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Entangled photons from semiconductor and violation of Bell's inequality

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Preliminary results: Nature **431,** 167-170 (2004)

Outline

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1. Introduction
   - Quantum photon sources using semiconductors
   - Generation of entangled photon pairs:
     Atomic cascade, parametric down-conversion (PDC), and hyper parametric scattering (HPS)
   - Biexciton-resonant HPS in CuCl crystal
2. Experimental procedure
3. Results and discussion
   - Detection of correlated photon pairs via HPS
   - Measurement of the two-photon polarization state -quantum state tomography-
   - Violation of CHSH-Bell's inequality
4. Summary and outlook

Quantum photon sources using semiconductors

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Near-future goal: SPED, EPED

Single photon sources

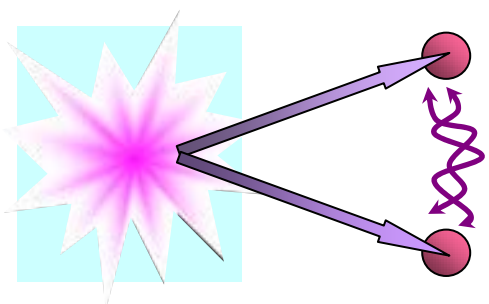
Optically pumped quantum dot

P. Michler, *et al*., Science **290**, 2282 (2000)
C. Santoni, *et al*., PRL **86**, 1502 (2001)

Current-driven quantum dot

Z. Yuan, *et al*., Science **295**, 102 (2002)

Entangled photon source of semiconductors ?



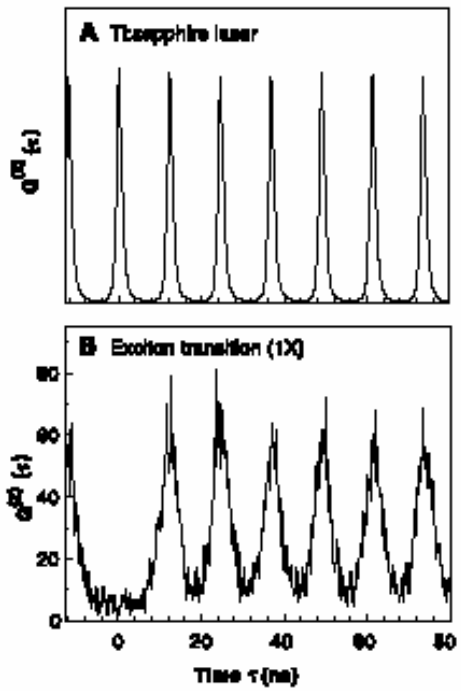


Fig. 3. Measured unnormalized correlation function $G^{(2)}(\tau)$ of (**A**) a mode-locked Ti:sapphire laser (FWHM = 250 fs) and (**B**) a single QD excitonic ground state (1X) emission under pulsed excitation conditions (82 MHz). The QD 1X transition was out of resonance with the microdisk modes.

Generation of polarization-entangled photon pairs

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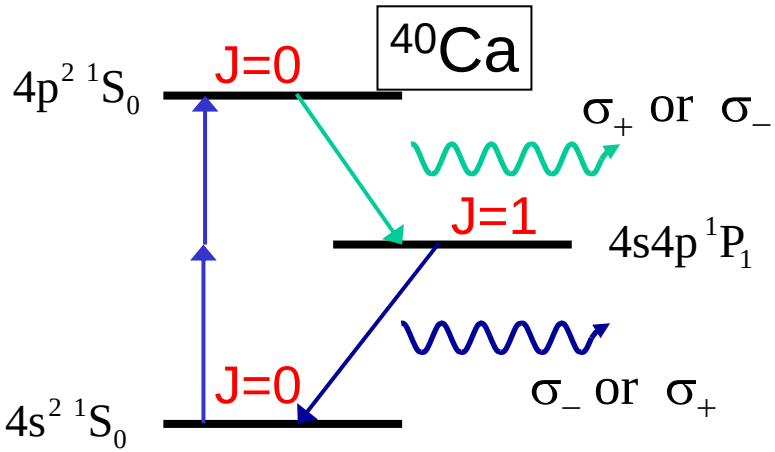
Cascade emission from an atom

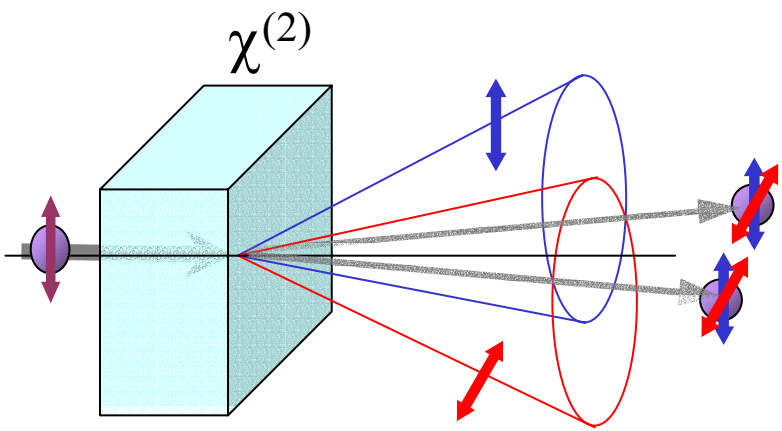


$$\frac{1}{\sqrt{2}}\left(|R\rangle_1|L\rangle_2+|L\rangle_1|R\rangle_2\right)$$

$$=\frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2+|V\rangle_1|V\rangle_2\right)$$

A. Aspect, *et al.*, PRL 47, 460 (1981)

Parametric down conversion (Nonlinear crystal)



$$\frac{1}{\sqrt{2}}\left(|H\rangle_1|V\rangle_2+e^{i\alpha}|V\rangle_1|H\rangle_2\right)$$

P.G. Kwiat *et al.*, PRL 75, 4337 (1995)
P.G. Kwiat *et al.*, PRA 60, R773 (1999)

Entangled photon-pair generation via biexciton states

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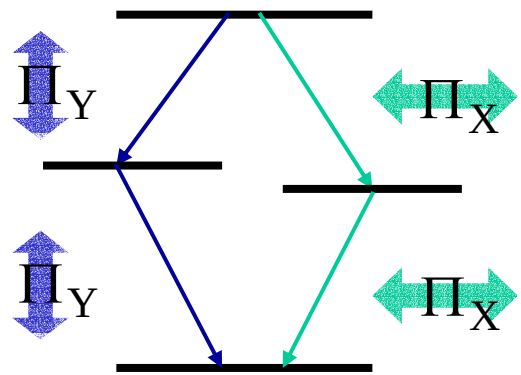
Biexciton cascade emission from a quantum dot

