Violations of Bell inequalities for light in the turbulent atmosphere

made by

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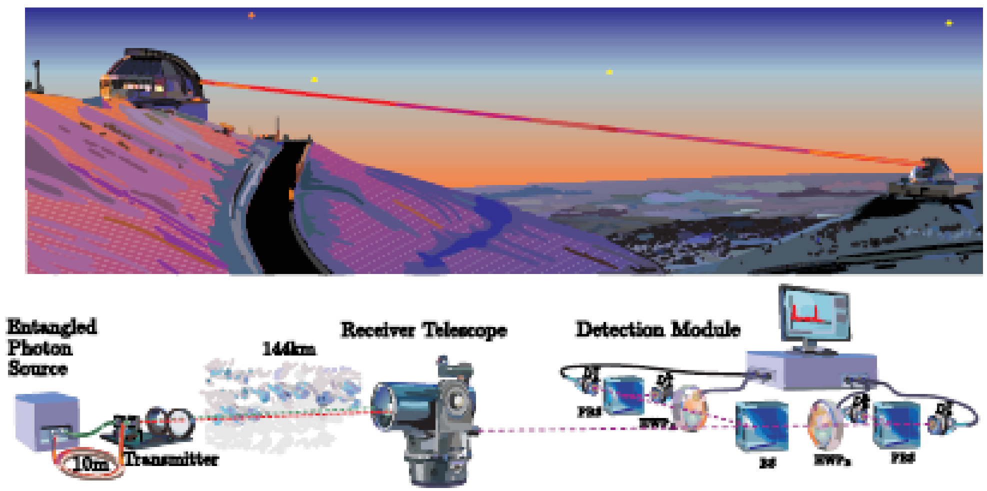
Violations of Bell inequalities

