Exclusive $b \to s\,\mu^+\mu^-$ decays, the current status of the theory

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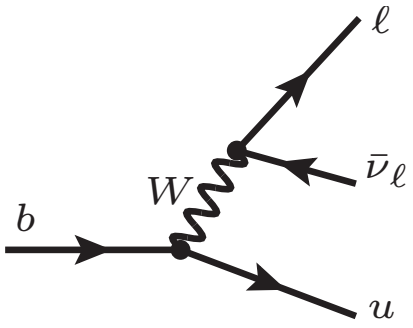
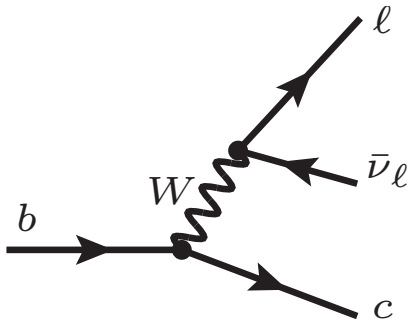
Flavourful semileptonic decays of b-quark in SM

- flavour-changing charged weak currents ($\ell = e, \mu, \tau$)

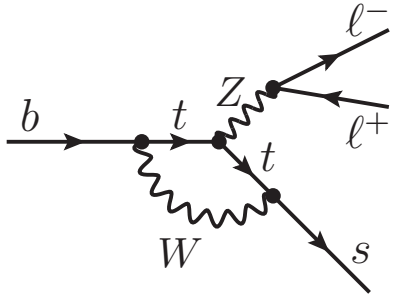
- sensitive to V_{ub}, V_{cb}
- probe beyond SM charged currents

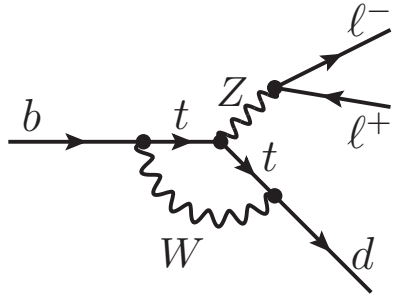




- flavour-changing neutral currents (FCNC)

- sensitive to V_{tb}, V_{ts}, V_{td}
- trace new heavy particles in the loops





Switching on quark-gluon interactions (QCD) in the b-quark decay

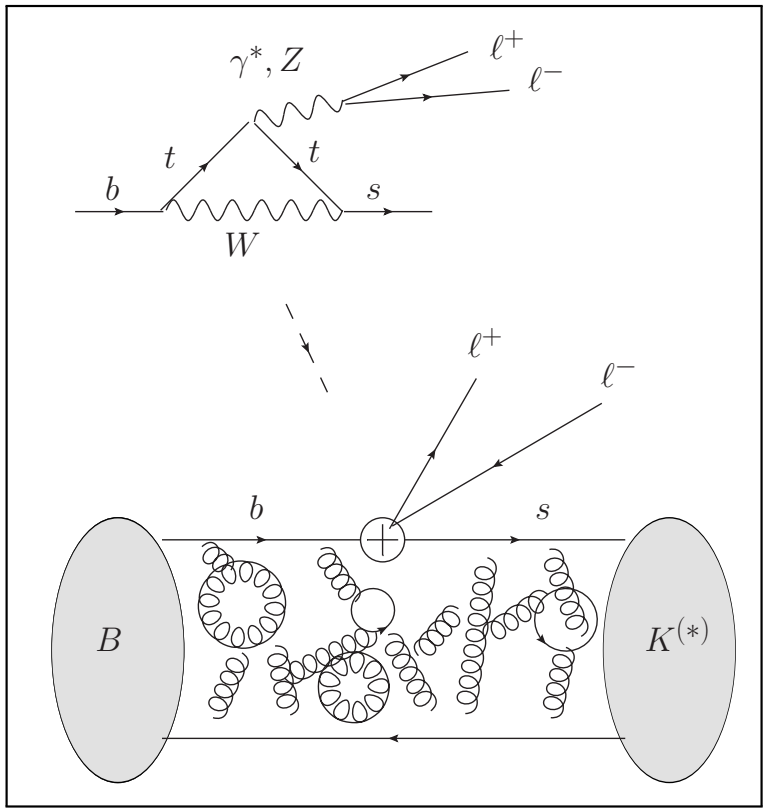
- the $b \to s\ell^+\ell^-$ loop diagrams reduced
to effective local interactions,
since t, Z, W are much heavier than b

