D→Klν **semileptonic decay using lattice QCD with HISQ at physical pion masses**

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With HPQCD collaboration:

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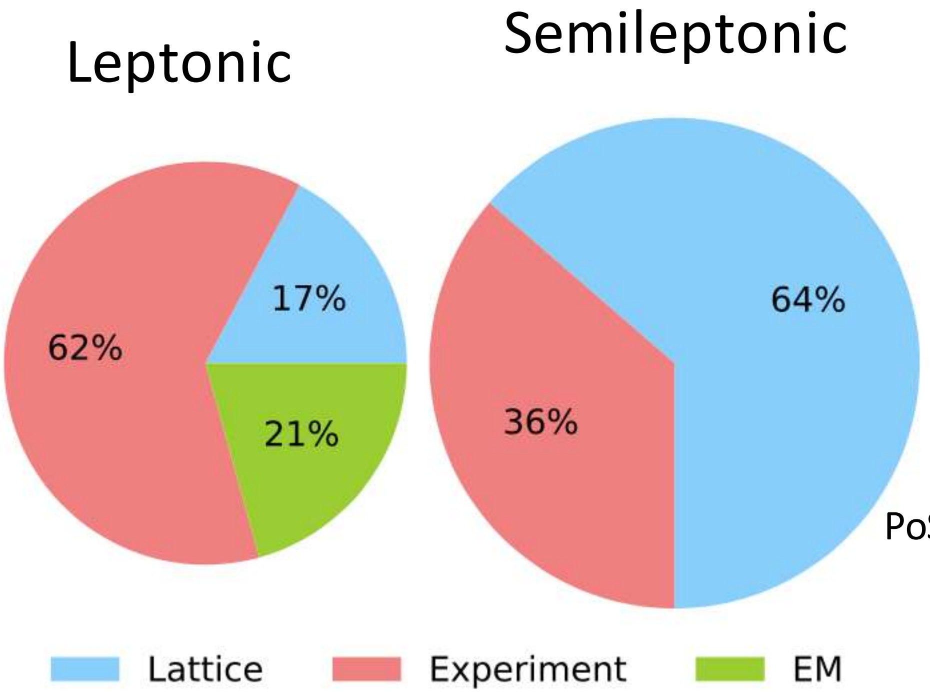

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

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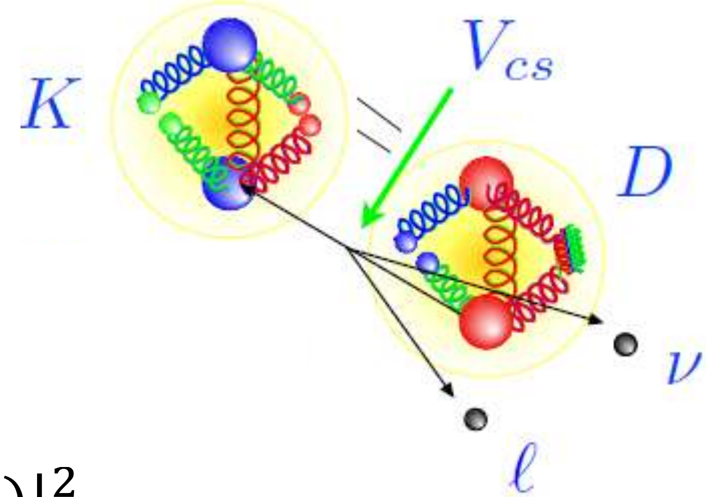
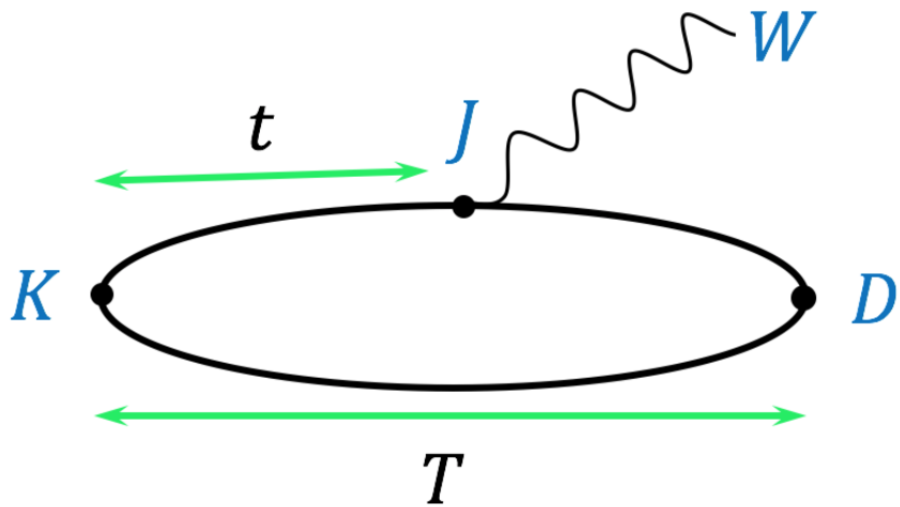


