PROCEEDINGS OF SCIENCE

Experimental overview

Marco Gersabeck[∗†]
The University of Manchester
E-mail: marco.gersabeck@manchester.ac.uk

This paper reviews charm physics by linking the past to its future. The pre-workshop status is discussed in the first part, covering production, spectroscopy and decays, as well as mixing and *CP* violation. The second part covers future facilities and the challenges that can be expected to arise as well as the potential for charm physics over the coming decade.

VIII International Workshop On Charm Physics
5-9 September, 2016
Bologna, Italy

[∗]Speaker.

[†]The author acknowledges support from STFC, UK, through grant ST/J004332/1.

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

PoS(CHARM2016)002

Part I: From past to present

1. The very beginning

Charm physics encompasses studies of the production, the properties, and the decays of particles containing charm quarks[1]. These are separated in open-charm particles, which contain one charm quark, and charmonium particles, which contain charm anti-charm quark pairs. The earliest direct hint of the existence of charm quarks dates back to 1971 when decays in flight of cosmic ray showers were recorded in emulsion chambers. The signal was found to be consistent with the decay of a charged D meson into a neutral pion and a charged hadron [1, 2]. The momentum of the hardest decay product excluded interpretation as a decay of the strange particle and the relatively long decay-time rendered the interpretation as a resonance impossible.

Much more striking evidence of the existence of charm quarks followed in 1974 when two teams at Brookhaven and SLAC observed enhancements consistent with a strongly decaying resonance with a mass of about 3.1 GeV. The Brookhaven team studied the reaction $p + \mathrm{Be} \to e^- e^+ + x$ by measuring the $e^- e^+$ mass spectrum [3], while the team at SLAC used $e^- e^+$ collisions of different centre-of-mass energies and studied the production of hadrons as well as electron and muon pairs [4]. Both groups observed statistically significant signals of decays of the charmonium state J/ψ.

Nowadays J/ψ decays tower over the spectrum of di-muon signals recorded around the LHC with billions of signal candidates having been produced. Figure 1 shows as an example data from the CMS experiment recorded at a centre-of-mass energy of 13 TeV in 2015 [5].

2. Different states of charm

As already mentioned, charm particles can exist as open charm or charmonium. The open-charm particles can be either mesons with a charm quark and a lighter anti-quark or baryons with

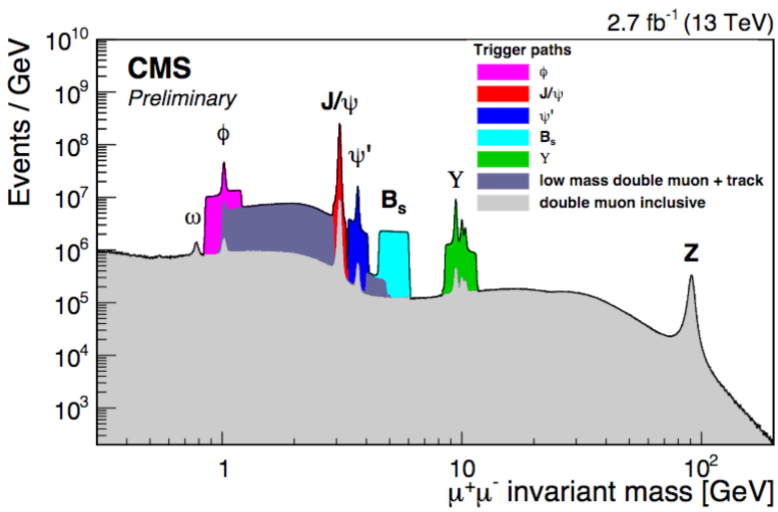

Figure 1: CMS di-muon spectrum. Reproduced from Ref. [5]

[1] Charge conjugation is implied throughout unless mentioned otherwise.

PoS(CHARM2016)002

one, two, or three charm quarks. Beyond their ground state a rich spectroscopy of excited states exists. However, the observed states do not all overlap with those predicted by the quark model. On the one hand, many predicted states have not yet been observed; while on the other hand, some of the detected states appear to be of exotic origin. In 2003, the BaBar collaboration reported the observation of a state decaying to D_s^+ with a mass of $2.32\,\mathrm{GeV}/c^2$ and a narrow width, which did not fit any prediction. In general, a careful analysis of the production and decay mechanisms as well as of the masses, widths, and quantum numbers of the states is required to determine their nature.

Even more exotic states emerged more recently, with one of the most discussed being the charged $Z_c(3900)^-$. The observed decays into $J/\psi\pi^-$ [6, 7] and the large width imply that this state must be a form of a four-quark state. A previous edition of this workshop already dedicated a discussion session to this topic and the precise nature of the state remains to be understood. Similarly puzzling is the state $X(4140)$, whose measured parameters from different experiments do not yield a consistent picture [8–16]. A recent analysis by LHCb indicated that this state may be interpreted as a re-scattering cusp [17, 18].

