Quantum Optics Group

Dipartimento di Fisica and Unità INFM

Università di Roma “La Sapienza”

IST Contract n° 2000-29681
ATESIT

Research lines

- Quantum Cloning and Universal NOT gate
  F. De Martini, F. Sciarrino, C. Sias, D. Pelliccia, V. Schettini
  (coll. with V. Buzek)

- Pauli Tomography
  F. De Martini, A Mazzei, M. Ricci (coll. with M. D’Ariano)

- Frequency Hopping in Quantum Interferometry
  F. De Martini, P. Mataloni, G. Giorgi

- Active Teleportation of a Quantum Bit
  F. De Martini, F. Sciarrino, E. Lombardi, S. Giacomini, G. Milani
  (coll. with S. Popescu)

- High Brilliant source of Polarization Entangled States
  (F. De Martini, P. Mataloni, G. Giorgi, G. Di Nepi)

A New High-Brilliant Optical Parametric Source of Polarization Entangled States

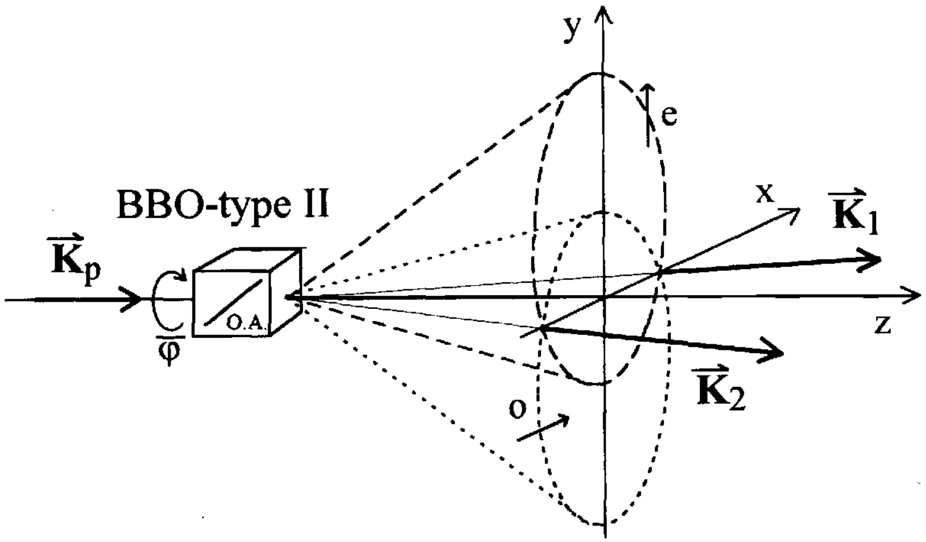
G. Giorgi, G. Di Nepi, P. Mataloni, F. de Martini,
"A High Brightness Parametric Source of Entangled Photon States",
Laser Physics, accepted for publication

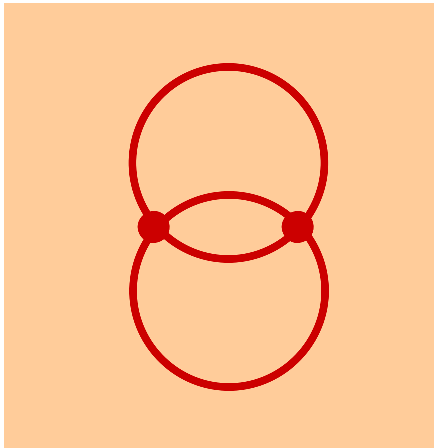
Polarization entangled "Bell States" generated in Quantum Optics by Spontaneous Parametric Down Conversion:

$$|H>_1|V>_2 \pm |V>_1|H>_2 \qquad\qquad |H>_1|H>_2 \pm |V>_1|V>_2$$

- Non-collinear type II phase matching

(Kwiat et al. PRL '95)



