Flavor Physics with Lattice QCD

Andreas S. Kronfeld

17 June 2009

Motivation

Flavor Physics

- Flavor physics studies where the different species of quarks (and leptons) come from.
- Many insights have come from this study:
  - earth-shattering: *P* and *CP* violation;
  - anticipation: existence of charm, mass of top.
- How many quark flavors in the LHC Era? 6

Flavor Physics

- Flavor physics studies where the different species of quarks (and leptons) come from.
- Many insights have come from this study:
  - earth-shattering: *P* and *CP* violation;
  - anticipation: existence of charm, mass of top.
- How many quark flavors in the LHC Era? ~~6~~ 9

Quarks

- 3 SU(2) doublets
  - $Y = 1/6$
    - $(u \;\; d')_L$
    - $(c \;\; s')_L$
    - $(t \;\; b')_L$
- $'$ = electroweak basis

- 6 SU(2) singlets
  - $Y = 2/3 \quad -1/3$
    - $u_R \qquad d'_R$
    - $c_R \qquad s'_R$
    - $t_R \qquad b'_R$
- Different fields.

Line of Attack

- Continuation of Belle at KEK-B.
- LHC*b* at LHC.
- BES in Beijing.
- SuperBelle, Super*B*?, SuperDuper*B*???
- QCD, especially lattice QCD.

Standard Model

and slightly beyond

- A sector with doublet structure breaks SU(2).
- The richness of flavor physics comes from the mass matrix that arises when this stuff (inevitably) interacts with L and R quark fields.
- Eigenvalues: masses.
- Eigenvectors/wf phases: CKM matrix.

CKM Matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM Matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

this talk

CKM Matrix

this talk

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

f_{D_s} puzzle

- V_{CKM} in 4-parameter subset of SU(3), with one irreducible phase ⇒ *CP* violation.

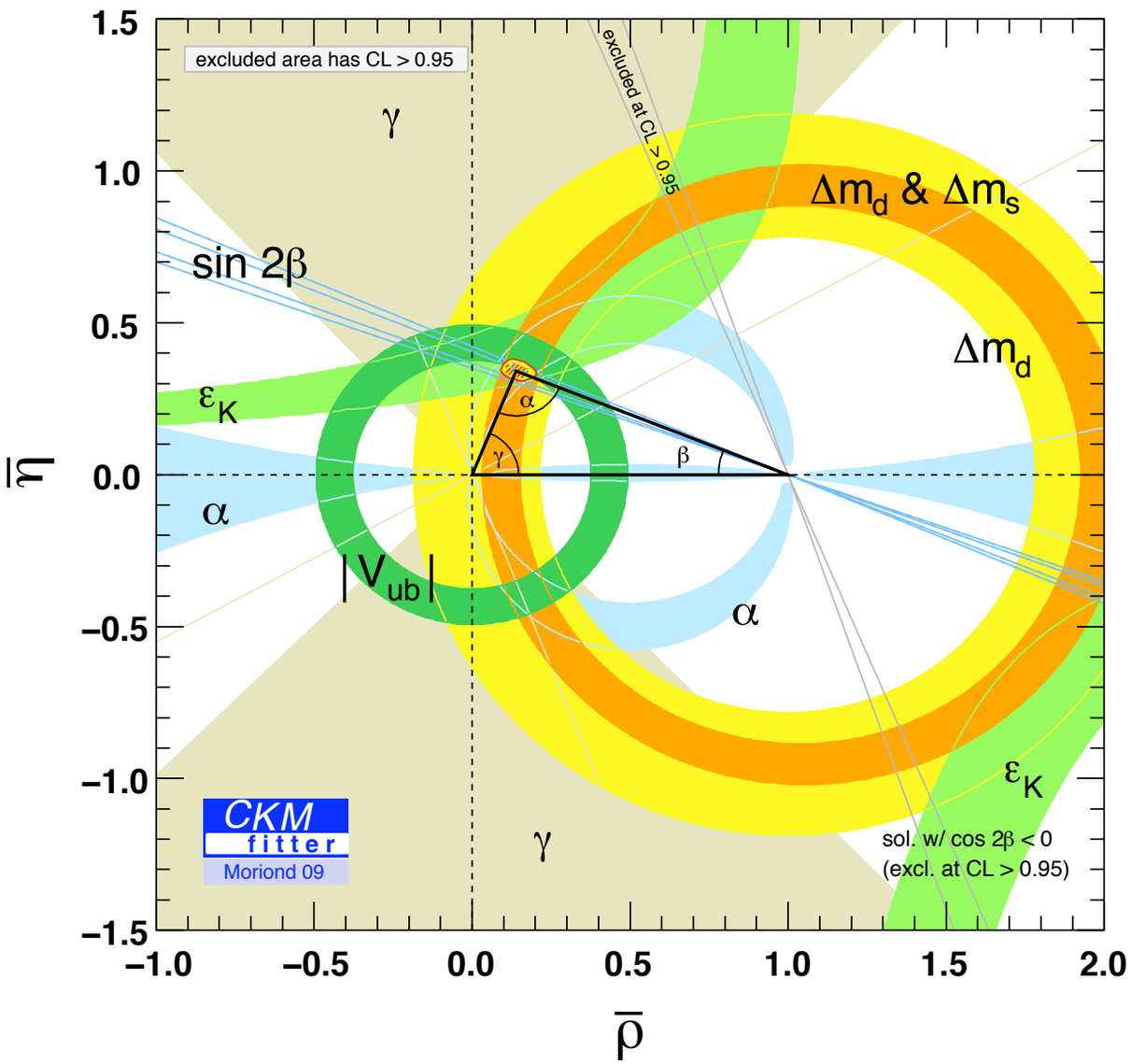
- Unitarity:

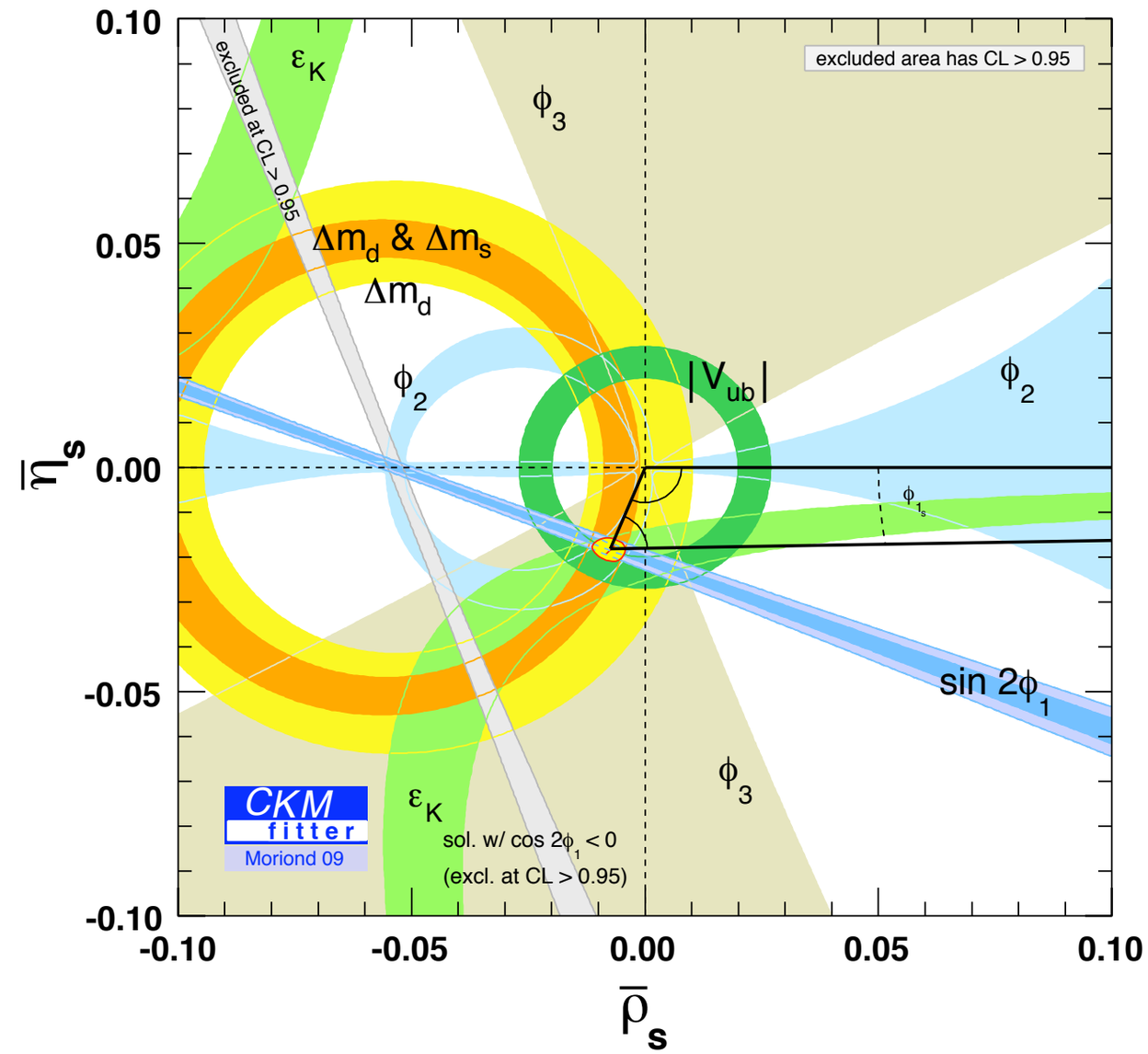
  - 6 dot-product constraints;

  - 6 cross-product constraints: triangles.

- CKM-ness implies that all triangles have same area: $A = \frac{1}{2}\mathrm{Im}[V^*_{ud}\, V_{ub}/V^*_{cd} V_{cb}] = \bar{\eta}/2$.

CKM Now





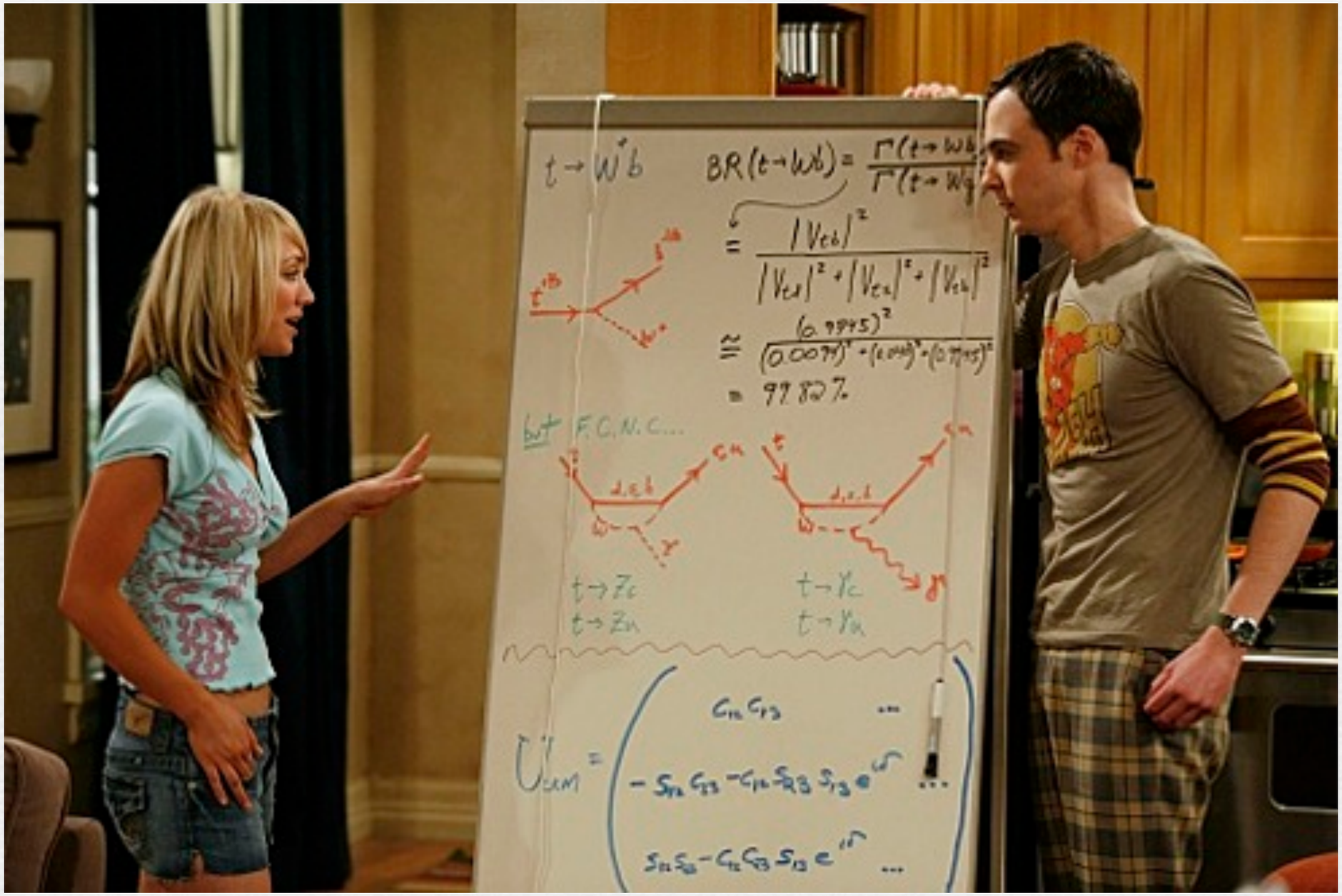
$$(\beta, \alpha, \gamma) = (\phi_1, \phi_2, \phi_3)$$

Outline

- Status of lattice QCD.
- Determination of $|V_{cb}|$ and $|V_{ub}|$.
- The f_{D_s} Puzzle.