- the decaying b-quark is bounded
inside the initial B meson,

- the final-state quarks are
converted into hadrons,

- exclusive channels
(with a fixed final state)
experimentally clean,
provide specific observables

- recent measurements of
$B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\ell^+\ell^-$
(LHCb, Belle II, CMS)
revealed tensions with SM,
'B-anomalies', but no lepton flavour universality violation anymore !



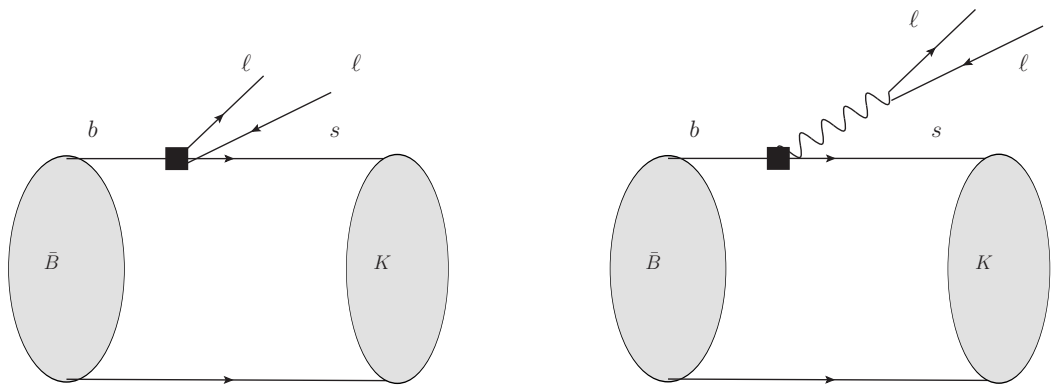
$B \to K\mu^+\mu^-$ in Standard Model

- diagrams with W, Z, t $\Rightarrow$ ten effective interactions

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i O_i$$

- most important are the pointlike $b \to s\ell\ell$, $b \to s\gamma^{(*)}$ interactions (the local operators $O_{9,10}$ and $O_7\gamma$) generated from heavy loops

$C_9(m_b) \simeq 4.4$,
$C_{10} \simeq -4.7$,
$C_7(m_b) \simeq -0.3$



- the contributions of these operators factorize into leptonic part and $B \to K$ hadronic form factors

$$\langle K(p)|\bar{s}\Gamma b|B(p+q)\rangle \sim \{f^+(q^2), f^0(q^2), f^T(q^2)\}$$

