B-meson semileptonic rare decay phenomenology from lattice QCD

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Fermilab

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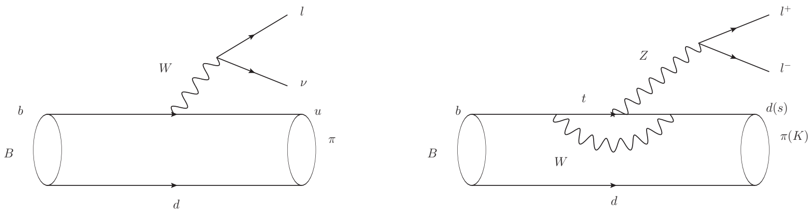
Heavy to light semileptonic decays



Tree-level diagram

Loop-level diagram

- B-meson semileptonic decays through tree-level diagram ($b \to ul\nu$). For example, $B \to \pi l\nu$, $B_s \to Kl\nu$, $\Lambda_b \to pl\nu$
- B-meson semileptonic decays through loop-level diagram ($b \to s(d)ll$) For example, $B \to K(\pi)l^+l^-$, $B \to K(\pi)\nu\bar{\nu}$, $\Lambda_b \to \Lambda ll$

Standard Model prediction

The Standard Model prediction can be written in a generic form:

$$\text{Theo. pred.} \quad = \quad (\text{prefactors}) \times (\text{CKMfactor}) \times \langle f|\hat{O}|i\rangle$$

- Prefactors contain the Wilson coefficients (short distance physics).
- CKM factor depends on the processes.
- Lattice QCD calculates $\langle f|\hat{O}|i\rangle$ non-perturbatively from first principle. (long distance physics)

Hadronic matrix elements and form factors

- Matrix elements in $B \to K(\pi)ll$ and $B \to \pi l\nu$ processes:

$\langle B(p)|\bar{b}\gamma^\mu s|K(k)\rangle$, $\langle B(p)|\bar{s}\sigma^{\mu\nu}b|K(k)\rangle$

$$\langle B(p)|\bar{b}\gamma^\mu s|K(k)\rangle = f_+(p^\mu + k^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu) + f_0\frac{m_B^2 - m_K^2}{q^2}q^\mu$$

$$= \sqrt{2m_B}\left[f_\parallel \frac{p^\mu}{m_B} + f_\perp k_\perp^\mu\right]$$

$$\begin{cases} f_\parallel(E_K) = \dfrac{\langle B(p)|\bar{b}\gamma^0 s|K(k)\rangle}{\sqrt{2m_B}} \\ f_\perp(E_K) = \dfrac{\langle B(p)|\bar{b}\gamma^i s|K(k)\rangle}{2\sqrt{m_B}}\dfrac{1}{p_i} \end{cases}$$

$$\begin{cases} f_0(E_K) = \dfrac{2m_B}{m_B^2 - m_K^2}\left[(m_B - E_K)f_\parallel(E_K) + (E_K^2 - m_K^2)f_\perp(E_K)\right] \\ f_+(E_K) = \dfrac{1}{\sqrt{2m_B}}\left[f_\parallel(E_K) + (m_B - E_K)f_\perp(E_K)\right] \end{cases}$$

Hadronic matrix elements and form factors

Semileptonic $B \to Kll$ transition from tensor current:

$$q_\nu \langle K(k)|\bar{s}\sigma^{\mu\nu} b|B(p)\rangle = \frac{i f_T}{m_B + m_K}\left[q^2(p^\mu + k^\mu) - (m_B^2 - m_K^2)q^\mu\right]$$

Solve for f_T:

$$f_T = \frac{m_B + m_K}{\sqrt{2m_B}} \frac{\langle K(k)|ib\sigma^{0i}s|B(p)\rangle}{\sqrt{2m_B}k^i}$$

