# An Experimental Implementation of Hardy's Paradox

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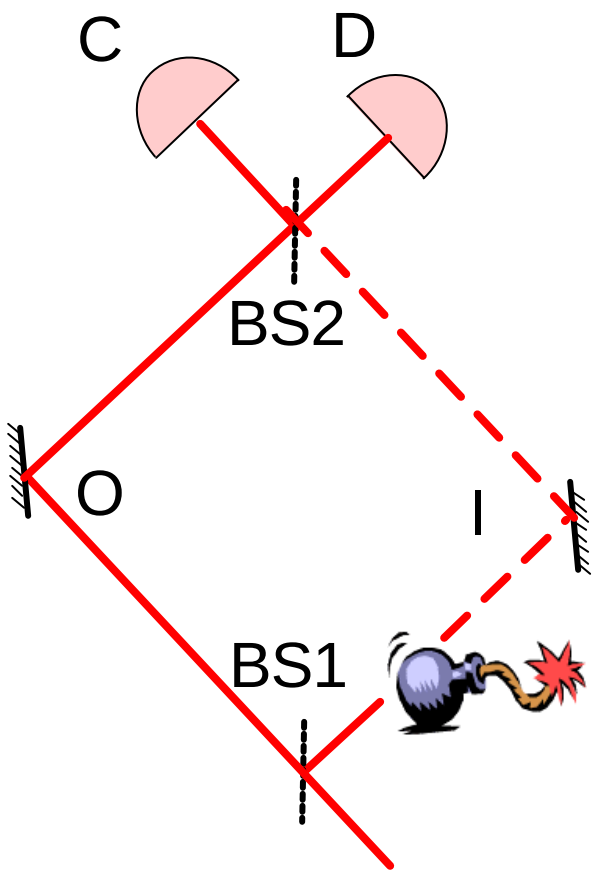
*Zeno's Paradox : Achilles and The Tortoise*

# Interaction-Free Measurement

A. C. Elitzur, and L. Vaidman, Found. Phys. **23**, 987 (1993)



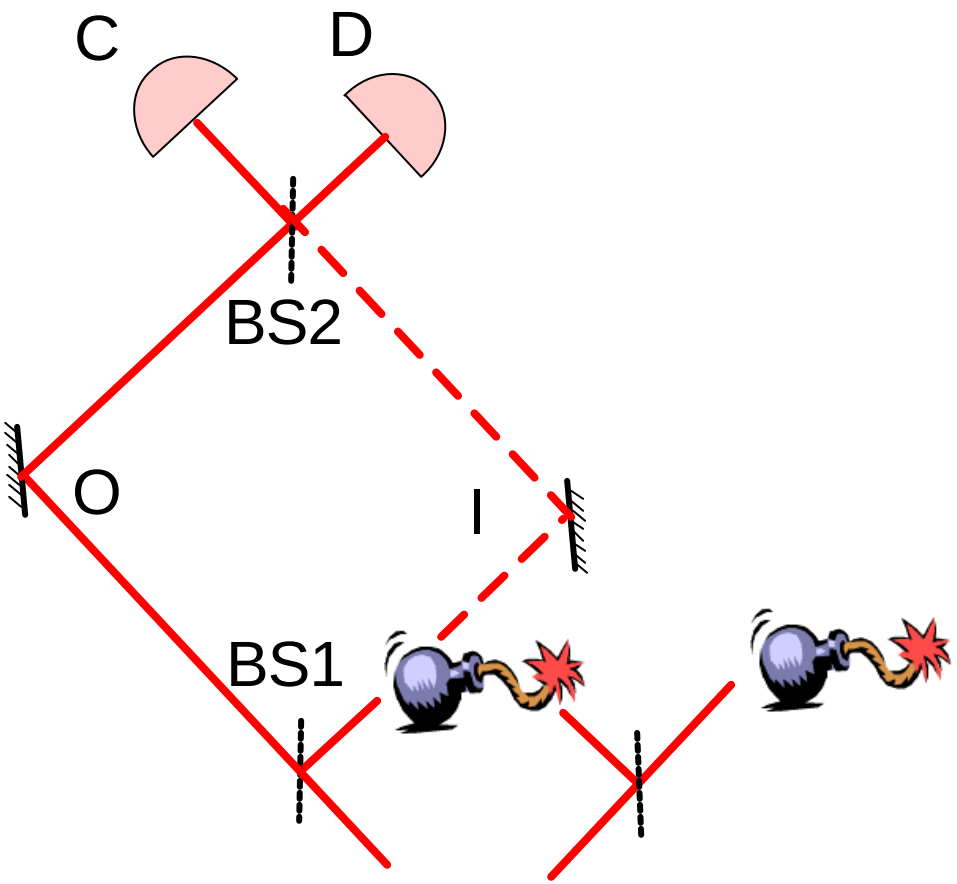

Bomb Absent:

**Only detector C fires**

Bomb Present:

| **Detector** | **Prob.** | **Result** |
|---|---|---|
| C | ¼ | None |
| D | ¼ | Present |
| Neither | ½ | Bang |

