Flavor in the LHC Era

Andreas S. Kronfeld

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

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- How many quark flavors in the LHC Era? ~~6~~ 9

Quarks

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

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

Line of Attack

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

Standard Model

and slightly beyond

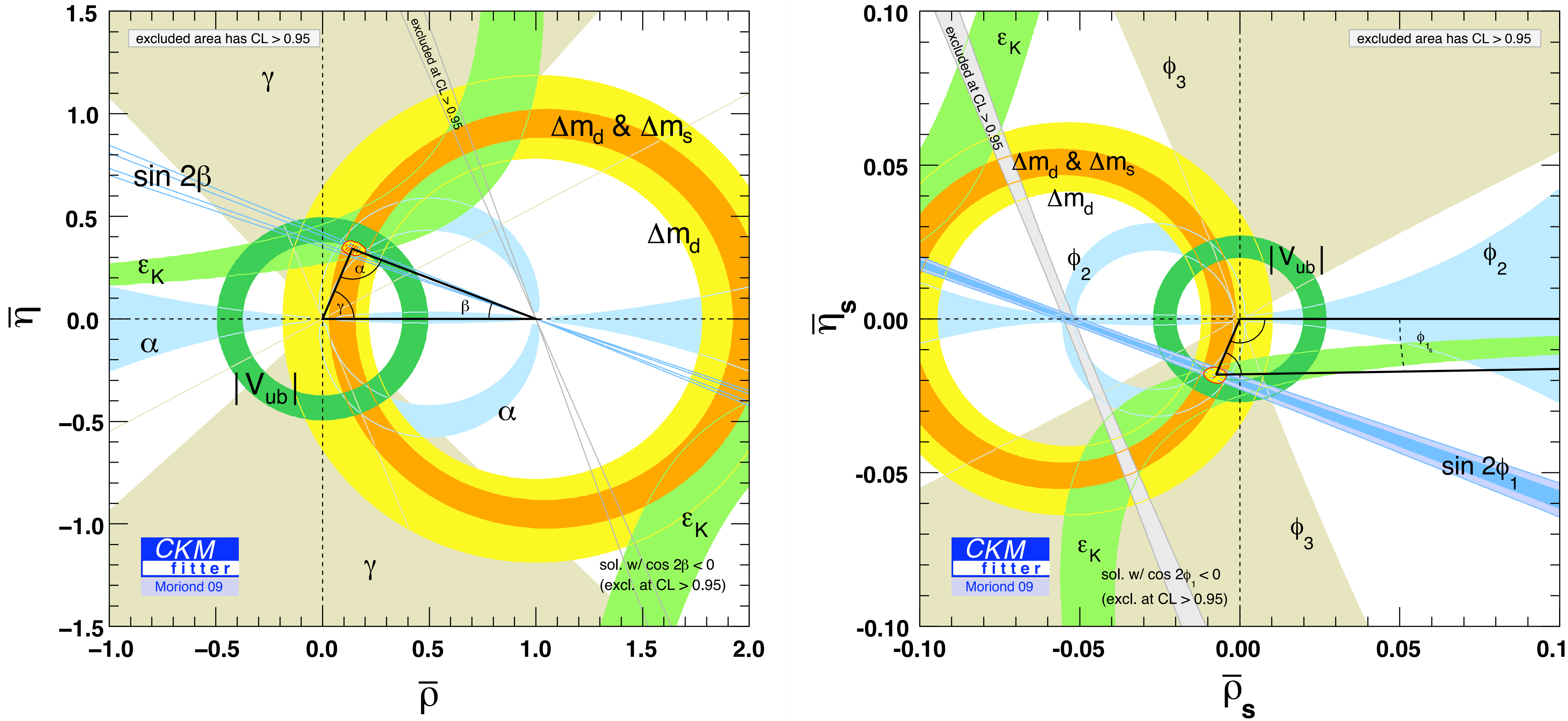
- A sector with doublet structure(s) breaks SU(2).
- The richness of flavor physics comes from the mass matrix that arises when this stuff (inevitably) interacts with L and R quark fields.
- Eigenvalues: masses.
- Eigenvectors/wf phases: CKM matrix.

CKM Matrix

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

- 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: $A = ½\mathrm{Im}[V^*_{ud} V_{ub}/V^*_{cd}V_{cb}] = \bar{\eta}/2$.

CKM Now



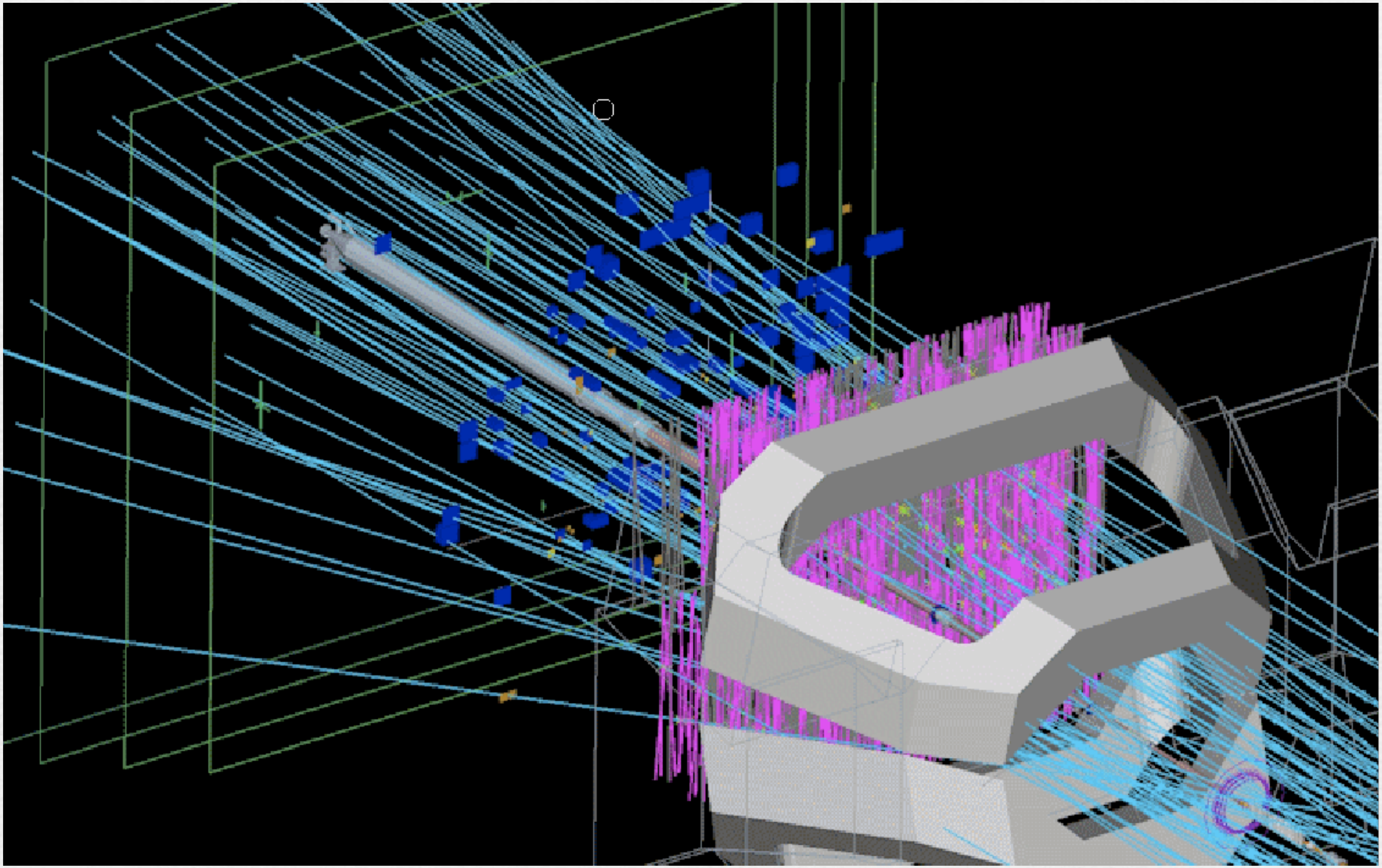
$(\beta, \alpha, \gamma) = (\phi_1, \phi_2, \phi_3)$

Outline

- Future experimental tools.
- Lattice QCD.
- A pardigm shift?
- Interplay of flavor and high-p_T observations.

Future Experiments

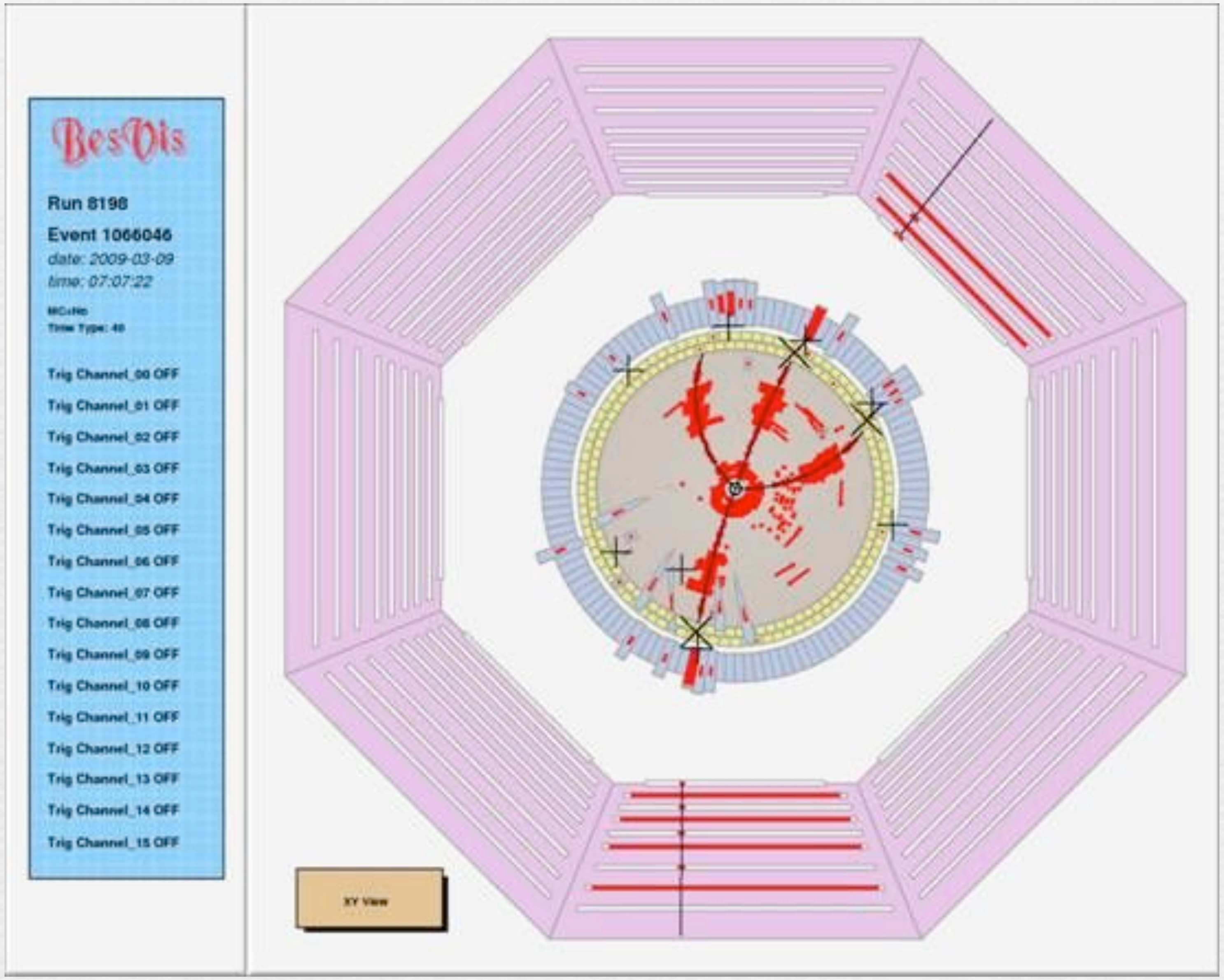
LHC*b*



- LHC*b* physics:
  - definitive measurement of $(\Delta\Gamma_{Bs}, \phi_s)$;
  - multitude of rare decays;
  - precise measurement of $\gamma = \delta_{KM}$ via (weak) tree-level processes:
    - γ to 5° (2.5°) in 2 (10) fb^{-1}, *i.e.*, $\sin \delta_{KM}$ to 1% (0.6%).

