2007 IC Postdoctoral Research Fellowship Colloquium

Quantum Teleportation with Entangled Multimode Photons

Travis S. Humble

Oak Ridge National Laboratory
humblets@ornl.gov

PI: Warren Grice IC: Susan Durham

Agenda

Quantum Information and Teleportation

Entangled Multimode Photons

Teleportation with Multimode Photons

Communicating and Computing Applications

Sensing and Security Applications

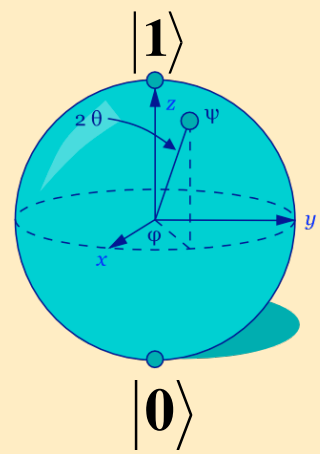
“Information is Physical”

Classical bit: 0 or **1**

1 High voltage

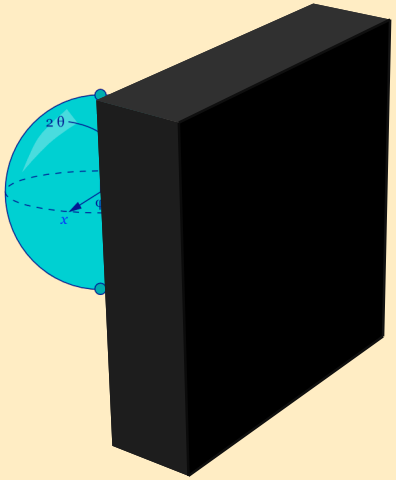
0 Low voltage

Quantum bit: $\alpha|0\rangle + \beta|1\rangle$

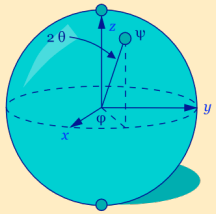


“Information is Physical”

Multiple Qubits



$$\left|0_1,1_2\right\rangle + \left|1_1,0_2\right\rangle$$



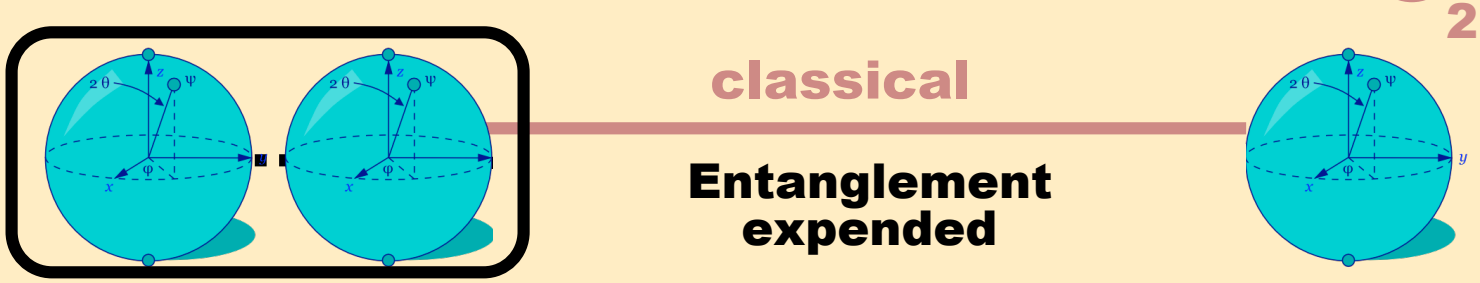
Entanglement

Quantum Teleportation

$\psi_1 = (\alpha, \beta)$

$\psi_3 = U_j \psi_1$

2 bits



1 BSM 2

3

1. Qubit at 1 destroyed, entanglement expended.

2. Qubit at 3 encrypted ψ_1

3. Encryption key is BSM outcome (2 bits).

4. Qubit does not traverse intervening space.

From Theory to Practice

Quantum bit	⟷	**Quantum system**
	Photon	
$\alpha\lvert\mathbf{0}_1\rangle + \beta\lvert\mathbf{1}_1\rangle$	$\mathbf{0} = h$ and $\mathbf{1} = v$	$\alpha\lvert h_1\rangle + \beta\lvert v_1\rangle$
$\lvert\mathbf{0}_2,\mathbf{1}_3\rangle + \lvert\mathbf{1}_2,\mathbf{0}_3\rangle$		$\lvert h_2,v_3\rangle + \lvert v_2,h_3\rangle$

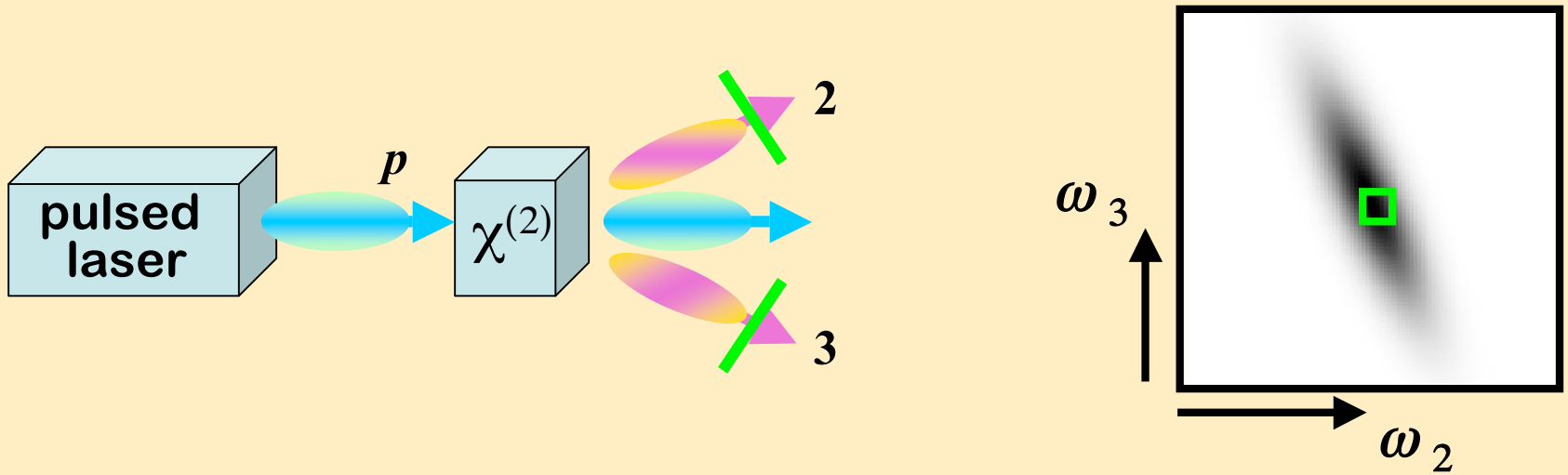
Other physical properties complicate this relationship!