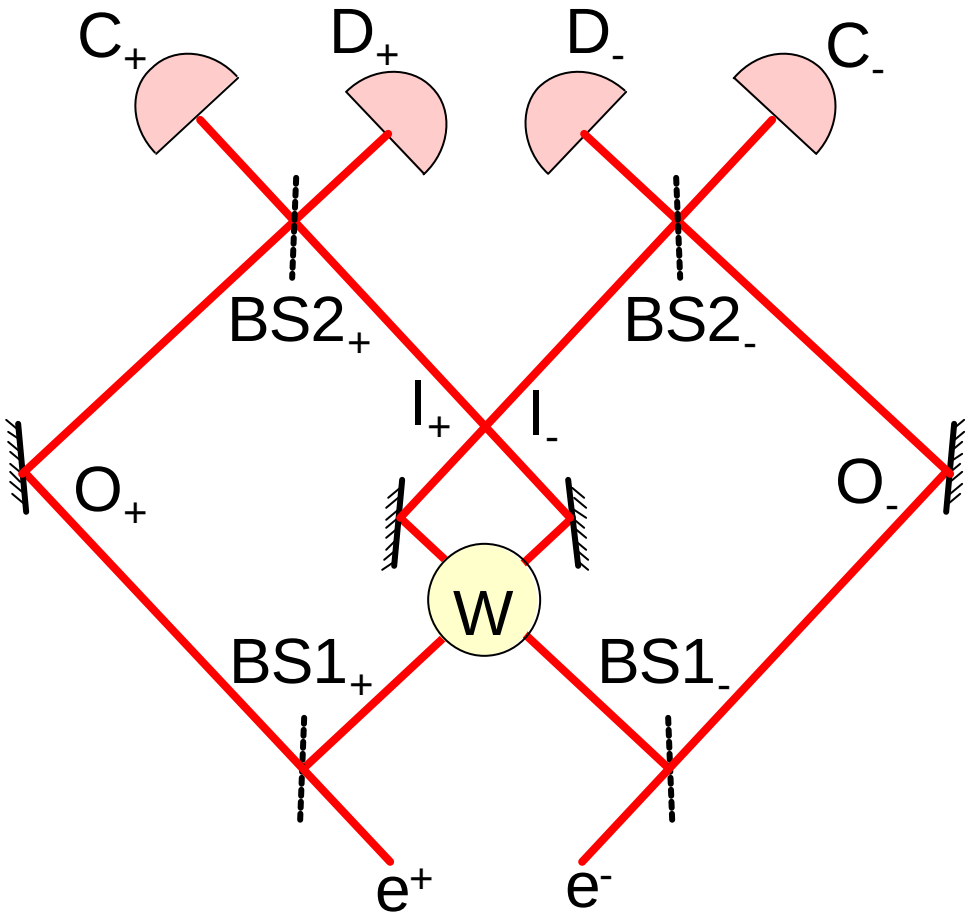
# IFM On A Quantum Object




A click at D collapses the bomb's superposition

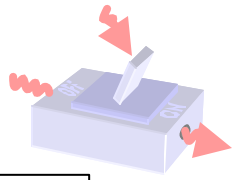
# Hardy's Paradox

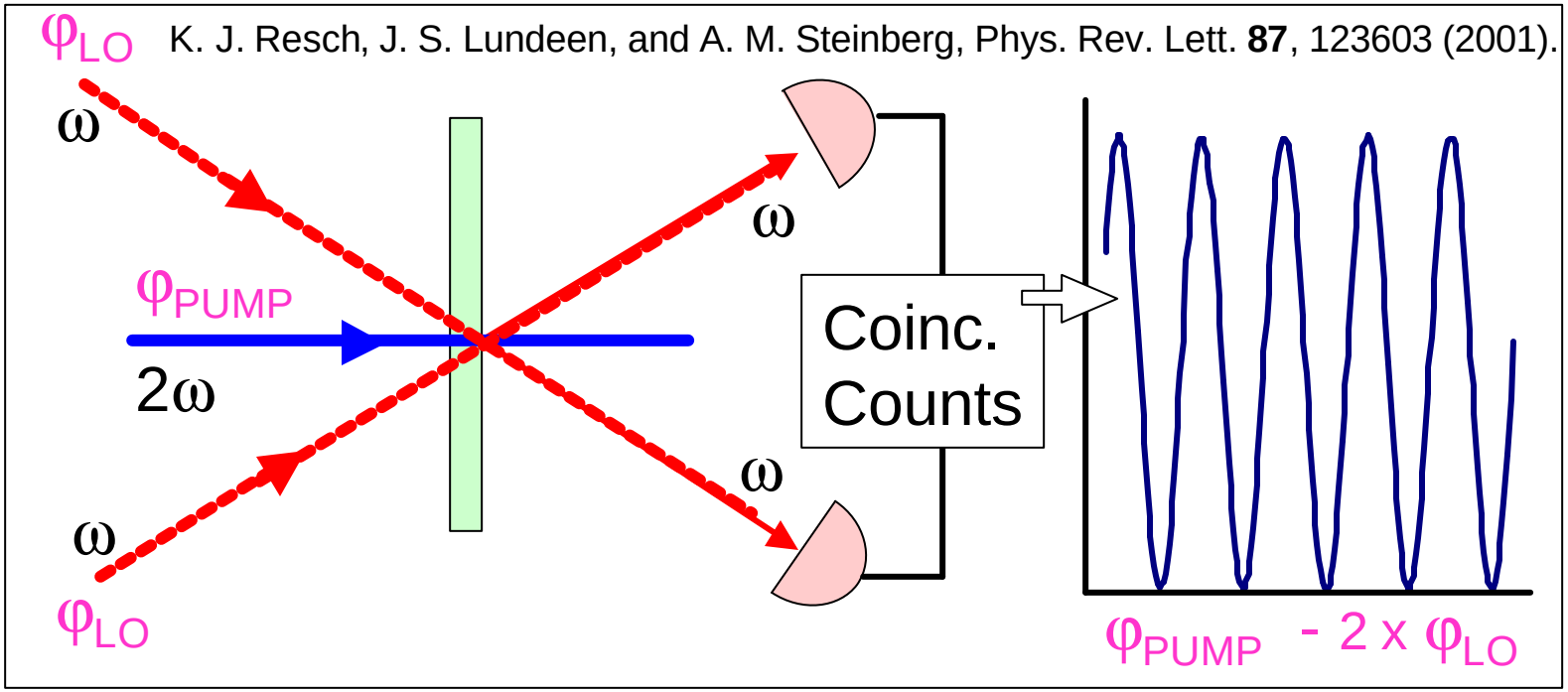
L. Hardy, Phys. Rev. Lett. **68**, 2981 (1992)

