CHARM 2018

# Review of recent developments on leptonic and semileptonic charm decays from lattice QCD

Università di Roma Tre, INFN Roma Tre, LPT Orsay

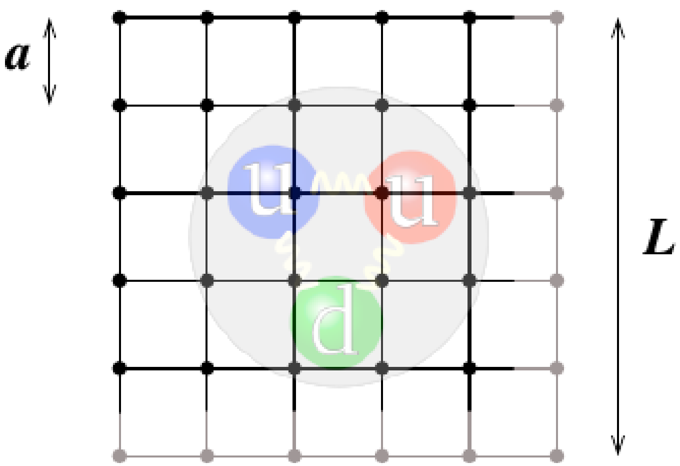
# Lattice QCD

$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f (\not{D} + m_f)\psi_f + \frac{1}{4}\mathrm{tr} F_{\mu\nu}F^{\mu\nu}$$

Non-perturbative QCD contributions from first principles

⇓

Control all systematic uncertainties




- Discrete Euclidean Space-Time
- Finite spatial volume and time extent
- Path integrals rigorously defined and computed via Monte Carlo methods

# Lattice QCD

$$\mathcal{L}_{\mathrm{QCD}} = \sum_f \bar{\psi}_f (\not{D} + m_f)\psi_f + \frac{1}{4}\mathrm{tr} F_{\mu\nu}F^{\mu\nu}$$

Non-perturbative QCD contributions from first principles

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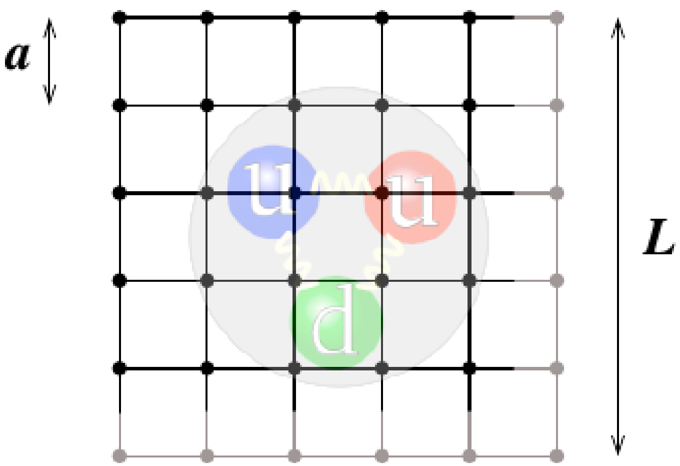



Parameters in a simulation:

- Lattice spacing: $a$
- Finite volume and time: $L,\ T$
- Quark masses: $m_{ud},\ m_s,\ m_c,\ m_b$
- # see quarks: $N_f = 2,\ 2+1,\ 2+1+1, \ldots$

# Lattice QCD

$$\mathcal{L}_{\text{QCD}} = \sum_f \bar{\psi}_f (\not{D} + m_f)\psi_f + \frac{1}{4}\text{tr} F_{\mu\nu}F^{\mu\nu}$$

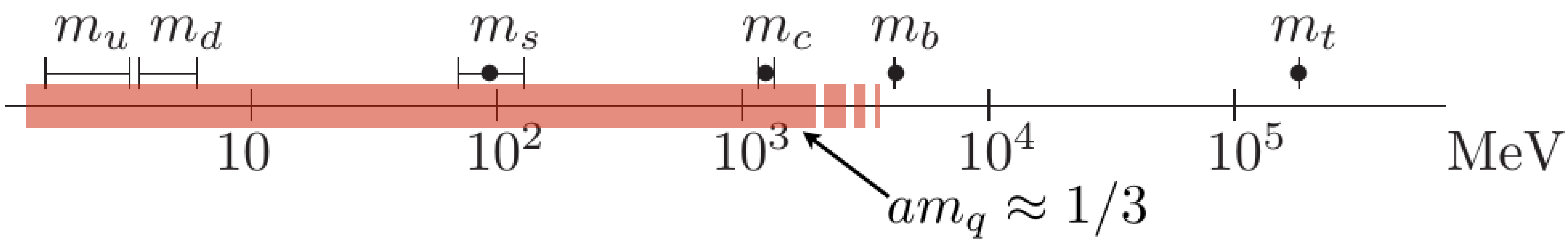
QCD recovered by removing cutoffs

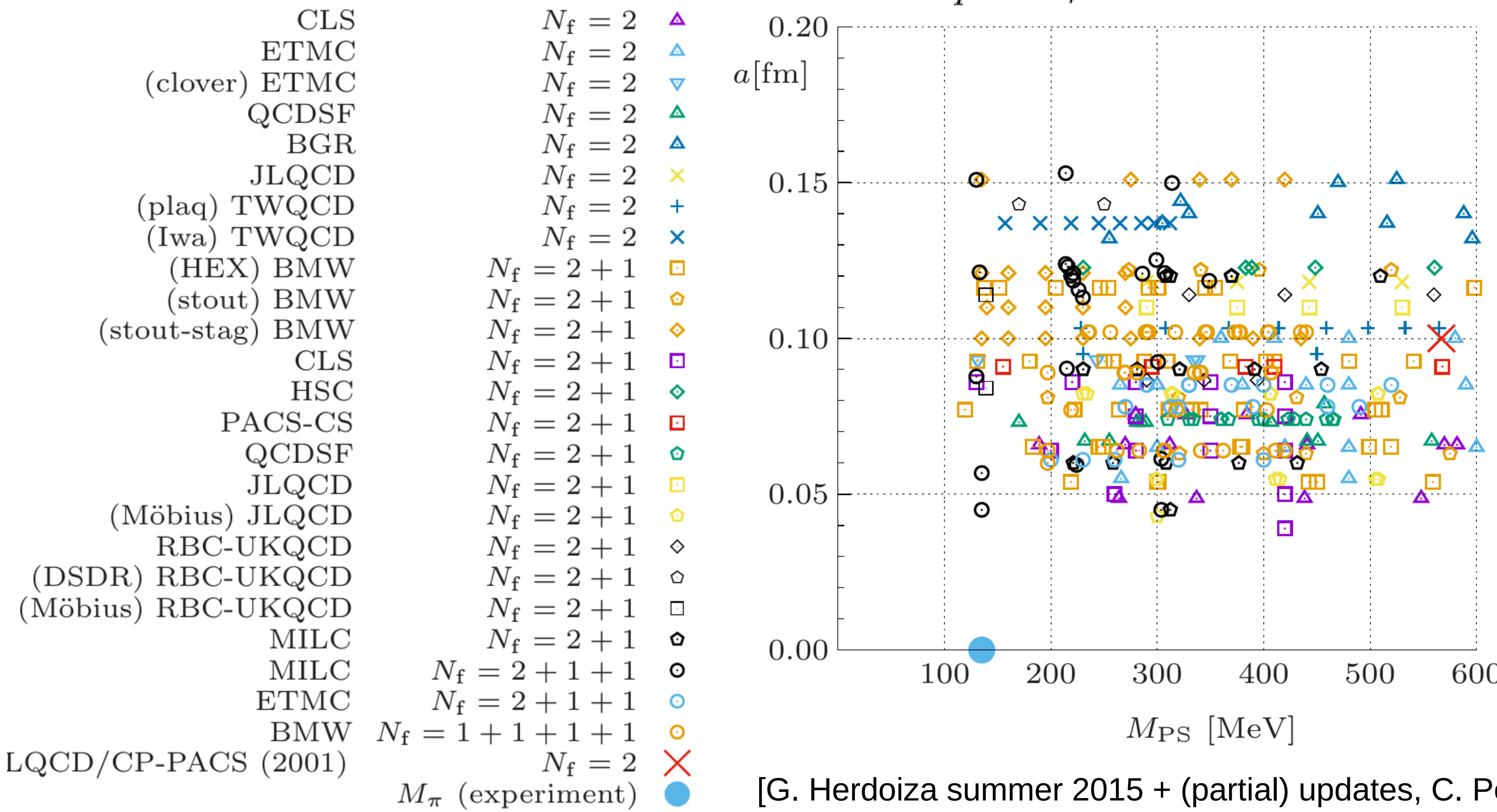
- Continuum limit: $a \to 0$
- Infinite volume limit: $L,\, T \to \infty$
- Interpolation/Extrapolation to physical quark masses: $m_f \to m_f^{phys}$

To reliably estimate systematic errors:

repeat the calculation for several lattice spacing, volumes and sea-quark masses

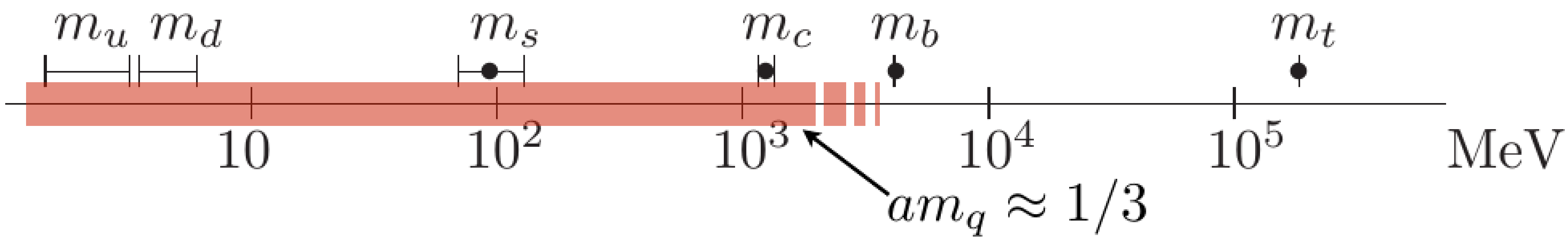
# Lattice QCD - State of the art




[G. Herdoiza summer 2015 + (partial) updates, C. Pena]

# Quark masses on the lattice




**Light quarks**: discretization errors $\sim (a\Lambda_{QCD})^n$

finite size effects $\sim \exp\left[-M_\pi L\right]$

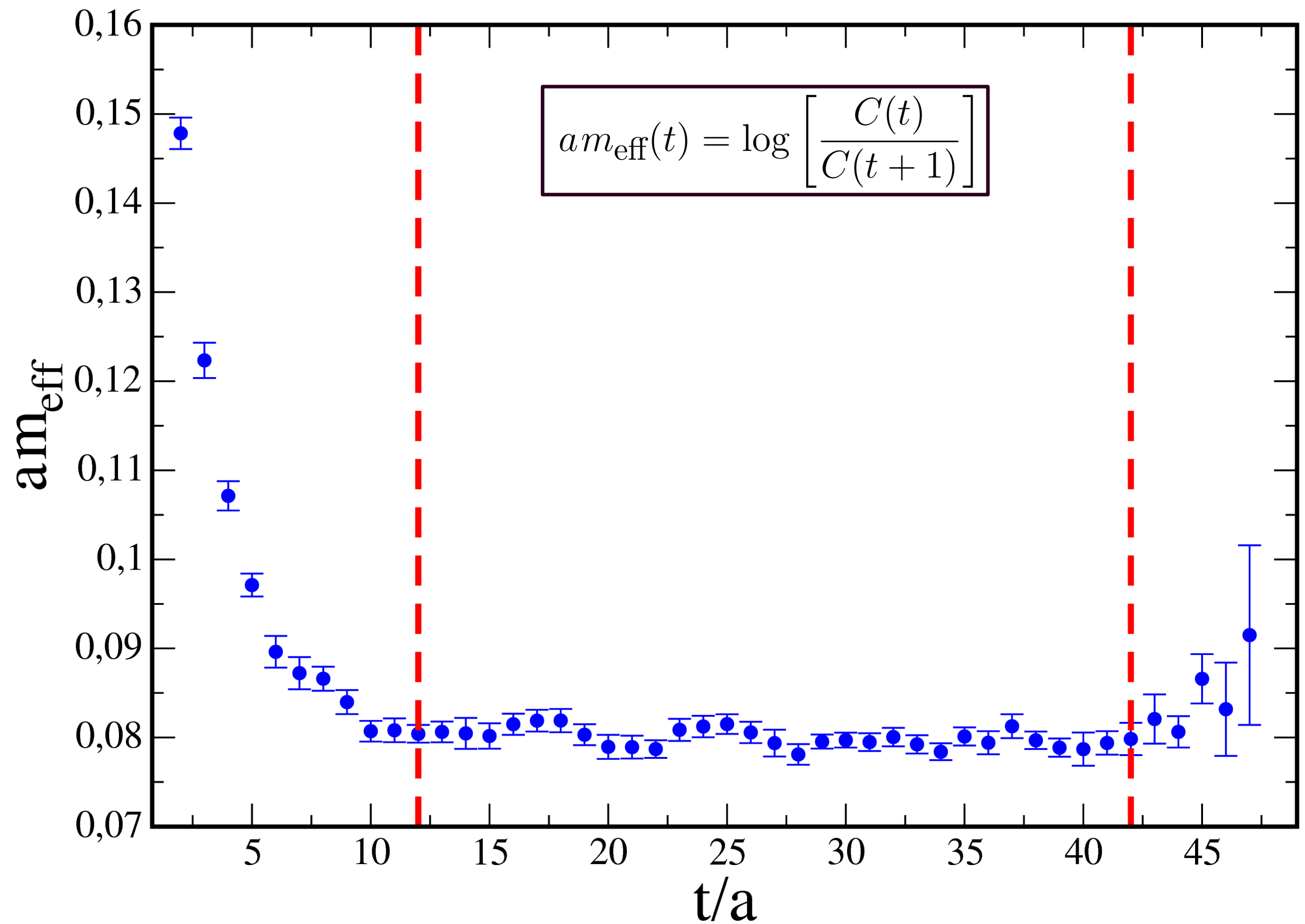
Extrapolation in $m_{u,d}$ often necessary (ChPT)

**Heavy quarks**: discretization errors $\sim (am_h)^n$

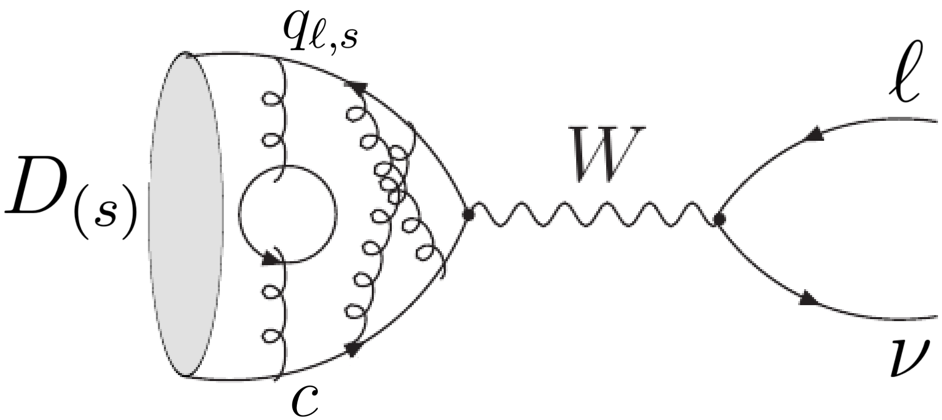
- Charm quarks: $am_c \sim 0.3$
  directly accessible on the lattice
- Bottom quarks: $am_b \gtrsim 1$
  extrapolation or an effective theory (HQET, NRQCD, ...) is needed

