Techniques for hadron spectroscopy studies at LHCb

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Summary. — The large heavy-flavor dataset collected by the LHCb experiment offers a good opportunity to investigate the inner structure of hadrons and helps improve the knowledge of the strong interaction. With the ever larger data samples collected by LHCb, constant improvements of analysis methods are in demand, including for example advanced computing techinques to handle the huge data sample and the phenomenological tools to reduce the systematic uncertainties. Several selected developments in the past few years will be presented in this proceeding.

1. – Introduction

The LHCb experiment is one of the four large experiments located at the Large Hadron Collider (LHC). It was originally designed as a precision-frontier experiment to search for indirect evidence of New Physics beyond the Standard Model, and has nowadays been developed to a general-purpose experiment covering a wide range of physics programs beyond the scope of the original target. LHCb has made a outstanding contribution to enrich the experimental knowledge about the hadron spectroscopy. It discovered more than 60 new heavy-flavor hadrons, and also performed precise measurements on properties of a variety of heavy-flavor hadrons. Hadron spectroscopy studies in LHCb benefit from the large production yield of beauty and charm hadrons at the Large Hadron Collider, and also the detector performance that is optimized for reconstructing and selecting signal decays of heavy-flavor particles. Besides, it also benefits from the development and utilization of advanced analysis techniques, with which physical observables can be inferred. In this proceeding, several selected developments of analysis techniques for hadron spectroscopy studies at LHCb are presented.

2. – Development of helicity-based amplitude formalism

Amplitude analysis of multi-body decays is one of the most powerful tools for spectroscopy studies at LHCb. It extracts the contributions from different partial-wave re-

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action amplitudes, and can measure the spin-parity quantum numbers of intermediate states. It also provides a method to describe the amplitudes of different decay sequences in a natural way, thus acting as a good approach to model the interference and reflection between different resonances.

The helicity formalism [1] is a widely-used technique for building the matrix element of amplitude analyses in LHCb. In these analyses, multi-body decays are considered as a cascade process of several two-body decay nodes, and each decay node contributes a Wigner-D function to the corresponding partial-wave amplitude, acting as a representation of the rotation operators that associate the initial and final states in the helicity base. Different decay sequences are named as different decay chains, and amplitudes of multiple decay chains are combined together after properly rotating the helicity states of decaying products for a consistent definition of the final states in each single-chain matrix element.

In recent years, a deeper understanding is made on the general formula of helicity-based amplitude formalism, benefiting a wide range of spectroscopy studies in LHCb. Traditionally, angular variables in both the single-chain amplitude and the alignment rotations are obtained by calculating the angles between particle momenta and momentum planes. This approach is not good enough when describing the rotations of spin states when baryons are involved in the multi-body decay process [3, 4]. Quantum effects are missing ([1]), leading to an misalignment of final-state definitions between different decay chains and wrong interference distributions. As reported in Ref. [4], if using the traditional approach to construct the helicity-based amplitude formalism for baryon decays, there is a risk of generating an unexpected discontinuity in the distribution of the interference between different decay chains as a function of decay angles, and the total interference can wrongly vanish when integrating over the whole phase space.

Several phenomenological techniques [3, 4, 7] are proposed to overcome this issue. References [3, 4] suggest finding a proper representation of rotation operators ([2]), where the impact of missing quantum effects mentioned above is visible, to check the alignment of final-state definitions between different decay chains. It has been implemented in several recent LHCb amplitude analyses of baryon decays, for example the amplitude analysis of $\Xi_b^- \to J/\psi \Lambda K^-$ decays [5] where an evidence of a pentaquark decaying into $J/\psi\Lambda$ is reported, and the amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ decays [6] which provides an up-to-date knowledge about the partial-wave decomposition about this widely-used Λ_c^+ decay pattern. Another solution is proposed in Ref. [7], and it identifies the problem with a mismatch of the overall rotation of the reaction plane, which involves three Euler angles including one polar and two azimuthal angles. The authors propose a remedy by employing a unified overall rotation for all decay chains, which aligns the reaction plane with the x-z plane. It is argued that the overall rotation is determined by the decay particle spin, rather than particular dynamics of the decay, and therefore can be factored out. This factorization also makes the alignment rotations related to the final-state particles straightforward, as explicitly demonstrated in Ref. [7] for the general three-body decays. This new formalism has been used in the amplitude analysis of

([1]) In the traditional approach, one could not set any well-motivated preference for an angular variable to have a value of ϕ or $\phi + 2\pi$. This arbitrary 2π factor could however generate an arbitrary "-1" term if it contributes to an angular term related to spin-half particles.

