Non-monotonic quantum-to-classical transition in multi-particle interference

Andreas Buchleitner

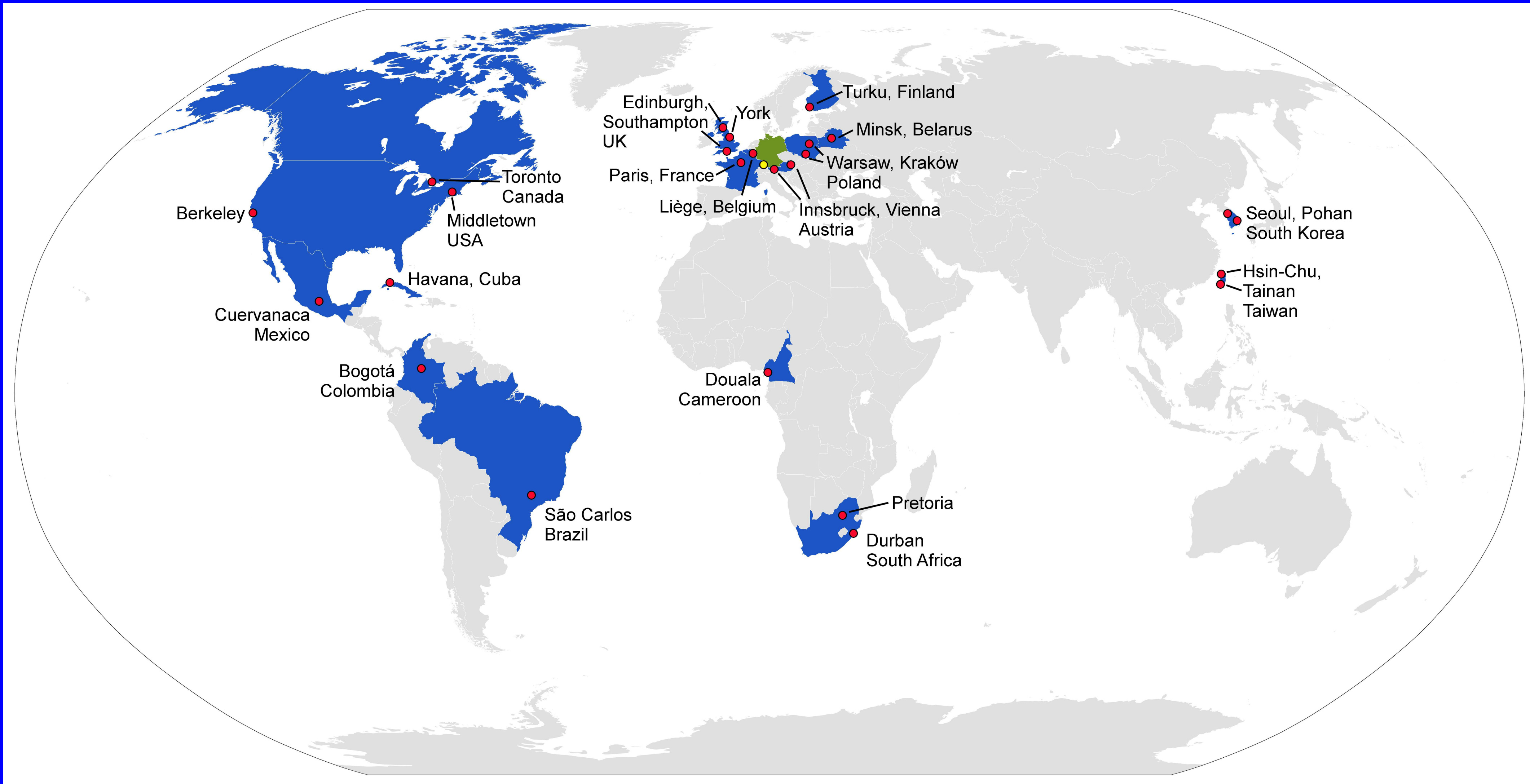
Quantum optics and statistics
Institute of Physics, Albert Ludwigs University of Freiburg

