Improved Sample Upper and Lower Bounds for Trace Estimation of Quantum State Powers

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Abstract

As often emerges in various basic quantum properties such as entropy, the trace of quantum state powers $\mathrm{tr}(\rho^q)$ has attracted a lot of attention. The recent work of Liu and Wang (SODA 2025) showed that $\mathrm{tr}(\rho^q)$ can be estimated to within additive error ε with a dimension-independent sample complexity of $\widetilde{O}(1/\varepsilon^{3+\frac{2}{q-1}})$ for any constant $q > 1$,[1] where only an $\Omega(1/\varepsilon)$ lower bound was given. In this paper, we significantly improve the sample complexity of estimating $\mathrm{tr}(\rho^q)$ in both the upper and lower bounds. In particular:

- For $q > 2$, we settle the sample complexity with matching upper and lower bounds $\widetilde{\Theta}(1/\varepsilon^2)$.
- For $1 < q < 2$, we provide an upper bound $\widetilde{O}(1/\varepsilon^{\frac{2}{q-1}})$, with a lower bound $\Omega(1/\varepsilon^{\max\{\frac{1}{q-1},2\}})$ for dimension-independent estimators, implying there is only room for a quadratic improvement.

Our upper bounds are obtained by (non-plug-in) quantum estimators based on weak Schur sampling, in sharp contrast to the prior approach based on quantum singular value transformation and samplizer.

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[1]Throughout this paper, $\widetilde{O}(\cdot)$, $\widetilde{\Omega}(\cdot)$, and $\widetilde{\Theta}(\cdot)$ suppress polylogarithmic factors in ε.

1 Introduction

Testing the properties of quantum states is a fundamental problem in the field of quantum property testing [MdW16], where the spectra of quantum states turn out to be crucial, as they fully characterize unitarily invariant properties. Given samples of the quantum state to be tested, in [OW21], testing the spectrum was extensively studied, with several significant applications such as mixedness testing and rank testing. In [OW17], they further investigated the sample complexity of the spectrum tomography of quantum states. Subsequently, as a representative unitarily invariant quantity, the entropy of a quantum state was known to have efficient estimators in [AISW20, BMW16, WZ25b].

The traces of quantum state powers, $\mathrm{tr}(\rho^q)$, of a quantum state ρ are one of the simplest functionals of quantum states. The quantity $\mathrm{tr}(\rho^q)$ has connections to the Rényi entropy $\mathrm{S}_q^{\mathrm{R}}(\rho) = \frac{1}{1-q}\ln(\mathrm{tr}(\rho^q))$ [Rén61] and the Tsallis entropy $\mathrm{S}_q^{\mathrm{T}}(\rho) = \frac{1}{1-q}(\mathrm{tr}(\rho^q) - 1)$ [Tsa88]. The estimation of $\mathrm{tr}(\rho^q)$ is at the core of Tsallis entropy estimation, with a wide range of applications in physics. A notable example is the Tsallis entropy of order $q = \frac{3}{2}$ for modeling fluid dynamics systems [Bec01, Bec02]. In addition, for $q = 1.001$ (close to 1), the Tsallis entropy $\mathrm{S}_q^{\mathrm{T}}(\rho)$ serves as a lower bound on the von Neumann entropy, whereas the former can be estimated exponentially faster than the latter, as noted in [LW25]. In particular, $\mathrm{tr}(\rho^2)$ refers to the purity of ρ, and it is well-known that the purity $\mathrm{tr}(\rho^2)$ can be estimated to within additive error using $O(1/\varepsilon^2)$ samples of ρ via the SWAP test [BCWdW01]. For the case of constant integer $q \geq 2$, $\mathrm{tr}(\rho^q)$ can be estimated using $O(1/\varepsilon^2)$ samples of ρ via the Shift test proposed in [EAO+02], generalizing the SWAP test. For non-integer $q > 0$ and $q \neq 1$, the estimation of $\mathrm{tr}(\rho^q)$ was considered in [WGL+24] with the corresponding quantum algorithms presented with time complexity $\mathrm{poly}(r, 1/\varepsilon)$,[2] where r is the rank of ρ. Recently in [LW25], it was discovered that for every non-integer $q > 1$, $\mathrm{tr}(\rho^q)$ can be estimated using $\widetilde{O}(1/\varepsilon^{3+\frac{2}{q-1}})$ samples of ρ, removing the dependence on r (which we call dimension-independent as it depends on neither the rank nor the dimension of ρ). Thus, this exponentially improving the results in [WGL+24] and the results implied by other works [AISW20, WZL24, WZ25b] on Rényi entropy estimation. However, the sample complexity in [LW25] is far from being optimal, as only a lower bound of $\Omega(1/\varepsilon)$ on the sample complexity of estimating $\mathrm{tr}(\rho^q)$ for non-integer $q > 1$ was known in [LW25, Theorem 5.9]. To our knowledge, only a matching lower bound of $\Omega(1/\varepsilon^2)$ was known for the case of $q = 2$, i.e., estimating the purity $\mathrm{tr}(\rho^2)$ (see [CWLY23, Theorem 5] and [GHYZ24, Lemma 3]).

In this paper, we further investigate the sample complexity of estimating $\mathrm{tr}(\rho^q)$ for non-integer $q > 1$, achieving significant improvements over the prior results in both the upper and lower bounds. In particular, for $q > 2$, we provide an estimator that is *optimal* only up to a logarithmic factor in the precision ε. Our results are collected in Section 1.1. In addition, it is noteworthy that our techniques are conceptually and technically different from those in [LW25]. In comparison, our estimator is based on weak Schur sampling [CHW07] while the estimator in [LW25] is based on quantum singular value transformation [GSLW19] and samplizer [WZ25a, WZ25b]. For more details, see Section 1.2.

1.1 Main Results

To illustrate our results, we present them in two parts separately: $q > 2$ and $1 < q < 2$.

[2] In [WGL+24], their main results only consider the quantum query complexity, as they assume access to the state-preparation circuit of ρ. Even though, their results also imply a sample complexity of $\mathrm{poly}(r, 1/\varepsilon)$ (with a polynomial overhead compared to the corresponding query complexity) using the techniques in [GP22], as noted in [WGL+24, Footnote 2].

The case of $q > 2$. For $q > 2$, we provide a quantum estimator with optimal sample complexity $\widetilde{\Theta}(1/\varepsilon^2)$ only up to a logarithmic factor in ε. This result is formally stated in the following theorem.

Theorem 1.1 (Optimal estimator for $q > 2$, Theorems 3.3 and 4.1). *For every $q > 2$, it is necessary and sufficient to use $\widetilde{\Theta}(1/\varepsilon^2)$ samples of the quantum state ρ to estimate $\operatorname{tr}(\rho^q)$ to within additive error ε.*

The case of $1 < q < 2$. For $1 < q < 2$, we provide a quantum estimator with sample complexity $\widetilde{O}(1/\varepsilon^{\frac{2}{q-1}})$, only with room for quadratic improvements due to the lower bound $\Omega(1/\varepsilon^{\max\{\frac{1}{q-1},2\}})$. This result is formally stated in the following theorem.

Theorem 1.2 (Improved estimator for $1 < q < 2$, Theorems 3.5, 4.1 and 4.2). *For every $1 < q < 2$, it is sufficient to use $\widetilde{O}(1/\varepsilon^{\frac{2}{q-1}})$ samples of the quantum state ρ to estimate $\operatorname{tr}(\rho^q)$ to within additive error ε. On the other hand, when the dimension of ρ is sufficiently large, $\Omega(1/\varepsilon^{\max\{\frac{1}{q-1},2\}})$ samples of ρ are necessary.*

Our estimators for Theorems 1.1 and 1.2 can be efficiently implemented with quantum time complexity $\operatorname{poly}(\log(d), 1/\varepsilon)$ for any constant $q > 1$ (see Section 3.4), where d is the dimension of ρ.

Both Theorems 1.1 and 1.2 improve the prior best upper bound $\widetilde{O}(1/\varepsilon^{3+\frac{2}{q-1}})$ and lower bound $\Omega(1/\varepsilon)$ in [LW25]. It is also noted that Theorem 1.1 gives a matching lower bound of $\Omega(1/\varepsilon^2)$ on the sample complexity of estimating $\operatorname{tr}(\rho^q)$ for every integer $q \geq 3$, implying that the Shift test in [EAO+02] is sample-optimal to estimate $\operatorname{tr}(\rho^q)$ to within an additive error, generalizing the lower bounds in [CWLY23, GHYZ24] for the optimality of the SWAP test [BCWdW01] to estimate $\operatorname{tr}(\rho^2)$. We summarize the developments for the sample complexity of estimating $\operatorname{tr}(\rho^q)$ in Table 1.

