The f_{Ds} Puzzle

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based on

Accumulating Evidence for Nonstandard Leptonic Decays of D_s Mesons

arXiv: 0803.0512 [hep-ph]

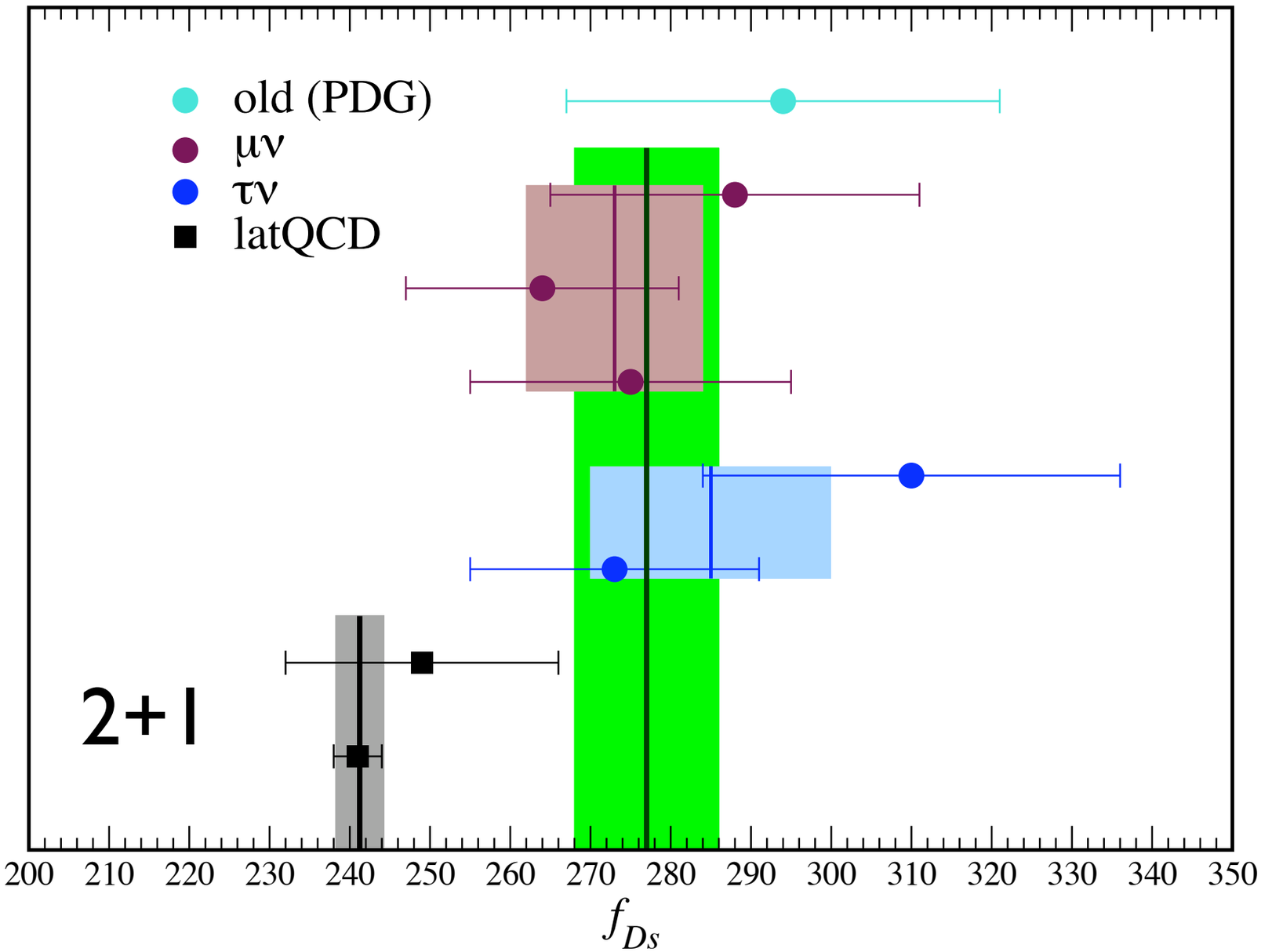
with Bogdan Dobrescu

Context

$D_s \to l\nu$

- The leptonic decay $D_s \to l\nu$ has been advertised as a good test of lattice QCD.
- Counting experiment at CLEO, *B* factories.
- A simple matrix element $\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s\rangle$
- No light valence quarks.
- New physics thought to be *very unlikely*.

And then something funny happened ...



