Charm Physics from the Lattice

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Charm Physics on the Lattice has witnessed dramatic improvements and increased activity in recent years.

This has come about for several reasons.

— "fully relativistic" treatment of charm quarks now feasible and one is no longer reliant just on "effective theories".

— previous worries that $am_c = \frac{m_c}{cutoff}$ too large now overcome.

— more accurate, more highly improved lattice quark actions available today

— more simulations at smaller lattice spacings ($a \leq 0.12$fm)

— experimentalists are pushing (gently)

We have entered an era of precision charm physics on the lattice

This certainly is timely since experiments have witnessed impressive improvements as well.

OUTLINE

- **New Approaches to Charm, advantages etc.**
- D **and** D_s **Meson Leptonic Decays**
- D **Semileptonic Decays**
- **Quark Masses**
- **(Spectroscopy)**
- **Implications for** B **Physics**
- **Summary**

Charm Quarks on the Lattice

In the past mainly "effective theories"

NRQCD
HQET
"Heavy Clover" (Fermilab, Columbia, JLQCD)

In recent years "fully relativistic" approaches have become feasible due to high level of improvement.

HISQ (Highly Improved Staggered Quark) Action :
(HPQCD 2007)
all (am_c), $(am_c)^2$ lattice artifacts removed.
all $\alpha_s(am_c)^2$ and $(am_c)^4$ errors removed at leading order in v/c.

$\Longrightarrow$ most accurate quark action on market.

Other relativistic approaches use "Twisted Mass Wilson" or "Overlap" quark actions.

Advantages of Relativistic Formalism for both Charm and Light Quarks

- Operator matching in many cases is either unnecessary (decay constants, $f_0(q^2)$) or can be done nonperturbatively.

- PCAC and PCVC relations can be used to fix normalization of currents

- Quark masses can be tuned accurately. Mass ratios easily obtained

- The HISQ action, for instance, is also numerically fast

Actions used in Results presented in this Talk

	Fermilab/MILC	HPQCD	ETM
glue	MILC(AsqTad) $N_f = 2+1$	MILC(AsqTad) $N_f = 2+1$	Twist. Mass $N_f = 2$
light valence	AsqTad	HISQ	Twist. Mass
charm	heavy clover	HISQ	Twist. Mass

(AsqTad : Improved Stagg., HISQ : Highly Imp. Stagg.,
Twisted Mass : Wilson type)

Several new projects being pursued using rather different lattice actions and approaches.
Success of these Charm Physics projects will hopefully also influence future B Physics calculations as well.

DECAY CONSTANTS

Pseudoscalar Meson Decay Constants provide good testing grounds for Lattice QCD calculations versus experiment. They are often also important for extracting other phenomenologically relevant quantities.

— $\frac{f_K}{f_\pi} \Longrightarrow |V_{us}|$
consistency check of more traditional K_{l3} method.

— very interesting fruitful interplay between theory and experiment recently for f_D and f_{D_s}

— f_B and f_{B_s} very important (together with bag parameters) in CKM physics

— f_{B_s} relevant in many Beyond the SM expressions.

Decay constants are intrinsically nonpertubative QCD quantities defined through,

$\langle 0|A_\mu|PS\rangle = p_\mu f_{PS}$ ... needs Z_{A_μ}

or

$f_{PS} = \frac{m_1+m_2}{M_{PS}^2}\langle 0|J_5|PS\rangle$ ... if PCAC can be used

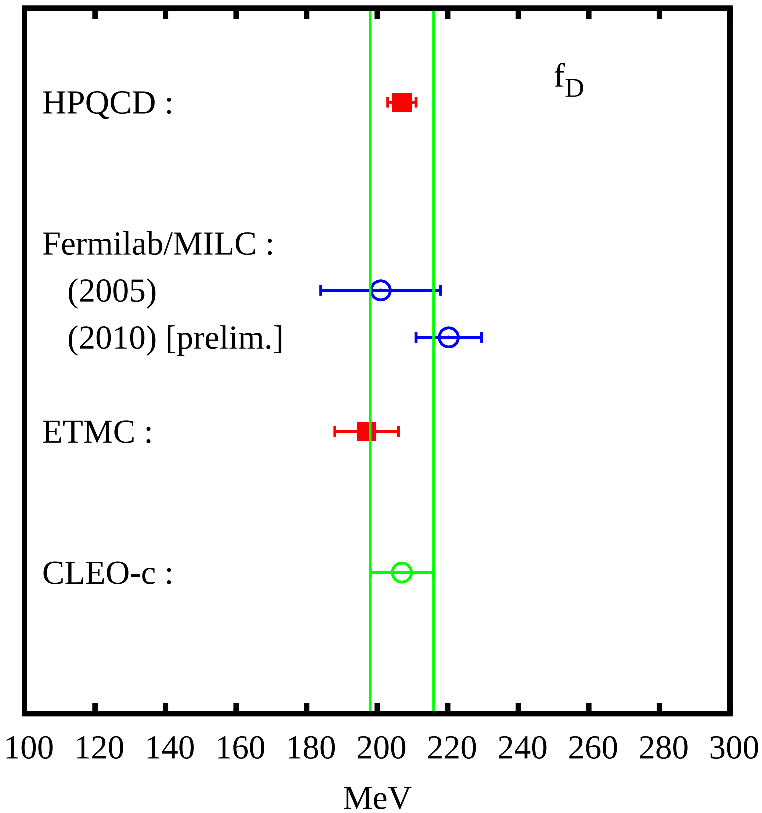
(no Z-factors needed)