Nonlinear Dynamics in Quantum Systems

VIth Workshop on Quantum Chaos and Localisation Phenomena, Warszawa, 25 May 2013

Nonlinear Dynamics in Quantum Systems

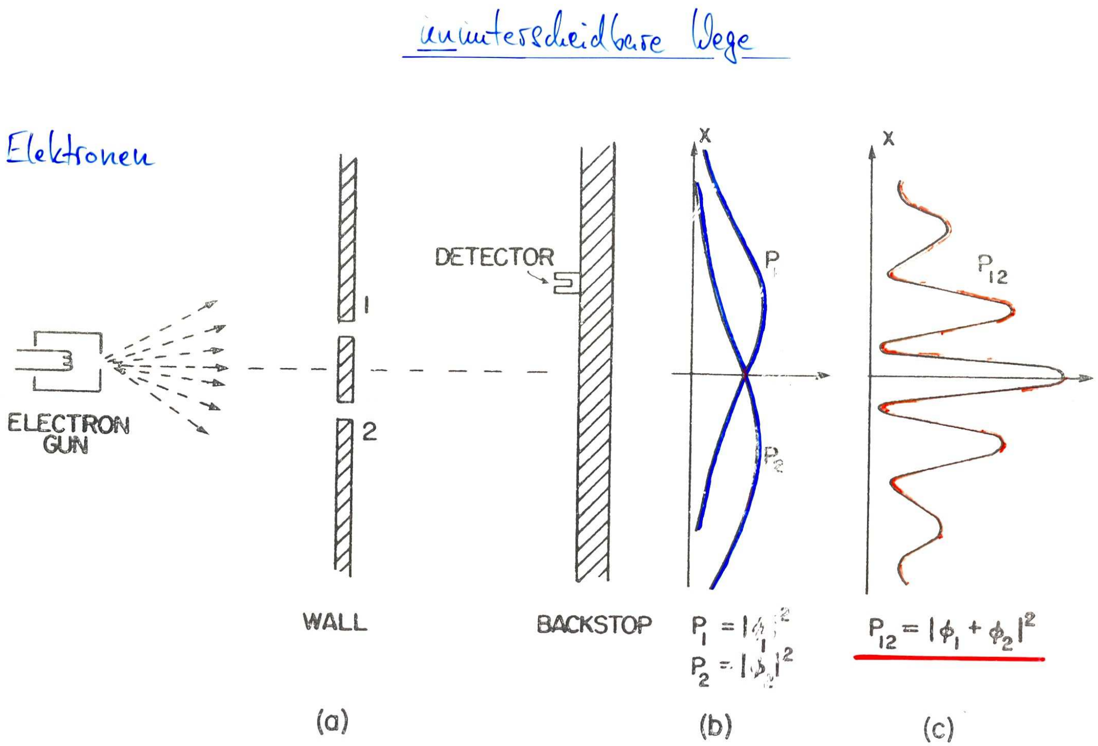
In Collaboration with . . .



. . . M. Tichy, F. Mintert, Y.-S. Ra, H.-T. Lim, O. Kwon, Y.-H. Kim

Single particle quantum interference

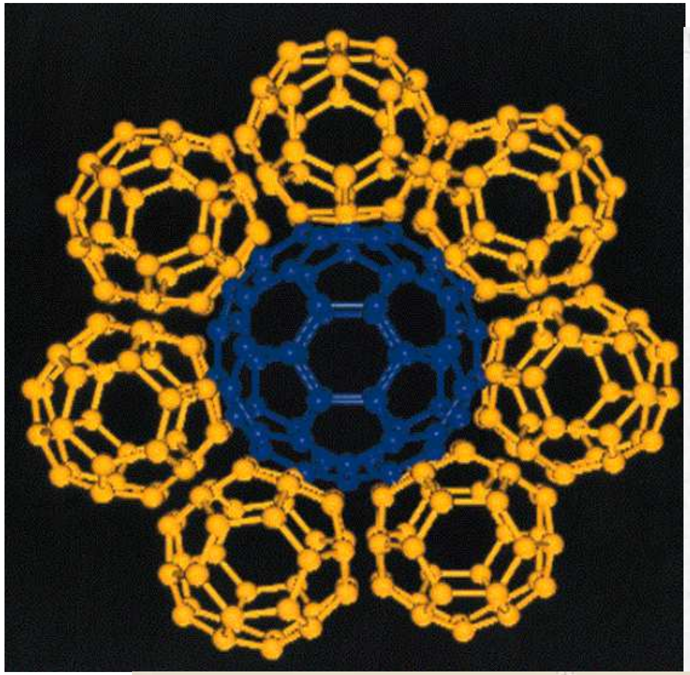
- Coherent superposition of single particle amplitudes