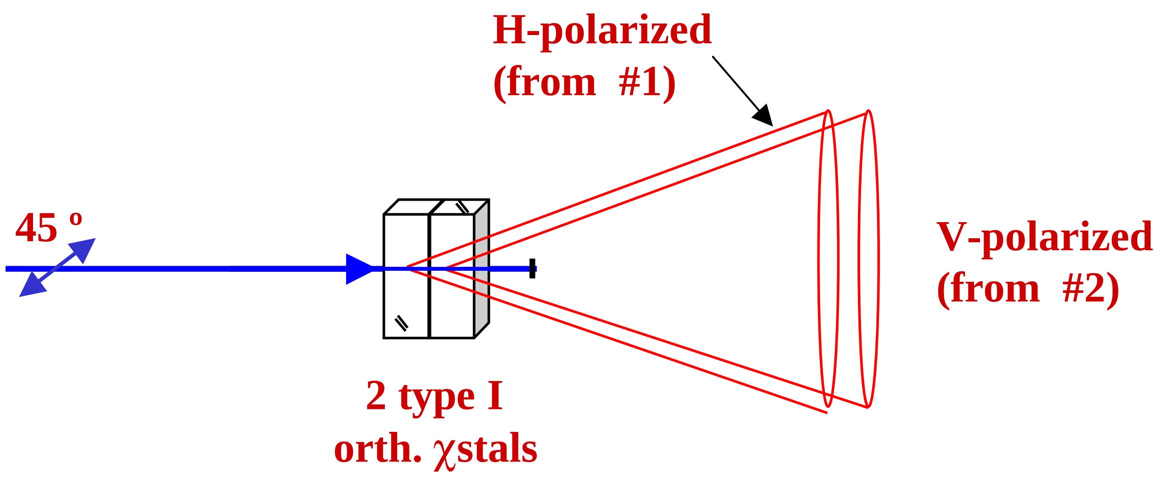


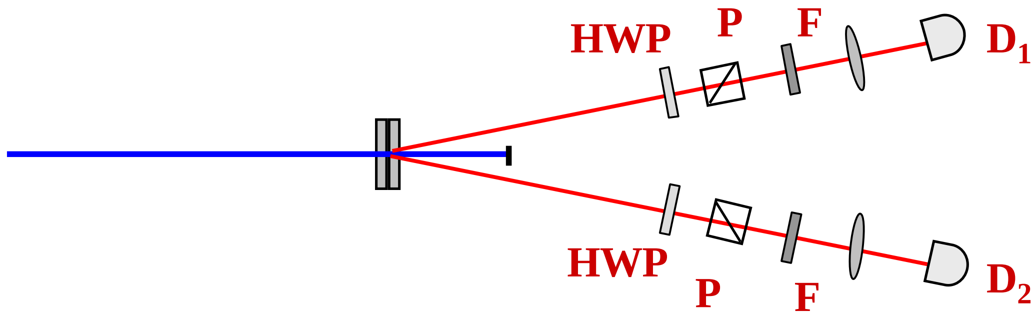
$|\Psi\rangle = |H\rangle_1 |V\rangle_2 + e^{i\phi} |V\rangle_1 |H\rangle_2$

Φ = 0: triplet state; $\Phi = \pi$: singlet state

-Two type I crystal geometry

Strong enhancement of the brightness (Kwiat et al PRA '99)



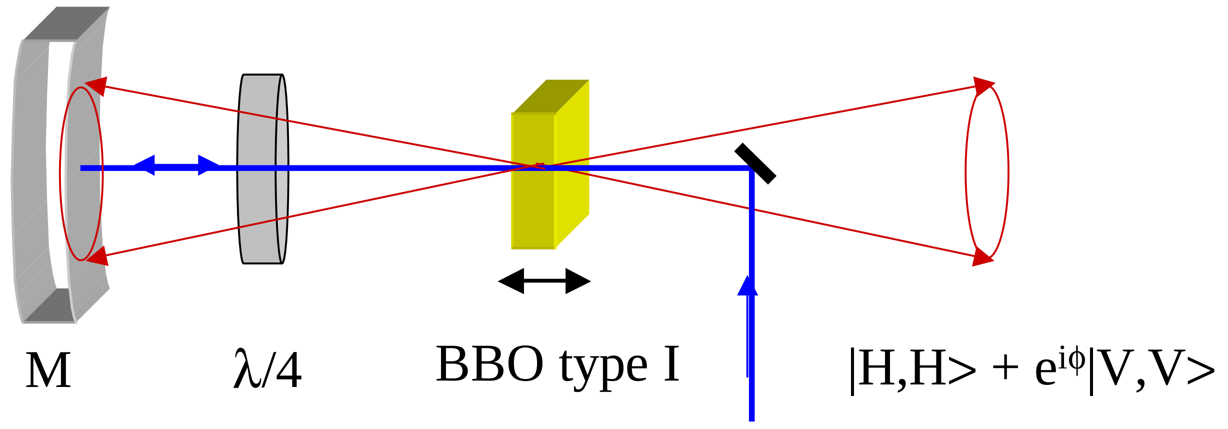


$|\Psi\rangle = |H\rangle_1 |H\rangle_2 + e^{i\phi} |V\rangle_1 |V\rangle_2$ or $|\Psi\rangle = |H\rangle_1 |V\rangle_2 + e^{i\phi} |V\rangle_1 |H\rangle_2$

- Our proposal:

Polarization entangled photon pairs generated by a single type I phase matched crystal

- Complete overlapping of the emission cones
- Possible detection of the whole emission cone
- $\rightarrow$ brightness enhancement



1) Detection of the SPDC particle pairs over the entire set of the wavevectors

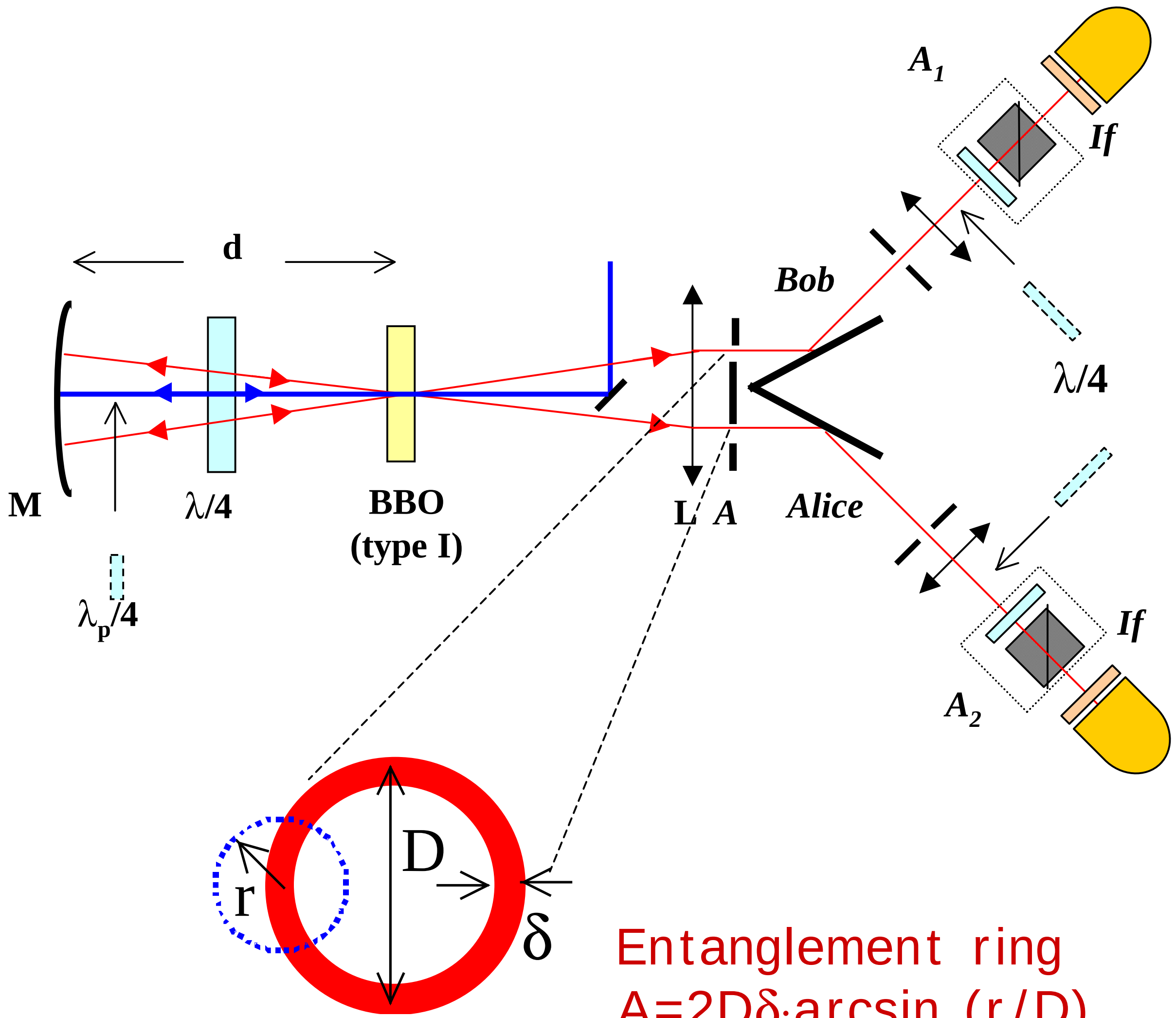
$\rightarrow$ entangled state accessible to the detection apparatus $\equiv$ pure state

