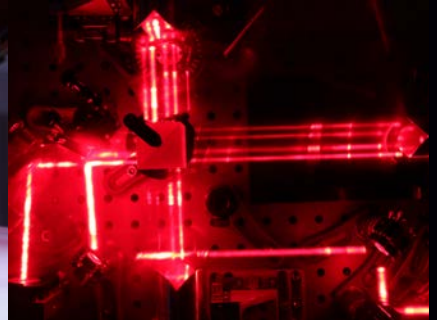
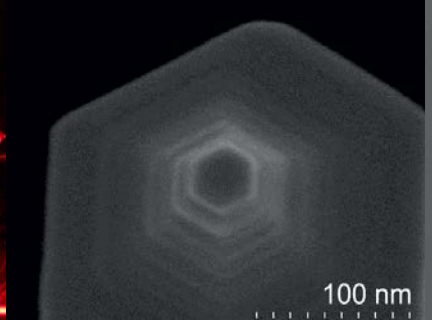
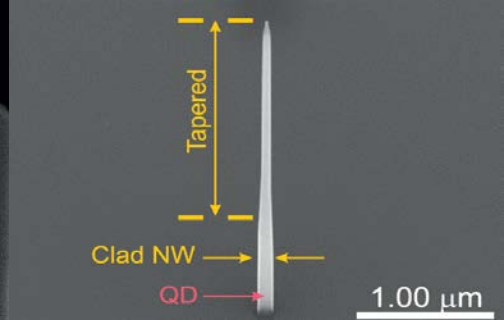





Quantum dots as quantum light sources: from hyper-entanglement to photon triplets

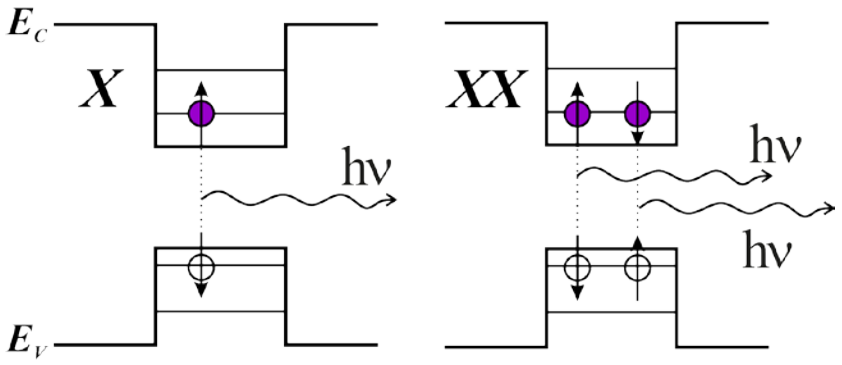
A. Predojević

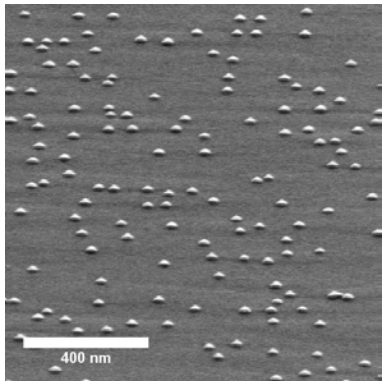
Ulm University, Germany

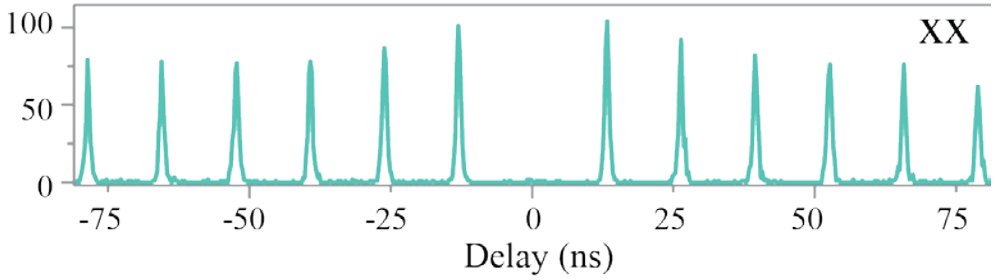
FWF
Der Wissenschaftsfonds.

Why quantum dots?

-semiconductor embedded artificial atom



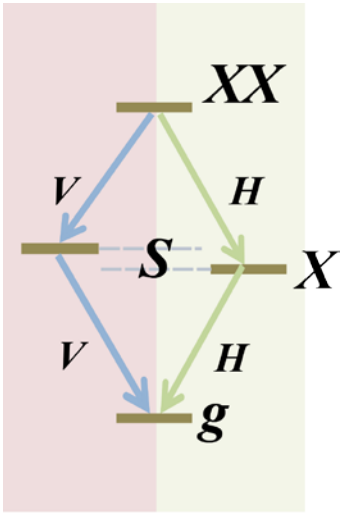




- sub-Poissonian statistics
- high photon generation probability

- **generation of photon pairs**
- **limiting factors a side from semiconductor environment**
- **time-bin entanglement of photons obtained from a single quantum dot**
- **extension to hyper-entanglement**
- **photon-triplet emitting system**

Quantum dots and photon entanglement



XX – Biexciton
X – Exciton
g – ground state

Recovery of the level degeneracy:

- electric field, magnetic filed tuning
- optical Stark effect
- growth
- simultaneous electric and strain tuning

Bennett et al. *Nat.Phys.* **6**, 947 (2010)
Stevenson et al. *PRB* **73,** 033306 (2006)

Mueller et al. *PRL* **103,** 217402 (2009)

Kuroda et al. *PRB* **88,** 041306 (2013)
Juska et al. *Nat.Photonics* **7,** 527 (2013)
Huber et al. *Nano Lett.* **14**, 7107 (2014)

Trotta et al. *PRL* **109,** 147401 (2013)

H. Jayakumar, et al. Nat. Communications 5, 4251, 2014

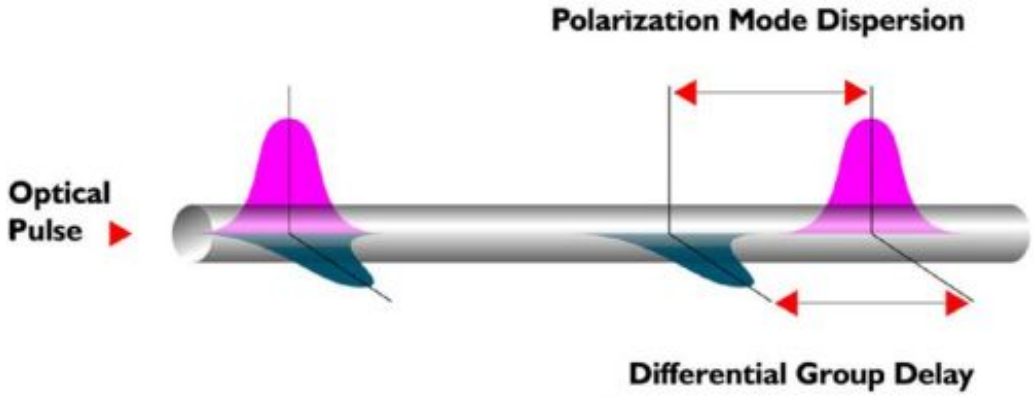
VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

Bell Inequality for Position and Time

J. D. Franson
Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20707-6099
(Received 24 October 1988)

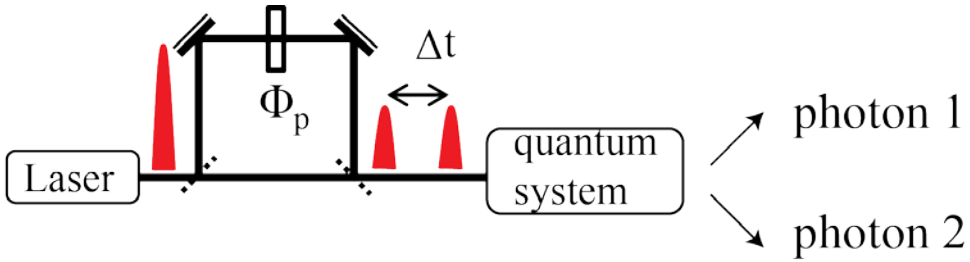
The quantum-mechanical uncertainty in the position of a particle or the time of its emission is shown to produce observable effects that are inconsistent with any local hidden-variable theory. A new experimental test of local hidden-variable theories based on optical interference is proposed.

