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Flavour physics and the Large Hadron Collider beauty experiment

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An exciting new era in flavour physics has just begun with the start of the Large Hadron Collider (LHC). The LHCb (where b stands for beauty) experiment, designed specifically to search for new phenomena in quantum loop processes and to provide a deeper understanding of matter–antimatter asymmetries at the most fundamental level, is producing many new and exciting results. It gives me great pleasure to describe a selected few of the results here—in particular, the search for rare $B_s^0 \to \mu^+\mu^-$ decays and the measurement of the B_s^0 charge-conjugation parity-violating phase, both of which offer high potential for the discovery of new physics at and beyond the LHC energy frontier in the very near future.

Keywords: Large Hadron Collider beauty; flavour; charge-conjugation parity; LHCb

1. The beauty of flavour

Flavour[1] physics plays a crucial role in the search for new phenomena at the Large Hadron Collider (LHC). Its pedigree is excellent, providing the first evidence for the existence of the charm quark, the third generation of quarks and leptons, the high mass scale of the top quark and matter–antimatter asymmetries through the discovery of CP violation.[2] The nature of flavour physics is such that it allows one to probe processes at energies beyond the LHC centre-of-mass energy and therefore has an enormous potential to provide the first evidence for new physics, which may hold the key to open scientific questions such as 'Why are there three generations of quarks and leptons (if there are only three)?', 'What determines the hierarchy of quark masses?' and 'What is the origin of CP violation?' Furthermore, two of the very few observations that cannot be accommodated by the Standard Model (SM), namely the baryon–antibaryon asymmetry in the Universe and the non-zero neutrino mass, are intimately related to flavour physics.

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[1] Flavour is a label that distinguishes between the different members in the two groups of elementary particles, the quarks and leptons.

[2] The violation of the combination of discrete symmetries, charge conjugation (C) and parity (P), which leads to an asymmetry between matter and antimatter.

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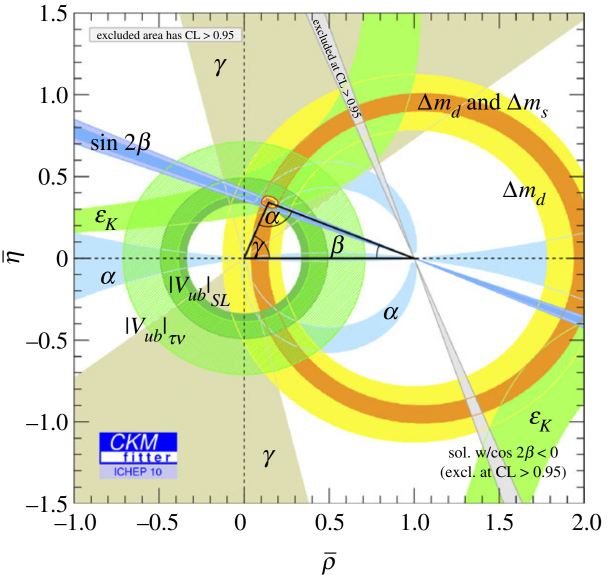

Figure 1. The current status of the unitarity triangle, taken from Charles *et al.* [2]. (Online version in colour.)

The heart of flavour physics in the SM lies in the very successful Cabibbo–Kobayashi–Maskawa (CKM) picture of the interactions between the different quark flavours (see the review on *The CKM quark-mixing matrix* in Nakamura *et al.* [1]). The CKM matrix describes the relationship between the weak and mass eigenstates; it is unitary and incorporates CP violation through the complex phases of the matrix elements. The state-of-the-art knowledge is encapsulated in the so-called 'unitarity triangle' (figure 1), which shows a consistency between all the experimental measurements made over many decades and is a beautiful validation of the CKM picture [2]. Even so, there is still plenty of room for new physics [3] that may be uncovered in the near future by the LHC beauty (LHCb) experiment at the LHC.

