USQCD US Lattice Quantum Chromodynamics

Lattice QCD
and the
Search for New Physics

Andreas S. Kronfeld

LQCD-ext ⊕ LQCD-ARRA Review, May 10–11, 2011

Existential Questions

- What breaks electroweak symmetry?
- What generates flavor? Flavor change V?
- Why is $m_u < m_d$? Is $m_u = 0$ (at some scale)?
- With δ_{KM} (and θ), what causes *CP* violation?
- Without these, no chemistry or biology.

- Most particle physicists expect to find the answers beyond the SM:
  - experimenters searching for signals;
  - theorists building models.
- To recognize BSM, need precision SM.
- Half the parameters are "obscured" by nonperturbative QCD: need lattice QCD.
- Kuti: lattice gauge theory applied to EWSB.

Standard Model

19 Parameters

- Gauge couplings: α_s, α_{QED}, $\alpha_W = (m_W/v)^2/\pi$;
- Lepton masses: m_e, m_μ, m_τ;
- Quark masses: $m_u e^{i\theta}$, m_d, m_s, m_c, m_b, m_t;
- CKM: V_{us}, V_{cb}, V_{ub}, $\exp(i\delta_{KM})$;
- EWSB: $v = 246$ GeV, $\lambda = (m_H/v)^2/2$.
- Need lattice QCD, lattice Yukawa.

SM Status

- Gauge symmetry
- Law of Nature

- Quantum numbers
- Law of Nature

- Higgs sector
- Explore at LHC

- Flavor interactions
- Test with intensity

LHC Era

- New phenomena seen at CERN's LHC (Large Hadron Collider, 7–14 TeV pp) ⇒
  - models of new particles ⇒
  - effects on low-energy processes.
- Effects suppressed by $(\Lambda_{\rm SM}/\Lambda_{\rm new})^{1\ \textit{or}\ 2}$, where $\Lambda_{\rm SM}$ could be $\Lambda_{\rm QCD}$, m_c, M_W, ….

Outline

- Drinks: Introduction & Data Sets
- Bread and Butter: Spectroscopy
- Appetizer: Quark Masses
- Main Course: Flavor Physics
- Dessert: Muon g–2
- Digestiv: Perspective

Lattice QCD Data

USQCD Data Mines

what \ who	MILC		RBC/UKQCD		JLab
sea	staggered		domain-wall		Wilson
action	asqtad	HISQ	std	AuxDet	clover
n_f	2+1	2+1+1	2+1	2+1	2+1
a (fm)	0.045–0.18	0.045–0.15	0.09–0.13	0.143	0.12 (a_s)
m_q	$m_s/10$	$m_s/27$	$m_s/5$	$m_s/15$	$m_s/9$
# configs	500–2000	100 → 1000	600–1800	380 → 650	400–2500

Non-US Data Mines

- MILC ensembles with $n_f = 2{+}1$ asqtad sea most extensive anywhere.
- CP-PACS/PACS-CS and BMW ensembles ≈ RBC-UKQCD, but focus on masses, f_K/f_π.
- ETM $n_f = 2$ ensembles: serious SM pheno underway; also have started $n_f = 2{+}1{+}1$.
- CLS generating suite of $n_f = 2$ ensembles.

- All results presented here obtained from USQCD data mines, because:
  - LQCD Projects under review today;
  - non-US SM calculations lag (either $n_f \leq 2$ or not written up).
- All "USQCD" data mines generated partly outside LQCD project: NSF, pre-LQCD; RBRC, UKQCD; DOE leadership class.

USQCD Bread & butter

Spectroscopy

Heavy-light Mesons and Quarkonium

Heavy-Light Mesons

Fermilab/MILC, Phys. Rev. D **83** (2011) 034503

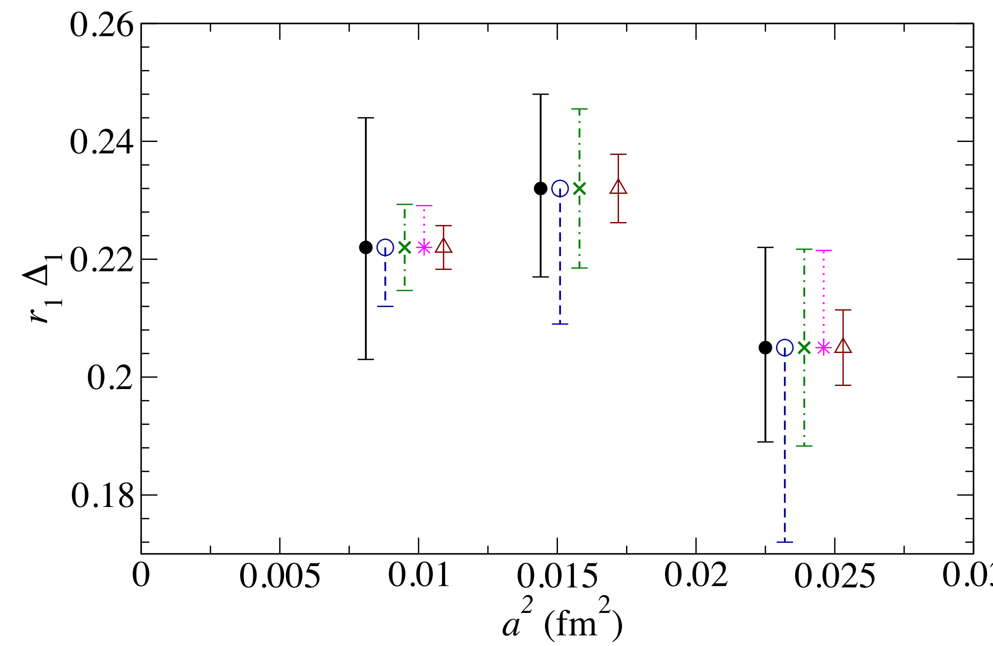
- Heavy-light spin-average used to set (bare) m_c, m_b.
- Hyperfine splittings test.
- Historically disappointing.
- Recent Fermilab/MILC:

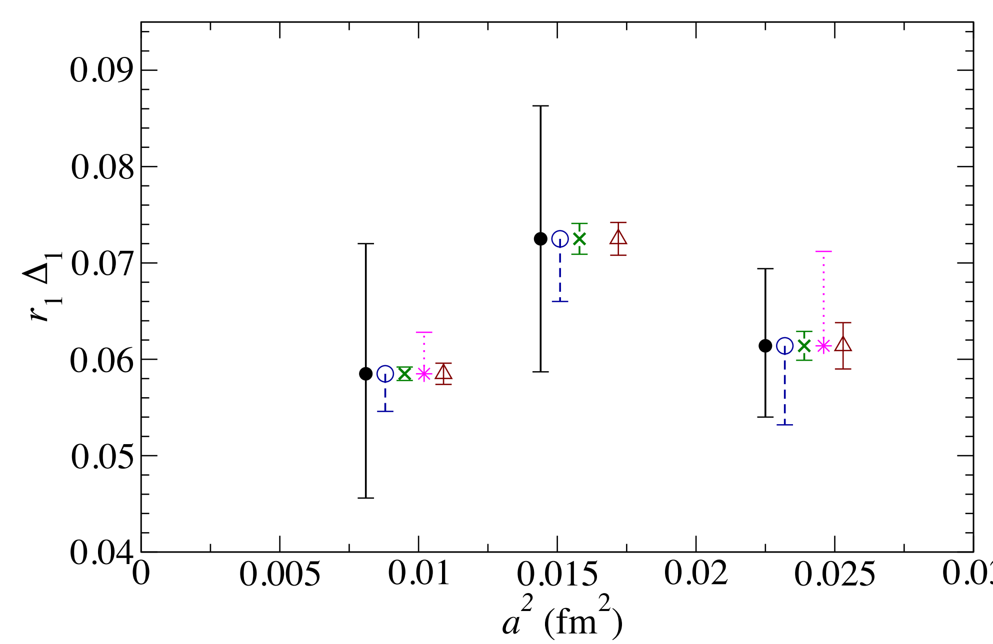
$$\Delta_{D_s} = 145 \pm 15 \text{ MeV}$$

exp't 143.9 ± 0.4 MeV

$$\Delta_{B_s} = 40 \pm 9 \text{ MeV}$$

exp't 41.6 ± 1.5 MeV





Quarkonium

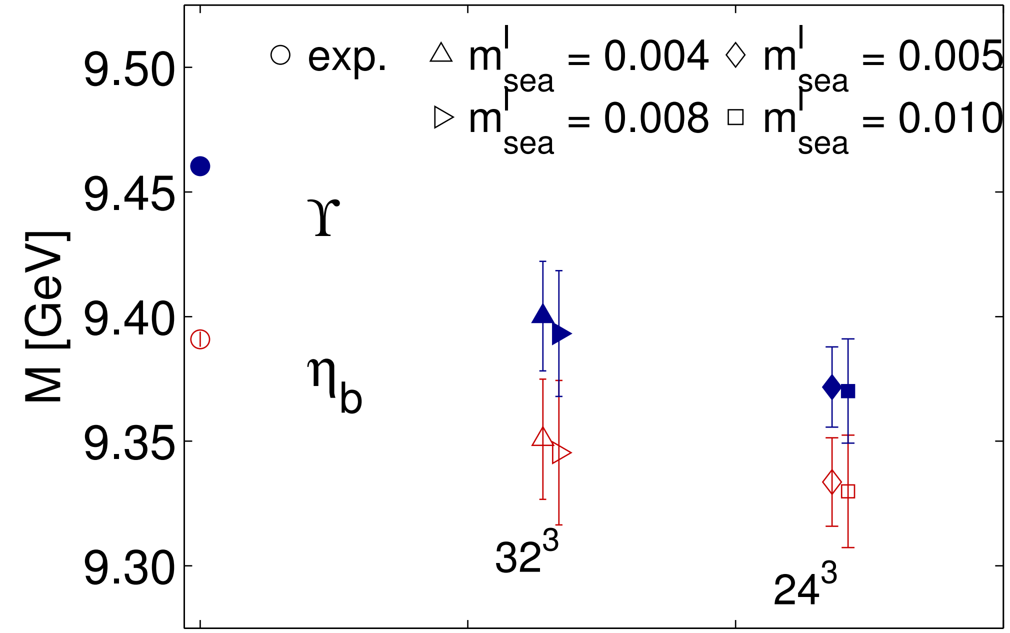
Fermilab/MILC, Phys. Rev. D **81** (2010) 034508

