Semileptonic B-meson decay phenomenology with lattice QCD

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(On behalf of the FNAL/MILC Collaborations)

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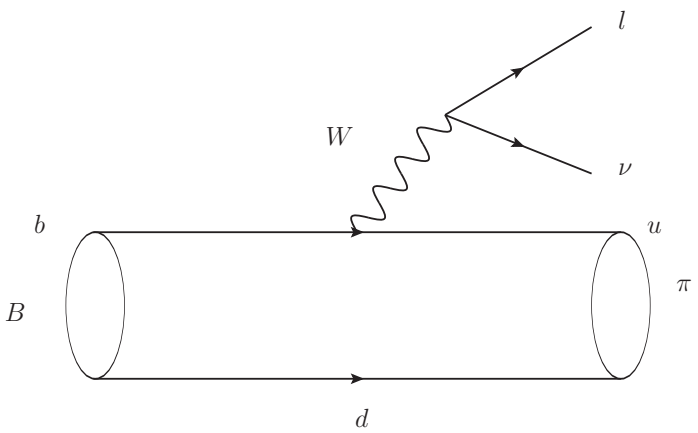
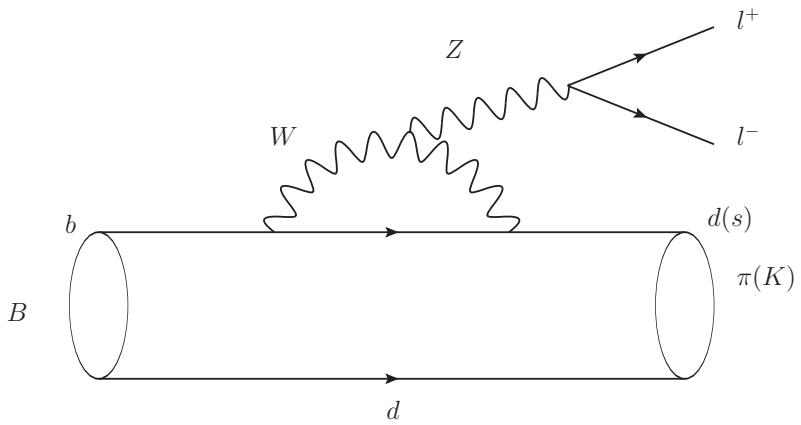
Theoretical Motivation



Tree-level diagram



Loop-level diagram

- B-meson semileptonic decays through tree-level diagram ($B \to \pi l \nu$, $B_s \to K l \nu$)
- B-meson semileptonic decays through loop-level diagram ($B \to K(\pi) l^+ l^-$, $B \to K(\pi) \nu \bar{\nu}$)
- Standard Model contribution is suppressed in the loop-level diagram. (Suitable processes to detect physics BSM)
- Studied by many experiment groups (BABAR, Belle, CDF, LHCb, B-factory *etc.*)

Standard Model prediction

The effective Hamiltonian of the $b \to d(s) l^+ l^-$ transition under OPE with α_s and Λ/m_b corrections is:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V^*_{td(s)} V_{tb} \sum_{i=0}^{10} C_i(\mu) O_i(\mu) + ... \quad (1)$$

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

$$\text{Theo. pred.} = (\text{prefactors}) \times (\text{CKMfactor}) \times \langle f|\hat{O}|i\rangle \quad (2)$$

- 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)
- The tree-level diagram shares the same form factors as the loop-level diagram.

Hadronic matrix elements and form factors

- Form factors in $B \to K(\pi) l^+ l^-$ semileptonic decays:

$$\begin{aligned}
\langle K(k)|\bar{s}\gamma^\mu b|B(p)\rangle &= f_+(q^2)\left(p^\mu + k^\mu - \frac{M^2-m^2}{q^2}q^\mu\right) + \\
&\quad f_0(q^2)\frac{M^2-m^2}{q^2}q^\mu \\
q_\nu\langle K(k)|\bar{s}\sigma^{\mu\nu} b|B(p)\rangle &= \frac{i f_T(q^2)}{M+m}\left[q^2(p^\mu + k^\mu) - (M^2-m^2)q^\mu\right]
\end{aligned}$$

- These three form factors (f_+, f_0, and f_T) are sufficient to describe (Beyond) Standard Model(s) predictions.