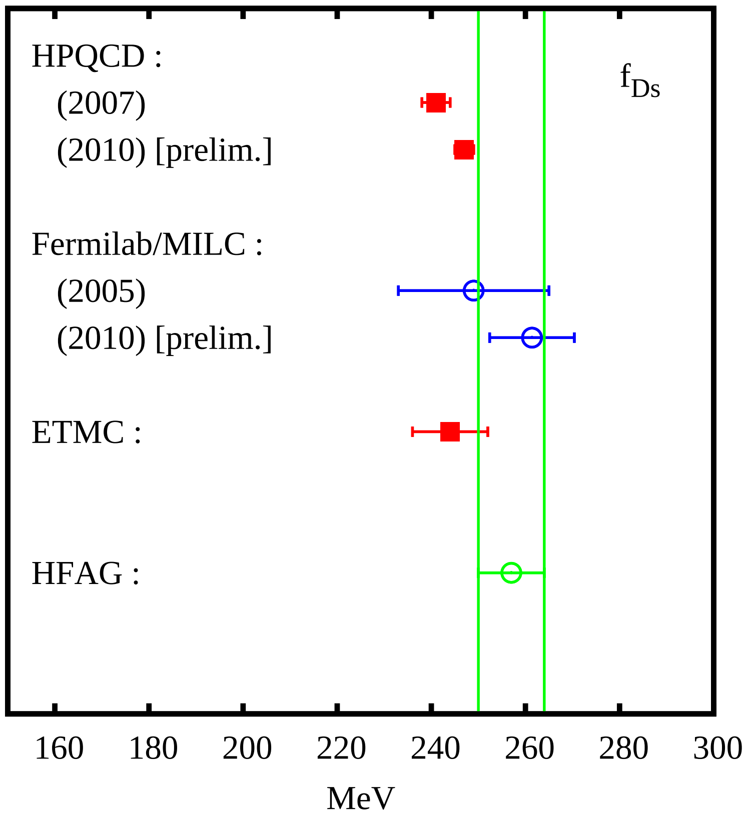
Results for Charmed Meson Decay Constants

Collaboration (year)	f_D (MeV)	f_{D_s} (MeV)	f_{D_s}/f_D
Fermlab/MILC (2005)	201 ± 17	249 ± 16	1.24 ± 0.07
Fermlab/MILC (2010) (preliminary)	220.3 ± 9.3	261.4 ± 9.2	1.187 ± 0.020
HPQCD (2007)	207 ± 4	241 ± 3	1.164 ± 0.011
HPQCD (2010) (preliminary)		247 ± 2	
ETM (2009)	197 ± 9	244 ± 8	1.24 ± 0.03