Calculating $B \to K$ Form Factors in QCD

- $B \to K$ form factors from lattice QCD

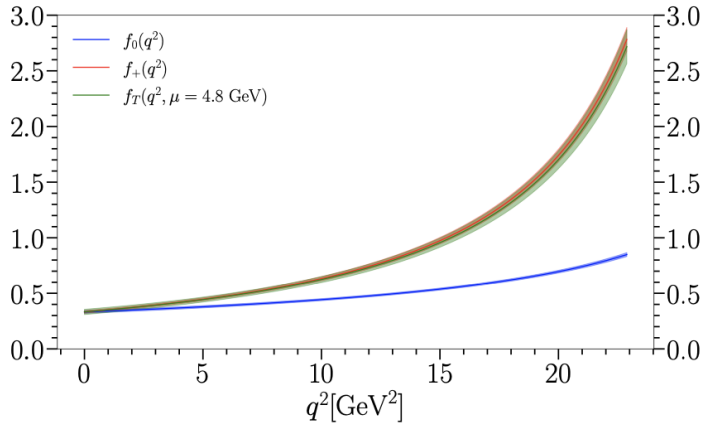


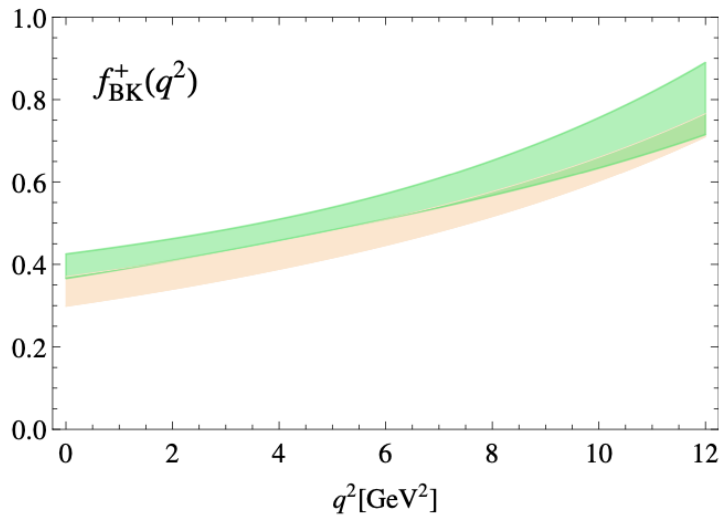
FIG. 8. Final $B \to K$ form factor results at the physical point across the full q^2 range.

- HPQCD collaboration,
  W.G. Parrott et al , 2207.12468
- $q^2 \sim 0$, extrapolation error ?
  $f^+_{BK}(0) = 0.332 \pm 0.012$

- QCD Light-cone sum rules
  AK, A.Rusov, 1703.04765

$f^+_{BK}(0) = 0.395 \pm 0.033$

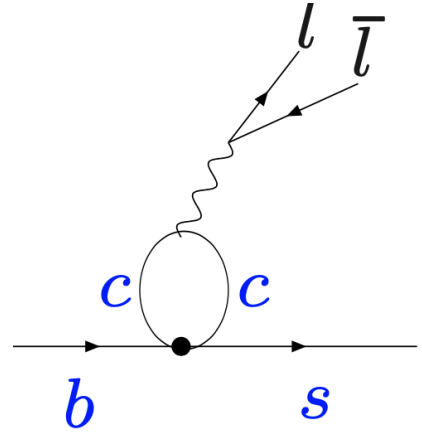
brown band - lattice QCD, Fermilab MILC Collab.1503.078



$\square$ $B \to K\mu^+\mu^-$, nonlocal contributions

- a chain of transitions:

weak $b \to s\bar{c}c \oplus$ electromagnetic $\bar{c}c \to \gamma^* \to \ell^+\ell^-$
mimics the FCNC decay



- four-quark effective interactions (W-exchange),

$$O_1^{(c)} = [\bar{s}_L\gamma_\rho c_L][\bar{c}_L\gamma^\rho b_L]\,, \qquad C_1(m_b) \simeq 1.1$$
$$O_2^{(c)} = [\bar{c}_L\gamma_\rho c_L][\bar{s}_L\gamma^\rho b_L]\,, \qquad C_2(m_b) \simeq -0.25$$

- this charm loop effect is essentially nonlocal,
charmonium resonances at $q^2 \geq m^2_{J/\psi}$

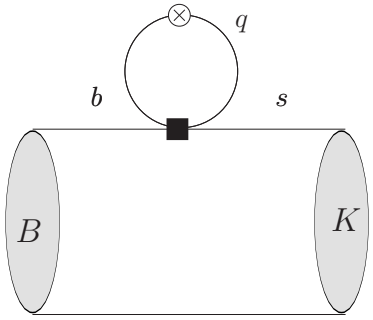
- quark-antiquark-gluon and four-quark
effective interactions generated by heavy loops

$O_{8g} \sim \bar{s}bG$, $\quad C_8(m_b) \simeq 0.2$

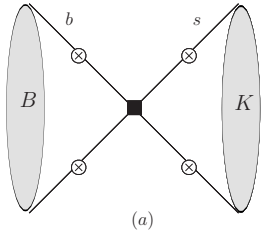
O_{3-6} - quark-penguin operators , $\quad C_{3,4,5,6}(m_b) < 0.03$