Table 1: Sample complexity of estimating $\operatorname{tr}(\rho^q)$.

$q \geq 2$	$1 < q < 2$	References
$O(1/\varepsilon^2)$, $q \in \mathbb{N}$	/	[BCWdW01, EAO+02]
$\Omega(1/\varepsilon^2)$, $q = 2$	/	[CWLY23, GHYZ24]
$O(\operatorname{poly}(r, 1/\varepsilon))$		[AISW20, WGL+24, WZL24, WZ25b]
$\widetilde{O}(1/\varepsilon^{3+\frac{2}{q-1}})$, $\Omega(1/\varepsilon)$		[LW25]
$\widetilde{\Theta}(1/\varepsilon^2)$	$\widetilde{O}(1/\varepsilon^{\frac{2}{q-1}})$ $\Omega(1/\varepsilon^{\max\{\frac{1}{q-1},2\}})$	This Work

1.2 Techniques

Upper bounds. Since the trace of quantum state power $\operatorname{tr}(\rho^q)$ is a unitarily invariant quantity, it is well-known that there exists a canonical estimator performing weak Schur sampling [CHW07, MdW16, OW21] on $\rho^{\otimes n}$ to obtain a Young diagram outcome λ and then predicting the final result $\operatorname{tr}(\rho^q)$ based on λ. The most straightforward way to do this is to treat each λ_i/n, where λ_i is the i-th row of λ, as an estimate of the i-th large eigenvalue of ρ, and then output $\sum_i(\lambda_i/n)^q$ as the final result, which is what is called the *plug-in estimator*. Existing quantum plug-in estimators are known for, e.g., von Neumann entropy and Rényi entropy in [AISW20, BMW16].

However, directly using the plug-in estimator with current error bounds for weak Schur sampling in [OW17] seems to be difficult to avoid the dependence on the dimension (or rank) of ρ appearing in the accumulation of errors. This is very different from the classical empirical estimation. For example, the classical plug-in estimators for $\sum_i p_i^q$ in [JVHW15, JVHW17] suffice to achieve the optimal sample complexity, while the same strategy might introduce an *unexpected* factor of $\mathrm{poly}(d)$ in the quantum case, where d is the dimension. To overcome this limitation, we develop non-plug-in estimators for $\mathrm{tr}(\rho^q)$. Our non-plug-in estimator adopts a simple but effective truncation strategy which eliminates the dimension (or rank) in the complexity. Specifically, having obtained an estimated spectrum $\hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2, \ldots, \hat{\alpha}_d)$ of ρ to certain precision with $\hat{\alpha}_1 \geq \hat{\alpha}_2 \geq \cdots \geq \hat{\alpha}_d$ (with $\alpha = (\alpha_1, \alpha_2, \ldots, \alpha_d)$ the true sorted spectrum of ρ), our non-plug-in estimator is then of the form

$$\hat{P} = \sum_{j=1}^{m} \hat{\alpha}_j^q,$$

where m is a truncation parameter such that the lower-order errors are controlled by the eigenvalues (which are finally suppressed due to constantly upper bounded partial sums), and the higher-order errors are accumulated with scaling only depending on m (thus suppressed with negligible truncation bias). In sharp contrast to the quantum plug-in estimators in the literature [AISW20, BMW16], our non-plug-in construction can be shown to achieve optimal sample complexity only up to a logarithmic factor (see Sections 3.2 and 3.3 for more details). As a result, we obtain sample upper bounds $\widetilde{O}(1/\varepsilon^2)$ for $q > 2$ and $\widetilde{O}(1/\varepsilon^{\frac{1}{q-1}})$ for $1 < q < 2$. Note that the exponent of the upper bound does not depend on q for constant $q > 2$, which is in contrast to $1 < q < 2$. This is because we borrow a factor α_i from α_i^q to control the error $|\hat{\alpha}_i - \alpha_i|$ (to avoid d-dependence), and the fluctuation of $\hat{\alpha}_i^{q-1}$ is small enough when $q > 2$ (see Equation (4)), causing q to disappear from the exponent.

Lower bounds. Our lower bounds consist of two parts: $\Omega(1/\varepsilon^{\frac{1}{q-1}})$ and $\Omega(1/\varepsilon^2)$.

The former lower bound $\Omega(1/\varepsilon^{\frac{1}{q-1}})$ for $1 < q < 2$ is obtained by reducing a discrimination task on ensembles of quantum states. Specifically, we consider two unitarily invariant ensembles of quantum states that are maximally mixed with respect to different dimensions. Then, we show that the discrimination between these ensembles can be characterized by the discrimination between certain Schur-Weyl distributions in their total variation distance. To bound the total variation distance, we recall the relationship between the Schur-Weyl distributions and Plancherel distributions shown in [CHW07], which demands a linear scaling with the dimensions. With carefully chosen dimension parameters, we can obtain our lower bound.

The latter lower bound $\Omega(1/\varepsilon^2)$ for any constant $q > 1$ is obtained by reducing from a state discrimination task with a simple but effective hard instance from [CWLY23, GHYZ24].

1.3 Related Work

After the work of [BCWdW01, EAO+02], there have been a series of subsequent work focusing on the estimation of $\mathrm{tr}(\rho^q)$ for integer $q \geq 2$ [Bru04, vEB12, JST17, SCC19, YS21, QKW24, ZL24, SLLJ24]. As the classical counterpart, estimating the functional $\sum_{j=1}^N p_j^q$ of a probability distribution p to within an additive error was studied in [AK01] for integer $q \geq 2$, and later in [JVHW15, JVHW17] for non-integer q; its estimation to a multiplicative error was studied in [AOST17] for Rényi entropy estimation. In addition, Shannon entropy estimation was studied in [Pan03, Pan04, VV11a, VV11b, VV17, WY16].

Given sample access to the quantum states to be tested, quantum estimators and testers for their properties have been investigated in the literature. The first optimal quantum tester was discovered in [CHW07], which distinguishes whether a quantum state has a spectrum uniform on r or $2r$ eigenvalues. This was later generalized to an optimal tester for mixedness in [OW21] and to quantum state certification in [BOW19]. In addition, optimal estimators are known for Rényi entropy of integer order [AISW20], and the closeness (trace distance and fidelity) between pure quantum states [WZ24b]. A distributed optimal estimator was known for the inner product of quantum states [ALL22]. Estimators and testers with incoherent measurements are also known for purity [CCHL21, GHYZ24], unitarity [CCHL21, CWLY23], certification [CHLL22, LA24], and $\operatorname{tr}(\rho^q)$ for integer q (further used for spectrum estimation) [PTTW25]. In addition to those that were known to be optimal, there are also estimators for entropy [AISW20, BMW16, WZ25b, LW25], relative entropy [Hay25], fidelity [GP22], and trace distance [WZ24a].

1.4 Discussion

In this paper, we presented quantum estimators for estimating $\operatorname{tr}(\rho^q)$ for non-integer $q > 1$, significantly improving the prior approaches. In particular, for $q > 2$, our estimators achieve optimal sample complexity only up to a logarithmic factor. Our (non-plug-in) estimators are directly constructed by weak Schur sampling with optimal sample complexity (although every estimator for unitarily invariant properties is known to imply a canonical estimator based on weak Schur sampling [MdW16, Lemma 20]), in addition to the (plug-in) optimal estimator for Rényi entropy of integer order [AISW20], the optimal testers for mixedness [OW21] and quantum state certification [BOW19], and the optimal learners for full tomography [HHJ+17, OW16]. At the end of the discussion, we list some questions in this direction for future research.

1. Can we remove the logarithmic factor from the sample complexity obtained in this paper?
2. Can we improve the upper or the lower bound for $1 < q < 2$?
3. Can we find more (plug-in or non-plug-in) optimal estimators based on weak Schur sampling?
4. Can we obtain optimal estimators for $\operatorname{tr}(\rho^q)$ with restricted measurements?
5. As the sample complexities of estimating $\operatorname{tr}(\rho^q)$ for $q \geq 2$ are known to be $\widetilde{\Theta}(1/\varepsilon^2)$ (thus they have almost the same difficulty in the sample complexity) but only the case of $q = 2$ is known to be BQP-hard [LW25], an interesting question is: can we show the BQP-hardness of estimating $\operatorname{tr}(\rho^q)$ for general $q > 2$?