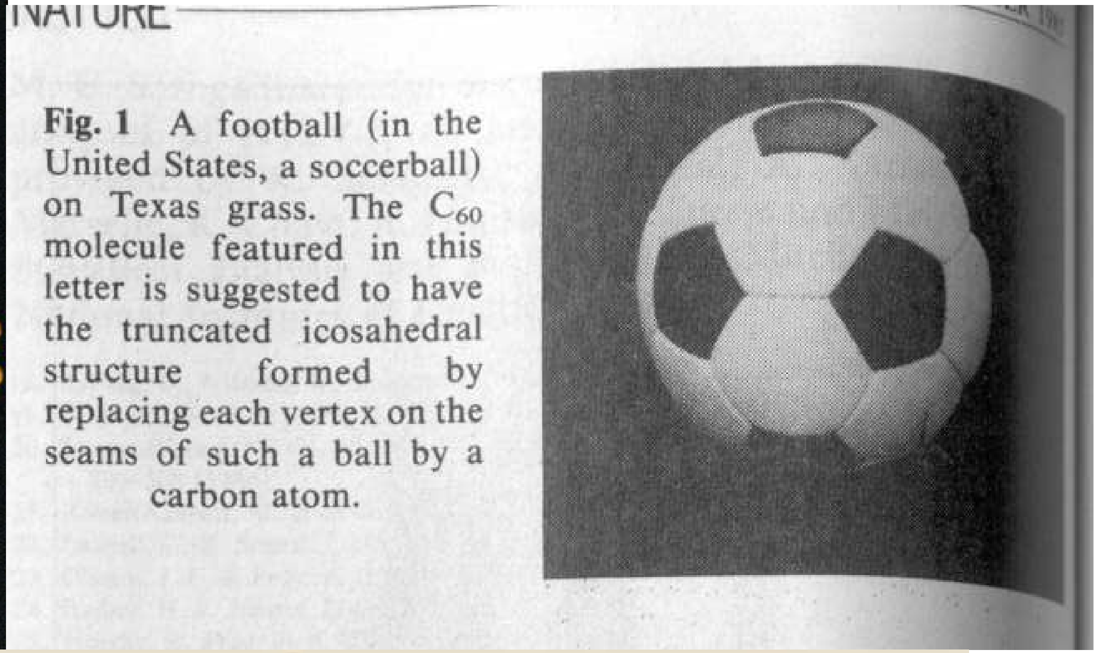


[Feynman, Lecture Notes on Quantum Mechanics]

- Which-way information induces decoherence

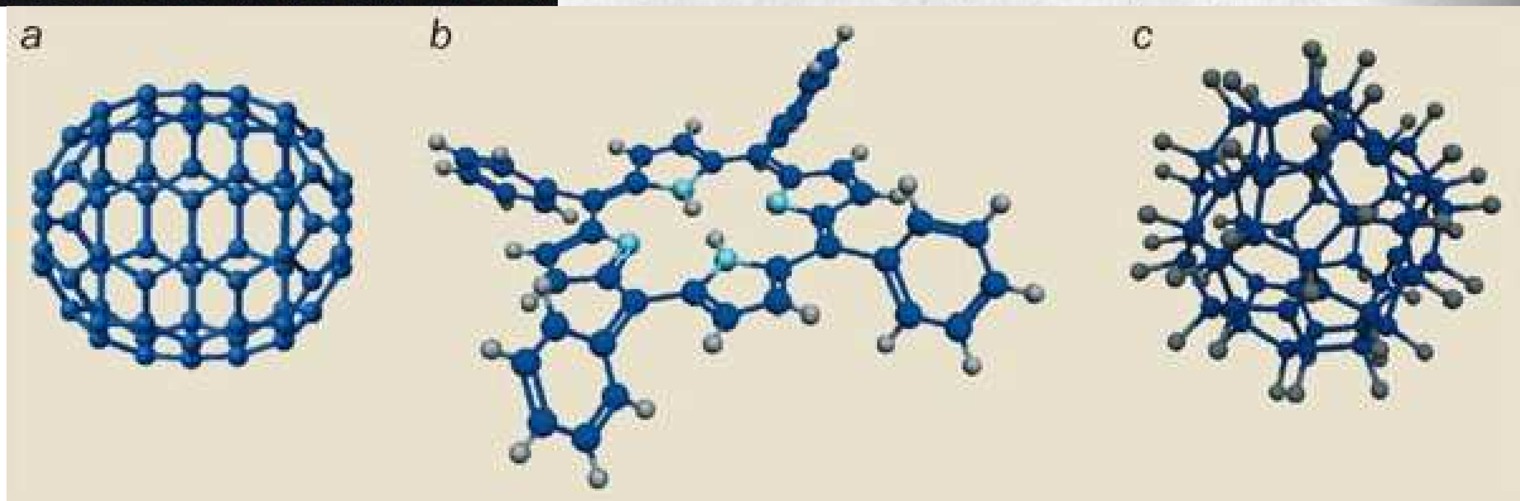
Also true for significantly larger objects