([2]) Using wigner D-functions for half-integer spin [3] or the SU(2) representation [3, 4] of rotation operators.

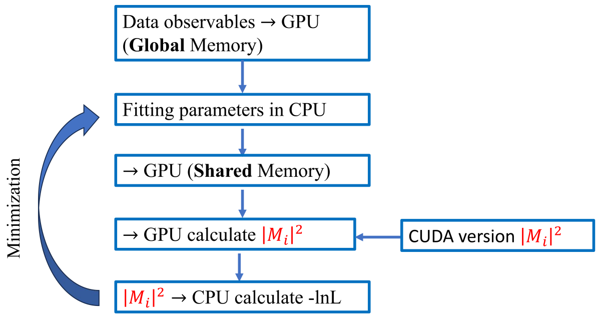

Fig. 1. – The data flow between the GPUs and CPUs in the fit framework of the $B^0 \to J/\psi K^0_S \phi$ amplitude analysis [12]. Data observables saved in the GPU global memory include all amplitude terms that keeps invariant during the minimization procedure.

$B^- \to J/\psi \Lambda \bar{p}$ decays, which leads to the most recent pentaquark-candidate observation from the LHCb experiment [8].

3. – Speed up amplitude fits using GPUs

The ever larger data sample collected by LHCb enables the investigation of hadron spectroscopy with unprecedented statistical precision. It also makes it increasingly challenging to handle the huge dataset in a reasonable time scale for many types of physics analysis, especially the ones relying on unbinned maximum likelihood fits where the complexity is directly related to the sample size. As the PDF calculation is independent between each single entry of the data sample, the GPU technique offers a promising approach to resolve this challenge by parallel computation. Several GPU fit techniques are being developed in LHCb using different approaches and software tools, for example the framework documented in Ref. [9] used for the Charge-Parity violation study in charmless B decays [10]. Another example is the fit framework [11] used for the $B^0 \to J/\psi K^0_S \phi$ amplitude analysis [12], which will be discussed in detail in this proceeding.

The amplitude analysis of the $B^0 \to J/\psi K^0_S \phi$ decay is based on joint unbinned maximum likelihood fits of a $B^+ \to J/\psi K^+ \phi$ sample with about twenty thousand candidates and a $B^0 \to J/\psi K^0_S \phi$ sample with about two thousand candidates. Apart from the real-data candidates, about 400 thousand simulated events are generated to numerically calculate the normalization factor of the PDFs. The decay amplitude is constructed using the helicity formalism, and contributions from about 20 intermediate states are considered. The default model contains about 160 float parameters, including about 30 line-shape parameters and about 130 partial-wave coupling parameters. To obtain a likelihood value, the complicated single-event decay amplitudes need to be calculated for each of the real-data candidates and simulated events.

A framework combining both CPUs and GPUs is used to speed up the amplitude fits. The GPU part of the framework is formed by CUDA-based [16] functions, which calculates the amplitude module square $|\mathcal{M}|^2$ of each single event in parallel. The resulting values of $|\mathcal{M}|^2$ are further transferred into the CPUs to build the likelihood function, and