Entanglement in time bin



$$DGD = PMD_{parameter} \times L^{1/2}$$

- single spacial mode linear optical quantum computing, *Phys. Rev. Lett. 111, 150501 (2013)*
- quantum communication, *Nature Physics 3, 692 - 695 (2007)*
- long-distance entanglement distribution via optical fiber, *Optics Express, 17, 11440 (2009)*



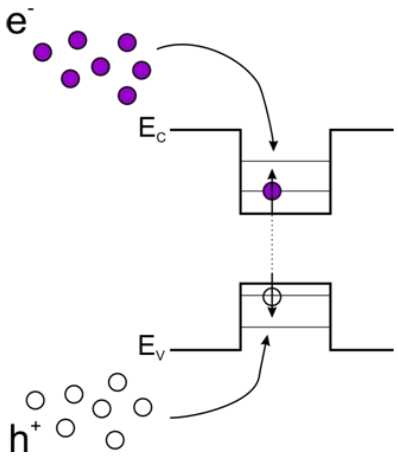
J. Brendel, N. Gisin, W. Tittel and H. Zbinden Phys. Rev. Lett. 82, 2594 (1999).

$$|\Phi\rangle_{pump} = \frac{1}{\sqrt{2}}(|early\rangle_p + e^{i\phi_p}|late\rangle_p)$$

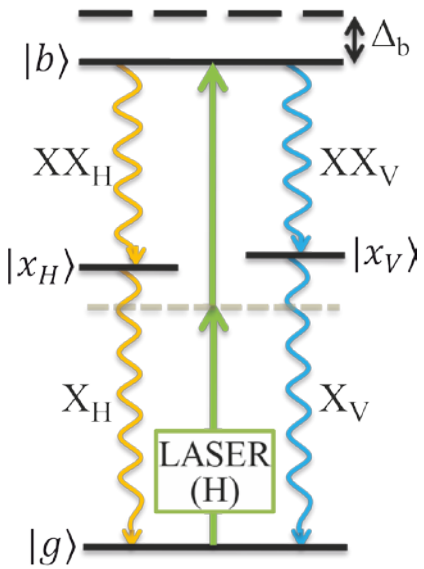
2-photon resonant biexciton excitation

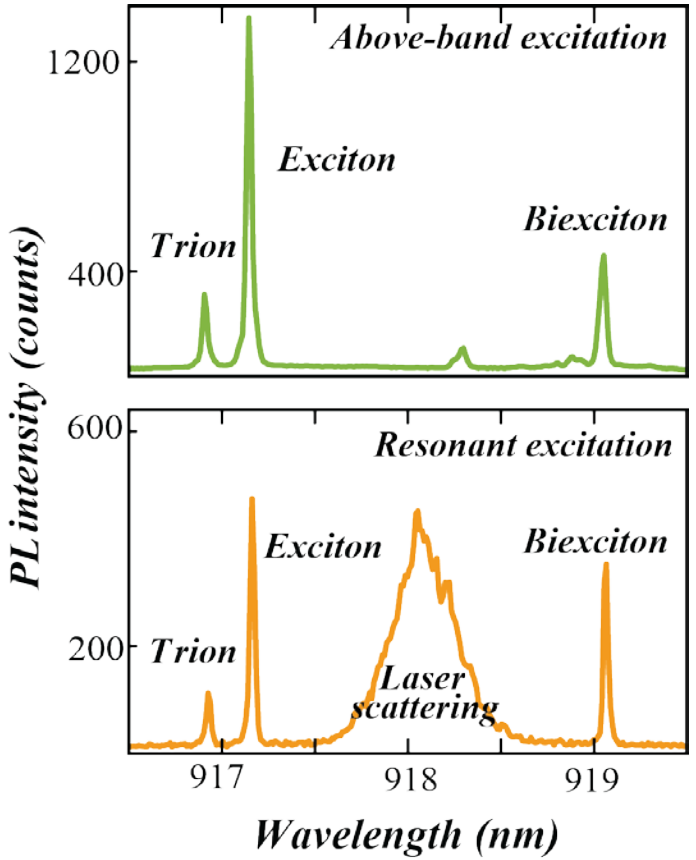
$$|\Phi\rangle_{pump} = \frac{1}{\sqrt{2}}(|early\rangle_p + e^{i\phi_p}|late\rangle_p)$$

a)



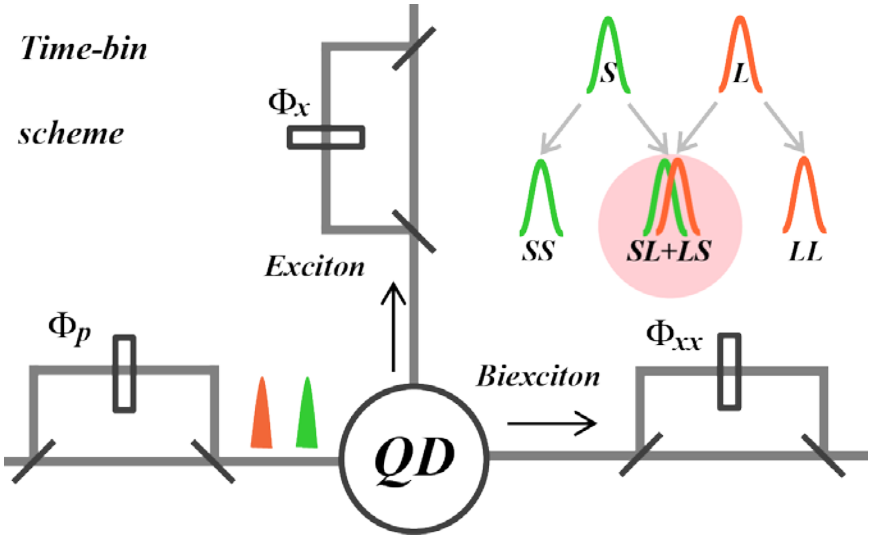
b)

