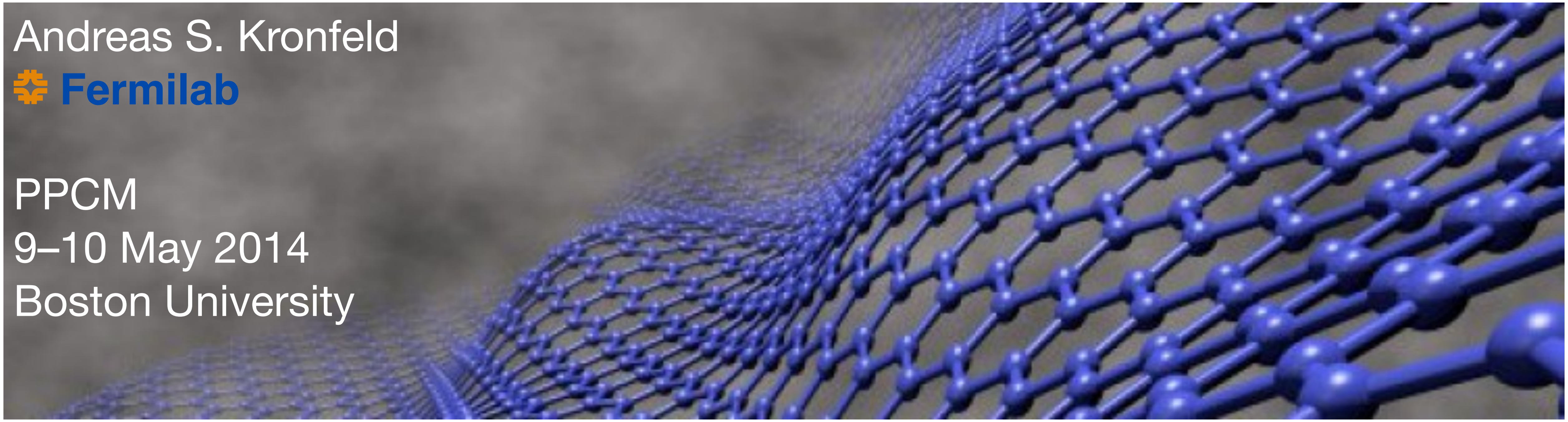
Massive Excitement in QCD and Beyond



Andreas S. Kronfeld
Fermilab

PPCM
9–10 May 2014
Boston University

Aim of this talk

- Provide a survey of results about QCD, obtained using numerical lattice gauge theory, that are both
    - quantitatively impressive and/or qualitatively noteworthy.
- Some quoted results have replaced ignorance, guesses, and beliefs with scientific knowledge.
- Others aid the interpretation of experiments or observations in particle physics, nuclear physics, and astrophysics.
- Examine whether other non-Abelian gauge theories could break electroweak symmetry.

Quantum Chromodynamics

- The most perfect theory—asymptotic freedom.
- Triumph of reductionism: quark model ⊕ parton model ⊕ color = QCD.
- Multi-scale problem: m_u, m_s, M_π, M_K, Λ_QCD, m_c, m_b, m_t; Q^2; a^{-1}; L^{-1}.
- Rich in symmetry: C, P, T; chiral symmetry, heavy-quark symmetry.
- Rich in emergent phenomena: hadron masses, chiral symmetry breaking, phase transitions, atomic nuclei ...
    - ... requiring nonperturbative methods (lattice gauge theory) and a full exploitation of symmetries, asymptotic freedom, *etc*.

Asymptotic Freedom

Politzer, *PRL* **30** (1973) 1346;
Gross, Wilczek, *PRL* **30** (1973) 1343

- At short-distances, the force in QCD looks similar to QED:

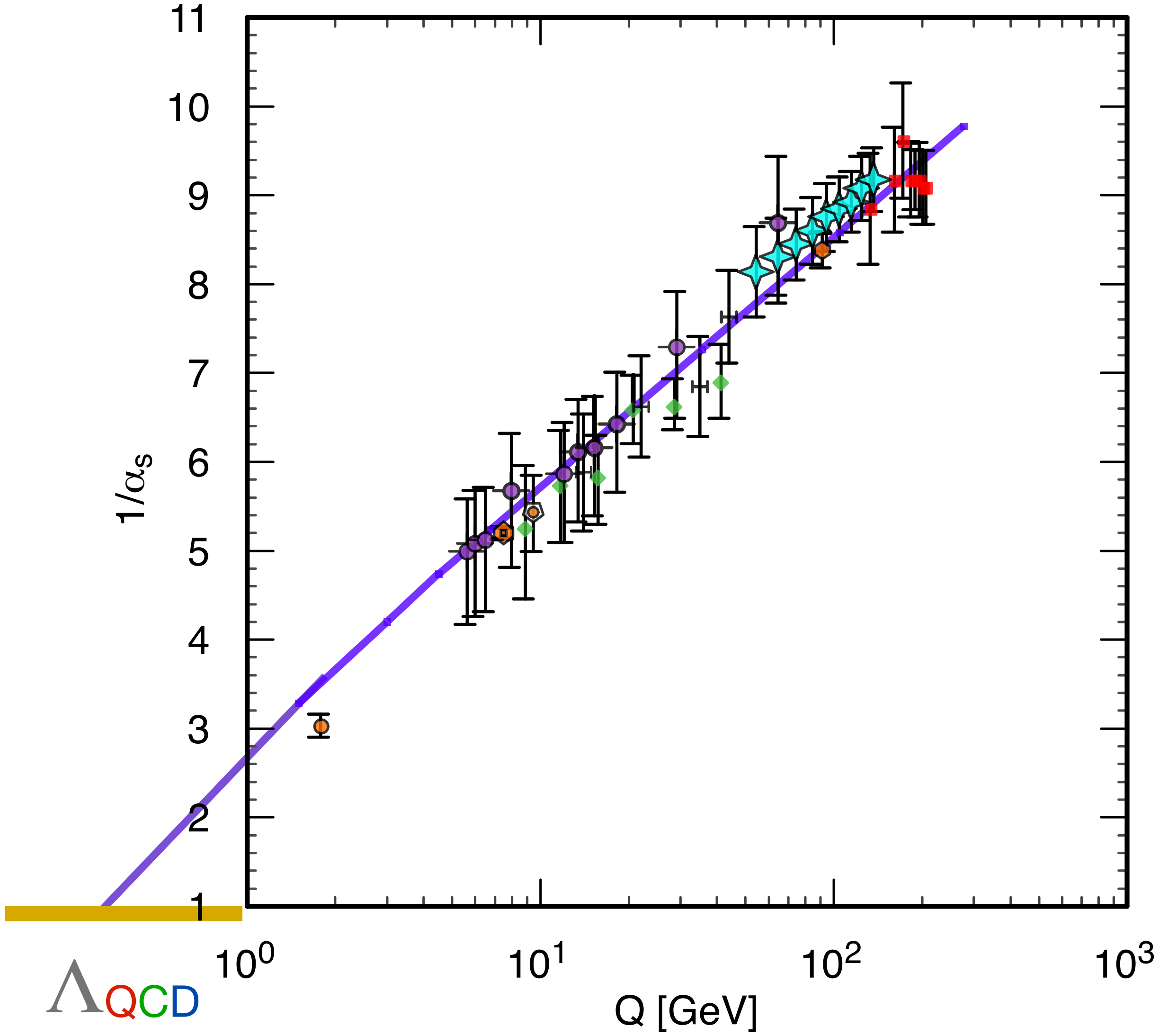
$$F(r) = -\frac{4}{3}\frac{\alpha_s(1/r)}{r^2}$$

where the 4/3 is a color factor.

- The key difference is that virtual gluons reduce the effective α_s at short distances (high energies).

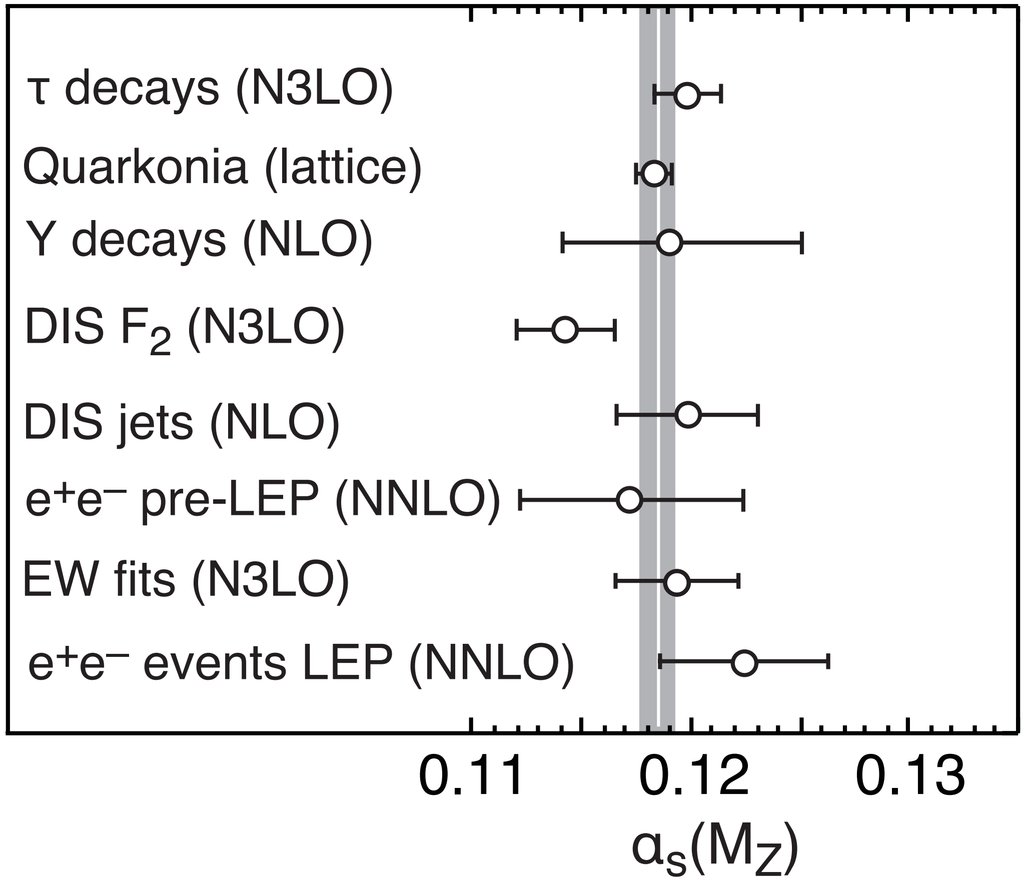
- Verified in experiment.

- Relates α_s to a physical scale, Λ_{QCD}.



ASK & Quigg, arXiv:1002.5032

QCD of hadrons = QCD of partons



Bethke, arXiv:0908.1135

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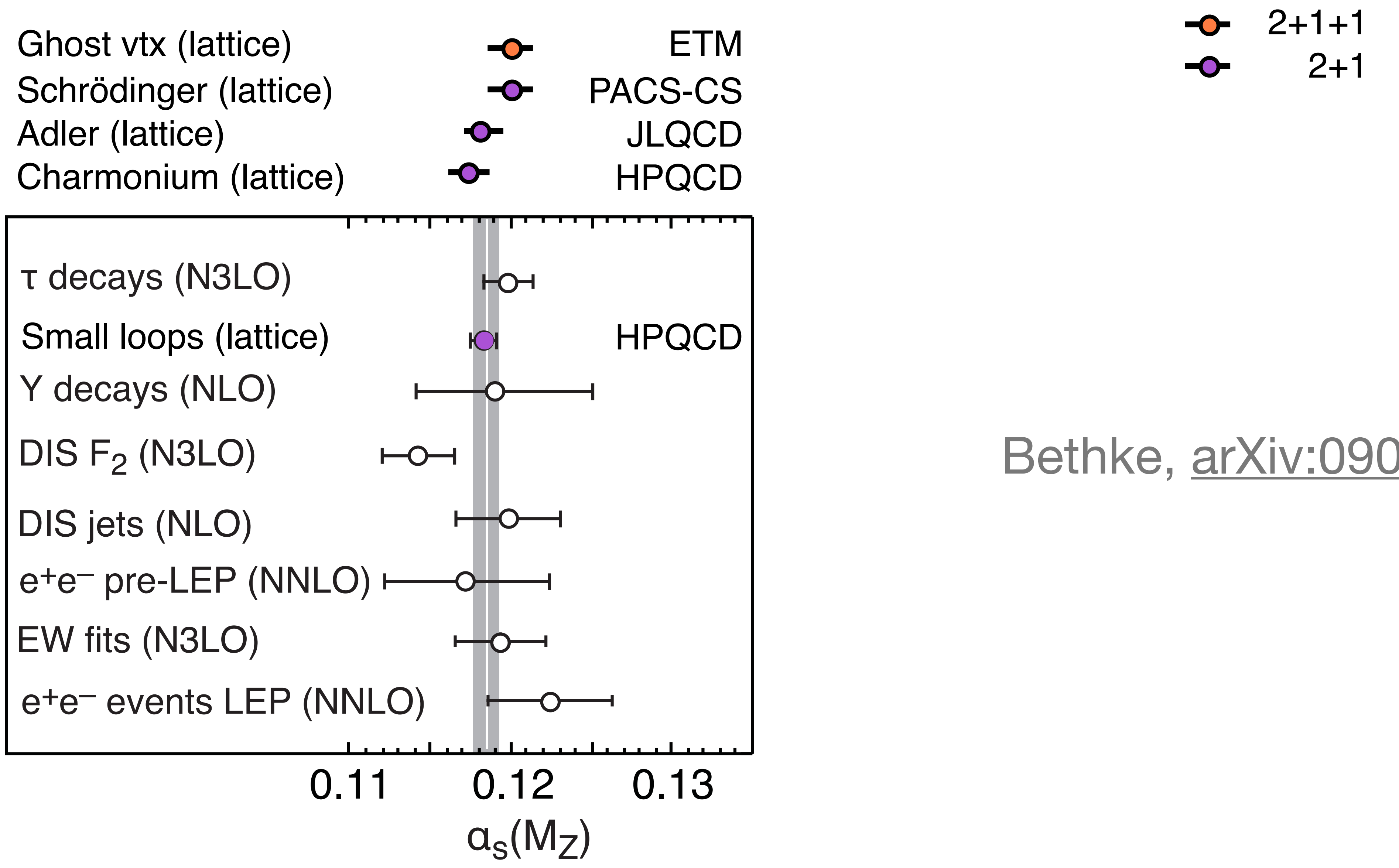