In 2015, the LHCb experiment observed for the first time signals for two states compatible with being a pentaquark [19]. The observation was the result of an amplitude analysis of $B^0 \to J/\psi\,pK^-$ decays with two new states having to be added to the $J/\psi\,p$ spectrum. Subsequently, a model-independent analysis confirmed the observation with a moments analysis of angular distributions, which confirmed the necessity for structures in the $J/\psi\,p$ spectrum [20]. These observations have also been confirmed in decays to $J/\psi\,p\pi^-$, albeit with less significance due to the smaller sample size [21].

Charm baryons have been observed since 1975 [22] with ground states of singly-charmed baryons as well as some excited states having been observed. Nevertheless, a large fraction of the predicted excited baryon states remains to be confirmed. Similarly, there is no confirmed observation of doubly or triply-charmed baryon states.

3. Production and decays

The production of charm particles offers a range of physics opportunities. First and foremost production measurements constrain QCD processes and those made at hadron colliders give input on parton distribution functions (PDFs). In general, the comparison of charm production in different types of collisions allows to extract information about the various aspects of quark production and hadronisation.

The forward charm production at high energy proton-proton collisions is particularly powerful in constraining the low-x gluon PDF [23]. In turn this permits the precise prediction of the production of very high-energy neutrinos in decays of charm particles produced by cosmic rays in the atmosphere.

Another aspect is the existence of intrinsic charm in protons, *i.e.* a significant component at high values of x as opposed to the sea quark distribution, which is limited to lower values of x. There are different proposals how to measure this, *e.g.* in electro-weak processes [24] or in proton-gas collisions at the LHC. Another option is discussed that utilises IceCube data to constrain the existence of intrinsic charm as this would impact the neutrino production mentioned above [25].

Charm decays are so far limited to hadronic and un-suppressed semi-leptonic final states. There is no sign of direct decays into leptonic (for D^0) or flavour-changing neutral current semi-leptonic

PoS(CHARM2016)002

decays. The latter type of final states has only been observed in decays to hadronic resonances that subsequently decay into leptons. However, most of the rare decay limits date back twenty years and more. The LHCb experiment has significantly reduced a few limits, though a vast range of results awaits improvements with current limits on branching fractions being greater than 10^{-5} [26]. Similarly, lepton-flavour and lepton-number violating decays are dominated by old limits begging to be confronted with the datasets of more recent experiments.

The much more abundant leptonic charged D decays and semi-leptonic decays have the potential for measurements of decay constants, CKM matrix elements and form factors. In addition, flavour-specific semi-leptonic D^0 decays in principle permit the extraction of the charm mixing rate, although the smallness of this quantity made this observation impossible with datasets to date. Finally, lepton universality tests is thus far an unexplored area in charm decays; however, in the light of recent measurements in B decays, hinting at possible departures from the standard model, this is clearly an area that deserves more attention in the future.

4. Mixing and indirect *CP* violation

The mixing discovery dates back to 2007 when this was achieved in the combination of several measurements from the B-factory experiments. In 2006, the BaBar results in the decays $D^0 \to K^+\pi^-\pi^\pm\pi^\mp$ [27] and $D^0 \to K^+\pi^-\pi^0$ [28] were still inconclusive. However, in combination with results from BaBar in $D^0 \to K^+\pi^-$ [29] and from Belle in $D^0 \to K^+K^-$ [30] decays, the no-mixing hypothesis was excluded at just over five standard deviations [26].

Mixing is parametrised with the masses $m_{1,2}$ and widths $\Gamma_{1,2}$ of the eigenstates of the Hamiltonian $D_{1,2}$. These Hamiltonian eigenstates are related to the flavour eigenstates by the linear combination $D_{1,2} = pD^0 + q\bar{D}^0$, whose coefficients satisfy $|p|^2 + |q|^2 = 1$. In the absence of *CP* violation, the states $D_{1,2}$ are *CP* odd and even eigenstates, respectively. It is convenient to define the dimensionless quantities $x \equiv (m_2 - m_1)/\Gamma$ and $y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)$.