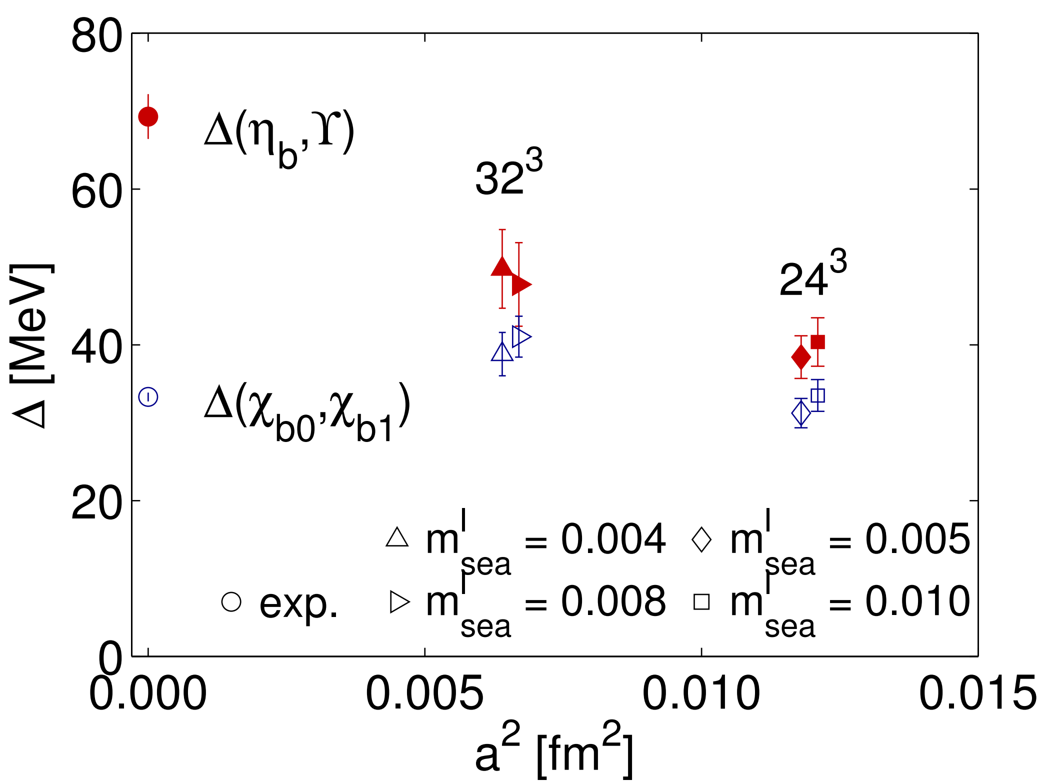
- Quarkonium spectra also provide tests.
- Broad agreement, but errors still large.

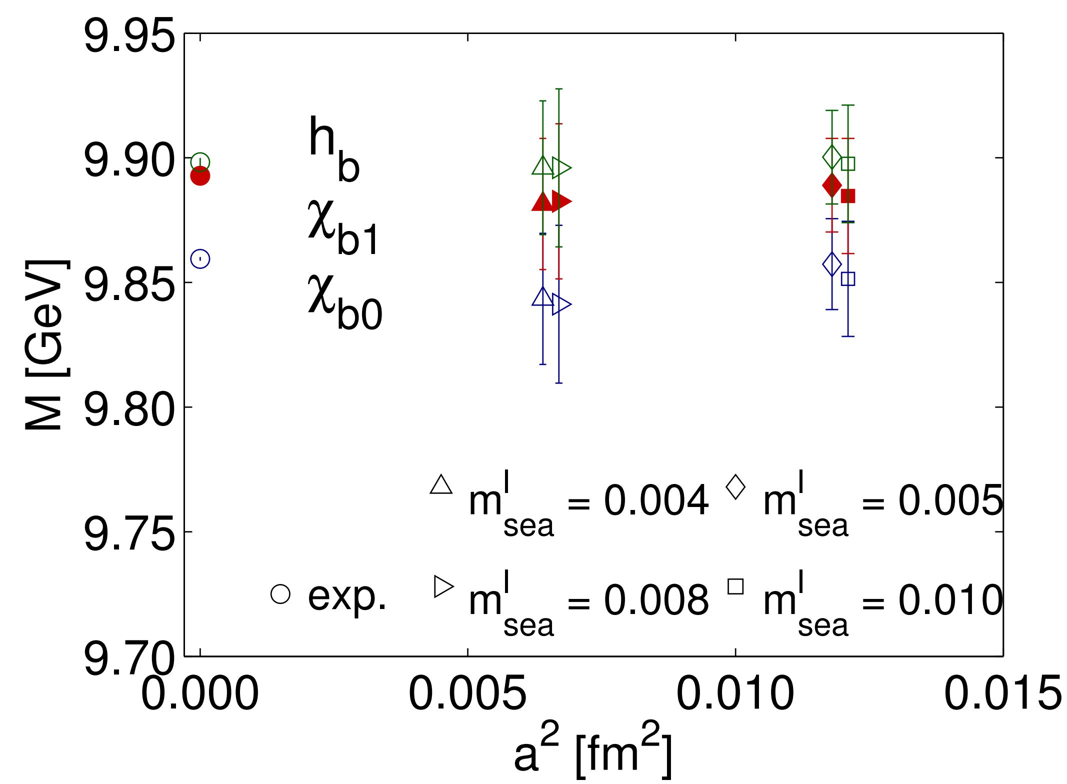
Splitting	Charmonium		Bottomonium	
	This work	Experiment	This work	Experiment
$\overline{1P}$-$\overline{1S}$	$473\pm12^{+10}_{-0}$	457.5 ± 0.3	$446\pm18^{+10}_{-0}$	457.1 ± 0.9
$^1P_1$-$\overline{1S}$	$469\pm11^{+10}_{-0}$	457.9 ± 0.4	$440\pm17^{+10}_{-0}$	—
$\overline{2S}$-$\overline{1S}$	$792\pm42^{+17}_{-0}$	606 ± 1	$599\pm36^{+13}_{-0}$	$(580.5\pm0.8)^1$
1^3S_1-1^1S_0	$116.0\pm7.4^{+2.6}_{-0}$	116.4 ± 1.2	$54.0\pm12.4^{+1.2}_{-0}$	69.4 ± 2.8
$1P$ tensor	$15.0\pm2.3^{+0.3}_{-0}$	16.25 ± 0.07	$4.5\pm2.2^{+0.1}_{-0}$	5.25 ± 0.13
$1P$ spin-orbit	$43.3\pm6.6^{+1.0}_{-0}$	46.61 ± 0.09	$16.9\pm7.0^{+0.4}_{-0}$	18.2 ± 0.2
$1S$ $\bar{s}Q$-$\bar{Q}Q$	$1058\pm13^{+24}_{-0}$	1084.8 ± 0.8	$1359\pm304^{+31}_{-0}$	1363.4 ± 2.3

RBC Collaboration

- Nonperturbatively match Fermilab heavy-quark action with heavy-light.
- Test w/ bottomonium.

