

Genuine Hidden Quantum Nonlocality

Marco Túlio Quintino

Université de Genève

12th August 2013



**UNIVERSITÉ
DE GENÈVE**

arXiv:1307.4404: F. Hirsch, M.T. Quintino, J. Bowles, N.
Brunner

Entanglement Vs. Nonlocality

Local Entangled States

POVMs...

Hidden Nonlocality

Genuine Hidden Nonlocality

Maximal Genuine Hidden Nonlocality

Discussions

Entanglement Vs. Nonlocality



Vs.



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Nonlocality

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POVMs...

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Discussions

Entanglement

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POVMs...

Hidden
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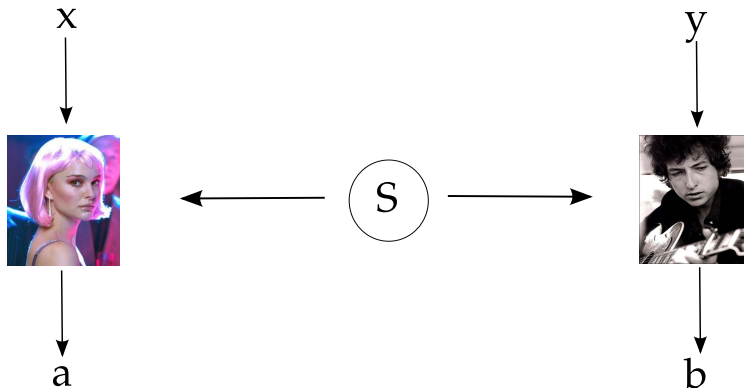
Genuine Hidden
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Maximal Genuine
Hidden
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Discussions

$$\rho_{AB} \neq \int \pi(\lambda) \rho_A^\lambda \otimes \rho_B^\lambda d\lambda$$

Bell Scenario



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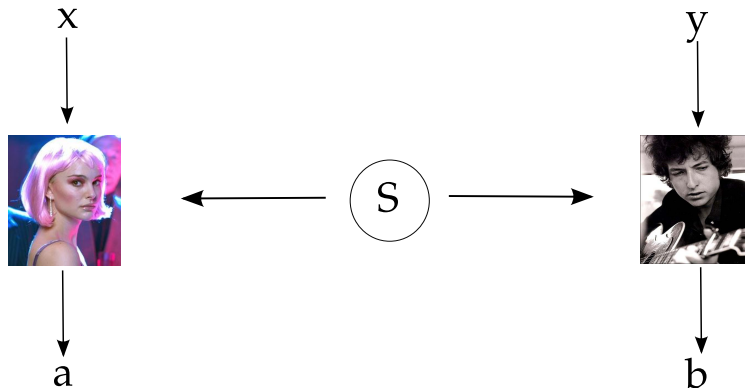
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Discussions

Bell Scenario



$$p(ab|xy)$$

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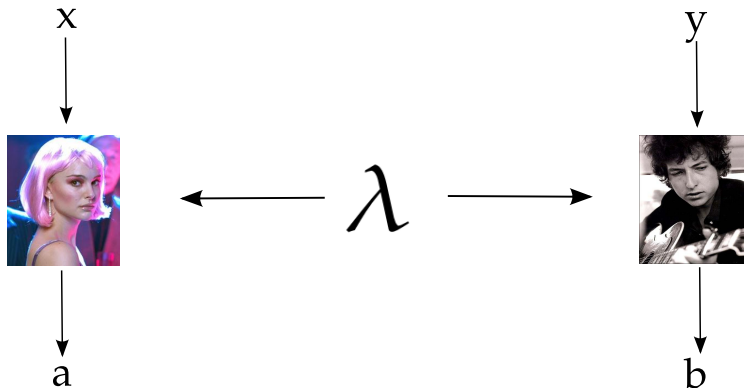
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Discussions

Locality



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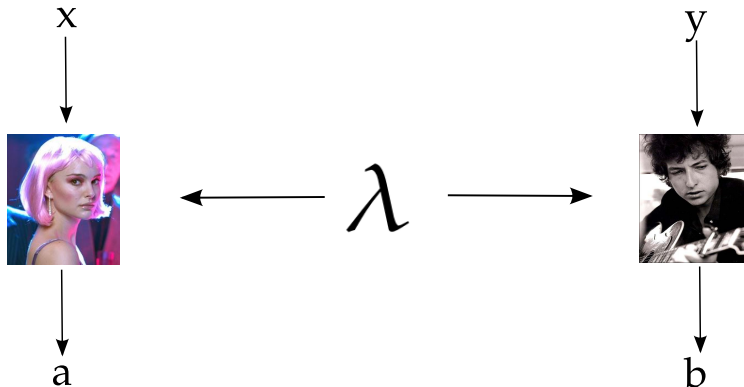
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Discussions

Locality



- ▶ Common cause:

$$p(ab|xy\lambda) = p(a|x\lambda)p(b|y\lambda)$$

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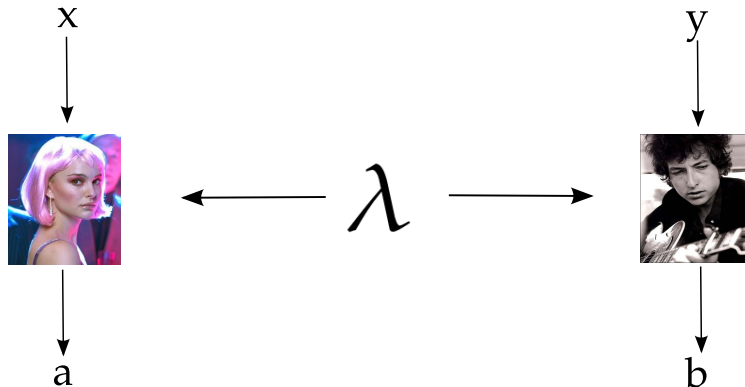
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Discussions

