Semileptonic D→K decay from full lattice QCD with HISQ

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- Flavour Physics is fertile ground for testing SM with high precision
- The flavour changing weak interactions can be parametrised in terms of the Cabbibo-Kobayashi-Maskawa (CKM) unitary matrix

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

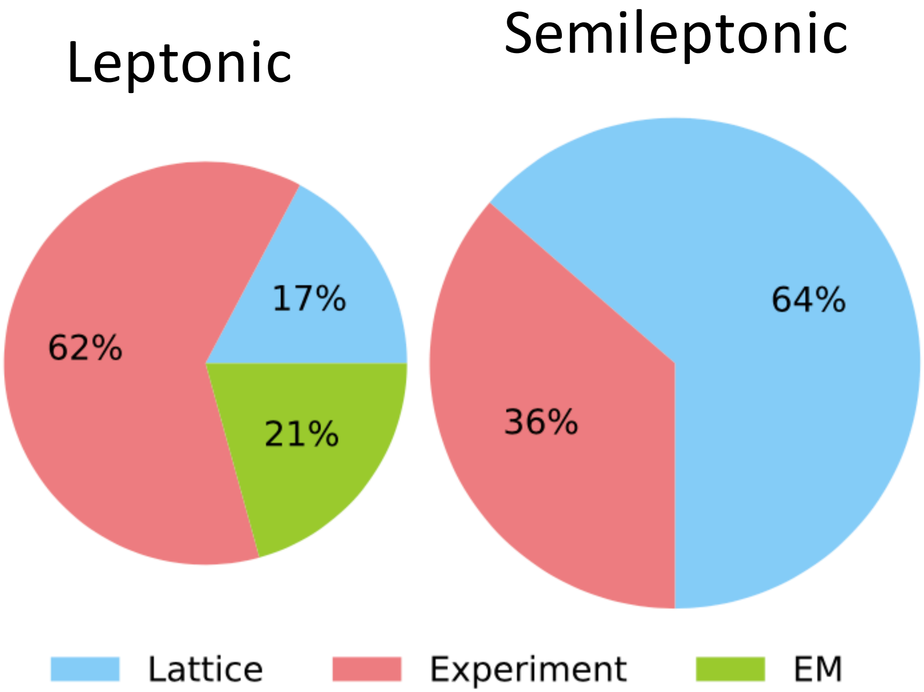
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9999 \pm 0.0006$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1.000 \pm 0.004$$

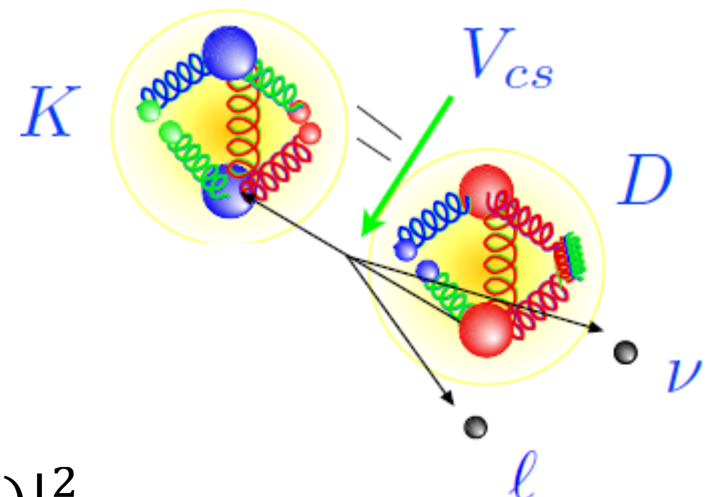
Not so precise -

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1.024 \pm 0.032.$$

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1.025 \pm 0.032$$

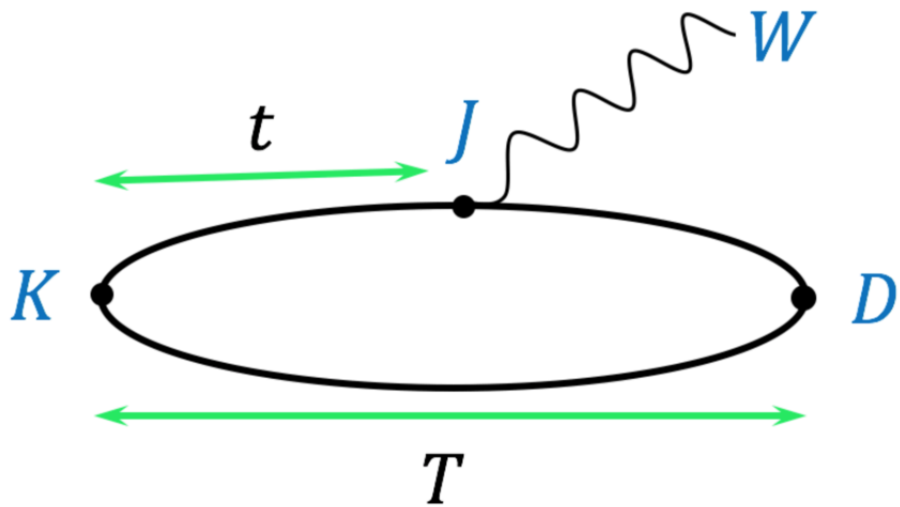


$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



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

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



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

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

- Only vector current would contribute here
- Calculate this matrix from lattice QCD