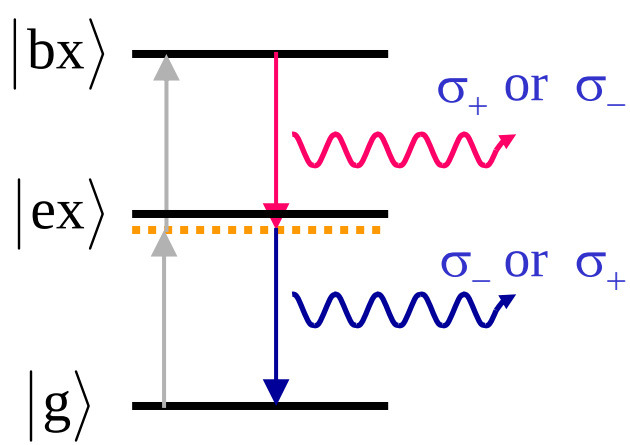


$$\frac{1}{\sqrt{2}}\left(|\sigma_+,\sigma_-\rangle + |\sigma_-,\sigma_+\rangle\right)$$

O. Benson, *et al.*, PRL **84**, 2513 (2000)
C. Santori, *et al*., PRB **66**, 045308 (2002)

No entanglement has been reported until recently

Hyper Parametric Scattering (HPS)



Bulk Crystal

$$\frac{1}{\sqrt{2}}\left(|\sigma_+,\sigma_-\rangle + |\sigma_-,\sigma_+\rangle\right)$$

Formation mechanism of polarization entanglement

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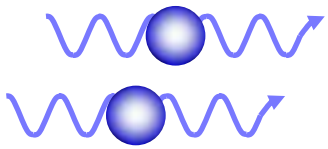
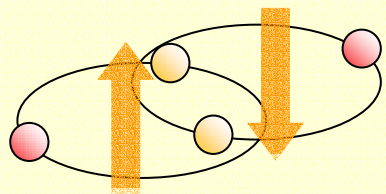
Pump photons (Laser light)



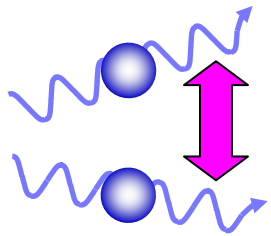
$$\begin{cases} |V\rangle|V\rangle \text{ or} \\ |H\rangle|H\rangle \text{ or} \\ |R\rangle|L\rangle \text{ or} \\ |L\rangle|R\rangle \end{cases}$$

Biexciton(J=0)



$$|+\rangle|-\rangle + |-\rangle|+\rangle$$

Scattered photon pair



Entangled!

$$|R\rangle|L\rangle + |L\rangle|R\rangle = |H\rangle|H\rangle + |V\rangle|V\rangle$$

The lowest biexciton state has zero angular momentum (J=0).

The generated photon pair has polarization entanglement

Biexciton-resonant HPS in CuCl: Two-photon resonant polariton scattering

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CuCl single crystal

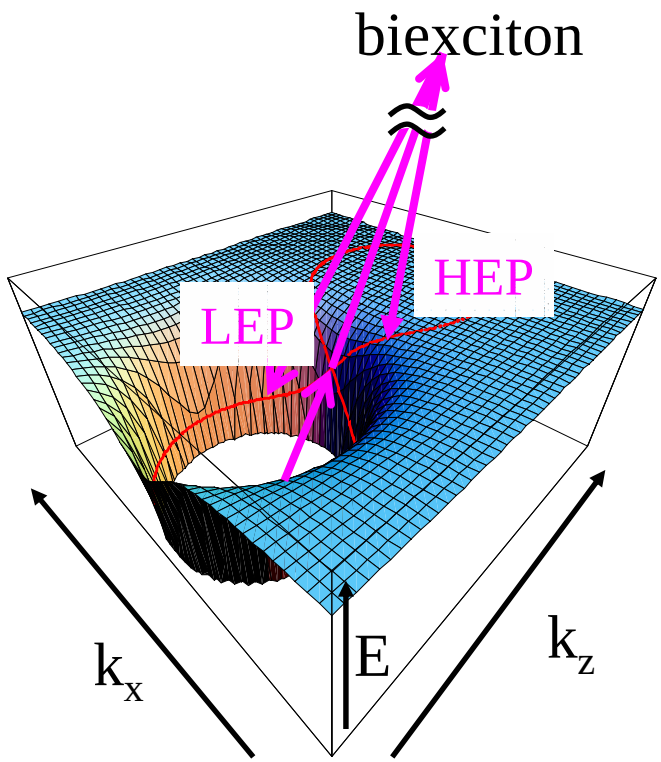
- Large bandgap (~3.4eV)
  $\Rightarrow$ photon pair generation in UV

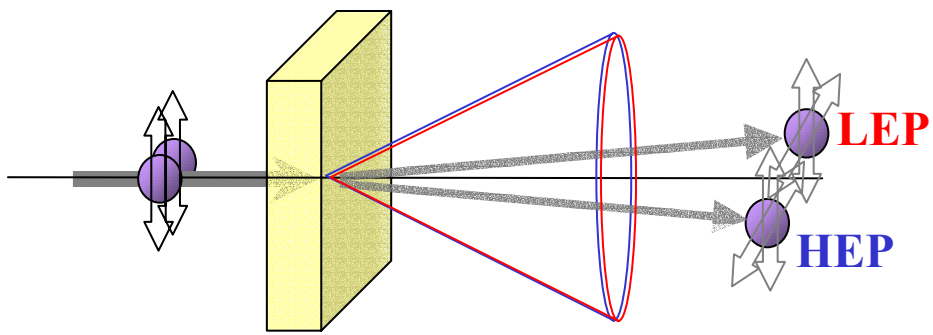
•Large binding energies of the exciton (200 meV) and biexciton (30 meV)