Locality



- ▶ Common cause:

$$p(ab|xy\lambda) = p(a|x\lambda)p(b|y\lambda)$$

- ▶ Locality:

$$p(ab|A_x B_y) = \int \pi(\lambda) p(a|x\lambda) p(b|y\lambda) d\lambda$$

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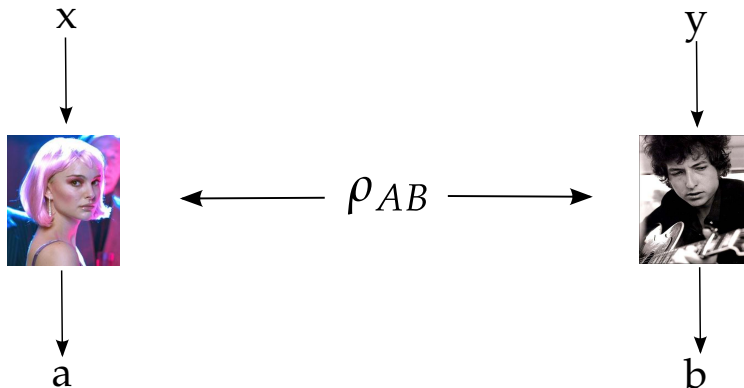
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Discussions

Quantum Experiments



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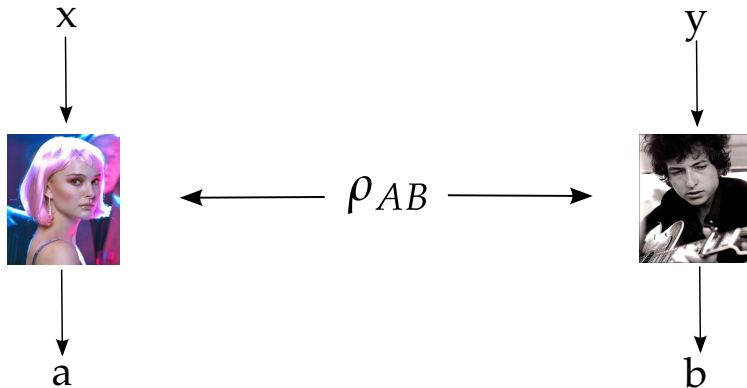
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Discussions

Quantum Experiments



- ▶ Quantum probabilities:

$$p(ab|xy) = \text{tr}(\rho_{AB} A_a^x \otimes B_b^y)$$

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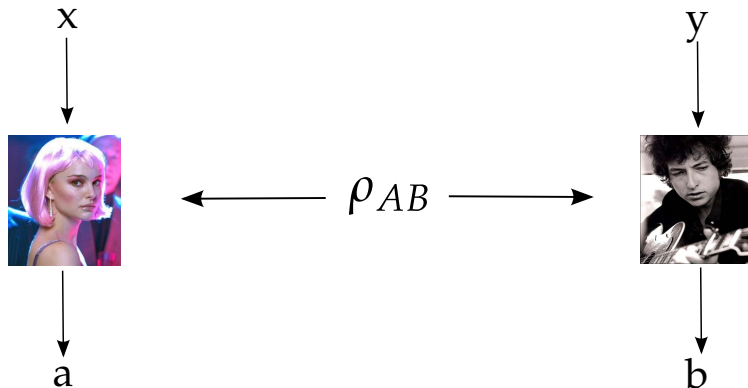
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Discussions

Quantum Experiments



- ▶ Quantum probabilities:

$$p(ab|xy) = \text{tr}(\rho_{AB} A_a^x \otimes B_b^y)$$

- ▶ “Quantum theory is nonlocal” (Bell 64)

$$\text{tr}(\rho_{AB} A_a^x \otimes B_b^y) \neq \int \pi(\lambda) p(a|x\lambda) p(b|y\lambda) d\lambda$$

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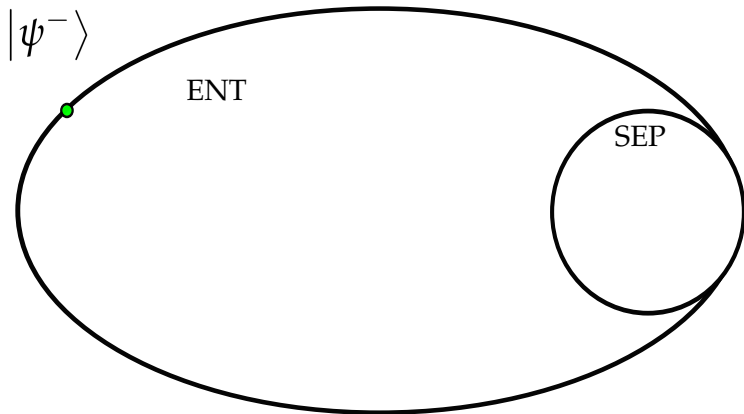
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Discussions

Separable/Entanglement



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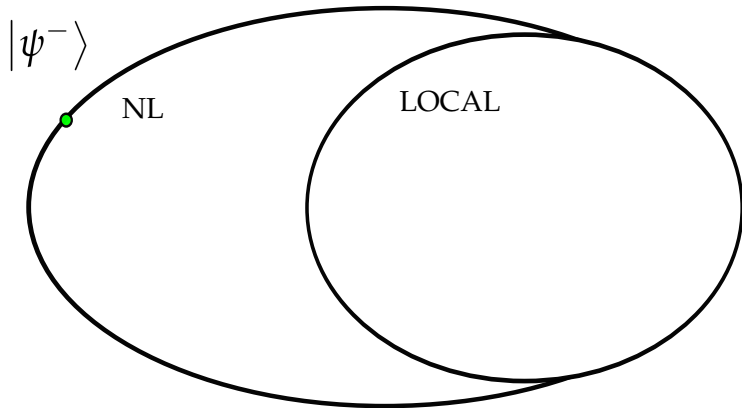
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Discussions