- the u quark loops $\sim V_{ub}V_{us}^*$ part neglected due to CKM suppression

□ Diagrams of nonlocal matrix elements at $q^2 \ll 4m_c^2$

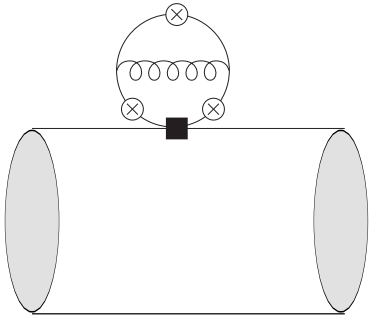


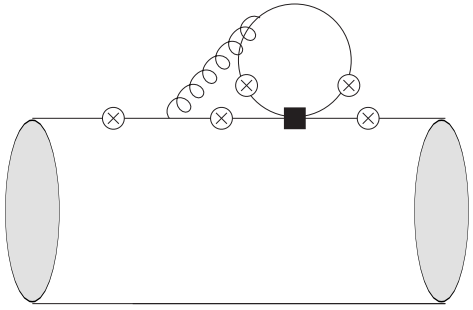
LO (factorizable)

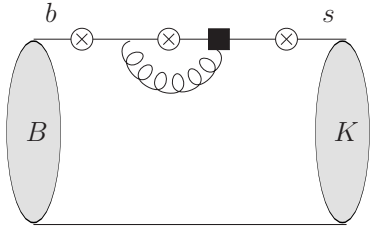


weak annihilation

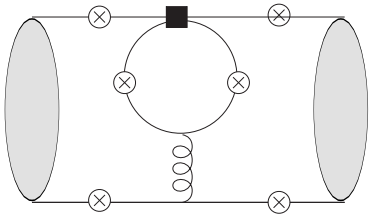
$\otimes$ -virtual photon





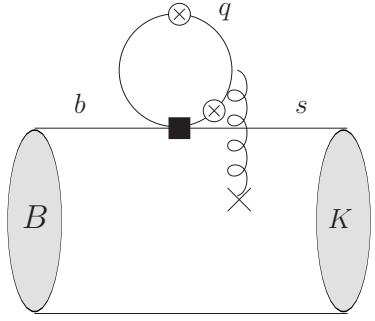


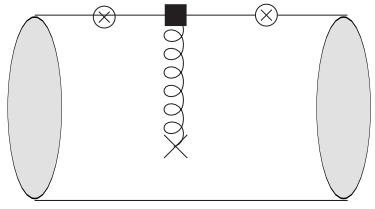
NLO (factorizable) H. Asatryan, C. Greub et al. (2001)



spectator (nonfactorizable)

M.Beneke, Th.Feldmann, D.Seidel (2001)





soft (low virtuality) gluons(nonfactor.)

, AK, T.Mannel, A.Pivovarov, Y.-M. Wang(2010)

Amplitude of $B \to K\ell\ell$ decay

$$A(B(p+q) \to K(p)\ell^+\ell^-) = \frac{G_F}{\sqrt{2}} \frac{\alpha_{em}}{\pi} V_{tb} V_{ts}^* \Bigg[\bar{\ell}\gamma_\mu \ell \, p^\mu \Bigg(C_9 f_{BK}^+(q^2) + \frac{2(m_b+m_s)}{m_B+m_K} C_7^{eff} f_{BK}^T(q^2) + \sum_{i=1,2,\ldots,6,8} C_i \, \mathcal{H}_i^{(BK)}(q^2) \Bigg) + \bar{\ell}\gamma_\mu\gamma_5 \ell \, p^\mu C_{10} f_{BK}^+(q^2) \Bigg]$$

- the leading contributions contain $B \to K$ form factors
- nonlocal matrix elements:

$$\langle K(p)| i \int d^4x \, e^{iqx} \, T\{j_\mu^{em}(x), O_i(0)\} |B(p+q)\rangle = p_\mu \mathcal{H}_i^{(BK)}(q^2)$$