NATURE

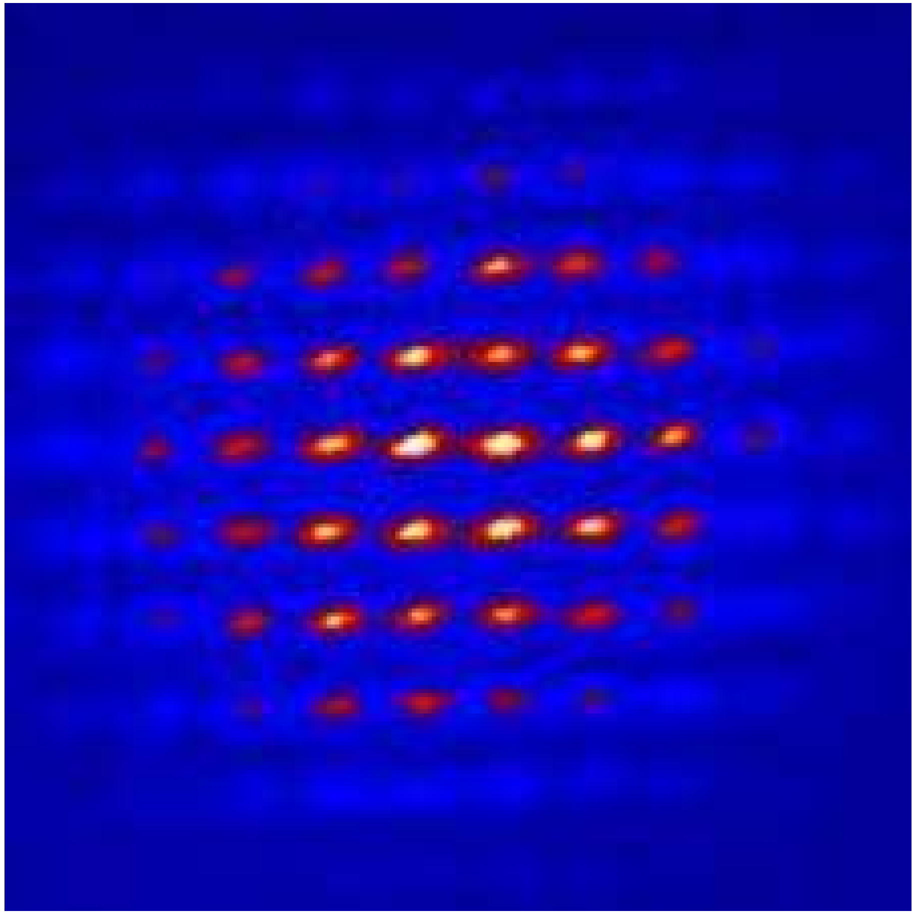
Fig. 1 A football (in the United States, a soccerball) on Texas grass. The C_{60} molecule featured in this letter is suggested to have the truncated icosahedral structure formed by replacing each vertex on the seams of such a ball by a carbon atom.



[Hornberger et al., Physics World 2005]

What about many-particle systems, e.g. (but not only) quantum computers?