BES III

- 100M $\psi(2S)$ in March-April 2009.
- 500M J/ψ later in 2009.
- Charm physics later.



SuperB Factories

The grass is always greener on the other side (?)

Very preliminary parameter set for nano beam @ KEK.
Without crab waist.
Will mature in 6 months.
High current nano beam scheme possible with more RF.

Table 1: Comparison of the High-Current and Nano-Beam Schemes

	High-Current	Nano-Beam	
Stored Current(LER/HER)	9.4 / 4.1	$\sim$ 2.6 / 1.5	A
Equiv. emittance(LER/HER)	$\sim$ 20 / 20	$\sim$ 1 / 1	nm
New arc magnets	None	LER dipoles + HER all	
New beam pipes	LER/HER	LER/HER	
More RF stations?	Yes	No	
Damping Ring	e^+	$e^\pm$	
Rel. construction cost	100	$\sim$ 70	%
Rel. operation cost	100	$\sim$ 80	%
Luminosity	4	8 (*)	10^{35}

(*) without crab waist

Y. Ushiroda @ HINTS

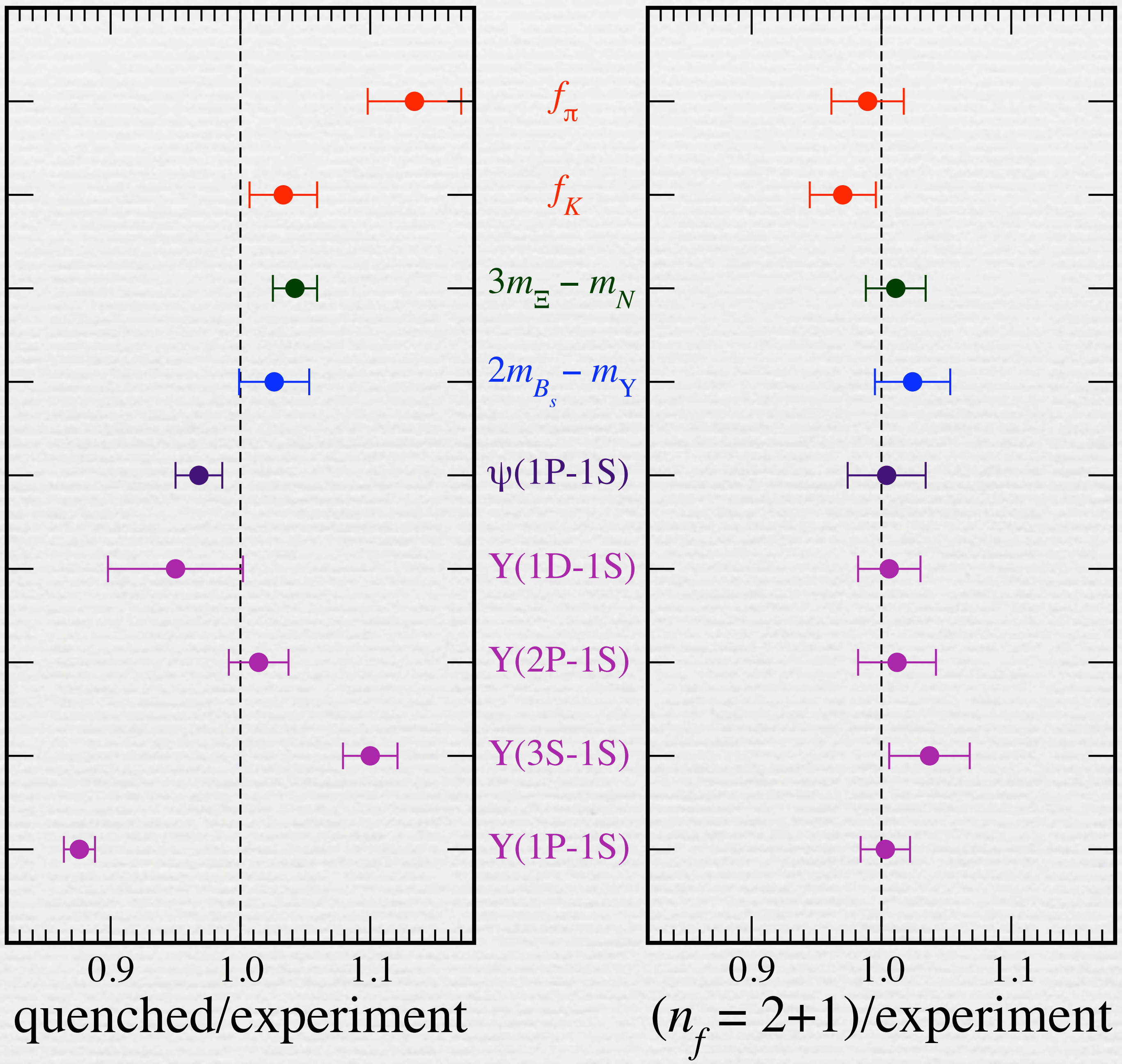
Lattice QCD

Lattice Status

- 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….

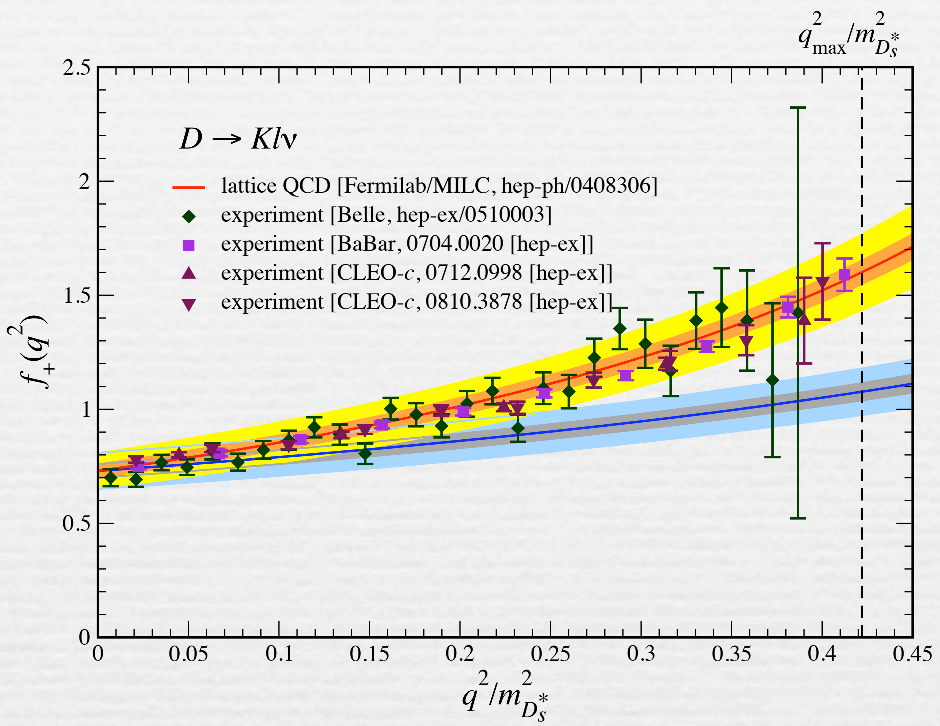
2+1 Sea Quarks!