Interplay

of flavor and high-p_T physics



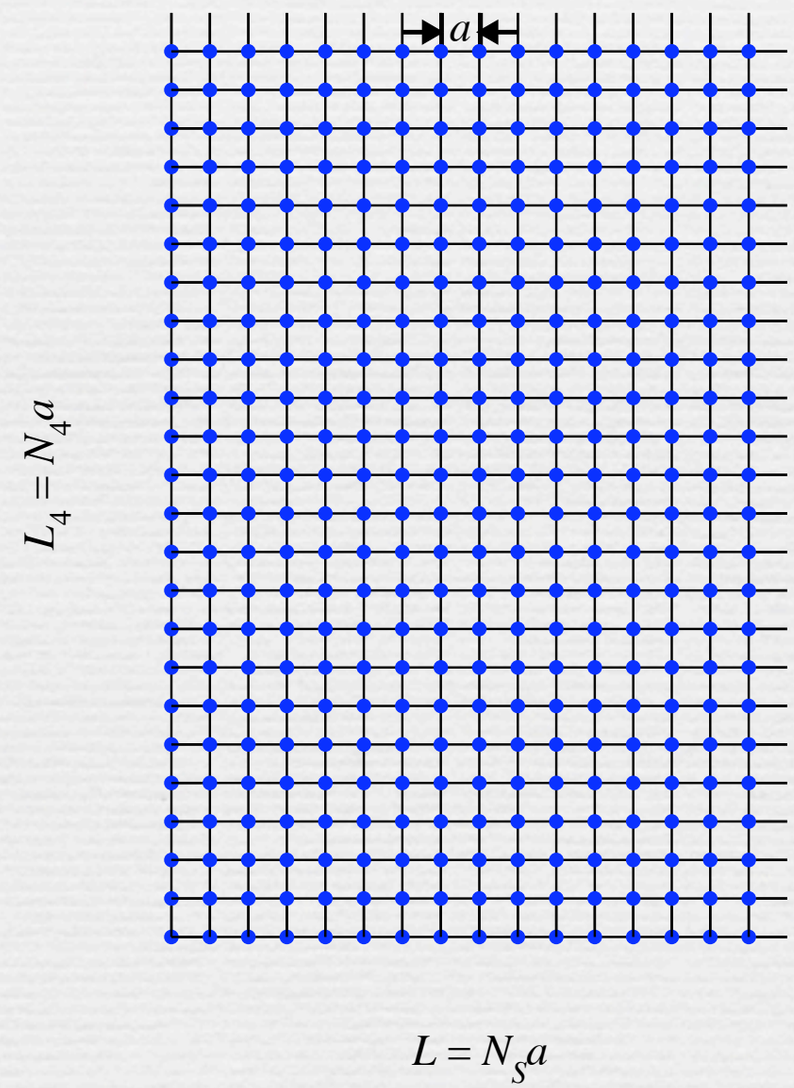
"Big Bang Theory" (an American TV comedy)

Lattice QCD

Lattice Gauge Theory

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \, \mathcal{D}\psi \, \mathcal{D}\bar{\psi} \exp(-S) \, [\bullet]$$

- Infinite continuum: uncountably many d.o.f.
- Infinite lattice: countably many; used to define QFT
- Finite lattice: can evaluate integrals on a computer; dimension ~ 10^8

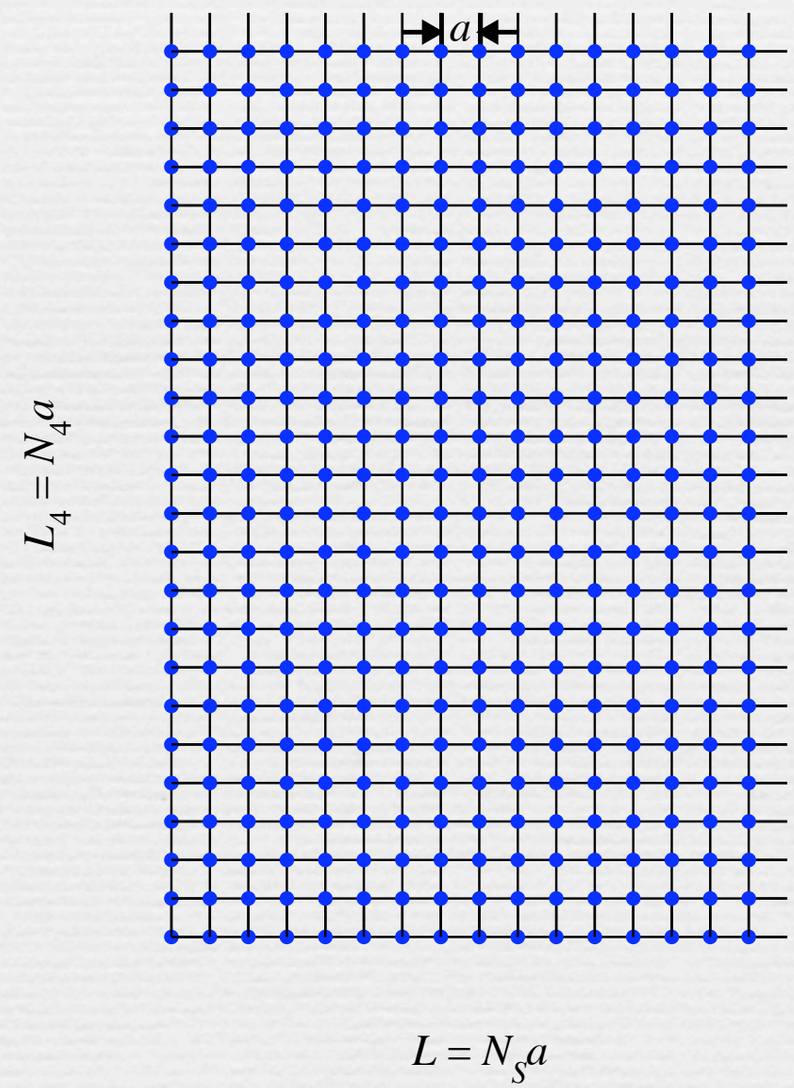


Lattice Gauge Theory

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \, \mathcal{D}\psi \mathcal{D}\bar{\psi} \exp(-S) \, [\bullet]$$

hand

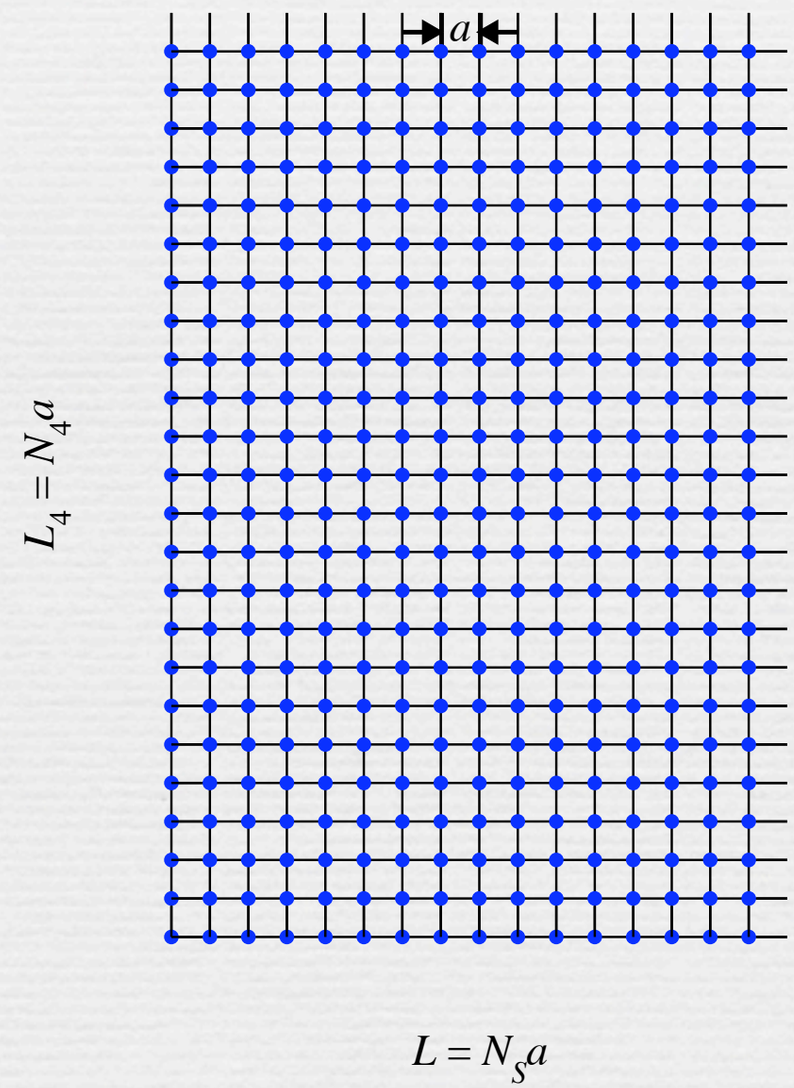
- Infinite continuum: uncountably many d.o.f.
- Infinite lattice: countably many; used to define QFT
- Finite lattice: can evaluate integrals on a computer; dimension ~ 10^8



Lattice Gauge Theory

$$\langle \bullet \rangle = \frac{1}{Z} \int \underbrace{\mathcal{D}U}_{\text{MC}} \underbrace{\mathcal{D}\psi \mathcal{D}\bar{\psi}}_{\text{hand}} \exp\left(-S\right) [\bullet]$$

- Infinite continuum: uncountably many d.o.f.
- Infinite lattice: countably many; used to define QFT
- Finite lattice: can evaluate integrals on a computer; dimension ~ 10^8



Some Jargon

- QCD observables (quark integrals by hand):

$$\langle \bullet \rangle = \frac{1}{Z} \int \mathcal{D}U \prod_{f=1}^{n_f} \det(\not{D} + m_f) \exp\left(-S_{\text{gauge}}\right) [\bullet]$$

- *Quenched* means replace det with 1.
- *Un*quenched means not to do that.
- *Partially* quenched doesn't mean "n_f too small" but $m_{\text{val}} \neq m_{\text{sea}}$, or even $\not{D}_{\text{val}} \neq \not{D}_{\text{sea}}$ ("mixed action").

Sea Quarks

- Staggered quarks, with rooted determinant, $O(a^2)$.
- Wilson quarks, $O(a)$:
  - tree or nonperturbatively $O(a)$ improved;
  - twisted mass term—auto $O(a)$ improvement.
- Ginsparg-Wilson (domain wall or overlap), $O(a^2)$:
  - $\not{D}\gamma_5 + \gamma_5\not{D} = 2a\not{D}^2$ implemented w/ sign($\not{D}_W$).

- Many numerical simulations with sea quarks are called (perhaps misleadingly) "full QCD."
  - n_f = 2: with *same* mass, omitting strange sea;
  - n_f = 3: may (or may not) imply 3 of *same* mass;
  - n_f = 2+1: strange sea + two as light as possible;
  - n_f = 2+1+1: add charmed sea to 2+1.
- "Full QCD" can also mean $m_{\mathrm{val}} = m_{\mathrm{sea}}$, $\not{D}_{\mathrm{val}} = \not{D}_{\mathrm{sea}}$.

- Many numerical simulations with sea quarks are called (perhaps misleadingly) "full QCD."
  - n_f = 2: with *same* mass, omitting strange sea;
  - n_f = 3: may (or may not) imply 3 of *same* mass;
  - n_f = 2+1: strange sea + two as light as possible;
  - n_f = 2+1+1: add charmed sea to 2+1.
- "Full QCD" can also mean $m_{\text{val}} = m_{\text{sea}}$, $\not{D}_{\text{val}} = \not{D}_{\text{sea}}$.

Correlators

- Two-point functions for masses $\pi(t) = \bar{\psi}_u \gamma_5 S \psi_d$:

$$\langle \pi(t)\pi^\dagger(0)\rangle = \sum_n |\langle 0|\hat{\pi}|\pi_n\rangle|^2 \exp(-\boxed{m_{\pi_n}} t)$$

- Two-point functions for decay constants:

$$\langle J(t)\pi^\dagger(0)\rangle = \sum_n \boxed{\langle 0|\hat{J}|\pi_n\rangle} \langle \pi_n|\hat{\pi}^\dagger|0\rangle \exp(-m_{\pi_n} t)$$

- Three-point functions for form factors, mixing:

$$\langle \pi(t)J(u)B^\dagger(0)\rangle = \sum_{mn} \langle 0|\hat{\pi}|\pi_m\rangle \boxed{\langle \pi_n|\hat{J}|B_m\rangle} \langle B_m|\hat{B}^\dagger|0\rangle$$
$$\times \exp[-m_{\pi_n}(t-u) - m_{B_m} u]$$

Two Challenges

- The second-greatest (numerical) challenge in LQCD is reducing the mass of valence quarks.
- The greatest challenge in LQCD is reducing the mass of sea quarks.
- Handle $m_{\mathrm{val}} \neq m_{\mathrm{sea}}$ with "partially quenched chiral perturbation theory":
  - non-unitary effective theory to describe a non-unitary underlying theory.