N **cold atoms in a matrix** [Birkl et al.]



many particle quantum register

$$|011001011101010001\rangle$$

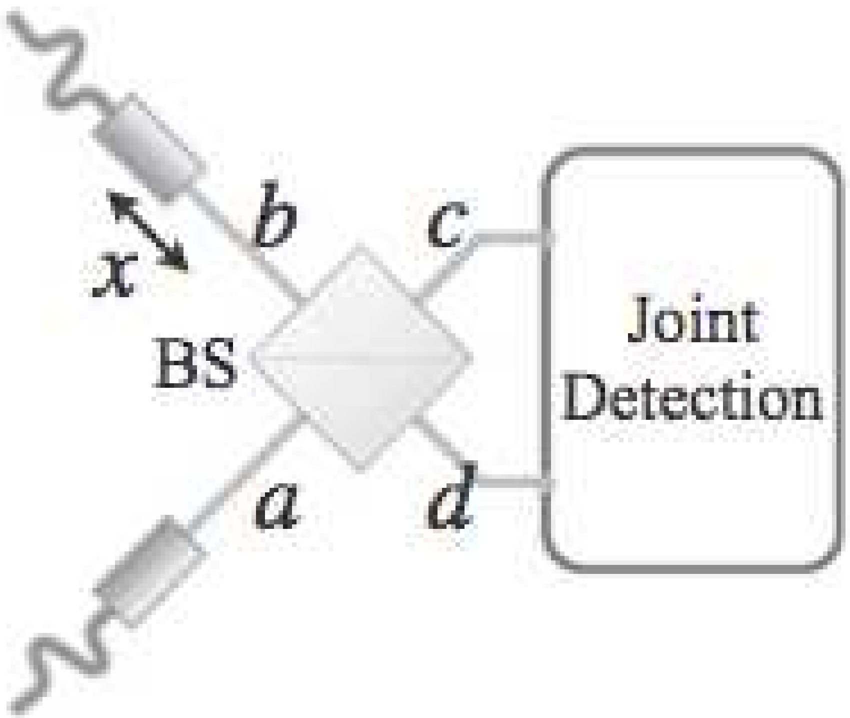
rely on coherent superposition/dynamics of 2^N many particle states

$$a|011001011101010001\rangle$$
$$+b|0\mathbf{0}1001011101010\mathbf{1}01\rangle$$
$$+c|0\mathbf{1}10010\mathbf{0}1101\mathbf{1}10\mathbf{01}1\rangle$$
$$+d|\mathbf{1}110010\mathbf{100}01\mathbf{0}100\mathbf{0}1\rangle$$
$$+\dots$$

what about (in-)distinguishability and/or (de-)coherence?

The Hong-Ou-Mandel effect

one photon in each mode a and b – distinguishability controlled by path delay x



coincident detection in output modes c and d

- coincidence probability if **distinguishable:** $P(2; 1, 1) = 1/2$

- coincidence probability if **indistinguishable:** $P(2; 1, 1) = 0$

if indistinguishable: destructive interference of two two-particle trajectories

[Shi & Alley (1986, 1988); Hong, Ou & Mandel (1987)]

What happens "in between"?

Continuous distinguishability-transition

inject (Gaussian) photon wave packet state $|1_{t_1}\rangle$ ($|1_{t_2}\rangle$) with beam splitter arrival time t_1 (t_2) in mode a (b) – then (Gram-Schmidt):

$$|1_{t_2}\rangle = \alpha|1_{t_1}\rangle + \sqrt{1-\alpha^2}|\tilde{1}_{t_1}\rangle\,,\ \alpha^2 = \exp\left(-(\Delta\omega)^2(t_2-t_1)^2/2\right)$$