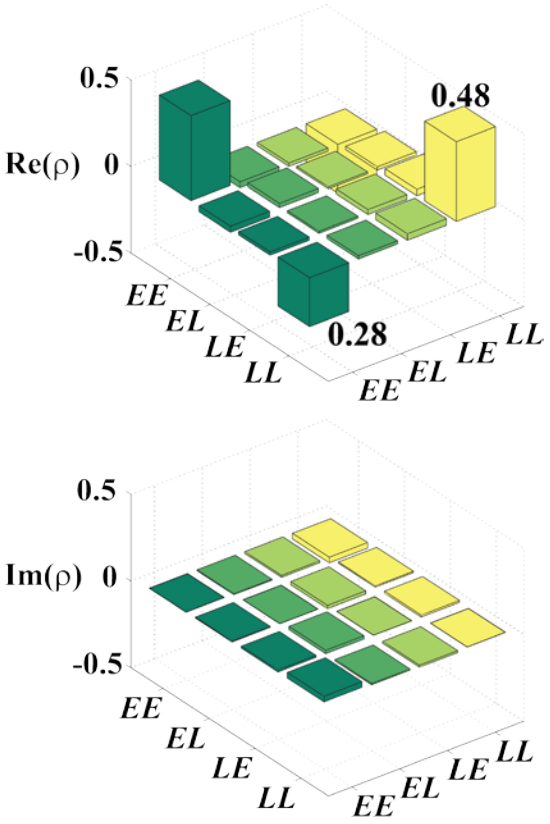




H. Jayakumar et al. Phys. Rev. Lett. **110**, 135505 (2013)

Entanglement in time bin: detection





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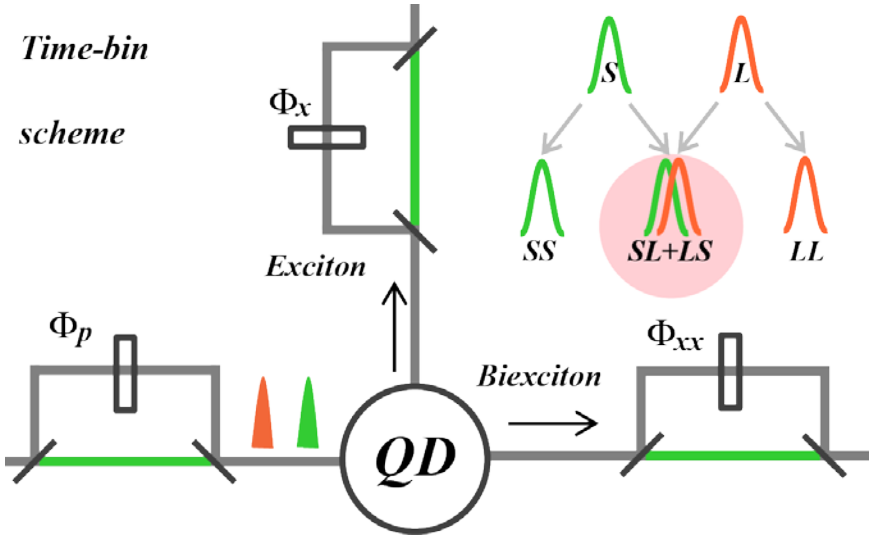
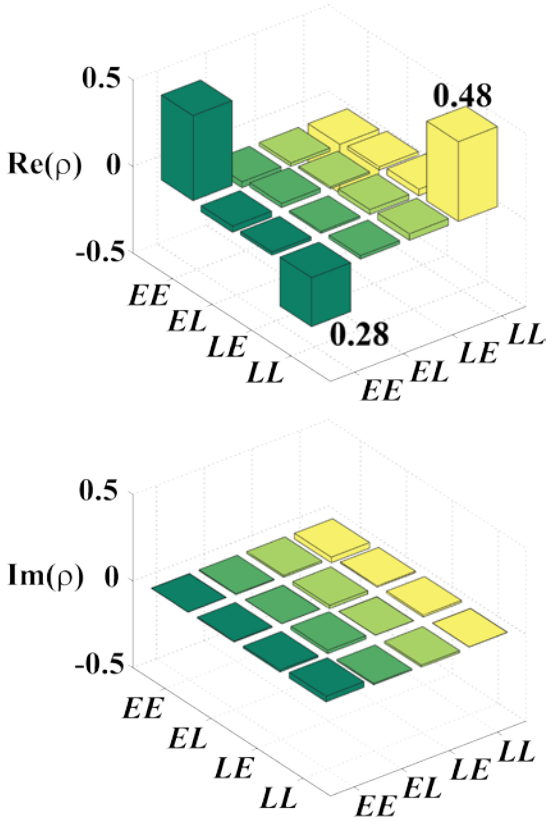
$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|early\rangle_X|early\rangle_{XX} + e^{i\phi_p}|late\rangle_X|late\rangle_{XX}$$

Concurrence	**0.56(7)**
Tangle	**0.31(9)**
Fidelity	**0.78(3)**

H. Jayakumar, et al.
Nature Communications **5**, 4251 (2014)

Entanglement in time bin: detection





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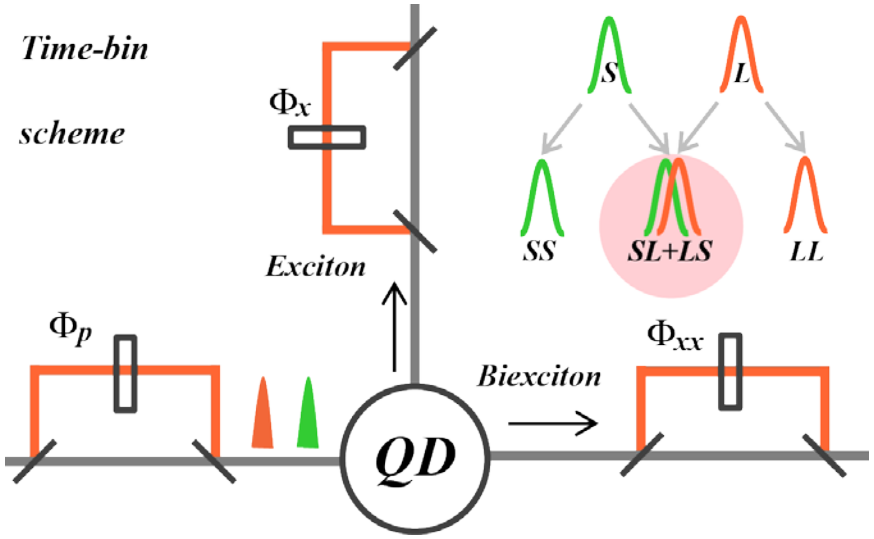

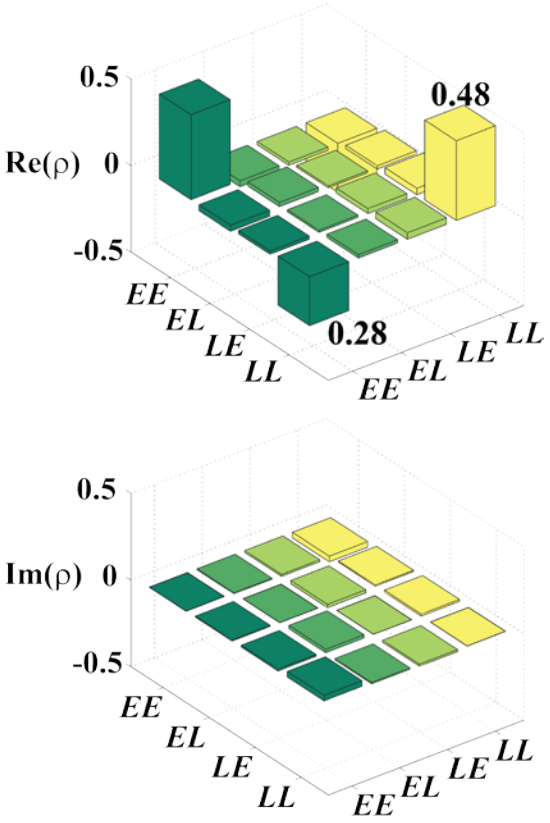

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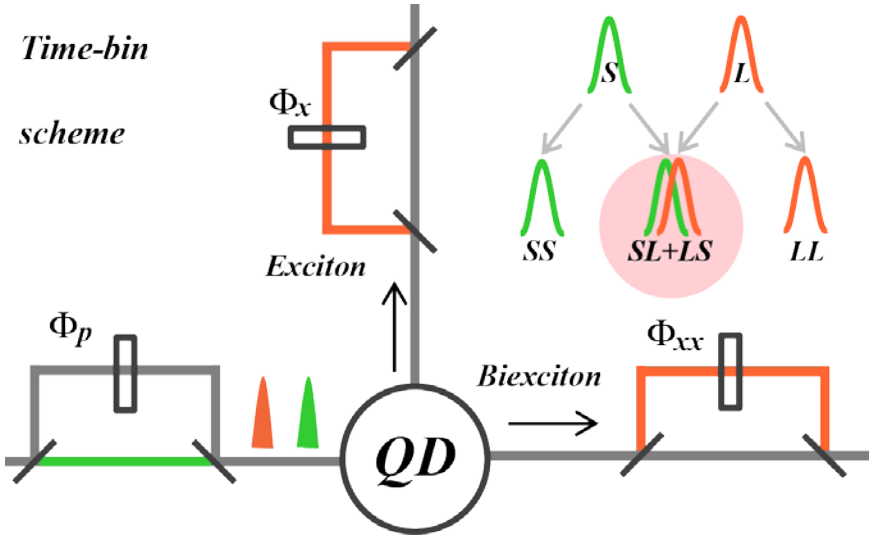

