NONLOCALITY IN QUANTUM PHYSICS AND BEYOND

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UNIVERSITÉ DE GENÈVE
University of BRISTOL

Grenoble Nov 2012

1. WHAT IS NONLOCALITY

2. ENTANGLEMENT VS NONLOCALITY

3. SUPER-ACTIVATION OF NONLOCALITY

4. EPR STEERING

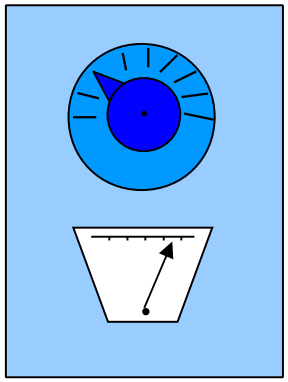
5. DEVICE-INDEPENDENT QIP

6. EXPERIMENTS

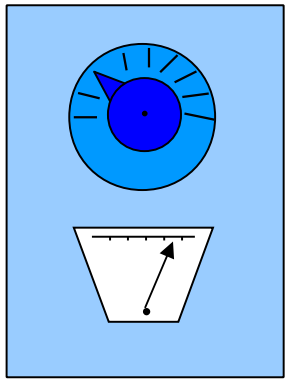
7. NONLOCALITY BEYOND QM

CORRELATIONS

ALICE (Geneva)



BOB (Grenoble)



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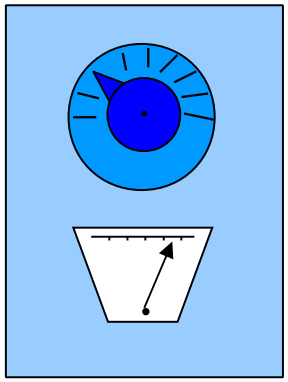

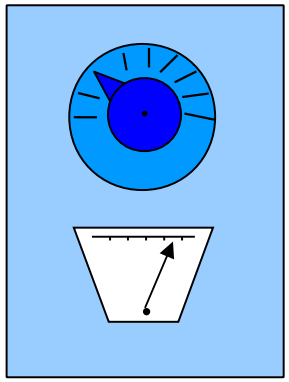

CORRELATED BEHAVIOUR

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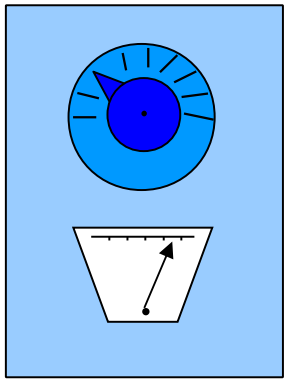

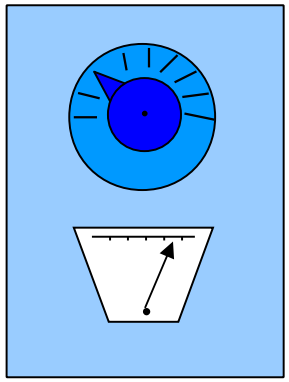

CORRELATED BEHAVIOUR

HOW DOES IT WORK?

CLASSICAL CORRELATIONS

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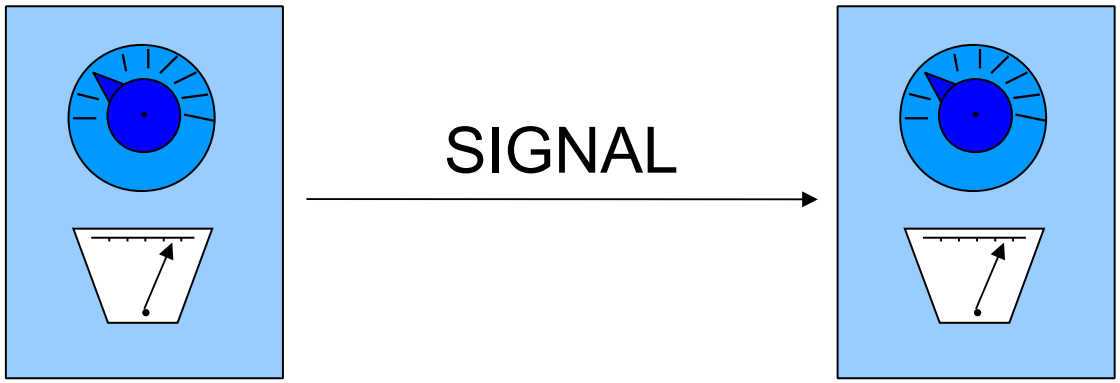

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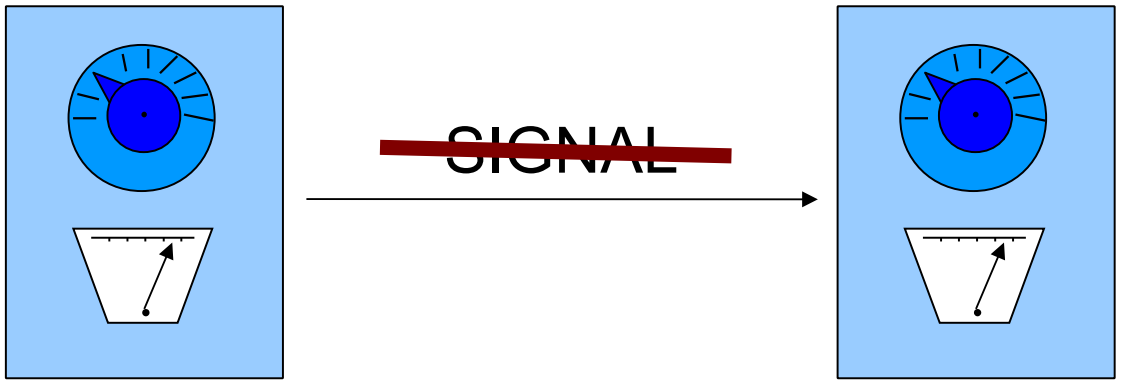

SPACE-LIKE SEPARATION → **NO SIGNAL**

CLASSICAL CORRELATIONS

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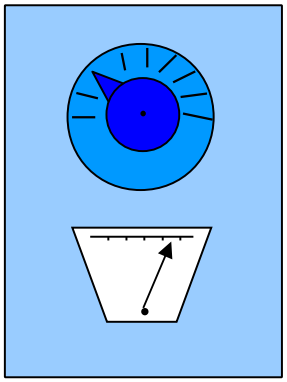

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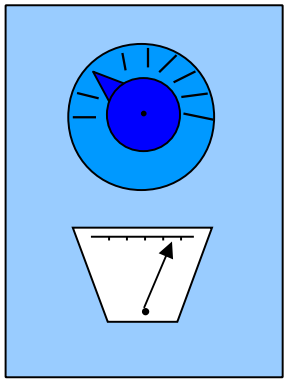

DEVICES HAVE A COMMON **STRATEGY**

PRE-ESTABLISHED CORRELATIONS

CLASSICAL CORRELATIONS

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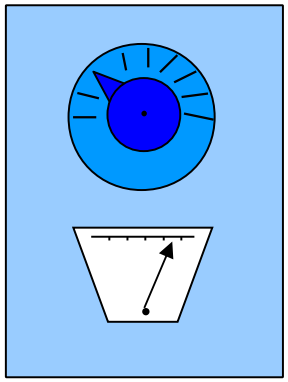

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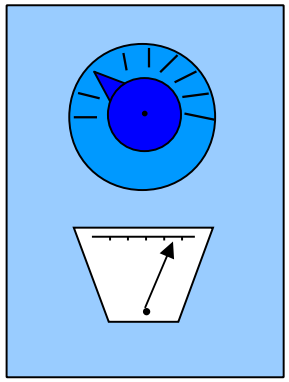

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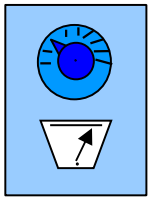
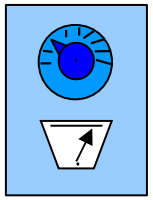
PRE-ESTABLISHED CORRELATIONS

CAN THIS BE TESTED?

GAME – BELL INEQUALITY

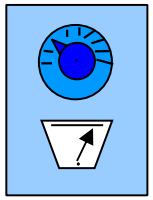
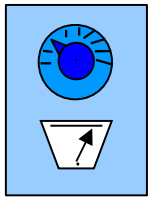
ALICE  BOB 

TWO QUESTIONS X_0 or X_1 (Alice) Y_0 or Y_1 (Bob)

TWO ANSWERS +1 or -1

Bell 64,Clauser-Horne-Shimony-Holt 69

GAME – BELL INEQUALITY

ALICE  BOB 

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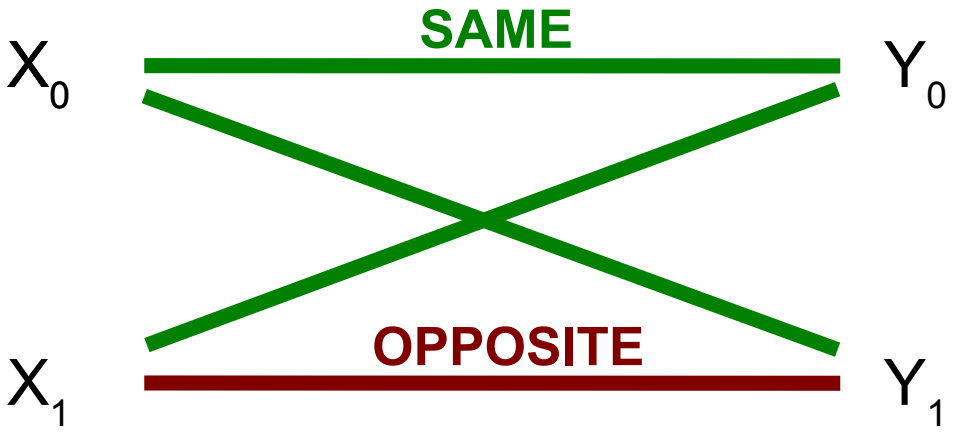

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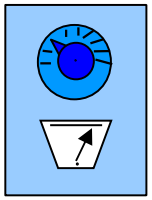
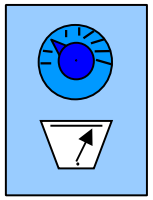
ALICE  BOB 

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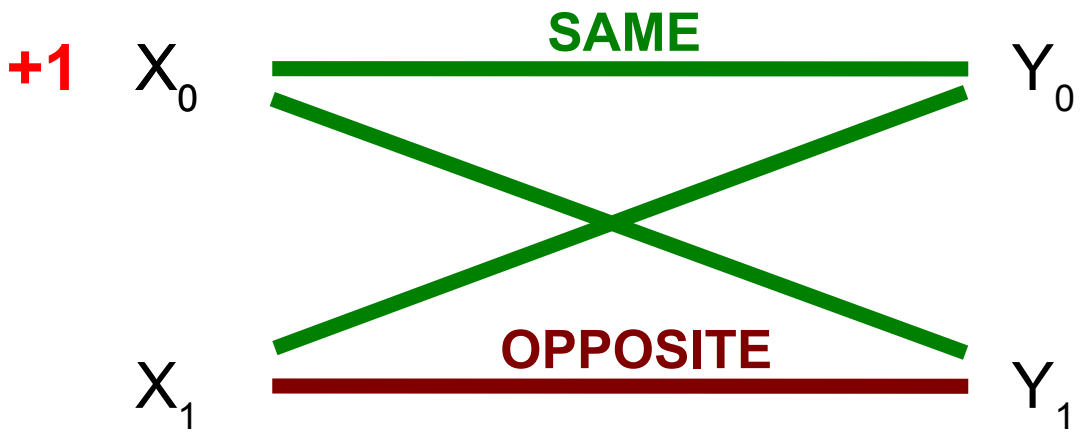

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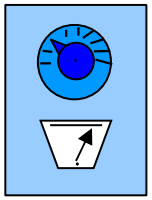
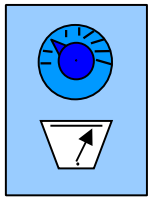
ALICE  BOB 

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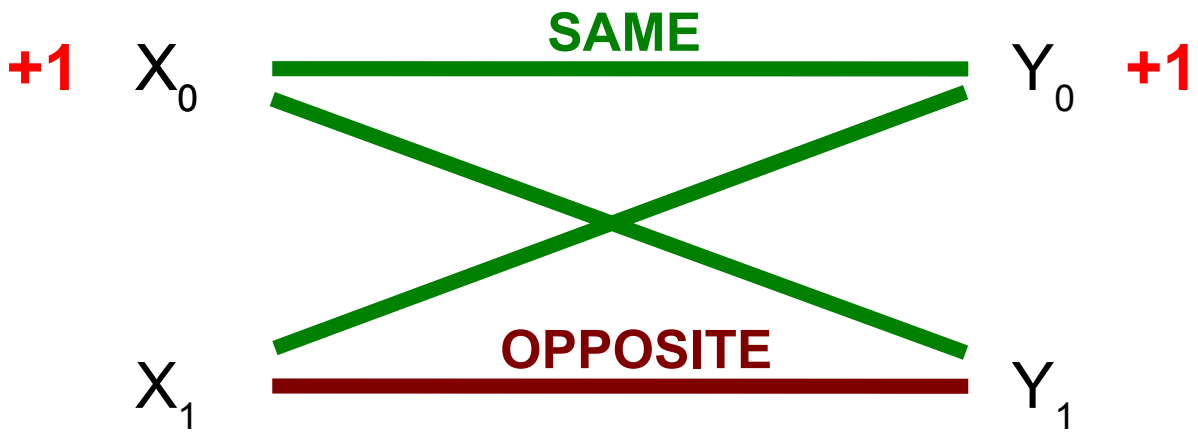

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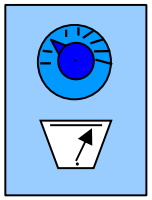
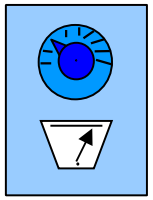
ALICE  BOB 

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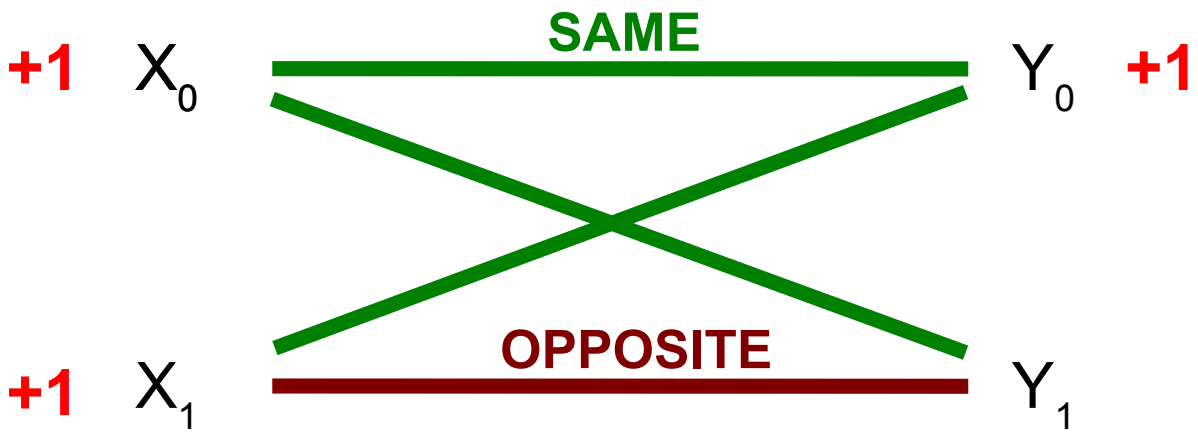