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

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

taste

Tastes

- The staggered Dirac operator can be written

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

taste

Tastes

- The staggered Dirac operator can be written

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

taste

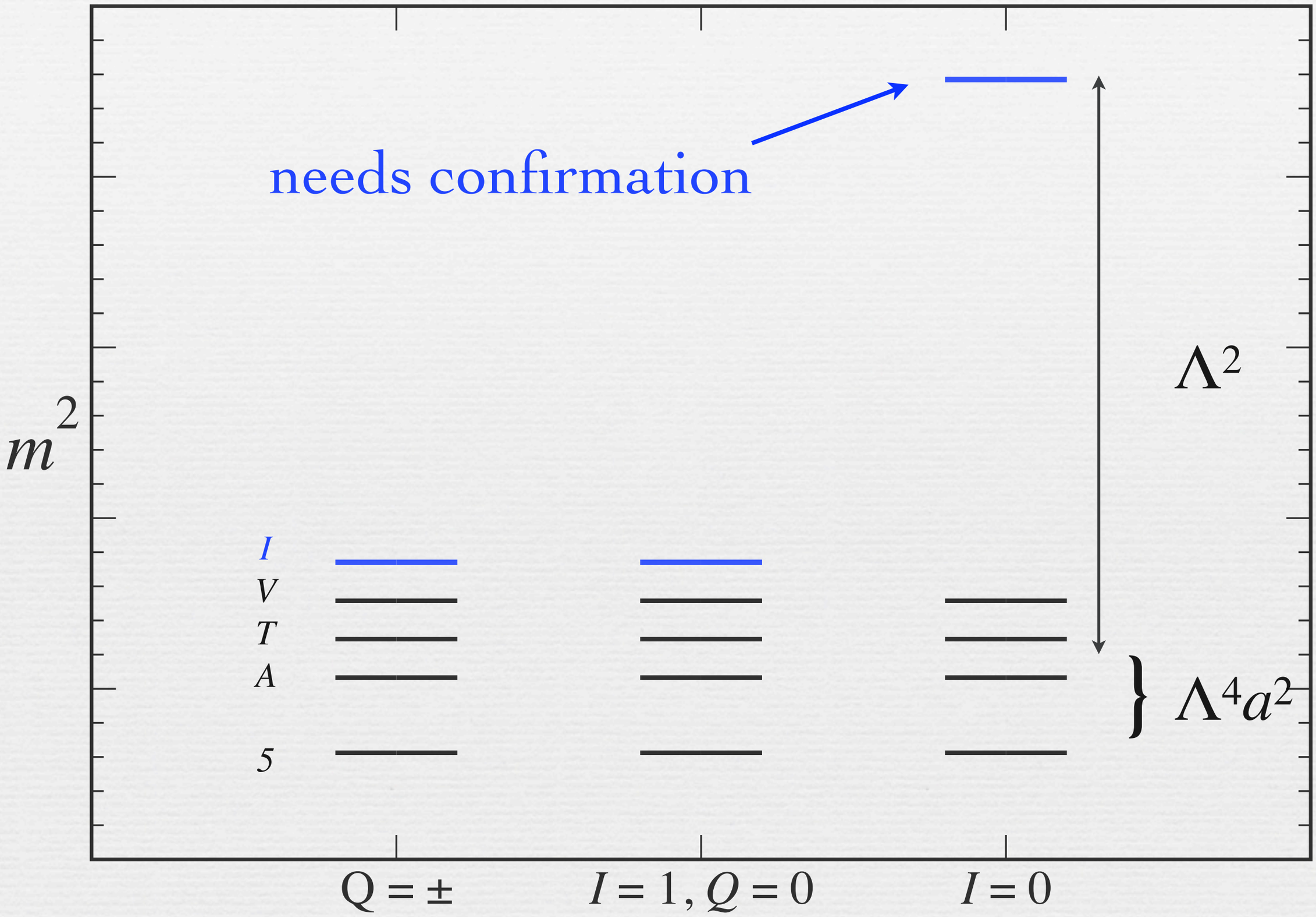
- Does the taste-breaking defect $a\Delta$ vanish in continuum limit?

- 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 (1983)].

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

Rooted & Staggered

- If the taste breaking does *not* vanish, then the phantoms' 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

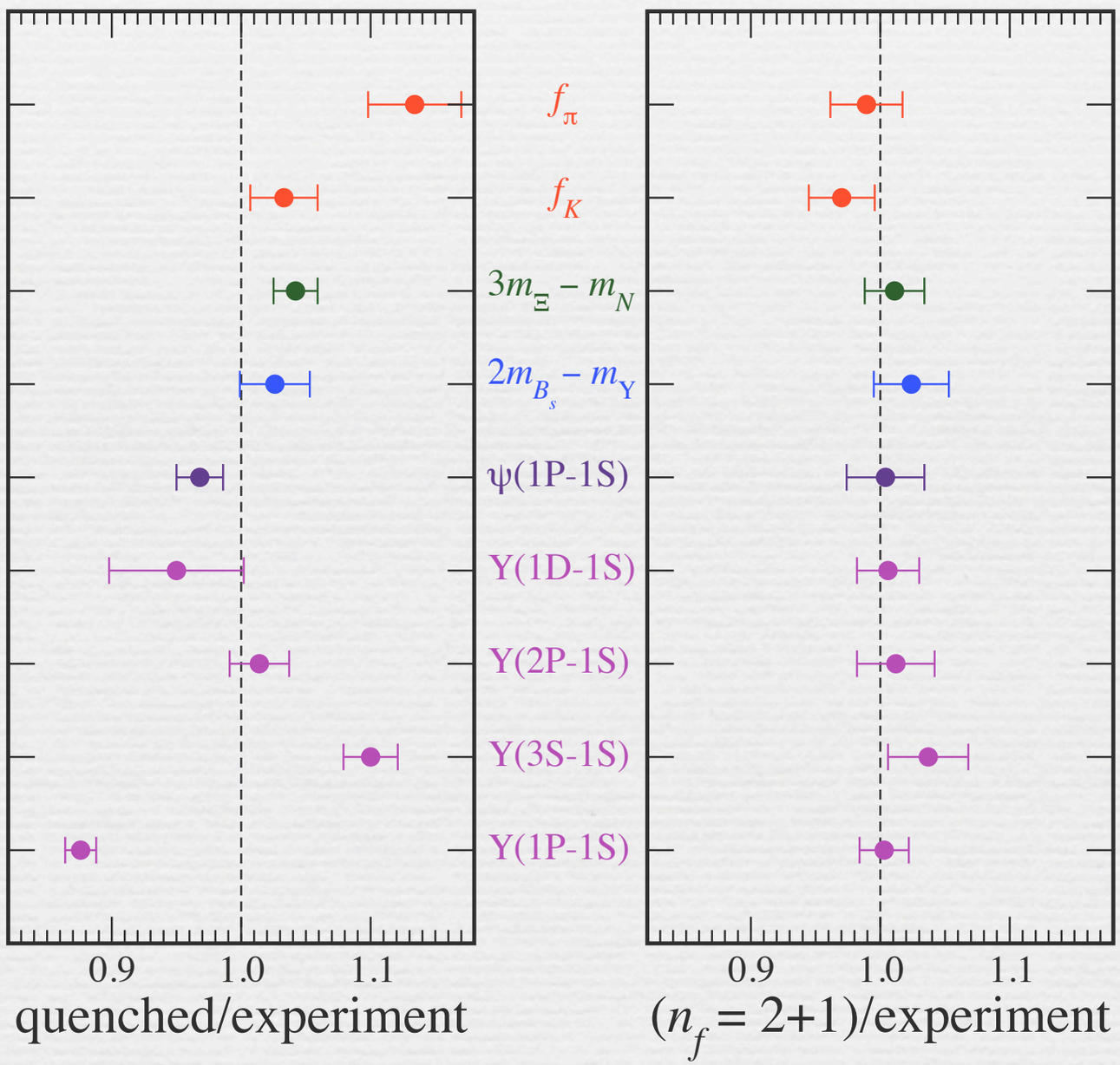
- The taste-breaking defect must vanish in the continuum limit:
  - supported by RG papers of Shamir and experience with scaling in QCD.
- Functional $\Gamma(\pi, \sigma, \ldots)$ must behave such that (non-unitary) RSχPT [Aubin, Bernard] to describe the computed correlators:
  - supported by numerical evidence.

What Others Want

- Famous theorist, December 2006:
  - "I'll believe a 3% lattice [QCD] theory error when the lattice has produced one successful prediction and several 3% postdictions."
- Nine 1–3% postdictions in March 2003 (in PRL).
- Three predictions in August 2004; November 2004; June 2005 (all in PRL). Verified by FOCUS, Belle, CLEO; CDF; CLEO, BaBar….

2+1 Sea Quarks

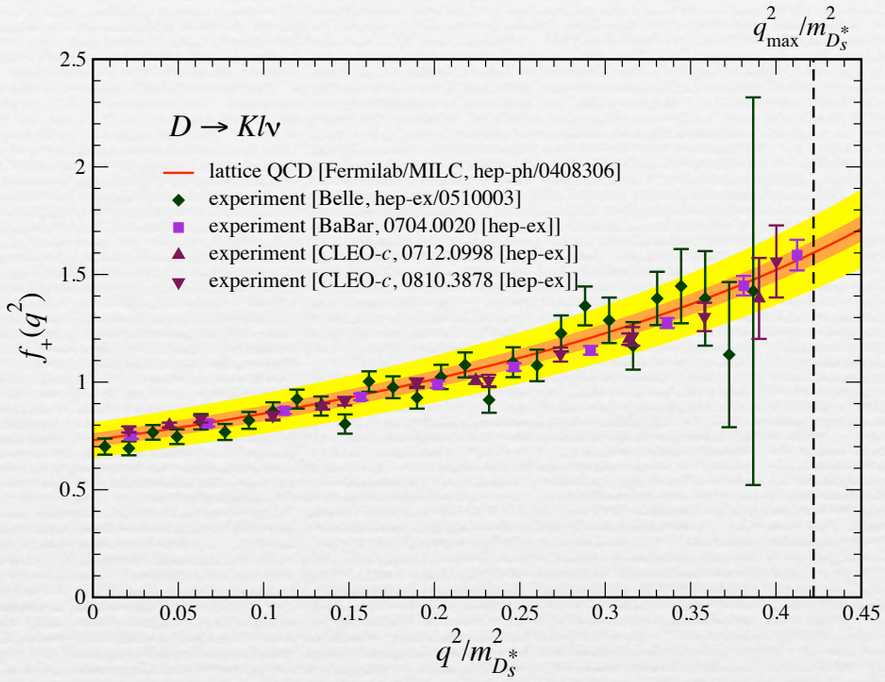
HPQCD, MILC, Fermilab Lattice, hep-lat/0304004



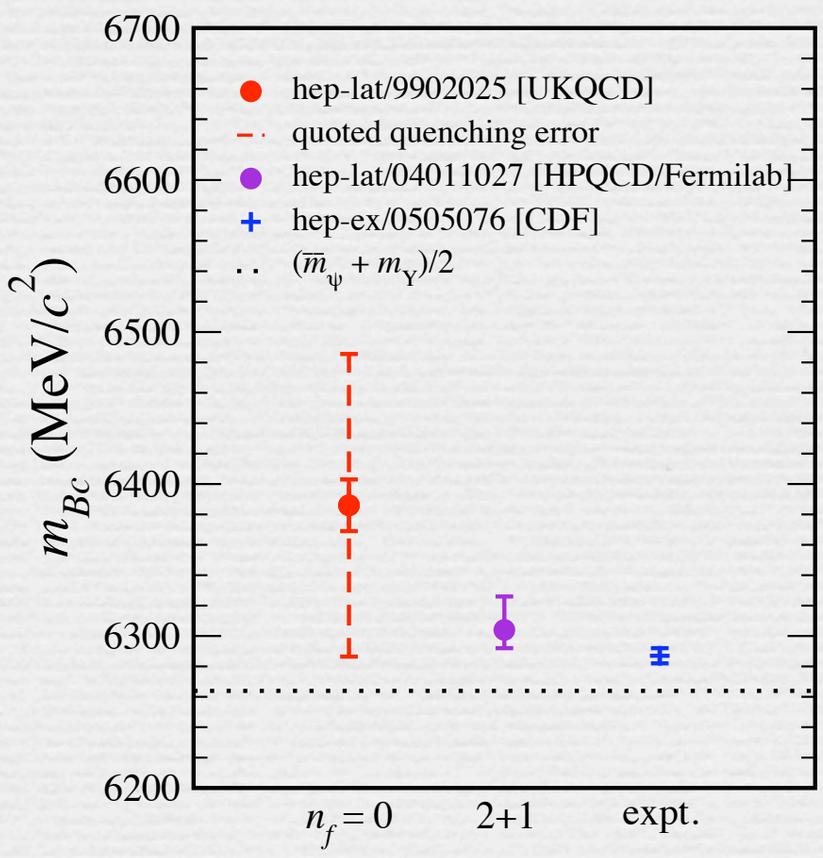
- a = 0.12 & 0.09 fm
- O(a^2) improved
- FAT7 smearing
- $2m_l < m_q < m_s$
- π, K, Υ(2S) input