Masses and hadronic matrix elements
are extracted from Euclidean Correlators

$$C(t) \equiv \langle O_\pi(t) O_\pi^\dagger(0) \rangle \approx \sum_n \frac{|\langle 0 | O_\pi(0) | n \rangle|^2}{2E_n} \exp[-E_n t] \xrightarrow[t\to\infty]{} \frac{|\langle 0 | O_\pi(0) | \pi \rangle|^2}{2M_\pi} \exp[-M_\pi t]$$



# Leptonic decays




$$D_{(s)} \to \ell\,\nu$$

Decay constants (Lattice QCD)

$$\langle 0|A^\mu_{cq}|D_q(p)\rangle = i f_{D_q}\, p^\mu_{D_q}$$
$$A^\mu_{cq} = \bar{c}\gamma_\mu\gamma_5 q$$

$$\Gamma(D_{(s)} \to \ell\nu) = |V_{cd(s)}|^2 \times f^2_{D_{(s)}} \times \frac{G_F^2}{8\pi} m_\ell^2 m_{D_{(s)}} (1 - m_\ell^2/m^2_{D_{(s)}})^2$$

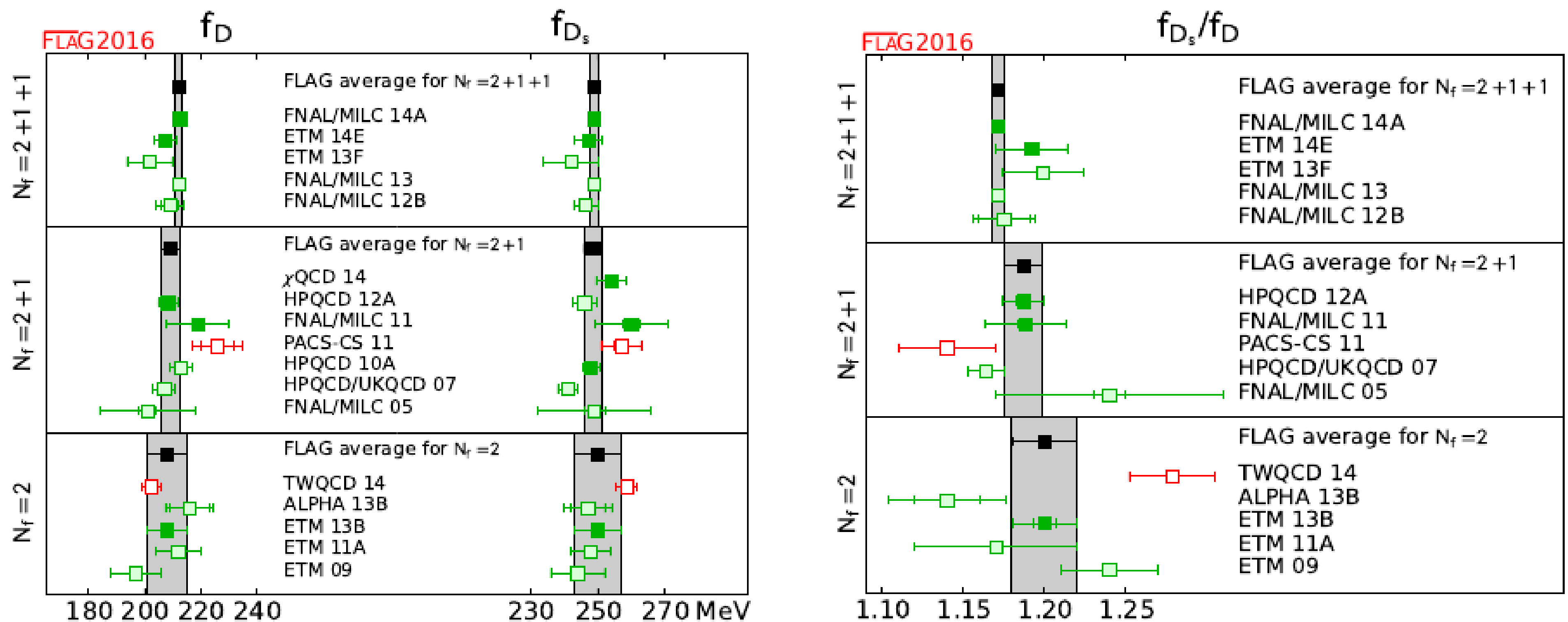
Decay rate (Experiments)

CKM matrix elements

- Experimental + LQCD inputs for the determination of CKM elements
- Systematic and statistical errors cancellation in the SU(3) ratio $f_{D_s}/f_D$

FLAG 2016

EPJC**77** no.2, 112




<u>FNAL/MILC 14A</u> PRD**90**, 074509

- Improved action
- Physical mass: $ud$, $s$, $c$
- $a \sim 0.06fm \div 0.15fm$

0.5%

<u>ETM 14E</u> PRD**91**, 054507

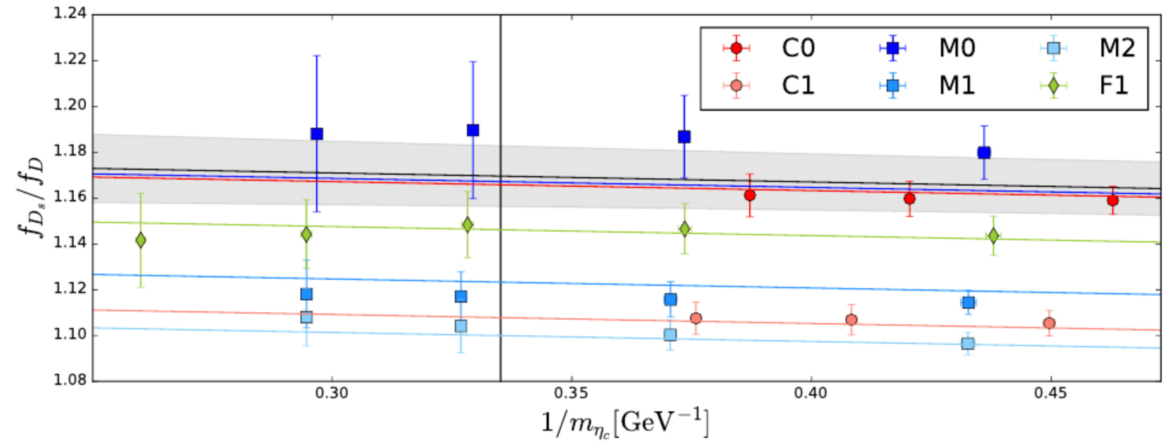
- Improved action
- Physical mass: $s$, $c$
- $a \sim 0.06fm \div 0.09fm$

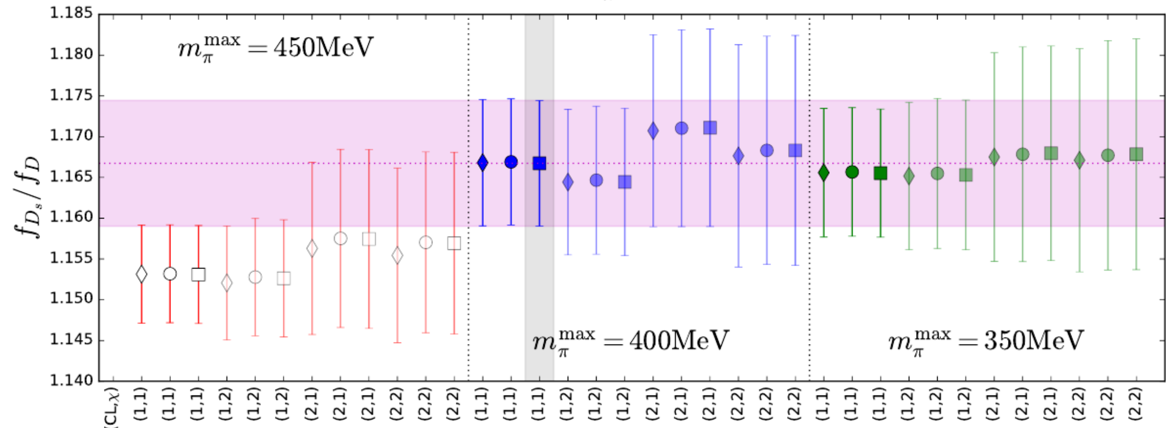
1.5%

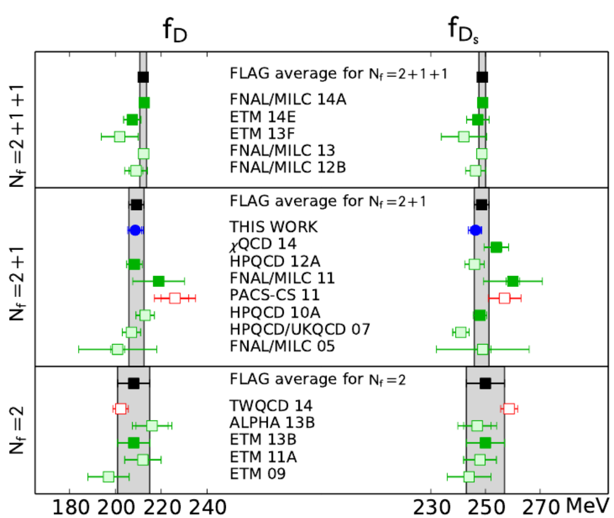
# Leptonic decays – New Results

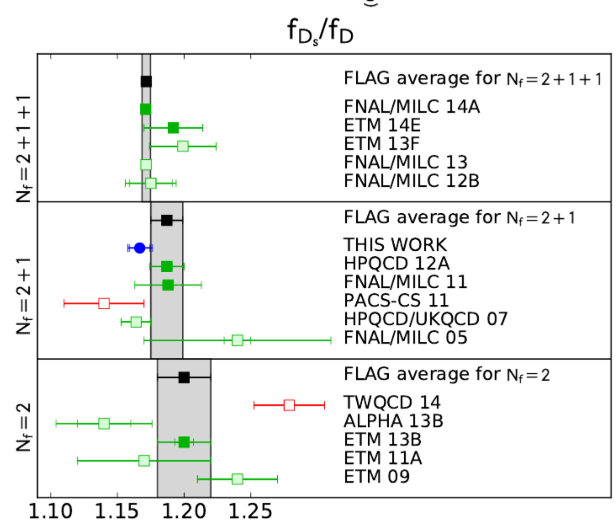
**RBC/UKQCD** JHEP**12** 008

- $N_f = 2+1$ DW fermions
- Physical mass: $ud,\ s,\ c$
- $a \sim 0.11 fm \div 0.07 fm$
- $am_c \lesssim 0.4$



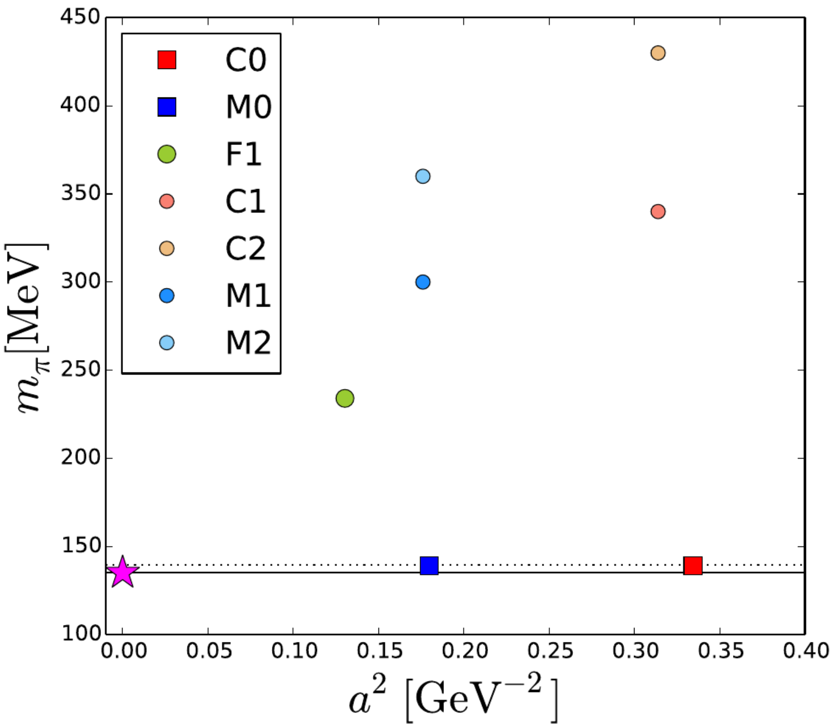



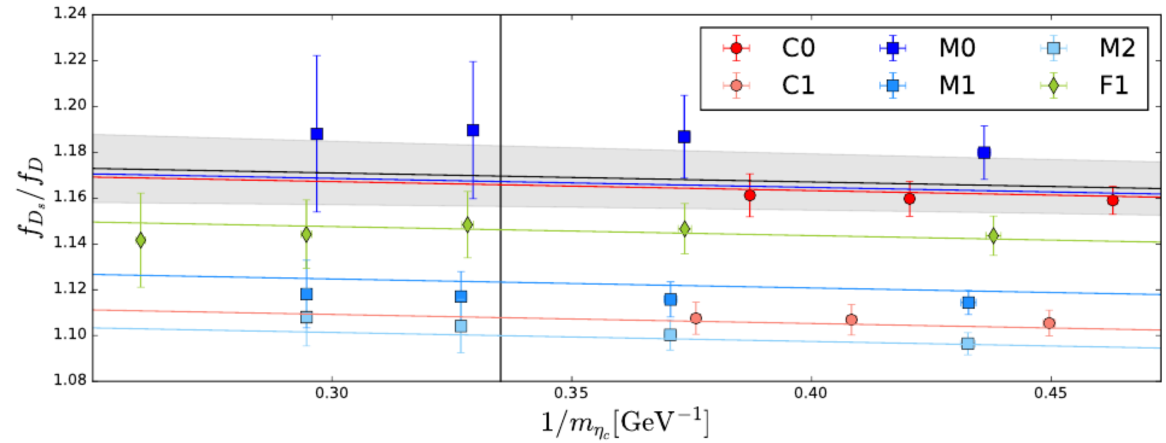

$$f_D = 208.7(2.8)_{\rm stat}(^{+2.1}_{-1.8})_{\rm sys}\ \mathrm{MeV}$$

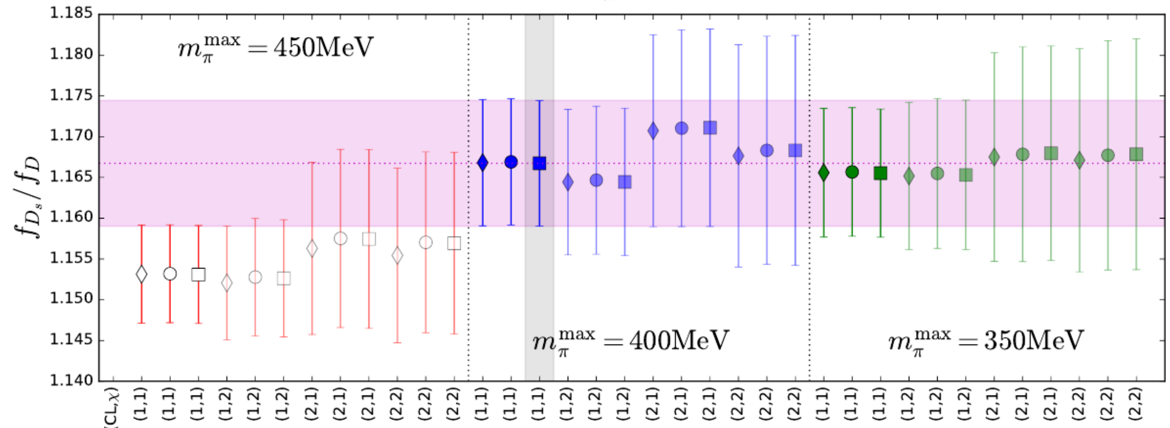
$$f_{D_s} = 246.4(1.9)_{\rm stat}(^{+1.3}_{-1.9})_{\rm sys}\ \mathrm{MeV}$$

