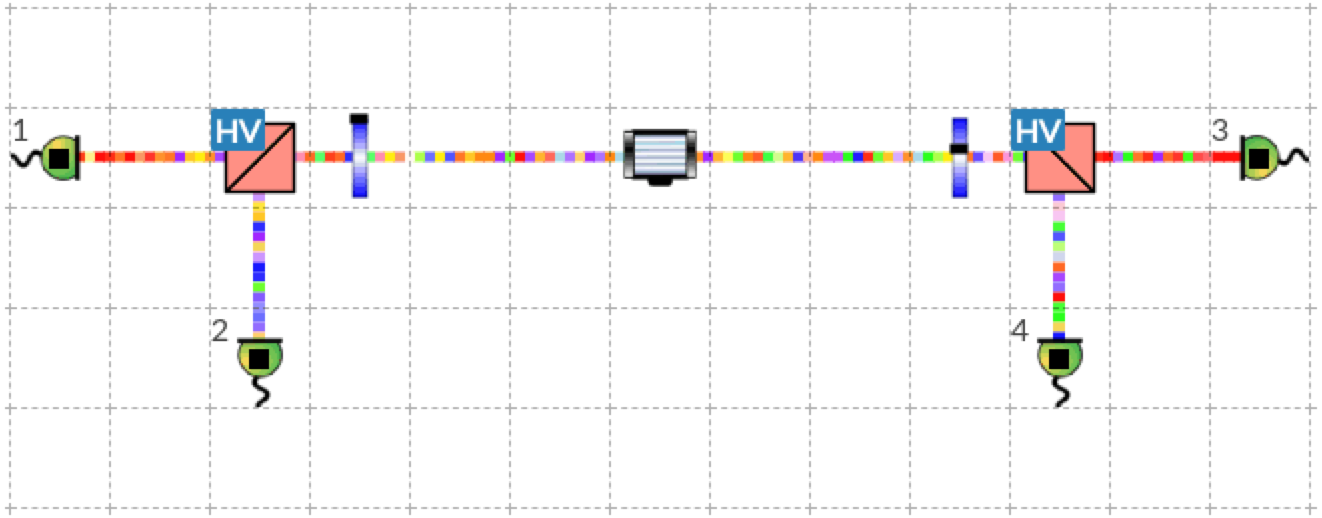
arXiv:2105.07300

www.vqol.org

Learning Quantum in a Virtual Optics Laboratory



Brian R. La Cour
Center for Quantum Research
Applied Research Laboratories
The University of Texas at Austin

QC Hackathon 23 October 2021

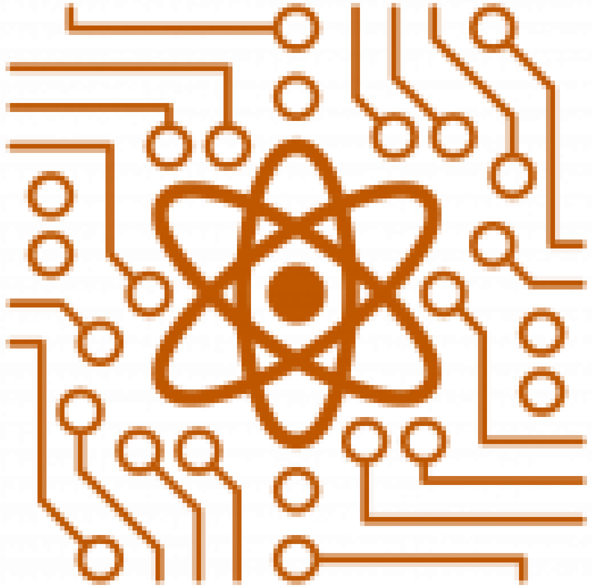
ARL:UT Center for Quantum Research (CQR)

Research unit under ARL:UT since July 2015

Members include ARL staff, students, and university affiliates

Focus on education and quantum technology development through exploration of the quantum-classical boundary

Freshman Research Initiative (FRI) at UT: Quantum Computing Stream



Spring Semester

- Freshmen in their first year, no background in quantum
- Focus on quantum physics, mathematics, applications

Summer Semester

- Optional experimental program, focus on quantum optics
- Hybrid in-person and remote structure

Fall Semester

- Focus on algorithms and programming
- Extensive use of Qiskit for implementation

Now open to non-FRI students!

UT QIS Certificate Program

Similar to a minor, now added to the 2020-2022 UT course catalog

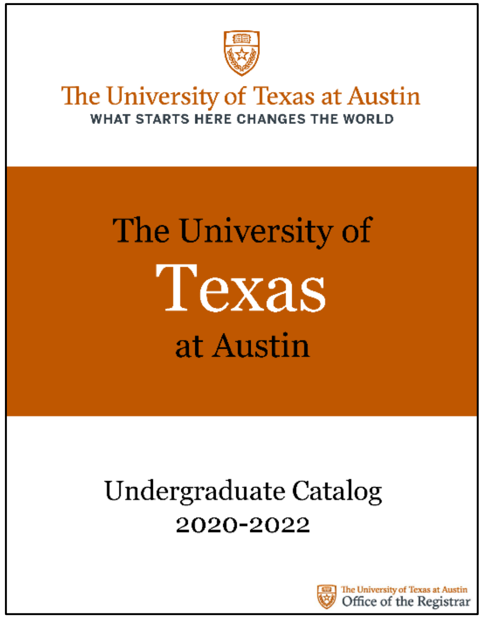
Transcript certification of expertise in quantum information science

6 hours from the following:

- Spring QC FRI, Fall QC FRI, Intro to Quantum Info (Aaronson)

12 hours from the following:

- Quantum Physics I and II (Phys), Algorithms and Complexity (CS), Intro to Quantum Info (Aaronson), Linear Algebra (Math), Independent Research Project (academia or industry)



The Virtual Quantum Optics Laboratory

Initially developed in the summer of 2019 (by students, for students)

- Used as an instructional tool in undergraduate and high school programs
- Replaced our "real" quantum optics lab for the summer 2020 program

Graphical "sandbox" where students can design and run experiments

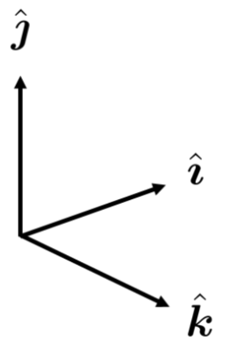
- Available online at www.vqol.org (log in as guest or via Google account)
- Linear components and sources of incoherent, coherent, and squeezed light

