Flavor Physics and muon $g - 2$ Summary

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Why precision flavor physics?

We know there is physics beyond the Standard Model from cosmology.

We don't know its scale, but intensity frontier experiments could help us pin this down if a discrepancy with the Standard Model is seen.

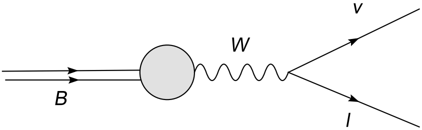
A number of tensions exist, including those within quark flavor physics and with the muon $g-2$. They might go away, or they might become 5σ observations of new physics, as new data pours in.

Lattice QCD is essential to make use of existing and planned experimental results at the intensity frontier. We are (relatively) cheap compared to these experiments. It would be bad for future funding of our field if we didn't come through for the experiments.

CKM matrix

$$\begin{pmatrix}
\mathbf{V_{ud}} & \mathbf{V_{us}} & \mathbf{V_{ub}} \\
\pi \to l\nu & K \to l\nu & B \to l\nu \\
 & K \to \pi l\nu & B \to \pi l\nu \\
\mathbf{V_{cd}} & \mathbf{V_{cs}} & \mathbf{V_{cb}} \\
D \to \pi l\nu & D \to K l\nu & B \to D^{(*)} l\nu \\
D \to l\nu & D_s \to l\nu & \Lambda_b \to \Lambda_c l\nu \\
\mathbf{V_{td}} & \mathbf{V_{ts}} & \mathbf{V_{tb}} \\
\langle B_d | \overline{B}_d \rangle & \langle B_s | \overline{B}_s \rangle &
\end{pmatrix}$$

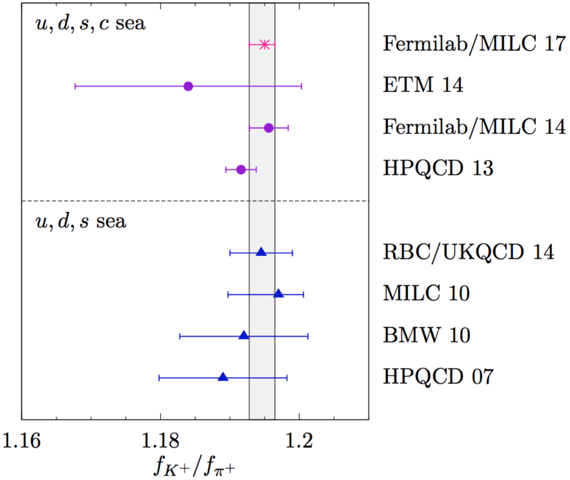
Nonperturbative input needed



$$\Gamma = (\text{known} \quad \text{factor})\,(\text{CKM} \quad \text{factor})(\text{QCD} \quad \text{factor}) \tag{1}$$

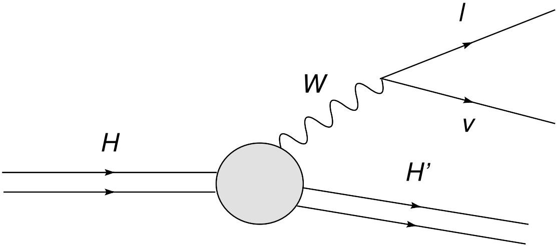
$$\mathcal{B}(B \to \tau \overline{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \tag{2}$$

Kaon and pion decay constant ratio



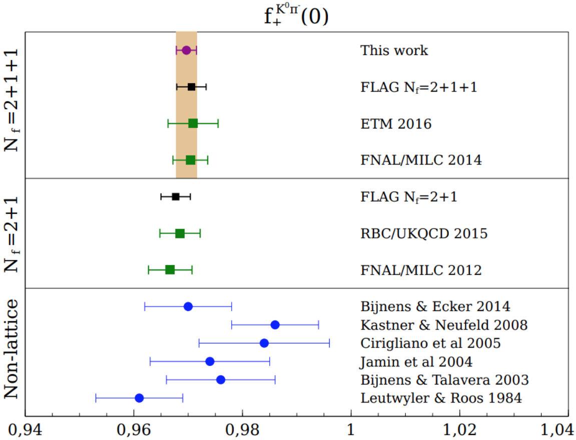
This and other plots courtesy of Steve Gottlieb (arXiv:1812.11211).

