Of all the puzzling features of the Standard Model of particle physics (SM), one of the most vexing is the arrangement of the elementary particles into families or generations. Each pair of fermions comes in three and apparently only three copies: the electron, muon, tau leptons and their associated neutrinos, and three pairs of quarks. The only known difference between generations is the different strengths of their interactions with the Higgs field, known as the Yukawa couplings. This results in different masses for each particle, giving a wide range of experimental signatures.

In the case of the charged leptons (electrons, muons and taus), this pattern also results in one simple post-diction, known as lepton universality (LU): other than effects related to their different masses, all the SM interactions treat the three charged leptons identically. During the past couple of decades, LU has been tested to sub-percent precision in interactions of photons and weak bosons, and in transitions between light quarks. These measurements were made, for example, at the Large Electron–Positron (LEP) collider at CERN in decays of W and Z bosons, by the PIENU and NA62 fixed-target experiments in decays of pions and kaons, and in J/ψ decays by the BES-III, CLEO and KEDR collaborations. However, LU has never been established to such a degree of precision in decays of heavy quarks.

A series of measurements from LHCb and B-factory experiments have tested whether the interactions of charged leptons agree with the Standard Model.
Lepton universality

The results so far concern two classes of transitions in b-quark hadron decays, exemplified in figure 1. Measurements of highly suppressed flavour-changing neutral-current (FCNC) decays, b → sℓℓ', hint at a difference involving muons and electrons, while measurements of the more frequent leading-order or tree-level decays, b → cℓν, hint at a difference between muons and taus. These two classes of decays present very different challenges, both experimentally and theoretically. The latter, semi-leptonic, decays of b-quark hadrons proceed through tree-level diagrams, in which a virtual W boson decays into a lepton–neutrino pair. Measurements of decays involving electrons and muons show no deviations with respect to the SM within the current level of precision. In contrast, measurements of decays involving τ leptons are only marginally in agreement with the SM expectation. The quantity that is experimentally measured is the ratio of branching fractions \( R_{\tau} = \frac{\text{BR}(B \to \tau \nu)}{\text{BR}(B \to \ell \nu)} \), with \( \ell = e, \mu \). This ratio is precisely predicted in the SM owing to the cancellations of the leading uncertainty that stems from the knowledge of the decay form-factors.

Interest in these decay modes was heightened in 2012 when the BaBar collaboration found values for \( R_{\tau} \) and \( R_{\mu} \) above the SM prediction. This was followed in 2015 by results from the Belle collaboration that were also consistently high. Experimentally, such semi-tauonic beauty decays are extremely difficult to measure because taus are not reconstructed directly and at least two undetected neutrinos are present in the final state. To get around this, the Ballar and Belle experiments used both B mesons produced in the proton–proton interaction.

The first measurement of \( R_{\tau} \) was performed by Belle at KEK and BaBar at PEP II, have hinted at potential deviations from the SM. None is statistically significant on its own, but taken together, the results have led to speculation on whether non-SM forces exist or phenomena that treat leptons differently depending on their flavour are at play. If a deviation from the SM was to be confirmed, it would be clear evidence for physics processes beyond the SM and perhaps a sign that we are finally moving towards an understanding of the structure of the fermions.

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The study of beauty-hadron decays to final states involving τ leptons was deemed not to be feasible at hadron colliders such as the LHC. This is a result of the unknown momentum of the colliding partons and the significantly more complex environment with respect to electron–positron B-factories in terms of particle densities, detector occupancy, trigger and detection efficiencies. However, due to the significant Lorentz boost and the excellent performance of the LHCb vertex locator, the decay vertices of the b-hadrons produced at the LHC are well separated from the proton–proton interaction point. This enables the collaboration to approximate the b-hadron momentum and its decay kinematics with sufficient resolution to preserve the discrimination between signal and background.

Exploiting the tau

The first measurement of R_{τ} at a hadron collider was performed by LHCb researchers in 2015 using the decays of the τ meson into muon and two neutrons. This measurement again came out higher than the SM prediction, thus strengthening the tension between theory and experiment raised by Belle and BaBar.

In 2017, LHCb reported another R_{τ} measurement by exploiting the decay of the τ lepton into three charged pions and a neutrino. This measurement was considered to be even more difficult than the previous one due to the large backgrounds from B decays and the apparent lack of discriminating variables. Nevertheless, the presence of a τ decay vertex significantly detached from the b-hadron decay vertex allows the most abundant backgrounds to be suppressed. The residual background, due to b-hadrons decaying to a D* and another charm meson that subsequently gives three pions in a detached vertex topology, is reduced by exploiting the different resonant structure of the three-pion system. The resulting measurement of R_{τ} is larger than, although compatible with, the

The combined world average of R_{τ} and R_{B} remains in tension with the Standard Model.