Predictions

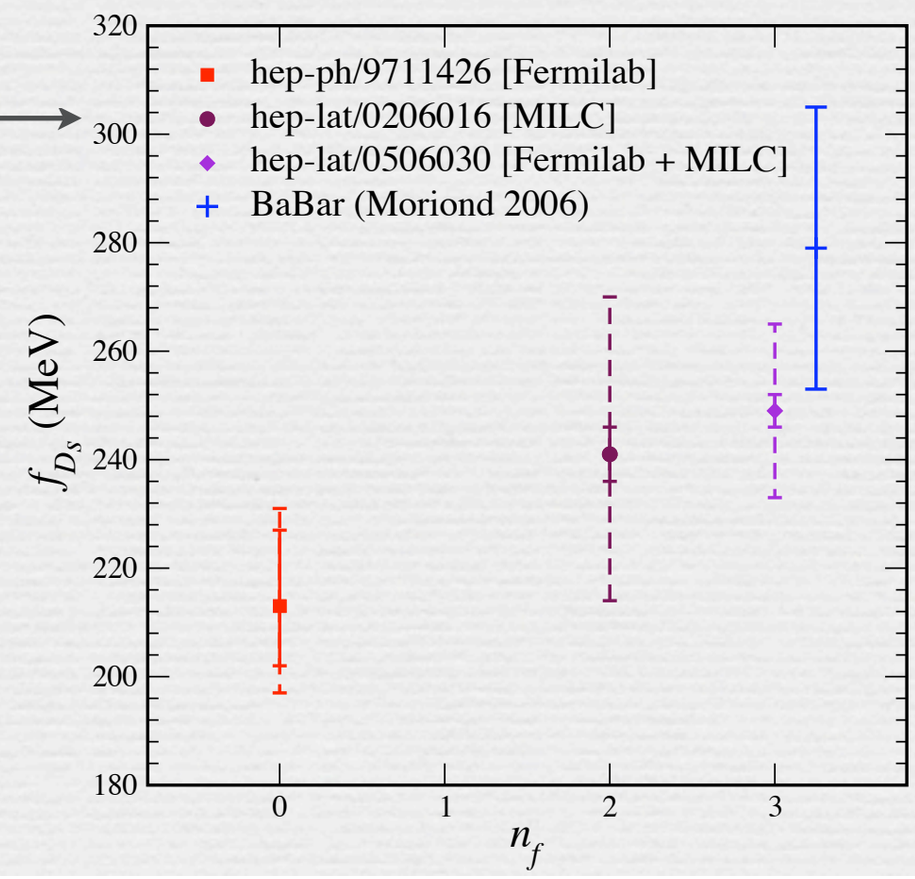
- Semileptonic form factor for $D \to Kl\nu$
- Mass of B_c meson
- Charmed decay constants



2004



2005



CKM

Scope of this talk

- Neutral meson mixing: K, B, B_s.
- Semileptonic form factors:
  - $K \to \pi l \nu$ for $|V_{us}|$: RBC+UKQCD, 2007
  - $D \to K l \nu$, $D \to \pi l \nu$: Fermilab+MILC, 2004
  - $B \to D^* l \nu$ for $|V_{cb}|$; $B \to \pi l \nu$ for $|V_{ub}|$
- Leptonic decay constants: f_π, f_K, f_D, f_{D_s}, f_B.

Scope of this talk

- Neutral meson mixing: K, B, B_s.
- Semileptonic form factors:
  - $K \to \pi l \nu$ for $|V_{us}|$: RBC+UKQCD, 2007
  - $D \to K l \nu$, $D \to \pi l \nu$: Fermilab+MILC, 2004
  - $B \to D^* l \nu$ for $|V_{cb}|$; $B \to \pi l \nu$ for $|V_{ub}|$
- Leptonic decay constants: f_π, f_K, f_D, f_{D_s}, f_B.

$|V_{cb}|$

alia et Jack Laiho *et al.*, arXiv:0808.2519

- $|V_{us}|$, $|V_{ub}|$, and $|V_{cb}|$ are the three real parameters of the CKM matrix.
- $|V_{cb}|$ normalizes the unitarity triangle: enters all flavor physics.
- Inclusive $b \to cl\nu$: OPE + PT + measured moments.
- Exclusive $B \to D^* l\nu$: (zero recoil) form factor:

$$\mathcal{F}(1) = h_{A_1}(1), \quad \langle D^* | \mathcal{A}_\mu | B \rangle = i\sqrt{2m_{D^*} 2m_B}\,\bar{\varepsilon}^*_\mu h_{A_1}(1)$$

- Previous quenched calculation (2001):

$$\mathcal{F}(1) = 0.913^{+0.024}_{-0.017} \pm 0.016^{+0.003}_{-0.014}{}^{+0.000}_{-0.016}{}^{+0.006}_{-0.014}$$

stats match a χPT n_f=0

used till now with HFAG $|V_{cb}|\mathcal{F}(1)$ to get $|V_{cb}|$.

- Three double ratios, devised so that all uncertainties scale with $\mathcal{F}$–1, not $\mathcal{F}$.

- Update to 2+1 sea quarks with a *single* ratio — more direct & much less computer time.

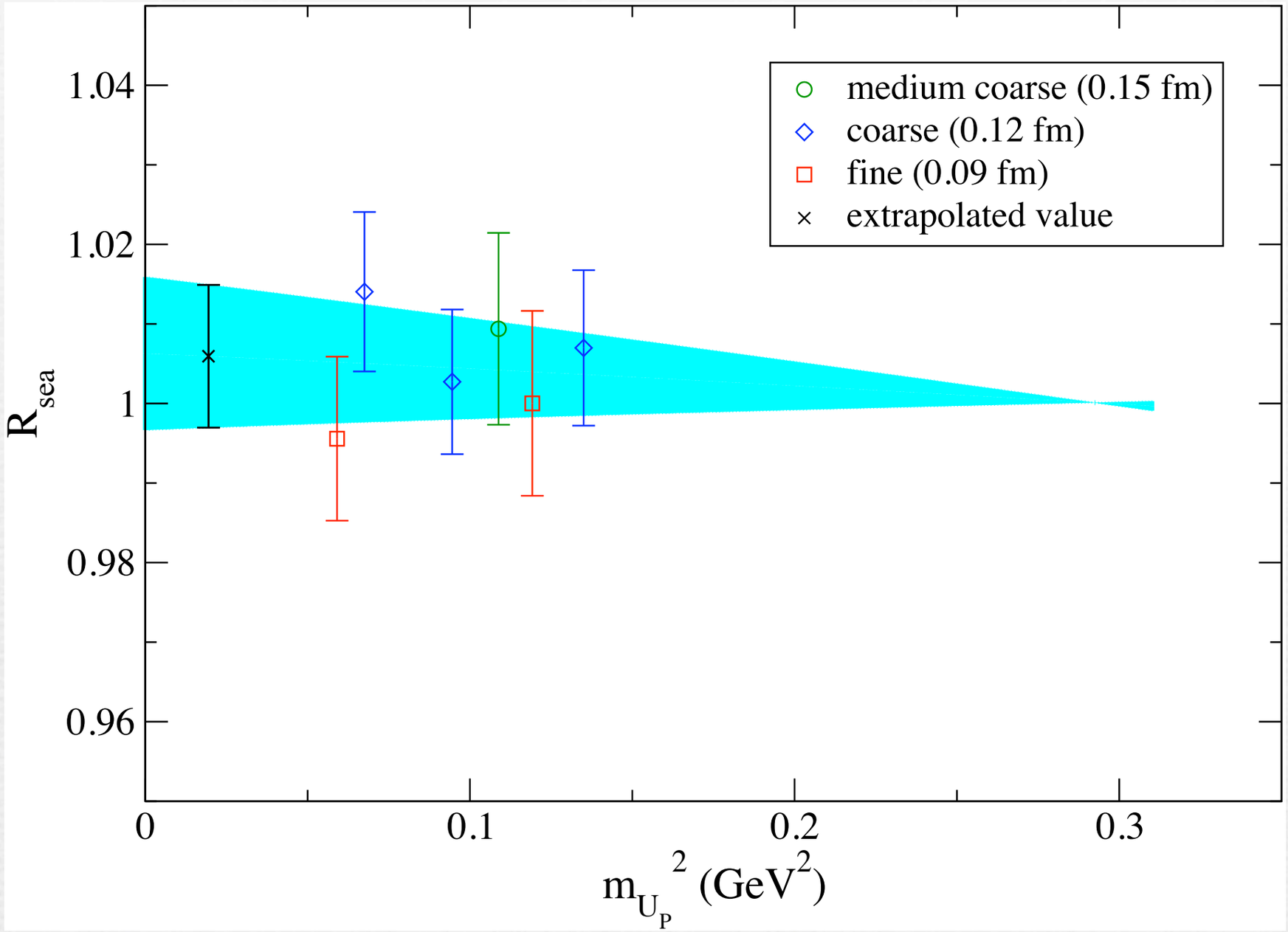
- Also introduces ratios of matrix elements to disentangle chiral extrapolation from heavy-quark discretization effects:

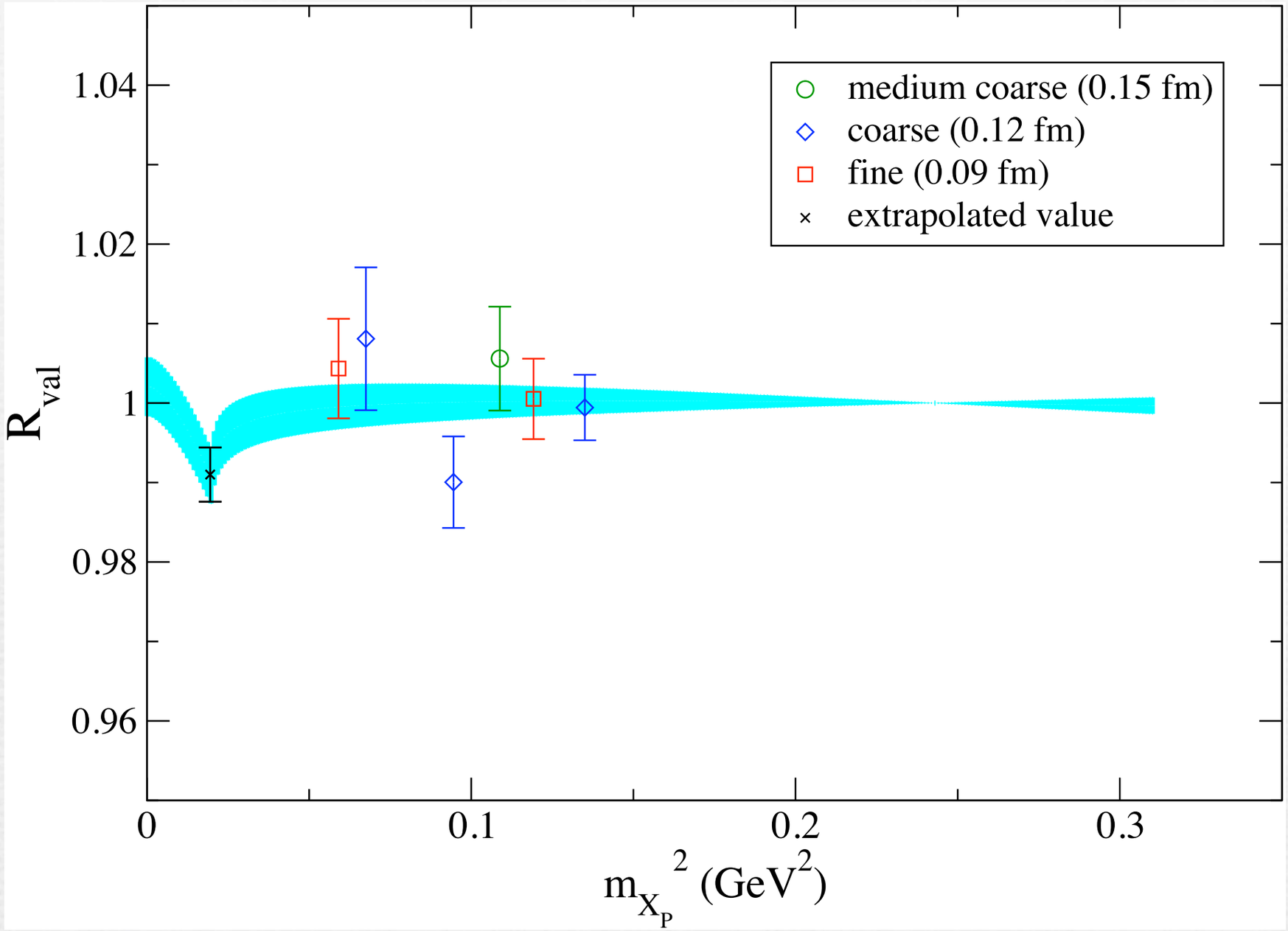
$$\mathcal{R}_{\rm val}(m_x, \hat{m}', m_s', a) \;:=\; \frac{h_{A_1}(m_x, \hat{m}', m_s', a)}{h_{A_1}(m_x^{\rm fid}, \hat{m}', m_s', a)},$$