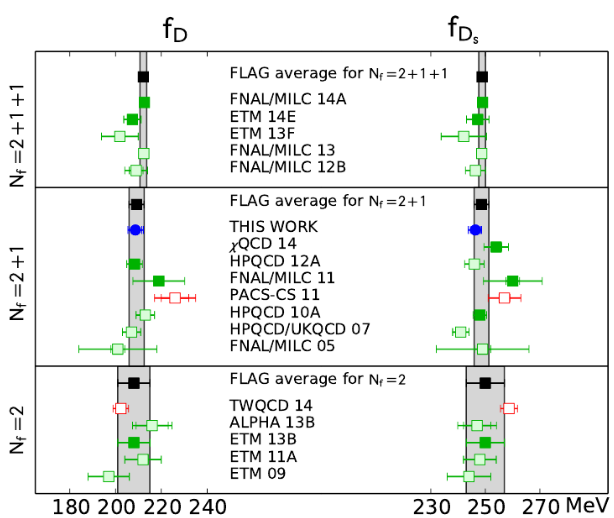
# Leptonic decays – New Results

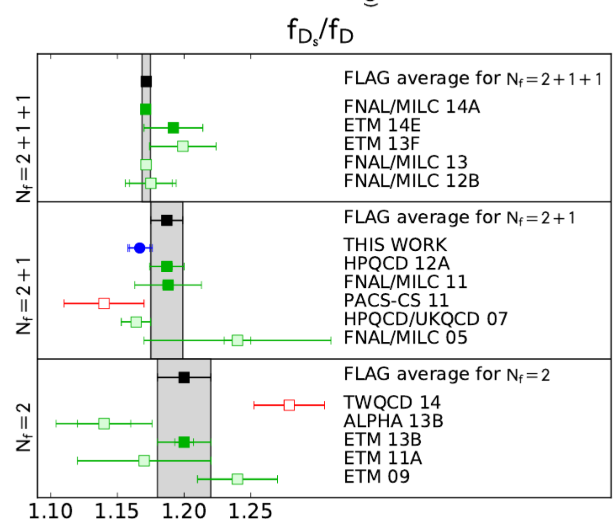
RBC/UKQCD — JHEP**12** 008



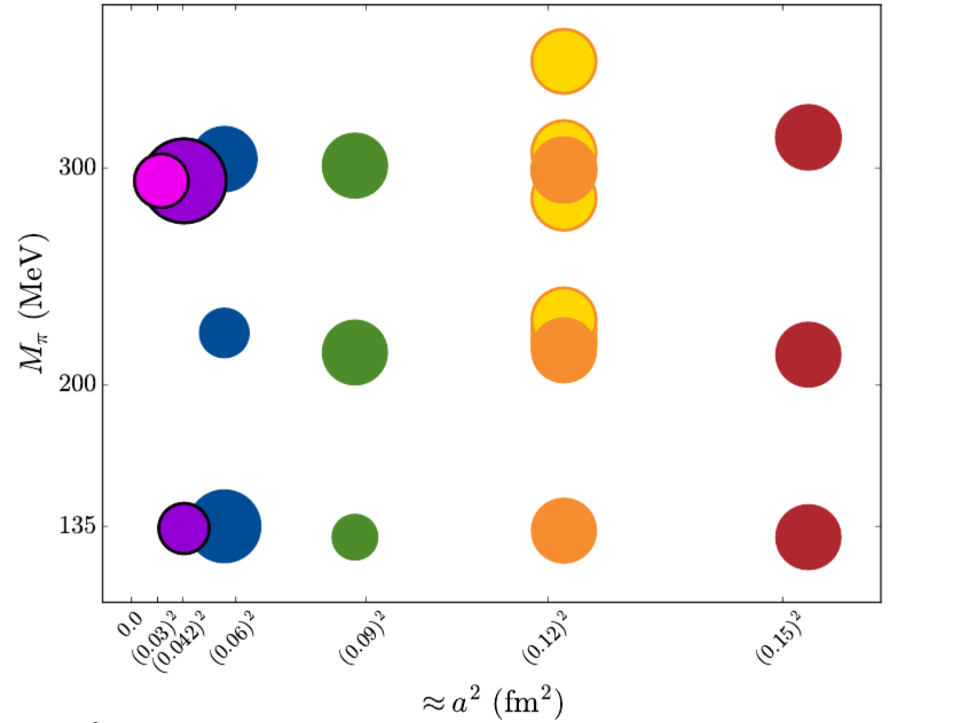

$$f_D = 208.7(2.8)_{\rm stat}({}^{+2.1}_{-1.8})_{\rm sys}\ \text{MeV}$$

$$f_{D_s} = 246.4(1.9)_{\rm stat}({}^{+1.3}_{-1.9})_{\rm sys}\ \text{MeV}$$

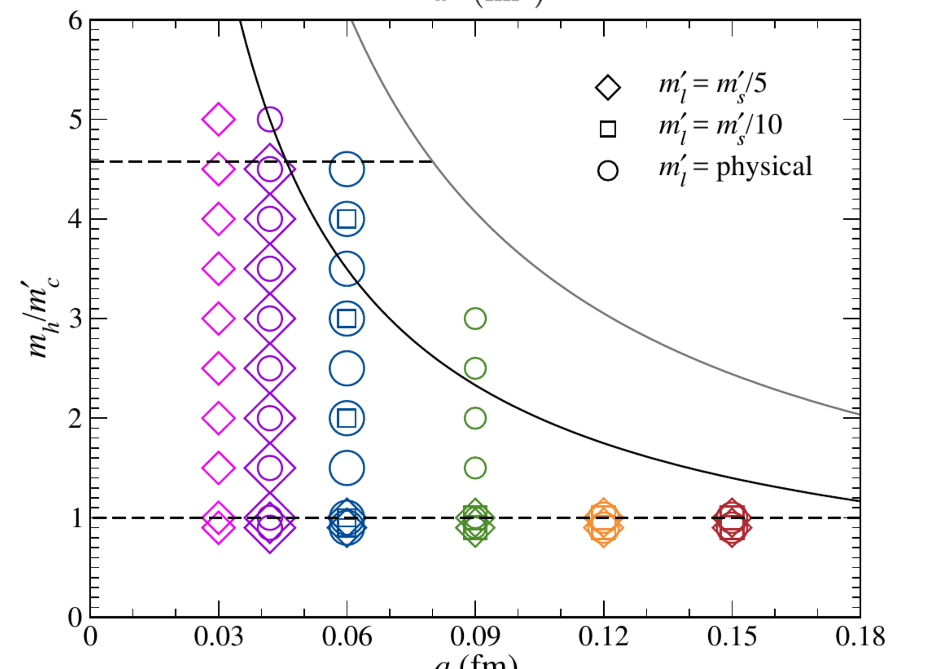
# Leptonic decays – New Results

**FNAL/MILC** arXiv:1712.09262

- $N_f = 2 + 1 + 1$
- 20 ensembles
- Light-quark mass down to $\frac{1}{2}(m_u + m_d)$
- down to $a \sim 0.03 fm$
- Very high statistics (1000x4 samples)
- Big volumes (up to: $144^3$ x 288, 6 *fm*)



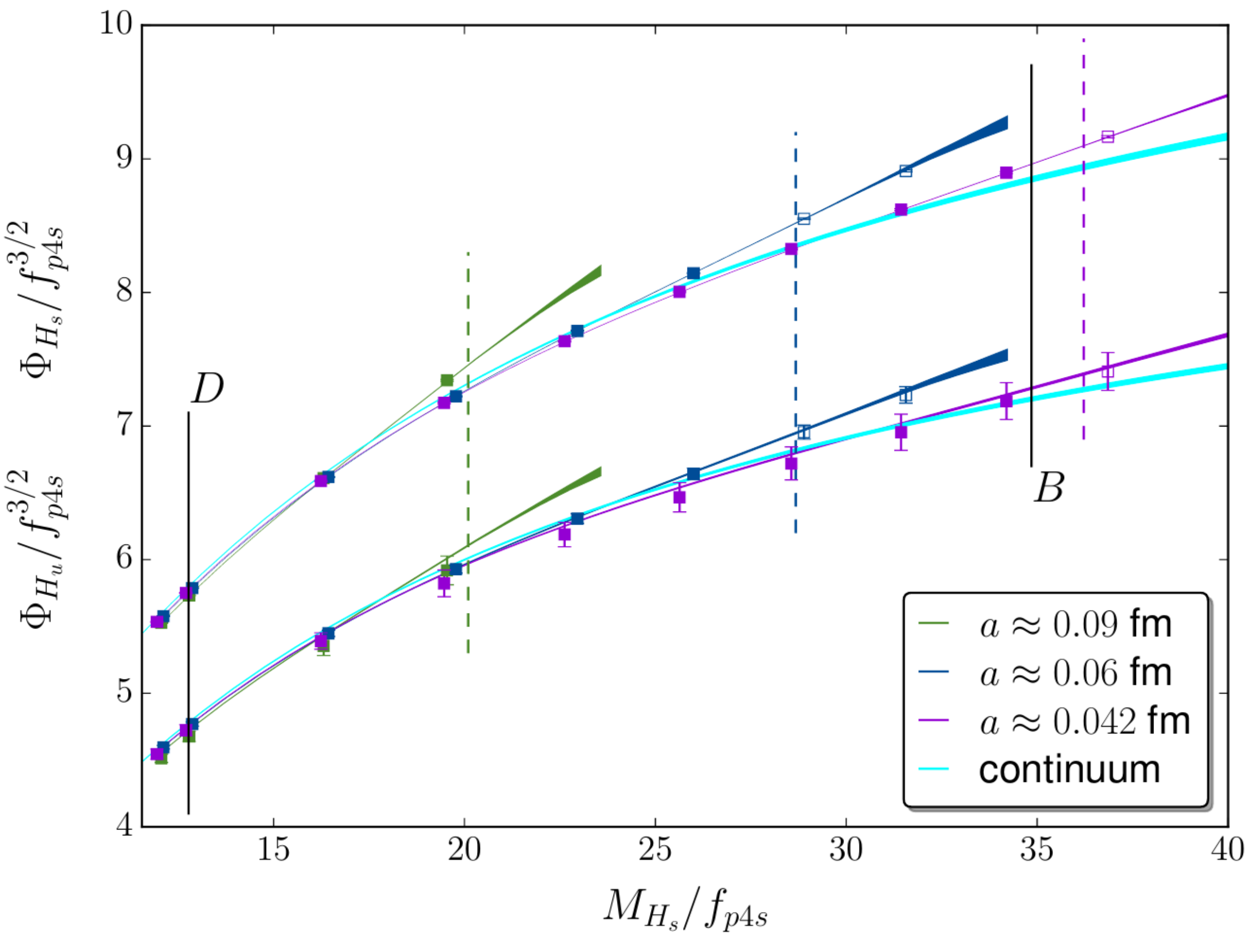

- always $0.9m_c$, $m_c$;
- omit $am_c \geq 0.9$ from heavy-quark fits (need < π/2);



# Leptonic decays – New Results

FNAL/MILC

- 492 data pts;
- 60 parameters;
- $\chi^2/\mathrm{dof} = 466/432$;



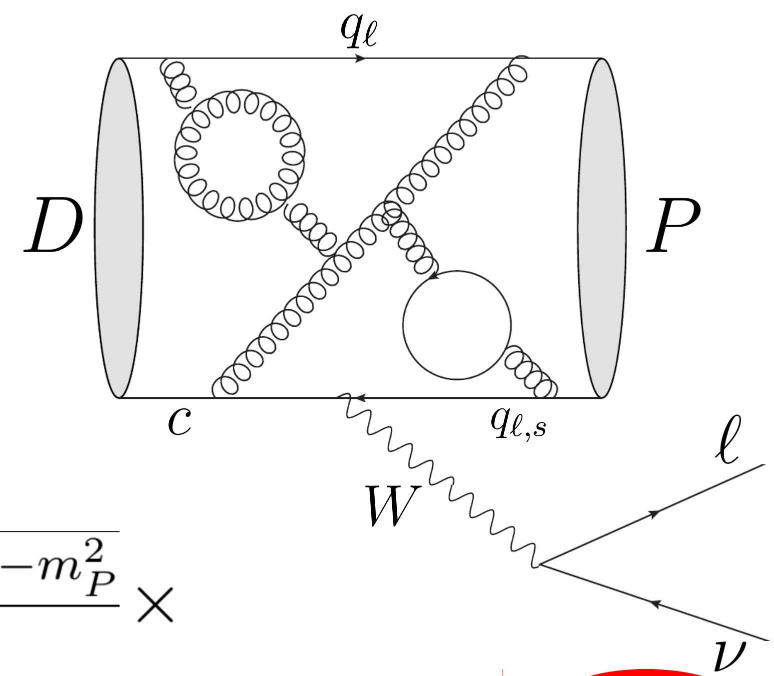

$$f_D = 212.1(0.3)_{\mathrm{stat}}(0.3)_{\mathrm{syst}}(0.2)_{f_{\pi,\mathrm{PDG}}}\ \mathrm{MeV}$$

$$f_{D_s} = 249.8(0.3)_{\mathrm{stat}}(0.3)_{\mathrm{syst}}(0.2)_{f_{\pi,\mathrm{PDG}}}\ \mathrm{MeV}$$

0.2%

# Semileptonic decays

$$D \to \pi(K)\ell\nu$$




CKM matrix elements

$$\frac{d\Gamma}{dq^2}(D \to P\ell\nu) = \frac{G_F^2}{24\pi^3}|V_{cd(s)}|^2 \frac{(q^2-m_\ell^2)^2\sqrt{E_P^2-m_P^2}}{q^4 m_D^2} \times$$

$$\times \left[\left(1+\frac{m_\ell^2}{2q^2}\right) m_D^2(E_P^2-m_P^2)|f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(m_D^2-m_P^2)^2|f_0(q^2)|^2\right]$$

Form factors (Lattice QCD)

- Experimental + LQCD inputs for the determination of CKM elements
- Determination of the forms factors in all the physical q2 range
- Momentum dependence of the tensor form factor for BSM analysis