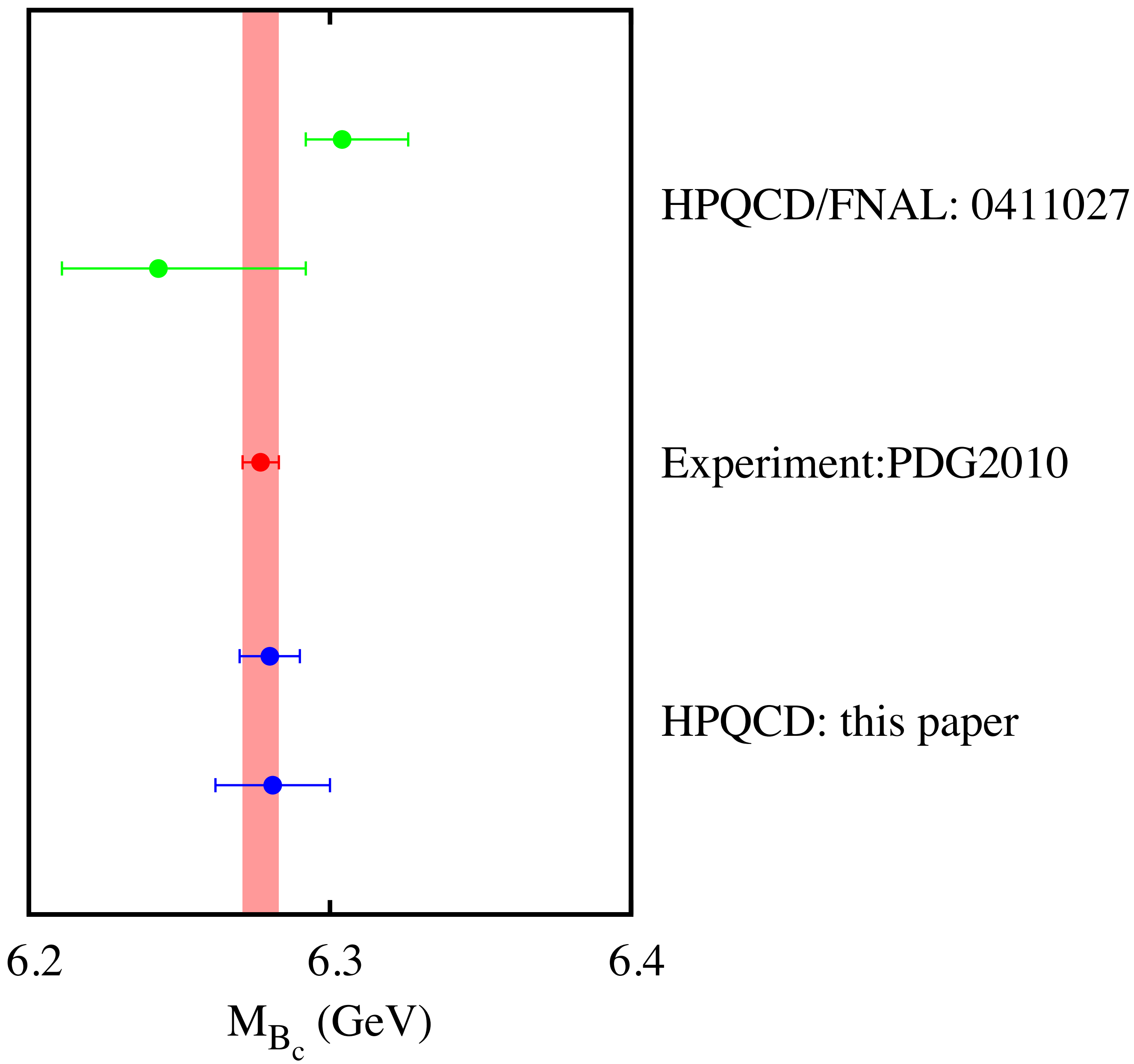






B, B_s, B_c Spectra

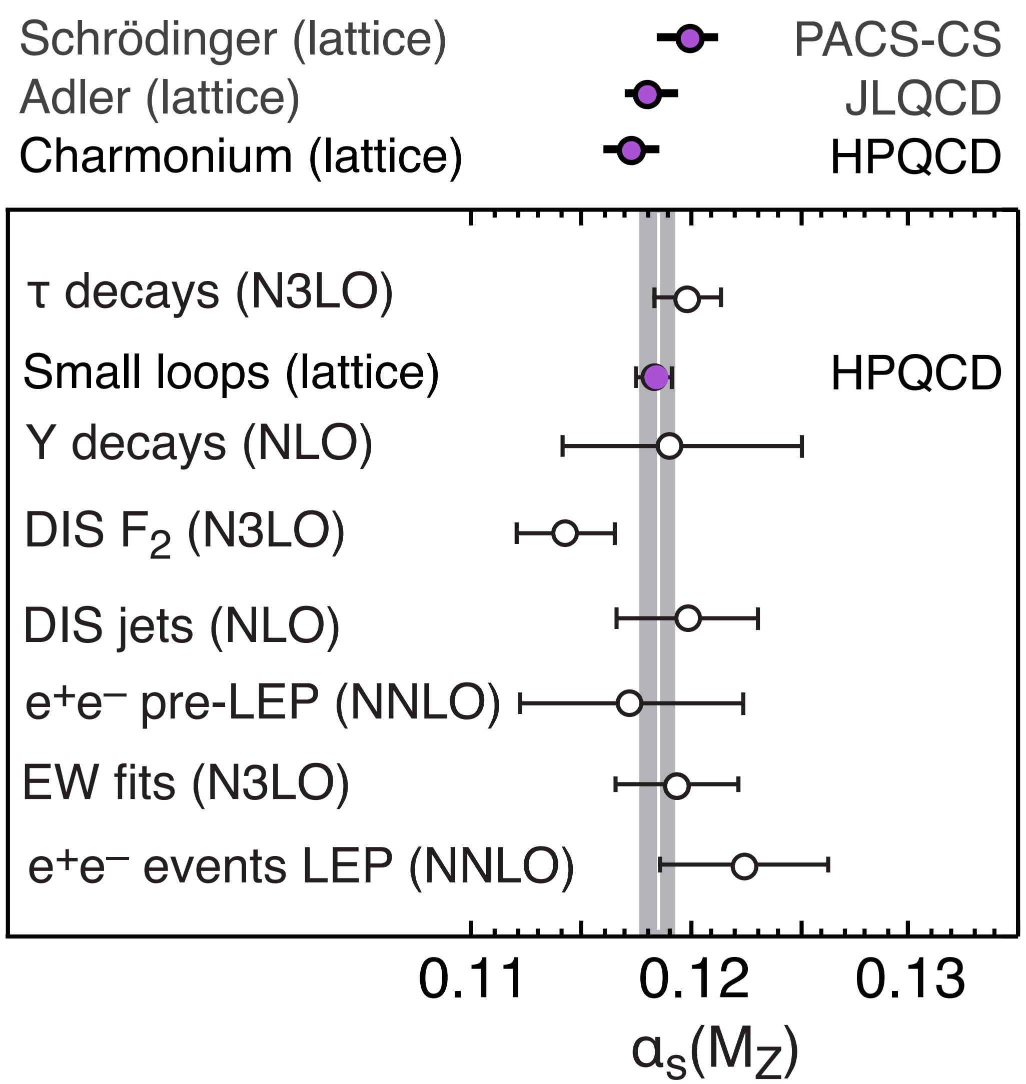
HPQCD, Phys. Rev. D **83** (2010) 014506



- B_c is meson with beauty and charm.
- Mass prediction of LQCD confirmed (2005).
- Now with higher precision.

QCD Parameters

QCD of hadrons = QCD of partons



Bethke, arXiv:0908.1135

- Perhaps more intriguing:
  - determine α_s with lattice QCD;
  - discover new physics in HEP scattering.
- HEP folks still digesting this suggestion.
- February 2011 workshop.

Light Quark Masses

Lattice QCD	MILC	RBC	BMW	HPQCD
$\overline{m}_u(2\text{ MeV})$	1.9 ± 0.2	2.24 ± 0.35	2.15 ± 0.11	
$\overline{m}_u(2\text{ MeV})$	4.6 ± 0.3	4.65 ± 0.35	4.79 ± 0.14	
$\overline{m}_s(2\text{ MeV})$	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
when	2009	2010	2010	2009–10

High-Scale Puzzles

- Inequalities: $m_t > m_b$, $m_c > m_s$, but $m_u < m_d$!
  - needed for proton to be stable.
- Light masses 4 & 9 times electron mass.
- Still nonzero: too large to solve strong *CP* problem ($\vartheta = \theta - \arg\det y \neq 0$?!?):
  - need axion (searched by, e.g., gammeV).

Strong *CP* Problem

- Quark masses arise from Yukawa couplings, $\boldsymbol{m} = v\boldsymbol{y}$ & from low-energy QCD instantons.
- *CP* violation $\propto \vartheta = \theta_{\mathrm{QCD}} - \arg\det \boldsymbol{y} < 10^{-11}$.
- If $\boldsymbol{y}$ has a zero mode, then its phase can be chosen so that $\vartheta = 0$. No *CP* violation.
- Though m_u small, no evidence for instanton effect big enough for a zero mode in $\boldsymbol{y}$.

USQCD Main course

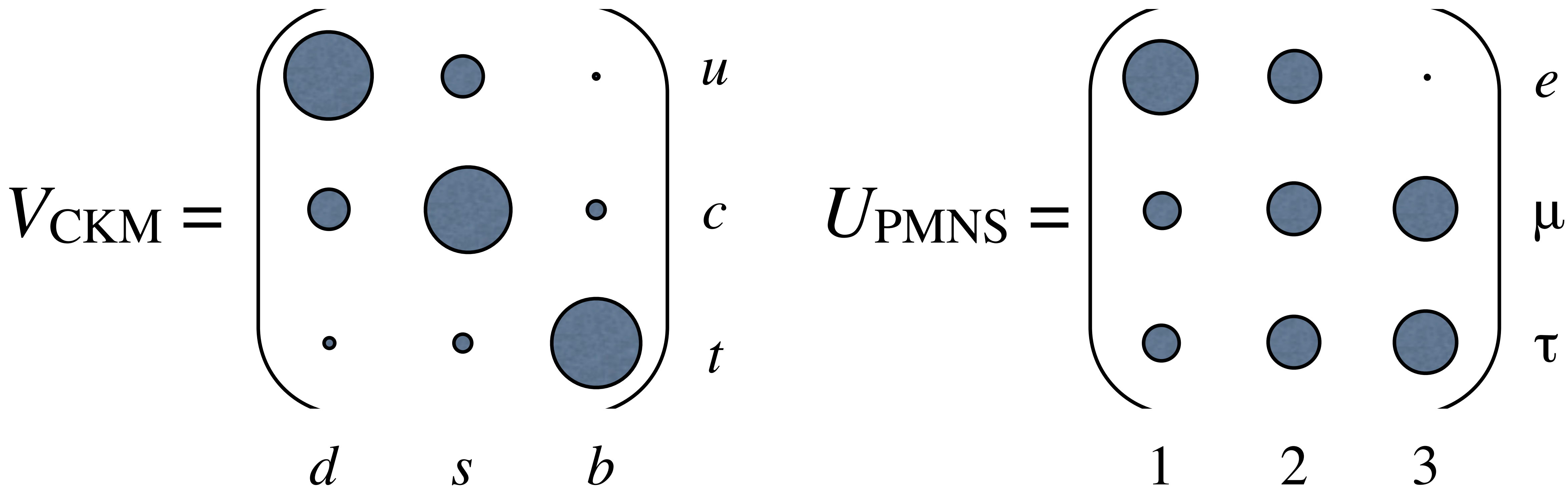
Flavor Physics

cf. Laiho, Lunghi, Van de Water, arXiv:0910.2928

Flavor Physics

- The physics of identity:
  - origin of masses and CP violation;
  - flavor-changing interactions.
- Quarks (CKM) *vs.* leptons (ν oscillations).
- Tight constraints on models of new physics: more lattice QCD $\Rightarrow$ more tests.

