Device-independent violation of definite causal order and locality in the quantum switch

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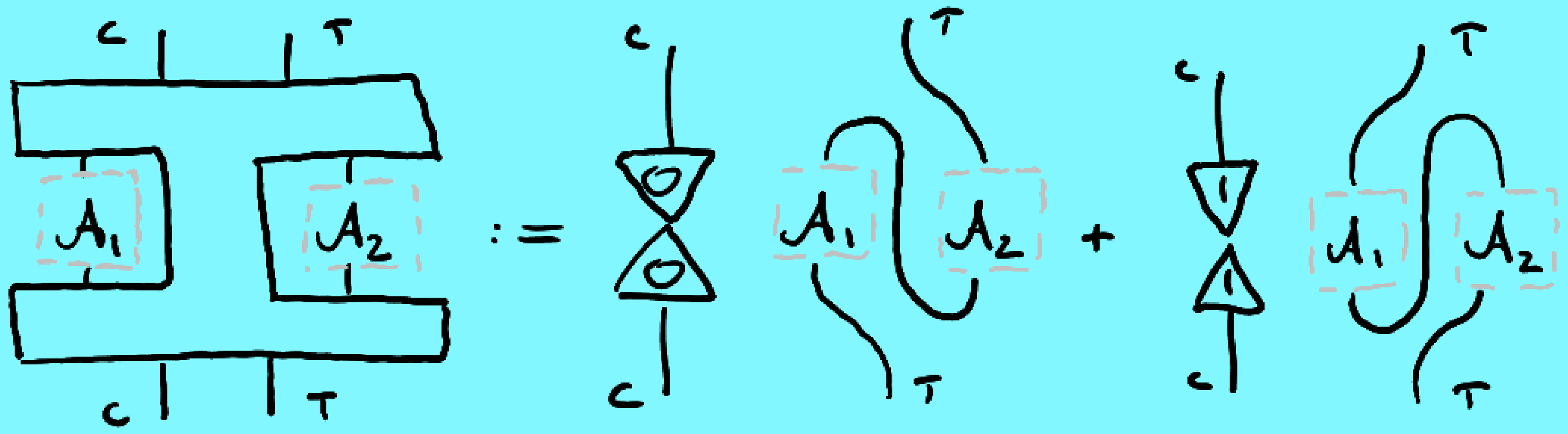
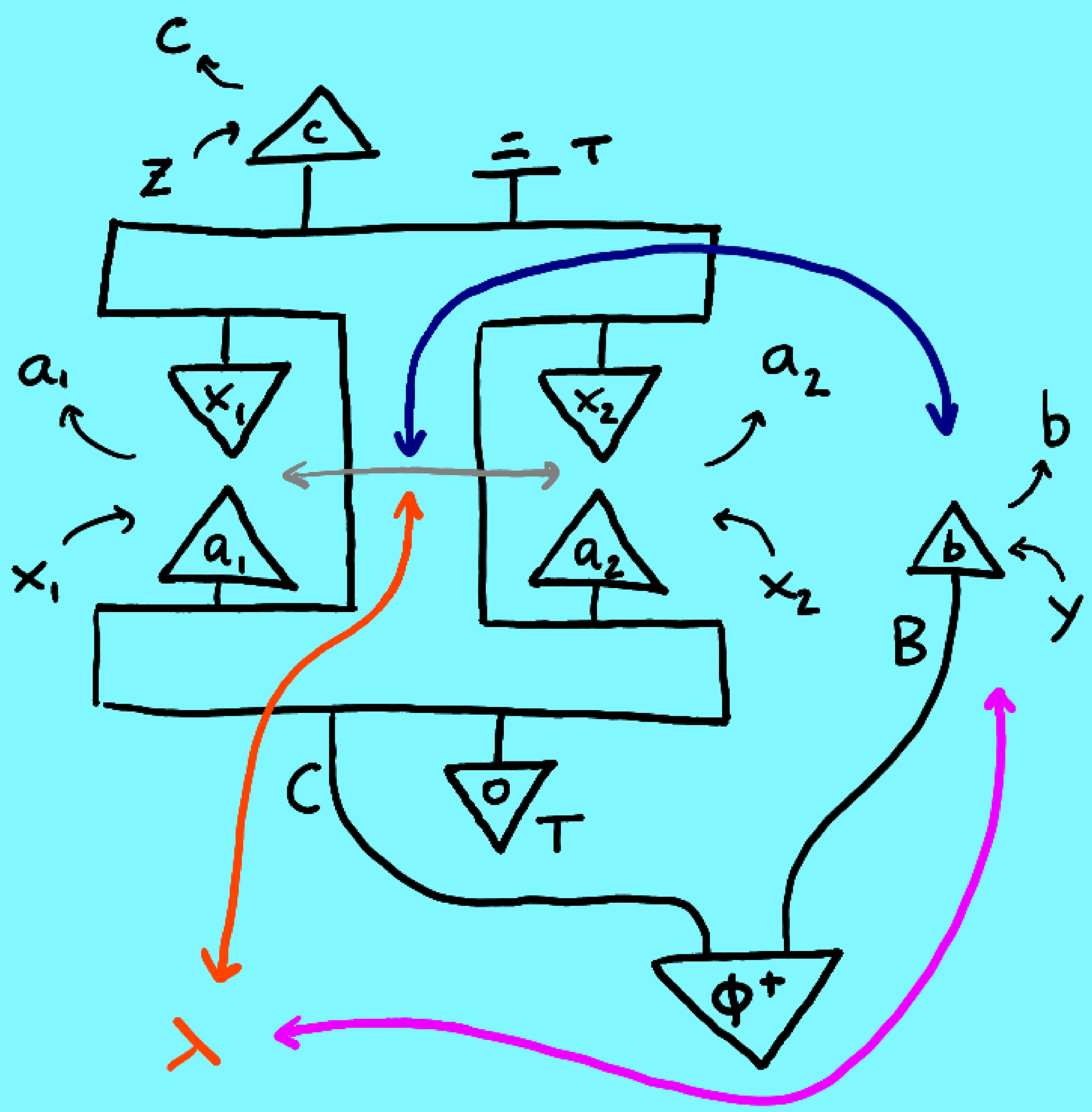
The quantum switch