Lattice formalism

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

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

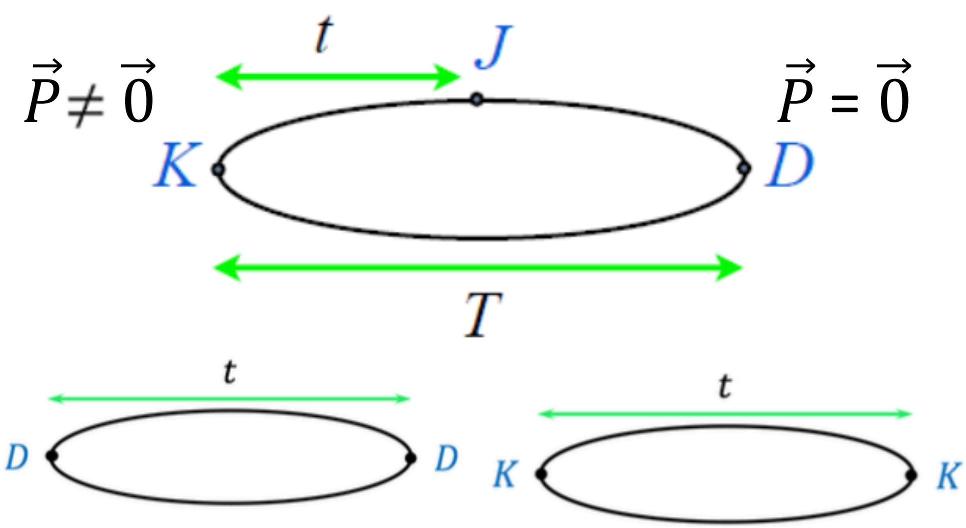
$$\langle K | S | D \rangle = f_0^{D\to K}(q^2) \frac{M_D^2 - M_K^2}{m_{0_c} - m_{0_s}}$$

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

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

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

Extract



- Local temporal vector current
- Non-goldstone D meson for that – local $\gamma_0\gamma_5$
- “Sequential technique” for three-points correlators

Analysis Ingredients

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

- ❑ Physical $m_{u/d}$
- ❑ Three lattice spacings from 0.09 -0.15 fm
- ❑ Valence strange and charm quark masses tuned accurately

Twisted boundary Conditions:

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

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

Random wall sources:

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

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

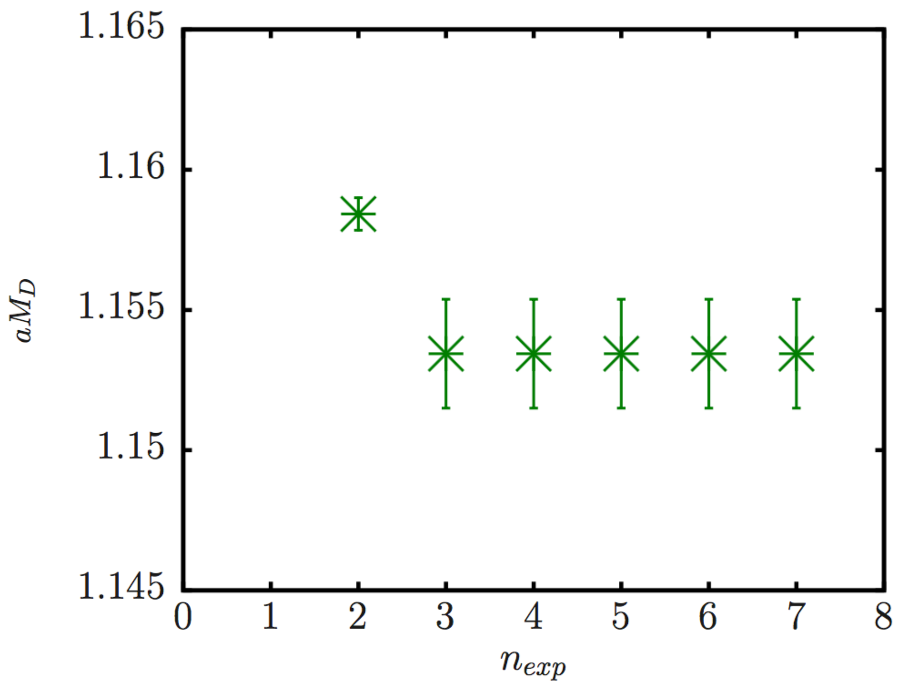
Previous HPQCD work with 2+1 Asqtad:
J. Koponen *et. al.*
arXiv:1305.1462