Information may be loss: decoherence and decay

Qubits may be distinguishable: spatial and spectral modes

Entangled Multimode Photons

Pulsed Spontaneous Parametric Down-conversion (SPDC)

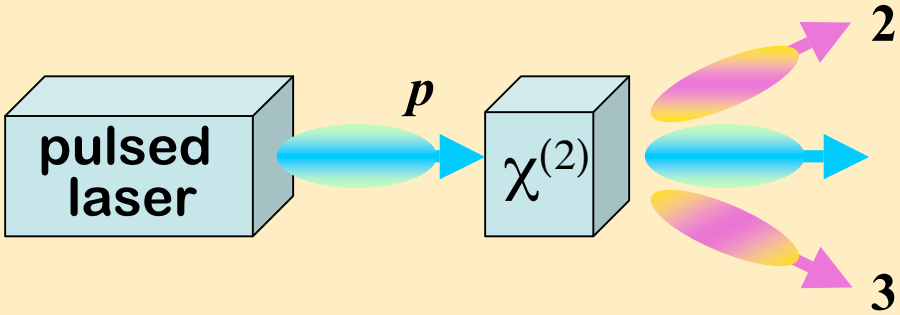


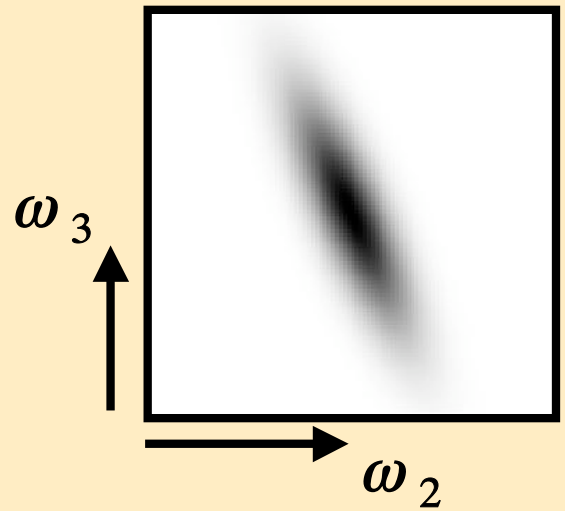
Polarization-entangled single-mode photon pair

$$\left|\varphi_{23}\right\rangle = \frac{1}{\sqrt{2}}\left|h_2(\omega), v_3(\omega)\right\rangle + \left|v_2(\omega), h_3(\omega)\right\rangle$$

Entangled Multimode Photons

Pulsed Spontaneous Parametric Down-conversion (SPDC)





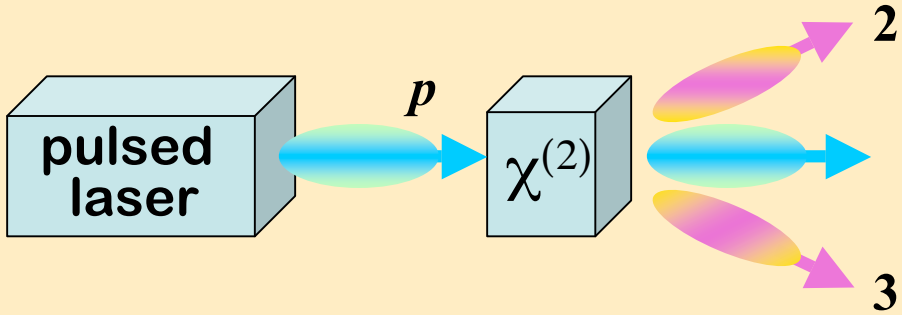
Polarization-entangled multi-mode photon pair

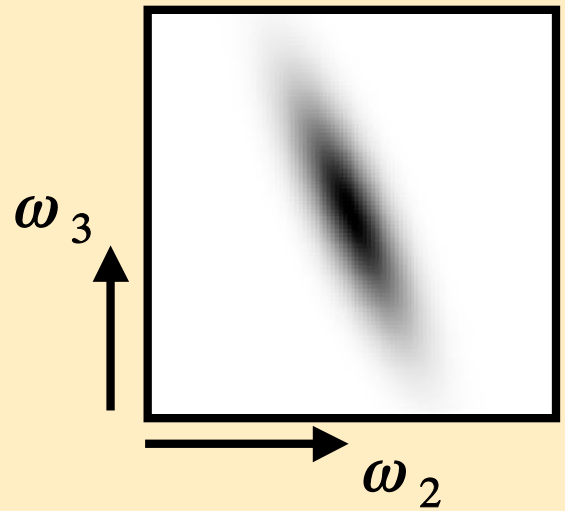
$$|\varphi_{23}\rangle = \frac{1}{\sqrt{2}} \int d\omega_2 \int d\omega_3 \Big[\underline{f(\omega_2,\omega_3)} \big| h_2(\omega_2), v_3(\omega_3) \big\rangle$$

$$\underline{+g(\omega_2,\omega_3)} \big| v_2(\omega_2), h_3(\omega_3) \big\rangle \Big]$$

Entangled Multimode Photons

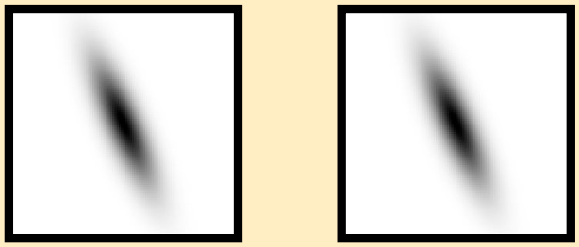
Pulsed Spontaneous Parametric Down-conversion (SPDC)





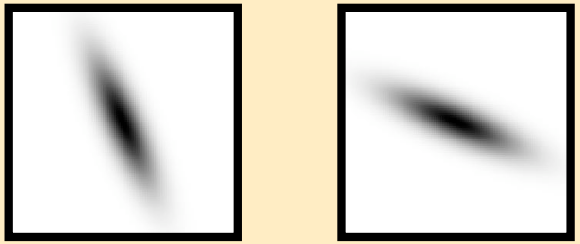
Type-I SPDC

$$f(\omega_2,\omega_3) = g(\omega_2,\omega_3)$$



Type-II SPDC

$$f(\omega_2,\omega_3) = g(\omega_3,\omega_2)$$



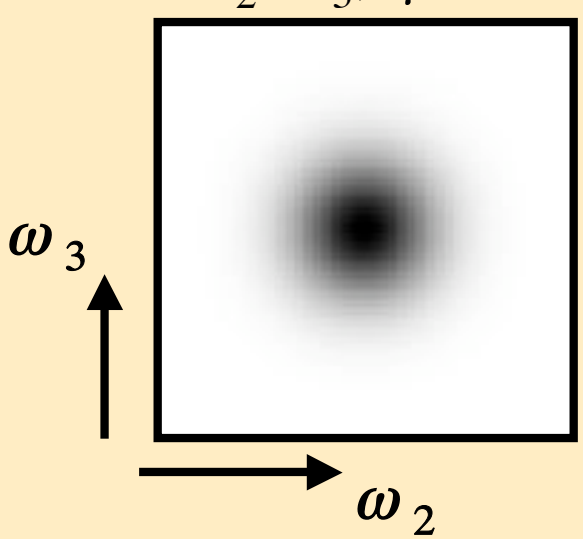
Joint Spectral Amplitude

Analytical Approximation

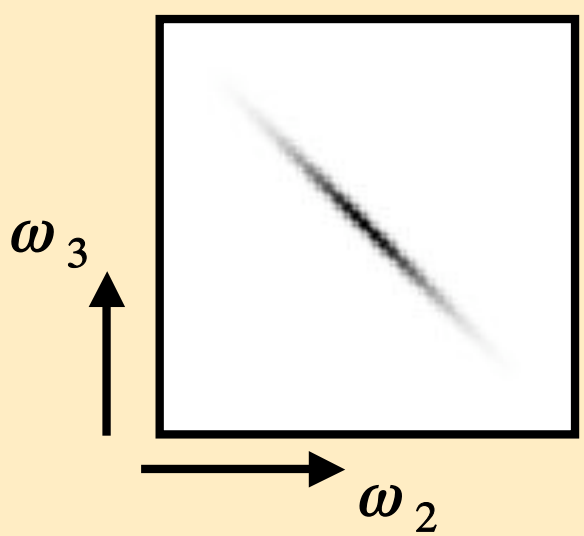
$$f(\omega_2,\omega_3) \propto \exp\left[-\frac{1}{2(1-\mu^2)}\left(\frac{\omega_2^2}{\sigma_2^2} - \frac{2\mu\omega_2\omega_3}{\sigma_2\sigma_3} + \frac{\omega_3^2}{\sigma_3^2}\right)\right]$$

σ_2, σ_3 bandwidth, μ linear spectral correlation

$\sigma_2=\sigma_3$, $\mu=0$



$\sigma_2=\sigma_3$, $\mu=-1$



How much entanglement?