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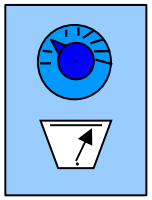
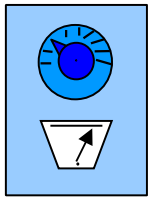
ALICE  BOB 

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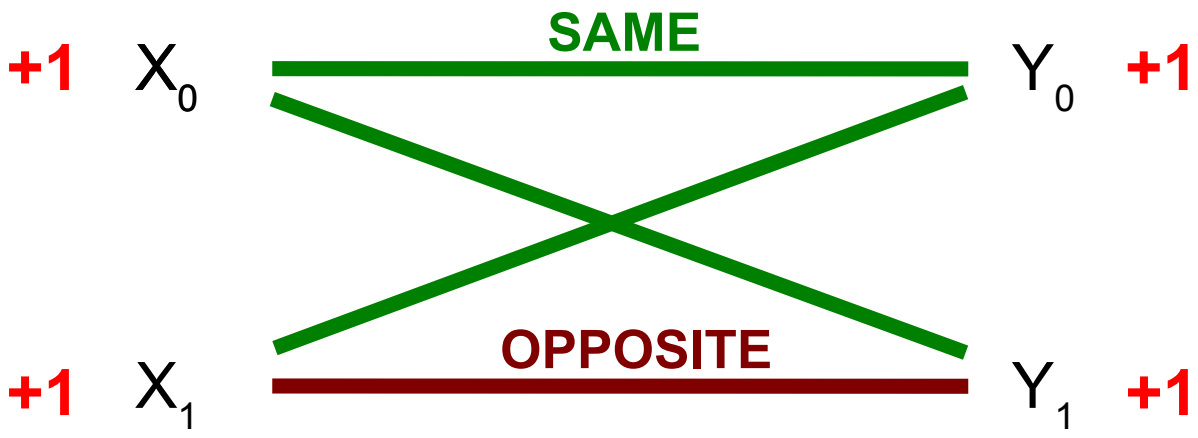

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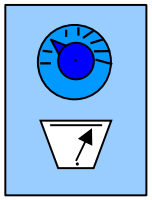
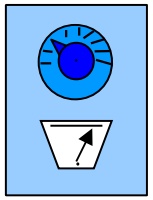
ALICE  BOB 

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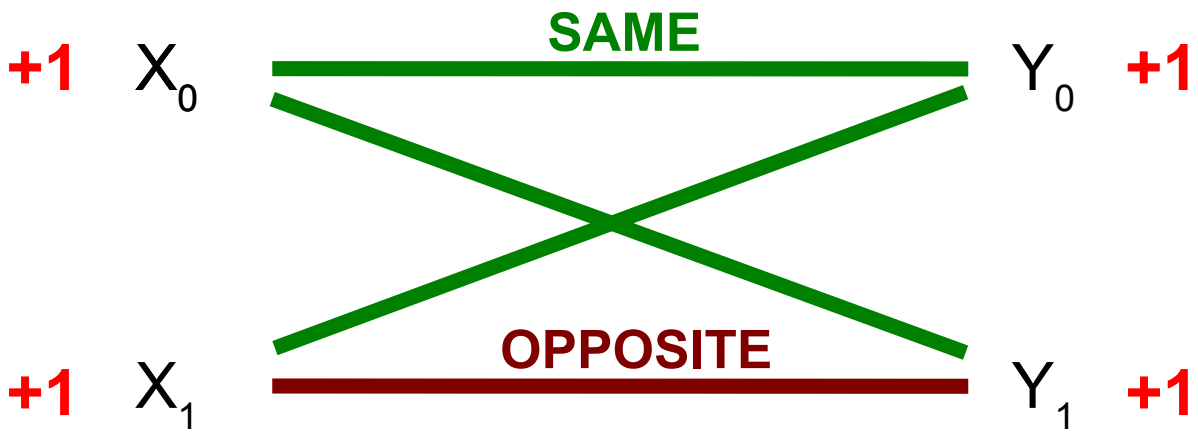

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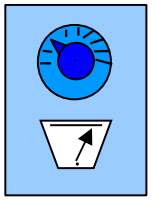
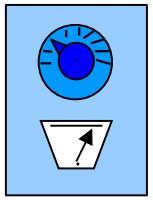
ALICE  BOB 

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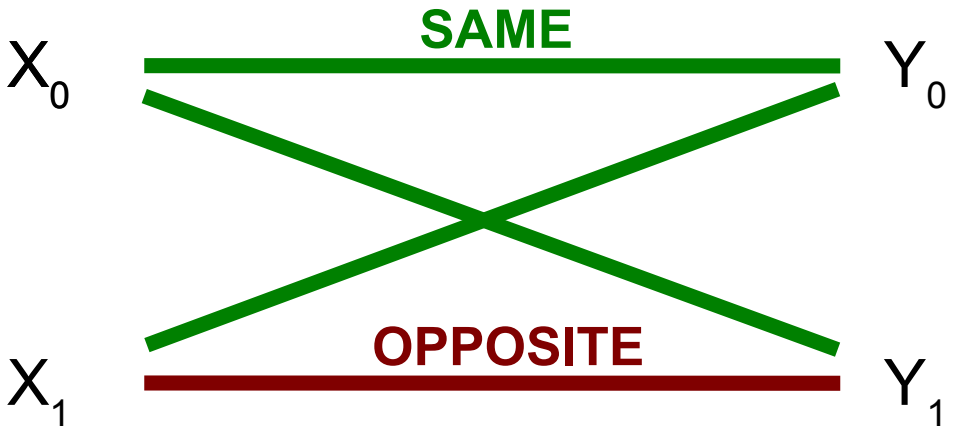
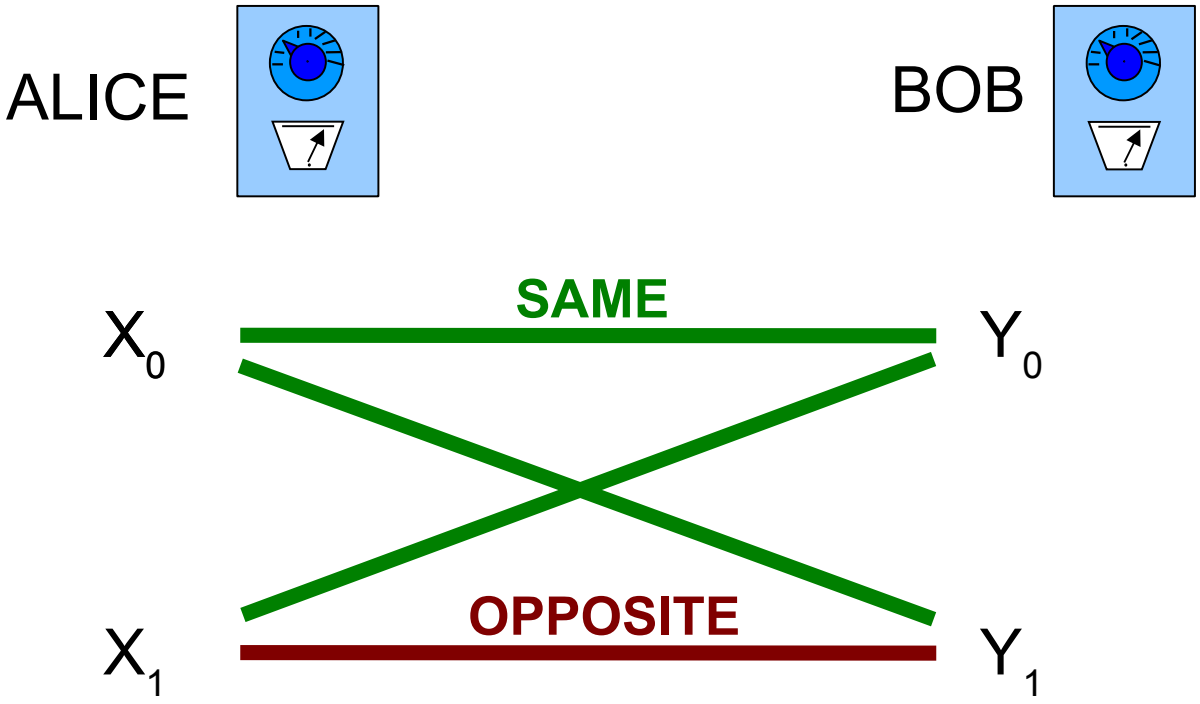


Score $\leq$ ¾ FOR ANY CLASSICAL STRATEGY

Bell 64,Clauser-Horne-Shimony-Holt 69

CHSH BELL INEQUALITY



Correlation function: $E(X_0,Y_1) = P(X_0=Y_1) - P(X_0\neq Y_1)$

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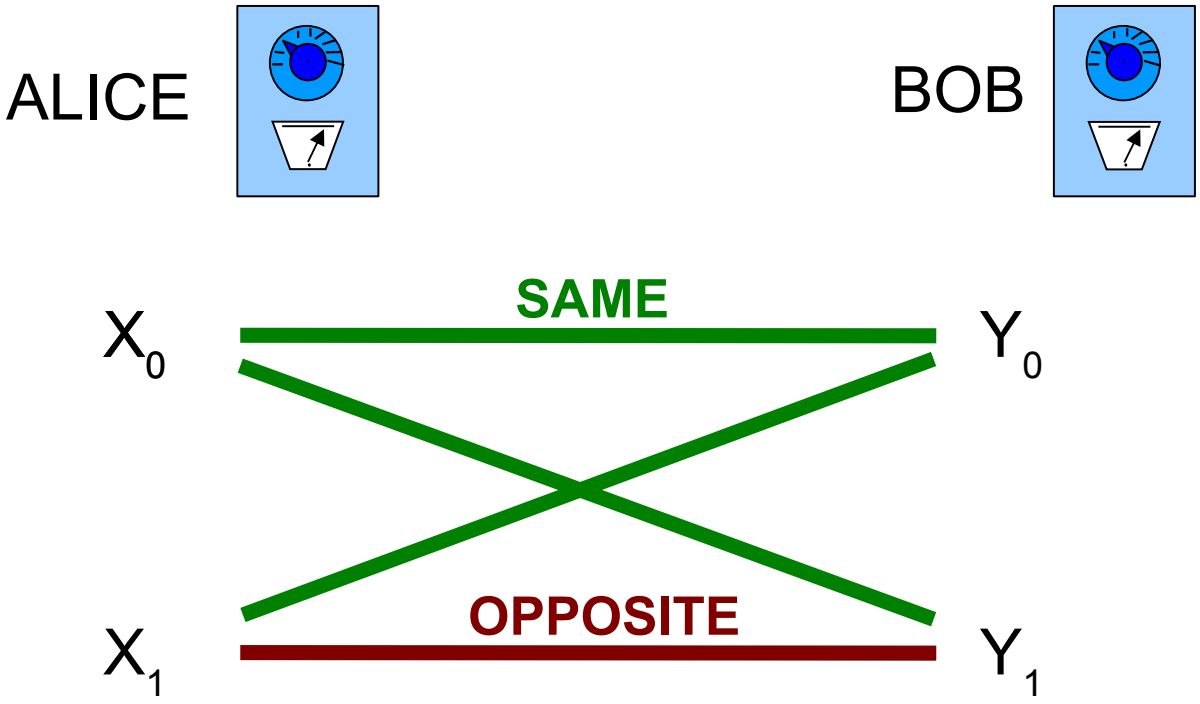

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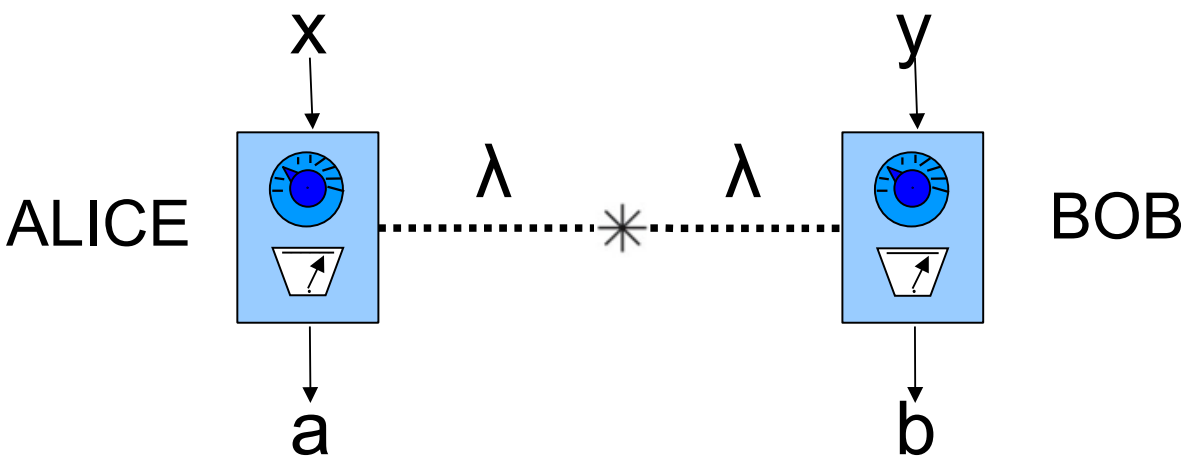
$$CHSH = E(X_0,Y_0) + E(X_0,Y_1) + E(X_1,Y_0) - E(X_1,Y_1) \leq 2$$

Clauser-Horne-Shimony-Holt 69

LOCAL HIDDEN VARIABLES



LOCALITY: $P(a,b|x,y) = \int d\lambda\, P(a|x,\lambda)\, P(b|y,\lambda)$

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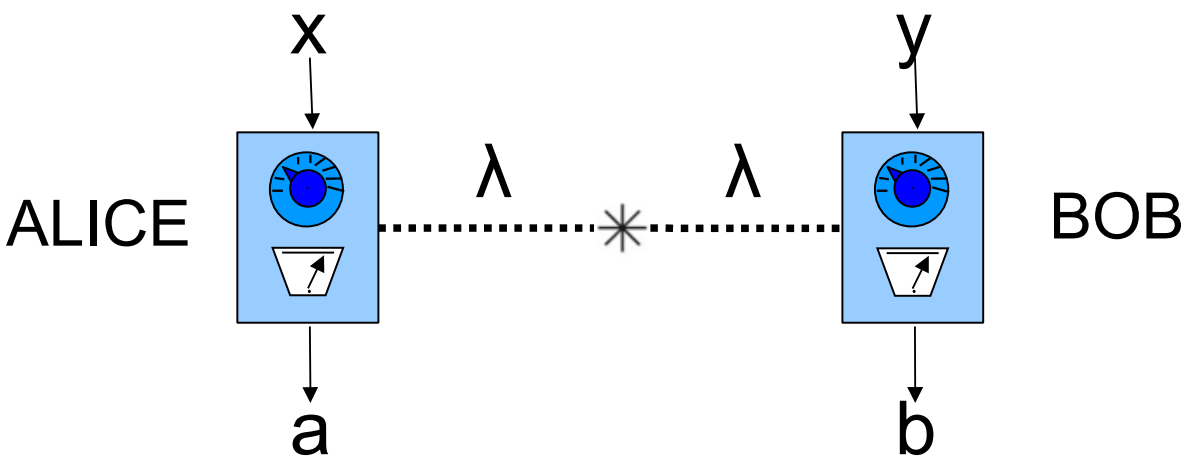