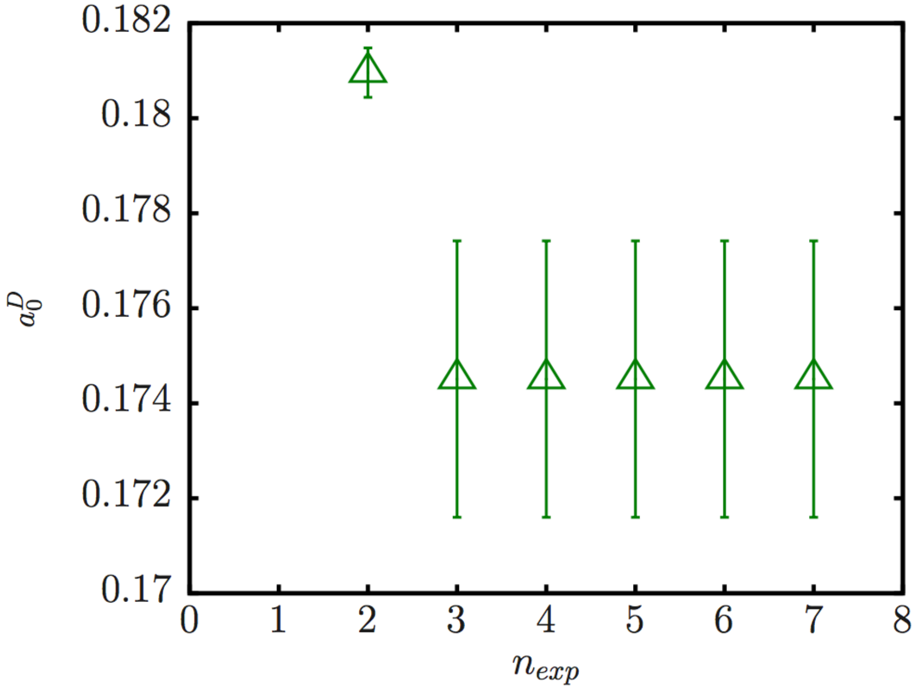
Multi-exponential Bayesian fitting

$$
\begin{aligned}
G^{2\text{pt}}(t;\vec{p}) &= \sum_{n} a_n^2 \left(e^{-E_n t} + e^{-E_n (T-t)}\right) \\
&\quad + (-1)^t \sum_{n_o} a_{n_o}^2 \left(e^{-E_{n_o} t} + e^{-E_{n_o}(T-t)}\right)
\end{aligned}
$$