Outline

In this talk, I will show the Standard Model predictions and experimental results in these four processes:

- $B \to \pi l^+ l^-$ $(l = e, \mu, \tau)$ (arXiv:1503.07839, arXiv:1507.01618)
- $B \to K l^+ l^-$ $(l = e, \mu, \tau)$
- $B \to \pi \nu \bar{\nu}$
- $B \to K \nu \bar{\nu}$

Experimental results of the $B \to \pi l^+ l^-$ semileptonic decay

- The $B \to \pi l^+ l^-$ decay occurs through $b \to d l^+ l^-$ (Flavor Changing Neutral Current).
- The $B \to \pi l^+ l^-$ decay was first observed in 2012 by LHCb (arXiv:1210.2645).
- The branching function of the $B \to \pi \mu^+ \mu^-$ process is

$$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) = [2.3 \pm 0.6(stat.) \pm 0.1(syst.)] \times 10^{-8} \quad (3)$$

- The ratio of $B^+ \to \pi^+ \mu^+ \mu^-$ to $B^+ \to K^+ \mu^+ \mu^-$ is

$$\frac{\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)} = 0.053 \pm 0.014(stat.) \pm 0.001(syst.) \quad (4)$$

- More detailed results on the branching ratio rate from LHCb could be available soon. (2015 Meeting of the APS Division of Particles and Fields (DPF 2015) held this August.)

Theoretical results of the $B \to \pi l^+ l^-$ semileptonic decay

Some papers on the standard Model predictions (The form factors were calculated in different methods.):

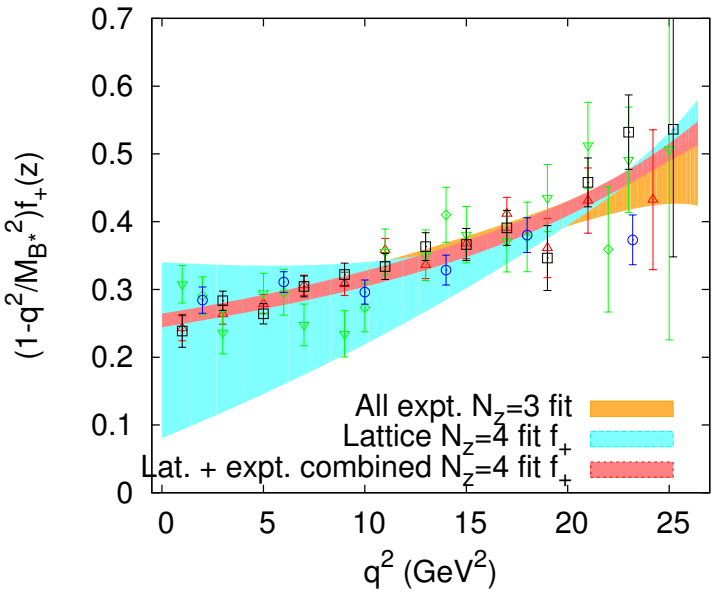
- Wen-Fei Wang *et al.* 1207.0265 (QCD factorization)
- Ahmed Ali *et al.* 1312.2523 (lattice, LCSR, $B \to \pi l \nu$ exp.)
- R. N. Faustov *et al.* 1403.4466 (relativistic quark model)
- Wei-Shu Hou *et al.* 1403.7410 (LCSR)
- Zuo-Hong Li *et al.* 1411.0466 (LCSR)
- Christian Hambrock *et al.* 1506.07760 (LCSR)