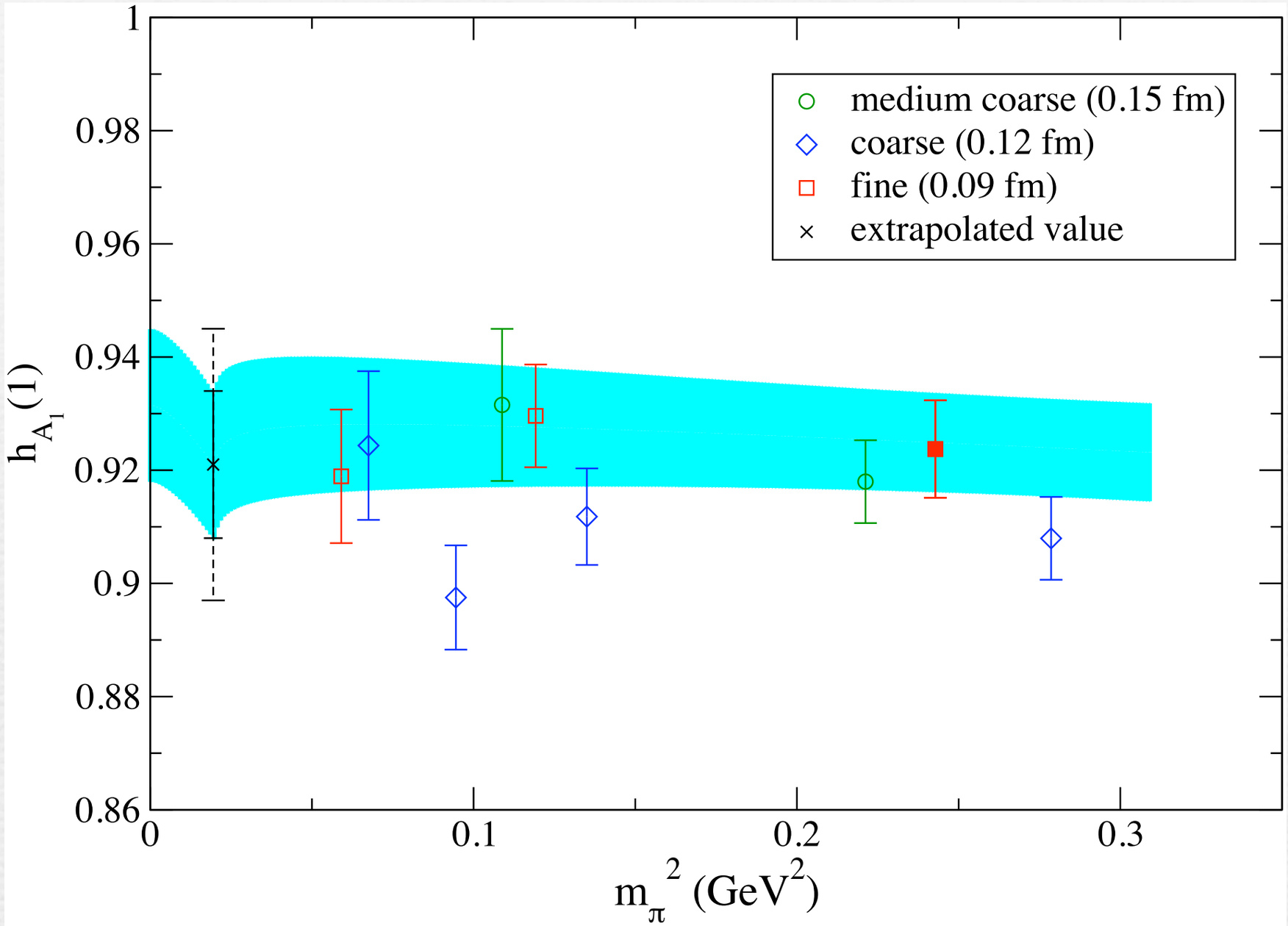
$$\mathcal{R}_{\rm sea}(\hat{m}', m_s', a) \;:=\; \frac{h_{A_1}(m_x^{\rm fid}, \hat{m}', m_s', a)}{h_{A_1}(m_x^{\rm fid}, \hat{m}^{\rm fid}, m_s^{\rm fid}, a)}.$$

- Reconstruct

$$\begin{aligned} h_{A_1} \;=\; & h_{A_1}(m_x^{\rm fid}, \hat{m}^{\rm fid}, m_s^{\rm fid}, a \to 0) \\ & \times \mathcal{R}_{\rm val}(m_x, \hat{m}', m_s', a) \times \mathcal{R}_{\rm sea}(\hat{m}', m_s', a) \end{aligned}$$


medium coarse (0.15 fm)
coarse (0.12 fm)
fine (0.09 fm)
extrapolated value
1.04
1.02
1
0.98
0.96
R_sea
0
0.1
0.2
0.3
m_U_P^2 (GeV^2)


medium coarse (0.15 fm)
coarse (0.12 fm)
fine (0.09 fm)
extrapolated value
1.04
1.02
1
0.98
0.96
R_val
0
0.1
0.2
0.3
m_X_P^2 (GeV^2)



$$\mathcal{F}(1) = 0.921 \pm 0.013 \pm 0.008 \pm 0.008 \pm 0.014 \pm 0.007$$

stats $\quad g_{D^*D\pi} \quad \chi$PT $\quad$ match $\quad m_Q$

$|V_{ub}|$

alia et Ruth Van de Water, arXiv:0811.3640

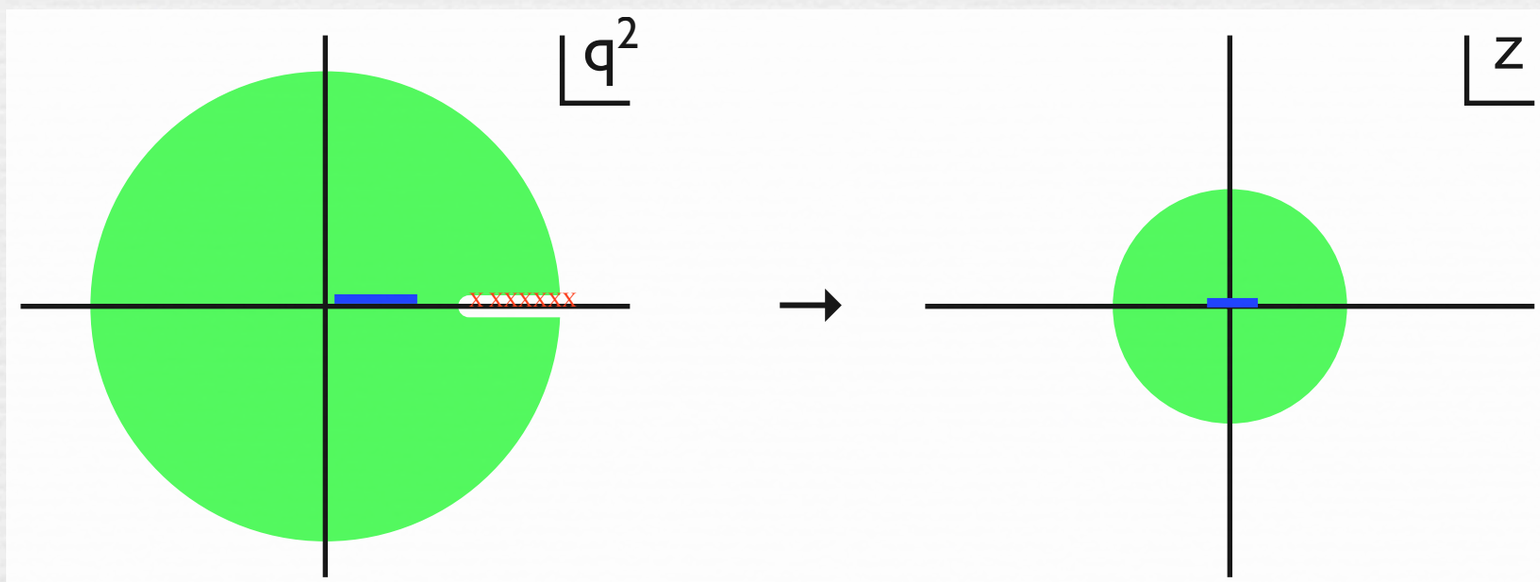
- $|V_{us}|$, $|V_{ub}|$, and $|V_{cb}|$ are the three real parameters of the CKM matrix.
- $|V_{ub}|$ gives a tree constraint comparable to sin 2β.
- Inclusive $b \to ul\nu$: keep control of OPE (or shape functions, or ...) in region with no charm.
- Exclusive $B \to \pi l\nu$: form factor $f_+(q^2)$

$$\langle \pi | \mathcal{V}^\mu_\perp | B \rangle = (p_B + p_\pi)^\mu_\perp f_+(q^2), \quad q \cdot p_\perp = 0$$

- Problem to determine $|V_{ub}|$:
  - lattice best when p_π small, so $q^2 \approx q^2_{\text{max}}$,
  - but event rate highest when $q^2 \approx 0$.
- Until now: find least bad q^2 of both worlds, or introduce *Ansatz* for q^2 dependence.
- Here: a model *independent* simultaneous fit.

- Let $z = \dfrac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$, $\quad t_\pm = (m_B \pm m_\pi)^2$, $\quad t_- < t_0 < t_+$

  inspired by unitarity.



- For $B \to \pi/\nu$ kinematics $-0.34 < z < 0.22$.

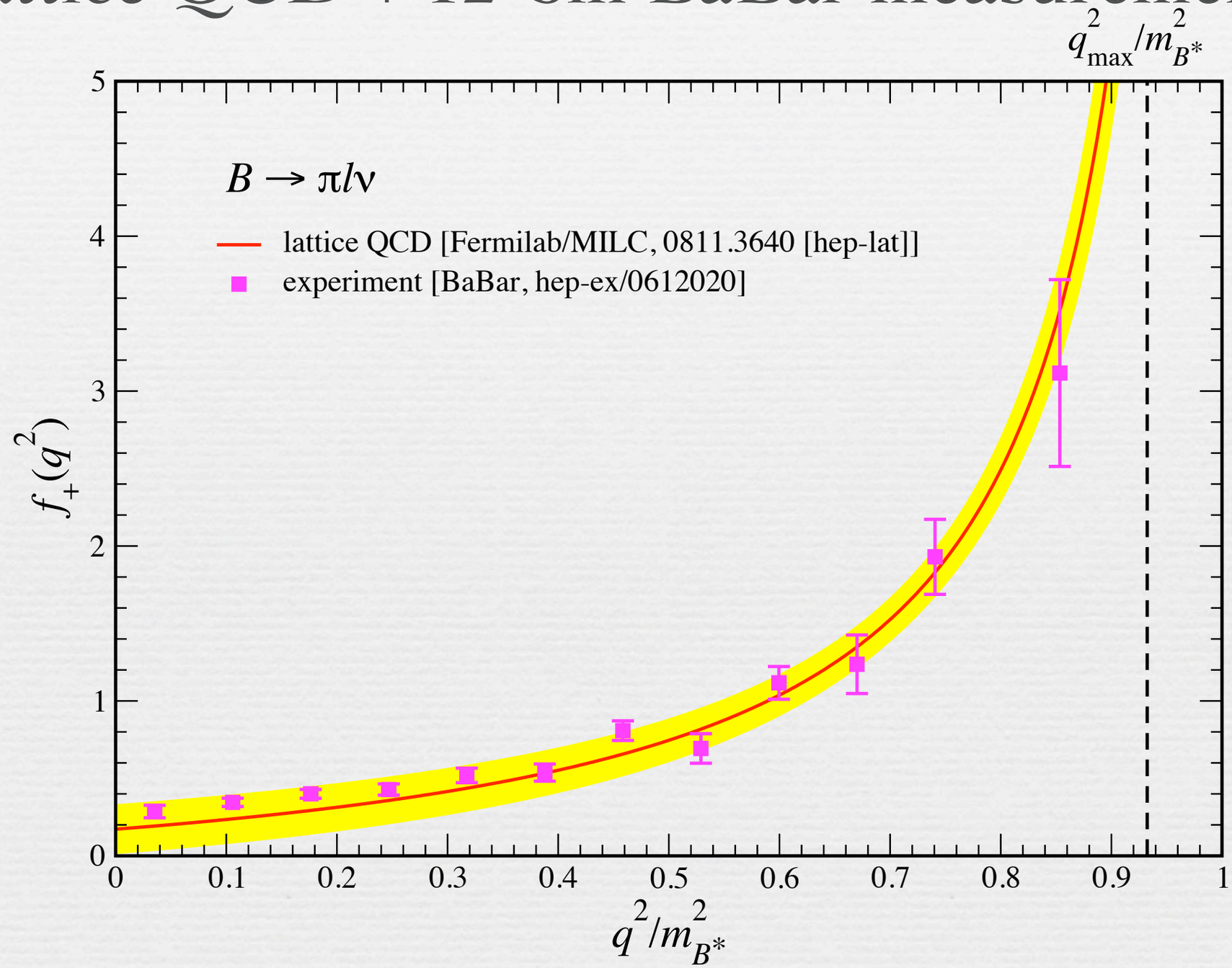
- Unitarity guarantees convergent expansion in $z(t)$:

$$P(t)\phi(t,t_0)f(t) = \sum_{k=0}^{\infty} a_k z^k, \quad \sum_{k=0}^{N} a_k^2 \leq 1$$