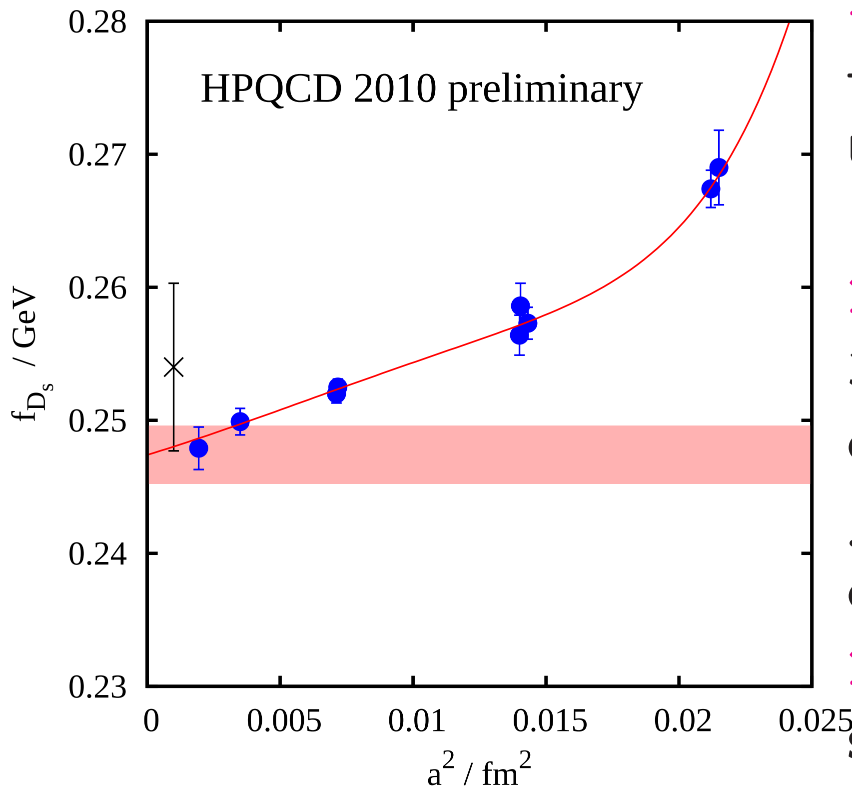
red numbers are preliminary

Charmed Meson Decay Constants (cont'd)





HPQCD's f_{D_s}



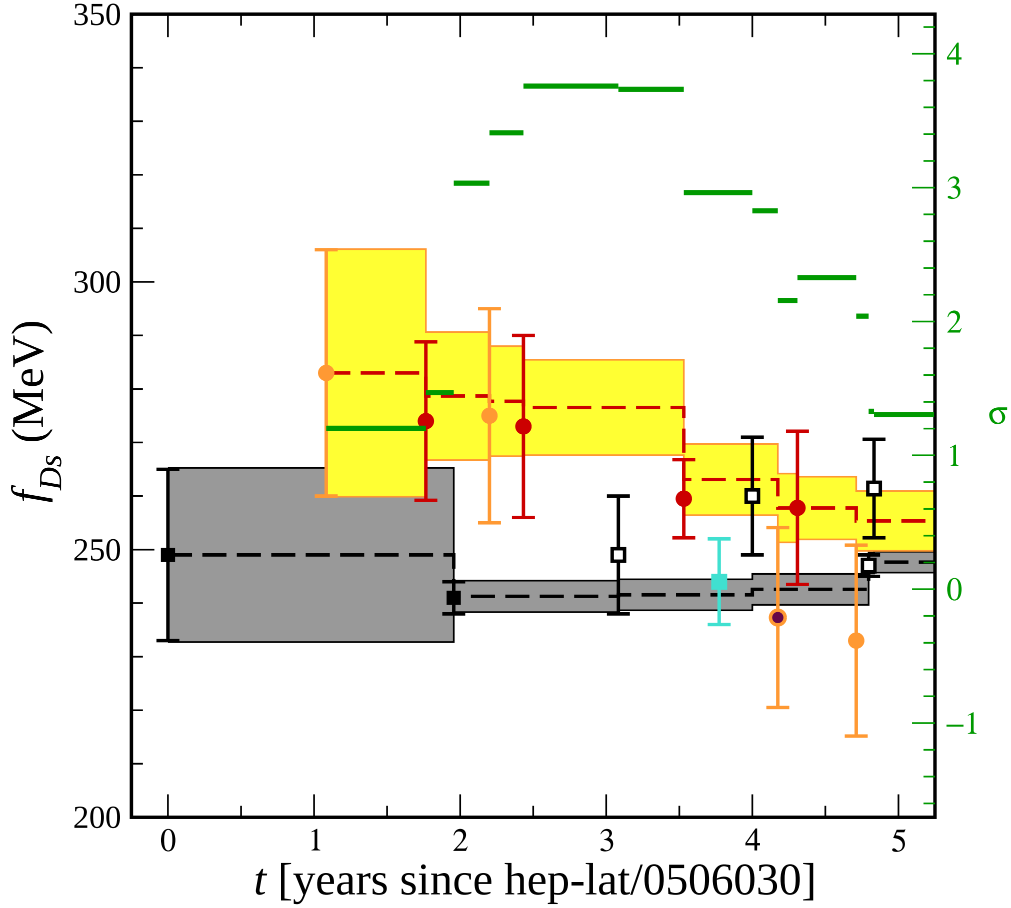
2007 3 lattice spacings (0.15 - 0.09fm). Largest source of uncertainty was the "**scale**" (from Υ 2S - 1S)

2009 new scale setting using 3 input quantities simultaneously (2S - 1S, $M_{D_s} - \frac{1}{2}M_{\eta_c}$, f_{η_s}). **Increase by $\sim 2.5\%$** (unexpectedly large shift)

2010 new f_{D_s} from 5 lattice spacings (0.15 - 0.045fm) with new scale

$\Longrightarrow f_{D_s} = 247(2)$**MeV (preliminary)**

History of the D_s Meson Decay Constant



Green: σ

Yellow: expt. average

Gray: lattice average

– Circles: expts.

– Squares: lattice

full: published

open: prelimin.

