

# Uncertainty relations from simple entropic properties

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Uncertainty relations provide constraints on how well the outcomes of sets of incompatible measurements can be predicted, and are fundamental to our understanding of quantum theory. Here we shed new light on the entropic form of these relations, showing that they follow from a few simple entropic properties, including the data processing inequality. We prove these relations without relying on the exact expression for the entropy, and hence show that a single technique applies to several entropic quantities, including the von Neumann entropy, min- and max-entropies and the Rényi entropies.

## I. INTRODUCTION

Uncertainty relations form a central part of our understanding of quantum mechanics, and give a dramatic illustration of the separation between quantum and classical physics. They provide fundamental constraints on how well the outcomes of various incompatible measurements can be predicted, as first noted by Heisenberg in the case of position and momentum measurements [1, 2]. This and other early uncertainty relations [3, 4] were formulated using the standard deviation as the measure of uncertainty.

With the advent of information theory, it became natural to develop relations using entropies to measure uncertainty [5–9]. Furthermore, the most recent versions also account for the possibility of observers holding additional side-information which they can use to predict the measurement outcomes [10–12], and the measurements can be general POVMs (Positive Operator Valued Measures) [13, 14]. When formulated in this way, uncertainty relations can be applied more directly to problems related to information processing tasks, or to cryptography, since the quantities involved (conditional entropies) have direct operational meanings.

One way to think about uncertainty relations is in the following tripartite scenario. Consider a system,  $A$ , which will be measured using one of two measurements,  $X$  and  $Z$ , which can be described in terms of their POVM elements,  $\{X_j\}$  and  $\{Z_k\}$ . If  $X$  is measured, an observer (Bob) holding information  $B$  is asked to predict the outcome of this measurement, while if  $Z$  is measured, a second observer (Charlie) holding  $C$  is asked to predict the outcome. In general, the information  $B$  and  $C$  held by the observers may be quantum, and, most generally, the state before measurement is described by a tripartite density operator,  $\rho_{ABC}$ . Uncertainty relations provide quantitative limits on the prediction accuracy, often giving a *trade-off* between Bob's ability to predict  $X$  and Charlie's ability to predict  $Z$ .

There are many different ways to measure uncertainty, and for much of this paper, we need not specify precisely which measure we are using. We use  $H_K(X|B)$

to denote the uncertainty about the outcome of measurement  $X$  given  $B$ , and likewise  $H_{\hat{K}}(Z|C)$  to denote the uncertainty about the outcome of measurement  $Z$  given  $C$  (note that in general our uncertainty relations will be about different, but related entropies). A tripartite uncertainty relation then gives a lower bound on  $H_K(X|B) + H_{\hat{K}}(Z|C)$  which depends on the measurements  $X$  and  $Z$ , and reflects their complementarity. For example, in the case where  $X$  and  $Z$  are composed of commuting projectors, i.e. where there exist states that allow both predictions to be correctly made, this lower bound will be trivial (i.e. 0).

In this work, we show that such uncertainty relations follow from a few simple entropic properties. Among them, the data-processing inequality forms a central part. Roughly speaking, this states that if  $B$  provides information about  $A$ , then processing  $B$  cannot decrease the uncertainty about  $A$ , which is clearly what one would expect from an uncertainty measure.

We also obtain relations for the bipartite case where only one measurement will be made (i.e. where we only ask Bob to predict the outcome of the measurement of  $X$ ). The state-independent relation we obtain is trivial if  $X$  is projective (then there is always a state for which  $H_K(X|B) = 0$ ), but gives an interesting bound for more general measurements. Furthermore, we give an additional relation which depends on the entropy of the initial state.

More precisely, our main result is that for any entropy  $H_K$  that satisfies our set of properties (stated in Section II), the relations

$$H_K(X|B) + H_{\hat{K}}(Z|C) \geq \log \frac{1}{c(X, Z)}, \quad (1)$$

$$H_K(X|B) \geq \log \frac{1}{c(X)}, \quad \text{and} \quad (2)$$

$$H_K(X|B) \geq \log \frac{1}{c'(X)} + H_K(A|B) \quad (3)$$

hold for any state  $\rho_{ABC}$ , where  $c(X, Z) = \max_{jk} \|\sqrt{X_j} \sqrt{Z_k}\|_{\infty}^2$ ,  $c(X) = c(X, \{\mathbb{1}\})$  and  $c'(X) = \max_j \text{Tr}(X_j)$  (the infinity norm of an operator is its largest singular value). Here,  $H_{\hat{K}}$  is the

entropy dual to  $H_K$  in the sense that for any pure state  $\rho_{ABC}$ ,  $H_K(A|B) + H_{\widehat{K}}(A|C) = 0$ . (While the base of the logarithm is conventionally taken to be 2, so that entropies are measured in *bits*, our results apply for any base (provided the same one is used throughout)).

In particular, our proof applies to the von Neumann entropy, the min- and max-entropies, and a range of Rényi entropies. For the tripartite relation, the first two cases were already known [12–14], while the latter is new, and for the bipartite relations we extend previous work on this idea [14–16] to allow for other entropies or quantum side information. To emphasize, the main contribution of the present work is that it provides a unified proof of these relations.