Lattice ensembles used in $B \to K(\pi)ll$ calculations

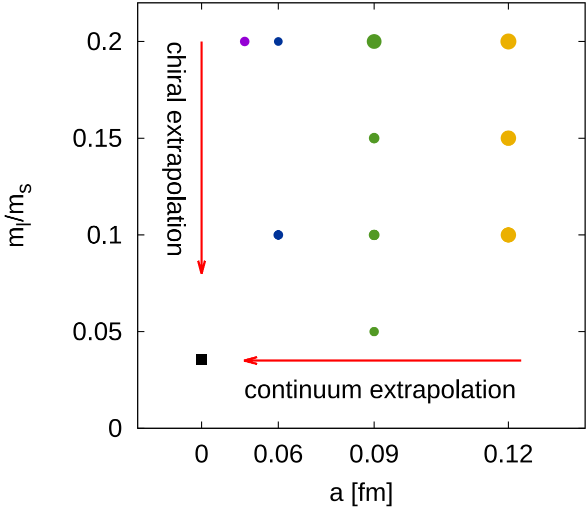


Figure : Ensembles of QCD gauge field configurations used in the simulations.

$f_\parallel$, $f_\perp$ chiral-continuum extrapolations

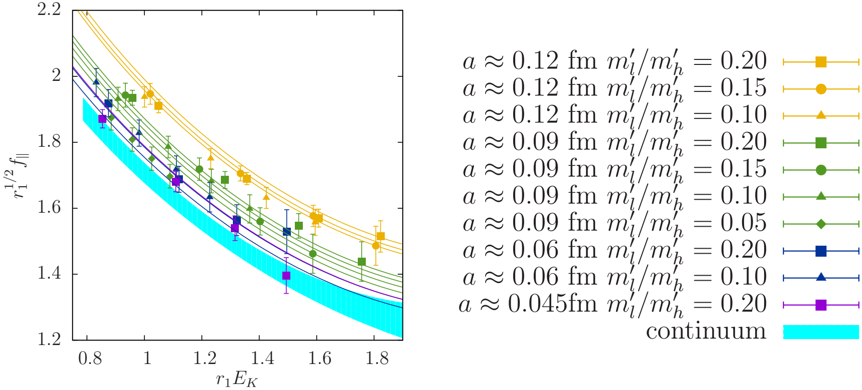


Figure : Chiral-continuum extrapolation on $f_\parallel$ (left).

- Lattice-QCD simulations are in the low $E_{K(\pi)}$ region.
- Form factors in the full q^2 range are obtained from z-expansion fit.

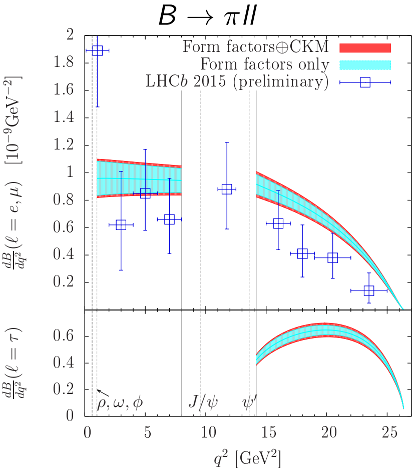
Heavy to light semileptonic rare decays (Loop level)

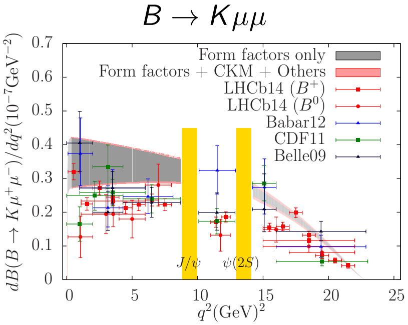
New results on B-meson rare decays

	Fermilab/MILC	Fermilab/MILC	Detmold and Meinel
process	$B \to Kll$,	$B \to \pi ll$	$\Lambda_b \to \Lambda$
kinematics	full q^2	full q^2	full q^2
ensembles	MILC asqtad	MILC asqtad	RBC/UKQCD DWF
N_f	2+1	2+1	2+1
a	4/0.045-0.12	4/0.045-0.12	2/0.09-0.12
$M_\pi^{\min}$	260	260	227
light quark	asqtad	asqtad	DWF
b quark	Fermilab	Fermilab	RHQ
Ref.	PRD.93.025026	PRL.115.152002	PRD.93.074501

- PRD.93.034005 (Fermilab/MILC, B rare decay pheno)
- PRD.94.013007 (Meinel and van Dyk, Λ_b rare decay pheno)
- PRD.88.054509, PRL.111.162002 (HPQCD, $B \to Kll$ ff and pheno), PRD.89.094501, PRL.112.212003 ($B \to K^*ll$ ff and pheno)