As already mentioned, there is a range of ways to measure charm mixing. The effective decay rate into *CP* eigenstates, *e.g.* K^+K^-, is $\Gamma_{CP\pm}$, which, in the absence of *CP* violation, is either Γ_1 or Γ_2 and, in combination with the average D^0 meson lifetime, yields the mixing parameter y. Decays of the type $D^0 \to K^{(*)+}\pi^- h$, where h can be any number (including zero) of additional hadrons, can occur through a doubly Cabibbo-suppressed tree diagram or via D^0-$\bar{D}^0$ mixing followed by a Cabibbo-allowed decay. The study of their time-dependence yields sensitivity to the mixing rate $x^2 + y^2$ and to the individual mixing parameters rotated by the strong phase difference of the two interfering decay amplitudes. In the case of the two-body decay, the latter part results in sensitivity to $y' = y\cos\delta_{K\pi} + x\sin\delta_{K\pi}$, which yields almost exclusively sensitivity to y as the strong phase difference in this case is small. In multi-body decays, the strong phase difference varies across phase space, which, through analyses of the decay-time dependence of the phase-space structure, gives access to both x and y rotated by the strong phase difference between the favoured and suppressed amplitudes. For $D^0 \to K^0_S\pi^+\pi^-$ decays both of these amplitudes are accessible in the same phase-space and hence the phase difference can be measured directly, leading to sensitivity to the bare parameters x and y. To date, high-precision multi-body analyses that exploit the decay-time evolution of the phase-space have only been performed in the decay $D^0 \to K^0_S\pi^+\pi^-$. Hence, the sensitivity to x is significantly worse than that to y and its sign is not yet well established.

PoS(CHARM2016)002

In addition to mixing, the aforementioned measurements are also sensitive to *CP* violation when executed separately for D^0 and $\bar{D}^0$ decays. The asymmetry of the effective decay rates of D^0 and $\bar{D}^0$ decays to *CP* eigenstates essentially determines the rate at which both mass eigenstates decay to *CP* eigenstates. This asymmetry is commonly called ΔY or A_Γ and measures

$$A_\Gamma = \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi, \tag{4.1}$$

where ϕ is the phase between the ratio q/p and the ratio of the decay amplitudes involved $\overline{A}_{\overline{f}}/A_f$. Furthermore, $A_\Gamma = -a_{CP}^{ind}$ introduces indirect *CP* violation, which combines *CP* violation in mixing ($|q/p| \neq 1$) and in the interference between mixing and decay $\phi \neq 0, \pi$. If one assumes no *CP*-violating phases in the decay then ϕ is equal to the universal phase $\phi_D \equiv \arg(q/p)$.

In addition to ΔY one can consider the values of x measured in D^0 and $\bar{D}^0$ decays to obtain

$$x^\pm = \left|\frac{q}{p}\right|^{\pm 1} (x\cos\phi \pm y\sin\phi), \tag{4.2}$$

where $x^{+,-}$ stands for D^0 and $\bar{D}^0$ decays, respectively. It is apparent that this quantity is particularly sensitive to deviations from unity of the magnitude of q/p. Similarly to there being no existing measurement with high sensitivity to the mixing parameter x, the power of measurements of $x^\pm$ remains to be exploited by future measurements.

To date the most powerful constraints of the parameters governing indirect *CP* violation come from measurements of $D^0 \to K^+\pi^-$, which provide stringent constraints of the magnitude of q/p for small values of the phase. Further constraints come from measurements of A_Γ, which determines a diagonal in the plane of magnitude and phase of q/p, provided that the mixing parameters x and y are constrained, *e.g.* through a measurement of $D^0 \to K^0_S\pi^+\pi^-$.

Measurements of *CP* violation parameters with $D^0 \to K^0_S\pi^+\pi^-$ decays have yet to be published with LHC data. In general, multi-body decays hold a significant unexplored potential as they allow measurements of x and hence $x^\pm$. Their challenge lies in the fact that these measurements require either an amplitude model or a measurement of the effective *CP* content in regions of phase space. The latter requires input from quantum-correlated measurements at threshold. But also the development of amplitude models benefits from an inter-experiment collaboration.

In the end, the mixing and *CP* violation parameters are determined in global fits that combine data from all available measurements to extract the common underlying theory parameters. These fits, such as those traditionally being performed by the Heavy Flavour Averaging Group, have achieved a precision of about 10% on the magnitude and 10° on the phase of q/p [26].

Under the assumption that there is no new weak phase in addition to that present in the Standard Model, one can relate the mixing and indirect *CP* violation parameters in a way that reduces the number of parameters from four to three [31, 32]. This can either be done by making one of the four parameters redundant or by introducing a new set of three parameters, which are more theoretically motivated: x_{12}, y_{12}, and ϕ_{12}. This re-parametrisation comes with a tremendous increase in precision, reducing the uncertainties to the percent level for the magnitude and to degree level for the phase of q/p. However, the exact precision on *e.g.* ϕ_{12} depends strongly on the value of x_{12}, underlining once more the importance of progress on measurements of x (x and x_{12} are sufficiently closely related to