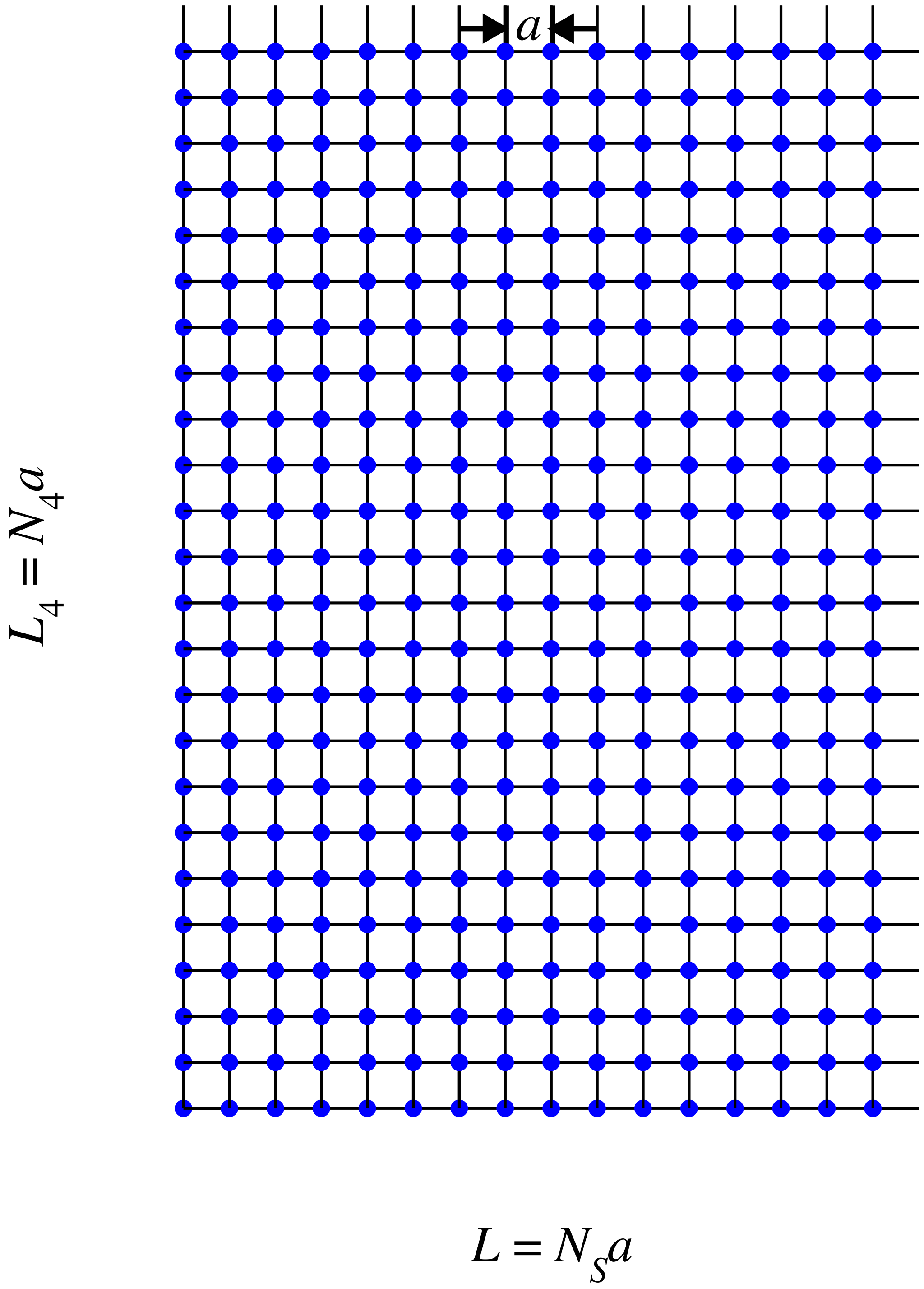
Bethke, arXiv:0908.1135

Lattice Gauge Theory

K. Wilson, *PRD* **10** (1974) 2445

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

- Infinite continuum: uncountably many d.o.f. (⇒ UV divergences);
- Infinite lattice: countably many; used to define QFT;
- Finite lattice: finite dimension ~ 10^8, so compute integrals numerically.



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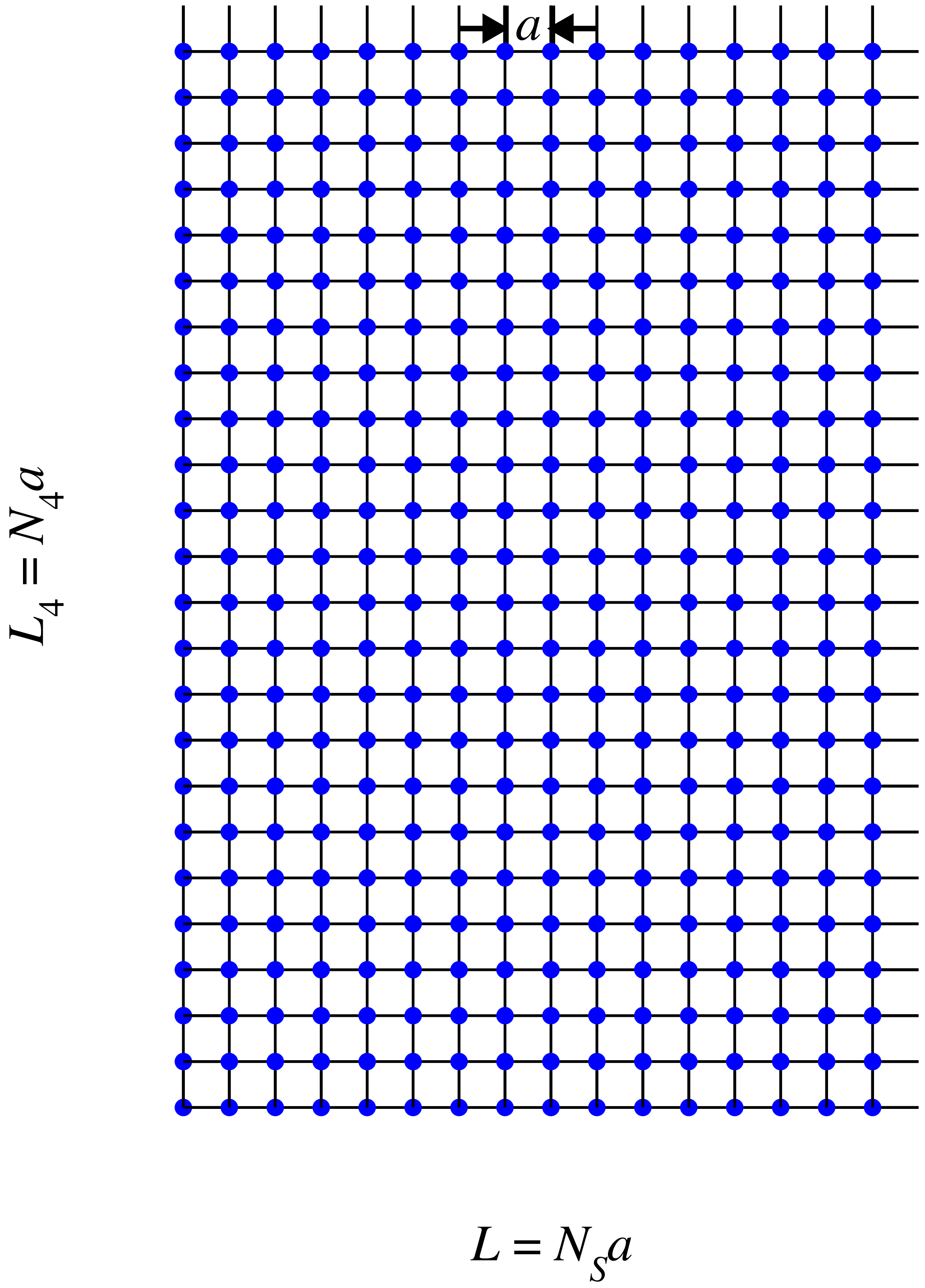

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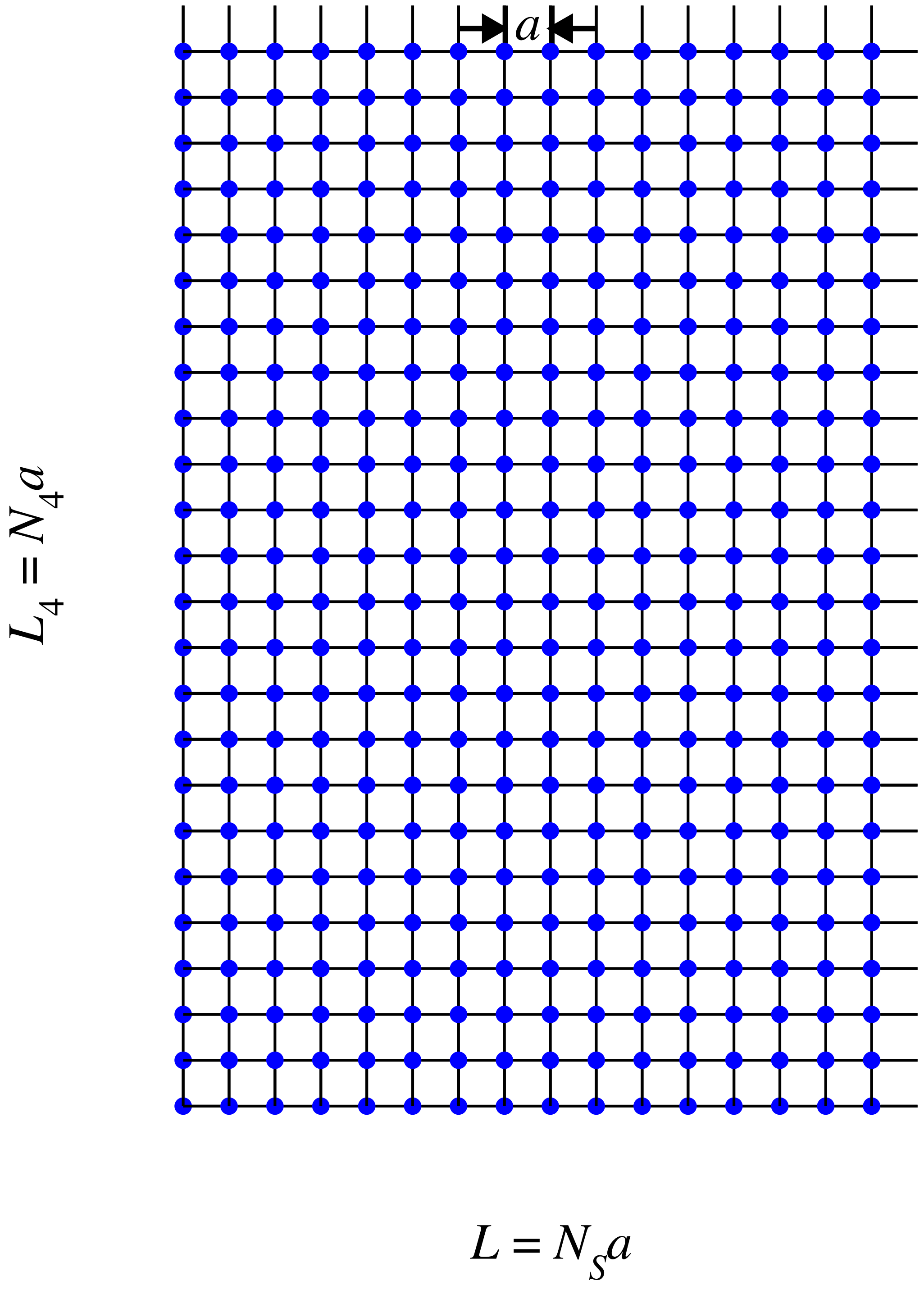


Some Jargon

- 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. (Obsolete.)

- *Un*quenched means not to do that.

- *Partially* quenched (usually) 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").