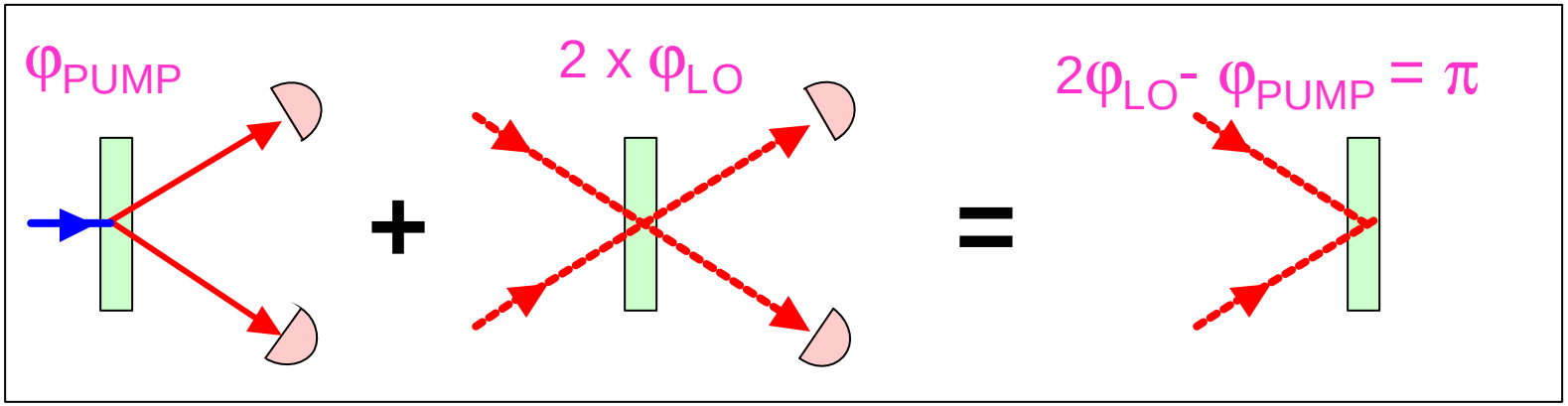



| **Outcome** | **Prob** |
|---|---|
| $D_+$ and $C_-$ | 1/16 |
| $D_-$ and $C_+$ | 1/16 |
| $C_+$ and $C_-$ | 9/16 |
| $D_+$ and $D_-$ | 1/16 |
| Explosion | 4/16 |

