Non-Standard Physics in (Semi)Leptonic Decays

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based on (and complementing) Dobrescu & ASK,
PRL **100,** 241802 (2008) [arXiv:0803.0512 [hep-ph]]

Outline

- Conventional wisdom
- The f_{D_s} puzzle
- New physics: W', charged Higgs, leptoquarks
- Semileptonic decays
- Conclusions

Leptonic Decay

- The branching fraction for $D_s \to l\nu$ is

$$B(D_s \to \ell\nu) = \frac{m_{D_s}\tau_{D_s}}{8\pi} f_{D_s}^2 \, |G_F V_{cs}^* m_\ell|^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

where the decay constant f_{Ds} is defined by

$$\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s(p)\rangle = i f_{D_s} p_\mu$$

- Usually experiments quote f_{Ds}.

Semileptonic Decay

- The differential rate for $D \to K\mu\nu$ is

$$\frac{d\Gamma}{dq^2} = \frac{m_K^3 G_F^2 |V_{cs}|^2}{192\pi^2} \left[\mathtt{PS}_+ |f_+(q^2)|^2 + \frac{m_\mu^2}{m_K^2} \mathtt{PS}_0 |f_0(q^2)|^2 \right]$$

where the form factors are defined by

$$\langle K(k)|\bar{s}\gamma^\mu c|D(p)\rangle = (p+k)^\mu_\perp f_+(q^2) + q^\mu f_0(q^2),$$

where $q \cdot (p+k)_\perp = 0.$

- Standard decay amplitudes are tree-level, W-mediated.

- Non-Standard amplitudes would have to be large to be noticeable.

- Non-Standard models are *popular* only if they are *predictive*, hence *constrained*.

- New physics is implausible, so $hl\nu$ are used to determine CKM, and $l\nu$ to test latQCD.

(By the way,

process	measures	CKM how?	comment
$\pi \to l\nu$ $l = e, \mu$	$\lvert V_{ud}\rvert f_\pi$	nuclear β $0^+ \to 0^+$	Anyone here understand it?
$K \to l\nu$ $l = e, \mu$	$\lvert V_{us}\rvert f_K$	$K \to \pi l\nu$	Hence, $f_K/f_+(0)$.
$D \to \mu\nu$	$\lvert V_{cd}\rvert f_D$	CKM unitarity	Hence $\lvert V_{us}\rvert$.
$D_s \to l\nu$ $l = \mu, \tau$	$\lvert V_{cs}\rvert f_{D_s}$	CKM unitarity	Hence $\lvert V_{us}\rvert$ & $\lvert V_{ud}\rvert$.
$B \to \tau\nu$	$\lvert V_{ub}\rvert f_B$	$b \to ul\nu$ $B \to \pi l\nu$	Which $\lvert V_{ub}\rvert$?

one of our acid tests relies on nuclear physics.)