$\chi^2/\mathrm{dof} = 0.57$

BaBar

CLEO

Belle

CLEO $\pi\nu$

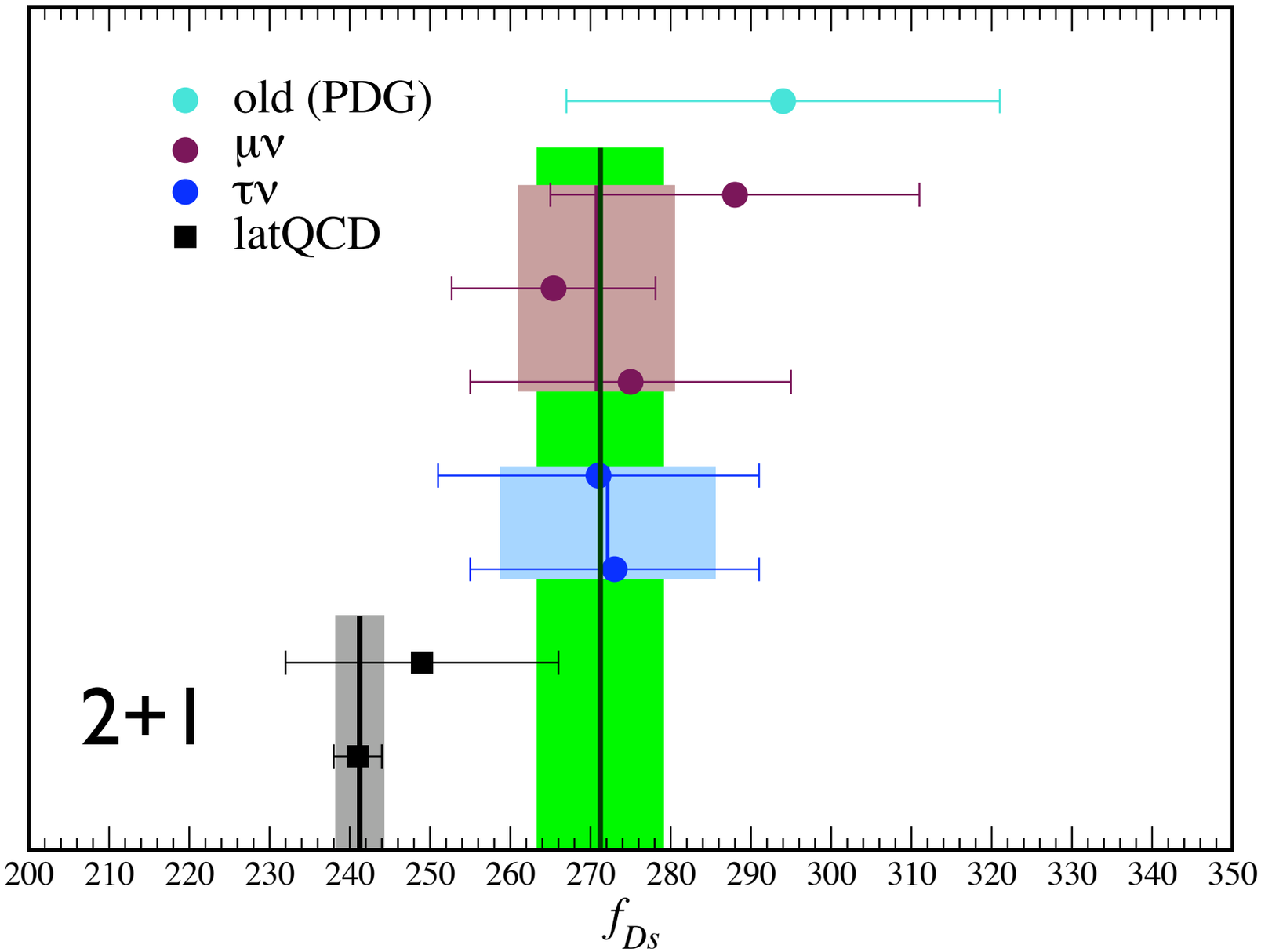
CLEO $e\nu\nu$

Fermilab/MILC

HPQCD

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

With CLEO's update from FPCP last week ...



$\chi^2/\mathrm{dof} = 0.13$

BaBar

CLEO

Belle

CLEO $\pi\nu$

CLEO $e\nu\nu$

Fermilab/MILC

HPQCD

a 3.6σ discrepancy, or $2.9\sigma \oplus 2.2\sigma$.

A Puzzle

- Excluding BaBar [Rosner, Stone], it is 3.5σ; including the old experiments, it is 4.1σ.
- What is the origin of the discrepancy?
  - experiments or radiative corrections
  - lattice QCD
  - non-Standard phenomena

The Decay

- The branching fraction is

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

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}.

- The $\mu\nu$ final state is helicity suppressed,

$$\frac{m_\mu^2}{m_{D_s}^2} = 2.8 \times 10^{-3}$$

- The $\tau\nu$ final state is phase-space suppressed

$$\left(1 - \frac{m_\tau^2}{m_{D_s}^2}\right)^2 = 3.4 \times 10^{-2}$$

Experiments

CLEO ($\mu\nu$)

- CLEO produces $D_s D_s^{(*)}$ pairs just above threshold, where the multiplicity is low.
- Neutrino is "detected" by requiring missing mass-squared to be consistent with 0.
- Events with $E_\gamma > 300\ \mathrm{MeV}$ are rejected, to suppress non-helicity suppressed radiation.

CLEO ($\tau\nu$)

- Same production mechanism as above.
- Two daughter τ decay modes: $\tau \rightarrow e\nu\nu$, and $\tau \rightarrow \pi\nu$.
- Also veto radiative events, but here it is more a matter of τ detection/identification.
- No constraint on missing mass-squared.