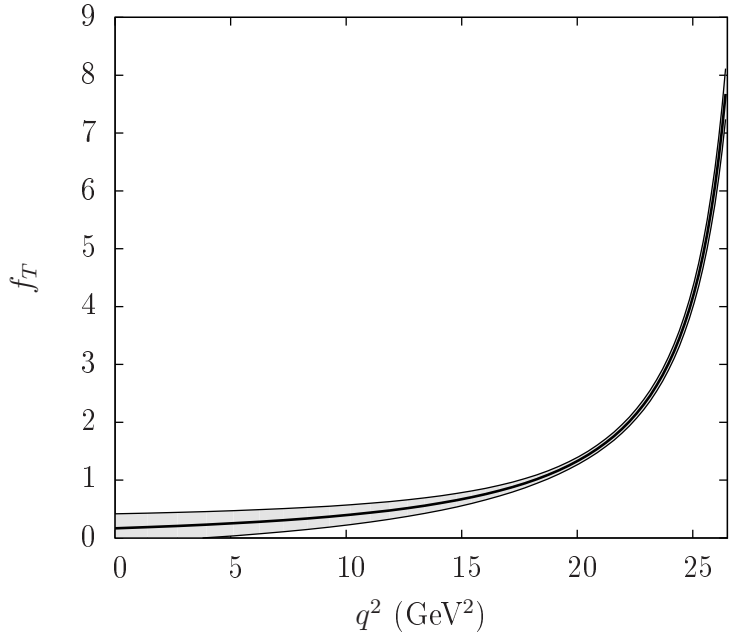
Compared with these works, we use

- The most recent f_+ and f_0 from MILC(asqtad) lattice ensembles and experiments (arXiv:1503.07839).
- First result of f_T in $B \to \pi l^+ l^-$ process from lattice-QCD calculation (arXiv:1507.01618)
- NNLO Wilson coefficients (arXiv:0512066).

$B \to \pi$ form factors

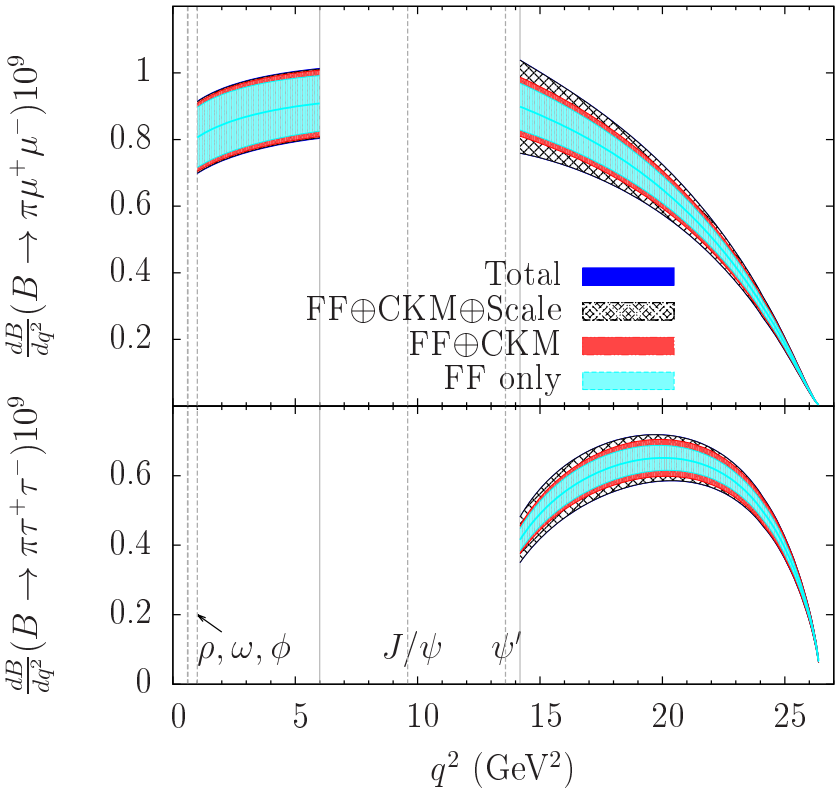
The plots on this page will be provided by Daping.