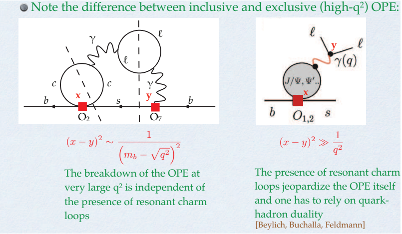
Standard Model predictions of B rare decays



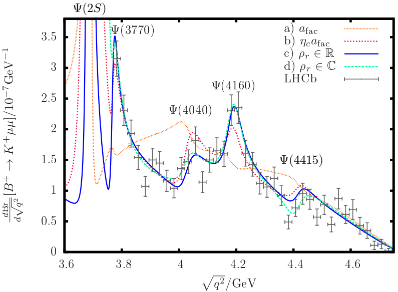


- Standard-Model predictions of the differential decay rate in $B \to \pi ll$ and $B \to Kll$ process (PRL.115.152002, PRD.93.034005).

Resonance states and non-lattice errors



E. Lunghi at KITP 2015

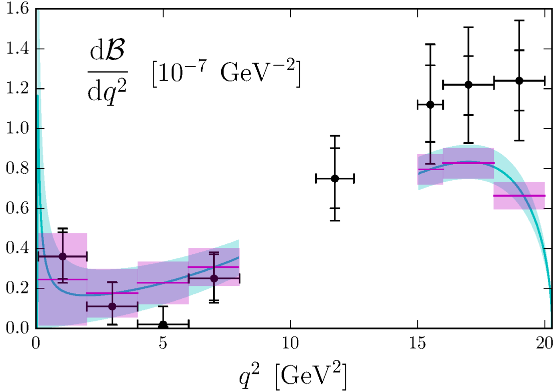


1406.0566

- As the form factor errors become smaller, cautious is needed to treat the non-lattice errors in the Standard-Model predictions.
- The resonance states could introduce the violation of quark-hadron duality in the high q^2 range (1406.0566, PRD.70.114005, EPJC.71.1625).
- For all non-lattice errors, please refer to E. Lunghi's talk at KITP Program "Lattice Gauge Theory for the LHC and Beyond"

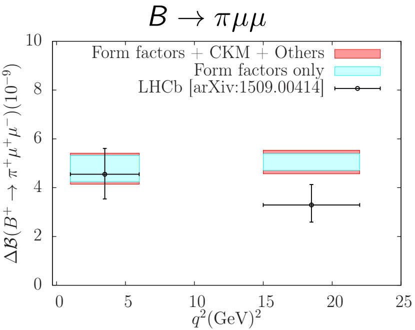
Standard Model predictions of B rare decays

$\Lambda_b \to \Lambda l l$



- Standard-Model predictions of the differential decay rate in $\Lambda_b \to \Lambda l l$ processes. (PRD.93.074501)

Standard Model predictions of B rare decays



- Four measurements combined disfavor the Standard-Model hypothesis at the 1.7σ level (PRD.93.034005).

Constraints on New Physics.

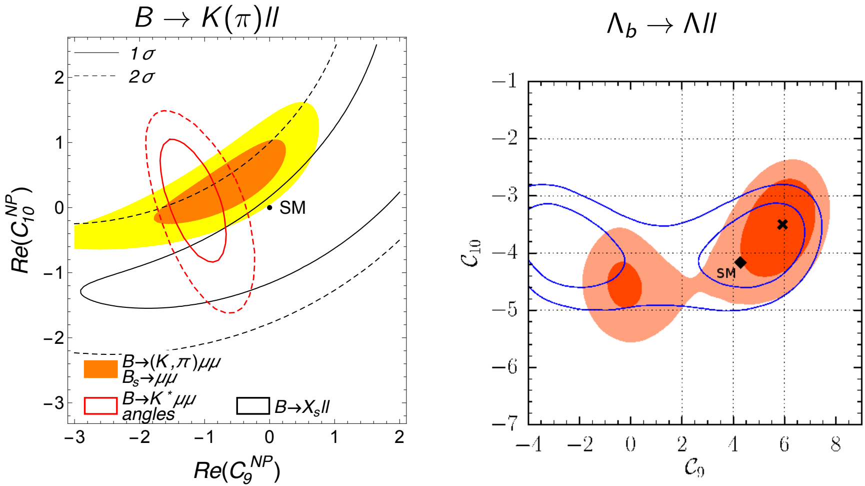
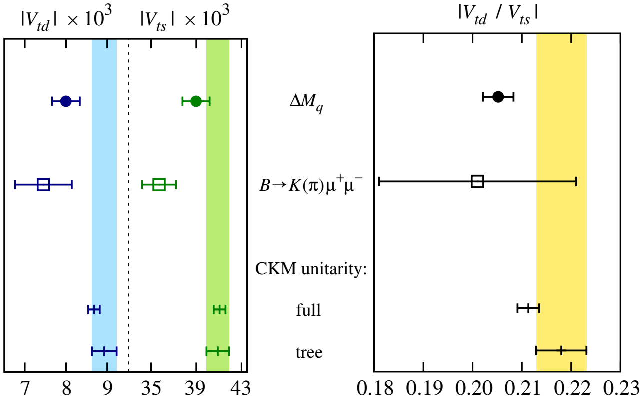