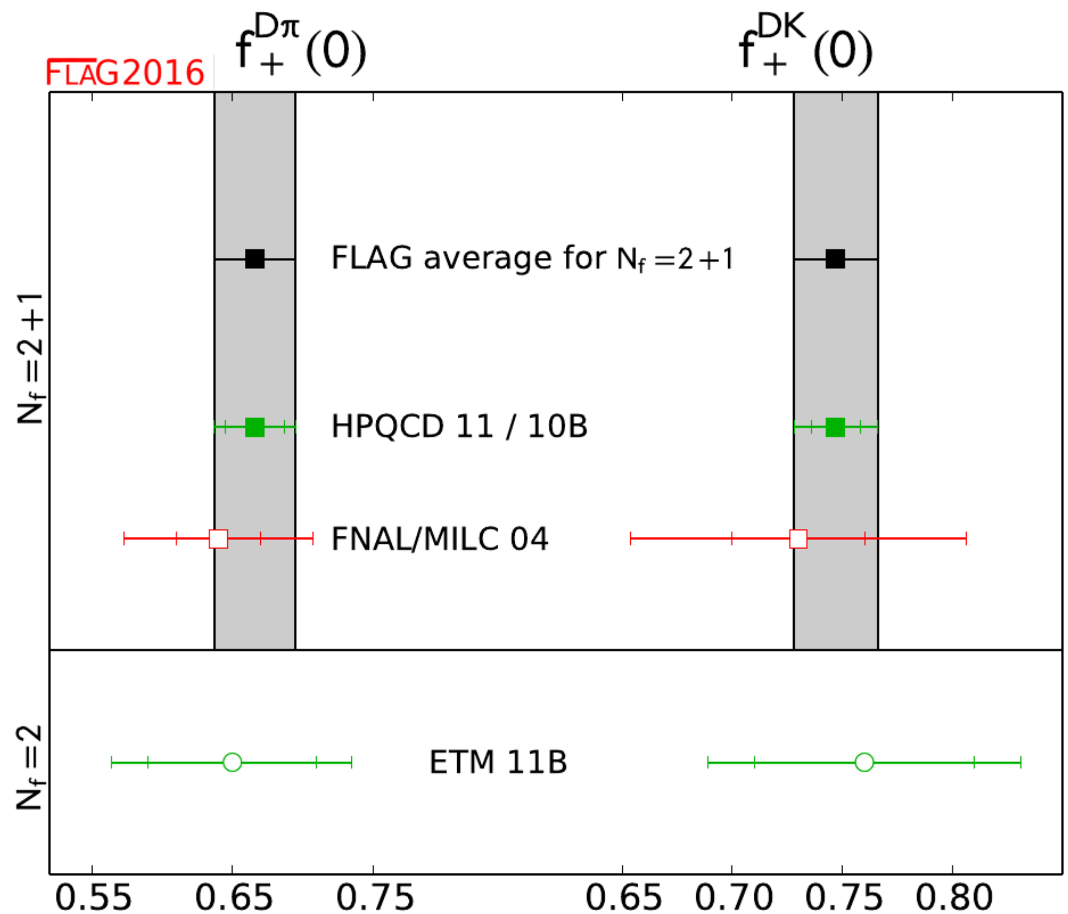
FLAG2016

EPJC**77** no.2, 112

## HPQCD

PRD**82**, 114506
PRD**84**, 114505

- $N_f = 2+1$ flavors of HISQ
- Improved action
- Physical mass: $s,\ c$
- $a \sim 0.09fm \div 0.12fm$
- No renormalization
- D at rest frame
- Modified z-expansion
- $f_0$ from the Scalar matrix element




2.5%

4.5%

# Semileptonic decays - New Results

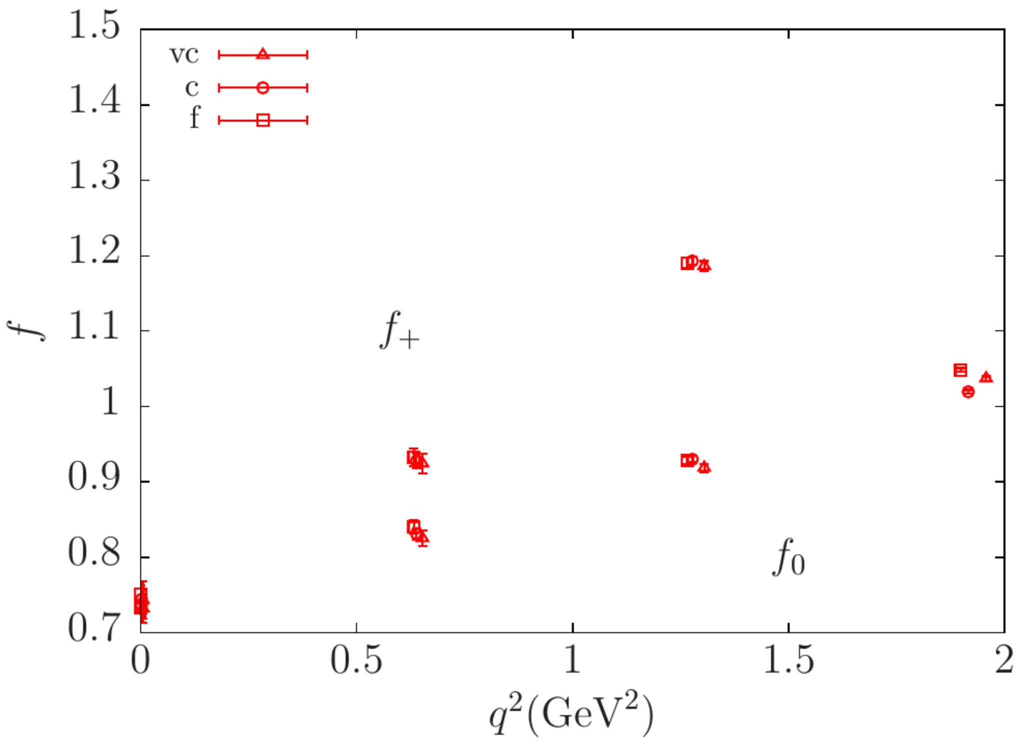
New (Preliminary)
(B. Chakraborty) @ LATTICE 2017

<u>HPQCD</u>

PRD**82**, 114506
PRD**84**, 114505

- $N_f = 2+1$ flavors of HISQ
- Improved action
- Physical mass: $s,\ c$
- $a \sim 0.09fm \div 0.12fm$
- No renormalization
- D at rest frame
- Modified z-expansion
- $f_0$ from the Scalar matrix element

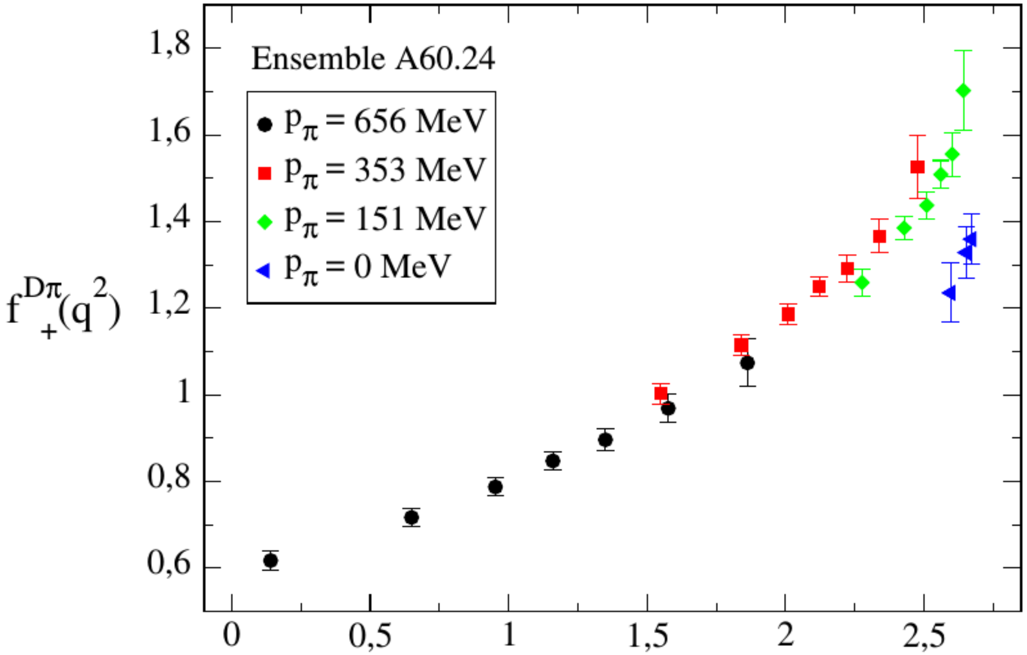
- $N_f = 2+1+1$
- Physical u/d quarks
- Both $f_+$ and $f_0$ over whole $q^2$-range

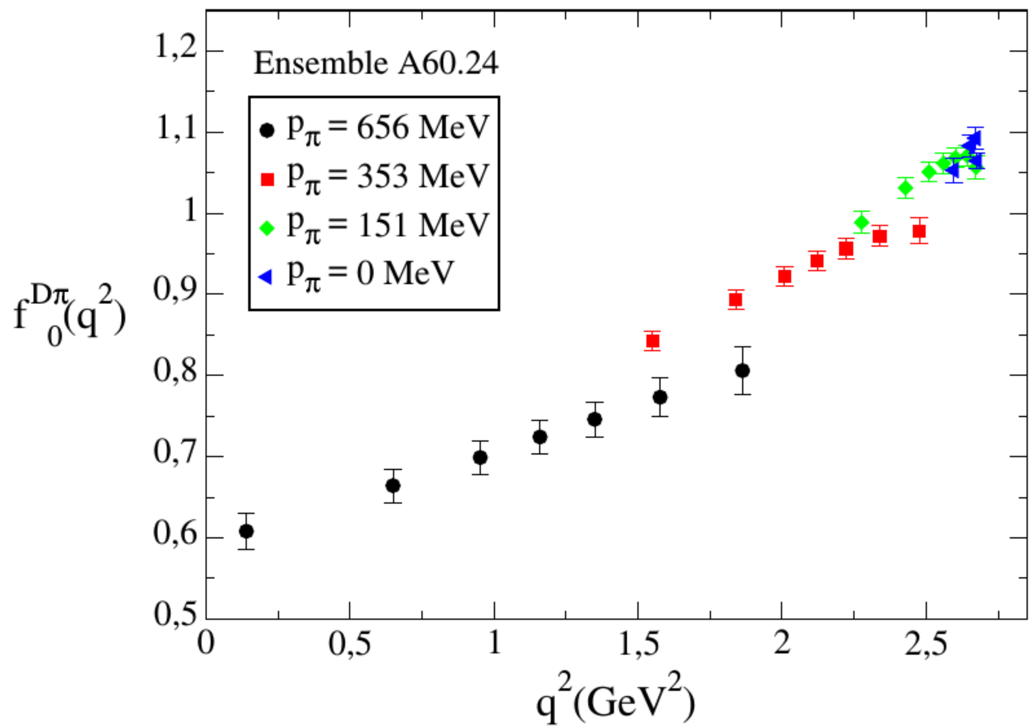


# Semileptonic decays - New Results

**ETMC** PRD**96** no.5, 054514
arXiv:1803.04807

- $N_f = 2+1+1$ flavors of tmW
- Improved action
- Physical mass: $s$, $c$
- $a \sim 0.06 fm \div 0.09 fm$
- No renormalization
- $f_{+,0}$ and $f_T$ over whole $q^2$-range
- Hypercubic discretization effects
- Modified z-expansion
- Vector & Scalar matrix elements



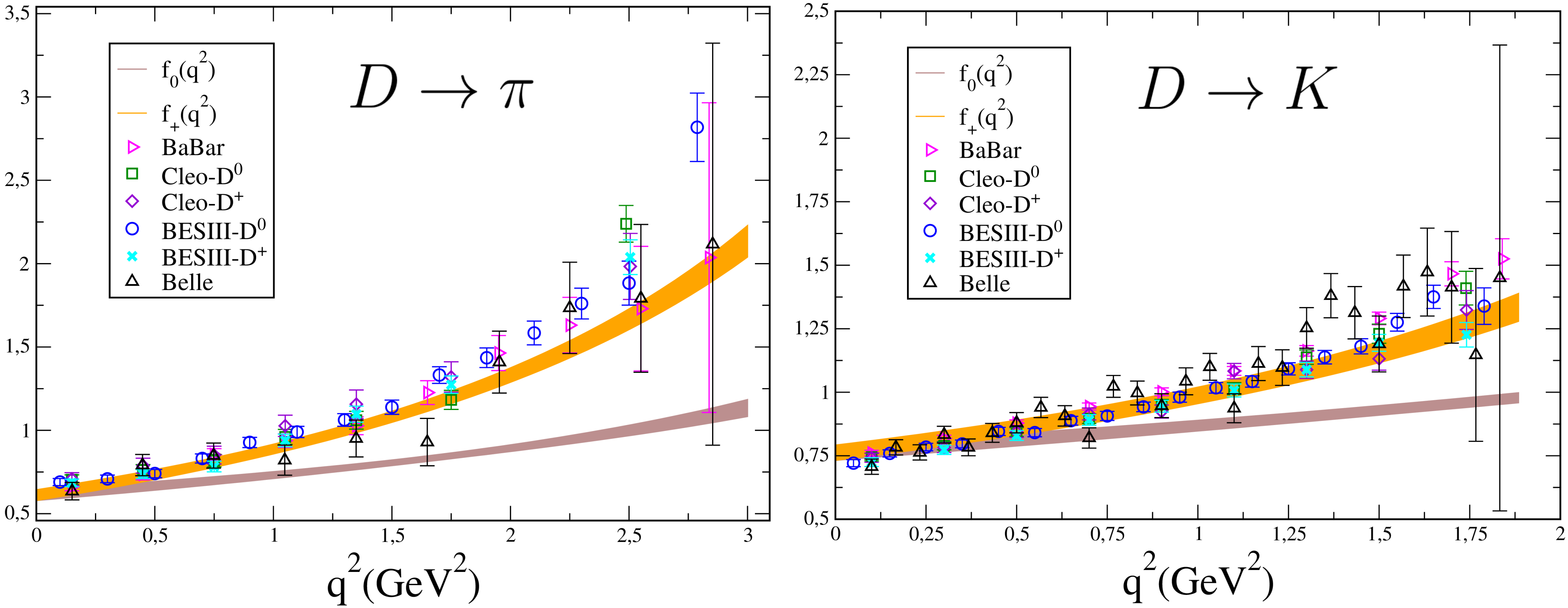



# Semileptonic decays - New Results

## $f_0(q^2)$ and $f_+(q^2)$ at the physical point

ETMC

$$\chi^2/d.o.f. = 1.2 \quad d.o.f. \approx 1100$$



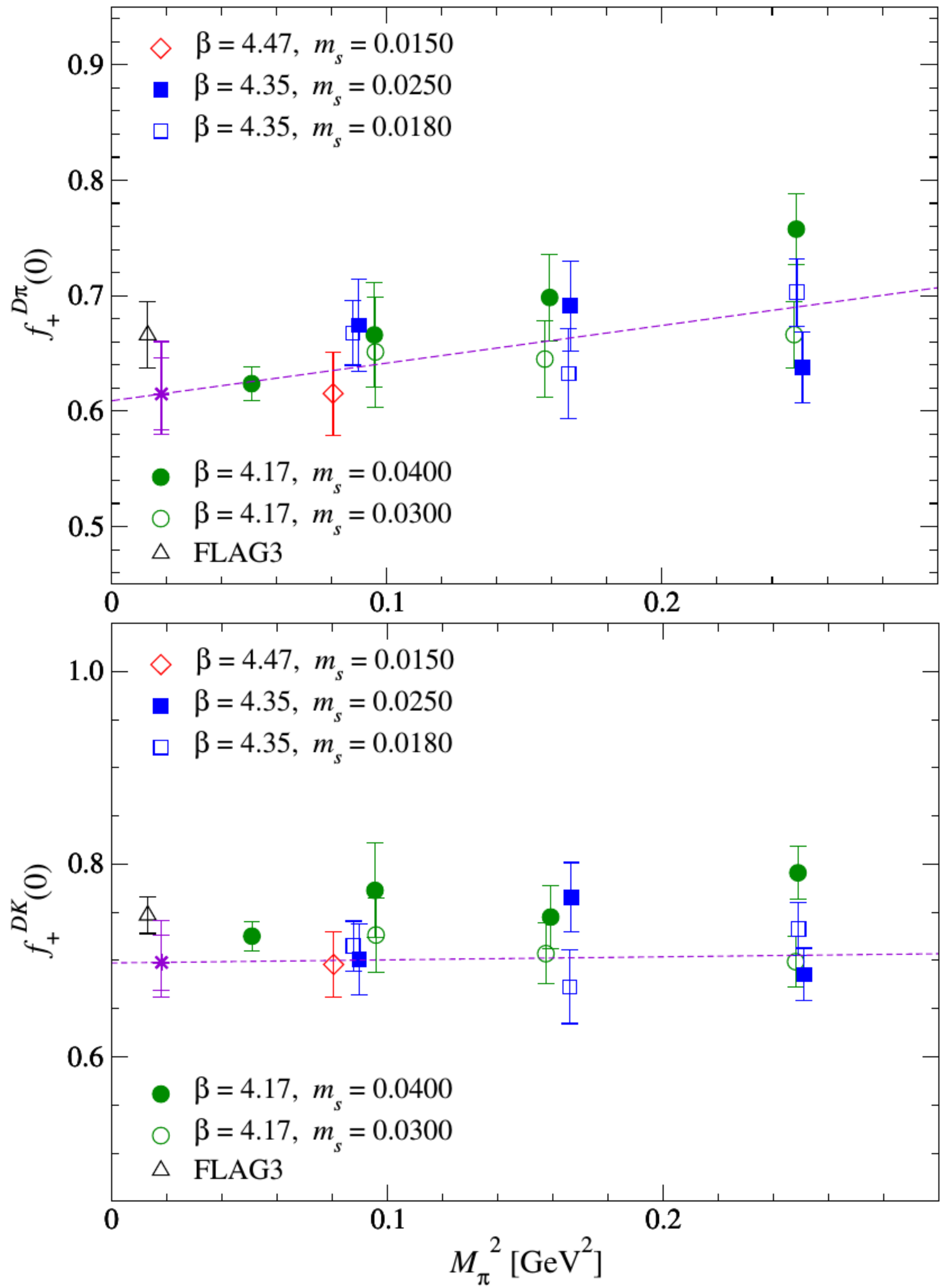

$$f_+^{D\to\pi}(0) = 0.612\,(35)_{\mathrm{Stat+fit}}\,(4)_{\mathrm{Ch}}\,(7)_{\mathrm{FSE}}\,(1)_{\mathrm{Disc}} = 0.612\,(36)$$

$$f_+^{D\to K}(0) = 0.765\,(29)_{\mathrm{Stat+fit}}\,(11)_{\mathrm{Ch}}\,(1)_{\mathrm{Disc}} = 0.765\,(31)$$