– cyan: 2 flavors

from Kronfeld,arXiv:0912.0543

D MESON SEMILEPTONIC DECAYS

Meson **Semileptonic Decays** allow for direct determination of **CKM** matrix elements

$B \to D^*(D) l\nu \quad |V_{cb}|$

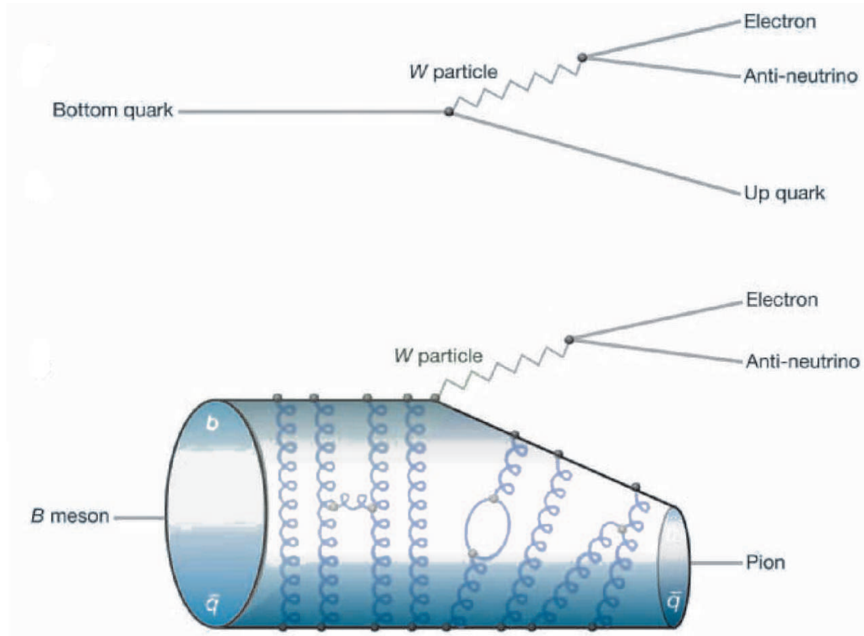
$B \to \pi l\nu \quad |V_{ub}|$

$D \to K l\nu \quad |V_{cs}|$

$D \to \pi l\nu \quad |V_{cd}|$

$D_s \to K^*(K) l\nu \quad |V_{cd}|$

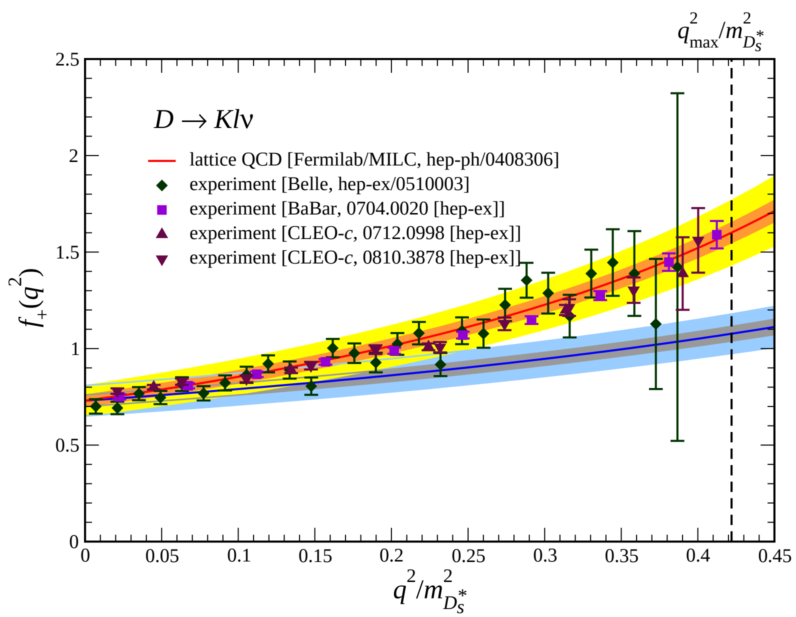
$K \to \pi l\nu \quad |V_{us}|$



provided certain nonperturbative QCD inputs from theory (**form factors**) are available.

D Semileptonic Decays with Heavy Clover Charm and AsqTad Light Quarks

(Fermilab Lattice and MILC Collaboration)



2004 Lattice prediction for shape of $f_+(q^2)$

Experimental verification in subsequent years (Belle, BaBar, CLEO-c)

Next goal is to significantly reduce lattice errors

$\sim 10\% \Longrightarrow \sim 4.5\%$

2010 in the process of analyzing new high statistics data.

D Semileptonic Decays with HISQ

Charm and Light Quarks

(HPQCD Collaboration)

$f_+(q^2 = 0)$ from the Scalar Current

Experimentalists have provided precise measurements of

$$f_+(0)\,|V_{cq}|$$

1.1% accuracy for $D \to K$ and 3.1% for $D \to \pi$.