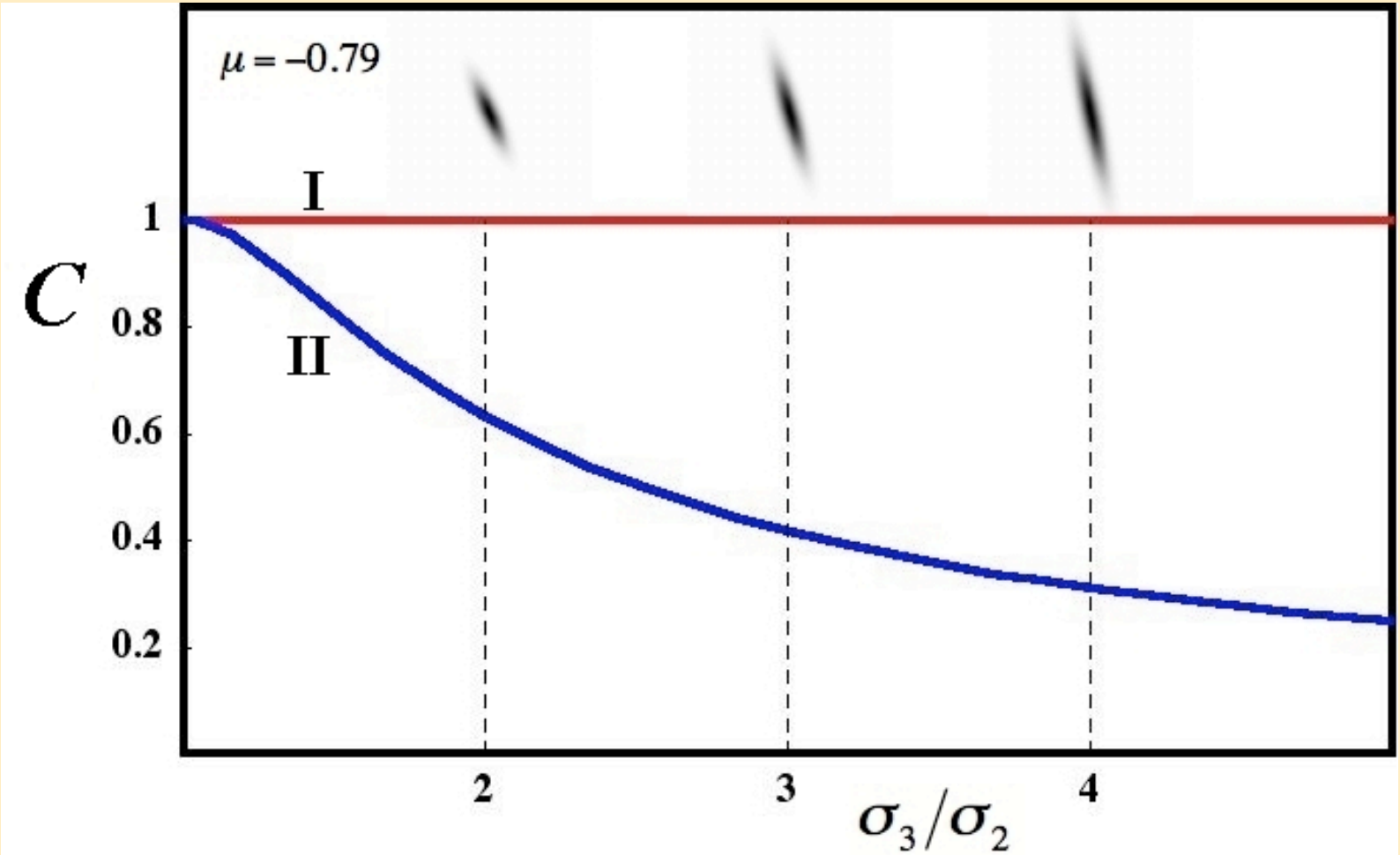
Concurrence $$C = \int d\omega_2 \int d\omega_3 f(\omega_2,\omega_3) g(\omega_2,\omega_3)$$

Type-I SPDC $$C^{\mathrm{I}} = 1$$

Type-II SPDC $$C^{\mathrm{II}} = 2\sigma_2^2\sigma_3^2\left(1-\mu^2\right) \Big/ \sqrt{\left(\sigma_2^2-\sigma_3^2\right)^2 - 4\sigma_2^2\sigma_3^2\mu^2}$$

How much entanglement?

Concurrence $$C = \int d\omega_2 \int d\omega_3 f(\omega_2,\omega_3) g(\omega_2,\omega_3)$$

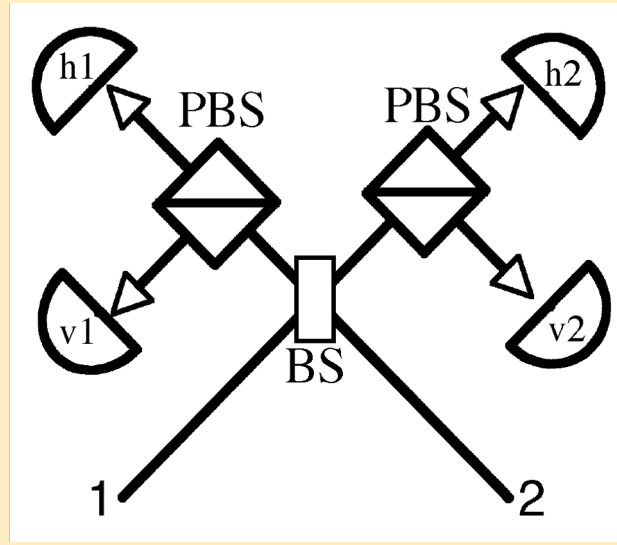


Quantum Teleportation with Entangled Multimode Photons

Input $$\tilde{\rho}_1 = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* \\ \alpha^*\beta & |\beta|^2 \end{pmatrix}$$

Output $$\tilde{\rho}_3 = \begin{pmatrix} |\alpha|^2 & \alpha\beta^* J \\ \alpha^*\beta J^* & |\beta|^2 \end{pmatrix}$$

BSM



Error

$$J = \int \left(\int s(\omega) f(\omega,\omega')^* d\omega \right) \left(\int s(\omega)^* g(\omega,\omega')^* d\omega \right) d\omega'$$

How good is it?