# Semileptonic decays - New Results

JLQCD (T. Kaneko) @ LATTICE 2017
Preliminary

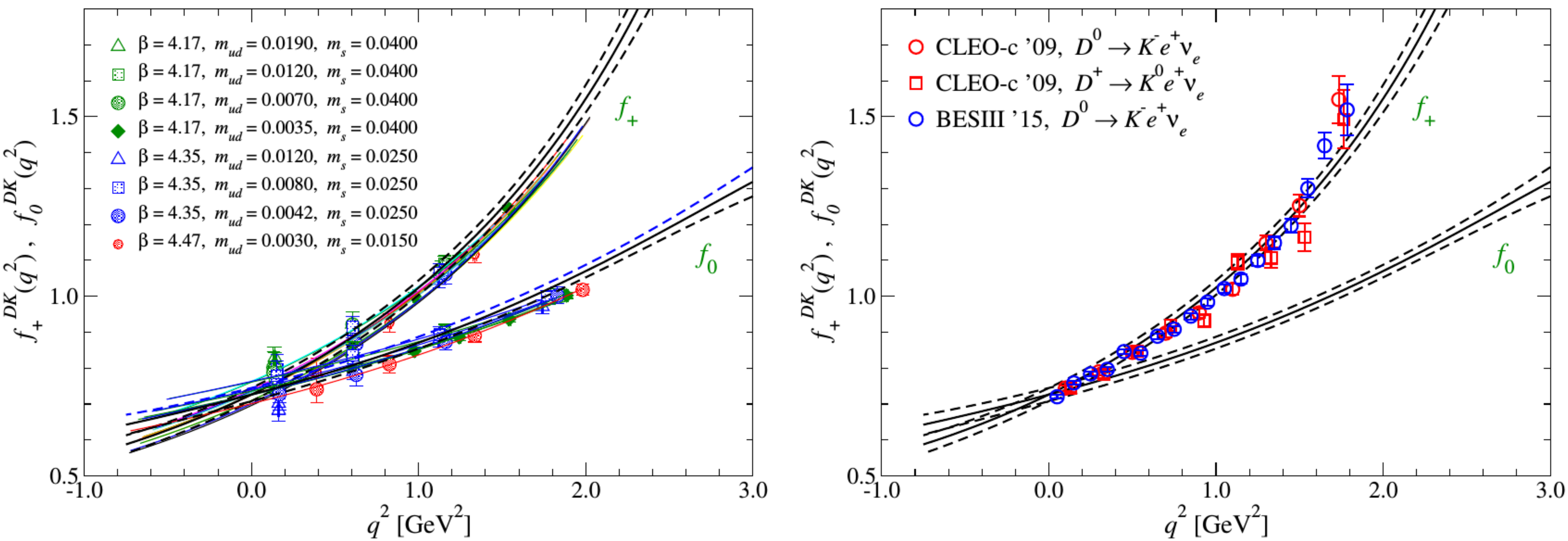
- $N_f = 2 + 1$ of DW fermions
- New ensembles: fine lattice spacing
- Improved action
- Physical mass: $s,\ c$
- $a \sim 0.05 fm \div 0.09 fm$
- Both $f_+$ and $f_0$ over whole $q^2$-range
- D at rest frame
- $q^2=0$ through BCL z-expansion



# Semileptonic decays - New Results

JLQCD (T. Kaneko) @ LATTICE 2017

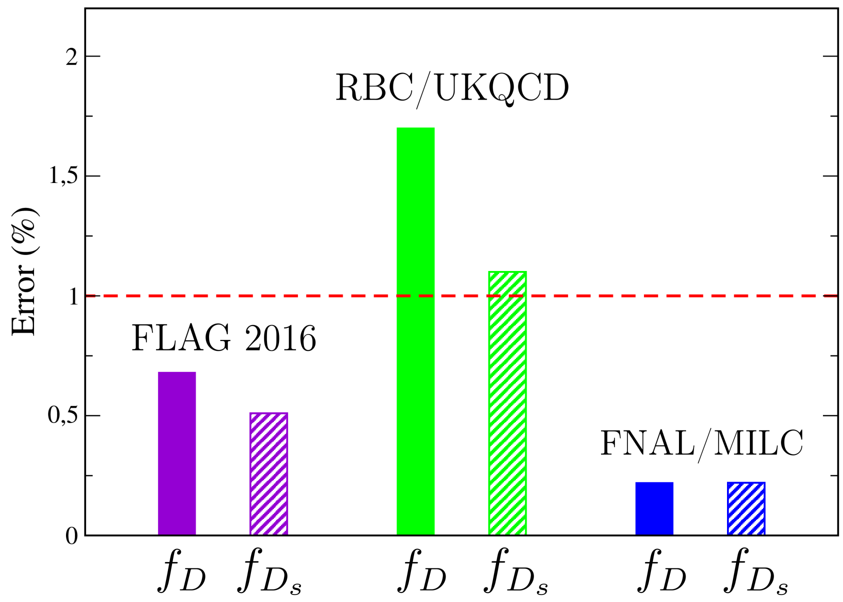
Preliminary

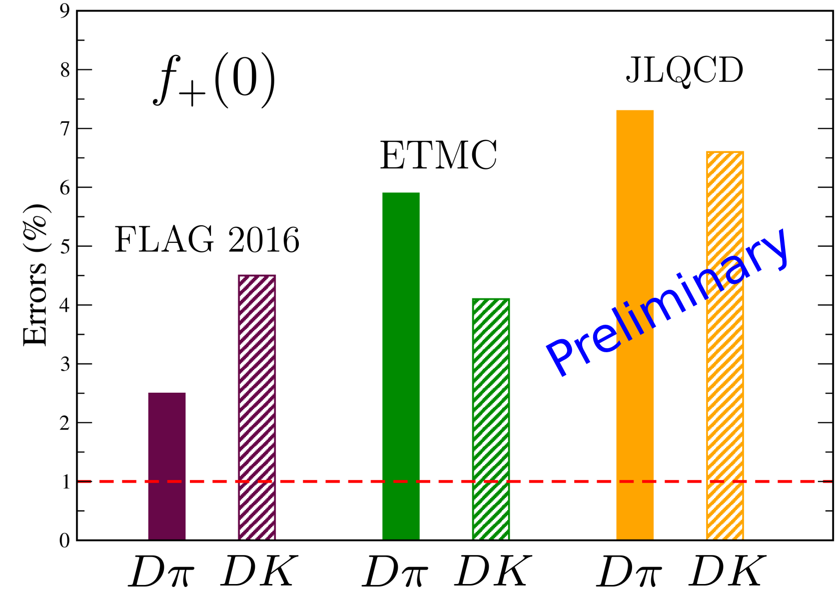


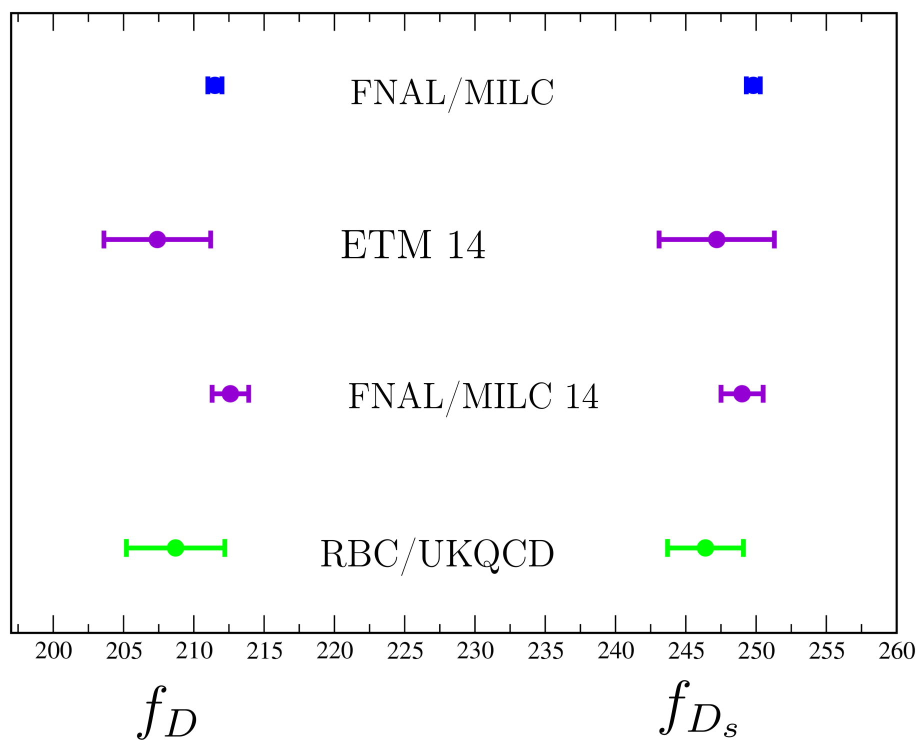

$$f_+^{D\pi}(0) = 0.615(31)_{\rm stat}\begin{pmatrix}+17\\-16\end{pmatrix}_{q^2\to 0}\begin{pmatrix}+28\\-7\end{pmatrix}_{a\to 0,\rm chiral}$$

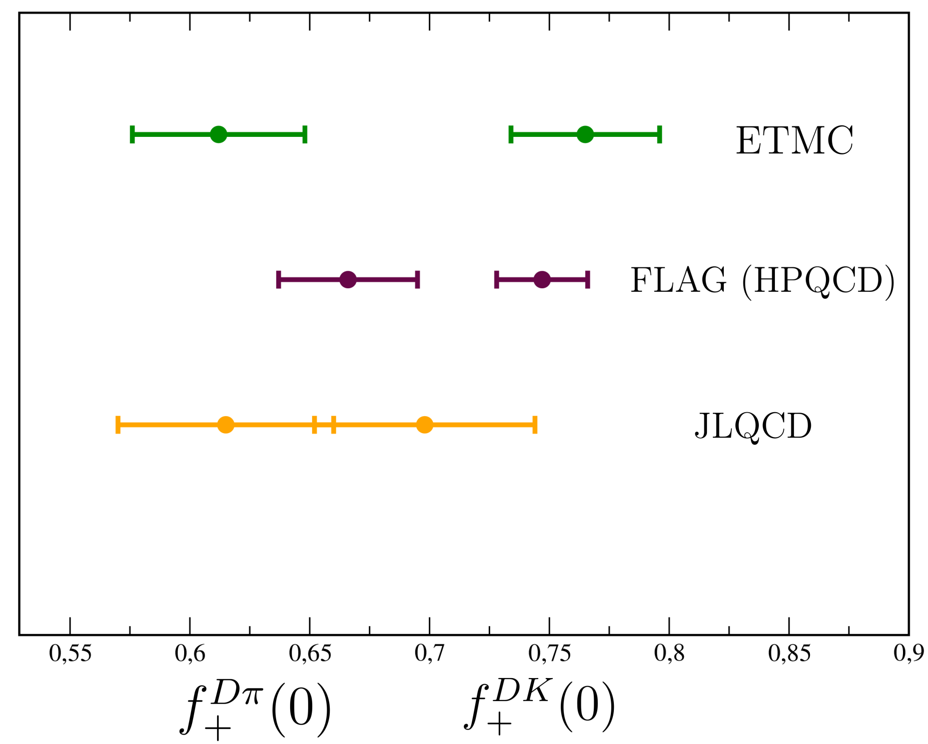
$$f_+^{DK}(0) = 0.698(29)_{\rm stat}(-18)_{q^2\to 0}\begin{pmatrix}+32\\-12\end{pmatrix}_{a\to 0,\rm chiral}$$

# Summary of results

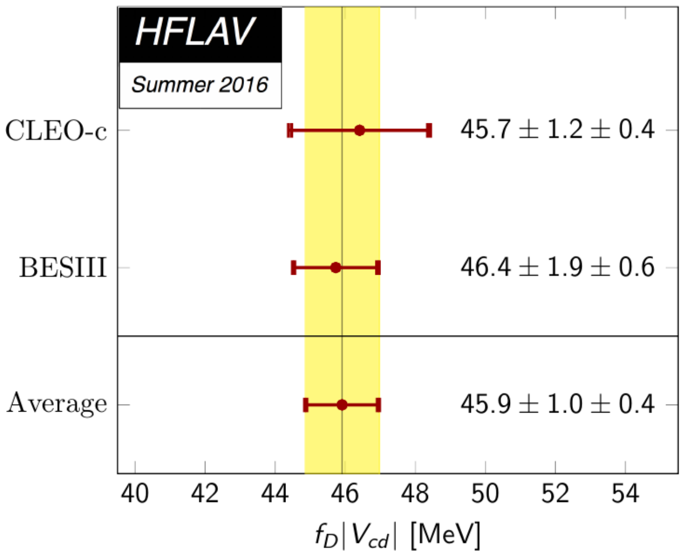


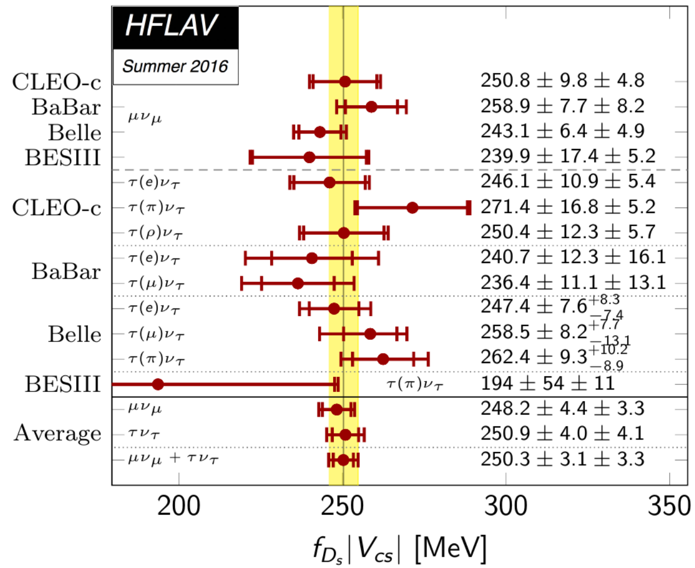



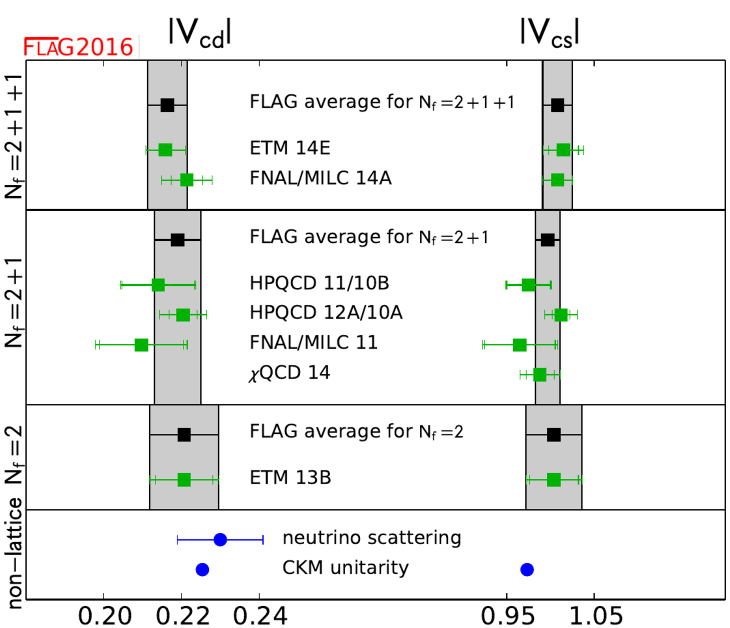
# Determination of $V_{cd}$ and $V_{cs}$