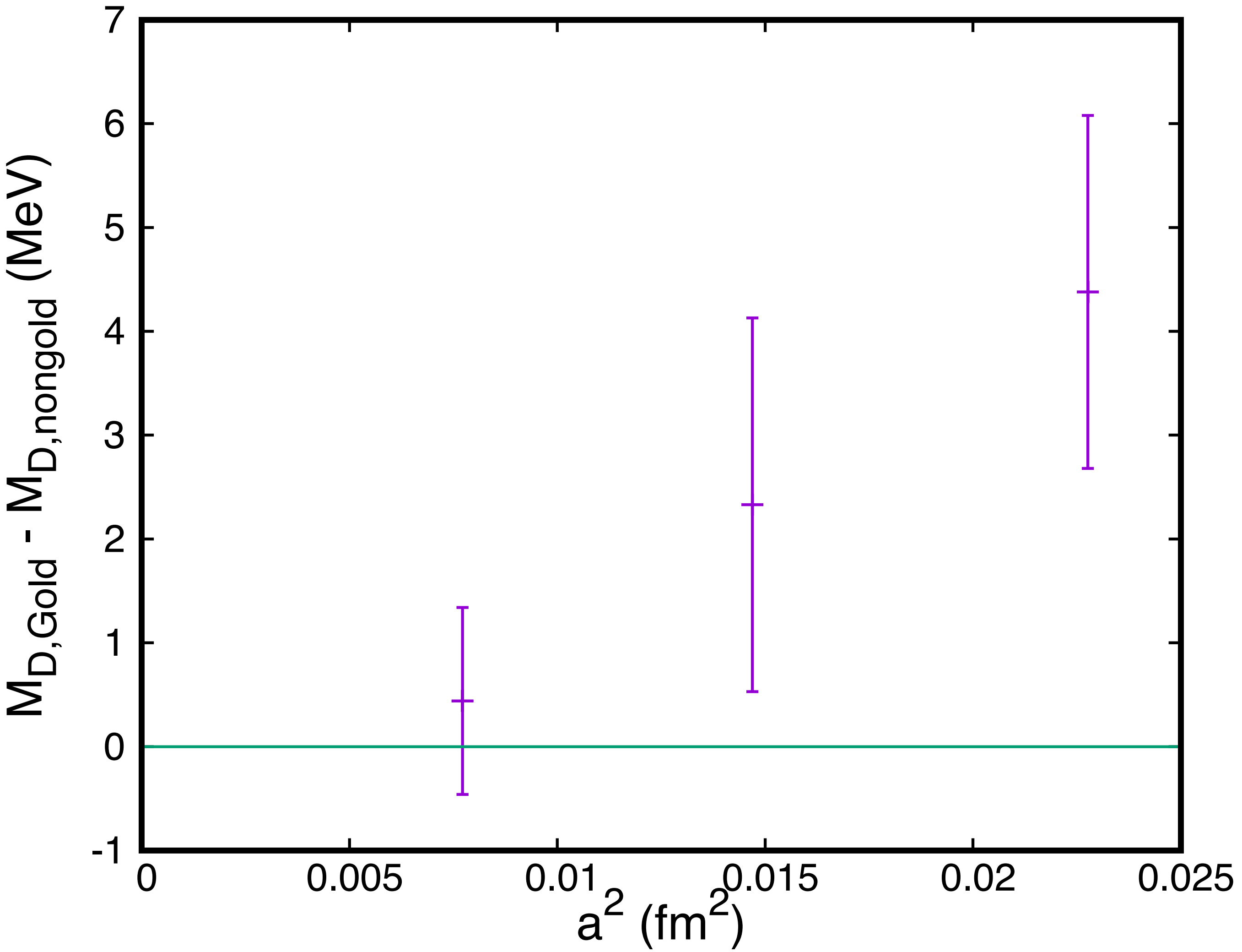
$$
\begin{aligned}
G^{3\text{pt}}(t;T) &= \sum_{n_1,n_2} a_{n_1} a_{n_2} V^{nn}_{n_1 n_2} \left(e^{-E_{n_1} t} + e^{-E_{n_2}(T-t)}\right) \\
&\quad + (-1)^t \sum_{n_1 o, n_2} a_{n_1 o} a_{n_2} V^{on}_{n_1 o n_2} \left(e^{-E_{n_1 o} t} + e^{-E_{n_2}(T-t)}\right) \\
&\quad + (-1)^T \sum_{n_1, n_2 o} a_{n_1}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