2 Preliminaries

2.1 Basics in quantum computing

A d-dimensional (mixed) quantum state can be described by a $d \times d$ complex-valued positive semidefinite matrix $\rho \in \mathbb{C}^{d\times d}$ satisfying $\operatorname{tr}(\rho) = 1$. The trace distance between two quantum states ρ_0 and ρ_1 is defined by

$$\frac{1}{2}\|\rho_0 - \rho_1\|_1 = \frac{1}{2}\operatorname{tr}(|\rho_0 - \rho_1|).$$

The fidelity between two quantum states ρ_0 and ρ_1 is defined by

$$\mathrm{F}(\rho_0, \rho_1) = \operatorname{tr}\left(\sqrt{\sqrt{\sigma}\rho\sqrt{\sigma}}\right).$$

To discriminate two quantum states, we include the following well-known results. The following theorem can be found in [Wil13, Section 9.1.4], [Hay16, Lemma 3.2], and [Wat18, Theorem 3.4].

Theorem 2.1 (Quantum state discrimination, cf. [Wil13, Section 9.1.4], [Hay16, Lemma 3.2], and [Wat18, Theorem 3.4]). *Any POVM $\Lambda = \{\Lambda_0, \Lambda_1\}$ that distinguishes two quantum states ρ_0 and ρ_1 (each with a priori probability $1/2$) with success probability*

$$\frac{1}{2}\operatorname{tr}(\Lambda_0\rho_0) + \frac{1}{2}\operatorname{tr}(\Lambda_1\rho_1) \leq \frac{1}{2}\left(1 + \frac{1}{2}\|\rho_0 - \rho_1\|_1\right).$$

The following fact was noted in [HHJ+17, Section 1] using the quantum Chernoff bound [NS09, ACMT+07].

Fact 2.2. *The sample complexity for distinguishing two quantum states ρ_0 and ρ_1 is $\Omega(1/\gamma)$, where $\gamma = 1 - \mathrm{F}(\rho_0, \rho_1)$ is the infidelity.*

2.2 Basic representation theory

A *representation* of a group G is a pair $(\mu, \mathcal{H})$, where $\mathcal{H}$ is a (complex) Hilbert space, and $\mu : G \to \mathrm{GL}(\mathcal{H})$ is a group homomorphism from G to the general linear group on $\mathcal{H}$.[3] We also call $\mu(g)$ the action of $g \in G$ on $\mathcal{H}$. When the group action is clear from the context, we may omit μ and directly use $\mathcal{H}$ to refer to the representation of G.

A *sub-representation* of $(\mu, \mathcal{H})$ is a representation $(\mu', \mathcal{H}')$, where $\mathcal{H}'$ is a subspace of $\mathcal{H}$ and $\mu'(g)$ is the restriction of $\mu(g)$ to $\mathcal{H}'$. A representation $\mathcal{H}$ of G is *irreducible* if the only sub-representations of $\mathcal{H}$ are $\{0\}$ and $\mathcal{H}$ itself. A *representation homomorphism* between two representations $(\mu_1, \mathcal{H}_1), (\mu_2, \mathcal{H}_2)$ of group G is a linear operator $F : \mathcal{H}_1 \to \mathcal{H}_2$ which commutes with the action of G, i.e.,

$$F\mu_1(g) = \mu_2(g)F.$$

A *representation isomorphism* is a representation homomorphism that is also a full-rank linear map. Two representations $\mathcal{H}_1$ and $\mathcal{H}_2$ of a group G are said to be *isomorphic* if there exists an representation isomorphism between them, and we write $\mathcal{H}_1 \overset{G}{\cong} \mathcal{H}_2$. Then, we introduce the Schur's Lemma, which is an important and basic result in representation theory.

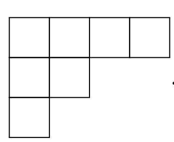
Fact 2.3 (Schur's Lemma, see, e.g. [EGH+11, Proposition 2.3.9]). *Let $\mathcal{H}_1, \mathcal{H}_2$ be irreducible representations of a group G. If $F : \mathcal{H}_1 \to \mathcal{H}_2$ is a non-zero homomorphism of representations, then F is an isomorphism.*

The following is a direct and useful corollary of Schur's Lemma.

Corollary 2.4. *Suppose $\mathcal{H}$ is an irreducible representation of G and $F : \mathcal{H} \to \mathcal{H}$ is a representation homomorphism. Then $F = cI$ where c is a complex number.*

2.2.1 Schur-Weyl duality

A *Young diagram* λ with n boxes and at most d rows is a partition $\lambda = (\lambda_1, \ldots, \lambda_d)$ of n such that $\sum_i \lambda_i = n$ and $\lambda_1 \geq \cdots \geq \lambda_d \geq 0$. For example, the Young diagram with 8 boxes and 3 rows, identified by the partition $(4, 2, 1)$ is:


.

[3] In this paper, we mostly consider the case that G is finite or compact, where without loss of generality we can assume $\mu : G \to \mathbb{U}(\mathcal{H})$ is unitary.

We use $\lambda \vdash n$ to denote that λ is a Young diagram with n boxes.

Consider the actions of the symmetric group $\mathfrak{S}_n$ and the unitary group $\mathbb{U}_d$ on the Hilbert space $(\mathbb{C}^d)^{\otimes n}$. For any $U \in \mathbb{U}_d$, U acts on $(\mathbb{C}^d)^{\otimes n}$ by

$$|\psi_1\rangle \otimes \cdots \otimes |\psi_n\rangle \mapsto U|\psi_1\rangle \otimes \cdots \otimes U|\psi_n\rangle,$$

and for any $\pi \in \mathfrak{S}_n$, π acts on $(\mathbb{C}^d)^{\otimes n}$ by

$$|\psi_1\rangle \otimes \cdots \otimes |\psi_n\rangle \mapsto |\psi_{\pi^{-1}(1)}\rangle \otimes \cdots \otimes |\psi_{\pi^{-1}(n)}\rangle.$$

For convenience, we directly use $U^{\otimes n}$ and π to denote the action of $U \in \mathbb{U}_d$ and $\pi \in \mathfrak{S}_n$ on $(\mathbb{C}^d)^{\otimes n}$.

Note that $U^{\otimes n}$ and π commutes with each others, which means $(\mathbb{C}^d)^{\otimes n}$ is also a representation of the group $\mathfrak{S}_n \times \mathbb{U}_d$. This is characterized by the following renowned Schur-Weyl duality.

Fact 2.5 (Schur-Weyl duality [FH13, EGH+11]).

$$(\mathbb{C}^d)^{\otimes n} \overset{\mathfrak{S}_n \times \mathbb{U}_d}{\cong} \bigoplus_{\lambda \vdash n} \mathcal{P}_\lambda \otimes \mathcal{Q}_\lambda^d,$$

where $\mathcal{P}_\lambda$ and $\mathcal{Q}_\lambda^d$ are irreducible representations of $\mathfrak{S}_n$ and $\mathbb{U}_d$, respectively, and are labeled by a Young diagram $\lambda \vdash n$.[4]

For $\pi \in \mathfrak{S}_n$ and $U \in \mathbb{U}_d$, we use $\mathsf{p}_\lambda(\pi)$ and $\mathsf{q}_\lambda(U)$ to denote their actions on $\mathcal{P}_\lambda$ and $\mathcal{Q}_\lambda^d$, respectively.

Remark 2.1. *In fact, q_λ can be extended naturally to the actions of the group $\mathrm{GL}(\mathbb{C}^d)$ on $\mathcal{Q}_\lambda^d$, and further by continuity to the action of any matrix in $\mathrm{End}(\mathbb{C}^d)$ on $\mathcal{Q}_\lambda^d$.*

For any matrix $X \in \mathrm{End}(\mathbb{C}^d)$, $X^{\otimes n}$ is invariant under permutations (the actions of $\mathfrak{S}_n$). It is not hard using Schur's Lemma to show the following fact.

Fact 2.6. *$X^{\otimes n}$ has the following form:*

$$X^{\otimes n} = \bigoplus_{\lambda \vdash n} I_{\mathcal{P}_\lambda} \otimes \mathsf{q}_\lambda(X),$$

where $\mathsf{q}_\lambda(X)$ is the action of X on $\mathcal{Q}_\lambda^d$ (see Remark 2.1).