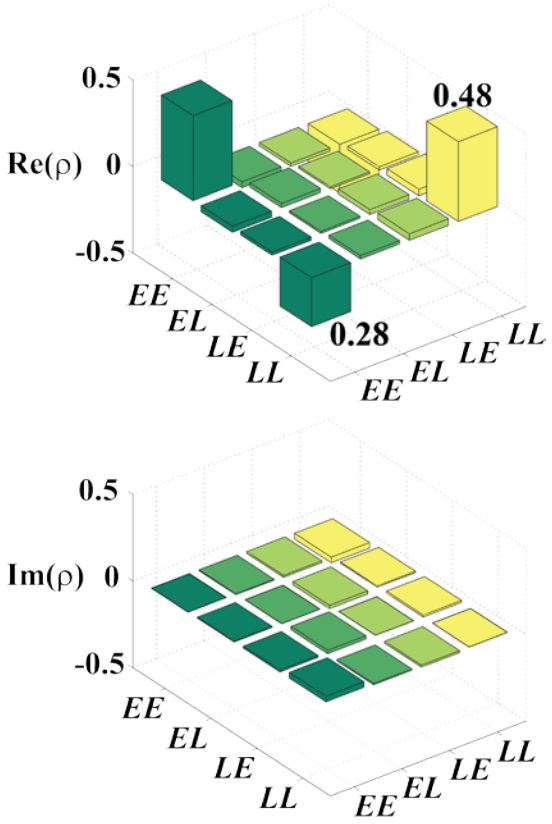

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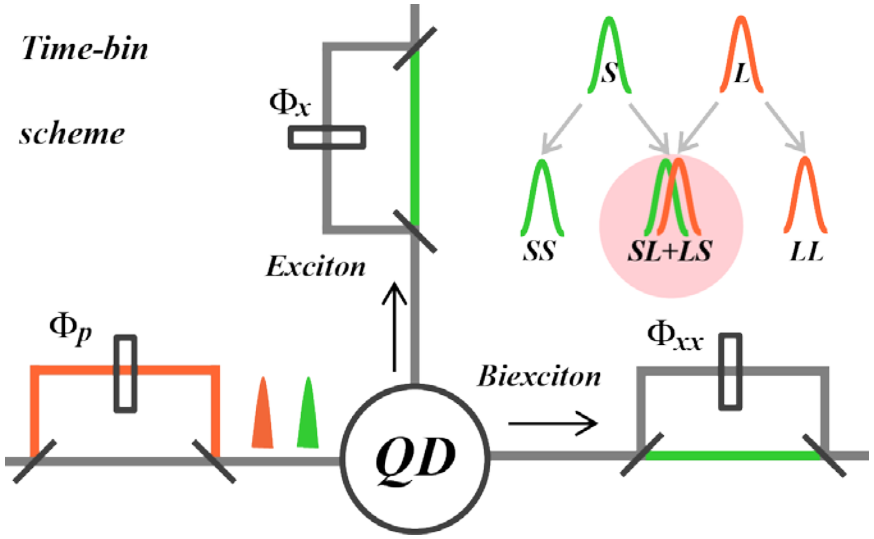

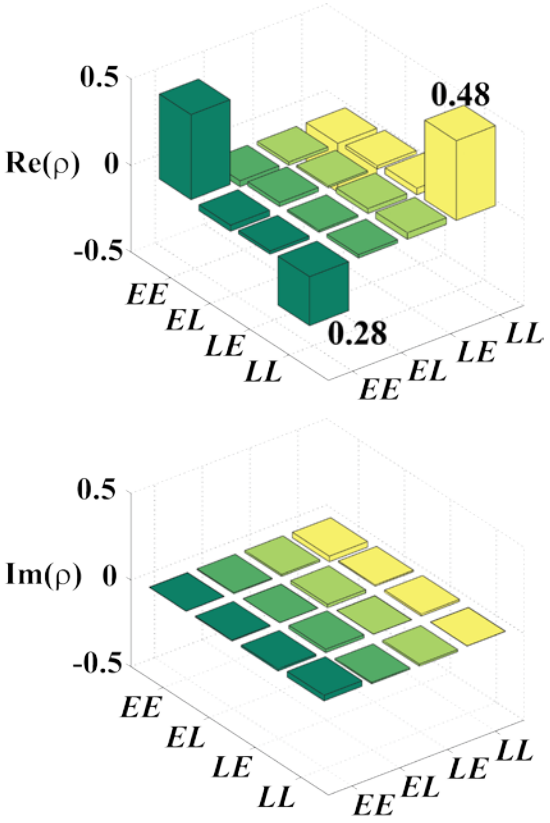

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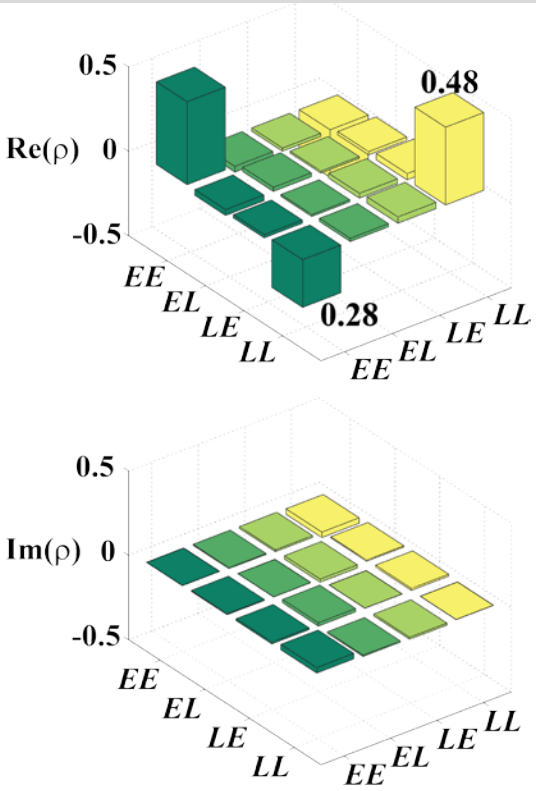
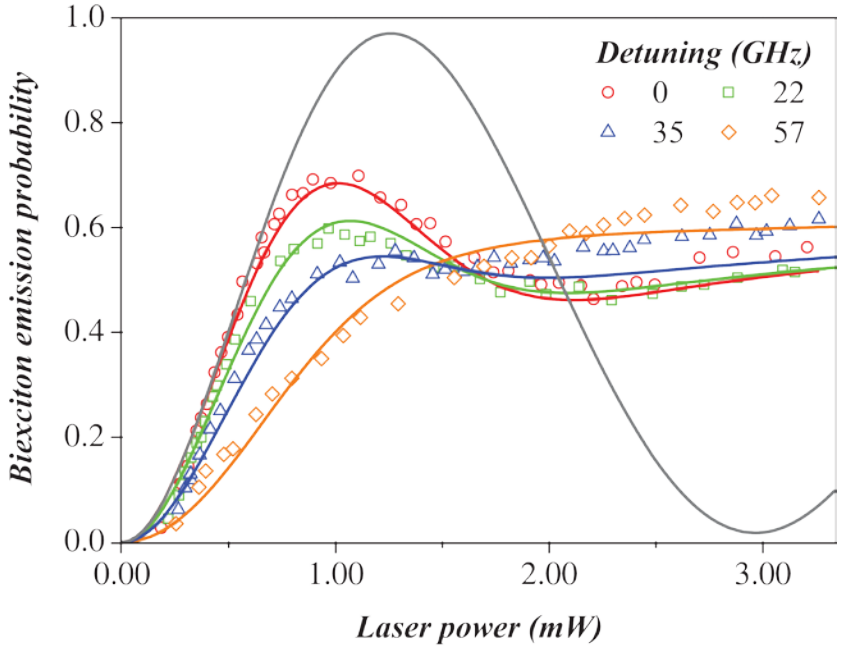
H. Jayakumar, et al.
Nature Communications **5**, 4251 (2014)

