# Solutions to the flavour physics problems.

**Sam Cunliffe**
sam.cunliffe@desy.de

Solutions to the problems accompanying the flavour physics lecture in the Terascale Summer School 2020.
**Please email me if you have questions or spot corrections!**
11 August 2020.

### 1. Basics

Secret bonus points for anyone who managed to answer all of Q1 without looking at the slides.

a. Flavour changing neutral current.

b. $q^2 \equiv (p_{\mu^+} + p_{\mu^-})^\alpha (p_{\mu^+} + p_{\mu^-})_\alpha$

c. $5279.65 \pm 0.12\,\mathrm{MeV}/c^2$. The Particle Data Group (PDG) website: https://pdg.lbl.gov.

d. $10579.1 \pm 1.2\,\mathrm{MeV}/c^2 \approx 10.58\,\mathrm{GeV}/c^2$

e. $b\bar{b}$

f. $\sqrt{s} = 2\sqrt{7 \times 4} = 10.58\,\mathrm{GeV}$

g. $13\,\mathrm{TeV}$

h. $1.638 \pm 0.004\,\mathrm{ps}$

i. Despite that they only live for a very short time, at both LHCb and Belle II, the particles recieve a lot of energy from the collision. From special relativity we remember in our laboratory frame, we observe a particle moving relativistically as having a dilated lifetime. So they can exist for a measurable time before decaying.

j. To resolve the flight length of the $B$ meson. From the point of creation to it's decay.

### 2. Branching fractions and observables

a. According to the PDG2020: $(1.006 \pm 0.027) \times 10^{-3}$.

b. $5.961 \pm 0.033\%$.

c. Use the formula on page 35 of the slides. We are using the "charmonium" or "resonance" channel as for normalisation since we know the branching fraction of $B \to J/\psi K$ to a good degree of precision, we can use it as a reference for what that means for the rare decay.

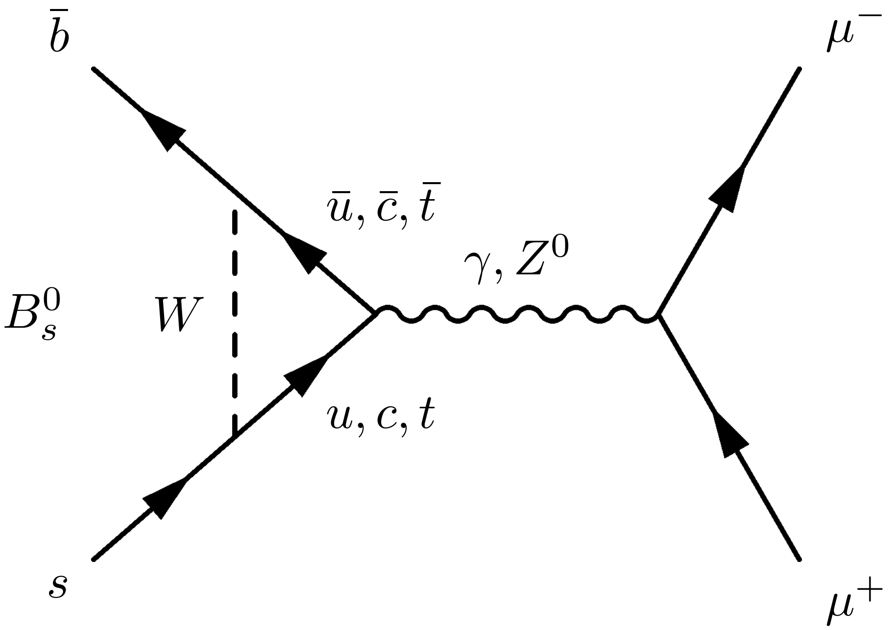
$$\begin{aligned}\mathcal{B} &= \frac{N[B \to K\mu\mu]}{N[B \to J/\psi(\to \mu\mu)K]} \cdot 1 \cdot \mathcal{B}[B \to J/\psi K] \cdot \mathcal{B}[J/\psi \to \mu\mu] \\ &\approx \frac{5}{700} \times 10^{-3} \times 0.06 \\ &\approx 4.3 \times 10^{-7}\end{aligned}$$

d. $R_{D^*}$ is formula $z$. $R$ because it is a ratio (not an asymmetry or anything). Note that the definition is a bit messy when compared to $R_{K^*}$, it is a test of lepton universality but testing a different pair of generations.