2) Bell'inequalities violation in conditions of measurement of the ensemble joint detection probabilities

$\rightarrow$ no need for supplementary assumptions as "fair sampling" and "no-enhancement"

Garuccio, PRA, '95; Santos, PRL '91;
Clauser,Horne,Shimony,Holt, PRL '69 Clauser,Horne, PRD '74

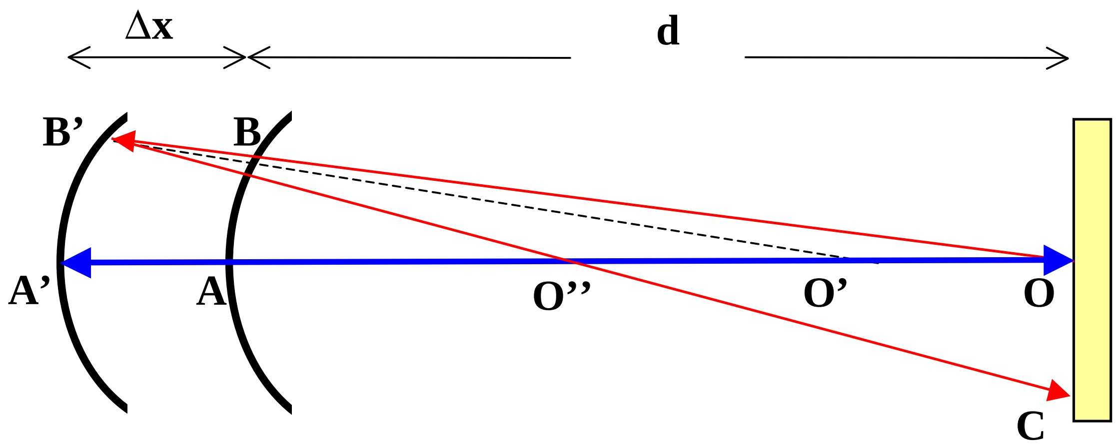
High brilliant Source - Experimental setup



Entanglement ring

$A = 2D\delta \cdot \arcsin(r/D)$

Phase control

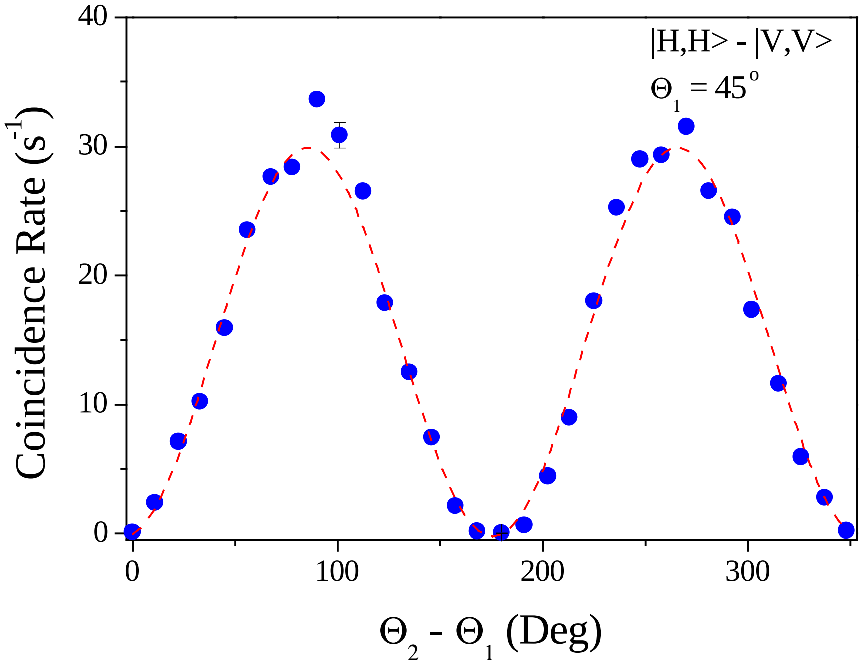


ϕ easily adjusted by micrometric translation of mirror M respect to the crystal:

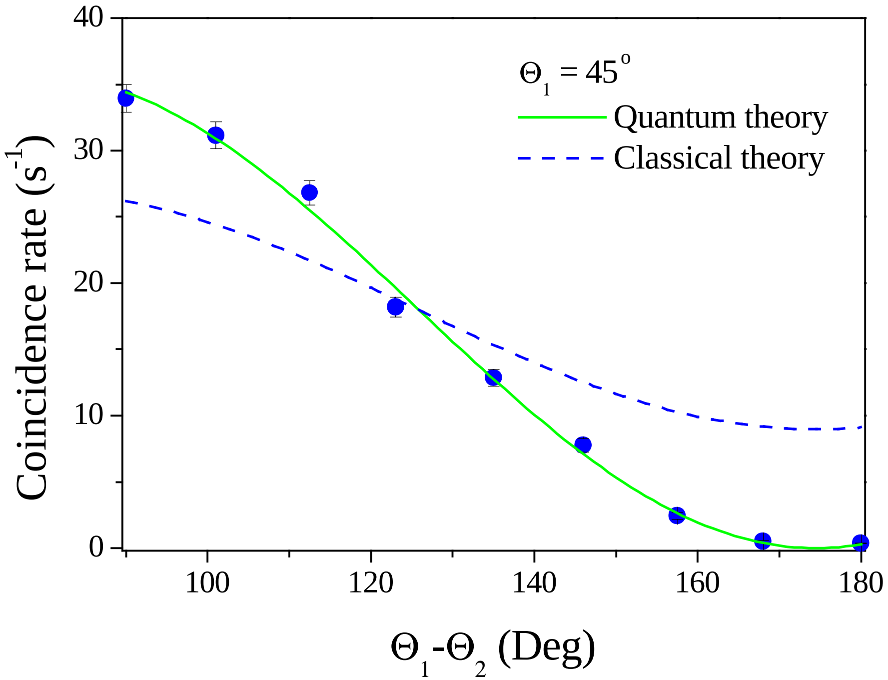
round-trip optical path delay: 2(OA') - 2(OB' + B'C) = $\lambda/2$

$\rightarrow$ $\phi = \pi \Leftrightarrow \Delta x \equiv AA' = 55\ \mu m$ (OC ≈ 5 μm)