$j_{em}^\rho = \sum_{q=u,d,s,c,b} Q_q \bar{q}\gamma^\rho q$, the hierarchy: $O_i = O_{1,2}^{(c)}, O_{8g}, O_{3,4,5,6}^{(q)}, O_{1,2}^{(u)}$

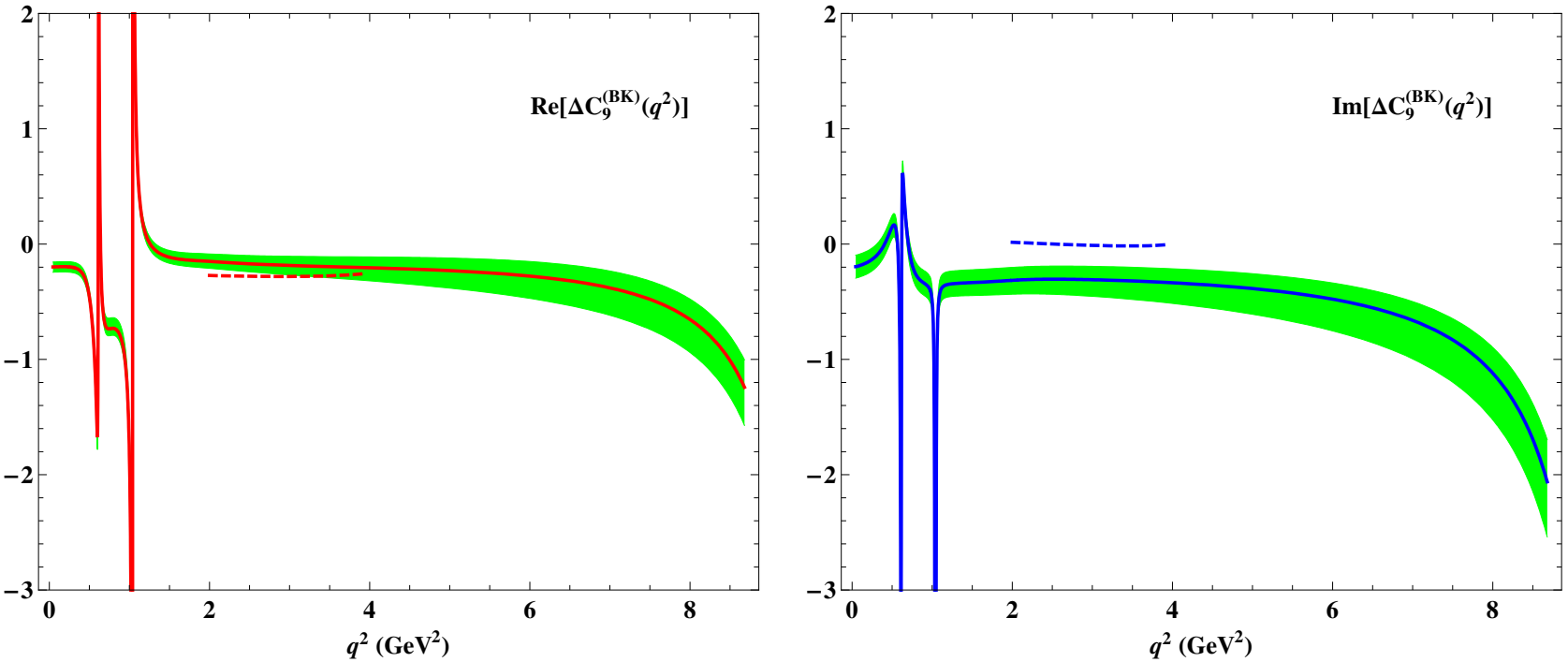
$\Rightarrow$ parametrized as corrections to short-distance coefficient C_9 :

$C_9 \to C_9 + \sum_i \Delta C_9^{(BK,i)}(q^2)$ (q^2- and process-dependent)

- have to be estimated one by one to obtain the whole amplitude

$\Delta C_9(q^2)$ below charmonia region

[AK, T. Mannel, Y.M . Wang 1211.0234 [hep-ph]]