Check 1: Stability of the fits with multiple exponentials



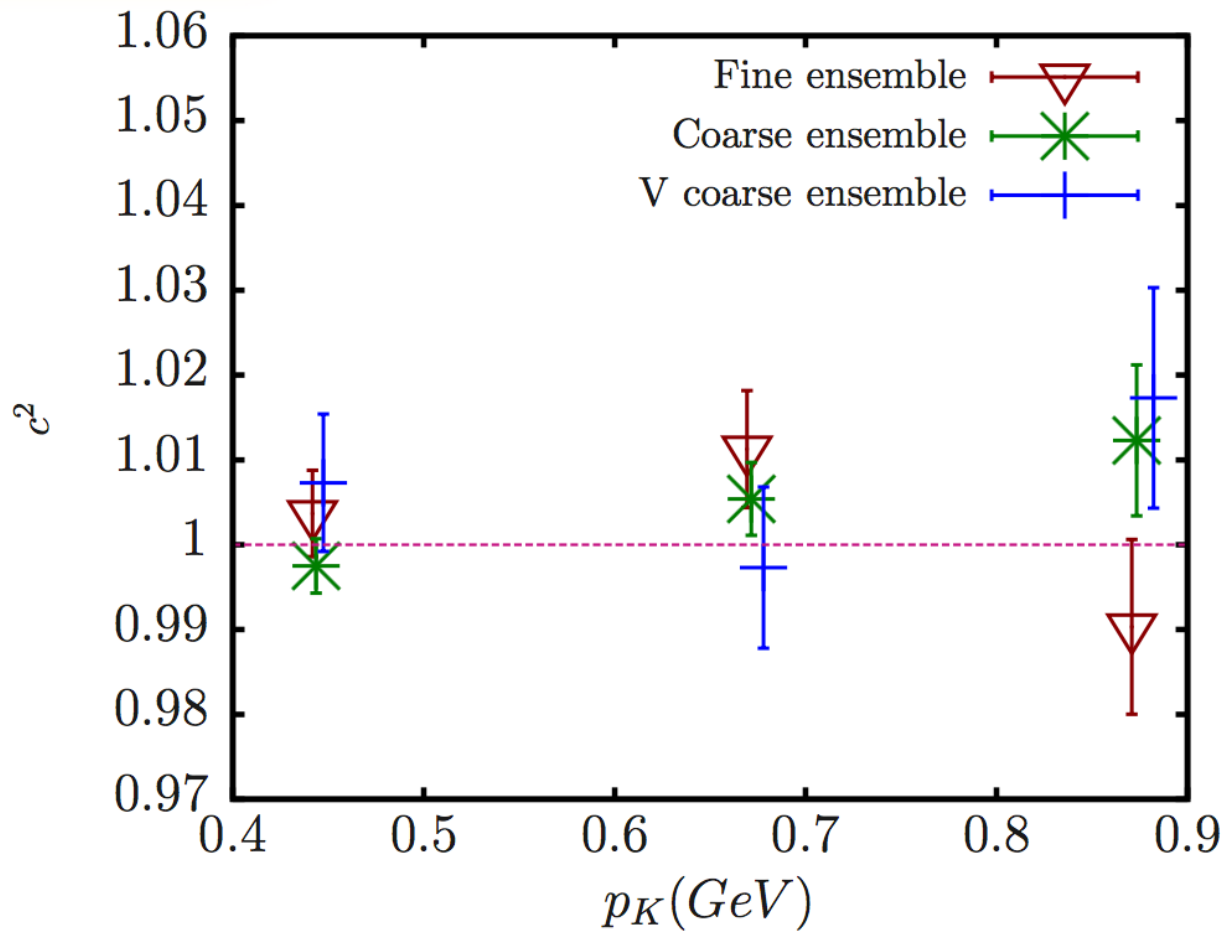


Check 2: Mass difference: Goldstone and non-goldstone D mesons

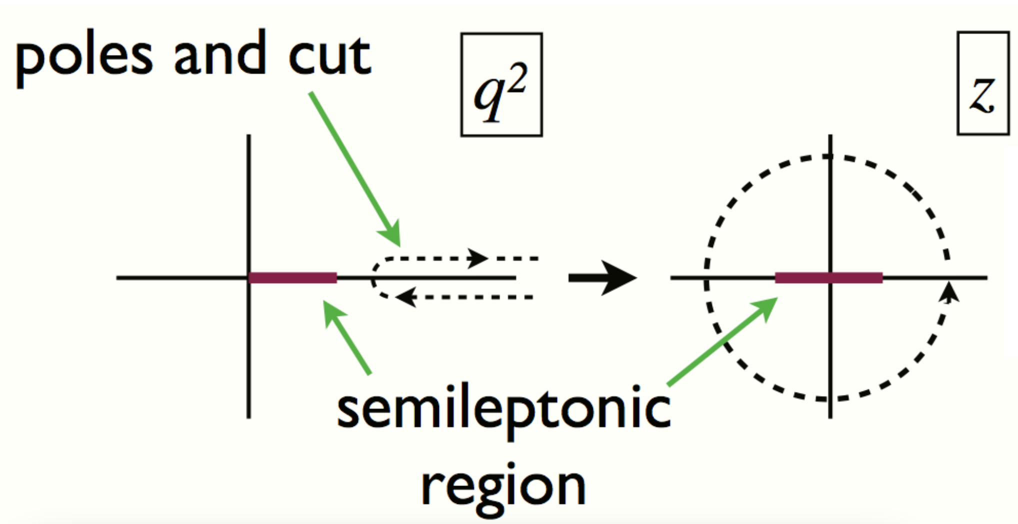


Check 3 : Relativistic dispersion relation on lattice

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



Z-expansion



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