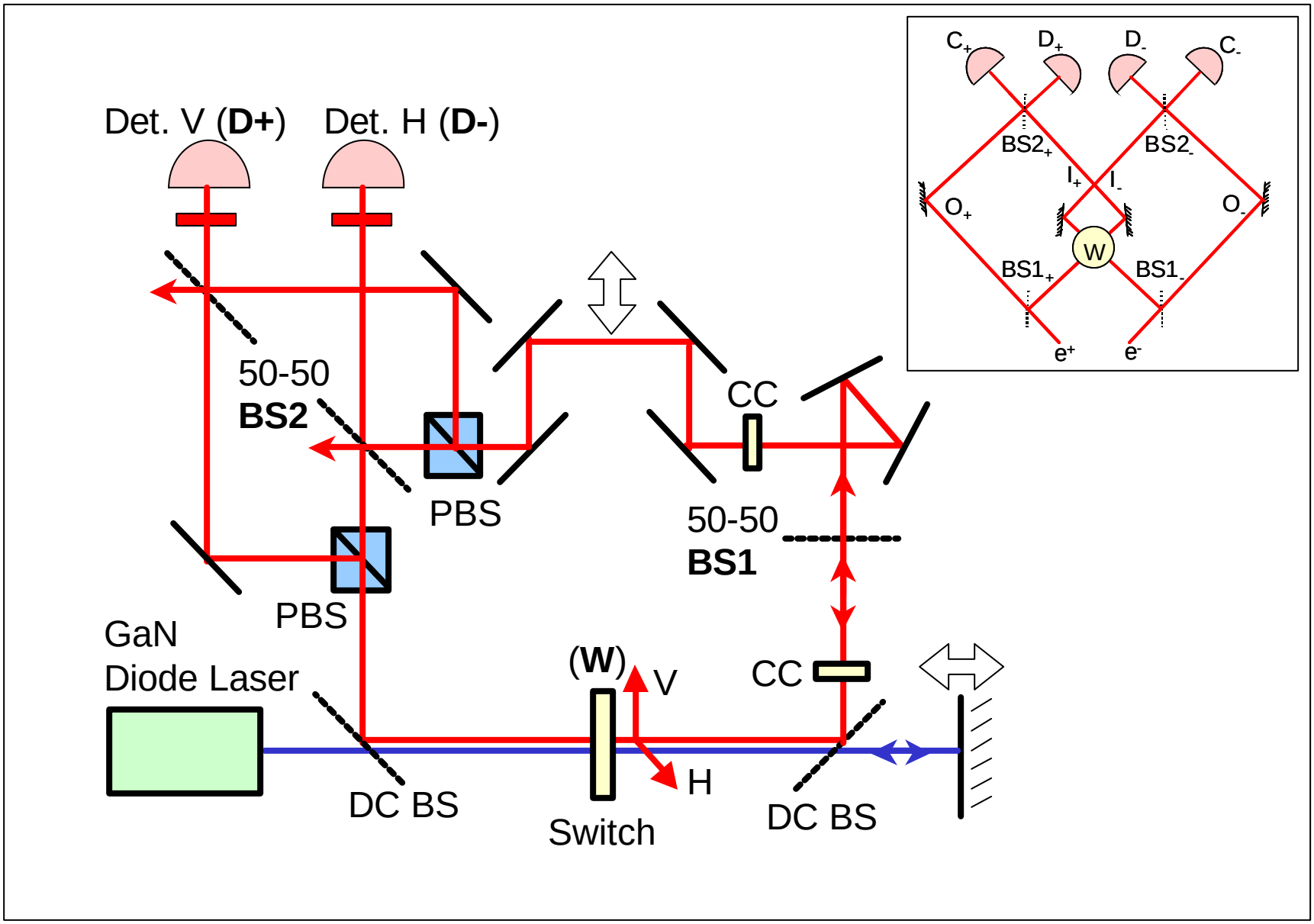
# The Switch

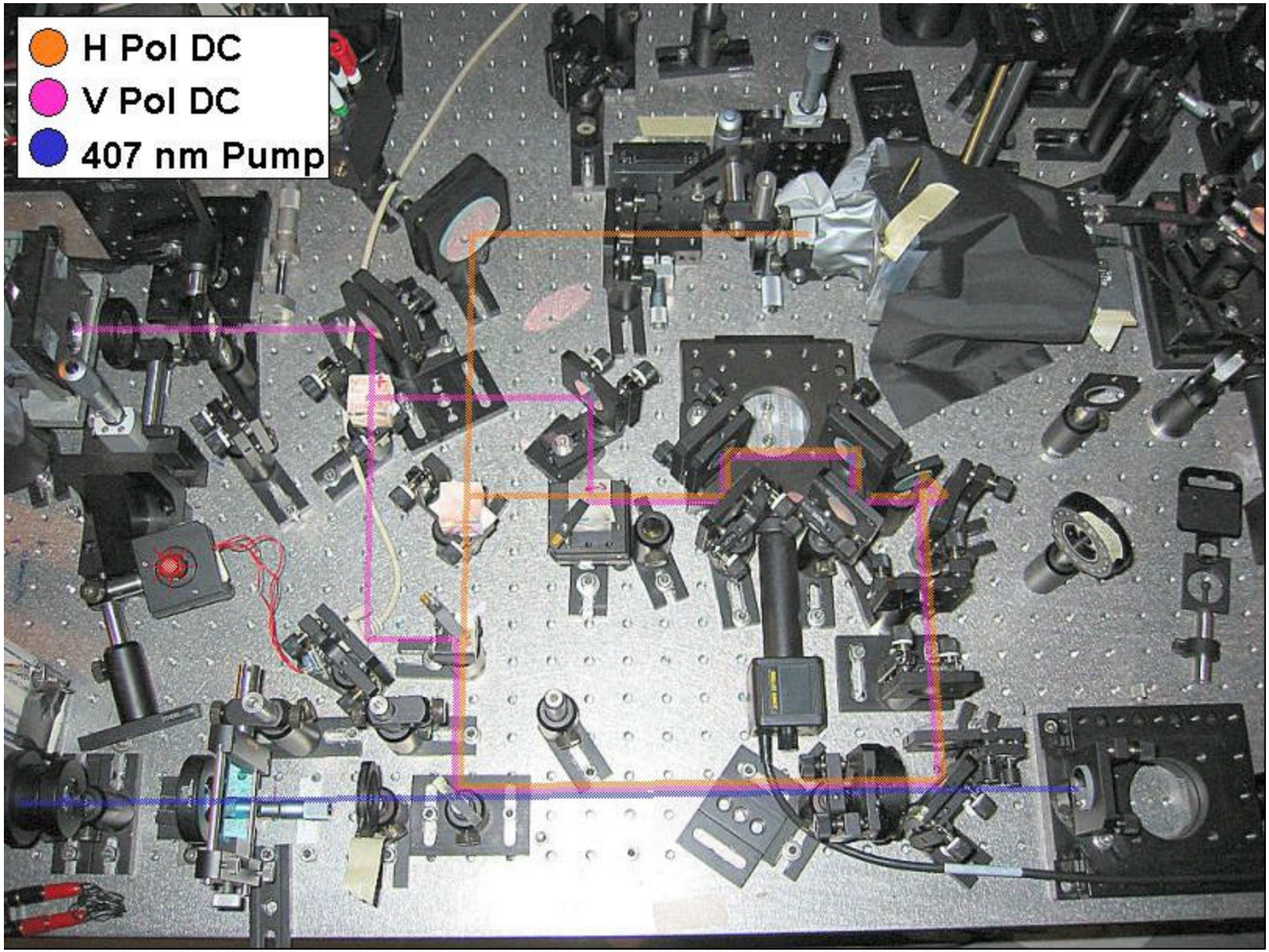



φLO
K. J. Resch, J. S. Lundeen, and A. M. Steinberg, Phys. Rev. Lett. 87, 123603 (2001).
ω
φPUMP
2ω
ω
ω
φLO
Coinc.
Counts
φPUMP - 2 x φLO