Local/Nonlocal



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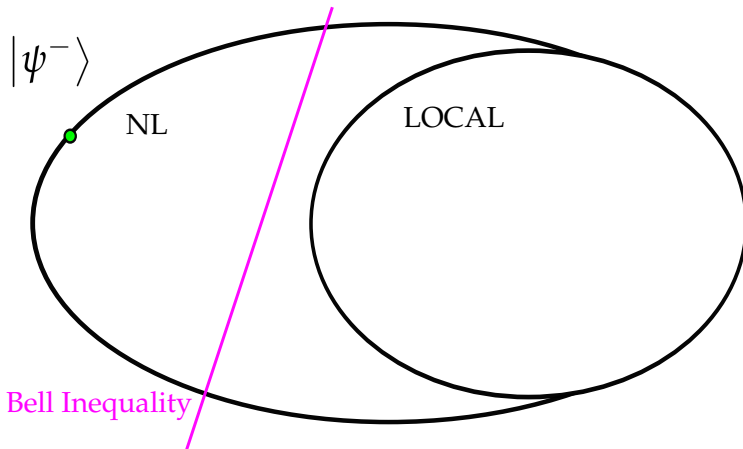
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Discussions

Bell inequalities



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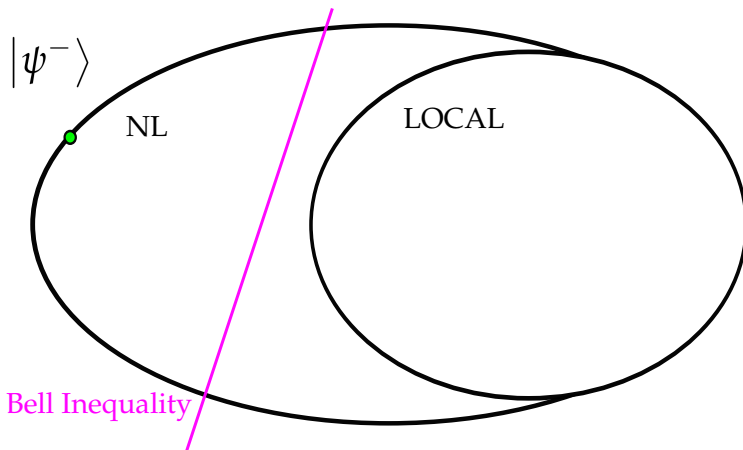
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Discussions

Bell inequalities



e.g.:

$$CHSH = A_0 \otimes B_0 + A_0 \otimes B_1 + A_1 \otimes B_0 - A_1 \otimes B_1$$

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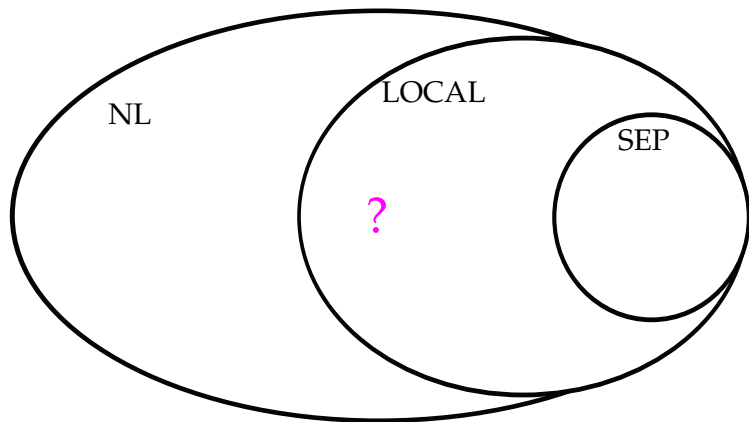
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Discussions

Separable $\stackrel{?}{=}$ Local



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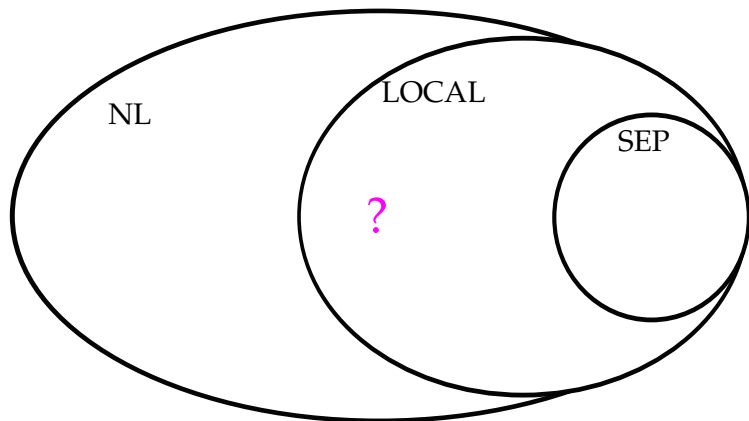
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Discussions

Separable $\stackrel{?}{=}$ Local



$$\rho_{AB} \neq \int \pi(\lambda) \rho_A^\lambda \otimes \rho_B^\lambda d\lambda$$

$$p(ab|xy) \neq \int \pi(\lambda) p(a|x\lambda) p(b|y\lambda) d\lambda$$

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Discussions

Entanglement $\overset{?}{\iff}$ Nonlocality

- ▶ Do all entangled states violate a Bell Inequality?

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POVMs...

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Discussions

Entanglement $\overset{?}{\iff}$ Nonlocality

- ▶ Do all entangled states violate a Bell Inequality?
- ▶ Pure states: Yes (Gisin 91, Popescu and Rohrlich 92)

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Discussions

Entanglement $\overset{?}{\iff}$ Nonlocality

- ▶ Do all entangled states violate a Bell Inequality?
- ▶ Pure states: Yes (Gisin 91, Popescu and Rohrlich 92)
- ▶ Mixed states: ???

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Discussions

Local simulation of quantum states

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Discussions

PHYSICAL REVIEW A

VOLUME 40, NUMBER 8

OCTOBER 15, 1989

Quantum states with Einstein-Podolsky-Rosen correlations admitting a hidden-variable model

Reinhard F. Werner*

Dublin Institute for Advanced Studies, 10 Burlington Road, Dublin 4, Ireland

(Received 1 May 1989)

Local simulation of quantum states



$$\rho_{AB}$$

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Local simulation of quantum states