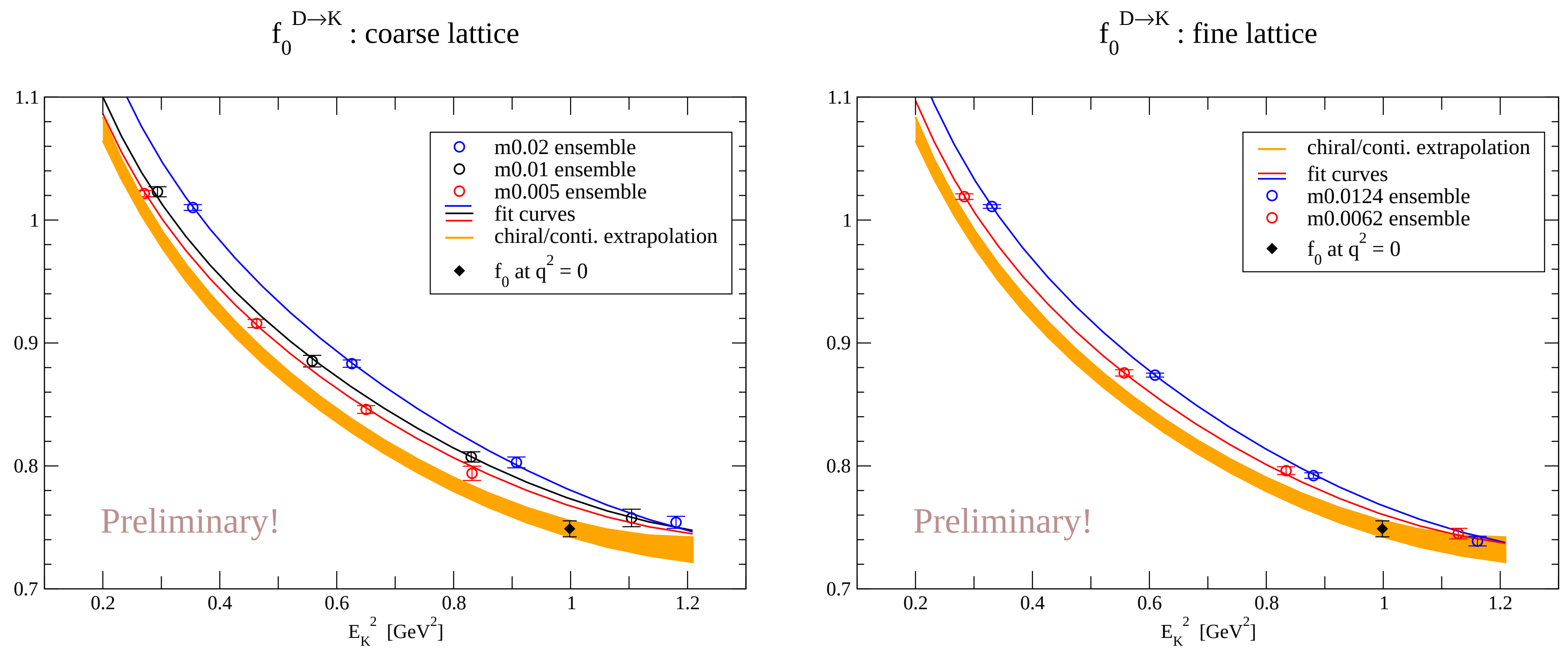
HPQCD's first priority is to obtain precision results for $f_+(0)$ and we will do so by exploiting the kinematic relation
$f_+(0) = f_0(0)$ and the relation $\langle S \rangle = \frac{m_D^2 - m_P^2}{m_c - m_q} f_0(q^2)$

$$f_0(q^2) = \frac{(m_c - m_q)\langle S \rangle}{m_D^2 - m_P^2}$$

($S \equiv \overline{\Psi}_q \Psi_c$)
No Z-factors required for this calculation.

