Tomography of a high-fidelity entangled spin-photon qubit pair

Peter McMahon

Yamamoto Group

Stanford University

Reference: K. De Greve*, P.L. McMahon*, L. Yu, J.S. Pelc, C. Jones, C. Natarajan, N.Y. Kim, E. Abe, S. Maier, C. Schneider, M. Kamp, S. Hoefling, R.H. Hadfield, A. Forchel, M.M. Fejer, Y. Yamamoto, *Nature Communications* (in press).

MSS, Wrocław, 4 July 2013.

* Equal contribution

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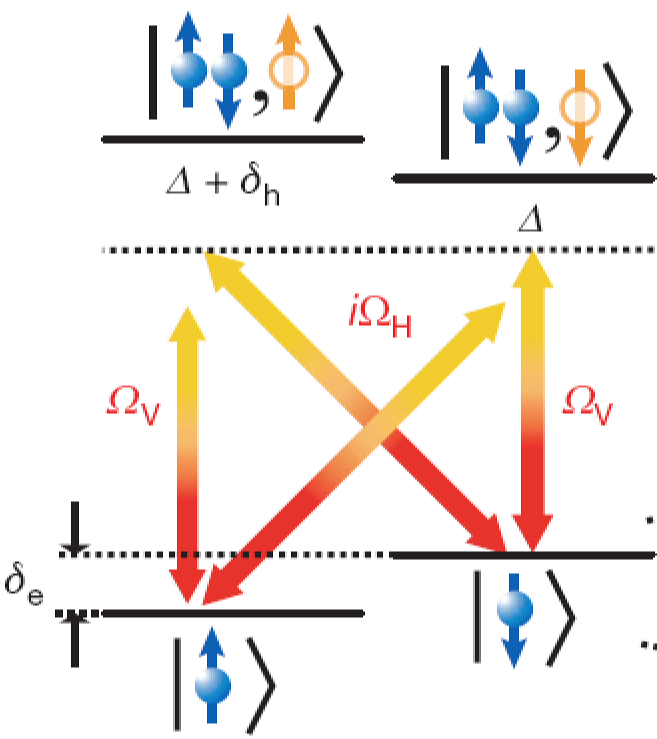
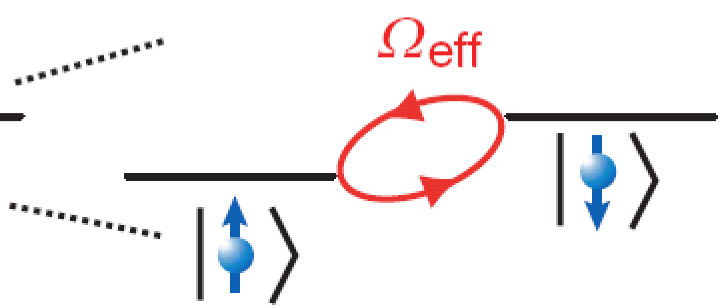
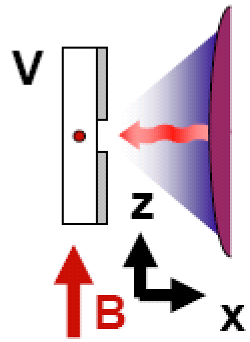
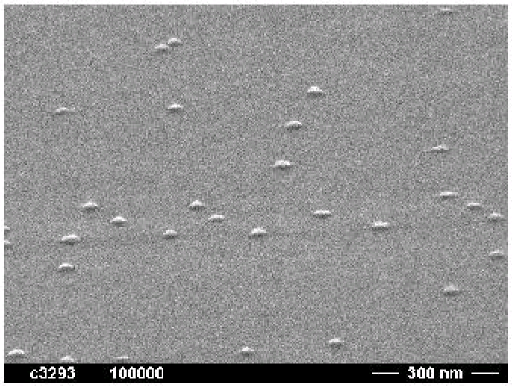
Quantum Dot Spin Qubits



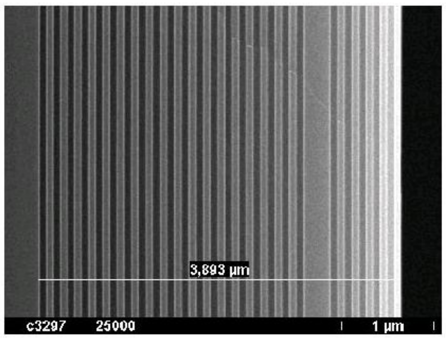




Voigt Geometry.



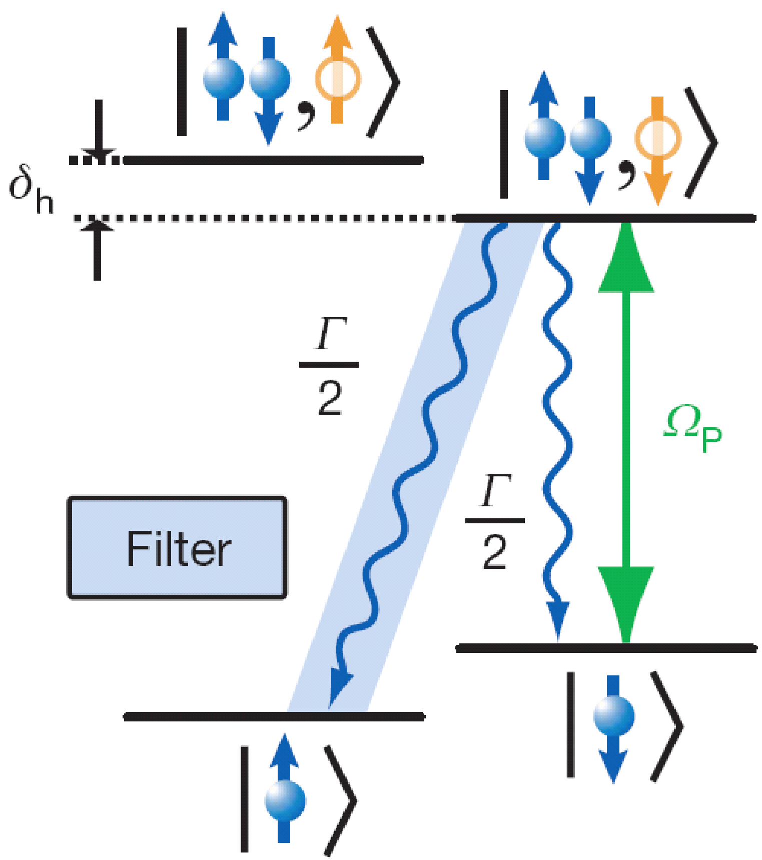
InAs QD SEM image.

