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Progress in Physics (56)

The $B^0 \rightarrow K^*(892)\, \mu^+\mu^-$ anomaly and the flavour jigsaw puzzle

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1 Introduction

The Standard Model of particle physics (SM) has been very successful in describing all microscopic physics phenomena with great precision. The SM tells us that protons and neutrons are made of quarks of different types. The proton is made of two u-quarks and one d-quark, while the neutron consists of two d-quarks and one u-quark. They are bound together via the strong interaction that is mediated by the gluon. The u- and d-quarks belong to the first family, as shown in Fig. 1. There are other two heavier "replicas" of this family. In the same way, in addition to the electron (and its associated neutrino ν_e), there are two other heavier charged leptons: the muon and the tau (and their associated neutrinos). The reason why there are three different replicas of the "same" particles is unknown and it goes under the name of "flavour puzzle". In addition to these particles, there are the gauge bosons which are responsible for the interactions, like the photon for the electromagnetic force. Finally, the Higgs boson is responsible for the mass of particles.

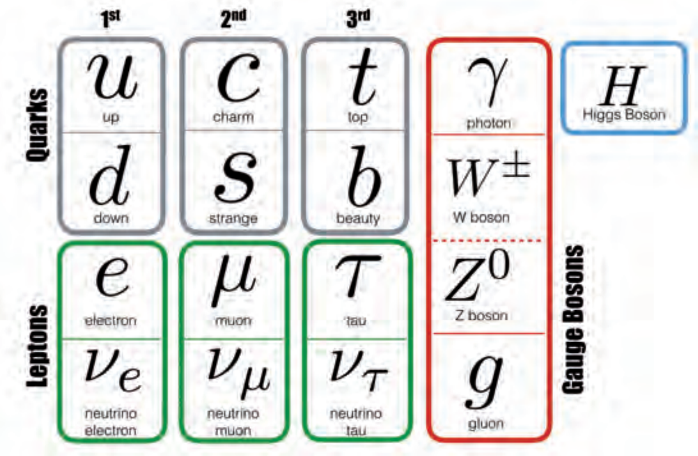

Fig. 1: Particle content of the Standard Model.

While particle physics plays a key role in astrophysics and cosmology, there is ample evidence that the SM is not complete. Two of the main reasons are the existence of Dark Matter and the matter-antimatter asymmetry in the Universe. First of all, most matter in the Universe consists of unknown massive elementary particles, which do not interact electromagnetically, known as Dark Matter.

Secondly, while the SM is "almost symmetric" between particles and anti-particles, our Universe consists mainly of matter, with a tiny amount of anti-matter. Assuming matter and anti-matter were produced in equal amounts during the big bang, we need a mechanism to create this asymmetry during the evolution of the Universe. While the SM has the basic ingredients to create such asymmetry (so called Sakharov conditions), it can only explain less than a billionth of the asymmetry we see in the Universe. In the last decades a plethora of models extending the SM to account for these problems, often referred to as New Physics (NP) models, have been proposed. Almost all these new theories predict the existence of new, heavy particles, unknown in the Standard Model, that would have played a fundamental role in the early, high energy phase of the Universe. The search for such new particles is one of the main goals of the experiments at the Large Hadron Collider (LHC) of CERN in Geneva.

There are two main different ways to search for physics beyond the SM: direct and indirect. The former consists of searching for new particles which might be produced when colliding known particles at high energies. The latter consists of performing precise measurements of decays of known particles to infer the existence of new particles which, interacting with SM particles, would change the decay properties. According to the Heisenberg uncertainty principle and Quantum Field Theory, these new particles can enter in the decays as virtual particles. Indirect searchers allow therefore to probe energies which are orders of magnitudes higher than those achievable by direct searches. However, they require good understanding of what is the predicted behaviour of such decays in the SM.

2 The LHCb experiment

Most NP models, in particular those aiming to solve the flavour puzzle, predict that new particles couple predominantly to the third family (consisting of b- and t-quarks). The LHCb experiment [1] at the LHC is mainly designed and optimized for indirect searches, in particular to measure properties of decays of b-hadrons (particles containing b-quarks).