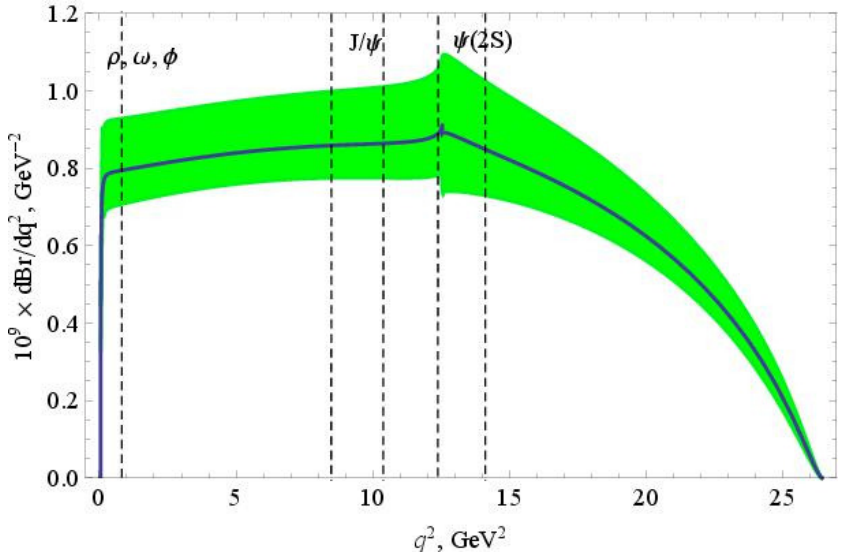




- Form factors in the $B \to \pi l^+ l^-$ and $B \to \pi l \nu$ decays. The left plot is from arXiv:1503.07839, and the right one is from arXiv:1507.01618.
- We assume the BSM contribution is smaller than the SM tree-level contribution in the $B \to \pi l \nu$ process. Therefore, we use the $B \to \pi l \nu$ experimental data to constrain the f_+ in the low q^2 region.
- Lattice-QCD provides accurate f_T in the high q^2 region.