A. Fedrizzi et al., Nature Physics **5**, 389 (2009)

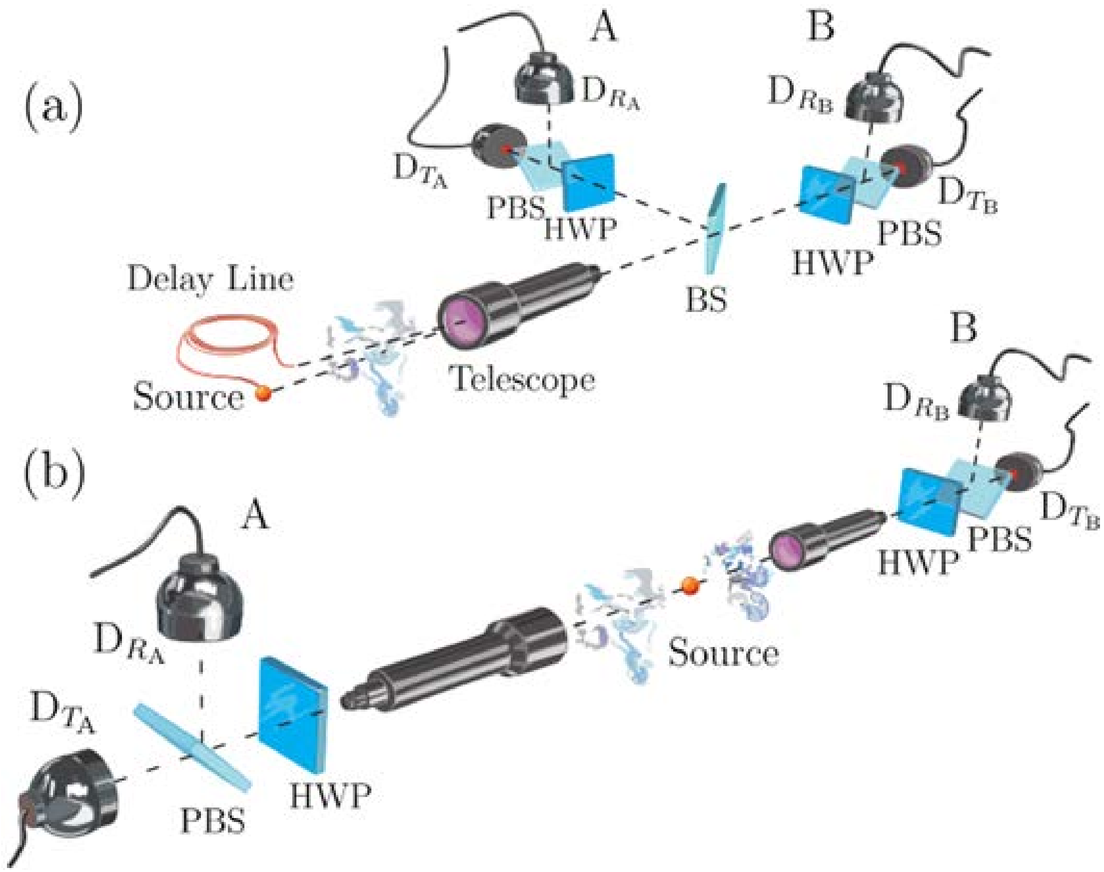


$$\mathcal{B} = 2.612 \pm 0.114$$

In 2008 Zeilinger with his group managed to transmit the entangled pair of photons over a distance of 144 km between the observatories on the islands of Palma and Tenerife.

$$B = \left|\mathrm{E}(\theta_A^{(1)}, \theta_B^{(1)}) - \mathrm{E}(\theta_A^{(1)}, \theta_B^{(2)})\right| + \left|\mathrm{E}(\theta_A^{(2)}, \theta_B^{(2)}) - \mathrm{E}(\theta_A^{(2)}, \theta_B^{(1)})\right| \le 2$$

Experimental schemes



(a) – copropagation scenario, (b) – conterpropagation scenario

Double-click events

$$
\begin{aligned}
P_{i_A,i_B}(\theta_A,\theta_B) = Tr(\hat{\Pi}^{(c)}_{i_A}\hat{\Pi}^{(c)}_{i_B}\hat{\Pi}^{(0)}_{j_A}\hat{\Pi}^{(0)}_{j_B}\hat{\rho}) + \\
+\frac{1}{2}Tr(\hat{\Pi}^{(c)}_{i_A}\hat{\Pi}^{(c)}_{i_B}\hat{\Pi}^{(c)}_{j_A}\hat{\Pi}^{(0)}_{j_B}\hat{\rho}) + \\
+\frac{1}{2}Tr(\hat{\Pi}^{(c)}_{i_A}\hat{\Pi}^{(c)}_{i_B}\hat{\Pi}^{(0)}_{j_A}\hat{\Pi}^{(c)}_{j_B}\hat{\rho}) + \\
+\frac{1}{4}Tr(\hat{\Pi}^{(c)}_{i_A}\hat{\Pi}^{(c)}_{i_B}\hat{\Pi}^{(c)}_{j_A}\hat{\Pi}^{(c)}_{j_B}\hat{\rho}),
\end{aligned}
$$

where

$$
\hat{\Pi}^{(0)}_{i_{A(\mathrm{B})}} =: \exp(-\eta \hat{a}^{\dagger}_{i_{A(\mathrm{B})}}\hat{a}_{i_{A(\mathrm{B})}} - \nu):
$$

$$
\hat{\Pi}^{(c)}_{i_{A(\mathrm{B})}} = 1 - : \exp(-\eta \hat{a}^{\dagger}_{i_{A(\mathrm{B})}}\hat{a}_{i_{A(\mathrm{B})}} - \nu):
$$

are the positive operator-valued measures for the detector $i_{A(\mathrm{B})}$, η i ν are the efficiency and the mean values of noise counts(originating from internal dark counts and background), and :: means normal ordering.

Bell states and parametric down-conversion(PDC) states

$$\left|PDC\right\rangle = \left(\cosh\xi\right)^{-2}\sum_{n=0}^{+\infty}\sqrt{n+1}\tanh^{n}\xi\left|\Phi_n\right\rangle,$$

where $$\left|\Phi_n\right\rangle = \frac{1}{\sqrt{n+1}}\sum_{m=0}^{n}(-1)^m\left|n-m\right\rangle_{H_A}\left|m\right\rangle_{V_A}\left|m\right\rangle_{H_B}\left|n-m\right\rangle_{V_B}$$