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$D_s \to l\nu$ $l = \mu, \tau$	$\lvert V_{cs}\rvert f_{Ds}$	CKM unitarity	Hence $\lvert V_{us}\rvert$ & $\lvert V_{ud}\rvert$.
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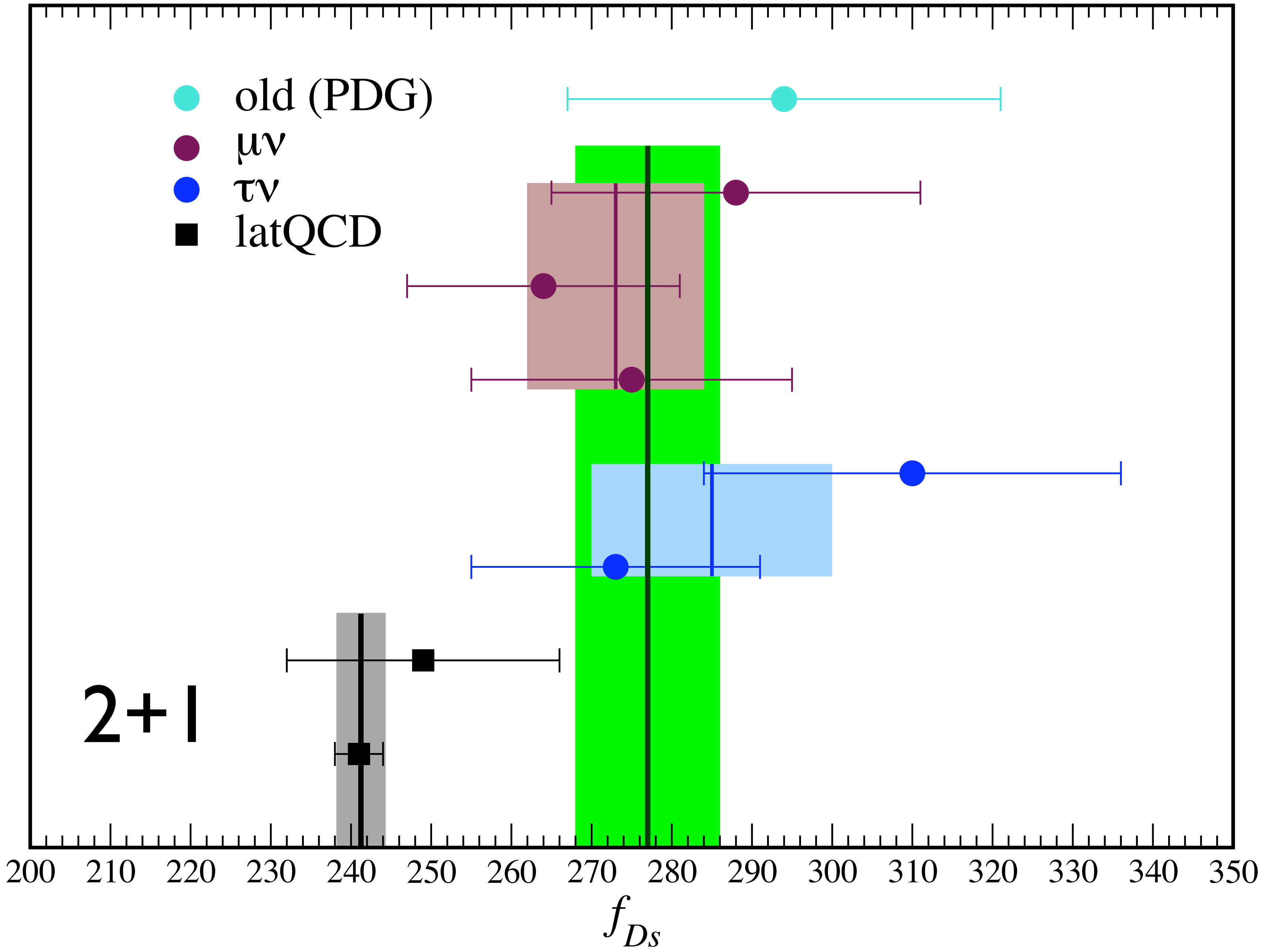
But something funny happened ...