$$F_{\text{avg}} = \frac{2+J}{3}$$

Fidelity: overlap between input and output

Optimal input photon

$$s(\omega) \propto \exp\left[-\omega_1^2/2\sigma_1^2\right]$$

Type I

$$\sigma_1^{\text{opt}} = \sigma_2 \sqrt[4]{1-\mu^2}$$

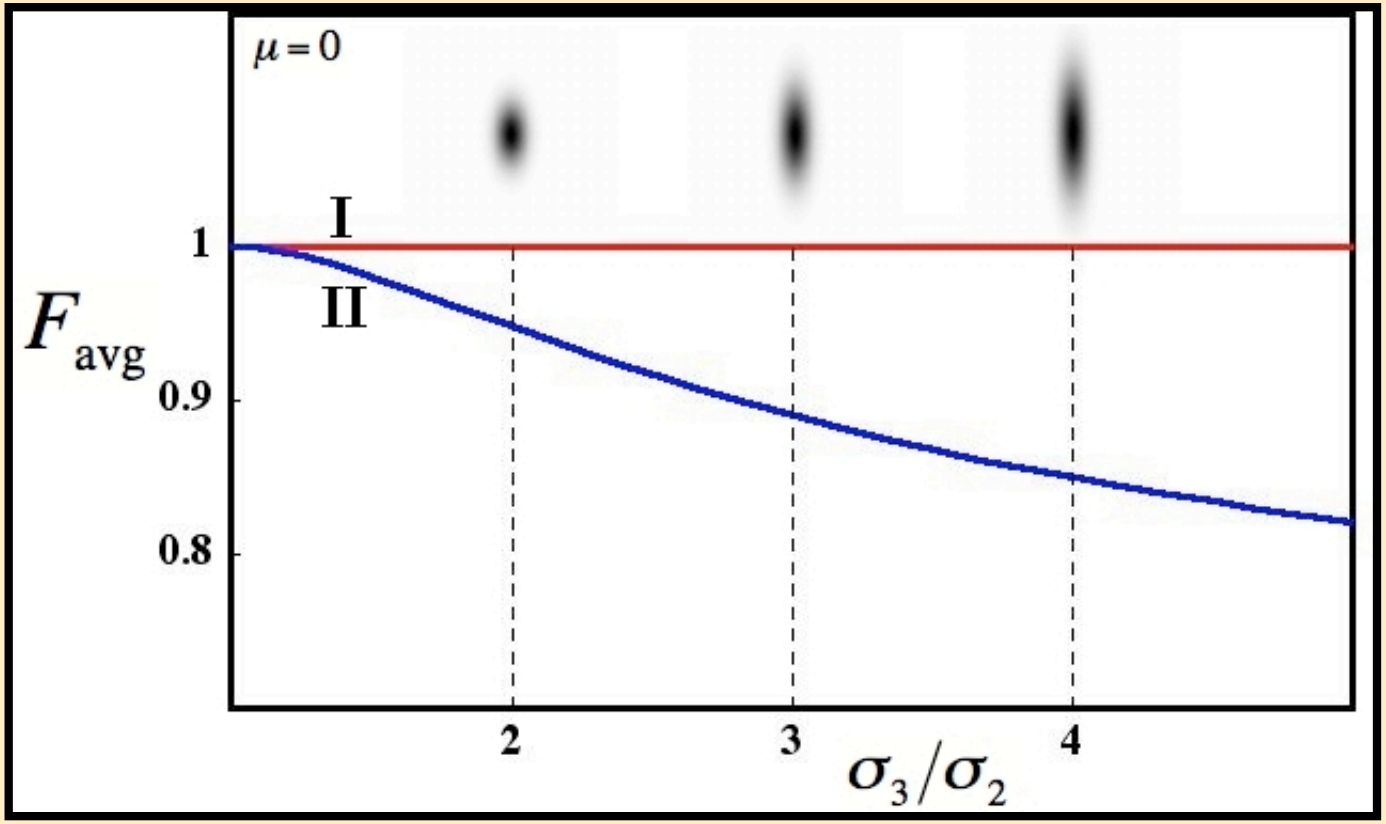
Type II

$$\sigma_1^{\text{opt}} = \sqrt[4]{\sigma_2^2\sigma_3^2\left(1-\mu^2\right)}$$

How good is it?

$$F_{\text{avg}} = \frac{2 + \operatorname{Re} J}{3}$$

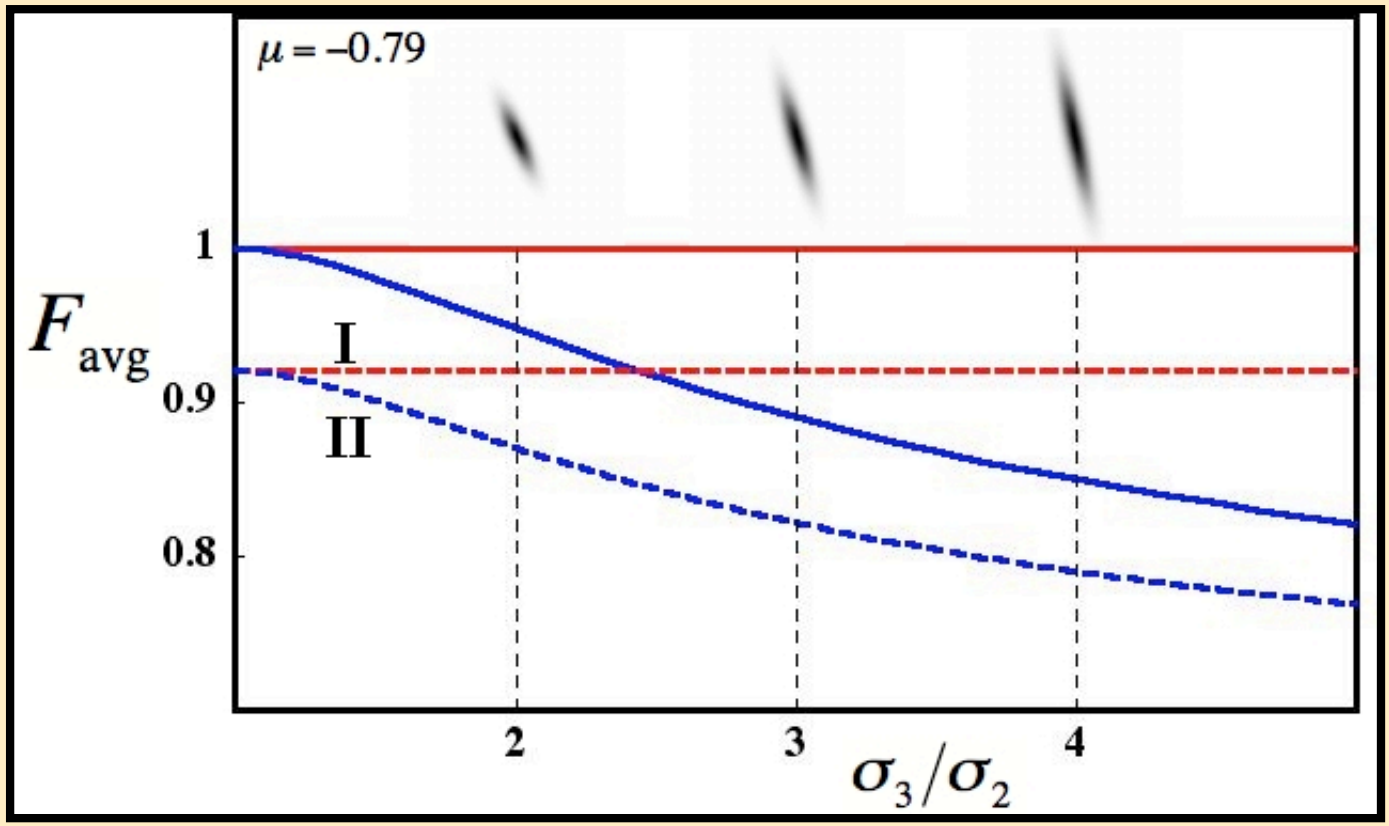
No spectral correlation



How good is it?