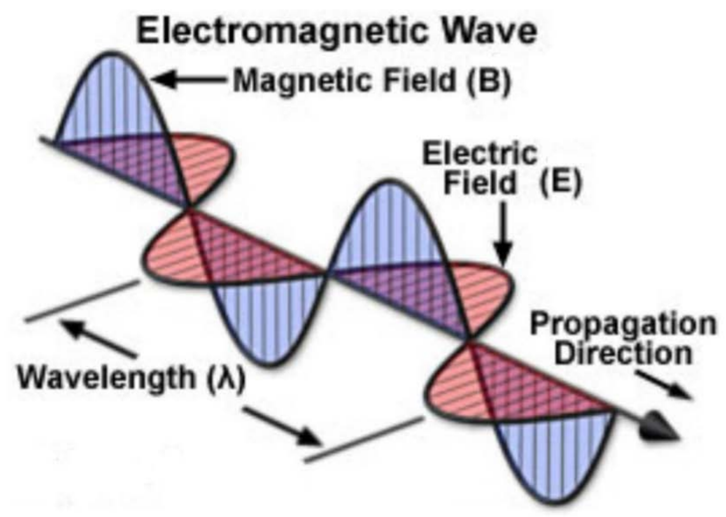
A classical implementation of quantum optics

- Vacuum modes treated as pervasive, reified Gaussian noise
- Detectors treated as deterministic amplitude threshold-crossing devices

Polarization as Qubits

$$\begin{aligned}\boldsymbol{E}(x,t) &= E_0\cos\theta\,\cos(kx-\omega t+\phi_0)\,\hat{\boldsymbol{\imath}} \;+\; E_0\sin\theta\,\cos(kx-\omega t+\phi_0+\phi)\,\hat{\boldsymbol{\jmath}}\\ &= \tfrac{1}{2}E_0 e^{i\phi_0}\;e^{i(kx-\omega t)}\left(\cos\theta\,\hat{\boldsymbol{\imath}}+e^{i\phi}\sin\theta\,\hat{\boldsymbol{\jmath}}\right)\;+\;\text{complex conjugate}\\ &= \left(a_H\,\hat{\boldsymbol{\imath}}+a_V\,\hat{\boldsymbol{\jmath}}\right)e^{i(kx-\omega t)}\;+\;\text{c.c.}\end{aligned}$$





Jones Vector: $\boldsymbol{a} = \begin{pmatrix} a_H \\ a_V \end{pmatrix} \in \mathbb{C}^2$

CENTER FOR QUANTUM RESEARCH

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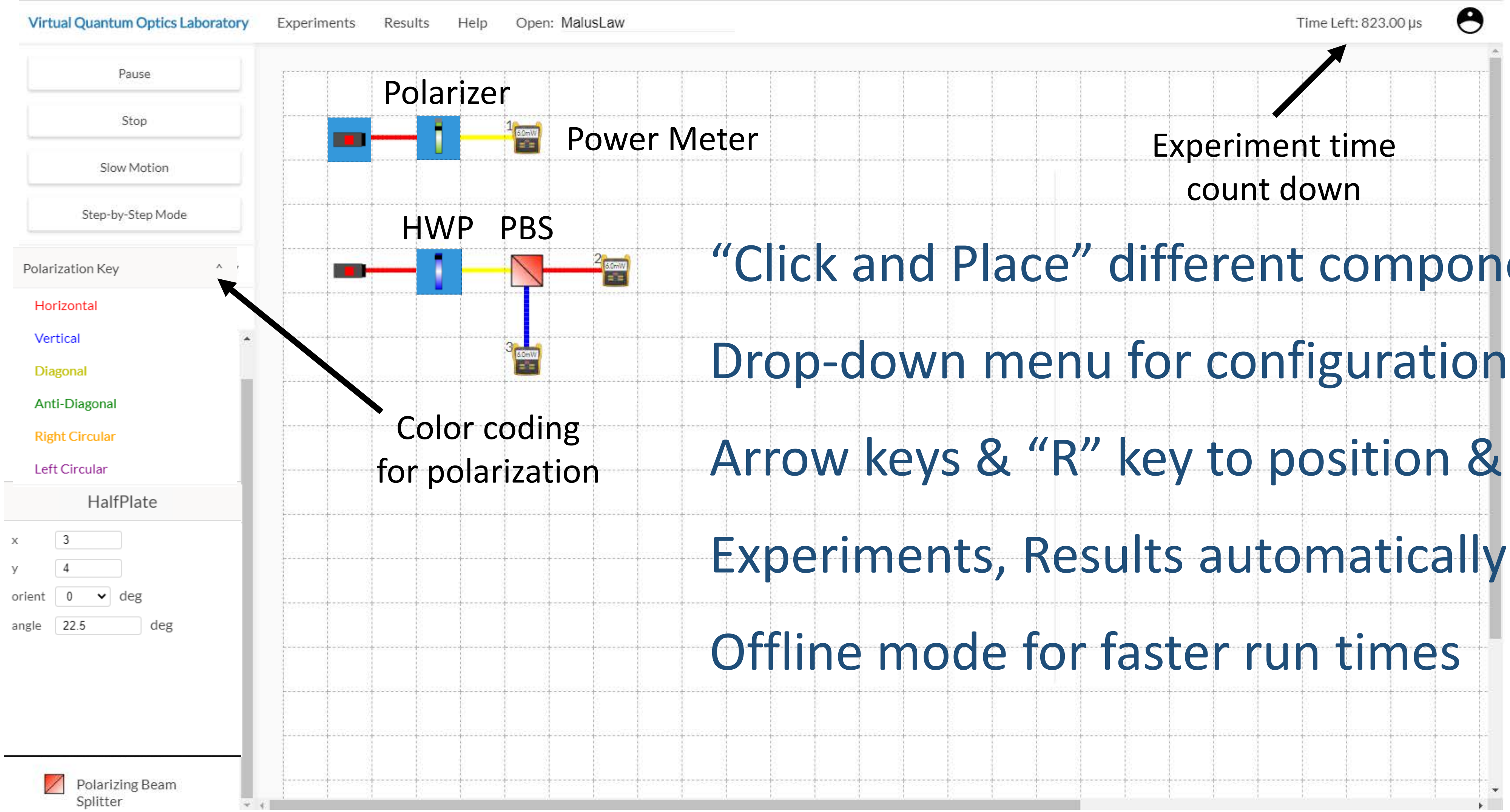
APPLIED RESEARCH LABORATORIES