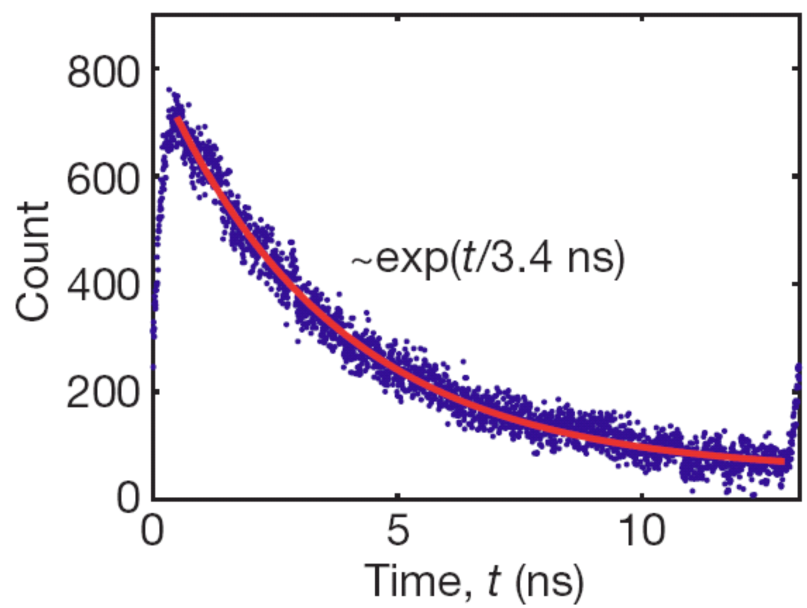


Cavity SEM image.

Figures from Press, *et al*. *Nature* 2008 and U. Würzburg.

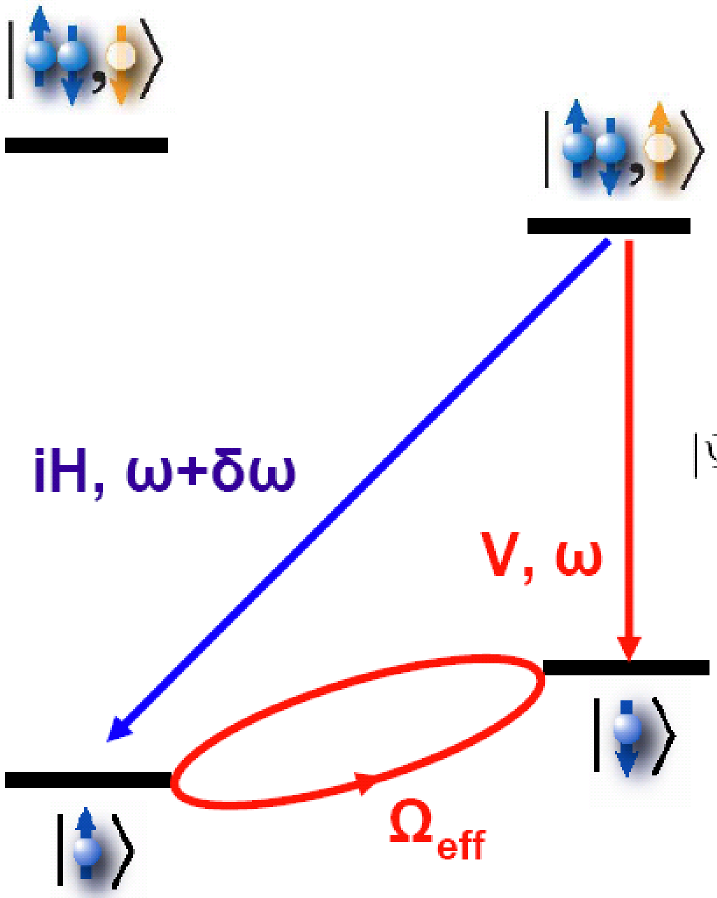
Initialization and Readout





Figures from Press, *et al*. *Nature* 2008.

Spin-Photon Entanglement



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(i\,|\uparrow\rangle \otimes |\mathrm{H}\rangle \otimes |\omega + \delta\omega\rangle + |\downarrow\rangle \otimes |\mathrm{V}\rangle \otimes |\omega\rangle\right)$$

Polarization and *frequency* entanglement with the spin!

Figure from: K. De Greve, L. Yu*****, P.L. McMahon*****, J.S. Pelc*****, *et al*., *Nature* **491**, 7424, pp. 421-425 (2012).