## II. ENTROPIC PROPERTIES

In this work we use conditional entropies to measure uncertainty. We will use a number of different entropies, using  $H_K$  to denote a generic entropy. For a density operator  $\rho_{AB}$ , the conditional  $K$ -entropy of  $A$  given  $B$  is denoted  $H_K(A|B)$ .

As mentioned above, we will be concerned with the uncertainties of POVM outcomes. A POVM,  $X$ , can be specified via a set of operators  $\{X_j\}$  which satisfy  $X_j \geq 0$ ,  $\sum_j X_j = \mathbb{1}$ . We also define an associated TPCPM (Trace Preserving Completely Positive Map),  $\mathcal{X}$ , from  $\mathcal{H}_A$  to  $\mathcal{H}_X$  given by

$$\mathcal{X} : \rho_A \mapsto \sum_j |j\rangle\langle j|_X \text{Tr}(X_j \rho_A), \quad (4)$$

where  $\{|j\rangle\}$  form an orthonormal basis in  $\mathcal{H}_X$ . Thus, for a state  $\rho_{AB}$ , we can define the conditional  $K$ -entropy of  $X$  given  $B$ , denoted  $H_K(X|B)$ , as the conditional  $K$ -entropy of the state  $(\mathcal{X} \otimes \mathcal{I})(\rho_{AB})$ .

A (bipartite) conditional entropy is a map from the set of density operators on a Hilbert space  $\mathcal{H}_{AB}$  to the real numbers. It turns out to be convenient to consider a generalized quantity,  $D_K(S||T)$ , which maps two positive semi-definite operators to the real numbers. Such quantities are often called relative entropies. We consider relative  $K$ -entropies that are constructed such that they generalize the respective conditional  $K$ -entropies in the sense that either  $H_K(A|B) = -D_K(\rho_{AB}||\mathbb{1} \otimes \rho_B)$ , or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB}||\mathbb{1} \otimes \sigma_B)]$ , depending on the entropy.

We now introduce the properties of  $D_K$  that allow us to prove our uncertainty relations:

- (a) Decrease under TPCPMs: If  $\mathcal{E}$  is a TPCPM, then  $D_K(\mathcal{E}(S)||\mathcal{E}(T)) \leq D_K(S||T)$ .
- (b) Being unaffected by null subspaces:  $D_K(S \oplus 0||T \oplus T') = D_K(S||T)$ .
- (c) Multiplying the second argument: If  $c$  is a positive constant, then  $D_K(S||cT) = D_K(S||T) + \log \frac{1}{c}$ .

- (d) Zero for identical states: For any density operator  $\rho$ ,  $D_K(\rho||\rho) = 0$ .

Property (a) implies the increase of  $H_K(A|B)$  under TPCPMs on  $B$ , i.e. the data processing inequality—doing operations on  $B$  cannot decrease the uncertainty about  $A$ . It also implies that  $D_K$  is invariant under isometries  $U$ , i.e.,

$$D_K(USU^\dagger||UTU^\dagger) = D_K(S||T). \quad (5)$$

This can be seen by invoking (a) twice in succession, first with the TPCPM corresponding to  $U$ , then with a TPCPM that undoes  $U$ , establishing that  $D_K(S||T) \geq D_K(USU^\dagger||UTU^\dagger) \geq D_K(S||T)$ , and hence (5).

The uncertainty relation (1) is expressed in terms of the entropy  $H_K$  and its dual  $H_{\widehat{K}}$ , the latter being defined by  $H_{\widehat{K}}(A|B) := -H_K(A|C)$ , where  $\rho_{ABC}$  is a purification of  $\rho_{AB}$ . That this is independent of the chosen purification (and hence that  $H_{\widehat{K}}$  is well-defined) is ensured by the invariance of  $H_K(A|B)$  under local isometries (see Lemma 8 in the Appendix), and the fact that purifications are unique up to isometries on the purifying system (see, for example, [17]). This definition also ensures that  $H_{\widehat{K}}(A|B)$  inherits many natural properties of  $H_K(A|B)$ , for example, increase under TPCPMs on  $B$  and invariance under local isometries.

We proceed by giving some examples of entropies that fit our criteria. The first is the von Neumann entropy, which can be defined via the von Neumann relative entropy. For two positive operators,  $S$  and  $T$ , this is given by

$$D(S||T) := \lim_{\xi \rightarrow 0} \frac{1}{\text{Tr} S} (\text{Tr}(S \log S) - \text{Tr}(S \log(T + \xi \mathbb{1}))).$$

Note that if  $T$  is invertible, the limit is not needed, and if  $S$  lies outside the support of  $T$  then  $D(S||T) = \infty$ . For a density operator  $\rho_{AB}$ , we can then define the conditional von Neumann entropy of  $A$  given  $B$  by  $H(A|B) := -D(\rho_{AB}||\mathbb{1} \otimes \rho_B)$ . The von Neumann entropy is its own dual, i.e. for any pure state  $\rho_{ABC}$ , we have  $H(A|B) = -H(A|C)$ .