BaBar ($\mu\nu$)

- BaBar observes $D_s^* \to D_s\gamma$ and counts the relative number of $D_s\gamma \to \mu\nu\gamma$, $D_s\gamma \to \phi\pi\gamma$.
- Then uses its own measurement of $B(D_s \to \phi\pi)$ to get $B(D_s \to \mu\nu)$.
- Subtlety: really a window of KK around ϕ in three-body $D_s \to KK\pi$, and $f_0 \to KK$ interferes [CLEO, 0801.0680 [hep-ex]].

Belle ($\mu\nu$)

- Belle also observes $D_s^* \to D_s\gamma$.
- Uses a Monte Carlo simulation to guide full reconstruction and obtain an absolute normalization.
- Thus, they obtain $B(D_s \to \mu\nu)$ directly.

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 $|V_{cs}| < 1$, and would need $|V_{cs}| > 1.1$ to explain effect.

Summary

- The modern measurements (BaBar, CLEO, Belle) do not depend on models* for interpretation of the central value or error bar.
- Hard to see a misunderstood systematic.
- Could all fluctuate high?
- * except the Standard Model!

Radiative Corrections

- Fermi constant from muon decay, so these 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 $D_s \to \tau\nu$.

Lattice QCD

2+1 Sea Quarks

- There are two calculations of f_{D_s} with 2+1 flavors of sea quarks:

$$f_{D_s} = 249 \pm 3 \pm 16 \text{ MeV}, \quad \text{hep-lat/0506030}$$

$$f_{D_s} = 241 \pm - \pm 03 \text{ MeV}, \quad \text{0706.1726 [hep-lat]}$$

- Compared with experimental averages:

$$f_{D_s} = 277 \pm 09 \text{ MeV} \rightarrow 271.2 \pm 7.9 \text{ MeV}, \quad \ell\nu$$

$$f_{D_s} = 273 \pm 11 \text{ MeV} \rightarrow 270.7 \pm 9.7 \text{ MeV}, \quad \mu\nu$$

$$f_{D_s} = 285 \pm 15 \text{ MeV} \rightarrow 272 \quad \pm 13 \text{ MeV}, \quad \tau\nu$$

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" (see below);
  - tiny statistical errors: 0.5% on f_{Ds}.

Many people do not like this:

- 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.

hep-lat/0509026, hep-lat/0610094, 0711.0699 [hep-lat]

- Combined fit to a^2, $m_{\rm sea}$, $m_{\rm val}$ dependence: not fully documented, but irrelevant for f_{Ds}.

Staggered Fermions

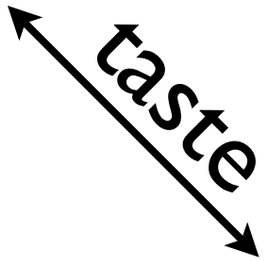
[Susskind; Karsten & Smit; Sharatchandra, Thun & Weisz]

- One Grassmann variable per site.
- Fermion doubling implies there are 16 degrees of freedom.
- Extensive theoretical and numerical evidence that these become 4 Dirac fermions in the continuum limit:
  - beta function, anomalies, ... in PT;
  - eigenvalues, index theorem, ... in MC.

Tastes

- The staggered Dirac operator can be written

$$(\not{D}+m)_{\text{stag}} = \begin{pmatrix} \not{D}+m & & & a\Delta \\ & \not{D}+m & & \\ & & \not{D}+m & \\ a\Delta & & & \not{D}+m \end{pmatrix}$$