Frequency Quantum Eraser

Goal: Eliminate *frequency* information

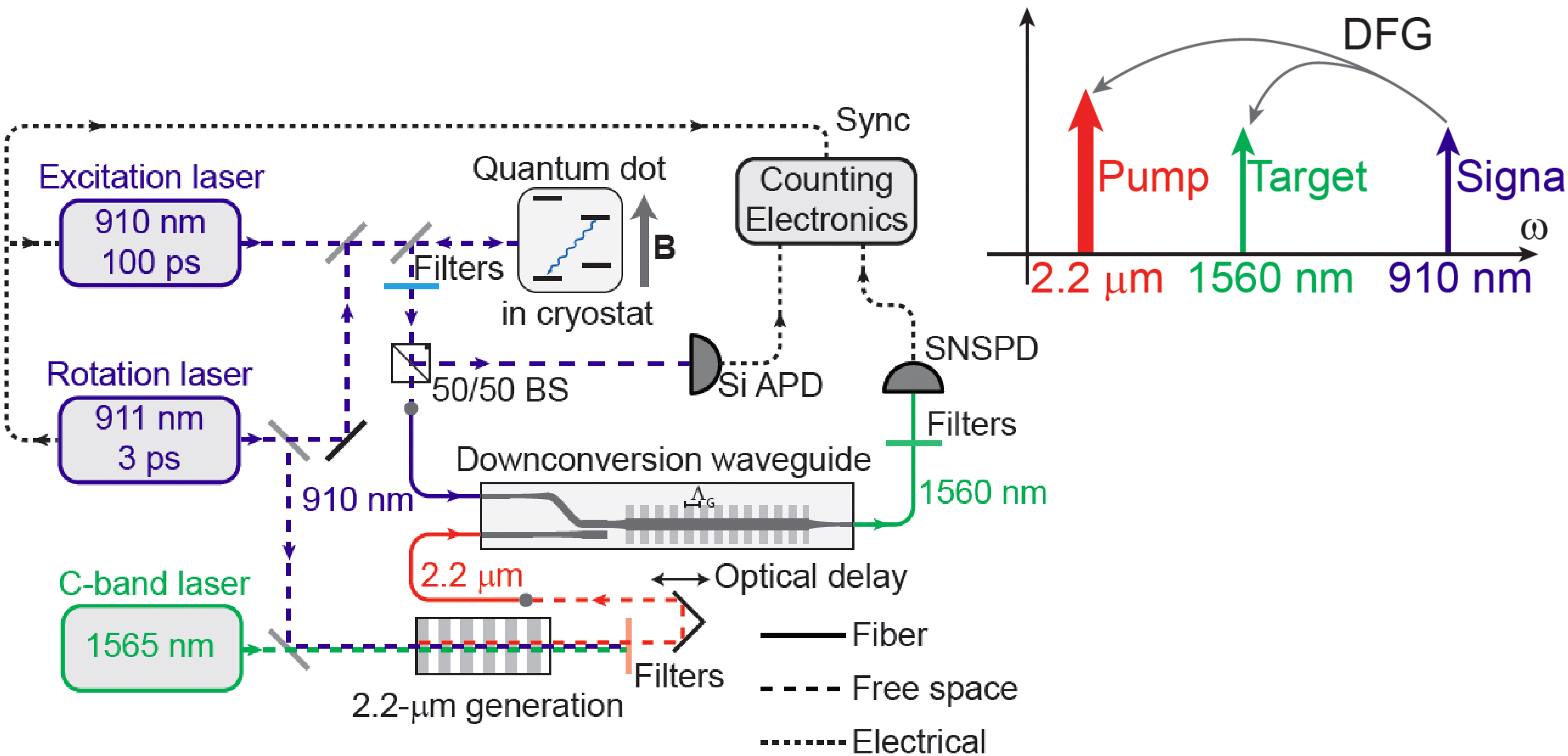
Method: Measure photon arrival time with precision much better than inverse of frequency/energy splitting.

$$\Delta t \Delta E \sim \hbar$$

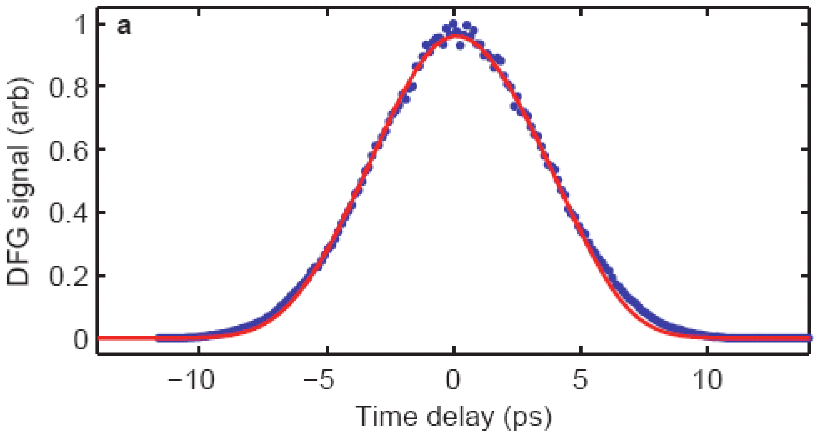
In our experiment, the frequency splitting is ~20 GHz. Therefore we need to measure with timing accuracy << 50 ps

Ultrafast Frequency Downconversion

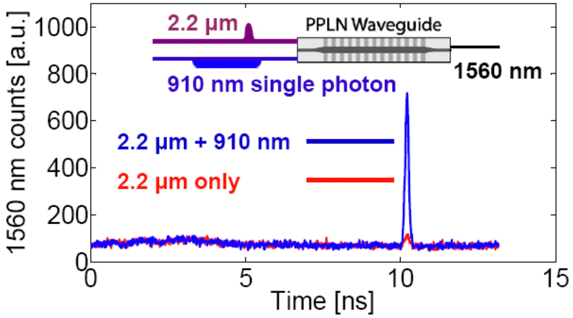
See paper **Pelc, Yu*, De Greve*, McMahon*, *et al*., *Optics Express* 20, 25, pp. 27510-27519 (2012)** for details.

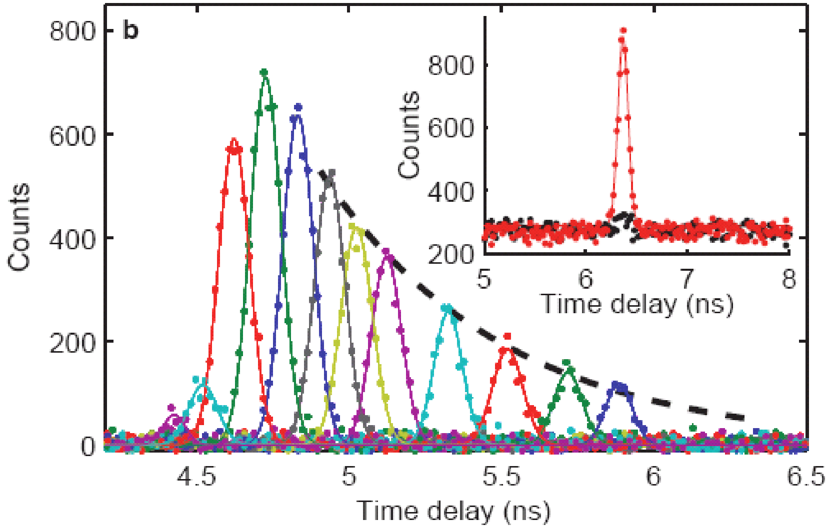


Downconversion Results



Cross-correlation with ~3 ps 910 nm pulse shows **~8 ps timing resolution** → bound on spin-photon entanglement fidelity of ~95%.