- Strong coupling between excitons and photons

$\Rightarrow$ very large $\chi^{(3)}$ at the biexciton resonance

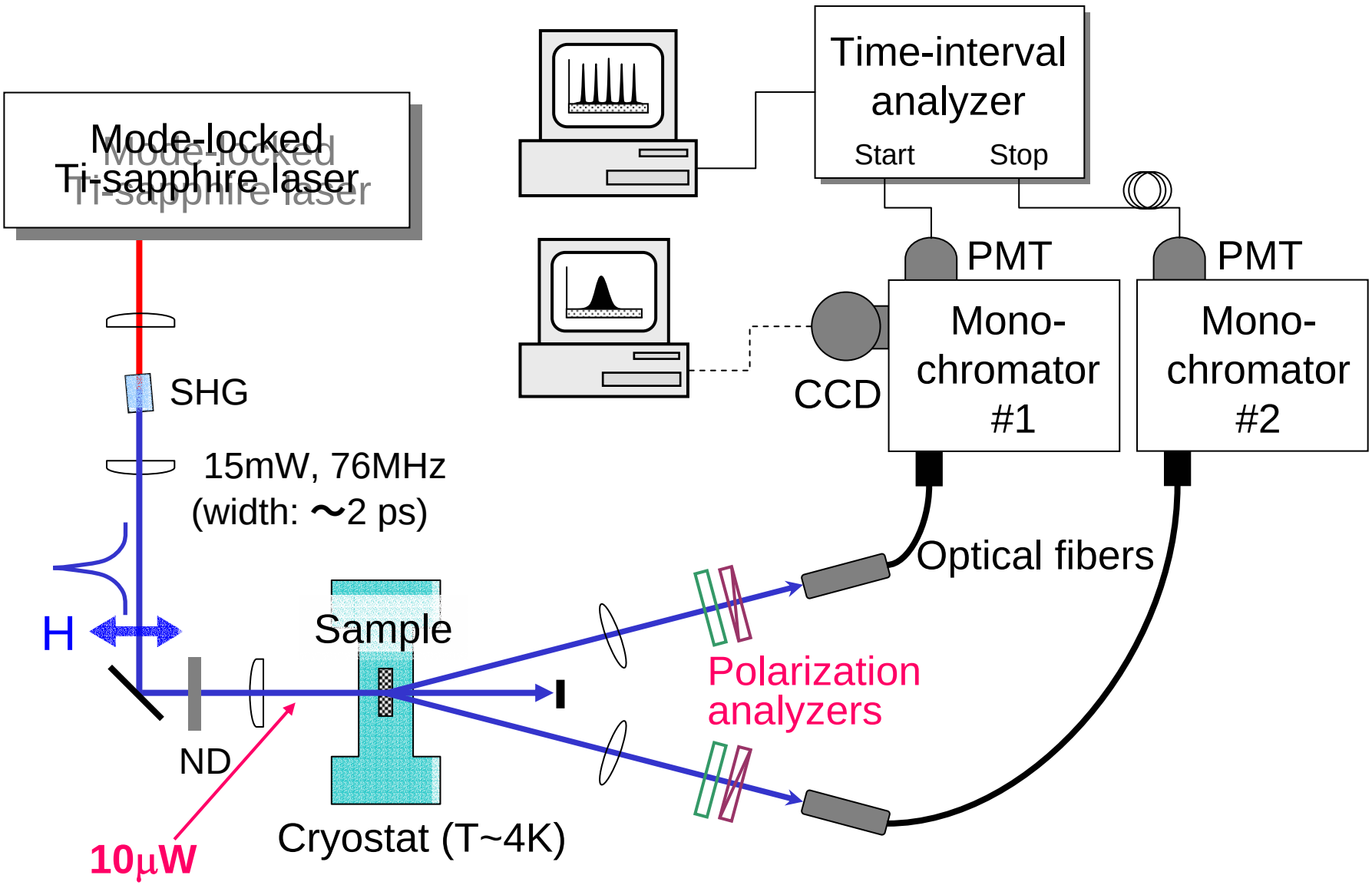
$\Rightarrow$ **Efficient HPS is expected**