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

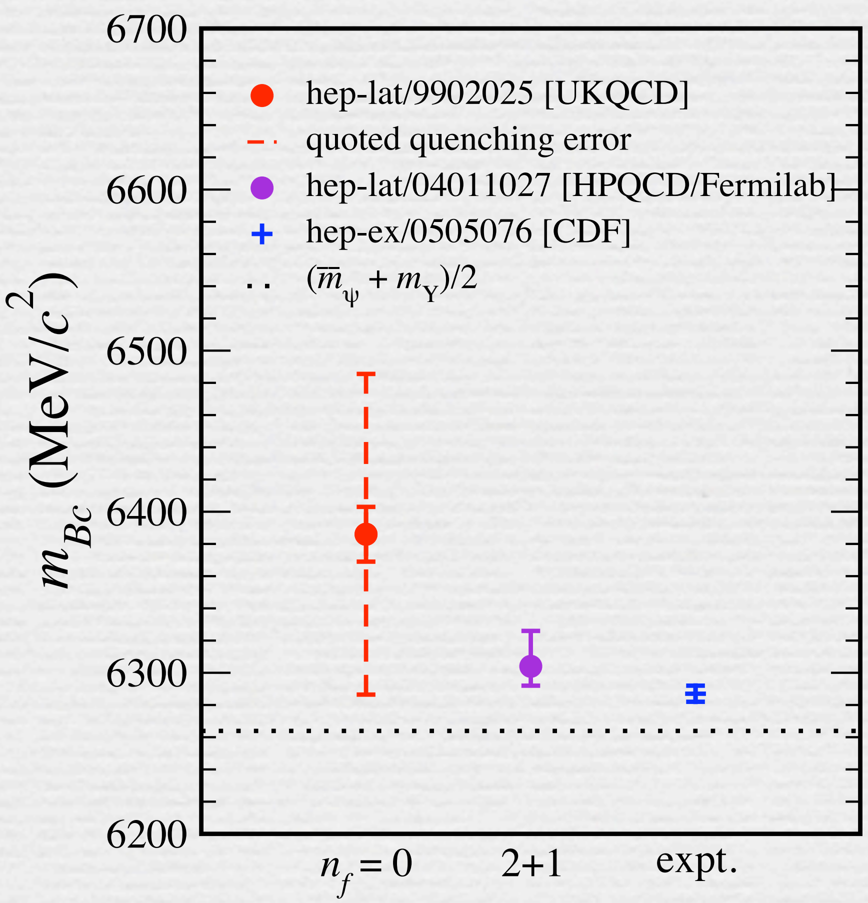
Predictions

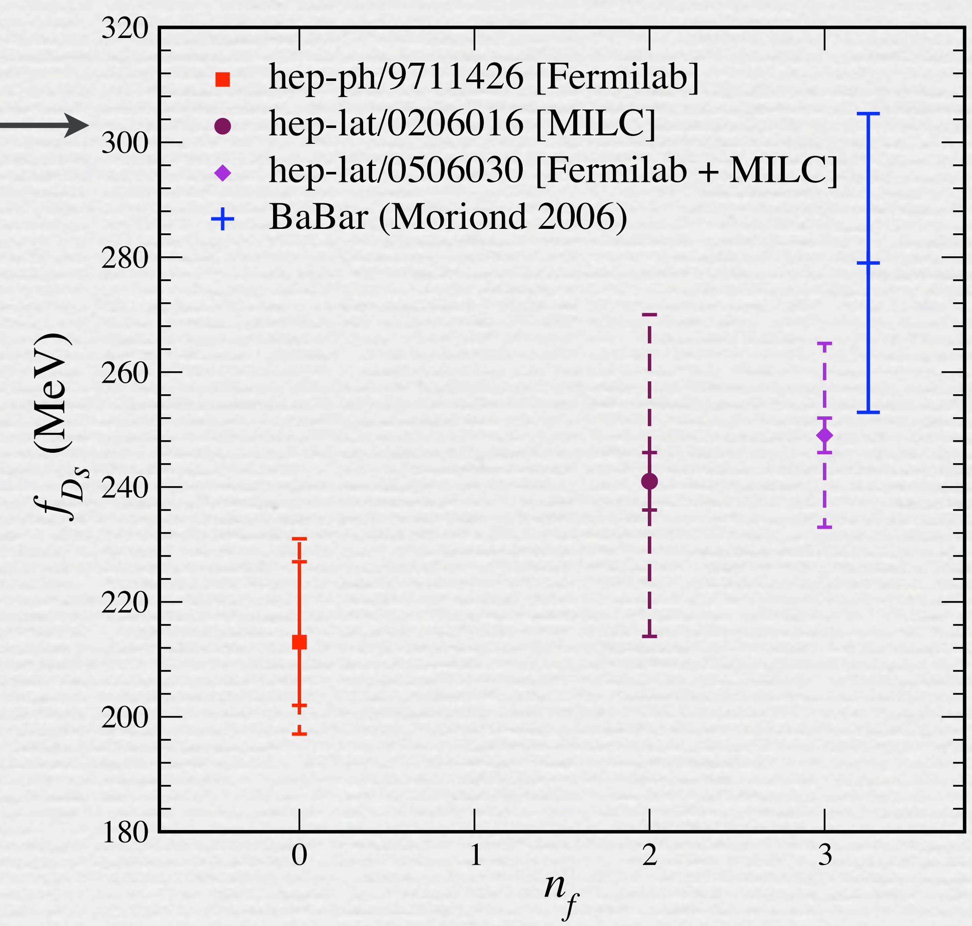


- Semileptonic form factor for $D \to Kl\nu$
- Mass of B_c meson
- Charmed decay constants

2004

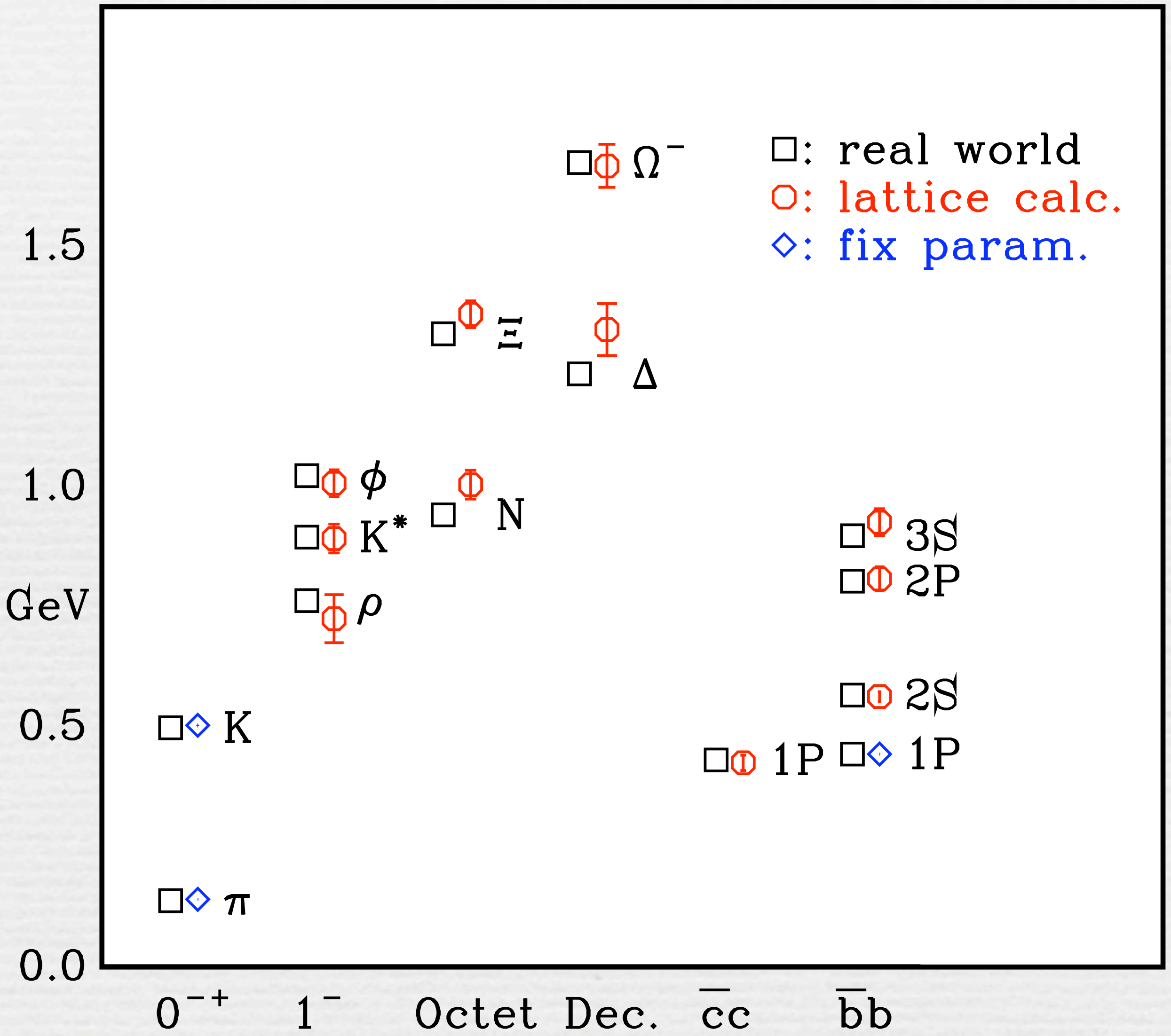
2005





Hadron Spectrum 1

MILC Col'n, *PRD* **70**, 094505 (2004); arXiv:0903.3598



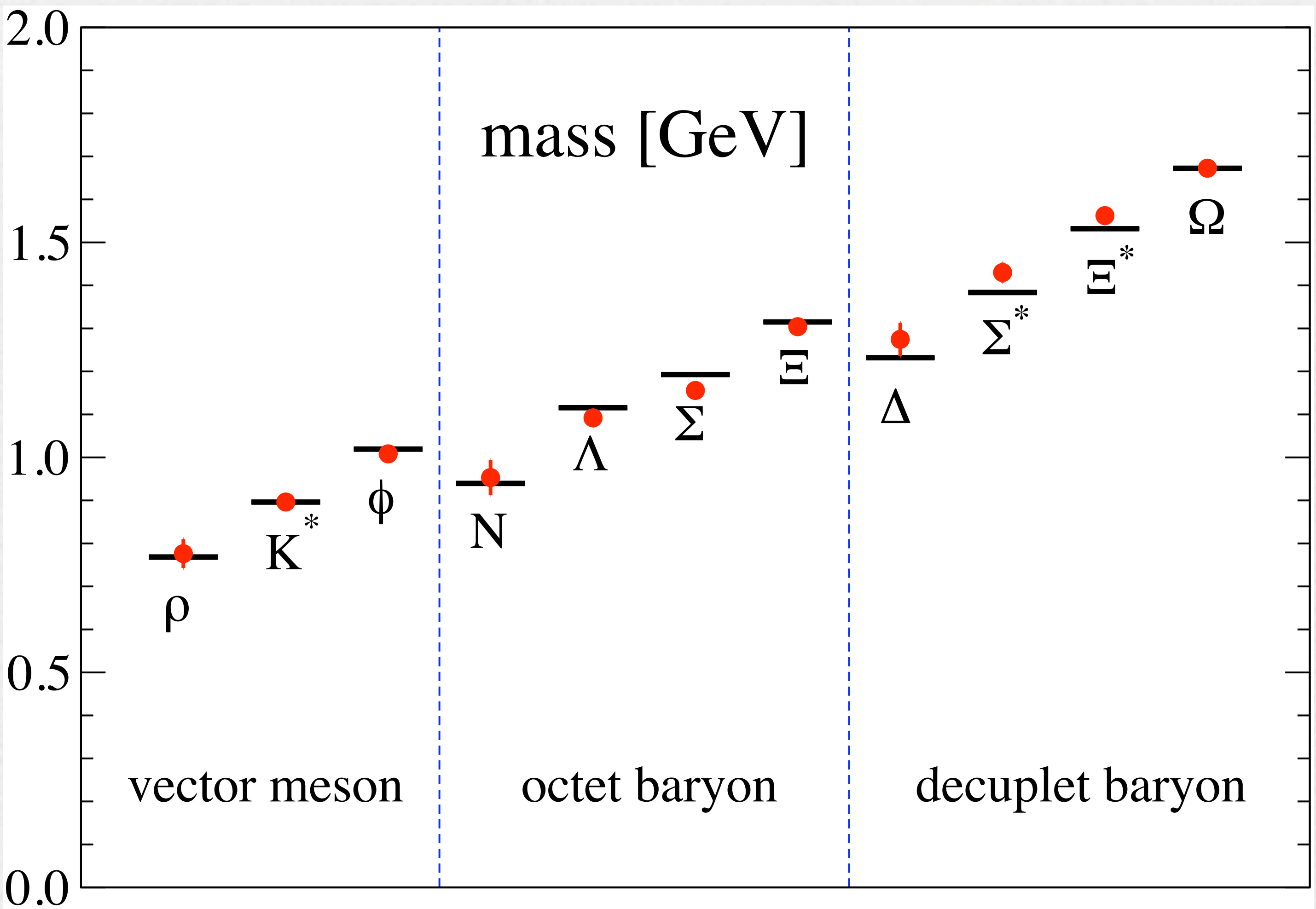
- a = 0.12 & 0.09 fm
- O(a^2) staggered
- FAT7 smearing
- $2m_l < m_q < m_s$
- π, *K*, Υ(1P) input

QCD postdicts the low-lying hadron masses!