$\chi^2/\mathrm{dof} = 0.67$

BaBar

CLEO

Belle

CLEO $\pi\nu$

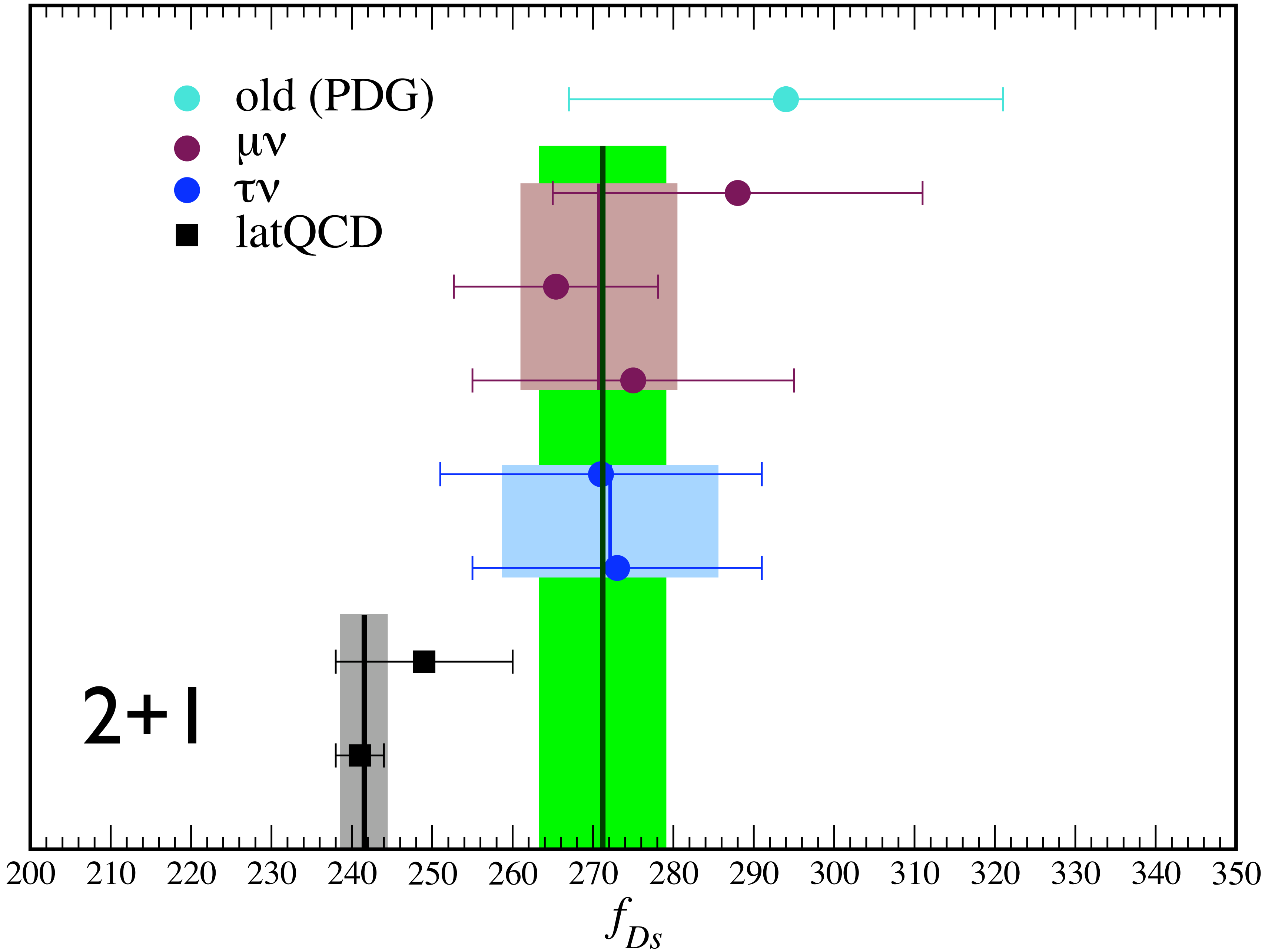
CLEO $e\nu\nu$

Fermilab/MILC

HPQCD

a 3.8σ discrepancy, or $2.7\sigma \oplus 2.9\sigma$.

With CLEO's (our) update from FPCP (Lat08)...



χ^2/dof = 0.13

BaBar

CLEO

Belle

CLEO $\pi\nu$

CLEO $e\nu\nu$

Fermilab/MILC

HPQCD

a 3.5σ discrepancy, or $2.9\sigma \oplus 2.2\sigma$.

Experiments

- Measurements by BaBar, CLEO, Belle do not depend on models* for interpretation of the central value or the error bar.
- CLEO and Belle have absolute $B(D_s \to l\nu)$.
- Hard to see a misunderstood systematic.
- Could all fluctuate high?
- * except the Standard Model!

CKM

- Experiments take $|V_{cs}|$ from 3-generation unitarity, either with PDG's global CKM fit or setting $|V_{cs}| = |V_{ud}|$. No difference.
- Even n-generation CKM requires $|V_{cs}| < 1$; would need $|V_{cs}| > 1.1$ to explain effect.
- (Note that from $D \to Kl\nu$, $|V_{cs}| > 1$.)