A second class of entropies to which our results apply are a range of Rényi entropies [18, 19]. For positive operators,  $S$  and  $T$ , and for  $\alpha \in (0, 1) \cup (1, 2]$ , the Rényi relative entropy of order  $\alpha$  is defined by

$$D_\alpha(S||T) := \lim_{\xi \rightarrow 0} \frac{1}{\alpha - 1} \log \text{Tr}(S^\alpha(T + \xi \mathbb{1})^{1-\alpha}).$$

Furthermore, we define

$$\begin{aligned} D_0(S||T) &:= \lim_{\alpha \rightarrow 0^+} D_\alpha(S||T) \quad \text{and} \\ D_1(S||T) &:= \lim_{\alpha \rightarrow 1} D_\alpha(S||T) = D(S||T). \end{aligned}$$

Hence, the von Neumann relative entropy can be seen as a special case. The relative entropy  $D_\alpha$  gives rise to the conditional Rényi entropy

$$H_\alpha(A|B) := -D_\alpha(\rho_{AB}||\mathbb{1} \otimes \rho_B),$$

which satisfies the duality relation that  $H_\alpha(A|B) = -H_{2-\alpha}(A|C)$  for pure  $\rho_{ABC}$  [20].

Furthermore, the min and max relative entropies

$$D_{\min}(S||T) := \log \min\{\lambda : S \leq \lambda T\}$$

$$D_{\max}(S||T) := -2 \log \text{Tr} \sqrt{\sqrt{S} T \sqrt{S}}$$

can be used to define the related conditional entropies

$$H_{\min}(A|B) := \max_{\sigma_B} [-D_{\min}(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$$

$$H_{\max}(A|B) := \max_{\sigma_B} [-D_{\max}(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$$

which satisfy the duality relation  $H_{\min}(A|B) = -H_{\max}(A|C)$  [21]. We also consider the entropies

$$\widehat{H}_\alpha(A|B) := \max_{\sigma_B} [-D_\alpha(\rho_{AB} || \mathbb{1} \otimes \sigma_B)].$$

While, in general we do not have alternative expressions for the duals of the latter entropies, it has been shown [22] that  $\widehat{H}_{\min}(A|B) = -\widehat{H}_0(A|C)$  for pure  $\rho_{ABC}$ , where  $\widehat{H}_{\min}(A|B) := -D_{\min}(\rho_{AB} || \mathbb{1} \otimes \rho_B)$ .

### III. MAIN RESULTS

Our main result is that the properties discussed above are sufficient to establish the following uncertainty relations (unless given, all proofs are in the Appendix).

**Theorem 1.** Let  $X = \{X_j\}$  and  $Z = \{Z_k\}$  be arbitrary POVMs on  $A$ , and  $H_K(A|B)$  be such that either  $H_K(A|B) = -D_K(\rho_{AB} || \mathbb{1} \otimes \rho_B)$  or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$ , for all  $\rho_{AB}$ , where  $D_K$  satisfies Properties (a)–(c). It follows that for all  $\rho_{ABC}$

$$H_K(X|B) + H_{\widehat{K}}(Z|C) \geq \log \frac{1}{c(X, Z)},$$

where  $c(X, Z) = \max_{j,k} \|\sqrt{Z_k} \sqrt{X_j}\|_\infty^2$ .

The ideas behind this proof are illustrated in Section IV where we give a proof for the special case where  $H_K$  is the von Neumann entropy, and  $X$  and  $Z$  are composed of rank-one projectors.

We also have the following single-measurement uncertainty relation.

**Lemma 2.** Let  $X = \{X_j\}$  be an arbitrary POVM on  $A$ , and suppose that  $H_K$  and its related  $D_K$  satisfy the conditions given in Theorem 1, as well as Property (d). Then, for all  $\rho_{AB}$ ,

$$H_K(X|B) \geq \log \frac{1}{c(X)}, \quad (6)$$

where  $c(X) := c(X, \{\mathbb{1}\}) = \max_j \|X_j\|_\infty$ .

*Proof.* This follows from Theorem 1 and the first part of Lemma 9 (see the Appendix) in the case  $Z = \{\mathbb{1}\}$ .  $\square$

However, there is an alternative single-measurement relation, which can give a stronger bound than (6).

**Lemma 3.** Let  $X = \{X_j\}$  be an arbitrary POVM on  $A$ , and  $H_K(A|B)$  be such that either  $H_K(A|B) = -D_K(\rho_{AB} || \mathbb{1} \otimes \rho_B)$  or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$ , for all  $\rho_{AB}$ , where  $D_K$  satisfies Properties (a)–(c). It follows that

$$H_K(X|B) \geq \log \frac{1}{c'(X)} + H_K(A|B),$$

where  $c'(X) = \max_j \text{Tr}(X_j)$ .

We remark that the bounds in these results can be generalized in the following way. Suppose  $\Pi$  is a projector on  $\mathcal{H}_A$  whose support includes the support of  $\rho_A$ . The above results hold if  $c(X, Z)$  is replaced by  $c(X, Z; \Pi) := \max_{j,k} \|\sqrt{Z_k} \Pi \sqrt{X_j}\|_\infty^2$ , and if  $c'(X)$  is replaced by  $c'(X; \Pi) = \max_j \text{Tr}(X_j \Pi)$ . See [23] for further ways to take advantage of knowledge of the state to derive tighter uncertainty relations for the von Neumann entropy.

We have shown that, in order to establish that a particular entropy satisfies these uncertainty relations, it suffices to verify that it satisfies a few properties. (Recall that for any entropy satisfying our properties, its dual is automatically well defined; it is not necessary to have an alternative expression for it in order for (1) to hold.)