THE UNIVERSITY OF TEXAS AT AUSTIN

Malus's Law with VQOL



"Click and Place" different components

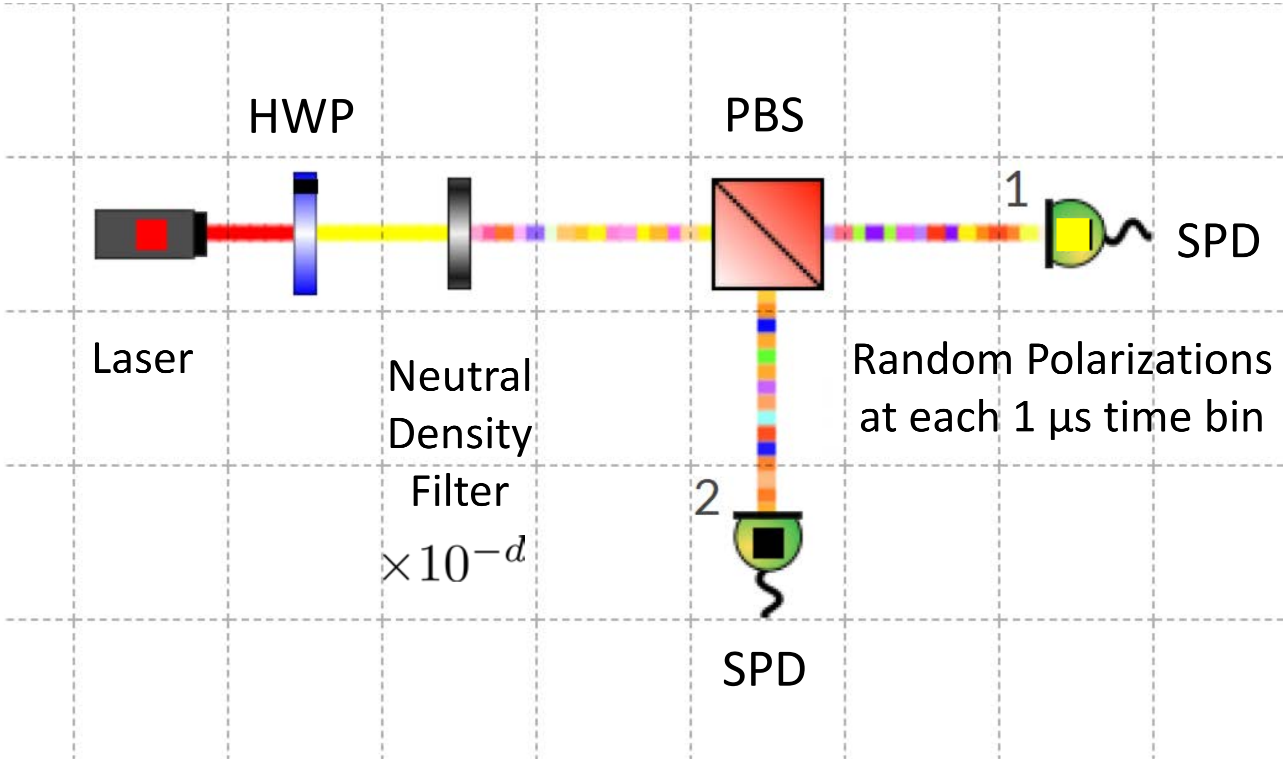
Drop-down menu for configuration

Arrow keys & "R" key to position & rotate

Experiments, Results automatically saved

Offline mode for faster run times

Born Rule with Polarizing Beam Splitter



$$|\psi\rangle = |\alpha_H\rangle \otimes |\alpha_V\rangle$$ Quantum Coherent State

$$\boldsymbol{a} = \begin{pmatrix} \alpha_H \\ \alpha_V \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} z_H \\ z_V \end{pmatrix}$$ Stochastic Jones Vector

z_H, z_V are iid standard complex Gaussians

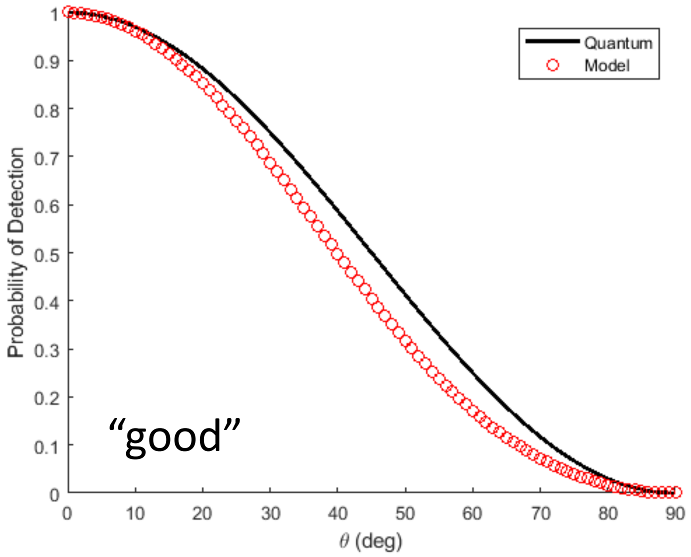
$$\Pr\Big[\text{Detection}\Big] = \Pr\Big[|a_H| > \gamma \text{ or } |a_V| > \gamma\Big]$$

$$p_d = 1 - \left(1 - e^{-2\gamma^2}\right)^2$$ Dark Count Rate (counts/μs)

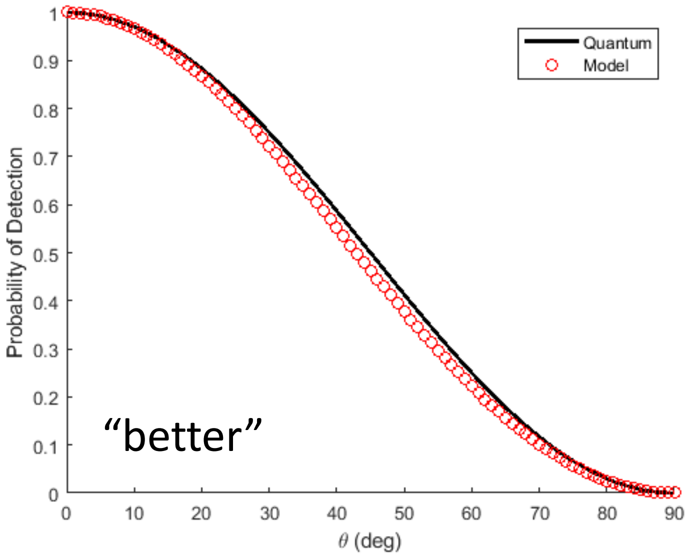
"Emergence of the Born rule in quantum optics," https://arxiv.org/abs/2004.08749 [Quantum **4**, 350 (2020)]