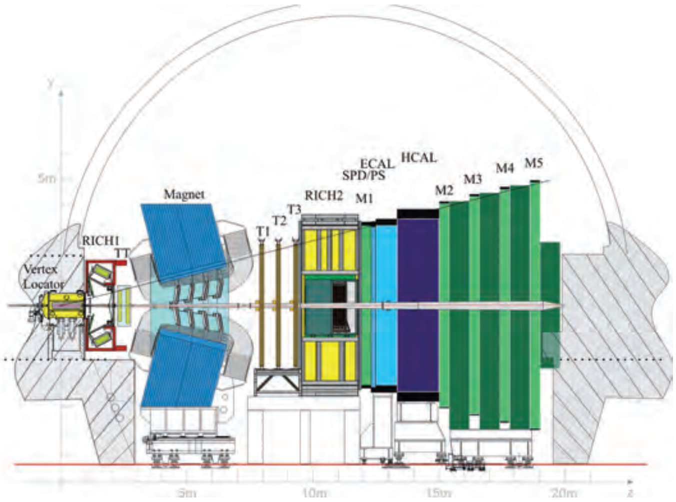

Fig. 2: Schematic view of the LHCb detector.

At the LHC two protons collide at a maximum energy of 14 TeV, which is comparable to the kinetic energy of a flying mosquito, and corresponding to the average thermal energy that particles had a few billionth of a second after the big bang. During the first run of LHC (Run1) the LHCb experiment collected 1 fb^{-1} of p-p collisions at 7 TeV in 2011 and 2 fb^{-1} at 8 TeV in 2012. These collisions produce roughly 10^{12} b-hadrons per fb^{-1}. B-hadrons have in general long lifetimes, i.e. they decay about 1 cm far away from the vertex where the two protons collide. The Vertex Locator (VELO) of LHCb allows to make a precise measurement of the decay point of the b-hadron and to distinguish the signal from the background. In addition, the LHCb detector has a tracking system which allows to make precise measurements of particle momenta, with δp/p ~ 0.5%. Finally, the two RICH detectors, the muon system and the calorimeter system, allow to tell the different particles (muons, pions, kaons etc...) apart from each other. A schematic view of the LHCb detector is shown in Fig. 2. The second run of LHC (Run2) started in 2015 and will continue till 2018. In this period the LHCb experiment is expected to collect about 8 fb^{-1} of data at 13 TeV. In 2018 the LHCb detector will be upgraded, allowing to collect about 50 fb^{-1} in the third run of LHC.

3 The $B^0 \to K^*$ (892) $\mu^+\mu^-$ anomaly

Promising places to search for new particles are rare decays of B-mesons, since the SM contribution is small and NP can enter with a similar strength. The B^0 meson is a bound state of an anti b-quark ($\bar{b}$) and a d-quark (d). The transition $\bar{b} \to \bar{s}$ cannot happen directly in the SM, but only via a second order process that involves a "loop", as shown in Fig. 3 (top). The d-quark does not take part in the interaction and it is referred to as "spectator". The final state consists of a muon and an anti-muon (we will call this system di-muon in the following) and a K^* (892) meson, which is composed of the spectator d-quark and the $\bar{s}$-quark. The K^* (892) is not a stable particle and decays immediately into a charged kaon K^+ and a charged pion π^-. The same reasoning applies to the $\bar{B}^0$ which decays into the final state $\mu^+\mu^-K^-\pi^+$ with a b → s transition. In the following we will refer in general to b → s transitions to indicate both processes. In the detector the trajectory, energy and momentum of the four particles $\mu^+\mu^-K^\pm\pi^\mp$ are measured.