$$F_{\text{avg}} = \frac{2 + \operatorname{Re} J}{3}$$

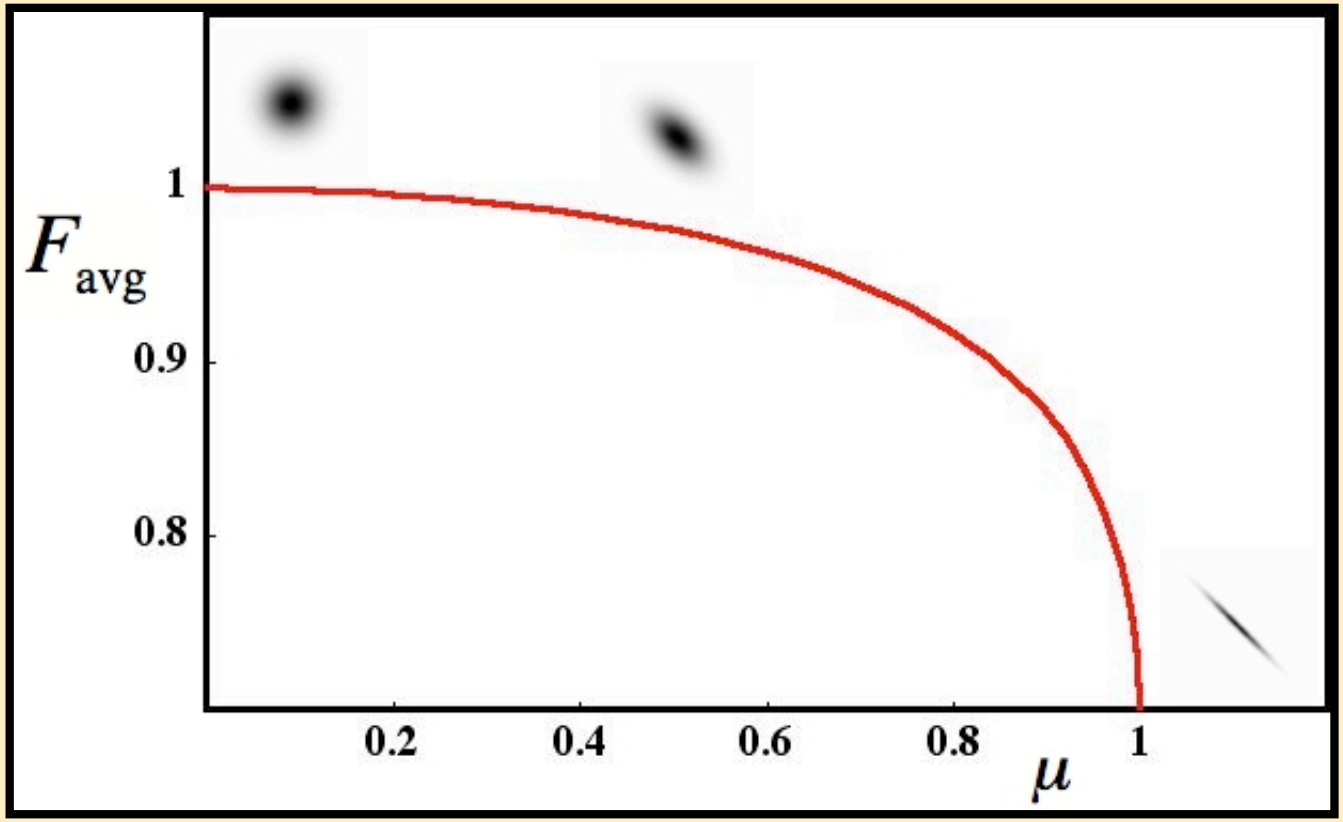
Spectrally correlated



How good is it?

$$F_{\text{avg}} = \frac{2 + \operatorname{Re} J}{3}$$

Equal bandwidths: Type-I = Type-II



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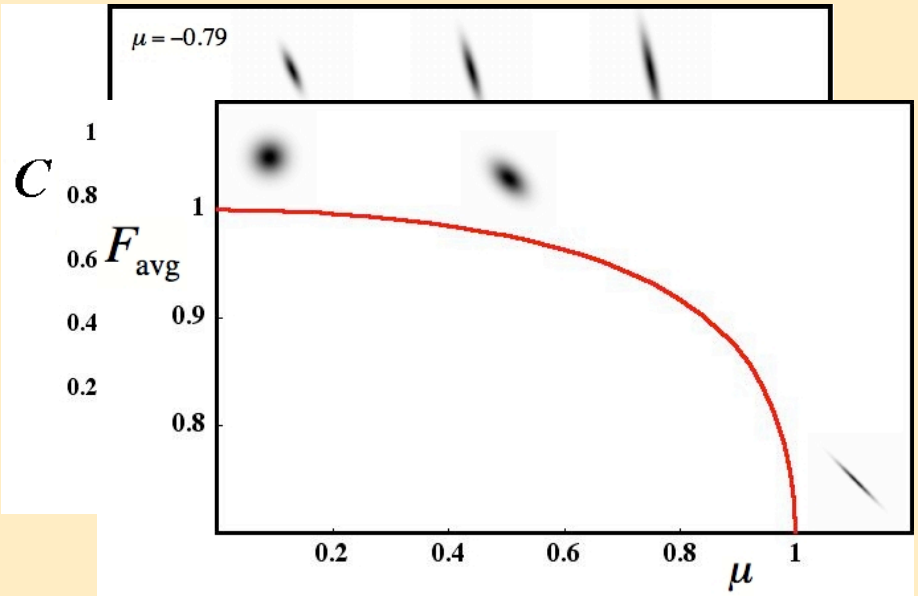
Review of Quantum Teleportation with Entangled Multimode Photons

Purpose:

- Characterize multimode effects in QT
- Quantify polarization entanglement
- Quantify fidelity
- Optimize fidelity

Results:



Related Protocols:

- Entanglement Swapping (Quantum Repeater)
- Fusion Gates and Cluster States (Quantum Computing)
- Quantum Key Distribution

Contact Information

Travis S. Humble
Oak Ridge National Laboratory
humblets@ornl.gov
865.574.6162
ornl.gov/~hqt