Comparison of $|V_{CS}|$ Error-
Radius proportional to total error

$$\frac{d\Gamma^{D\to K}}{dq^2} = \frac{G_F^2 p^3}{24\pi^3} |V_{CS}|^2 |f_+^{D\to K}(q^2)|^2$$



$$\langle K^- l^+ \nu | J_W | D^0 \rangle = \frac{G_F}{\sqrt{2}} V_{cs} \bar{v}(l) \gamma_\mu (1-\gamma_5) u(\nu) \langle K^- | \bar{\psi}_s \gamma_\mu (1-\gamma_5) \psi_c | D^0 \rangle .$$

$$\langle H_\mu \rangle = \langle K^- | \bar{s} \gamma_\mu (1-\gamma_5) c | D^0 \rangle$$

Lattice formalism

$$Z_{V,t} \times \langle K^- | V^\mu | D^0 \rangle = f_+^{D\to K}(q^2)[p_D^\mu + p_K^\mu - \frac{M_D^2 - M_K^2}{q^2} q^\mu] + f_0^{D\to K}(q^2) \frac{M_D^2 - M_K^2}{q^2} q^\mu$$

$$\langle K | V^\mu | D \rangle = f_+^{D\to K}(q^2) \left[p_D^\mu + p_K^\mu - \frac{M_D^2 - M_K^2}{q^2} q^\mu \right] + f_0^{D\to K}(q^2) \frac{M_D^2 - M_K^2}{q^2} q^\mu \quad \to f_0(0) = f_+(0)$$

$$\langle K | S | D \rangle = f_0^{D\to K}(q^2) \frac{M_D^2 - M_K^2}{m_{0_c} - m_{0_s}}$$

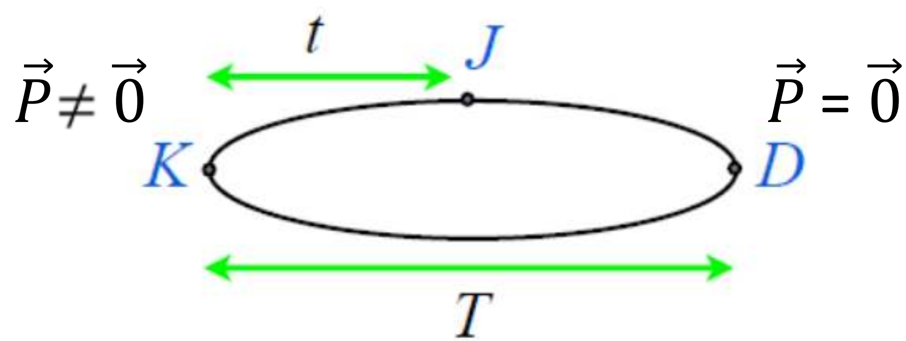
$$q^\mu = p_D^\mu - p_K^\mu$$

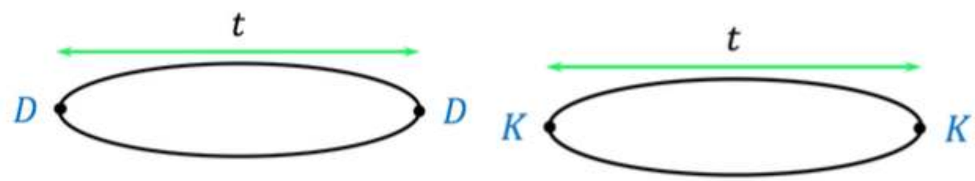
$$q^2 = q^2_{\max} = (M_D - M_K)^2 :$$

$$\begin{aligned} Z_{V,t} \times \langle K^- | V^0 | D^0 \rangle &= f_+^{D\to K}(q^2)[M_D + M_K - (M_D + M_K)] \\ &\quad + f_0^{D\to K}(q^2)(M_D + M_K) \\ &= (M_D + M_K) \times f_0^{D\to K}(q^2_{\max}) \end{aligned}$$

Extract

- Local temporal vector current
- Non-goldstone D meson for that – local $\boldsymbol{\gamma_0\gamma_5}$
- "Sequential technique" for three-points correlators