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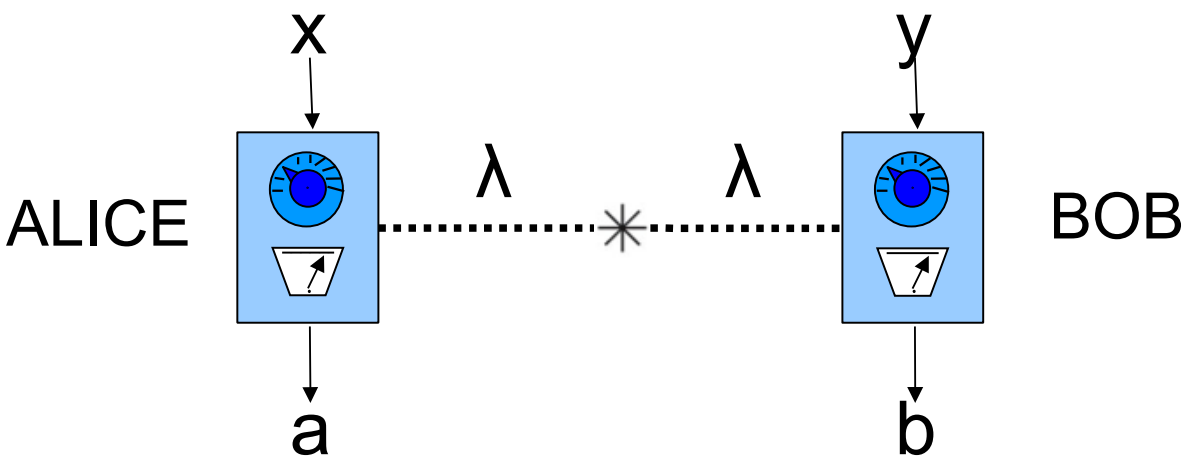

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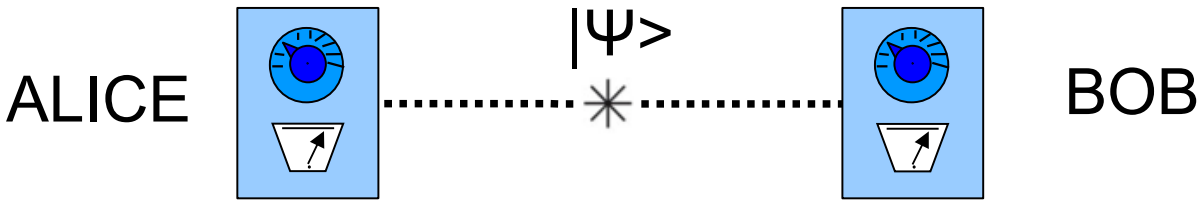
VIOLATION OF BELL INEQUALITY ⟹ **NONLOCALITY**

USING QUANTUM RESOURCES



QUANTUM STATEGY

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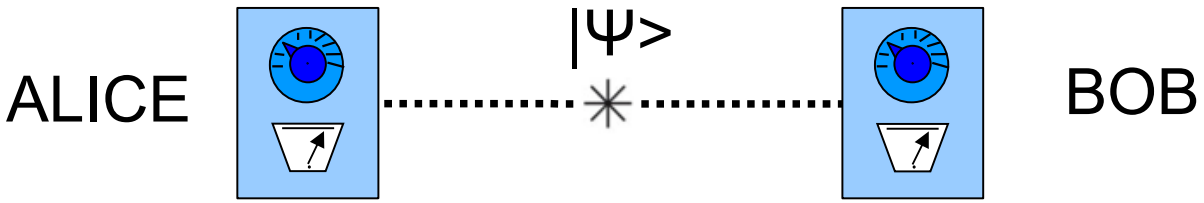
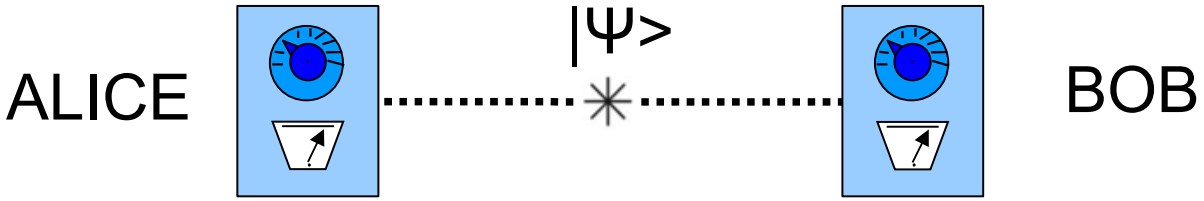


QUANTUM STATEGY

1. ENTANGLED STATE $|\Psi\rangle = |0,1\rangle - |1,0\rangle$

2. LOCAL MEAS $X_0 = \vec{z}$ $X_1 = \vec{x}$ and $Y_0 = -\vec{x}\vec{z}$ $Y_1 = \vec{x}\vec{z}$

USING QUANTUM RESOURCES



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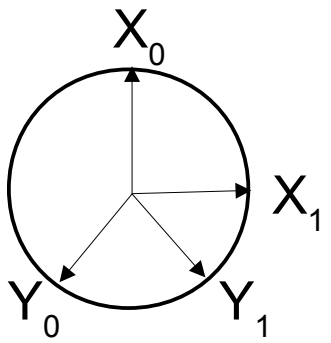
$$E(\vec{a},\vec{b}) = \langle\Psi|\, \vec{a}\ \vec{b}\, |\Psi\rangle = -\,\vec{a}\ \vec{b}$$



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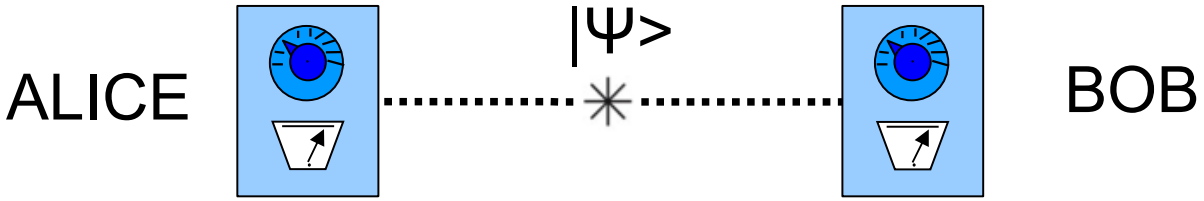

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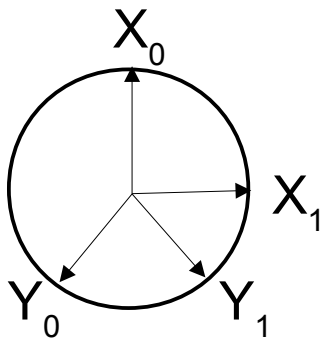

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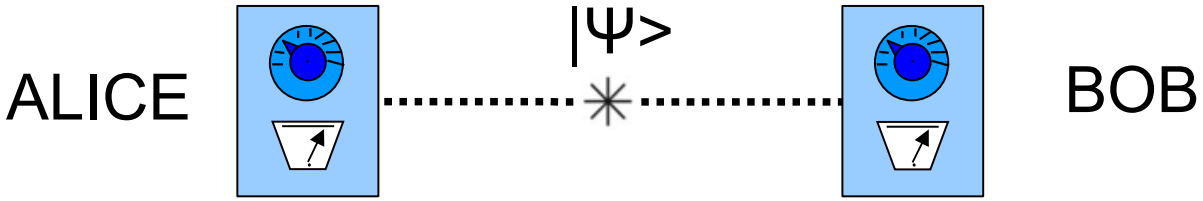

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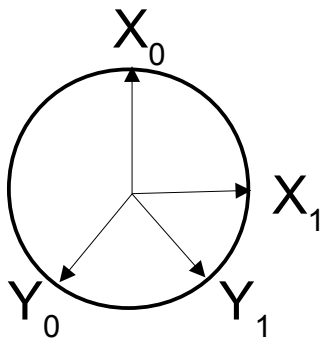

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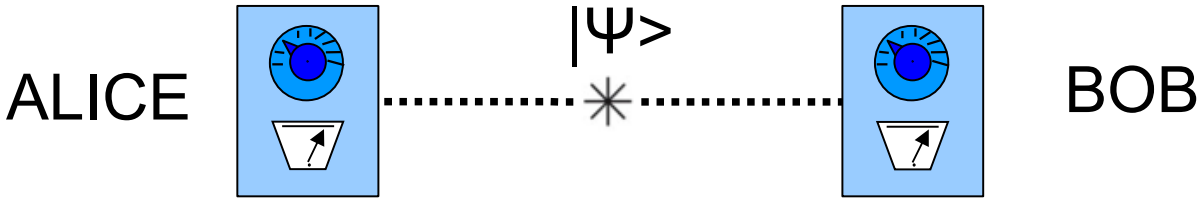
USING QUANTUM RESOURCES



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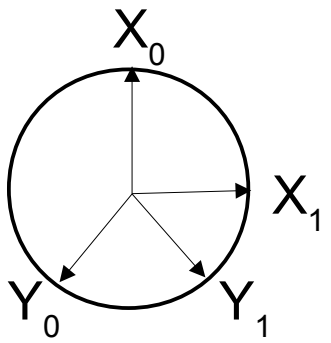

$$CHSH = E(X_0,Y_0) + E(X_0,Y_1) + E(X_1,Y_0) - E(X_1,Y_1)$$

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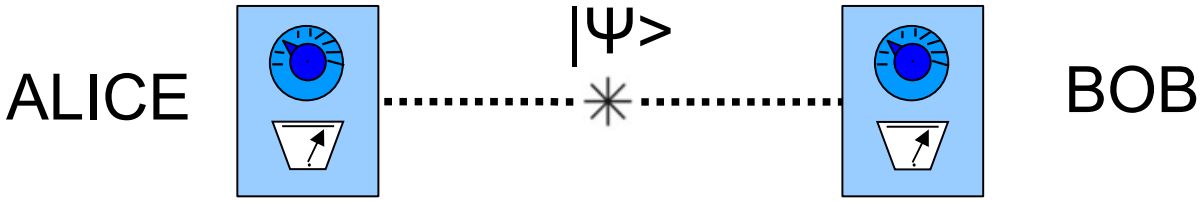

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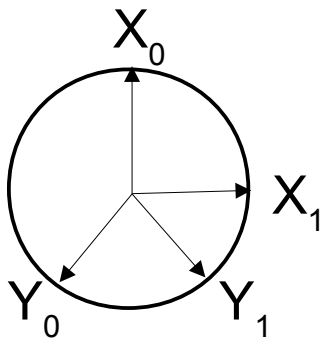

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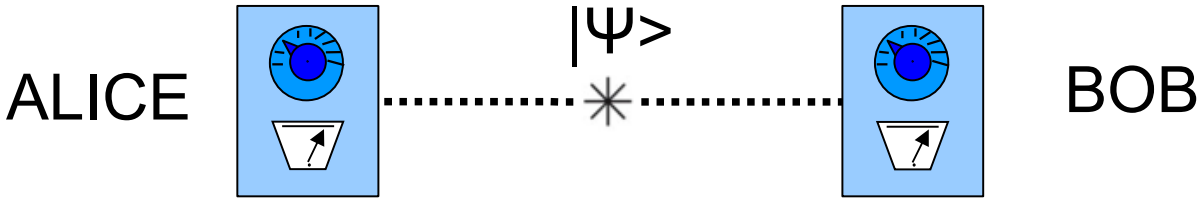

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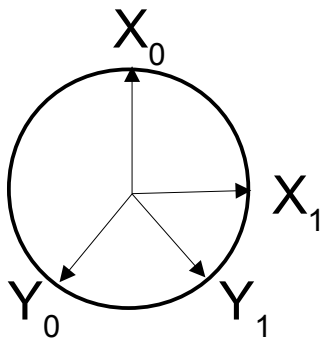

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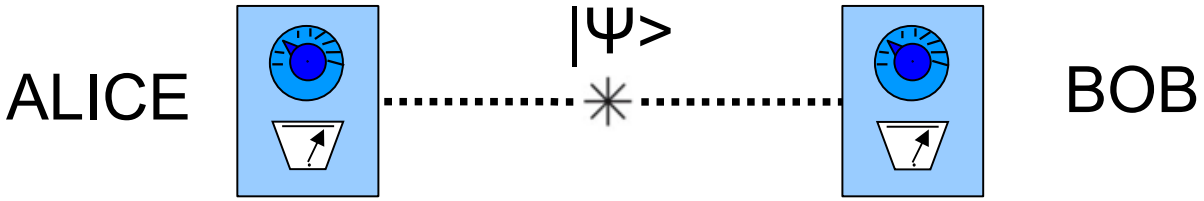

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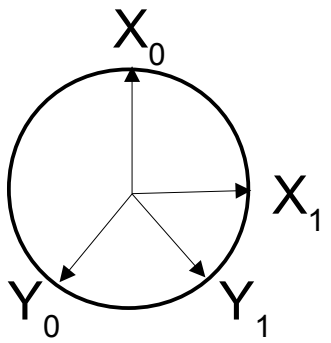

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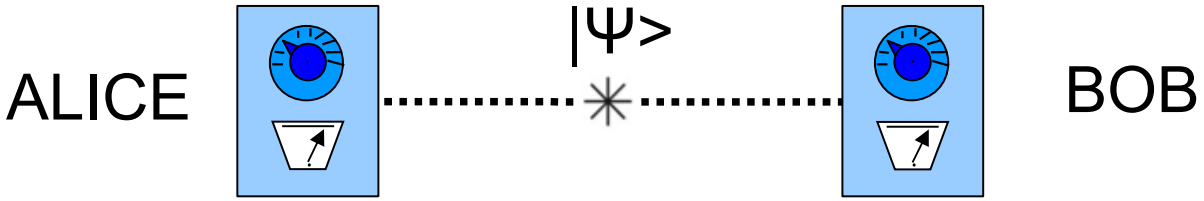

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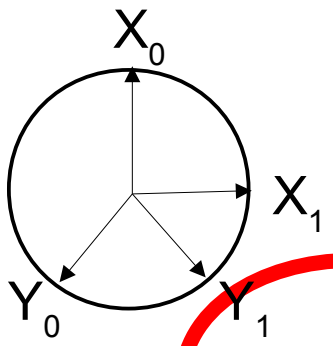

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QUANTUM NONLOCALITY

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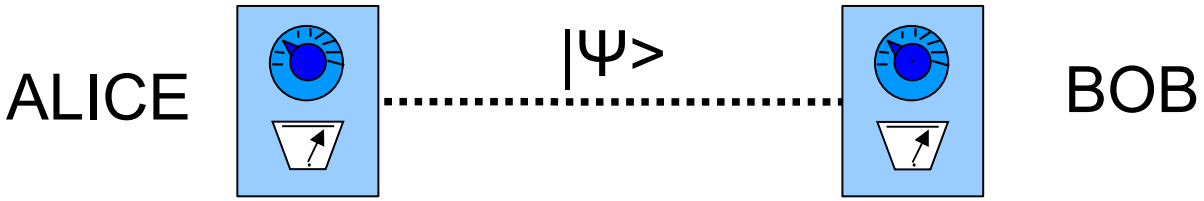


QUANTUM CORRELATIONS ARE **NONLOCAL**

STRONGER THAN **ANY** LOCAL CORRELATIONS

ANY THEORY SATISFYING LOCALITY
IS INCOMPATIBLE WITH QUANTUM MECHANICS

ENTANGLEMENT VS NONLOCALITY

CONCEPTUAL DIFFERENCE

ENTANGLEMENT

CONCEPT OF
QUANTUM MECHANICS

NONLOCALITY

BASED ON STATISTICS

MODEL INDEPENDENT

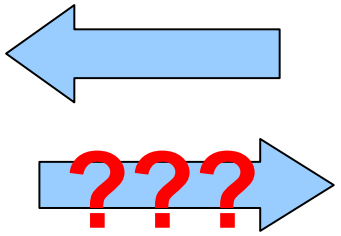
HOW TO COMPARE THEM?