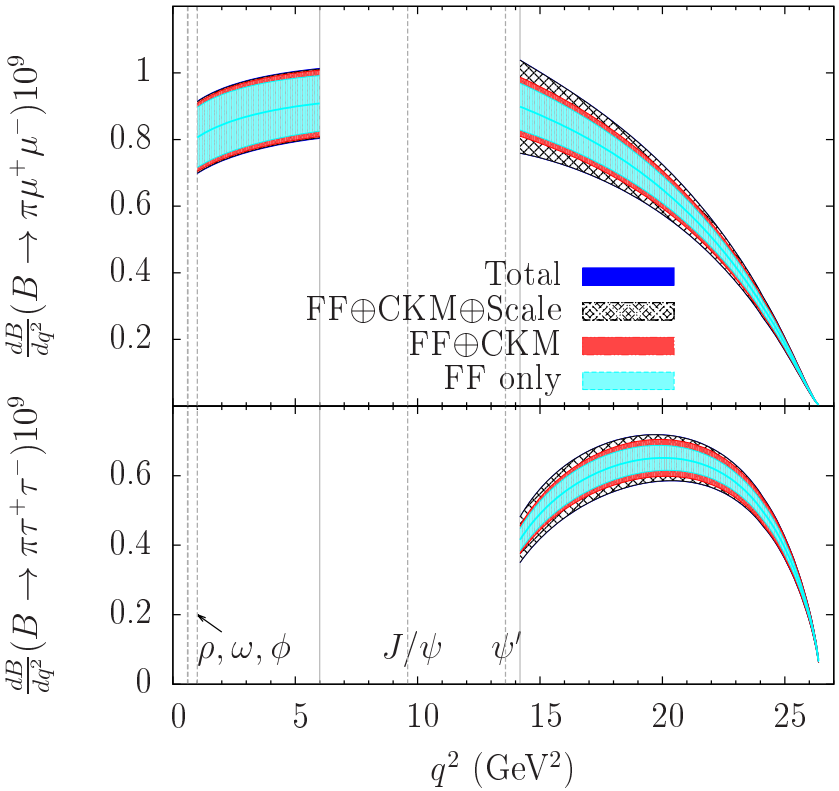
Standard Model predictions

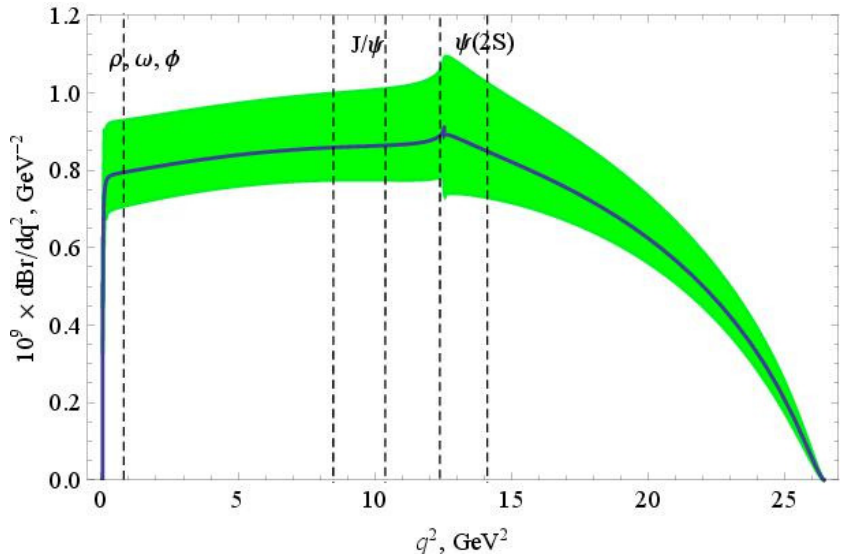




- Left panel: new FNAL/MILC $B \to \pi$ lattice data + exp (arXiv:1503.07839)
- Right panel (arXiv:1312.2523): old FNAL/MILC $B \to \pi$ lattice data (arXiv:0811.3640) + HPQCD's $B \to K$ lattice data(arXiv:1306.2384) + exp + LCSR + model

Standard Model predictions





- Errors shown are from the CKM elements, form factors, Wilson coefficients, and other contributions, respectively. In some q^2 bins, the form factor error is comparable with the errors from other sources.
- Total branching ratio $\mathrm{BR}(B^+ \to \pi^+\mu^+\mu^-)$=19.5(2.2) $\times 10^{-9}$ agrees with the previous LHCb result (23(6) $\times 10^{-9}$). (arXiv:1210.2645)