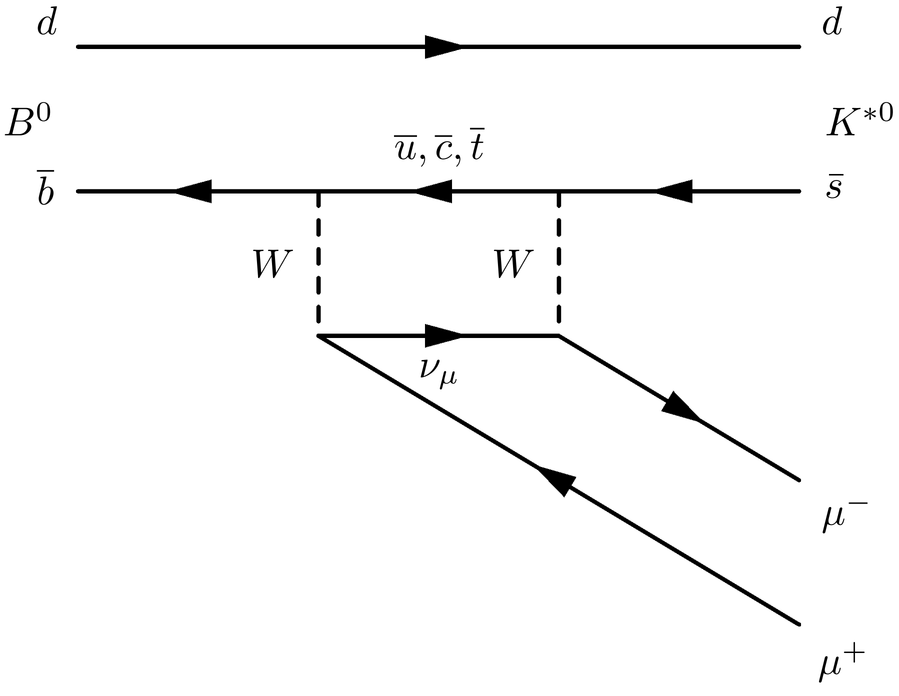
e. $w$ is called the "isospin asymmetry" for $B \to K^*\mu\mu$. $x$ is the CP asymmetry of $B \to K\pi$ decays, and $y$ is $R_{K^*}$.