Furthermore, it is known that $\mathrm{tr}(\mathsf{q}_\lambda(X)) = s_\lambda(\alpha)$, where s_λ is the *Schur polynomial* [FH13] indexed by λ and $\alpha = (\alpha_1, \ldots, \alpha_d)$ are the eigenvalues of X.

2.3 Weak Schur sampling as quantum estimators

Suppose we have n samples of an unknown d-dimensional quantum state ρ. Consider the task of estimating a quantitative property $F(\rho)$ of ρ (e.g., the purity $\mathrm{tr}(\rho^2)$). Without loss of generality, the estimator can be described by a POVM $\{M_i\}$ applied on $\rho^{\otimes n}$,[5] and $f(i)$ is returned as an estimate if the measurement outcome is i.

Note that $\rho^{\otimes n}$ is invariant under permutations of the tensors, i.e., for any $\pi \in \mathfrak{S}_n$, $\pi\rho^{\otimes n}\pi^\dagger = \rho^{\otimes n}$. This means we can "factor out" the action of the symmetric group $\mathfrak{S}_n$ to obtain a permutation invariant estimator. Furthermore, if the quantitative property $F(\rho)$ is unitarily invariant, i.e., for

[4] Note that if the Young diagram λ has more than d rows, then $\mathcal{Q}_\lambda^d = 0$.

[5] Here, we assume the POVM is discrete, the continuous case can be treated similarly.

any $U \in \mathbb{U}_d$, $F(U\rho U^\dagger) = F(\rho)$, we can also factor out the action of the unitary group $\mathbb{U}_d$ to obtain a unitarily invariant estimator with the performance no worse than the original one. Specifically, we define the canonical permutation-invariant and unitary-invariant estimator $\{\overline{M}_i\}$ as:

$$\overline{M}_i = \frac{1}{n!} \sum_{\pi \in \mathfrak{S}_n} \pi \mathop{\mathbb{E}}_{U \in \mathbb{U}_d} \left[U^{\otimes n} M_i U^{\dagger \otimes n} \right] \pi^\dagger.$$

The following shows that the estimator $\{\overline{M}_i\}_i$ is at least as powerful as the original estimator $\{M_i\}_i$ (see also, e.g., [MdW16, Hay25]).

Fact 2.7. *If $\{M_i\}$ is an estimator of the quantitative property F achieving additive error ε with success probability $1-\delta$, then $\{\overline{M}_i\}$ can also achieve additive error ε with probability $1-\delta$.*

Note that $\overline{M}_i$ commutes with both $U^{\otimes n}$ and π for any $U \in \mathbb{U}_d$ and $\pi \in \mathfrak{S}_n$. By the Schur-Weyl duality (see Fact 2.5) and Corollary 2.4, we have

$$\overline{M}_i = \bigoplus_{\lambda \vdash n} c_{i,\lambda} \cdot I_{\mathcal{P}_\lambda} \otimes I_{\mathcal{Q}_\lambda^d},$$

where $c_{i,\lambda}$ is a positive number such that $\sum_i c_{i,\lambda} = 1$. Then, by Fact 2.6, we can see that the estimator $\{\overline{M}_i\}$ applied on $\rho^{\otimes n}$ is equivalent to

1. sample a $\lambda \vdash n$ from the distribution $\{\mathrm{tr}(I_{\mathcal{P}_\lambda} \otimes \mathsf{q}_\lambda(\rho))\}_\lambda = \{\dim(\mathcal{P}_\lambda) \cdot s_\lambda(\alpha)\}_\lambda$, where s_λ is the Schur polynomial and $\alpha = (\alpha_1, \ldots, \alpha_d)$ are the eigenvalues of ρ such that $\alpha_1 \geq \cdots \geq \alpha_d$.

2. sample an i from the distribution $\{c_{i,\lambda}\}_i$.

It is worth noting that, the second step is entirely classical, while the first step is a quantum measurement independent of the specific task, which is called *weak Schur sampling* [CHW07]. In step 1, the distribution $\{\dim(\mathcal{P}_\lambda) \cdot s_\lambda(\alpha)\}_\lambda$ is referred to as the *Schur-Weyl distribution* [OW17] and is denoted by $\mathrm{SW}^n(\alpha)$ or $\mathrm{SW}^n(\rho)$. Specifically,

$$\Pr_{\lambda' \sim \mathrm{SW}^n(\alpha)}[\lambda' = \lambda] = \dim(\mathcal{P}_\lambda) \cdot s_\lambda(\alpha).$$

Furthermore, the Young diagram $\lambda \sim \mathrm{SW}^n(\alpha)$ provides a good approximation of the eigenvalues $\alpha_1, \ldots, \alpha_d$ of ρ, which is characterized by the following result.

Lemma 2.8 (Adapted from [OW17, Theorem 1.5])**.** *For $j \in [d]$,*

$$\mathop{\mathbb{E}}_{\lambda \sim \mathrm{SW}^n(\alpha)} \left[(\lambda_j - \alpha_j n)^2 \right] \leq O(n).$$

We use SW_d^n to denote $\mathrm{SW}^n(\alpha)$ when $\alpha = (1/d, \ldots, 1/d)$,[6] i.e., ρ is maximally mixed. Furthermore, when $d \to \infty$, the distribution tends to a limiting distribution $\mathrm{Planch}(n)$, called *Plancherel distribution* over the symmetric group $\mathfrak{S}_n$. We will use the following result which provides both upper and lower bounds of the convergence of SW_d^n to $\mathrm{Planch}(n)$.

Lemma 2.9 ([CHW07, Lemma 6])**.** *If $2 \leq n \leq d$, then*

$$\frac{n}{36d} \leq \| \mathrm{SW}_d^n - \mathrm{Planch}(n) \|_1 \leq \sqrt{2} \frac{n}{d}.$$

[6] In some papers, SW_d^n is also called Schur-Weyl distribution [OW21] or simply Schur distribution [CHW07].

3 Upper Bounds

In this section, we provide quantum algorithms that estimate the value of $\mathrm{tr}(\rho^q)$ for $q > 2$ and $1 < q < 2$ respectively in Section 3.2 and Section 3.3. For these, we also provide a simple approach to the quantum spectrum estimation with entry-wise bounds in Section 3.1.

In both of our quantum algorithms, we use the following three parameters m, δ', ε', where m is the position where the truncation is taken, and δ' and ε' are, respectively, the failure probability and the precision when applying the quantum spectrum estimation with entry-wise bounds in Section 3.1. Specifically, $m \in [d]$ is a positive integer and $\delta', \varepsilon' \in (0, 1)$ are real numbers, all of which are to be determined later. In addition, we assume that ρ has the spectrum decomposition:

$$\rho = \sum_{j=1}^{d} \alpha_j |\psi_j\rangle\langle\psi_j|,$$

where $\alpha_1 \geq \alpha_2 \geq \cdots \geq \alpha_d \geq 0$ with $\sum_{j=1}^{d} \alpha_j = 1$ and $\{|\psi_j\rangle\}$ is an orthonormal basis.

3.1 Quantum spectrum estimation with entry-wise bounds

Efficient approaches to quantum spectrum estimation were given in [OW16] in the ℓ_1 and ℓ_2 distances and in [OW17] in the Hellinger-squared distance, chi-squared divergence, and Kullback-Liebler (KL) divergence. In this section, we provide an efficient approach to quantum spectrum estimation with entry-wise bounds based on the results of [OW17], which will be used as a subroutine in our estimators for $\mathrm{tr}(\rho^q)$ in Section 3.

Algorithm 1 `SpectrumEstimation`$(\rho, \varepsilon, \delta)$

Input: Sample access to a d-dimensional mixed quantum state ρ; $\varepsilon, \delta \in (0, 1)$.
Output: A d-dimensional vector $\hat{\alpha} \in \mathbb{R}^d$.

```
1: n ← Θ(1/ε²), k ← Θ(log(1/δ)).
2: for l = 1, 2, ..., k do
3:     λ^(l) ~ SW^n(ρ).
4: end for
5: for j = 1, 2, ..., d do
6:     α̂_j ← median{λ_j^(1), λ_j^(2), ..., λ_j^(k)}, where λ_j^(l) = λ_j^(l)/n.
7: end for
8: return (α̂_1, α̂_2, ..., α̂_d).
```

Line 1: $n \leftarrow \Theta(1/\varepsilon^2)$, $k \leftarrow \Theta(\log(1/\delta))$. Line 3: $\lambda^{(l)} \sim \mathrm{SW}^n(\rho)$. Line 6: $\hat{\alpha}_j \leftarrow \mathrm{median}\{\underline{\lambda}_j^{(1)}, \underline{\lambda}_j^{(2)}, \ldots, \underline{\lambda}_j^{(k)}\}$, where $\underline{\lambda}_j^{(l)} = \lambda_j^{(l)}/n$.

