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AUSTRALIAN INSTITUTE OF PHYSICS CONGRESS

Quantum control in foundational experiments,

or *HV in XXI*

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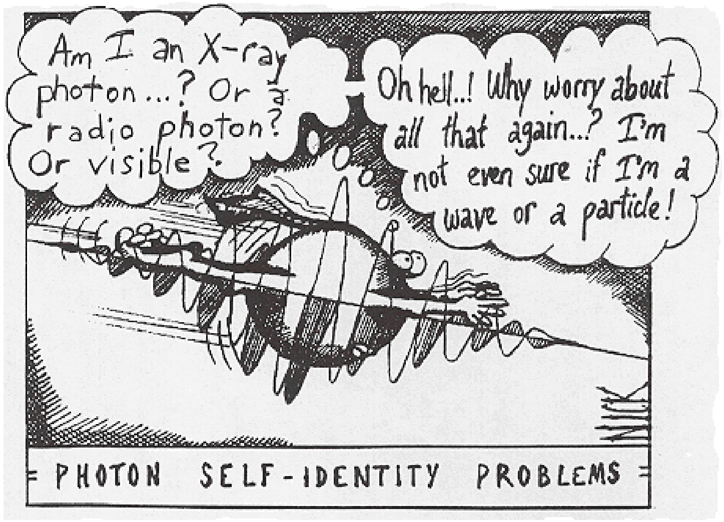
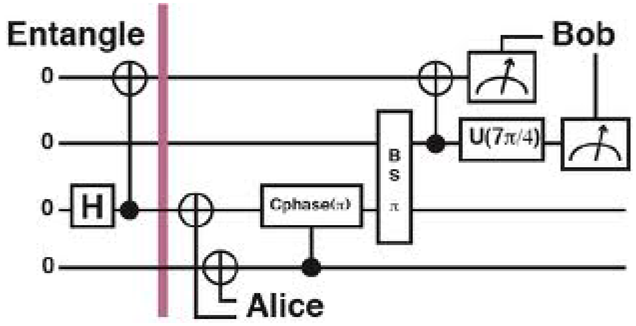
two parts of the story



Wave particle duality
Complementarity
Delayed choice experiments
and their HV interpretation

Gates and quantum control
in service of quantum foundations



references & promo

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- Brandenburger & Yanofsky,
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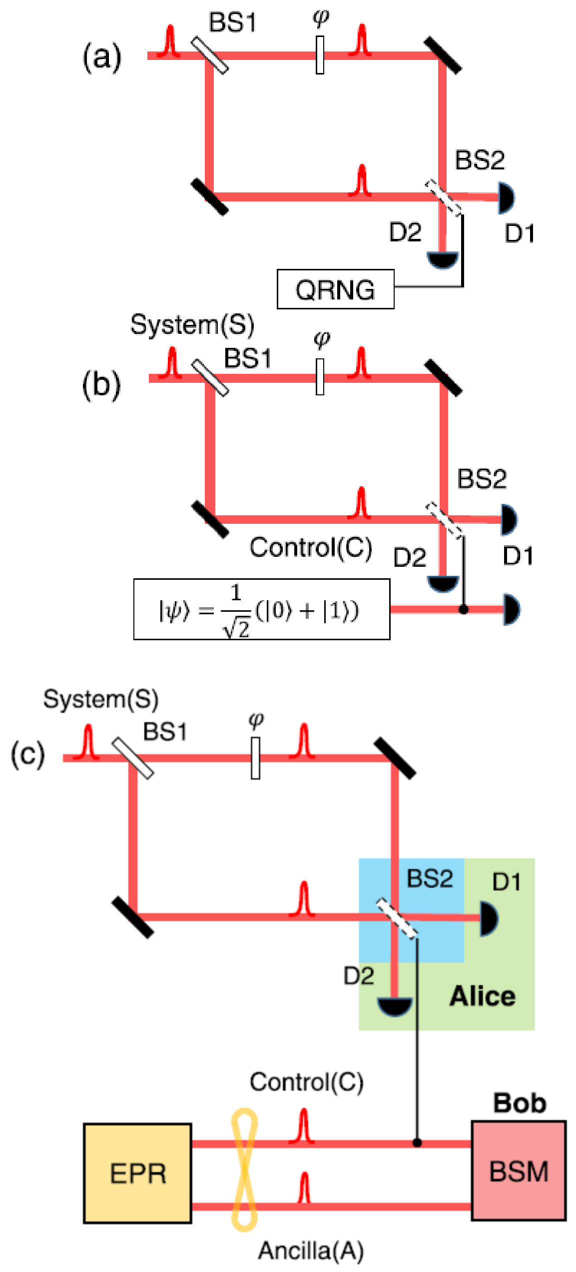
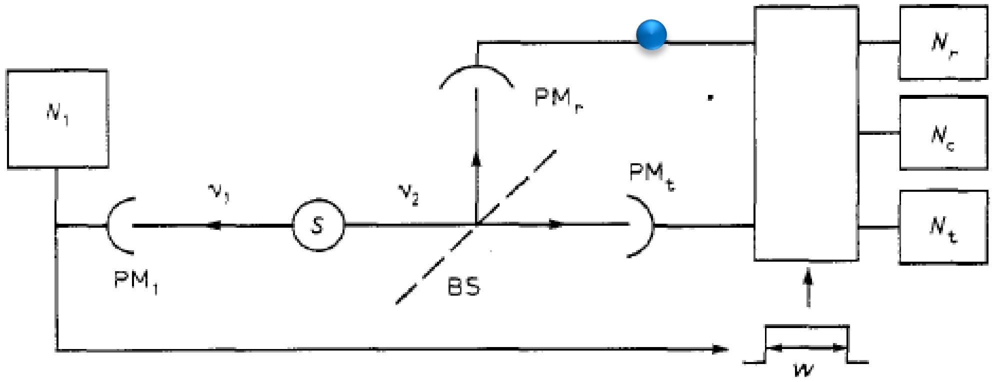
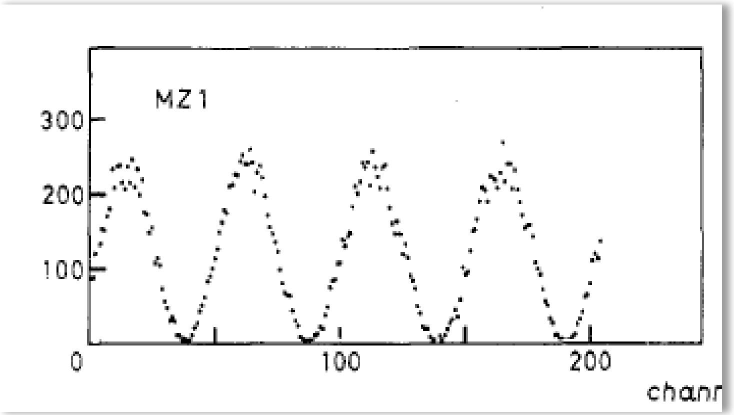