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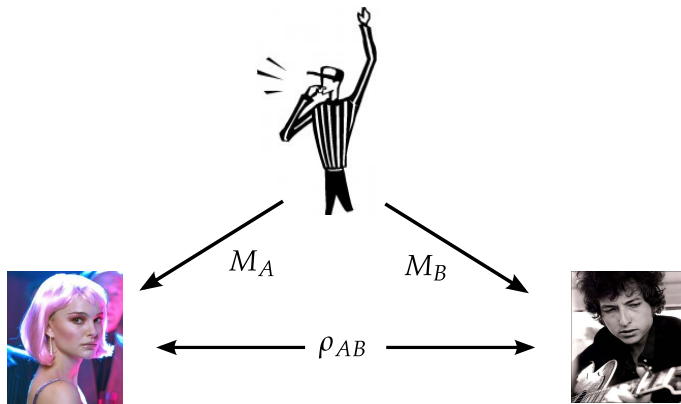
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$\longleftrightarrow \rho_{AB} \longrightarrow$



Local simulation of quantum states



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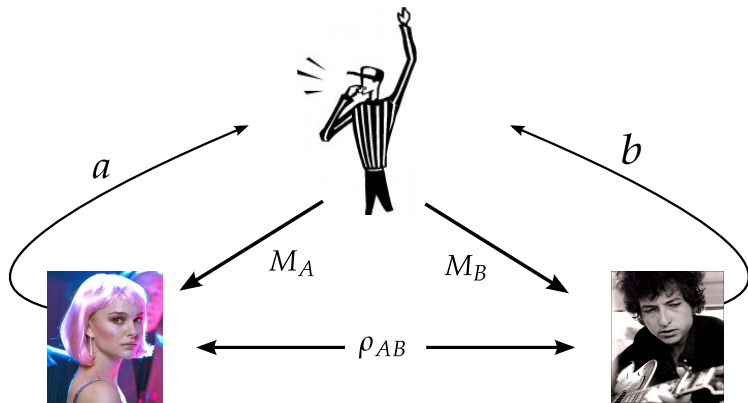
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Discussions

Local simulation of quantum states



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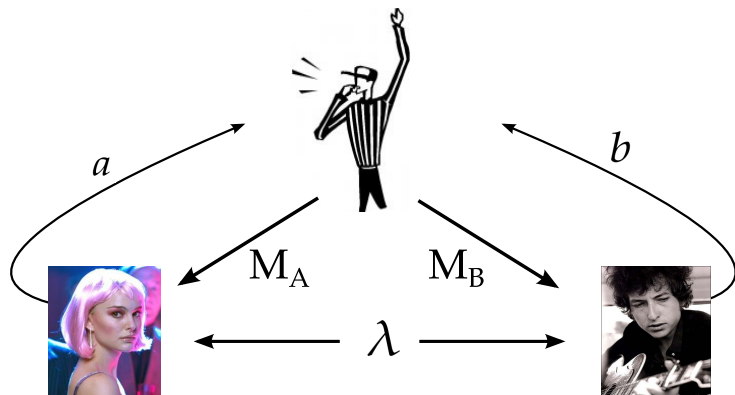
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Discussions

Local simulation of quantum states



$$p(ab|xy) = \text{tr}(\rho_{AB} M_A^a \otimes M_B^b)$$

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Local simulation of quantum states



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Local simulation of quantum states

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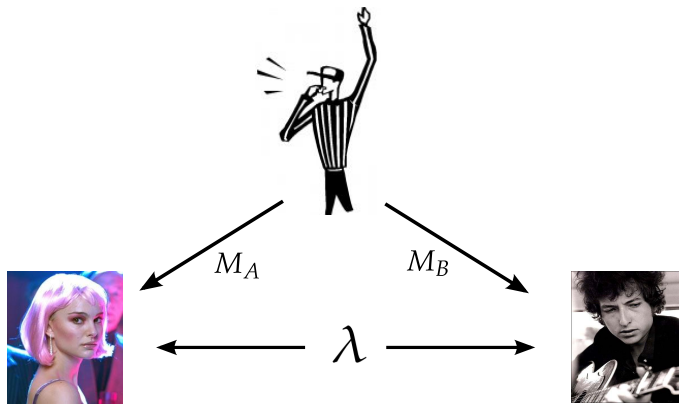
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Discussions



Local simulation of quantum states



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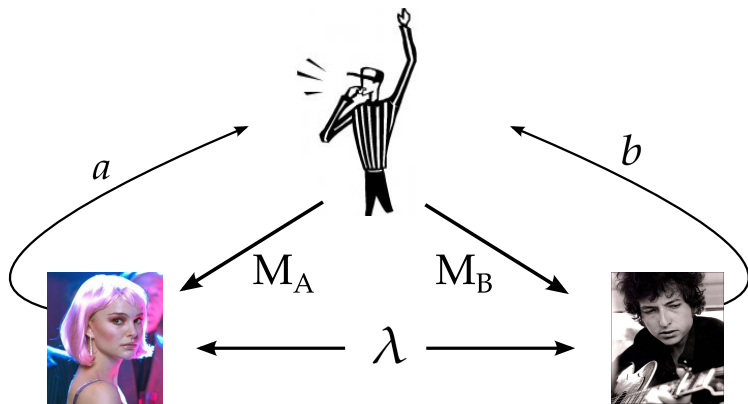
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Discussions

Local simulation of quantum states



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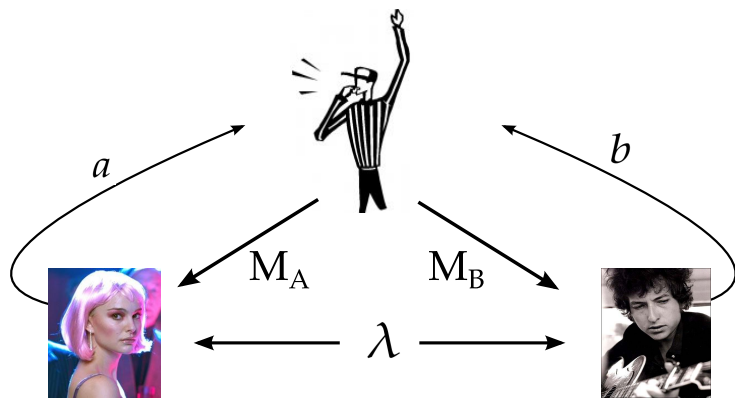
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Discussions

Local simulation of quantum states



$$\int \pi(\lambda) p_A(a|\lambda) p_B(b|\lambda) d\lambda = \text{tr}(\rho_{AB} M_A^a \otimes M_B^b)$$