Simulation Results for Born Rule Experiment

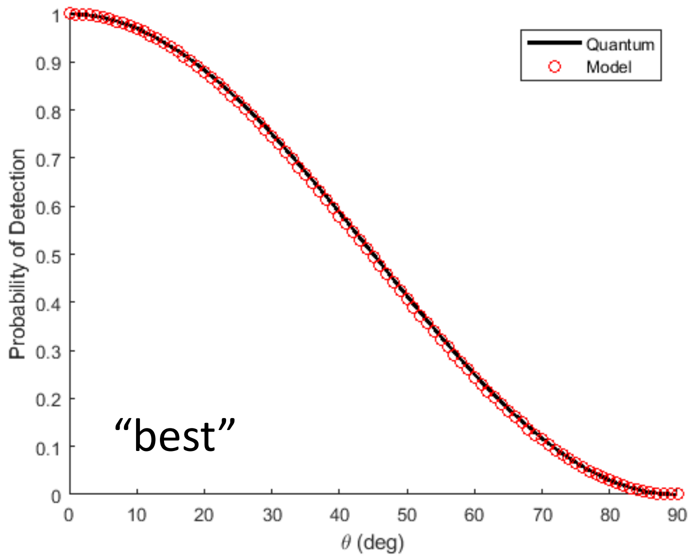
$d = 10 \quad p_d = 0.1$



$d = 11 \quad p_d = 0.01$



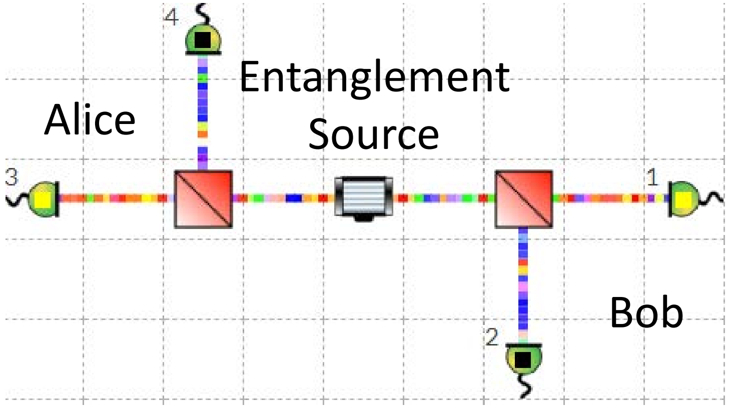
$d = 12 \quad p_d = 0.001$

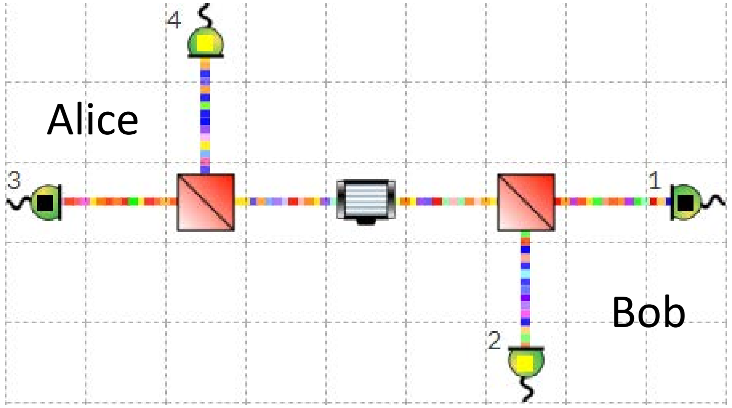


$$\text{Probability} = \frac{\text{Counts} - \text{MinCounts}}{\text{MaxCounts} - \text{MinCounts}}$$

High attenuation and a large detection threshold gives a good "poor man's" single-photon source.

Entanglement in VQOL





Entanglement Source modeled as a multi-mode squeezed state

$$|\Phi\rangle = \frac{|HH\rangle + e^{i\varphi}|VV\rangle}{\sqrt{2}}$$

Entangled Quantum State

Replace *operators* with *random variables* in the Bogoliubov transformation:

$$\begin{pmatrix} b_{RH} \\ b_{RV} \\ b_{LH} \\ b_{LV} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} z_{RH}\cosh r + z_{LH}^* \sinh r \\ z_{RV}\cosh r + e^{i\varphi} z_{LV}^* \sinh r \\ z_{LH}\cosh r + z_{RH}^* \sinh r \\ z_{LV}\cosh r + e^{i\varphi} z_{RV}^* \sinh r \end{pmatrix}$$

The result is an *improper* complex Gaussian random vector.

“Entanglement and impropriety,” https://arxiv.org/abs/2008.04364 [*Quantum Stud.: Math. Found.* **8,** 307–314 (2021)]

Fun Experiments You Can Do in VQOL

“Way of the Single Photon”

The Born Rule

Quantum State Tomography

Hyperentanglement

Optical Deutsch-Jozsa Algorithm

Mach-Zehnder Interferometer

Wheeler’s Delayed Choice

“Way of the Entangled Photons”