Figure : Constraints to new physics from $B \to K(\pi)ll$ plus $B_s \to \mu\mu$ decays (PRD.93.034005) and $\Lambda_b \to \Lambda ll$ decay (PRD.94.013007).

Impact from new B-mixing results



- Determinations of $|V_{td}|$ and $|V_{ts}|$, and their ratio from B-mixing and rare $B \to K(\pi)\mu\mu$ decays (PRD.93.113016, PRD.93.034005).
- Tension between FCNC and tree processes: results from B-mixing (rare B decays) lie below the determinations from CKMfitters full global unitarity triangle fit using only tree-level inputs by 1.2–2.1σ.

Theoretical studies of the $B \to K(\pi)\nu\bar{\nu}$

In the Standard Model, the decay rate for $B \to K(\pi)\nu\bar{\nu}$ is:
(arXiv:1409.4557, arXiv:0902.0160)

$$\frac{dB(B \to K(\pi)\nu\bar{\nu})}{dq^2} = 3\tau_B |N_{K(\pi)}|^2 \frac{X_t^2}{(\sin^2\theta_W)^4} \rho_{K(\pi)}(q^2) \,, \qquad (1)$$

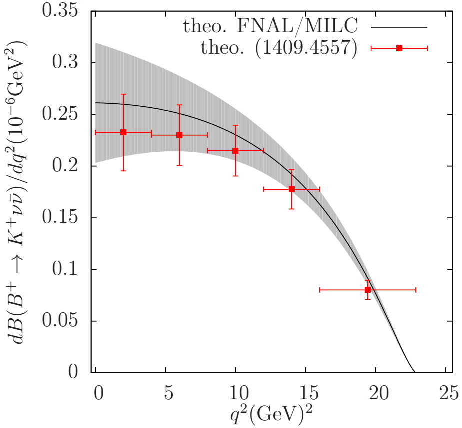
where the numerical coefficient $N_{K(\pi)}$ depends upon the relevant CKM factors and $\rho_{K(\pi)}$ is the rescaled hadronic form factor:

$$N_{K(\pi)} = V_{tb} V^*_{ts(d)} \frac{G_F \alpha_{EW}}{16\pi^2} \sqrt{\frac{M_B}{3\pi}} \,, \qquad (2)$$

$$\rho_{K(\pi)}(q^2) = \frac{\lambda^{3/2}(q^2)}{M_B^4} f_+^2(q^2) \,. \qquad (3)$$

- The form factor f_+ is the same as in the $B \to K(\pi) l^+ l^-$ lattice-QCD calculations.

Theoretical studies of the $B \to K\nu\bar{\nu}$



- Grey band: theoretical result from FNAL/MILC $B \to K$ form factor
- Red points: theoretical result from and lattice-QCD plus LCSR form factor results (arXiv:1409.4557).

Summary

- There are many progresses in the heavy flavor physics from lattice calculations since 2015.
- Many new 2σ hints of NP have been revealed by the improvements of lattice calculations.
- Belle II and LHCb will improve measurements and observe new decays.
- We will continue to sharpen tests of SM and may reveal presence of NP.