Radiative Corrections

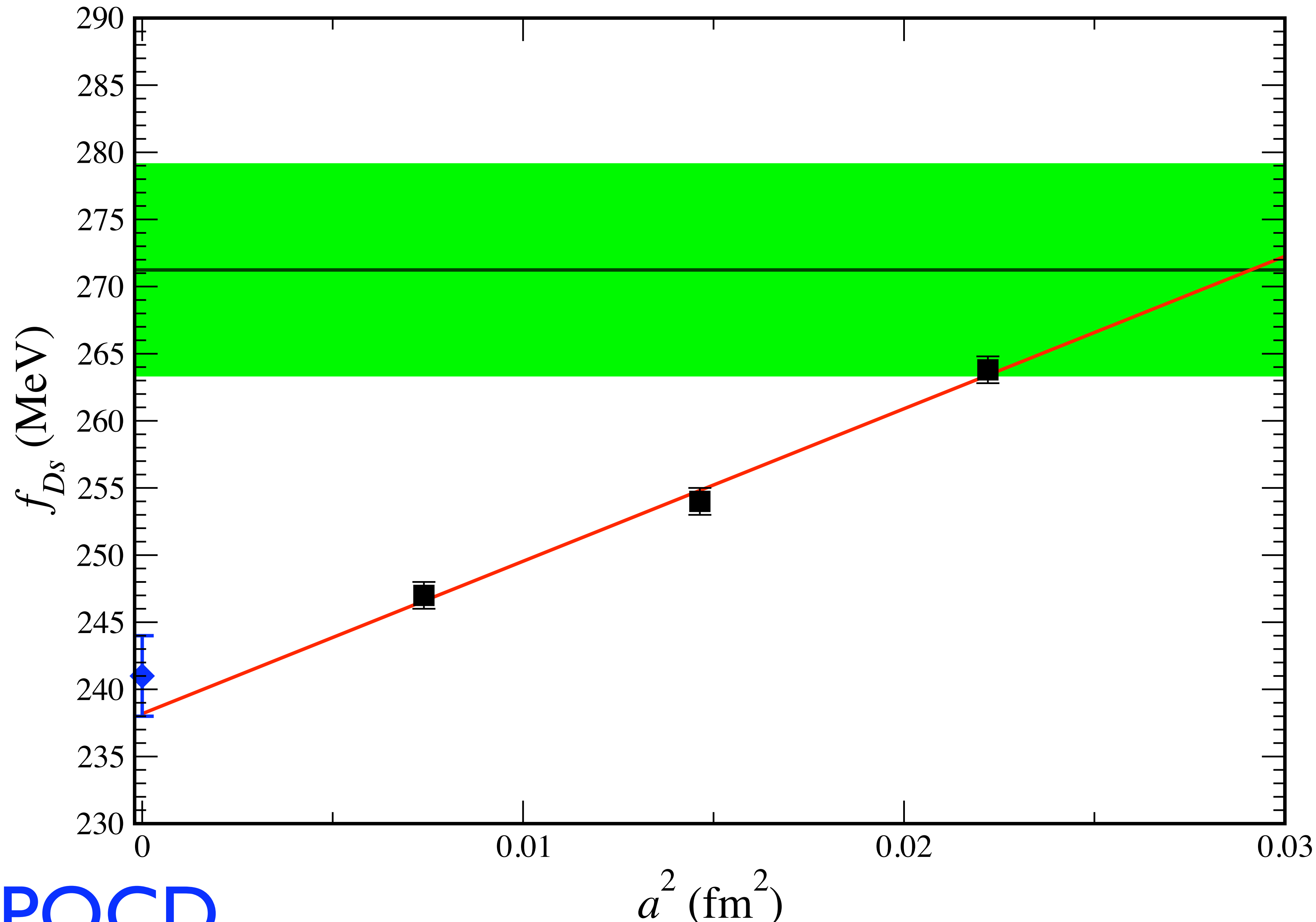
- Fermi constant from muon decay, so its radiative corrections implicit in $\mu\nu$ and $\tau\nu$.
- Standard treatment [Marciano & Sirlin] has a cutoff, set (for f_π) to m_ρ. Only 1–2%.
- More interesting is $D_s \to D_s^*\gamma \to \mu\nu\gamma$, which is *not* helicity suppressed. Applying CLEO's cut 1% for $\mu\nu$ [Burdman, Goldman, Wyler].
- Only $9.3\ \mathrm{MeV}$ kinetic energy in $D_s \to \tau\nu$.

Elements of HPQCD

- Staggered valence quarks
  - HISQ (highly improved staggered quark) action;
  - discretization errors $O(\alpha_s a^2)$, $O(a^4)$;
  - absolutely normalization from PCAC;
  - less taste breaking;
  - tiny statistical errors: 0.5% on f_{Ds}.

- 2+1 rooted staggered sea quarks:
  - Lüscher-Weisz gluon + asqtad action;
  - discretization errors $O(\alpha_s a^2)$, $O(a^4)$;
  - discretization errors cause small violations of unitarity, controllable by chiral perturbation theory.
- Combined fit to $a^2, m_{\rm sea}, m_{\rm val}$ dependence: not fully documented, but irrelevant for f_{Ds}.

As the lattice gets finer, the discrepancy grows:

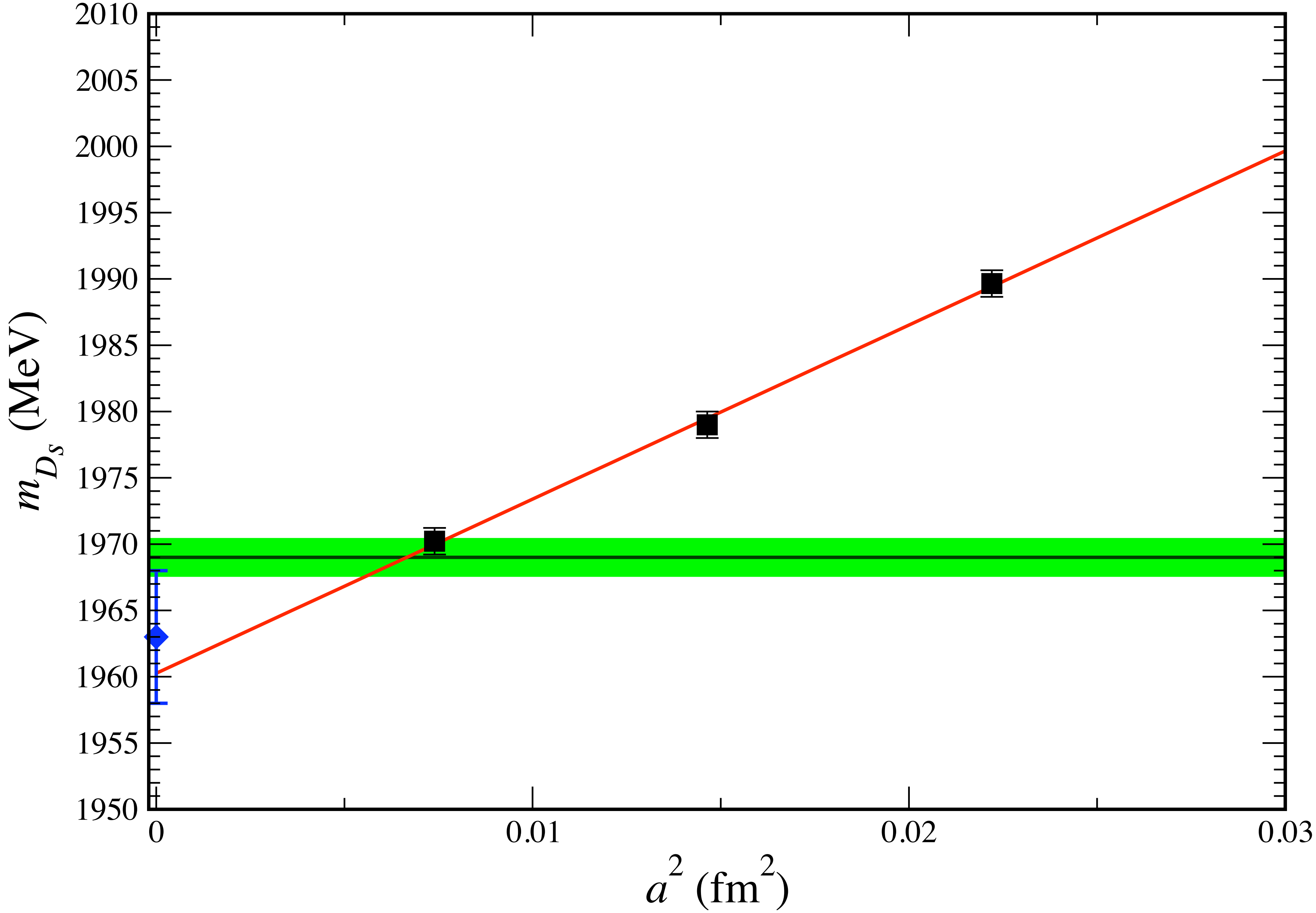


271.2±7.9 MeV

slope is $O(\alpha_s m_c \Lambda a^2)$ as expected

HPQCD 241±3

linear in a^2: 239; quad in a^2: 242; linear in a^4: 245.



If m_c (set from η_c) were retuned to flatten this, f_{Ds} (at $a \neq 0$) would not change much.

Error Budget

$\Delta_q = 2m_{Dq} - m_{\eta c}$

	f_K/f_π	f_K	f_π	f_{D_s}/f_D	f_{D_s}	f_D	Δ_s/Δ_d
r_1 uncerty.	0.3	1.1	1.4	0.4	1.0	1.4	0.7
a^2 extrap.	0.2	0.2	0.2	0.4	0.5	0.6	0.5
Finite vol.	0.4	0.4	0.8	0.3	0.1	0.3	0.1
$m_{u/d}$ extrap.	0.2	0.3	0.4	0.2	0.3	0.4	0.2
Stat. errors	0.2	0.4	0.5	0.5	0.6	0.7	0.6
m_s evoln.	0.1	0.1	0.1	0.3	0.3	0.3	0.5
m_d, QED, etc.	0.0	0.0	0.0	0.1	0.0	0.1	0.5
Total %	0.6	1.3	1.7	0.9	1.3	1.8	1.2

charmed sea $\ll 1\%$?

Other Results

what	expt	HPQCD	
$m_{J/\psi} - m_{\eta c}$	118.1	111 ± 5‡	MeV
m_{Dd}	1869	1868 ± 7	MeV
m_{Ds}	1968	1962 ± 6	MeV
Δ_s/Δ_d	1.260 ± 0.002	1.252 ± 0.015	
f_π	130.7 ± 0.4	132 ± 2	MeV
f_K	159.8 ± 0.5	157 ± 2	MeV
f_D	206.7 ± 8.9*	207 ± 4	MeV

*CLEO @ FPCP ‡annihilation corrected

What if

- ... the discrepancy is real?
- Then it must be non-Standard physics.
- How wacky would a non-Standard model be?
- It turns out particles that are already being considered can do the trick.

Effective Lagrangian

- The new particles will be heavy. Write

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} &= M^{-2} C_A^l (\bar{s}\gamma^\mu\gamma_5 c)(\bar{\nu}_L\gamma_\mu l_L) + M^{-2} C_P^l (\bar{s}\gamma_5 c)(\bar{\nu}_L l_R) \\
&- M^{-2} C_V^l (\bar{s}\gamma^\mu c)(\bar{\nu}_L\gamma_\mu l_L) + M^{-2} C_S^l (\bar{s}c)(\bar{\nu}_L l_R) \\
&+ M^{-2} C_T^l (\bar{s}\sigma^{\mu\nu} c)(\bar{\nu}_L\sigma_{\mu\nu} l_R)
\end{aligned}
$$

with left-handed neutrinos only.