Semileptonic decays

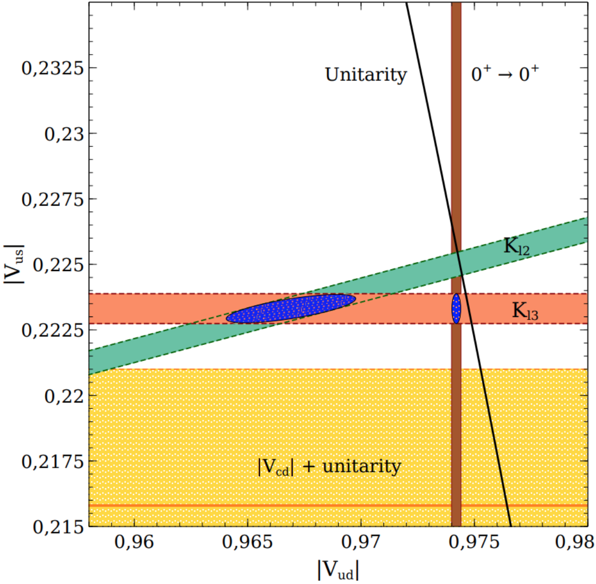


Vertex proportional to $|V_{qq'}|$. In order to extract it, a nonperturbative determination of the form factors is needed.