Coherence of excitation





Lifetime	***XX***	**405 ps**
	X	**711 ps**
Coherence length	***XX***	**214 ps**
	X	**111 ps**

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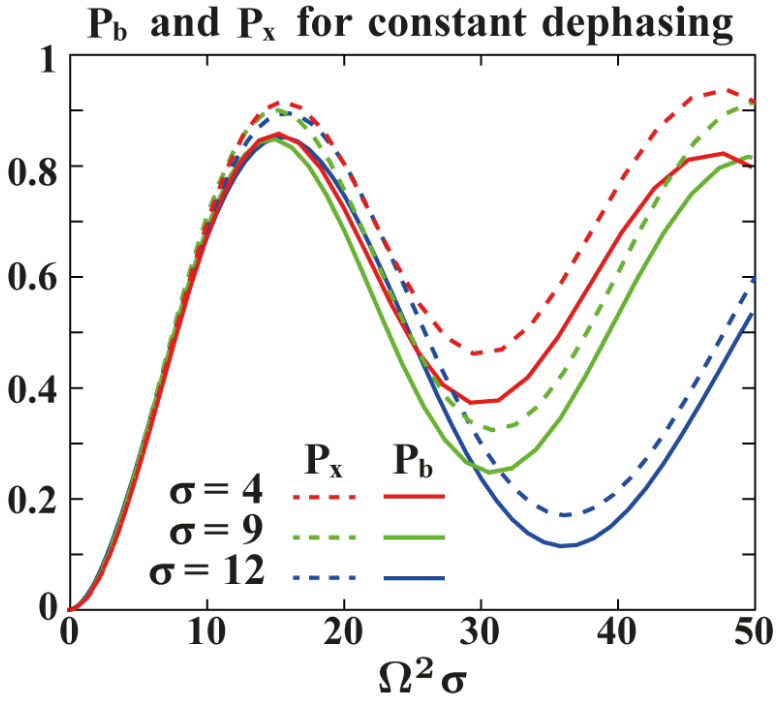
Nature Communications **5**, 4251 (2014)

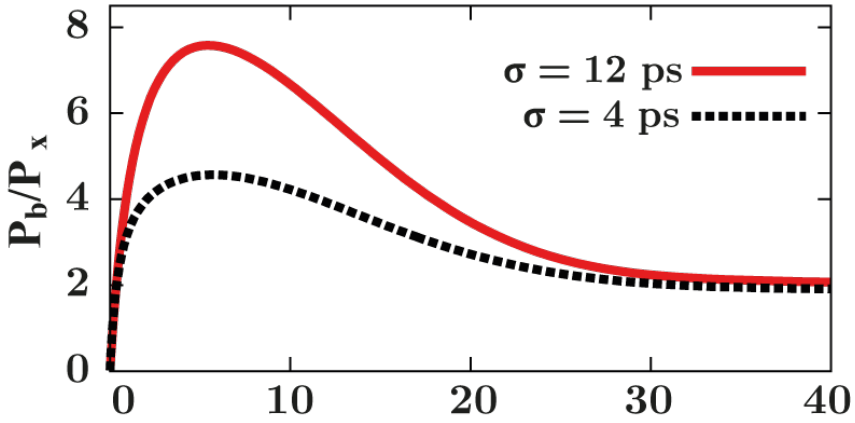
$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \sum_{i=1}^{4} \mathcal{L}_i(\rho)$$

$$H = \hbar \begin{pmatrix} 0 & \frac{\Omega_1(t)}{2} & 0 \\ \frac{\Omega_1(t)}{2} & -\Delta_b + \Delta_e & \frac{\Omega_2(t)}{2} \\ 0 & \frac{\Omega_2(t)}{2} & -2\Delta_b \end{pmatrix}$$



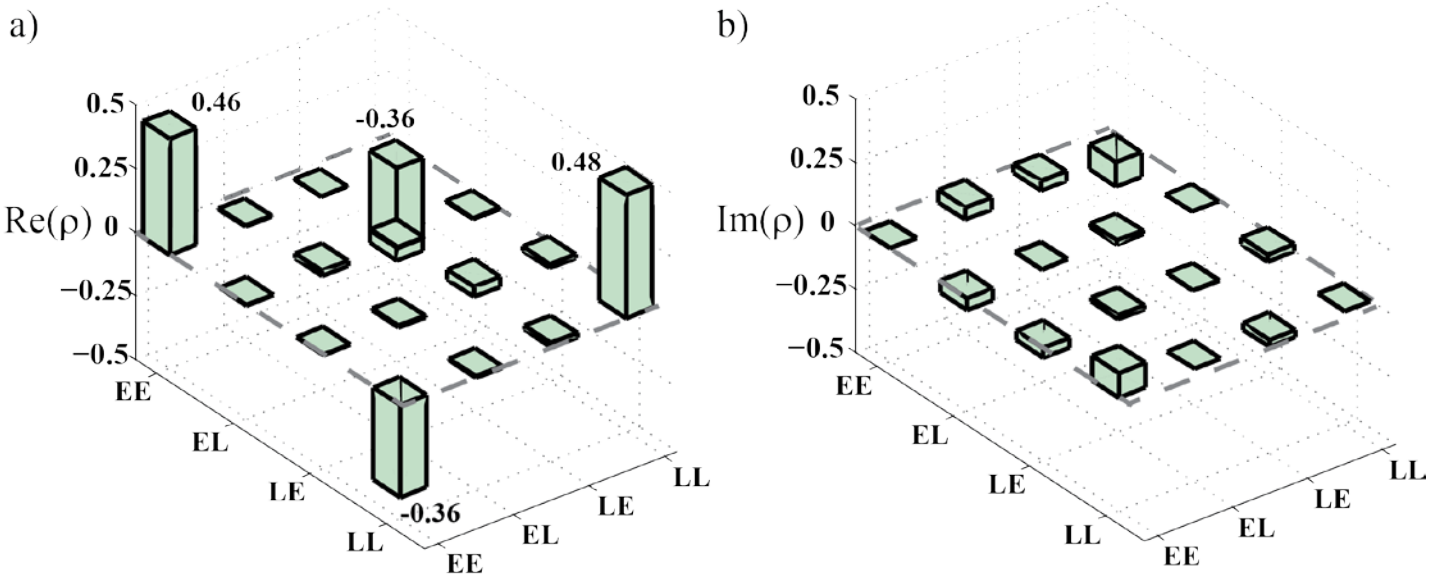
- ***pulse bandwidth***
- ***power – linear***
- ***power – quadratic***

$$\gamma_\Omega(t) = \gamma_{I_0} \cdot \left(\frac{\Omega(t)}{\Omega_0}\right)^{n_p}$$



T. Huber et al. PRB **93**, 201301(R) (2016)

emission probability of ≈ 90%



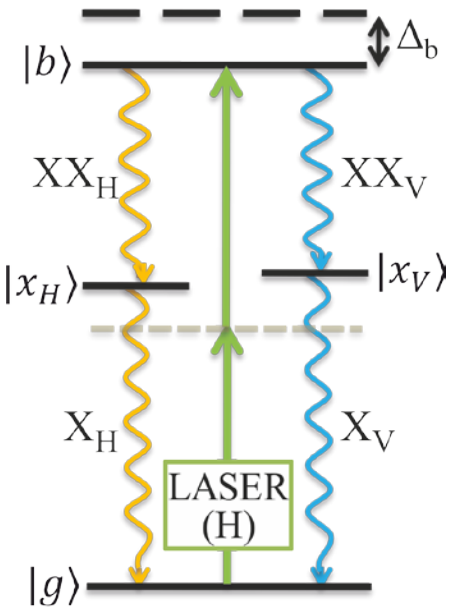
pulse length (ps)	concurrence	fidelity	coherence
4	0.56(7)	0.78(3)	-0.28(3)
9	0.71(6)	0.83(3)	-0.36(3)
12	0.78(6)	0.88(3)	-0.39(3)
15	0.78(5)	0.88(3)	-0.40(3)
20	0.61(5)	0.80(3)	-0.32(3)