Quantum Eraser

Grangier Photon Anticorrelation

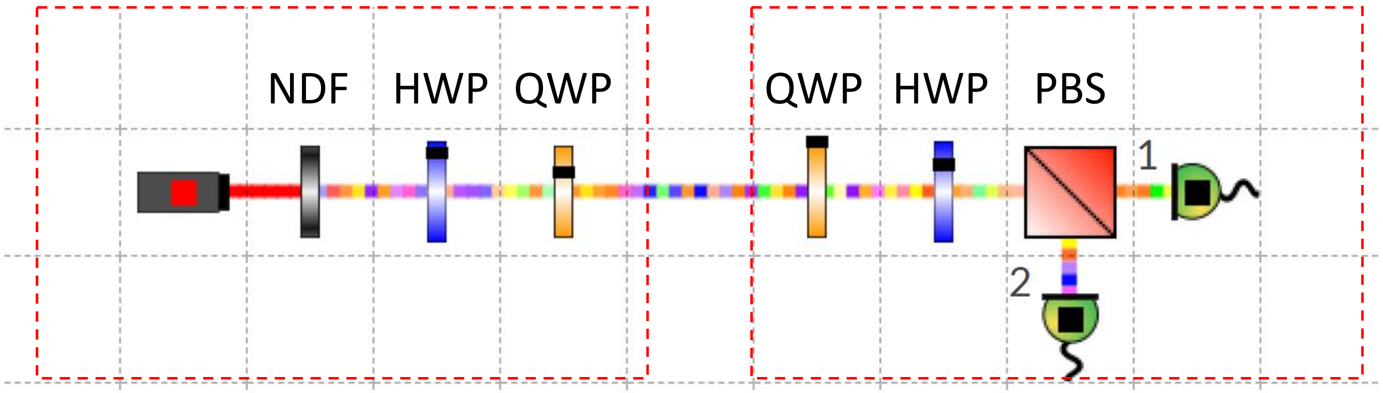
Hong-Ou-Mandel Effect

Quantum Teleportation

Entanglement Swapping

Bell-CHSH Inequality Violations

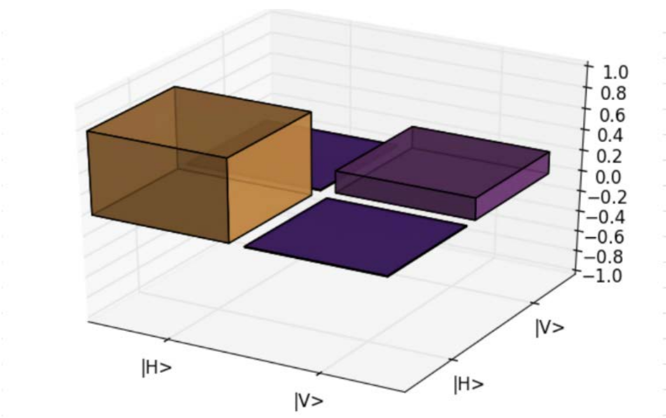
Quantum State Tomography



State Preparation

Measurement

Re[$\boldsymbol{\rho}$]



Fidelity = 0.98

$$|\psi\rangle = \mathbf{QWP}(\phi)\ \mathbf{HWP}(\theta) \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

ideal quantum state

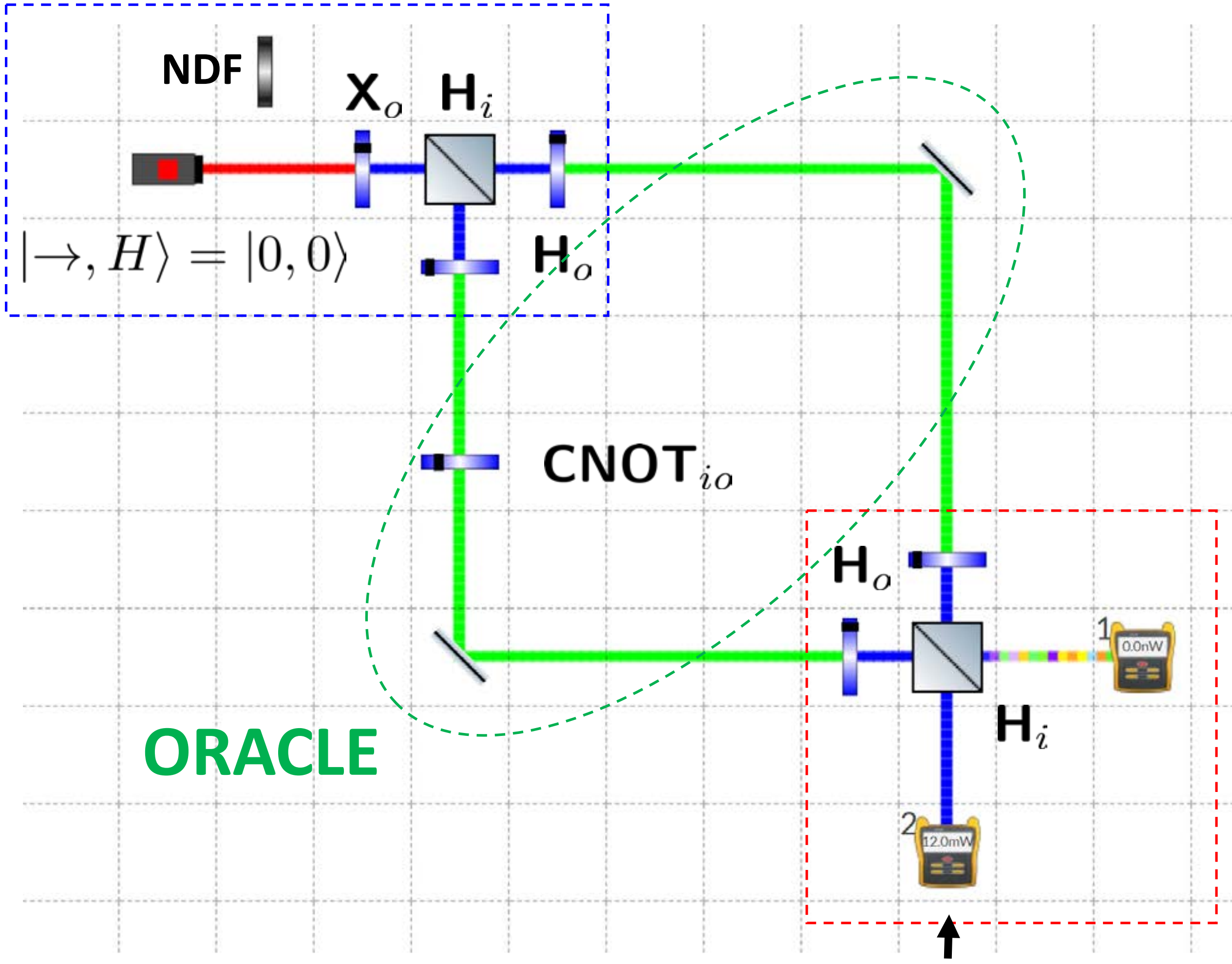
$$\boldsymbol{\rho} = \tfrac{1}{2}\mathbf{I}\mathrm{Tr}[\boldsymbol{\rho}\mathbf{I}] + \tfrac{1}{2}\mathbf{X}\mathrm{Tr}[\boldsymbol{\rho}\mathbf{X}] + \tfrac{1}{2}\mathbf{Y}\mathrm{Tr}[\boldsymbol{\rho}\mathbf{Y}] + \tfrac{1}{2}\mathbf{Z}\mathrm{Tr}[\boldsymbol{\rho}\mathbf{Z}]$$

measured mixed state

$$\begin{pmatrix} a_H \\ a_V \end{pmatrix} = \mathbf{QWP}(\phi)\ \mathbf{HWP}(\theta) \left[10^{-d} \begin{pmatrix} \alpha + z_H/\sqrt{2} \\ z_V/\sqrt{2} \end{pmatrix} + \left(1 - 10^{-d/2}\right) \frac{1}{\sqrt{2}} \begin{pmatrix} z'_H \\ z'_V \end{pmatrix}\right]$$