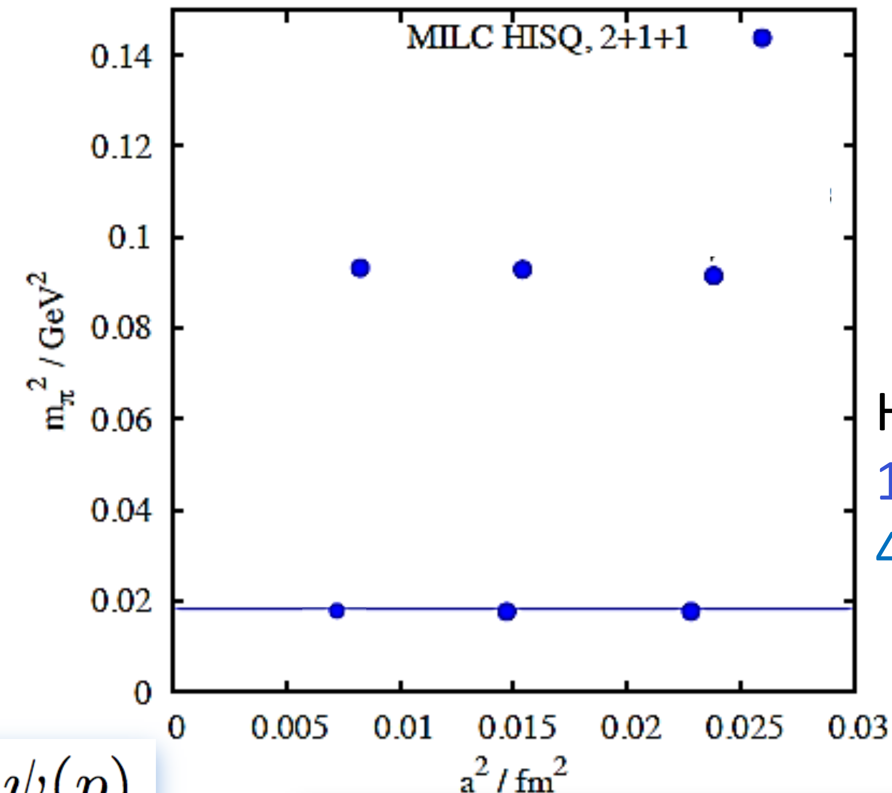


Analysis Ingredients

MILC configurations : up/down, strange, charm quarks in the sea: $m_u = m_d$

Multiple $m_{u/d}$
Including physical

Valence strange and charm quark masses tuned accurately



Lattice spacing
a ~ 0.09 -0.15 fm

High statistics:
1,000 configurations,
4-16 time sources

Twisted boundary Conditions:

$$\psi(p + L_\mu \hat{\mu}) = e^{i\theta_\mu}\psi(p).$$

Random wall sources:

$$\eta(i_t) = \begin{cases} e^{i\theta} & \text{for } i_t = t_0, \\ 0 & \text{for } i_t \neq t_0. \end{cases}$$

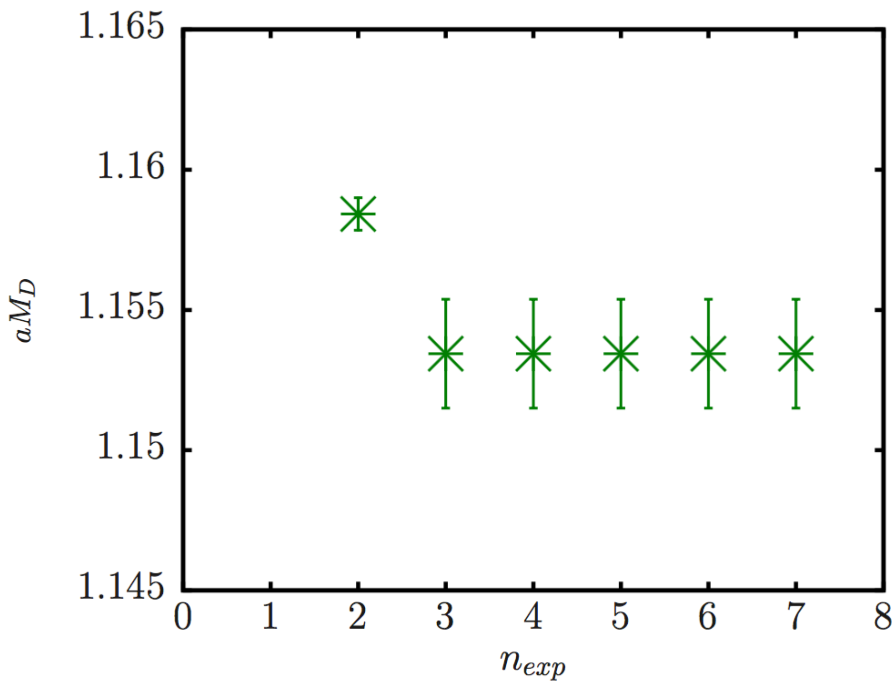
$$\langle \eta^\dagger(i')\eta(i)\rangle = \delta_{ii'}$$

