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PERSPECTIVE

Is my boson sampler working?

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Abstract

Is it possible to assess the correct functioning of a quantum device which eludes efficient computation of the expected results? The BosonSampling protocol is one of the best candidates to experimentally demonstrate the superior computational power of quantum mechanics, but the problem of its results certification requires the development of new methodologies, when the size of the problem becomes too large for a complete classical simulation. A recent work (Walschaers *et al* 2016 *New J. Phys.* **18** 032001) has provided a significant step forward in this direction, by developing a statistical test to identify particle types in a many-body interference pattern. This tool can be applied in a general scenario to assess and investigate multi-particle coherent dynamics.

The strong efforts towards development of quantum simulation and computation devices are motivated by the widespread expectation that they should allow superpolynomial speedup for several tasks. The most celebrated example is given by Shor's algorithm [1], which allows for the factorization of numbers using polynomial quantum resources. The realization of a device able to clearly demonstrate this superior computational power is, however, still missing. There are two main reasons, one more on the practical side and the other more on the formal one. First, the technological requirements for challenging a classical device using Shor's algorithm are still largely out of reach. Second, the absence of efficient classical algorithms for problems such as factorization has not been formally demonstrated. The aim of the BosonSampling [2] (BS) protocol is to bypass these two obstacles. It consists in simulating the evolution of n bosons through a random unitary transformation over m spatial modes, and in particular to sample from the corresponding output probability distribution. The computational hardness of this problem is based on the well known complexity of calculating complex matrices' permanents [3], which finds its foundation on solid theoretical basis. At the same time, the opportunity to challenge a classical counterpart with few tens of photons in few hundreds of spatial modes is not too far from current technologies. This motivated strong experimental efforts to start providing proof-of-principle implementations [4–12].

However, all this comes at a cost. In the spirit of giving an unambiguous proof of post-classical computation, the assumptions on the internal functioning of the quantum device should be as few as possible. In this sense, while certifying the results of a factoring problem is trivial, complete certification of BS is not yet completely understood [13]. Clearly, a brute force approach relying on comparing the measured distribution with the expected one would depend on calculating an (exponentially) large number of permanents and on collecting an (exponentially) large data sample. Another correlated problem is given by the unavoidable sparseness of a dataset sample, which will be always present in medium-large scale experiments. In front of these difficulties, the use of statistical techniques has allowed, up to now, to efficiently reject the alternative hypothesis of uniform sampling [9, 10, 14]. Validations against alternative distributions, which partially mimic the genuine BS one, are more difficult to perform [9, 10]. In fact, the strong difference in computational complexity between problems such as genuine BS and, for example, sampling with distinguishable particles, is reflected in fine-grained differences in the resulting probability distributions, which are very difficult to spot with limited-size datasets. First results have been obtained by using statistical tests which require the calculation of a small number of permanents [9], or by exploiting bunching properties of indistinguishable photons [10]. The use of highly-

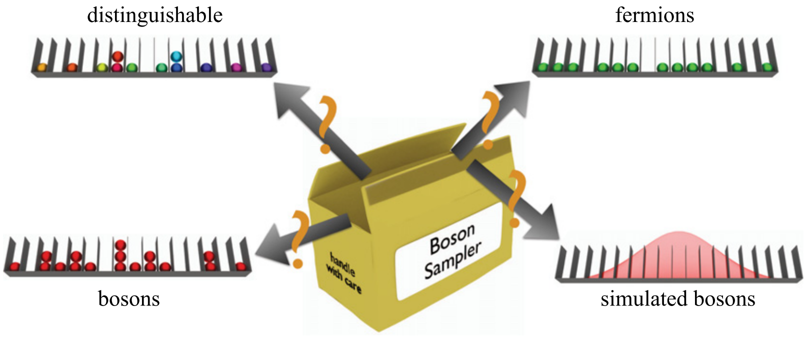

Figure 1. Statistical analysis of a Boson Sampler: the particle type is identified from the output pattern of the device.

symmetric transformations is able to magnify the differences between different particle statistics [15–17], but at the cost of partially detaching from the original computational problem. Furthermore, a protocol to certify state preparation by exploiting homodyne detection has been theoretically proposed in [18].

A novel approach towards the certification of boson sampling experiments has now been proposed in [19]. The key tool behind the method is based on state correlation functions, which store all the statistical information on a many-particle wavefunction. In the boson sampling case, knowledge of the complete set of correlation functions is not fully accessible due to the computational complexity of the problem. To overcome this limitation, Walschaers and coworkers [19] prove that relevant key properties of the many-body state can be retrieved by accessing only low-order correlation functions. More specifically, they show that measuring only two-mode correlators provides sufficient information to assess the nature of the input state. Indeed, different particle types present quantitative differences in the moments of the two-mode correlator distributions. Given a certain unitary matrix, analytical formulas and random matrix theory averages can be exploited to predict these moments, and no complex permanent calculations have to be performed. Interestingly, this method combines mathematical tools common to other fields, such as many-body quantum theory. The statistical approach of [19] is an efficient and reliable strategy to discriminate between different particle types, such as bosons, distinguishable particles or fermions (whose evolution does not share the same complexity of bosons since it is related to the calculation of matrix determinants). Furthermore, it can be applied to exclude the case of ‘simulated bosons’ [16], a physical model which allows to mimic some collective bosonic properties (such as bunching and clouding [10]) by single-photon interference and phase average. Last but no least, the authors discuss the experimental requirements to perform the test. Namely, they provide an argument supporting that the number of measurements required is polynomial in n and m. The latter issue is indeed a relevant point in any verification protocol.

The results of [19] represent the first efficient statistical test able to identify the nature of many-particle states among a set of different hypothesis, independently from the linear unitary evolution. This opens the way for its experimental verification with current state-of-the art photonic systems, and to the potential application of the method to recently proposed alternative boson sampling platforms [20, 21]. The achievements of Walschaers and coworkers can lead to new perspectives, as they could be useful in the whole quantum simulation and quantum computation field for the certification of quantum devices. From a fundamental point of view the proposed method represents a thoughtful insight on many-body interference, and may help in shedding light on the very properties of the different types of particle statistics.

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