φPUMP
2 x φLO
2φLO- φPUMP = π
+
=

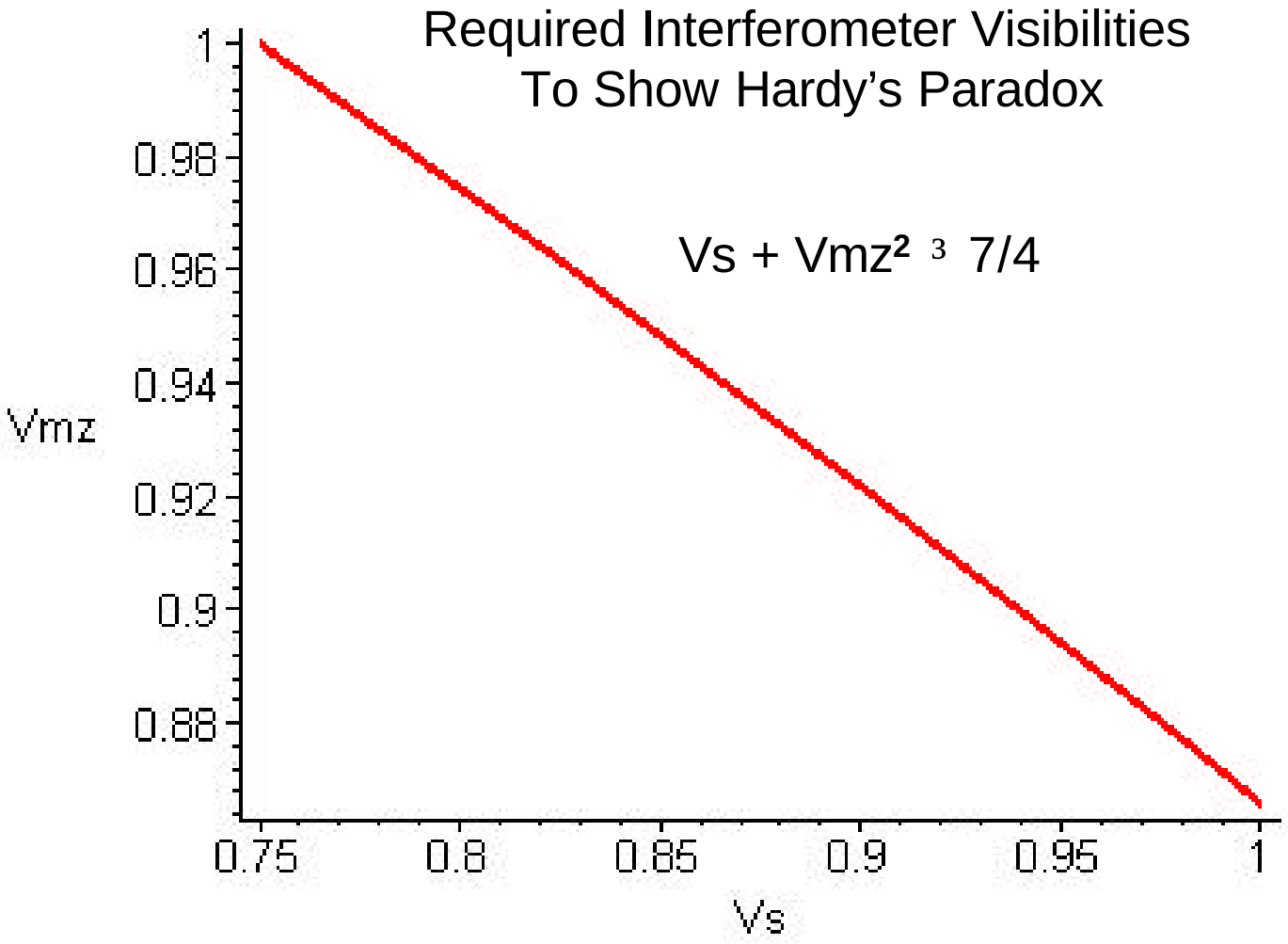
# Experimental Setup

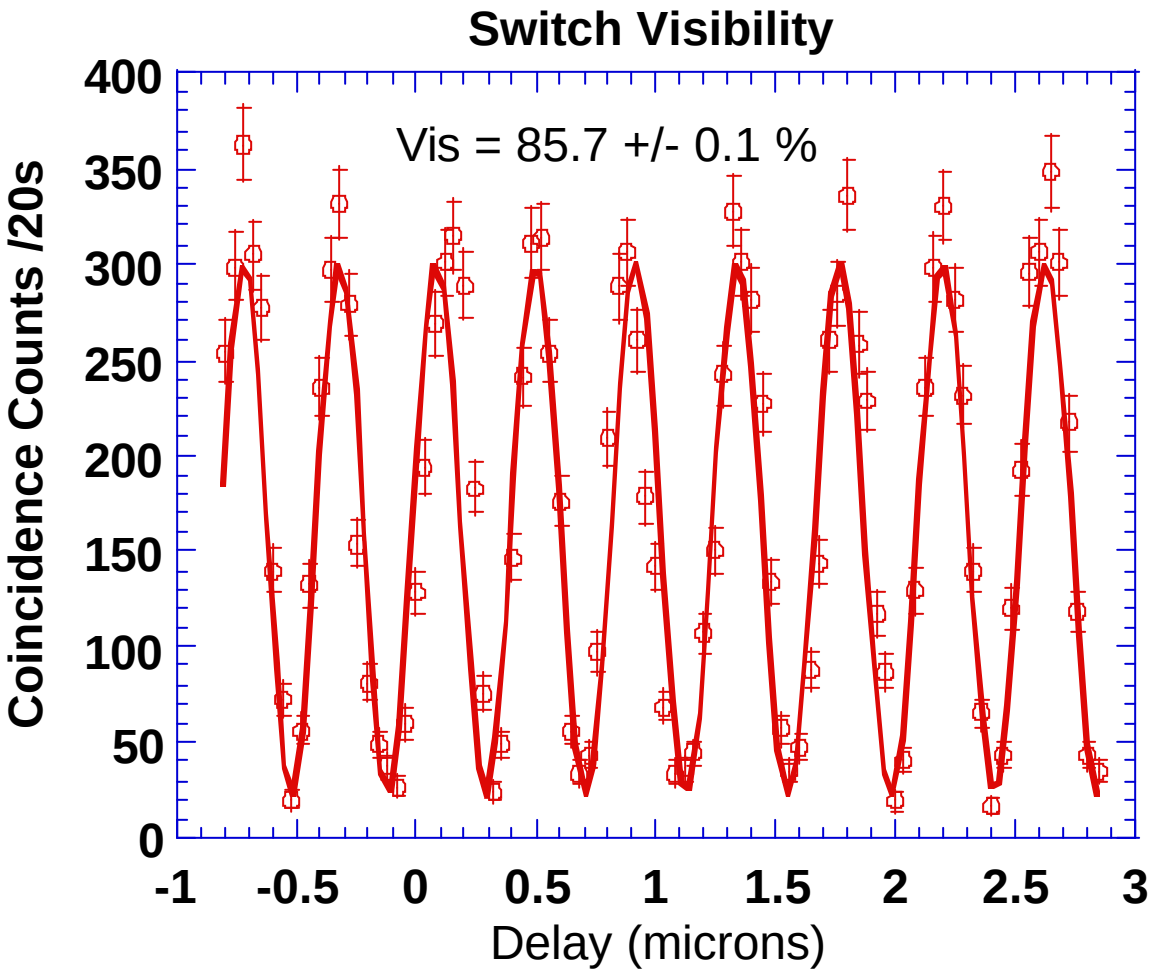


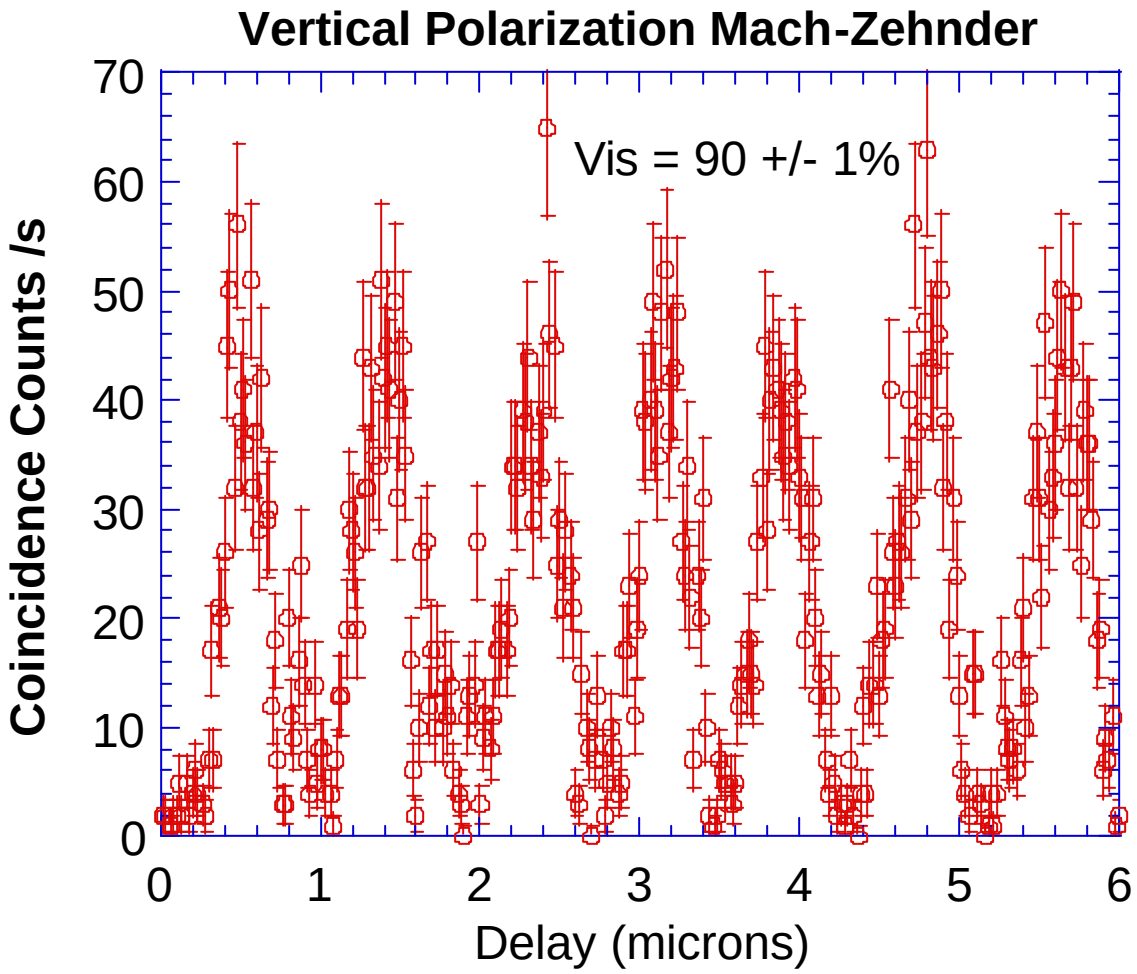

H Pol DC
V Pol DC
407 nm Pump

# What do we need to measure?

| Ideally | For a Real Apparatus |
| --- | --- |
| If $D_+$ clicks Þ - photon is in $I_-$ | $Vis_{Hor\ Int}$ |
| $IFM_+$ | |
| If $D_-$ clicks Þ + photon is in $I_+$ | $Vis_{Vert\ Int}$ |