Measurement of the polarization entanglement

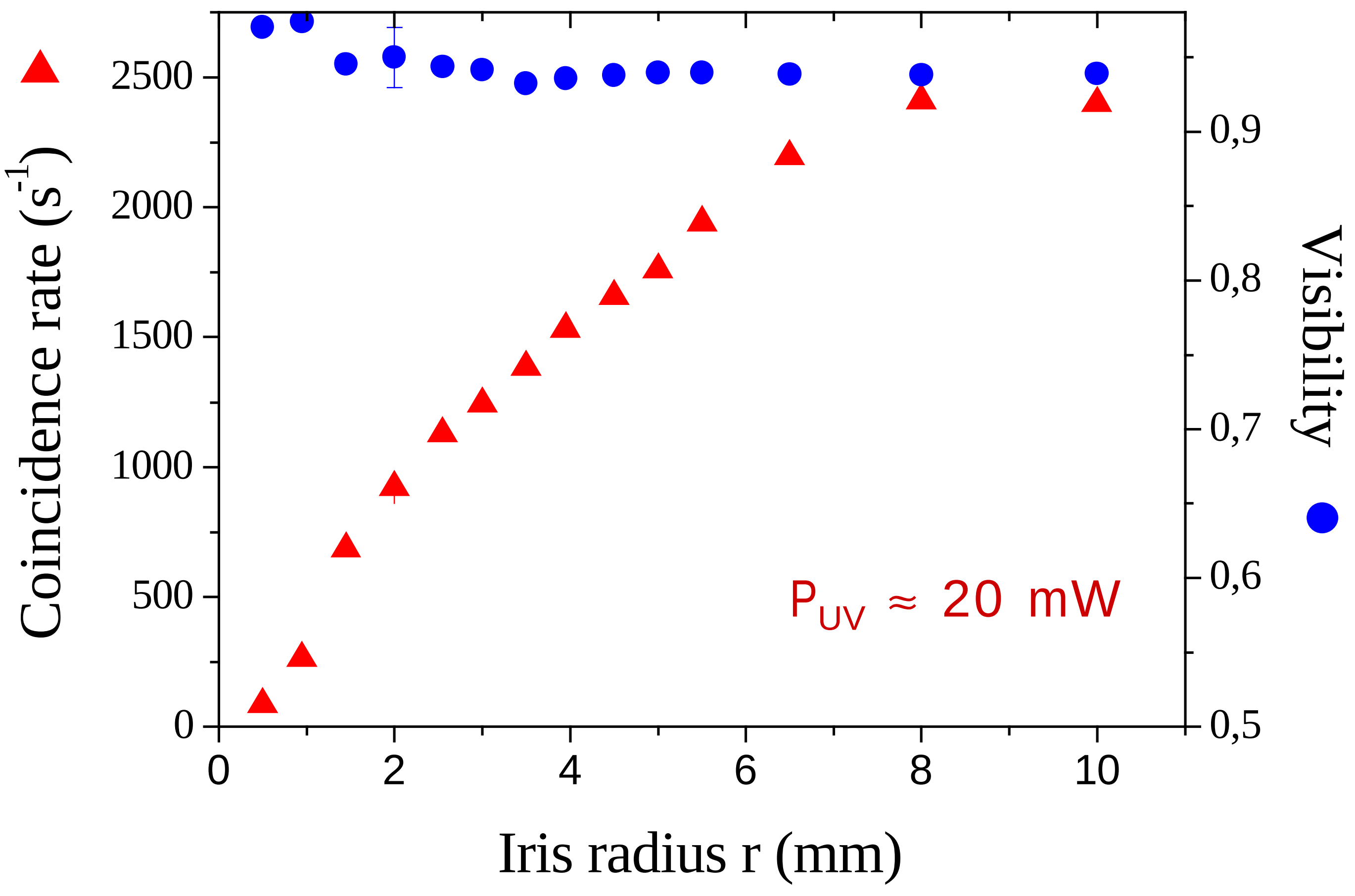


Visibility ≥ 99 %



Measurement of the robustness and brightness

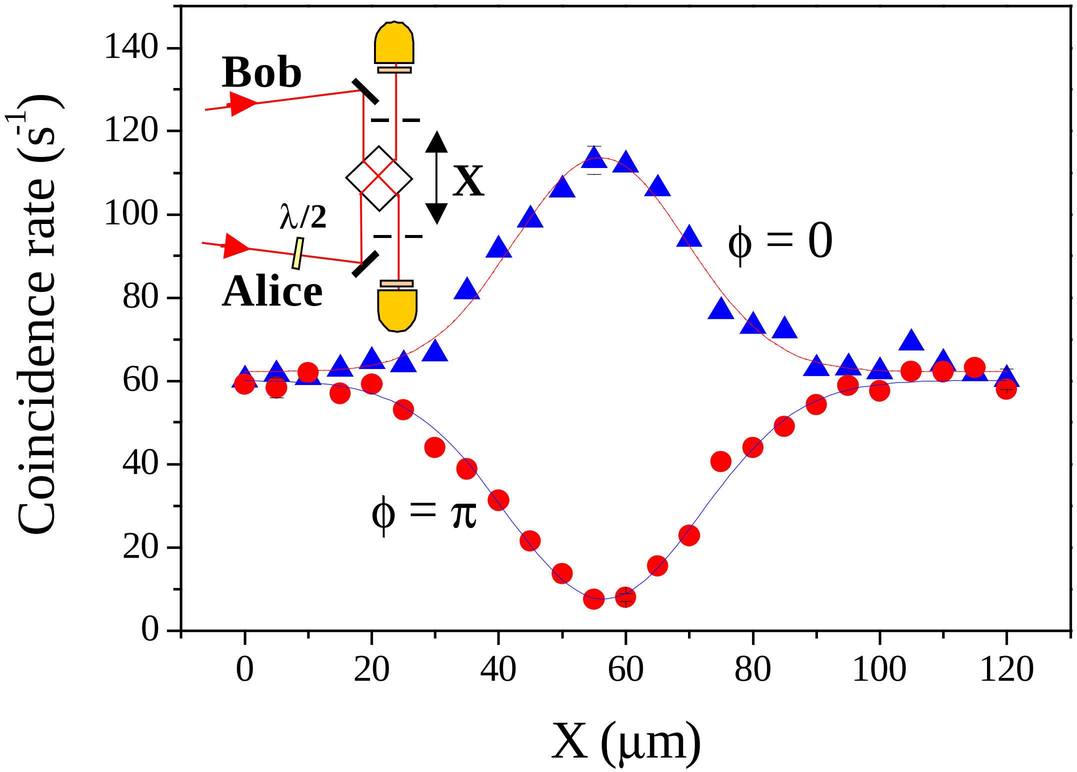
- more than $2 \cdot 10^5$ s^{-1} entangled photon pairs produced over the entire emission cone

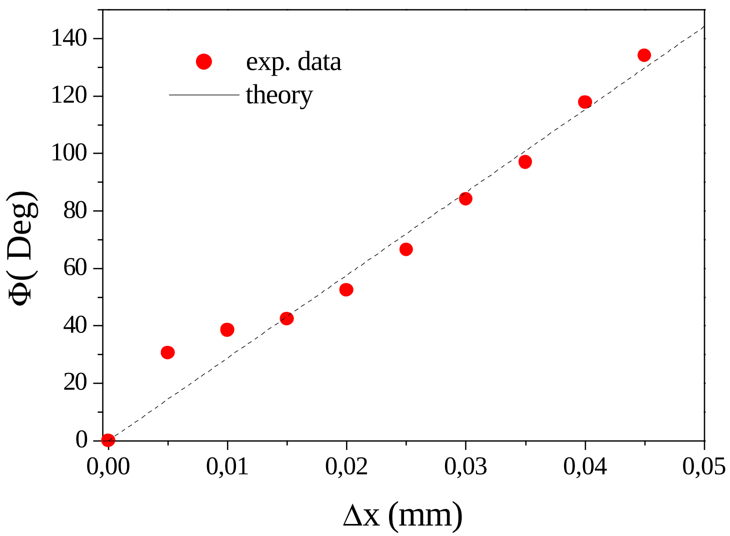


Ou-Mandel Interferometry

|H,V> + $e^{i\phi}$|V,H>

Vis. ≈ 88%
FWHM = 35 μm



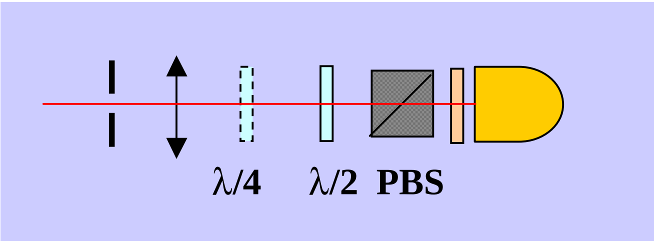


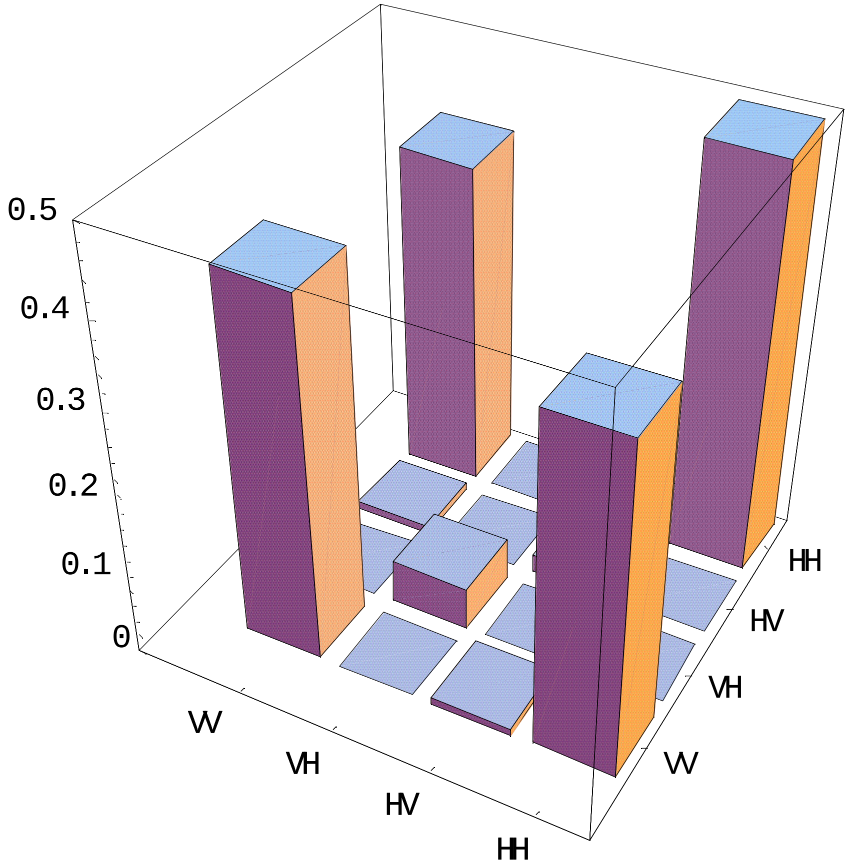
Transition from triplet to singlet easily obtained by varying Δx:

$\phi = \arccos\,(C_{\Delta x} / C_0)$

Tomographic reconstruction of the density matrix

- obtained by inserting the λ/4 plates on the detection arms





$|\Psi\rangle = 1/\sqrt{2}(|H,H\rangle + |V,V\rangle)$

Measurement performed over ≈ 50% of the ring

Contribution of the imaginary terms is negligible

Violation of Bell inequality

State $|\Psi\rangle = 1/\sqrt{2}(|H,H\rangle - |V,V\rangle)$

$$2 \geq S = |P(\theta_1, \theta_2) - P(\theta_1, \theta'_2)| + |P(\theta'_1, \theta_2) + P(\theta'_1, \theta'_2)|$$

$$P(\theta_1, \theta_2) = \frac{C(\theta_1, \theta_2) + C(\theta^{\perp}_1, \theta^{\perp}_2) - C(\theta_1, \theta^{\perp}_2) - C(\theta^{\perp}_1, \theta_2)}{C(\theta_1, \theta_2) + C(\theta^{\perp}_1, \theta^{\perp}_2) + C(\theta_1, \theta^{\perp}_2) + C(\theta^{\perp}_1, \theta_2)}$$

$\theta_1 = 0°$, $\theta_2 = 22.5°$, $\theta'_1 = 45°$, $\theta'_2 = 67.5°$, $\theta^{\perp}_i = \theta_i + 90°$

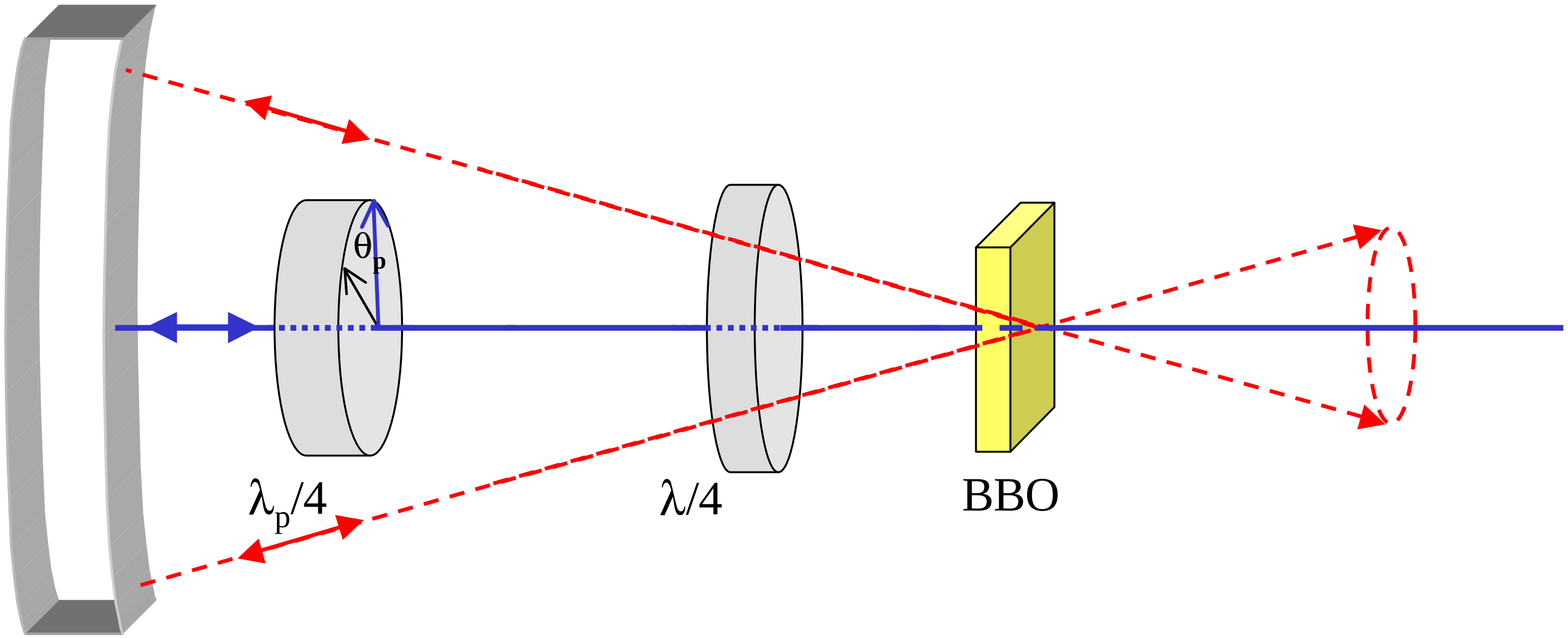
Over 180 s statistics:

r = .075 cm: $S = 2.6888 \pm .0048 \rightarrow$ 143-σ violation

no diaphragm: $S = 2.5564 \pm .0026 \rightarrow$ 213-σ violation

Generation of non maximally entangled states

- inserting the $\lambda_p/4$ plate between mirror and crystal
- pump vector rotation (after 2 passes) = $2\theta_p$