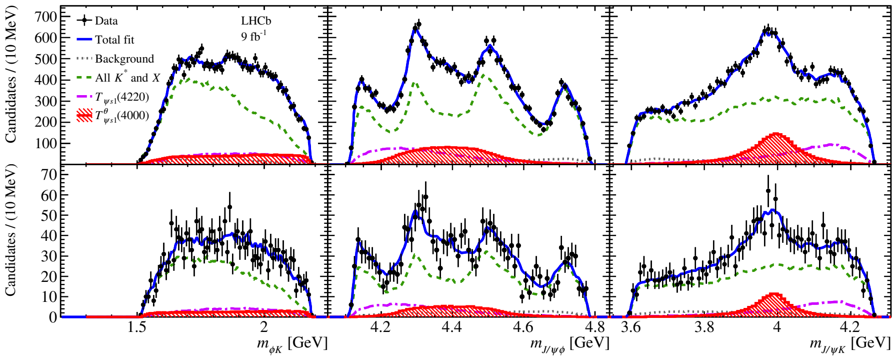

Fig. 2. – The (left) ϕK, (middle) $J/\psi\phi$ and (right) $J/\psi K$ mass distributions, overlaid with projections of a simultaneous amplitude fit of the (upper) $B^+ \to J/\psi\phi K^+$ and (lower) $B^0 \to J/\psi\phi K^0_S$ samples collected by the LHCb experiment. A GPU-based fit framework is used for the amplitude analysis. The red area shows the contribution of the (upper) $T^{\theta}_{\psi s1}(4000)^+$ and (lower) $T^{\theta}_{\psi s1}(4000)^0$ tetraquark candidates [12].

the Minuit of RooFit package [13] is used to handle the minimization of negative log-likelihood values ([3]). The general data flow between GPUs and CPUs of the framework is shown in Fig. 1. During the analysis, the performance of the framework is investigated and further optimized by using Nsight Systems [14] and Nsight Compute [15] provided by NVIDIA. Several technical solutions are implemented to speed up the GPU calculations, including

- Memory allocation only once for parameters of the fit model, single-even amplitude values and the likelihood value, and reuse the memory,
- Use float to replace double precision when calculating single-event amplitudes,
- Limit the number of registers, to reduce the register pressure and increase the number of working threads,

Besides, the data flow between GPUs and CPUs is re-optimized by migrating the likelihood calculation into the GPU, and only transfer the log-likelihood values from GPU to CPU, instead of all the single-event matrix elements of data and simulation. After the optimization, it takes about 10 minutes with one RTA 3090 GPU to run a complicated joint amplitude fit of $B^0 \to J/\psi K^0_S\phi$ and $B^+ \to J/\psi K^+\phi$ decays, which is an unbinned maximum-likelihood fit on more than twenty thousand data and about 400 thousand simulation events using a fit function of O(100) float parameters. It is 200 times faster compared to a traditional RooFit-based CPU framework without using the parallel computation technique (Intel(R) Xeon(R) Gold 5218 CPU). Finally, an evidence is found for a new tetraquark candidate $T^{\theta}_{\psi s1}(4000)^0$ decaying into $J/\psi K^0_S$, which is a good candidate of isospin partner of the $T^{\theta}_{\psi s1}(4000)^+$ state observed as a $J/\psi K^+$ structure in $B^+ \to J/\psi K^+\phi$ decays [17]. Given the good performance of the speed of the fit, this framework is also used in several on-going amplitude analyses in LHCb.

([3]) Strategy 1 of MIGRAD minimization is used. It converges when the estimated distance to minimum (EDM) is smaller than 3×10^{-3}. MINOS is used to estimate statistical uncertainties.

4. – Summary

The LHCb experiment has made a great contribution to hadron spectroscopy studies. The ever larger data samples from the upgrade data-taking will bring an improvement of the statistical precision, but will also lead to a more strict requirement on the computing techniques and phenomenological tools with which physical observables can be inferred.

In order to be able to handle the huge data flow, LHCb has developed a fully software-based trigger system which can perform real-time physics analysis under an offline-like reconstruction and alignment quality [18]. Also, groups of advanced software tools are developed for data processing and offline analysis, and one example is the development of GPU-based amplitude analysis frameworks presented in this proceeding. LHCb is also developing and using new phenomenological models in data analysis, to minimize relevant systematic uncertainties and match the ever improved statistical precision. One example presented in this proceeding is the development of the general formalism of helicity amplitudes. All these efforts will help the LHCb experiment to smoothly boost its hadron spectroscopy studies to a new level.

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