Twentieth *vs*. Twenty-first Century Lattice QCD

- Quenched calculations (of the twentieth century) were really model calculations, which matched neither our own aspirations or HEP's.

- Famous theorist, December **2006**:

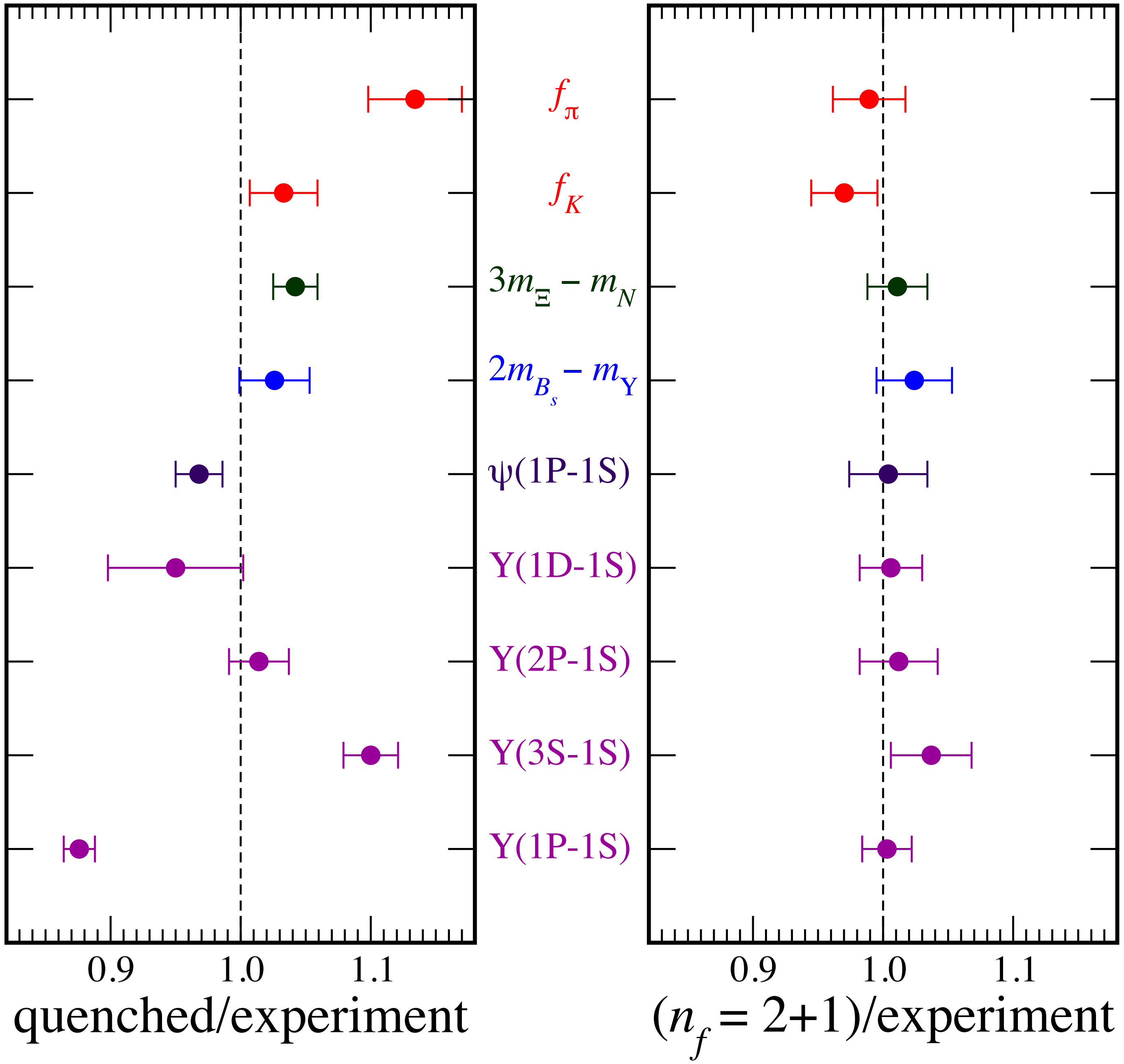
  - "I'll believe a 3% lattice [QCD] theory error when the lattice has produced one successful prediction and several 3% postdictions."

- 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….

Nine Postdictions

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

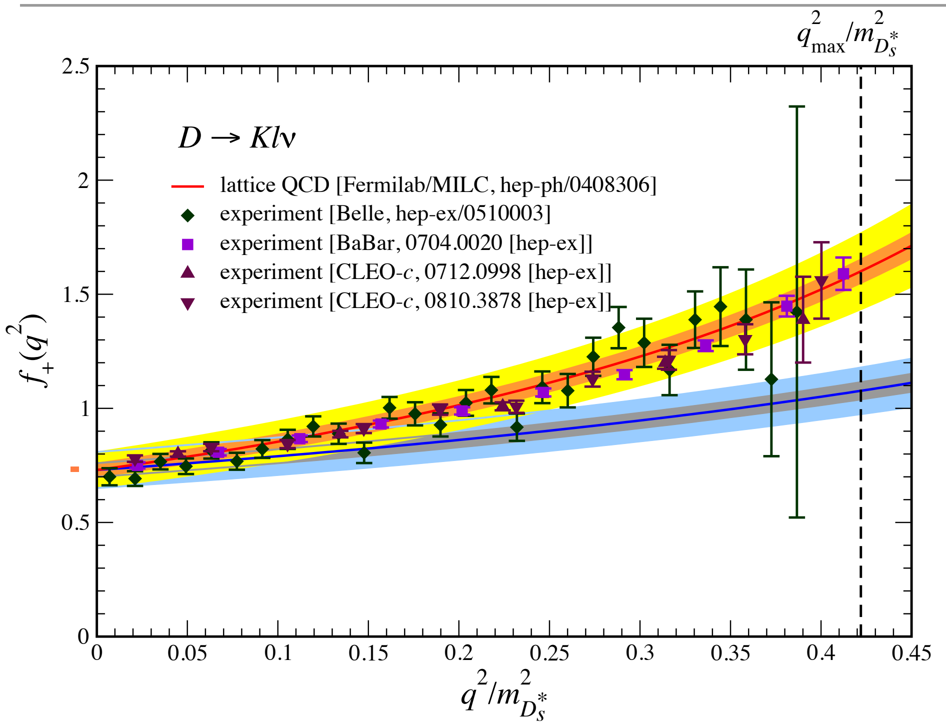


- $a = 0.12$ & 0.09 fm;
- $O(a^2)$ improved: asqtad;
- FAT7 smearing;
- $2m_l < m_q < m_s$;
- π, K, Υ(2S-1S) input.

Three Predictions

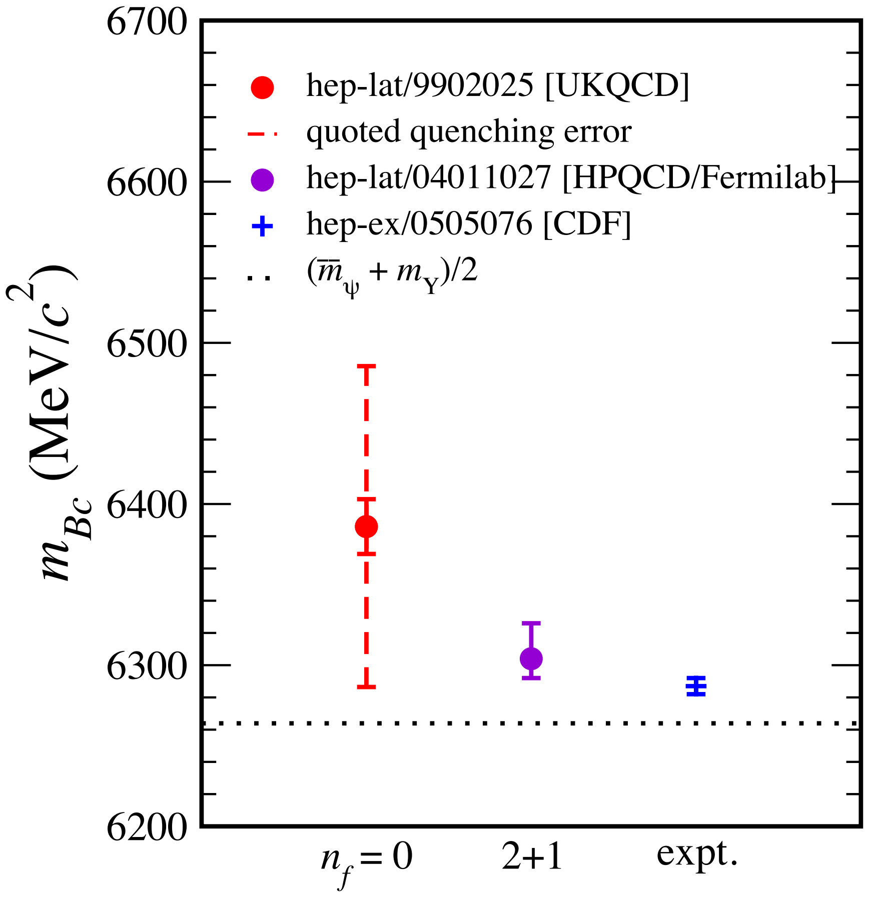
Fermilab Lattice, MILC, HPQCD,
hep-ph/0408306, hep-lat/0411027, hep-lat/0506030

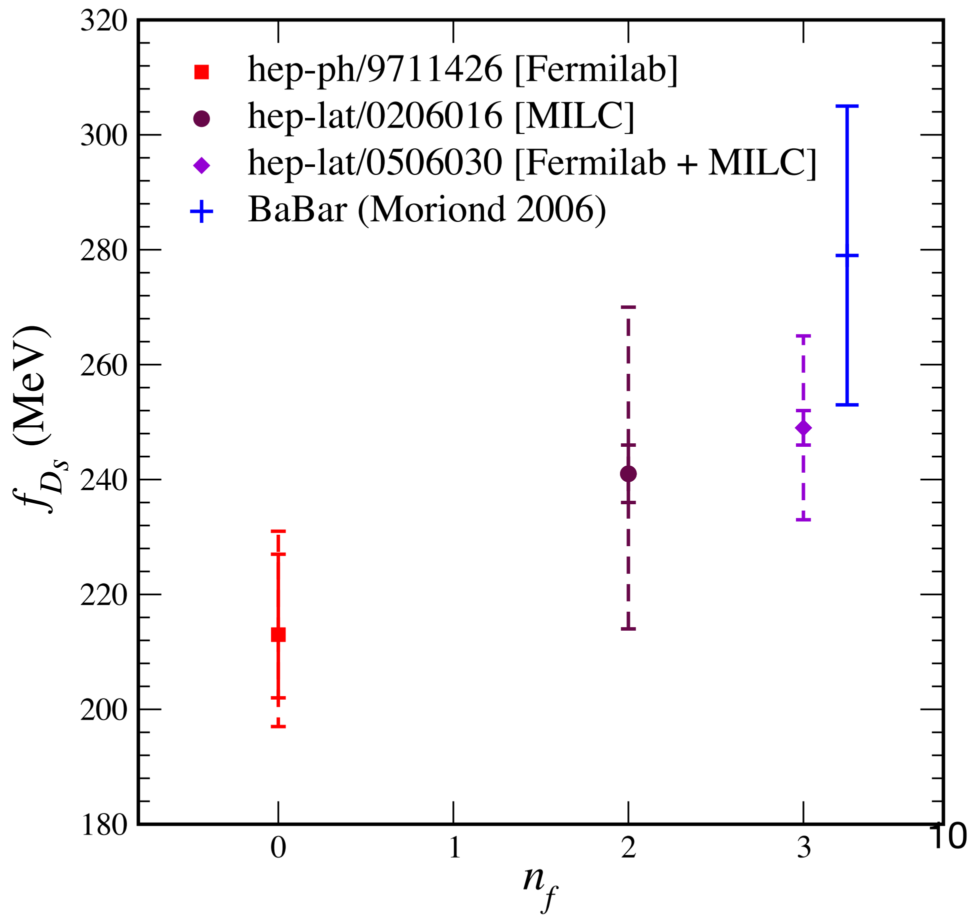
- Semileptonic form factor for $D \to Kl\nu$
- Mass of B_c meson
- Charmed-meson decay constants