| Expt. $D \to K\ell\nu_\ell$ | Mode | $\lvert V_{cs}\rvert f_+^K(0)$ |
|---|---|---|
| BES III (tagged) [1155] | $(D^0)$ | 0.7195(35)(43) |
| CLEO-c (tagged) [1159] | $(D^0, D^+)$ | 0.7189(64)(48) |
| CLEO-c (untagged) [1160] | $(D^0, D^+)$ | 0.7436(76)(79) |
| *BABAR* [1158] | $(D^0)$ | 0.7241(64)(60) |
| Belle [1157] | $(D^0)$ | 0.700(19) |
| FOCUS [1162] and others | | 0.724(29) |
| **Combined** | $(D^0, D^+)$ | **0.7226(22)(26)** |

| Expt. $D \to \pi\ell\nu_\ell$ | mode | $\lvert V_{cd}\rvert f_+^\pi(0)$ |
|---|---|---|
| BES III (tagged) [1155] | $(D^0)$ | 0.1422(25)(10) |
| CLEO-c (tagged) [1159] | $(D^0, D^+)$ | 0.1507(42)(11) |
| CLEO-c (untagged) [1160] | $(D^0, D^+)$ | 0.1394(58)(25) |
| *BABAR* [1158] | $(D^0)$ | 0.1381(36)(22) |
| Belle [1157] | $(D^0)$ | 0.142(11) |
| **Combined** | $(D^0, D^+)$ | **0.1426(17)(8)** |



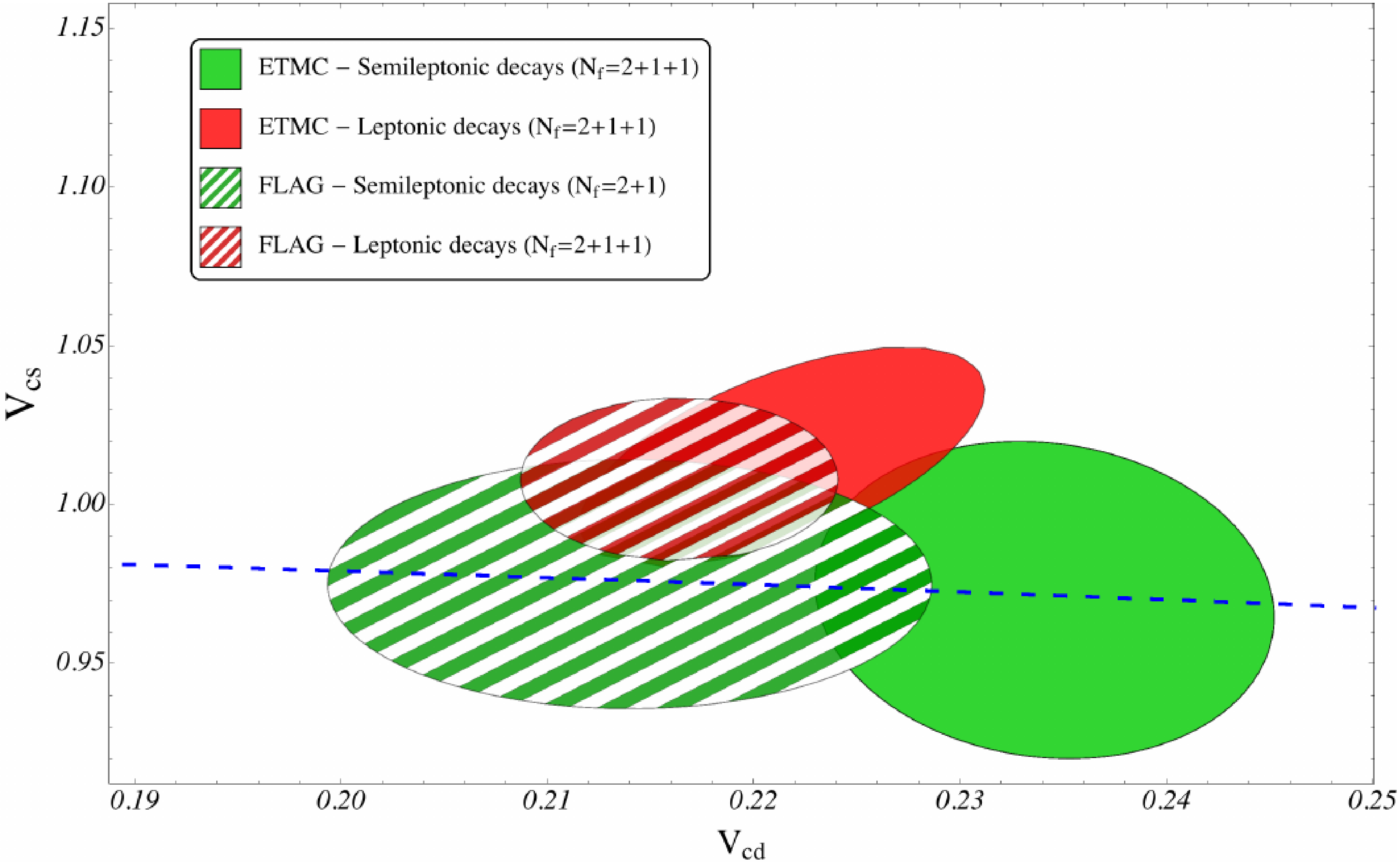

## $V_{cd(s)}$ from semileptonic decays
## (errors dominated by theoretical inputs)

| | $V_{cd}$ | $V_{cs}$ |
|---|---|---|
| FLAG 2016 | $0.2140\,(93)_{\rm lat}\,(29)_{\rm exp}$ | $0.975\,(25)_{\rm lat}\,(7)_{\rm exp}$ |
| ETMC | $0.2330\,(133)_{\rm lat}\,(31)_{\rm exp}$ | $0.945\,(38)_{\rm lat}\,(4)_{\rm exp}$ |
| JLQCD | $0.232\,(17)_{\rm lat}\,(3)_{\rm exp}$ | $1.035(64)_{\rm lat}\,(5)_{\rm exp}$ |

## $V_{cd(s)}$ from leptonic decays
## (errors dominated by experimental inputs)

| | $V_{cd}$ | $V_{cs}$ |
|---|---|---|
| FLAG 2016 | $0.2164\,(14)_{\rm LQCD}\,(49)_{\rm exp}$ | $1.008\,(5)_{\rm LQCD}\,(16)_{\rm exp}$ |
| FNAL/MILC | $0.2144\,(5)_{\rm LQCD}\,(49)_{\rm exp}\,(13)_{\rm EM}$ | $0.997\,(2)_{\rm LQCD}(16)_{\rm exp}\,(6)_{\rm EM}$ |
| RBC/UKQCD | $0.2185\,(37)_{\rm LQCD}(50)_{\rm exp}$ | $1.011\,(11)_{\rm LQCD}(16)_{\rm exp}$ |

# CKM 2nd-row Unitarity




$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 - 1 = 0.06(3) \qquad N_f = 2+1+1$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 - 1 = 0.04(3) \qquad N_f = 2+1$$

# Conclusions & Outlooks

- LQCD simulations with very small lattice spacings and light see quarks at their physical masses are being performed
  - No need (reduced) of chiral extrapolation ⇒ better precision

- LQCD predictions of the decay constants of the D and $D_s$ mesons are very precise (errors below 1%, now ~0.2%). Uncertainties in CKM matrix elements dominated by experimental inputs
  - New determinations are required to confirm systematic errors are under control

- Determinations of $D_{(s)}$ semileptonic form factors still need to be improved. Uncertainties in CKM matrix elements dominated by LQCD inputs
  - $f_{+,0}$ over whole $q^2$-range
  - $f_T$ over whole $q^2$-range

Thank you for the attention

# Other results

## ETMC

$N_f = 2+1+1$

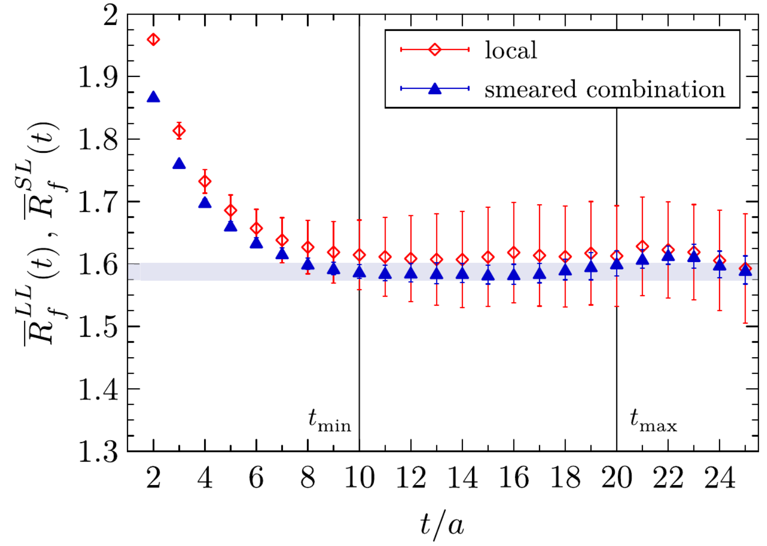
PRD**96**, 034524

$$\langle 0|\hat{V}_\mu|H_\ell^*(\vec{p},\lambda)\rangle = f_{H_\ell^*} M_{H_\ell^*} \epsilon_\mu^\lambda$$

$$(m_h + m_\ell)\langle 0|\hat{P}|H_\ell(\vec{p})\rangle = f_{H_\ell} M_{H_\ell}^2$$

$$f_{D^*}/f_D = 1.078(31)_{\rm stat}(5)_{\rm input}(6)_{t_{\rm min}}(8)_{\rm disc}(9)_{\rm chir}[36]$$

$$f_{D_s^*}/f_{D_s} = 1.087(16)_{\rm stat}(6)_{\rm input}(6)_{t_{\rm min}}(7)_{\rm disc}(5)_{\rm chir}[20]$$




## CLS ensembles

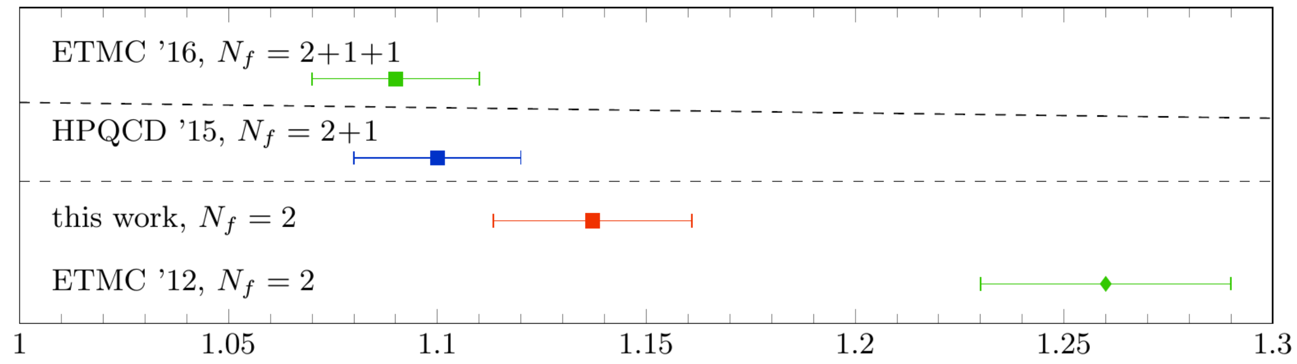
$N_f = 2$

arXiv:1803.03065

B. Blossier, J. Heitger, M. Post

| id | $\beta$ | $(L/a)^3 \times (T/a)$ | $\kappa_{\rm sea}$ | $a$ [fm] | $m_\pi$ [MeV] | $Lm_\pi$ | # cfgs | $\kappa_s$ | $\kappa_c$ |
|---|---|---|---|---|---|---|---|---|---|
| E5 | 5.3 | $32^3 \times 64$ | 0.13625 | 0.0653 | 439 | 4.7 | 200 | 0.135777 | 0.12724 |
| F6 | | $48^3 \times 96$ | 0.13635 | | 313 | 5 | 120 | 0.135741 | 0.12713 |
| F7 | | $48^3 \times 96$ | 0.13638 | | 268 | 4.3 | 200 | 0.135730 | 0.12713 |
| G8 | | $64^3 \times 128$ | 0.13642 | | 194 | 4.1 | 176 | 0.135705 | 0.12710 |
| N6 | 5.5 | $48^3 \times 96$ | 0.13667 | 0.0483 | 341 | 4 | 192 | 0.136250 | 0.13026 |
| O7 | | $64^3 \times 128$ | 0.13671 | | 269 | 4.2 | 160 | 0.136243 | 0.13022 |

$$f_{D_s^*}/f_{D_s} = 1.14(2)$$



# Extraction of the form factors

The two semileptonic form factors f $_0$ and f $_+$ can be determined from the matrix element of the vector current

$$f_+(q^2) = \frac{(E_D - E_P)\,\langle \widehat{V}_i \rangle - (p_{D\,i} - p_{P\,i})\,\langle \widehat{V}_0 \rangle}{2E_D\,p_{P\,i} - 2E_P\,p_{D\,i}}$$

$$f_-(q^2) = \frac{(p_{D\,i} + p_{P\,i})\,\langle \widehat{V}_0 \rangle - (E_D + E_P)\,\langle \widehat{V}_i \rangle}{2E_D\,p_{P\,i} - 2E_P\,p_{D\,i}}$$