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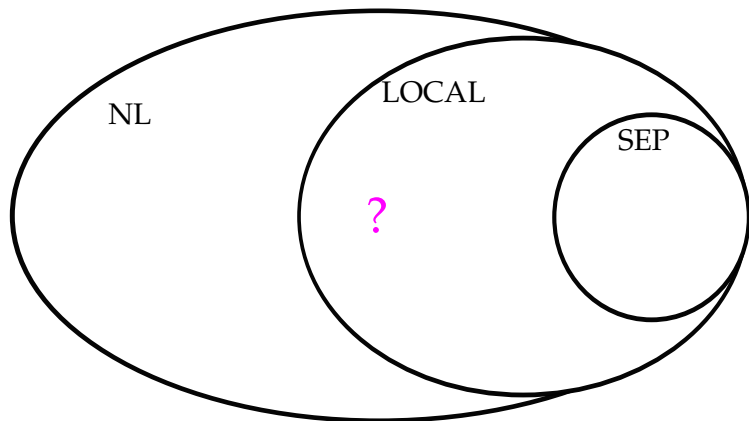
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Local simulation of quantum states



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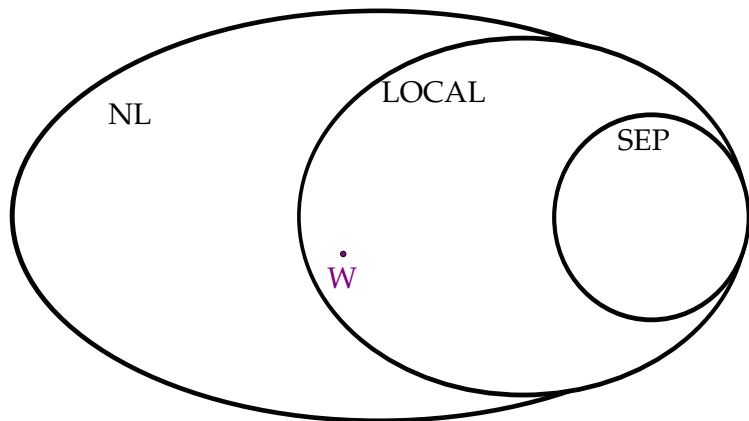
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Local simulation of quantum states



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POVMs...

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Discussions

End of story?

- ▶ Entanglement \neq Locality!

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POVMs...

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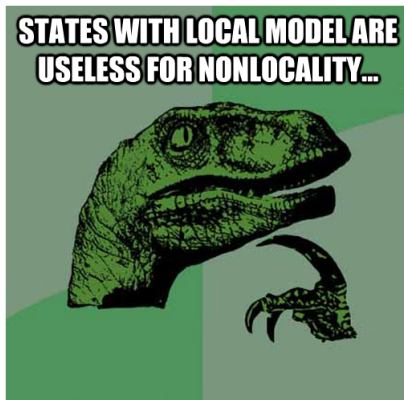
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Discussions

End of story?

- ▶ Entanglement \neq Locality!
- ▶ Well...



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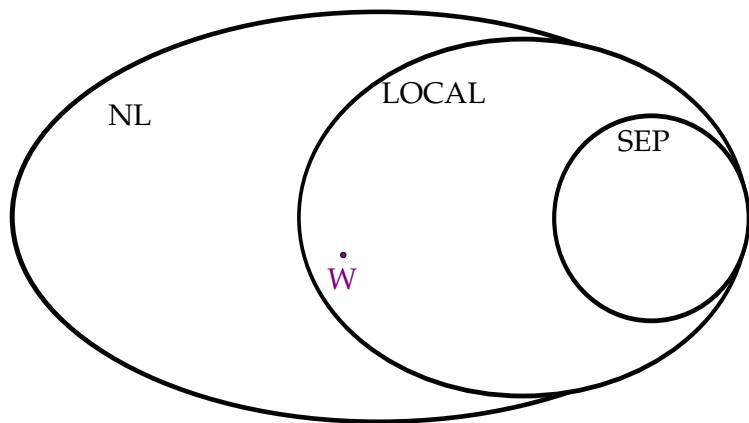
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Local simulation of quantum states



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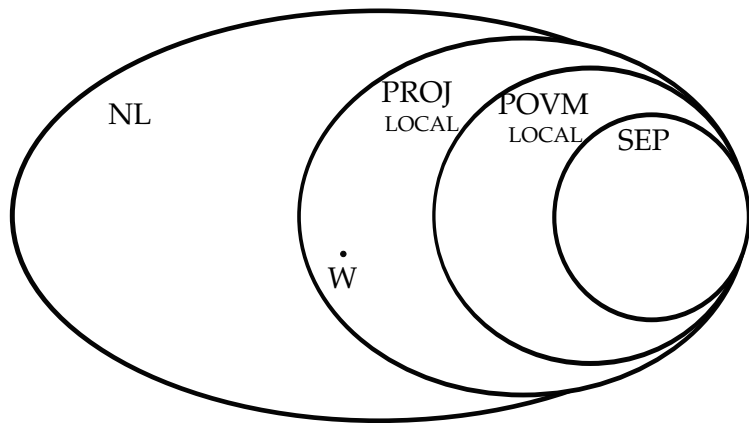
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Discussions

And if we consider POVMs?



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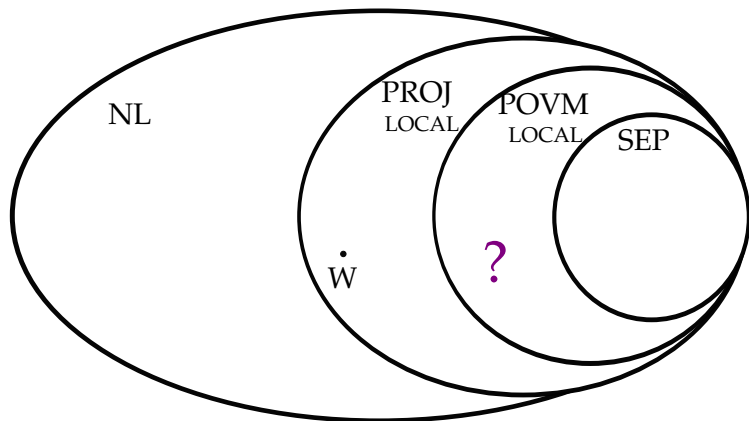
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And if we consider POVMs?