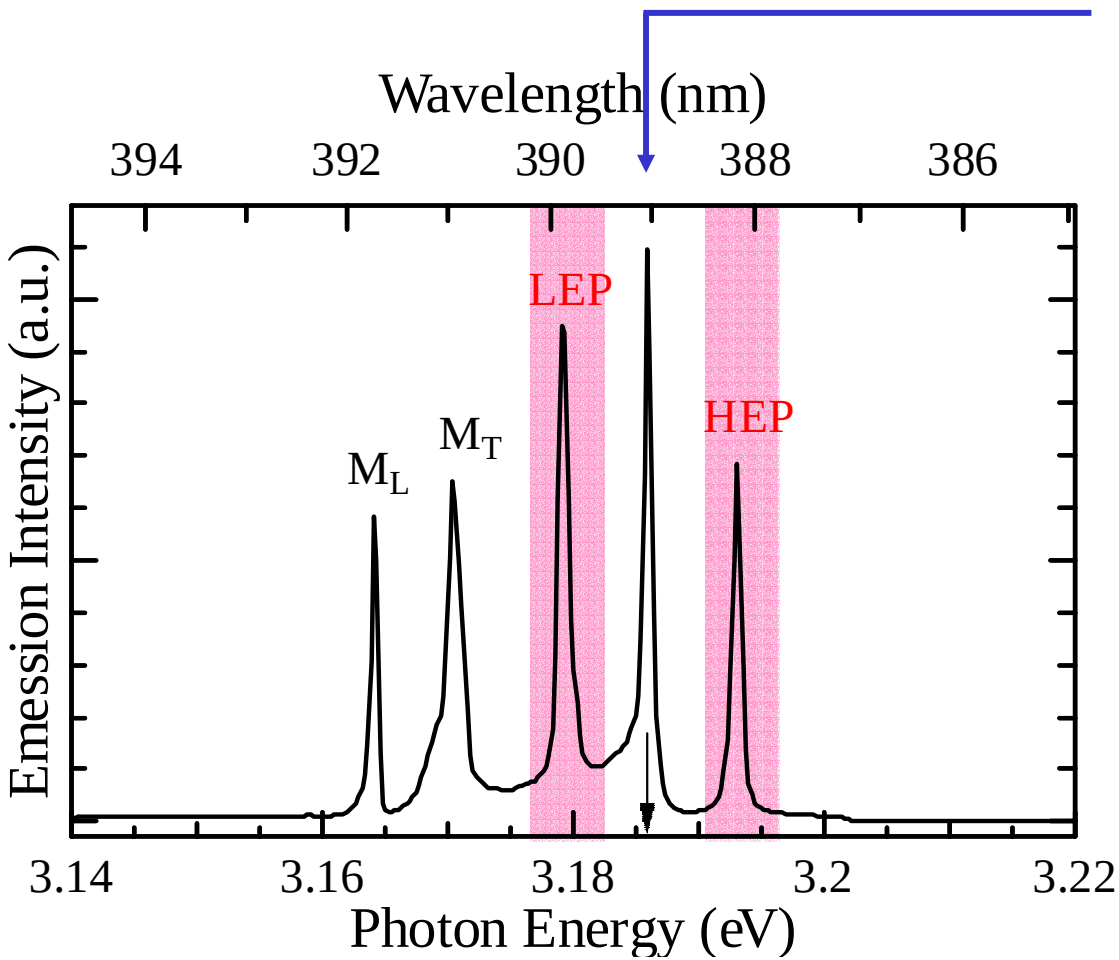


M. Inoue and E. Hanamura,
J. Phys. Soc. Jpn. **41**, 1273 (1976)

Experimental setup



HPS spectrum of CuCl crystal



Excitation @ two-photon resonance to the biexciton

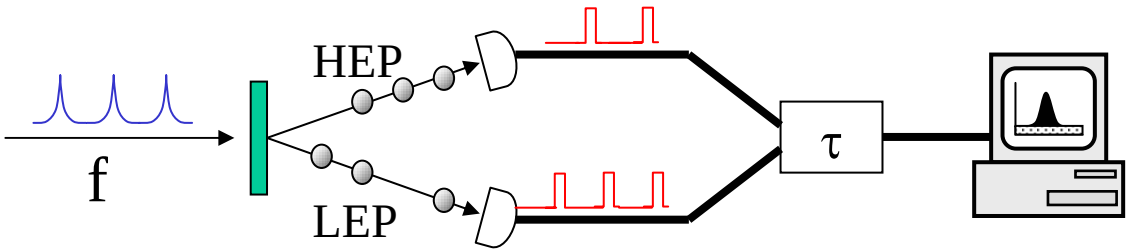
HEP: High Energy Polariton

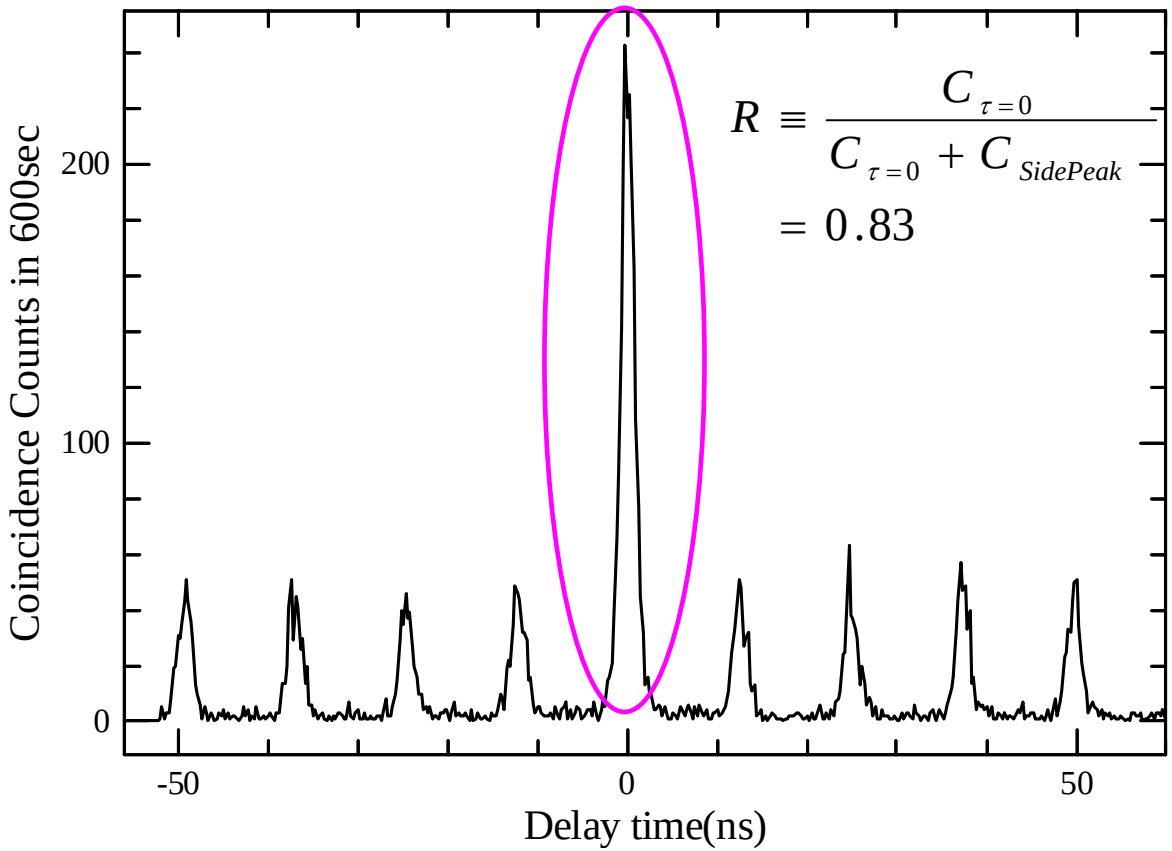
LEP: Low Energy Polariton

M_T: Biexciton emission that leaves transverse exciton

M_L: Biexciton emission that leaves longitudinal exciton

Time-correlation measurement





Central peak ($\tau = 0$)

HEP-LEP coincidence from one biexciton

Side peaks ($\tau \neq 0$)

Accidental coincidence from independent biexcitons excited by different pulses

Polarization-correlation measurement

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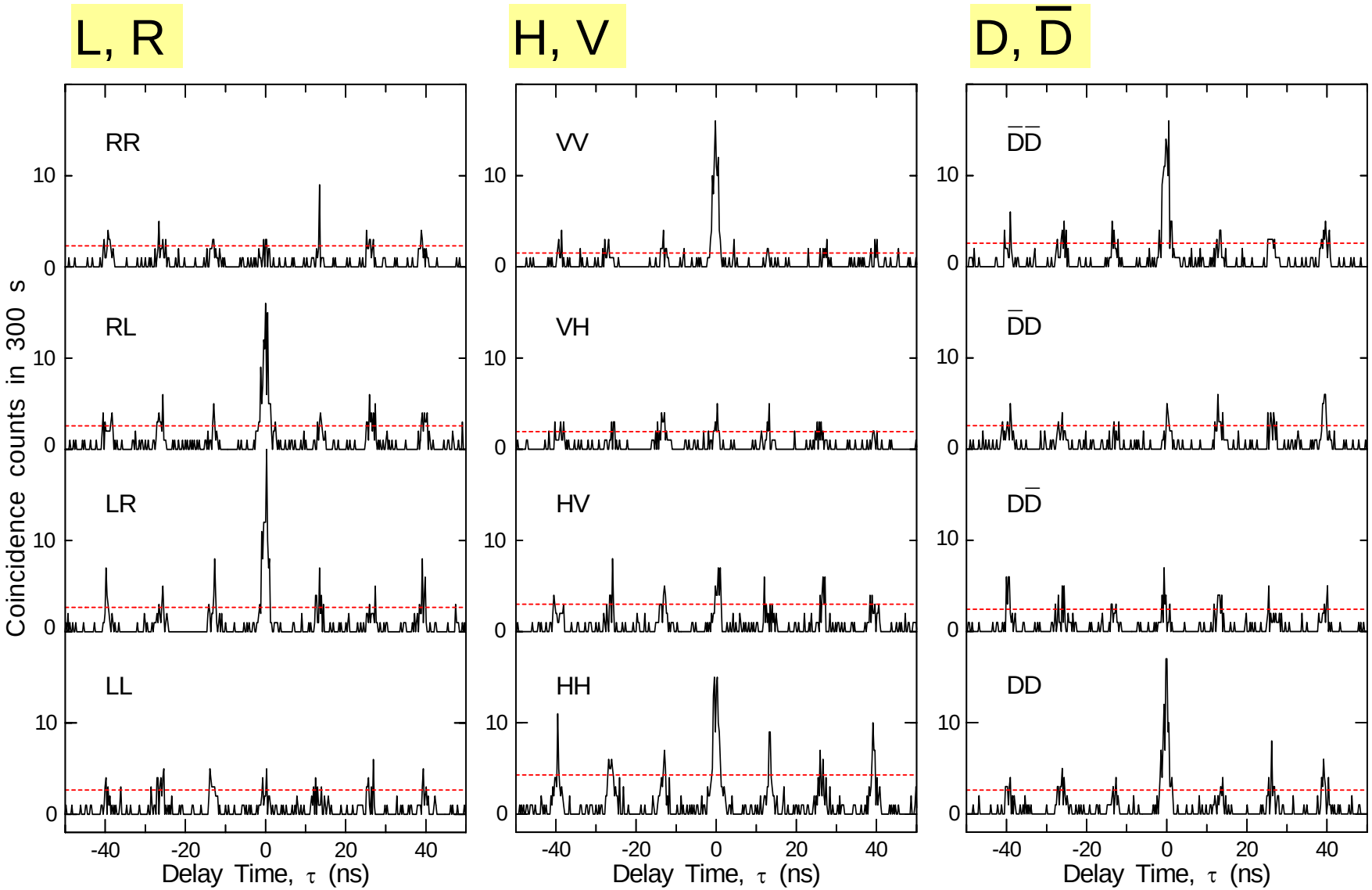