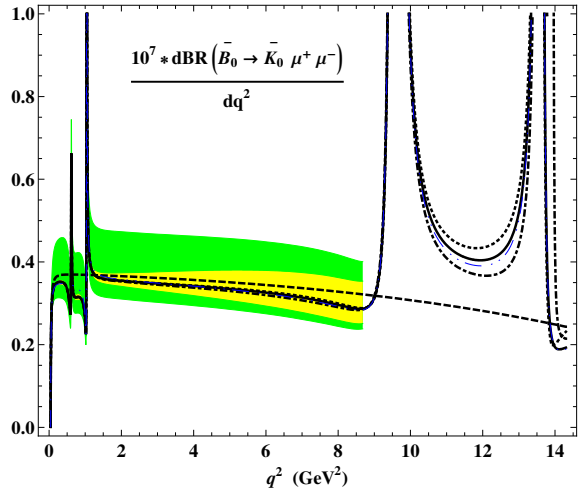
the red (blue) solid curve corresponds to the Re (Im) part obtained from the hadronic dispersion relation, fitted to the QCD calculation at q2 < 0. The shaded areas indicate the uncertainties. The dashed curves - prediction of QCDF.

Differential width of $B \to K\mu^+\mu^-$

- [AK, T. Mannel, Y.M . Wang 1211.0234 [hep-ph]]

– the long-dashed line - without nonlocal contributions.

– the green (yellow) area - with (without)
the uncertainties of $B \to K$ form factors



- [N. Gubernari, M. Reboud, D. van Dyk and J. Virto, 2206.03797]

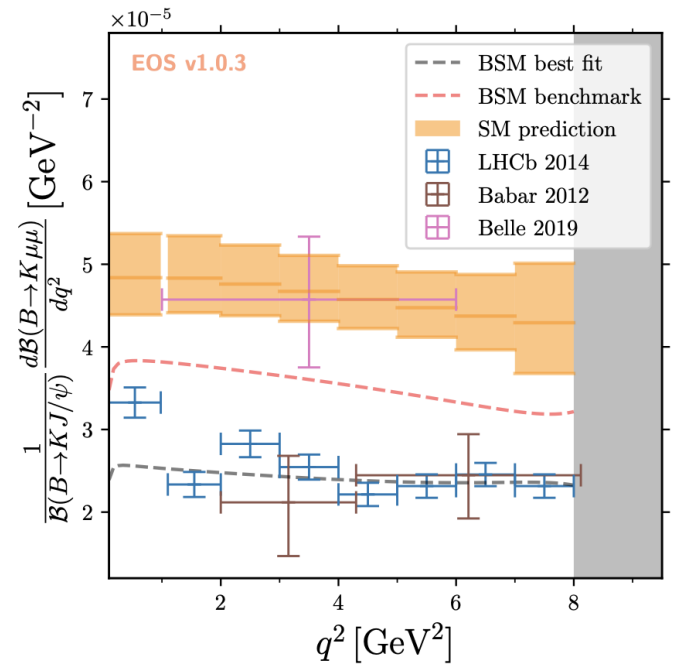
– more precise $B \to K$ form factors.

– major update of NLO factor.diags,

H.Asatryan, C.Greub, J.Virto (2020)

– updated soft nonlocal effect

– Bayesian (EOS) analysis of the uncertainti



□ Differential width of $B \to K\mu^+\mu^-$

- most recent CMS data (CMS PAS BPH-22-005)

see also the talk by G.Karathanasis (CMS) at EPS-HEP, Hamburg (2023)