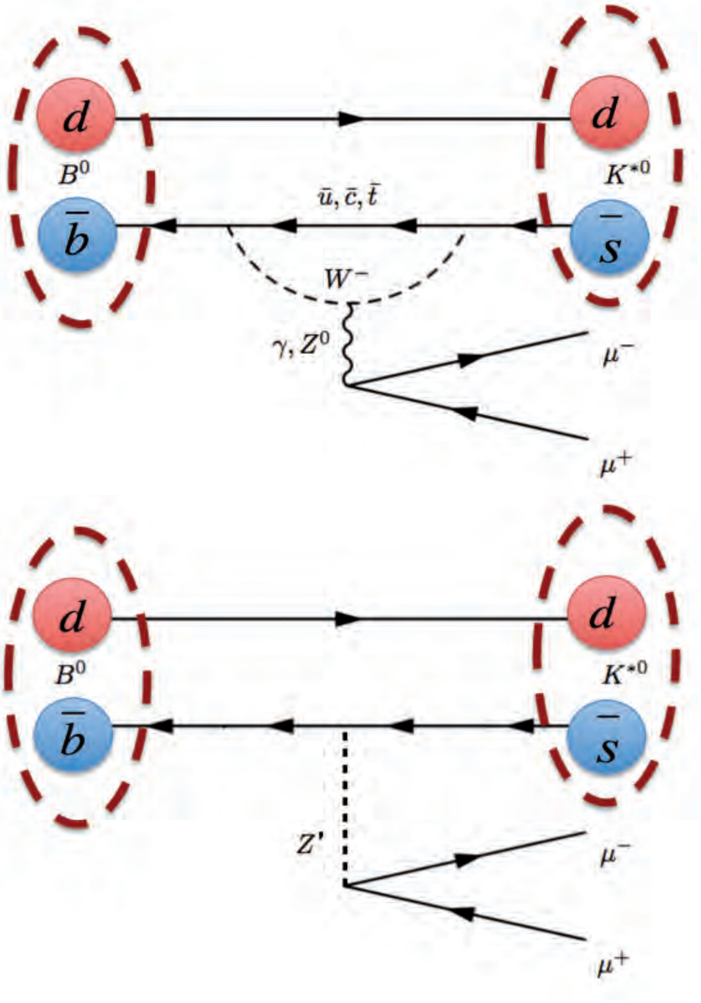

Fig. 3: Feynman diagram for the decay $B^0 \to K^*\mu^+\mu^-$ in the SM (top) and in a possible NP model (bottom).

The SM predicts the branching ratio of this decay (i.e. the probability that the B^0 meson decays into this final state) and also the angular distributions of the decay products. If new particles exist, additional diagrams would in general contribute to the same decay, modifying these properties. An example is given in Fig. 3 (bottom), where the possible contribution of a Z′ boson, not present in the SM is shown. The $B^0 \to K^*$ (892) $\mu^+\mu^-$ decay is completely described by three angles θ_ℓ, θ_K and ϕ (the exact definition of the angles can be found in Ref [2]) in addition to the dimuon invariant mass squared q^2. The differential decay rate as a function of the three angles, for a given q^2 value is:

$$\begin{aligned}\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} &= \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K \\ &+ F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell \\ &+ S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi \\ &+ \sqrt{F_L(1-F_L)}\,P'_5\sin 2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell \\ &+ S_7\sin 2\theta_K\sin\theta_\ell\sin\phi + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi \\ &+ S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\,\Big] \qquad (3.1)\end{aligned}$$

By measuring the colored quantities in Eq. 3.1 we can infer which diagrams contribute to the decay. A discrepancy of the measured observables with respect to SM predictions would indicate new particles contributing to this decay. The interpretation of these measurements is complicated by the fact that we cannot observe free quarks, but they are always bound by the strong interaction in $q\bar{q}$ (mesons) or qqq (baryons) states. Quantum chromodynamics (QCD) describes the strong interaction. However, since it is not perturbative at low energies, QCD computations have often a large uncertainty associated. At the EPS conference in 2013, the measurements of the full set of angular observables were presented for the first time by the LHCb collaboration. The