The main flavour physics programme of the LHCb experiment is to make very precise measurements of CP-violating asymmetries and to search for new phenomena in quantum loop processes using particle decays involving heavy (bottom and charm) quarks. The indirect approach taken by LHCb is complementary to the direct search for new physics by the general purpose detectors ATLAS (A Toroidal LHC ApparatuS) and CMS (compact muon solenoid), and will provide information about the masses, couplings, spins and CP phases of newly discovered particles. Interestingly, if new particles exist at the TeV mass scale, as is expected, then current measurements already indicate that the flavour couplings of the new physics have a very particular flavour structure so as not to have given rise to effects inconsistent with SM expectations. The minimal flavour violation (MFV) hypothesis, in which all sources of flavour and CP violation in the quark sector have the same pattern as the SM, namely the CKM matrix, has been proposed to resolve this dilemma (see references in Charles *et al.* [2]). One illustration of the power of flavour physics is therefore demonstrated by measurement of the $B^0_{d,s} \to \mu^+\mu^-$ decay rates, which are highly sensitive to new physics contributions but can also prove or exclude the MFV hypothesis by testing whether physics beyond the SM exhibits the characteristic flavour-universality pattern.

2. The LHCb experiment

The LHCb experiment [4] is designed to search for new physics and to make precision measurements of CP-violating asymmetries using the decays of hadrons involving bottom and charm quarks. The bottom quark (b quark) is of particular interest because

- it resides in the third generation of elementary particles and is therefore intimately linked to CP violation;
- it is the heaviest quark (mass approx. $4.7\,\mathrm{GeV\,c^{-2}}$) that forms hadronic bound states;
- it must decay to quarks outside the third generation, which means that its decay is suppressed resulting in an observable long lifetime (approx. $1.6\,\mathrm{ps}$);
- its high mass means that there are many accessible final states; and
- all of the b-flavoured hadron species, such as $B^+(\equiv \bar{b}u)$, $B^0_d(\equiv \bar{b}d)$, $B^0_s(\equiv \bar{b}s)$, $B^+_c(\equiv \bar{b}c)$ and $\Lambda_b(\equiv \mathrm{bud})$, are produced in high-energy proton–proton (pp) collisions.

The LHCb experiment provides a large acceptance for the decay products of b-flavoured hadrons and is optimized to select, reconstruct and identify the particles produced in the subsequent decay. The production of $b\bar{b}$ pairs in pp collisions at the LHC is strongly peaked forward–backward and correlated, such that if the b quark goes in the forward direction, then so does the $\bar{b}$ antiquark. The experiment is therefore configured as a forward single-arm spectrometer with excellent tracking provided by the high-precision silicon VELO (VErtex LOcator) detector and other tracking detectors, excellent particle identification provided by two ring-imaging Cherenkov (RICH) detectors, a calorimeter system and a muon tracking system, and a highly efficient trigger system. The VELO and RICH detectors, in particular, are critical to the success of the experiment. The VELO detector provides a primary interaction vertex resolution of approximately $5\,\mu\mathrm{m}$ (for 25 tracks) transverse to the beam direction and approximately $75\,\mu\mathrm{m}$ along the beam direction. The RICH detectors provide charged pion–kaon particle identification over a large range of momentum (2–$100\,\mathrm{GeV\,c^{-1}}$).

The results presented here were accomplished using the first pp collision data from LHCb and correspond to an integrated luminosity of approximately $38\,\mathrm{pb^{-1}}$ (equivalent to approx. $10^{10}\,b\bar{b}$ pairs) collected during 2010; one of the first pp collision events observed in LHCb is shown in figure 2. Owing to the design of the experiment and a three times higher $b\bar{b}$ cross section at the LHC [5,6], LHCb is already competitive with the Tevatron experiments at Fermilab, which has analysed $6000\,\mathrm{pb^{-1}}$ of data collected over many years. At the time of writing, the LHCb experiment is running smoothly and expects to collect approximately $300\,\mathrm{pb^{-1}}$ by the summer of 2011 and $1\,\mathrm{fb^{-1}}$ by the end of the year.

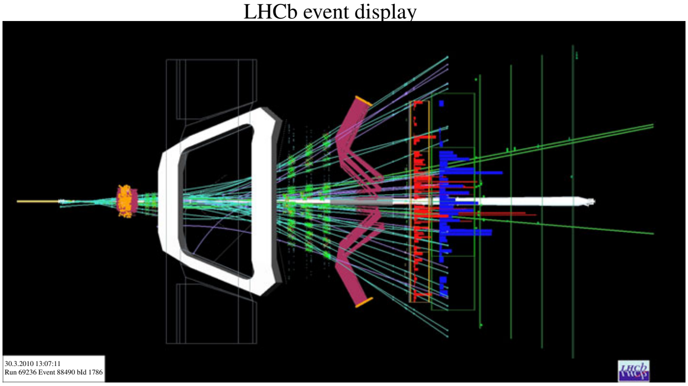

Figure 2. An event display of one of the first pp collisions observed in the LHCb detector. (Online version in colour.)