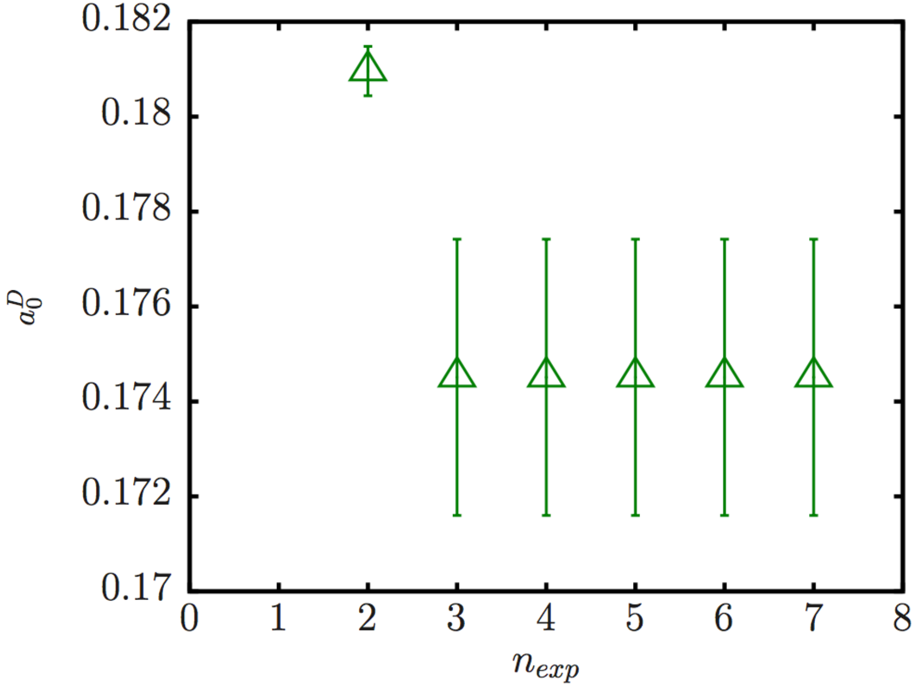
Multi-exponential Bayesian fitting

$$G^{2\text{pt}}(t;\vec{p}) = \sum_n a_n^2 (e^{-E_n t} + e^{-E_n(T-t)}) + (-1)^t \sum_{n_o} a_{n_o}^2 (e^{-E_{n_o} t} + e^{-E_{n_o}(T-t)})$$

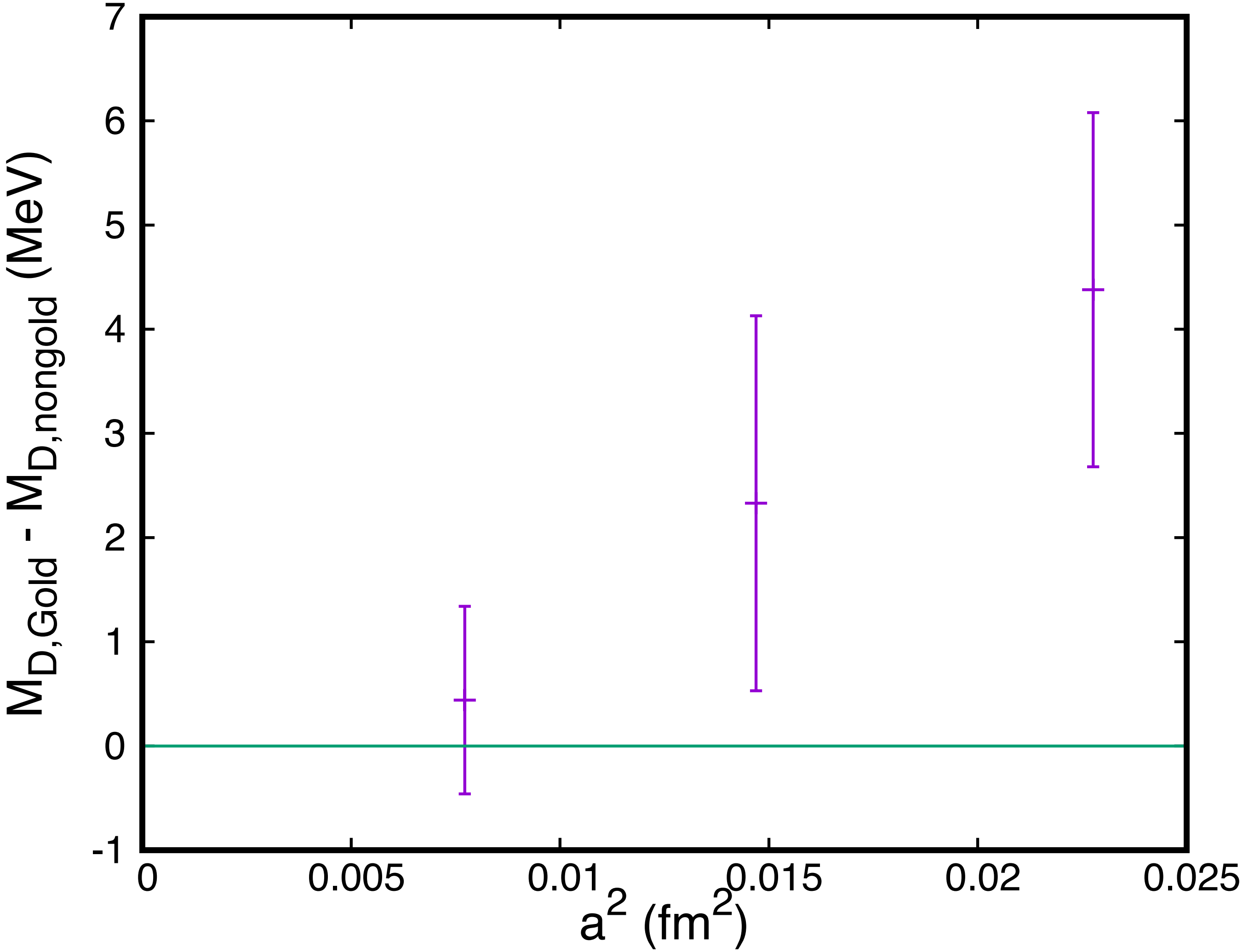
$$\begin{aligned} G^{3\text{pt}}(t;T) = &\sum_{n_1,n_2} a_{n_1} a_{n_2} V^{nn}_{n_1 n_2} (e^{-E_{n_1} t} + e^{-E_{n_2}(T-t)}) \\ &+(-1)^t \sum_{n_1 o, n_2} a_{n_1 o} a_{n_2} V^{on}_{n_1 o n_2} (e^{-E_{n_1 o} t} + e^{-E_{n_2}(T-t)}) \\ &+(-1)^T \sum_{n_1, n_2 o} a_{n_1} a_{n_2 o} V^{no}_{n_1 n_2 o} (e^{-E_{n_1} t} + e^{-E_{n_2 o}(T-t)}) \\ &+(-1)^{t+T} \sum_{n_1 o, n_2 o} a_{n_1 o} a_{n_2 o} V^{oo}_{n_1 o n_2 o} (e^{-E_{n_1 o} t} + e^{-E_{n_2 o}(T-t)}) \end{aligned}$$