Hadron Spectrum 2

PACS-CS Collaboration, *PRD* **79**, 034503 (2009).

cf. earlier work by CP-PACS

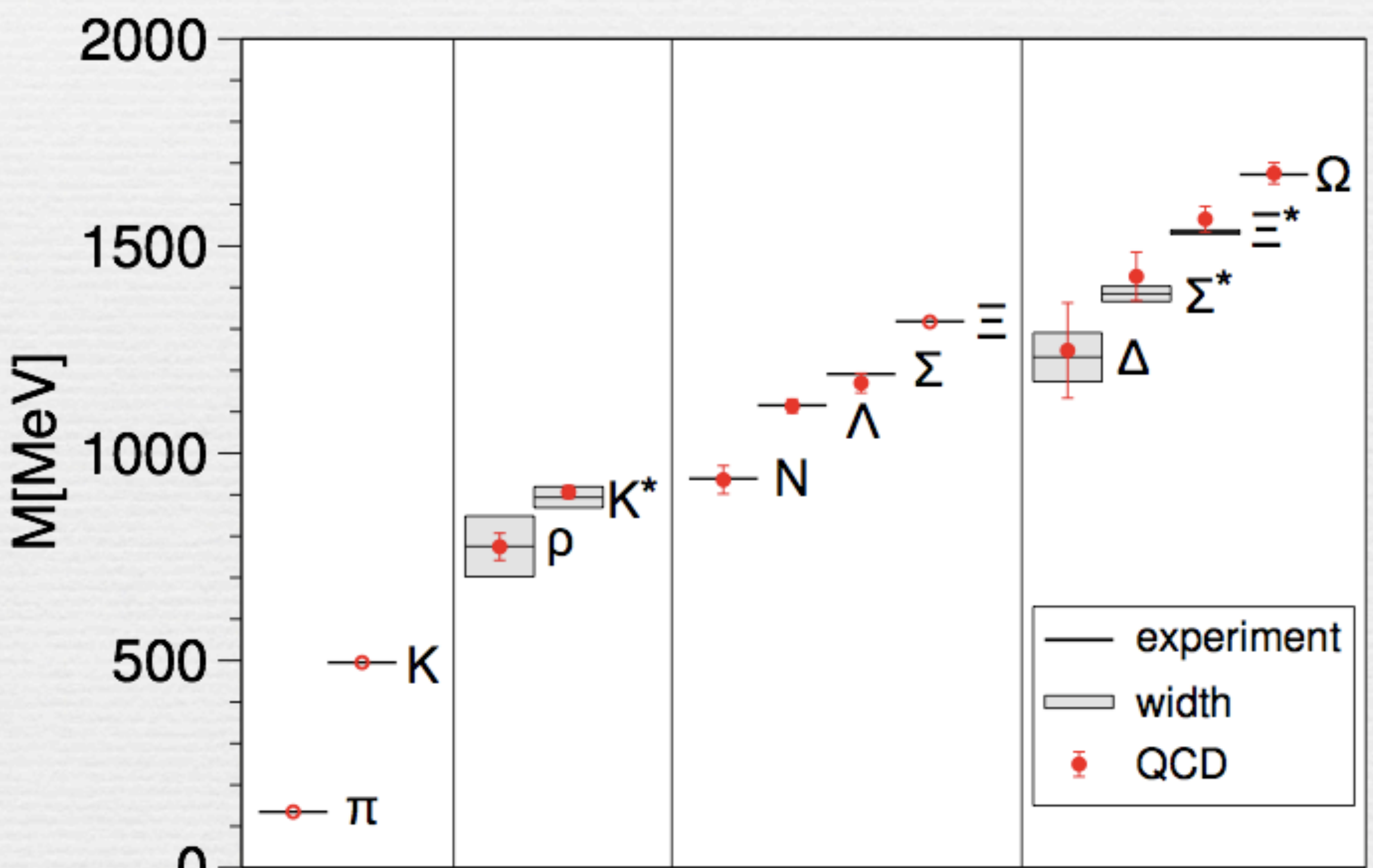


- a = 0.091 fm
- NP O(a) Wilson
- no smearing
- $m_q \approx 1.3 m_l$
- π, K, Ω input

QCD postdicts the low-lying hadron masses!

Hadron Spectrum 3

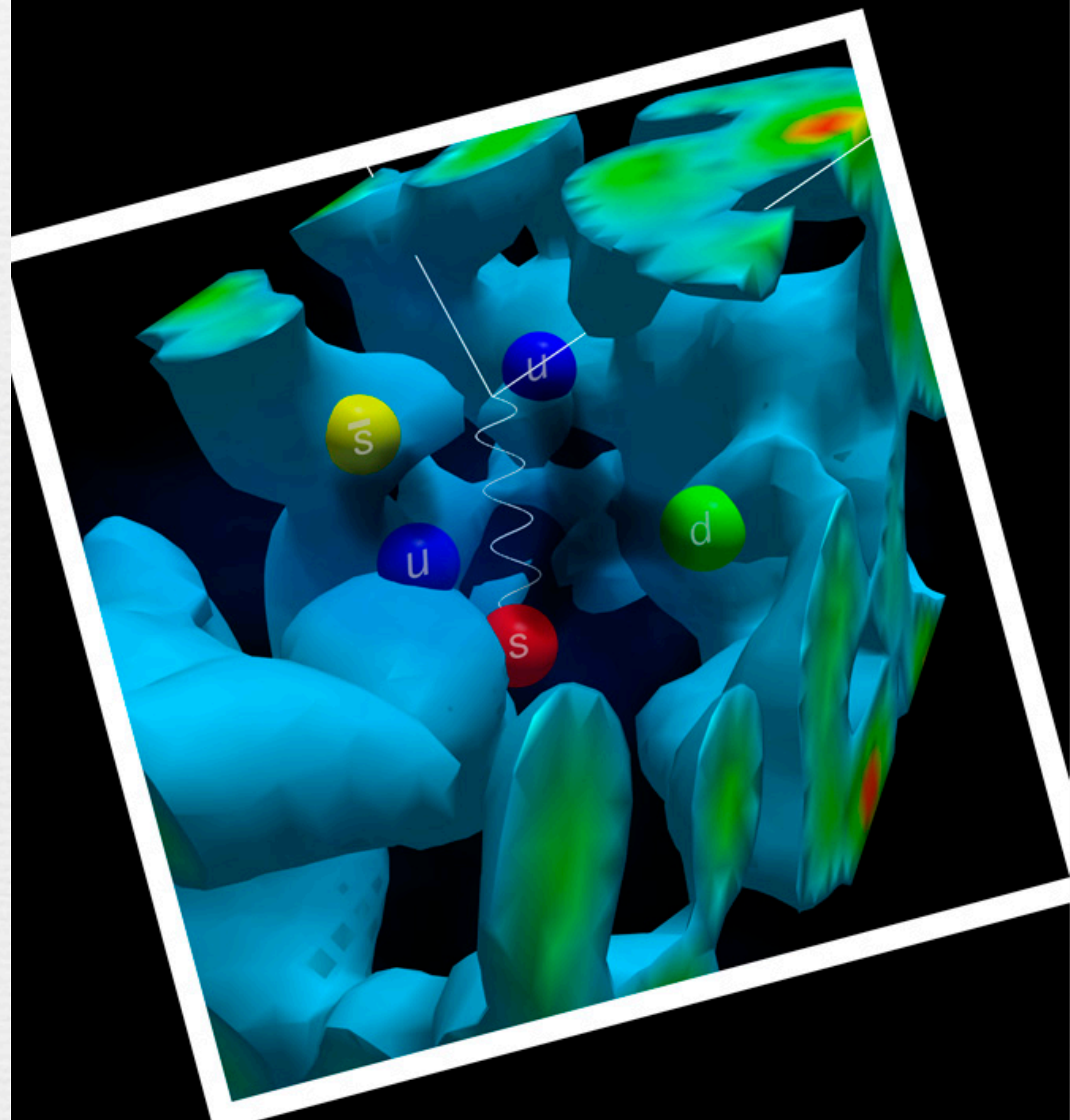
BMW Collaboration: *Science* **322**, 1224 (2008).



- a = 0.125, 0.085, & 0.065 fm
- tree O(a) Wilson
- 6× stout smearing
- $2m_l < m_q < 1.7m_s$
- π, K, Ξ input

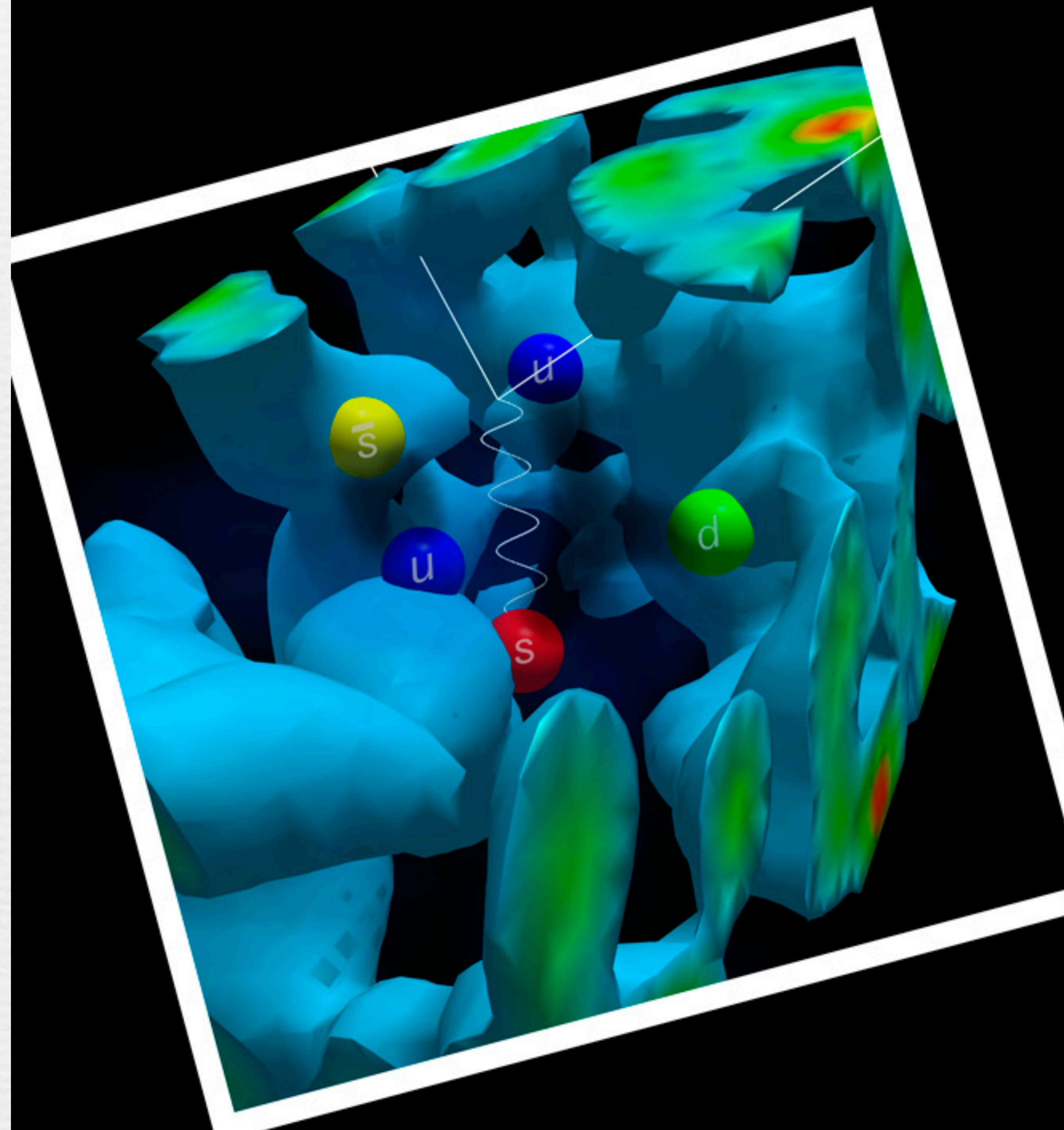
QCD postdicts the low-lying hadron masses!

$$m = E/c^2$$



$$m = E/c^2$$

The source of your weight problem is quantum chromodynamics



Quark Masses & α_s

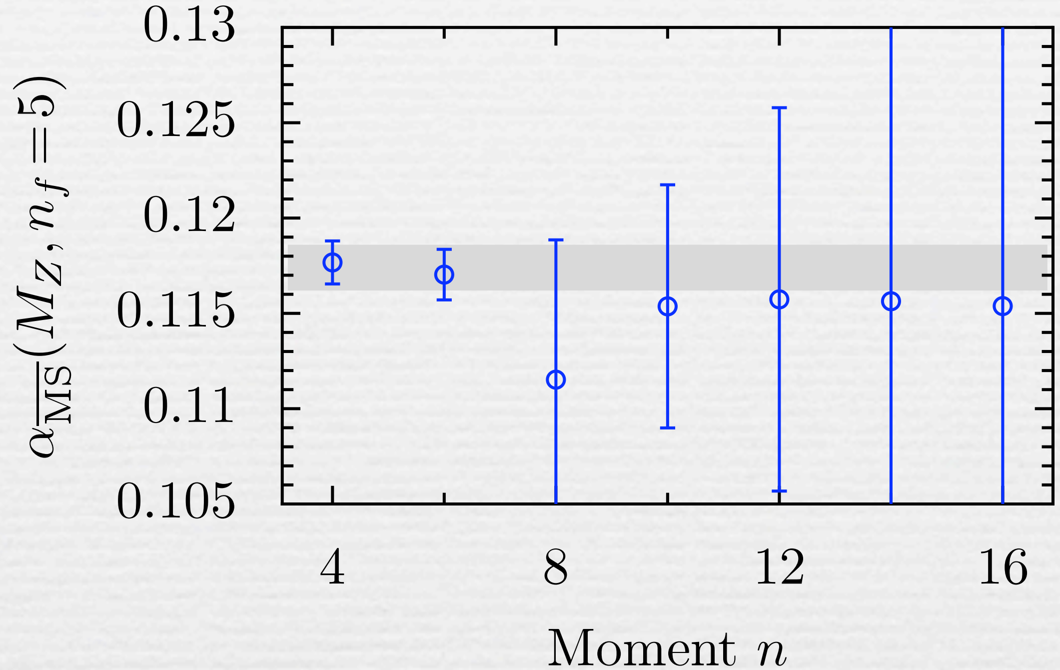
- Light quark masses (MILC+HPQCD):

$$m_u = 1.9 \pm 0.2 \text{ MeV},$$
$$m_d = 4.6 \pm 0.3 \text{ MeV},$$
$$m_s = 88 \pm 5 \text{ MeV}.$$

  with two-loop matching.