PoS(CHARM2016)002

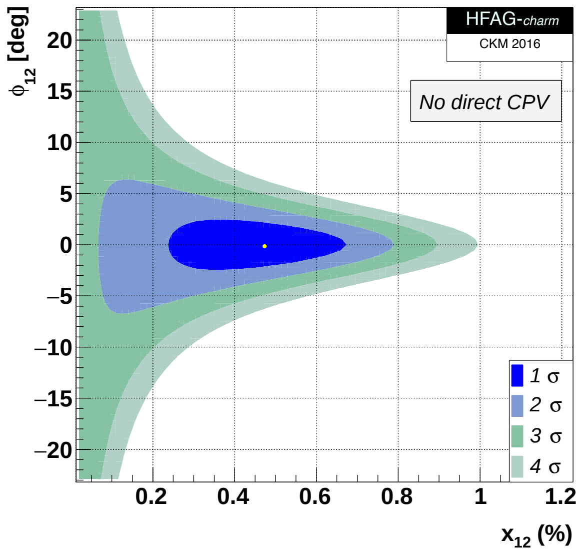

Figure 2: World average constraints on x_{12} and ϕ_{12}. Reproduced from Ref. [26]

support this statement; in the absence of *CP* violation one has $x_{12} = x/2$). This is also seen in Fig. 2, which shows the latest world average [26].

With the advances in precision expected over the coming decade the validity of the assumption above has to be questioned. In general, one can expect doubly Cabibbo-suppressed (DCS) decays to be free of new phases. The same is not true for singly Cabibbo-suppressed (SCS) decays, which can have significant penguin contributions. Therefore, one may want to compare the constraints obtained from averaging results of SCS and DCS modes. A discrepancy in the results may indicate the action of a new *CP* violating phase in the SCS decays. Alternatively, one can introduce additional parameters to allow for extra phases; although, the associated reduction in precision may be comparable to the original four-parameter notation.

5. *CP* violation in decays

In addition to the mixing-related *CP* violation described so far, matter-antimatter asymmetries can also arise in decays, also named direct *CP* violation. This requires a decay to be governed by several amplitudes, such as tree and penguin diagrams, which have a different weak phase. Depending on the measurement, also a difference in the strong phase of the amplitudes is required. As these amplitudes vary from one decay to the next, the observed *CP* violation would be expected to vary as well. This has as a consequence that relationships between different channels such as sum rules can be exploited to identify the source of *CP* violation once it has been discovered.

Once upon a time there was evidence for *CP* violation in decays to singly Cabibbo-suppressed final states (see Fig. 3). The saga [33] progressed and the significance of the observed *CP* violation reduced following updates of the original measurements and in particular with the addition of

PoS(CHARM2016)002

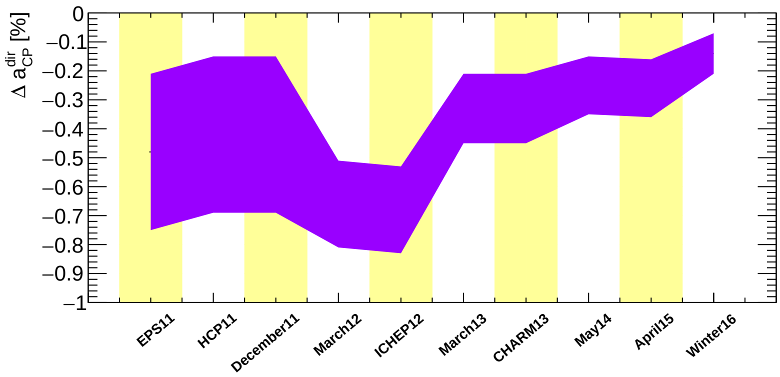

Figure 3: Evolution of the World average of the difference in direct *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays.

new precision measurements with a second independent flavour-tagging method by the LHCb collaboration. While the two LHCb measurements with different flavour tagging methods initially appeared to be in tension, their updates with the full Run 1 dataset are in good agreement, but sadly also with an asymmetry of zero.

Regardless of this particular measurement, the approach to discover direct *CP* violation is to measure many two and multi-body decay modes and, where initially differences of asymmetries have been measured, to attempt also measurements of the individual asymmetries. This of course increases the chances of a discovery, but also eventually allows to exploit the relationships between different channels mentioned before.

For multi-body final states there are different approaches to measure *CP* asymmetries. The most straightforward is to measure the total decay-rate asymmetry; however, this risks diluting or even cancelling asymmetries that exist in local regions of phase space. Alternatively, one can select a local region of phase-space, *e.g.* to single out a resonance, and measure the rate asymmetry for these events. This approach is sensitive to local asymmetries, but ignores possible admixture or interference effects in the selected region or changes in the asymmetry across the resonance. Finally, one can opt for a generic search for local asymmetries in phase space.

The most straightforward strategy for discoveries of asymmetries are approaches that do not require a full amplitude model. There are binned and unbinned methods to search for local asymmetries that have been applied to charm measurements in the past. For a recent review of these methods please refer to Ref. [34]. In the case of a discovery, these methods will not permit the identification of the exact source of *CP* violation. This requires an amplitude analysis for which a detailed model describing the dynamics across phase-space is required.