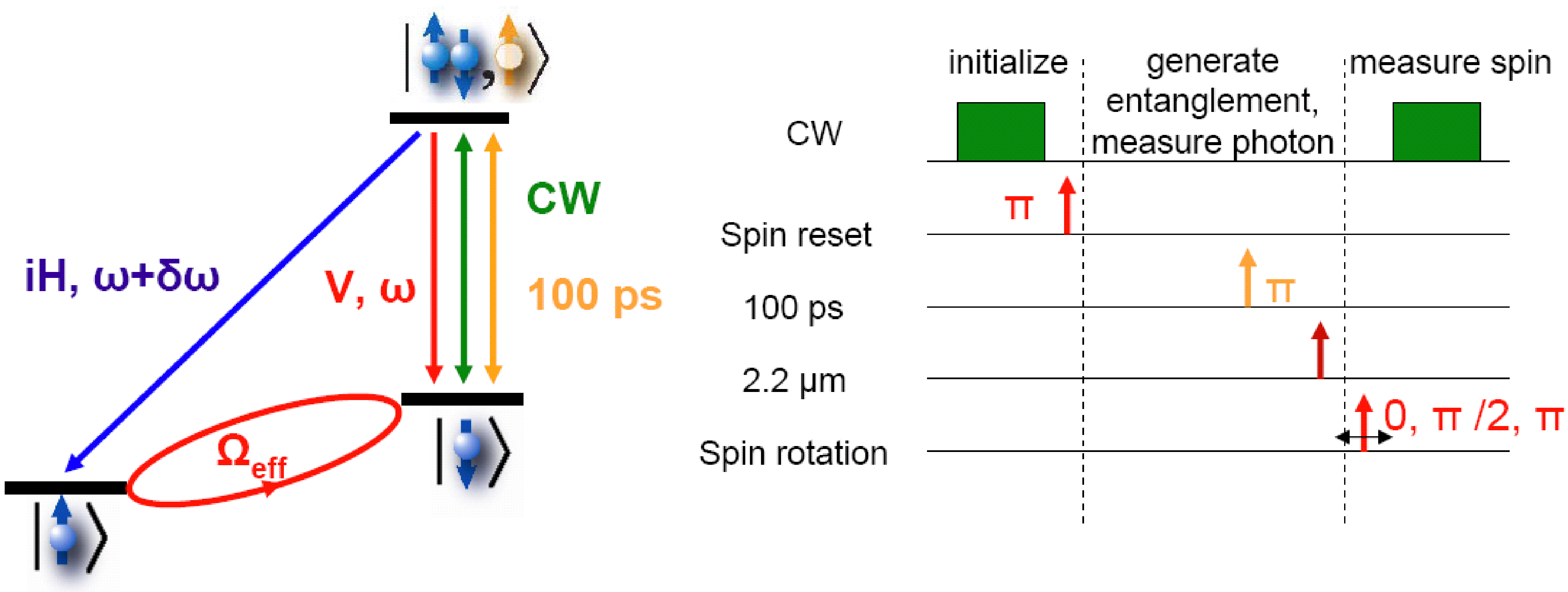




Scanning pump delay reproduces ~**600 ps** QD **decay time** at ~**1560 nm**.

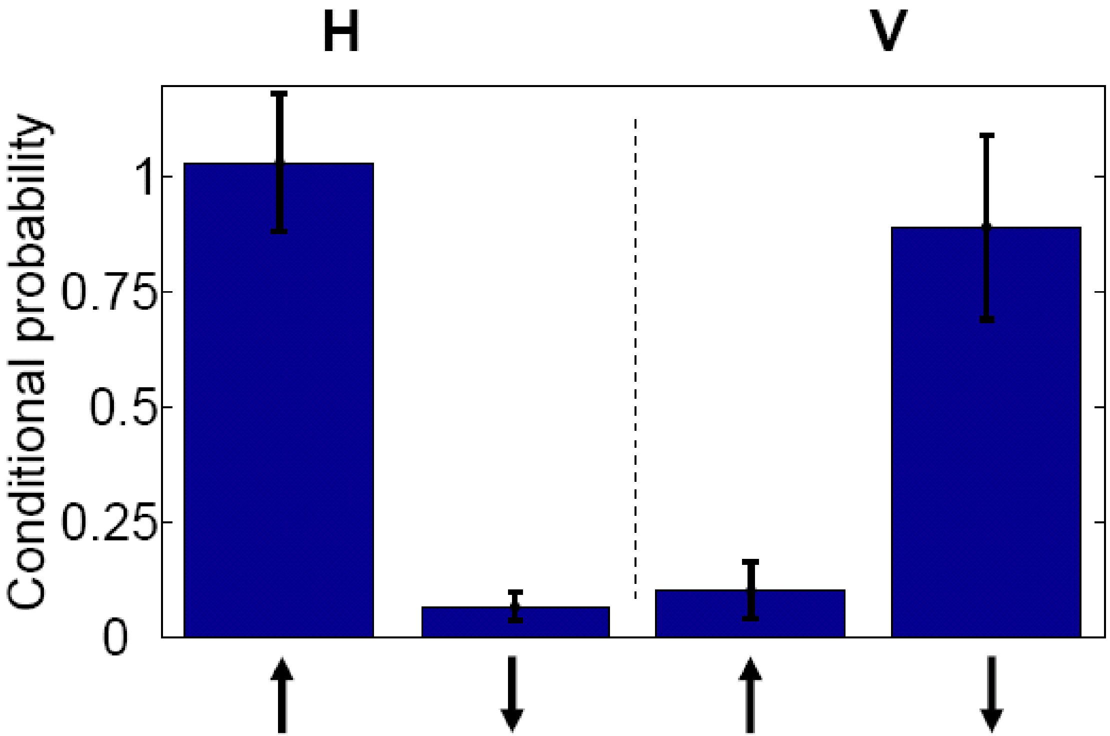
Entanglement Verification using Downconversion

Goal: Measure photon and spin in two orthogonal bases.



Figures from: K. De Greve, L. Yu*, P.L. McMahon*, J.S. Pelc*, *et al.*, *Nature* **491**, 7424, pp. 421-425 (2012).