**Lemma 4.** All the relative entropies defined in Section II satisfy Properties (a) through (d).

*Proof.* Properties (b), (c), and (d) follow directly from the definitions of these entropies. Property (a) was discussed in, e.g., [17] for the von Neumann relative entropy, in [19, 20] for the Rényi relative entropies ( $D_0$  being a special case), and in [24] for the min relative entropy. For the max relative entropy, it follows because the fidelity is monotonically increasing under TPCPMs [25].  $\square$

This implies that the dual entropy pairs  $(H, H)$ ,  $(H_\alpha, H_{2-\alpha})$ ,  $(H_{\min}, H_{\max})$  and  $(\widehat{H}_{\min}, \widehat{H}_0)$  each satisfy Eq. (1), and that each of the entropies  $H$ ,  $H_\alpha$ ,  $H_{\min}$ ,  $H_{\max}$ ,  $\widehat{H}_\alpha$  and  $\widehat{H}_{\min}$  satisfy Eqs. (2) and (3).

### IV. ILLUSTRATION OF THE PROOF TECHNIQUE

In order to illustrate how our properties combine to yield uncertainty relations, we give a proof in the special case of the von Neumann entropy and where  $X = \{|X_j\rangle\langle X_j|\}$  and  $Z = \{|Z_k\rangle\langle Z_k|\}$  are orthonormal bases. Although more straightforward, this proof features all of the essential ideas of its generalization. We note that in this case  $c(X, Z) = \max_{j,k} |\langle X_j | Z_k \rangle|^2$ , and the resulting uncertainty relation,

$$H(X|B) + H(Z|C) \geq \log \frac{1}{c(X, Z)}, \quad (7)$$

is the one conjectured in [11] and proven in [12].

We first show that all relative  $K$ -entropies are decreasing under increases of its second argument.

**Lemma 5.** If  $D_K(S||T)$  satisfies Properties (a) and (b), then for all positive operators  $S$  and  $T$ , and for  $\tilde{T} \geq T$ ,

$$D_K(S||T) \geq D_K(S||\tilde{T}). \quad (8)$$

*Proof.* Denote  $\mathcal{H}_\mu$  as the Hilbert space on which  $S$ ,  $T$  and  $\tilde{T}$  are defined and introduce  $\mathcal{H} = \mathcal{H}_\mu \oplus \mathcal{H}_\nu$  with  $\mathcal{H}_\mu \cong \mathcal{H}_\nu$  where  $\mathcal{H}_\mu$  and  $\mathcal{H}_\nu$  have orthonormal bases  $\{|\mu_j\rangle\}$  and  $\{|\nu_j\rangle\}$  respectively. Also introduce a TPCPM  $\mathcal{F} : S \mapsto F_1 S F_1^\dagger + F_2 S F_2^\dagger$ , with  $F_1 = \sum_j |\mu_j\rangle\langle\mu_j|$  and  $F_2 = \sum_j |\mu_j\rangle\langle\nu_j|$ . For  $W := \tilde{T} - T$ , we have

$$\begin{aligned} D_K(S||T) &\stackrel{(b)}{=} D_K(S \oplus 0||T \oplus W) \\ &\stackrel{(a)}{\geq} D_K(\mathcal{F}(S \oplus 0)||\mathcal{F}(T \oplus W)) \\ &\stackrel{(b)}{=} D_K(S \oplus 0||(T + W) \oplus 0) = D_K(S||\tilde{T}). \end{aligned}$$

□

Now, define the isometry  $V_X := \sum_j |j\rangle \otimes X_j$  associated with the  $X$  measurement on system  $A$ , and the state  $\tilde{\rho}_{XABC} := V_X \rho_{ABC} V_X^\dagger$ . We proceed to give the proof for the case of pure  $\rho_{ABC}$ . The impure case follows by considering a purification,  $\rho_{ABCD}$ , and using  $H(X|C) \geq H(X|CD)$  (from Property (a)). Applying the duality to  $\tilde{\rho}_{XABC}$  gives:

$$\begin{aligned} H(X|C) &= -H(X|AB) = D(\tilde{\rho}_{XAB}||\mathbb{1} \otimes \tilde{\rho}_{AB}) \\ &\stackrel{(b)}{=} D(V_X \rho_{AB} V_X^\dagger || V_X \sum_j X_j \rho_{AB} X_j V_X^\dagger) \\ &\stackrel{(5)}{=} D(\rho_{AB} || \sum_j X_j \rho_{AB} X_j) \\ &\stackrel{(a)}{\geq} D(\bar{\rho}_{ZB} || \sum_{j,k} |\langle X_j|Z_k\rangle|^2 Z_k \otimes \text{Tr}_A\{X_j \rho_{AB}\}) \\ &\stackrel{(8)}{\geq} D(\bar{\rho}_{ZB} || c(X, Z) \mathbb{1} \otimes \rho_B) \\ &\stackrel{(c)}{=} \log(1/c(X, Z)) + D(\bar{\rho}_{ZB} || \mathbb{1} \otimes \rho_B) \\ &= \log(1/c(X, Z)) - H(Z|B), \end{aligned} \quad (9)$$

where we have used  $\bar{\rho}_{ZB} := \sum_k Z_k \rho_{AB} Z_k$ .