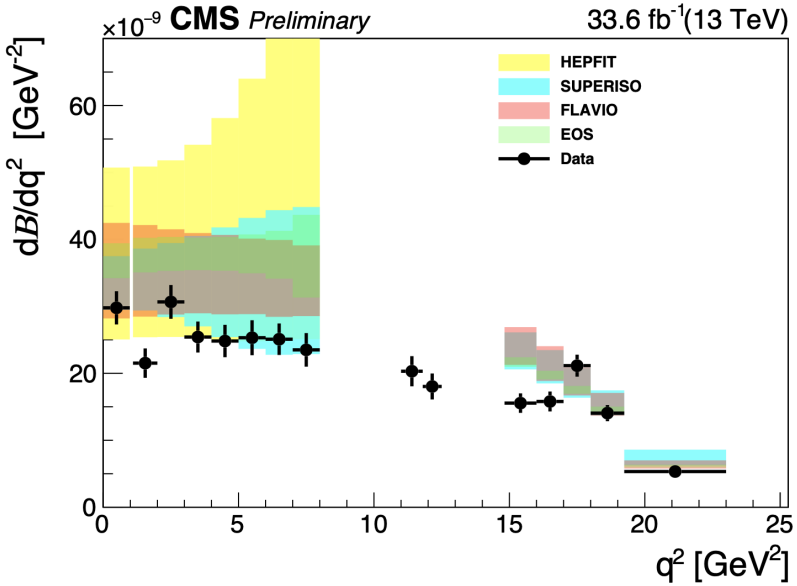


Figure 10: Comparison of the measured differential $B^+ \to K^+\mu^+\mu^-$ branching fraction with the theoretical predictions obtained using FLAVIO, SUPERISO, HEPFIT, and EOS packages.

- good agreement with LHCb,
- need more details on “theoretical predictions” ?

Is there an anomaly in $B \to K\ell\ell$?

- We observe a consideraable difference between predicted in SM and measured $dBR(B \to K\mu^+\mu^-)/dq^2$,
- three possibilities:
  - there are unaccounted and large nonlocal effects

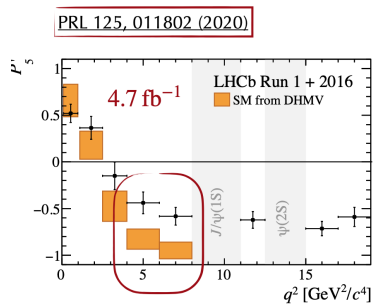
    need lattice QCD calculations, update of LCSR approach is planned
  - there a shift of C_9 due to new heavy particles in the loops

    see e.g. B.Capdevila, A.Crivellin, J.Matias, 2309.01311
  - both lattice and LCSR $B \to K$ form factros are unreliable...

□ Other $b \to s\ell\ell$ channels

- $B \to K^*\ell\ell$

from the talk by J.Nicolini (LHCb) at Hamburg EPS-HEP (2023)



- Update of JHEP 02 (2016) 104
- Same selection as Run1 result, minor changes for 2016
- $P'_i = \dfrac{S_i}{\sqrt{F_L(1-F_L)}}$ observables to reduce FF uncertainties

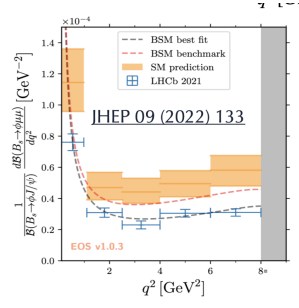
  → non-local uncertainties ($c\bar{c}$ loop) remain
- Simultaneous fit to $[\theta_h, \theta_l, \phi, m(K^+\pi^-\mu^+\mu^-)]$

- angular observable P'_5 independent of FFs (but not of nonlocal effects !)
- detected $B \to K\pi\ell\ell$ state , $K^*(892)$ is a resonance,
  > instability of K^* in lattice QCD:

  A. Agadjanov, V. Bernard, U. G. Meissner and A. Rusetsky,1605.03386 [hep-lat]].

  > LCSR calculations of $B \to K\pi$ form factors: S. Descotes-Genon, AK, J. Virto, 1908.02267

- $B_s \to \phi\ell\ell$



Most precise BF measurement

$\mathrm{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \pm 0.22 \pm 0.16 \pm 0.39 \pm 0.03) \times 10^{-7}$
stat. syst. abs. BF q2 extrapol.

In q^2[1.1,6.0] GeV^2/c^4: 3.6σ (LCSR+Lattice) and 1.8σ (LCSR)

- the predicted width larger than the measured

- observation of $B \to K\nu\bar{\nu}$ by Belle-II (reported at EPS-HEP in Hamburg) :

a very clean decay in SM, no nonlocal effects , $B \to K$ form factor has to be increased !