При $n=1$ ⇨

⇨ $$\left|\Phi_1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|1\right\rangle_{H_A}\left|0\right\rangle_{V_A}\left|0\right\rangle_{H_B}\left|1\right\rangle_{V_B} - \left|0\right\rangle_{H_A}\left|1\right\rangle_{V_A}\left|1\right\rangle_{H_B}\left|0\right\rangle_{V_B}\right)$$

- Bell state.

$$\hat{\rho} = \left|PDC\right\rangle\left\langle PDC\right| = f(\xi) \quad \Rightarrow \quad P_{i_A,i_B}(\theta_A,\theta_B)$$

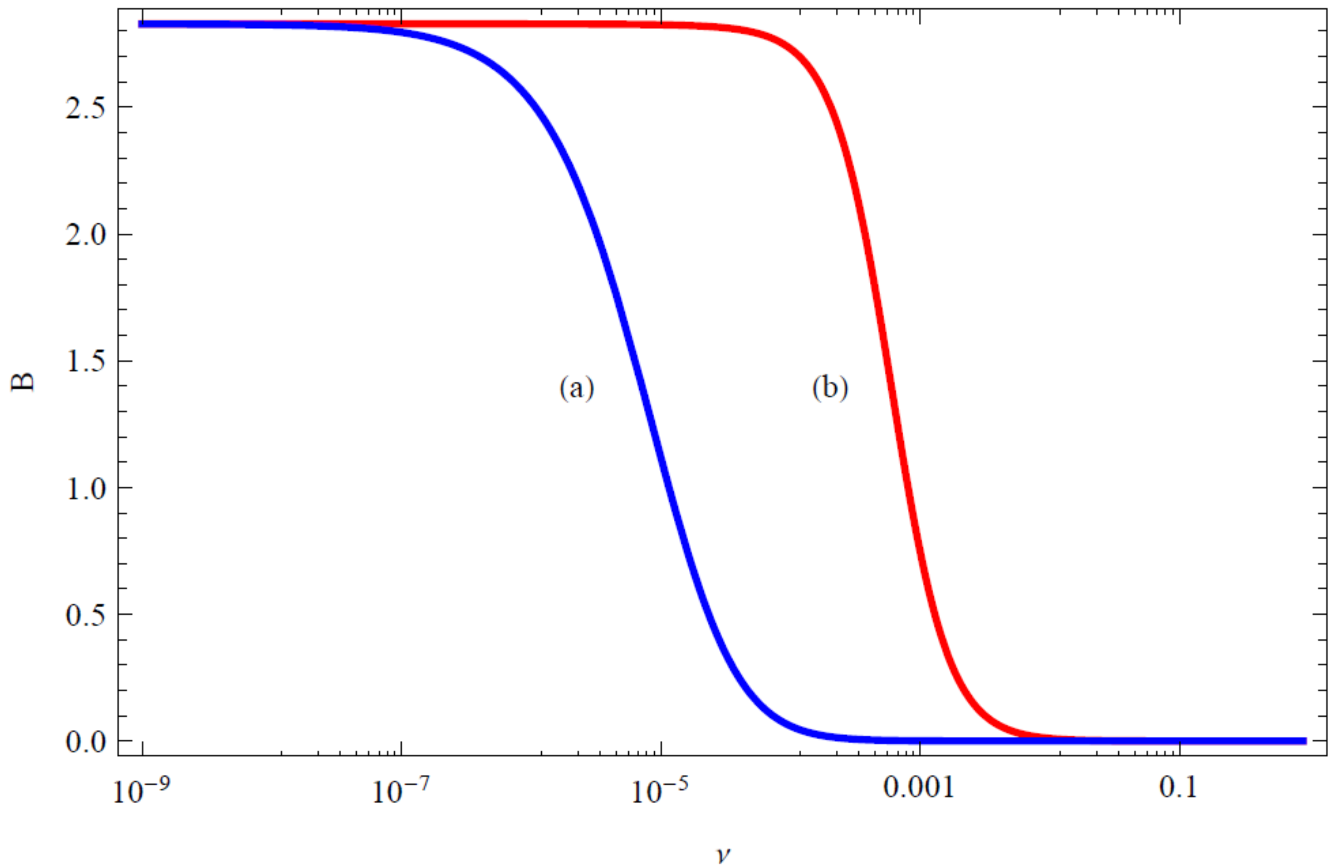
$$P_{same}(\theta_A,\theta_B) = P_{T_A,\mathrm{T}_B}(\theta_A,\theta_B) + P_{R_A,\mathrm{R}_B}(\theta_A,\theta_B)$$

$$P_{different}(\theta_A,\theta_B) = P_{T_A,\mathrm{R}_B}(\theta_A,\theta_B) + P_{R_A,\mathrm{T}_B}(\theta_A,\theta_B)$$