For multi-body final states other than three pseudo-scalars one can define triple products that are odd under parity reversal. Selecting regions in phase space that differ by the sign of the triple product and using these regions to measure asymmetries gives access to *P*-odd *CP* violation. This is complementary to the *P*-even measurement of rate asymmetries as it has different sensitivity to the strong phase variation.

To date, *CP* violation remains to be discovered in charm particles. Therefore, it is advisable to continue the search on as broad a base as possible in terms of both final states and methods.

PoS(CHARM2016)002

Part II: Whereto next?

6. Echoes from the past

In their fictitious dialogue of an enthusiast and a devil's advocate, Gaillard, Lee, and Rosner wrote in 1975 that "the study of spectroscopy, decay modes, and production mechanisms of the charmed particles" are "worthwhile" [35]. Among others, they consider "Super CERN" as a possible machine for these measurements, thereby referring to the SPS whose location was not yet decided to be CERN at that point. Nowadays "Super CERN" usually refers to the FCC effort at CERN or the large future colliders planned in China, CEPC and SPPC. These may not be the most obvious flavour factories, among other reasons because all of electroweak physics would be boosted to the forward region where flavour physics is successfully exploited by LHCb, but they are also a fairly long time down the road. In the meantime, there is a wealth of other opportunities for advances in flavour physics.

7. Future facilities

Currently, the Belle II detector is under construction and will start delivering physics results after 2018. This will be followed by the upgrade of the LHCb experiment in 2019 and 2020. Of course the other LHC experiments will continue playing their role. For ATLAS and CMS, their contribution will critically depend on their ability to trigger on light states with ever increasing pileup. The ALICE experiment will continue to probe production in heavy ion environments.

On the same timescale as Belle II and the LHC experiments, also BESIII will continue to act as a main player in charm physics. The measurements with quantum-entangled states and threshold production of a range of states will be crucial input to the field overall. In the early 2020s, also PANDA is expected to join the landscape of running experiments with important contributions to hadron spectroscopy and more.

Among other facilities with a less-certain future the most relevant to charm physics is a future tau-charm factory. This has been proposed at various sites none of which has confirmed the construction so far. A threshold factory that would significantly extend the reach of BESIII would be a great opportunity to drive down systematic uncertainties of multi-body *CP* violation measurements in charm and of the related measurements of the CKM angle γ. Of course, it would have similar impact on spectroscopy and tau production at threshold. Charm physics at a linear collider or at a very high-energy circular collider will be more of a fringe topic and its physics case would have to be driven by the success of the above programme.

8. Charm the challenge champion

Charm particles are among the most abundant produced in LHC collisions. At 14 TeV centre-of-mass energy the cross-section for producing $c\bar{c}$ pairs inside the LHCb acceptance is roughly 3 mb [36]. With an integrated luminosity of about 8 fb^{-1} expected per year during Run 3 of the LHC, this equates to 24×10^{12} $c\bar{c}$ pairs or roughly 10^{12} $D^0 \to K^-\pi^+$ decays being produced per year. Accounting for reconstruction, selection, and flavour tagging via $D^{*+} \to D^0\pi^+$ decays this

PoS(CHARM2016)002

should still yield about 10^9 usable candidates per year, which is easily a factor 20 greater than during Run 1. Even Belle II can expect to reconstruct in excess of 10^8 $D^0 \to K^-\pi^+$ candidates. In the long term, LHCb plans to increase their instantaneous luminosity by roughly another order of magnitude.

While Belle II clearly does not reach a competitive level with two-body charged final states, they will likely dominate for final states with neutral particles and also not suffer from significant acceptance losses for multi-body charged final states. Therefore, the two experiments will both face severe challenges in terms of the increase in data sample size. This will impact all of data processing (reconstruction and selection), simulation, and final analysis and will require new concepts to overcome these hurdles. Charm analyses are likely to lead the way due to the relative abundance of signal events compared to beauty analyses.

The high rates of particles with rather low transverse momentum require complex decisions to be taken early on in the trigger chain. This is because coarse decisions come with heavy penalties in terms of efficiencies and such an approach would risk burning the detector (in terms of radiation damage) for little gain in signal. As every processing step is very costly when executed for many events, the target has to be to reuse information as much as possible, ideally by having offline-quality data available in the trigger and thereby removing the need for offline processing altogether. Storage is also often found to be a significant cost driver; hence, analyses based on the largest samples may well have to get by with storing a reduced set of information. The challenge in this concept is obviously to tailor the information stored to the analyses that use these data in a way that ensures usability at the same time as permitting sufficient reduction of disk footprint.