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Visualization of the electric field norm and 3D far field due to a transmitting antenna. Antennas are intentionally large in this tutorial model.

Lepton universality

Fig. 1. Feynman diagrams in the Standard Model for two classes of processes relevant to the study of lepton universality in heavy quark: a charged current b → c ℓ, tre-level transition (top) and a neutral-current b → s ℓ  loop-level transition (bottom).

SM prediction, and consistent with previous determinations.

The combined world average of Rl+ and Rl measurement, known to precisions of 5 and 10%, respectively, remains in tension with the SM prediction at a level of four standard deviations (figure 2). This provides solid motivation for further LU tests in semi-tauonic decays of B hadrons. In the next years, the LHCb collaboration will therefore extend the Rl measurement to the data sets collected in Run 2 and continue to study semi-tauonic decays of other b-quark hadrons.

In early 2018 the first measurement of Rl+ was performed, probing LU in the B+ sector. While the result was higher than the SM, the current uncertainty is large and the SM prediction is not yet firm. However, it can be an interesting test for the future. An important extension of this already rich physics programme, already being explored by Belle, will consider observables other than branching fractions, such as polarisation and angular distributions of the final-state particles. This will provide crucial insight when interpreting the current anomalies in terms of new-physics models.

The plot thickens

The results described above concern tree-level semi-leptonic decays. In contrast, the other relevant class of transitions for testing LU in the B sector is the one-loop transition b → c ℓν, which is beyond tree level. This effect is usually not present in the Standard Model and can be used to test LU in the B sector. The LHCb collaboration has performed a measurement of Rl+ and Rl in the B0 → K+μ−μ+ transition and found them to be consistent with the SM, albeit with a larger uncertainty.

Assuming that rather than being statistical fluctuations these deviations arise from new physics, one can ask the question: what is driving the Rl+ and Rl anomalies? Is the electron decay rate being enhanced or the muon suppressed, or both? One could get an answer to this question by looking at the differential branching fractions of the decays B+ → K+μ+μ− and B0 → K±μ±ν. Although with small statistical significance, all these branching fractions consistently sit below the SM predictions, indicating that something could be destructively interfering with the muonic decay amplitude. If a new particle was really contributing to the B decay amplitude, then one would naturally expect it to also influence the angular distribution of the decay products. Intriguingly, by studying the angular distribution of B+ → K+μ+μ− decays one observes discrepancies that can be interpreted as being compatible with the expectation based on the central values of Rl+ and Rl.

Can we conclude it is due to new physics? Unfortunately not. Information such as branching fractions and angular observables are affected by non-perturbative QCD effects. In principle, these
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SM prediction, and consistent with previous determinations.

The combined world average of \( R_{D} \) and \( R_{D^*} \) measurements, known to precisions of 5 and 10%, respectively, remains in tension with the SM prediction at a level of four standard deviations (figure 2). This provides solid motivation for further LU tests in semi-tauonic decays of B hadrons. In the next years, the LHCb collaboration will therefore extend the \( R_{D} \) measurement to the data-sets collected in Run 2 and continue to study semi-tauonic decays of other b-quark hadrons.

In early 2018 the first measurement of \( R_{D} \) was performed, probing \( LU \) in the \( B \) sector. While the result was higher than the SM, the current uncertainty is large and the SM prediction is not yet firm. However, it can be an interesting test for the future. An important extension of this already rich physics programme, already being explored by Belle, will consider observables other than branch- ing fractions, such as polarisation and angular distributions of the final-state particles. This will provide crucial insight when interpreting the current anomalies in terms of new-physics models.

The plot thickens

The results described above concern tree-level semi-leptonic decays. In contrast, the other relevant class of transitions for testing \( LU \), \( b \rightarrow c \ell \bar{\nu} \), are highly suppressed because there are no tree-level FCNCs in the SM. This increases the sensitivity to the possible existence of new physics. The presence of new particles contributing to these processes could lead to a sizeable increase or decrease in the rate of particular decays, or change the angular distribution of the final-state particles. Tests of \( LU \) in these decays involve measurements of the ratio of branching fractions between muon and electron decay modes \( R_{e} = \frac{B(B \rightarrow \ell \nu \ell \nu)}{B(B \rightarrow K^{+} \mu^{+} \nu)} \).