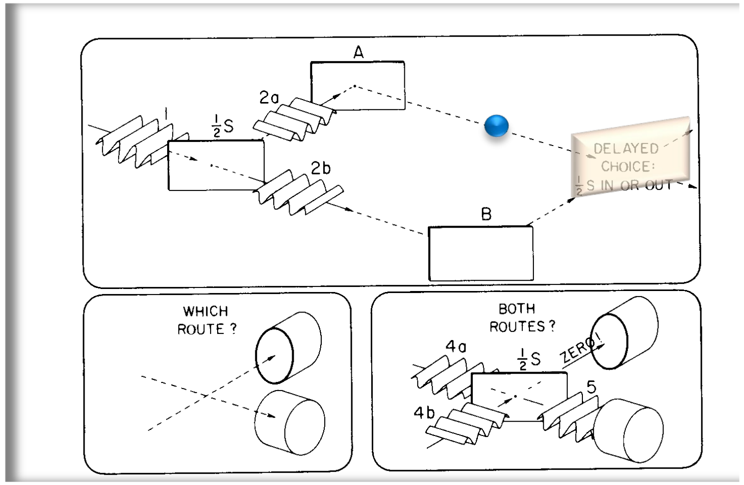
wave-particle duality





Single photons behave as particles
Single photons behave as waves

P. Grangier, G. Roger and A. Aspect Europhys. Lett. **1**, 173 (1986)

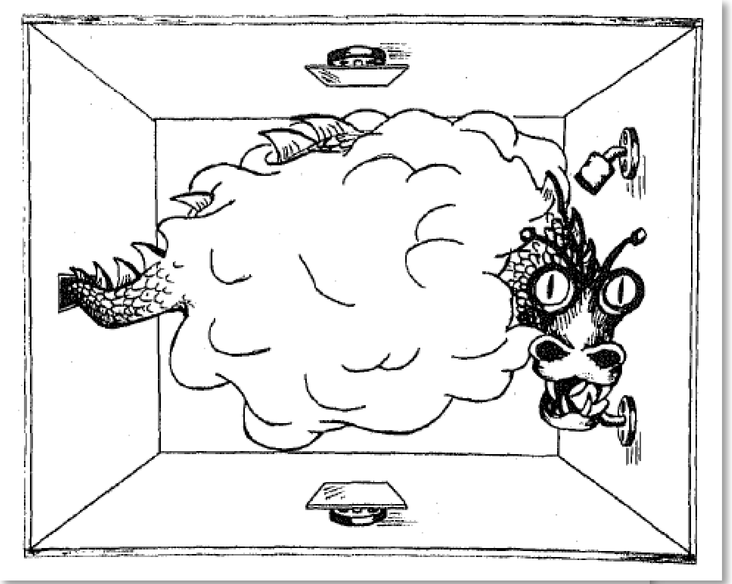


DEFINITIONS
Particles: no interference, ▶ single path
Waves: interference, ▶ both paths

complementarity

... the information provided by different experimental procedures that in principle cannot, because of the physical character of the needed apparatus, be performed simultaneously, cannot be represented by any mathematically allowed quantum state of the system. The elements of information obtainable from incompatible measurements are said to be *complementary.*

Stapp, in *Compendium of Quantum Physics*



complementarity

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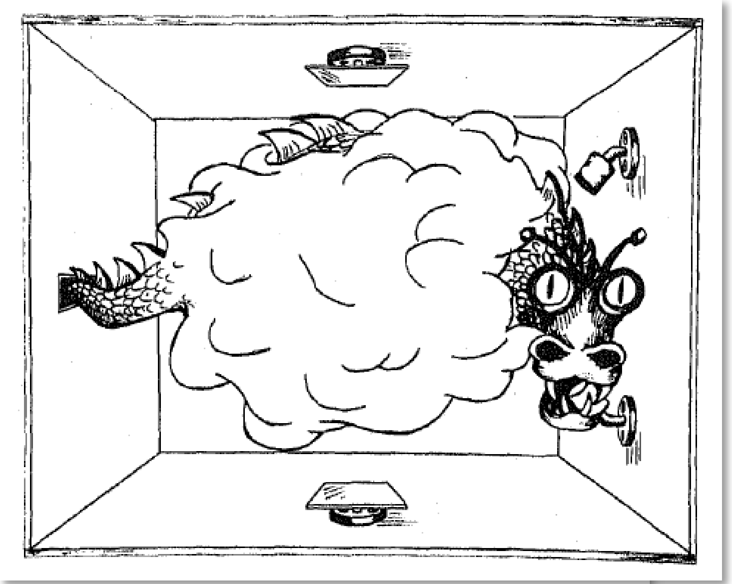


conspiracy

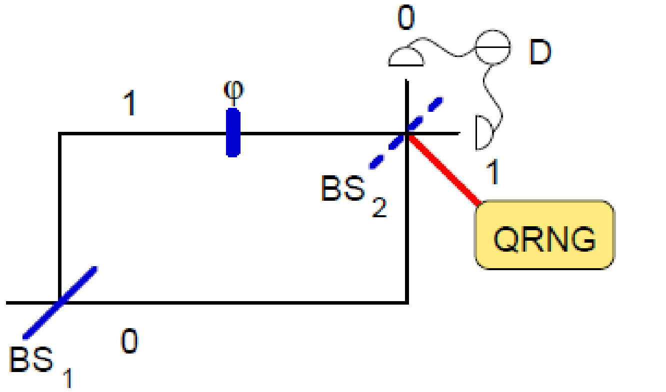
The photon could know in advance of entering the apparatus whether the latter has been set up in the “wave” configuration with BS_2 in place or the “particle” one (BS_2 removed) and adjust accordingly.

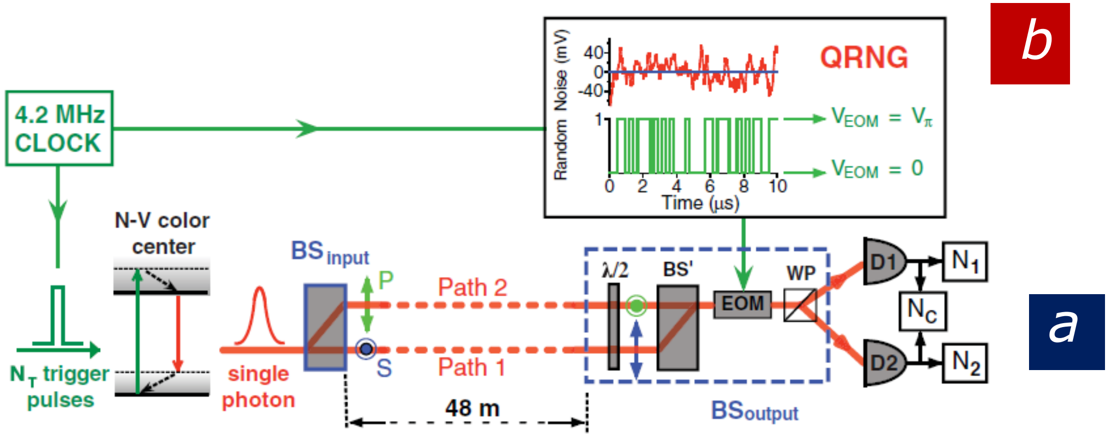
delayed choice

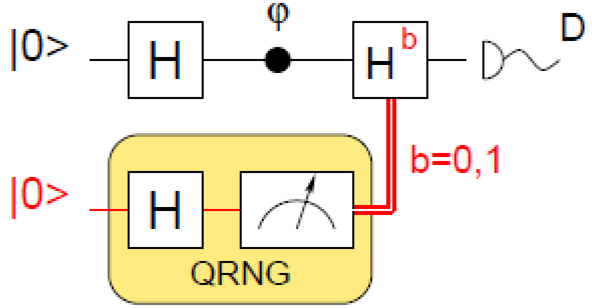
+ QRNG

Open interferometer [particle] $n(a) = (\frac{1}{2}, \frac{1}{2})$

Closed interferometer [wave] $n(a) = (\cos^2 \frac{\varphi}{2}, \sin^2 \frac{\varphi}{2})$







Jacques *et al.*,
Science **315**, 966 (2007)

Spacelike separation between the source and the RNG

control the world without attracting attention

HV M. Born, *Quantenmechanik der Stoßvorgänge*,
Z. Physik **38**, 803 (1926).