2004

2005





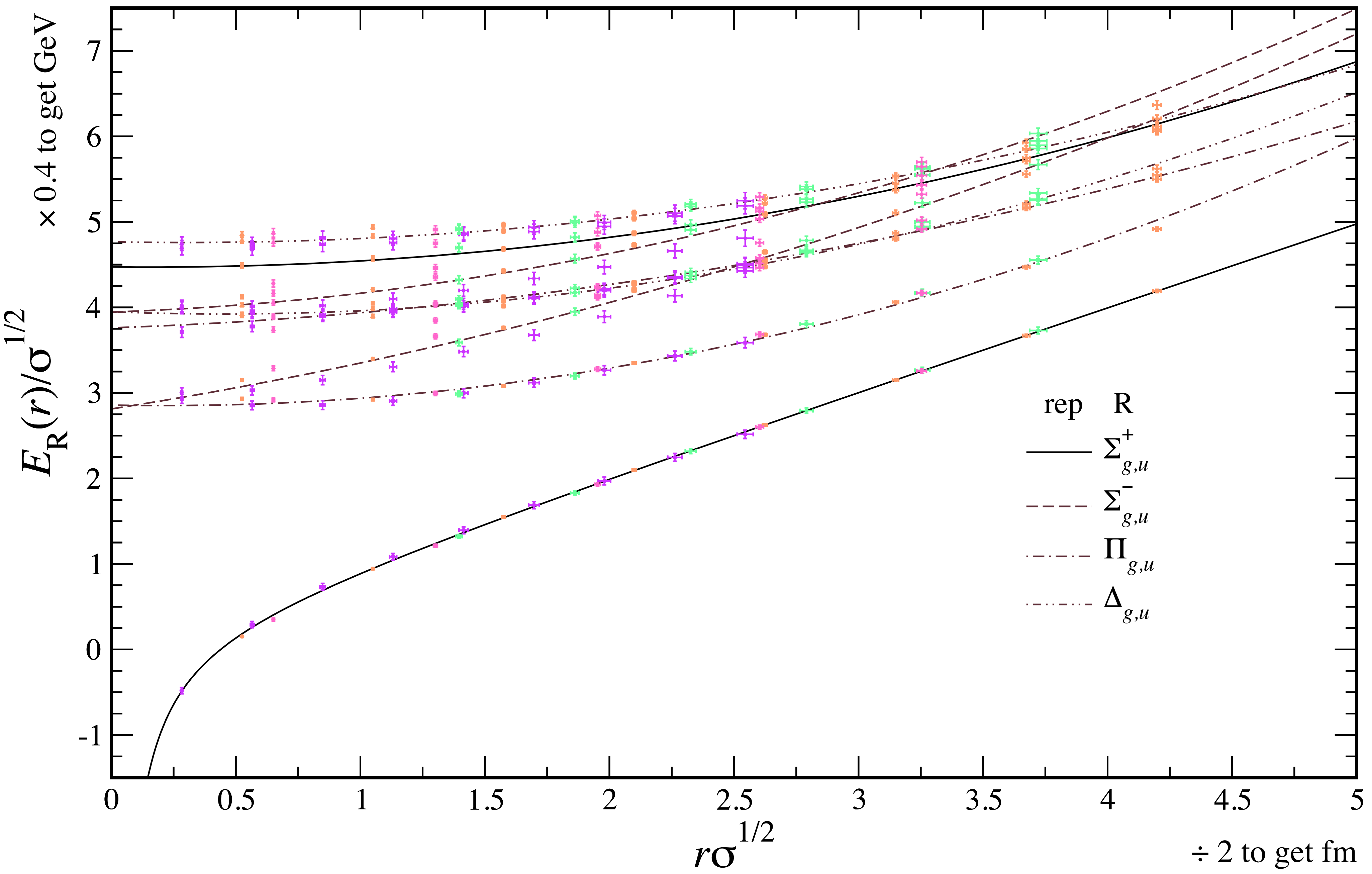
Massive Excitement I

Why Compute Hadron Masses?

- Show that the QCD Lagrangian generates hadron masses.
- Understand more deeply the only known mechanism for generating masses.
- Study first the chromodynamic energy stored between static sources:
    - lowest level is the potential energy: at short distances, it is Coulombic, but at large distances, it soon turns linear, as a string would;
    - excitations are interesting too: at short distances, level-ordering and level-spacing is QED-like; at hadronic distances (~1–2 fm), the level-ordering becomes string-like; at very large distances (> 2 fm), the spacing too.

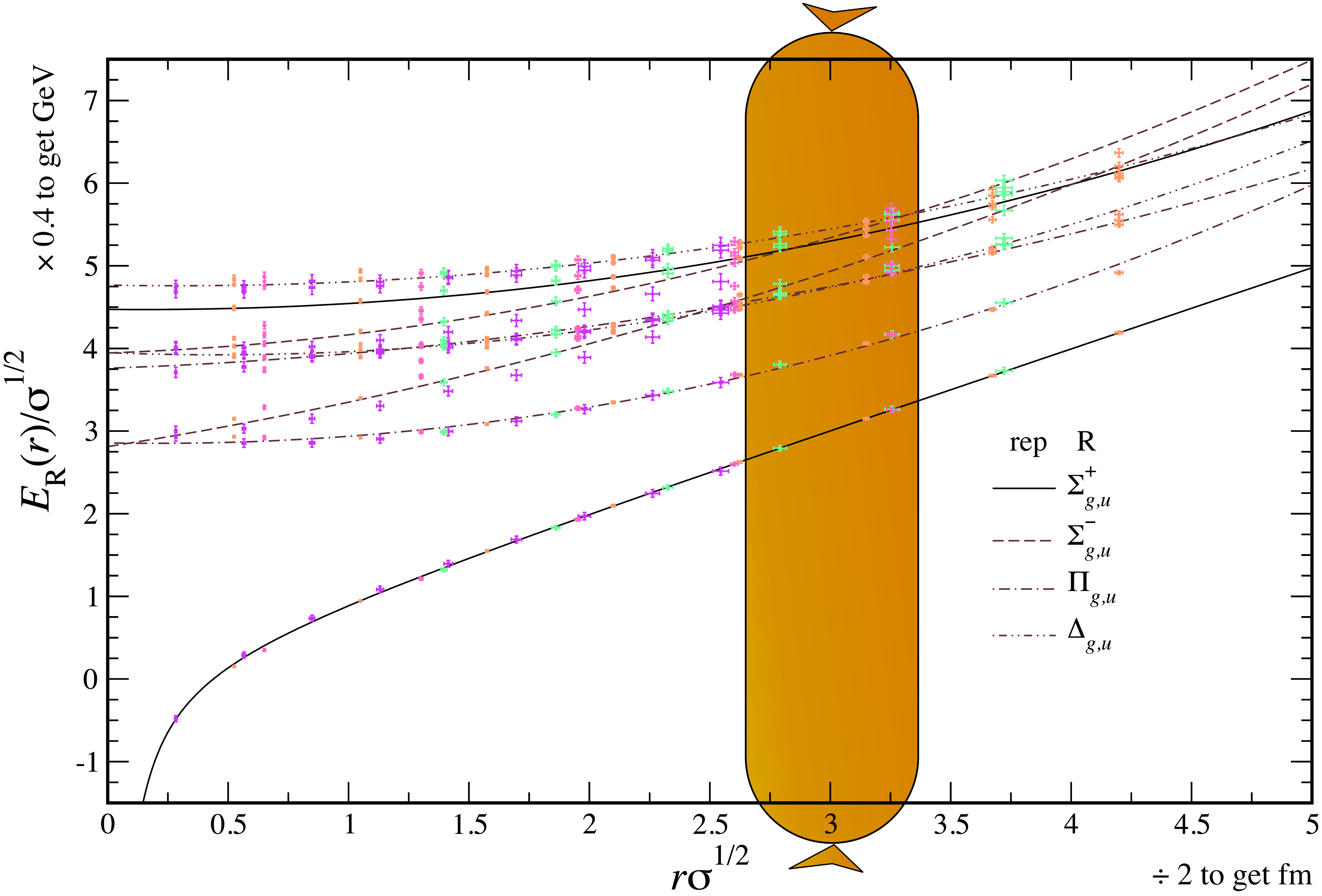
The QCD String

K. Juge, J. Kuti, & C. Morningstar, *PRL* **90** (2003) 161601



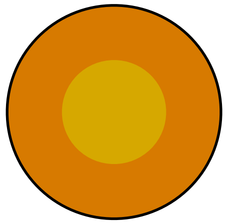
The QCD ~~String~~ Sausage

K. Juge, J. Kuti, & C. Morningstar, *PRL* **90** (2003) 161601



Hadron Masses: Qualitative & Quantitative

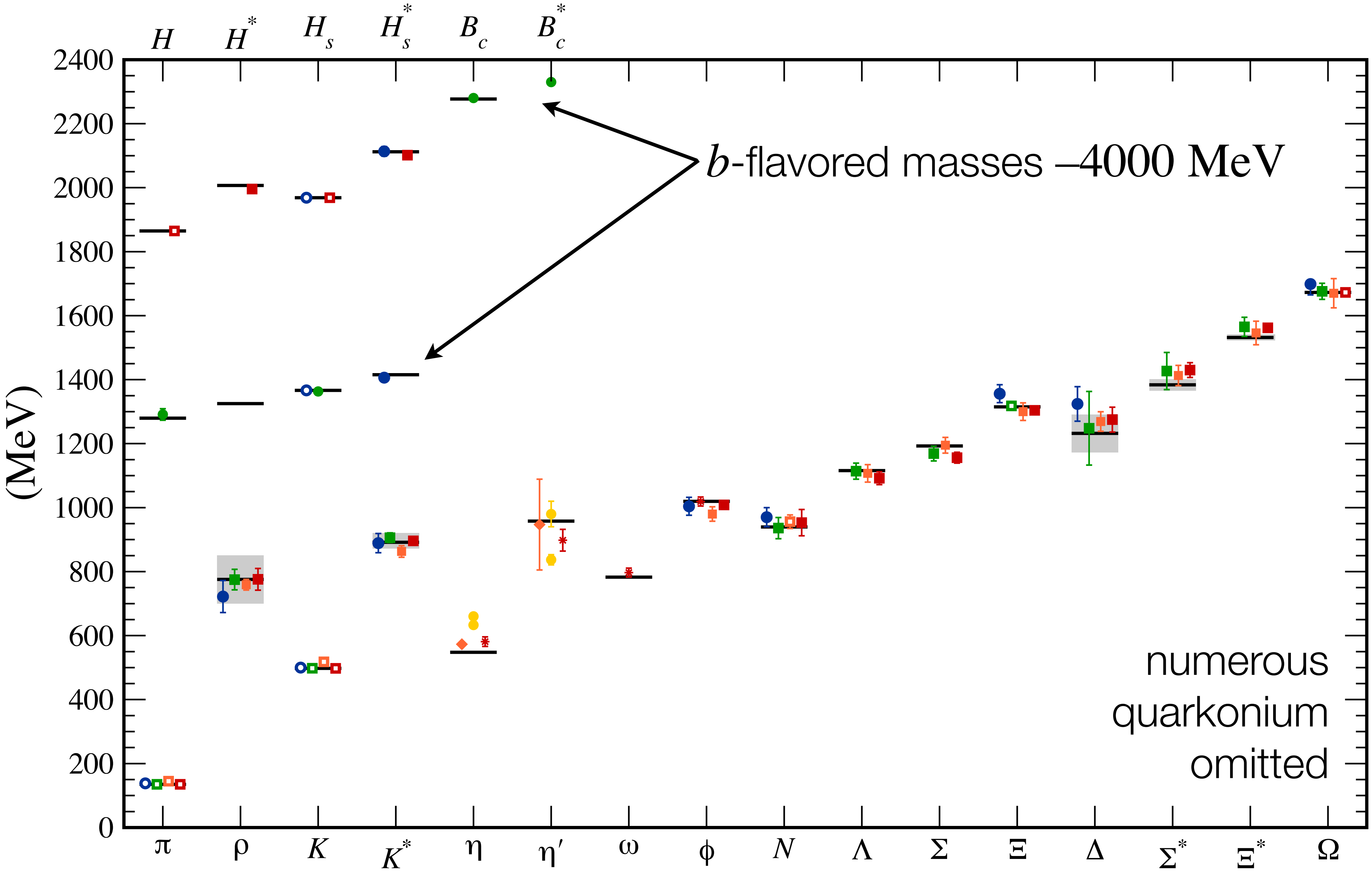
- In QCD, the energy in the sausage generates the mass of all hadrons.
- Glueballs (hadrons without quarks) consist only of this stuff.



  - $M(0^{++}) \approx 1700$ MeV [$f_J(1710)$]; $M(0^{-+})$ & $M(2^{++}) \sim 800$–900 MeV higher.
- The mass of hadrons with light quarks (like protons and neutrons) comes from this kind of energy, plus the kinetic energy of (relativistic) quarks confined.
- This is the source of mass for atomic nuclei and, thus, everyday objects …
  - … including you.