B^* pole asymptotics

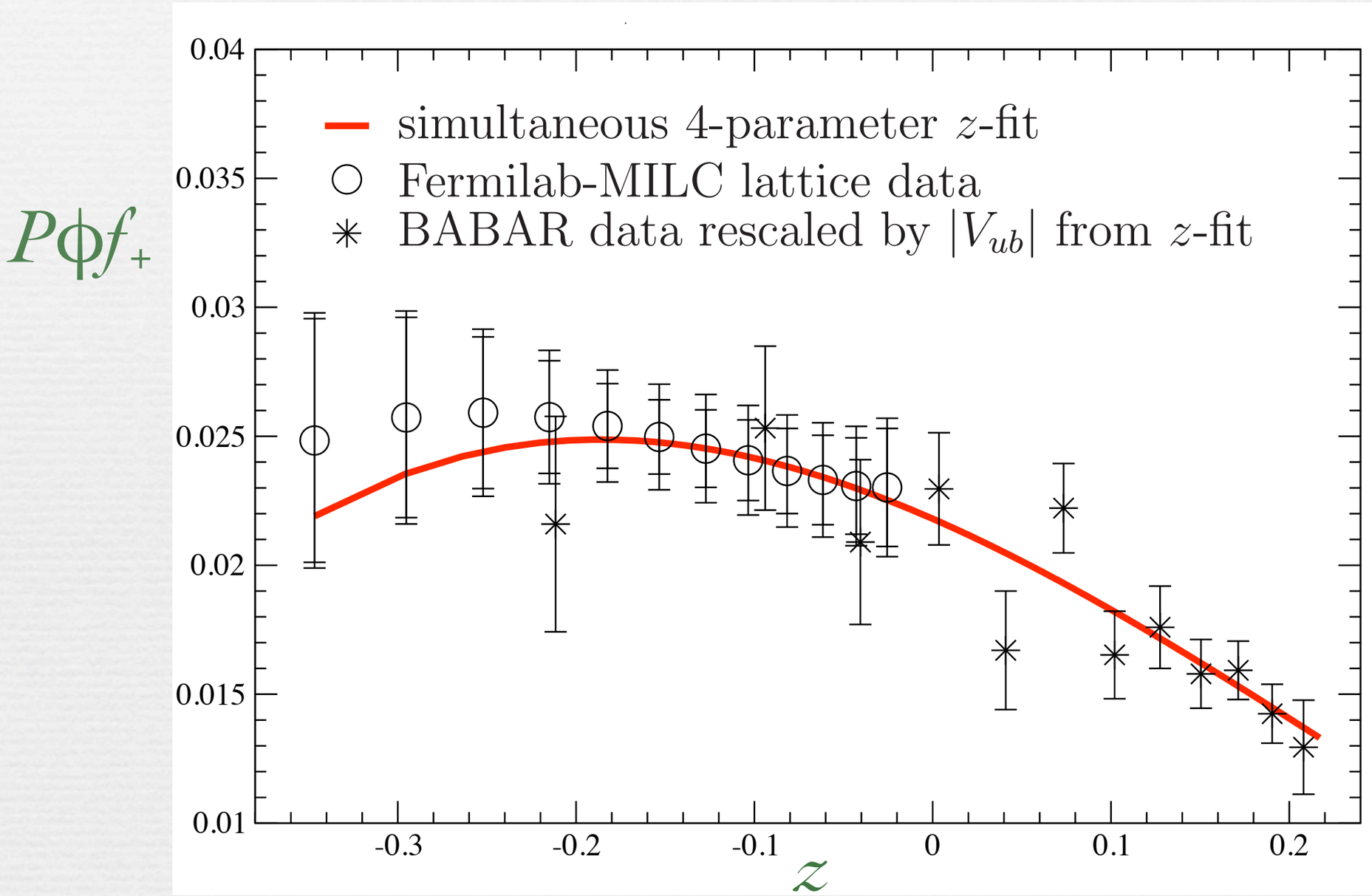
- New approach
  - fit lattice & expt separately: compare a_k/a_0;
  - fit lattice & expt together, yielding $|V_{ub}|$.

Lattice QCD + 12-bin BaBar measurement.

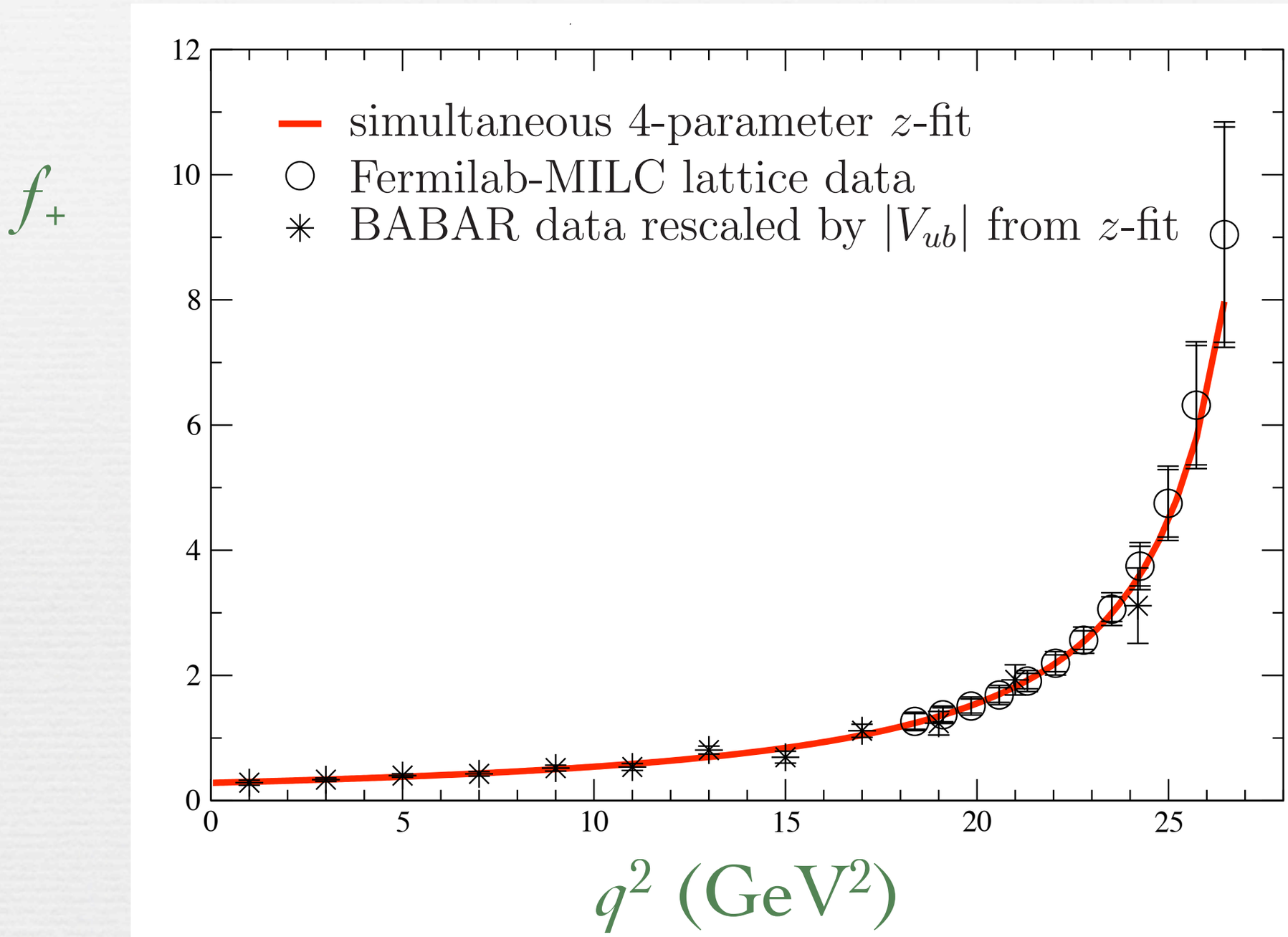


plot from arXiv:0906.2498

Lattice QCD + 12-bin BaBar measurement.



4 fit parameters: $|V_{ub}|$, a_0, a_1, a_2.



Fermilab Lattice + MILC

$|V_{cb}|$ & $|V_{ub}|$

- Using $\mathcal{F}(1)$ to get $|V_{cb}|$:

  $10^3|V_{cb}| = 38.7(9)(10)$

  with latest HFAG.

- Compared to inclusive:

  $10^3|V_{cb}| = 41.6(8)$

  from HFAG/ICHEP08.

- Final z-fit to get $|V_{ub}|$:

  $10^3|V_{ub}| = 3.38(36)$

  with BaBar 12-bin data.

- Compared to inclusive:

  $10^3|V_{ub}| = (3.76\text{–}4.87) \pm 0.35$

  from HFAG/ICHEP08.

Being sorted out for CKM 2008 report.

f_{D_s} Puzzle

Leptonic Decay

- The branching fraction for a pseudoscalar meson to decay into a lepton-neutrino pair, in the SM, is

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

  - quark-W vertex leads to CKM;
  - helicity ($m_l \ll m_D$) or phase-space ($m_l \approx m_D$) suppression.
  - lattice QCD for f_{D_s}.

Leptonic Decay

- The branching fraction for a pseudoscalar meson to decay into a lepton-neutrino pair, in the SM, is

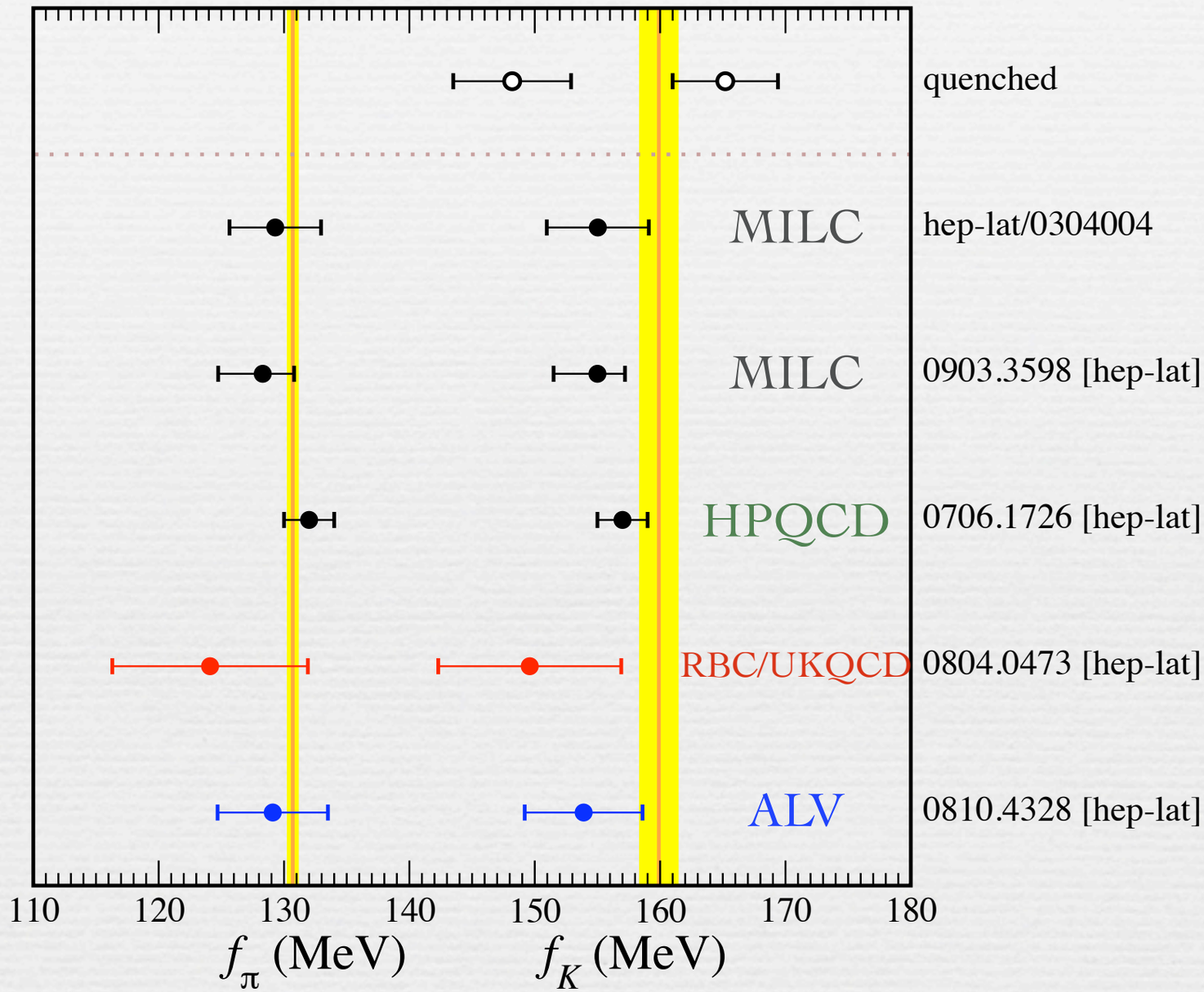
$$B(D_s \to \ell\nu) = \frac{m_{D_s}\tau_{D_s}}{8\pi} f_{D_s}^2 |G_F V_{cs}^* m_\ell|^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

  - quark-W vertex leads to CKM;
  - helicity ($m_l \ll m_D$) or phase-space ($m_l \approx m_D$) suppression.
  - lattice QCD for f_{D_s}.

f_π and f_K

- These are thought of as tests of (lattice) QCD.
- Experiments yield $|V_{ud}|f_\pi$ and $|V_{us}|f_K$:
  - $|V_{ud}|$ from nuclear $0^+ \to 0^+$ transitions;
  - $|V_{us}|$ from semileptonic $K \to \pi l \nu$.
- Many groups (MILC, RBC, NPLQCD, Aubin-Laiho-Van deWater, HPQCD, BMW) have these (or ratio f_K/f_π) with accuracy at 2% level.

- Reproducible:
  - Asqtad on asqtad
  - HISQ on asqtad
  - DWF on DWF
  - DWF on asqtad
- Others have f_K/f_π.



