B Physics and $b \to s$ transitions

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Outline

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- The $B \to K^* \ell^+ \ell^- \to K\pi\ell^+\ell^-$ decay
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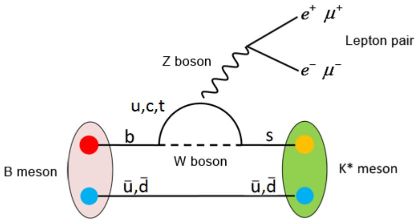
Motivating B Physics

- B physics provides a powerful general tool to search for New Physics and to test our understanding of the Standard Model (SM).
- The SM is the most successful theory of nature we know, but is incomplete.
- Written in terms of free quarks and gluons, but in nature we see mesons and baryons, ie bound states.
- Calculations within the SM are therefore difficult and incompletely understood.
- Additionally we are searching for signs of New Physics, which in B Physics would show up as a deviation from the SM prediction, independent of the New Physics model.

Motivating B Physics

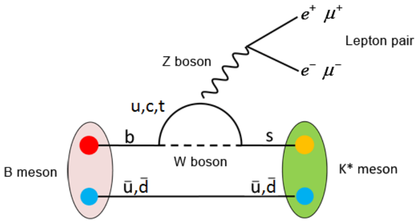
- B mesons contain a bottom (or "beauty") quark, the heaviest quark that can hadronize.
- Gives access to highest energy scales in the SM (weak scale), while still involving non-perturbative physics.
- Probes most of the structure and parameters in the SM, such as the *CKM* matrix.
- A rich variety of decay channels, providing multiple tests.

The $B \to K^* \ell^+ \ell^- \to K\pi\ell^+\ell^-$ decay



- This decay is particularly interesting because it is predicted to be rare within the SM, as it cannot occur at tree level (requires a $b \to s$ transition).
- New physics could adjust this rate either by adding new particles to that loop, or by introducing a new tree-level interaction.

The $B \to K^*\ell^+\ell^- \to K\pi\ell^+\ell^-$ decay



- The loop itself is interesting, as charm quarks running through the loop can form resonances.
- The K^* is a vector meson – allowing for polarization effects in the angular distribution that lead to a richer structure than for its (pseudo-)scalar equivalent the K.
- This decay has a well-defined CP-conjugate, so can be used to search for CP-violating effects in B physics.

Effective Weak Theory

- The W boson involved in the decay is far heavier than the kinematic scale of the process, so we can integrate it out, along with top quarks, Z bosons, and any new heavy particles.
- We can do this for a whole set of general decay structures (including ones that aren't present in the SM), leading to an effective Hamiltonian

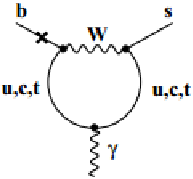
$$\langle K^* \ell^+ \ell^- | \mathcal{H}_{eff} | B \rangle \sim |V_{CKM}|^2 \, G_F \sum \underbrace{C_i(\mu)}_{\text{UV}} \overbrace{\langle K^* \ell^+ \ell^- | \mathcal{O}_i(\mu) | B \rangle}^{\text{IR}}$$

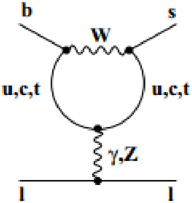
- This factorizes the decay into pieces representing long-range ($\mathcal{O}_i(\mu)$) and short-range ($C_i(\mu)$) dynamics.

Effective Weak Theory

- Typical structures for the effective operators $\mathcal{O}_i(\mu)$ involved in $b \to s\ell^+\ell^-$ processes include:

$$\mathcal{O}_7 = \frac{m_b}{e}\bar{s}\sigma^{\mu\nu}P_R b F_{\mu\nu} \qquad , \qquad \mathcal{O}_9 = \bar{s}\gamma_\mu P_L b \bar{\ell}\gamma^\mu \ell$$





Wilson Coefficients

- The Wilson coefficients $C_i(\mu)$ contain the internal (UV) dynamics of the theory.
- Can be calculated independent of the external states, and to a high degree of accuracy (including multi-loop corrections).
- The μ is a renormalization (or factorization) scale, so RG analysis required – in general the Wilson coefficients and operators mix under renormalization.
- Important to study and calculate these in order to be able to make predictions.

Form Factors and Matrix Elements

- The hadronic matrix element $\langle K^{*} | \mathcal{O}_i(\mu) | B \rangle$ is non-perturbative, so cannot be exactly calculated using perturbative techniques.
- Instead we parametrize matrix elements in terms of form factors, eg for our decay (and with $q = p_B - p_{K^*}$)

$$\langle K^{*}(p_{K*}, \eta) | \mathcal{O}_i(\mu) | B(p_B) \rangle = \sum f_i(p_B, p_{K^*}, \eta) F_i(q^2),$$

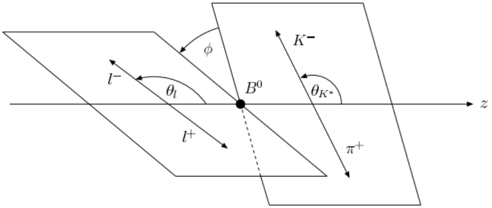
- with the $f_i(p_B, p_{K^*}, \eta)$ containing information about the kinematics, Lorentz structure, and any conservation laws (η is the polarization of the K^*).

Form Factors and Matrix Elements

- The form factors $F_i(q^2)$ must be calculated for each decay, and depend on the external states.
- The $F_i(q^2)$ are also non-perturbative objects, but numerous calculation techniques exist eg Lattice QCD (numerical) or Light Cone Sum Rules (analytic).
- These and the Wilson Coefficients form the basis of predictions for SM rates.

- The kinematic information encoded in the matrix elements turns into angular distributions, dependent on all the inputs discussed so far.
- This provides an ideal experimental testing ground for various predictions, especially if certain angular structures can be shown to vanish in the SM.
- In the $B \to K^* \ell^+ \ell^- \to K \pi \ell^+ \ell^-$ decay we can define three angles (between the leptons, the K and π, and between the two separate decay planes) forming 12 distinct angular structures. One of these in particular vanishes in the SM.

Angular Distribution



- The angles are defined as in the diagram above, in the rest frame of the B meson.

Summary and Recent Progress

- B physics, and in particular, $B \to K^* \ell^+ \ell^-$, provides a potentially sensitive signal to generic New Physics.
- With many different sources of input it is important to understand this decay within the SM, and how it would depend on various New Physics scenarios.
- Recent work (yet to be published, and in colloboration with Roman Zwicky and Markus Hopfer) has provided a potentially powerful new tool to extract this information from the decay.
- Data gathered at the LHC (in particular LHCb) should be able to test these predictions.

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- Thanks for listening!

Parametrization of the angular distribution

- Using the angles defined before, we can write the angular distribution for this decay as:

$$
\begin{aligned}
I = & (J_{1s} + J_{2s}\cos 2\theta_L + J_{6s}\cos\theta_L)\sin^2\theta_K \\
& + (J_{1c} + J_{2c}\cos 2\theta_L + J_{6c}\cos\theta_L)\cos^2\theta_K \\
& + (J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_K\sin^2\theta_L \\
& + (J_4\cos\phi + J_8\sin\phi)\sin 2\theta_K\sin 2\theta_L \\
& + (J_5\cos\phi + J_7\sin\phi)\sin 2\theta_K\sin\theta_L\,,
\end{aligned}
$$

- Of these J_{6c} vanishes in the SM.