- Charmed quark mass [PT by Karlsruhe]:
  - $m_c(m_c)$ = 1.268(9) GeV [HPQCD lattice],
  - $m_c(m_c)$ = 1.268(12) GeV [e^+e^- data].

Strong Coupling α_s



- Charmonium moments:
  - $\alpha_s = 0.1174(12)$
- Wilson loops:
  - $\alpha_s = 0.1183(8)$, HPQCD, arXiv:0807.1687;
  - $\alpha_s = 0.1192(11)$, Maltman, arXiv:0807.2020;
  - $\alpha_s = 0.1185(9)$, PDG non-lat average (2008).

Assuming the SM:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \text{nuke } 0^+ \to 0^+ & K^+ \to \ell^+\nu & B \to \pi\ell\nu \\ \pi^+ \to \pi^0 e^+\nu & K \to \pi\ell\nu & b \to u\ell\nu \\ V_{cd} & V_{cs} & V_{cb} \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu \\ D^+ \to \ell^+\nu & D_s \to \ell^+\nu & B \to D\ell\nu \\ V_{td} & V_{ts} & V_{tb} \\ B_d^0 \leftrightarrow \bar{B}_d^0 & B_s^0 \leftrightarrow \bar{B}_s^0 & t \to Wb,\ Wb \to t \end{pmatrix}$$

trees

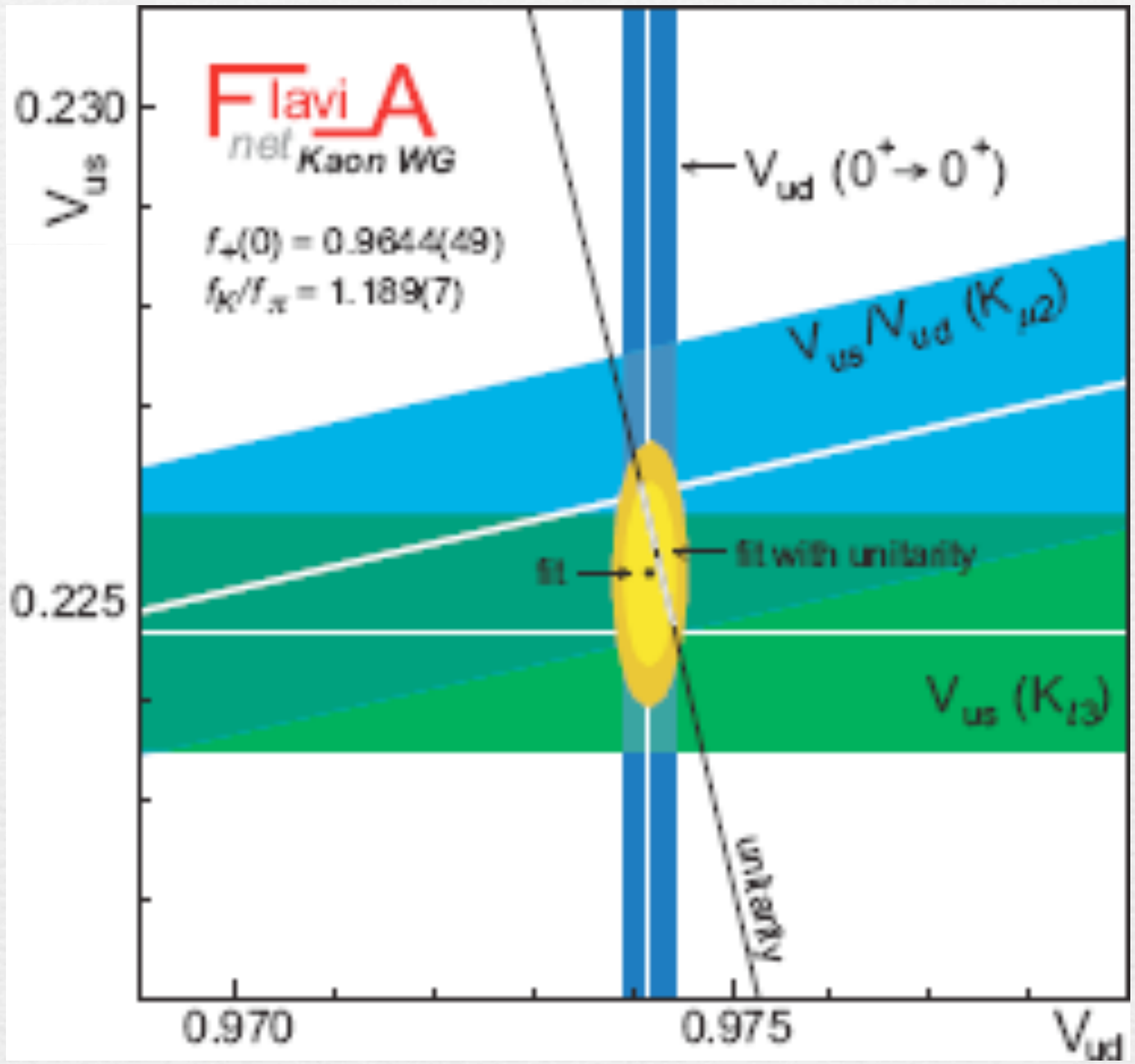
loops

no go

$|V_{us}|$

Flavianet Kaon WG: http://ific.uv.es/flavianet/

- V_{ud} from nuclear
- $f_+(0)$ from arXiv: 0710.5136 [RBC/UKQCD]
- f_K/f_π from arXiv: 0706.1726 [HPQCD]



$|V_{cb}|$

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 everything.

- Exclusive $B \to D^* l\nu$: (zero recoil) form factor:

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

- Unquenched lattice QCD calculation:

$$\mathcal{F}(1) = 0.921 \underset{\text{stats}}{\pm 0.013} \underset{g_{D^*D\pi}}{\pm 0.008} \underset{\chi\text{PT}}{\pm 0.008} \underset{\text{match}}{\pm 0.014} \underset{m_Q}{\pm 0.007}$$

$|V_{ub}|$

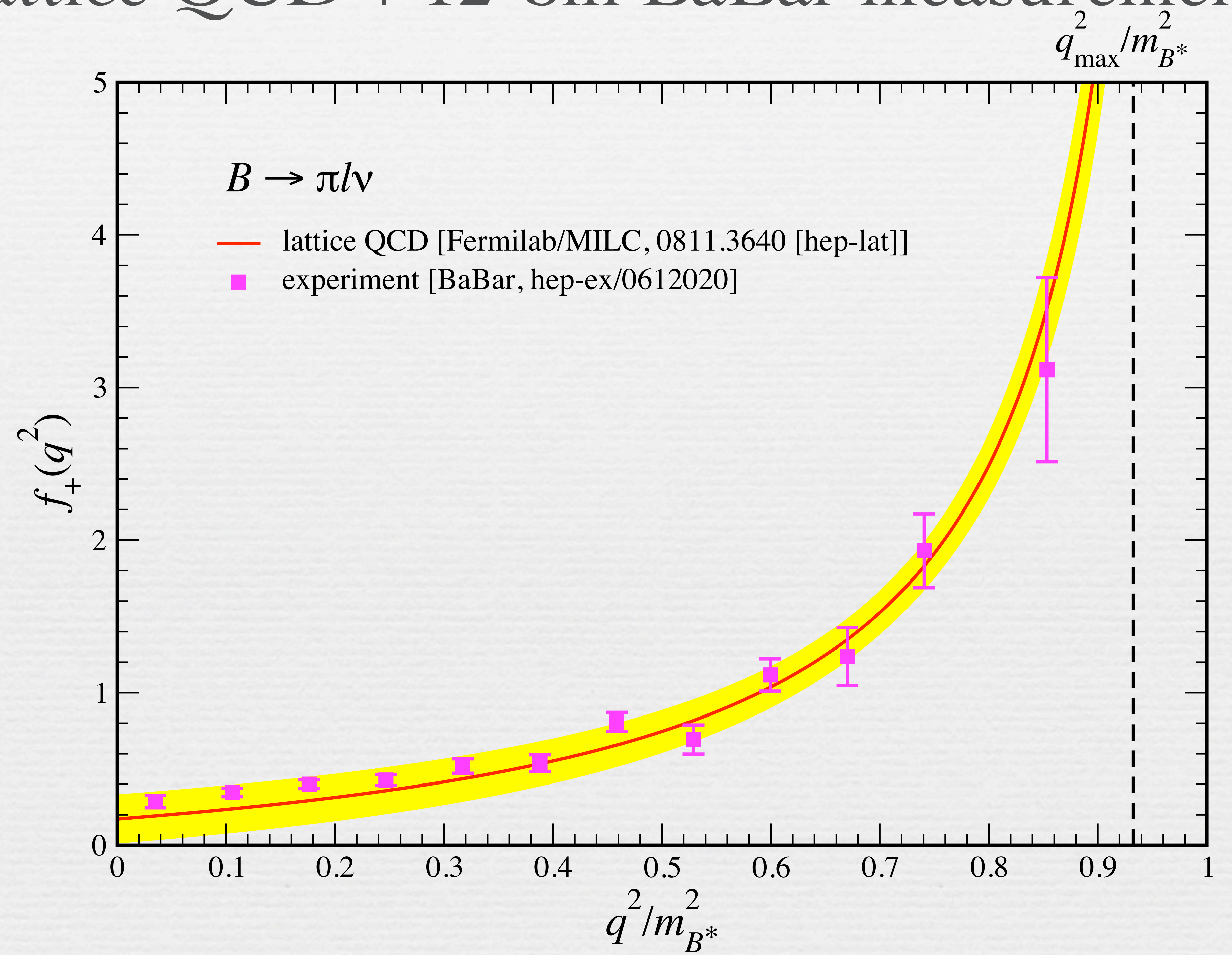
alia et Ruth Van de Water, arXiv:0811.3640

- $|V_{us}|$, $|V_{ub}|$, and $|V_{cb}|$ are the three real parameters of the CKM matrix.
- Exclusive $B \to \pi l \nu$: form factor $f_+(q^2)$

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

- Model-independent analysis of q^2 dependence.
- Combined z-fit with BaBar: $10^3 |V_{ub}| = 3.38(36)$.