Density matrix and fidelity

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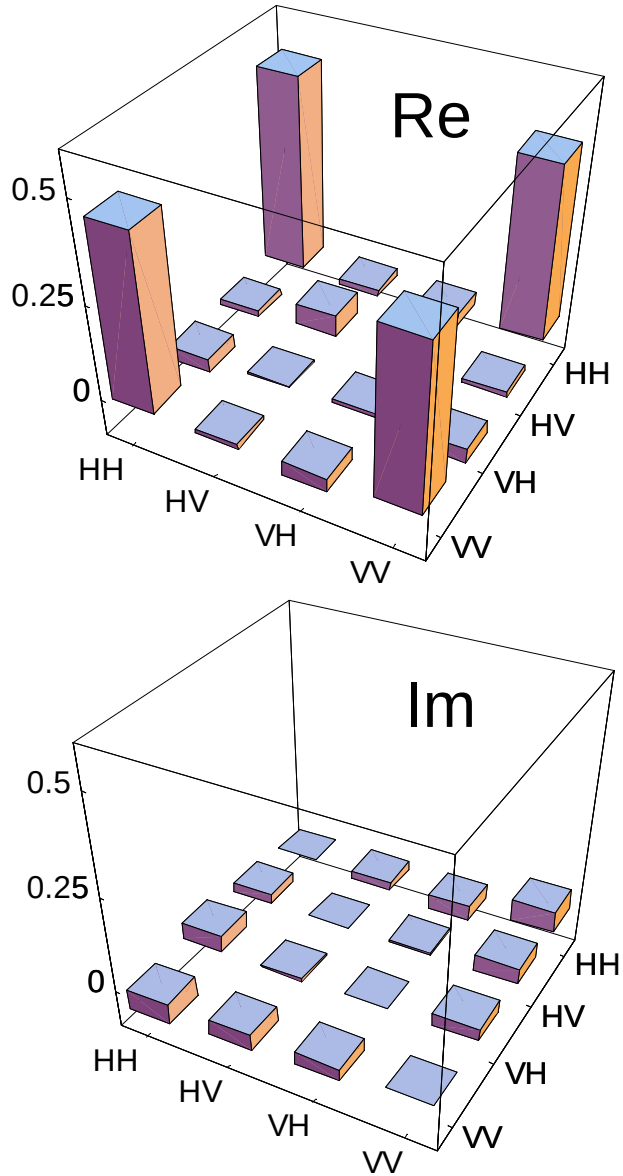
Reconstructed density matrix

(after subtraction of accidental photon coincidence)



Fidelity

$$F \equiv \langle \psi_\theta | \boldsymbol{\rho} | \psi_\theta \rangle$$

Assumed wave function:

$$|\psi_\theta\rangle = \frac{1}{\sqrt{2}}\left(|HH\rangle + |VV\rangle\right)$$

$F = 0.92$

>> 0.5 (classical limit of fidelity)

Elimination of accidental coincidence signals

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Background (BG) signal:
accidental coincidence