Measurements and settings:
$A,A';B,B'$

Outcomes
$a,a';b,b'$

Purpose: reproduce observed statistics and maintain classical concepts

Construction: HV exist, control the world, but are unknown

$$p(a,b...|A,B...) := \sum_{\lambda} p(a,b...|A,B...;\lambda)p(\lambda)$$

Adequacy: reproduce observed statistics

$$p(a,b...|A,B...) \equiv q(a,b...|A,B...)$$

control the world without attracting attention

HV M. Born, *Quantenmechanik der Stoßvorgänge*, Z. Physik **38**, 803 (1926).

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Counter-HV action

- ◇ consider a set-up
- ◇ make a QM prediction
- ◇ make a HV prediction
- ◇ compare
  get a contradiction
- ◇ make an experiment

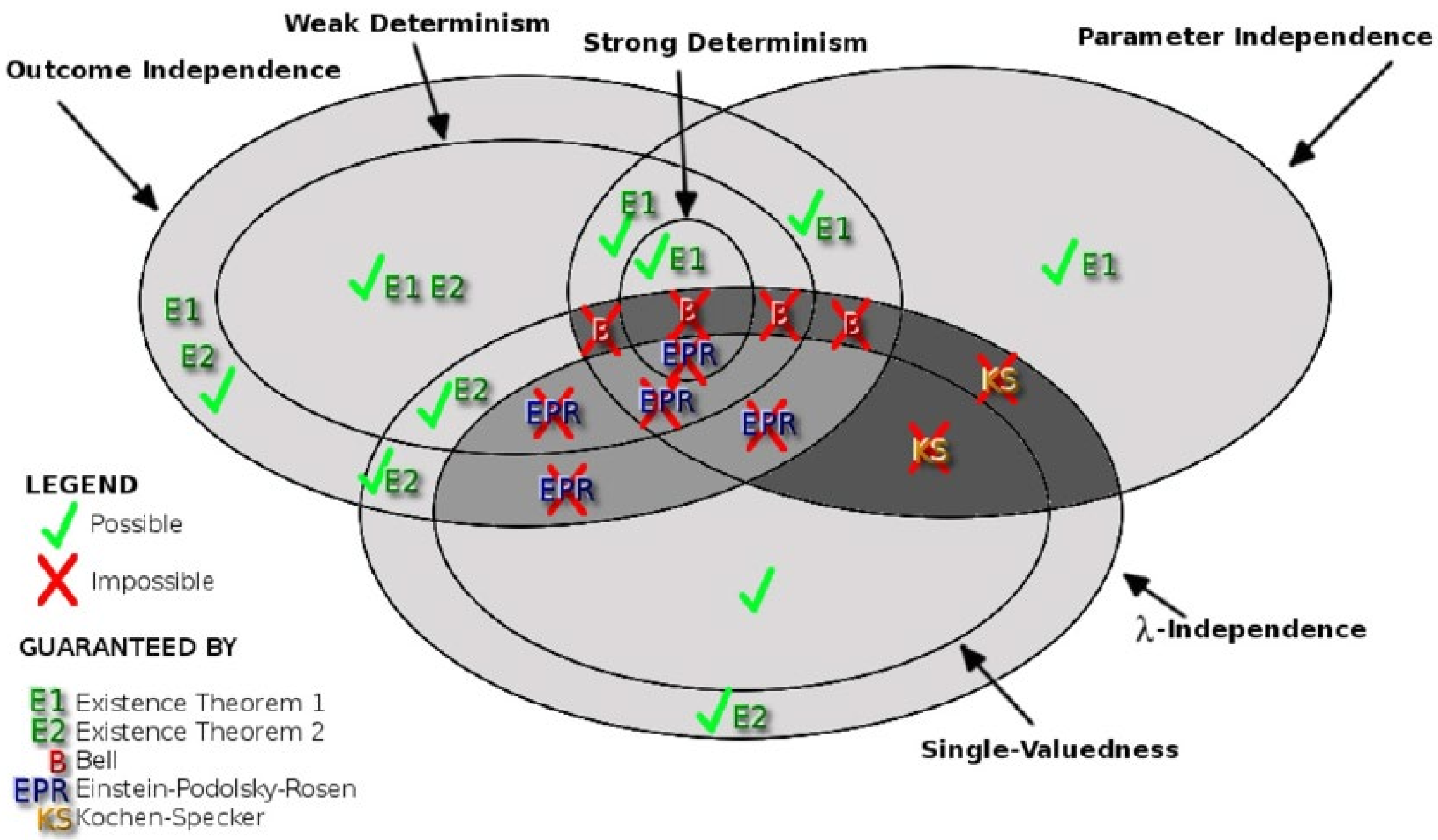
Counter-counter-HV action

- ❑ find a loophole
- ❑ introduce conspiratorial correlations

Brandenburger & Yanofsky
JPA **41** 425302 (2008)

how to…

HIDDEN VARIABLES



outcome independence +parameter independence
= Bell's locality

❑**Determinism**: once hidden variables are defined, there are no residual randomness [several flavors]

❑ **Parameter independence**: the outcome of any measurement depends only on the HV and the set-up of this measurement

$$p(a\,|\,A,B,C,...,\lambda)=p(a\,|\,A,\lambda)$$

❑ **HV (λ-)independence**: determination of the hidden variable is independent of the choice of measurement

$$p(\lambda\,|\,A,B...)=p(\lambda\,|\,A',B'...)$$

HV theories: objectivity [definiteness]

- What is the basis for assertion of wave-particle duality?
  - ❑ Can we detect “it” first and decide what was it later?
  - ❑ Is space-like separation necessary?
  - ❑ What if the controlling devices are quantum?

Extensions & questions

HV theories: objectivity [definiteness]

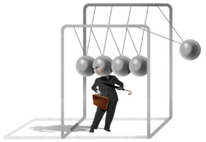
- What is the basis for assertion of wave-particle duality?
- ❑ Can we detect "it" first and decide what was it later?
- ❑ Is space-like separation necessary?
- ❑ What if the controlling devices are quantum?