These modes represent a considerable challenge because the highly energetic LHC environment causes electrons to emit a large amount of bremsstrahlung radiation as they traverse the material of the LHCb detector. This effect complicates the analysis procedure, for example making it more difficult to separate the signal and backgrounds where one or more particles have not been recon- structed. Fortunately, there are several control samples in the data that can be used to study electron reconstruction effects, such as the resonant decays \( B \rightarrow K^{\mp} (\psi^{0} \rightarrow e^{+} e^{-}) \), and ultimately the precision is dominated by the statistical uncertainty of the decays involving electrons. Despite this, the LHCb measurements dominate the world precision.

Three measurements of \( R_{D^*} \) have been performed by the LHCb experiment with the Run 1 data: two in the \( B^+ \rightarrow K^{*0} \mu^+ \nu \) decay mode \( R_{D^*} \) and one in the \( B^+ \rightarrow K^{*0} \mu^+ \nu \) decay mode \( R_{D^*} \). The results are more precise than those performed at previous experiments, and all have a tendency to sit below the SM predictions (figure 3). The Ballar and Belle experiments have also measured these LU ratios and found them to be consistent with the SM, albeit with a larger uncertainty.

Assuming that rather than being statistical fluctuations these deviations arise from new physics, one can ask the question: what is driving the \( R_{D} \) and \( R_{D^*} \) anomalies? Is the electron decay rate being enhanced or the muon suppressed, or both? One could get an answer to this question by looking at the differential branch- ing fractions of the decays \( B^+ \rightarrow K^{*0} \mu^+ \nu \), \( B^+ \rightarrow K^{*+} \mu^+ \nu \) and \( B^+ \rightarrow K^{*0} \mu^+ \nu \). Although with small statistical significance, all these branching fractions consistently sit below the SM predic- tions, indicating that something could be destructively interfer- ing with the muonic decay amplitude. If a new particle was really contributing to the \( B^0 \) decay amplitude, then one would naturally expect it to also influence the angular distribution of the decay products. Intriguingly, by studying the angular distribution of \( B^0 \rightarrow K^{*0} \mu^+ \nu \) decays one observes discrepancies that can be interpreted as being compatible with the expectation based on the central values of \( R_{D} \) and \( R_{D^*} \).

Can we conclude it is due to new physics? Unfortunately not. Information such as branching fractions and angular observables are affected by non-perturbative QCD effects. In principle, these
Another interesting avenue, recently taken up by Belle, is to compare the data directly. All the results so far probing LU at LHCb are based on LHC Run 1 data recorded at a centre-of-mass energy of 7 and 8 TeV. Measurements of the $R_K$ and $R_{K^*}$ ratios can be significantly improved over future years with the analysis of the full Run 2 data at an energy of 13 TeV. LHCb will also broaden its search for LU violation to other types of FCNC decays, such as $B^- \rightarrow \psi \mu^+ \mu^-$. Another interesting avenue, recently taken up by Belle, is to compare the angular distributions of the decays $B^- \rightarrow K^- \psi \mu^+$ and $B^- \rightarrow K^- \psi e^-$. If LU were indeed violated, then one would expect to see differences between the angular distributions of muons and electrons as well as the decay rates.

**Potential explanations**

It is possible that the anomalies seen in tree-level and FCNC decays are related. The tree-level decays are sensitive to new physics at the TeV scale, whereas the FCNC decays are sensitive to scales of the order 10 TeV on account of the SM suppression of loop-level decays. If one would like to explain both anomalies with a single model, then this model may also be suppressed in its contribution to $B^- \rightarrow \tau^+ \nu$ compared to $B^- \rightarrow \mu^+ \nu$. This can be done by either forbidding FCNC processes at tree level, like in the SM, or by having a hierarchical flavour structure where the coupling to third-generation leptons is enhanced with respect to muons. Amongst several speculations, the most promising model in this regard introduces the well-known concept of leptoquarks, which are particles that carry both lepton and quark quantum numbers (figure 4). The mass scale for such a leptoquark could be around 1 TeV, which is clearly very interesting for direct searches at the LHC.

The theoretical options open up if one would like to explain only one set of anomalies. For example, the loop-level anomalies can be explained with a $Z'$ boson of a few TeV in mass, although the allowed parameter space for such a model competes with the constraints imposed by B-mass–antimatter oscillations. Overall, there are many possible models proposed that can explain one or both of these anomalies, and differentiating between them would become an exciting challenge if these were to be confirmed.