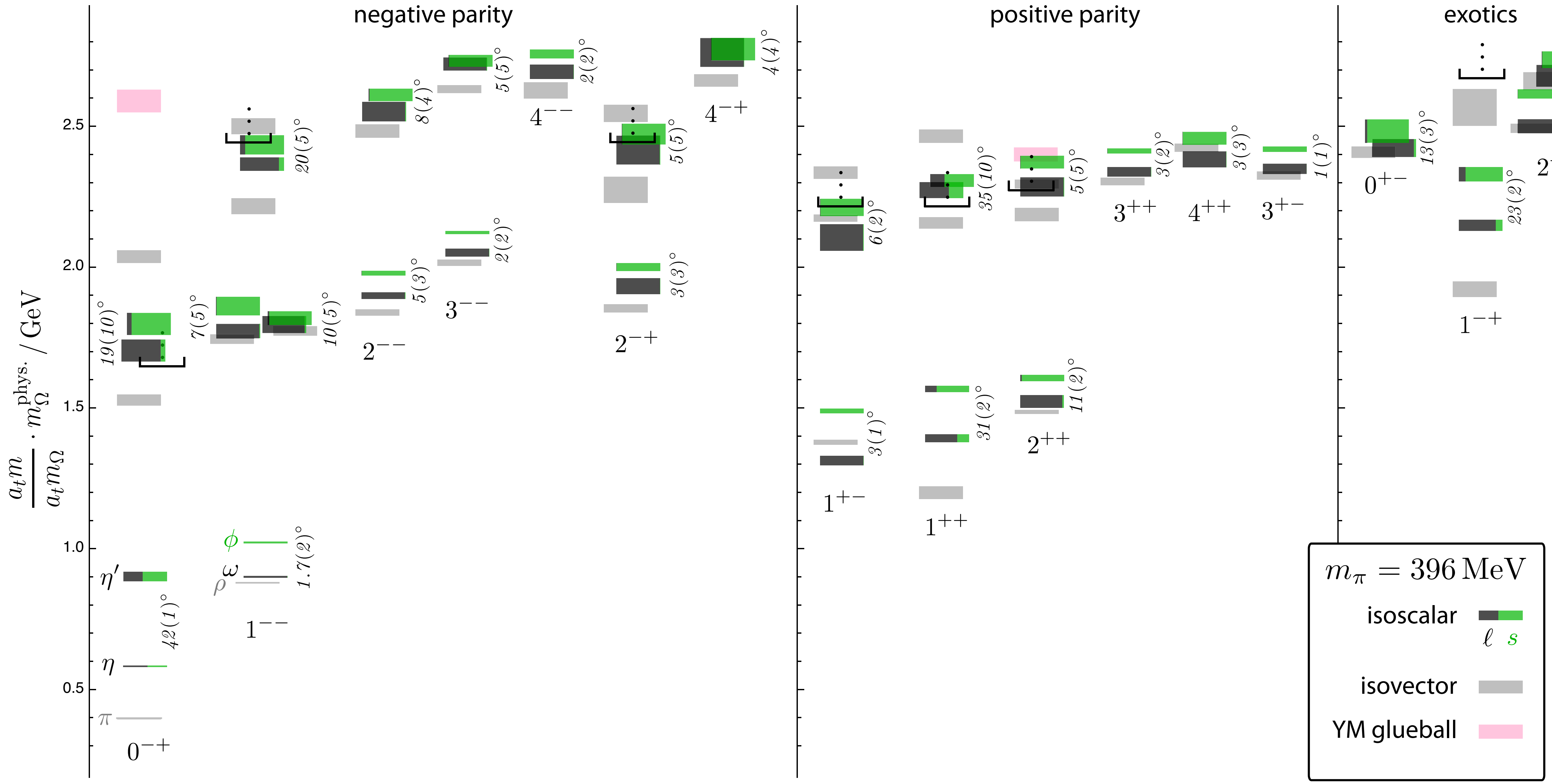
QCD Hadron Spectrum

$\pi \ldots \Omega$: BMW, MILC, PACS-CS, QCDSF;
η-η': RBC, UKQCD, Hadron Spectrum (ω);
D, B: Fermilab, HPQCD, Mohler&Woloshyn



Excited States

e.g., Hadron Spectrum Collaboration, *PRD* **83** (2011) 111502



- Future applications to glueball spectra, hybrids, excited baryons, and mixing.

Now, quark masses are MeV not GeV (see below), therefore

$$m_N = E_{\text{▬}}/c^2$$

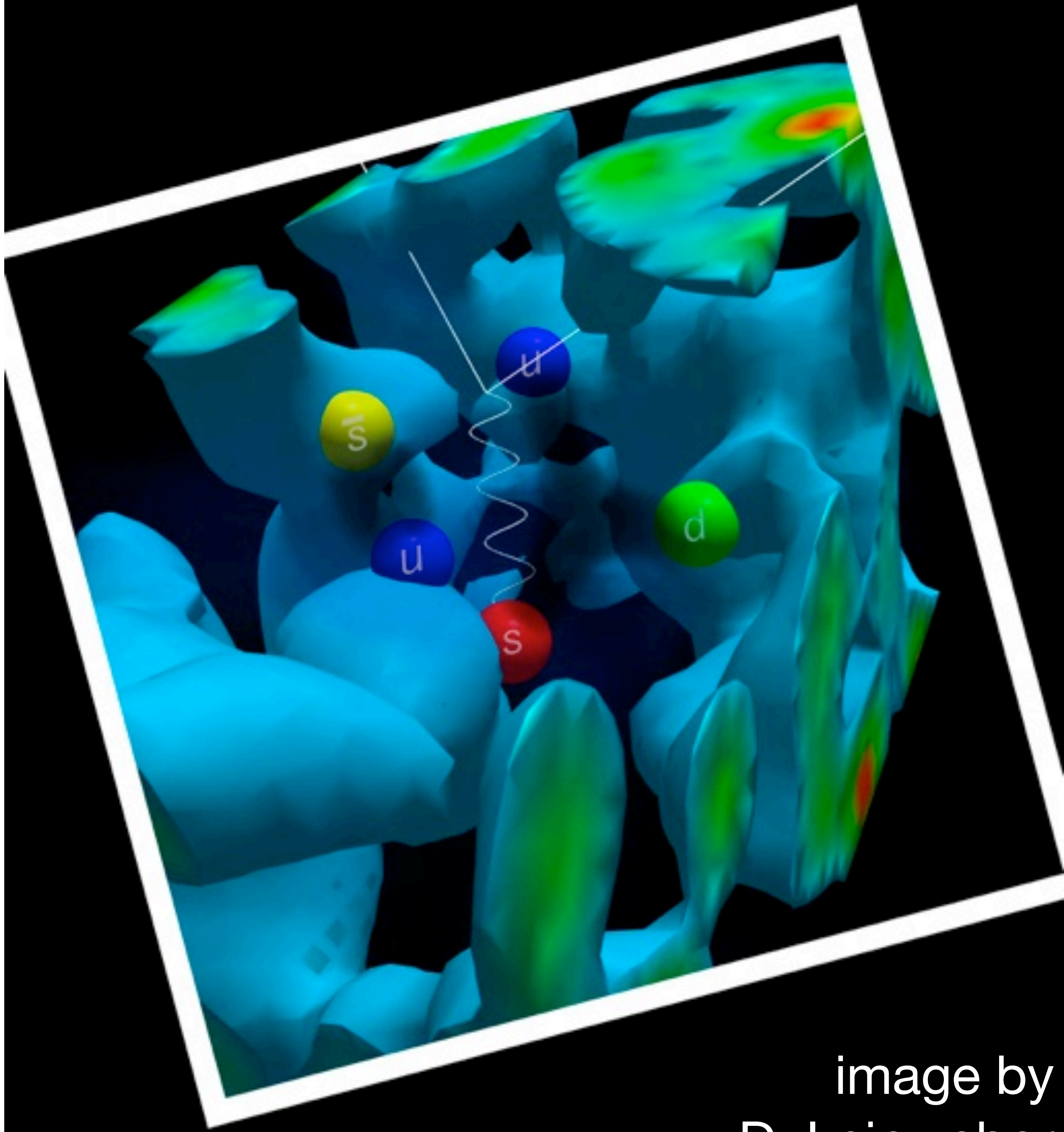


image by
D. Leinweber

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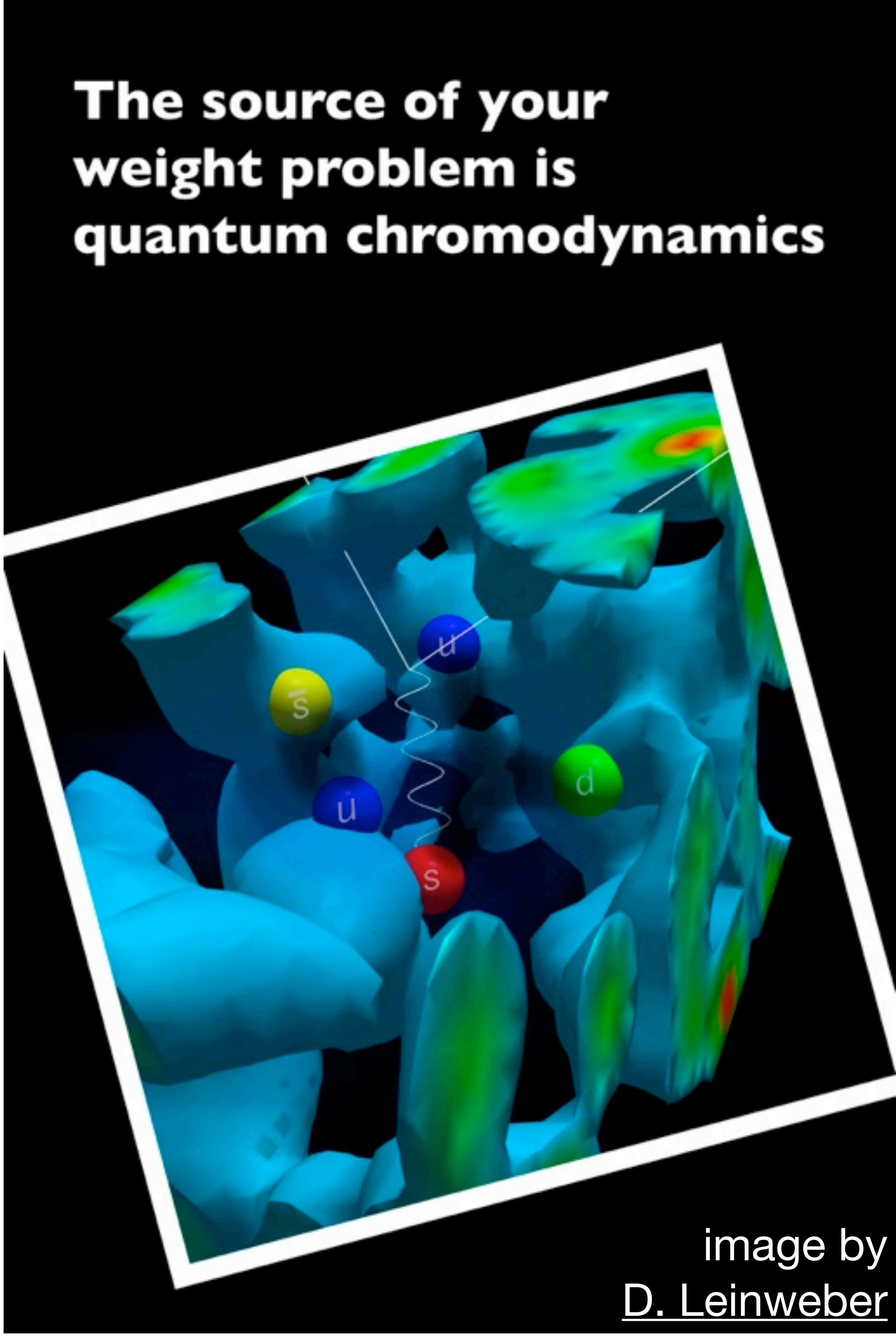

image by D. Leinweber

Massive Excitement II

Weak Interactions

- At energies probed by the Tevatron and the LHC, left- and right-handed quarks are different (weak eigenbasis):

$$
\begin{aligned}
Q_L &= \left(\begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \right), & Y_{Q_L} = -\frac{1}{6} \\
U_R &= (\quad u_R \quad c_R \quad t_R \quad), & Y_{U_R} = +\frac{2}{3} \\
U_R &= (\quad d_R \quad s_R \quad b_R \quad), & Y_{D_R} = -\frac{1}{3}
\end{aligned}
$$

9 fields: 3 doublets and 6 singlets under $SU_L(2)\times U_Y(1)$.

Identity from Higgs and Yukawa

- Whatever breaks electroweak symmetry has a weak-SU(2) doublet, Φ, so it can have Yukawa interactions

$$y^u_{ij}\bar{Q}^i_L\Phi U^j_R + y^d_{ij}\bar{Q}^i_L\tilde{\Phi}^* D^j_R + \text{h.c.} =$$

$$y^u_{ij}\begin{pmatrix}\bar{U} & \bar{D}\end{pmatrix}^i_L\begin{pmatrix}\Phi^0 \\ \Phi^-\end{pmatrix}U^j_R + y^d_{ij}\begin{pmatrix}\bar{U} & \bar{D}\end{pmatrix}^i_L\begin{pmatrix}\Phi^+ \\ \bar{\Phi}^0\end{pmatrix}D^j_R + \text{h.c.}$$

where indices label generations.

- Spontaneous symmetry breaking driven by $\Phi = \begin{pmatrix} v \\ 0 \end{pmatrix}$:
  - generates masses for the quarks and gauge bosons.