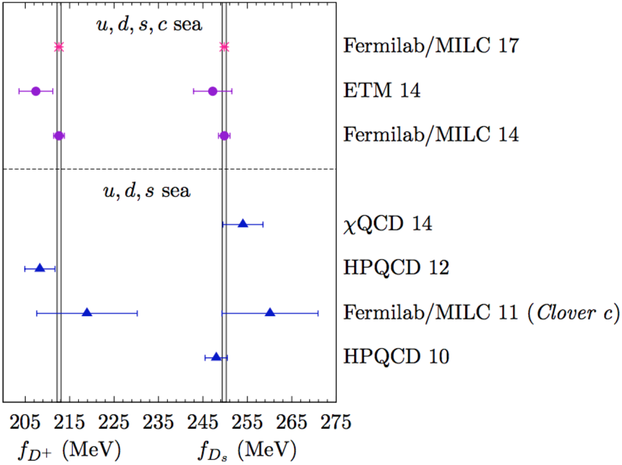
$K \to \pi\ell\nu$ Decay



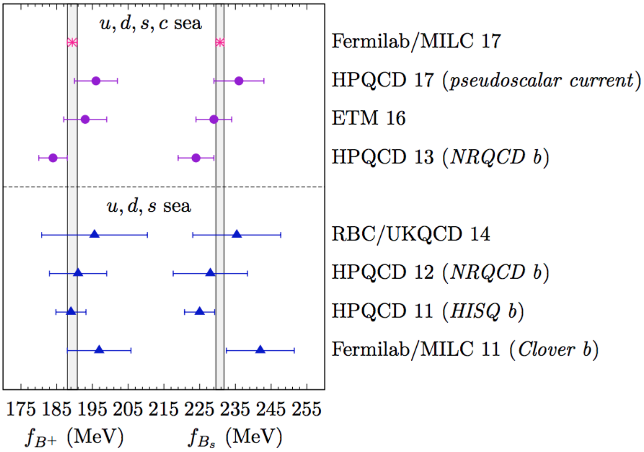
First Row Unitarity



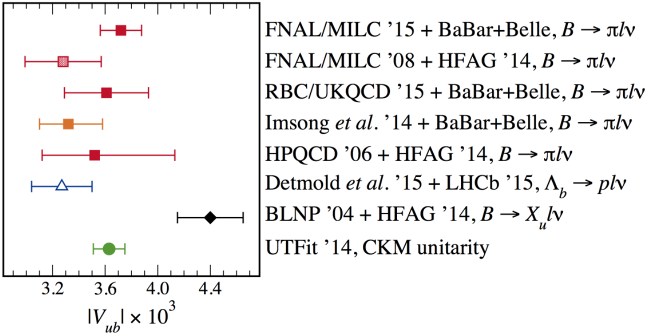
D-meson decay constants



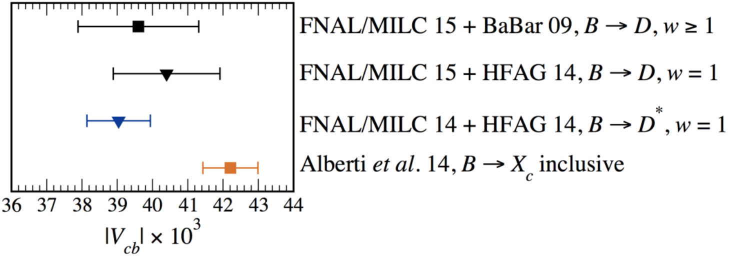
B-meson decay constants



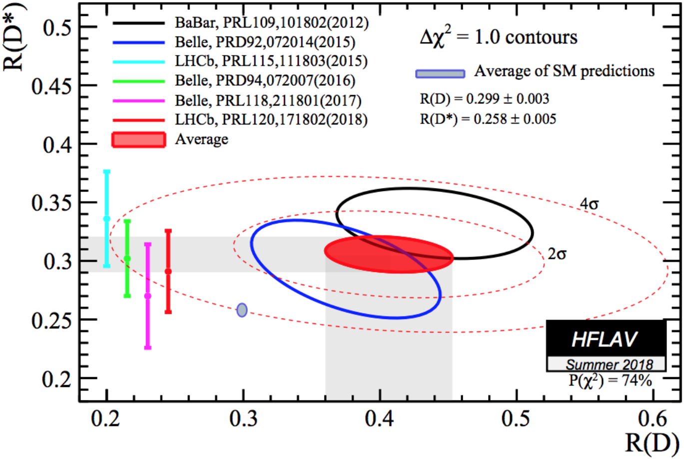
V_{ub} Summary


FNAL/MILC ’15 + BaBar+Belle, $B \to \pi l \nu$
FNAL/MILC ’08 + HFAG ’14, $B \to \pi l \nu$
RBC/UKQCD ’15 + BaBar+Belle, $B \to \pi l \nu$
Imsong *et al*. ’14 + BaBar+Belle, $B \to \pi l \nu$
HPQCD ’06 + HFAG ’14, $B \to \pi l \nu$
Detmold *et al*. ’15 + LHCb ’15, $\Lambda_b \to p l \nu$
BLNP ’04 + HFAG ’14, $B \to X_u l \nu$
UTFit ’14, CKM unitarity
3.2
3.6
4.0
4.4
$|V_{ub}| \times 10^3$