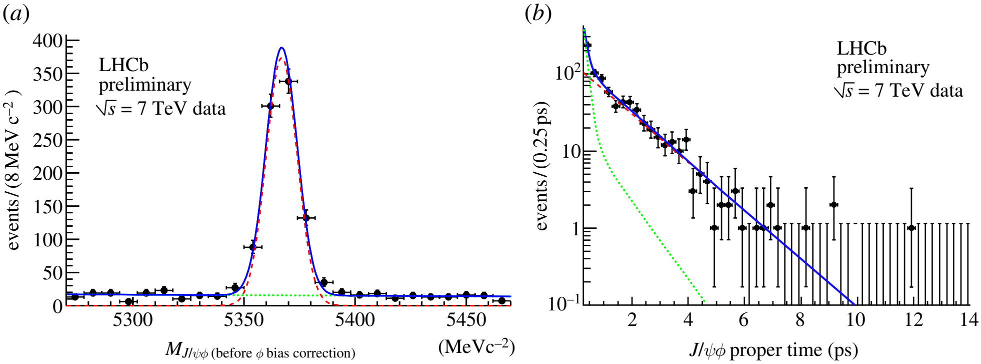

Figure 3. (a) The $B_s^0 \to J/\psi\phi$ mass [7] and (b) proper time [8] distributions. The total fit is represented by a solid line, the signal distribution by a dashed line and the background distribution by a dotted line. (Online version in colour.)

The excellent performance of the LHCb detector is best illustrated with the wealth of physics measurements that are now emanating from the experiment. For example, the excellent knowledge of the momentum scale (1 part in 10^4) provides mass resolutions of 6–10 MeV c^{-2} for $B \to J/\psi X$ (X represents a hadron) decay modes and the world's best B hadron mass measurements [7]. The resolution of the tracking system provides a proper time resolution of approximately 50 fs and precision measurements of the B hadron lifetimes [8]. Examples of the B mass and proper time distributions are shown in figure 3. Further illustrations of the excellent physics performance of LHCb and the tantalizing first physics results in flavour physics are given in the following section.

3. Fruitful flavour

(a) *Flavour production*

Charm and bottom quarks are produced in copious amounts at the LHC. It is therefore only natural that some of the early physics measurements for the

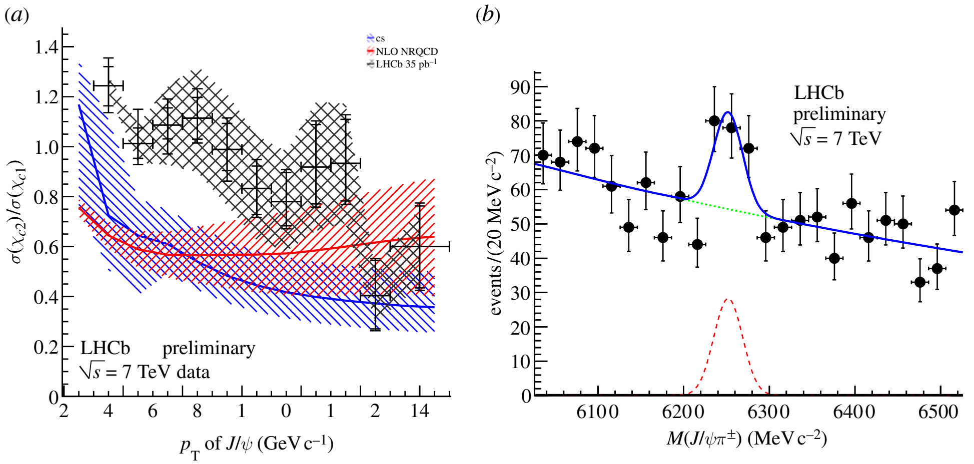

Figure 4. The ratio of the prompt production cross sections for the χ_{c2} to χ_{c1} charmonium states compared with theoretical predictions (*a*) [11] and the $B_c^\pm \to J/\psi\pi^\pm$ mass distribution (*b*) [12]. (Online version in colour.)