Extensions & questions

HV Conspiracy

- ❑ A hidden variable *λ*=*p*,*w* set at production/before splitting

$$p(a\,|\,b=1,\lambda=w)=(\cos^2\tfrac{\phi}{2},\sin^2\tfrac{\phi}{2})$$



$$p(a\,|\,b=0,\lambda=p)=(\tfrac{1}{2},\tfrac{1}{2})$$

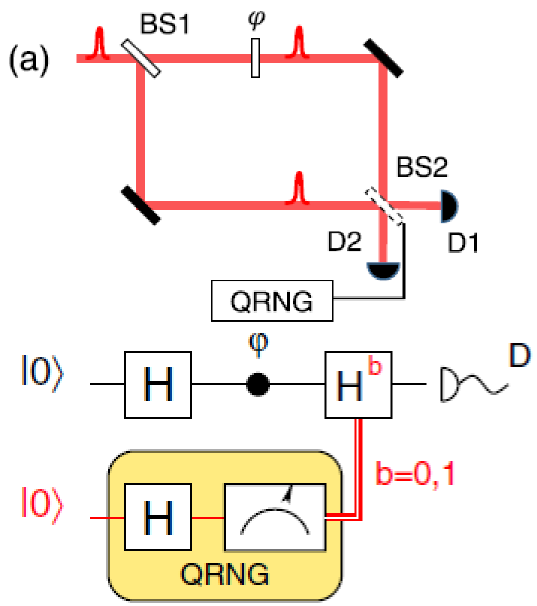
- ❑ Emission probability with *λ*=*p*,*w*

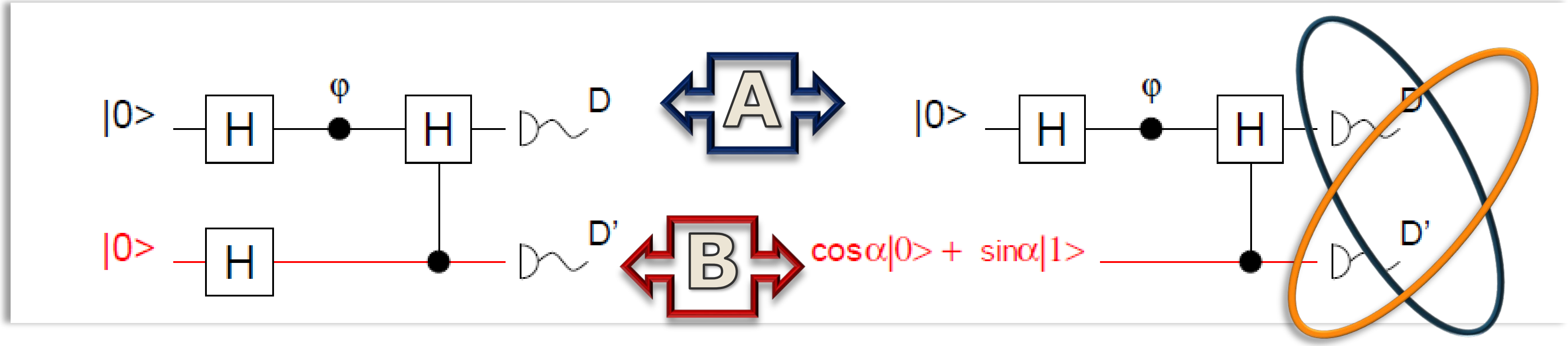
$$p(\lambda)=(f,1-f)$$

$$p(a\,|\,b=0,\lambda=w)=(x,1-x)$$

$$p(a\,|\,b=1,\lambda=p)=(y,1-y)$$

quantum control





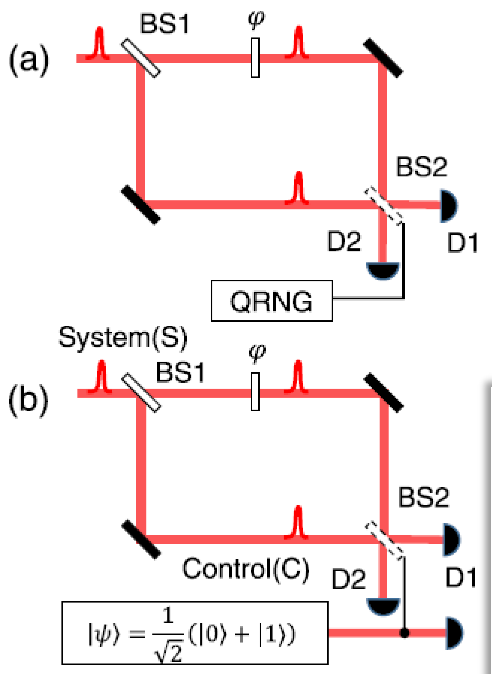
State after the gates [before the detectors]

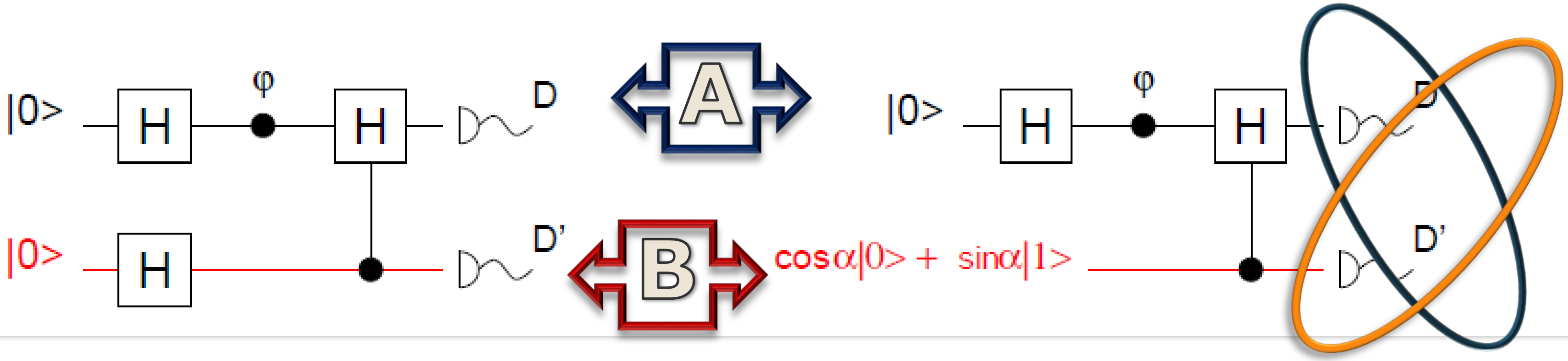
$$|\psi_f\rangle = \cos\alpha|\psi_p\rangle|0\rangle + \sin\alpha|\psi_w\rangle|1\rangle$$