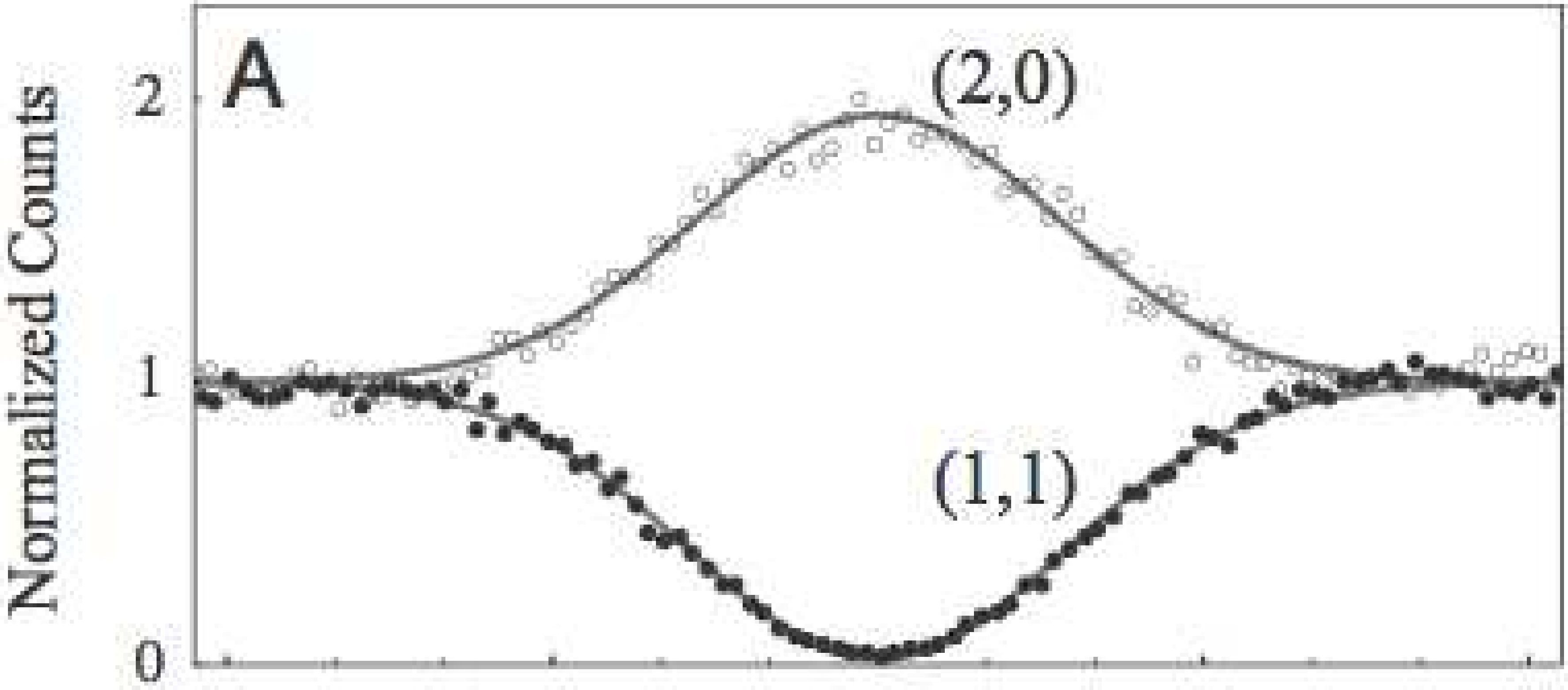
HOM two-photon state impinging on beam splitter:

$$a^\dagger_{t_1} b^\dagger_{t_2}|0\rangle = \alpha|1,1\rangle + \sqrt{1-\alpha^2}|1,\tilde{1}\rangle\,,$$

with the photons in $|1,1\rangle$ ($|1,\tilde{1}\rangle$) in(-distinguishable) – $\alpha \in \{0,1\}$ quantifies distinguishability (fully indistinguishable for $\alpha = 1$).

Ergo: **Monotonic** disappearance of interference signal in coincident detection as α decreases!

Experimental confirmation



The more two-particle which-way information, the less interference – as for single-particle scenario!

Something new happens for more particles!

Inject **two photons per mode**, and write in Gram-Schmidt decomposition with respect to temporal overlap:

$$\frac{1}{2}(a_{t_1}^\dagger)^2(b_{t_2}^\dagger)^2|0\rangle = \alpha^2|2,2\rangle + \sqrt{2}\alpha\sqrt{1-\alpha^2}|2,1,\tilde{1}\rangle + (1-\alpha^2)|2,\tilde{2}\rangle\,,$$