ENTANGLEMENT = Q NONLOCALITY ?

ENTANGLEMENT  **QUANTUM NONLOCALITY**

ENTANGLEMENT = Q NONLOCALITY ?

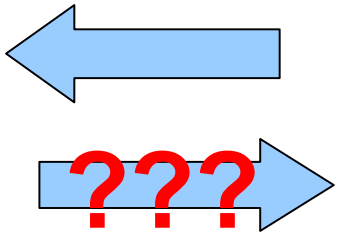
ENTANGLEMENT



QUANTUM NONLOCALITY

ENTANGLEMENT = Q NONLOCALITY ?

ENTANGLEMENT



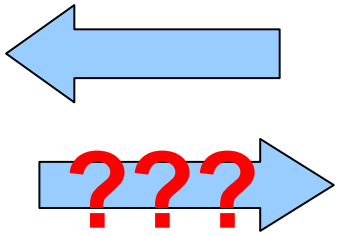
QUANTUM NONLOCALITY

Q STATE

Q STATE + MEAS.

ENTANGLEMENT = Q NONLOCALITY ?

ENTANGLEMENT



QUANTUM NONLOCALITY

Q STATE

Q STATE + MEAS.

DO ALL ENTANGLED STATE VIOLATE A BELL INEQUALITY?

PURE STATES

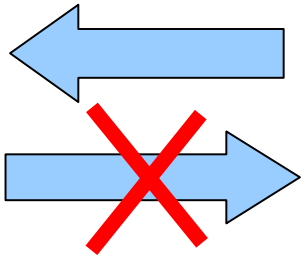
ENTANGLEMENT  **QUANTUM NONLOCALITY**

GISIN 1991 2 PARTIES

POPESCU-ROHRLICH 1992 N PARTIES

MIXED STATES

ENTANGLEMENT



QUANTUM NONLOCALITY

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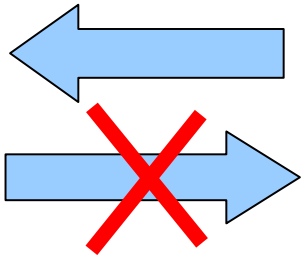


QUANTUM NONLOCALITY

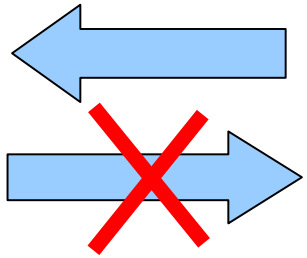
THERE EXIST MIXED ENTANGLED STATE WHICH ARE LOCAL

PROJECTIVE MEAS. — POVMs

WERNER 1989 — BARRETT 2002

MIXED STATES

ENTANGLEMENT



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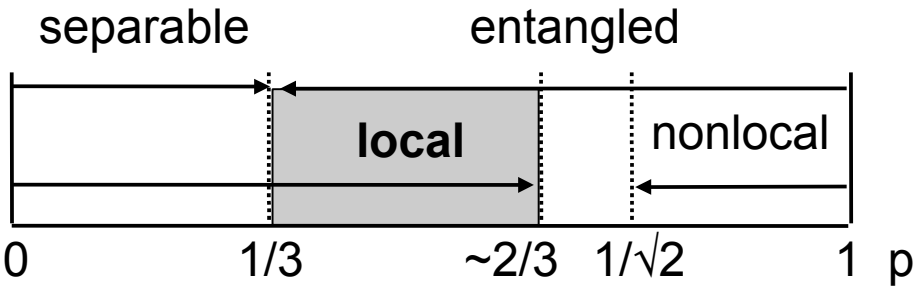

MIXED STATES

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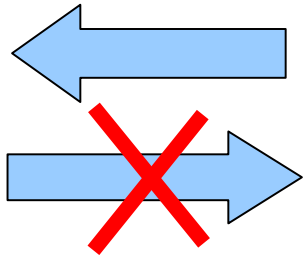

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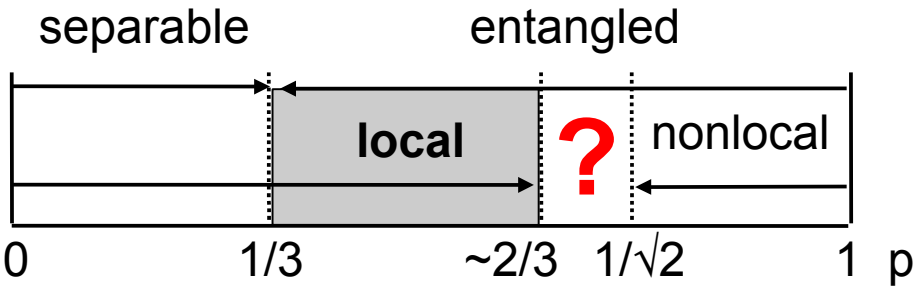
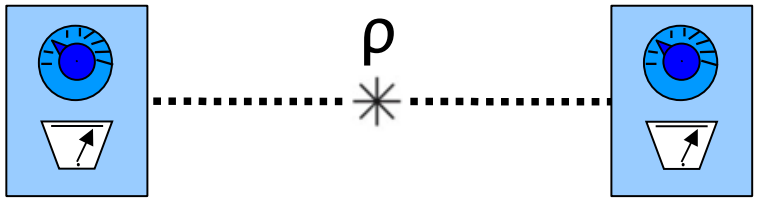
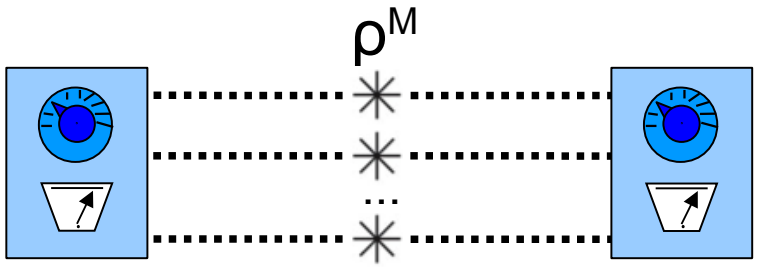


MORE GENERAL SCENARIO

ONE COPY



MULTIPLE COPIES CAN BE PROCESSED JOINTLY



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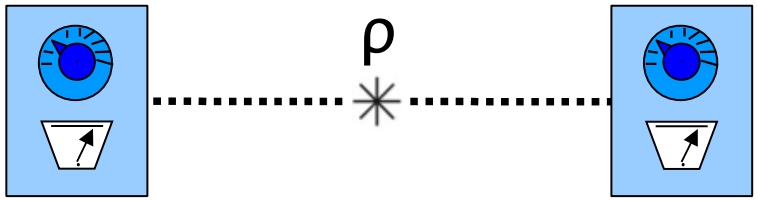

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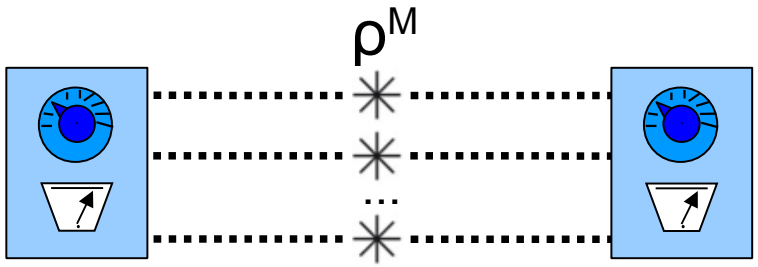
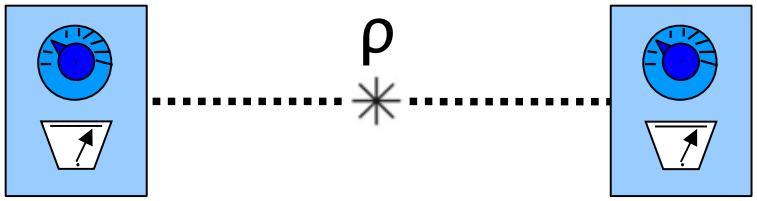


IS NONLOCALITY ADDITIVE ?

SUPER-ACTIVATION OF NONLOCALITY

LOCAL



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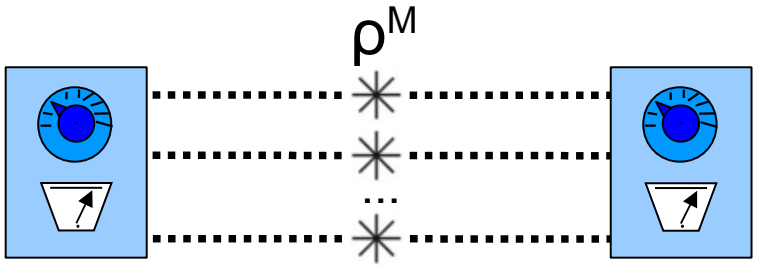
NONLOCAL

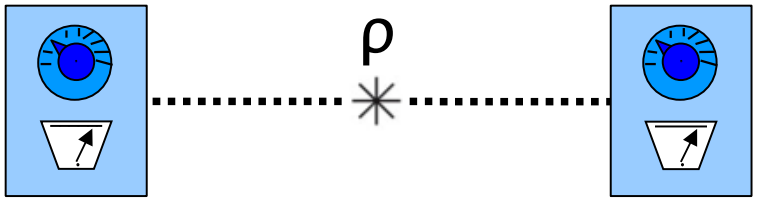


0 + … + 0 > 0

PALAZUELOS PRL 2012

SUPER-ACTIVATION OF NONLOCALITY

LOCAL



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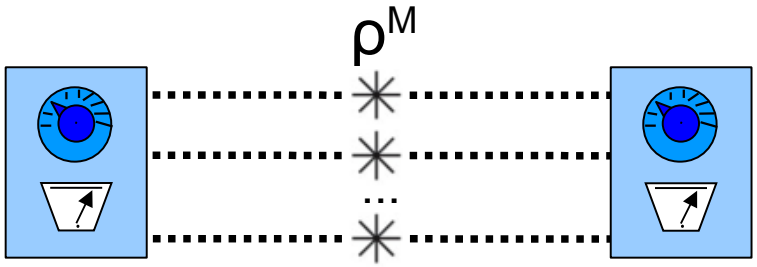

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NONLOCALITY IS **SUPER-ADDITIVE**

ENTANGLED MEASUREMENTS

PALAZUELOS PRL 2012

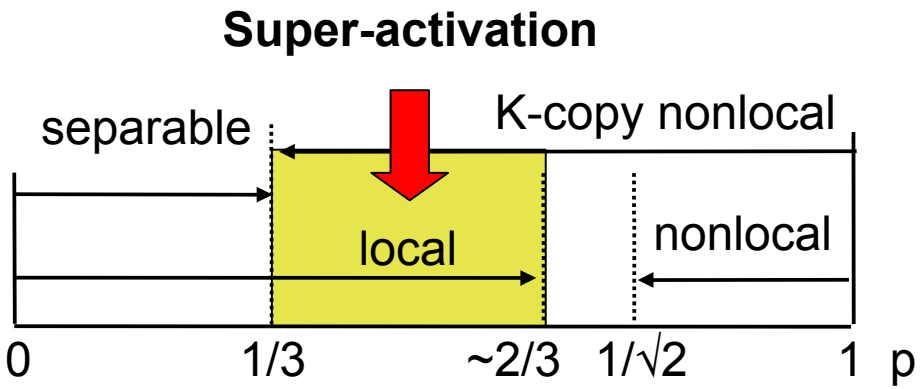
NONLOCALITY AND TELEPORTATION

USEFUL FOR TELEPORTATION → **NONLOCAL**

LARGE CLASS OF ENTANGLED STATES

Werner states

$\rho = p\,|\Psi\rangle\langle\Psi| + (1-p)\,I/4$



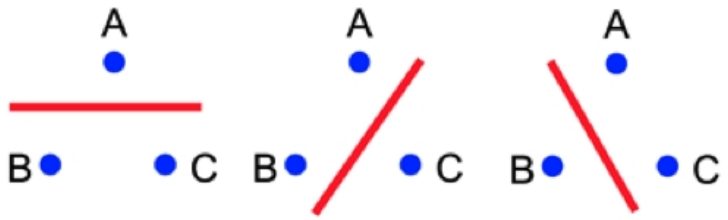
CAVALCANTI, ACIN, NB, VERTESI arxiv 2012

IS ENTANGLEMENT = NONLOCALITY ?

PERES CONJECTURE (1999):
BOUND ENTANGLED STATES ARE LOCAL

BIPARTITE CASE ?