We remark that the third line of the proof above relates  $H(X|C)$  to the relative entropy of  $\rho_{AB}$  to a state that is decohered (i.e. diagonal) in the  $X$  basis, as in [14, 26]. This ‘‘decoherence relation’’ has application to the fundamental understanding of both decoherence and quantum discord [26], and can be generalized to other entropies, including  $H_\alpha$  and  $\hat{H}_0$ , as shown in the Appendix.

We also note that our proof technique points to a method for finding states that satisfy the uncertainty relation (7) with equality. In the case of pure states  $\rho_{ABC}$  and mutually unbiased bases  $X$  and  $Z$  (for which  $|\langle X_j|Z_k\rangle|$  is independent of  $j, k$ ), the only inequality remaining is a single use of Property (a) (the fourth line of (9)). In this case, (7) is satisfied with equality if (a) is, for the particular TPCPM used in the proof.

For the von Neumann relative entropy, (a) is satisfied with equality [27, 28] if and only if there exists a TPCPM,  $\hat{\mathcal{E}}$ , that undoes the action of  $\mathcal{E}$  on  $S$  and  $T$ , i.e.

$$(\hat{\mathcal{E}} \circ \mathcal{E})(S) = S, \quad (\hat{\mathcal{E}} \circ \mathcal{E})(T) = T. \quad (10)$$

Hence, states of minimum uncertainty are closely connected to the *reversibility* of certain quantum operations. For specific examples, we refer the reader to [29].

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## APPENDIX

### A. Additional Properties

Here we show some additional useful relations that follow from our properties.

**Lemma 6.** If  $D_K$  satisfies Properties (a) and (d), then for density operators  $\rho$  and  $\sigma$ ,

$$D_K(\rho||\sigma) \geq 0, \quad (11)$$

with equality if  $\rho = \sigma$ .

*Proof.* Using Property (a), we have  $D_K(\rho||\sigma) \geq D_K(\rho||\rho)$ , where we consider the TPCPM corresponding to tracing the original system and replacing it with  $\rho$ . The result then follows from (d).  $\square$

The next lemma implies that for conditional entropies of the form  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB}||\mathbb{1} \otimes \sigma_B)]$ , one can restrict the maximization over  $\sigma_B$  to states in the support of  $\rho_B$ .

**Lemma 7.** For all  $\rho_{AB}$ , there exists a state  $\tilde{\sigma}_B$  that lies in the support of  $\rho_B$  such that  $\max_{\sigma_B} [-D_K(\rho_{AB}||\mathbb{1} \otimes \sigma_B)] = -D_K(\rho_{AB}||\mathbb{1} \otimes \tilde{\sigma}_B)$ , where  $D_K$  satisfies Properties (a) and (b).

*Proof.* Let  $\Pi$  be the projector onto the support of  $\rho_B$ , and consider the TPCPM  $\mathcal{E} : \sigma \mapsto \Pi\sigma\Pi \oplus (\mathbb{1} - \Pi)\sigma(\mathbb{1} - \Pi)$ . For an arbitrary density operator  $\bar{\sigma}_B$ , defining  $\hat{\sigma}_B := \frac{1}{\text{Tr}(\Pi\bar{\sigma}_B)}\Pi\bar{\sigma}_B\Pi$ , we have

$$\begin{aligned} D_K(\rho_{AB}||\mathbb{1} \otimes \bar{\sigma}_B) &\stackrel{(a)}{\geq} D_K(\rho_{AB}||\mathbb{1} \otimes \mathcal{E}(\bar{\sigma}_B)) \\ &\stackrel{(b)}{=} D_K(\rho_{AB}||\mathbb{1} \otimes \Pi\bar{\sigma}_B\Pi) \\ &\stackrel{(8)}{\geq} D_K(\rho_{AB}||\mathbb{1} \otimes \hat{\sigma}_B). \end{aligned}$$

In other words, for any  $\bar{\sigma}_B$ , the density operator  $\hat{\sigma}_B$  is at least as good for achieving the maximization over  $\sigma_B$ , which implies the stated result.  $\square$

The next lemma shows that the conditional entropy is invariant under local isometries (this property is needed to ensure that the dual entropy is well-defined; see the main text).

**Lemma 8.** Let  $H_K(A|B)$  be such that either  $H_K(A|B) = -D_K(\rho_{AB}||\mathbb{1} \otimes \rho_B)$  or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB}||\mathbb{1} \otimes \sigma_B)]$ , for all  $\rho_{AB}$ , where  $D_K$  satisfies Properties (a) and (b). For arbitrary (local) isometries  $V_A : \mathcal{H}_A \mapsto \mathcal{H}_{A'}$  and  $V_B : \mathcal{H}_B \mapsto \mathcal{H}_{B'}$ , an arbitrary state  $\rho_{AB}$  and  $\rho_{A'B'} := (V_A \otimes V_B)\rho_{AB}(V_A^\dagger \otimes V_B^\dagger)$ , it follows that  $H_K(A|B) = H_K(A'|B')$ .