Subtraction of the BG

- ○ Proof of principle experiment
- × Practical entangled photon source

Main origins of the BG

Strong signal regime

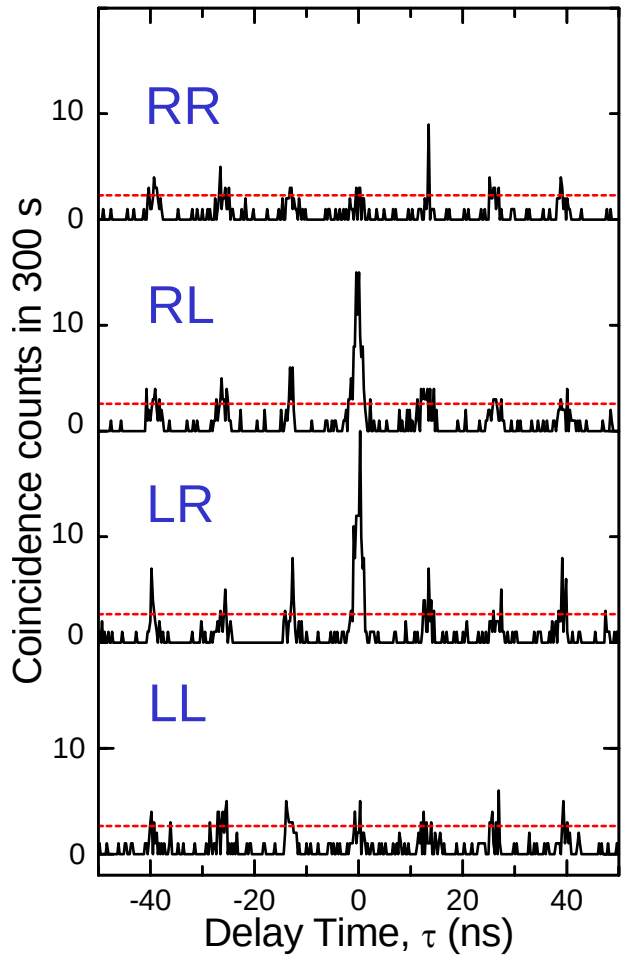
- Accidental count

$$I_{signal} \propto n$$

$$I_{accidental} \propto n^2$$

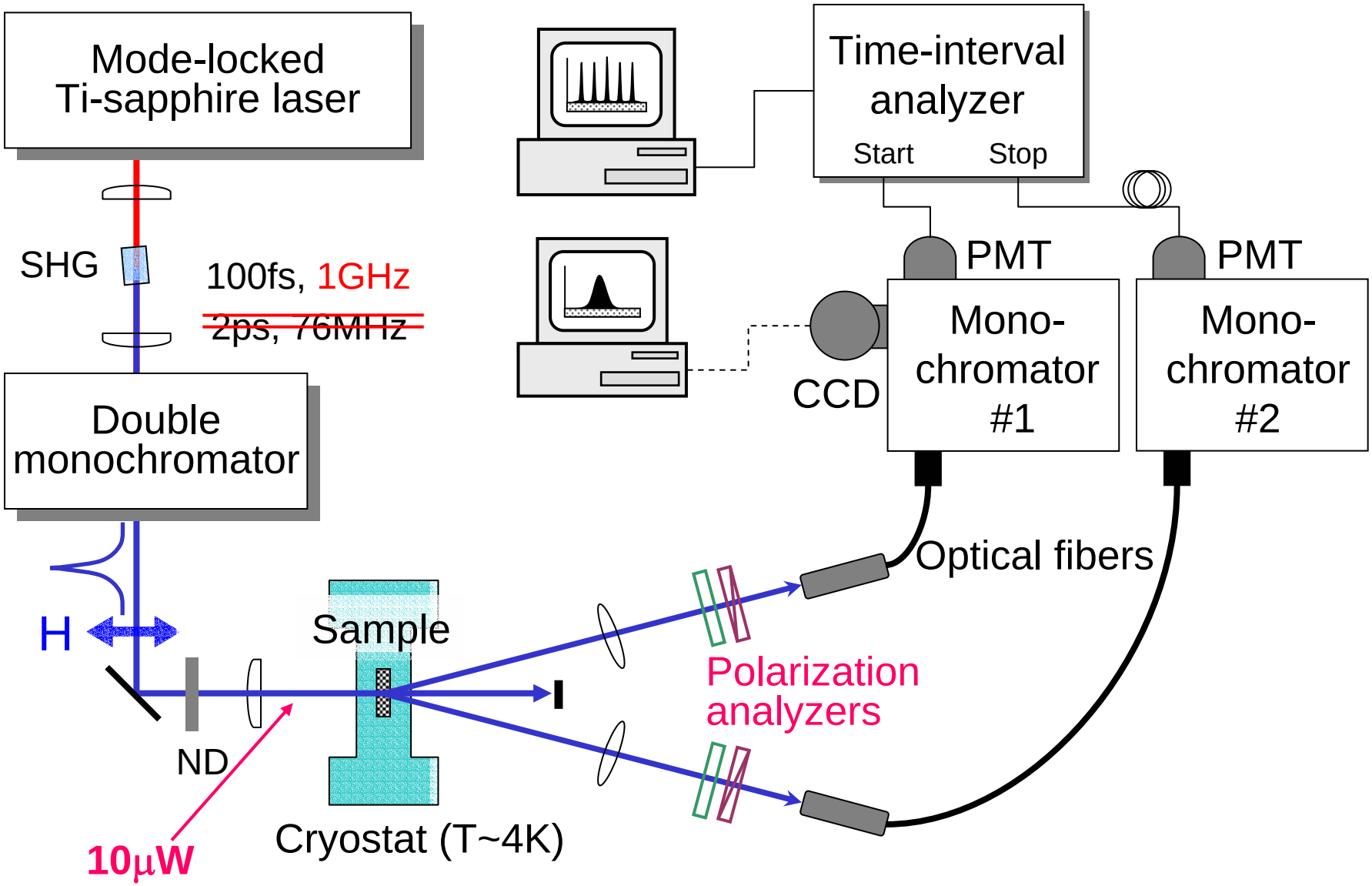
Weak signal regime

- Surface scattering
- Luminescence from impurity



Higher repetition pumping

Experimental setup: higher repetition pumping



Polarization-correlation measurements: elimination of accidental coincidences

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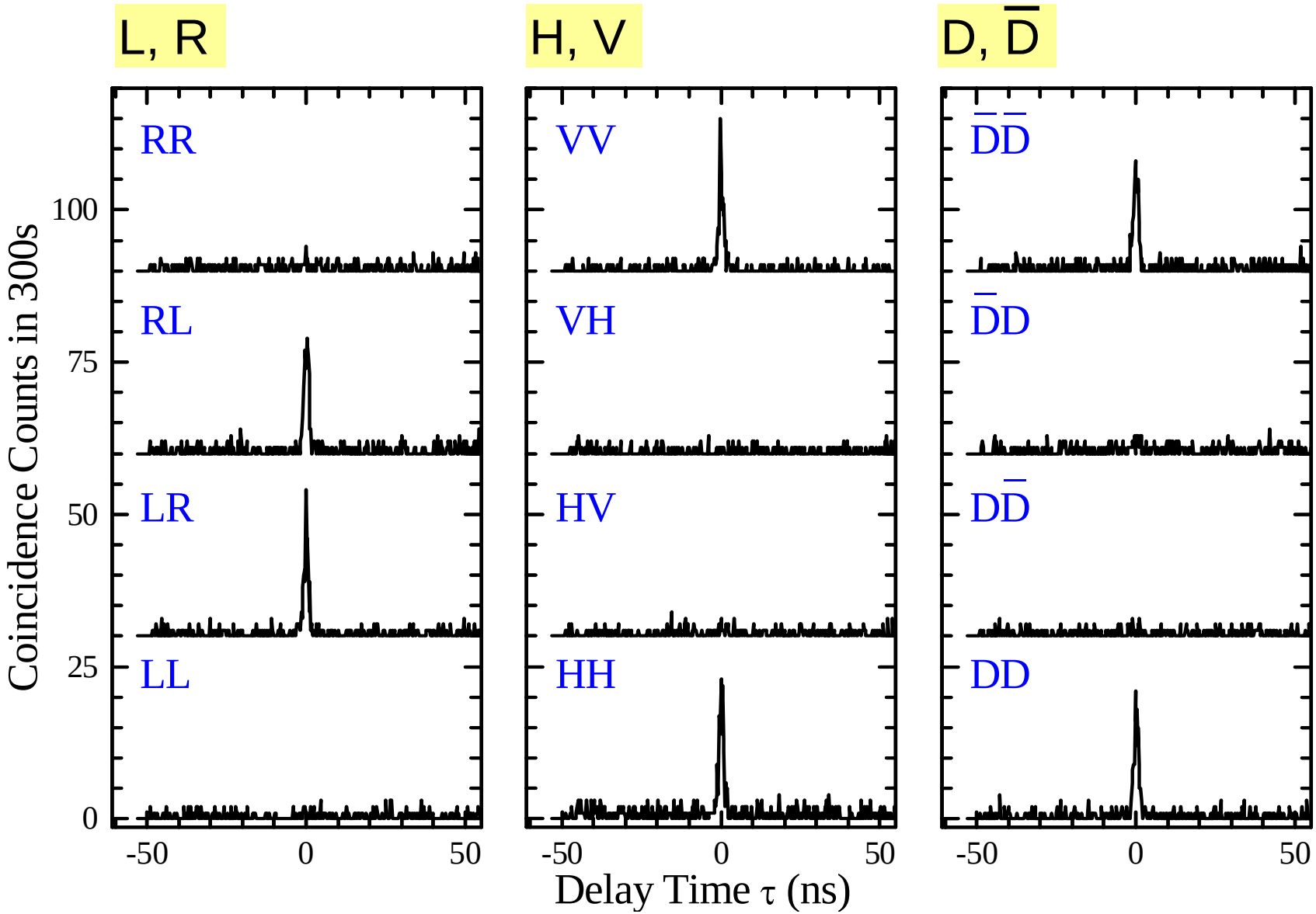