Results: Linear Basis

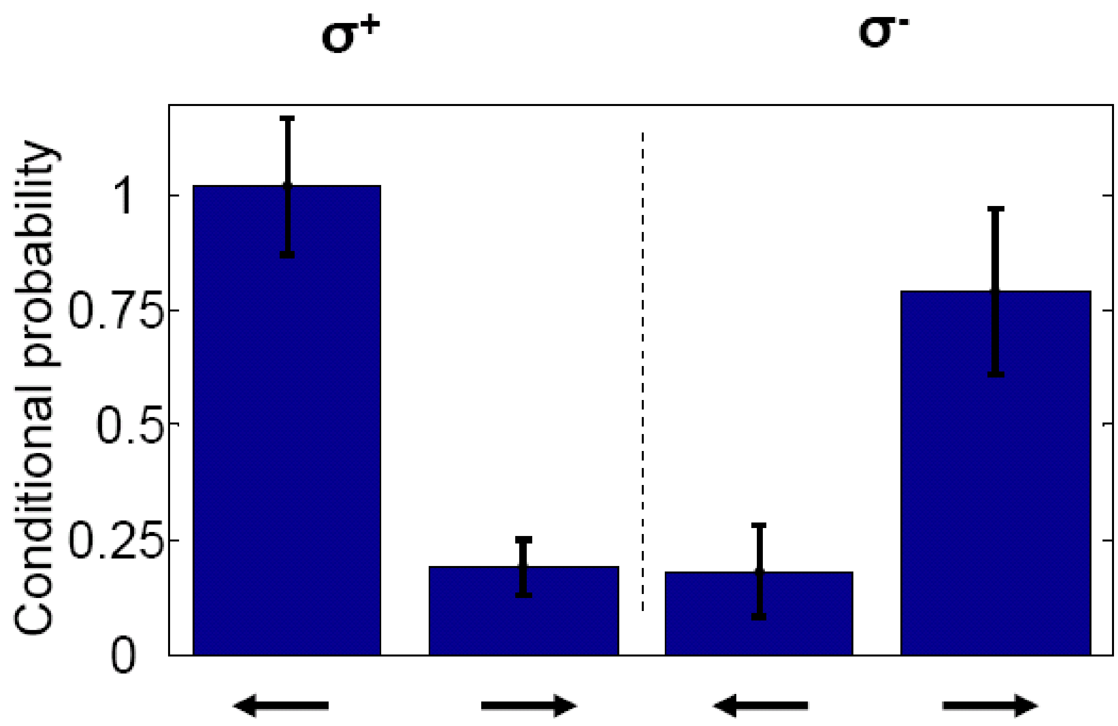


Interpretation: e.g., when we measure an H-polarized photon, we "always" measure the spin in state up, and "never" in state down.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(i\,|\uparrow\rangle \otimes |\mathrm{H}\rangle \otimes |\omega + \delta\omega\rangle + |\downarrow\rangle \otimes |\mathrm{V}\rangle \otimes |\omega\rangle)$$

Figure from: K. De Greve, L. Yu*****, P.L. McMahon*****, J.S. Pelc*****, *et al*., *Nature* **491**, 7424, pp. 421-425 (2012).

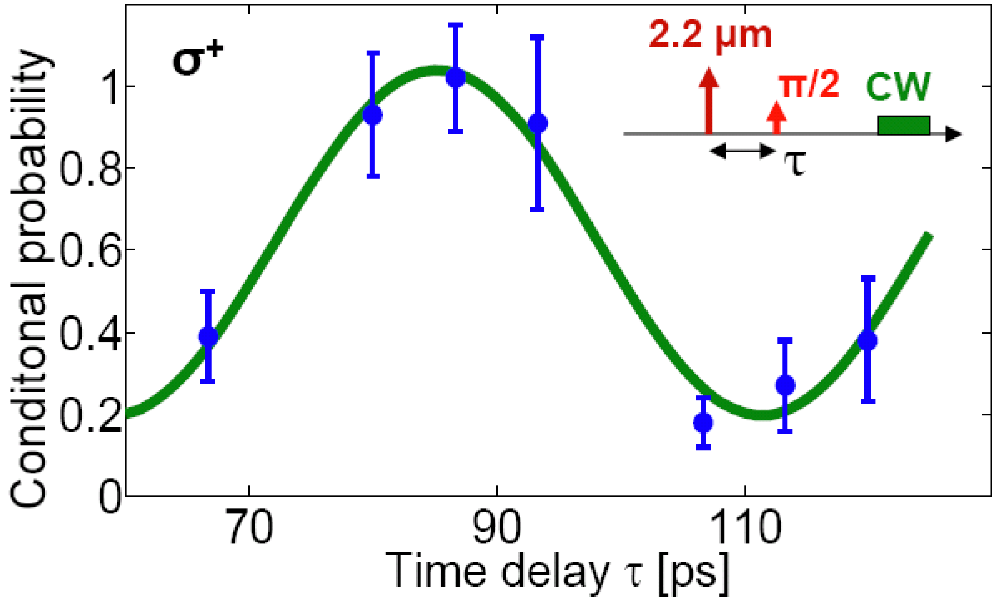
Results: Circular Basis



We see strong correlations in an orthogonal basis. This is only possible if the state was entangled (not simply a mixed, i.e. classical, state).

Figure from: K. De Greve, L. Yu*, P.L. McMahon*, J.S. Pelc*, *et al*., *Nature* **491**, 7424, pp. 421-425 (2012).

Results: Varying Spin Basis



$$|\Psi_{\text{spin},\sigma^+}(t)\rangle = \frac{1}{\sqrt{2}}(e^{i\delta\omega(t-t_1)}|\uparrow\rangle - |\downarrow\rangle)$$

After measuring the photon, the spin will precess at the Larmor frequency. Thus varying the delay between the photon "generation" and the measurement pi/2 pulse results in a measurement in continuously varying bases ("between" x and y).

Figure from: K. De Greve, L. Yu*, P.L. McMahon*, J.S. Pelc*, *et al.*, *Nature* **491**, 7424, pp. 421-425 (2012).

Previous Spin-Photon Results

Atomic and Overall Record Holder ⇨ (row 2)

Solid-state Record Holder ⇨ (row 6)

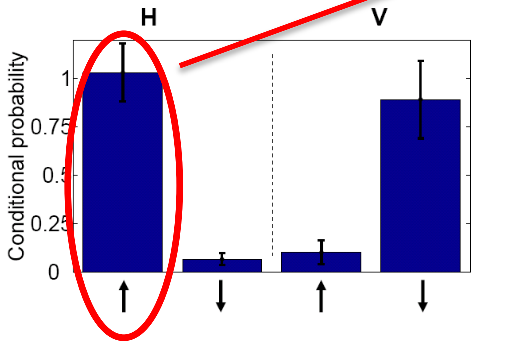
Physical System	Wavelength	Entanglement Fidelity	Institution (PI)
Trapped ion ($^{111}Cd^+$)	214.5 nm	>= 87% [1]	U. Maryland (Monroe)
Trapped ion ($^{40}Ca^+$)	854 nm	97.4 +/- 0.2% [2]	U. Innsbruck (Blatt)
NV centre	637 nm	>= 70 +/- 7% [3]	Harvard U. (Lukin)
Neutral atom (^{87}Rb)	780 nm	> 86.0(4)% [4]	MPI Garching (Rempe)
Quantum dot (InGaAs)	967 nm	>= 68 +/- 5% [5]	ETH Zürich (Imamoglu)
Quantum dot (InAs)	910 nm, converted to 1560 nm	>= 80 +/- 8.5% [6]	Stanford U. (Yamamoto)
Quantum dot (InAs)	~900 nm	>= 59 +/- 4% [7]	U. Michigan (Steel)