→ DISPROVED IN MULTIPARTITE CASE



NONLOCALITY
WITHOUT DISTILLABILITY

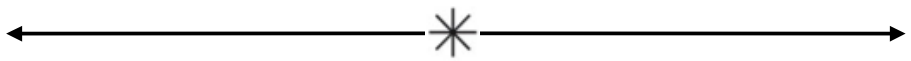
VERTESI & NB PRL 2012

(EPR) STEERING

BACK TO SCHRODINGER (1935)

BY PERFORMING A LOCAL MEASUREMENT
ALICE CAN STEER THE STATE OF BOB

$$|\Psi\rangle = |0,1\rangle - |1,0\rangle$$



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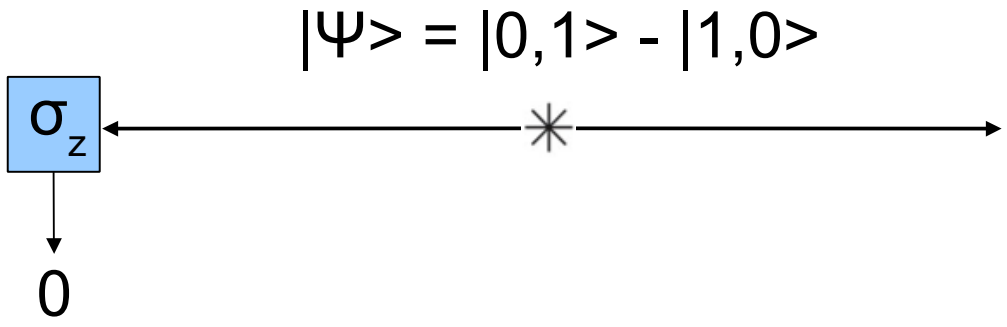

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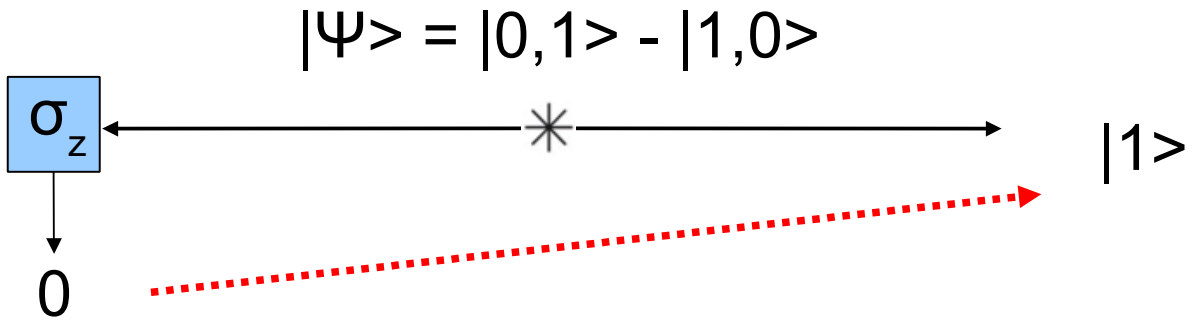

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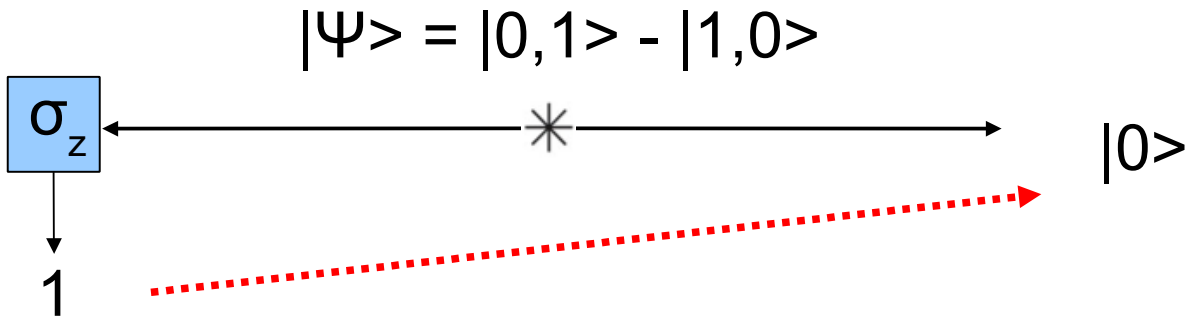

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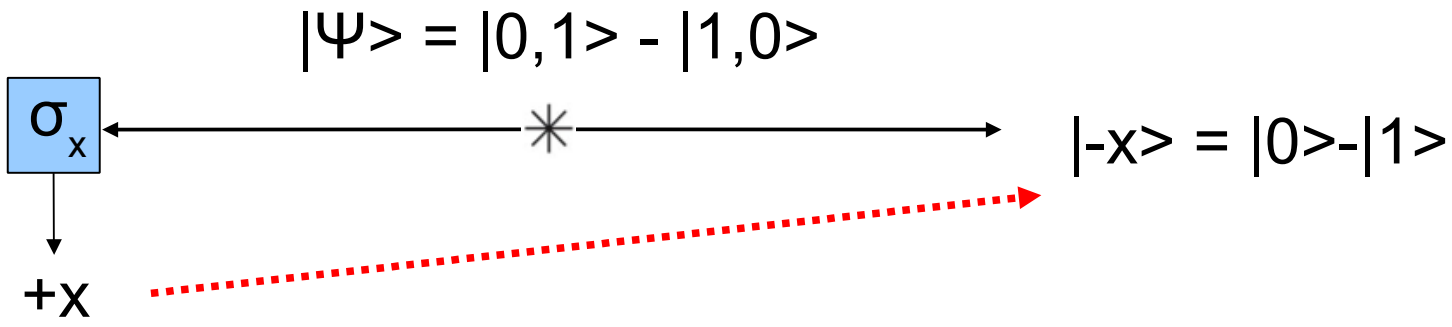

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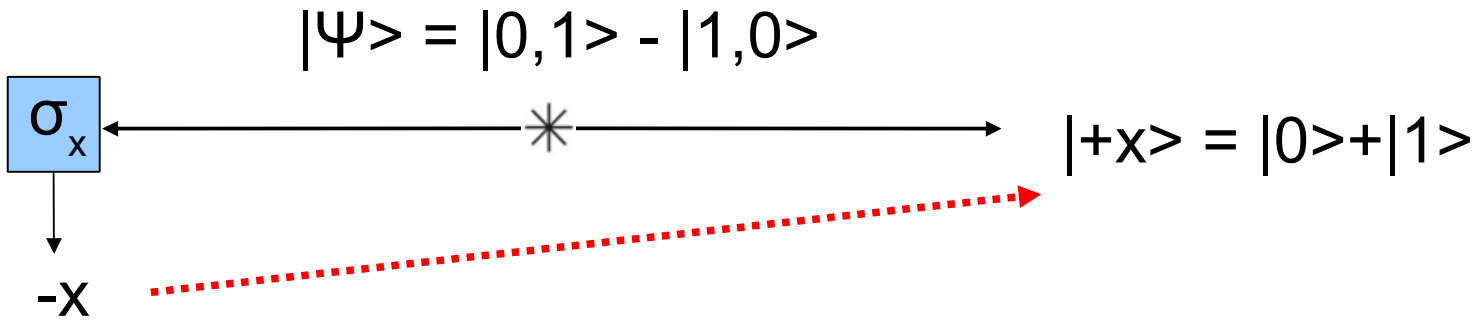
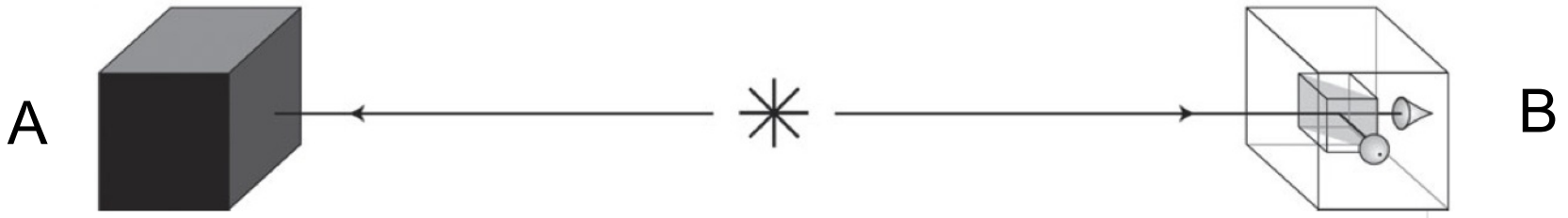


~ REMOTE STATE PREPARATION

STEERING AS INFORMATION TASK

DISTRIBUTION OF ENTANGLEMENT FROM AN UNTRUSTED PARTY



WISEMAN, JONES, DOHERTY PRL 2007

STEERING AS INFORMATION TASK

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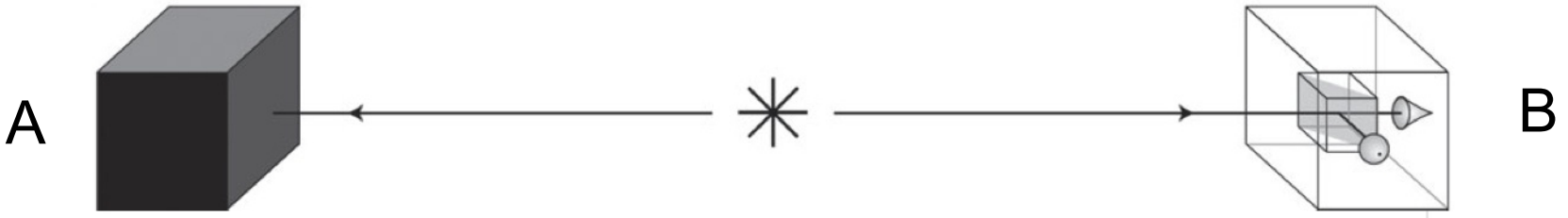

1. A SENDS STATE TO B
2. B CHOOSES MEAS BASIS AND TELLS A
3. A GUESSES OUTCOME OF B

WISEMAN, JONES, DOHERTY PRL 2007

STEERING AS INFORMATION TASK

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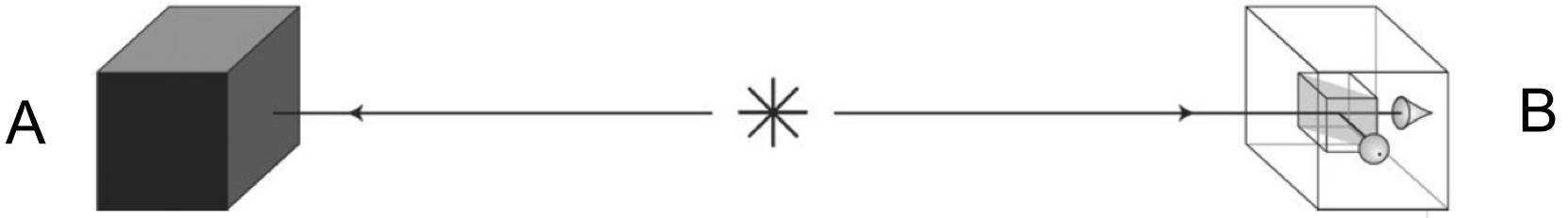

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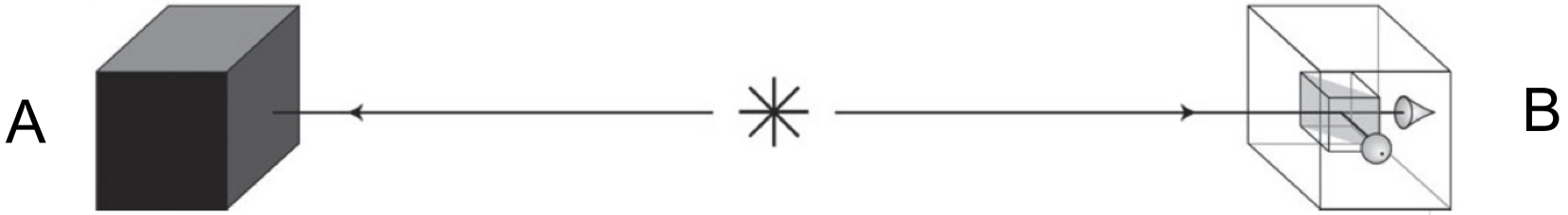
B ESTIMATES CORRELATIONS

WISEMAN, JONES, DOHERTY PRL 2007

STEERING INEQUALITIES



LOCAL UNCERTAINTY RELATION $H(\sigma_x) + H(\sigma_z) \geq 1$

STEERING INEQUALITY $H(\sigma_x|A) + H(\sigma_z|A) \geq 1$

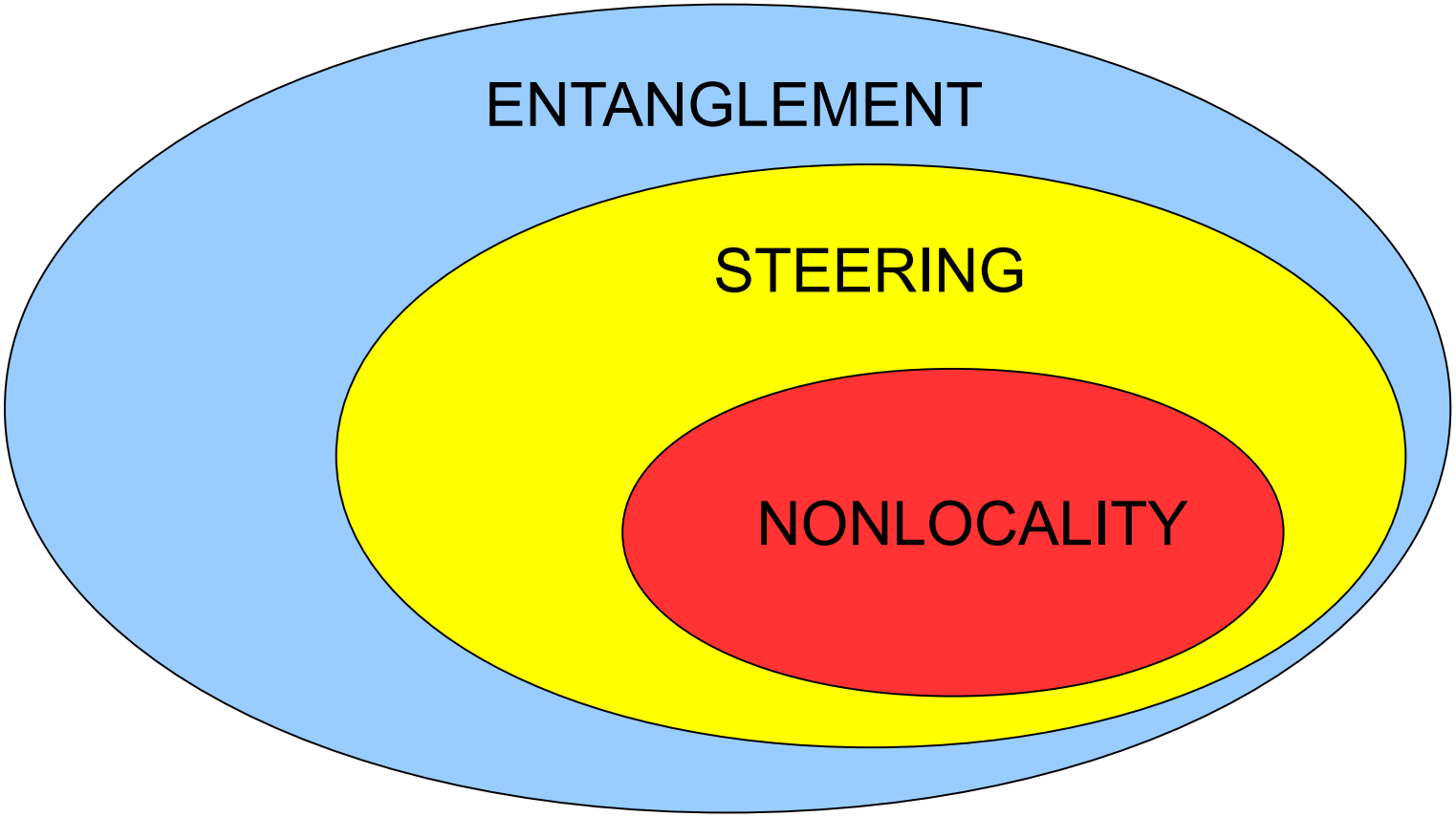
HOLDS FOR ANY CHEATING STRATEGY

WITH ENTANGLED STATE $H(\sigma_x|A) + H(\sigma_z|A) = 0$

NB & CAVALVANTI arxiv 2012

SUMMARY

3 FORMS OF INSEPARABILITY IN QM



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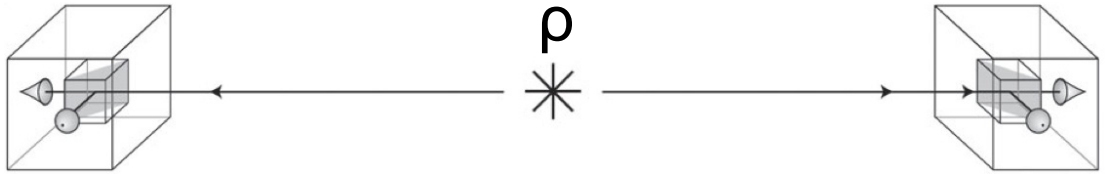
3 DIFFERENT CONCEPTS