In any case, the amount of data analysed for the measurements described here corresponds to just one-third of what will be available by the end of 2018 at LHCb. Meanwhile, following a major overhaul of the KEK accelerator, the Belle-II experiment is about to start operations in Japan and is expected to collect data until 2025 (CERN Courier September 2016 p32). The two experiments are designed for the study of heavy-flavour physics, and their complementary characteristics will allow researchers to perform ultra-precise measurements of decays of b-quark hadrons. Hence, the prospects for continuing to test lepton universality in the next decade and beyond are excellent.

**Further reading**

LHCb Collaboration 2017 JHEP 01 055.

**Résumé**

Les quarks bâtonnent bousculent l’universalité leptonique

De récentes mesures des désintégrations de hadrons de beauté effectuées par l’expérience LHCb, venant s’ajouter aux précédents résultats de Belle au KEK et de Babar au PEP-II, semblent induire de légers écarts par rapport à l’universalité leptonique. Mais individuellement, ces résultats ne sont pas significatifs statistiquement. Considérés tous ensemble, en revanche, ils intriguent, car ils montrent que les forces du Modèle standard ne sont pas insensibles à la saveur leptonique. Si un écart par rapport à l’universalité leptonique était confirmé, il s’agirait d’un indice fort de l’existence d’une physique au-delà du Modèle standard, et cela permettrait de mieux comprendre le classement en trois générations des fermions. Les physiciens attendent donc avec impatience de nouvelles données pour voir si ces effets sont confirmés ou non.

Simone Bifani, University of Birmingham; Concezio Bozzi, CERN and INFN; Gregory Ciezarek, CERN; and Patrick Owen, University of Zurich.

**Fig. 3.** LHCb measurements of the lepton universality ratios $R_K$ and $R_{K^*}$. BaBar and Belle have made similar measurements, although with larger uncertainties.

**Fig. 4.** An example of a Feynman diagram for leptoquark-mediated $b \rightarrow c \tau \nu$ and $b \rightarrow s \tau \nu$ singular transitions.
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Résumé
Les quarks beau exactement l’universalité leptique.
Beyond UHV: the new ZAO® alloy for HV applications

While NEG pumps are perfectly suitable for usage in the ultra-high and extremely-high vacuum range (UHV-XHV), one of their main limitations has always been the possibility to effectively use them in the high vacuum (HV) range, corresponding to $10^{-6}$–$10^{-9}$ mbar. The main residual gas in typical UHV systems is H$_2$, for which a NEG pump can provide a high pumping speed and a virtually infinite sorption capacity prior to requiring a reactivation. On the contrary, HV systems are often unbaked and viton-sealed, thus the gas loads and the gas composition are different: H$_2$ is no longer the main residual gas and a key role is played by H$_2$O, N$_2$, and O$_2$ also, as well as by CO and CO$_2$. In these conditions, the single-run sorption capacity of a NEG pump is often too limited to allow an efficient employment with no need for frequent reactivation.

The latest step forward made by SAES in NEG technology is the recent development of ZAO® alloy (Zr-V-Ti-Al), which gives the possibility to overcome this intrinsic limitation in the usage of NEG pumps. As a matter of fact, ZAO pumps can work either at room temperature or in warm conditions (150–200 °C), enabling their adoption not only in the usual UHV-XHV range but also in HV systems thanks to the following features:

- a lower H$_2$ equilibrium pressure;
- lower H$_2$ emission during the activation;
- a larger capacity for all the active gases; by keeping the NEG cartridge at the indicated moderate temperatures, more than 20 sorption cycles in HV conditions are possible;
- a higher H$_2$ embrittlement limit;
- better mechanical properties: ZAO disks are intrinsically more robust than St172 ones;
- improved performance of N$_2$ sorption;
- better pressure stability at 10$^{-6}$ mbar, as they are able to efficiently deal with large air leaks and/or big amounts of carbon contaminants while ensuring a very good mechanical stability over time.

The sorption capacity of a getter can be enhanced by operating it at moderate temperature (e.g., ~200 °C) and moderate pressure (e.g., 10–50 W, depending on the model), which promotes gas diffusion from the surface to the bulk. However, high-load sorption cycles might be detrimental for traditional St172-based getter alloys, leading to a progressive efficiency loss in the getter reactivation, as sorbed gases keep accumulating inside the bulk.