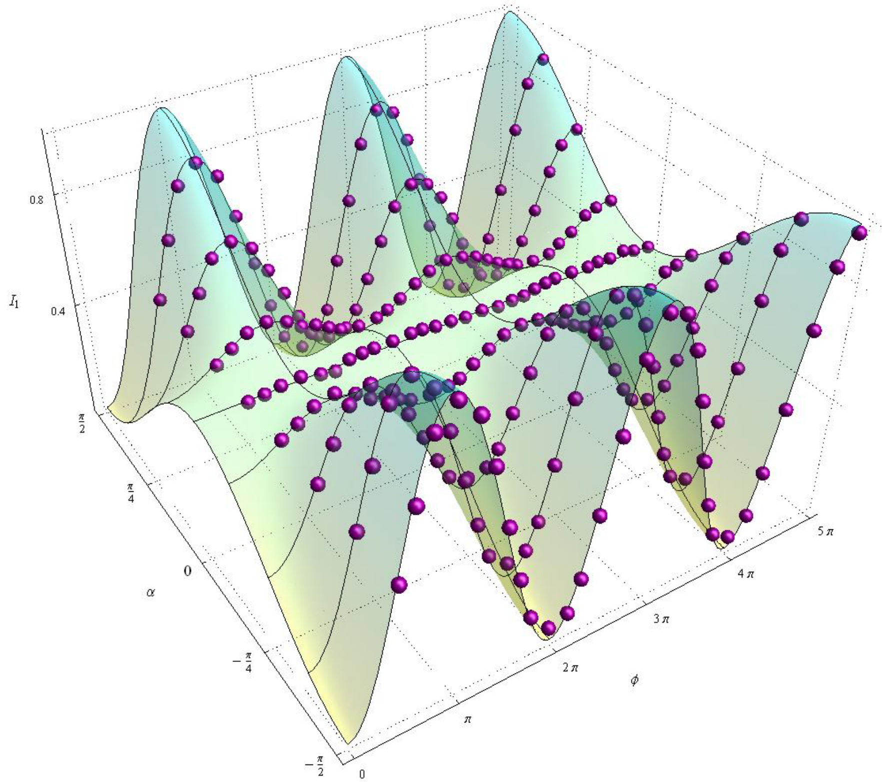
$$|\psi_p\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + e^{i\phi}|1\rangle\right)$$

$$|\psi_w\rangle = \frac{1}{\sqrt{2}}e^{i\phi/2}\left(\cos\tfrac{\phi}{2}|0\rangle - i\sin\tfrac{\phi}{2}|1\rangle\right)$$

quantum control







State after the gates [before the detectors]

$$\left|\psi_f\right\rangle = \cos\alpha\left|\psi_p\right\rangle\left|0\right\rangle + \sin\alpha\left|\psi_w\right\rangle\left|1\right\rangle$$

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$$\left|\psi_w\right\rangle = \frac{1}{\sqrt{2}}e^{i\phi/2}\left(\cos\tfrac{\phi}{2}\left|0\right\rangle - i\sin\tfrac{\phi}{2}\left|1\right\rangle\right)$$

Tang *et al.*,
Nature Phot. **6**, 602 (2012)

countering HV

HV model maintains

- ◇ objectivity
- ◇ determinism
- ◇ ?

HV model must be adequate

$$q(a,b) = \sum_{\lambda=p,w} p(a,b,\lambda)$$

countering HV

HV model maintains
- ◇ objectivity
- ◇ determinism
- ◇ ?

HV model must be adequate

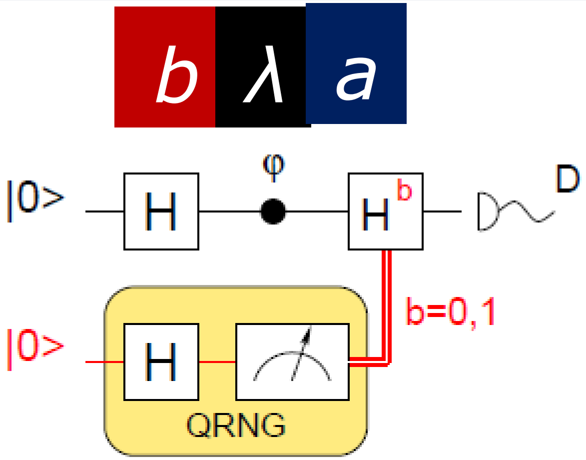
$$q(a,b) = \sum_{\lambda=p,w} p(a,b,\lambda)$$

HV in WDC
adequacy is possible if

$$q(a,b) = n(a,b) = \sum_{\lambda} p(a \mid b,\lambda)\, p(\lambda \mid b)\, n(b)$$

$$p(\lambda \mid b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1}$$

[violation of parameter independence]
[countered by the spacelike separation]
[counter-countered by the conspiracy: settings of QRNG with λ]



countering HV

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◇ objectivity
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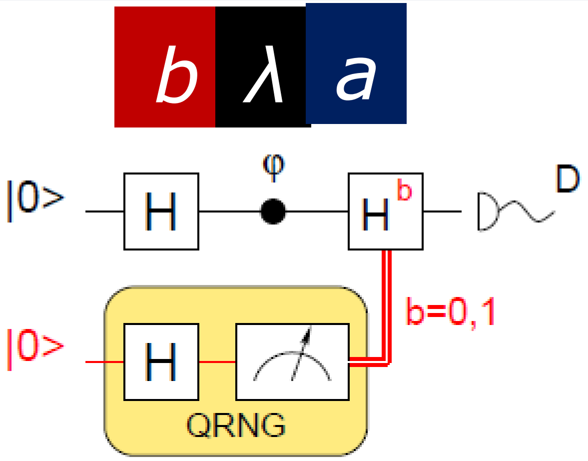
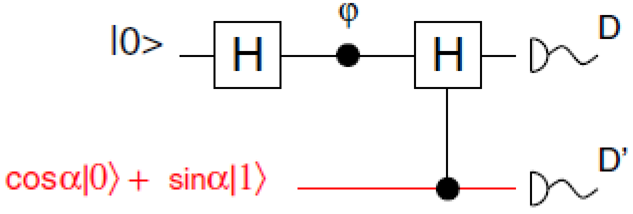
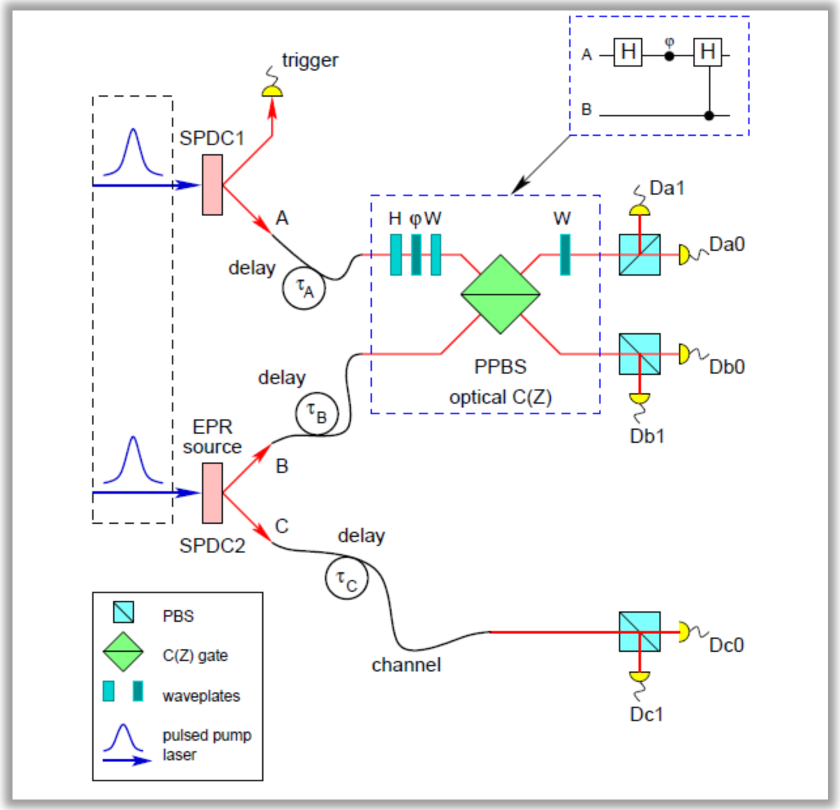
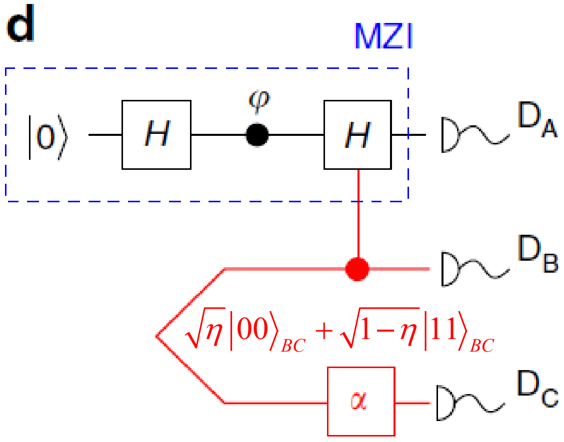