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Discussions

(Barrett, 02)

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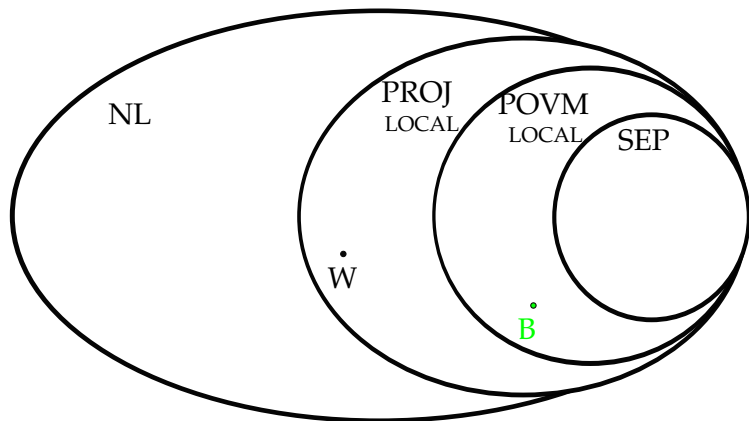
POVMs...

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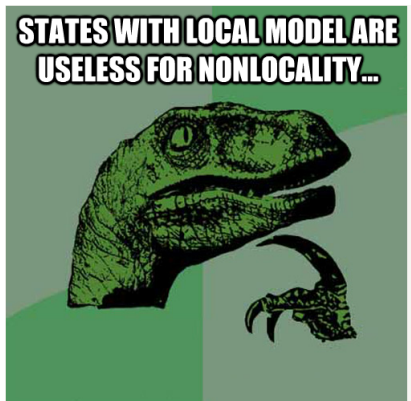
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Discussions



POVM locality



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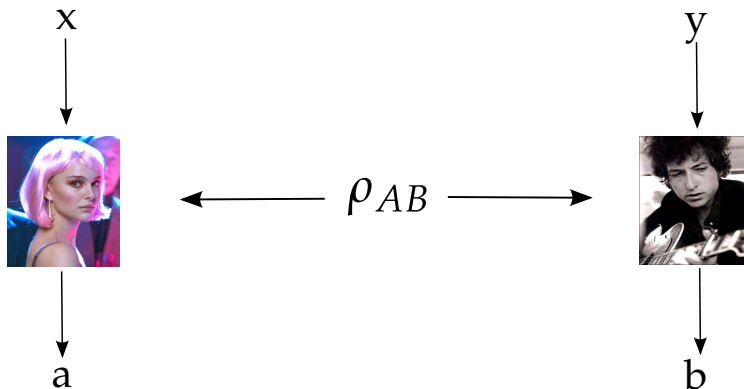
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Discussions

Single measurement



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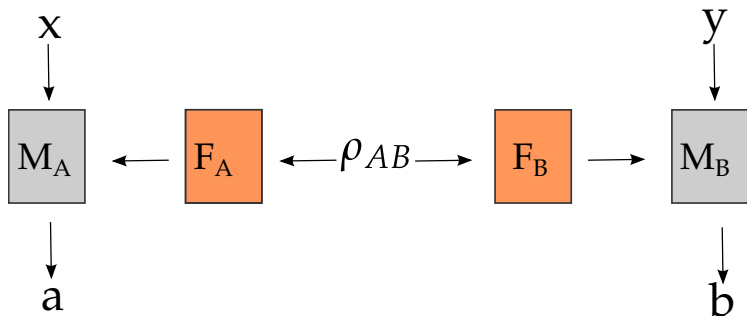
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Discussions

Sequential measurements



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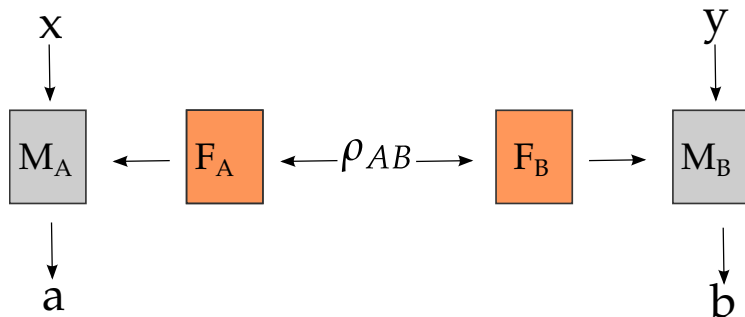
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Discussions

No additional loophole



► Step 1 - Filtering

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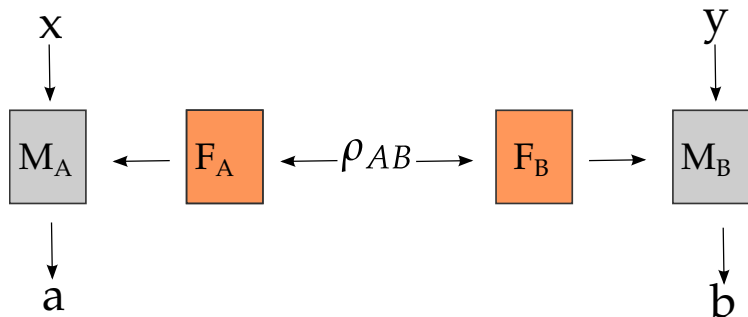
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Discussions

No additional loophole



- ▶ Step 1 - Filtering
- ▶ Step 2 - Usual Bell test

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POVMs...