[1] B. Blinov, *et al*. *Nature* **428**, pp. 153 – 157 (2004). doi:10.1038/nature02377
[2] A. Stute, *et al*. *Nature* **485**, pp. 482 – 485 (2012). doi:10.1038/nature11120
[3] E. Togan, *et al*. *Nature* **466**, pp. 730 – 734 (2010). doi:10.1038/nature09256
[4] T. Wilk, *et al*. *Science* **317**, pp. 488 – 490 (2007). doi:10.1126/science.1143835
[5] W. Gao, *et al*. *Nature* **491**, pp. 426 – 430 (2012). doi:10.1038/nature11573
[6] K. De Greve, *et al*. *Nature* **491**, pp. 421 – 425 (2012). doi:10.1038/nature11577
[7] J. Schaibley, *et al*. *PRL* **110**, 167401 (2013). doi:10.1103/PhysRevLett.110.167401

Two-Qubit Tomography

$$\rho_{\text{reconstruct}} = \frac{1}{4} \times \sum_{i,j} r_{i,j} \sigma_i \otimes \sigma_j \qquad r_{i,j} = 4 \times \text{Tr}[\rho_{\text{reconstruct}} \sigma_i \otimes \sigma_j]$$

Use 16 correlation measurements



$P(\uparrow|\text{H})$

$P(\downarrow|\text{H})$

$P(\uparrow|\text{V})$

$P(\downarrow|\text{V})$

$P(\leftarrow_\text{x}|\text{H}), \leftarrow_\text{x} = \frac{\uparrow - \downarrow}{\sqrt{2}}$

$P(\rightarrow_\text{y}|\text{H}), \rightarrow_\text{y} = \frac{\uparrow + i\downarrow}{\sqrt{2}}$

$P(\leftarrow_\text{x}|\text{V})$

$P(\rightarrow_\text{y}|\text{V})$

$P(\leftarrow_\text{x}|\sigma^+), \sigma^+ = \frac{H + iV}{\sqrt{2}}$

$P(\rightarrow_\text{y}|\sigma^+),$

$P(\uparrow|\sigma^+)$

$P(\downarrow|\sigma^+)$

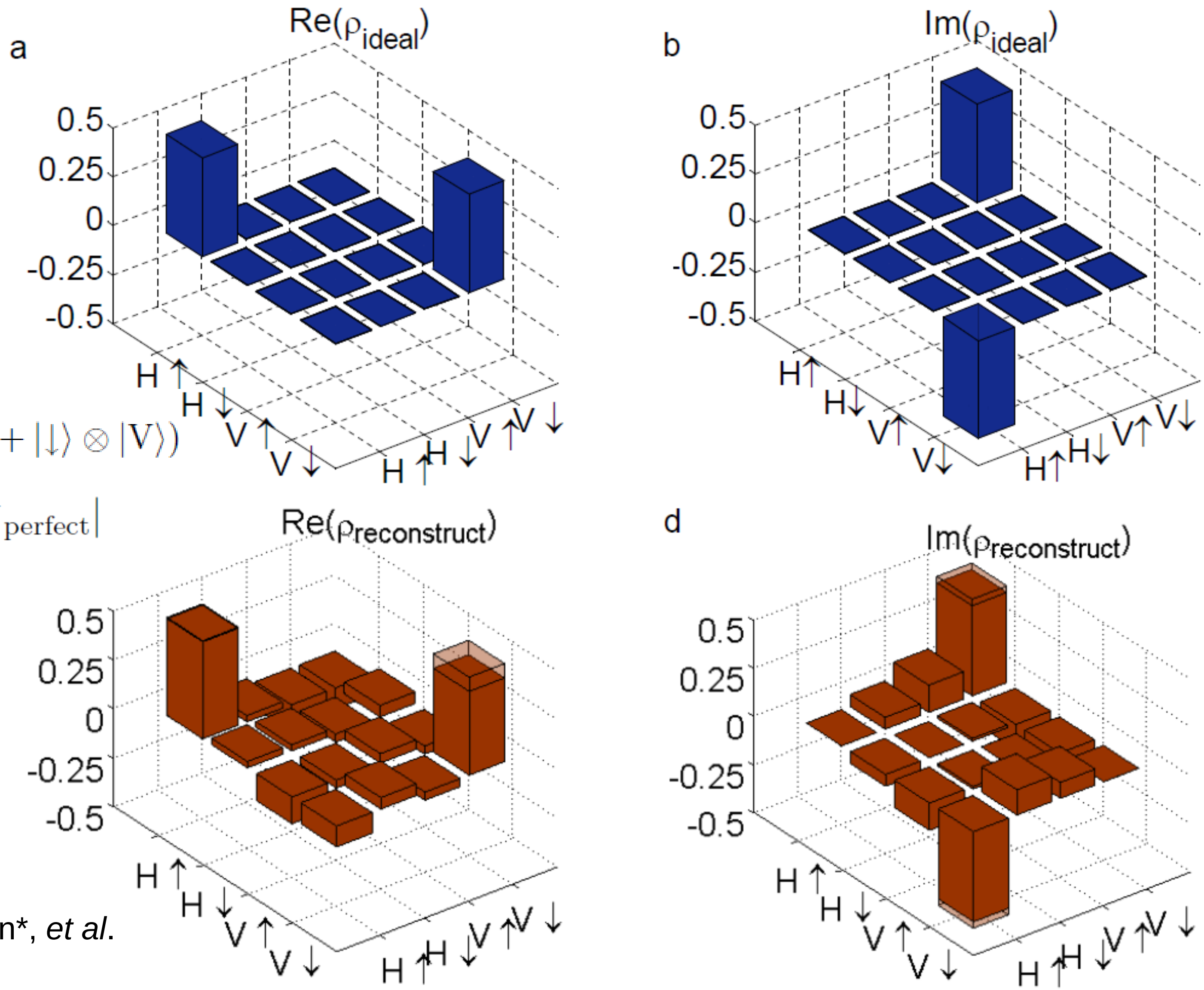
$P(\leftarrow_\text{x}|D^+), D^+ = \frac{H + V}{\sqrt{2}}$

$P(\leftarrow_\text{y}|D^+), \leftarrow_\text{y} = \frac{\uparrow - i\downarrow}{\sqrt{2}}$