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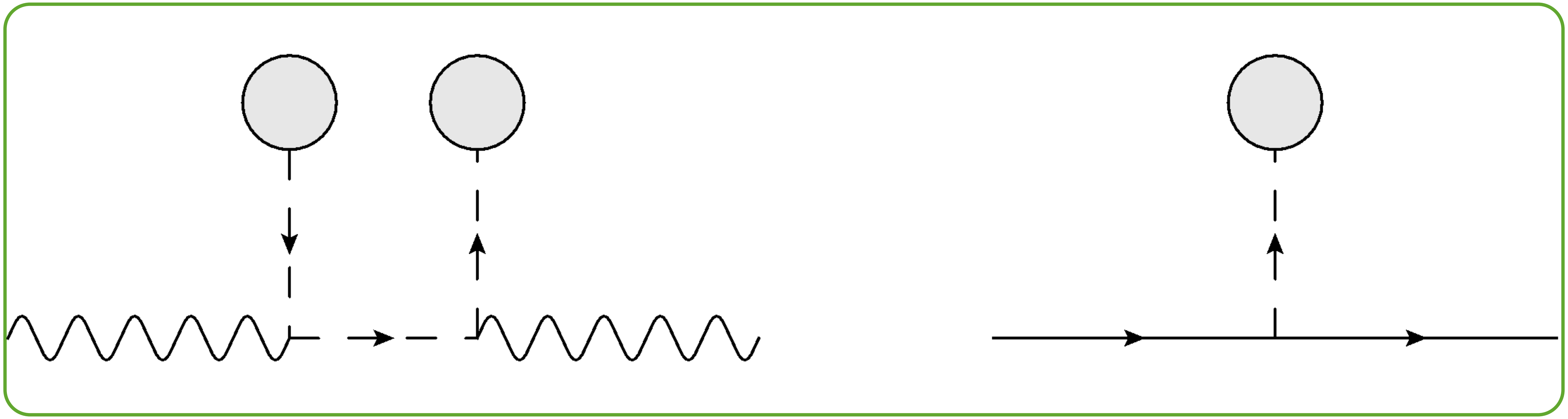

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Quark Masses

- Adjust the bare mass in lattice QCD so one hadron mass comes out right.

- Convert to a conventional renormalization scheme:

Lattice QCD	**MILC**	**RBC**	**BMW**	**HPQCD**
$\overline{m}_u(2\text{ MeV})$	1.9 ± 0.2	2.24 ± 0.35	2.15 ± 0.11	2.01 ± 0.14
$\overline{m}_d(2\text{ MeV})$	4.6 ± 0.3	4.65 ± 0.35	4.79 ± 0.14	4.79 ± 0.16
$\overline{m}_s(2\text{ MeV})$	88 ± 5	97.6 ± 6.2	95.5 ± 1.9	92.4 ± 1.5
$\overline{m}_c(\overline{m}_c)$				1273 ± 6
$\overline{m}_b(\overline{m}_b)$				4164 ± 23

- The up & down masses are ~4 & ~9 times electron mass.

- The up mass is far from 0: the strong CP problem is indeed a problem.

CKM Matrix

Cabibbo, *PRL* **10** (1963) 531;
Kobayashi, Maskawa, *Prog. Theor. Phys.* **49** (1973) 652

- Mass couples left to right: has to break $SU_L(2)$ and $U_Y(1)$ (spontanesously).
- Weak and mass eigenbases related by unitary transformation, $D_L = V_{\text{CKM}} D'_L$.
- Global symmetries reduce parameter count of CKM matrix to 4:
  - $|V_{\text{us}}|$, $|V_{\text{cb}}|$, $|V_{\text{ub}}|$, $\delta_{\text{KM}} = \arg V^*_{\text{ub}}$—as fundamental as electron mass.
- Unitarity relations, *e.g.*, $V^*_{ud}V_{ub} + V^*_{cd}V_{cb} + V^*_{td}V_{tb} = 0$: triangles in the complex plane.
- Probed by many measurements + corresponding QCD.

CKM and Lattice QCD

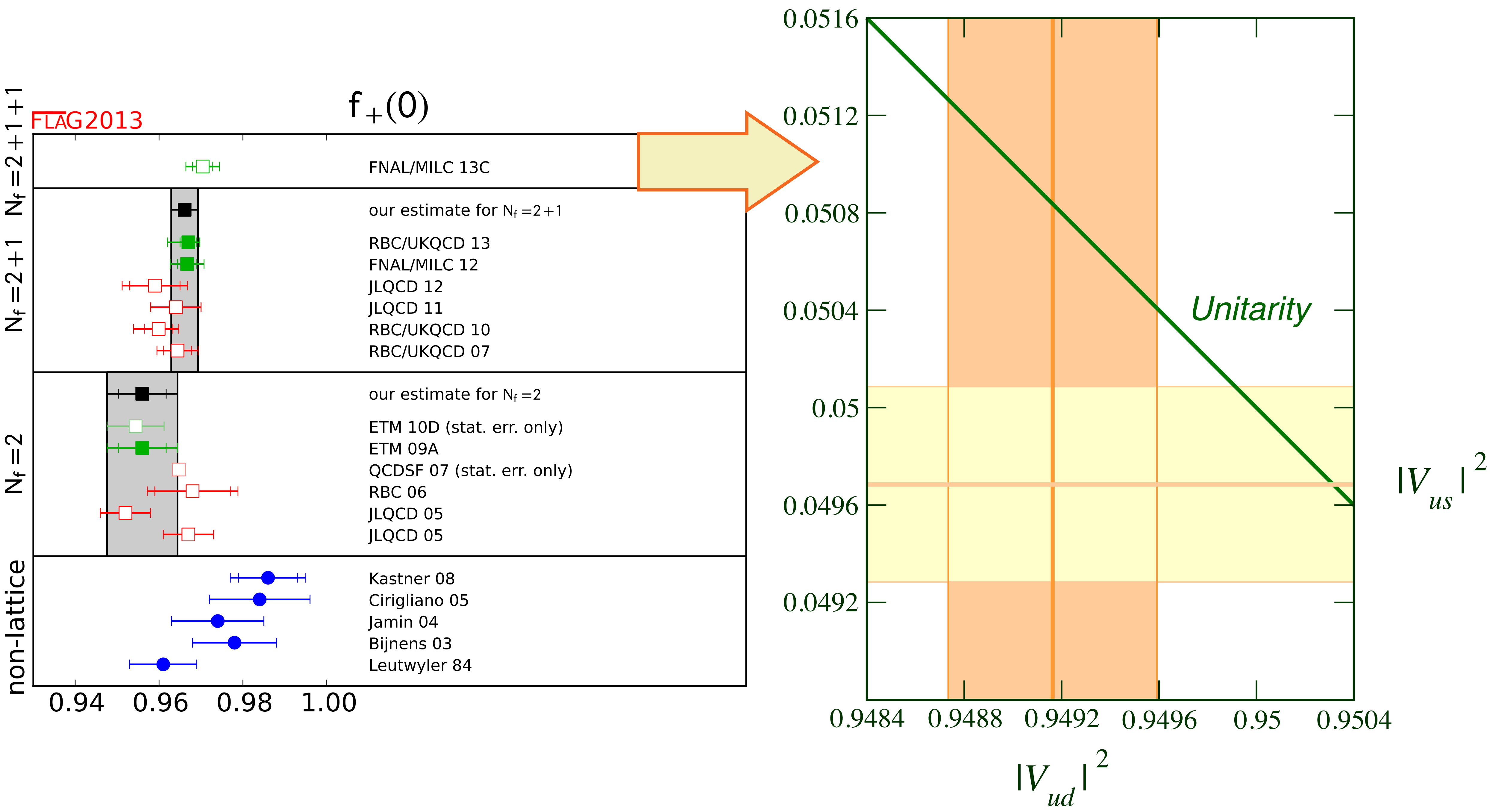
- Gold-plated quantities available to (over)determine CKM matrix:

$$V = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| & \arg V_{ub}^* \\ \pi \to \ell\nu & K \to \ell\nu & B \to \tau\nu & \langle K^0|\bar{K}^0\rangle \\ n \to pe^-\bar{\nu} & K \to \pi\ell\nu & B \to \pi\ell\nu & \\ |V_{cd}| & |V_{cs}| & |V_{cb}| & \\ D \to \ell\nu & D_s \to \ell\nu & B \to D\ell\nu & \\ D \to \pi\ell\nu & D \to K\ell\nu & B \to D^*\ell\nu & \\ |V_{td}| & |V_{ts}| & |V_{tb}| & \\ \langle B_d|\bar{B}_d\rangle & \langle B_s|\bar{B}_s\rangle & (\text{no } t\bar{q} \text{ hadrons}) & \end{pmatrix}$$

- loops vs. trees

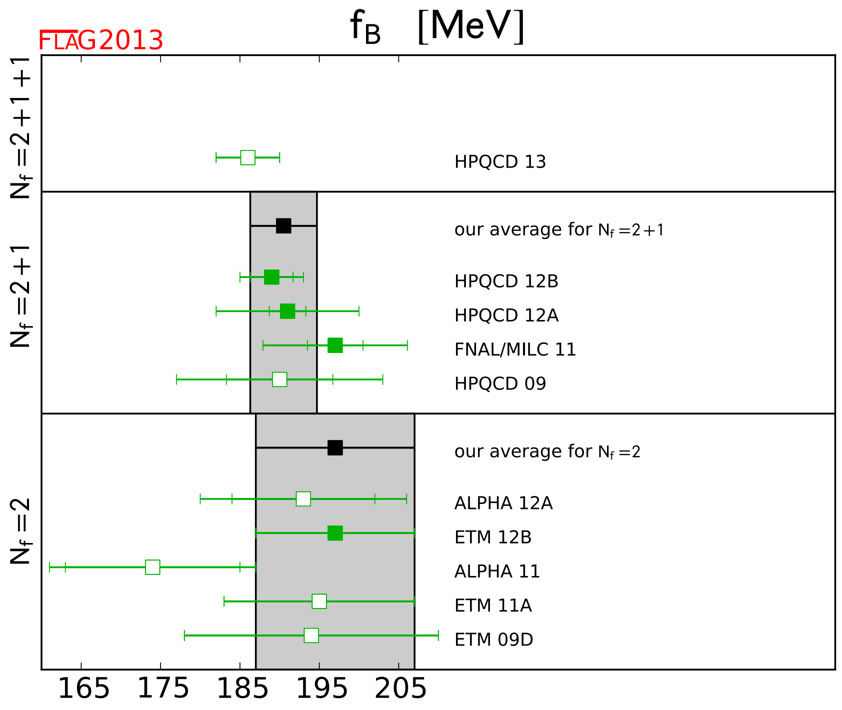
$|V_{us}|$

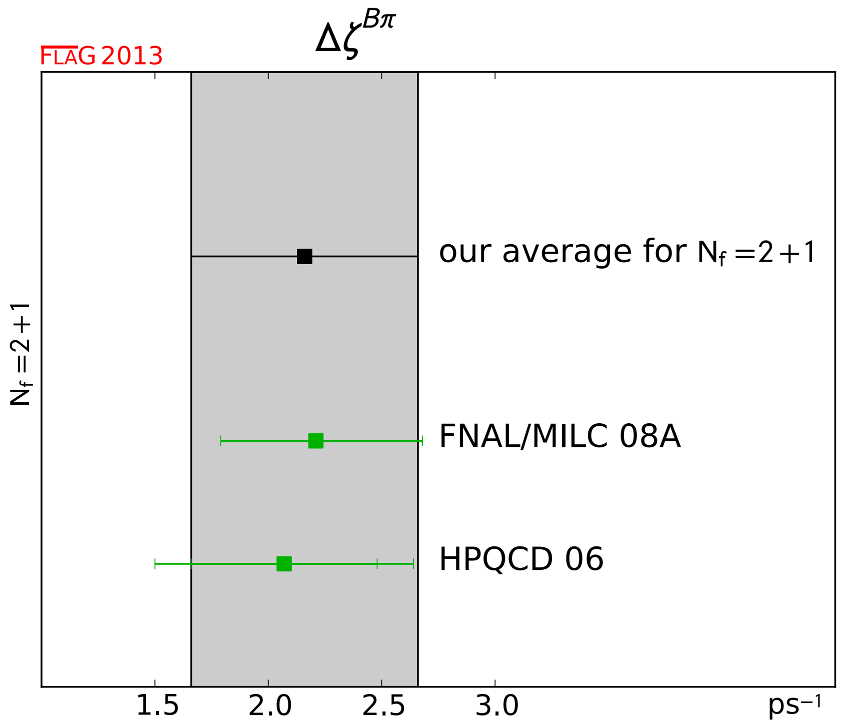
G. Colangelo *et al*. [FLAG], arXiv: 1310.8555;
alia et E. Gámiz *et al*. [Fermilab/MILC], arXiv:1312.1228