does not violate causal inequalities.

...so can we device-independently certify its indefinite causal order?



Introduce spacelike-separated, entangled party Bob

⇝ data $p(a_1a_2bc|x_1x_2yz)$

On $y=0$, Bob measures computational basis

⇒ If $y=0, b=0$ then $a_2=x_1$;
if $y=0, b=1$ then $a_1=x_2$.

Suppose ∃ a hidden causal order λ.

Then λ determines b for $y=0$!

BUT:

Determinism of 1 outcome + locality (P.I.) ⇒ Bell inequalities

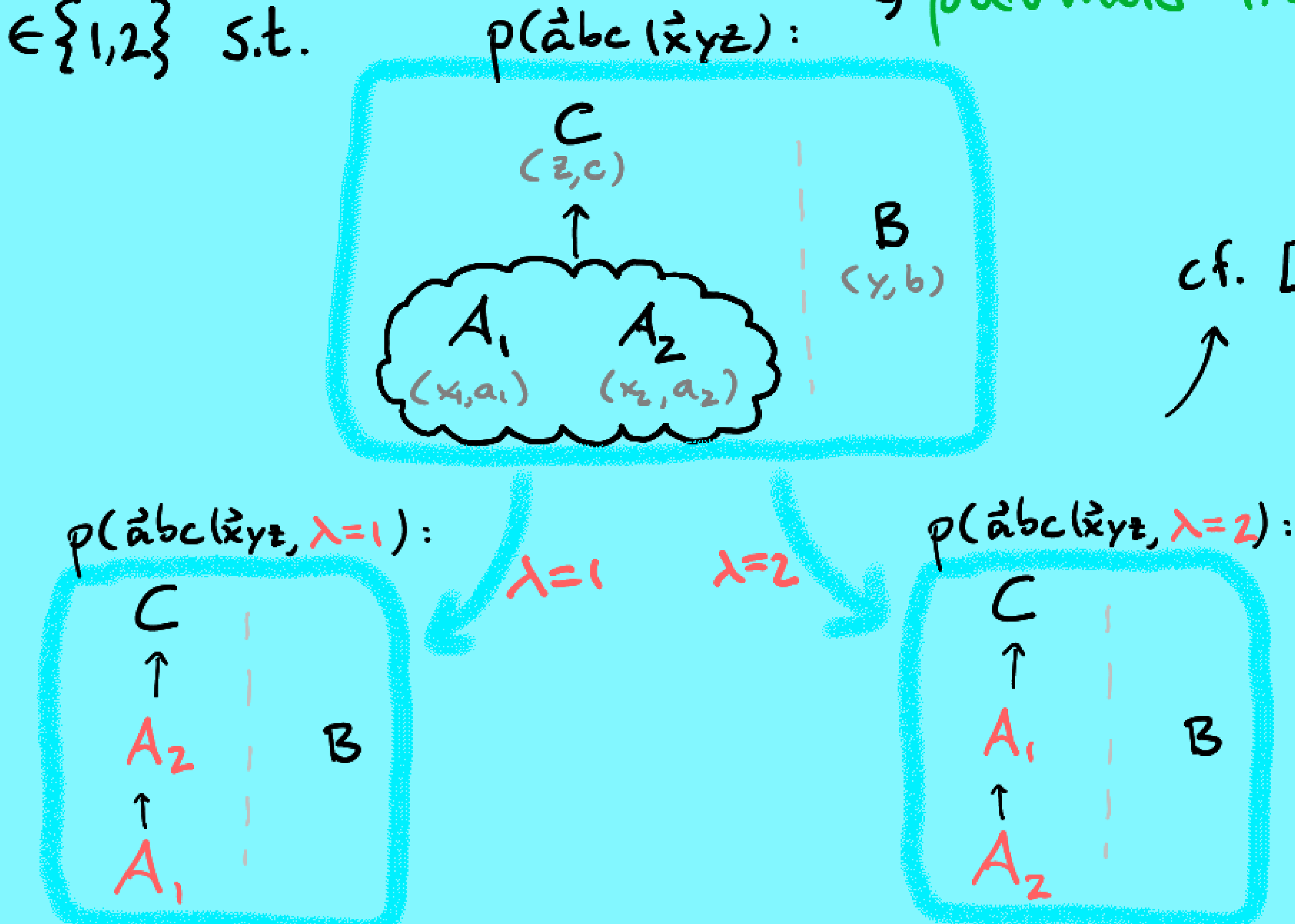
⇒ $p(bc|yz, x_1=x_2=0)$ satisfies all CHSH inequalities ↯

$\mathcal{LC}$: set of $p(a_1a_2bc|x_1x_2yz)$ compatible with

definite causal order, locality (P.I.) and free randomness

↳ parameter independence

i.e. $\exists\, \lambda \in \{1,2\}$ s.t.



cf. [2]

$\lambda=1$: $a_1a_2c \perp\!\!\!\perp y$, $b \perp\!\!\!\perp x_1x_2z$ (P.I.); $a_1b \perp\!\!\!\perp x_2$; $a_1a_2c \perp\!\!\!\perp z$

$\lambda=2$: $a_1a_2c \perp\!\!\!\perp y$, $b \perp\!\!\!\perp x_1x_2z$ (P.I.); $a_2b \perp\!\!\!\perp x_1$; $a_1a_2c \perp\!\!\!\perp z$

⇒ 'local causal inequality': $\forall p \in \mathcal{LC}$,

$$\boxed{p(b=0,a_2=x_1|y=0)+p(b=1,a_1=x_2|y=0) + p(b\oplus c=yz|x_1=x_2=0) \leq \tfrac{7}{4}}$$

Quantum switch: $1 + \frac{1}{2}+\frac{\sqrt{2}}{4} > \frac{7}{4}$

Definite causal order + locality (P.I.) ⇒ 'local causal inequality'

[1] TvdL, JB, GC (2022) arXiv: 2208.00719
[2] S. Gogioso, N. Pinzani (2022) arXiv: 2206.08911