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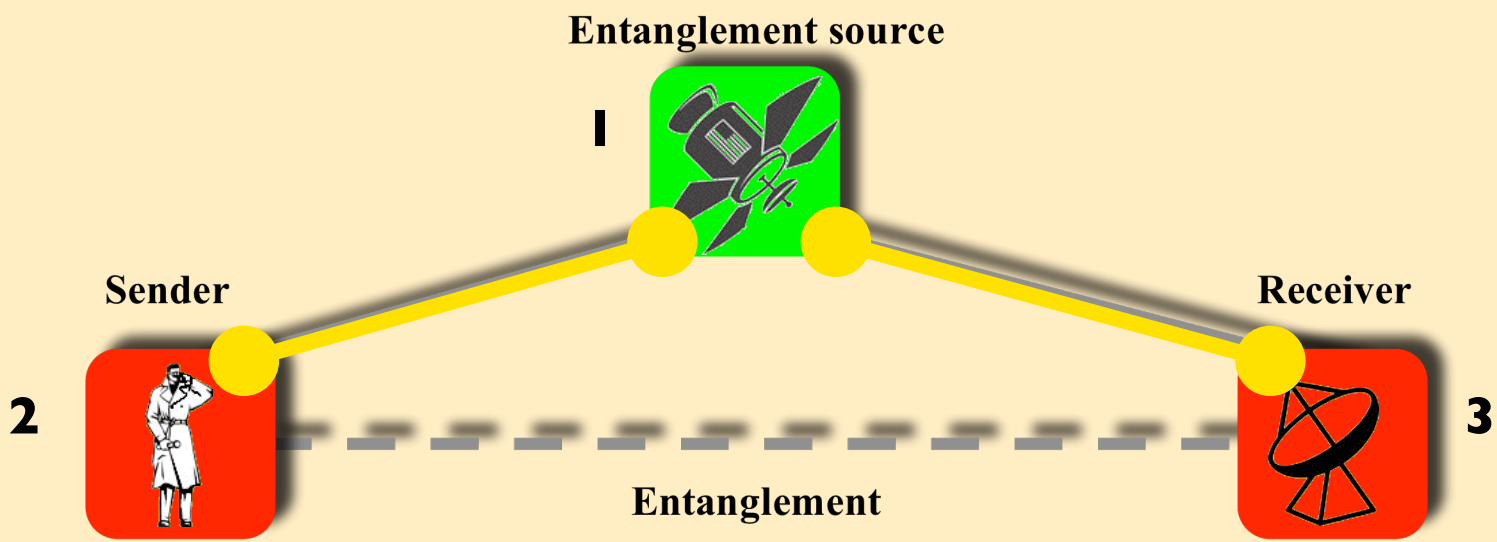
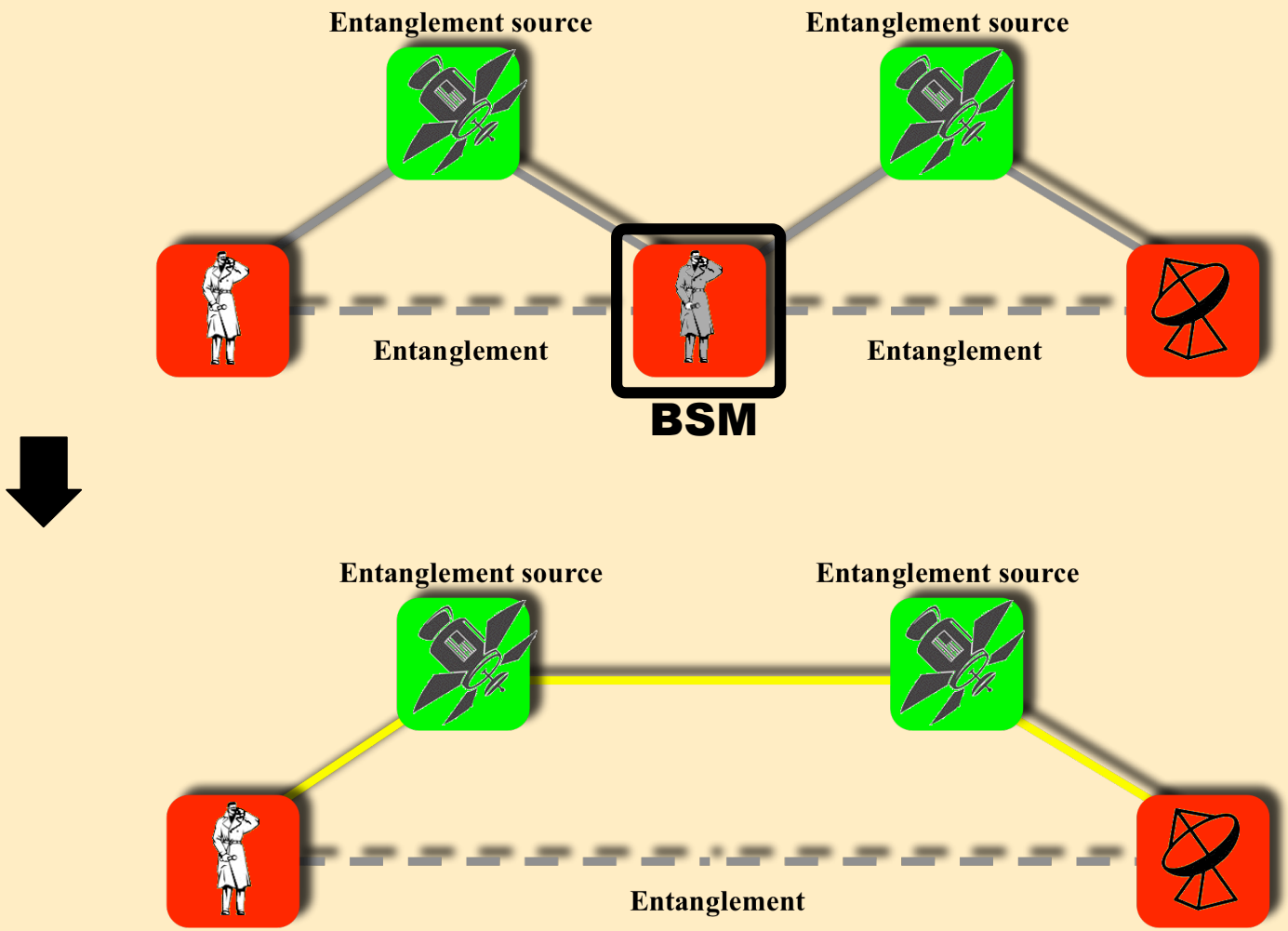
Quantum Teleportation