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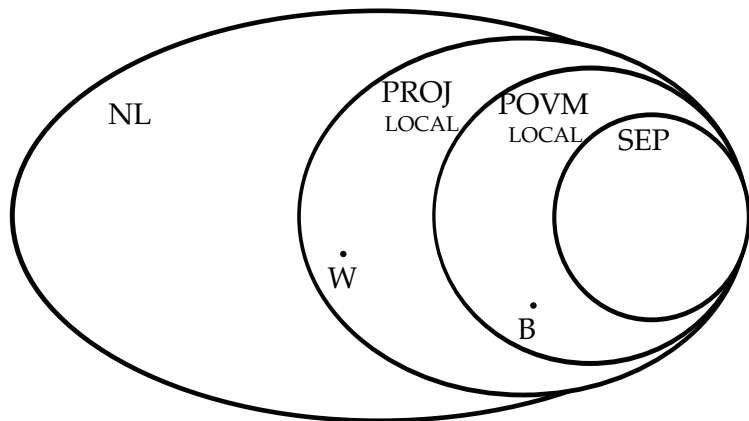
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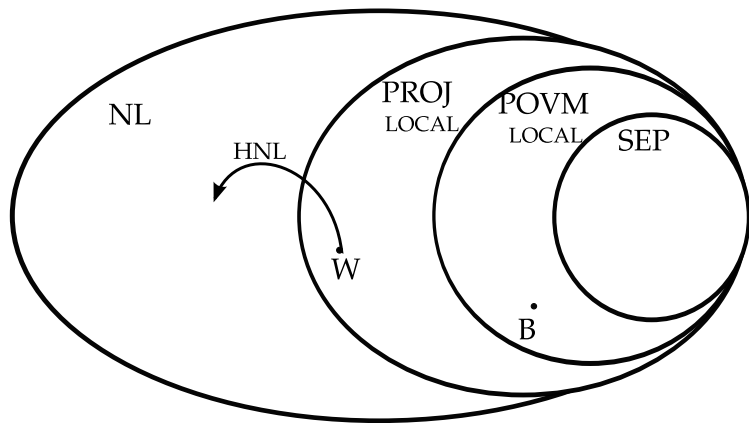
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Nonlocality

Discussions

(Popescu, 95)



Genuine Hidden
Quantum
Nonlocality

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Entanglement Vs.
Nonlocality

Local Entangled
States

POVMs...

Hidden
Nonlocality

Genuine Hidden
Nonlocality

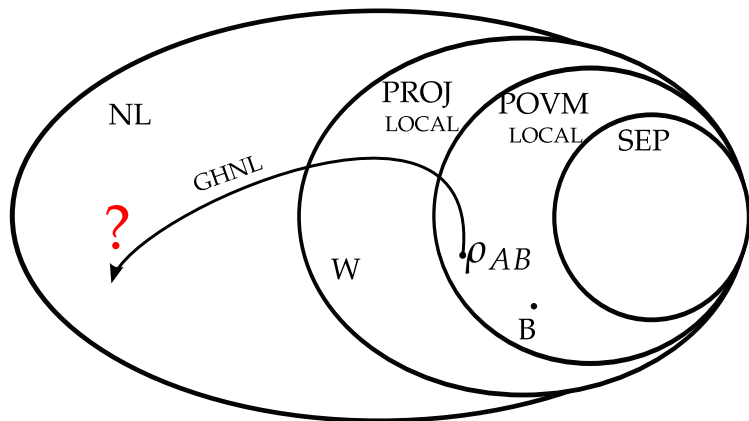
Maximal Genuine
Hidden
Nonlocality

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Genuine Hidden Nonlocality?

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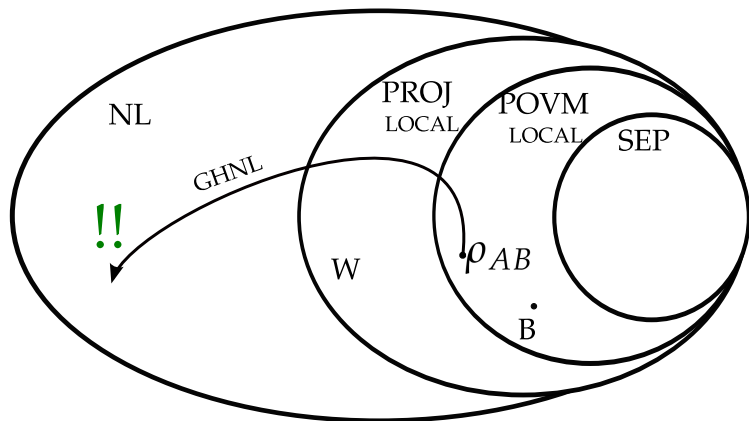
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Examples of Genuine Hidden Nonlocality

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- ▶ Local model for projective measurements

$$\rho_L = \frac{1}{2} \left(|\psi^-\rangle\langle\psi^-| + |0\rangle\langle 0| \otimes \frac{I}{2} \right)$$

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- ▶ Local model for projective measurements

$$\rho_L = \frac{1}{2} \left(|\psi^-\rangle\langle\psi^-| + |0\rangle\langle 0| \otimes \frac{I}{2} \right)$$

- ▶ If ρ_{AB} is local for projective measurements,

$$\rho'_{AB} = \frac{1}{4} (\rho_{AB} + \rho_A \otimes \sigma_B + \sigma_A \otimes \rho_B + \sigma_A \otimes \sigma_B)$$

is local for all POVMs

ρ_A, ρ_B are the partial trace of ρ_{AB} and σ_A, σ_B are arbitrary qubit states

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Examples of Genuine Hidden Nonlocality

- ▶ Local model for projective measurements

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ρ_A, ρ_B are the partial trace of ρ_{AB} and σ_A, σ_B are arbitrary qubit states

- ▶ Genuine hidden nonlocality with qubits!

Examples of Genuine Hidden Nonlocality

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$$\rho_G = \frac{1}{8}|\psi^-\rangle\langle\psi^-| + \frac{3}{8}\left(|0\rangle\langle 0| \otimes \frac{I}{2}\right) + \frac{1}{8}\left(\frac{I}{2} \otimes |0\rangle\langle 0|\right) + \frac{3}{8}|00\rangle\langle 00|$$