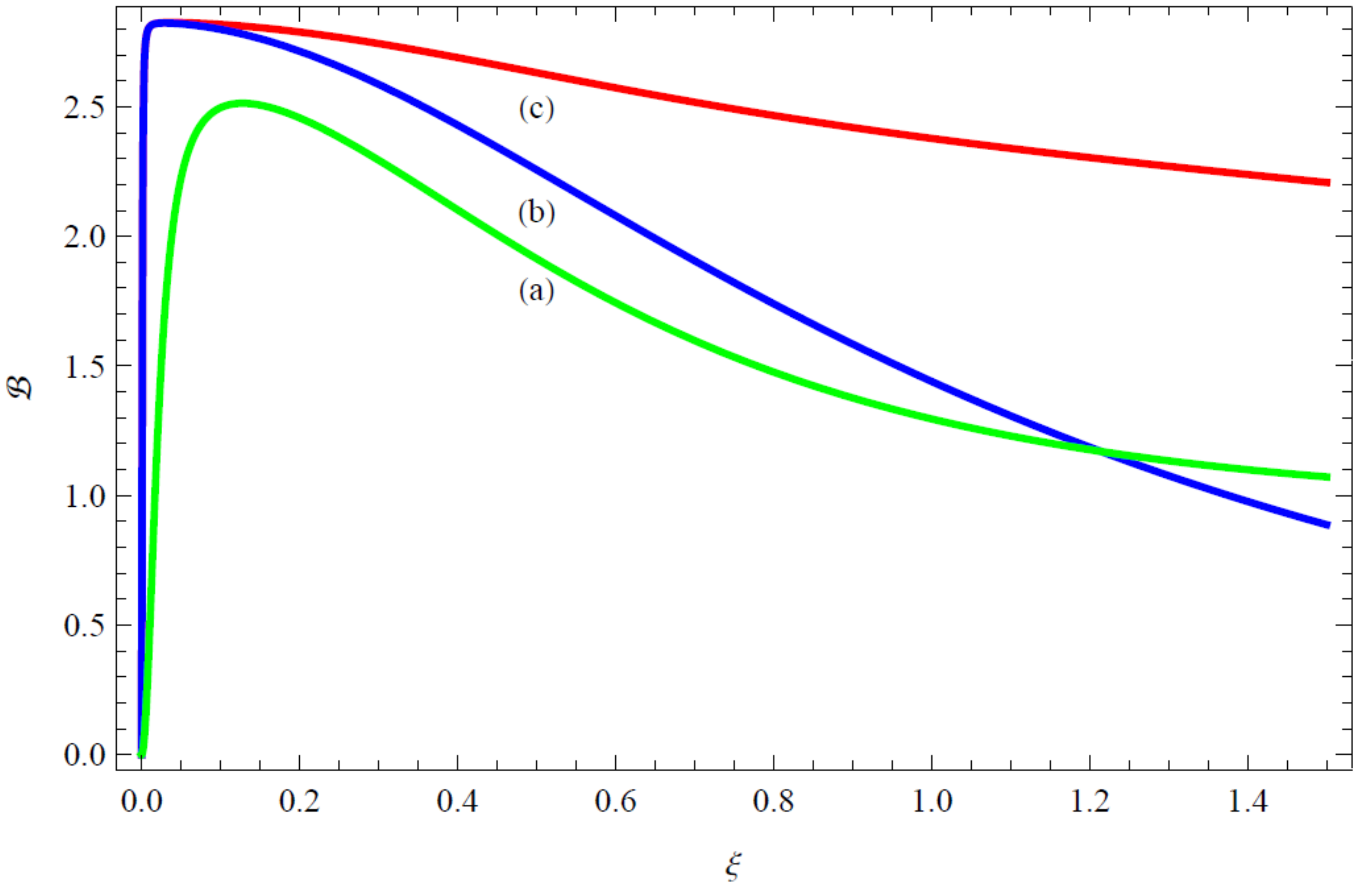
$$\mathrm{E}(\theta_A,\theta_B) = \frac{P_{same}(\theta_A,\theta_B) - P_{different}(\theta_A,\theta_B)}{P_{same}(\theta_A,\theta_B) + P_{different}(\theta_A,\theta_B)}$$