Simulation is costly in terms of computing power in particular at the LHC where the high-energy proton-proton collisions produce of the order of 100 particles to be simulated in each event. For many charm analyses a simulation of all particles with full detector detail cannot be performed to match the sample sizes of the analysis; whereas, in many cases it would be advantageous to work with simulated samples that exceed the size of those recorded from real collisions. Individual analyses may be recording their signal with up to 100 Hz while the full simulation of one LHCb event requires of the order of 100 s, *i.e.* one would have to use $10,000$ CPU cores to match the data samples with simulation for just one analysis.

As these numbers will increase in the future the use of fast simulation techniques will be

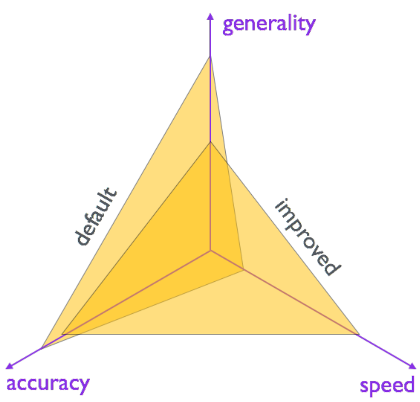

Figure 4: Interplay of speed, accuracy, and generality for fast simulation concepts.

PoS(CHARM2016)002

inevitable. The optimal approach will depend on a case-by-case basis as one needs to balance three factors (see Fig. 4):

- Speed: the computing time required to simulate an event and therefore the ability to simulate fewer or more events.
- Accuracy: the required precision of the simulation will depend strongly on the analysis as some make little or no use of specific detector components while requiring precise detail for others.
- Generality: the applicability of the simulated sample to several analyses will determine the overall computing power required. There is no gain in having to perform simulations for many analyses with small time savings for each but with an overall increase in computing power.

There is a range of solutions being explored from parametrising the detector interaction, over switching off the simulation of whole detector parts, or simulating exclusively the signal particles of interest, to re-using the simulation of the underlying event. In addition to these approaches, which all come at some cost in accuracy, it is of course most useful to speed up the core simulation code itself to the extent possible as this would benefit all approaches.

Finally, the analyses themselves will become ever more challenging with the increase in data sample sizes over the coming years. This will make in particular un-binned analyses that exploit the maximum of information from the data very demanding if not impossible. In general, an ever more precise understanding of the detector response is required to maintain the ability to model the observed distributions. The processing of the large sample sizes will require new techniques such as parallelisation, be it on CPU or GPU architectures, to be used in analyses as well. As already stated for the simulation, efficient software will be paramount, which means that education in efficient programming will be of increasing importance.

9. Physics roadmap

As Yuval Grossman pointed out in his summary of the CHARM 2012 workshop, whether you are a mug or a bagel is irrelevant as they are topologically equivalent; "the issue is how can we keep on checking". This referred to direct *CP* violation for which hints had emerged at the time, but the conclusion is still true in general. In terms of *CP* violation this meant and still means that a multitude of ways has to be pursued simultaneously as *CP* violation will most likely show up in more than one process and even if only one search is successful, having the full picture will be crucial to pin down its source. As mentioned before, this refers the exploitation of two-body as well as multi-body decay modes to look for both time-dependent and time-independent asymmetries. In particular for multi-body final states the question remains whether more of them can be exploited to better the constraints on mixing and *CP* violation.

In addition to *CP* violation and the other areas of charm physics covered so far, there are further challenges ahead. One very powerful decay involving charm is that of a Higgs boson to a $c\bar{c}$ pair. This should be the second most abundant Higgs decay to a pair of quarks and its observation would reveal the flavour structure of Higgs decays, *i.e.* whether they are strictly governed by the mass scales involved or not. This observation will be extremely challenging as these decays have to

PoS(CHARM2016)002

be distinguished from the much more abundant decays to $b\bar{b}$ pairs. For ATLAS and CMS this distinction is a major hurdle, while for LHCb the number of Higgs bosons decaying inside the detector acceptance severely limits the reach.

Another aspect is the mean D^0 lifetime, whose world average is dominated by a single measurement [37]. Without intending to question this measurement by the FOCUS collaboration [38], it would be highly desirable to have at least a second measurement to affirm this average. This is because most time-dependent measurements use as part of their analysis verification the comparison to the world average lifetime. With the sample sizes available today, such a measurement would naturally be limited by systematic uncertainties, but both Belle (II) and LHCb (upgrade) should be able to provide such a result.

Returning to the topic of multi-body final states, it has already been stated above that these measurements require either an amplitude model or a measurement of the effective *CP* content in regions of phase space. As the latter is only possible at BESIII it is clear that this part of the BESIII physics programme is of great importance to the community as a whole. Amplitude models are already struggling to describe the phase space structure of existing data samples and this situation will worsen in the future. There are a number of theoretical efforts to provide a more robust description of the dynamics involved. On the experimental side, the experiments would do well to collaborate closely among each other and with the theory community to go the next step and reach a new level in the description of multi-body decays. While constructive competition is a healthy measure in many areas, this particular one will benefit more from maximally exploiting the complementarity of the relevant experiments; this includes not only those mentioned before but also lower energy ones such as COMPASS.