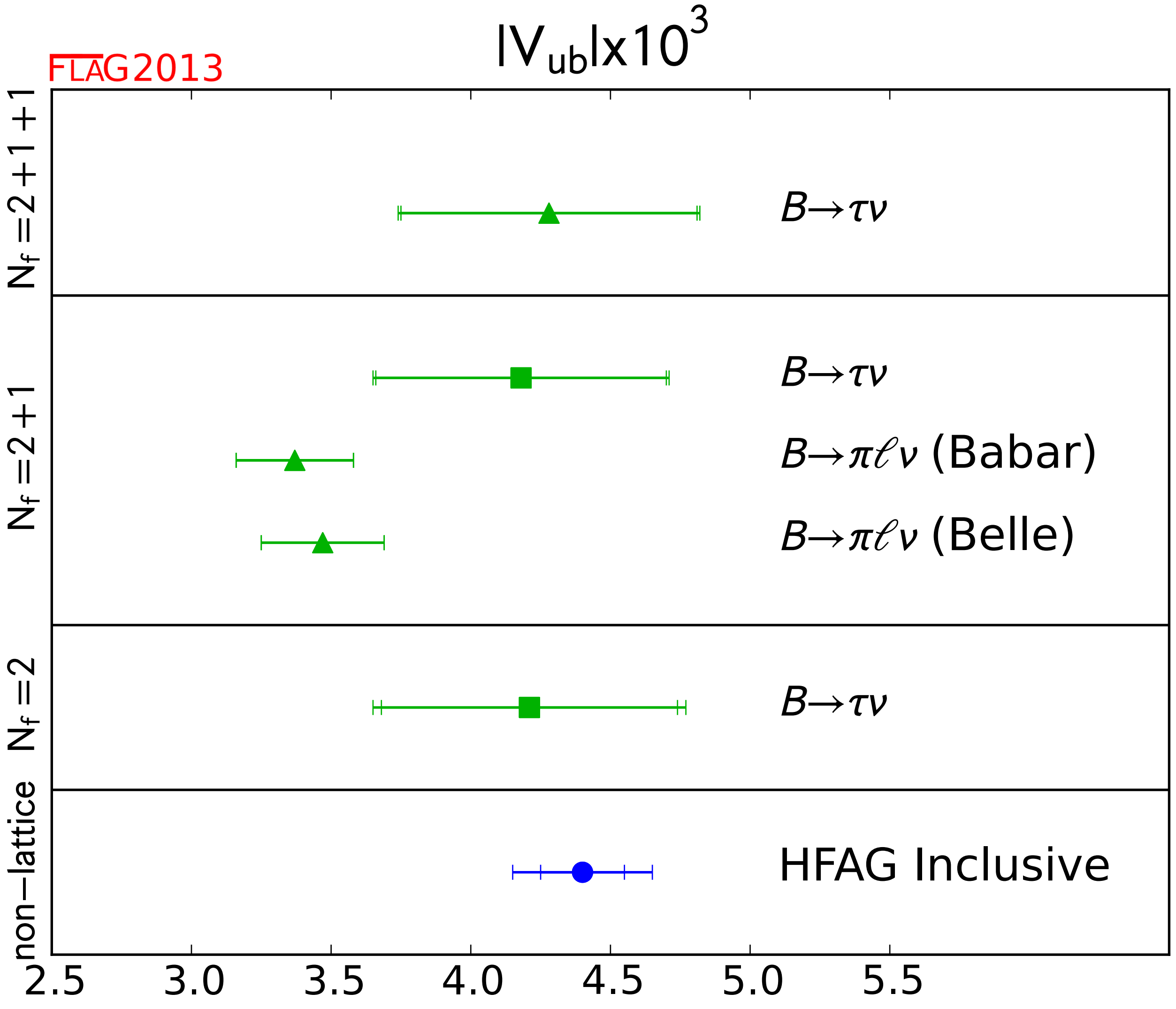


$|V_{ub}|$ from Lattice QCD

G. Colangelo *et al*. [FLAG], arXiv: 1310.8555

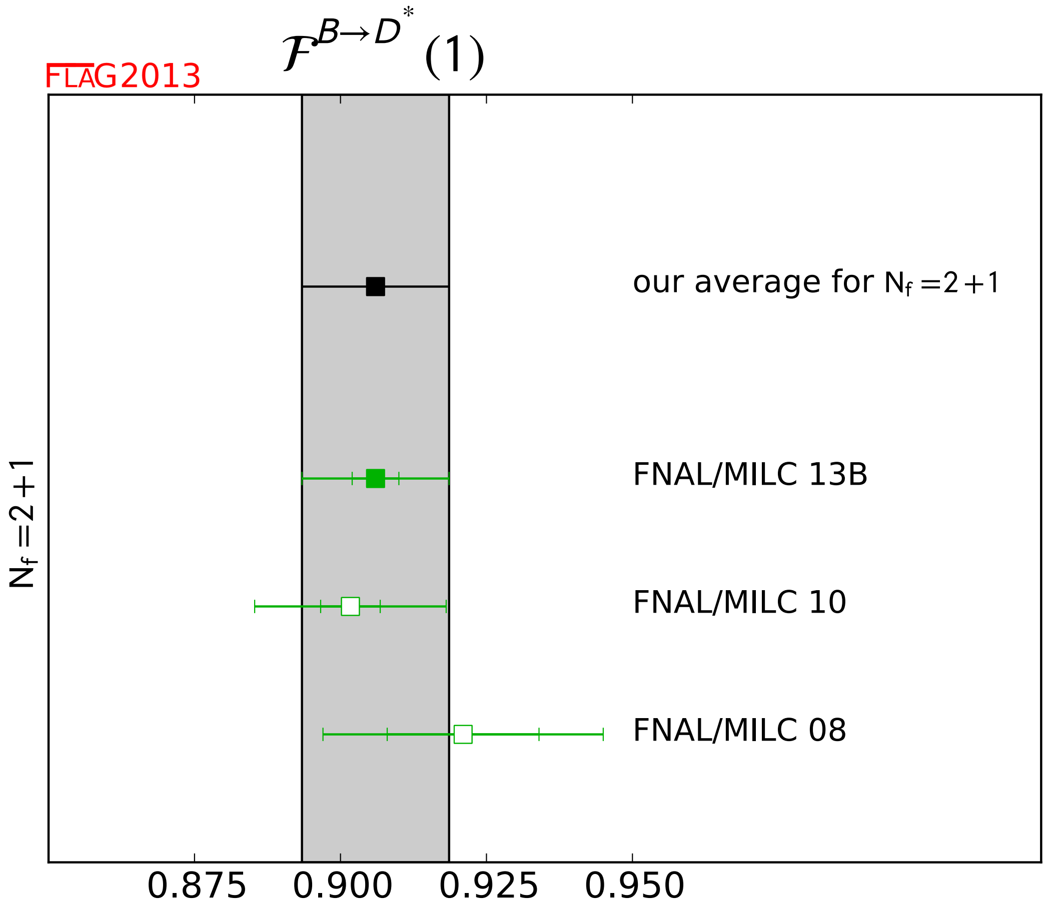


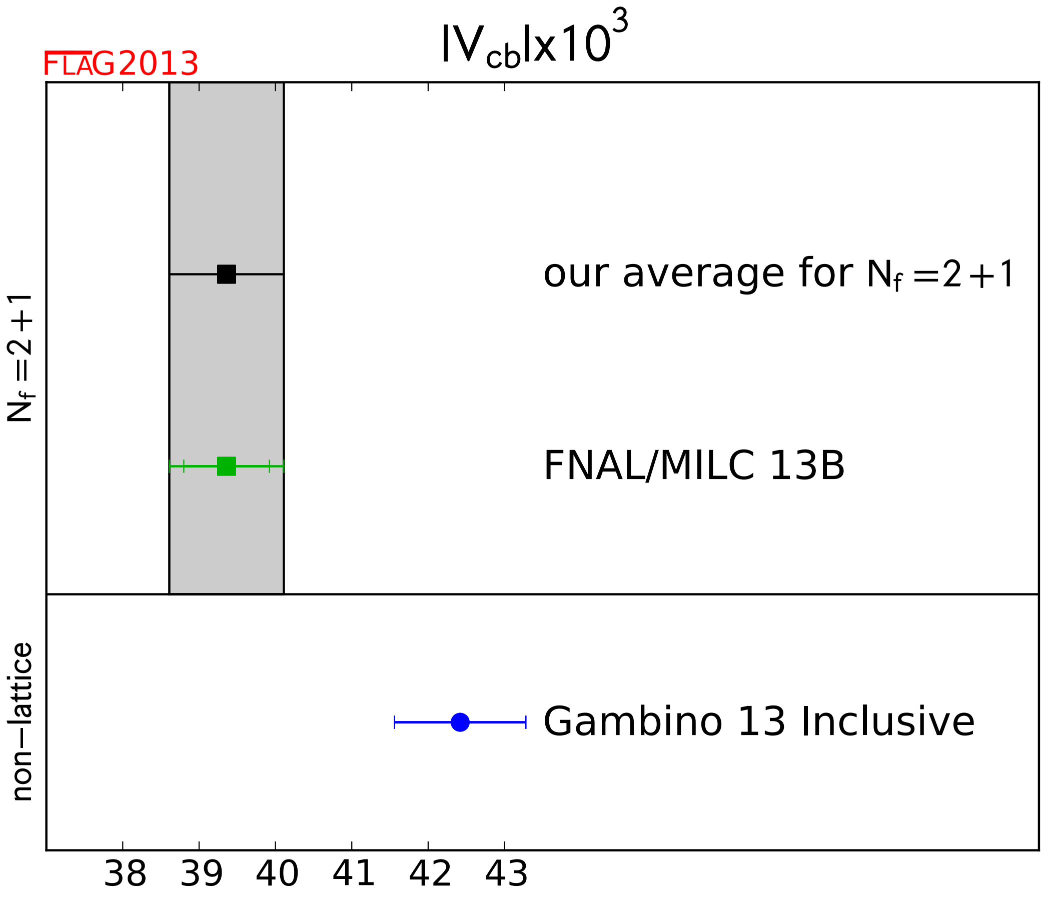




$|V_{cb}|$ from Lattice QCD

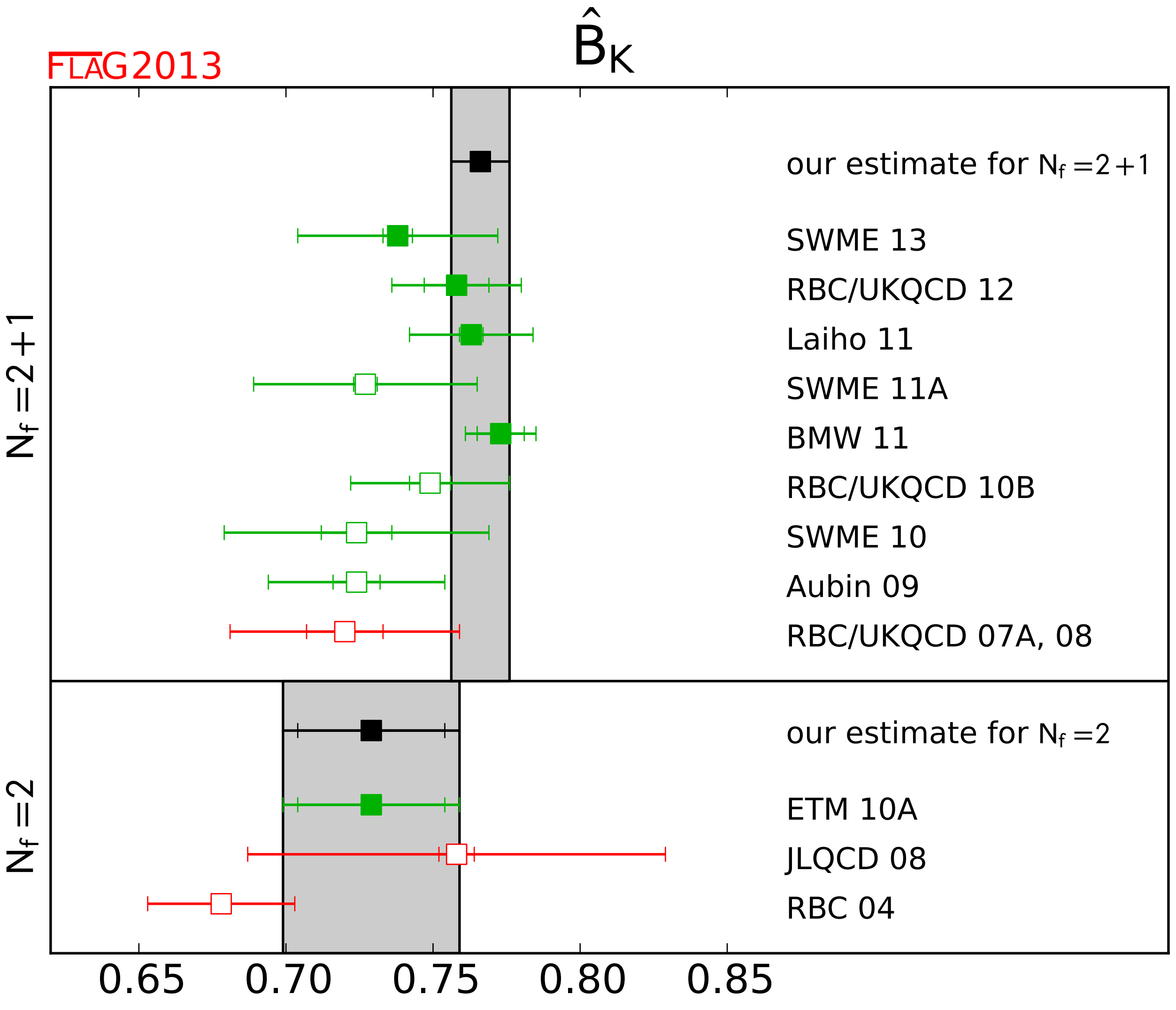
G. Colangelo *et al*. [FLAG], arXiv: 1310.8555