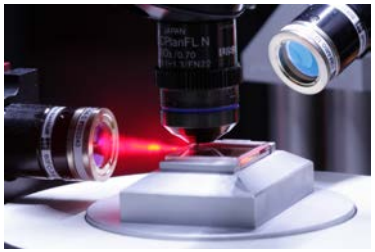
pulse length (ps)	E/L	E+L/E-L	E+iL/E-iL
12	94(2)%	74(5)%	67(5)%

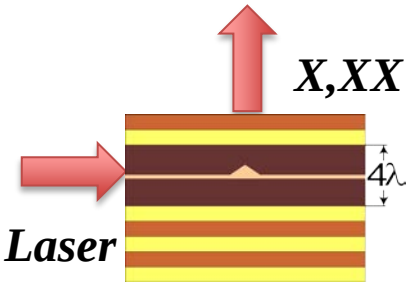
More than just entanglement?

$$|\Psi\rangle = (|H\rangle|H\rangle + |V\rangle|V\rangle) \otimes (|early\rangle|early\rangle + |late\rangle|late\rangle)$$

- complete Bell-state analysis with only linear components , *Physics Review A 58, R2623 (1998)*
- dense coding, *Nature Physics 4, 282 (2008)*
- quantum cryptography, *Reviews of Modern Physics, 74, 145 (2002).*







LETTERS
PUBLISHED ONLINE: 16 FEBRUARY 2014 | DOI: 10.1038/NPHOTON.2013.377
nature photonics

On-demand generation of indistinguishable polarization-entangled photon pairs

M. Müller[1†], S. Bounouar[1†*], K. D. Jöns[1], M. Glässl[2] and P. Michler[1*]

Generation of Hyperentangled Photon Pairs

Julio T. Barreiro,[1] Nathan K. Langford,[2] Nicholas A. Peters,[1] and Paul G. Kwiat[1]

[1]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801-3080, USA*
[2]*Department of Physics, University of Queensland, Brisbane, QLD 4072, Australia*

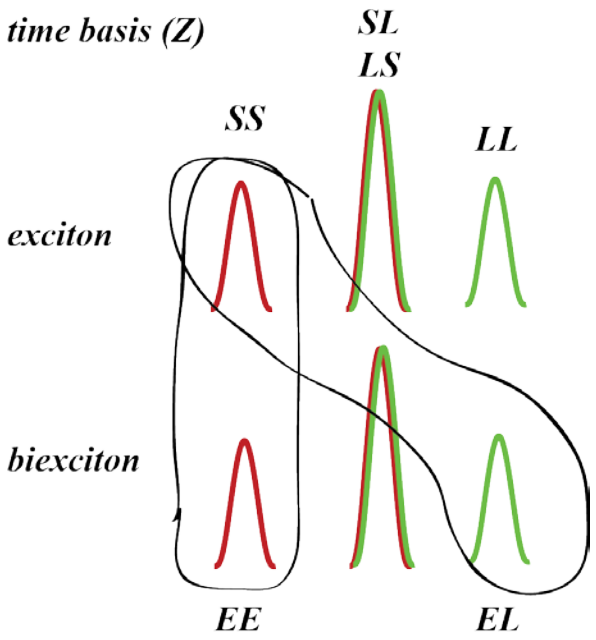
(Dated: May 15, 2009)

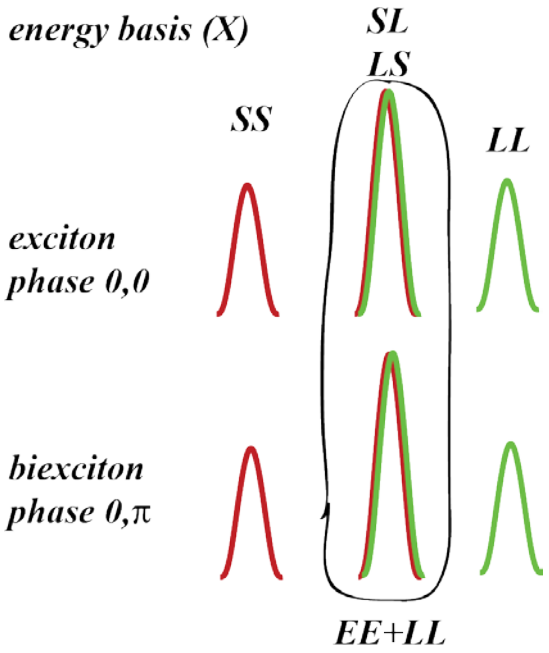
We experimentally demonstrate the first quantum system entangled in *every* degree of freedom (hyperentangled). Using pairs of photons produced in spontaneous parametric down-conversion, we verify entanglement by observing a Bell-type inequality violation in each degree of freedom: polarization, spatial mode and time-energy. We also produce and characterize maximally hyperentangled states and novel states simultaneously exhibiting both quantum and classical correlations. Finally, we report the tomography of a 2x2x3x3 system (36-dimensional Hilbert space), which we believe is the first reported photonic entangled system of this size to be so characterized.

PACS numbers: 03.65.Ud, 42.50.Dv, 03.67.Mn, 42.65.Lm

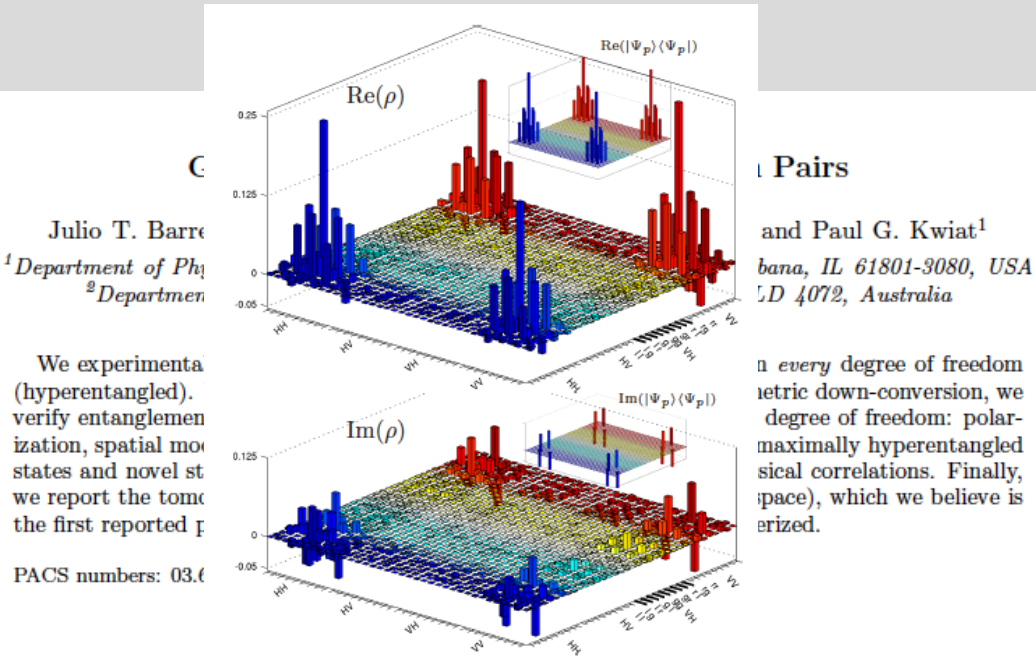
4 measurements

1	0	0
2	0	π/2
3	π/2	0
4	π/2	π/2





How?