HV in QDC adequacy is possible if either
[objectivity is lost] $p(a \mid b,\lambda) = p(a \mid b)$
[conspiracy: emission is governed by the gate settings] $f = \cos\alpha$



countering HV with entanglement (1)





three assumptions

(i) Determinism: HV determines all the outcomes (3 flavours)

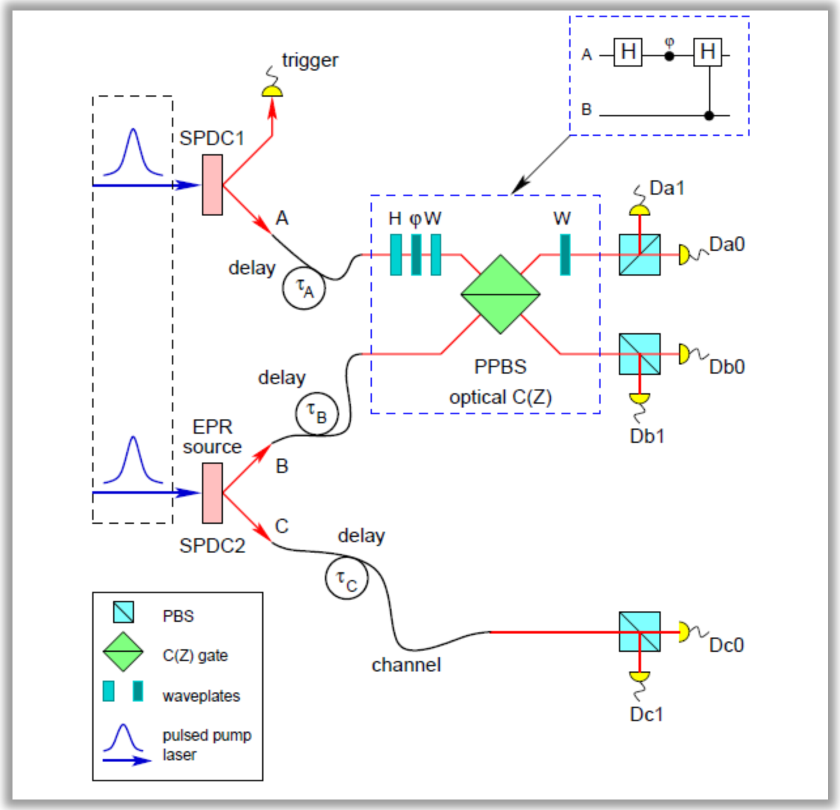
(ii) Λ-independence: HV are not influenced by the settings

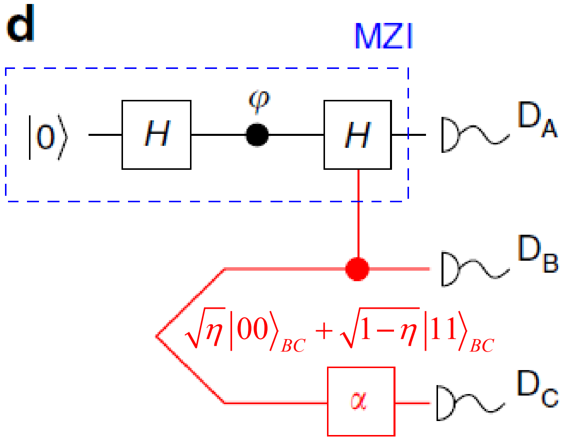
(iv) Local (λ) independence: the space of HV has a product structure and

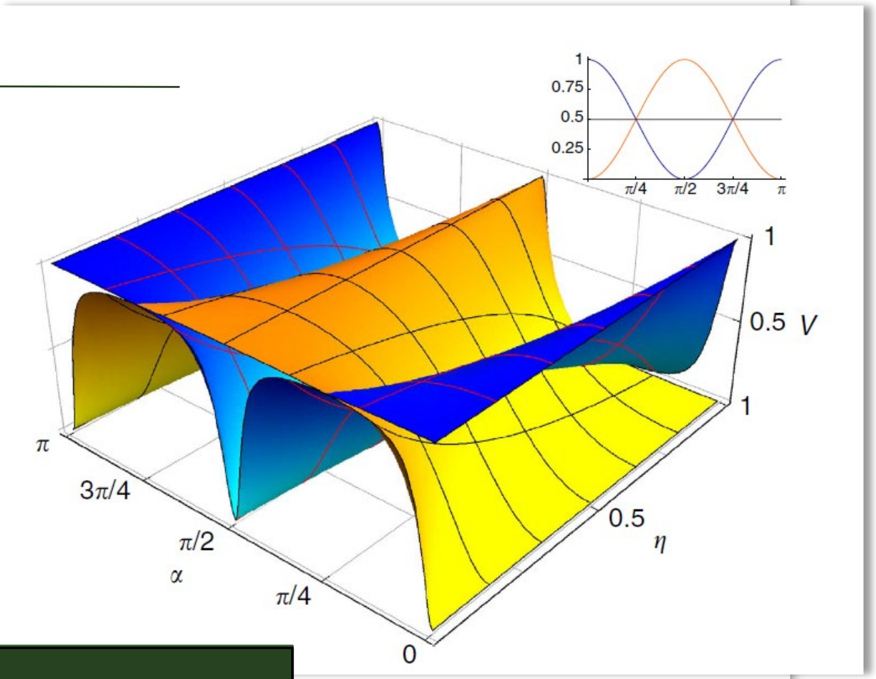
$$p(\lambda_S,\lambda_B)=p_S(\lambda_S)p_B(\lambda_B)$$

IJMT 2014

countering HV with entanglement (1)







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IJMT 2014

countering HV with entanglement (2)