$P(\uparrow|D^+)$

$P(\downarrow|D^+)$

Direct Density Matrix Reconstruction



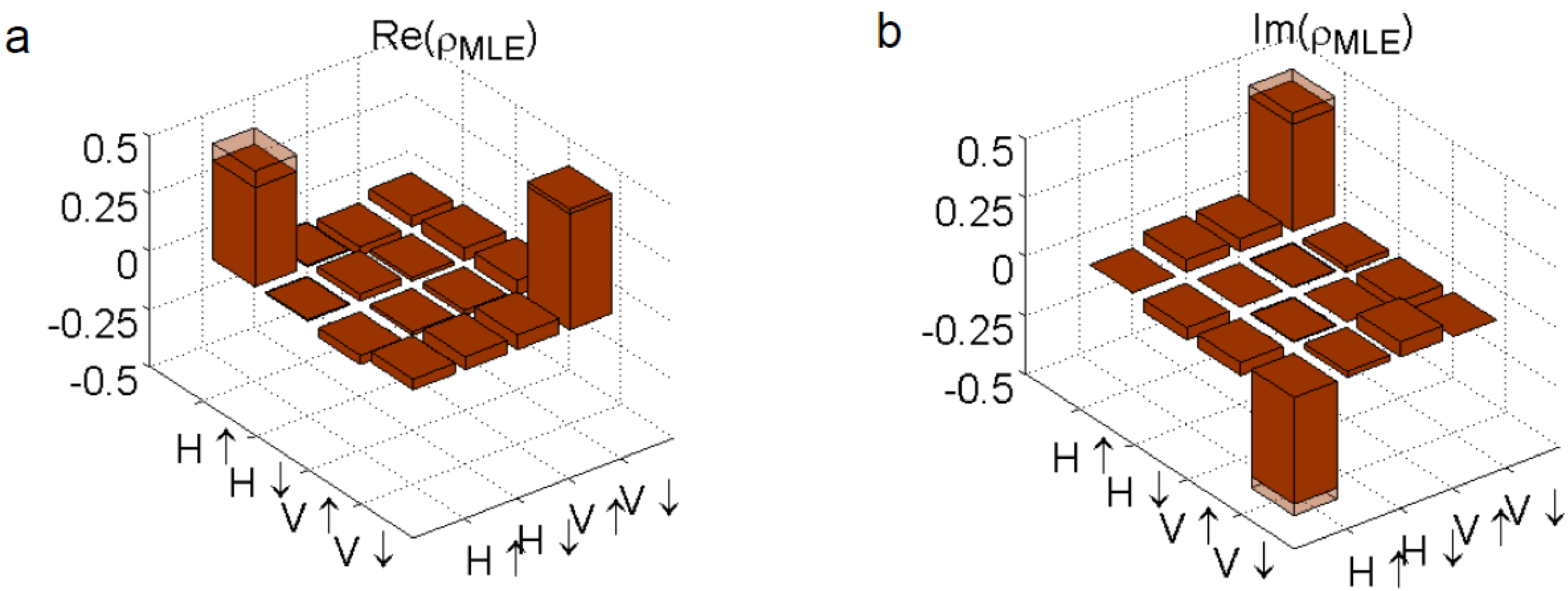
$$|\Psi_{\rm perfect}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle \otimes |i{\rm H}\rangle + |\downarrow\rangle \otimes |{\rm V}\rangle)$$

$$\rho_{\rm ideal} = |\Psi_{\rm perfect}\rangle \otimes \langle\Psi_{\rm perfect}|$$

K. De Greve*, P.L. McMahon*, *et al*.
(in press).

Maximum Likelihood Estimate Reconstruction

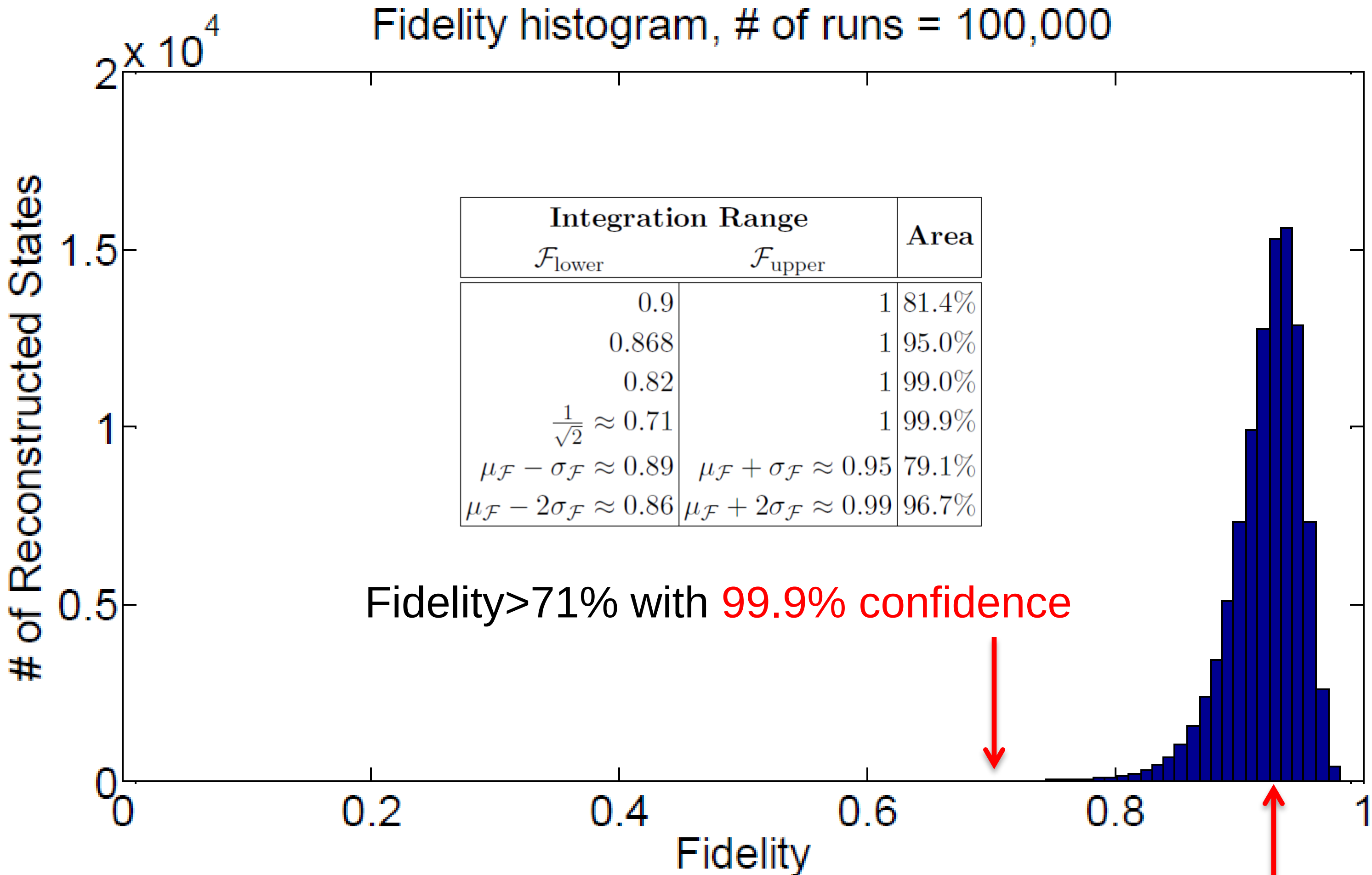
Find the most likely *physical* density matrix, given the obtained correlation results.