$$\Rightarrow \quad B = \left|\mathrm{E}(\theta_A^{(1)},\theta_B^{(1)}) - \mathrm{E}(\theta_A^{(1)},\theta_B^{(2)})\right| + \left|\mathrm{E}(\theta_A^{(2)},\theta_B^{(2)}) - \mathrm{E}(\theta_A^{(2)},\theta_B^{(1)})\right| = B(\xi)$$

Correlated fading channels

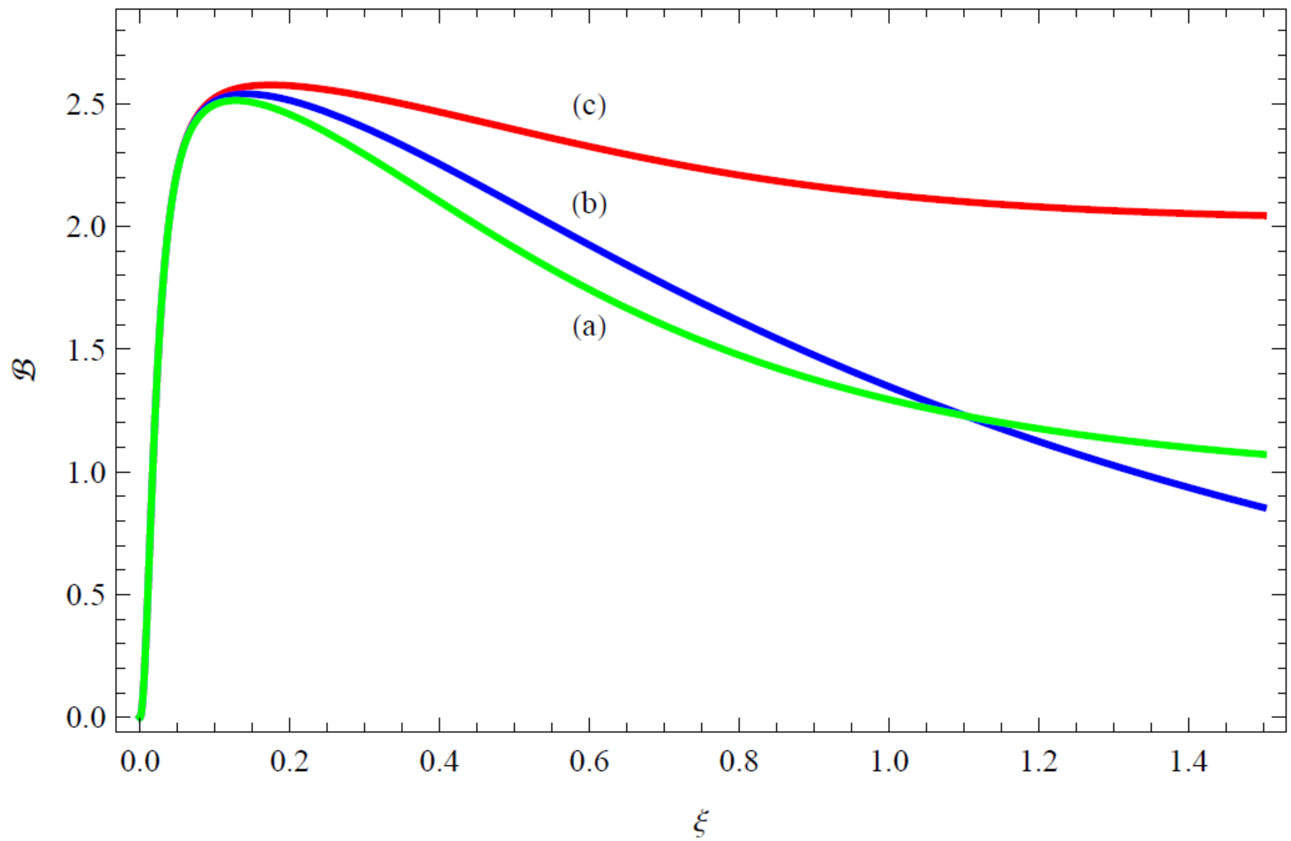


The Bell parameter B with the mean values of noise ν for Bell states: (a) – deterministic attenuation, (b) – with and without consideration of double-click events.