*Proof.* In the case  $H_K(A|B) = -D_K(\rho_{AB}||\mathbb{1} \otimes \rho_B)$ , we have

$$\begin{aligned} H_K(A|B) &\stackrel{(5)}{=} -D_K(\rho_{A'B'}||V_A V_A^\dagger \otimes \rho_{B'}) \\ &\stackrel{(b)}{=} -D_K(\rho_{A'B'}||I_{A'} \otimes \rho_{B'}) = H_K(A'|B'), \end{aligned}$$

as required. Now consider  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$ . In this case, we have

$$\begin{aligned} -H_K(A|B) &\stackrel{(5)}{=} \min_{\sigma_B} D_K(\rho_{A'B'} || V_A V_A^\dagger \otimes V_B \sigma_B V_B^\dagger) \\ &\stackrel{(b)}{=} \min_{\sigma_B} D_K(\rho_{A'B'} || I_{A'} \otimes V_B \sigma_B V_B^\dagger) \\ &= \min_{\sigma_{B'}} D_K(\rho_{A'B'} || I_{A'} \otimes \sigma_{B'}) = -H_K(A'|B'), \end{aligned}$$

where to get to the last line we used Lemma 7.  $\square$

**Lemma 9.** Let  $H_K(A|B)$  be such that either  $H_K(A|B) = -D_K(\rho_{AB} || \mathbb{1} \otimes \rho_B)$  or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$ , for all  $\rho_{AB}$ , where  $D_K$  satisfies Properties (a)–(d). Then

- (i)  $H_K(A|B) = 0$  for any state of the form  $\rho_{AB} = |\psi\rangle\langle\psi|_A \otimes \rho_B$ .
- (ii)  $H_K(A|B) \leq \log d_A$ , where  $d_A$  is the dimension of  $\mathcal{H}_A$ .

*Proof.* For (i), note that for such a state,

$$\begin{aligned} H_K(A|B) &= \max_{\sigma_B} [-D_K(|\psi\rangle\langle\psi|_A \otimes \rho_B || \mathbb{1} \otimes \sigma_B)] \\ &\stackrel{(b),(5)}{=} \max_{\sigma_B} [-D_K(\rho_B || \sigma_B)] \stackrel{(11)}{=} 0 \end{aligned}$$

(the case  $H_K(A|B) = -D_K(\rho_{AB} || \mathbb{1} \otimes \rho_B)$  follows similarly).

For (ii), note that

$$\begin{aligned} D_K(\rho_{AB} || \mathbb{1} \otimes \sigma_B) &\stackrel{(c)}{=} D_K(\rho_{AB} || \frac{\mathbb{1}}{d_A} \otimes \sigma_B) + \log \frac{1}{d_A} \\ &\stackrel{(11)}{\geq} \log \frac{1}{d_A}. \end{aligned}$$

The result then follows from the definition of  $H_K$ .  $\square$

Note that if Part (i) of Lemma 9 holds for  $H_K(A|B)$ , it also holds for the dual entropy,  $H_{\widehat{K}}(A|B)$ . It is additionally worth noting that if both  $H_K$  and  $H_{\widehat{K}}$  satisfy the conditions of Lemma 9, then it also follows that  $H_K(A|B) \geq -\log d_A$ .

**Lemma 10.** Let  $H_K(A|B)$  be such that either  $H_K(A|B) = -D_K(\rho_{AB} || \mathbb{1} \otimes \rho_B)$  or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB} || \mathbb{1} \otimes \sigma_B)]$ , for all  $\rho_{AB}$ , where  $D_K$  satisfies Properties (a)–(d). Then, for any POVM,  $X$ , on  $A$ , we have  $H_K(X|B) \geq 0$  with equality if the states  $\text{Tr}_A(X_j \rho_{AB})$  have orthogonal support.

*Proof.* That  $H_K(X|B) \geq 0$  follows from Lemma 2. The equality condition follows from Property (b) and Lemma 6.  $\square$

### B. Proof of Theorem 1

*Proof.* The proof uses an idea in [13] to consider the measurements in terms of two isometries. We introduce  $V_X$  and  $V_Z$  as two isometries from  $\mathcal{H}_A$  to either  $\mathcal{H}_X \otimes \mathcal{H}_{X'}$  or  $\mathcal{H}_Z \otimes \mathcal{H}_{Z'}$  respectively:

$$V_X := \sum_j |j\rangle_X \otimes |j\rangle_{X'} \otimes \sqrt{X_j} \quad (12)$$

$$V_Z := \sum_k |k'\rangle_Z \otimes |k'\rangle_{Z'} \otimes \sqrt{Z_k}, \quad (13)$$

where  $\{|j\rangle\}$  is an orthonormal basis on  $\mathcal{H}_X \cong \mathcal{H}_{X'}$  and similarly  $\{|k'\rangle\}$  is an orthonormal basis on  $\mathcal{H}_Z \cong \mathcal{H}_{Z'}$ . We consider first the case where  $\rho_{ABC}$  is pure. Applying the duality to the (pure) state  $\bar{\rho}_{ZZ'ABC} = V_Z \rho_{ABC} V_Z^\dagger$ , gives  $H_{\widehat{K}}(Z|C) = -H_K(Z|Z'AB)$ . Then note that