10. Conclusions

With charm particles first observed 45 years ago and charm mixing discovered ten years ago it is time for the next big discovery, namely charm *CP* violation. This may be around the corner, but even if not will very likely emerge in the coming decade, facilitated by the next generation flavour experiments Belle II and the LHCb upgrade.

But there is more to be expected from the near-term future. The ground-state baryon spectrum will hopefully be completed soon and more detailed studies of baryon properties such as *CP* violation may still hold surprises. A range of charmed exotic states has emerged, but may well be complemented by more and at the very least by more understanding of their nature.

The road to these future successes is paved with major challenges, technical as well as on the physics side, which is valid for theory and experiment alike. The key to overcoming this is being innovative and sometimes this may involve inter-experiment collaboration to exploit synergies where they overpower the benefits of competition. A wealth of results is discussed in the remainder of the proceedings of this workshop, which have deliberately not been referred to in detail to avoid duplication. These are a strong testament to the field of charm physics being very much alive with a bright future ahead.

PoS(CHARM2016)002

Acknowledgements

The author would like to thanks Alex Kagan, Alberto Correa Dos Reis, Michael Creutz, Miriam Gandelman, Alex Lenz, and Patrick Spradlin for enlightening discussions that found their way into the material discussed here.

References

[1] K. Niu, E. Mikumo, and Y. Maeda, *A possible decay in flight of a new type particle*, Prog. Theor. Phys. **46** (1971) 1644.

[2] K. Hoshino *et al.*, *On the x particles observed in the cosmic ray jet showers*, Conf. Proc. **C750815V7** (1975) 2442.

[3] E598, J. J. Aubert *et al.*, *Experimental observation of a heavy particle J*, Phys. Rev. Lett. **33** (1974) 1404.

[4] SLAC-SP-017, J. E. Augustin *et al.*, *Discovery of a narrow resonance in e^+e^- annihilation*, Phys. Rev. Lett. **33** (1974) 1406, [Adv. Exp. Phys.5,141(1976)].

[5] CMS Collaboration, *Dimuon spectrum 2015*, Dec, 2015. CMS-DP-2015-055.

[6] BESIII, M. Ablikim *et al.*, *Observation of a charged charmoniumlike structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26\,\mathrm{GeV}$*, Phys. Rev. Lett. **110** (2013) 252001, arXiv:1303.5949.

[7] T. Xiao, S. Dobbs, A. Tomaradze, and K. K. Seth, *Observation of the charged hadron $Z_c^{\pm}(3900)$ and evidence for the neutral $Z_c^0(3900)$ in $e^+e^- \to \pi\pi J/\psi$ at $\sqrt{s} = 4170$ MeV*, Phys. Lett. **B727** (2013) 366, arXiv:1304.3036.

[8] CDF, T. Aaltonen *et al.*, *Evidence for a narrow near-threshold structure in the $J/\psi\phi$ mass spectrum in $B^+ \to J/\psi\phi K^+$ decays*, Phys. Rev. Lett. **102** (2009) 242002, arXiv:0903.2229.

[9] Belle, C. P. Shen *et al.*, *Evidence for a new resonance and search for the Y(4140) in the $\gamma\gamma \to \phi J/\psi$ process*, Phys. Rev. Lett. **104** (2010) 112004, arXiv:0912.2383.

[10] J. Brodzicka, *Heavy flavour spectroscopy*, Conf. Proc. **C0908171** (2009) 299, [,299(2009)].

[11] CDF, T. Aaltonen *et al.*, *Observation of the $Y(4140)$ structure in the $J/\psi\,\phi$ Mass Spectrum in $B^{\pm} \to J/\psi\,\phi K$ decays*, arXiv:1101.6058.

[12] LHCb, R. Aaij *et al.*, *Search for the $X(4140)$ state in $B^+ \to J/\psi\phi K^+$ decays*, Phys. Rev. **D85** (2012) 091103, arXiv:1202.5087.

[13] D0, V. M. Abazov *et al.*, *Search for the $X(4140)$ state in $B^+ \to J/\psi\,\phi K^+$ decays with the D0 detector*, Phys. Rev. **D89** (2014), no.~1 012004, arXiv:1309.6580.

[14] CMS, S. Chatrchyan *et al.*, *Observation of a peaking structure in the $J/\psi\phi$ mass spectrum from $B^{\pm} \to J/\psi\phi K^{\pm}$ decays*, Phys. Lett. **B734** (2014) 261, arXiv:1309.6920.

[15] BaBar, J. P. Lees *et al.*, *Study of $B^{\pm,0} \to J/\psi K^+K^-K^{\pm,0}$ and search for $B^0 \to J/\psi\phi$ at BABAR*, Phys. Rev. **D91** (2015), no.~1 012003, arXiv:1407.7244.