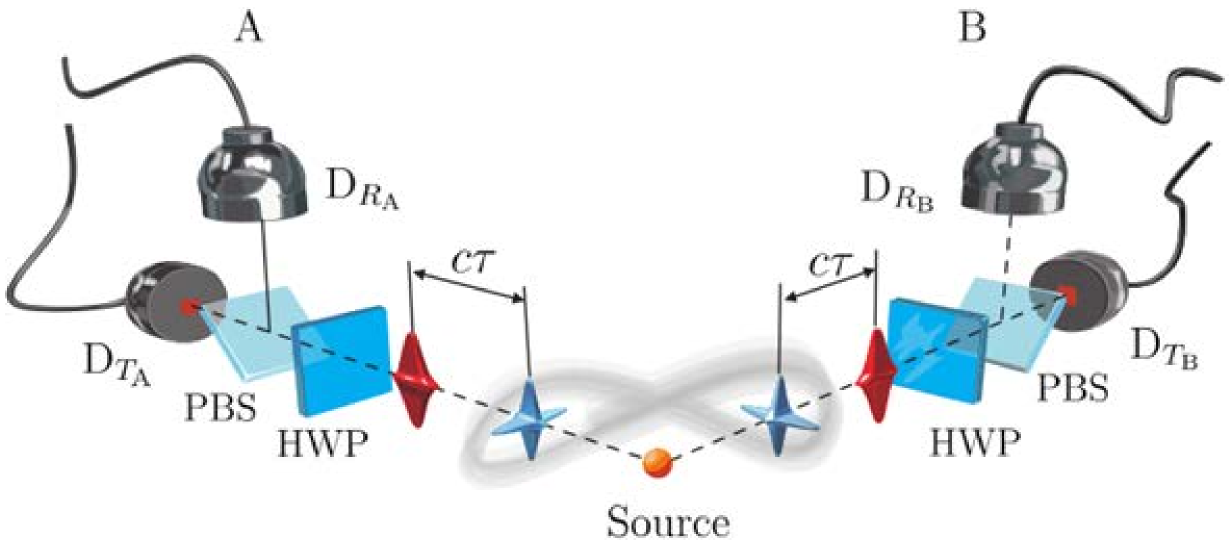
The Bell parameter B with the squeezing parameter ξ for PDC states: (a) – deterministic attenuation, (b), (c) – with and without consideration of double-click events.

Uncorrelated fading channels



The Bell parameter B with the squeezing parameter ξ for PDC states: (a) – deterministic attenuation, (b), (c) – with and without consideration of double-click events.