Figure 1 is an example of ZAO’s ability to continuously work at moderate temperature in HV conditions. Ten CO$_2$ sorption cycles have been made at 1–10$^{-5}$ Torr with a CapaciTorr® HV200 pump working at 200 °C. Each cycle at such pressure corresponds to 1 year of operation at 5–10$^{-4}$ Torr. The pumping performances have been substantially the same all along the series, without any substantial performance variation between the first and the tenth cycles. This demonstrates how ZAO is able to withstand several reactivation cycles under high gas loads while keeping its performance close to the nominal one, thanks to its higher carbon, oxygen, and nitrogen diffusivity to the bulk.

In addition, H$_2$ could be partially released from standard getter alloys (such as St172 and St707) working at 200 °C, whereas ZAO—having an intrinsically-lower equilibrium pressure—does not release H$_2$ while operating at 200 °C.

A practical example is given by the Pixel detector of CMS at CERN, where 16 vacuum insulated transfer lines (each ~17 m long) with liquid CO$_2$ are used. The lines are grouped 4x4 in 4 sectors with 4 vacuum manifolds, originally pumped by a turbomolecular pump. While the goal was to keep the overall pressure below 10$^{-4}$ mbar, the presence of a huge magnetic field in the manifold region did not allow to keep either turbomolecular or sputter-ion pumps permanently running. 4 CapaciTorr® HV200 replaced the turbomolecular pumps, succeeded in keeping the Pressure in the 10$^{-5}$–10$^{-7}$ mbar range for months with no need for any getter reactivation.

1. Download the full white paper at http://cerncourier.com/cms/article/whitepapers/71254
SAES Group is the world leader in the field of getters and it has pioneered this technology for more than 70 years. Non-evaporable getter (NEG) pumps, in particular, are one of the company’s core businesses and SAES has steadily contributed to the growth of NEG technology over the years, by introducing a wide range of getter alloys for different applications, as well as by innovating pumps’ design, manufacturing processes and testing techniques.

Beyond UHV: the new ZAO® alloy for HV applications
While NEG pumps are perfectly suitable for usage in the ultra-high and extremely-high vacuum range (UHV-XHV), one of their main limitations has always been the possibility to effectively use them in the high vacuum (HV) range, corresponding to 10⁻⁶–10⁻⁹ mbar. The main residual gas in typical UHV systems is H₂, for which a NEG pump can provide a high pumping speed and a virtually infinite sorption capacity prior to requiring a reactivation. On the contrary, HV systems are often unbaked and viton-sealed, thus the gas loads and the gas composition are different: H₂ is no more the main residual gas and a key role is played by H₂O, N₂, and O₂ also, as well as by CO and CO₂. In these conditions, the single-run sorption capacity of a NEG pump is often too limited to allow an efficient employment with no need for frequent reactivation.

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The sorption capacity of a getter can be enhanced by operating it at moderate temperature (e.g., ~200 °C) and moderate power (e.g., 10–50 W, depending on the model), which promotes gas diffusion from the surface to the bulk. However, high-load sorption cycles might be detrimental for traditional St707®-based getter alloys, leading to a progressive efficiency loss in the getter reactivation, as sorbed gases keep accumulating inside the bulk.

Figure 1 is an example of ZAO’s ability to continuously work at moderate temperature in HV conditions. Ten CO₂ sorption cycles have been made at 1·10⁻⁷ Torr with a CapaciTorr HV200 pump working at 200 °C. Each cycle at such pressure corresponds to 1 year of operation at 5·10⁻⁸ Torr. The pumping performances have been substantially the same all along the series, without any substantial performance variation between the first and the tenth cycles. This demonstrates how ZAO is able to withstand several reactivation cycles under high gas loads while keeping its performance close to the nominal one, thanks to its higher carbon, oxygen, and nitrogen diffusivity to the bulk.

In addition, H₂ could be partially released from standard getter alloys (such as St172 and St707) working at 200 °C, whereas ZAO—having an intrinsically lower equilibrium pressure—does not release H₂ while operating at 200 °C.

A practical example is given by the Pixel detector of CMS at CERN, where 16 vacuum insulated transfer lines (each ~17 m long) with liquid CO₂ are used. The lines are grouped 4x4 in 4 sectors with 4 vacuum manifolds, originally pumped by a turbomolecular pump. While the goal was to keep the overall pressure below 10⁻⁸ mbar, the presence of a huge magnetic field in the manifold region did not allow to keep either turbomolecular or sputter-ion pumps permanently running. 4 CapaciTorr HV200 replaced the turbomolecular pumps, succeeded in keeping the Pressure in the 10⁻⁸–10⁻⁹ mbar range for months with no need for any getter reactivation.


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