Textures of Mixing



- Patterns & their disparity not understood:
  - lies beyond the Standard Model.

SM Flavor Predictions

- For numerous processes:

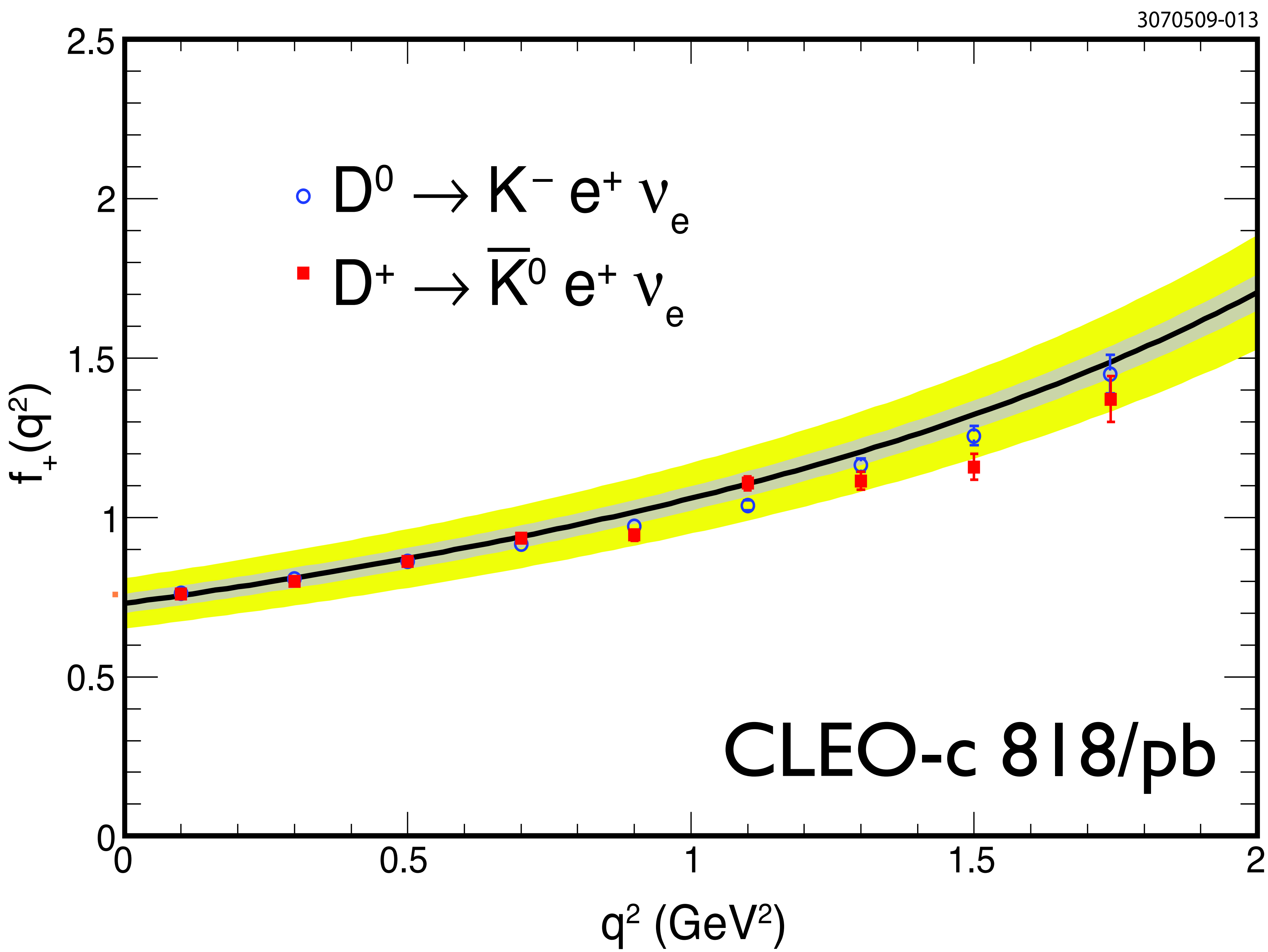
$$\Gamma = \begin{pmatrix} \text{known} \\ \text{factors} \end{pmatrix} \begin{pmatrix} \text{CKM} \\ \text{factors} \end{pmatrix} \begin{pmatrix} \text{QCD} \\ \text{factor} \end{pmatrix}$$

- Decay constants, form factors, bag factors.
- Leptonic decays, semileptonic, meson mixing.
- Same & related QCD factors needed BSM.

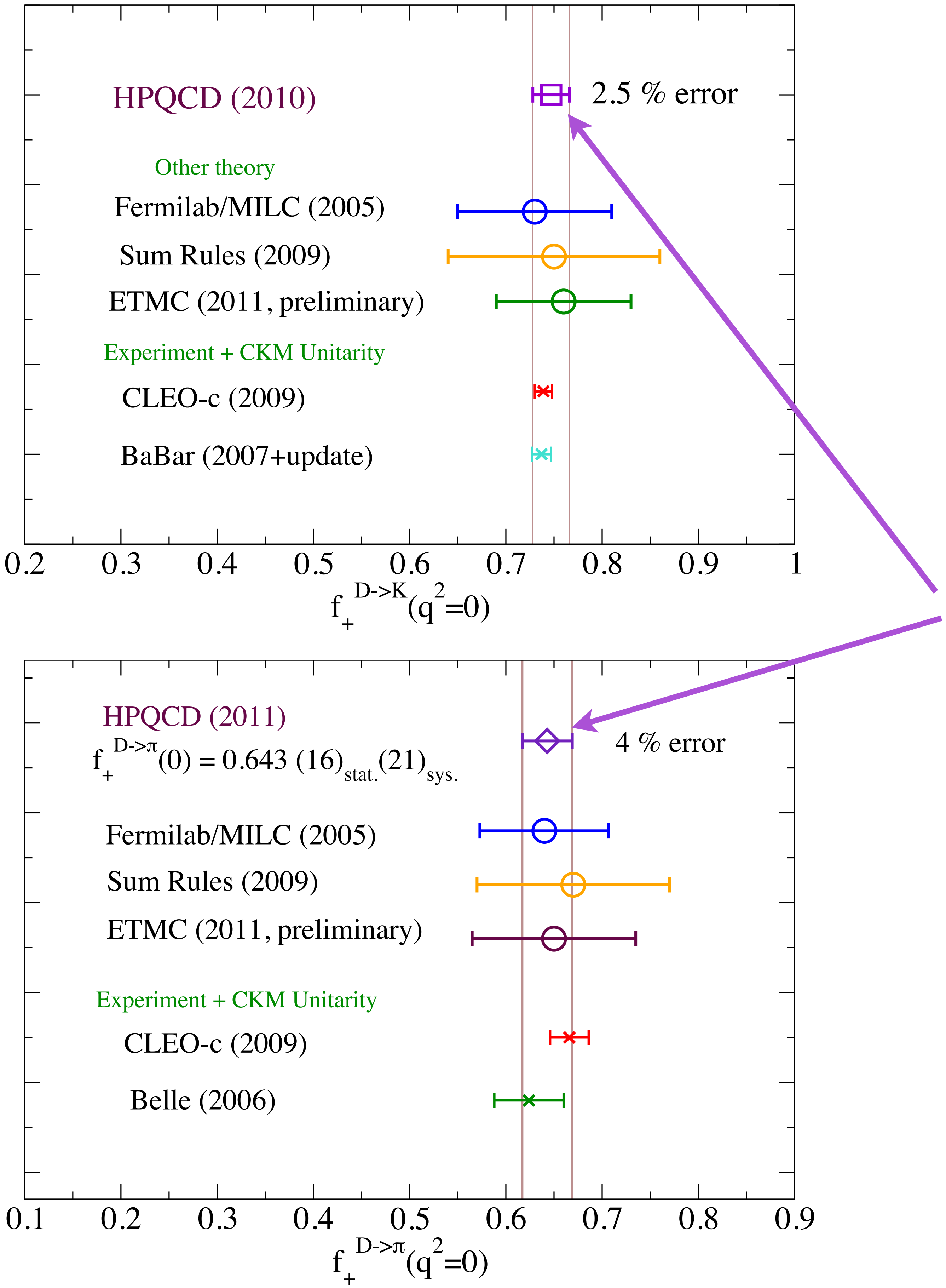
Semileptonic Decays

- Before confronting ideas new physics with flavor, must "measure" CKM.
- Semileptonic decays are usually used: compute form factor, e.g., with lattice QCD.
- Approach used for $|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cd}|$, $|V_{cs}|$, $|V_{cb}|$—all but $|V_{tq}|$.
- In SM, $|V_{tq}|$ follows because V_{CKM} is unitary.