1. Distribute entangled particles
2. Teleport quantum information
3. Relay classical information

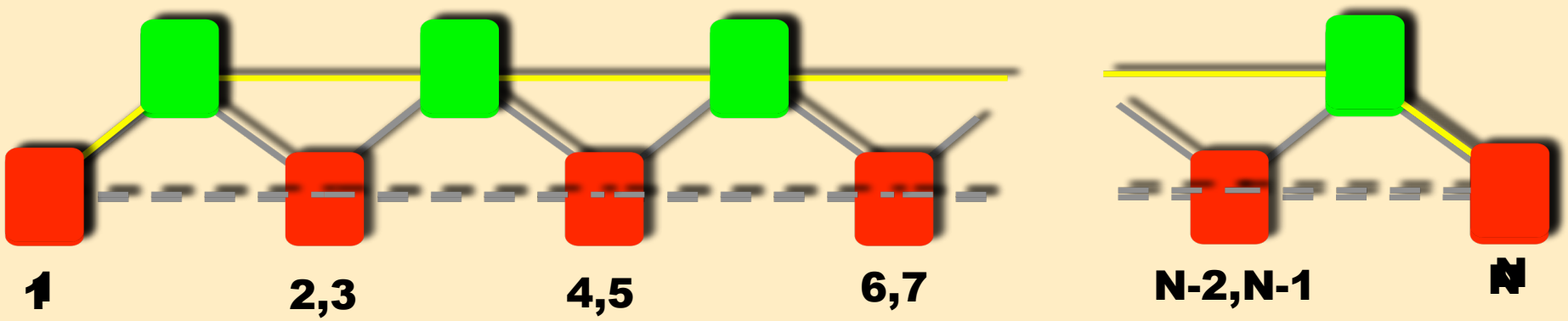
Entanglement Swapping

Teleporting entanglement



Quantum Repeater

Repetitive entanglement swapping

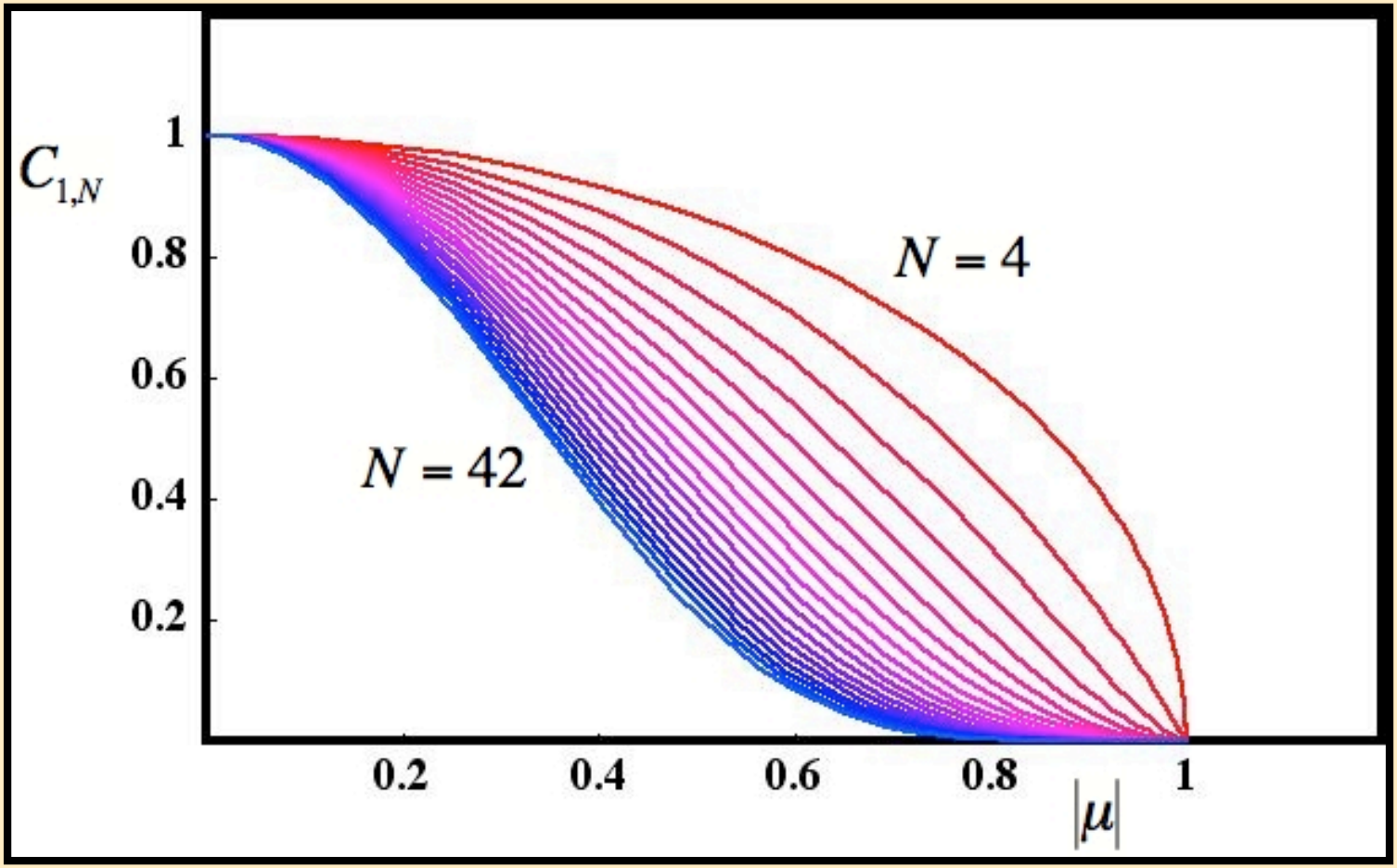


Concurrence

$$C_{1,N} = \left| \int dx \int dy \left(\int d\mathbf{z}_n f_{12}(x,z_1) g_{34}(z_1,z_2)^* \ldots g_{N-1,N}(z_n,y)^* \right) \right.$$
$$\left. \times \left(\int d\mathbf{z}_n g_{12}(x,z_1) f_{34}(z_1,z_2)^* \ldots f_{N-1,N}(z_n,y)^* \right) \right|$$