$B \to K$ form factors

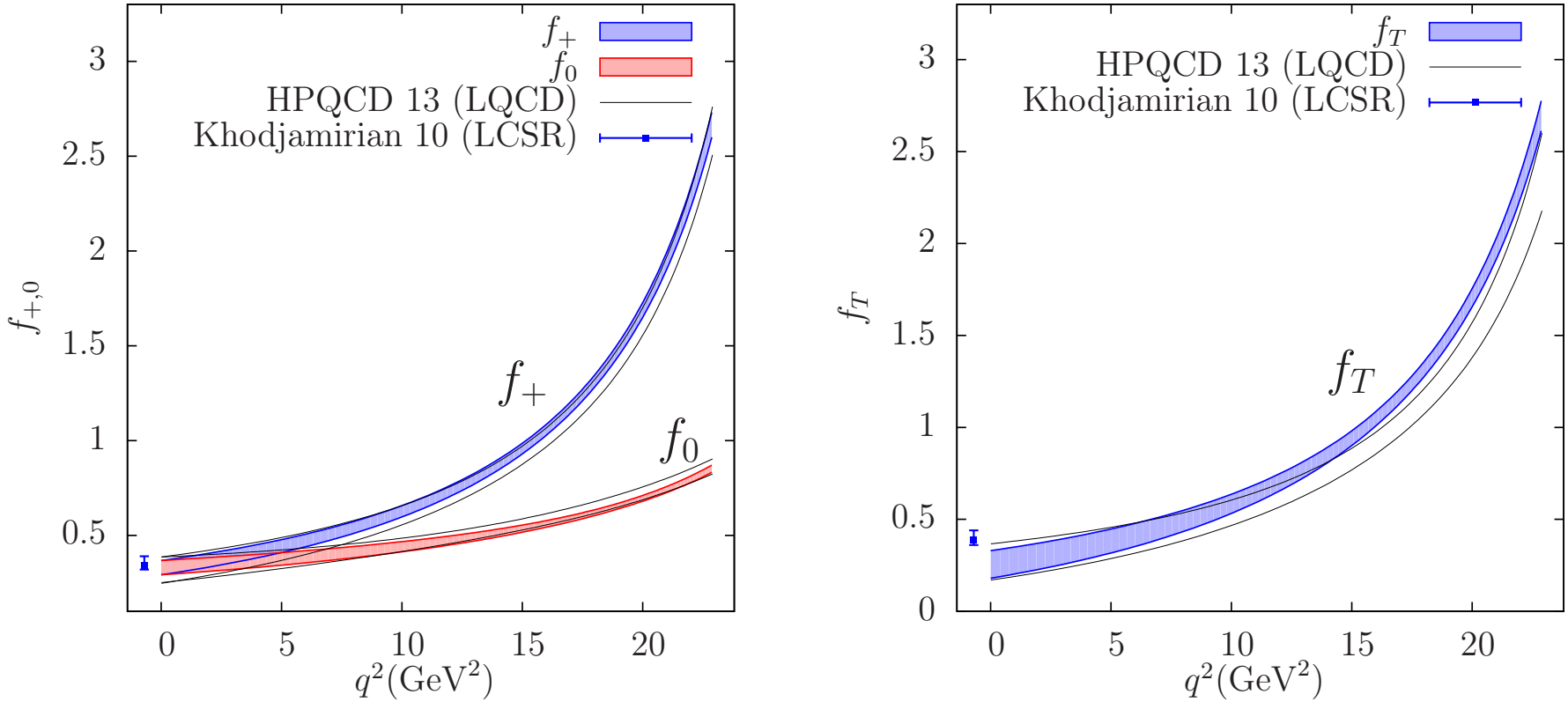
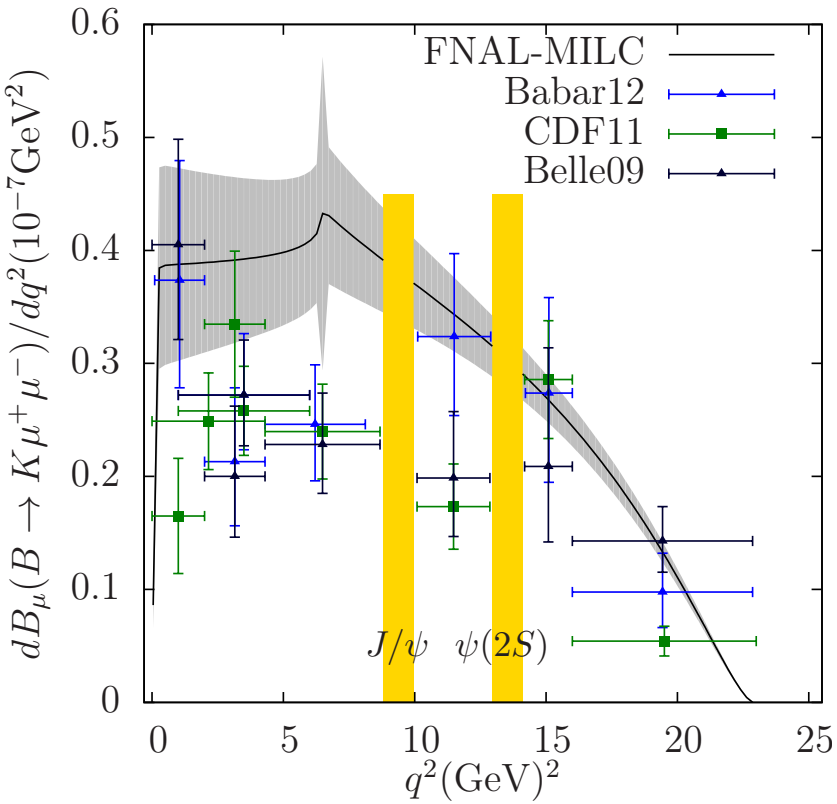
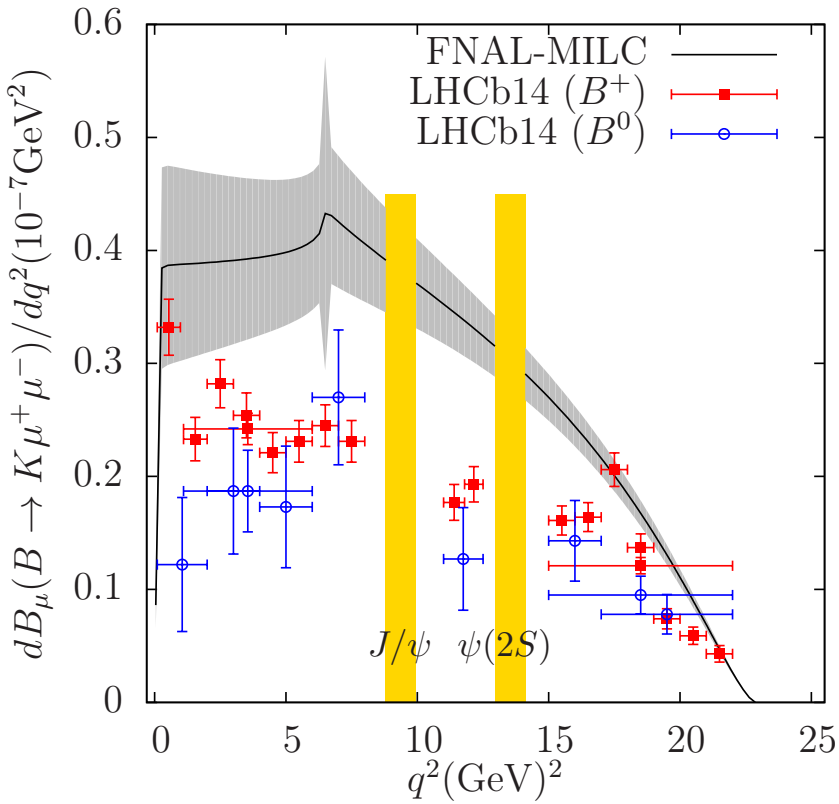