Check 1: Stability of the fits with multiple exponentials



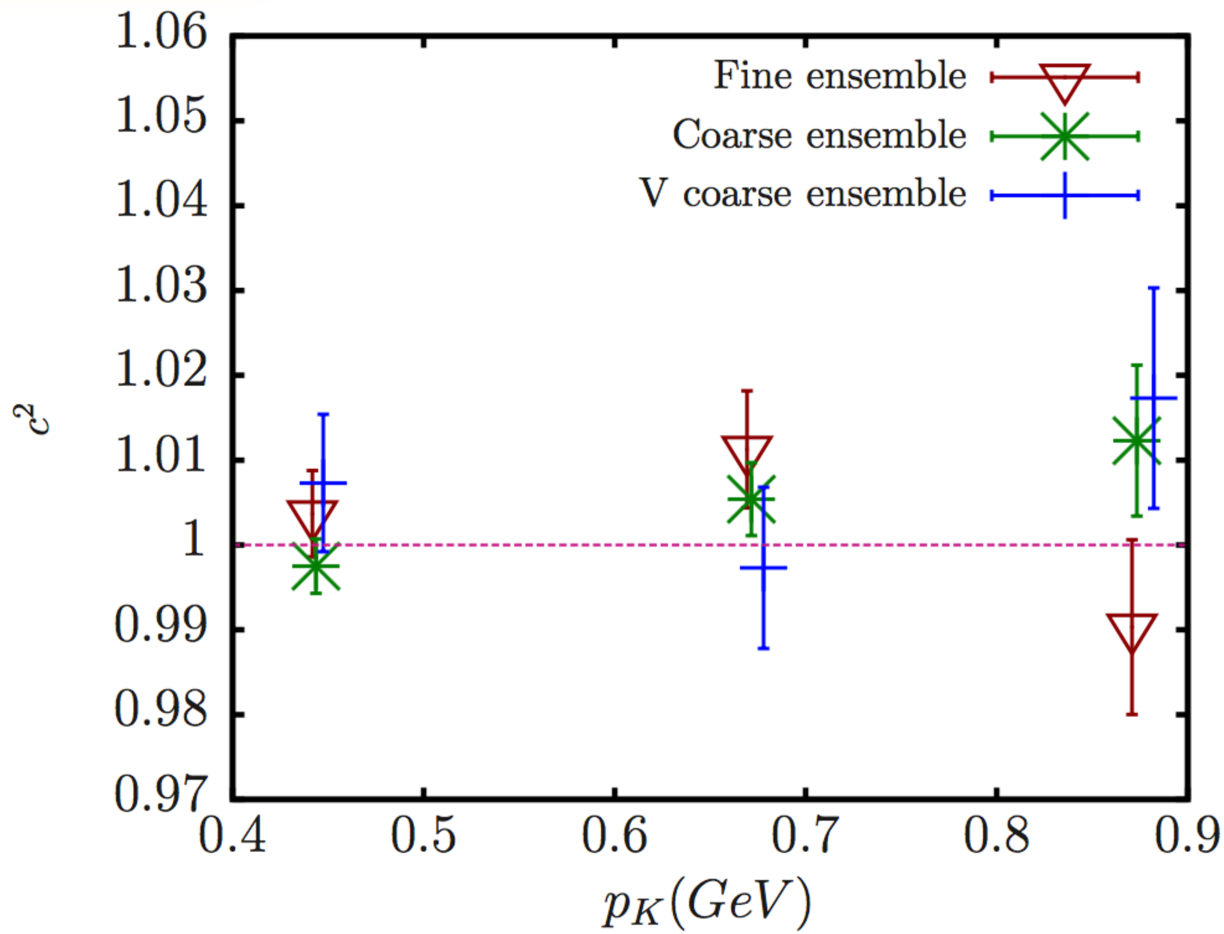


Check 2: Mass difference: Goldstone and non-goldstone D mesons

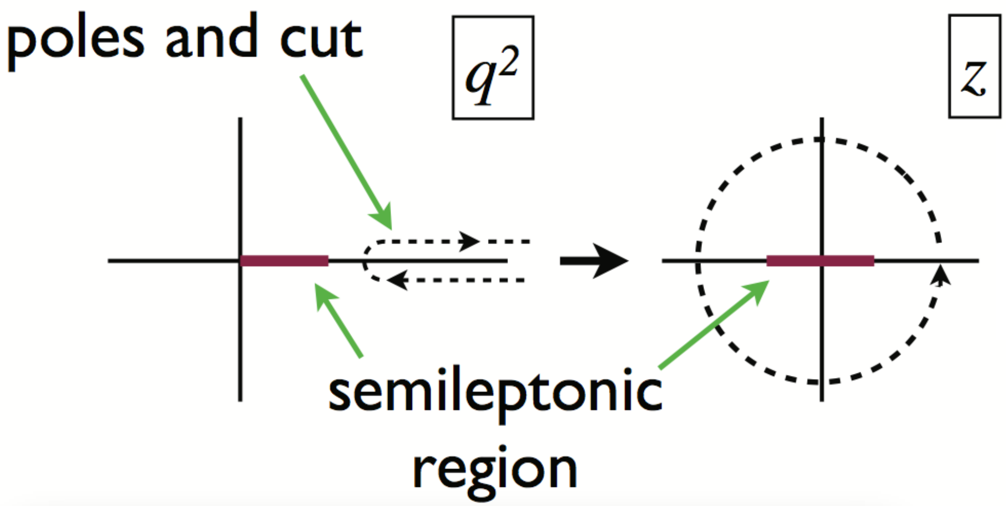


Check 3 : Relativistic dispersion relation on lattice