G … Pairs

Julio T. Barre … and Paul G. Kwiat[1]

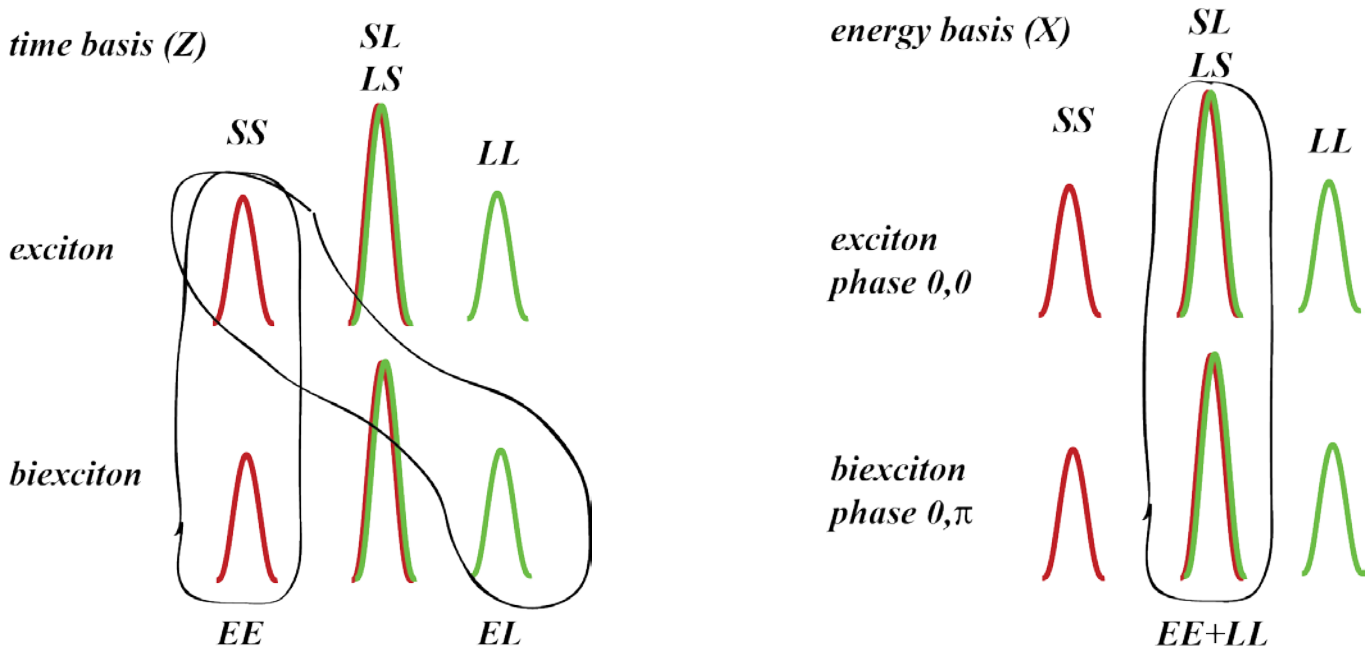
[1]Department of Ph… bana, IL 61801-3080, USA
[2]Departmen… LD 4072, Australia

We experimenta… n every degree of freedom (hyperentangled). … etric down-conversion, we verify entanglemen… degree of freedom: polarization, spatial mo… maximally hyperentangled states and novel st… sical correlations. Finally, we report the tom… space), which we believe is the first reported p… erized.