- First two: leptonic; last three: semileptonic.

- Because V_{cs} has a small imaginary part (in PDG parametrization), one of C_A, C_P must be real and positive, to explain the effect.

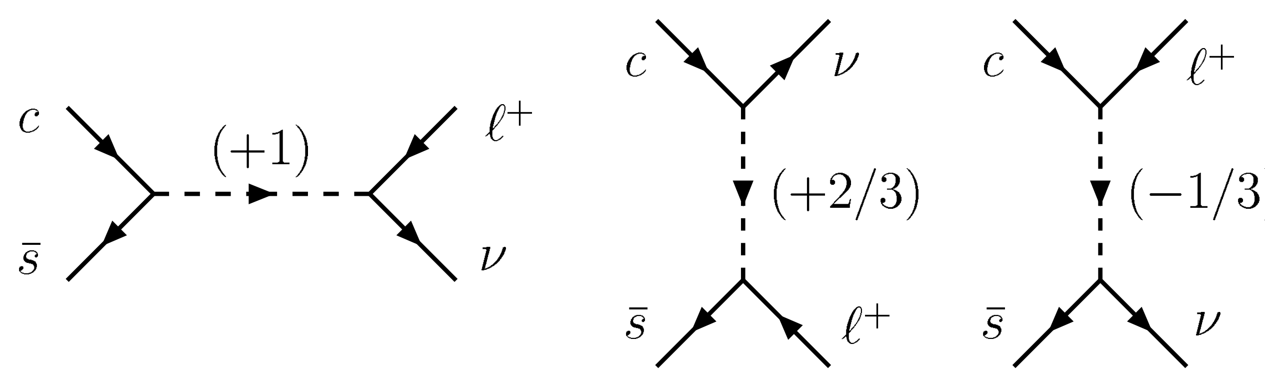
- To reduce each effect to 1σ,

$$\frac{M}{(\mathrm{Re}\,C_A^\ell)^{1/2}} \lesssim \begin{cases} 710\ \mathrm{GeV} & \text{for } \ell = \tau \\ 850\ \mathrm{GeV} & \text{for } \ell = \mu \end{cases},$$

$$\frac{M}{(\mathrm{Re}\,C_P^\ell)^{1/2}} \lesssim \begin{cases} 920\ \mathrm{GeV} & \text{for } \ell = \tau \\ 4500\ \mathrm{GeV} & \text{for } \ell = \mu \end{cases}.$$

New Particles

- The effective interactions can be induced by heavy particles of charge $+1$, $+2/3$, $-1/3$.



- Charged Higgs, new W'; leptoquarks.

Leptonic Decay

- In the amplitude, replace

$$G_F V_{cs}^* m_l \to G_F V_{cs}^* m_l + \frac{1}{\sqrt{2} M^2} \left(C_A^l m_l + \frac{C_P^l m_{D_s}^2}{m_c + m_s} \right)$$

so C_A can be l independent and still cause the same shift in both modes.

W'

- Contributes only to C_A and C_V.
- New gauge symmetry, but couplings to left-handed leptons constrained by other data.
- If W and W' mix, electroweak data imply it's too weak to affect $D_s \to l\nu$.
- Seems unlikely, barring contrived, finely tuned scenarios.

Charged Higgs

- Multi-Higgs models include Yukawa terms

$$y_c \bar{c}_R s_L H^+ + y_s \bar{c}_L s_R H^+ + y_\ell \bar{\nu}_L^\ell \ell_R H^+ + \text{H.c.},$$