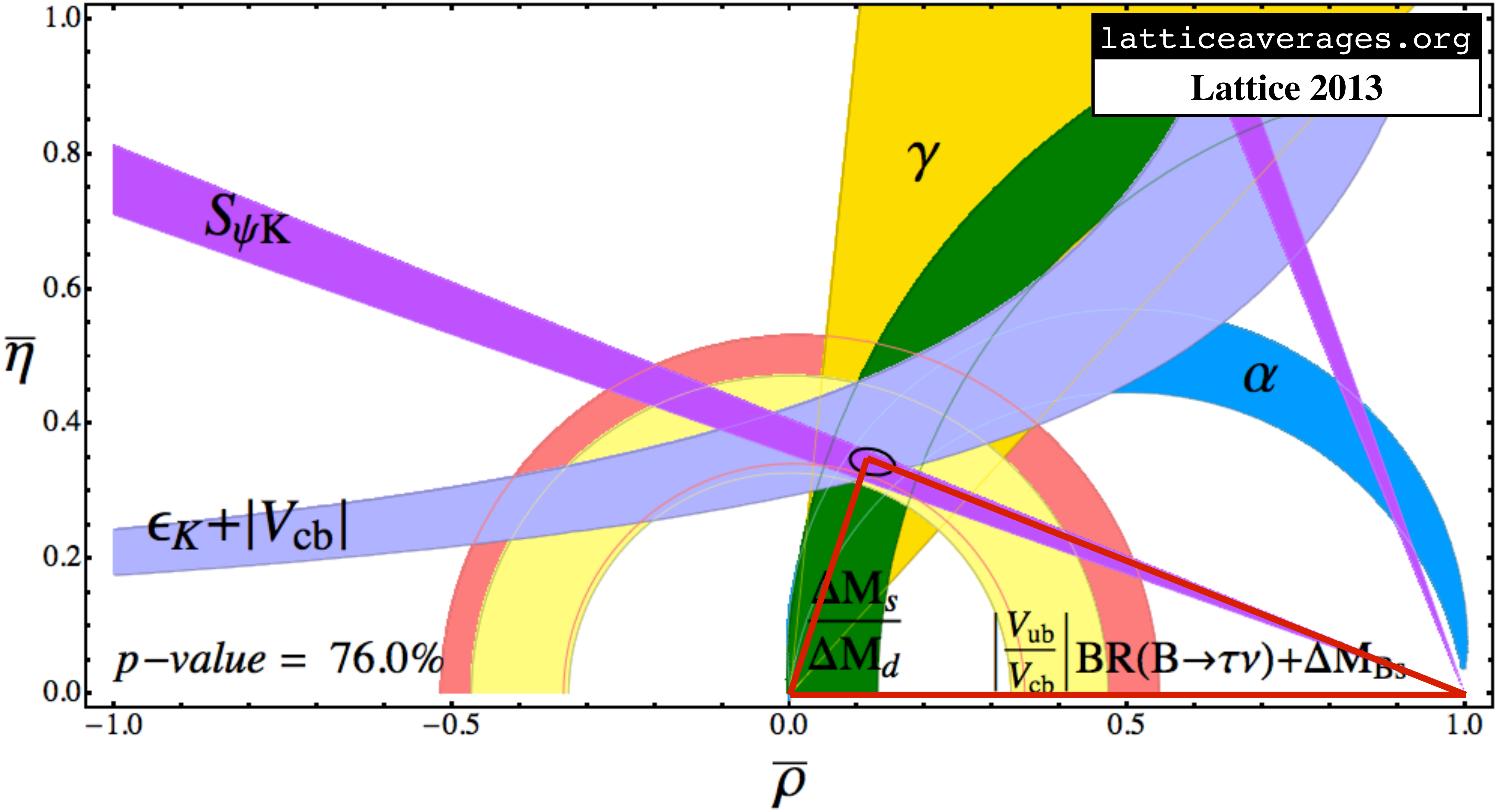
arg V_{ub} from Lattice QCD

G. Colangelo *et al*. [FLAG], arXiv: 1310.8555



Unitarity Triangle

c.f., Laiho, Lunghi, Van de Water, arXiv:0910.2928



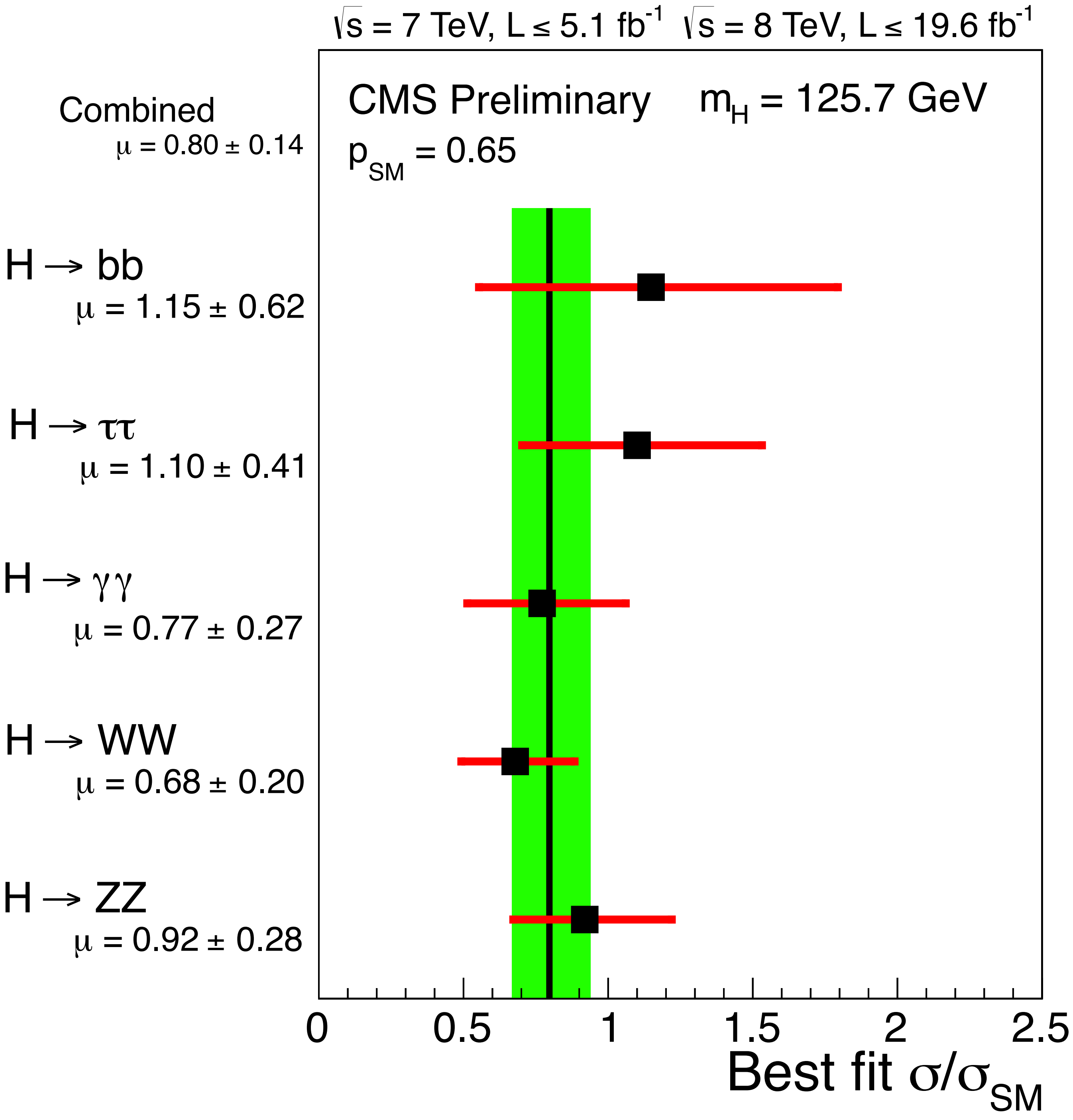
Lessons

- Lattice QCD plays a crucial role for neutral-meson mixing (K, B, B_s).
- Lattice QCD plays a key role in $|V_{\mathrm{us}}|$, $|V_{\mathrm{cs}}|$, $|V_{\mathrm{ub}}/V_{\mathrm{cb}}|$, $|V_{\mathrm{cb}}|$.
- Suite of experiments, pQCD, and lQCD shows that CKM flavor violation and KM CP violation predominates.
- Still room for new physics: tension at 2–3σ level:
  - confidence level of global fit improves more, if NP in kaon mixing [LLV];
  - ε_K band uses corrections of Nierste, Ligeti, ASK [hep-ph/0201071].

Massive Excitement III

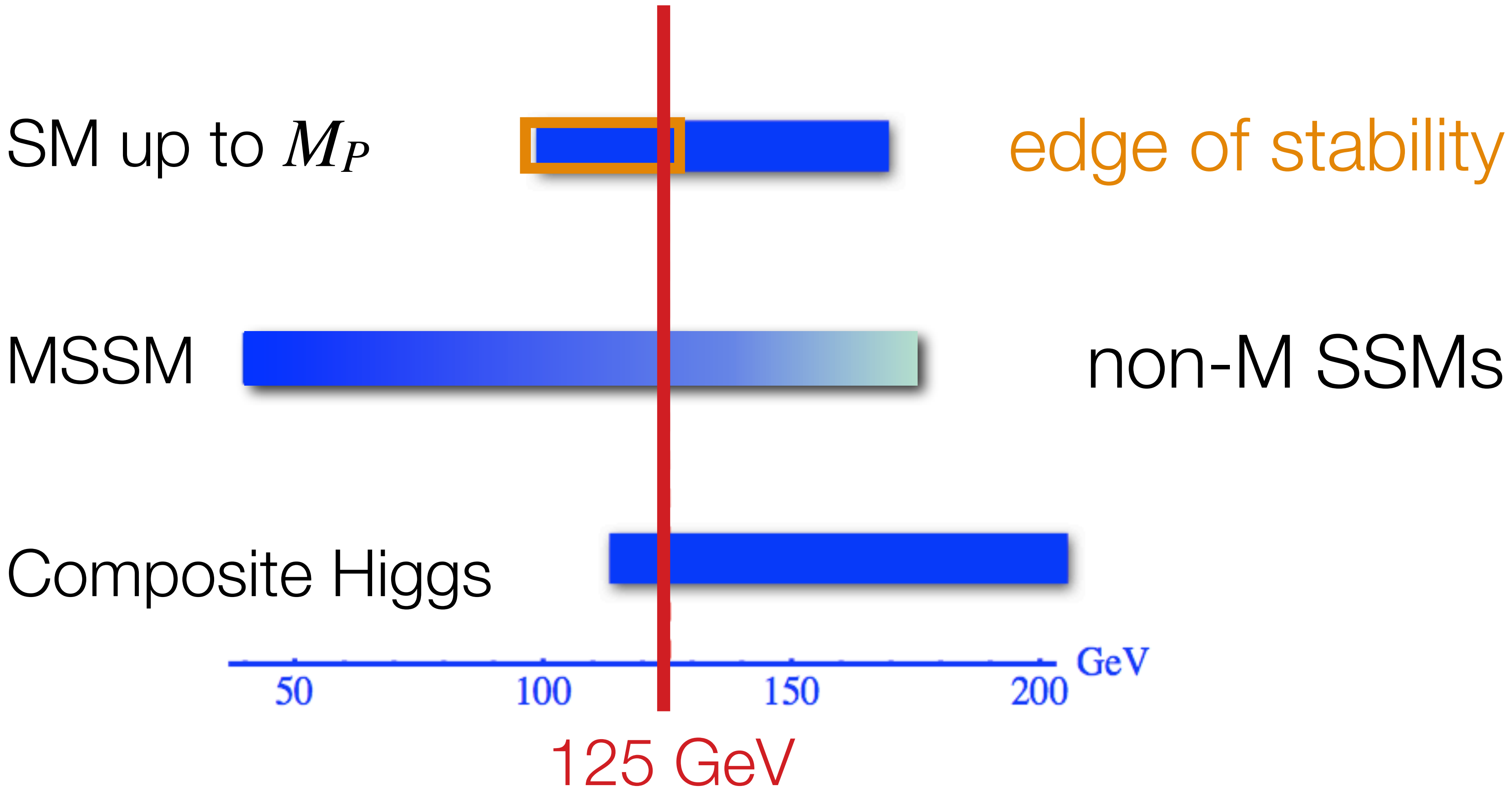
LHC and Its Scalar Boson

- First observation July 4, 2012.
- Mass 125.7 GeV.
- Decay patterns consistent with the Standard Model of one Higgs doublet: $W_L^{\pm}, Z_L^0, H^0$.
- But the SM is unsatisfactory on physical, philosophical, and mathematical grounds.
- What is going on?



What Does Higgs Mass Say?

from M. Carena and others



- Supersymmetry: where are the superpartners?
- Could a new kind of sausage generates theses masses too?

Requirements on Strongly-Coupled EWSB

- Isolated scalar boson with mass 126 GeV and correct couplings.
- Isolation means that the spectrum cannot be too much like QCD
  - Higgs boson and longitudinal gauge bosons could be pseudo-Goldstones;
  - the “running” of the coupling could be very slow, such that the dynamics are approximately conformal over a wide range of scales.
- Theory space is huge:
  - Which gauge group? Which fermion representation?

Outlook

- Many topics in lattice QCD omitted here:
    - muon g–2 experiment at Fermilab relies on a QCD calculation of the hadronic contribution;
    - flavor physics experiments at LHCb and Belle 2 require better (achievable) precision;
    - future studies of Higgs BRs need more precise quark masses (achievable).
- In many cases, effects of EM and $m_d - m_u$ must now be incorporated.
- The importance of lattice QCD in nuclear physics cannot be overstated.