VQOL representation

Optical Deutsch-Jozsa Algorithm



balanced function

Spatial Mode $(\rightarrow = 0,\ \downarrow = 1)$ as input register (L)

Polarization $(H = 0,\ V = 1)$ as output register (R)

HWP set to $45°$ for NOT gate on output $(\mathbf{X}_o)$

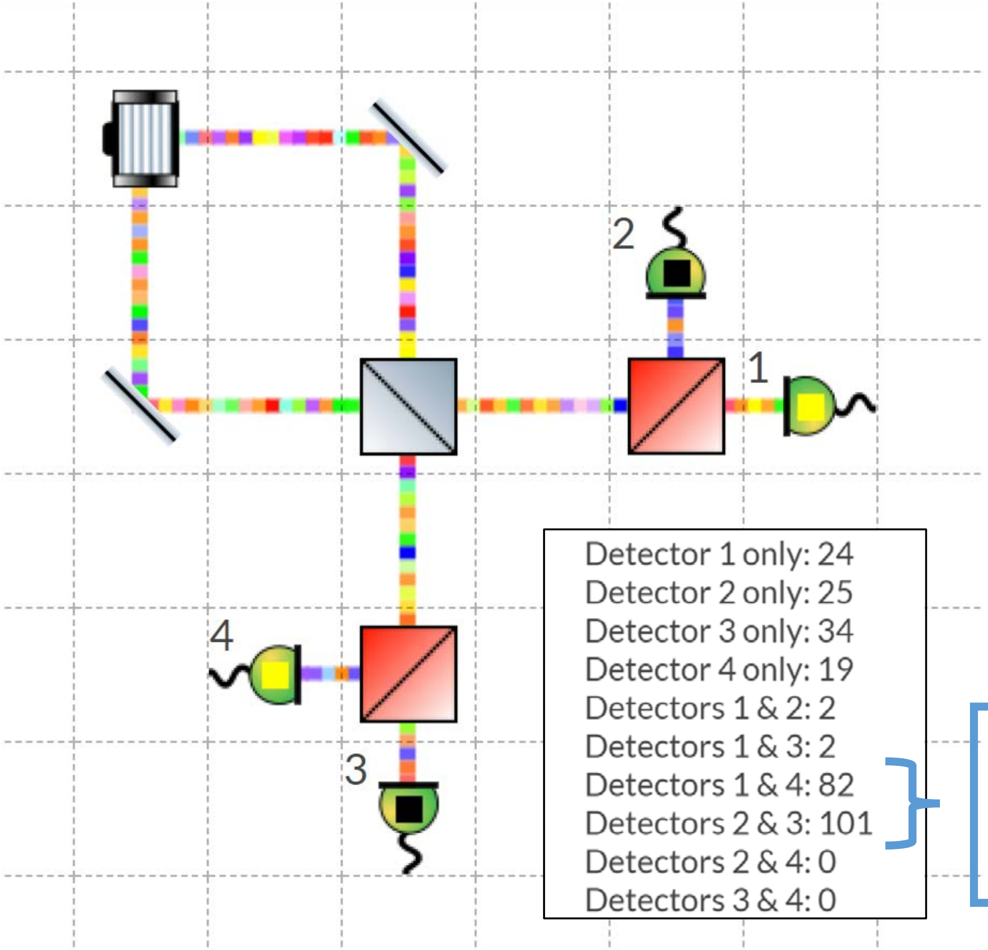
HWP set to $22.5°$ for Hadamard gate on output $(\mathbf{H}_o)$

50/50 BS for Hadamard gate on input $(\mathbf{H}_i)$

Oracle: CNOT gate using HWP on $\downarrow$ spatial mode

Final spatial mode determines constant/balanced

Hong-Ou-Mandel Effect



Detector 1 only: 24
Detector 2 only: 25
Detector 3 only: 34
Detector 4 only: 19
Detectors 1 & 2: 2
Detectors 1 & 3: 2
Detectors 1 & 4: 82
Detectors 2 & 3: 101
Detectors 2 & 4: 0
Detectors 3 & 4: 0

$$|\Psi^-\rangle = \frac{|HV\rangle - |VH\rangle}{\sqrt{2}}$$

$$D_1 = \left\{\frac{1}{\sqrt{2}}|b_{1H} + b_{2H}| > \gamma \text{ or } |a_{3V}| > \gamma\right\}$$

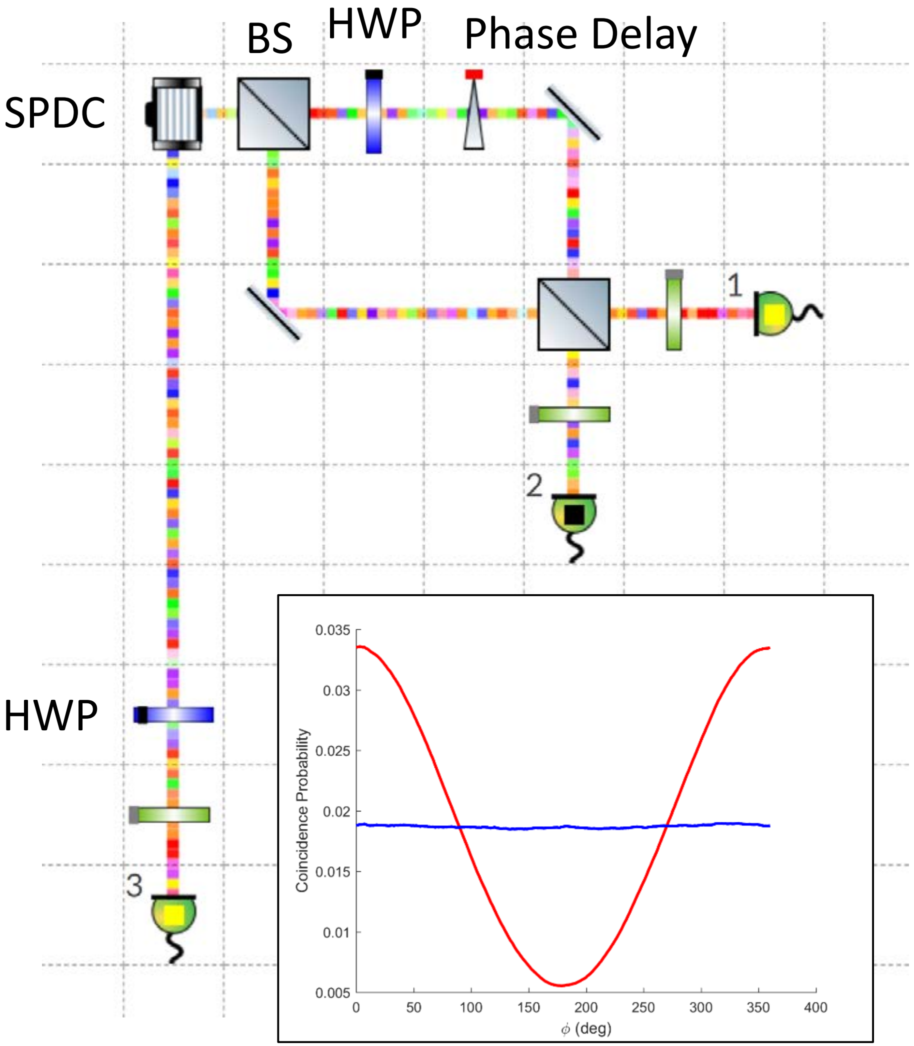
$$D_2 = \left\{|a_{3H}| > \gamma \text{ or } \frac{1}{\sqrt{2}}|b_{1V} + b_{2V}| > \gamma\right\}$$