[16] D0, V. M. Abazov *et al.*, *Inclusive production of the X(4140) state in $p\bar{p}$ collisions at D0*, Phys. Rev. Lett. **115** (2015), no.~23 232001, arXiv:1508.07846.

[17] LHCb, R. Aaij *et al.*, *Observation of $J/\psi\phi$ structures consistent with exotic states from amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays*, arXiv:1606.07895.

PoS(CHARM2016)002

[18] LHCb, R. Aaij *et al.*, *Amplitude analysis of $B^+ \to J/\psi\phi K^+$ decays*, arXiv:1606.07898.

[19] LHCb, R. Aaij *et al.*, *Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ Decays*, Phys. Rev. Lett. **115** (2015) 072001, arXiv:1507.03414.

[20] LHCb, R. Aaij *et al.*, *Model-independent evidence for $J/\psi p$ contributions to $\Lambda_b^0 \to J/\psi pK^-$ decays*, Phys. Rev. Lett. **117** (2016), no.~8 082002, arXiv:1604.05708.

[21] LHCb, R. Aaij *et al.*, *Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p\pi^-$ decays*, Phys. Rev. Lett. **117** (2016), no.~8 082003, arXiv:1606.06999, [Addendum: Phys. Rev. Lett.117,no.10,109902(2016)].

[22] E. G. Cazzoli *et al.*, *Evidence for $\Delta S = -\Delta Q$ currents or charmed baryon production by neutrinos*, Phys. Rev. Lett. **34** (1975) 1125.

[23] R. Gauld and J. Rojo, *Precision determination of the small-x gluon from charm production at LHCb*, arXiv:1610.09373.

[24] T. Boettcher, P. Ilten, and M. Williams, *Direct probe of the intrinsic charm content of the proton*, Phys. Rev. **D93** (2016), no.~7 074008, arXiv:1512.06666.

[25] R. Laha and S. J. Brodsky, *IC at IC: IceCube can constrain the intrinsic charm of the proton*, arXiv:1607.08240.

[26] Y. Amhis *et al.*, *Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016*, arXiv:1612.07233.

[27] BaBar, B. Aubert *et al.*, *Search for $D^0-\bar{D}^0$ mixing in the decays $D^0 \to K^+\pi^-\pi^+\pi^-$*, in *Proceedings of the 33rd International Conference on High Energy Physics (ICHEP '06): Moscow, Russia, July 26-August 2, 2006*, 2006. arXiv:hep-ex/0607090.

[28] BaBar, B. Aubert *et al.*, *Search for $D^0-\bar{D}^0$ mixing and branching-ratio measurement in the decay $D^0 \to K^+\pi^-\pi^0$*, Phys. Rev. Lett. **97** (2006) 221803, arXiv:hep-ex/0608006.

[29] BaBar collaboration, B. Aubert *et al.*, *Evidence for $D^0-\bar{D}^0$ mixing*, Phys. Rev. Lett. **98** (2007) 211802.

[30] Belle collaboration, M. Staric *et al.*, *Evidence for $D^0-\bar{D}^0$ mixing*, Phys. Rev. Lett. **98** (2007) 211803.

[31] M. Ciuchini *et al.*, *$D-\bar{D}$ mixing and new physics: General considerations and constraints on the MSSM*, Phys. Lett. **B655** (2007) 162, arXiv:hep-ph/0703204.

[32] A. L. Kagan and M. D. Sokoloff, *On indirect CP violation and implications for $D^0-\bar{D}^0$ and $B_{(s)}-\bar{B}_{(s)}$ mixing*, Phys. Rev. **D80** (2009) 076008, arXiv:0907.3917.

[33] A. Lenz, *What did we learn in theory from the ΔA_{CP}-saga?*, in *Proceedings, 6th International Workshop on Charm Physics (Charm 2013): Manchester, UK, August 31-September 4, 2013*, 2013. arXiv:1311.6447.

[34] C. Parkes, S. Chen, J. Brodzicka, and M. Gersabeck, *On model-independent searches for direct CP violation in multi-body decays*, arXiv:1612.04705.

[35] M. K. Gaillard, B. W. Lee, and J. L. Rosner, *Search for charm*, Rev. Mod. Phys. **47** (1975) 277.

[36] LHCb, R. Aaij *et al.*, *Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **03** (2016) 159, arXiv:1510.01707, [Erratum: JHEP09,013(2016)].

[37] Particle Data Group, C. Patrignani *et al.*, *Review of particle physics*, Chin. Phys. **C40** (2016) 100001.

[38] FOCUS, J. M. Link *et al.*, *New measurements of the D^0 and D^+ lifetimes*, Phys. Lett. **B537** (2002) 192, arXiv:hep-ex/0203037.

PoS(CHARM2016)002