Lemma 3.1 (Quantum spectrum estimation with entry-wise bounds)**.** *For every $\varepsilon, \delta \in (0, 1)$, we can use $O(\log(1/\delta)/\varepsilon^2)$ samples of ρ to obtain a sequence of random variables $\hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2, \ldots, \hat{\alpha}_d) \in \mathbb{R}^d$ such that for every $j \in [d]$, it holds with probability at least $1 - \delta$ that $|\hat{\alpha}_j - \alpha_j| \leq \varepsilon$.*

To bound the success probability, we need Hoeffding's inequality.

Theorem 3.2 (Hoeffding's inequality, [Hoe63, Theorem 2])**.** *Let $X_1, X_2, \ldots, X_n$ be independent and identical random variables with $X_j \in [0, 1]$ for all $1 \leq j \leq n$. Then,*

$$\Pr\left[\left|\frac{1}{n}\sum_{j=1}^{n} X_j - \mathbb{E}[X_1]\right| \leq t\right] \geq 1 - 2\exp\bigl(-2nt^2\bigr).$$

Proof of Lemma 3.1. We present a formal description of our approach in Algorithm 1. In the following proof, all expectations are computed over $\lambda \sim \mathrm{SW}^n(\alpha)$. Let $\underline{\lambda}_j = \lambda_j/n$. By Lemma 2.8, we have

$$\mathbb{E}\big[(\underline{\lambda}_j - \alpha_j)^2\big] \le \frac{c}{n},$$

for some constant $c > 0$. Therefore,

$$\begin{aligned}\Pr\left[|\underline{\lambda}_j - \alpha_j| \ge 2\sqrt{\frac{c}{n}}\right] \cdot 4 \cdot \frac{c}{n} &\le \mathbb{E}\big[(\underline{\lambda}_j - \alpha_j)^2\big] \qquad (1)\\ &\le \frac{c}{n},\end{aligned}$$

where Equation (1) is by Markov's inequality that $\Pr[|X| \ge a]\cdot a^k \le \mathbb{E}[|X|^k]$ for any random variable X, integer $k \ge 1$, and $a > 0$. This implies

$$\Pr\left[|\underline{\lambda}_j - \alpha_j| \ge 2\sqrt{\frac{c}{n}}\right] \le \frac{1}{4}.$$

Let $k \ge 1$ be an odd integer. Now we draw k independent samples $\lambda^{(1)}, \lambda^{(2)}, \dots, \lambda^{(k)}$ from $\mathrm{SW}^n(\alpha)$, and for each $j \in [d]$ let

$$\hat{\alpha}_j = \mathrm{median}\Big\{\underline{\lambda}_j^{(1)}, \underline{\lambda}_j^{(2)}, \dots, \underline{\lambda}_j^{(k)}\Big\}.$$

Let $X_j^{(l)} \in \{0,1\}$ be a random variable such that $X_j^{(l)} = 1$ if $|\underline{\lambda}_j^{(l)} - \alpha_j| \ge 2\sqrt{c/n}$ and 0 otherwise. By Hoeffding's inequality (Theorem 3.2) with $t = 1/12$, we have

$$\Pr\left[\left|\frac{1}{k}\sum_{l=1}^{k} X_j^{(l)} - \mathbb{E}\Big[X_j^{(1)}\Big]\right| \le \frac{1}{12}\right] \ge 1 - 2\exp\left(-\frac{k}{72}\right).$$

Note that $\mathbb{E}[X_j^{(1)}] \le 1/4$, then

$$\Pr\left[\frac{1}{k}\sum_{l=1}^{k} X_j^{(l)} \le \frac{1}{3}\right] \ge 1 - 2\exp\left(-\frac{k}{72}\right),$$

which means that $\hat{\alpha}_j$, the median of $\underline{\lambda}_j^{(1)}, \underline{\lambda}_j^{(2)}, \dots, \underline{\lambda}_j^{(k)}$, satisfies $|\hat{\alpha}_j - \alpha_j| \le 2\sqrt{c/n}$ with probability

$$\Pr\left[|\hat{\alpha}_j - \alpha_j| \le 2\sqrt{\frac{c}{n}}\right] \ge 1 - 2\exp\left(-\frac{k}{72}\right).$$

By taking $n = \lceil 4c/\varepsilon^2 \rceil$ and $k = \lceil 72\ln(2/\delta) \rceil$, we have

$$\Pr[|\hat{\alpha}_j - \alpha_j| \le \varepsilon] \ge 1 - \delta,$$

which uses $nk = O(\log(1/\delta)/\varepsilon^2)$ samples of ρ. $\square$

Algorithm 2 `PowerTrace`(ρ, q, ε) for $q > 2$

Input: Sample access to a d-dimensional mixed quantum state ρ; $q \in (2, +\infty)$ and $\varepsilon \in (0, 1)$.
Output: An estimate of $\mathrm{tr}(\rho^q)$.

1: $\varepsilon' \leftarrow \varepsilon/(q+3)$, $m \leftarrow \min\{\lceil 1/\varepsilon' \rceil, d\}$, $\delta' \leftarrow 1/3m$.
2: $\hat{\alpha} \leftarrow$ `SpectrumEstimation`$(\rho, \varepsilon', \delta')$.
3: $\hat{P} \leftarrow \sum_{j=1}^{m} \hat{\alpha}_j^q$.
4: **return** $\hat{P}$.

3.2 $q > 2$

For $q > 2$, the sample complexity of estimating $\mathrm{tr}(\rho^q)$ is given as follows.

Theorem 3.3. *For every constant $q > 2$, we can estimate $\mathrm{tr}(\rho^q)$ to within additive error ε using $O(\log(1/\varepsilon)/\varepsilon^2)$ samples of ρ.*

Our estimator for Theorem 3.3 is formally given in Algorithm 2. To prove Theorem 3.3, we need the following inequalities.

Fact 3.4. *For $\alpha > 1$ and $x, y \in [0, 1]$, we have $x^\alpha \leq x$ and $|x^\alpha - y^\alpha| \leq \alpha|x - y|$.*

Proof. This fact follows by applying the mean value theorem on the function $f(x) = x^\alpha$. □

Now we are ready to prove Theorem 3.3.

Proof of Theorem 3.3. Let parameters $m \in \mathbb{N}$ and $\delta', \varepsilon' \in (0, 1)$ to be determined later. By Lemma 3.1, we can use $O(\log(1/\delta')/\varepsilon'^2)$ samples of ρ to obtain a sequence $\hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2, \ldots, \hat{\alpha}_d)$ such that for every $j \in [d]$,

$$\Pr\left[|\hat{\alpha}_j - \alpha_j| \leq \varepsilon'\right] \geq 1 - \delta'. \tag{2}$$

Then, we consider the estimator:

$$\hat{P} := \sum_{j=1}^{m} \hat{\alpha}_j^q.$$

The additive error is bounded by

$$\begin{aligned} \left|\hat{P} - \mathrm{tr}(\rho^q)\right| &= \left|\sum_{j=1}^{m} \left(\hat{\alpha}_j^q - \alpha_j^q\right) - \sum_{j=m+1}^{d} \alpha_j^q\right| \\ &\leq \sum_{j=1}^{m} \left|\hat{\alpha}_j^q - \alpha_j^q\right| + \sum_{j=m+1}^{d} \alpha_j^q. \end{aligned} \tag{3}$$