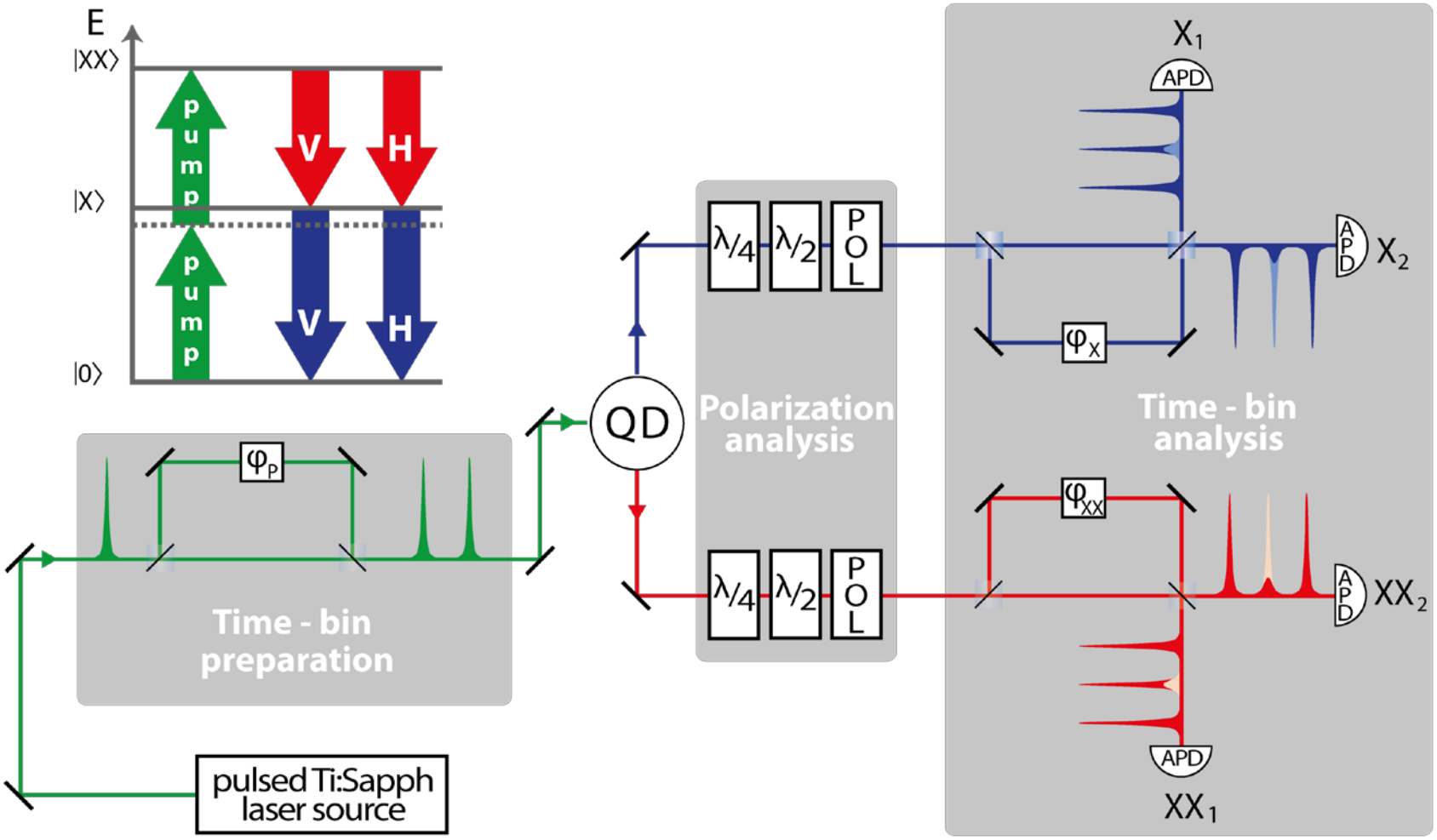
PACS numbers: 03.6…

4 measurements

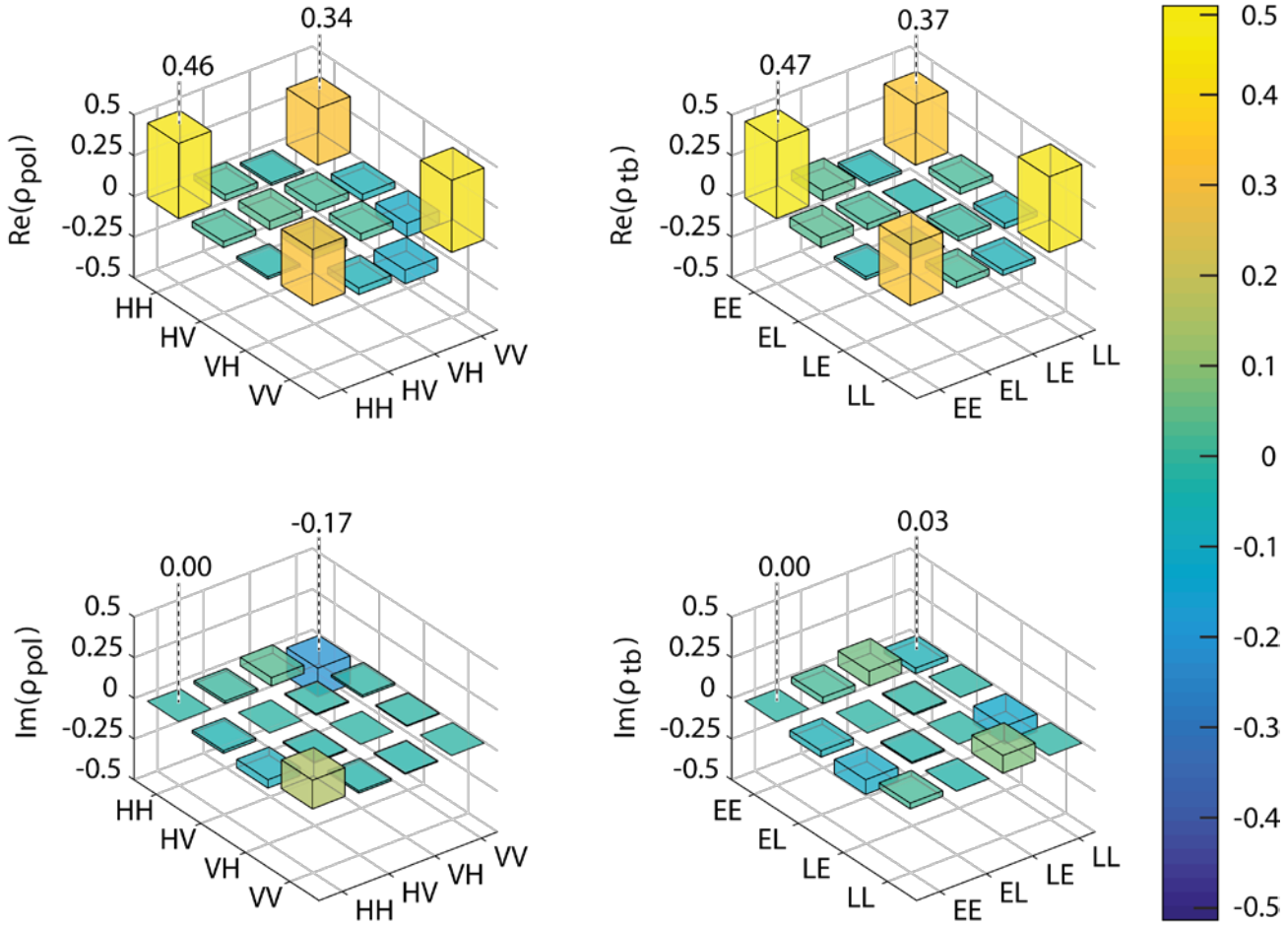
1	0	0
2	0	$\pi/2$
3	$\pi/2$	0
4	$\pi/2$	$\pi/2$



Experimental set-up



Results



		polarization	time bin
Results separately	concurrence	**0.70(7)**	**0.71(7)**
	fidelity	**0.81(3)**	**0.78(3)**
Results simultaneously	concurrence	**0.71 (7)**	**0.76 (7)**
	fidelity	**0.80(3)**	**0.87(3)**

We have…

demonstrated

- resonant excitation
- photon pair generation efficiency of ≈ 90%

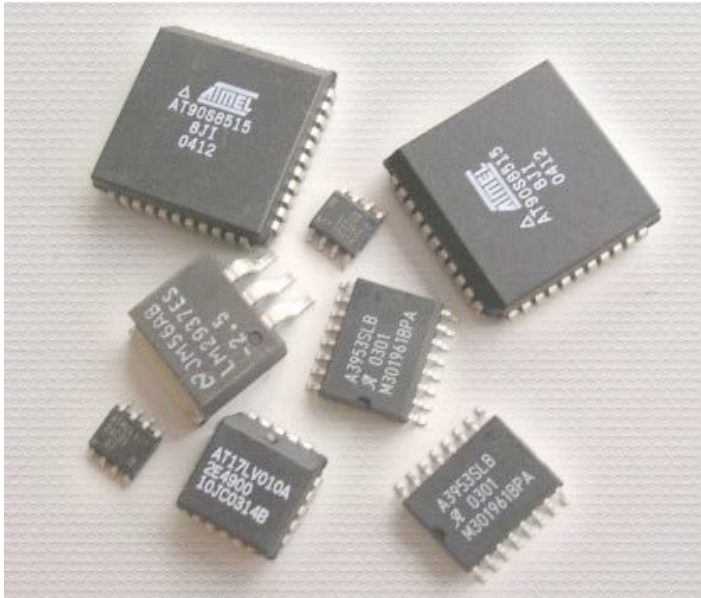
measured

~~a moderate~~ considerable degree of time-bin entanglement and hyper-entanglement

- Purcell-enhanced emission
- higher collection efficiency

important!

design of devices, based on
optimal pulse length



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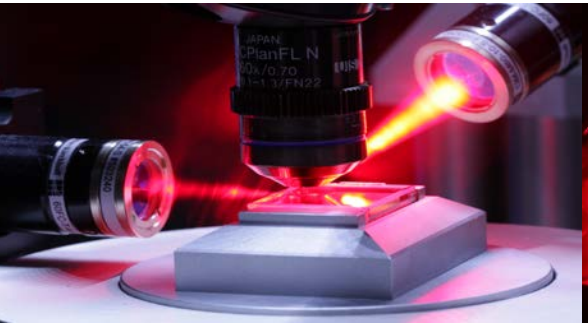
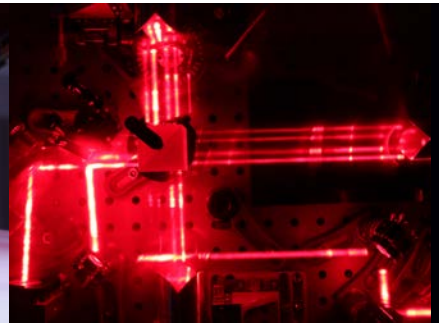
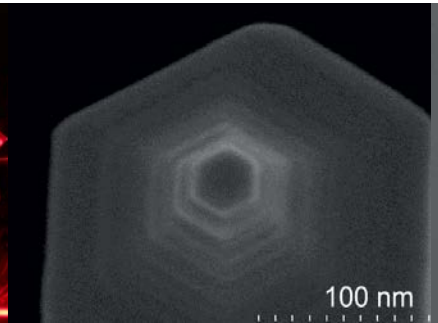
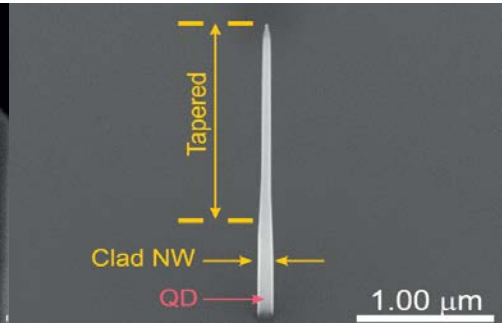
University Innsbruck

Laurin Ostermann
Helmut Ritsch

NIST and University of Maryland

Glenn S. Solomon

Stuttgart University

Markus Müller
Peter Michler

FWF
Der Wissenschaftsfonds.