Figure : FNAL/MILC form-factor results compared with light-cone sum rule results (arXiv:1006.4945) and HPQCD's unquenched lattice-QCD calculation (arXiv:1306.2384).

Standard Model predictions of $B \to K l^+ l^-$ process

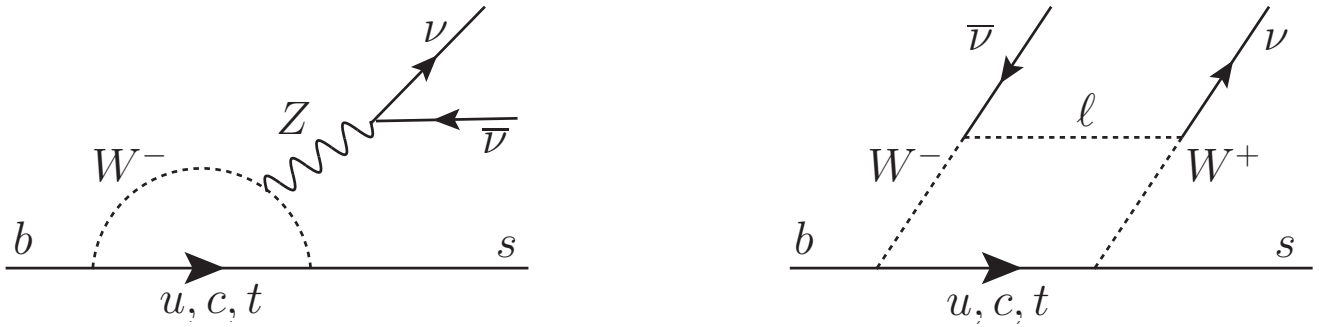
Theoretical prediction of dB/dq^2 (preliminary) compared with experimental results from Belle (arXiv:0904.0770), CDF (arXiv:1107.3753), BaBar (arXiv:1204.3933), and LHCb (arXiv:1403.8044).





$B \to K\nu\bar{\nu}$ and $B \to \pi\nu\bar{\nu}$

Feynman diagrams of the $b \to s\nu\bar{\nu}$ transition (from arXiv:1303.3719):



Experimental results:

- BaBar: $\mathrm{BR}(B^+ \to K^+\nu\bar{\nu}) < 3.2 \times 10^{-5}$ (90% CL) (arxiv:1303.7465)
- Belle: $\mathrm{BR}(B^+ \to K^+\nu\bar{\nu}) < 5.5 \times 10^{-5}$ (90% CL) (arxiv:1303.3719)
- Belle: $\mathrm{BR}(B^+ \to \pi^+\nu\bar{\nu}) < 9.8 \times 10^{-5}$ (90% CL) (arxiv:1303.3719)

Theoretical results:

- Wolfgang Altmannshofer *et al.* 0902.0160 (LCSR)
- Andrzej J. Buras *et al.* 1409.4557 (lattice, LCSR)
- Christian Hambrock *et al.* 1506.07760 (LCSR)

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)

$$\frac{dB(B \to K(\pi)\nu\bar{\nu})}{dq^2} = 3\tau_B |N_{K(\pi)}|^2 \frac{X_t^2}{(\sin^2\theta_W)^4} \rho_{K(\pi)}(q^2) \ , \quad (5)$$