Density matrix and Violation of Bell's inequality

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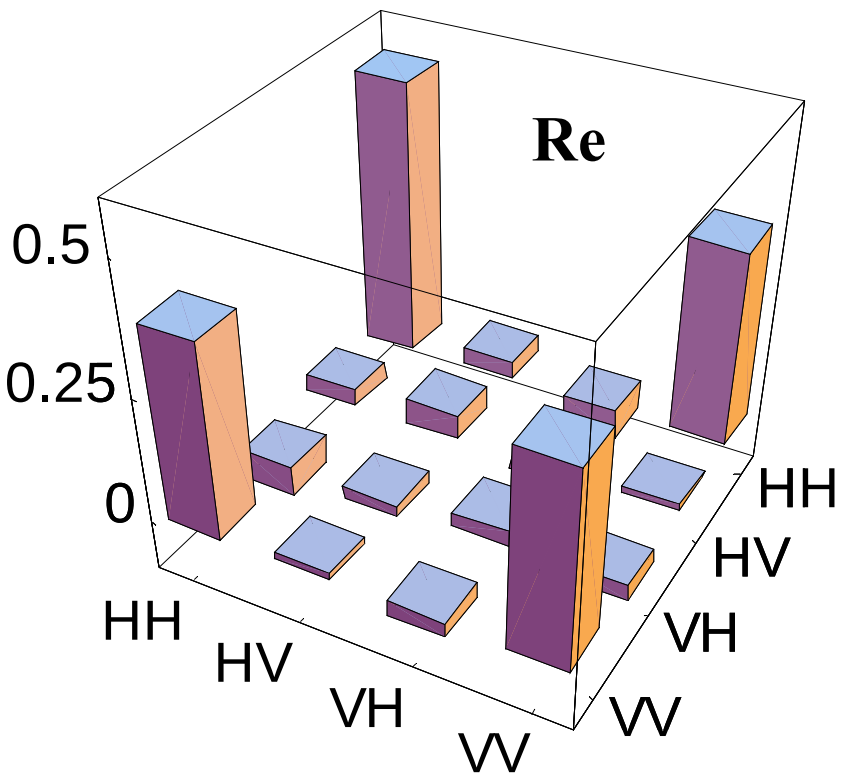

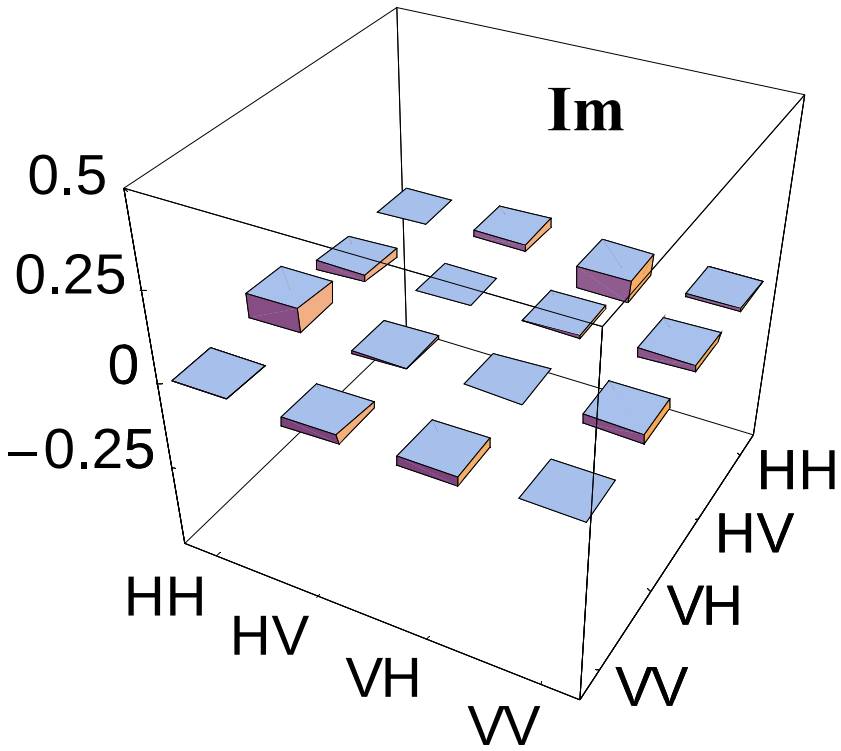

Fidelity

F=0.85

Violation of CHSH inequality

$S = 2.34 \pm 0.10 > 2$

Estimation of degree of disorder and entanglement

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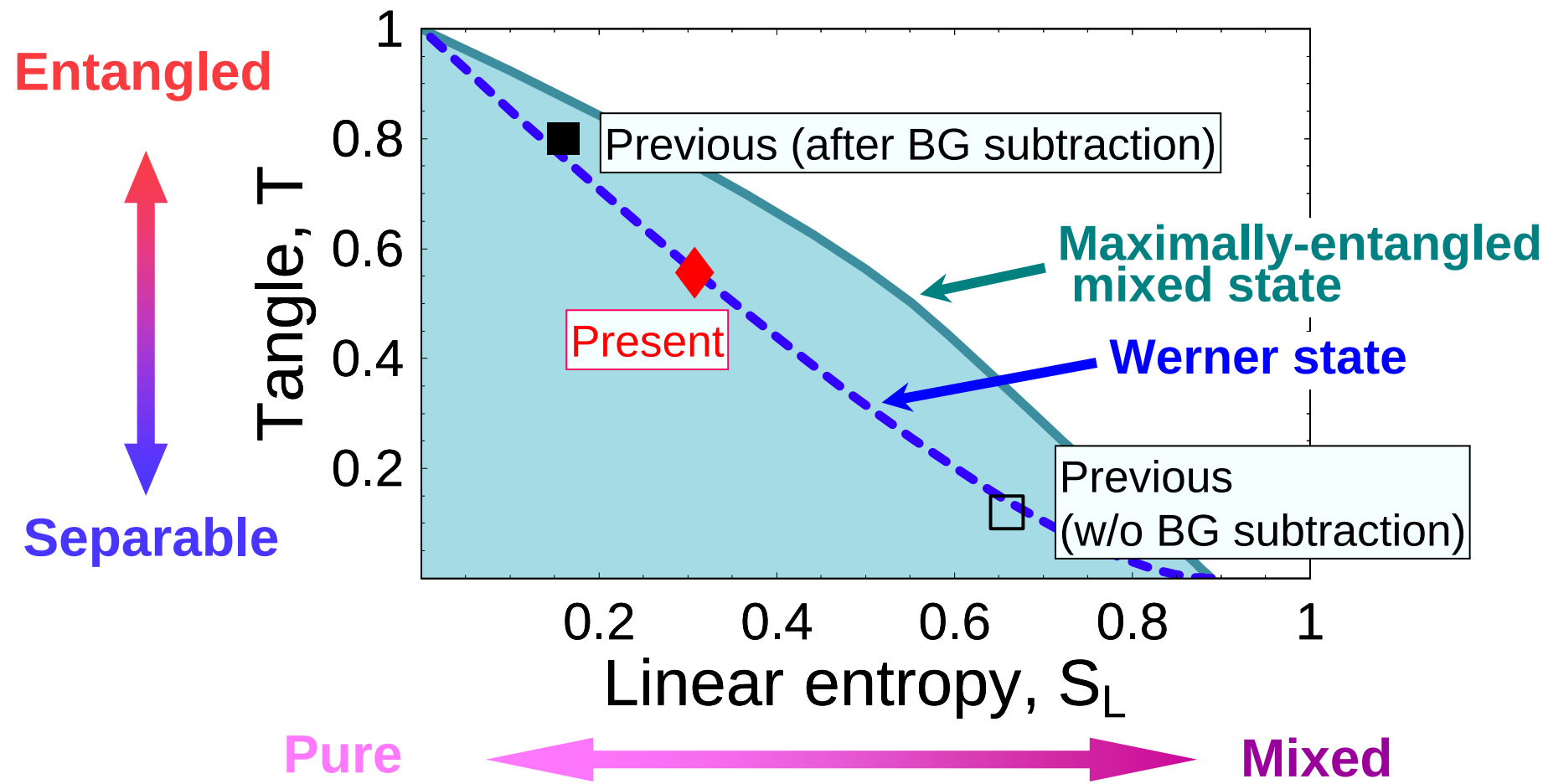
- Linear entropy S_L (degree of disorder): 0.31
- Tangle T (degree of entanglement) : 0.56
- Entanglement of formation EOF: 0.65