DO WE TRUST MEAS. DEVICES OR NOT



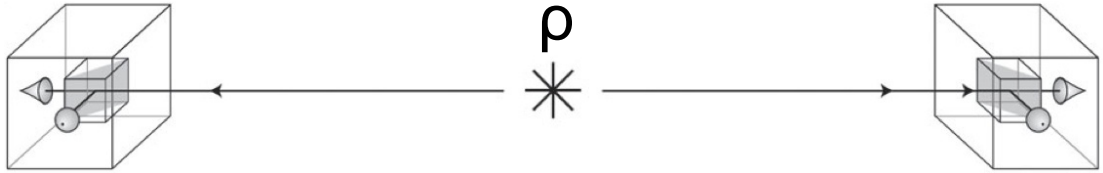
ENTANGLEMENT

$< W >_{\rho} \leq 0$ FOR ANY SEPARABLE ρ

TRUST MEAS

3 DIFFERENT CONCEPTS

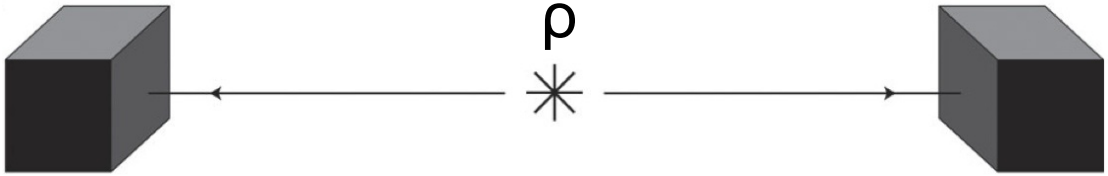
DO WE TRUST MEAS. DEVICES OR NOT



ENTANGLEMENT

$< W >_{\rho} \leq 0$ FOR ANY SEPARABLE ρ

TRUST MEAS



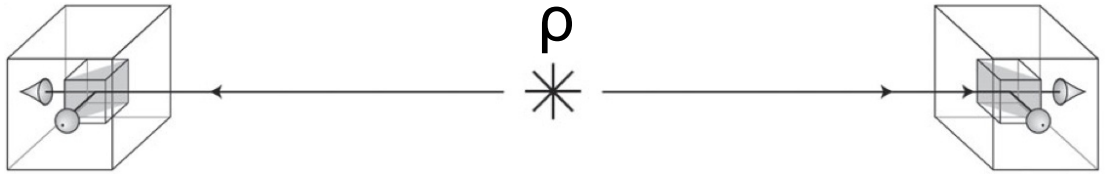
NONLOCALITY

BELL ≤ L FOR ANY LOCAL ρ

DO NOT TRUST MEAS

3 DIFFERENT CONCEPTS

DO WE TRUST MEAS. DEVICES OR NOT



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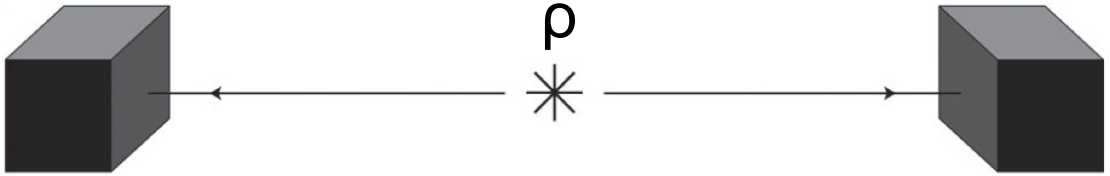

NONLOCALITY

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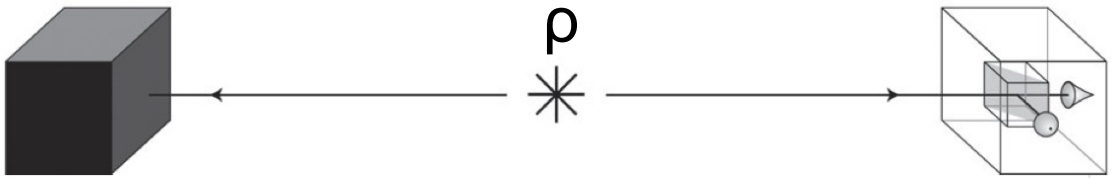


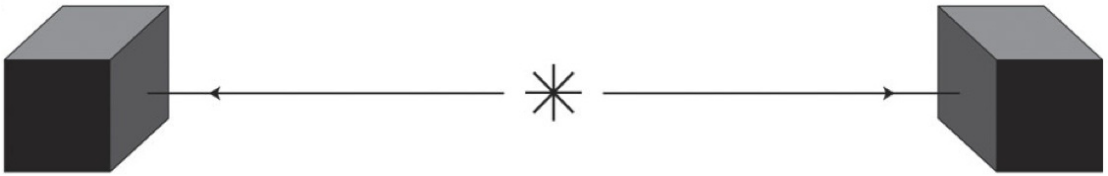
STEERING

$\Sigma < \sigma \mid A > \leq L$ IF A CHEATS

TRUST B BUT NOT A

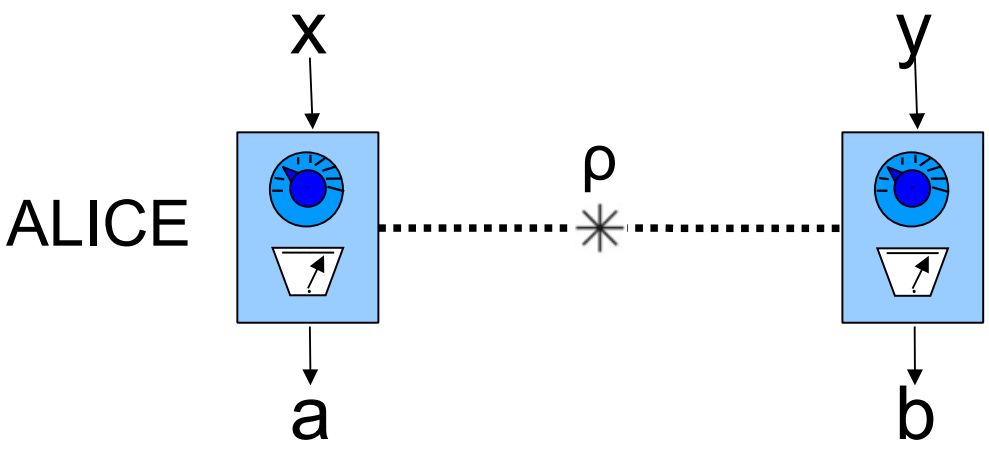
DEVICE-INDEPENDENT QIP

GOAL: ACHIEVE INFORMATION-THEORETIC TASKS
WITHOUT PLACING ASSUMPTIONS ON
THE FUNCTIONING OF THE DEVICES USED
IN THE PROTOCOL



NO ASSUMPTION ABOUT HILBERT SPACE DIMENSION
OR ALIGNMENT OF MEASUREMENT DEVICES

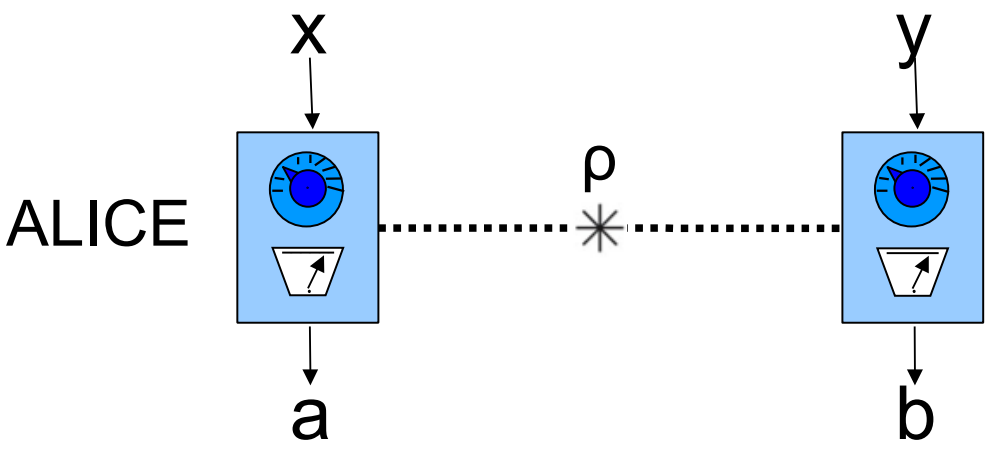
CERTIFIED RANDOMNESS



BELL INEQ VIOLATION ⇒ TRULY RANDOM OUTCOMES

PIRONIO et al. NATURE 2010, COLBECK PhD 2007

CERTIFIED RANDOMNESS

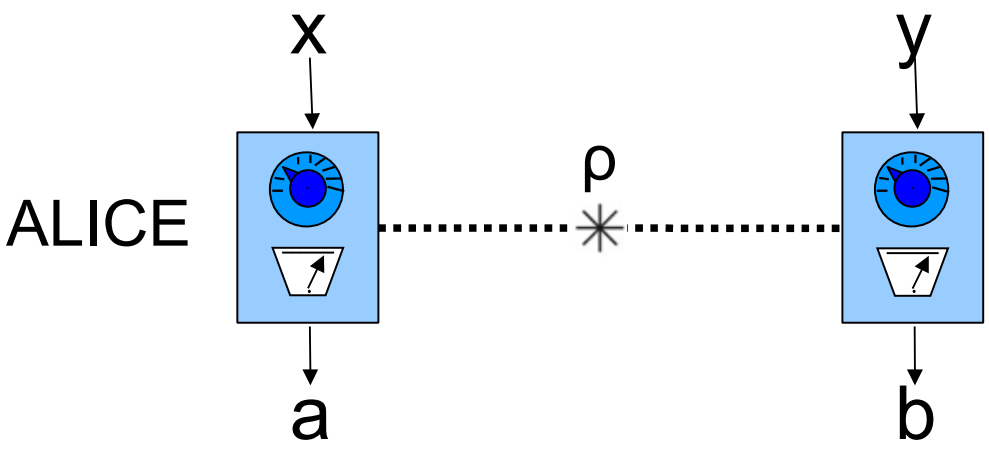


BELL INEQ VIOLATION ⇒ TRULY RANDOM OUTCOMES

OUTCOMES CANNOT BE CORRELATED
TO ANY OTHER PHYSICAL SYSTEM

PIRONIO et al. NATURE 2010, COLBECK PhD 2007

CERTIFIED RANDOMNESS



BELL INEQ VIOLATION ⇒ TRULY RANDOM OUTCOMES

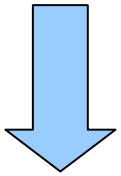
OUTCOMES CANNOT BE CORRELATED
TO ANY OTHER PHYSICAL SYSTEM

NO-SIGNALING + NONLOCALITY ⇒ **RANDOMNESS**

PIRONIO et al. NATURE 2010, COLBECK PhD 2007

DEVICE-INDEPENDENT Q CRYPTOGRAPHY

BELL INEQUALITY VIOLATION



LOCAL OUTCOMES ARE RANDOM
AND UNCORRELATED FROM EVE

ACIN, NB, GISIN, MASSAR, PIRONIO, SCARANI PRL 2007

DEVICE-INDEPENDENT Q CRYPTOGRAPHY

BELL INEQUALITY VIOLATION

LOCAL OUTCOMES ARE RANDOM
AND UNCORRELATED FROM EVE

SECURE EVEN IF EVE PREPARED THE DEVICES

MORE ROBUST TO DEVICE IMPERFECTIONS

ACIN, NB, GISIN, MASSAR, PIRONIO, SCARANI PRL 2007

EXPERIMENTS / LOOPHOLES

PRACTICAL IMPERFECTIONS OPEN LOOPHOLES

EXPERIMENTS / LOOPHOLES

PRACTICAL IMPERFECTIONS OPEN LOOPHOLES

1. **LOCALITY LOOPHOLE**
   → SPACE-LIKE SEPARATION

   OPTICAL EXPERIMENTS

   ASPECT et al. PRL 1982, TITTEL et al. PRL 1998, WEIHS et al. PRL 1998

EXPERIMENTS / LOOPHOLES

PRACTICAL IMPERFECTIONS OPEN LOOPHOLES

1. **LOCALITY LOOPHOLE**
   → SPACE-LIKE SEPARATION

   OPTICAL EXPERIMENTS

   ASPECT et al. PRL 1982, TITTEL et al. PRL 1998, WEIHS et al. PRL 1998

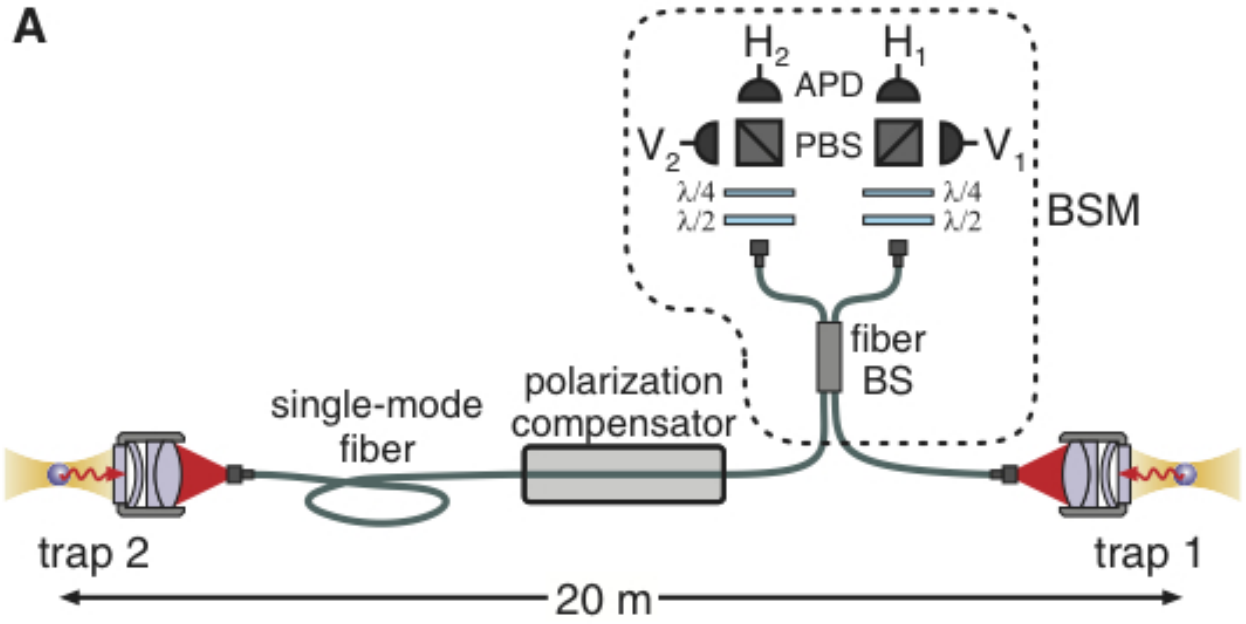
2. **DETECTION LOOPHOLE**
   → HIGH DETECTION EFFICIENCY