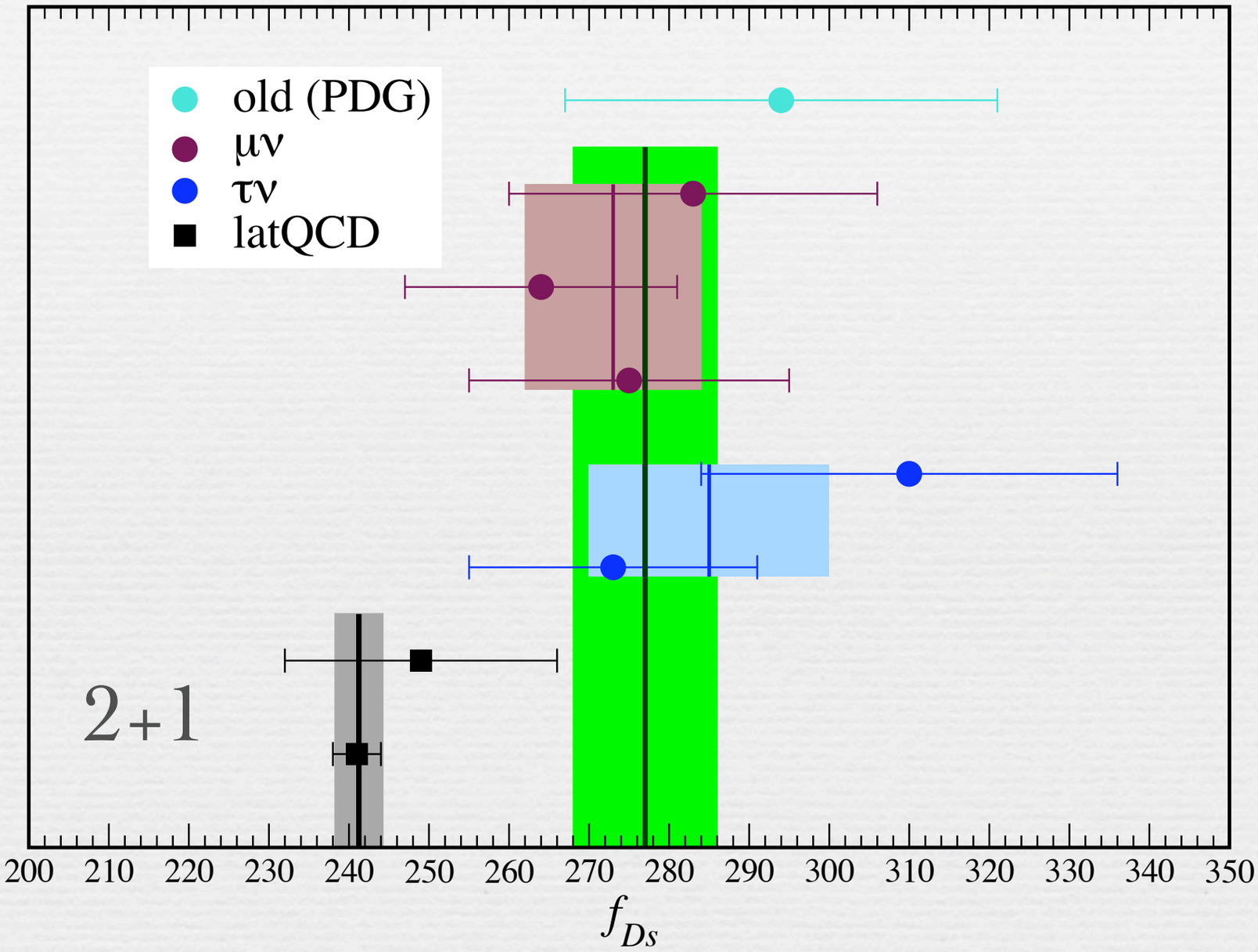
f_D and f_{D_s}

- These are thought of as tests of (lattice) QCD.
- Experiments (recently) yield $|V_{cd}|f_D$ and $|V_{cs}|f_{D_s}$:
  - $|V_{cx}|$ from CKM unitarity.
- First *un*quenched calculations [Fermilab/MILC] agreed, at 7% level, with first good measurements (CLEO for D, BaBar for D_s).

$D_s \to l\nu$

- $D_s \to l\nu$ should be the easiest leptonic decay for lattice QCD.
- A simple matrix element $\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s\rangle = i f_{D_s} p_\mu$.
- No light valence quarks.
- Counting experiment at CLEO, B factories.
- New physics thought to be *very unlikely*.

And then something funny happened (end 2007)...

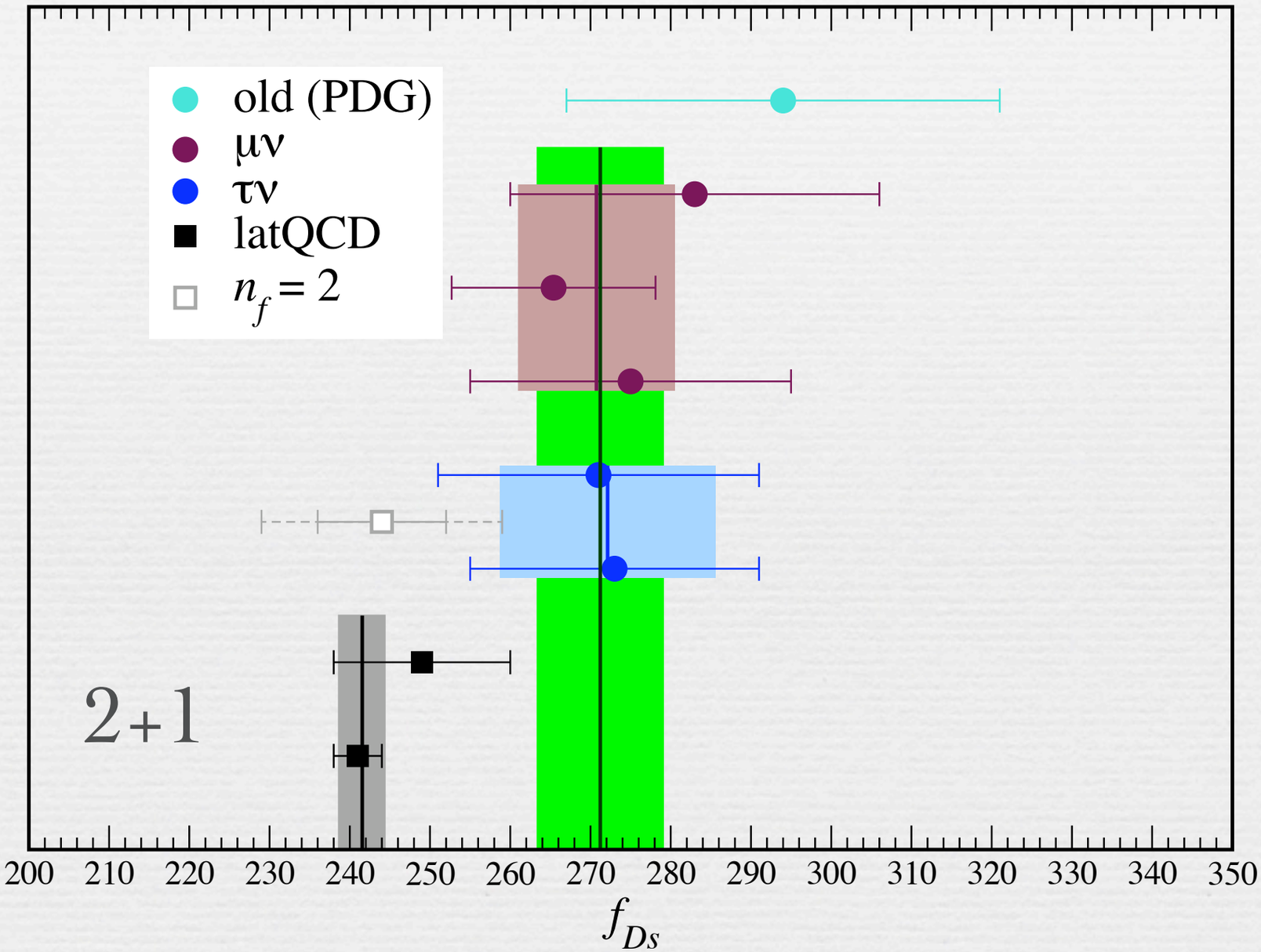


$\chi^2/\mathrm{dof} = 0.67$

BaBar
CLEO
Belle
CLEO πν
CLEO eνν
Fermilab/MILC
HPQCD

a 3.8σ discrepancy, or 2.7σ ⊕ 2.9σ.

Updates from FPCP (CLEO) and Lat'08 ...



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

BaBar

CLEO

Belle

CLEO πν

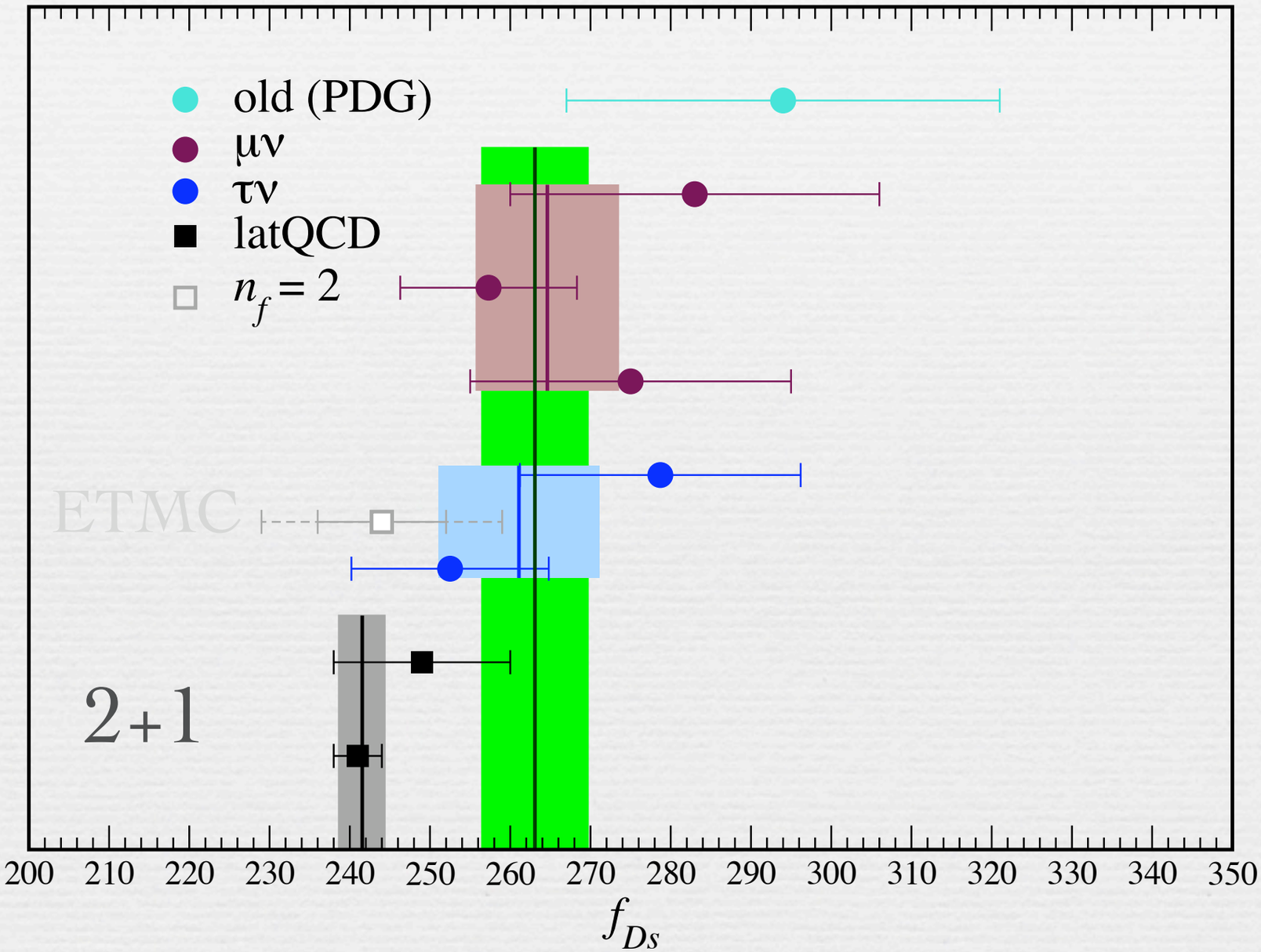
CLEO eνν

Fermilab/MILC

HPQCD

a 3.6σ discrepancy, or 2.9σ ⊕ 2.2σ.

With CLEO's papers of January 12, 2009



$\chi^2/\mathrm{dof} = 0.73$

BaBar

CLEO

Belle

CLEO $\pi\nu$

CLEO $e\nu\nu$

Fermilab/MILC

HPQCD

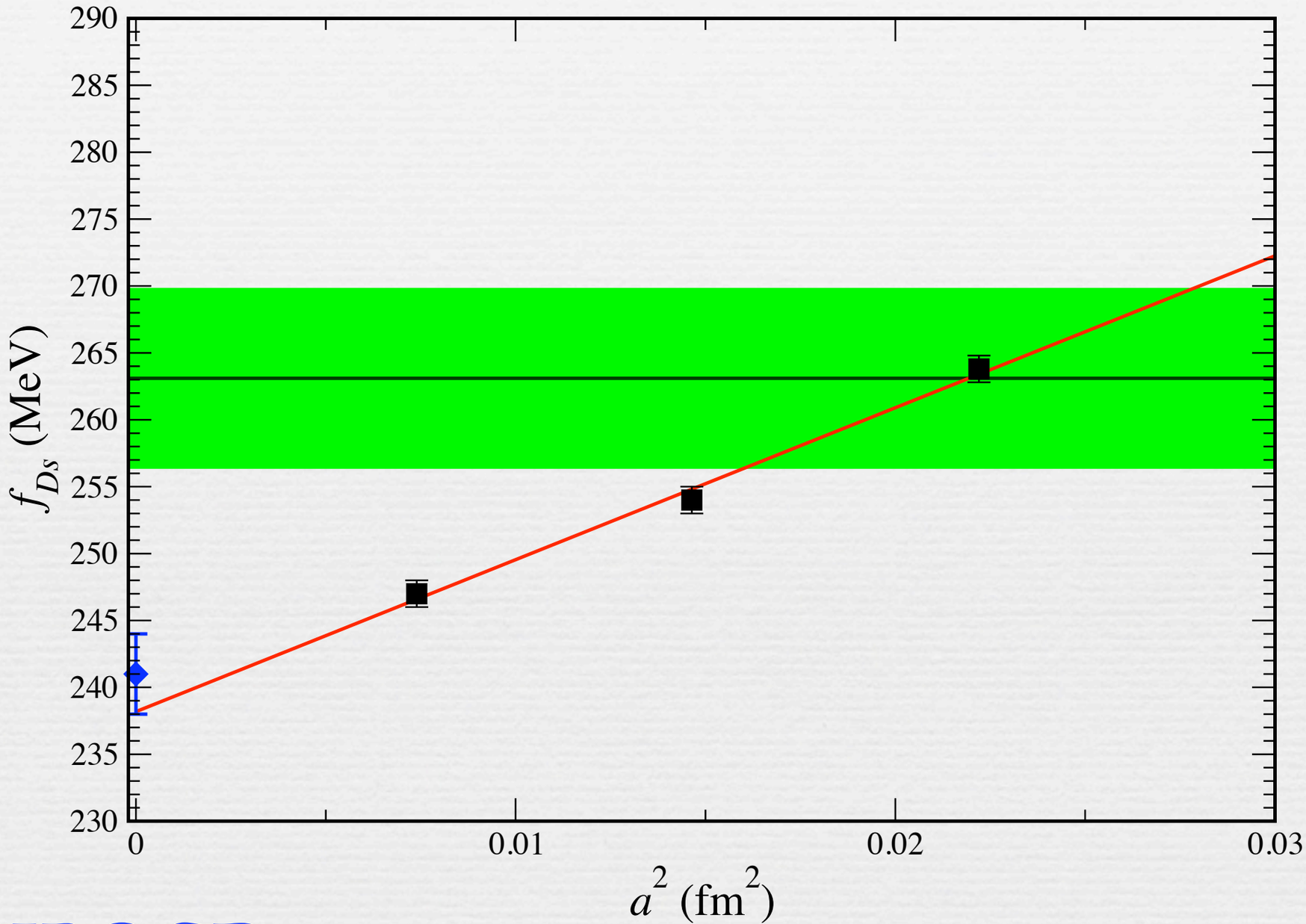
a 3.0σ discrepancy, or $2.5\sigma \oplus 1.9\sigma$.