Comparison with our previous data
(K. Edamatsu *et al*., Nature 431,167 (2004))

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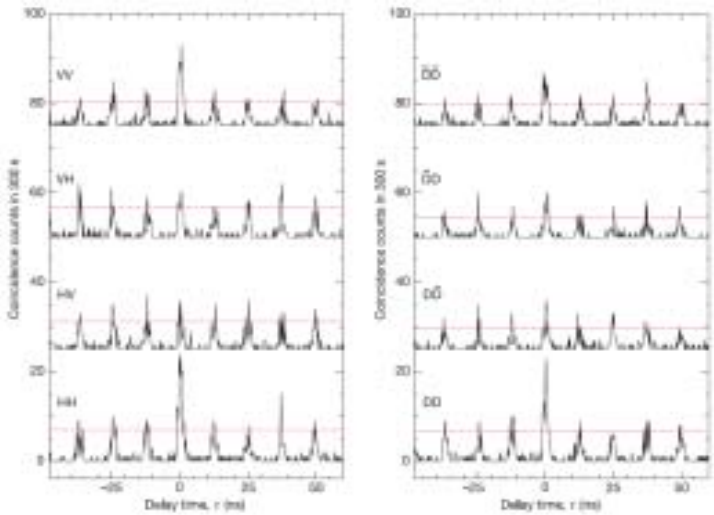


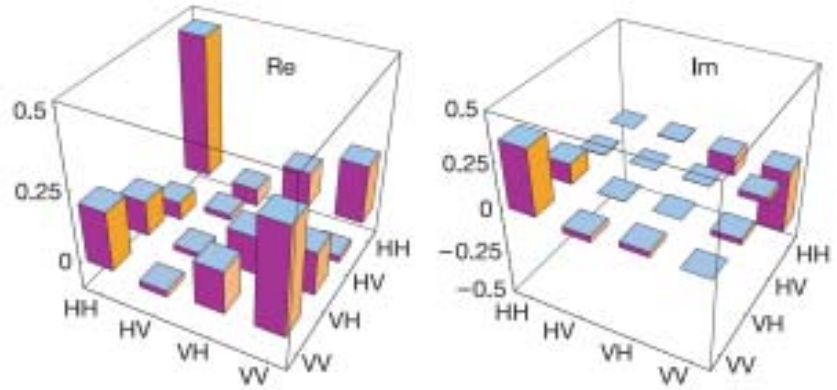
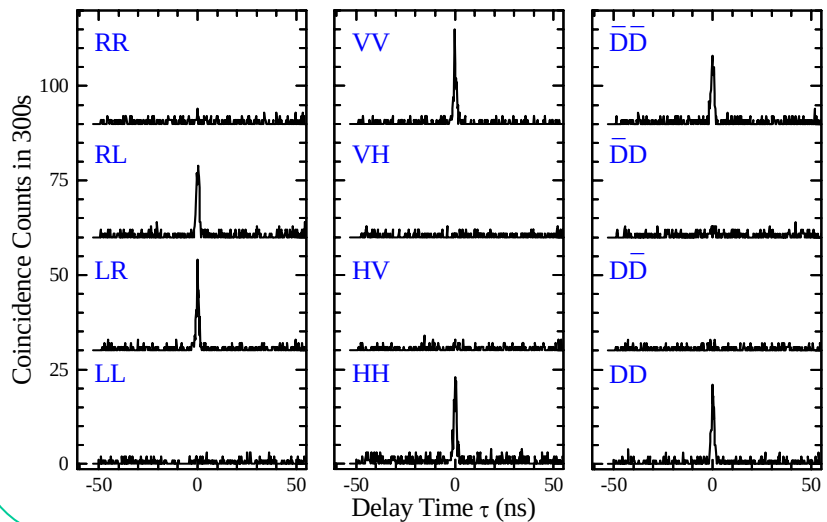
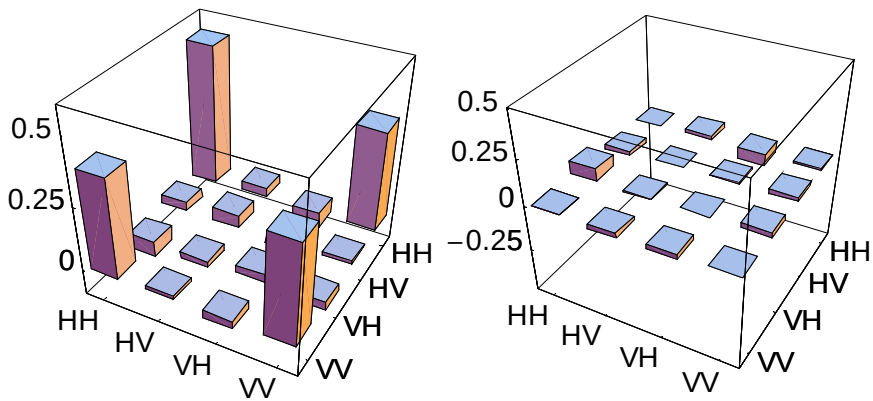


Figure 6 Graphical representation of the two-photon polarization density matrix reconstructed from the photon correlation measurements for 19 polarization combinations. Shown are the real (Re) and imaginary (Im) parts of the density matrix $\hat{\rho}$.

Present data





Summary

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- We have demonstrated the entangled photon pair generation via biexciton-resonant HPS in a semiconductor (CuCl crystal).
- Quantum state tomography of the two-photon polarization manifested the quantum polarization entanglement of the photon pair (F=0.85).
- Violation of CHSH-Bell's inequality (S=2.34)
- Theoretical and experimental studies using biexcitonic cavity QED are in progress.