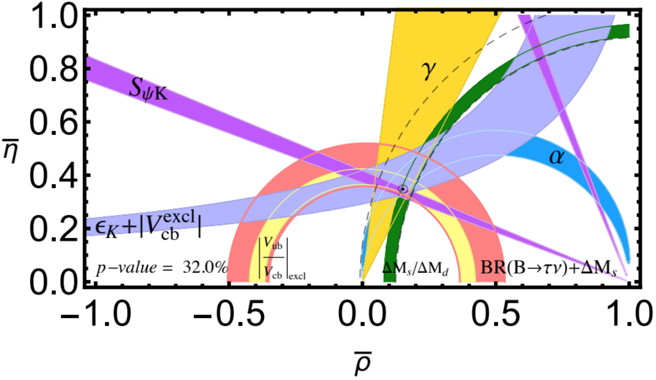
V_{cb} Summary


FNAL/MILC 15 + BaBar 09, $B \to D, w \geq 1$
FNAL/MILC 15 + HFAG 14, $B \to D, w = 1$
FNAL/MILC 14 + HFAG 14, $B \to D^*, w = 1$
Alberti *et al*. 14, $B \to X_c$ inclusive
36 37 38 39 40 41 42 43 44
$|V_{cb}| \times 10^3$

$R(D)$ and $R(D^*)$ Summary



Unitarity Triangle



From arXiv:1602.03560, fit courtesy of Enrico Lunghi.

$K \to \pi\pi$

$$\Re(\varepsilon'_K/\varepsilon) \sim \frac{\omega}{\sqrt{2}|\varepsilon_K|}\left(\frac{\Im(A_2)}{\Re(A_2)} - \frac{\Im(A_0)}{\Re(A_0)}\right) \tag{3}$$

where $\omega = \Re(A_2)/\Re(A_0)$, $A(K^0 \to \pi\pi(I)) = A_I e^{i\delta_I}$.

ε'/ε requires the $\Delta I = 1/2$ channel.

$$\mathrm{Re}(\varepsilon'_K/\epsilon_K) = (1.66 \pm 0.23) \times 10^{-3} \tag{4}$$

RBC/UKQCD result is

$$\mathrm{Re}(\varepsilon'_K/\epsilon_K) = 1.38(5.15)(4.43) \times 10^{-4}. \tag{5}$$

RBC/UKQCD $K \to \pi\pi$ calculation

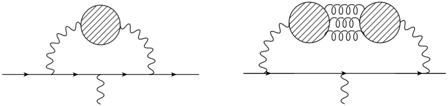
Direct approach of Lellouch-Lüscher.

To give the pions momentum without having to fit excited states, twisted boundary conditions ($\Delta I = 3/2$) or G-parity ($\Delta I = 1/2$) are used (Kim and Christ, Lattice 2002 [hep-lat/0210003], Sachrajda and Villadoro hep-lat/0411033).

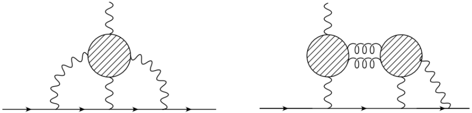
Big challenges in $\Delta I = 1/2$ channel, including power divergences, disconnected diagrams, potentially large excited state contamination. Improvements are underway by RBC/UKQCD.

Muon $g-2$ hadronic contributions

Hadronic vacuum polarization

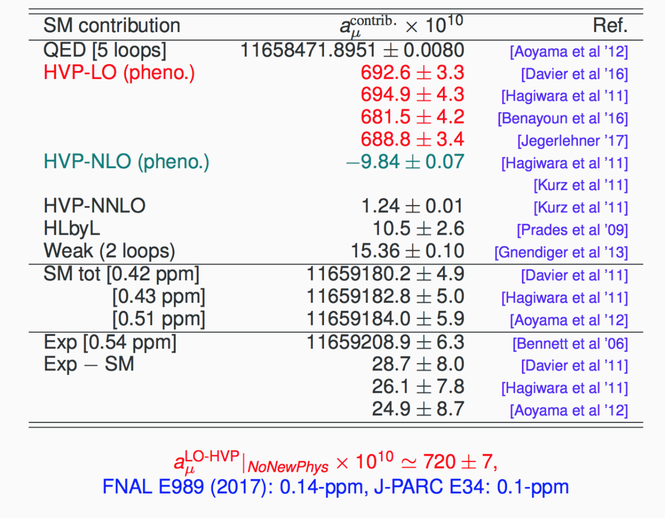


Hadronic light-by-light



(Figs from Project X white paper)