| $IFM_-$ | |
| There is never a photon in $I_-$ and $I_+$ | $Vis_{Switch}$ |
| Annihilation at W | |
| Sometimes both $D_+$ and $D_-$ click | $Vis_{Switch} + Vis_{Int}^2 \ge 7/4$ |
| The paradox | |


Required Interferometer Visibilities
To Show Hardy's Paradox
Vs + Vmz² ³ 7/4
Vmz
1
0.98
0.96
0.94
0.92
0.9
0.88
0.75
0.8
0.85
0.9
0.95
1
Vs


Switch Visibility
Vis = 85.7 +/- 0.1 %
Coincidence Counts /20s
400
350
300
250
200
150
100
50
0
-1
-0.5
0
0.5
1
1.5
2
2.5
3
Delay (microns)


Vertical Polarization Mach-Zehnder
Vis = 90 +/- 1%
Coincidence Counts /s
Delay (microns)
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6

# Weak Measurements

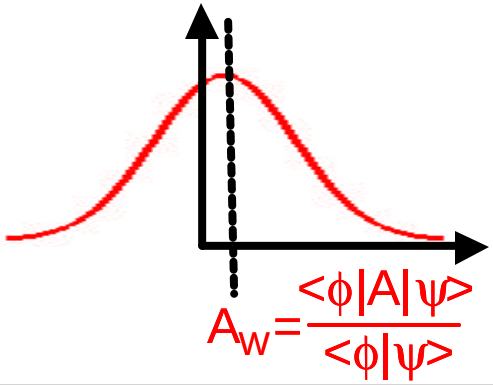
Y. Aharonov, A. Botero, S. Popescu, B. Reznik, J. Tollaksen, e-print quant-ph/0104062 (2001).