Chiral/Contin. Extrap. from Simult. Fits to All Data

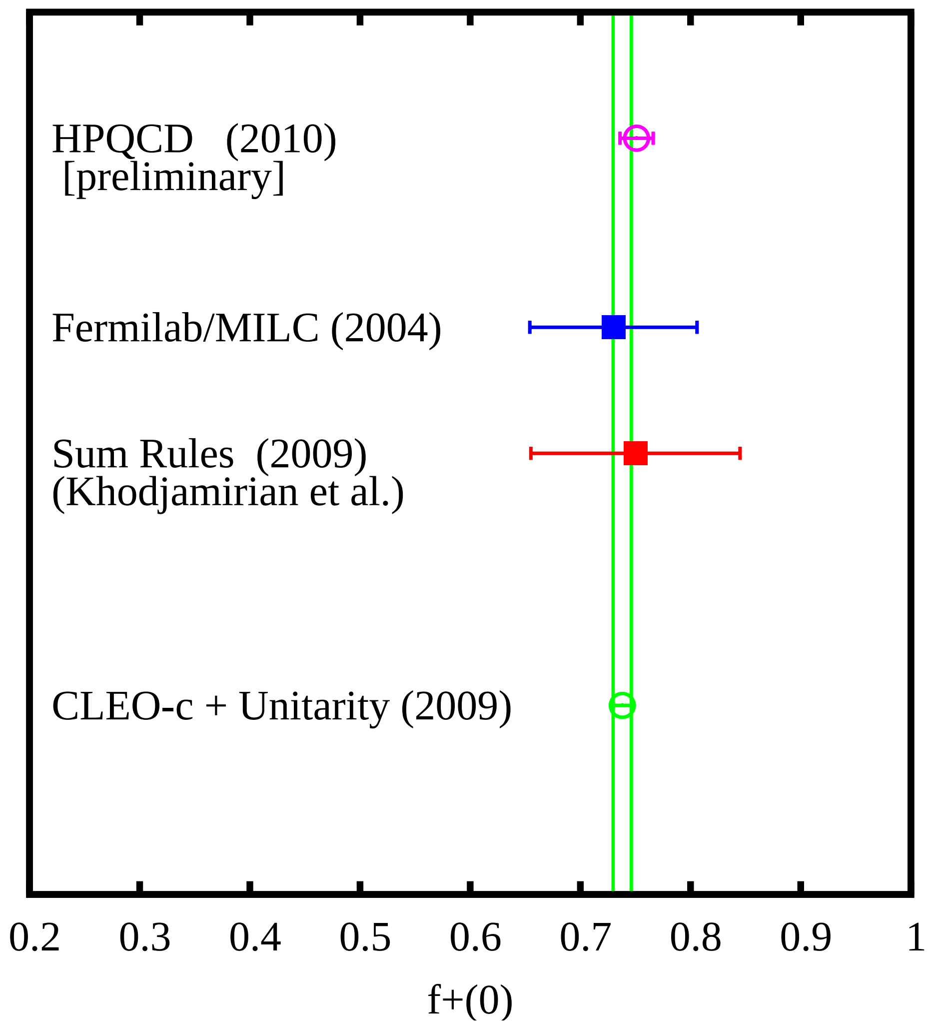
(Heechang Na, HPQCD)



HPQCD is still in the process of finalizing chiral/continuum extrapolations.

Nevertheless already clear that significant reduction in theory errors for $f_+(0) \equiv f_0(0)$ will be achieved.