Muon $g-2$ theory error budget

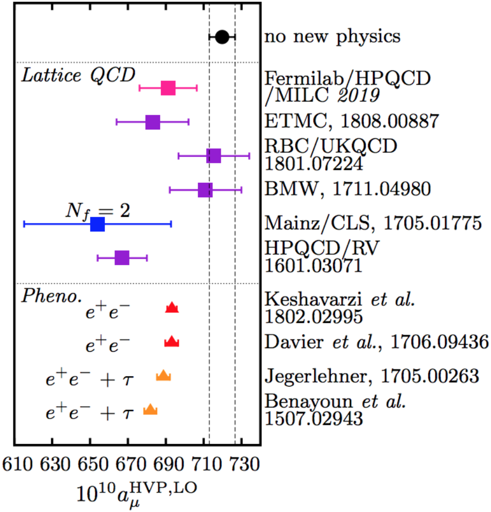


SM contribution	$a_\mu^{\text{contrib.}} \times 10^{10}$	Ref.
QED [5 loops]	11658471.8951 ± 0.0080	[Aoyama et al '12]
HVP-LO (pheno.)	692.6 ± 3.3	[Davier et al '16]
	694.9 ± 4.3	[Hagiwara et al '11]
	681.5 ± 4.2	[Benayoun et al '16]
	688.8 ± 3.4	[Jegerlehner '17]
HVP-NLO (pheno.)	-9.84 ± 0.07	[Hagiwara et al '11] [Kurz et al '11]
HVP-NNLO	1.24 ± 0.01	[Kurz et al '11]
HLbyL	10.5 ± 2.6	[Prades et al '09]
Weak (2 loops)	15.36 ± 0.10	[Gnendiger et al '13]
SM tot [0.42 ppm]	11659180.2 ± 4.9	[Davier et al '11]
[0.43 ppm]	11659182.8 ± 5.0	[Hagiwara et al '11]
[0.51 ppm]	11659184.0 ± 5.9	[Aoyama et al '12]
Exp [0.54 ppm]	11659208.9 ± 6.3	[Bennett et al '06]
Exp − SM	28.7 ± 8.0	[Davier et al '11]
	26.1 ± 7.8	[Hagiwara et al '11]
	24.9 ± 8.7	[Aoyama et al '12]

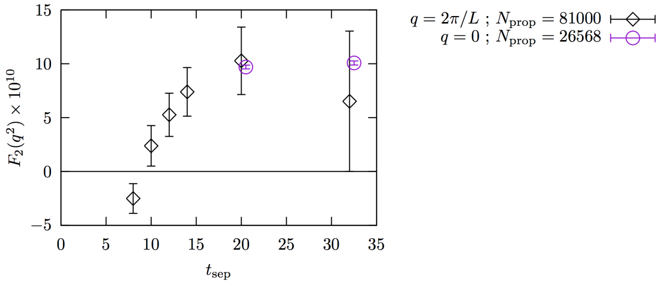
$a_\mu^{\text{LO-HVP}}|_{NoNewPhys} \times 10^{10} \simeq 720 \pm 7$,

FNAL E989 (2017): 0.14-ppm, J-PARC E34: 0.1-ppm

Muon $g-2$ hadronic vacuum polarization



Muon $g-2$ hadronic light-by-light



Result from RBC/UKQCD (reviewed by Luchang Jin at Lattice 2018) shows improved method compared to the original Blum et al. subtraction method. New method uses point sources for photon propagators so they are exact. Importance sampling is used to perform the 4-D summation. Moment method allows direct calculation at $q \to 0$ limit.

Other improvements: Calculate at physical pion mass, treatment of QED in infinite volume, include disconnected contributions.

Conclusion

Lattice QCD is crucial to make use of planned and existing experiments doing precision tests of the Standard Model.

A number of interesting tensions currently exist. Further work will provide important constraints on new physics scenarios and if we are lucky, a discovery...