| **Measurement** | **Pointer Position Uncertainty** |
|---|---|
| Ideal | Dirac Delta |
| Real | Width << Change in Position |
| Weak | Width >> Change in Position |

$\Delta X \Delta P \geq \hbar/2$

- small disturbance
- little system – pointer entanglement

$$\text{Pointer}(X) = \exp[-(X - gA_w)^2 / \Delta X]$$

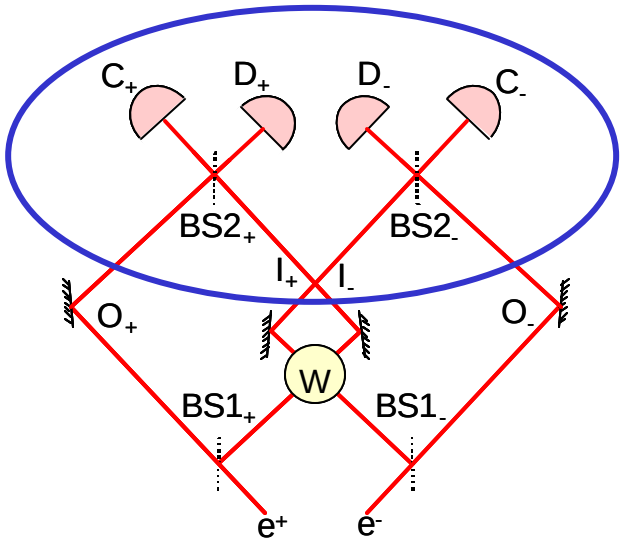



**No system disturbance**

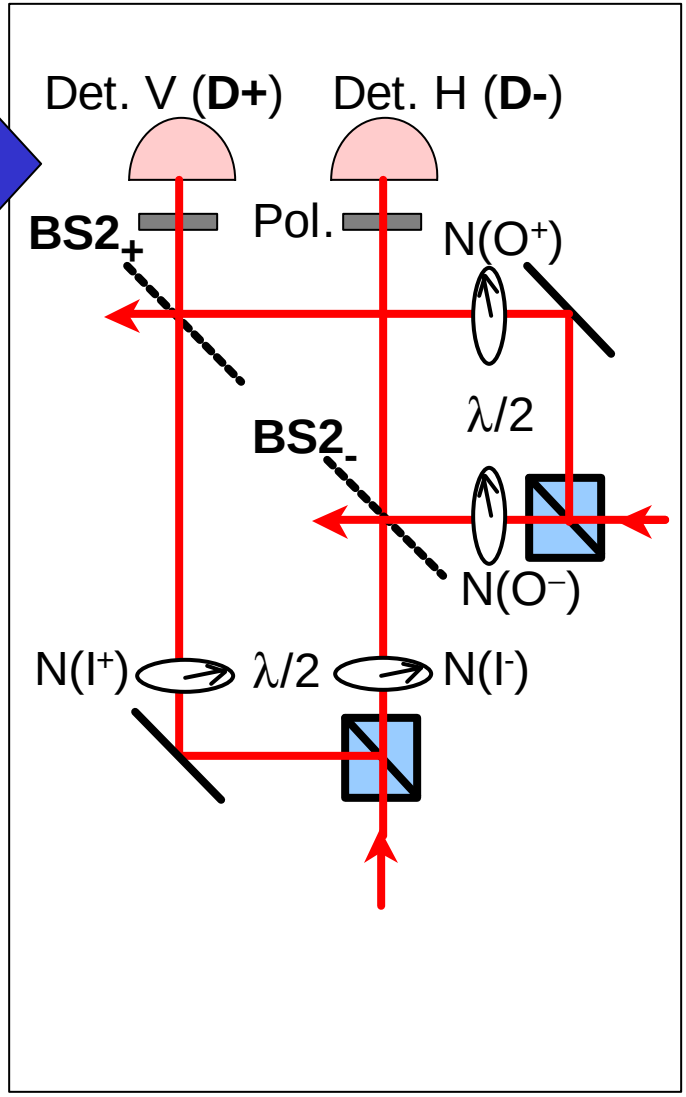
- simultaneous measure of different weak values.

# Weak Measurements in Hardy's Paradox

Y. Aharanov, A. Botero, S. Popescu, B. Reznik, J. Tollaksen, e-print quant-ph/0104062 (2001).




| # In Arm | N(I⁻) | N(O⁻) | |
|---|---|---|---|
| N(I⁺) | 0 | 1 | 1 |
| N(O⁺) | 1 | -1 | 0 |
| | 1 | 0 | |



# Conclusions

- An experimental implementation of Hardy's Paradox is now possible.
- A single-photon level switch allows photons to interact with a high efficiency.
- The first version of the experiment will be a polarization based system.
- A later extension will look at the results of weak measurements in Hardy's Paradox.