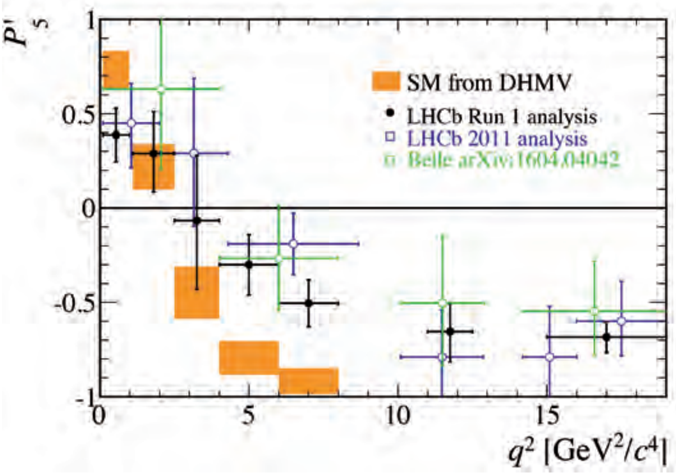

Fig. 4: The measurement of the observable P_5' by the experiments LHCb [3, 4] and Belle [5] are shown. The theory prediction from Ref. [6] is also shown.

result which attracted most of the attention was a significant discrepancy between measurements and predictions in the observable P_5' (the red quantity in Eq. 3.1). This analysis was done with data collected in 2011 at 7 TeV [3]. Later this result was confirmed by an analysis with the full Run1 dataset [4]. Recently the Belle experiment also confirmed this measurement [5]. The three experimental results and the theory predictions are shown in Fig. 4.

4 A coherent pattern?

The $B^0 \to K^*$ (892) $\mu^+\mu^-$ anomaly stimulated a large amount of theoretical work. Some theorists have argued that this is sign of new physics (see for instance Ref [7] and references therein). In particular, they interpreted the discrepancy in P_5' as the contribution of a new boson denoted as Z'. The main argument that supports this view is that there seems to be a coherent pattern between the deviation in P_5' and other smaller discrepancies with respect to SM predictions observed in other b → s transitions. Several branching ratios of decays of the type $B^0 \to h_s \mu^+\mu^-$, where h_s is a hadron containing the *s*-quark, have been measured to be lower than expectations. In particular, the ratio of branching ratios

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}$$

is found to be 2.6 standard deviations below unity [8], while the SM predicts that electrons and muons behave in the same way. The contribution of a Z' boson, coupling with a different strength to muons and electrons, would break the lepton universality of the SM. This is particularly intriguing since it could give us insight on the solution of the flavour puzzle.
Other theorists have pointed out that there is a possible QCD contribution which can mimic the effect of the Z' boson in the observable P_5' [9, 10]. This is related to the production of a $c\bar{c}$-quark pair with the emission of a photon (charm loop), as shown in Fig. 5.

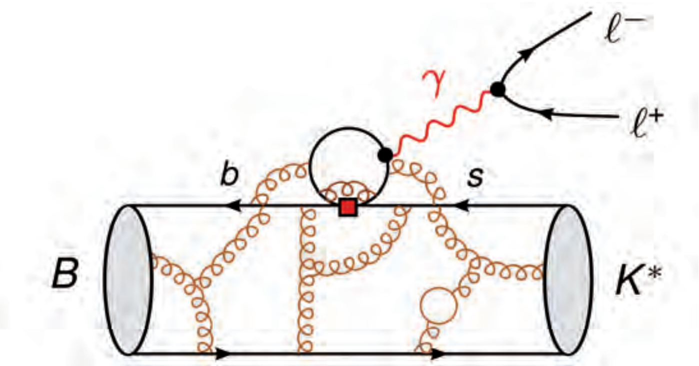

Fig. 5: QCD contribution to the decay $B^0 \to K^*$ (892) $\mu^+\mu^-$, known as charm loop. Reproduced from [11]