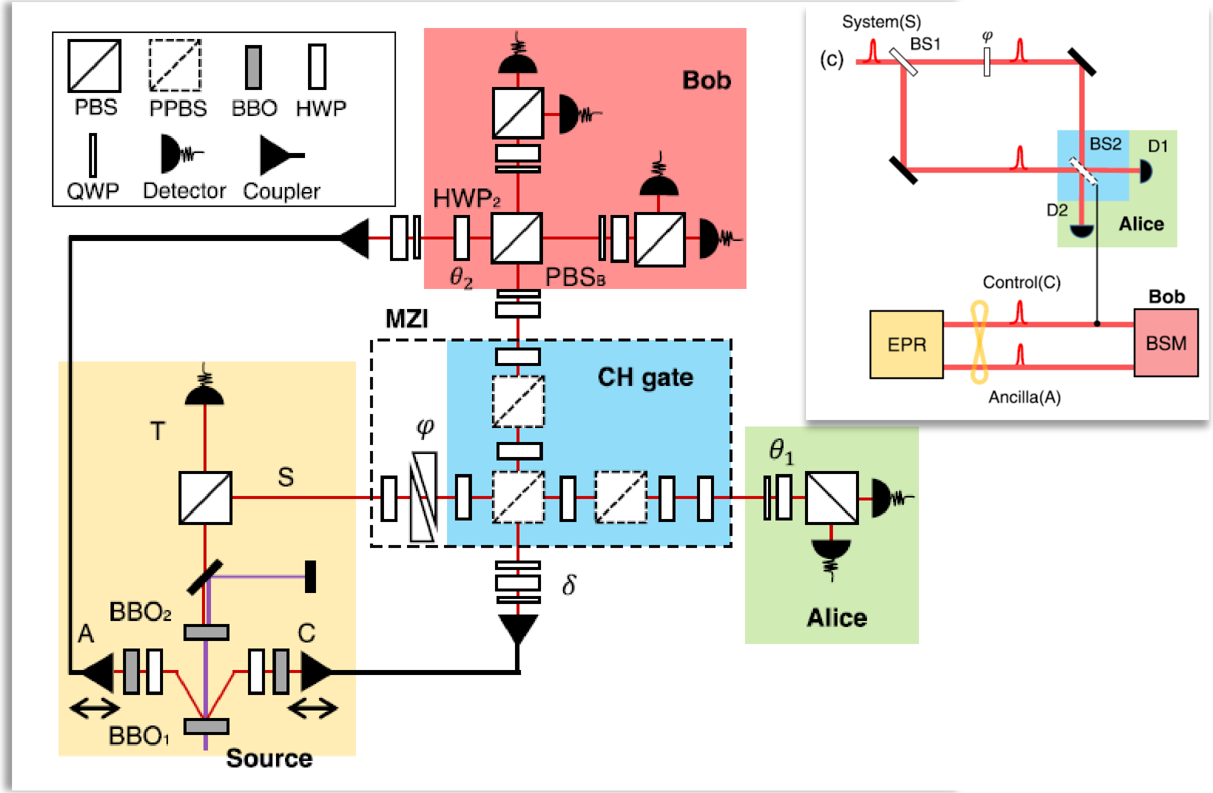

FIG. 2. Experimental setup. Entangled photons C and A are generated in the $|\psi^+\rangle$ state from a β-barium borate crystal (BBO1). From BBO2 we detect photon T and herald the existence of photon S. We then send photon S through the polarization Mach-Zehnder interferometer. Alice performs polarization measurements on photon S with two waveplates and a polarizing beam splitter, which project the polarization of photon S along θ_1. Photons C and A are sent to Bob, who employs a Bell-state analyzer to project these two photons onto a coherent superposition of $|\phi^-\rangle$ and $|\psi^+\rangle$. HWP_2 tunes the superposition of the bipartite states of photons C and A

- ❑ High-quality Bell state measurement [but not a good refutation of HV]

- ❑ Adequacy of (a/the) HV model(s) is achieved by the loss of objectivity: the state of BS_2 is undefined

countering HV with entanglement (2): details

The state of three photons:

$$|\psi^f\rangle = \frac{1}{2}[|p\rangle_S(|\phi^-\rangle_{CA} - i|\psi^+\rangle_{CA}) + e^{i\pi/4}|w\rangle_S(|\phi^-\rangle_{CA} + i|\psi^+\rangle_{CA})]$$

$$= \frac{1}{\sqrt{2}}\left[\frac{e^{i(\pi/4)}|w\rangle_S + |p\rangle_S}{\sqrt{2}}|\phi^-\rangle_{CA} + i\frac{e^{i(\pi/4)}|w\rangle_S - |p\rangle_S}{\sqrt{2}}|\psi^+\rangle_{CA}\right]$$

$$= \frac{1}{2}[(e^{i(\theta+\pi/4)}|w\rangle + e^{-i\theta}|p\rangle)_S(\cos\theta|\phi^-\rangle + \sin\theta|\psi^+\rangle)_{CA} + (e^{i(\theta-\pi/4)}|w\rangle + ie^{-i\theta}|p\rangle)_S(\sin\theta|\phi^-\rangle - \cos\theta|\psi^+\rangle)_{CA}]$$

$$|p\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle - e^{i\varphi}|V\rangle\right)$$

$$|w\rangle = \frac{1}{\sqrt{2}}e^{i\varphi/2}\left(\cos\tfrac{\varphi}{2}|V\rangle - i\sin\tfrac{\varphi}{2}|H\rangle\right)$$

Superpositions in *w/p* of *S* are created by projecting onto the Bell states; the Bell state superposition *w* & *p*

countering HV with entanglement (2): details

The state of three photons:

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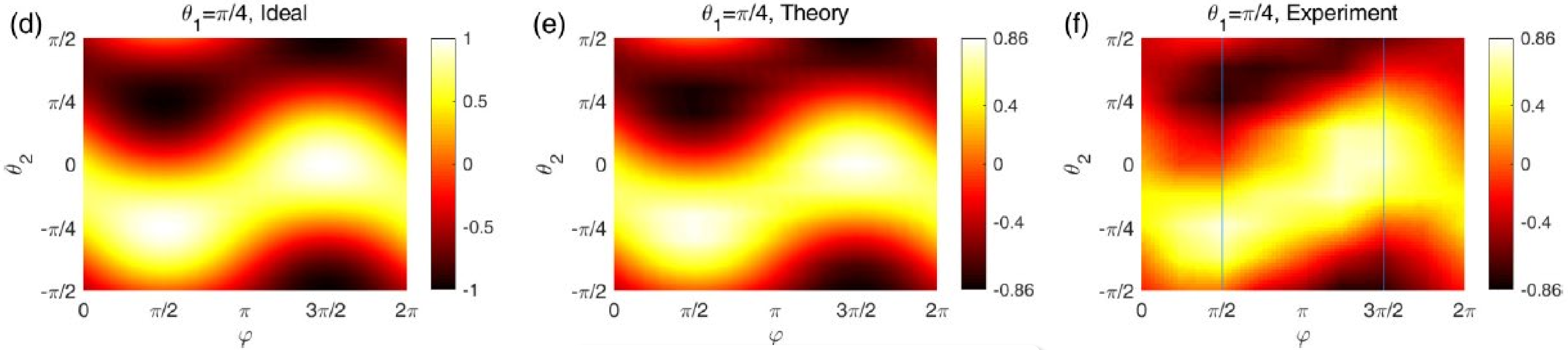