Lattice QCD + 12-bin BaBar measurement.



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.

CKM

- With $|V_{us}|$, $|V_{ub}|$, & $|V_{cb}|$ from (semi)leptonic decays and γ from CP measurements, all of CKM fixed via tree-level decays:
  - need LHC*b* for γ;
  - need lattice QCD for $|V_{qr}|$;
  - need SuperB(elle) for $|V_{ub}|$;
  - exploit BES (like CLEO) for checks.

f_B and B_B

Gamiz *et al.* [HPQCD], arXiv:0902.1815

- Recent 2+1 calculation of neutral B mixing:

$$f_{B_s} = 231 \pm 15 \text{ MeV} \qquad f_{B_s}\sqrt{B_{B_s}} = 266 \pm 18 \text{ MeV}$$

$$f_{B_d} = 190 \pm 13 \text{ MeV} \qquad f_{B_d}\sqrt{B_{B_d}} = 216 \pm 15 \text{ MeV}$$

$$\xi = 1.258 \pm 0.033$$

- Decay constants 1σ lower than in hep-lat/0507015, stemming from 2nd, finer lattice spacing.

- Fermilab/MILC (Lat'08 preliminary):

$$f_B = 195 \pm 11 \text{ MeV}, \; f_{B_s} = 243 \pm 11 \text{ MeV}.$$

Talk at
5:30 pm

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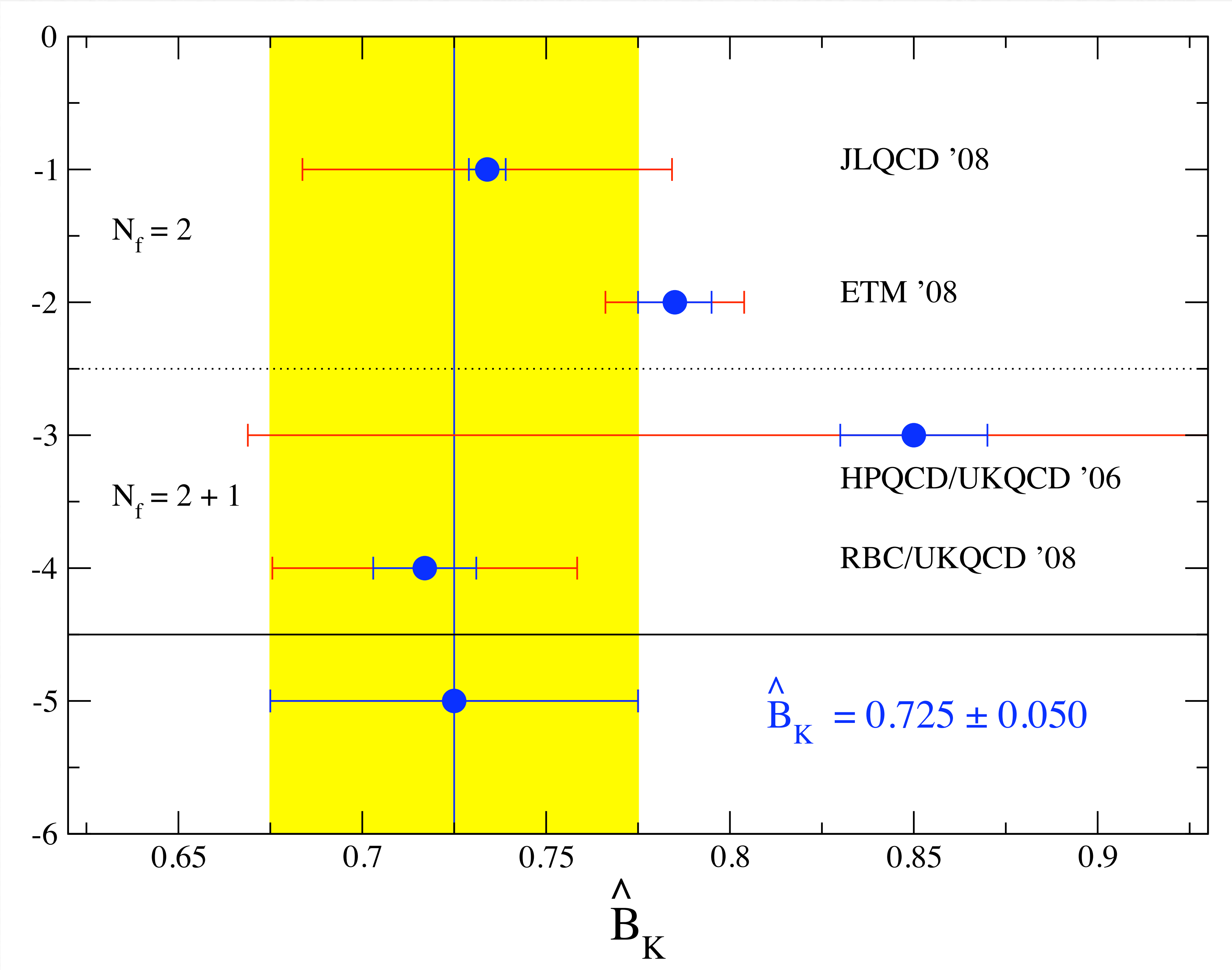
B_K



Lellouch
Lattice 2008

Sets width of
lime green
hyperbola

Note on $n_f = 2$

- This means that strange sea quarks are omitted.
- Sometimes it makes no difference; sometimes it can change results by 5% or so.
- Sometimes an error is assigned; sometimes not.
- Several authors in the latter camp advise us to "interpret results as $n_f = 2$."

Flavor$\otimes$LHC

Terascale Models

- The past 25 years of models have been guided by aesthetics:
  - hierarchy and fine-tuning problems;
  - technicolor, supersymmetry, extra dimensions.
- The next 25 years of models will, presumably, be guided by pragmatism:
  - new particles are seen: how do they couple?

- Paradigm of studies: take a model off the shelf; study it; ask whether it could be observed.

- Paradigm of experiments: observe & measure phenomena; study them; build simple *ad hoc* models.

- I'll be astonished if an off-the-shelf model can be matched up to observation.

New Physics & Flavor

- Given a non-Standard particle's coupling to Standard matter, you will want to know if there are related flavor-changing interactions.
- Calculate how it contributes to decays and neutral-meson mixing.
- Expect trouble: a generic TeV particle leads to contributions that are much too big:
  - the "new-physics flavor problem."

- The new-physics flavor problem stems from the SM's many suppression factors:
  - α_{EW}, CKM, $(m_q/m_W)^2$, loops, GIM, ...
- Particles of mass ~1 TeV must be just about as suppressed.
- Need mass of ~10^4 TeV to get away with generic coupling.

HINTS

http://belle.kek.jp/hints09/

- Several "hints," effects of 2 or more have appeared in the flavor sector, *e.g.*:
  - $(\Delta\Gamma_{Bs}, \phi_s)$ [DØ, CDF; UTFit];
  - $K\pi$ CP asymmetries [Hou: 4th gen?];
  - $\sin 2\phi_1$ tension [Lunghi, Soni];
  - V_{ub} tension [inc vs. exc: V+A currents?];
  - leptonic decays $B \to \tau\nu$ and $D_s \to l\nu$ ($l = \tau, \mu$).

Leptonic Decays

- Proceed by annihilation into W.
- Branching fraction (here D_s):

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

- Experiments usually quote decay constant f:

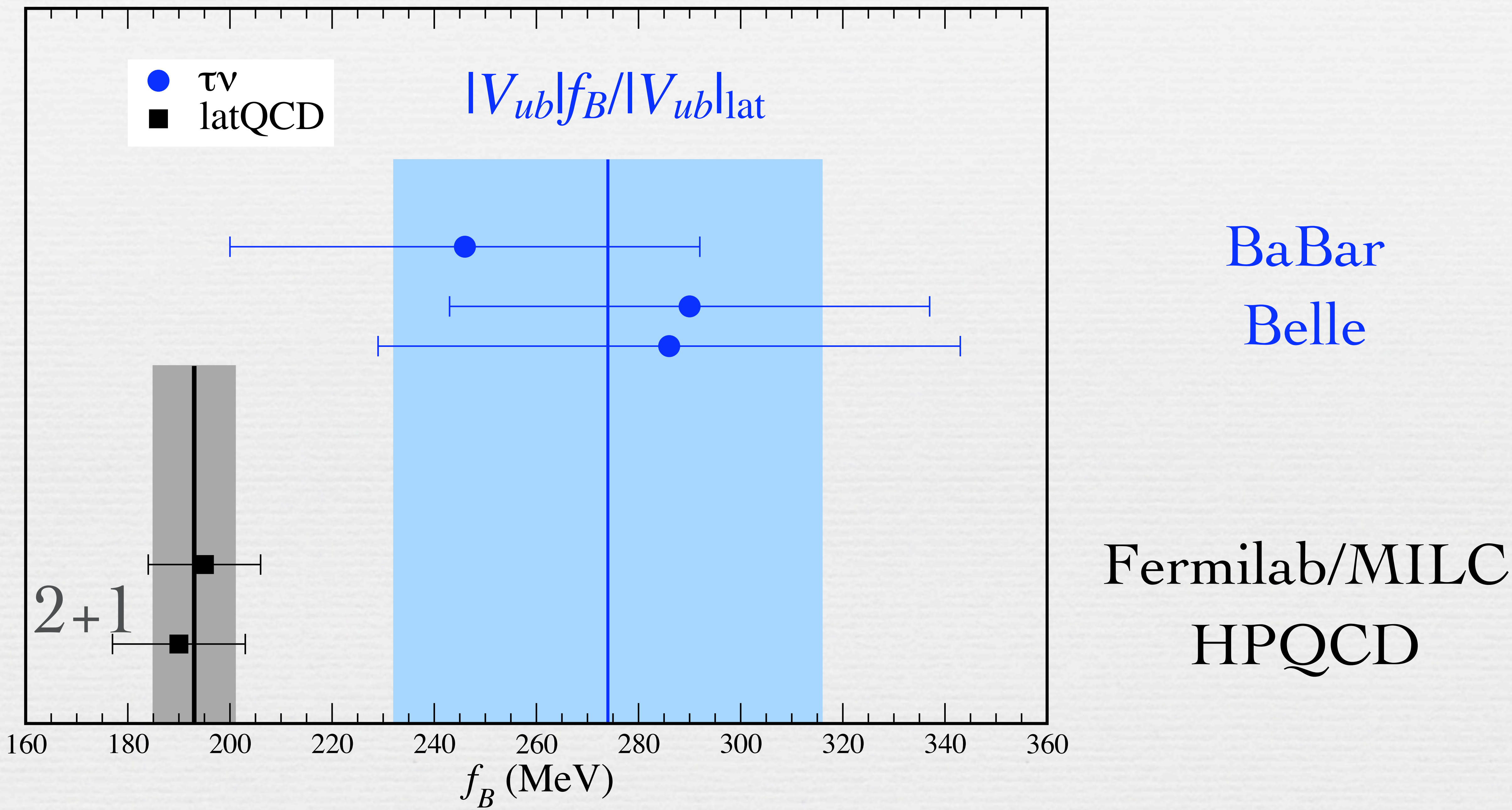
$$\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s\rangle = i f_{D_s} p_\mu.$$

or $V_{\mathrm{CKM}} f$.