For the first term of Equation (3), note that

$$\begin{aligned} \hat{\alpha}_j^q - \alpha_j^q &= (\hat{\alpha}_j - \alpha_j)\hat{\alpha}_j^{q-1} + \alpha_j \hat{\alpha}_j^{q-1} - \alpha_j^q \\ &= (\hat{\alpha}_j - \alpha_j)\hat{\alpha}_j^{q-1} + \alpha_j \left(\hat{\alpha}_j^{q-1} - \alpha_j^{q-1}\right), \end{aligned}$$

then we have

$$\begin{aligned} \left|\hat{\alpha}_j^q - \alpha_j^q\right| &\leq |\hat{\alpha}_j - \alpha_j||\hat{\alpha}_j|^{q-1} + |\alpha_j|\left|\hat{\alpha}_j^{q-1} - \alpha_j^{q-1}\right| \\ &\leq |\hat{\alpha}_j - \alpha_j||\hat{\alpha}_j| + |\alpha_j|(q-1)|\hat{\alpha}_j - \alpha_j| \qquad (4) \\ &\leq |\hat{\alpha}_j - \alpha_j|(|\alpha_j| + |\hat{\alpha}_j - \alpha_j|) + (q-1)|\alpha_j||\hat{\alpha}_j - \alpha_j| \\ &= q\alpha_j|\hat{\alpha}_j - \alpha_j| + |\hat{\alpha}_j - \alpha_j|^2, \qquad (5) \end{aligned}$$

where Equation (4) is by Fact 3.4. From Equation (5) and by Equation (2), the following holds with probability $\geq 1-\delta'$:

$$\left|\hat{\alpha}_j^q - \alpha_j^q\right| \leq q\alpha_j\varepsilon' + \varepsilon'^2.$$

Therefore, we have that with probability $\geq 1 - m\delta'$, the following holds:

$$\begin{aligned}\sum_{j=1}^{m}\left|\hat{\alpha}_j^q - \alpha_j^q\right| &\leq \sum_{j=1}^{m}\left(q\alpha_j\varepsilon' + \varepsilon'^2\right) \\ &= q\varepsilon'\sum_{j=1}^{m}\alpha_j + m\varepsilon'^2 \\ &\leq q\varepsilon' + m\varepsilon'^2. \end{aligned} \tag{6}$$

On the other hand, by noting that $\alpha_j \leq 1/j$ (since $j\alpha_j \leq \alpha_1 + \cdots + \alpha_j \leq 1$) for every $j \in [d]$, we have

$$\begin{aligned}\sum_{j=m+1}^{d}\alpha_j^q &\leq \sum_{j=m+1}^{d}\left(\frac{1}{j}\right)^q \\ &\leq \int_m^d \left(\frac{1}{x}\right)^q \mathrm{d}x \\ &= \frac{m^{1-q} - d^{1-q}}{q-1}. \end{aligned} \tag{7}$$

Combining Equations (6) and (7) in Equation (3), we have that with probability $\geq 1 - m\delta'$, the following holds:

$$\left|\hat{P} - \operatorname{tr}(\rho^q)\right| \leq q\varepsilon' + m\varepsilon'^2 + \frac{m^{1-q} - d^{1-q}}{q-1}. \tag{8}$$

By taking

$$\varepsilon' := \frac{\varepsilon}{q+3}, \qquad m = \min\left\{\left\lceil\frac{1}{\varepsilon'}\right\rceil, d\right\}, \qquad \delta' := \frac{1}{3m},$$

we have from Equation (8) that with probability $\geq 1 - m\delta' = 2/3$, it holds that

$$\left|\hat{P} - \operatorname{tr}(\rho^q)\right| \leq \varepsilon.$$

To see this, we consider the following two cases:

1. $1/\varepsilon' \leq d$. In this case, $1/\varepsilon' \leq m = \lceil 1/\varepsilon' \rceil < 1/\varepsilon' + 1$. We have

$$\begin{aligned}(8) &\leq q\varepsilon' + \left(\frac{1}{\varepsilon'} + 1\right)\varepsilon'^2 + \frac{1}{m} \\ &\leq q\varepsilon' + \varepsilon' + \varepsilon'^2 + \varepsilon' \\ &\leq (q+3)\varepsilon' \\ &= \varepsilon. \end{aligned}$$

2. $1/\varepsilon' > d$. In this case, $m = d < 1/\varepsilon'$. We have

$$\begin{aligned}(8) &= q\varepsilon' + d\varepsilon'^2 \\ &\leq (q+1)\varepsilon' \\ &< \varepsilon. \end{aligned}$$

To complete the proof, the sample complexity is

$$O\left(\frac{\log(1/\delta')}{\varepsilon'^2}\right) = O\left(\frac{\log(1/\varepsilon)}{\varepsilon^2}\right).$$

□

3.3 $1 < q < 2$

Algorithm 3 `PowerTrace`(ρ, q, ε) for $1 < q < 2$

Input: Sample access to a d-dimensional mixed quantum state ρ; $q \in (1, 2)$ and $\varepsilon \in (0, 1)$.
Output: An estimate of $\operatorname{tr}(\rho^q)$.

1: $\varepsilon' \leftarrow (\varepsilon/5)^{\frac{1}{q-1}}$, $m \leftarrow \min\{\lceil 1/\varepsilon' \rceil, d\}$, $\delta' \leftarrow 1/3m$.
2: $\hat{\alpha} \leftarrow$ `SpectrumEstimation`$(\rho, \varepsilon', \delta')$.
3: $\hat{P} \leftarrow \sum_{j=1}^{m} \hat{\alpha}_j^q$.
4: **return** $\hat{P}$.

We state the sample complexity of estimating $\operatorname{tr}(\rho^q)$ for the case of $1 < q < 2$ as follows.

Theorem 3.5. *For every constant $1 < q < 2$, we can estimate $\operatorname{tr}(\rho^q)$ to within additive error ε using $O(\log(1/\varepsilon)/\varepsilon^{\frac{2}{q-1}})$ samples of ρ.*

Our estimator for Theorem 3.5 is formally given in Algorithm 3. To show Theorem 3.5, we need the following inequalities.

Fact 3.6. *For $0 \le x \le y \le 1$ and $0 < s < 1$ we have*

$$y^s - x^s \le (y - x)^s.$$

Proof. This fact follows by considering the derivative of the function $f(x) \coloneqq (y - x)^s + x^s$. □

Fact 3.7. *For $0 < s < 1$ and $x_i \ge 0$, we have*

$$\sum_{i=1}^{k} x_i^s \le k^{1-s} \cdot \left(\sum_{i=1}^{k} x_i\right)^s.$$

Proof. Let $y_i = x_i^s$. By Roger–Hölder's inequality [Rog88, Höl89],

$$\sum_{i=1}^{k} x_i^s = \sum_{i=1}^{k} y_i \le \left(\sum_{i=1}^{k} 1^{\frac{1}{1-s}}\right)^{1-s} \left(\sum_{i=1}^{k} y_i^{\frac{1}{s}}\right)^s = k^{1-s} \cdot \left(\sum_{i=1}^{k} x_i\right)^s.$$

□

Lemma 3.8. *Suppose that $1 < q < 2$ and $x_1 \ge x_2 \ge \cdots \ge x_N \ge 0$ with $\sum_{i=1}^{N} x_i = 1$. For any positive integer $m \le N$, we have*

$$\sum_{i=m+1}^{N} x_i^q \le \frac{1}{m^{q-1}}.$$

Proof. Note that if $x_i \geq x_j$ and $0 \leq \Delta \leq x_j$, then it is easy to verify that

$$x_i^q + x_j^q \leq (x_i + \Delta)^q + (x_j - \Delta)^q.$$

For any sequence $x_m \geq x_{m+1} \cdots \geq x_N \geq 0$, we define a new sequence by the following process:

1. Find the smallest index j such that $x_j < x_m$, and then find the largest index k such that $k > j$ and $x_k > 0$. If there are no such j, k, then do nothing.

2. Upon the success of finding j, k, we define the new sequence by $x'_i = x_i$ for all $i \neq j, k$ and

$$x'_j = x_j + \Delta, \quad x'_k = x_k - \Delta,$$

   where $\Delta = \min\{x_m - x_j, x_k\}$.

It is obvious that

$$x_{m+1}^q + \cdots + x_N^q \leq (x'_{m+1})^q + \cdots + (x'_N)^q.$$

Starting from a sequence $x_m \geq x_{m+2} \cdots \geq x_N$, we define $A = \sum_{i=m+1}^N x_i$. Then, we iteratively apply this process and finally get a sequence like

$$x_m, \underbrace{x_m, x_m, \ldots, x_m}_{l}, y,$$

where $l = \lfloor A/x_m \rfloor$ and $y = A - l \cdot x_m$. Therefore

$$\begin{aligned}
\sum_{i=m+1}^N x_i^q &\leq l \cdot x_m^q + y^q \\
&= x_{m+1}^q \left(l + \left(\frac{A}{x_m} - l \right)^q \right) \\
&\leq x_m^q \cdot \frac{A}{x_m} \qquad (9) \\
&\leq x_m^{q-1}, \qquad (10)
\end{aligned}$$

where Equation (9) is because $A/x_m - l < 1$. Then, by noting that $x_m \leq 1/m$, we have

$$(10) \leq \frac{1}{m^{q-1}}.$$

□

Now we are ready to prove Theorem 3.5.