Examples of Genuine Hidden Nonlocality

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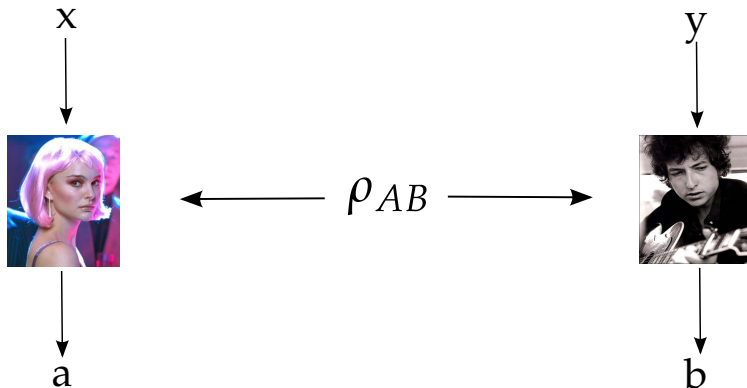


$$\rho_G = \frac{1}{8}|\psi^-\rangle\langle\psi^-| + \frac{3}{8}\left(|0\rangle\langle 0| \otimes \frac{I}{2}\right) + \frac{1}{8}\left(\frac{I}{2} \otimes |0\rangle\langle 0|\right) + \frac{3}{8}|00\rangle\langle 00|$$



$$F_A = F_B = \varepsilon|0\rangle\langle 0| + |1\rangle\langle 1|$$

Examples of Genuine Hidden Nonlocality



ρ_{AB} is useless

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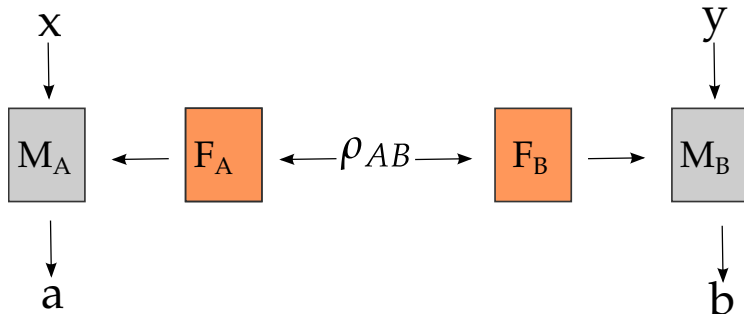
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Genuine hidden nonlocality



CHSH violation!!

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**Maximal Genuine
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Discussions

- ▶ Hidden nonlocality with qudits

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Discussions

- ▶ Hidden nonlocality with qudits
- ▶ $\rho_{AB} \mapsto |\psi^-\rangle$ after filtering (2 qutrits)

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Discussions

- ▶ Hidden nonlocality with qudits
- ▶ $\rho_{AB} \mapsto |\psi^-\rangle$ after filtering (2 qutrits)
- ▶ Maximal quantum nonlocality! ($CHSH = 2\sqrt{2}$)

Summary of the results

- ▶ Local model for “asymmetric states”

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Summary of the results

- ▶ Local model for “asymmetric states”
- ▶ Some completely (POVM) local states have hidden nonlocality

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Discussions

Summary of the results

- ▶ Local model for “asymmetric states”
- ▶ Some completely (POVM) local states have hidden nonlocality
- ▶ This phenomenon can be maximal

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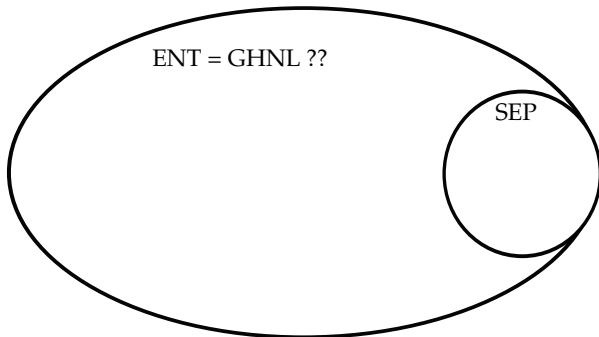
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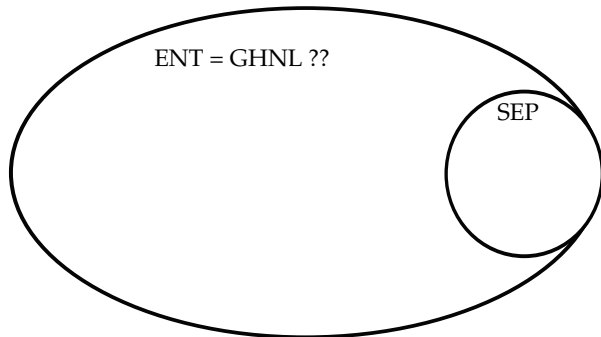
Related questions

- ▶ Hidden nonlocal \iff entangled ?



Related questions

- ▶ Hidden nonlocal \iff entangled ?



- ▶ Quantum local states?
Full locality condition?

A few more steps

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Activation in networks (Daniel Cavalcanti, Friday 12:00)

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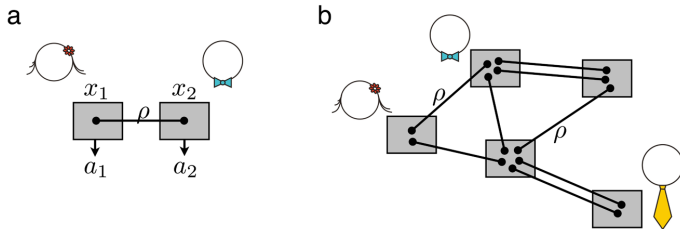
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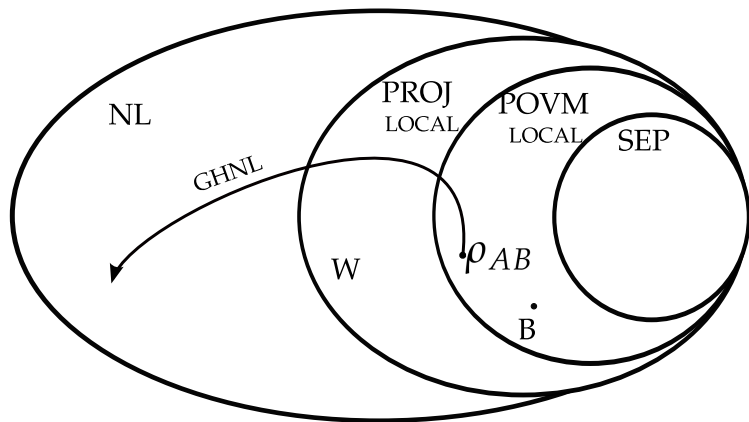
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Thank you!



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