LHCb experiment are the study of onia (bound $c\bar{c}$ and $b\bar{b}$ states) and related resonances, the measurements of the fractions of the different B species and the search for new B decays, especially in the little chartered territory of the B_s^0 system.

The production mechanism for onia systems at hadron colliders is not well understood and measurements from the LHC can provide invaluable new input. Owing to its forward acceptance and dedicated heavy flavour trigger, LHCb has the highest sample of J/ψ events with the distinctive signature $J/\psi \to \mu^+\mu^-$ at the LHC. LHCb has published results on inclusive J/ψ production [6], made the first observation of double J/ψ production at the LHC [9] and released preliminary results on upsilon ($b\bar{b}$) production [10]. LHCb has also reported results on the production of the χ_c states [11] (shown in figure 4*a*), the $X(3872)$ [13], the exact nature of which is still unclear, and exclusive $\mu^+\mu^-(\gamma)$ final states in low-multiplicity events [14].

Knowledge of the fractions of the different B species produced in pp collisions at the LHC is a very important input to many heavy flavour physics analyses. Already with the first data, LHCb has measured the fraction of B_s^0 produced compared with B_d^0 [15], and observed a significant B_c^+ signal [12] (shown in figure 4*b*), boding well for the future B_c^+ physics programme of LHCb.

(*b*) *Matter–antimatter asymmetries*

The asymmetry between matter and antimatter in our universe is one of the unsolved scientific mysteries. CP violation, a requirement to produce such an asymmetry, has so far been observed in the kaon and B^0 and B^+ systems (see review entitled *CP-violation in meson decays* in Nakamura *et al.* [1]). However, the magnitude of the observed effects is not sufficient to explain our matter-dominated Universe. LHCb will be the first experiment to perform precise studies

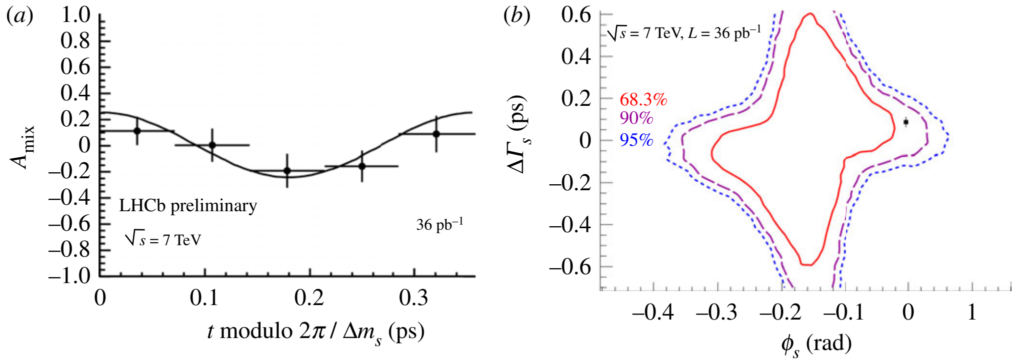

Figure 5. (a) The mixing asymmetry for B_s^0 signal candidates as a function of proper time modulo $2\pi/(\Delta m_s)$. (b) Contours indicating the allowed region for ϕ_s against $\Delta\Gamma_s$ from the preliminary LHCb analysis. Only statistical uncertainties are considered but these are dominant with the present dataset. The point with the small error bar close to $\phi_s = 0$ is the SM prediction. (Online version in colour.)

of CP violation in the B_s^0 system and to search for new sources of CP violation in a theoretically clean environment.

Already with the little data accumulated in 2010, it has been possible to discover new decay channels that will be important for future study. These include the decay channel $B_s^0 \to J/\psi f_0(980)$ [16] in which the final state is CP eigenstate and the gluonic–penguin-dominated decay $B_s^0 \to K^{*0}\overline{K^{*0}}$ [17], among others. The importance of the former channel is that it can be used, alongside the ‘golden’ decay mode, $B_s^0 \to J/\psi\phi$, to measure the B_s^0 phase which parametrizes mixing-induced CP violation.