Preliminary Result for $f_+^{D\to K}(0)$ and Comparisons

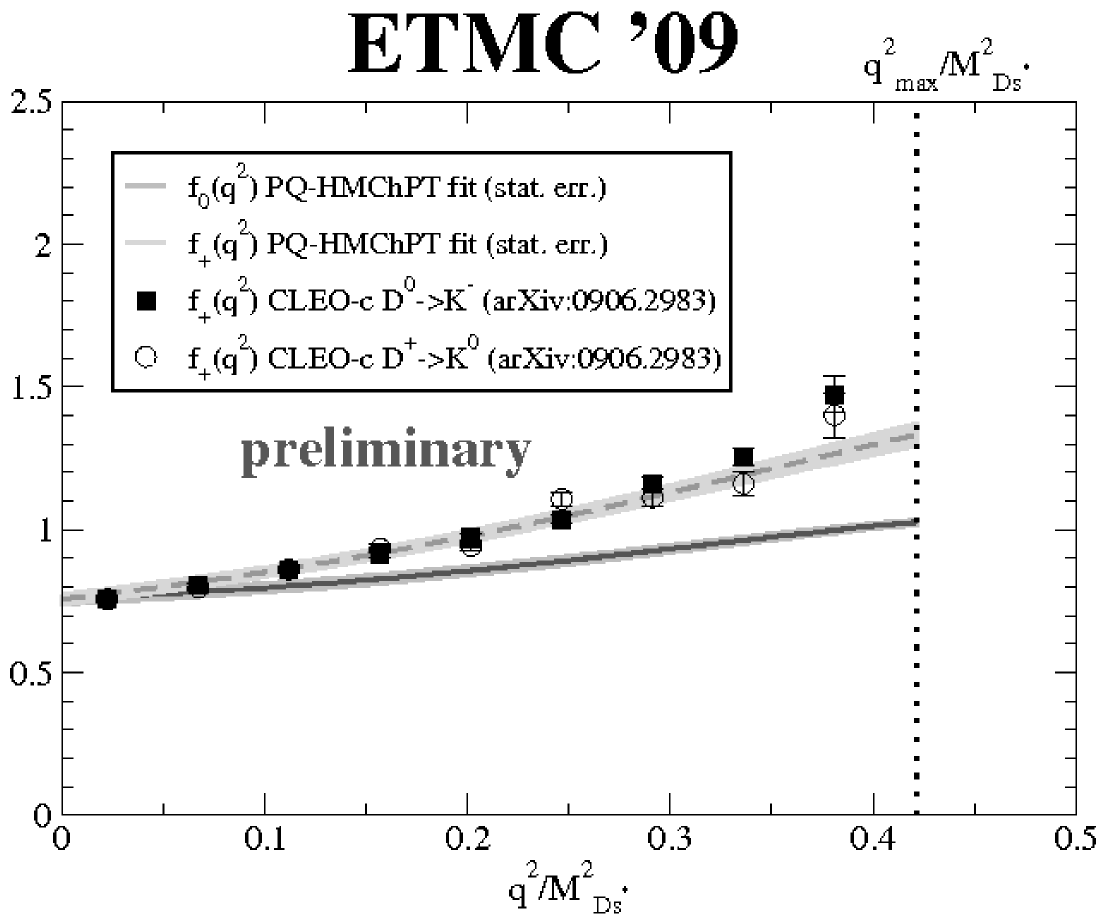


$\Longleftarrow$ theory errors reduced by factor $\sim$5

$\Longleftarrow$ uses $|V_{cs}| \approx |V_{ud}|$

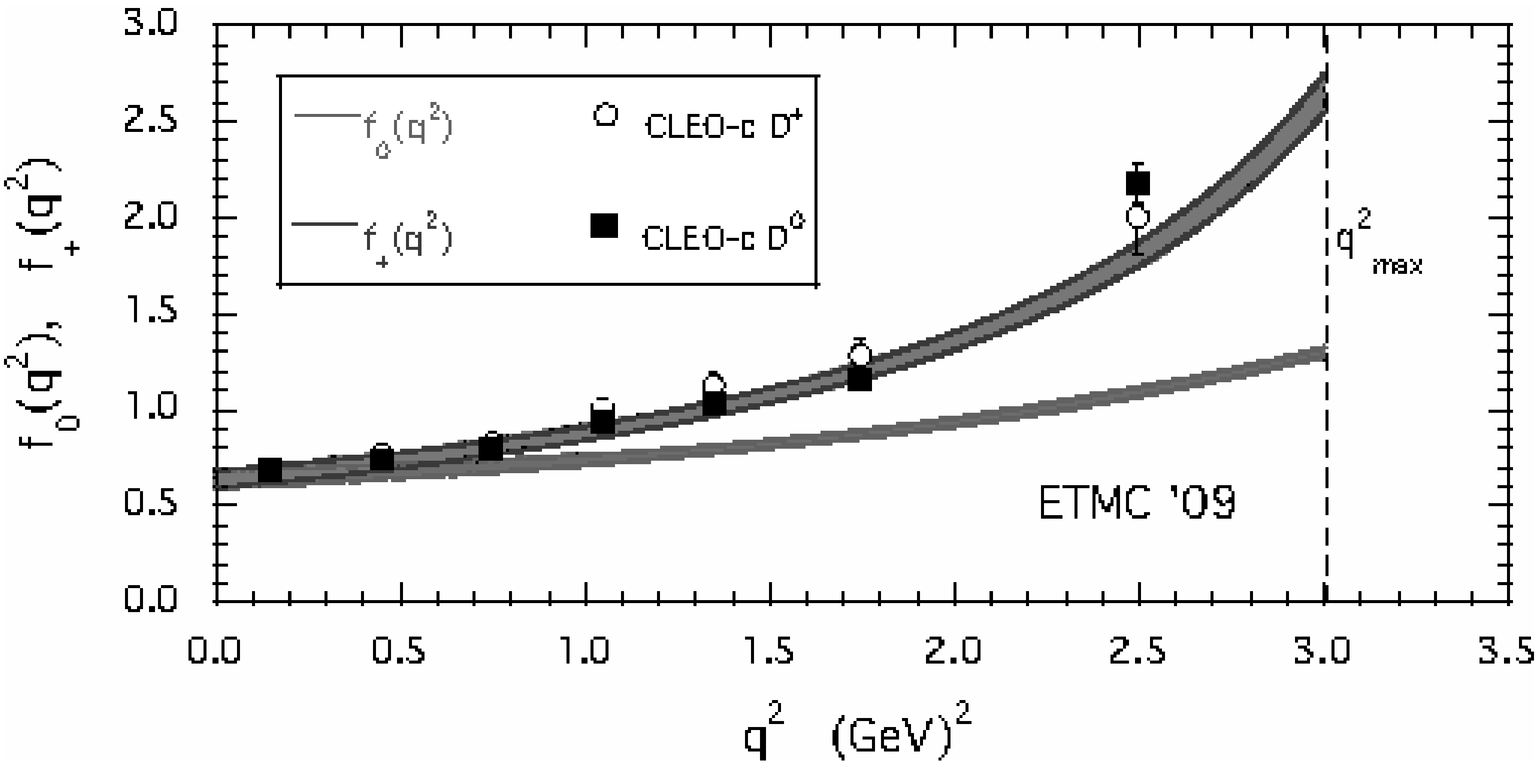
D Semileptonic Decays with Twisted Mass Quarks

$N_f = 2$



$D \to K$

$D \to \pi$ FF from ETMC and Comparison with CLEO-c arXiv:0906.2983 [hep-ex]



After chiral extrapolation at single 0.088fm lattice spacing
$f_+^{D\pi}(0) = 0.64 \pm 0.05$, $f_+^{DK}(0) = 0.76 \pm 0.02$
(statistical errors only)

Calculations at two further lattice spacings underway.