Proof of Theorem 3.5. Let parameters $m \in \mathbb{N}$ and $\delta', \varepsilon' \in (0, 1)$ to be determined later. By Lemma 3.1, we can use $O(\log(1/\delta')/\varepsilon'^2)$ samples of ρ to obtain a sequence $\hat{\alpha} = (\hat{\alpha}_1, \hat{\alpha}_2, \ldots, \hat{\alpha}_d)$ such that for every $j \in [d]$,

$$\Pr\left[|\hat{\alpha}_j - \alpha_j| \leq \varepsilon' \right] \geq 1 - \delta'. \qquad (11)$$

Then, we consider the estimator:

$$\hat{P} := \sum_{j=1}^m \hat{\alpha}_j^q.$$

We have

$$\begin{aligned}\left|\hat{P}-\operatorname{tr}(\rho^q)\right| &= \left|\sum_{j=1}^{m}\left(\hat{\alpha}_j^q-\alpha_j^q\right)-\sum_{j=m+1}^{d}\alpha_j^q\right| \\ &\le \sum_{j=1}^{m}\left|\hat{\alpha}_j^q-\alpha_j^q\right|+\sum_{j=m+1}^{d}\alpha_j^q. \end{aligned} \tag{12}$$

For the first term of Equation (12), note that

$$\begin{aligned}\left|\hat{\alpha}_j^q-\alpha_j^q\right| &= \left|(\hat{\alpha}_j-\alpha_j)\hat{\alpha}_j^{q-1}+\alpha_j(\hat{\alpha}_j^{q-1}-\alpha_j^{q-1})\right| \\ &\le |\hat{\alpha}_j-\alpha_j|\hat{\alpha}_j^{q-1}+\alpha_j\left|\hat{\alpha}_j^{q-1}-\alpha_j^{q-1}\right| \\ &\le |\hat{\alpha}_j-\alpha_j|\hat{\alpha}_j^{q-1}+\alpha_j|\hat{\alpha}_j-\alpha_j|^{q-1}, \end{aligned} \tag{13}$$

where the last inequality is by Fact 3.6. Then, by Equation (11), with probability $\ge 1-\delta'$, the following holds:

$$(13) \le \varepsilon'(\alpha_j+\varepsilon')^{q-1}+\alpha_j(\varepsilon')^{q-1}.$$

This implies, with probability $\ge 1-m\delta'$, we have

$$\begin{aligned}\sum_{j=1}^{m}\left|\hat{\alpha}_j^q-\alpha_j^q\right| &\le \varepsilon'\sum_{j=1}^{m}(\alpha_j+\varepsilon')^{q-1}+(\varepsilon')^{q-1}\sum_{j=1}^{m}\alpha_j \\ &\le \varepsilon'\sum_{j=1}^{m}(\alpha_j+\varepsilon')^{q-1}+(\varepsilon')^{q-1} \\ &\le \varepsilon' m^{2-q}\cdot\left(m\varepsilon'+\sum_{j=1}^{m}\alpha_j\right)^{q-1}+(\varepsilon')^{q-1} \qquad (14)\\ &\le \varepsilon' m^{2-q}\big(m\varepsilon'+1\big)^{q-1}+(\varepsilon')^{q-1}, \qquad (15)\end{aligned}$$

where Equation (14) is by Fact 3.7.

Combining Equation (15) with Equation (12), we have that, with probability $\ge 1-m\delta'$, it holds that

$$\left|\hat{P}-\operatorname{tr}(\rho^q)\right| \le \varepsilon' m^{2-q}\big(m\varepsilon'+1\big)^{q-1}+(\varepsilon')^{q-1}+\sum_{j=m+1}^{d}\alpha_j^q. \tag{16}$$

By taking

$$\varepsilon' := \left(\frac{\varepsilon}{5}\right)^{\frac{1}{q-1}}, \qquad m=\min\left\{\left\lceil\frac{1}{\varepsilon'}\right\rceil, d\right\}, \qquad \delta' := \frac{1}{3m},$$

we have from Equation (16) that with probability $\ge 1-m\delta' = 2/3$, it holds that

$$\left|\hat{P}-\operatorname{tr}(\rho^q)\right| \le \varepsilon.$$

To see this, we consider the following two cases:

1. $1/\varepsilon' \le d$. In this case, $1/\varepsilon' \le m = \lceil 1/\varepsilon' \rceil < 2/\varepsilon'$. We use Lemma 3.8 to obtain:

$$\sum_{j=m+1}^{d} \alpha_j^q \le \frac{1}{m^{q-1}}. \tag{17}$$

   Using Equation (17), we have

$$\begin{aligned}
(16) &\le \varepsilon'(2/\varepsilon')^{2-q}(2+1)^{q-1} + (\varepsilon')^{q-1} + (1/\varepsilon')^{1-q} \\
&\le 3(\varepsilon')^{q-1} + 2(\varepsilon')^{q-1} \\
&\le 5(\varepsilon')^{q-1} \\
&= \varepsilon.
\end{aligned}$$

2. $1/\varepsilon' > d$. In this case, $m = d < 1/\varepsilon'$. We have

$$\begin{aligned}
(16) &\le \varepsilon'(1/\varepsilon')^{2-q}(1+1)^{q-1} + (\varepsilon')^{q-1} \\
&\le 5(\varepsilon')^{q-1} \\
&= \varepsilon.
\end{aligned}$$

To complete the proof, the sample complexity is

$$O\left(\frac{\log(1/\delta')}{\varepsilon'^2}\right) = O\left(\frac{\log(1/\varepsilon)}{\varepsilon^{\frac{2}{q-1}}}\right).$$

□

3.4 Time efficiency

Our estimators in Theorems 3.3 and 3.5 can actually be implemented with quantum time complexity $\mathrm{poly}(\log(d), 1/\varepsilon)$ for any constant $q > 1$. This is because, in Algorithms 2 and 3, we only need the first m entries of the output of Algorithm 1, where $m \le O(1/\varepsilon^{\max\{1,\frac{1}{q-1}\}})$. On the other hand, Algorithm 1 uses $n = \widetilde{O}(1/\varepsilon^{\max\{\frac{2}{q-1},2\}})$ samples of ρ and can be implemented with quantum time complexity $O(n^3 \,\mathrm{polylog}(n, d)) = \widetilde{O}(1/\varepsilon^{\max\{\frac{6}{q-1},6\}}) \cdot \mathrm{polylog}(d)$ by weak Schur sampling.[7]

4 Lower Bounds

In this section, we prove a lower bound of $\Omega(1/\varepsilon^{\max\{\frac{1}{q-1},2\}})$ on the sample complexity of estimating $\mathrm{tr}(\rho^q)$ for $q > 1$. Specifically, for any constant $q > 1$, we show a lower bound of $\Omega(1/\varepsilon^2)$ in Theorem 4.1 by quantum state discrimination and a lower bound of $\Omega(1/\varepsilon^{\frac{1}{q-1}})$ in Theorem 4.2 using properties of Schur-Weyl distributions.

[7] This quantum time complexity was noted in [WZ24a, WZ25b, Hay25]. This is achieved by using the implementation of weak Schur sampling introduced in [MdW16, Section 4.2.2], equipped with the quantum Fourier transform over symmetric groups in [KS16].