$$D_3 = \left\{\frac{1}{\sqrt{2}}|b_{1H} - b_{2H}| > \gamma \text{ or } |a_{4V}| > \gamma\right\}$$

$$D_4 = \left\{|a_{4H}| > \gamma \text{ or } \frac{1}{\sqrt{2}}|b_{1V} - b_{2V}| > \gamma\right\}$$

Coincident detections on Detectors 1 & 4 or 2 & 3 indicate the presence of a $|\Psi^-\rangle$ state.

Quantum Eraser



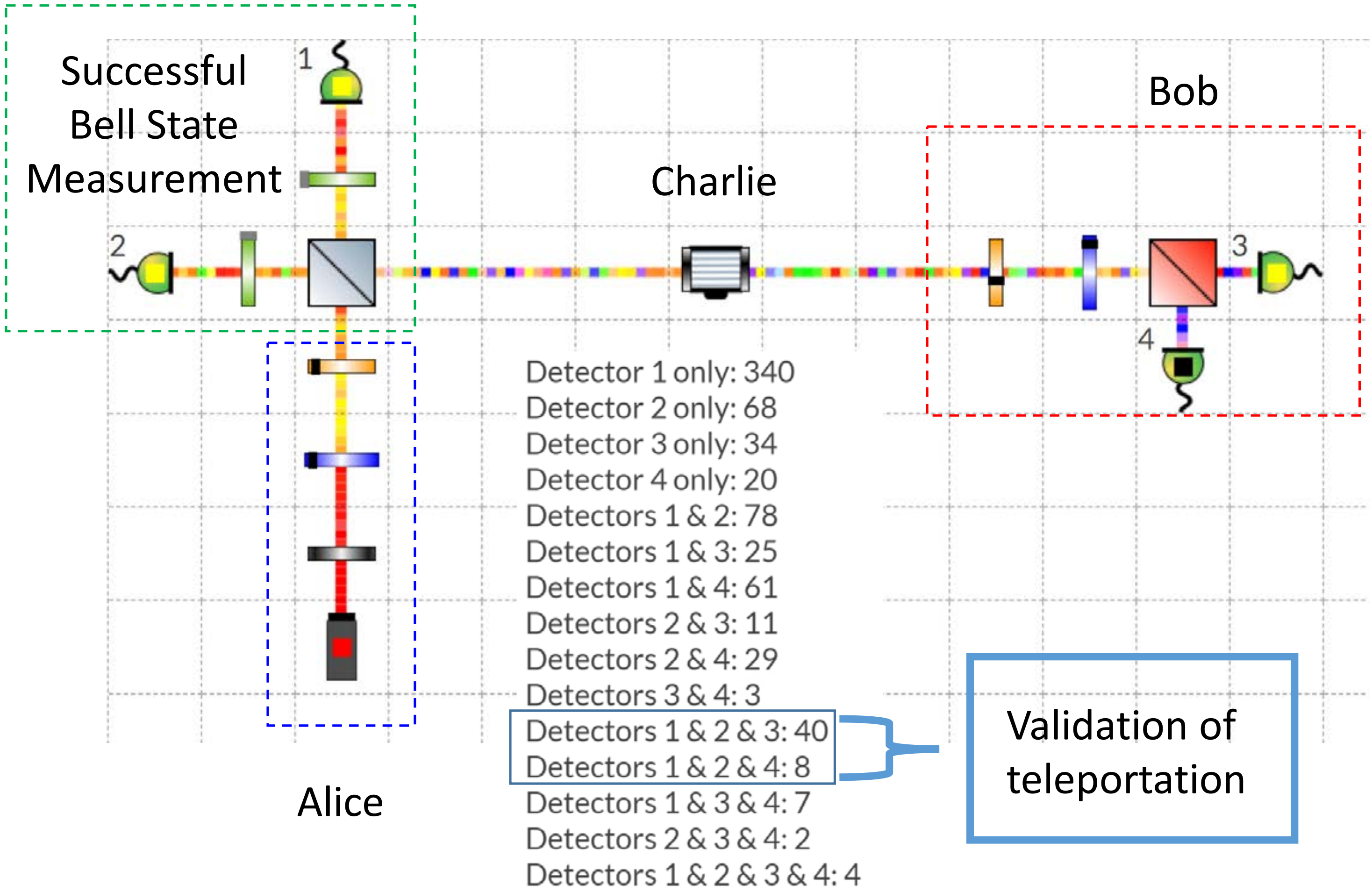
HWP in Mach-Zehnder Interferometer provides which-way information and destroys the interference pattern.

Inclusion of an entanglement source with measurement in the D/A basis can “erase” this which-way information.

Classical explanation: The post-selection of coincident detections on detectors 1 and 3 draws recovers the interference.