$|\Phi\rangle = \alpha|H,H\rangle + \beta|V,V\rangle$, $|\alpha| = \gamma/(1+\gamma^2)$, $|\beta| = 1/(1+\gamma^2)$, $\gamma = \cos(2\theta_p)$

$\rightarrow \quad 0 \leq \theta_p \leq 45° \Leftrightarrow 1 \leq \gamma \equiv |\alpha/\beta| \leq 0$ <u>No post-selection</u>

Hardy's ladder proof on non nonlocality with non maximally entangled states

Two photons, A & B, belonging to a generic polarization entangled state $|\Phi\rangle = |\alpha||H,H\rangle - |\beta||V,V\rangle$

Polarization measurements performed along the K+1 analyzer directions A_k and B_k ($k = 0$ to K)

$A_k = 1 \Leftrightarrow$ photon detected along direction A_k
$A_k = 0 \Leftrightarrow$ photon detected along direction $A^{\perp}_k$

the same for analyzer directions B_k

$$\Rightarrow \quad \begin{aligned} & P_K = \mathrm{Prob}(A_K = 1,\ B_K = 1) \neq 0 \\ & \mathrm{Prob}(A_k = 1,\ B_{k-1} = 0) = 0, \text{ for } k = 1 \text{ to } K \\ & \mathrm{Prob}(A_{k-1} = 0,\ B_k = 1) = 0, \text{ for } k = 1 \text{ to } K \\ & \mathrm{Prob}(A_0 = 1,\ B_0 = 1) = 0 \end{aligned}$$

Logical contraddiction of local realism given by violation of the inequality (given by 2K+2 terms):

$$\mathrm{Prob}(A_K = 1, B_K = 1) \leq \mathrm{Prob}(A_0 = 1, B_0 = 1) + \\ + \sum_{k=1}^{K} \left[\mathrm{Prob}(A_k = 1, B_{k-1} = 0) + \mathrm{Prob}(A_{k-1} = 0, B_k = 1)\right]$$

Hardy, PRL '93, Boschi et al., PRL '97

Experimental demonstration more and more difficult as K increases because of:

- unperfect definition of the state
- experimental uncertainties within the 2K+1 measurements

experiments performed up to now for $K \leq 3$

Ultrabright source useful for:

- High purity of the state
- High brilliance
- Possible detection of photon pairs over the entire cone of emission
- High phase stability
- Easy tunability of entanglement

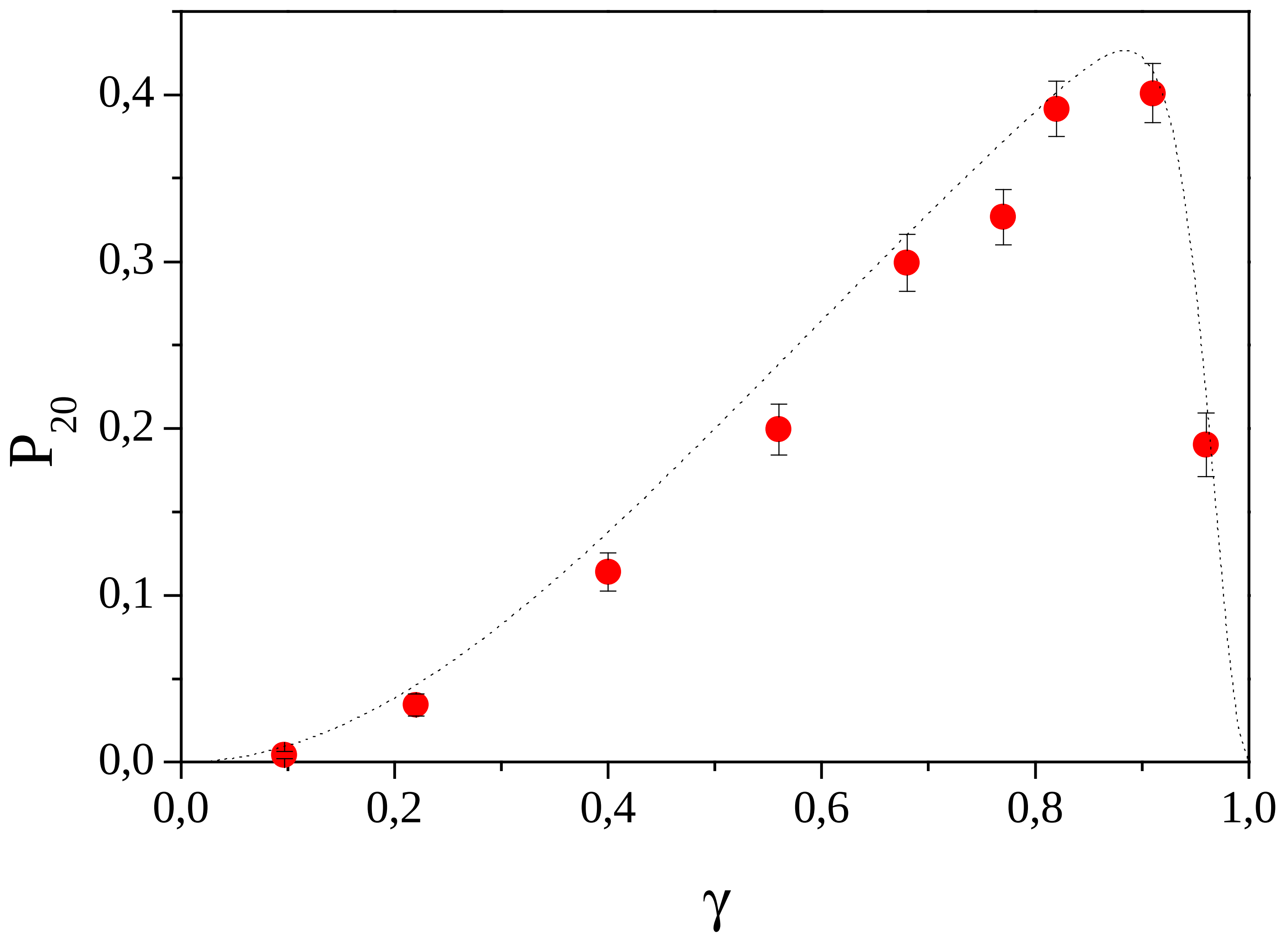
$\rightarrow$ Large values of K may be experimentally investigated