QUARK MASSES

Quark Masses from Lattice Simulations

Quark masses are free parameters of the Standard Model. They cannot be predicted from theory but must be determined from a combination of experimental and theory inputs.

One popular approach :

— Tune the bare mass m_0 in the lattice QCD action such that hadron masses agree with experiment.

— Convert the bare lattice mass to the $\overline{\mathrm{MS}}$ scheme

$$m^{\overline{\mathrm{MS}}}(\mu) = Z_m(\mu) m_0$$

— $Z_m(\mu)$ is evaluated either perturbatively (2-loop lattice + high order continuum) or using nonperturbative methods.

New Approach: Charm Mass from J-J Correlators

— No lattice perturbation theory or non-perturbative matching involved

— Compute t^n moments for correlators

$$G(t) = \sum_{\vec{x}} m_c^2 \langle 0 | J_5(\vec{x}, t) J_5(0,0) | \rangle$$

$J_5 = \overline{\Psi}_c \gamma_5 \Psi_c$

— Exploit very high order (3 or 4 loop) continuum perturbation theory results.

(Karlsruhe Group: Chetyrkin, Kuehn, Steinhauser, Sturm)

— Extract $\boxed{\frac{m_{\eta_c}}{2\overline{m}_c(\mu)}}$ $\boxed{\alpha_{\overline{MS}}(\mu)}$

Results for Quark Masses

(HPQCD Collaboration)

One finds :

$\boxed{m_c(3GeV) = 0.986(6)GeV}$ $\boxed{m_c(m_c) = 1.273(6)GeV}$

Previously Kuehn et al, using e^+e^- data, found
$m_c(3GeV) = 0.986(13)GeV$.

Using the same HISQ action for both charm and strange quarks allows for accurate determination of the mass ratio,

$$m_c/m_s = 11.85(16) \Longrightarrow \boxed{m_s(2GeV) = 92.2(1.3)MeV}$$

Use same method with *relativistic b-quarks*.
An extrapolation $m_H \to m_b$ from $m_H < m_b$ was required.

$$\Longrightarrow \boxed{m_b(m_b) = 4.164(23)GeV}$$

Compare with Kuehn et al. $m_b(m_b) = 4.163(16)GeV$.

Implications for B Physics

Most work with b-quarks to date have employed

Heavy Clover (Fermilab/MILC, RBC)

NRQCD (HPQCD)

Given the success with relativistic Charm can one contemplate "relativistic Bottom"?

near future

"relativistic heavy-quarks" + "effective theories"

HPQCD : relativistic b for B_s system. Look at quantities that do not require large volumes or light valence quarks (can go to small lattices spacings $<$ 0.045fm). Combine with precision ratios (e.g. f_{B_s}/f_B) from NRQCD b-quarks to get to B physics
(P.Lepage; USQCD All Hands Meeting 2010)

Hybrid Approaches (cont'd)

Fermilab/MILC: relativistic charm for f_{D_s}, f_D etc. Combine with ratios such as f_B/f_D from effective theory.
(C.Bernard; Lattice Meets Experiment Workshop 2010)

ETM: combine relativistic charm with information from HQET. Interpolate between charm and $M_H \to \infty$ static theory to bottom quarks.
(B.Blossier et al.;arXiv:0909.3187)

Other Lessons

Precision experimental and theoretical work in Charm Physics has already taught us a lot and is helping us test methods we are applying to B Physics. Charm physics is providing existence proofs of what precision flavor physics on the lattice should look like.

Summary

- Charm Physics on the Lattice has entered a "precision era". The accuracy achieved in decay constant and form factor calculations ($1 \sim 2$%) is a major step forward.

- Not coincidently, this has occured in large part due to "relativistic charm" quark approaches, in particular the HISQ action.

- Many lessons here for B Physics. Will immediately impact studies of B leptonic and semileptonic decays.

- Much work remains. e.g. spectroscopy, $D - \overline{D}$ mixing and implications for B mixing, ...

We are extremely grateful to the Experimental Community for keeping us on our toes and pressing constantly to reduce Lattice errors. We look forward to continued productive and enjoyable interactions for many more years to come.

Thank You !