Fermilab/MILC [hep-ph/0408306]: $f_+(q^2)$



HPQCD [arXiv:1008.4562]: $f_+(0) = 0.747 \pm 0.019$



- New normalization (HPQCD) almost as precise as CLEO, BaBar.
- same method as for $K \to \pi l \nu$.
- Preliminary: similar advance for $D \to \pi l \nu$.

Unitarity Triangle

- Dozens of measurements, but unitarity of CKM constrains SM predictions:

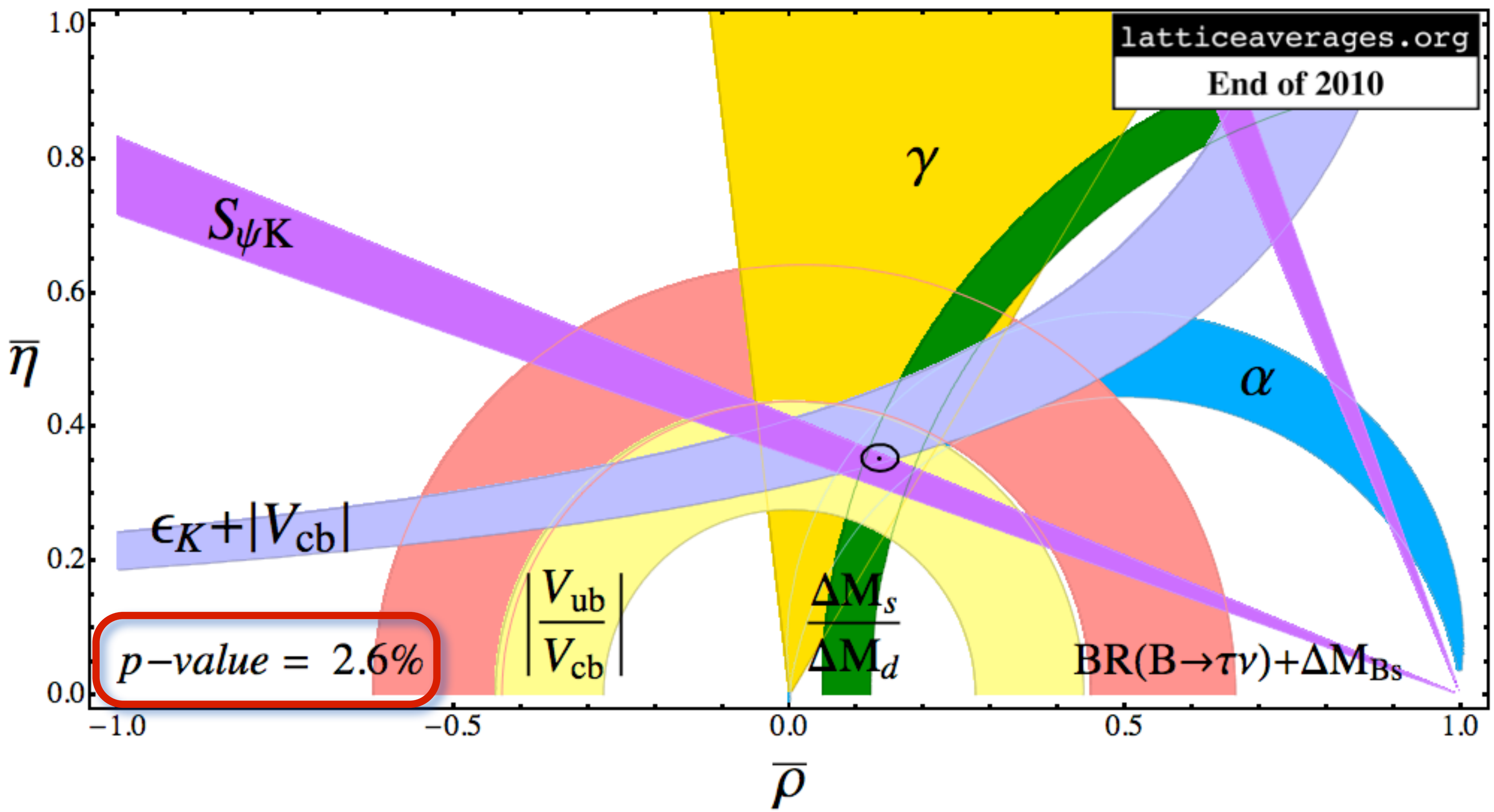
$$V_{ud}^{*}V_{ub} + V_{cd}^{*}V_{cb} + V_{td}^{*}V_{tb} = 0$$

tracing out a triangle on complex plane.

- Results often summarized with this so-called unitarity triangle.

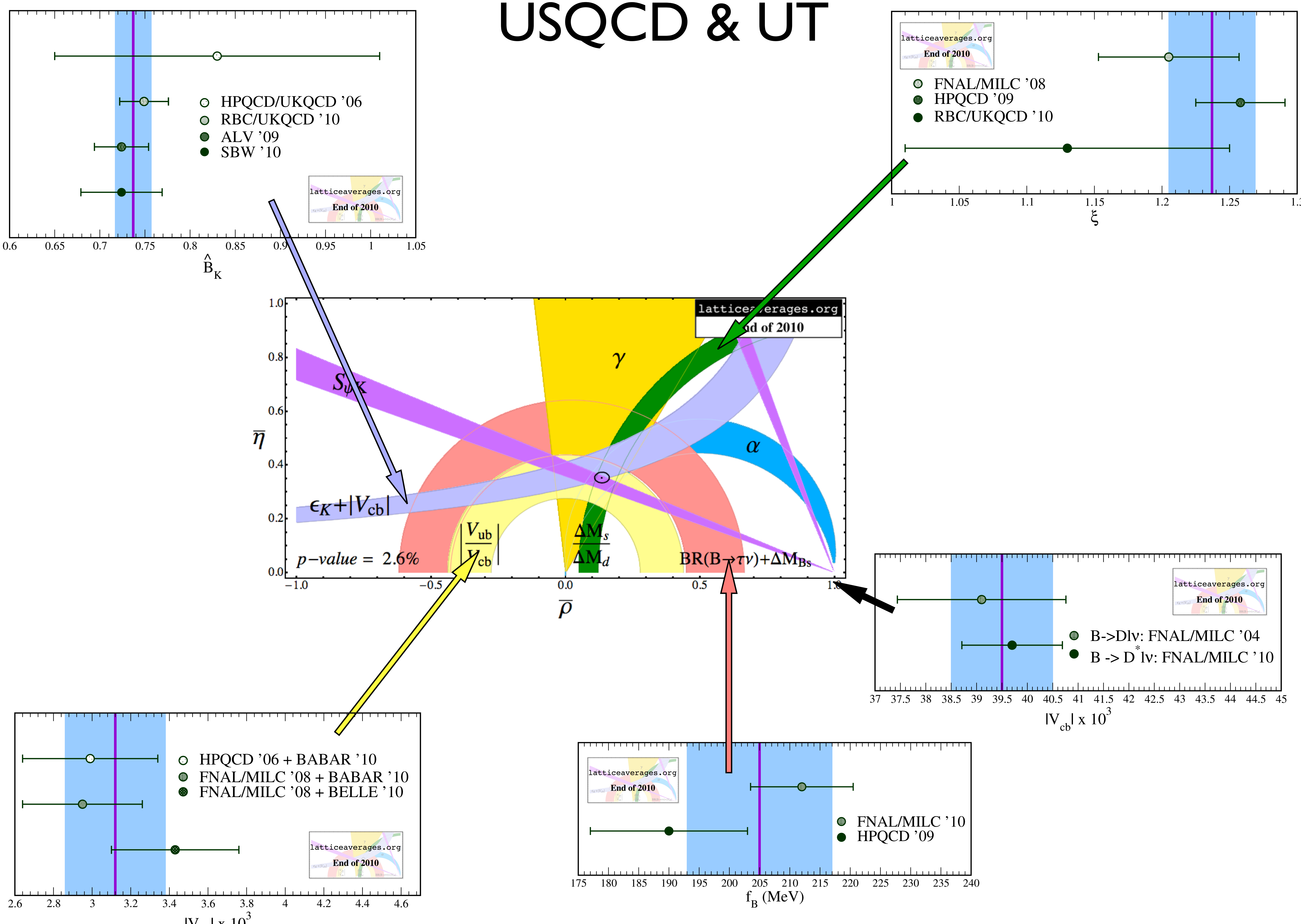
Unitarity Triangle

under tension: Lunghi, Soni; Lenz, Nierste; ….



- "tension" means the global fit prefers NP.