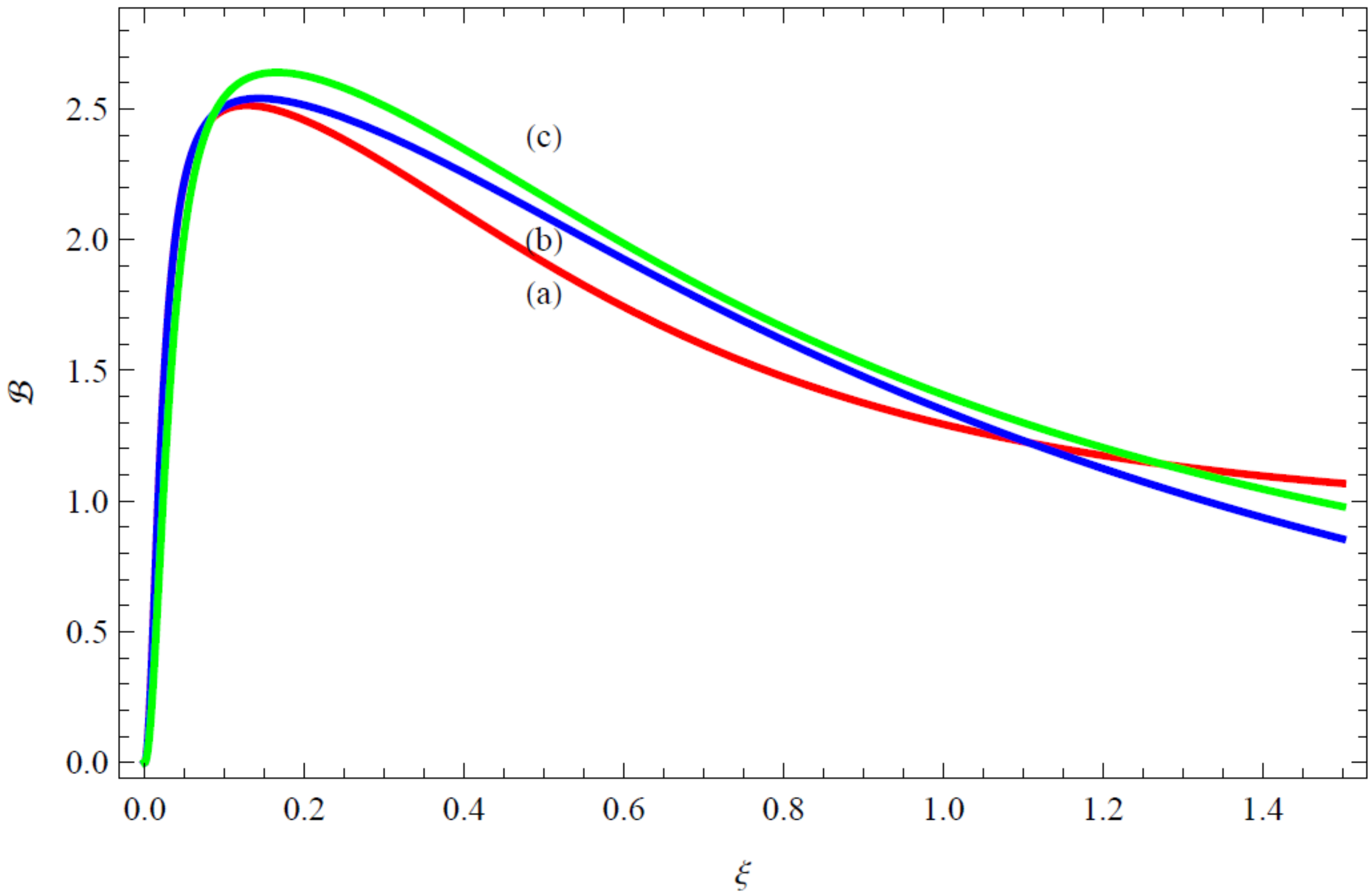
Adaptive correlation of uncorrelated channels



Intense classical-light pulses are sent before nonclassical pulses in order to test the transmittances of the channels. The time τ is much less than the characteristic time for which the atmosphere is changed..

If $T_A < T_B$, then $\mathrm{T}T_B = T_A$.

If $T_A > T_B$, then $\mathrm{T}T_A = T_B$.



The Bell parameter B with the squeezing parameter ξ for PDC states: (a) – deterministic attenuation, (b), (c) – scenario of counter-propagation with and without the application of adaptive protocol and consideration of double-click events..

Summary and conclusions

1. Double-click events do not affect sufficiently on Bell-parameter values in the case of co-propagation. However, with increasing the part of multi-photon pairs from the PDC source the corresponding Bell parameter diminishes much faster comparing to one for which double-click events have not been considered;

2. A different behavior takes a place in the scenario of counter-propagation, when fading channels are uncorrelated. The presence of multi-photon pairs leads to a relatively better result for fading channels comparing to the standard attenuation also for the case with double-click events;

3. Adaptive protocol may improve the result also in the case with double-click events for some optimal number of multi-photon pairs. Therefore, in the case of counter-propagation we have a possibility to explore advantages of fading in order to improve characteristics of quantum channels.

Thank you for attention!