Entanglement Swapping

Concurrence versus N **Equivalent bandwidths**

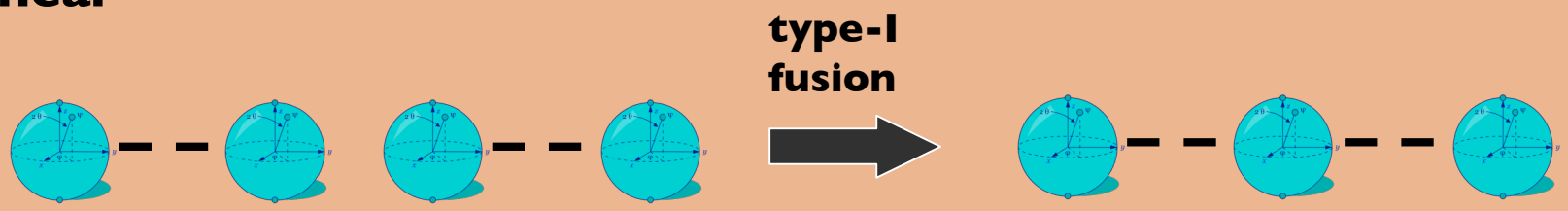


Does not incorporate entanglement distillation

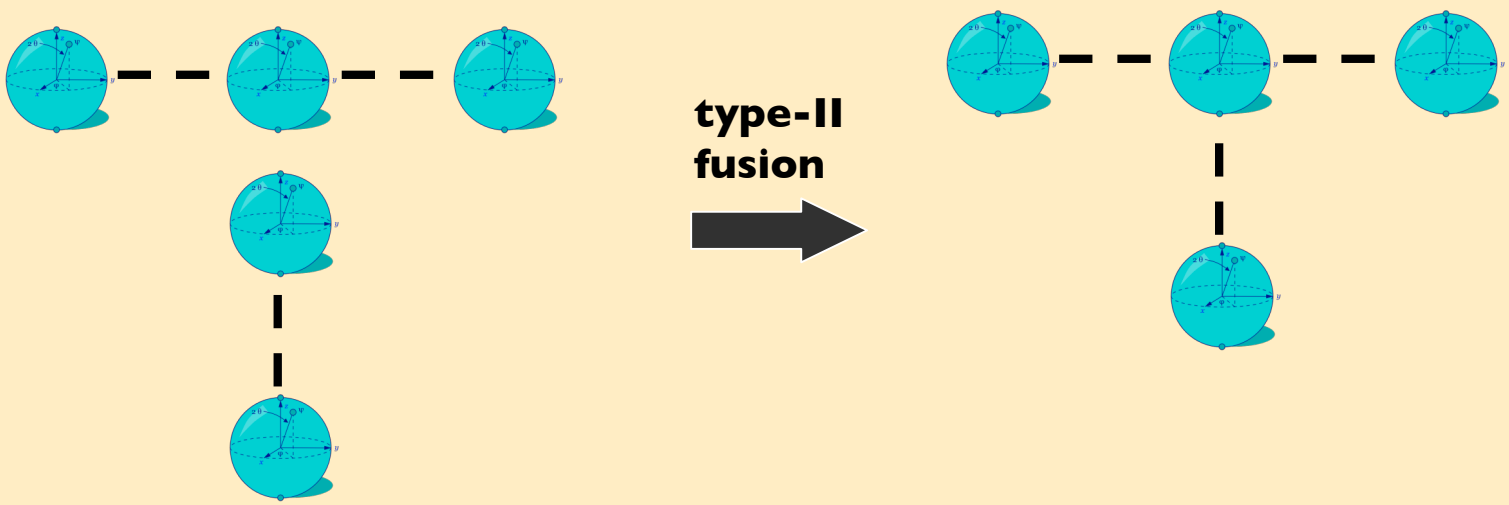
Fusion Gates and Cluster States

Adding together entangled states

Linear



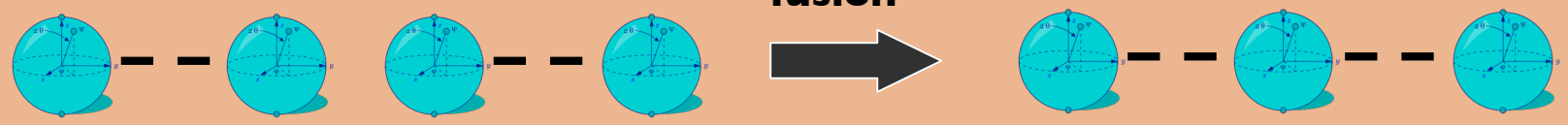
Branched



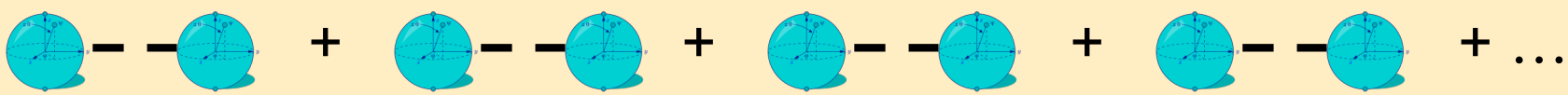
Fusion Gates and Cluster States

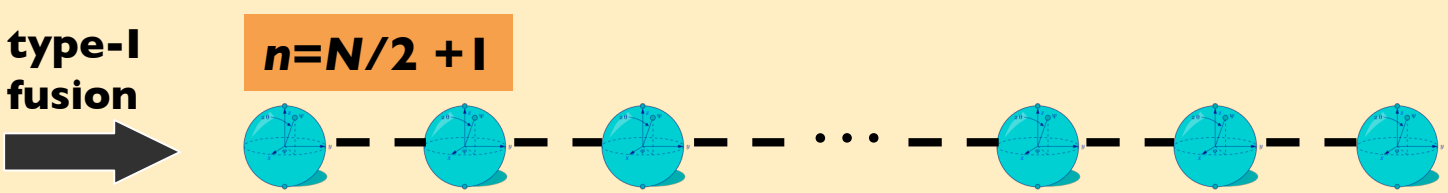
Adding together entangled states

Linear



***N* particles**

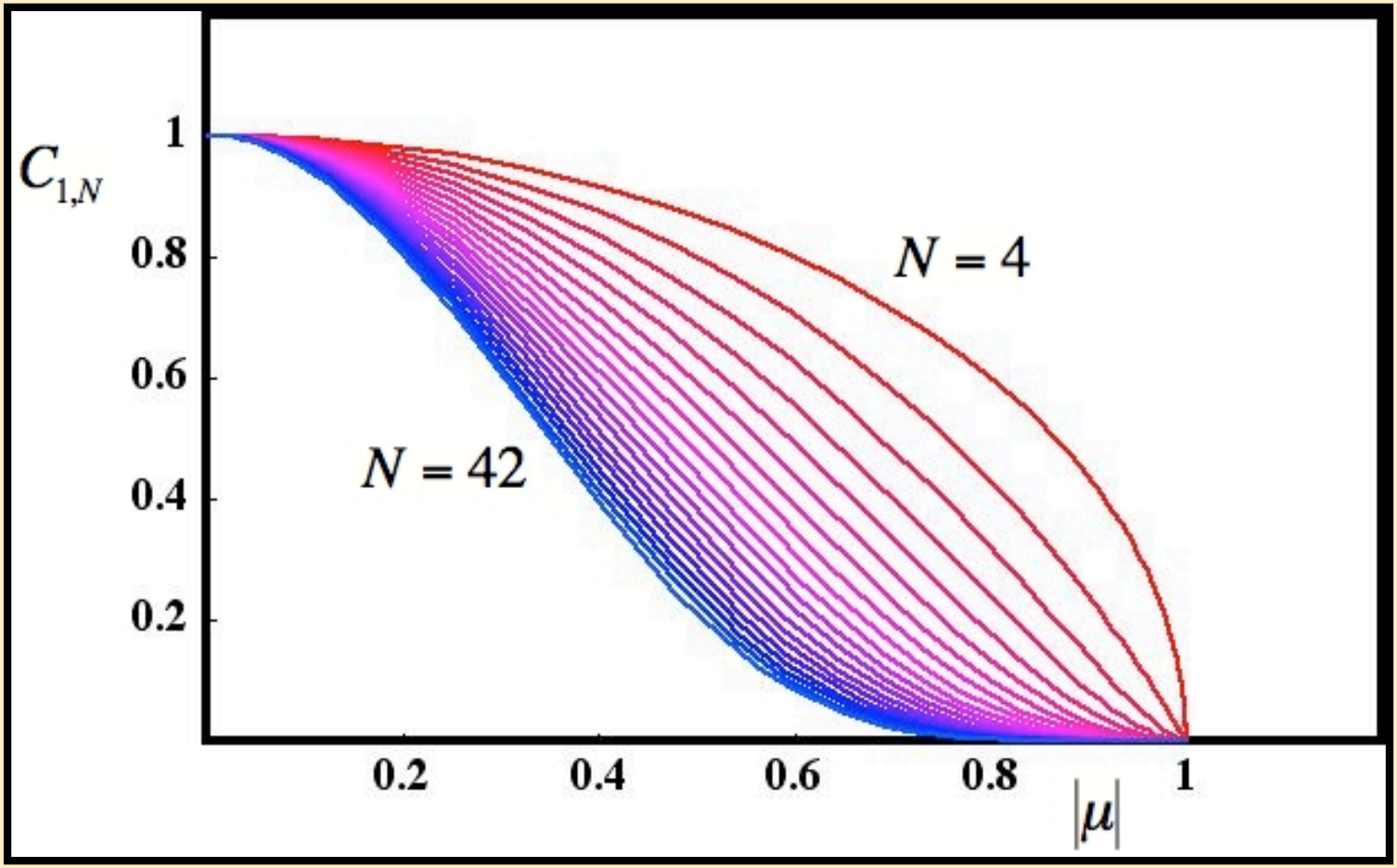




$$\frac{1}{\sqrt{2}}\left(\left|h_1,v_2,h_3,..v_n\right\rangle+\left|v_1,h_2,v_3,..h_n\right\rangle\right)$$

Fusion Gates and Cluster States

Concurrence versus N **Equivalent bandwidths**



Same as entanglement swapping (for identical sources)

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Review of Quantum Teleportation with Entangled Multimode Photons

Purpose:

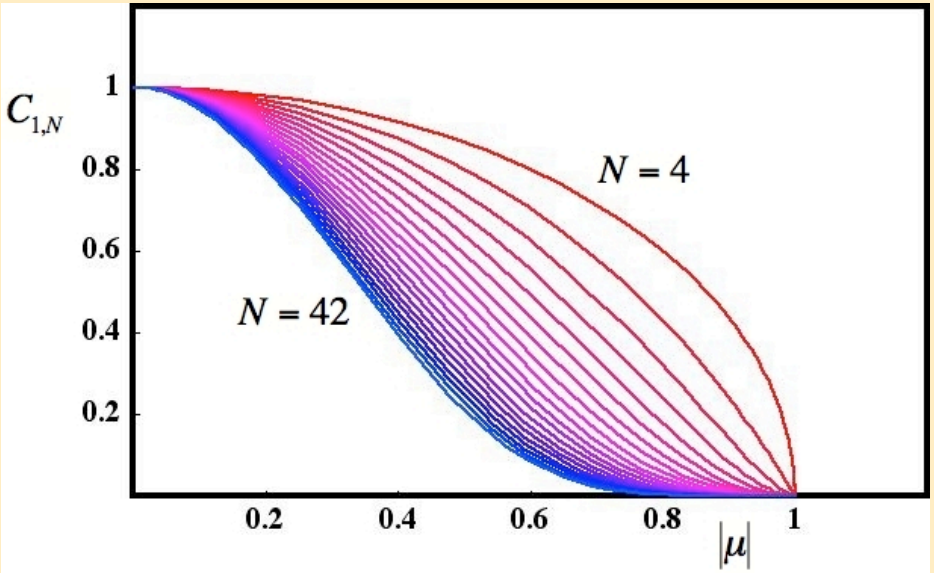
Analyze protocols related to QT

Entanglement swapping, type-I fusion

Quantify entanglement (concurrence)

Optimize configurations

Results:



Related Efforts:

Quantum Repeater

Incorporate Distillation

Building Quantum Networks

One-way quantum computing

Architecture modeling

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ornl.gov/~hqt