USQCD & UT



HPQCD/UKQCD '06
RBC/UKQCD '10
ALV '09
SBW '10
latticeaverages.org
End of 2010
0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1 1.05
$\hat{B}_K$
FNAL/MILC '08
HPQCD '09
RBC/UKQCD '10
1 1.05 1.1 1.15 1.2 1.25 1.3
ξ
γ
$S_{\psi K}$
α
$\epsilon_K + |V_{cb}|$
$\left|\frac{V_{ub}}{V_{cb}}\right|$
$\frac{\Delta M_s}{\Delta M_d}$
BR(B→τν)+ΔM$_{Bs}$
p−value = 2.6%
$\bar{\eta}$
$\bar{\rho}$
B->Dlν: FNAL/MILC '04
B -> D* lν: FNAL/MILC '10
$|V_{cb}| \times 10^3$
HPQCD '06 + BABAR '10
FNAL/MILC '08 + BABAR '10
FNAL/MILC '08 + BELLE '10
$|V_{ub}| \times 10^3$
FNAL/MILC '10
HPQCD '09
f_B (MeV)

Decay Constants

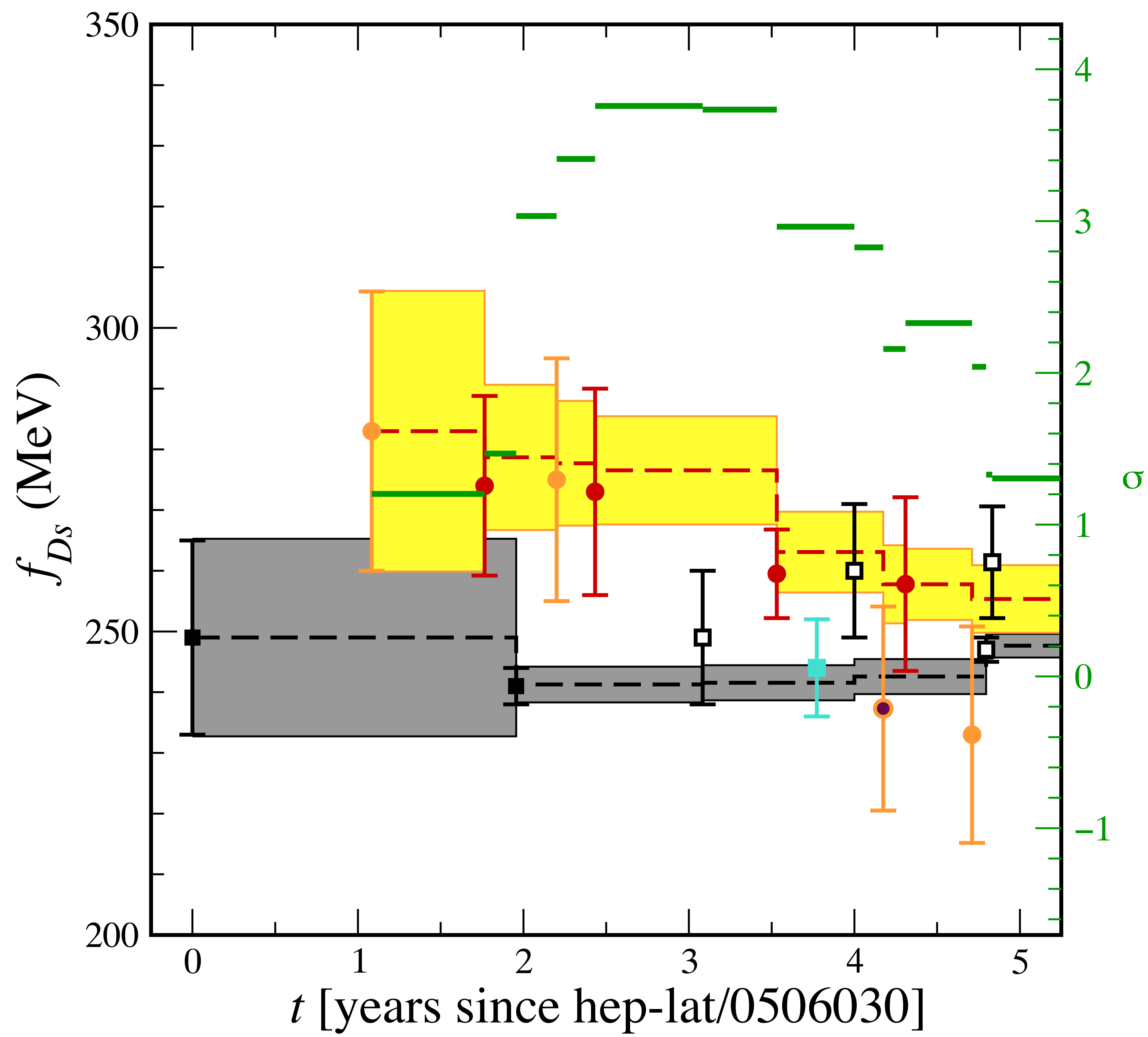
- One of the simplest quantities is decay constant of pseudoscalar mesons, f_π, *etc*.
- Some results (entries in MeV):

meson	MILC	FNAL/MILC	HPQCD	Exp't	Dev (σ)
π	128 ± 3	—	132 ± 2	130.7 ± 0.4	0.4
K	156.0 ± 0.8	—	159 ± 2	159.9 ± 1.5	1.7
D	—	220 ± 9	213 ± 4	206 ± 9	0.1
D_s	—	261 ± 9	248.0 ± 2.5	257.3 ± 5.3	1.6

D_s Puzzle

a deviation where none was expected

- Leptonic decays of $D_{(s)}$.
- "Easy" and validated for $D \to l\nu$.
- Was 3.8σ for $D_s \to l\nu$:
  - exptl statistical σ.
- Can't blame it on charm.
- Now ~1.5σ.