0

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

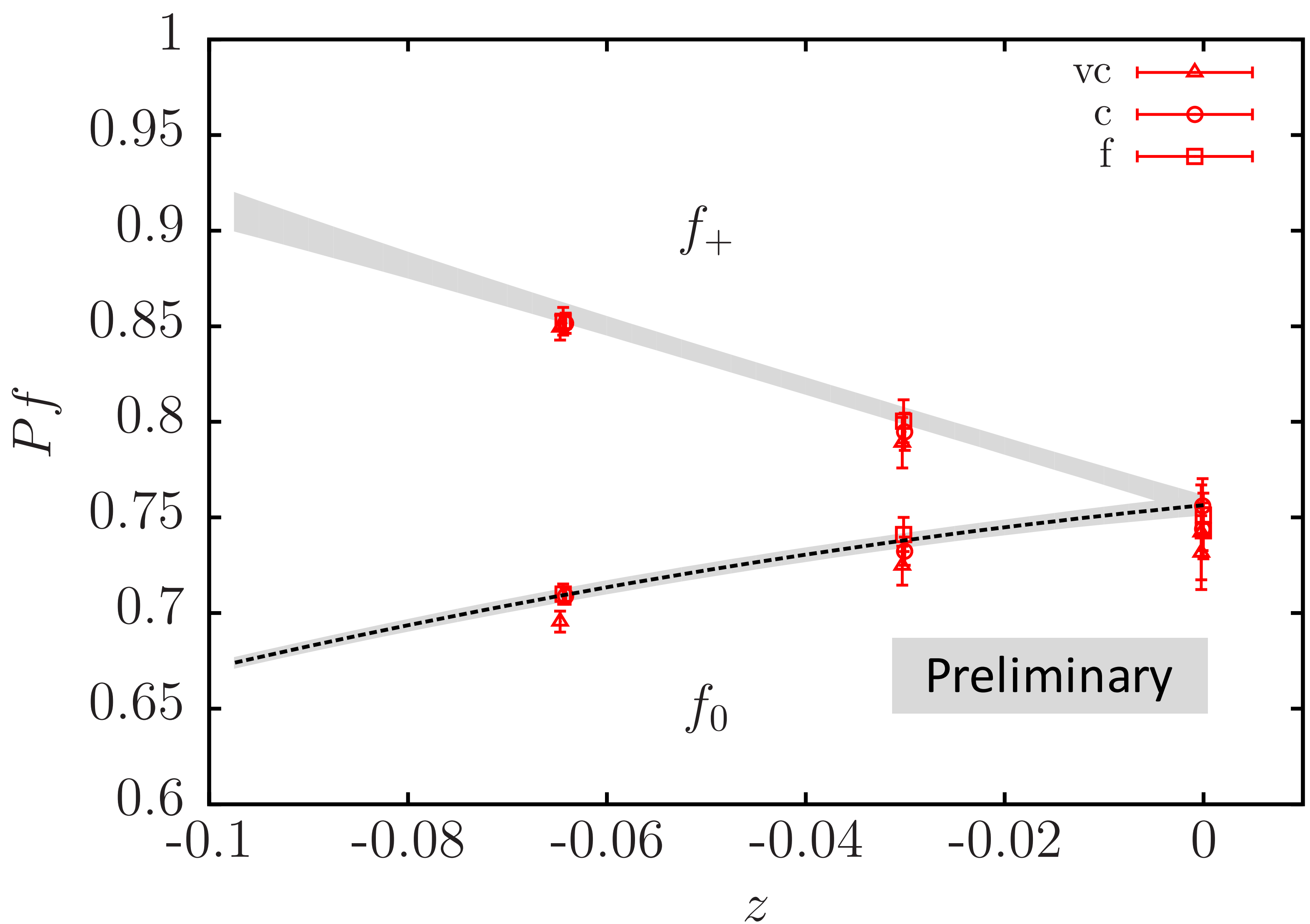
$$f(q^2) = \frac{1}{P(q^2)\Phi(q^2)} \sum_{n=0}^{N} b_n z^n$$

Pole masses

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

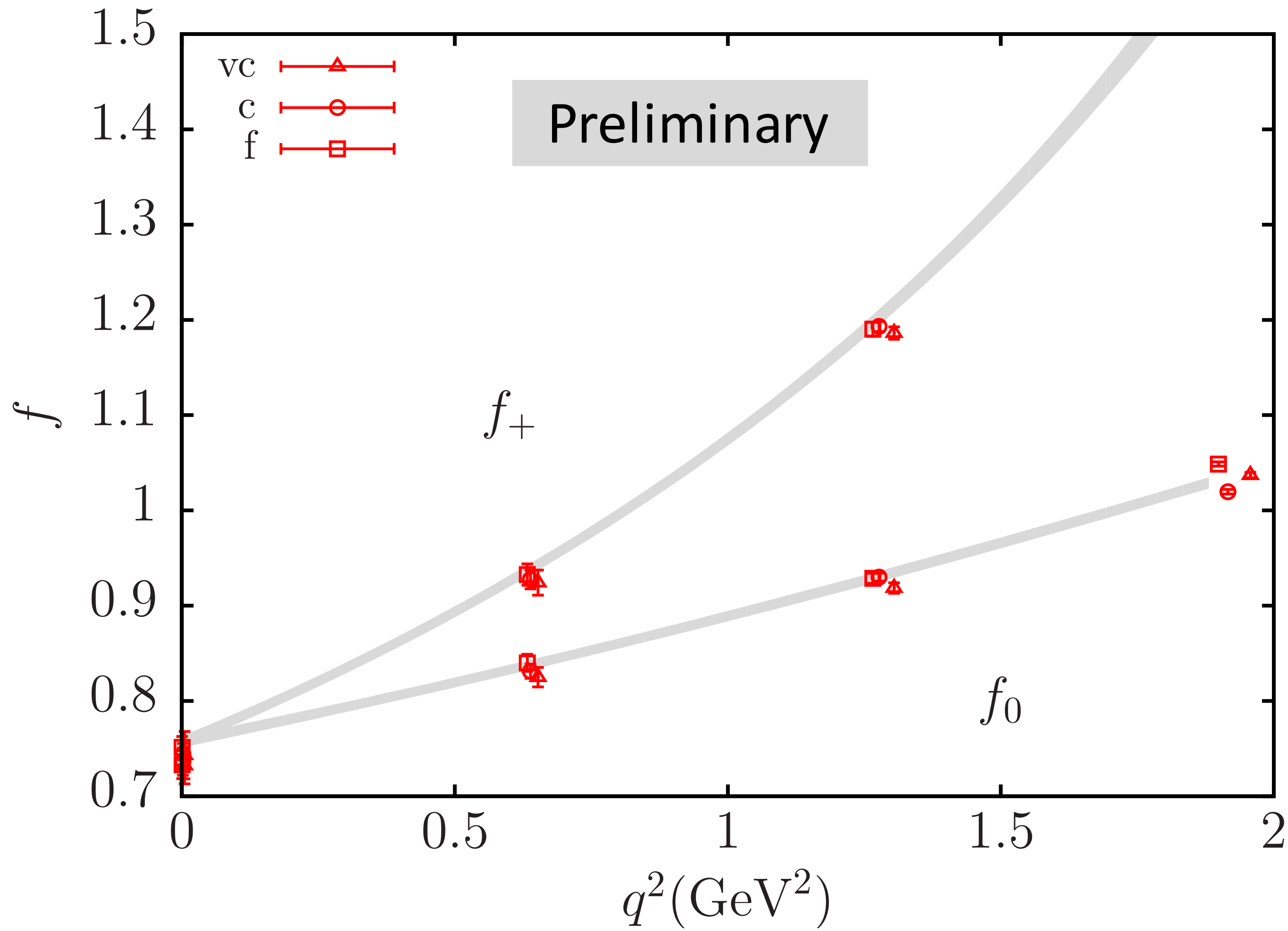
$$b_n(a, m_l) = A_n\{1 + B_n a^2 + C_n a^4 + D_n \delta_l + E_n(\delta_l \ln[\delta_l] + F_n a^2 \delta_l)\}$$