K = 20 experiment (2K+2 = 42 different sets of measurement)

time of measurement = 60 s $\rightarrow$ 10-σ violation of the inequality

(θ_A, θ_B)	$P(\theta_A, \theta_B)$
$\theta_{20} = 4.7, \theta_{20} = 4.7$	0.401 ± 0.00161
$\theta_{20} = 4.7, \theta^{\perp}_{19} = 84.7$	0.01117 ± 0.00027
$\theta^{\perp}_{19} = 84.7, \theta_{20} = 4.7$	0.0104 ± 0.00026
$\theta_{19} = -5.3, \theta^{\perp}_{18} = 96$	0.01348 ± 0.00029
$\theta^{\perp}_{18} = 96, \theta_{19} = -5.3$	0.00809 ± 0.00023
$\theta_{18} = 6, \theta^{\perp}_{17} = 83.3$	0.00963 ± 0.00025
$\theta^{\perp}_{17} = 83.3, \theta_{18} = 6$	0.00848 ± 0.00023
$\theta_{17} = -6.7, \theta^{\perp}_{16} = 97.6$	0.01156 ± 0.00027
$\theta^{\perp}_{16} = 97.6, \theta_{17} = -6.7$	0.00924 ± 0.00024
$\theta_{16} = 7.6, \theta^{\perp}_{15} = 81.4$	0.00924 ± 0.00024
$\theta^{\perp}_{15} = 81.4, \theta_{16} = 7.6$	0.00655 ± 0.00021
$\theta_{15} = -8.6, \theta^{\perp}_{14} = 99.6$	0.00963 ± 0.00025
$\theta^{\perp}_{14} = 99.6, \theta_{15} = -8.6$	0.00848 ± 0.00023
$\theta_{14} = 9.6, \theta^{\perp}_{13} = 79.1$	0.00886 ± 0.00024
$\theta^{\perp}_{13} = 79.1, \theta_{14} = 9.6$	0.00771 ± 0.00022
$\theta_{13} = -10.9, \theta^{\perp}_{12} = 102.2$	0.01309 ± 0.00029
$\theta^{\perp}_{12} = 102.2, \theta_{13} = -10.9$	0.00848 ± 0.00023
$\theta_{12} = 12.2, \theta^{\perp}_{11} = 76.2$	0.01272 ± 0.00029
$\theta^{\perp}_{11} = 76.2, \theta_{12} = 12.2$	0.01001 ± 0.00025
$\theta_{11} = -13.8, \theta^{\perp}_{10} = 105.5$	0.01425 ± 0.0003
$\theta^{\perp}_{10} = 105.5, \theta_{11} = -13.8$	0.01001 ± 0.00025
$\theta_{10} = 15.5, \theta^{\perp}_{9} = 72.6$	0.01001 ± 0.00025
$\theta^{\perp}_{9} = 72.6, \theta_{10} = 15.5$	0.00693 ± 0.00021
$\theta_{9} = -17.4, \theta^{\perp}_{8} = 109.5$	0.01001 ± 0.00025
$\theta^{\perp}_{8} = 109.5, \theta_{9} = -17.4$	0.00771 ± 0.00022
$\theta_{8} = 19.5, \theta^{\perp}_{7} = 68.2$	0.0104 ± 0.00026
$\theta^{\perp}_{7} = 68.2, \theta_{8} = 19.5$	0.00809 ± 0.00023
$\theta_{7} = -21.8, \theta^{\perp}_{6} = 114.3$	0.01079 ± 0.00026
$\theta^{\perp}_{6} = 114.3, \theta_{7} = -21.8$	0.00501 ± 0.00018
$\theta_{6} = 24.3, \theta^{\perp}_{5} = 62.9$	0.00848 ± 0.00023
$\theta^{\perp}_{5} = 62.9, \theta_{6} = 24.3$	0.01001 ± 0.00025
$\theta_{5} = -27.1, \theta^{\perp}_{4} = 120$	0.00771 ± 0.00022
$\theta^{\perp}_{4} = 120, \theta_{5} = -27.1$	0.00886 ± 0.00024
$\theta_{4} = 30, \theta^{\perp}_{3} = 56.9$	0.0054 ± 0.00019
$\theta^{\perp}_{3} = 56.9, \theta_{4} = 30$	0.00501 ± 0.00018
$\theta_{3} = -33.1, \theta^{\perp}_{2} = 126.4$	0.00924 ± 0.00024
$\theta^{\perp}_{2} = 126.4, \theta_{3} = -33.1$	0.01156 ± 0.00027
$\theta_{2} = 36.4, \theta^{\perp}_{1} = 50.2$	0.01117 ± 0.00027
$\theta^{\perp}_{1} = 50.2, \theta_{2} = 36.4$	0.01001 ± 0.00025
$\theta_{1} = -39.8, \theta^{\perp}_{0} = 133.2$	0.00693 ± 0.00021
$\theta^{\perp}_{0} = 133.2, \theta_{1} = -39.8$	0.00693 ± 0.00021
$\theta_{0} = 43.2, \theta 0 = 43.2$	0.00924 ± 0.00024

Tuning the degree of entanglement:
Probability of a coincidence measurement P_{20} vs. γ



Applications & Perspectives:

- Pulsed (femtosecond) regime (complete overlapping of the emission cones)
- Quantum Imaging (spatial extension of the entanglement ring)
- Production of different quantum states (mixed states, Werner states…...)