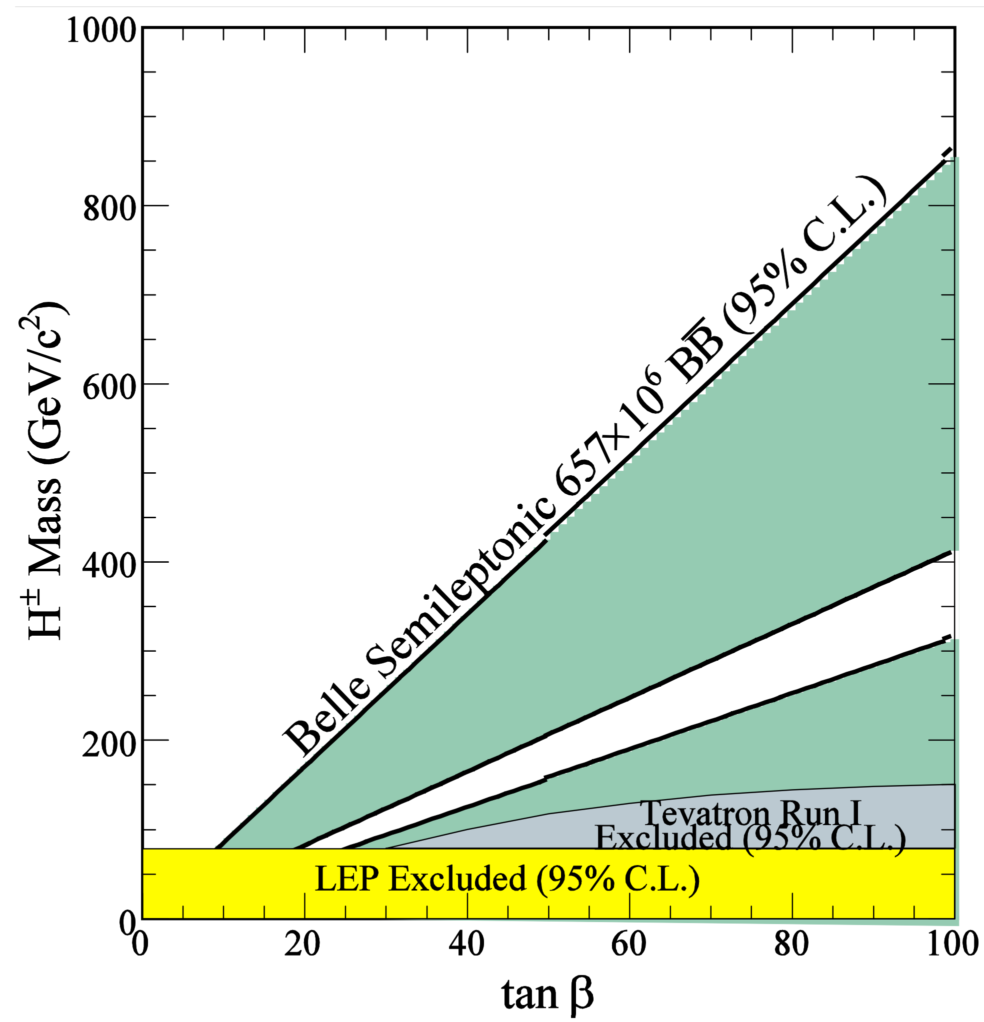


$B \to \tau\nu$

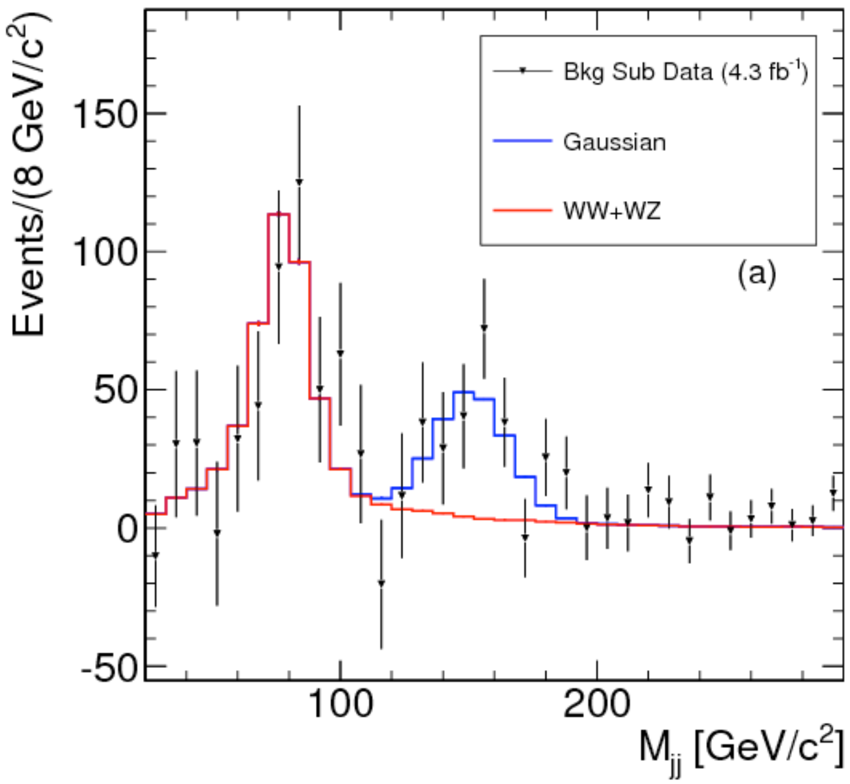
- HFAG (exp't): $\mathrm{BR} = (1.64 \pm 0.34) \times 10^{-4}$.
- With $|V_{ub}|$ and f_B from lattice QCD:
  - $\mathrm{BR} = (0.72 \pm 0.15) \times 10^{-4}$.
- Evidence for a non-Standard amplitude?
  - proposed in any extension of the standard model with a charged Higgs boson.

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 $W^{\pm}$.



Monday, May 9, 2011



$\Rightarrow$ $hypothesis(\Phi_{\mathrm{SM}}, \Phi_{\mathrm{new}})$

$\Downarrow$

$B^0 \leftrightarrow \overline{B}^0$

$B \rightarrow K l^+ l^-$

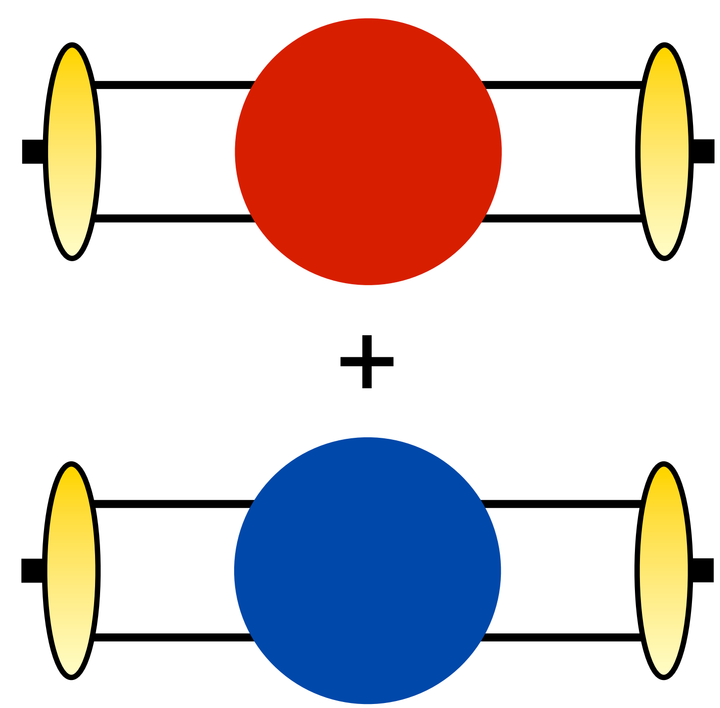
$B \rightarrow \tau\nu$

$K \rightarrow \pi\nu\overline{\nu}$

muon g–2

$\Leftarrow$

lattice QCD



Forecast

Future Error Budgets

- In most cases,* LQCD's CKM errors lag those of the corresponding measurements
  - and BES 3 and LHC-*b* will improve some!
- How will LQCD improve with continued computing (and postdoc) support?

- * except $B_{(s)}$ & $D_{(s)}$ decay constants

Error Budget for $f_B B_B^{1/2}$

Source (%)	HPQCD final		Fermilab/MILC preliminary	
statistics ⊕ chiral extrapolation	2.3	4.1	2.7	4.0
χPT ⊕ light quark discretization	—		0.4	2.5
heavy quark discretization	3.0	2.0	2.0	2.0
$r_1^{3/2}$ (aka setting a)	2.3	2.3	3.0	3.1
tuning quark masses	1.5	1.0	0.6	0.5
$g_{B^*B\pi}$	1.0	1.0	0.3	0.6
matching	4.0	4.0	4.0	4.0
relativistic corrections	2.5	2.5	—	
finite volume	<0.5	<0.5	<0.5	<0.5
TOTAL	6.7	7.1	6.1	7.3
(Elvira Gámiz)	B_s	B_d	B_s	B_d

Error Budget for ξ

(Elvira Gámiz) Source (%)	HPQCD final	Fermilab/MILC preliminary	RBC/UKQCD exploratory
statistics ⊕ chiral extrapolation	2.0	3.1	5–6
χPT ⊕ light quark discretization	—	2.8	7
heavy quark discretization	0.3	0.2	4
$r_1^{3/2}$ (aka setting a)	0.0	0.2	*
tuning quark masses	1.0	0.7	2
$g_{B^*B\pi}$	1.0	0.3	1
matching	0.7	<0.5	2
relativistic corrections	0.4	—	2
finite volume	<0.1	<0.1	1
TOTAL	2.6	4.3	9

ξ in Two Years

(Elvira Gámiz) Source (%)	HPQCD	Fermilab/MILC	improvement factor
statistics ⊕ chiral extrapolation	1.0	1.5	2
χPT ⊕ light quark discretization	—	1.6	2
heavy quark discretization	0.2	0.1	1.5
$r_1^{3/2}$ (aka setting a)	0.0	0.2	
tuning quark masses	0.5	0.3	2
$g_{B^*B\pi}$	0.5	0.2	1.5
matching	<0.5	<0.5	<1?
relativistic corrections	0.4	—	<1?
finite volume	<0.1	<0.1	
TOTAL	1.4	~2.3	~2

Longer View

when \ what	$f_B B_B^{1/2}$	ξ
now	6–7%	3–4%
two years	~4–5%	~1.5–2%
five years	~2%	~1%
(Claude Bernard)		

These are ambitious, but worthy goals, requiring CPU, GPU and HPU.

And yet Tevatron (LHC) reach is 0.4% (0.05%) for ξ.

Muon g–2

Muon, with Spin

- (Semiclassical) Dirac theory says the muon (or electron) magnetic moment should be

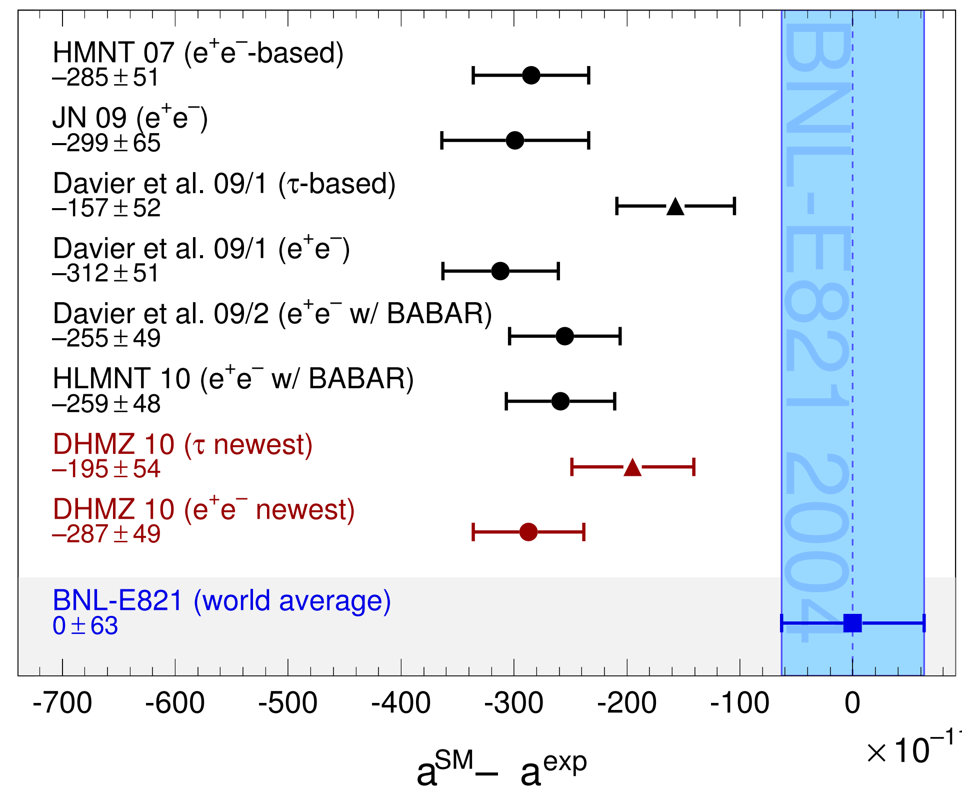
$$\boldsymbol{\mu} = g\frac{e}{2m}\boldsymbol{S}, \quad g_{\text{Dirac}} = 2$$

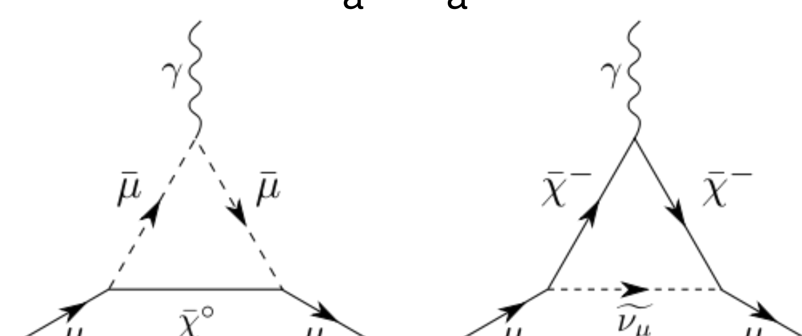
- Quantum mechanics makes $g–2 \neq 0$, from photon cloud *and* any sort of stuff inside it (W & Z, hadrons, nonStandard particles).