   ATOMIC EXPERIMENTS

   ROWE et al. NATURE 2001, MATSUKEVITCH et al. PRL 2007

PROGRESS (I)

BELL VIOLATION BETWEEN DISTANT IONS

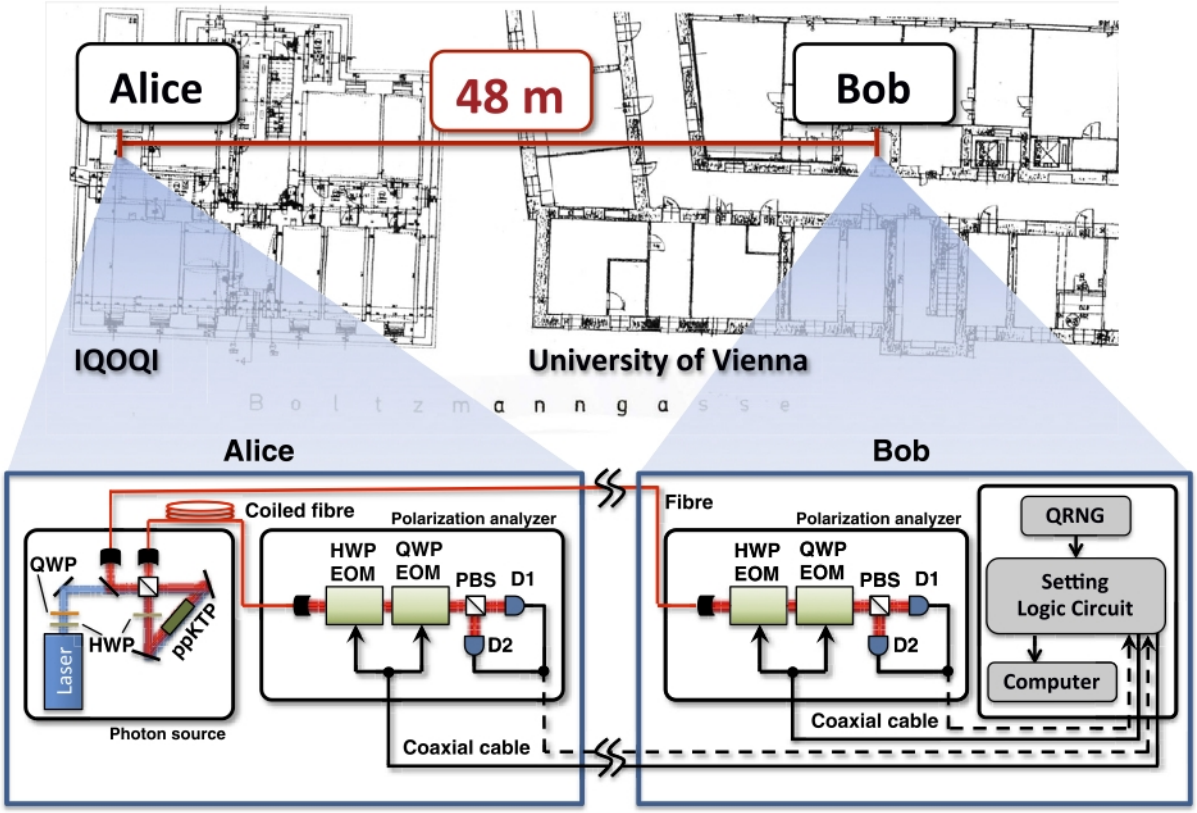


CHSH = 2.19 ± 0.09

HOFMANN et al. SCIENCE 2012

PROGRESS (II)

LOOPHOLE-FREE STEERING



Total efficiency ~ 38% Steering ineq. violated by > 20 σ

WITTMANN et al. NJP 2012

PROGRESS (III)

NEW PROPOSALS

ATOM-PHOTON ENTANGLEMENT

NB et al. PRL 2007, CABELLO & LARSSON PRL 2007, TEO et al. Arxiv 2012

CONTINUOUS VARIABLES

GARCIA-PATRON et al. PRL 2005, CAVALCANTI et al. PRA 2011

HIGHER DIMENSIONS

VERTESI, PIRONIO, NB PRL 2010

HERALDED AMPLIFIER

GISIN, PIRONIO, SANGOUARD PRL 2010, CABELLO & SCIARRINO PRX 2012

SUMMARY

EXPERIMENTAL AND THEORETICAL PROGRESS TOWARDS LOOPHOLE-FREE BELL TEST

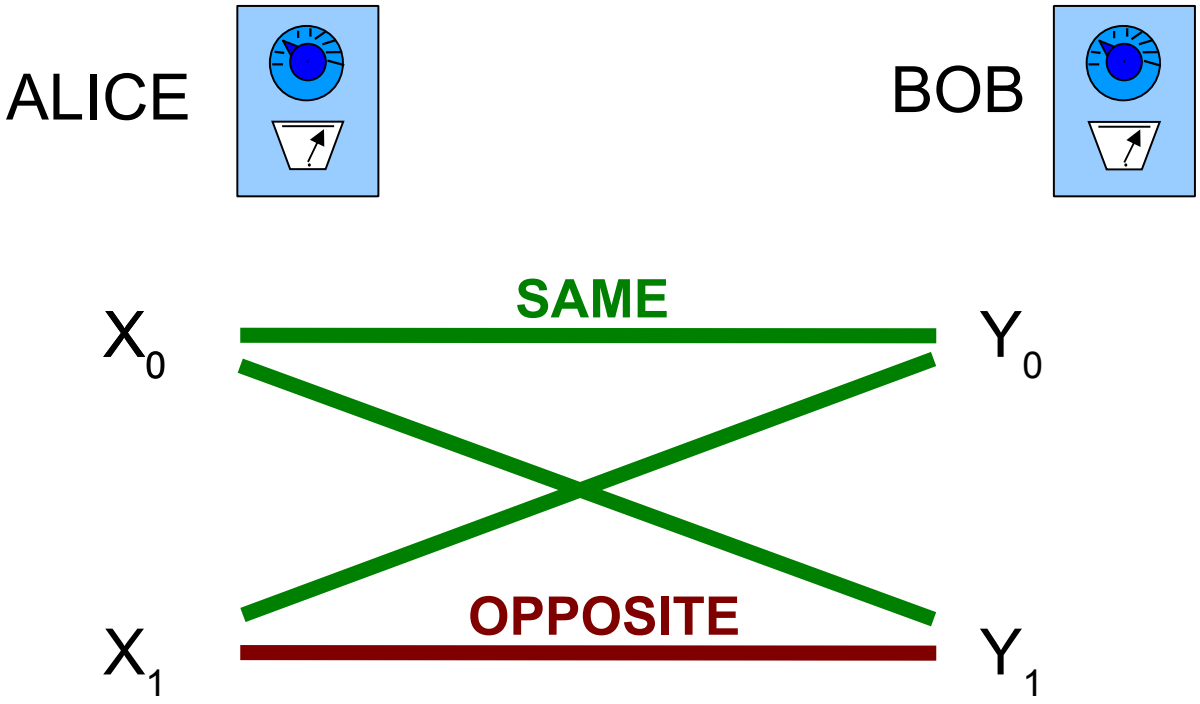
FINAL EXPERIMENT IN 3-4 YEARS ?

LAUNCH EXP. DEVICE-INDEPENDENT QIP

NIST: DI RANDOMNESS GENERATION

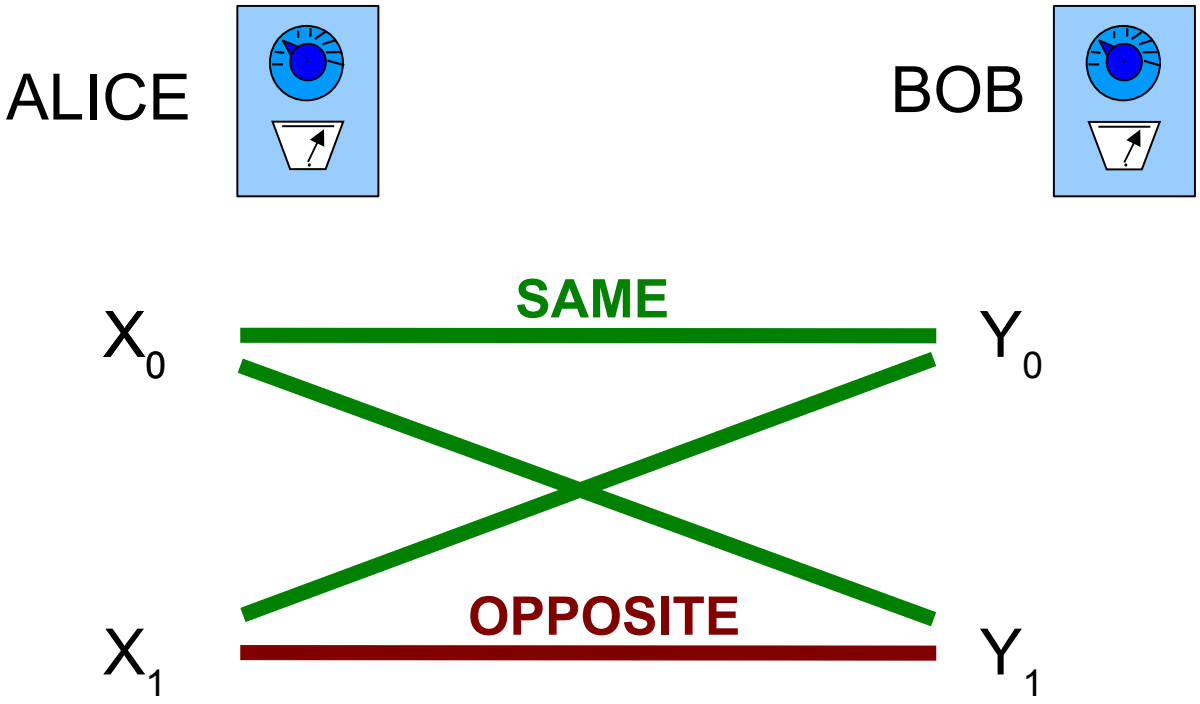
NONLOCALITY BEYOND QM

NONLOCALITY BEYOND QM



CAN WE HAVE CHSH = 4 ?

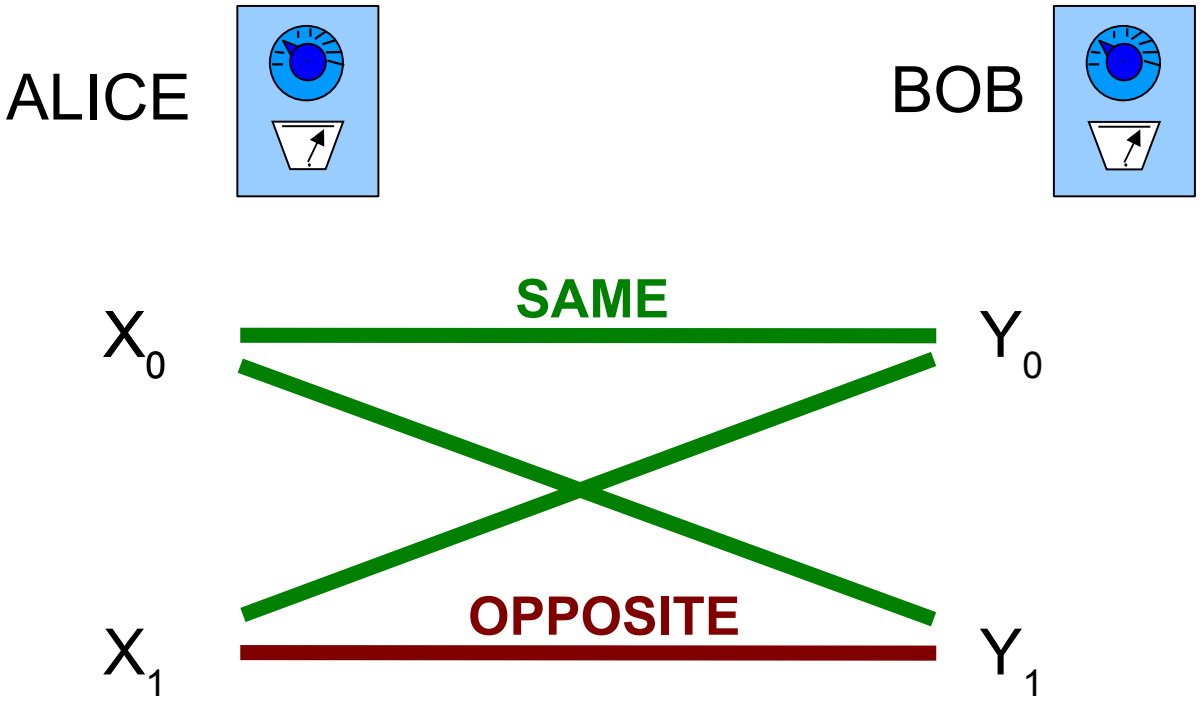
NONLOCALITY BEYOND QM



CAN WE HAVE CHSH = 4 ?

$E(X_0,Y_0) = E(X_0,Y_1) = E(X_1,Y_0) = 1$ AND $E(X_1,Y_1) = -1$

NONLOCALITY BEYOND QM

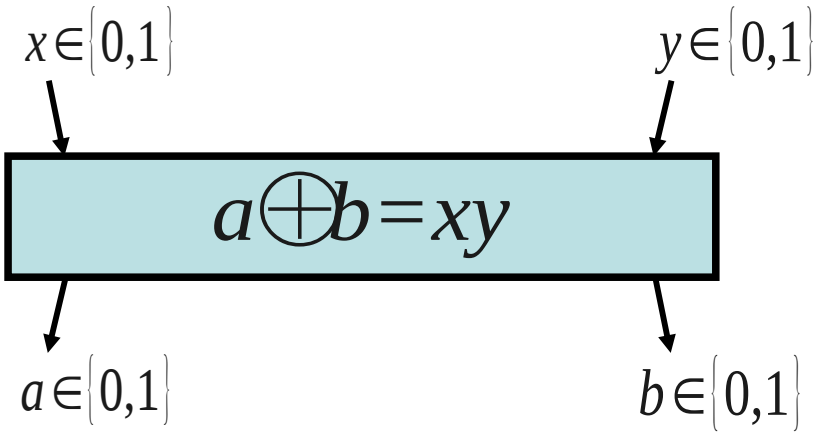


CAN WE HAVE CHSH = 4 ?