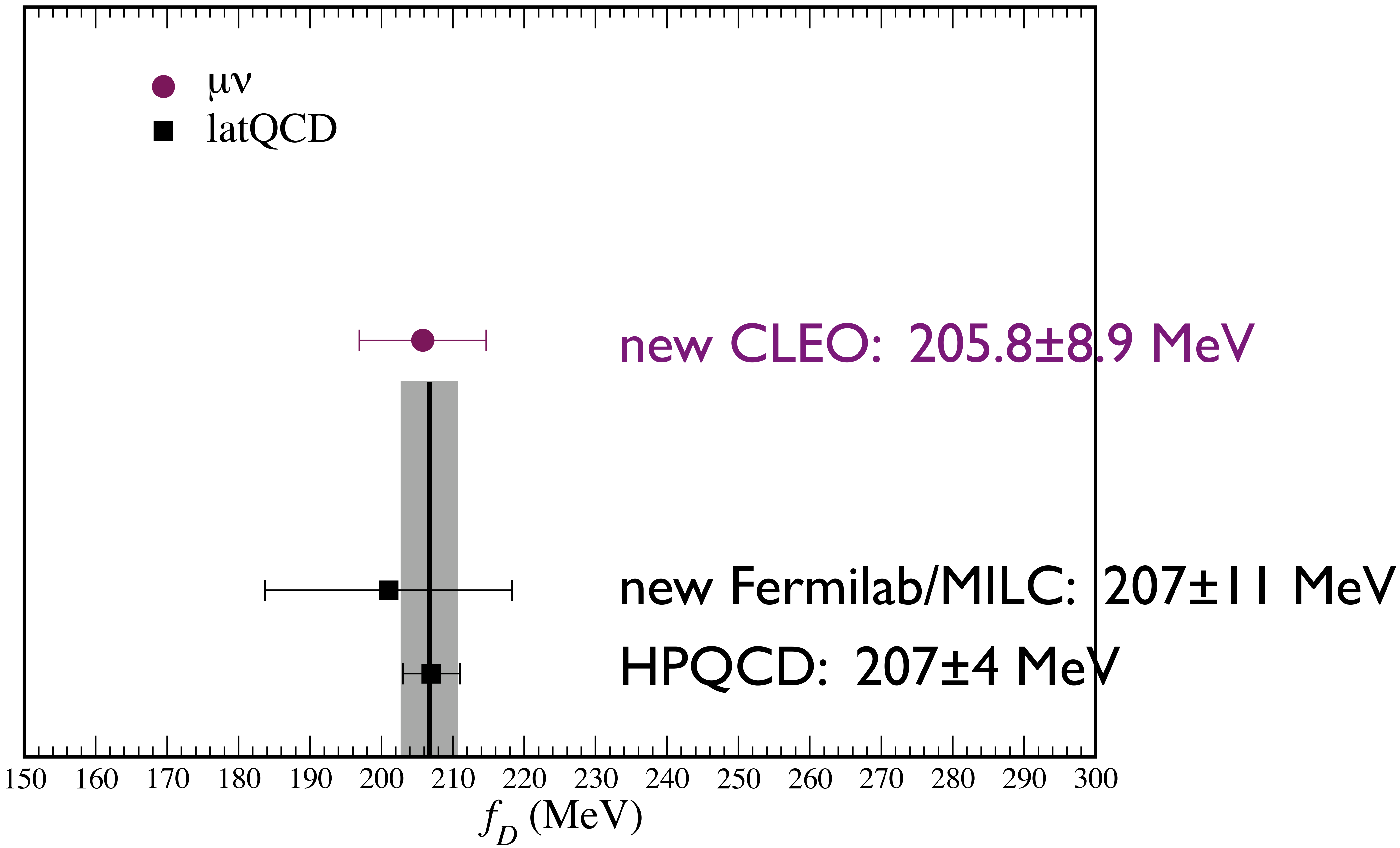
(mass-eigenstate basis) leading to

$$\begin{aligned} C_{P,S}^\ell &= \tfrac{1}{2}\left(y_c^* \mp y_s^*\right) y_\ell, \qquad M = M_{H^\pm} \\ &\propto V_{cs}^*(m_c \mp m_s \tan^2\beta) m_\ell \quad \text{in Model II} \end{aligned}$$

- Note that $C_{P,S}$ can have either sign.

- But consider a two-Higgs-doublet model
  - one for c, u, l, with VEV 2 GeV or so;
  - other for d, s, b, t, with VEV 245 GeV.
- No FCNC; CKM suppression.
- Need to look at one-loop FCNCs.
- Naturally has same-sized increase for μ & τ.

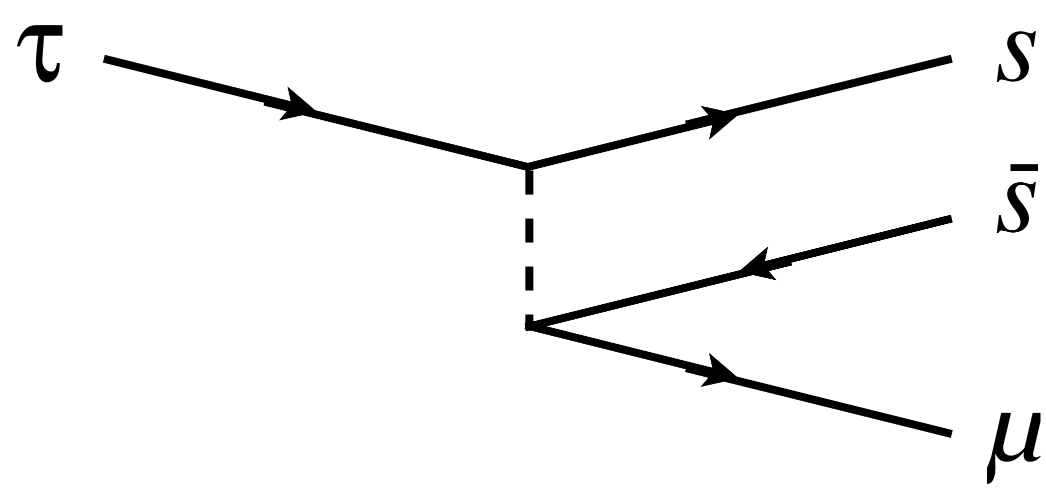
- This model predicts a similarly-sized deviation in $D \to l\nu$, so it is now disfavored:



Leptoquarks

- Color triplet, scalar doublet with $Y = +7/6$ has a component with charge $Q = +2/3$.
- Dobrescu and Fox use this in a new theory of fermion masses [arXiv:0805.0822].
- Leads to $C_A = C_V = 0, C_P = C_S = 4C_T$ of any phase, and no connection between μ & τ.
- LFV $\tau \to \mu s\bar{s}$ disfavors this.

- LFV $\tau \to \mu s\bar{s}$ disfavors any leptoquark with a charge +2/3 component:
    - J = 1, (3, 3, +2/3) and (3, 1, +2/3)
    - J = 0, (3, 3, –1/3)



- Way out: two leptoquarks, little mixing.

- But $J = 0, (3, 1, -1/3)$ seems promising:

$$\kappa_\ell(\bar{c}_L \ell_L^c - \bar{s}_L \nu_L^{\ell c})\tilde{d} + \kappa'_\ell \bar{c}_R \ell_R^c \tilde{d} + \text{H.c.}$$

(an interaction in R-violating SUSY), with

$$\begin{aligned} C_A^\ell = C_V^\ell &= \tfrac{1}{4}|\kappa_\ell|^2 \\ C_P^\ell = C_S^\ell &= \tfrac{1}{4}\kappa_\ell \kappa_\ell'^* = -2C_T^\ell \end{aligned}$$

- If $|\kappa'_\ell/\kappa_\ell| \ll m_\ell m_c/m_{D_s}^2$, then *automatically* the interference is constructive and creates the same per-cent deviation for $\mu\nu$ and $\tau\nu$.

Semileptonic Decay

$$\begin{aligned}\frac{d\Gamma}{dq^2} = \frac{m_D^3}{192\pi^2}\Bigg\{ & \mathtt{PS}_{++}|f_+(q^2)|^2\left|G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2}\right|^2 \\ & + \mathtt{PS}_{00}|f_0(q^2)|^2\left|\frac{m_\mu}{m_D}\left(G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2}\right) + \frac{q^2}{m_D(m_c - m_s)}\frac{C_S}{\sqrt{2}M^2}\right|^2 \\ & - \mathtt{PS}_{T+} B_T(q^2) f_+(q^2)\frac{m_\mu}{4m_D}\,\mathrm{Re}\left[\left(G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2}\right)\frac{C_T^*}{\sqrt{2}M^2}\right] \\ & - \mathtt{PS}_{T0}\, B_T(q^2) f_0(q^2)\frac{m_\mu}{4m_D}\,\mathrm{Re}\left[\left(G_F V_{cs} + \frac{C_V}{\sqrt{2}M^2}\right)\frac{C_T^*}{\sqrt{2}M^2}\right]\Bigg\}\end{aligned}$$

- C_V causes an effect comparable to $l\nu$, but C_S and C_T could hide: $m_\mu/m_D = 0.057$

- Effective couplings in semileptonic and leptonic decays are related.
- Enhancement in $D \to K\mu\nu$ favors model w/ naturally same-sized effects in $D_s \to \mu\nu, \tau\nu$.
- SM rate for $D \to K\mu\nu$ favors shift via C_P, with C_S, C_T shift hiding.
- For leptoquarks implies the Yukawa matrix is "just so".

- Leptoquarks come with Yukawa matrices:
  - no relation between c and b couplings;
  - aesthetically unappealing.
- If a signal is real, aesthetics are a secondary problem.
- If 1st generation coupling are small, these leptoquarks evade Tevatron bounds.

LHC

- The generic bounds on mass/coupling suggest that any non-Standard explanation of the effect is observable at the LHC.
- Charged Higgs: similar to usual search.
- Leptoquarks: $gg \to \tilde{d}\bar{\tilde{d}} \to \ell_1^+ \ell_2^- j_c j_c$.

Perspective

- The f_{D_s} puzzle is intriguing.
- More calculations of f_{D_s} needed—
  - with n_f = 2+1 or 2+1+1.
- Better (and more) calculations of $D \to K\mu\nu$ form factors needed, including tensor.