Unfortunately, the contribution of Fig. 5 cannot yet be calculated reliably. Some authors [9] argued that this contribution could shift P_5' as observed in data, while other have computed that a large charm loop contribution would actually enhance the anomaly [12]. In this confusing situation new measurements will be crucial to clarify which interpretation is correct. The Z' boson has to appear in a coherent way in the different q^2 regions and in all $B^0 \to h_s \mu^+\mu^-$ decays. This will allow in the future to disentangle a genuine NP contribution from QCD. In particular, QCD effects will not affect the universality of leptons, therefore if a value $R_K < 1.0$ will be confirmed this would rule out the QCD interpretation. Intriguingly, other recent measurements of semileptonic decays by the experiments BaBar [14], Belle [15, 16] and LHCb [13] seem to challenge the lepton universality between muons and taus. While these measurements are not directly related to the $B^0 \to K^*$ (892) $\mu^+\mu^-$ anomaly, in the context of NP models it is natural to have such a pattern. For instance, the semileptonic measurements could be explained with new $W^{\pm\prime}$ bosons belonging to a triplet that contains also the Z' boson, similarly to the triplet of weak gauge bosons ($W^\pm$, Z^0) of the SM.

5 Conclusions and outlook

Measurements of b-hadron decays are indirect probes for physics beyond the SM and allow to test energy scales much higher than direct searches. Recent measurements of b → s transitions at LHCb have shown a pattern of deviations with respect to SM predictions which seem to be consistent with new particles. In particular, the measurement of the angular observable P_5' in the $B^0 \to K^*$ (892) $\mu^+\mu^-$ decay has attracted large attention in the flavour physics community. Some authors have attributed this discrepancy to a possible new Z' boson, while others have pointed out a possible SM explanation involving a larger than expected charm loop contribution. This issue has stimulated an intense discussion in the theory community, however, it is likely that this will be solved only with new measurements. The Run2 of the LHC will tell us which of these interpretations is true and in any case we will learn more about Nature. Finally with the future upgrade of the LHCb experiment and the future BelleII experiment we will be able to make precise measurements which will shed light onto this open issue. Only a joint effort by theorists and experimentalists will tell us if we found a key piece to solve the flavour jigsaw puzzle.

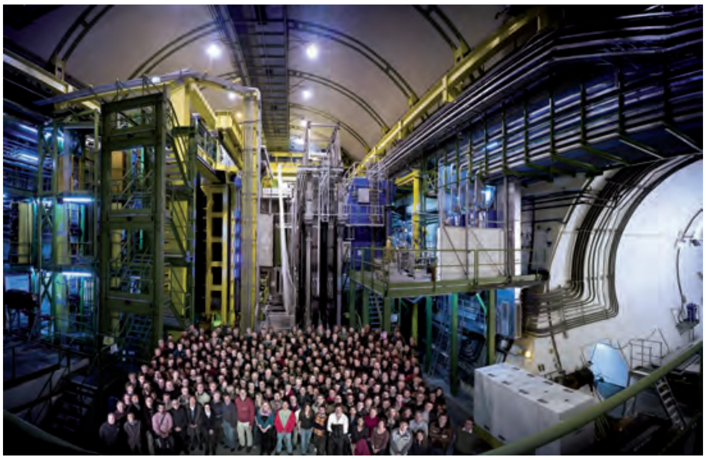

Fig 6: The LHCb detector and collaboration.

6 Acknowledgement

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Prof. **Nicola Serra** has been member of the LHCb experiment since 2005. He did his Ph.D. at the University of Cagliari working on B-meson decays with muons in the final state and he was visiting student at Imperial College of London in 2007.

After obtaining his Ph.D. in Particle Physics in 2008 he was postdoctoral researcher at the NIKHEF institute in The Netherlands, where he worked at various rare decay measurements. He also made the first measurement of the fragmentation fraction of B^0 and B$_s$ mesons at LHC.

Nicola Serra joined the University of Zurich in 2011, first as a postdoc and afterwords as an SNF professor. He continued working on measurements of rare decays of B-mesons and in particular he measured the $B^0 \to K^*\mu\mu$ anomaly.

He obtained an ERC Starting Grant in the ERC Backup Scheme in 2014. His group consists at the moment of 5 postdoctoral researchers and three Ph.D. students, mainly working on the flavour anomalies.