$$c^2(\vec{p}) = \frac{E_K^2(\vec{p}) - M_K^2}{\vec{p}^2}$$



Z-expansion



$$z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

0

$$t_\pm = (m_D \pm m_K)^2$$

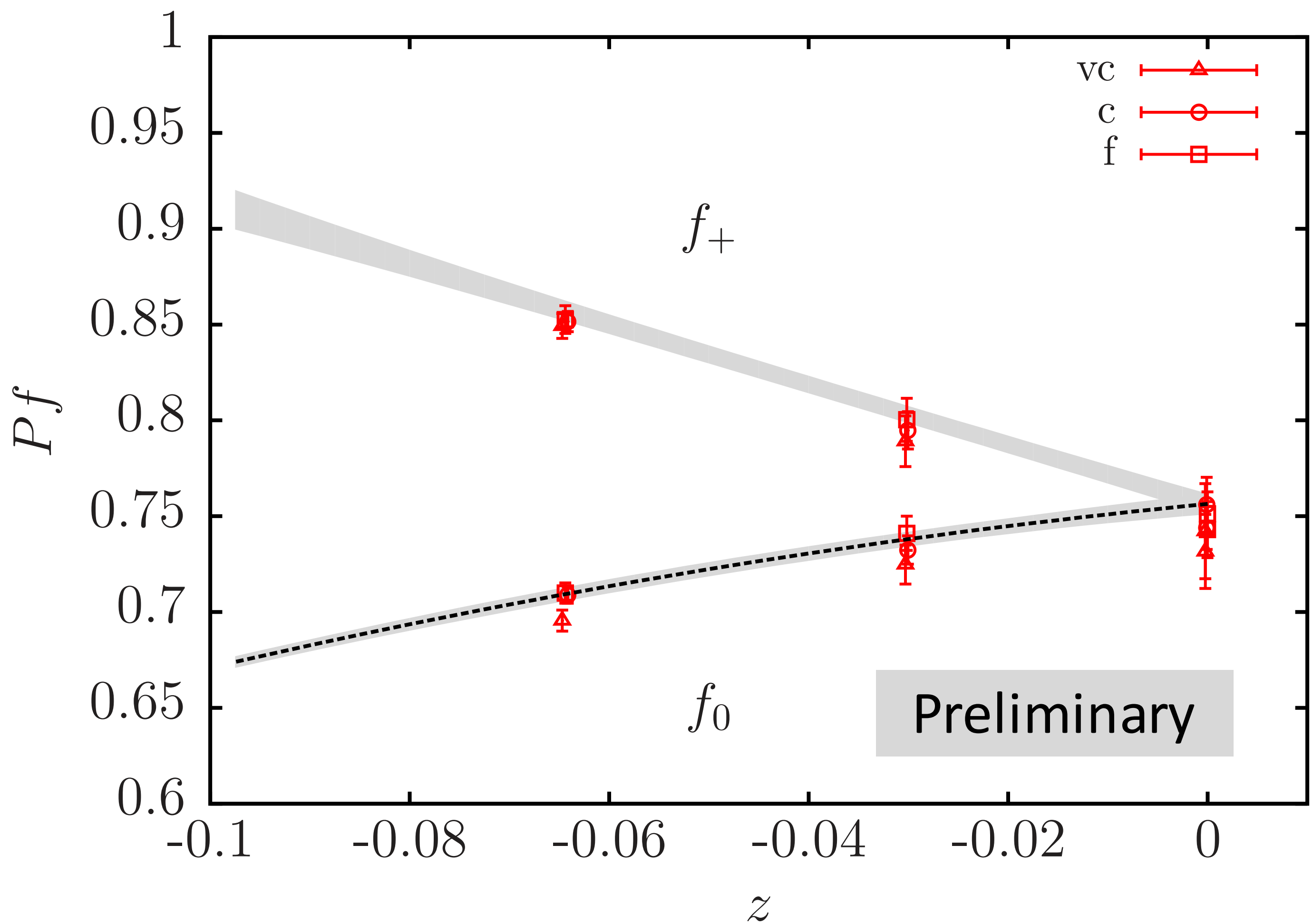
$$f(q^2) = \frac{1}{P(q^2)\Phi(q^2)} \sum_{n=0}^{N} b_n z^n$$