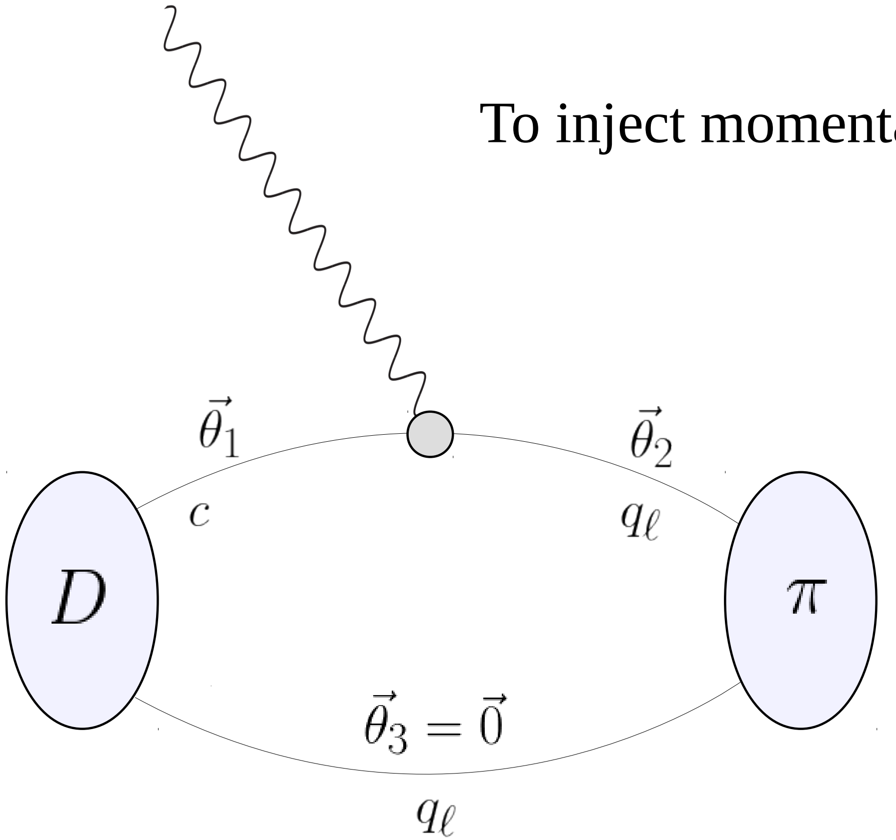
$$f_0(q^2) = f_+(q^2) + \frac{q^2}{M_D^2 - M_P^2}\, f_-(q^2)$$

$$V_\mu = \bar{c}\gamma_\mu d$$
$$S = \bar{c}d$$

An alternative way to determine f $_0$ is to use the scalar density

$$f_0(q^2) = \frac{\mu_c - \mu_q}{M_D^2 - M_P^2}\,\langle P(p_P)|S|D(p_D)\rangle$$

# Simulation Details




To inject momenta we used non-periodic boundary conditions

Both the D and the π(K) mesons can have non-zero momentum

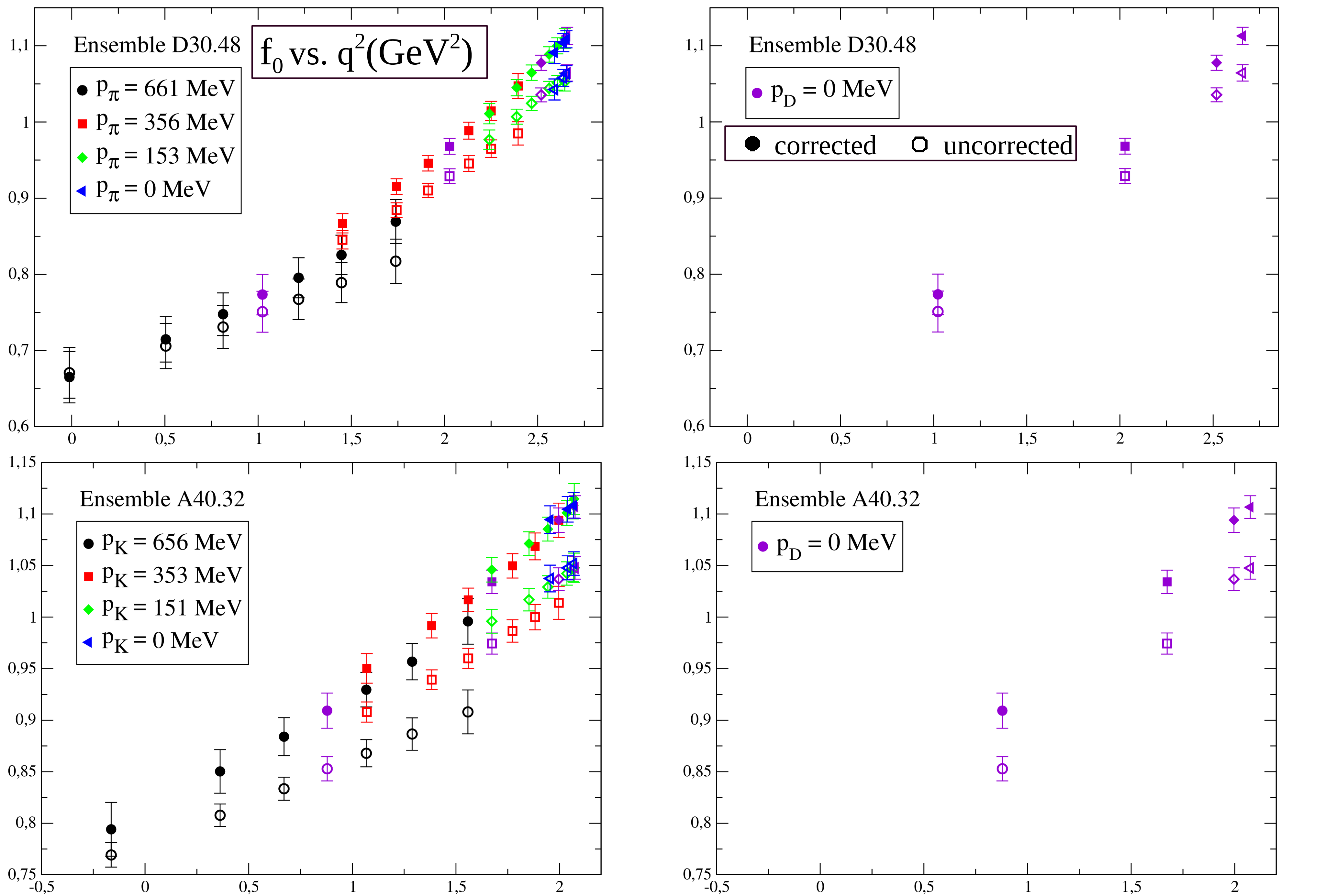
$$\vec{p}_D = \frac{2\pi}{L}\vec{\theta}_1$$

$$\vec{p}_\pi = \frac{2\pi}{L}\vec{\theta}_2$$

$$\vec{\theta} = \theta(1,1,1)$$

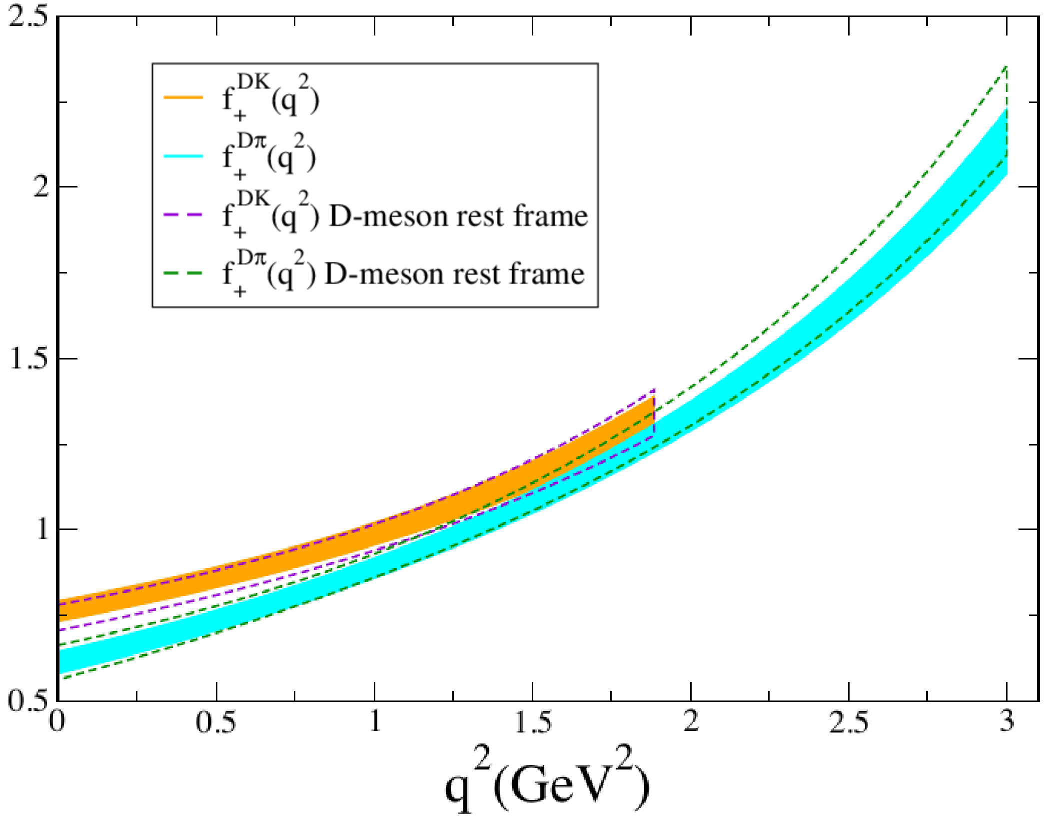
| $\beta$ | $V/a^4$ | $\theta$ |
|---|---|---|
| 1.90 | $32^3 \times 64$ | 0.0, ±0.200, ±0.467, ±0.867 |
| | $24^3 \times 48$ | 0.0, ±0.150, ±0.350, ±0.650 |
| 1.95 | $32^3 \times 64$ | 0.0, ±0.183, ±0.427, ±0.794 |
| | $24^3 \times 48$ | 0.0, ±0.138, ±0.321, ±0.596 |
| 2.10 | $48^3 \times 96$ | 0.0, ±0.212, ±0.493, ±0.916 |

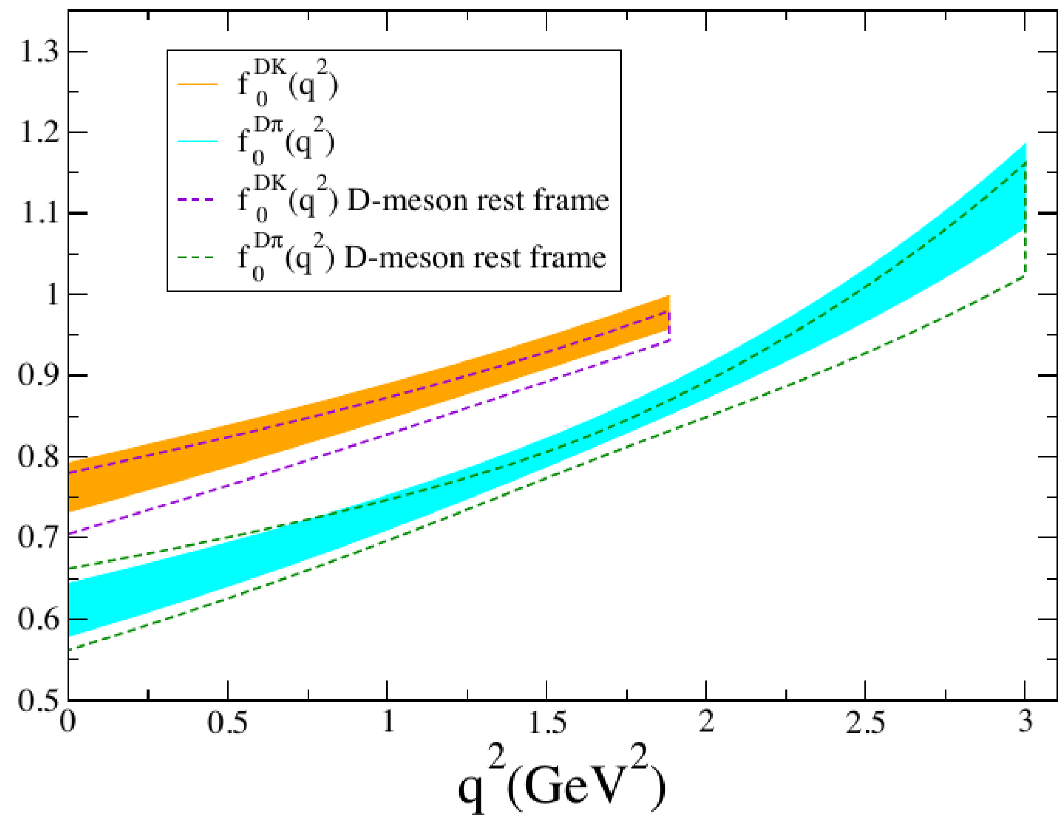
# Lorentz Symmetry Breaking



# Results

## In the continuum limit

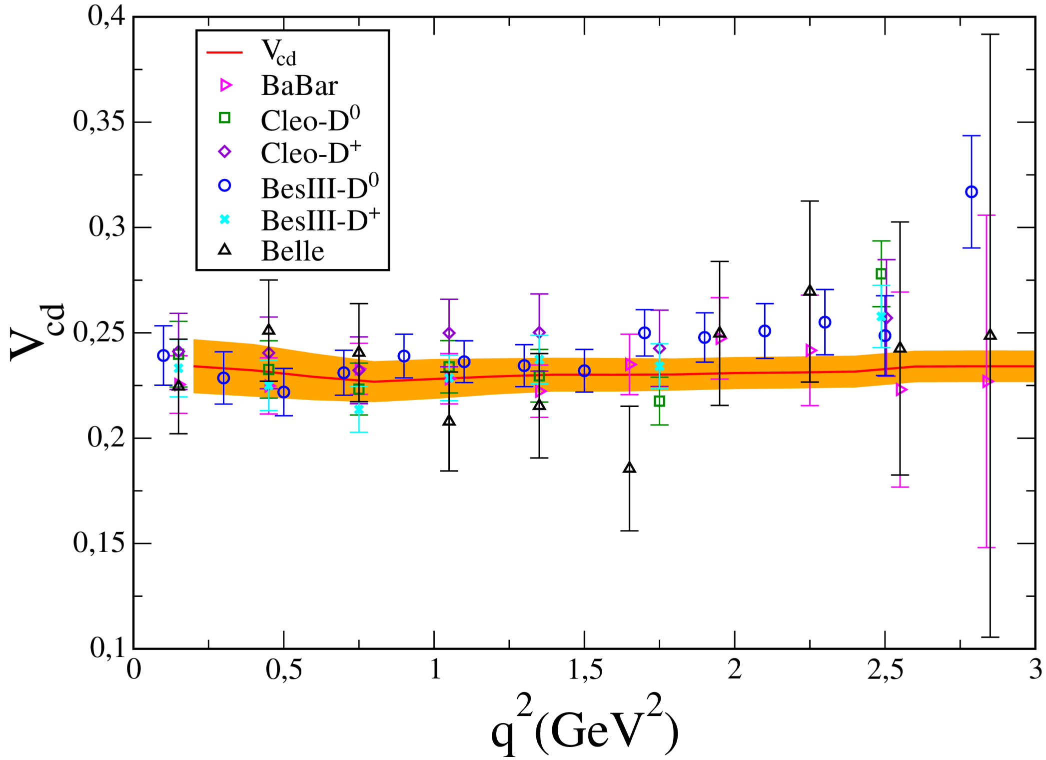


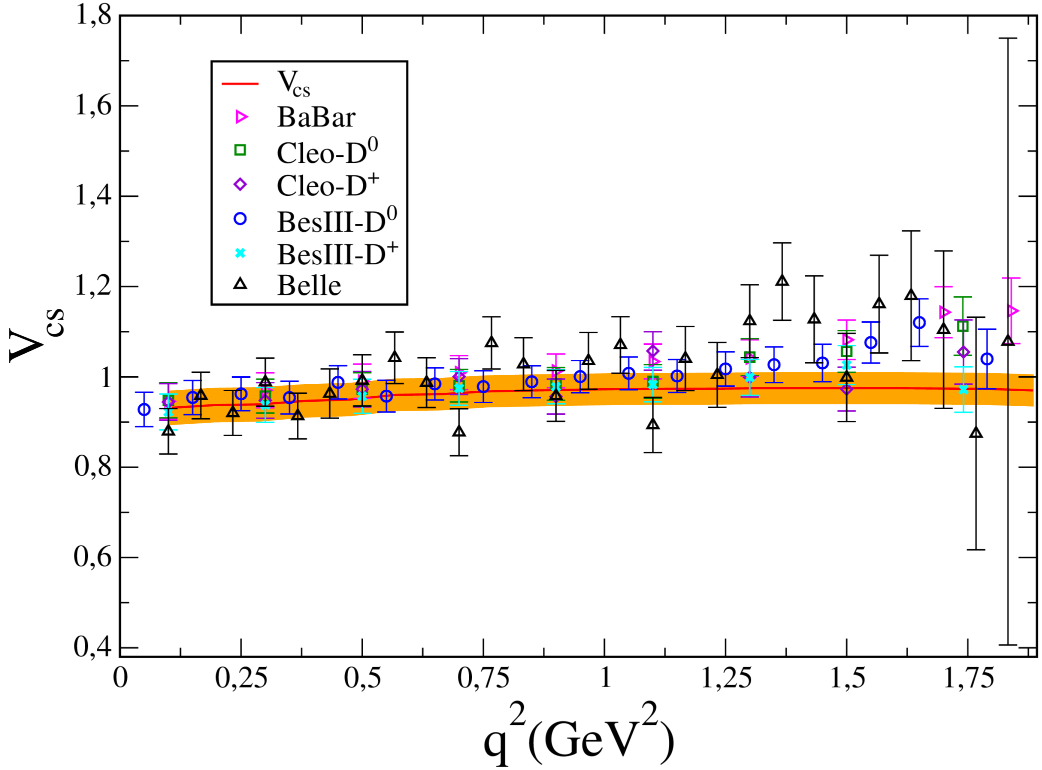



# Determination of $V_{cd}$ and $V_{cs}$

$$\frac{d\Gamma(D \to P\ell\nu)}{dq^2} = \frac{G_F^2 |V_{cx}|^2}{24\,\pi^3} |\vec{p}_P|^3 \, |f_+^{DP}(q^2)|^2 \quad \Rightarrow \quad V_{cx}(q_i^2) = \sqrt{\frac{24\pi^3}{G_F^2} \frac{\Delta\Gamma(q_i^2)}{I(q_i^2)}}$$