A Puzzle

- Experimental errors?
- Radiative corrections?
- CKM?
- Lattice QCD?

- Unlikely: stats limited.
- No: 1–2%
- No: need $|V_{cs}| > 1.1$.
- Let's see.

As the lattice gets finer, the discrepancy grows:

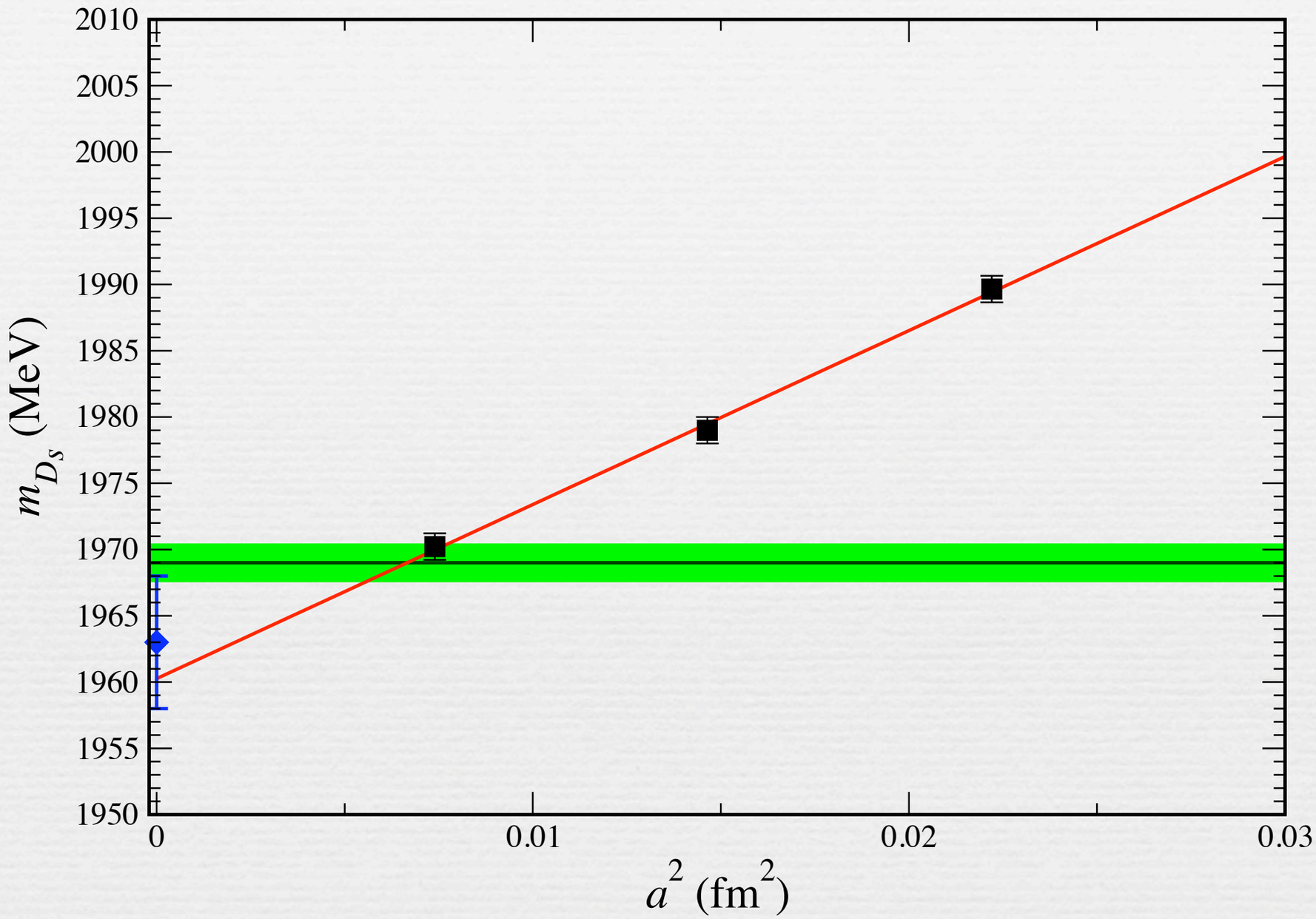


263.1 ± 6.7 MeV

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_{D_S} (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

arXiv:hep-lat/0610092 & arXiv:0706.1726 [hep-lat]

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	205.8 ± 8.9[*]	207 ± 4	MeV

[*]CLEO arXiv:08062112 [‡]annihilation corrected

What if

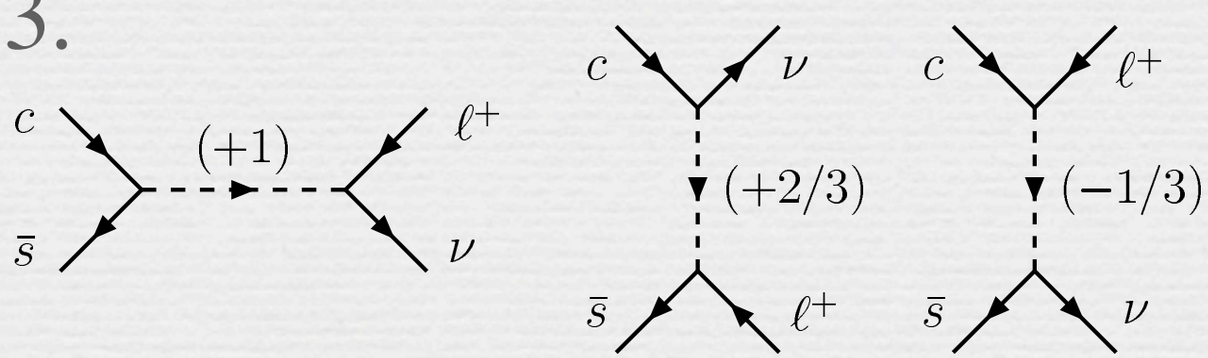
- ... the discrepancy is real?
- Then it must be non-Standard physics.
- How wacky would a non-Standard model be?
- It turns out particles that are already being considered can do the trick.
- B.A. Dobrescu & ASK, arXiv: 0803.0512

New Particles

- Effective interactions

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

  can be induced by heavy particles of charge +1, +2/3, –1/3.

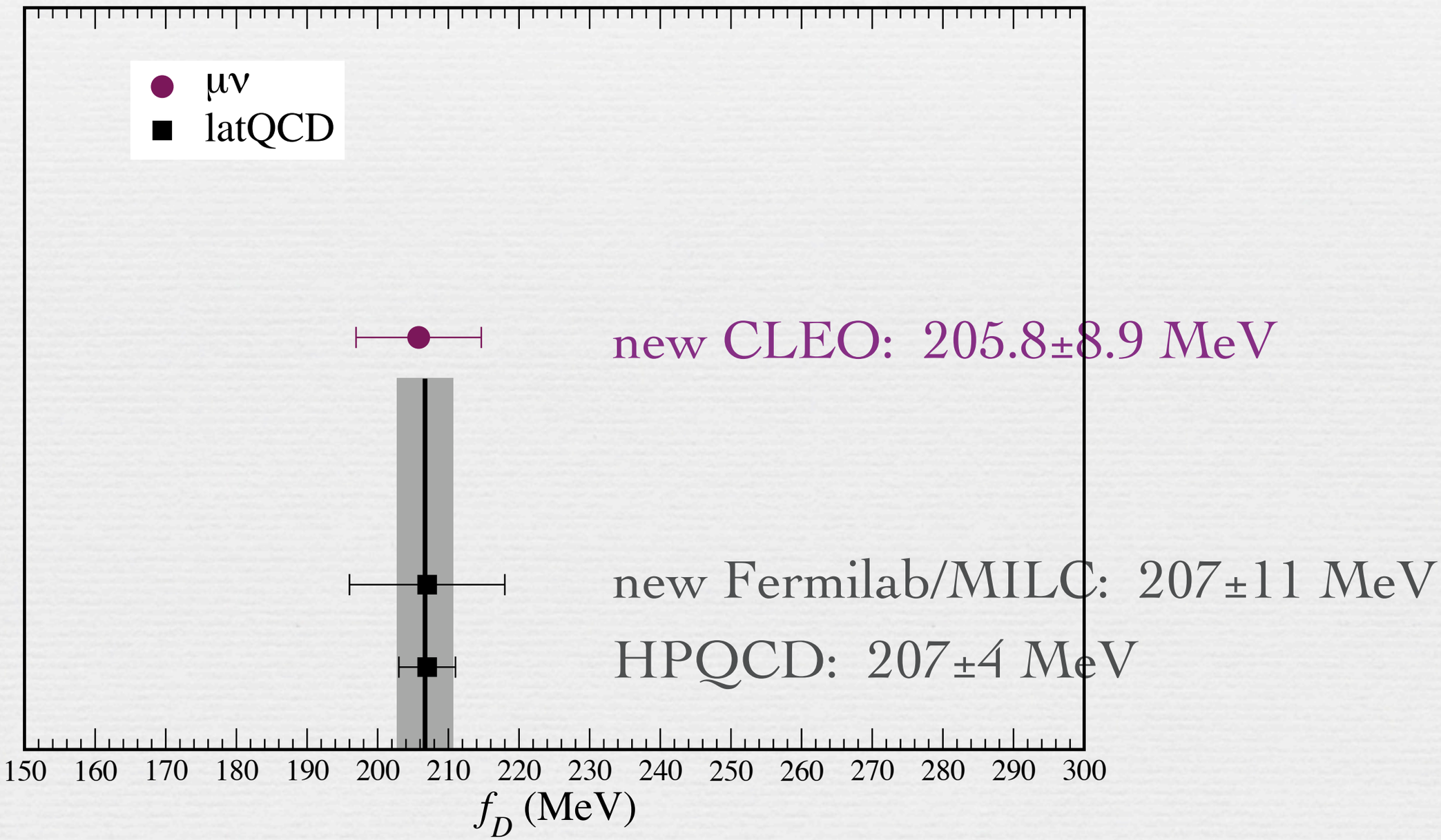


- Charged Higgs, new W'; leptoquarks.

Beyond SM

- New W' boson: unlikely.
- Charged Higgs:
  - Model II destructively interference;
  - BAD & ASK found new model.
- Leptoquarks:
  - $J = 0$, $(3, 1, -1/3)$, aka $\tilde{d}$, can explain the effect.

- Charged Higgs model predicts a similarly-sized deviation in $D \to l\nu$, now disfavored:



LHC

- The generic bounds on mass/coupling:

$$\frac{M}{(\mathrm{Re}\, C^{\ell}_{A,P})^{1/2}} \lesssim \begin{cases} 710\ \mathrm{GeV}, \quad 920\ \mathrm{GeV} \ \text{ for } \ell = \tau \\ 850\ \mathrm{GeV}, \ 4500\ \mathrm{GeV} \ \text{ for } \ell = \mu \end{cases}$$

  any non-Standard explanation of the effect is observable at the LHC.

- Leptoquarks: $gg \to \tilde{d}\bar{\tilde{d}} \to \ell_1^+ \ell_2^- \, j_c j_c$.

Conclusions

- Lattice QCD with 2+1 staggered sea quarks has provided many results since 2003;
  - now 2+1 Wilson and DWF sea too.
- Broad, and often precise, agreement with experiment in hadron masses, quarkonium splittings, decay properties; α_s.
- Enables new determinations of $|V_{cb}|$ & $|V_{ub}|$.
- (Matrix elements for neutral-meson mixing.)

- The outlier is f_{D_s}, which should be *easy*:
  - valence quarks aren't light;
  - PCAC normalization (w/ stag. or DWF).
- Experimental *statistical* error is yardstick for discrepancy: with 2×(lattice error) still 2.4σ.
- CLEO done; BaBar & Belle could revisit; BES will go further in a few years.
- If new particle, LHC will pair produce.

Backup

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 $\mu \neq 0$.)

- 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 $J^A \to \sigma^A$, $J_5^A \to \pi^A$; 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.