$$\begin{aligned} D_K(\bar{\rho}_{ZZ'AB} || \mathbb{1}_Z \otimes \sigma_{Z'AB}) &\stackrel{(a),(b)}{\geq} D_K(\bar{\rho}_{ZZ'AB} || V_Z V_Z^\dagger (\mathbb{1}_Z \otimes \sigma_{Z'AB}) V_Z V_Z^\dagger) \\ &\stackrel{(5)}{=} D_K(\rho_{AB} || V_Z^\dagger (\mathbb{1}_Z \otimes \sigma_{Z'AB}) V_Z) \\ &\stackrel{(5)}{=} D_K(\tilde{\rho}_{XX'AB} || V_X V_X^\dagger (\mathbb{1}_Z \otimes \sigma_{Z'AB}) V_X V_X^\dagger) \\ &= D_K(\tilde{\rho}_{XX'AB} || \sum_k V_X (|k'\rangle \otimes \sqrt{Z_k} \otimes \mathbb{1}_B) \sigma_{Z'AB} (|k'\rangle \otimes \sqrt{Z_k} \otimes \mathbb{1}_B) V_X^\dagger) \\ &\stackrel{(a)}{\geq} D_K(\tilde{\rho}_{XB} || \sum_{j,k} |j\rangle\langle j| \otimes \text{Tr}_{Z'A} (|k'\rangle\langle k'| \otimes \sqrt{Z_k} X_j \sqrt{Z_k} \otimes \mathbb{1}_B) \sigma_{Z'AB}) \\ &\stackrel{(8)}{\geq} D_K(\tilde{\rho}_{XB} || c(X, Z) \mathbb{1}_X \otimes \sigma_B) \\ &\stackrel{(c)}{=} \log \frac{1}{c(X, Z)} + D_K(\tilde{\rho}_{XB} || \mathbb{1}_X \otimes \sigma_B), \end{aligned} \quad (14)$$

where  $\tilde{\rho}_{XX'AB} := V_X \rho_{ABC} V_X^\dagger$ . Our use of (a) in the first line involved the TPCPM  $\rho \mapsto \Pi \rho \Pi + (\mathbb{1} - \Pi) \rho (\mathbb{1} - \Pi)$

with  $\Pi = V_Z V_Z^\dagger$ .

If  $H_K(A|B)$  takes the form  $-D(\rho_{AB}||\mathbb{1} \otimes \rho_B)$ , then we simply take  $\sigma_{Z'AB} = \rho_{Z'AB}$  in the above analysis to obtain the uncertainty relation

$$H_K(X|B) + H_{\hat{K}}(Z|C) \geq \log \frac{1}{c(X, Z)}.$$

Alternatively, if  $H_K(A|B)$  takes the form  $\max_{\sigma_B} -D(\rho_{AB}||\mathbb{1} \otimes \sigma_B)$ , then we take  $\sigma_{Z'AB}$  to be the state achieving the optimization for  $H_K(Z|Z'AB)$  so that, using (14) and  $H_K(X|B) \geq -D_K(\tilde{\rho}_{XB}||\mathbb{1}_X \otimes \sigma_B)$ , we obtain

$$H_K(X|B) + H_{\hat{K}}(Z|C) \geq \log \frac{1}{c(X, Z)}.$$

As presented so far, these relations hold for  $\rho_{ABC}$  pure. More generally, for mixed  $\rho_{ABC}$ , we can introduce a purification,  $\rho_{ABCD}$  and use  $H_K(X|B) \geq H_K(X|BD)$ , which follows from Property (a).  $\square$

### C. Proof of Lemma 3

*Proof.* Let  $\mathcal{X}$  be the TPCPM defined in (4). We have

$$\begin{aligned} & D_K(\rho_{AB}||\mathbb{1} \otimes \sigma_B) \\ & \stackrel{(a)}{\geq} D_K((\mathcal{X} \otimes \mathcal{I})(\rho_{AB})||\mathcal{X}(\mathbb{1}) \otimes \sigma_B) \\ & = D_K(\tilde{\rho}_{XB}||\sum_j \text{Tr}(X_j)|j\rangle\langle j| \otimes \sigma_B) \\ & \stackrel{(8)}{\geq} D_K(\tilde{\rho}_{XB}||\max_j \text{Tr}(X_j)\mathbb{1} \otimes \sigma_B) \\ & \stackrel{(c)}{=} D_K(\tilde{\rho}_{XB}||\mathbb{1} \otimes \sigma_B) + \log(1/c'(X)). \end{aligned}$$

In the case  $H_K(A|B) = -D_K(\rho_{AB}||\mathbb{1} \otimes \rho_B)$ , the result immediately follows. In the alternative case, take  $\sigma_B$  to be the state that achieves the optimum in  $H_K(A|B)$  to establish the result.  $\square$

### D. General decoherence relations

The following result applies to dual entropy pairs  $(H_K, H_{\hat{K}})$ , e.g., of the form  $(H, H)$ ,  $(H_\alpha, H_{2-\alpha})$ , and  $(\hat{H}_{\min}, \hat{H}_0)$ .

**Lemma 11.** Let  $X = \{X_j\}$  be an arbitrary POVM on  $A$  and  $H_K(A|B)$  be such that, for all  $\rho_{AB}$ ,  $H_K(A|B) = -D_K(\rho_{AB}||\mathbb{1} \otimes \rho_B)$  where  $D_K$  satisfies Properties (a) and (b). It follows that for all  $\rho_{ABC}$

$$H_{\hat{K}}(X|C) \geq D_K(\rho_{AB}||\sum_j X_j \rho_{AB} X_j), \quad (15)$$

with equality if  $\rho_{ABC}$  is pure and the  $X_j$  are projectors.