**arXiv**:1706.03657




$$q^2 \in [0, q^2_{\rm max}]$$

$$|V_{cd}| = 0.2341\ (74) \qquad |V_{cs}| = 0.970\ (33)$$

$$q^2 = 0$$

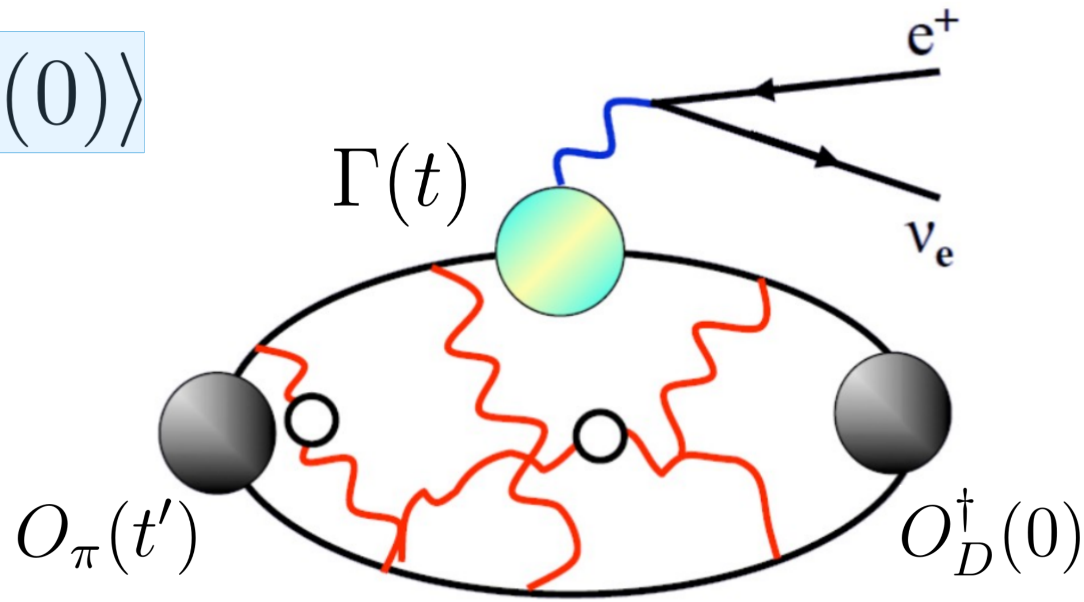
$$|V_{cd}| = 0.2330\ (137)$$

$$|V_{cs}| = 0.945\ (38)$$

# 3-points correlators

$$C_{\Gamma}^{DP}(t) \equiv \langle O_P(t')\Gamma(t)O_D^{\dagger}(0)\rangle$$

$\downarrow$ large $t$




$$\frac{\langle 0|O_{\pi}(0)|\pi(\mathbf{p}_{\pi})\rangle\langle D(\mathbf{p}_D)|O_D^{\dagger}(0)|0\rangle\, e^{-E_D t}e^{-E_{\pi}(t'-t)}}{(2E_D)(2E_{\pi})} \times \langle\pi(\mathbf{p}_{\pi})|\Gamma(0)|D(\mathbf{p}_D)\rangle$$

From 2-point correlators

Form factors

# Euclidean Correlators

$$C(t) \equiv \langle O_\pi(t) O_\pi^\dagger(0) \rangle \approx \sum_n \frac{|\langle 0| O_\pi(0) |n\rangle|^2}{2E_n} \exp[-E_n t] \xrightarrow[t\to\infty]{} \frac{|\langle 0| O_\pi(0) |\pi\rangle|^2}{2M_\pi} \exp[-M_\pi t]$$

Calculated on the lattice (Importance sampling Monte Carlo)

$$\frac{1}{Z}\int \mathcal{D}[\phi]\, O_1(\phi)\, O_2(\phi)\, e^{-S_E[\phi]} \simeq \frac{1}{N_c}\sum_{c=1}^{N_c} O_1(\phi_c)\, O_2(\phi_c)$$

$$(\Delta O)^2 = \frac{1}{N_c}\sum_{c=1}^{N_c} \left(O(\phi_c) - \langle O \rangle\right)^2$$

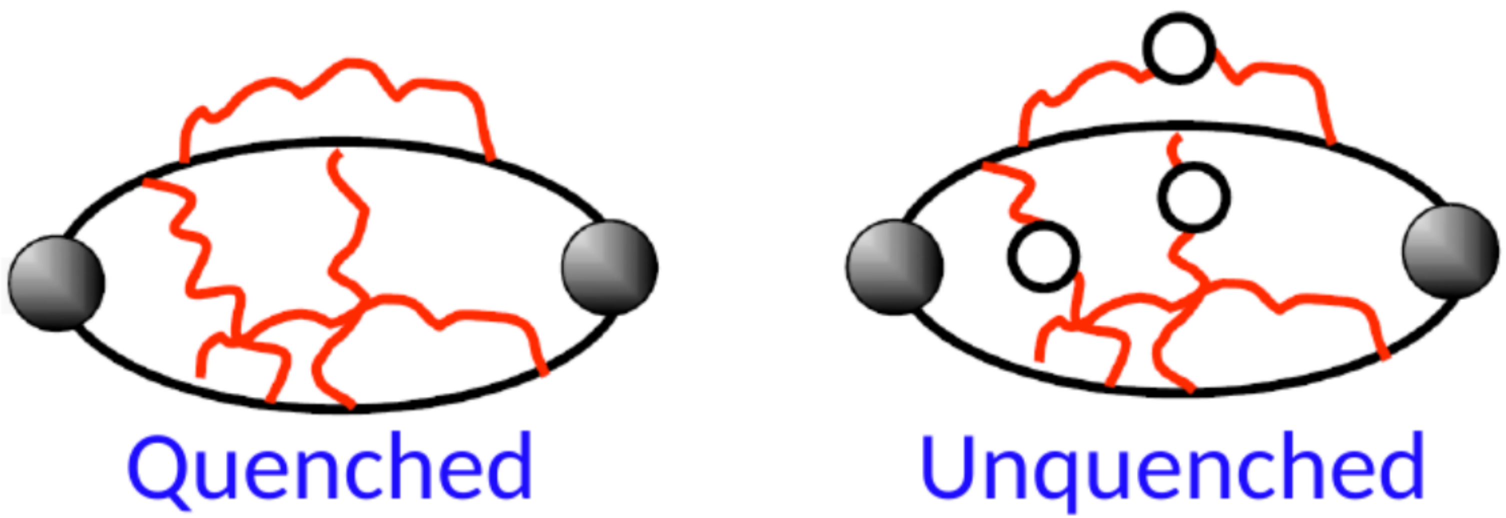
→ Statistical error $\sim \frac{1}{\sqrt{N_c}}$

# Quenching

$$\int \mathcal{D}[U]\ \mathcal{D}[\psi,\bar{\psi}]\ e^{-S_g[U]-\bar{\psi}\mathrm{M}\psi} = \int \mathcal{D}[U]\ \det\mathrm{M}\, e^{-S_g[U]}$$

Gaussian integral for anticommutative (Grassmann) variables

det M encodes the contribution of see quark loops



# Modified z-expansion

$$f_+^{D\to\pi}(q^2) = \frac{f^{D\to\pi}(0,a^2) + c_+(a^2)\,(z-z_0)\left(1+\frac{z+z_0}{2}\right)}{1-\frac{q^2}{M_V^2}}$$

$$f_0^{D\to\pi}(q^2) = \frac{f^{D\to\pi}(0,a^2) + c_0(a^2)\,(z-z_0)\left(1+\frac{z+z_0}{2}\right)}{1-\frac{q^2}{M_S^2}\,K_{FSE}^0(L)}$$

$$f_+^{D\to K}(q^2) = \frac{f^{D\to K}(0,a^2) + c_+(a^2)\,(z-z_0)\left(1+\frac{z+z_0}{2}\right)}{1-\frac{q^2}{M_{D_s^*}^2}(1+P_+a^2)}$$

$$f_0^{D\to K}(q^2) = f^{D\to K}(0,a^2) + c_0(a^2)\,(z-z_0)\left(1+\frac{z+z_0}{2}\right)$$

$$t_+ = (M_D + M_P)^2$$

$$t_0 = (M_D + M_P)(\sqrt{M_D} - \sqrt{M_P})^2$$

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

$$z_0 = z(q^2 = 0)$$

$c_+(a^2)$ and $c_0(a^2)$ have a polynomial dependence on $a^2$

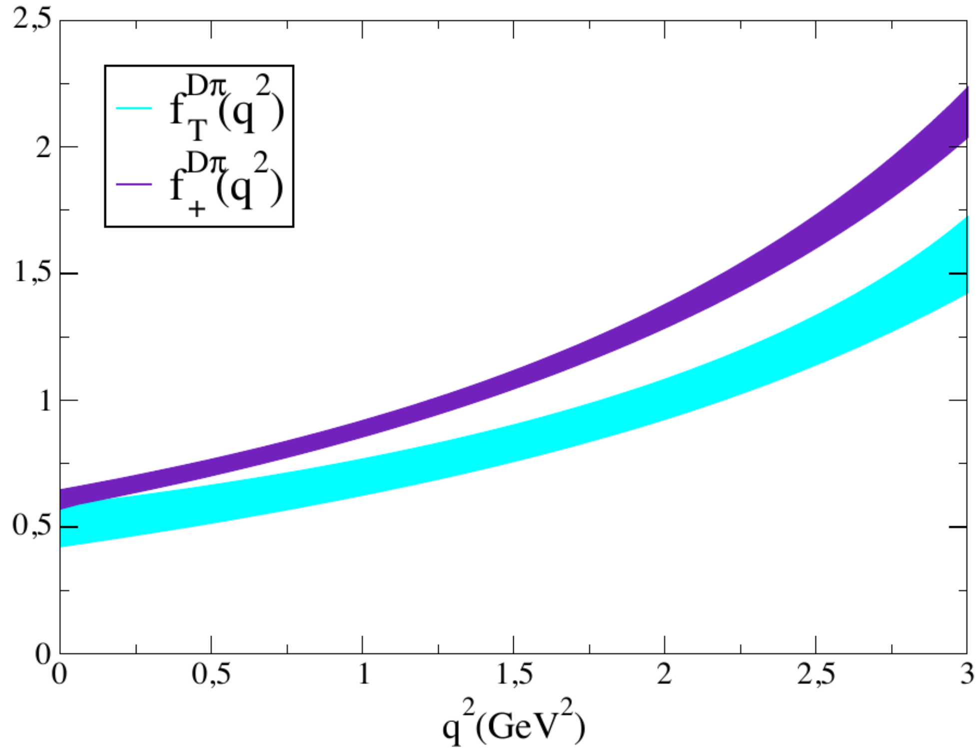
$M_V$ and $M_S$ are parameters left free to move in the fit

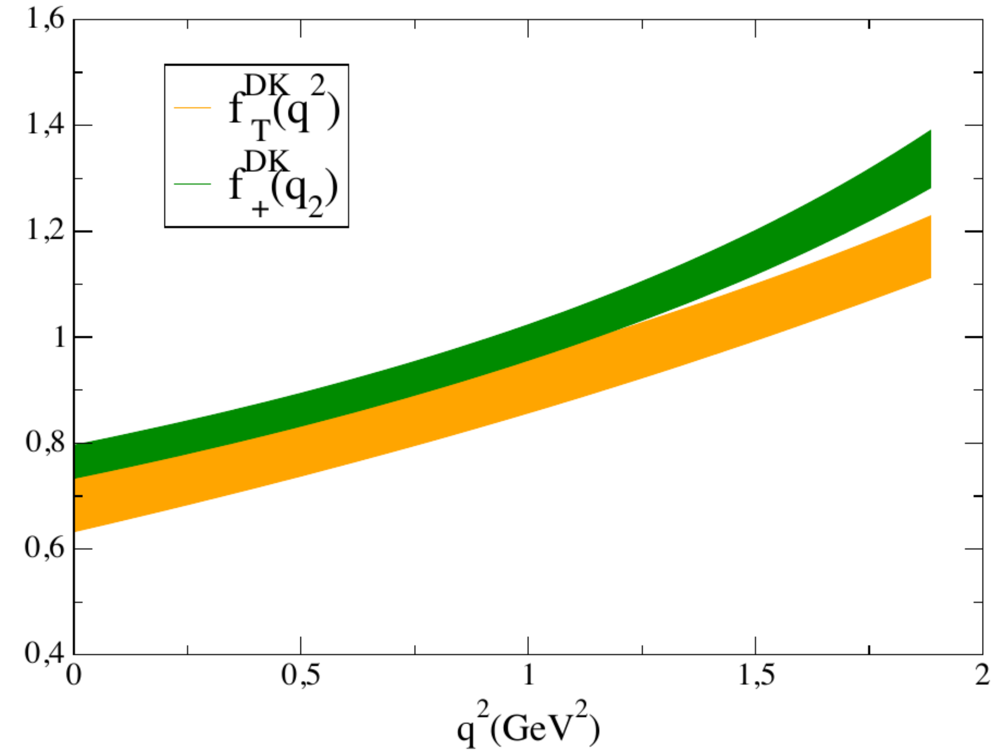
$$f_+(0,a^2) = f_0(0,a^2) \equiv f(0,a^2)$$

# ETMC – Tensor form factor

$f_T(q^2)$ at the physical point

ETMC




$$f_T^{D\pi}(0) = 0.506\ (79)$$

$$f_T^{DK}(0) = 0.687\ (54)$$