“Classical model of a delayed-choice quantum eraser,” https://arxiv.org/abs/2101.03371 [Phys. Rev. A **103**, 062213 (2021)]

Quantum Teleportation



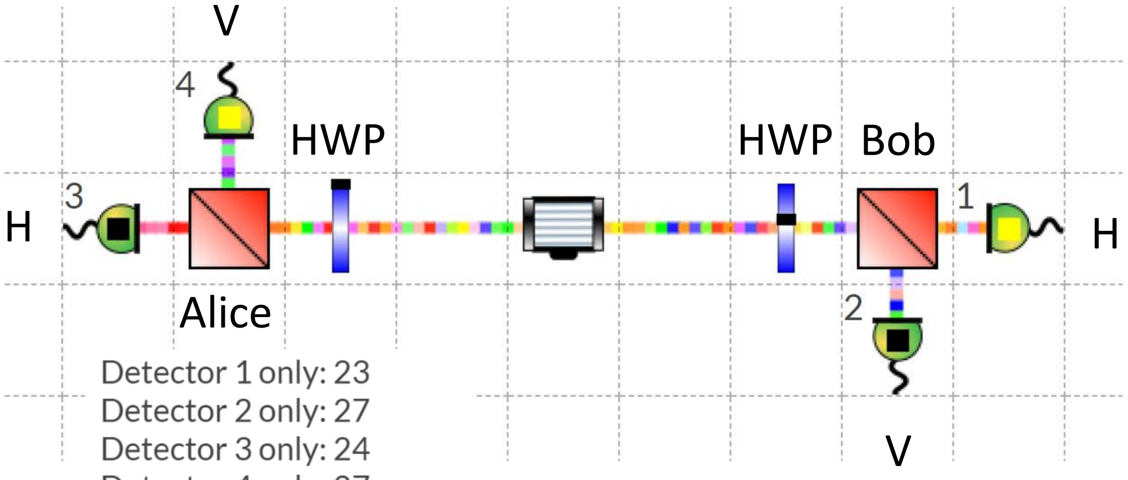
Alice prepares a qubit state

Charlie shares entangled qubits with Alice & Bob

Alice performs a BSM on her qubit and the one she got from Charlie.

Bob verifies that the state of his qubit is the same as the one Alice prepared.

Bell-CHSH Inequality Violations



Detector 1 only: 23
Detector 2 only: 27
Detector 3 only: 24
Detector 4 only: 27
Detectors 1 & 2: 0
Detectors 1 & 3: 7
Detectors 1 & 4: 52
Detectors 2 & 3: 45
Detectors 2 & 4: 10
Detectors 3 & 4: 0
Detectors 1 & 2 & 3: 3
Detectors 1 & 2 & 4: 3
Detectors 1 & 3 & 4: 3
Detectors 2 & 3 & 4: 3
Detectors 1 & 2 & 3 & 4: 2

Anticorrelation

$$|\Psi^-\rangle = \frac{|HV\rangle - |VH\rangle}{\sqrt{2}}$$

$r = 0.9$ squeezing parameter

Alice and Bob each choose one of two possible measurements.

Post-select on coincident detections

Violations over 2.828 possible!

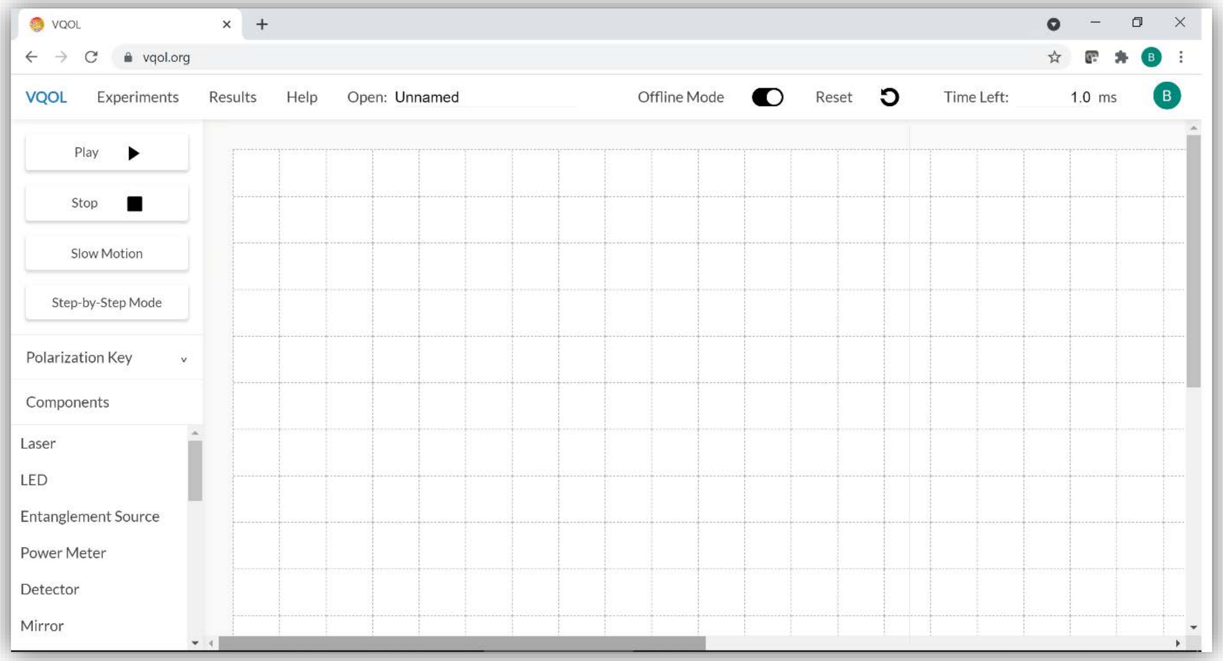
$$C_{11} = \frac{7 - 52 - 45 + 10}{10 + 52 + 45 + 10} = -0.68$$

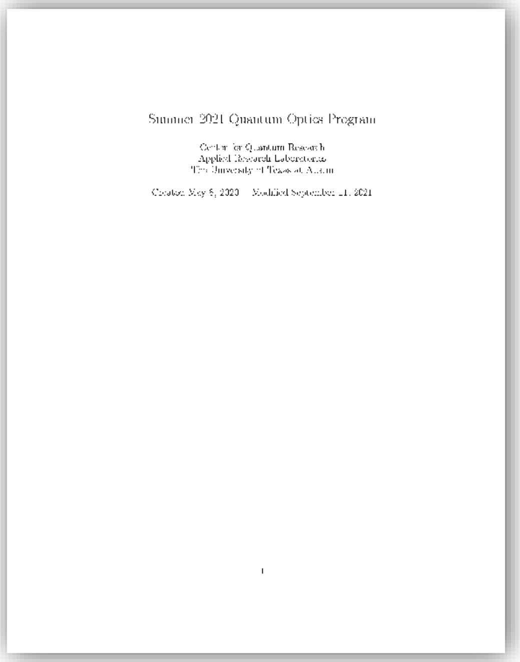
$$S = |C_{11} + C_{12}| + |C_{21} - C_{22}| = 2.74 > 2$$

Try it for Yourself!

VQOL is available online at **https://www.vqol.org**

Contact me (**blacour@arlut.utexas.edu**) for the laboratory manual.





Summer 2021 Quantum Optics Program

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