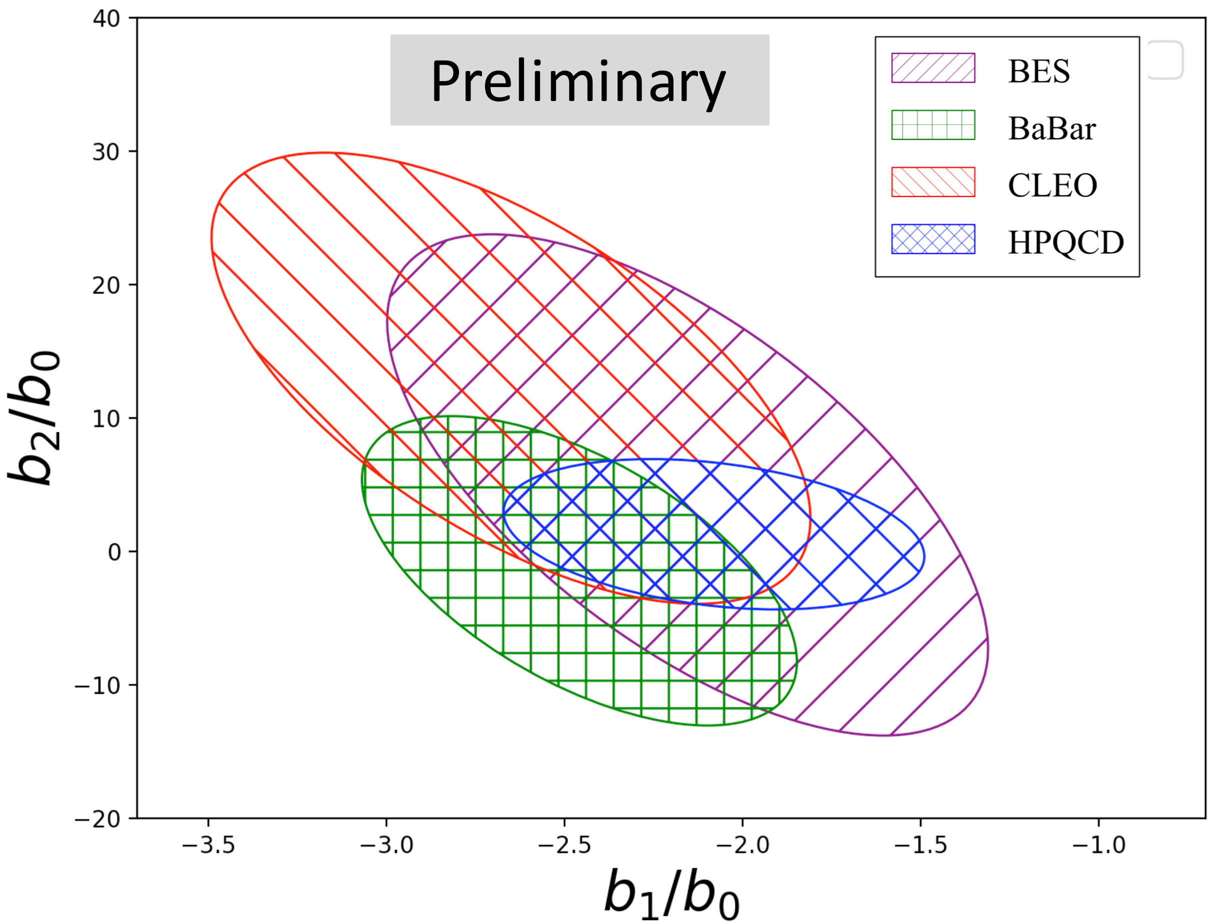
Shape of the form factors : $D \to K l\nu$