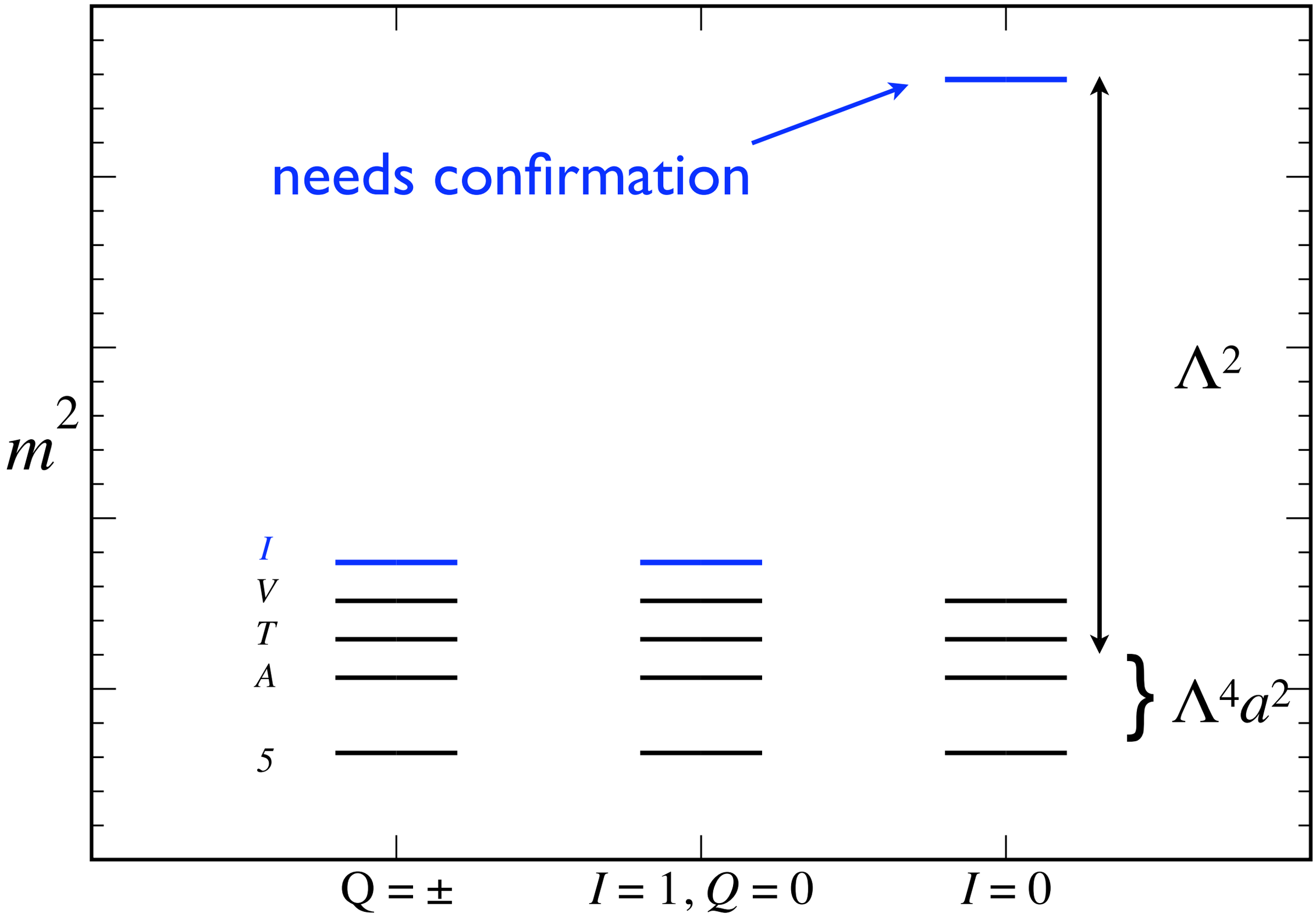
- Does the taste-breaking defect $a\Delta$ vanish in continuum limit?

- Does taste defect Δ have an anomalously large anomalous dimension?
- Most important consequence:

$$m^2_{\pi,\xi} = (m_u + m_d)B + a^2\Delta_\xi,$$
$$m^2_{K,\xi} = (m_d + m_s)B + a^2\Delta_\xi,$$

where ξ labels irrep of Γ_4 taste symmetry group (P, A, T, V, I); $\Delta_P = 0$.

- For n_f flavors, $(4n_f)^2 - 1$ Goldstones.


needs confirmation
m^2
Λ^2
I
V
T
A
5
$\Lambda^4 a^2$
$Q = \pm$
$I = 1, Q = 0$
$I = 0$

Rooting

- For sea quarks, reduce the number of tastes, by assuming

$$\left[\det{}_4(\not{D}_{\text{stag}} + m)\right]^{1/4} \doteq \det{}_1(\not{D}_{\text{cont}} + m)$$

  [Hamber, Marinari, Parisi, Rebbi].

- Uncontroversial for 20 years, until we saw that it reproduces experiment.

Gedanken Algorithm

- Suppose someone with a good imagination found a way to speed up "your favorite" fermions by substituting

$$\det{}_1(\not{D}+m) = \{\det{}_4[(\not{D}+m)\otimes 1_4]\}^{1/4}$$

with four "tastes," but no taste breaking.

- This is fine when $\det$ is real and positive.
- (So it doesn't work for $m < 0$, or $\mu \neq 0$.)

Go to the Source

- One can introduce sources:

$$\{\det_4[(\not{D}+m+J+J_5)\otimes 1_4]\}^{1/4}$$

where (J^a, J_5^a) is source for $\bar{\psi}(T^a, T^a\gamma_5)\psi$.

- Now generalize the sources:

$$\{\det_4[(\not{D}+m)\otimes 1_4+J+J_5]\}^{1/4}$$

which means "ask more."

- Start with ($\mathcal{D}\mathcal{U}$ = gauge-field measure)

$$Z(J,J_5) = \int \mathcal{D}\mathcal{U}\{\det{}_4[(\not{D}+m)\otimes 1_4 + J + J_5]\}^{1/4}$$

- All correlators taken in original, taste-symmetric ensemble.
- Legendre transform $J^A \to \sigma^A$, $J_5^A \to \pi^A$, and derive mass matrices (for constant fields)

$$\frac{\partial^2\Gamma}{\partial\sigma^A\partial\sigma^B}, \quad \frac{\partial^2\Gamma}{\partial\pi^A\partial\pi^B}$$

- Find usual pattern of spontaneous breaking.

- This formulation has $(4n_f)^2 - 1$ pseudo-Goldstone bosons, instead of $(n_f)^2 - 1$.
- The extra ones are phantoms—a figment of the algorithm's imagination.
- Their total contribution to any tasteless correlation function *must* cancel.
- Not unitary; not worrisome either.
- A safe house for phantom Goldstones.