$E(X_0,Y_0) = E(X_0,Y_1) = E(X_1,Y_0) = 1$ AND $E(X_1,Y_1) = -1$

IS CAUSALITY VIOLATED?

POPESCU-ROHRLICH (PR) BOX

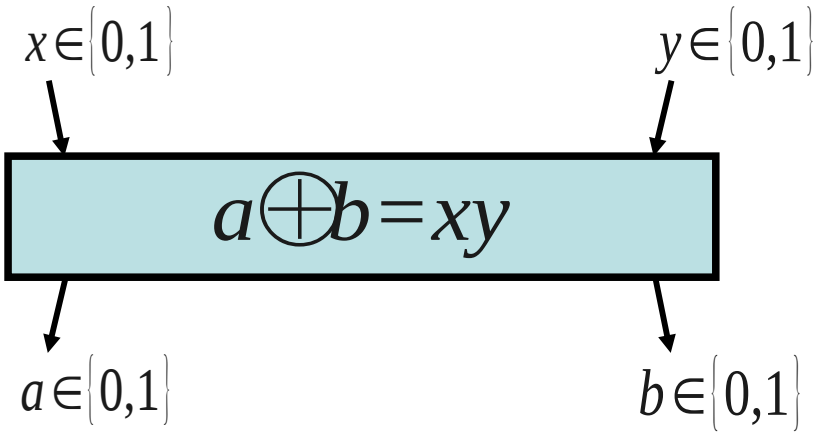


NONSIGNALING

MAXIMALLY NONLOCAL CHSH = 4

POPESCU & ROHRLICH 94, BARRETT et al. PRA 2005

POPESCU-ROHRLICH (PR) BOX



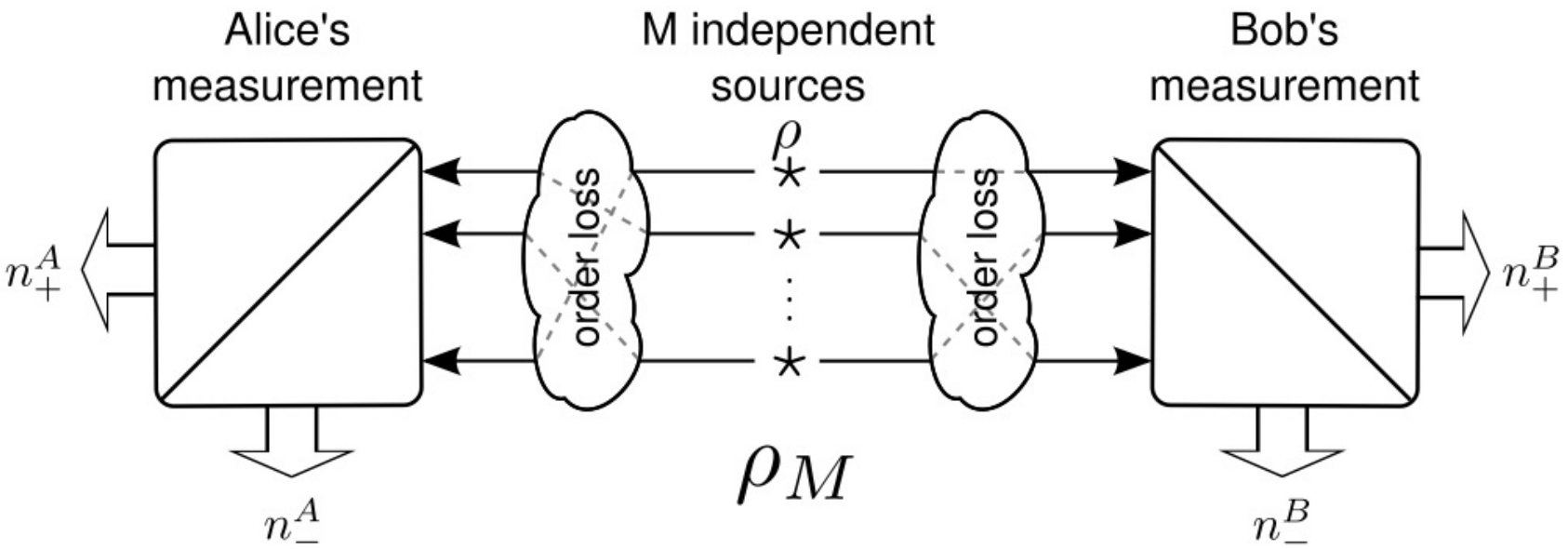
NONSIGNALING

MAXIMALLY NONLOCAL CHSH = 4

WHY DOES THE PR BOX NOT EXIST IN NATURE ?

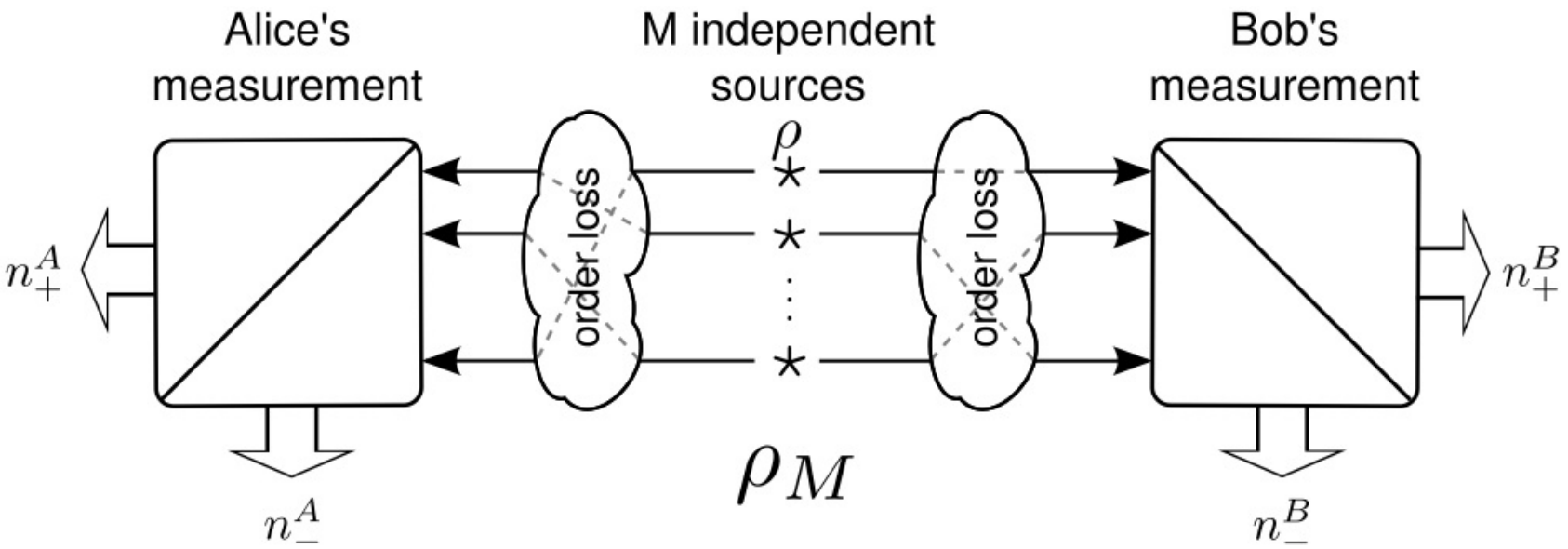
POPESCU & ROHRLICH 94, BARRETT et al. PRA 2005

MACROSCOPIC LIMIT



BANCAL et al. PRA 2008

MACROSCOPIC LIMIT

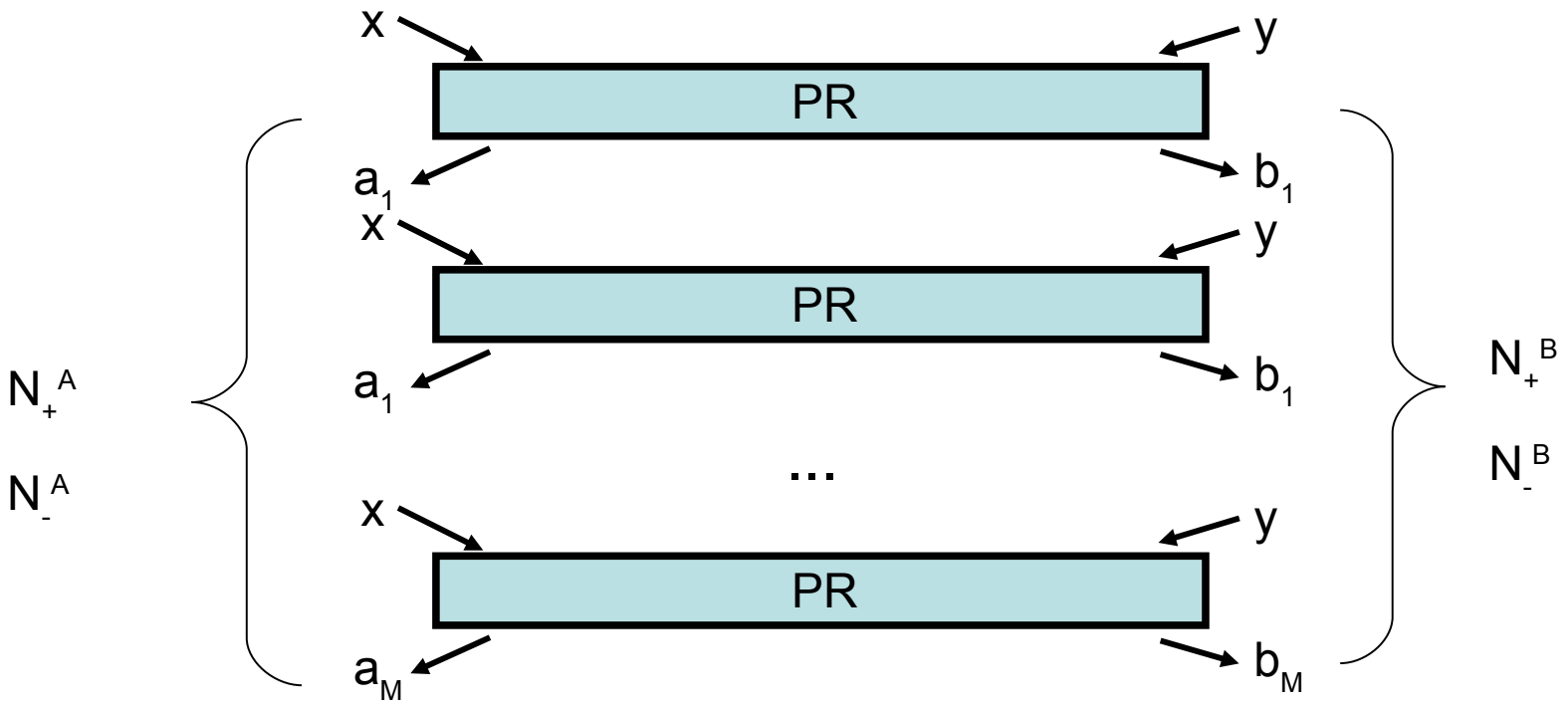


CHSH ~ 2 + 1/√M

MACROSCOPIC LIMIT (M → ∞) ⇒ LOCALITY

BANCAL et al. PRA 2008

WITH PR BOXES



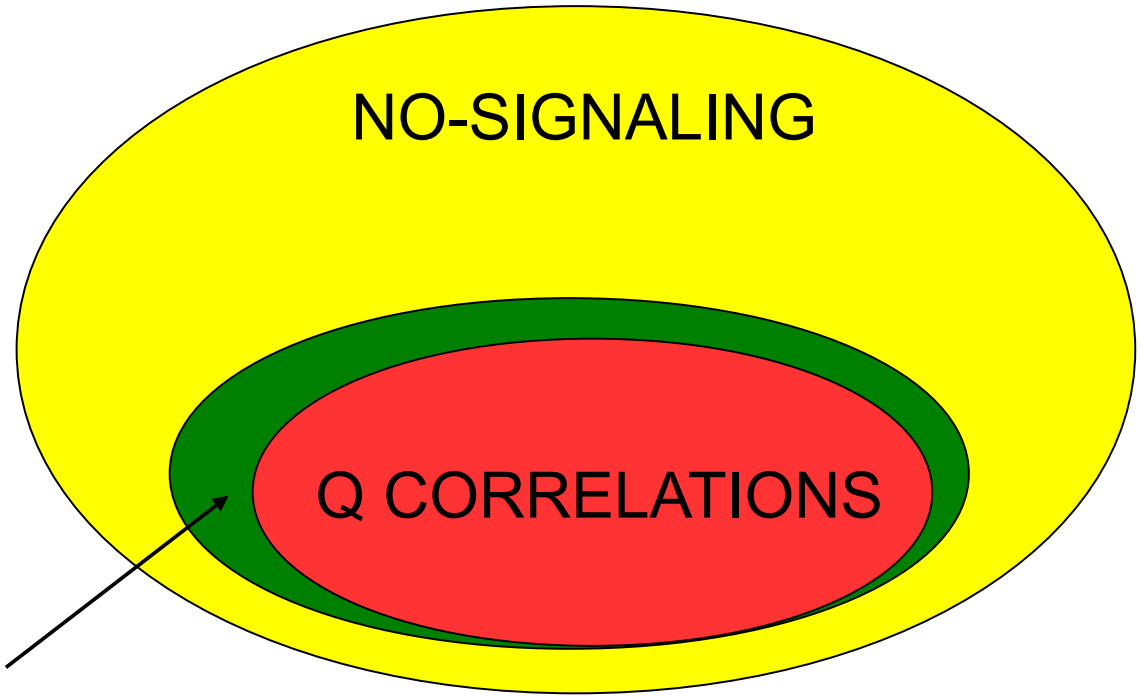
CHSH = 4 FOR ANY M !

NO MACROSCOPIC LIMIT NONLOCALITY AT ALL SCALES

NAVASCUES & WUNDERLICH 2010

MACROSCOPIC LOCALITY

PRINCIPLE: PHYSICAL CORRELATIONS BECOME LOCAL IN THE MACROSCOPIC LIMIT



MACROSCOPIC LOCALITY

NAVASCUES & WUNDERLICH 2010

CONCLUSION

NONLOCALITY IS FUNDAMENTAL IN QM

ENTANGLEMENT VS NONLOCALITY ?

USEFUL FOR QIP → DEVICE-INDEPENDENT QIP

NEW PERSPECTIVE ON FOUNDATIONS OF QM

REVIEW ARTICLE : NB, CAVALCANTI, PIRONIO, SCARANI, WEHNER
TO APPEAR SOON