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

Converting back to 'q ' space

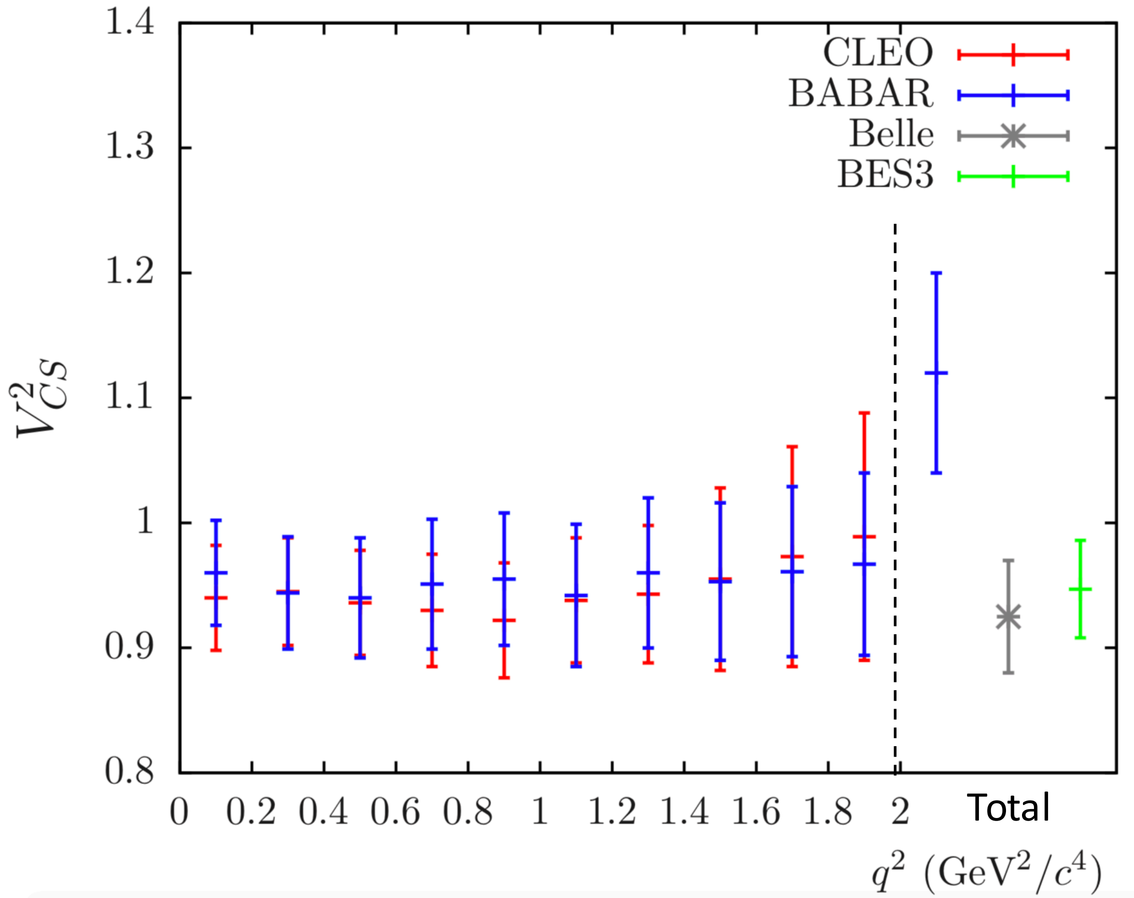




$$z = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

Comparison of $f_+(q^2)$ shape parameters

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



Preliminary

ETMC:
Phys. Rev. D96, 054514

MILC/Fermilab:

PoS LATTICE2016 (2017) 305

JLQCD:
arXiv:1701.00942

- Ratio : Expt/Lattice
- Looking for bin-to-bin correlation
- Extracting V_{CS} from fitting all bins

Thank you