S|CA correlation function

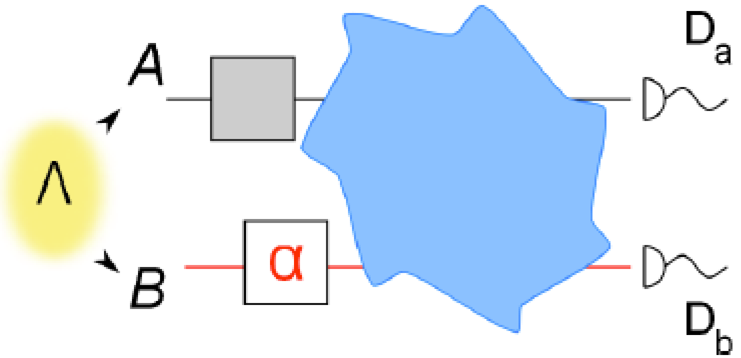
Thomas Jennewein
Rob Mann

Radu Ionicioiu

Časlav Brukner

Ma Xiaosong
Wang Kai
Zhu Xining

a bonus feature: HV & three incompatible assumptions



(*) Adequacy

Empirical statistics

$$e(a,b) = \big(xe_p, (1-x)e_w, x(1-e_p), (1-x)(1-e_w)\big)$$

$$e(b) = (x, 1-x)$$ ◀ *controller*

two types of stats ▶ $\bar{e}_{\mathrm{p}}(a) = (e_p, 1-e_p), \qquad \bar{e}_{\mathrm{w}}(a) = (e_w, 1-e_w)$

$$e(a,b) = p(a,b) = \sum_\Lambda p(a,b,\Lambda) = \sum_\Lambda p(a,b|\Lambda)\, p(\Lambda)$$

HV settings

The system is definitely one or another

$$p(a|b=1, \lambda = \mathrm{w}) = \bar{e}_{\mathrm{w}}(a)$$

$$p(a|b=0, \lambda = \mathrm{p}) = \bar{e}_{\mathrm{p}}(a)$$

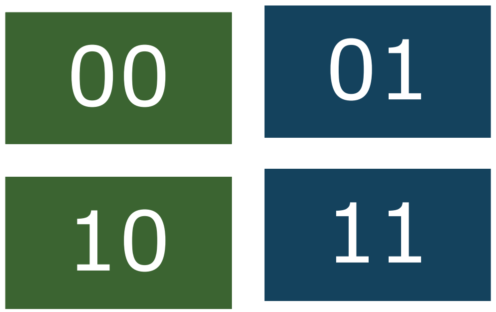
(O) Objectivity

$$\lambda = \lambda(\Lambda)$$

HV theory is (weakly) deterministic

$$p(a,b|\Lambda) = \chi_{ab}(\Lambda)$$

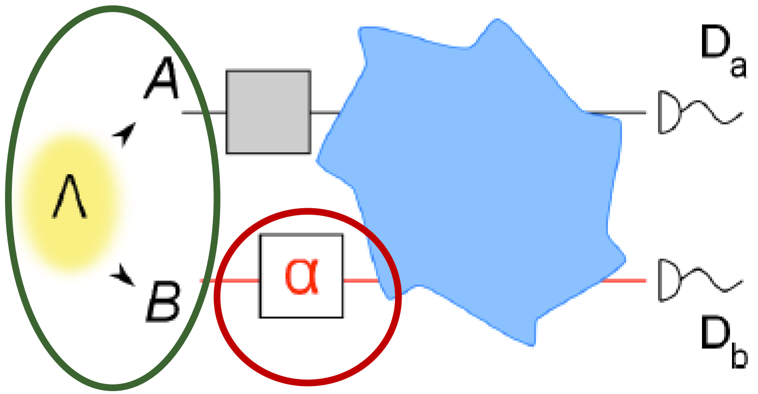
(i) Determinism



Boundaries of the regions depend on the settings

HV settings

Is λ-independent



(ii) Independence

$p(\lambda)$ is independent of the settings#

IMT, Phys. Rev. Lett. **114**, 060405 (2015)

Adequacy | three assumptions

Objectivity: two types of statistics e_p, e_w
Determinism: HV determines all the outcomes
Λ-independence: single HV that is not influenced by the settings

HV (i-ii) simulate QM

if we don't ask too much

- Assume a uniform distribution $p(\Lambda)$

  (ii) is satisfied

- Follow the weak determinism: let $\mathcal{L}_{ij}$ to depend on the measurement parameters

$$p(i,j\,|\,\alpha,\ldots,\Lambda)=1 \quad \forall\Lambda\in\mathcal{L}_{ij}$$

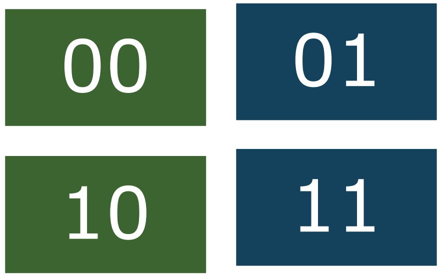
  (i) is built in

- Basically cheat:

$$q_{ij} =: p_{ij} = \sum_{\Lambda} p(i,j\,|\,\alpha;\Lambda)\,p(\Lambda)$$

$$= \sum_{\Lambda\in\mathcal{L}_{ij}} 1$$

  (adequacy) is satisfied



Boundaries of the regions depend on the settings

Follows Bell, not-so-famous-paper, 1964

a contradiction

LOGIC

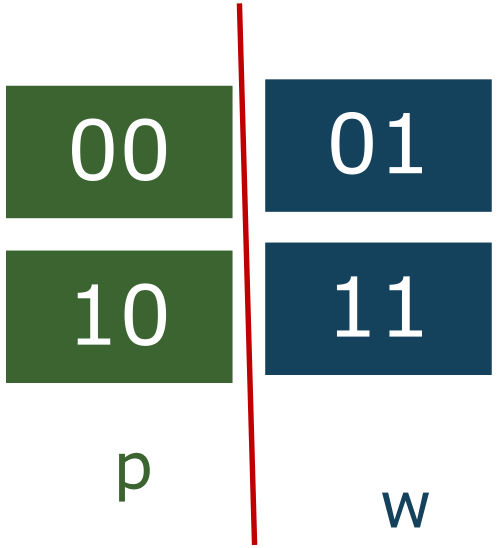
Stage 1: find a unique non-trivial solution to (i)+(ii)+(O)

Ignoring how it arises from Λ

Exists (very special), but

$$p_s(\lambda\,|\,b) = \delta_{\lambda p}\delta_{b0} + \delta_{\lambda w}\delta_{b1} = p_s(b\,|\,\lambda)$$

$$p_s(a, b, \lambda) = e(a, b)p_s(b|\lambda)$$



Stage 2: derive a contradiction

By checking how the boundaries shift (long) OR

$$p_s(\lambda) = [x(\alpha), 1 - x(\alpha)] \equiv p[\lambda(\Lambda)]$$