$$(1 - q^2/M_X^2)$$

Pole masses

$$b_n(a, m_l) = A_n\{1 + B_n a^2 + C_n a^4 + D_n \delta_l + E_n(\delta_l \ln[\delta_l] + F_n a^2 \delta_l)\}$$

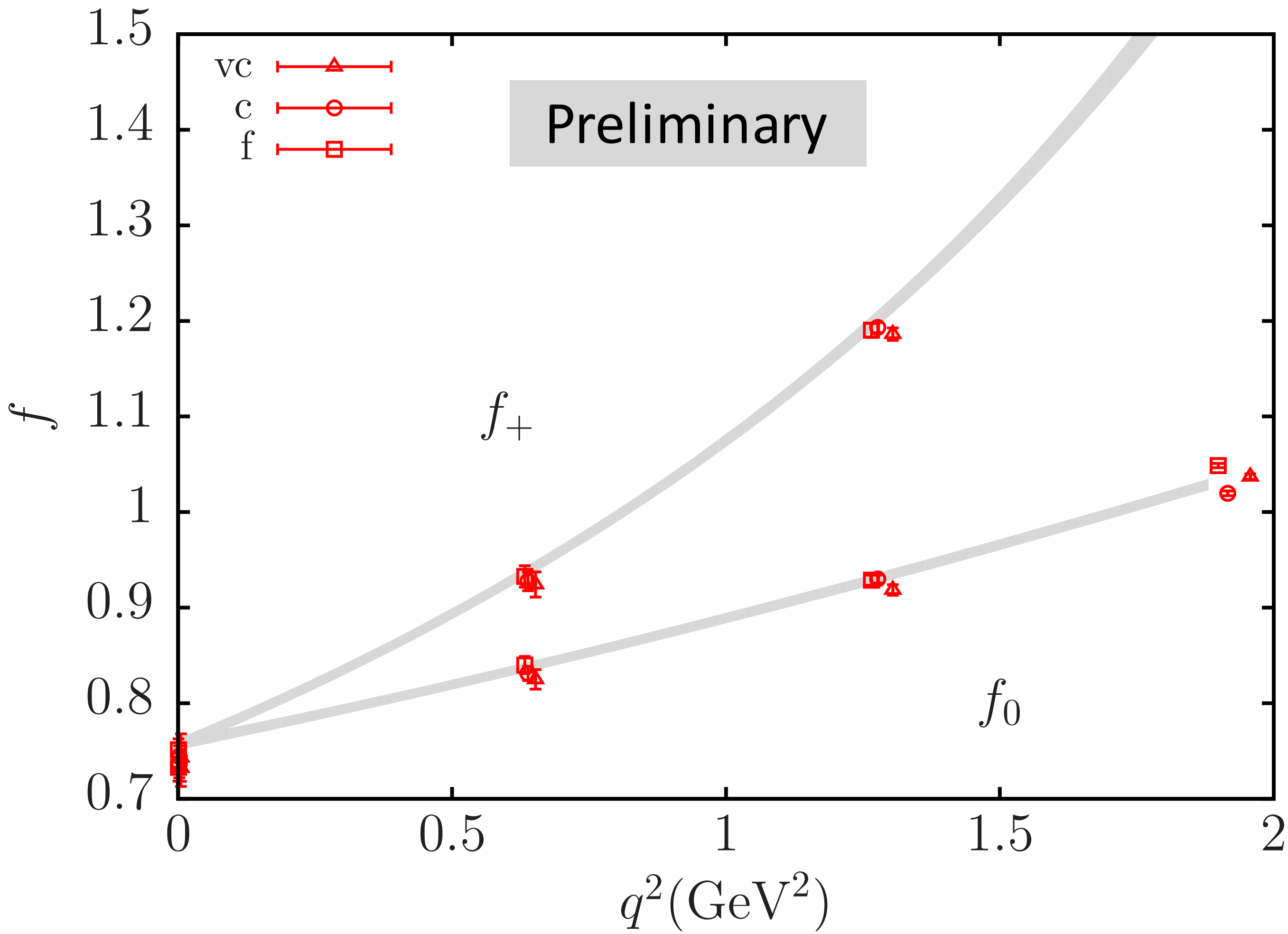
Shape of the form factors : $D \to K l\nu$