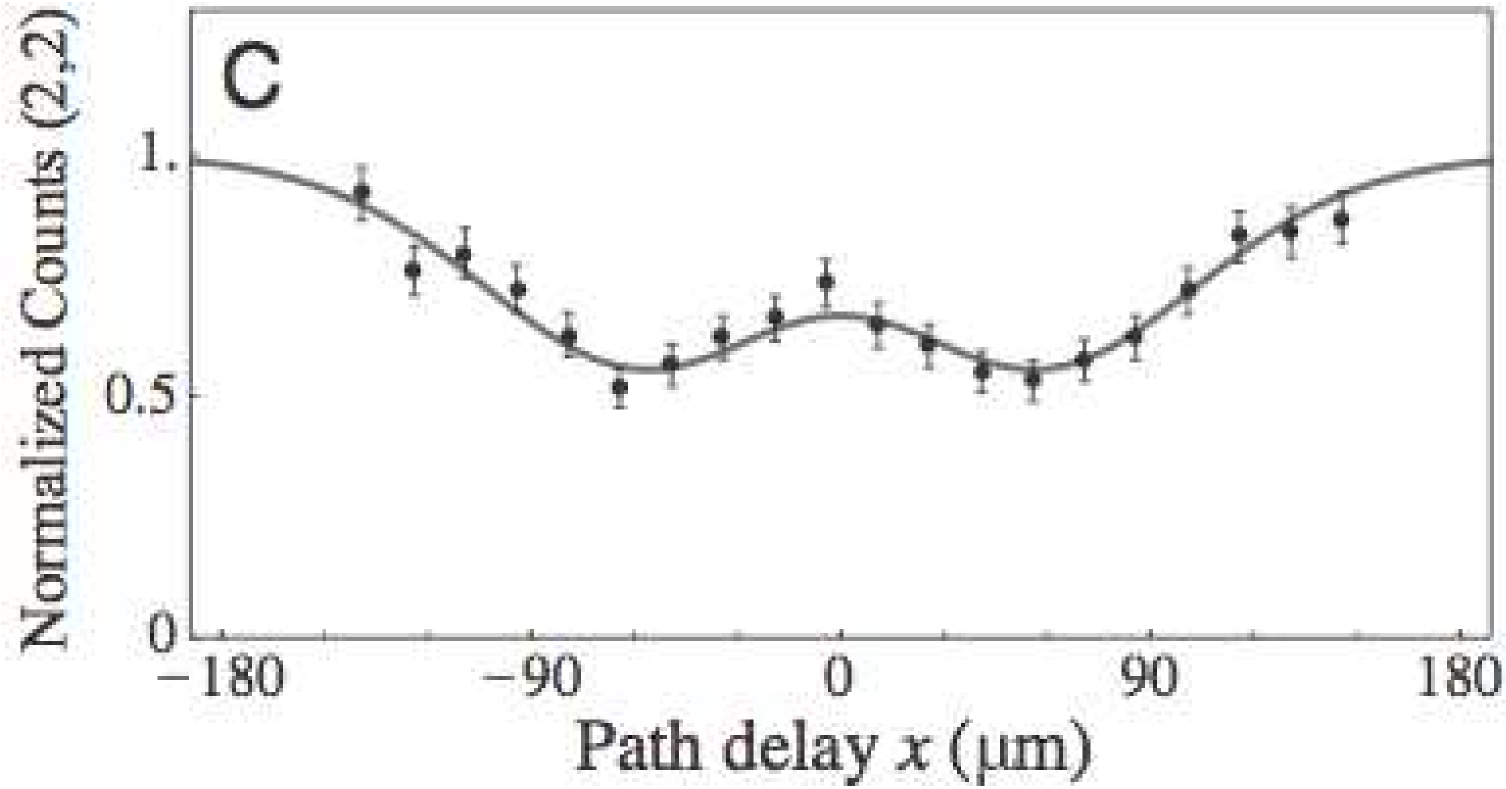
For more than one photons per mode, there **appear partially distinguishable contributions** – here, $|2,1,\tilde{1}\rangle$ implies the **interference of three-particle rather than four-particle paths, with weight $W_{\text{type}}^{(N;m,n)}$ non-monotonic in α!**

<u>General expression for (m,n)-event probability:</u>

$$P(N;m,n) = \sum_{\text{type}} p_{\text{type}}^{(N;m,n)} W_{\text{type}}^{(N;m,n)}$$

"type" – fully indistinguishable, fully distinguishable, partially distinguishable
p_{type} determined by mode mapping $a^\dagger \to (c^\dagger + d^\dagger)/\sqrt{2}$, $b^\dagger \to (c^\dagger - d^\dagger)/\sqrt{2}$.

Non-monotonic quantum-to-classical transition



With increasing distinguishability of the particles, the order of many-particle interferences is reduced from four- over three- to two-particle paths, with non-monotonic weights! Gaining which-path information at different multi-particle orders generically leads to a *non-monotonic* quantum-to-classical transition!

Conclusion/Perspective

- **The distinguishability transition affects different orders of many-particle interferences differently!**

- **Quantum interference in correlation functions thus fades away non-monotonically, in general!**

- **A probe for different types of system-environment interactions?**

– Phys. Rev. A 83, 062111 (2011); PNAS 110, 1227 (2013) –
– PhD Malte Tichy, Freiburg 2011; diploma Klaus Mayer, Freiburg 2011 –
www.quantum.uni-freiburg.de