Rooted & Staggered

- If the taste breaking does *not* vanish, then the phantom's spectrum is split.
  - The unitarity violations no longer cancel.
  - Taste non-singlet signals propagate faster than the (physical) taste singlets (non-local, but not the "expected" nonlocality).
- Still, we think, controlled by RSχPT.

Essentials

- The taste-breaking defect must vanish in the continuum limit.
  - Supported by RG papers of Shamir and experience with scaling in QCD.
- The functional $\Gamma(\pi, \sigma, ...)$ must be well-behaved enough for (non-unitary) RSχPT [Aubin, Bernard] to describe the computed correlators.

HPQCD

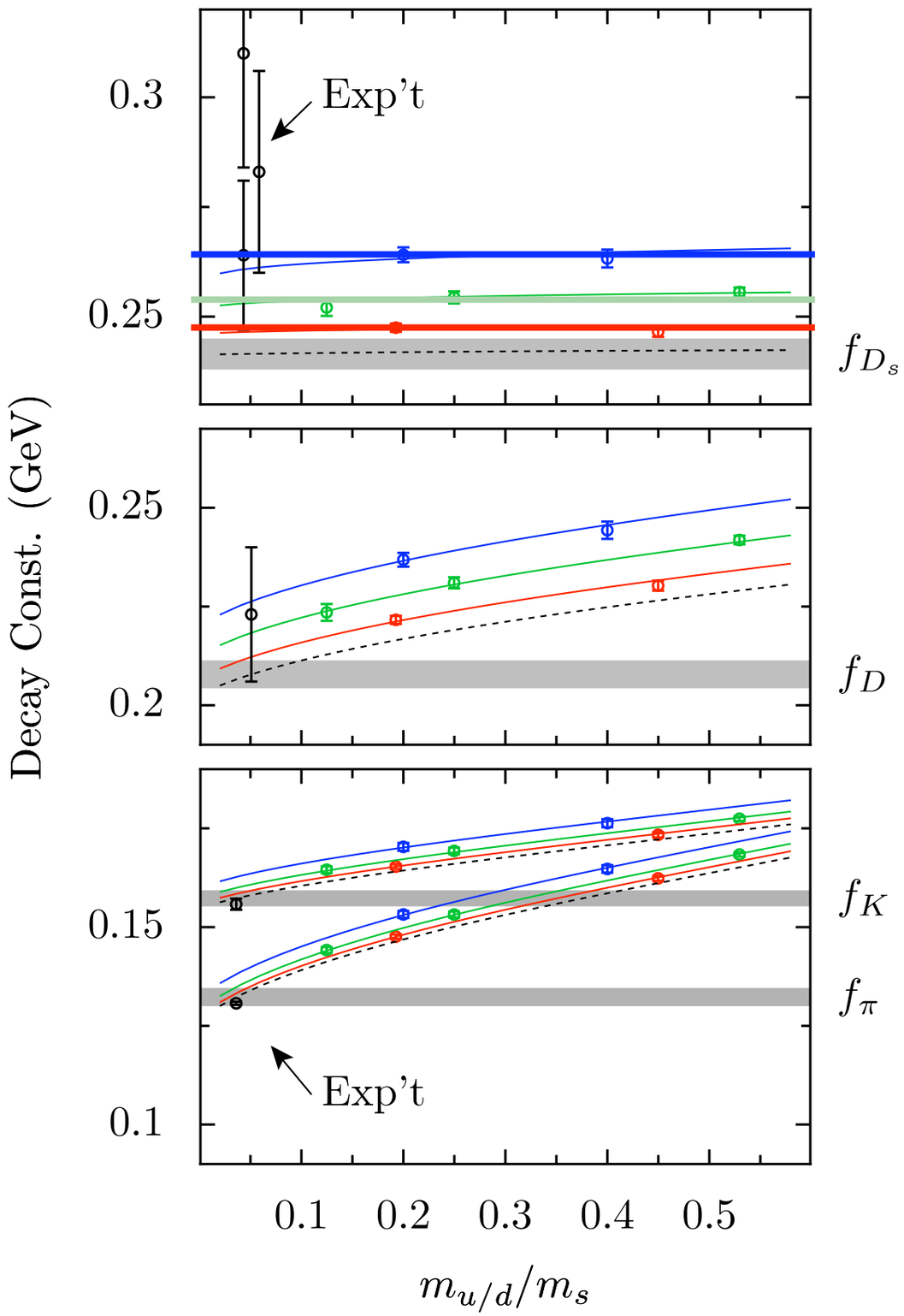
E. Follana, C.T.H. Davies, G.P. Lepage and J. Shigemitsu
[HPQCD Collaboration]