$$F_{\mathrm{MLE}} = \langle \Psi_{\mathrm{ideal}} | \rho_{\mathrm{MLE}} | \Psi_{\mathrm{ideal}} \rangle = 92.1\%$$

K. De Greve*, P.L. McMahon*, *et al*. (in press).

Fidelity Uncertainty Analysis



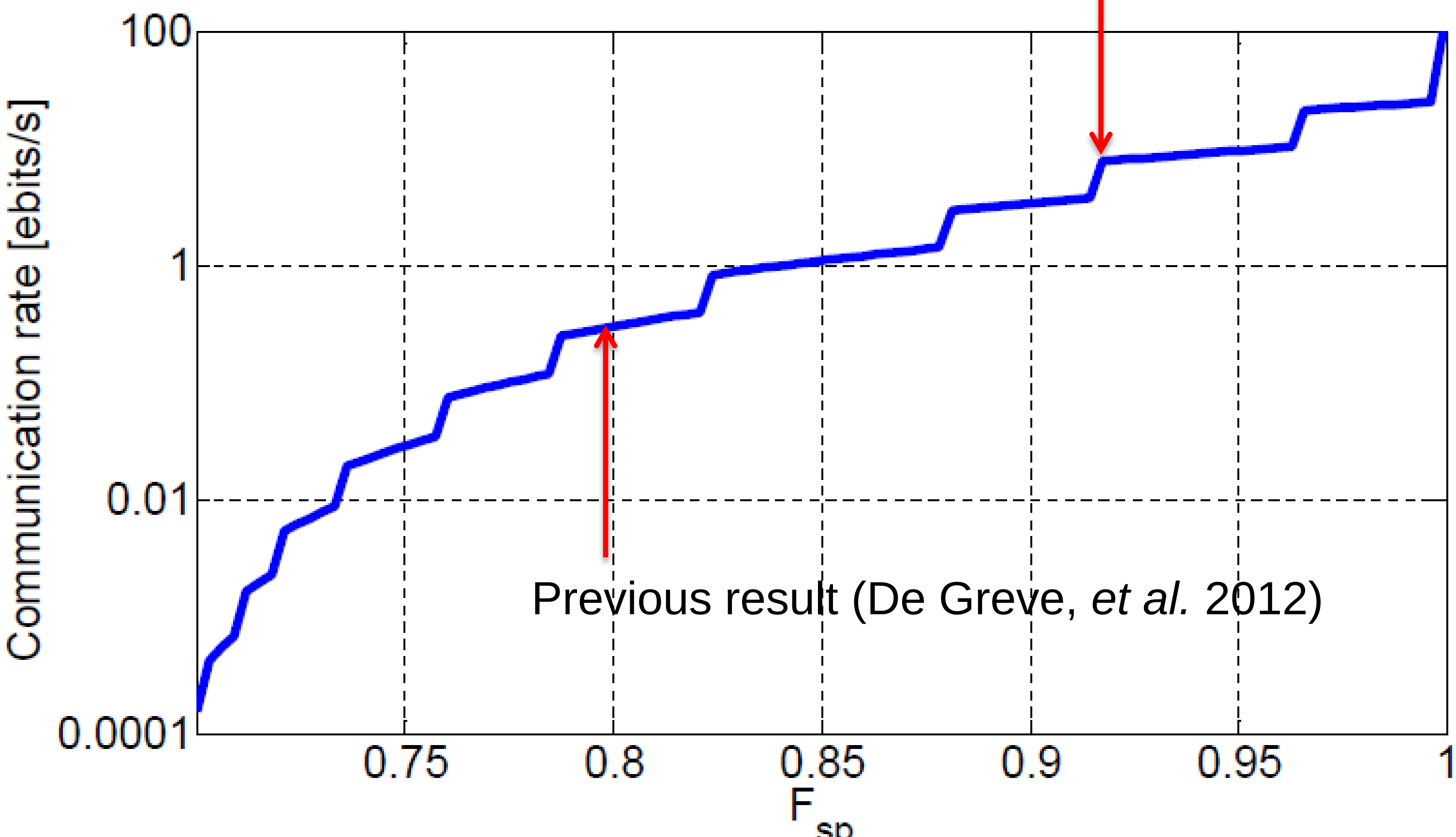
Integration Range $\mathcal{F}_{\text{lower}}$	$\mathcal{F}_{\text{upper}}$	Area
0.9	1	81.4%
0.868	1	95.0%
0.82	1	99.0%
$\frac{1}{\sqrt{2}} \approx 0.71$	1	99.9%
$\mu_{\mathcal{F}} - \sigma_{\mathcal{F}} \approx 0.89$	$\mu_{\mathcal{F}} + \sigma_{\mathcal{F}} \approx 0.95$	79.1%
$\mu_{\mathcal{F}} - 2\sigma_{\mathcal{F}} \approx 0.86$	$\mu_{\mathcal{F}} + 2\sigma_{\mathcal{F}} \approx 0.99$	96.7%

Fidelity is 92.1% +/- 3.2%

K. De Greve*, P.L. McMahon*, *et al*. (in press).

Fidelity and Entangled Pair Distribution Rate

Expected communication rate if F_{sp} ~ 92% (new result)



Previous result (De Greve, *et al.* 2012)

K. De Greve*, P.L. McMahon*, *et al*. (in press).

Summary

- We measured the density matrix of the entangled spin-photon state, which yielded a record-high fidelity for the solid-state.
- Fidelity rivals those achieved in many atomic/ionic experiments.
- We saturated the bound on how good our fidelity could be, given detection timing resolution.
- Entanglement verification was achieved through conversion to 1560 nm.