Status of $a_\mu = (g-2)/2$

Andreas Höcker, arXiv:1012.0055

how	$10^{11} a_\mu$	10^{11}×error
E821 μ^+	116 592 03–	90
E821 μ^-	116 592 14–	90
E821 $\mu^\pm$	116 592 080	63
SM(τ)	116 591 894	54
SM(e^+e^-)	116 591 802	49
HVP (lo)	6 923	42
HL×L	105	26
E989 μ^+	116 59– ——	**16**

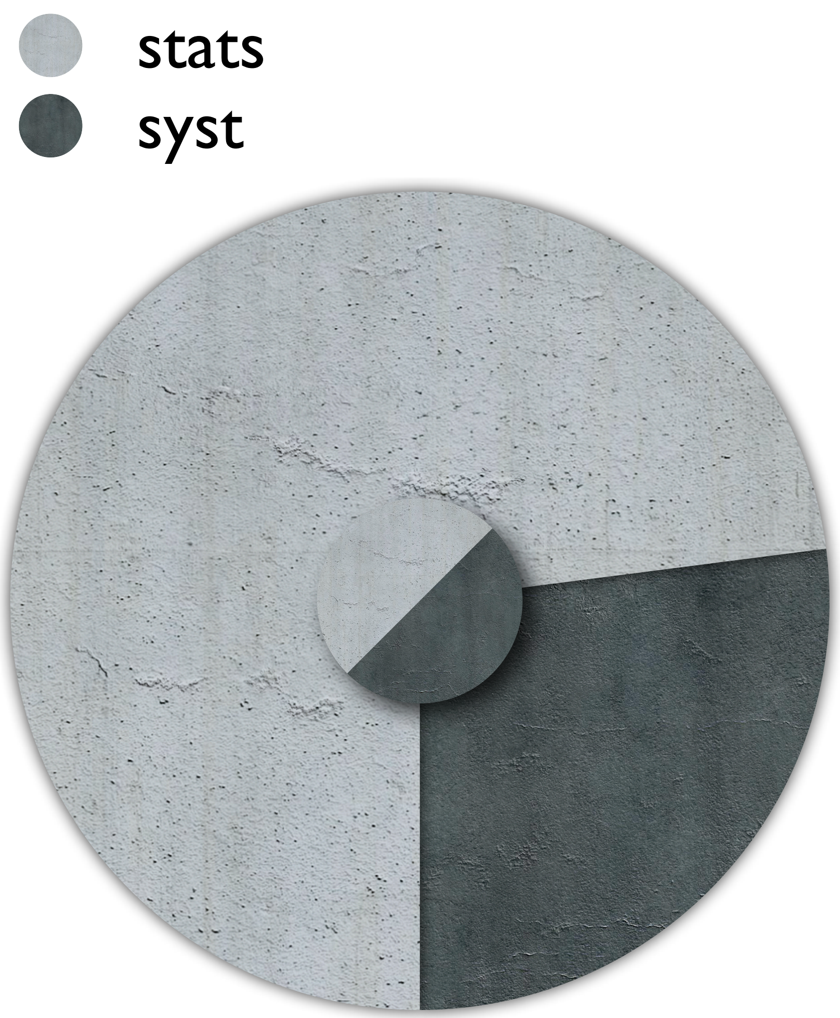




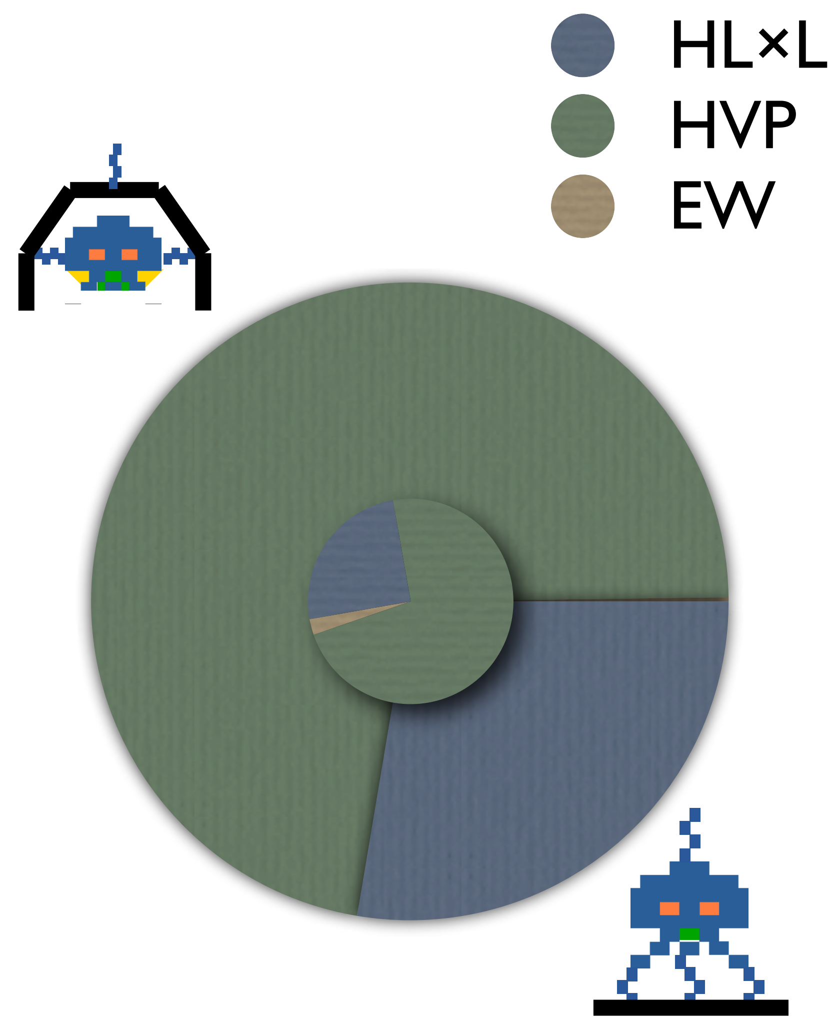
Monday, May 9, 2011

Error Budgets

error ∝ perimeter; area ∝ weight in sum in quadrature



BNL E821 → FNAL E989



Standard Model Calculation

- Only lattice QCD can reduce the theoretical uncertainty to match E989.

- HVP bibliography (omitting conference proceedings subsumed into publications):
  - T. Blum, Phys. Rev. Lett. 91, 052001 (2003) [hep-lat/0212018].
  - M. Göckeler et al., Nucl. Phys. B 688, 135 (2004) [hep-lat/0312032].
  - C. Aubin and T. Blum, Phys. Rev. D 75, 114502 (2007) [hep- lat/0608011].
  - D. B. Renner, X. Feng, K. Jansen, M. Petschlies, arXiv:1103.1392 [hep-lat].
  - A. Jüttner and M. Della Morte, PoS LAT2009, 143 (2009) [arXiv:0910.3755 [hep-lat]].

- HLxL bibliography:
  - M. Hayakawa, T. Blum, T. Izubuchi, N. Yamada, PoS LAT2005, 353 (2005) [hep-lat/0509016].
  - S. Chowdhury et al., PoS LATTICE2008, 251 (2008).
  - T. Blum and S. Chowdhury, Nucl. Phys. B Proc. Suppl. 189, 251 (2009).

- USQCD projects proposed for 2011-2012:
  - Christopher Aubin (PI): Hadronic contributions to the muon g–2 using Asqtad staggered fermions
  - Taku Izubuchi (PI): ... Hadronic contributions to the muon anomalous magnetic moment
  - Saul Cohen (PI): Radiative decays of neutral mesons

Perspective

Outlook

- Lattice QCD shaping HEP's perspective on α_s, quark masses, and flavor physics:
  - in some cases with no alternative.
- Still, however, at the beginning: LQCD precision lags experiment on f_π, f_K, meson mixing, and semileptonic form factors.

- At the outset of the LQCD Project, the USQCD Collaboration forecast the reduction in errors with LQCD resources.

  - A Case Study of the Impact of Increased Computational Resources on Lattice Gauge Theory Calculation: Constraints on Standard Model Parameters

- Key results (B_K, $f_B B_B^{1/2}$, ξ, $|V_{cb}|$ & $|V_{ub}|$) shown here have all met these aspirations.

- Experiments involved:
    - Kaon: E865, ISTRA+, KLOE, KTeV, NA48.
    - Charm: BES-3, FOCUS, CLEO-c, Belle, BaBar.
    - *B*: LHC-b, ATLAS, CMS; BaBar, Belle, CLEO, CDF, D0.
    - Future: rare *K*, super *B* factories.

- Science groups within the LQCD Project (USQCD collaboration) are the world leaders in flavor physics.

- Muon $g - 2$ is a new challenge: unacceptable not to rise to it.

Questions?