## 3. Rare decays and modern b-physics

a. $B_s^0 \to \mu^+\mu^-$

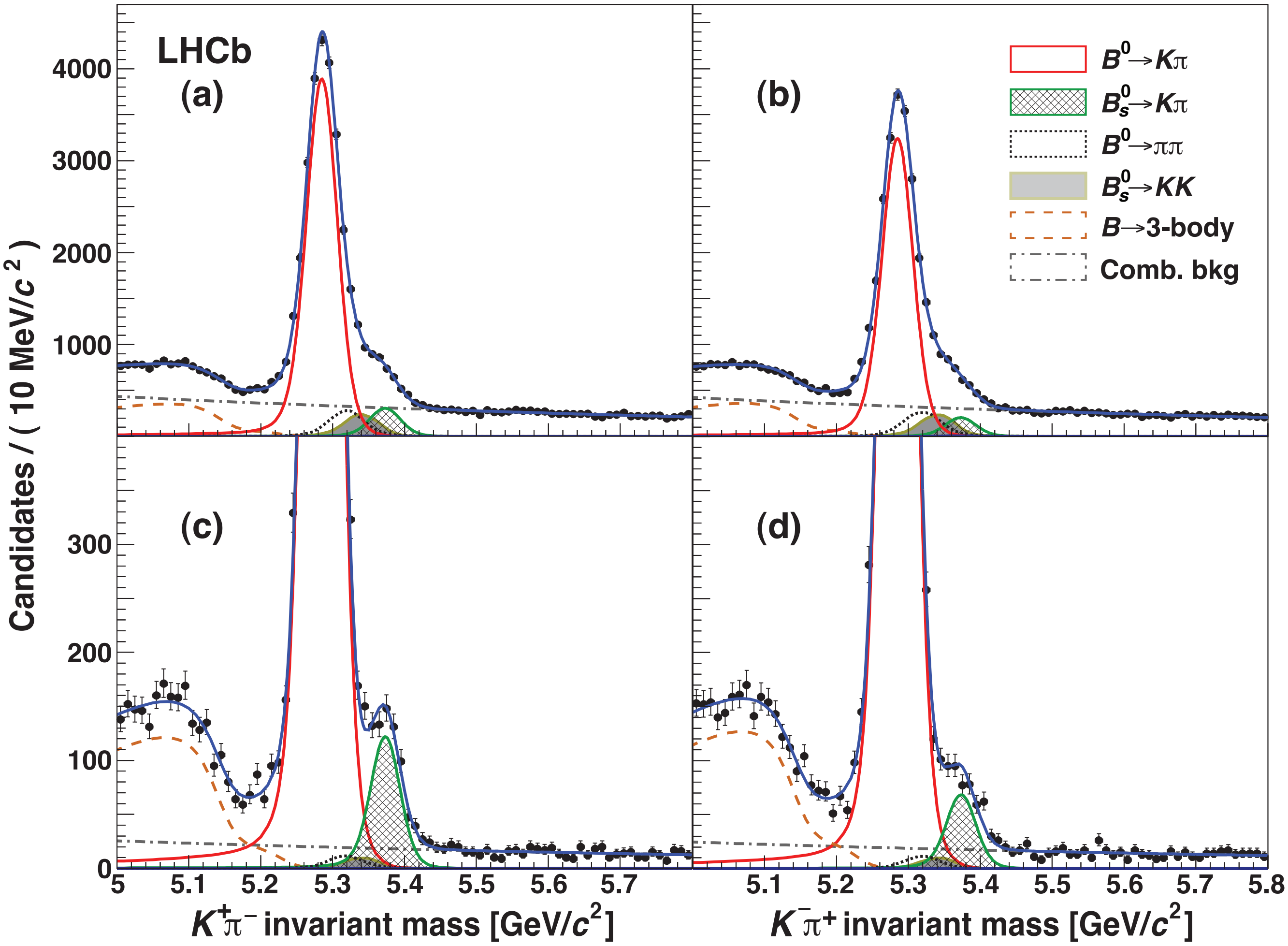


b. $B^0 \to K^{*0}\mu^+\mu^-$ via a “box” diagram



## 4. Advanced

Phys.Rev.Lett.**110**, 221601 is available for free download at: `https://doi.org/10.1103/PhysRevLett.110.221601`. Figure 1 of that paper is:



a. They measure the CP asymmetry in $B_s^0 \to K\pi$ decays (the green shaded component in the figure). As a side-product they also measured the CP asymmetry of $B^0 \to K\pi$ decays (the red line component in the figure).

b.

$$A_{CP} = \frac{\Gamma[\bar{B}_s^0 \to K^-\pi^+] - \Gamma[B_s^0 \to K^+\pi^-]}{\Gamma[\bar{B}_s^0 \to K^-\pi^+] + \Gamma[B_s^0 \to K^+\pi^-]} \tag{1}$$

c. CP violation! This is a difference between matter and antimatter. The “matter” version of the decay $B^0 \to K\pi$ happens more often than the “antimatter” version.

d. We need to see a much larger asymmetry *somewhere* between matter and antimatter in order to explain our universe.

## 5. To finish: a difficult one

This is very subtle. In part c of the previous question, the final state is the same in both the matter and antimatter versions. That is to say reconstructing $K^-\pi^+$ is going to be very very close to reconstructing $K^+\pi^-$ in terms of efficiencies. So you can almost ignore the effect because you can (almost) factorise the efficiencies out from the ratio and they (almost) cancel.

However, on page 53 LHCb are reconstructing $K\mu\mu$ compared to $Kee$. These are very different. A muon goes all the way through the detector and also through the iron. So muons are “easy” to detect and relatively clean. Note there is not a lot of background in the $K\mu\mu$ plot. By contrast, electrons will stop in the calorimeter (hopefully this is covered in previous lectures by Sarah and Ingrid). And, unfortunately, LHCb does not have a particularly good calorimeter. This means the efficiency to detect two electrons is much worse than that to detect muons. So the raw yield of electrons is lower. Once corrected for efficiencies, it ends up being a larger effective yield, so the ratio is smaller than one.

If you want to check this, you will be able to use your new-found paper-reading skills with `https://doi.org/10.1103/PhysRevLett.122.191801` (free link).