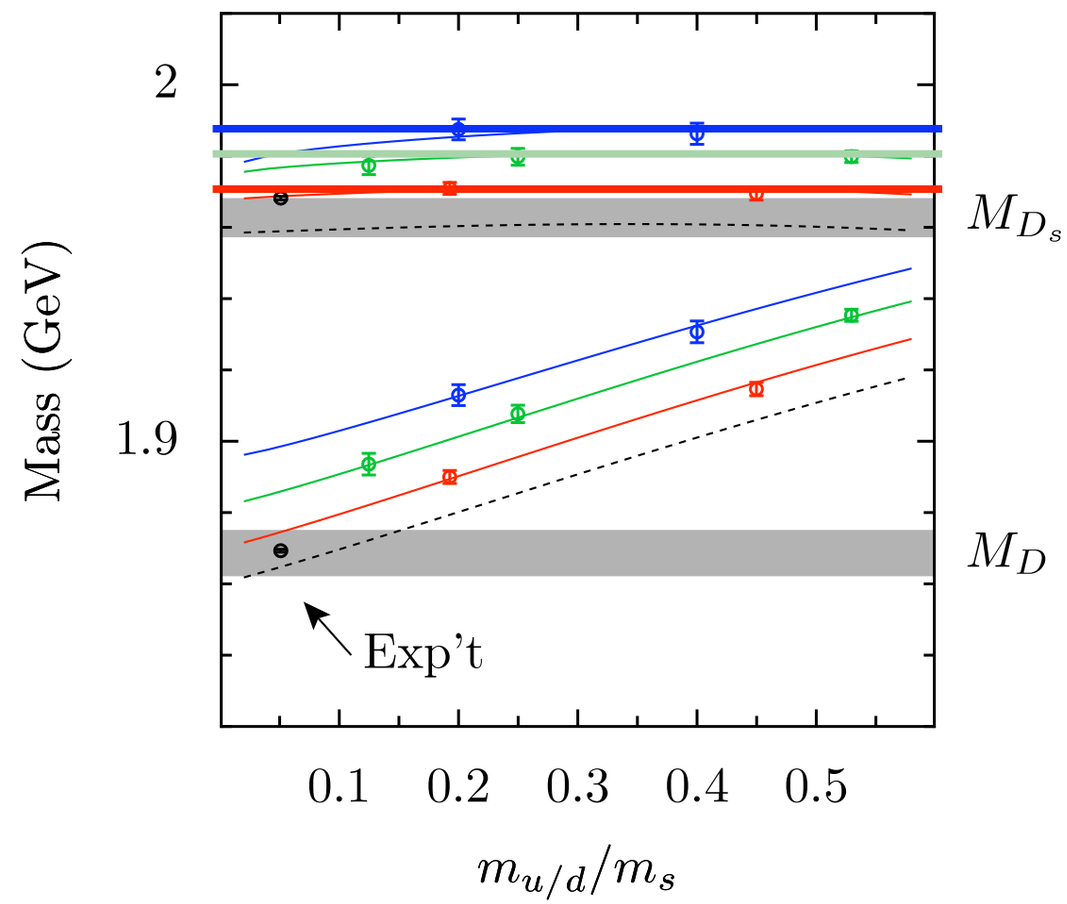
High Precision determination of the π, *K*, *D* and D_s decay constants from lattice QCD

Phys. Rev. Lett. **100**, 062002 (2008)
[arXiv:0706.1726 [hep-lat]]

Continuum Limit

- The key to HPQCD's result for f_{Ds} is the extrapolation to the continuum limit.
- RSχPT needed only for benign $m_K^2 \ln m_K^2$.
- I will show their plots, followed by my own back-of-the-envelope analysis.