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

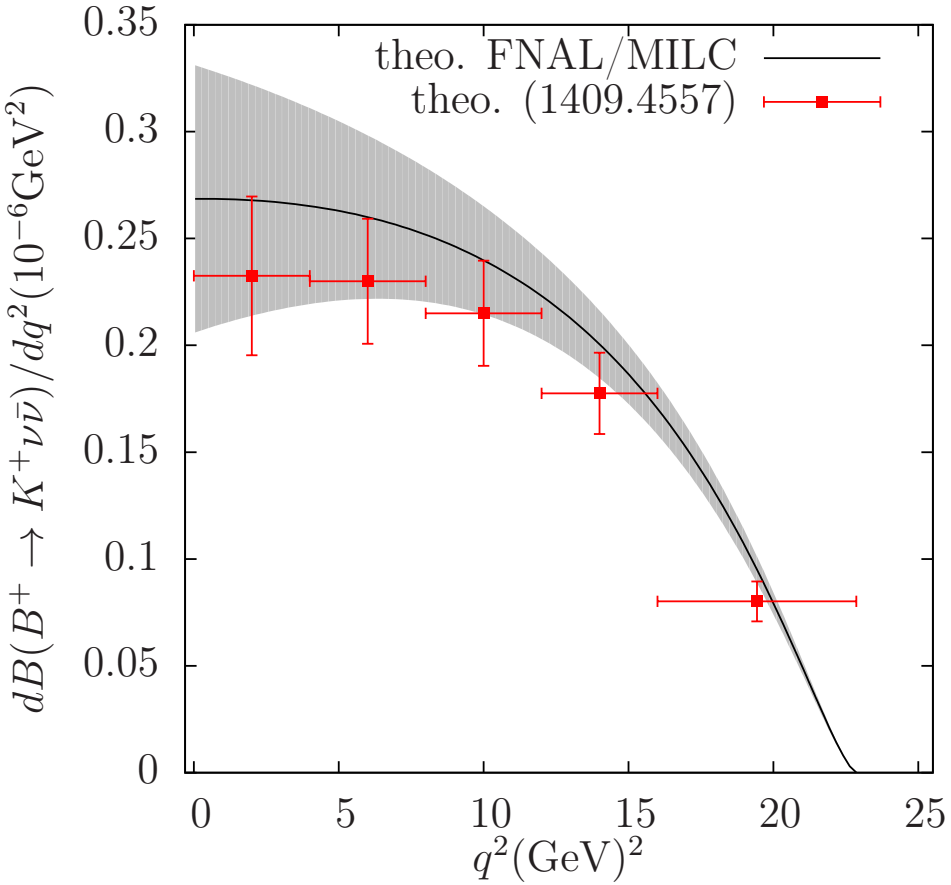
$$N_{K(\pi)} = V_{tb} V_{ts(d)}^* \frac{G_F \alpha_{EW}}{16\pi^2} \sqrt{\frac{M_B}{3\pi}} \ , \quad (6)$$

$$\rho_{K(\pi)}(q^2) = \frac{\lambda^{3/2}(q^2)}{M_B^4} f_+^2(q^2) \ . \quad (7)$$

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

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

(Preliminary)



- 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

- Theoretical predictions of the $B \to \pi l^+ l^-$ and $B \to K l^+ l^-$ process are shown and compared with the experiments.
- The $B \to \pi l^+ l^-$ form factors and theoretical predictions are available. (1503.07839, 1507.01618)
- The $B \to K l^+ l^-$ form factors and other theoretical predictions will be finished soon.
- New experimental results could be available soon. (DFP 2015)
- More studies on the B-meson semileptonic decay form factors on the HISQ ensembles are under investigation.

Backup Slides

Standard Model predictions

Theoretical prediction of dB/dq^2 in high q^2 region:

$$\frac{dB}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{td}^*|^2}{2^7\pi^5}|\mathbf{k}|\beta_+ \left\{ \frac{2}{3}|\mathbf{k}|^2\beta_+^2 \left| C_{10}^{\text{eff}} f_+(q^2) \right|^2 \right.$$
$$+ \frac{m_l^2(M_B^2 - M_K^2)^2}{q^2 M_B^2} \left| C_{10}^{\text{eff}} f_0(q^2) \right|^2$$
$$\left. + |\mathbf{k}|^2 \left[1 - \frac{1}{3}\beta_+^2 \right] \left| C_9^{\text{eff}} f_+(q^2) + 2C_7^{\text{eff}} \frac{m_b}{M_B + M_K} f_T(q^2) \right|^2 \right\}, \qquad (8)$$

where G_F, α, and V_{tq} are the Fermi constant, the (QED) fine structure constant, and CKM matrix elements, respectively, $|\mathbf{k}| = \sqrt{E_K^2 - M_K^2}$ is the kaon momentum in the B-meson rest frame, and $\beta_+^2 = 1 - 4m_l^2/q^2$, with m_l the lepton mass.