The measurement of CP violation in the B_s^0 system is extremely important, as any significant enhancement in the CP-violating phase above the small value predicted by the SM will be a clear sign of new physics. Indeed, current measurements from the Tevatron experiments, CDF and DØ, show a tantalizingly small difference from the SM prediction [18,19]. The $B_s^0 \to J/\psi\phi$ analysis is an exceedingly non-trivial study, being a time-dependent angular measurement. LHCb has established the components of the analysis, validating its proper time reconstruction with measurements of b hadron lifetimes [8], making the first studies of the untagged angular distributions in $B_s^0 \to J/\psi\phi$ and the control channel $B_d^0 \to J/\psi K^{*0}$ [20] and developing the flavour tagging strategy [21]. Critical to the measurement is the ability to resolve the very fast $B_s^0 - \overline{B_s^0}$ oscillations. This has been demonstrated, as shown in figure 5a, by one of the world’s best measurements of the oscillation parameter $\Delta m_s = 17.63 \pm 0.11(\mathit{stat.}) \pm 0.04\ (\mathit{syst.})\ \mathrm{ps}^{-1}$ [22].

LHCb has recently put all the elements of the $B_s^0 \to J/\psi\phi$ analysis together in a preliminary flavour-tagged study of the B_s^0 mixing phase, ϕ_s [23]. The sample size is not yet sufficient to extract a value of ϕ_s itself, but contours may be drawn in the plane of ϕ_s against $\Delta\Gamma_s$ (where $\Delta\Gamma_s$ is the width difference between the B_s^0 mass eigenstates). The result is shown in figure 5b. With the integrated luminosity expected in 2011, LHCb will be able to measure ϕ_s with a precision of about 0.13 radians and shed light on any new physics contributions.

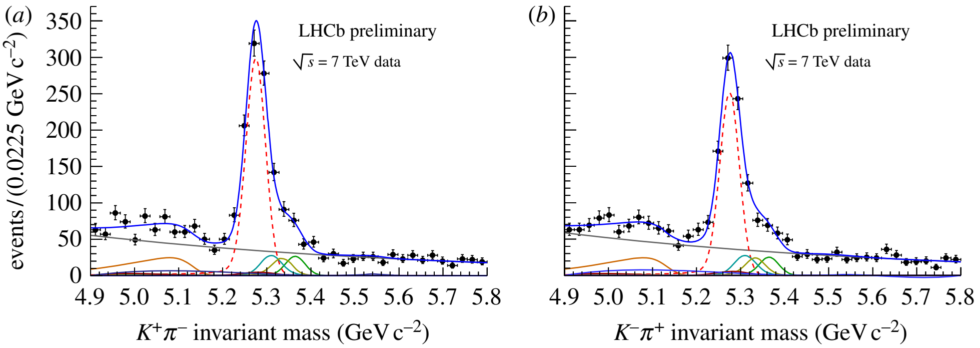

Figure 6. $B^0 \rightarrow K\pi$ events selected in the 2010 data. The fitted signal component is the dominant dashed curve. The difference in yields between (*a*) $K^+\pi^-$ and (*b*) $K^-\pi^+$ is driven by CP violation in the B^0 decay. The other curves show the contribution of background components. (Online version in colour.)

A major responsibility of LHCb is to provide a solid benchmark of the SM picture of quark flavour interactions against which new physics contributions can be judged. An important aspect of this exercise is the precise determination of the CKM unitarity triangle angle γ, both in tree-level decays, such as $B^\pm \rightarrow DK^\pm$, and in loop-dominated modes, such as $B^0 \rightarrow \pi^+\pi^-$. Although the data sample accumulated in 2010 is too small to allow γ to be measured, the foundations for this programme have already been laid with a series of studies that illustrate the potential of LHCb in hadronic final states and the power of the particle identification capabilities afforded by the RICH system. Studies of two-body *B* decays have provided the world's best measurement of the $B_s \rightarrow K^+K^-$ lifetime [24] and yielded evidence for CP violation in the channel $B^0 \rightarrow K\pi$ [25], shown in figure 6, with a value consistent with previous measurements. With the expected integrated luminosity in 2011 and 2012, LHCb expects to measure γ with a precision of about 5° [26].