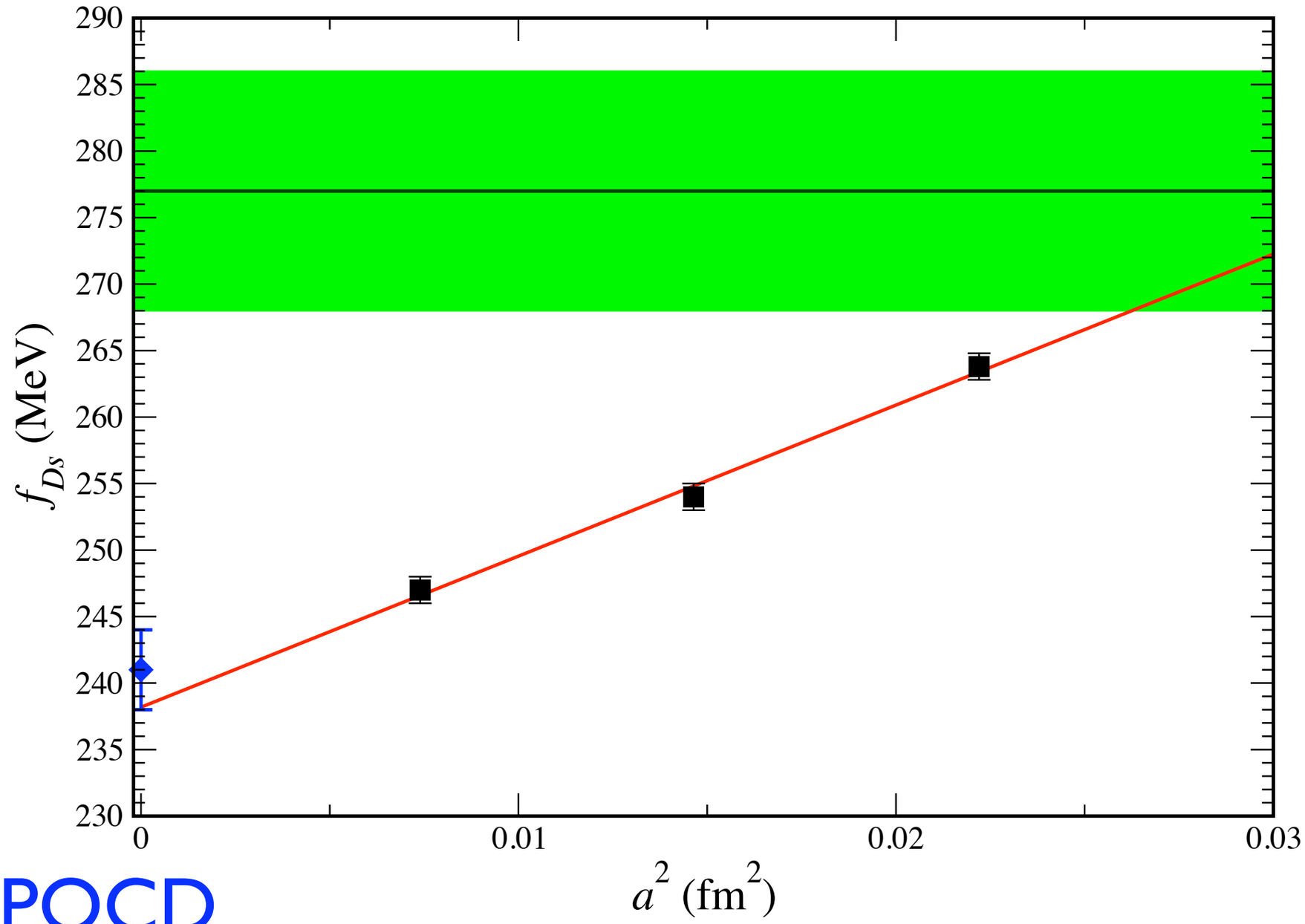


m_K and m_π set m_s, m_q

charmonium sets m_c

Assuming flat in $m_{\rm sea}$.

As the lattice gets finer, the discrepancy grows:

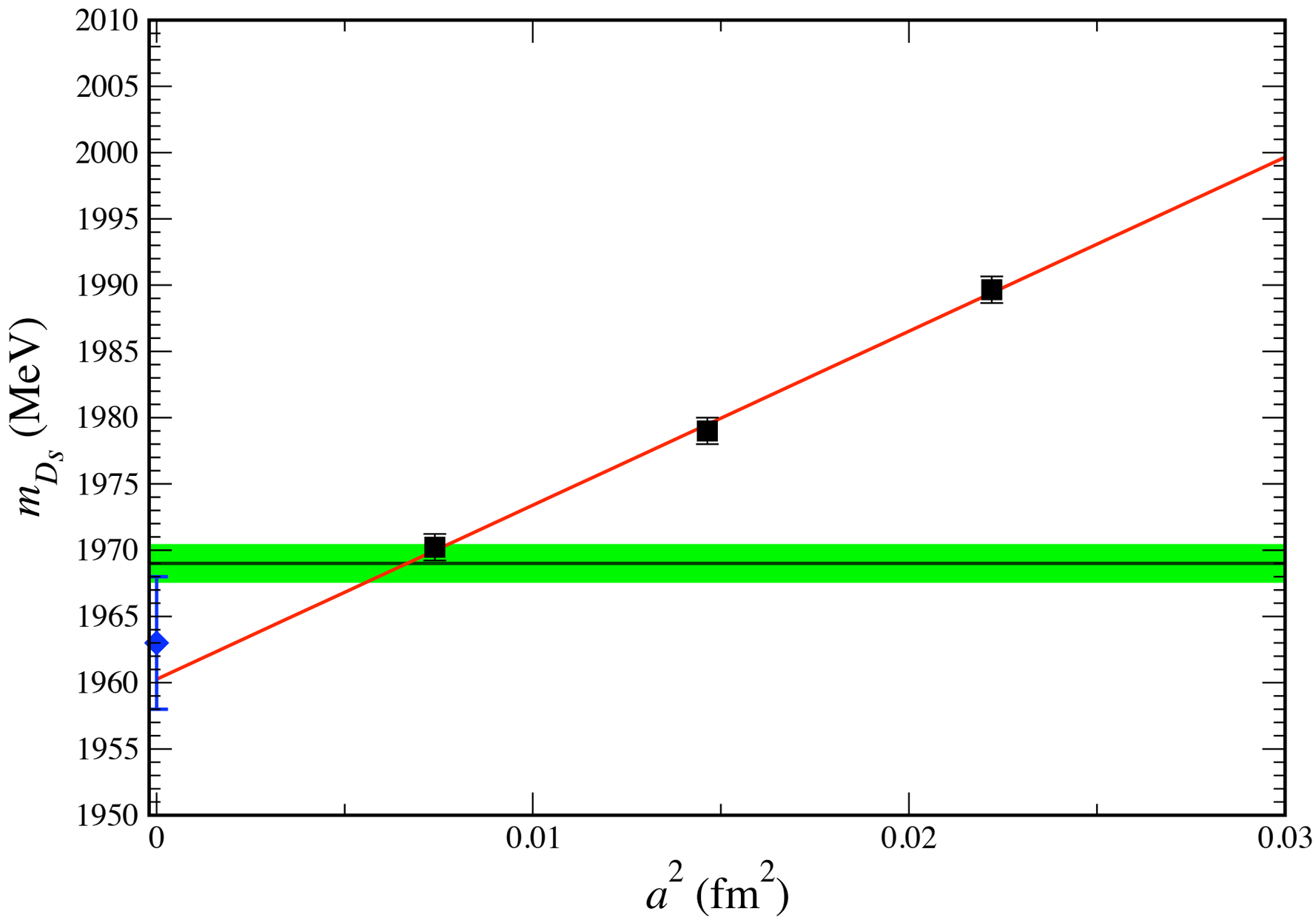


277±9 MeV

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

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 $\ll 5\%$?

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

HPQCD Summary

- The trend in lattice spacing drives a value around 240 MeV.
- Systematic errors are always devilish.
- Doubling theirs still leaves a discrepancy of a 3.5σ, or two of 2.5σ ($\mu\nu$) & 2.7σ ($\tau\nu$).
- So I believe their result, *i.e.*, values around 240-250 MeV, will prove to be robust.

New Physics

Sufficient Condition

- Tree-level & Cabibbo-favored, ...
- but this decay *could* be sensitive to new physics, if:
  - a new particle couples predominantly to leptons and up-type quarks,
  - but not to the first generation.

Necessary Condition

- To mediate $D_s \to l\nu$ we need

$$\mathcal{L}_{\text{eff}} = \frac{C_A^\ell}{M^2}\left(\bar{s}\gamma_\mu\gamma_5 c\right)\left(\bar{\nu}_L\gamma^\mu\ell_L\right) + \frac{C_P^\ell}{M^2}\left(\bar{s}\gamma_5 c\right)\left(\bar{\nu}_L\ell_R\right) + \text{H.c.}$$

- In rate, replace

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

because $\langle 0|\bar{s}\gamma_5 c|D_s\rangle = -i f_{D_s} m_{D_s}^2 (m_c + m_s)^{-1}$

- 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.

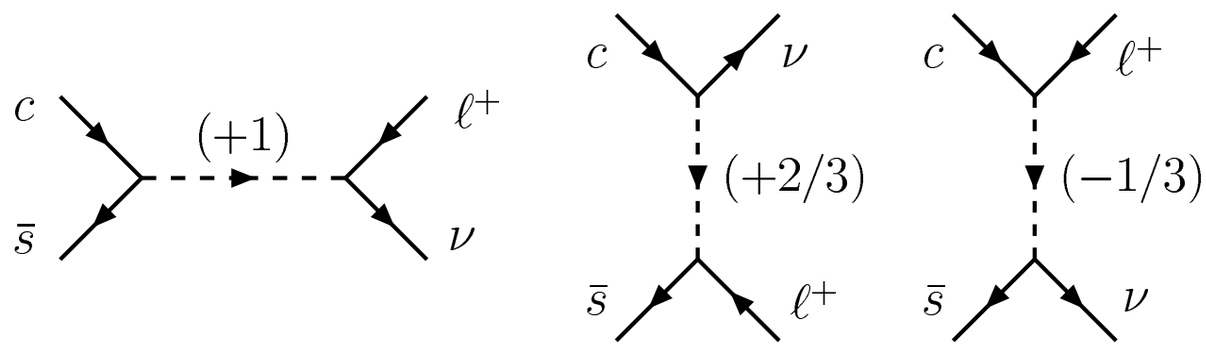
- To reduce each effect to 1σ,

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

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

New Particles

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



- Charged Higgs, new W'; leptoquarks.

W'

- Contributes only to C_A.
- 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

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

- Note that C_P 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, VEV 245 GeV.
- No FCNC; CKM suppression.
- Need to look at one-loop FCNCs.
- Naturally has same-sized increase for μ & τ.

Leptoquarks

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

- LFV $\tau \to \mu s \bar{s}$ also disfavors leptoquarks of
  - $J = 1, (3, 3, +2/3)$ and $(3, 1, +2/3)$
  - $J = 0, (3, 3, -1/3)$

- 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

$$C_A^\ell = \tfrac{1}{4}|\kappa_\ell|^2$$

$$C_P^\ell = \tfrac{1}{4}\kappa_\ell \kappa'^*_\ell$$

- 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 $\tau\nu$.

Summary

- Experiments are statistics limited
  - CLEO will get +50% (+100%) for $\mu\nu$ ($\tau\nu$);
  - and Belle, BES (also D^+), *Super-B*.
- Radiative corrections should, perhaps, be collected into a single place.
- Lattice calculations must be done by other groups, with other sea quarks.

LHC

- Prejudice against new physics in this decay should be questioned.
- Mass/coupling bounds suggest new particles
  - evade Tevatron bounds if $C_{P,A}$ are largish;
  - are observable at the LHC.
- Charged Higgs: similar to usual search.
- Leptoquarks: $gg \to \tilde{d}\bar{\tilde{d}} \to \ell_1^+ \ell_2^- \, j_c j_c \, .$