$B \to \tau\nu$

- Assuming the SM, $|V_{ub}|f_B = 0.925 \pm 0.101$ MeV.
- With $|V_{ub}|$ from the exclusive method, this implies $f_B = 274 \pm 42$ MeV.
- Rather higher than LQCD avg: $f_B = 193 \pm 8$ MeV.
- What could explain the discrepancy?
- A non-Standard charged, recently observed (in the theoretical literature).

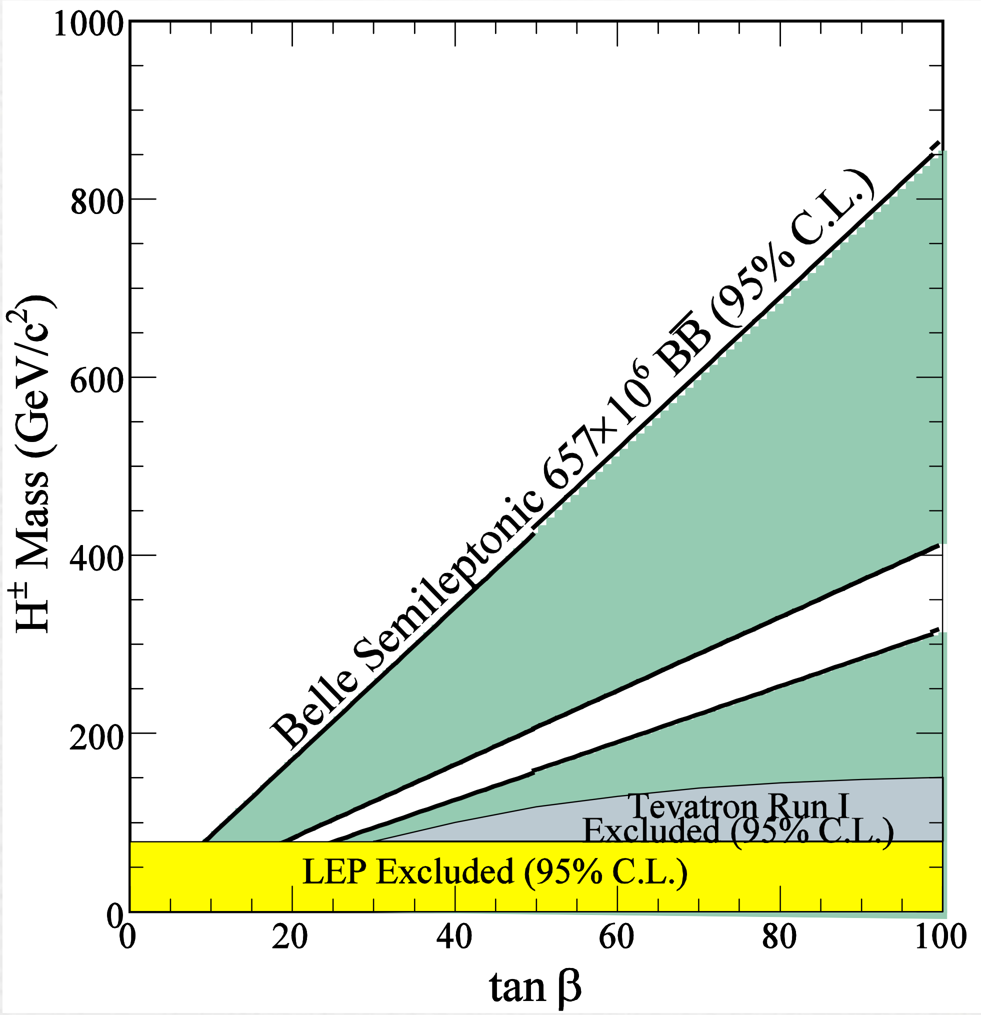
A graphical view:



a 1.9σ discrepancy.

Exclusion Plot

- Charged Higgs: multiply BR with $[1 - \tan^2\beta\ (m_B/m_H)^2]^2$
- Exclude part of $(\tan\beta, m_H)$ plane.
- Non-standard $H^{\pm}$ overwhelms $W^{\pm}$.

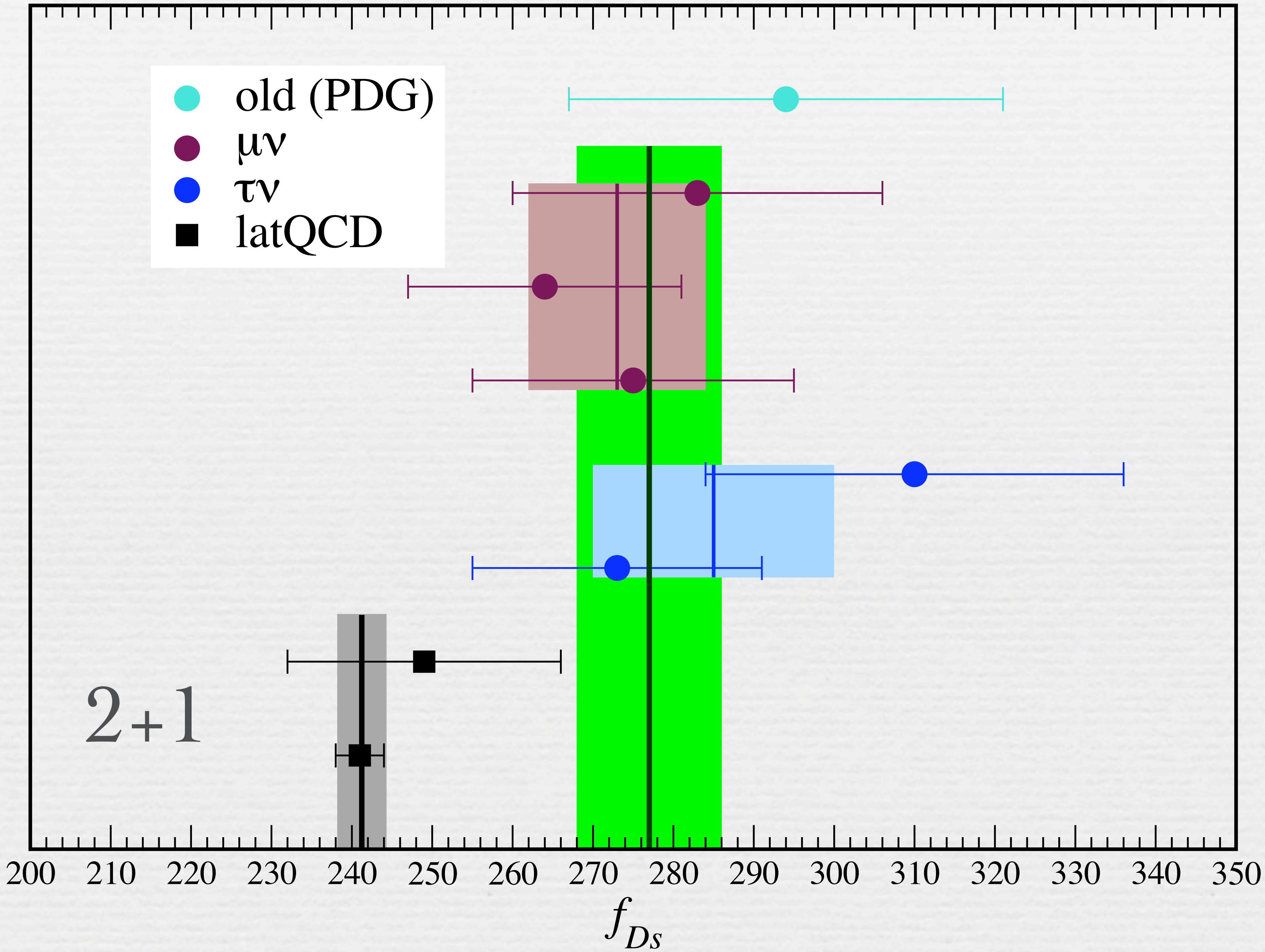


- Alas, this doesn't make any sense (to me).
- The interference in Model II is destructive, so this model is *not* a natural candidate.
- If the "observation" of the particle had been in an experiment, it would not come equipped with a full-blown model.
- You would (wouldn't you?) look for a way to couple $H^{\pm}$ that isn't so extreme.

$D_s \to l\nu$

- $D_s \to l\nu$ 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)...



χ^2/dof = 0.67

BaBar

CLEO

Belle

CLEO πν

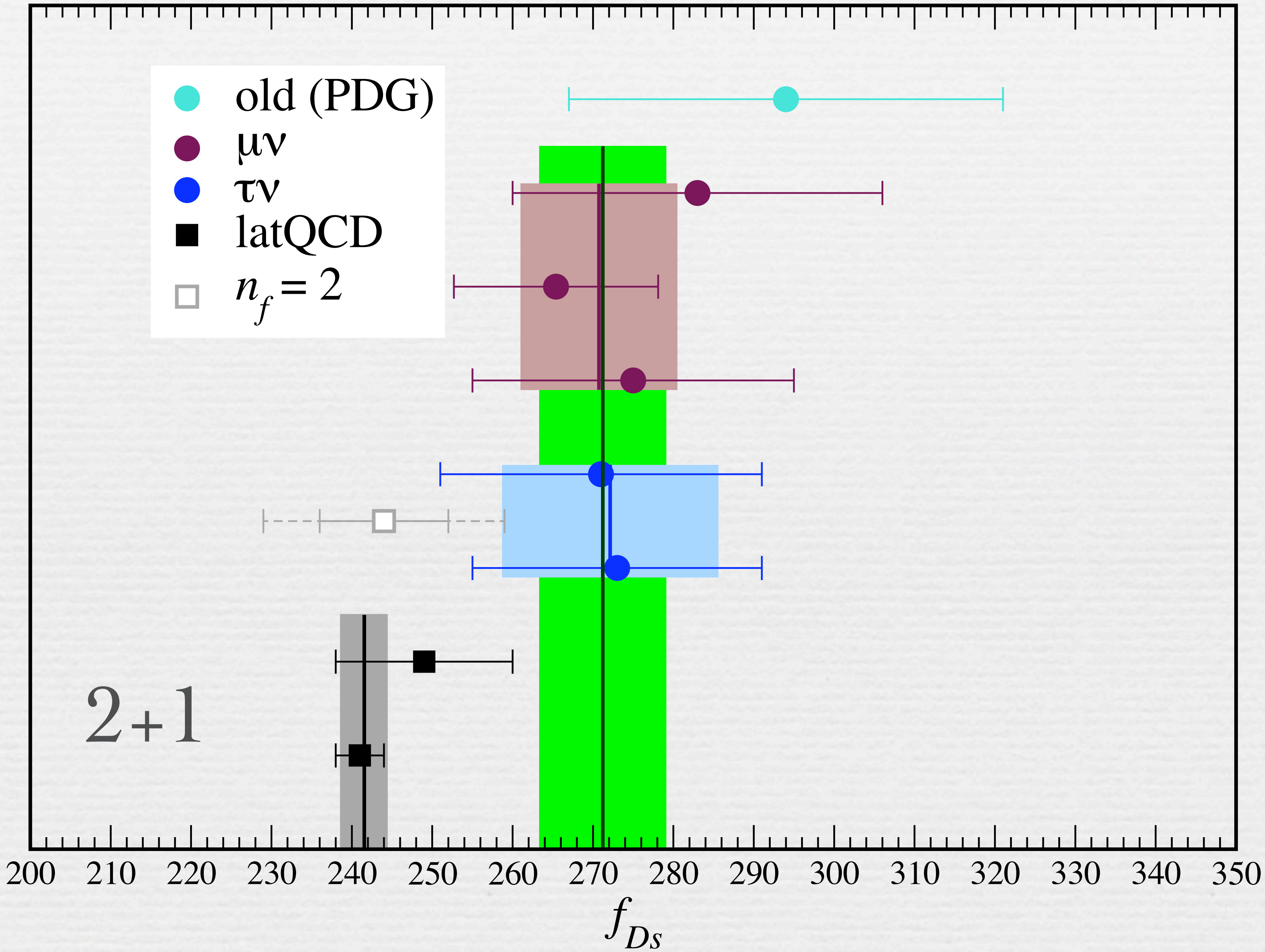
CLEO eνν

Fermilab/MILC

HPQCD

a 3.8σ discrepancy, or 2.7σ ⊕ 2.9σ.