*Proof.* Define  $V_X$  as in (12). Suppose  $\rho_{ABC}$  is a general state and let  $D$  purify it, so that  $\tilde{\rho}_{XX'ABCD} =$

$V_X \rho_{ABCD} V_X^\dagger$  is pure. Then applying the duality to this state gives

$$\begin{aligned} H_{\hat{K}}(X|C) & = -H_K(X|X'ABD) \stackrel{(a)}{\geq} -H_K(X|X'AB) \\ & = D_K(\tilde{\rho}_{XX'AB}||\mathbb{1}_X \otimes \tilde{\rho}_{X'AB}) \\ & \stackrel{(a),(b)}{\geq} D_K(\tilde{\rho}_{XX'AB}||V_X V_X^\dagger(\mathbb{1}_X \otimes \tilde{\rho}_{X'AB})V_X V_X^\dagger) \\ & \stackrel{(5)}{=} D_K(\rho_{AB}||V_X^\dagger(\mathbb{1}_X \otimes \tilde{\rho}_{X'AB})V_X) \\ & = D_K(\rho_{AB}||\sum_j (|j\rangle \otimes \sqrt{X_j}) \tilde{\rho}_{X'AB} (|j\rangle \otimes \sqrt{X_j})) \\ & = D_K(\rho_{AB}||\sum_j X_j \rho_{AB} X_j), \end{aligned}$$

where  $\tilde{\rho}_{X'AB} = \sum_k |k\rangle\langle k| \otimes \sqrt{X_k} \rho_{AB} \sqrt{X_k}$ . For pure  $\rho_{ABC}$ , the first inequality is not needed, and, for projectors  $\{X_j\}$ , the second inequality becomes an equality by invoking (b).  $\square$

### E. Generalizations

Of the properties we use to prove uncertainty relations, (c) is the only one which establishes anything quantitative about the entropy. However, there are other entropies that scale differently in this sense. These may still satisfy modified uncertainty relations, as outlined in the following lemma.

**Lemma 12.** Let  $X = \{X_j\}$  and  $Z = \{Z_k\}$  be arbitrary POVMs on  $A$ , and  $H_K(A|B)$  be such that either  $H_K(A|B) = -D_K(\rho_{AB}||\mathbb{1} \otimes \rho_B)$  or  $H_K(A|B) = \max_{\sigma_B} [-D_K(\rho_{AB}||\mathbb{1} \otimes \sigma_B)]$ , for all  $\rho_{AB}$ , where  $D_K$  satisfies Properties (a), (b) and (d), and

$$D_K(S||cT) = f(c)D_K(S||T) + g(c) \quad (16)$$

for positive operators  $S$  and  $T$  and constant  $c > 0$ . It follows that for all  $\rho_{ABC}$

$$\begin{aligned} H_K(X|B) + f(c(X, Z))H_{\hat{K}}(Z|C) & \geq g(c(X, Z)) \\ H_K(X|B) & \geq g(c(X)) \\ f(c'(X))H_K(X|B) & \geq g(c'(X)) + H_K(A|B) \end{aligned}$$

*Proof.* This follows by replacing all uses of (c) by uses of (16) in the proofs of Theorem 1 and Lemmas 2 and 3.  $\square$

Note that, in order to interpret these inequalities as uncertainty relations in the usual sense, the functions  $f(c)$  and  $g(c)$  ought to be positive for  $0 < c \leq 1$ . (It is clear that setting  $f(c) = 1$  and  $g(c) = \log(1/c)$  recovers our main results.) Furthermore, the same relations hold even if we can only establish an inequality,  $D_K(S||cT) \geq f(c)D_K(S||T) + g(c)$ .

As a concrete example, consider the Tsallis relative and conditional entropies [30]. For positive operators  $S$

and  $T$ , and density operator  $\rho_{AB}$ , these can be defined as follows:

$$\begin{aligned} D_{T,\alpha}(S||T) &:= \lim_{\xi \rightarrow 0} \frac{1}{\alpha - 1} (\text{Tr}(S^\alpha(T + \xi \mathbb{1})^{1-\alpha}) - 1) \\ H_{T,\alpha}(A|B) &:= -D_{T,\alpha}(\rho_{AB}||\mathbb{1} \otimes \rho_B) \\ \widehat{H}_{T,\alpha}(A|B) &:= \max_{\sigma_B} [-D_{T,\alpha}(\rho_{AB}||\mathbb{1} \otimes \sigma_B)] \end{aligned}$$

for  $\alpha \in (0, 1) \cup (1, 2]$ . These are analogous to the Rényi entropies defined in the main text with  $\log(x)$  replaced by  $(x - 1)$ . Furthermore, they are directly related via

$$\log((1 - \alpha)H_{T,\alpha}(A|B) + 1) = (1 - \alpha)H_\alpha(A|B). \quad (17)$$

The duality relation  $H_{T,\alpha}(A|B) = -H_{T,2-\alpha}(A|C)$  follows from the analogous relation for the Rényi entropies.

The Tsallis relative entropies inherit Properties (a), (b) and (d) from the Rényi entropies, and also satisfy (16) with  $f(c) = c^{1-\alpha}$  and  $g(c) = \frac{1-f(c)}{1-\alpha}$ . They hence satisfy the corresponding uncertainty relations of Lemma 12, as well as the relation in Lemma 11. We also note that the uncertainty relations for Tsallis entropies can be shown by rearrangement of those of the Rényi entropies using (17).