ m_\pi^2/2m_K^2)$

PRELIMINARY $N_f = 2+1+1$ result : $f_K/f_\pi = 1.224(13)$ stat. errors only

f_K/f_π



(FLAG, 2011)



ETMC $N_f = 2+1+1$: (PRELIMINARY)

$$f_K/f_\pi = 1.224(13)$$

FLAG, 2011 :

$$f_K/f_\pi = 1.210(18) \qquad N_f = 2$$
$$f_K/f_\pi = 1.193(05) \qquad N_f = 2+1$$
$$|V_{us}| = 0.2254(9)$$
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = 0.002(15)$$

ongoing : B_K