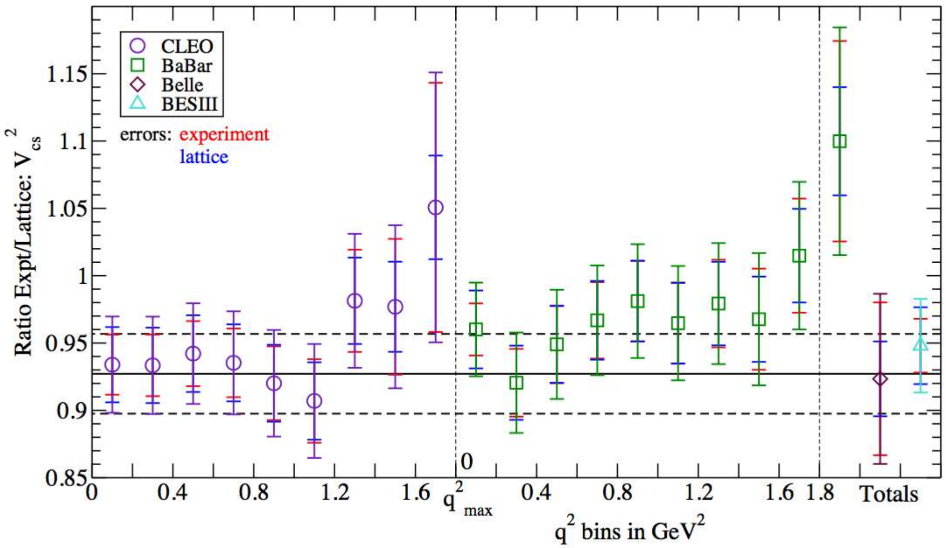


Only physical pion masses included; uncorrelated fit

Shape of the form factors : $D \to K l\nu$

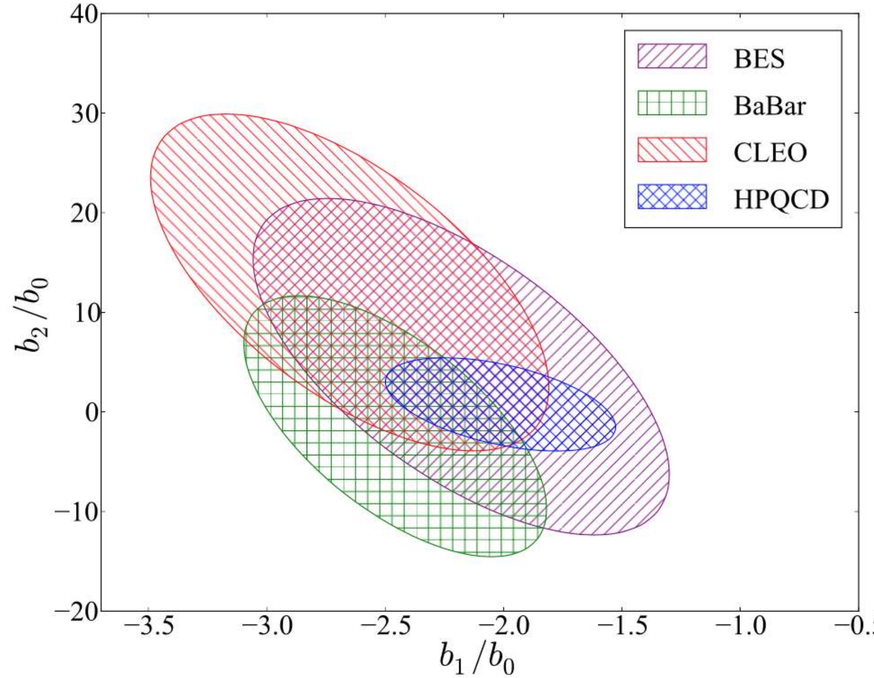
Converting back to ‘q ‘ space





Previous HPQCD results:
J. Koponen et. al. arXiv:1305.1462

Will be looking for bin-to-bin correlation



- Add more ensembles – pion mass dependence
- Refine analysis to include all correlations
- Include a common Z-expansion with

$$t_0 = t_+(1-(1-t_-/t_+0)^{1/2})$$

MILC/Fermilab:

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ETMC:

arXiv: 1306.03657