4.1 Simple lower bounds by quantum state discrimination

Theorem 4.1. *For any constant $q > 1$, any quantum estimator to additive error ε for $\operatorname{tr}(\rho^q)$ requires sample complexity $\Omega(1/\varepsilon^2)$.*

Proof. Consider the problem of distinguishing the two quantum states $\rho_\pm$, where

$$\rho_\pm = \left(\frac{2}{3} \pm \varepsilon\right)|0\rangle\langle 0| + \left(\frac{1}{3} \mp \varepsilon\right)|1\rangle\langle 1|.$$

Then,

$$\operatorname{tr}(\rho_\pm^q) = \left(\frac{2}{3} \pm \varepsilon\right)^q + \left(\frac{1}{3} \mp \varepsilon\right)^q.$$

$$\operatorname{tr}(\rho_+^q) - \operatorname{tr}(\rho_-^q) = \left(\left(\frac{2}{3} + \varepsilon\right)^q - \left(\frac{2}{3} - \varepsilon\right)^q\right) + \left(\left(\frac{1}{3} - \varepsilon\right)^q - \left(\frac{1}{3} + \varepsilon\right)^q\right).$$

By the direct calculation that

$$\lim_{\varepsilon \to 0} \frac{\operatorname{tr}(\rho_+^q) - \operatorname{tr}(\rho_-^q)}{\varepsilon} = 2q\left(\left(\frac{2}{3}\right)^{q-1} - \left(\frac{1}{3}\right)^{q-1}\right) = \Theta(1),$$

we conclude that

$$\operatorname{tr}(\rho_+^q) - \operatorname{tr}(\rho_-^q) = \Theta(\varepsilon).$$

Therefore, any quantum estimator for $\operatorname{tr}(\rho^q)$ to additive error $\Theta(\varepsilon)$ can be used to distinguish ρ_+ and ρ_-. On the other hand, if the quantum estimator for $\operatorname{tr}(\rho^q)$ to additive error ε has sample complexity S, then $S \geq \Omega(1/\gamma)$. A direct calculation shows that the infidelity

$$\gamma = 1 - \mathrm{F}(\rho_+, \rho_-) = 1 - \left(\sqrt{\frac{4}{9} - \varepsilon^2} + \sqrt{\frac{1}{9} - \varepsilon^2}\right) = \Theta(\varepsilon^2).$$

By Fact 2.2, we have $S = \Omega(1/\varepsilon^2)$. □

4.2 Lower bounds by Schur-Weyl distributions

Theorem 4.2. *For every constant $1 < q < 2$, when the dimension of ρ is sufficiently large, any quantum estimator to addtive error ε for $\operatorname{tr}(\rho^q)$ requires sample complexity $\Omega(1/\varepsilon^{\frac{1}{q-1}})$.*

Proof. Given integers $1 \leq r \leq d$, we use $D_{r,d}$ to denote the $d \times d$ diagonal matrix:

$$D_{r,d} \coloneqq \operatorname{diag}(\underbrace{\tfrac{1}{r}, \ldots, \tfrac{1}{r}}_{r}, \underbrace{0, \ldots, 0}_{d-r}).$$

Let

$$r = \left\lfloor \frac{1}{(2\varepsilon)^{\frac{1}{q-1}}} \right\rfloor \quad \text{and} \quad d = \left\lfloor \frac{1}{\varepsilon^{\frac{1}{q-1}}} \right\rfloor + 1.$$

If the number of samples $n > r$, then we directly have $n \geq \Omega(1/\varepsilon^{\frac{1}{q-1}})$. Therefore, we assume

$$n \leq r. \tag{18}$$

Then, consider the following distinguishing problem.

Problem 1. *Suppose a d-dimensional quantum state ρ is in one of the following with equal probability:*

1. *$\rho = \rho_1 \coloneqq U D_{r,d} U^\dagger$, where $U \sim \mathbb{U}_d$ is a d-dimensional Haar random unitary.*
2. *$\rho = \rho_2 \coloneqq D_{d,d}$.*

The task is to distinguish between the above two cases.

Note that $\operatorname{tr}(\rho_1^q) = 1/r^{q-1} \geq 2\varepsilon$ and $\operatorname{tr}(\rho_2^q) = 1/d^{q-1} \leq \varepsilon$. Therefore, any estimator of $\operatorname{tr}(\rho^q)$ to additive error $\frac{1}{2}\varepsilon = \Theta(\varepsilon)$ is able to distinguish the two cases in Problem 1.

On the other hand, suppose we have n samples of ρ. Then, for the first case (i.e., $\rho = \rho_1$), we have

$$
\begin{aligned}
\mathbb{E}\big[\rho_1^{\otimes n}\big] &= \mathop{\mathbb{E}}_{U \sim \mathbb{U}_d}\Big[U^{\otimes n} D_{r,d}^{\otimes n} U^{\dagger \otimes n}\Big] \\
&= \bigoplus_{\lambda \vdash n} I_{\mathcal{P}_\lambda} \otimes \mathop{\mathbb{E}}_{U \sim \mathbb{U}_d}\Big[\mathfrak{q}_\lambda(U)\mathfrak{q}_\lambda(D_{r,d})\mathfrak{q}_\lambda(U)^\dagger\Big] && (19)\\
&= \bigoplus_{\lambda \vdash n} I_{\mathcal{P}_\lambda} \otimes I_{\mathcal{Q}_\lambda^d} \cdot \frac{s_\lambda(D_{r,d})}{\dim(\mathcal{Q}_\lambda^d)}, && (20)
\end{aligned}
$$

where Equation (19) can be seen by Fact 2.6, in Equation (20) is by Corollary 2.4 and the observation that $\mathbb{E}_{U\sim\mathbb{U}_d}\big[\mathfrak{q}_\lambda(U)\mathfrak{q}_\lambda(D_{r,d})\mathfrak{q}_\lambda(U)^\dagger\big]$ commutes with the actions of $U \in \mathbb{U}_d$, in which $s_\lambda(D_{r,d})$ refers to $s_\lambda(\underbrace{1/r, \ldots, 1/r}_{r}, \underbrace{0, \ldots, 0}_{d-r})$. Similarly, for the second case (i.e., $\rho = \rho_2$), we have

$$
\mathbb{E}\big[\rho_2^{\otimes n}\big] = \bigoplus_{\lambda \vdash n} I_{\mathcal{P}_\lambda} \otimes I_{\mathcal{Q}_\lambda^d} \cdot \frac{s_\lambda(D_{d,d})}{\dim(\mathcal{Q}_\lambda^d)}.
$$

By Theorem 2.1, the success probability of distinguishing $\mathbb{E}[\rho_1^{\otimes n}]$ and $\mathbb{E}[\rho_2^{\otimes n}]$ is upper bounded by

$$
\frac{1}{2} + \frac{1}{4}\big\|\mathbb{E}\big[\rho_1^{\otimes n}\big] - \mathbb{E}\big[\rho_2^{\otimes n}\big]\big\|_1.
$$

Note that

$$
\begin{aligned}
\big\|\mathbb{E}\big[\rho_1^{\otimes n}\big] - \mathbb{E}\big[\rho_2^{\otimes n}\big]\big\|_1 &= \sum_{\lambda \vdash n} |\dim(\mathcal{P}_\lambda) \cdot s_\lambda(D_{r,d}) - \dim(\mathcal{P}_\lambda) \cdot s_\lambda(D_{d,d})| \\
&= \|\operatorname{SW}_r^n - \operatorname{SW}_d^n\|_1, && (21)
\end{aligned}
$$

where in Equation (21) we use the stability of Schur polynomial, i.e.,

$$
s_\lambda(D_{r,d}) = s_\lambda(\underbrace{\tfrac{1}{r}, \ldots, \tfrac{1}{r}}_{r}, \underbrace{0, \ldots, 0}_{d-r}) = s_\lambda(\underbrace{\tfrac{1}{r}, \ldots, \tfrac{1}{r}}_{r}).
$$

Then, since $n \leq r \leq d$ (see Equation (18)), by Lemma 2.9, we have that

$$
\frac{n}{36r} \leq \|\operatorname{SW}_r^n - \operatorname{Planch}(n)\|_1 \leq \sqrt{2}\frac{n}{r},
$$

and

$$
\frac{n}{36d} \leq \|\operatorname{SW}_d^n - \operatorname{Planch}(n)\|_1 \leq \sqrt{2}\frac{n}{d}.
$$

This means

$$\begin{aligned}\| \mathrm{SW}_r^n - \mathrm{SW}_d^n \|_1 &\le \| \mathrm{SW}_r^n - \mathrm{Planch}(n)\|_1 + \| \mathrm{SW}_d^n - \mathrm{Planch}(n)\|_1 \\ &\le \sqrt{2}\frac{n}{r} + \sqrt{2}\frac{n}{d}.\end{aligned}$$

Therefore, if the success probability is at least 2/3, then

$$\frac{2}{3} \le \frac{1}{2} + \frac{1}{4}\Big(\sqrt{2}\frac{n}{r} + \sqrt{2}\frac{n}{d}\Big) \le \frac{1}{2} + \frac{n}{\sqrt{2}r},$$

which means

$$n \ge \frac{\sqrt{2}r}{6} = \frac{\sqrt{2}}{6}\left\lfloor \frac{1}{(2\varepsilon)^{\frac{1}{q-1}}} \right\rfloor = \Omega\left(\frac{1}{\varepsilon^{\frac{1}{q-1}}}\right).$$

□

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