(*c*) *Rare B decays*

Searching for the very rare decay mode $B_s^0 \rightarrow \mu^+\mu^-$ is of paramount importance in flavour physics, because the value of its branching fraction is predicted with good precision in the SM, $(0.32 \pm 0.2) \times 10^{-8}$, but large enhancements are possible in many variants of SuperSymmetry and alternative new physics models. This analysis therefore represents one of the most promising ways to look for new physics at the LHC. LHCb has recently published the results of the search for this decay based on the data collected in 2010 [27]. No signal is yet observed, and an upper limit is placed on the branching fraction of 5.6×10^{-8} at the 95% confidence level, as shown in figure 7*a*. This limit is very similar to that achieved by the Tevatron experiments, but is based on around two orders of magnitude less data. With the data foreseen in 2011–2012, it will be possible to improve the sensitivity of the search to around the SM value of the branching fraction; the discovery potential is illustrated in figure 7*b*. This means that the LHCb experiment has the potential to discover new physics beyond the SM within the next 2 years or to severely constrain viable new physics scenarios.

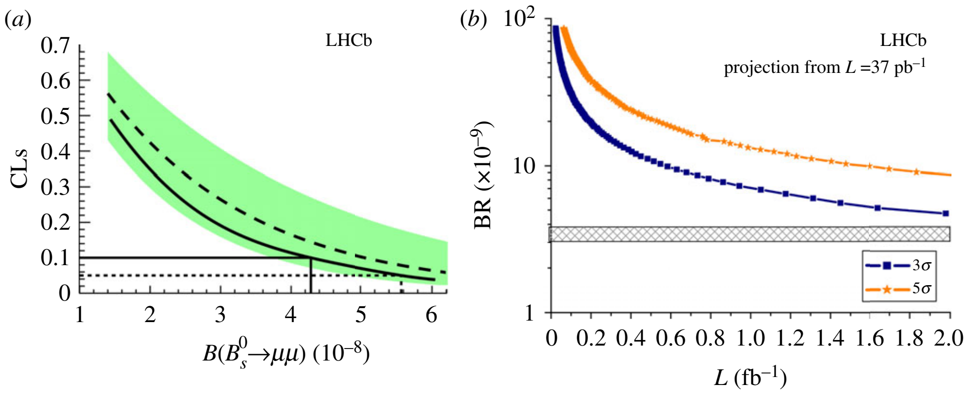

Figure 7. (*a*) Observed (solid curve) and expected (dashed curve) confidence levels as a function of the $B_s^0 \to \mu^+\mu^-$ branching fraction from the 2010 data. The shaded area contains the $\pm 1\sigma$ interval of possible results compatible with the expected value when only background is observed. The 90% (95%) confidence level observed is indicated by the solid (dashed) line. (*b*) The 3σ observation and 5σ discovery curves as a function of integrated luminosity. (Online version in colour.)

4. Summary

Flavour physics now perches on the brink of potential new discoveries with the turn-on of the LHC. The LHCb experiment has made a tremendous start and is already producing world-class measurements and exploring new avenues using the many new decay modes observed. LHCb is also producing many new results not mentioned here, such as mixing and CP violation in the charm quark system and electroweak measurements using $W^\pm$ and Z^0 production, which will make a very significant impact on our understanding of flavour physics, the SM and beyond. LHCb aims to collect a total integrated luminosity of $5\,\mathrm{fb}^{-1}$ by 2017, followed by an upgrade of the experiment to collect $5\,\mathrm{fb}^{-1}$ per year thereafter [28]. This will enable LHCb not only to discover and to identify new physics in flavour, but also to extend the scope of the experiment to include possibilities for interesting discoveries over a whole range of phenomena, including searches for Majorana neutrinos, exotic Higgs decays and precision electroweak measurements.

LHCb is now at the forefront of a new era of discoveries and precision measurements in flavour physics. It is a privilege to be part of the exciting times ahead!

I thank my colleagues on LHCb for all their tremendous effort in producing many beautiful first results from LHCb and as we look forward to a very fruitful future. I would also like to make a personal thank you to Prof. George Kalmus and the rest of the organizing committee for making this Discussion Meeting a very enjoyable experience.

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