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



χ^2/dof = 0.13

BaBar

CLEO

Belle

CLEO πν

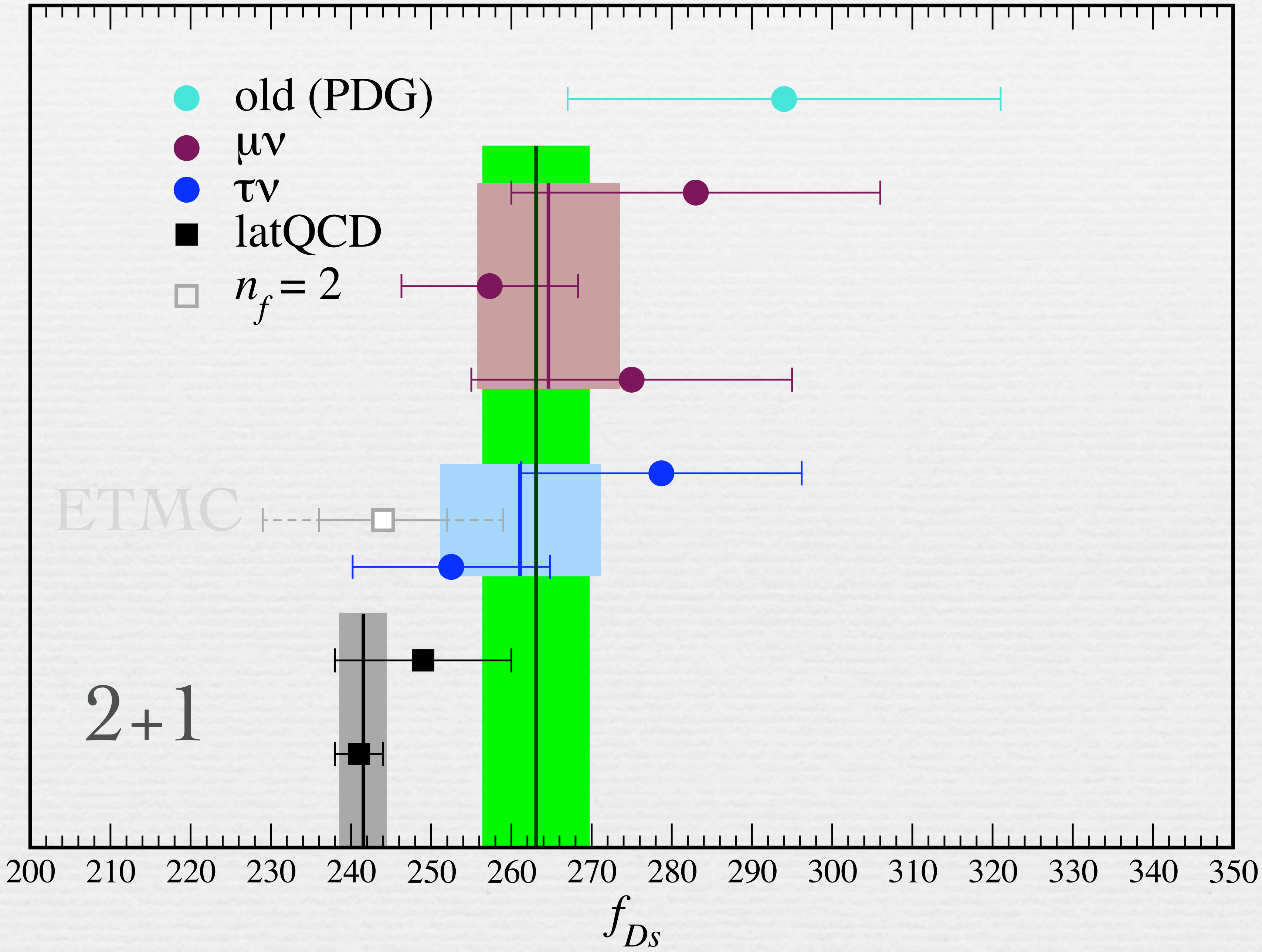
CLEO eνν

Fermilab/MILC

HPQCD

a 3.6σ discrepancy, or 2.9σ ⊕ 2.2σ.

With CLEO's papers of January 12, 2009



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

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 $|V_{cs}| > 1.1$.
- Unlikely.

Necessary Condition

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

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

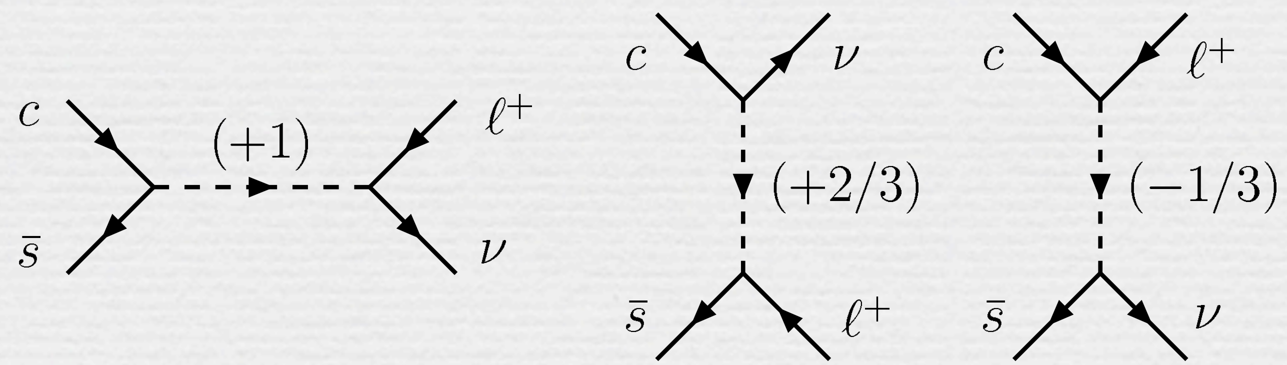
- In rate, replace

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

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

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

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

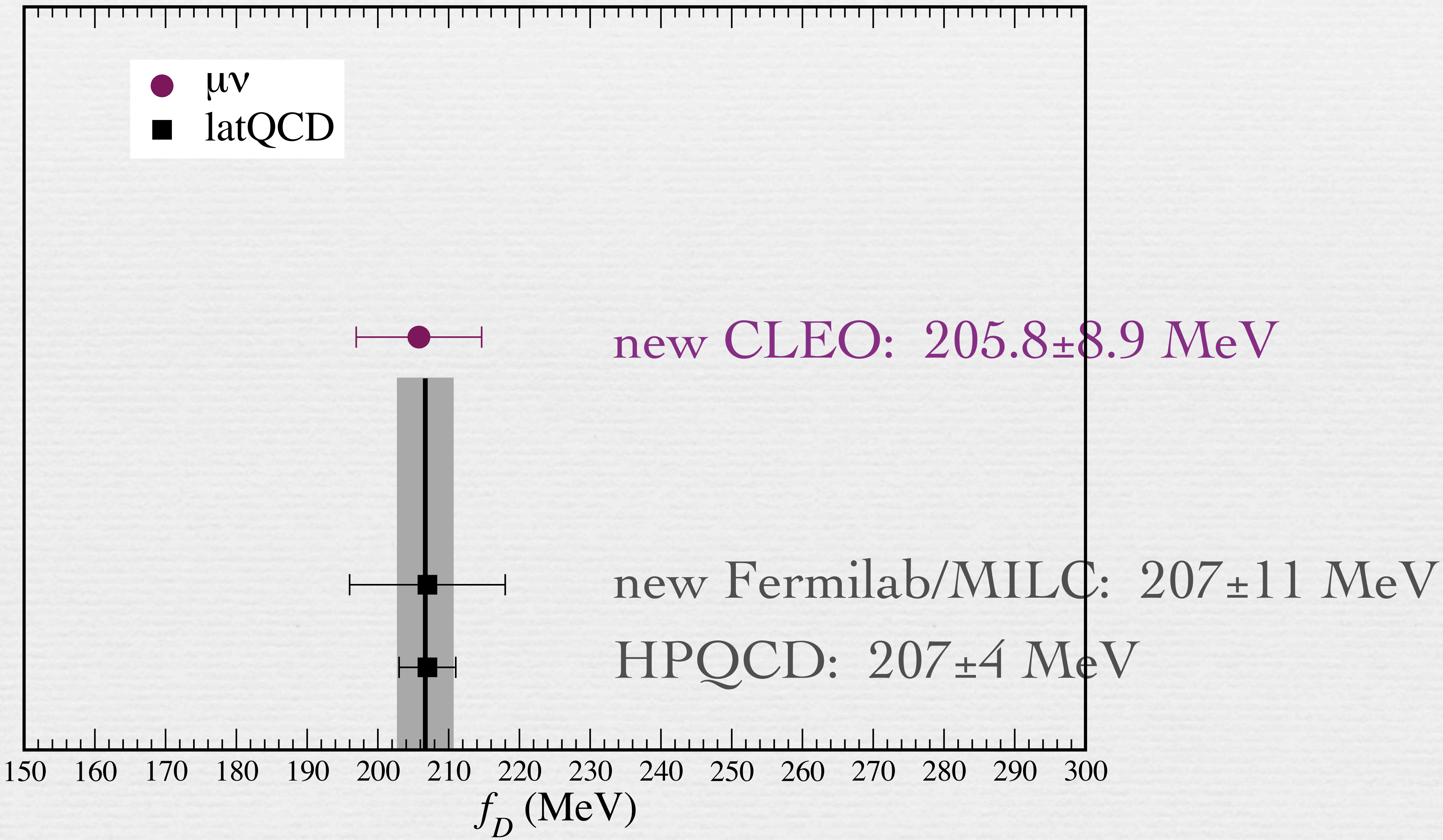
(mass-eigenstate basis) leading to

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

- 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.

- 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 +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:

$$\kappa_{2l}(\bar{c}_L l_L^c - \bar{s}_L \nu_L^{lc})\tilde{d} + \kappa'_{2l}\,\bar{c}_R l_R^c \tilde{d} + \mathrm{H.c.}$$

(an interaction in R-violating SUSY), with

$$C_A^l = \tfrac{1}{4}|\kappa_{2l}|^2, \qquad C_P^l = \tfrac{1}{4}\kappa_{2l}\kappa'^{*}_{2l}.$$

- If $|\kappa'_l/\kappa_l| \ll m_l m_c / m_{D_s}^2$, independent of lepton, or if $\kappa'_l \propto m_l$, then the interference is constructive and creates the same-sized deviation for $\mu\nu$ and $\tau\nu$.

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

Outlook

- We’ve all been waiting, since grad school, for the LHC to change our lives.
- It should also change the way we think about flavor physics:
  - LHC particles are in the loops, perhaps even in the trees, of flavor transitions.
- Likewise, deviations in flavor transitions can point the way to LHC searches.

- It would have been nice to have a high-energy lepton collider in conversation with LHC.

- Barring that, flavor experiments are willing and useful alternatives.

- Need to know SM flavor: lattice QCD will be crucial.

- It may take 20 years to sort it out.