A strong loophole-free test of local realism

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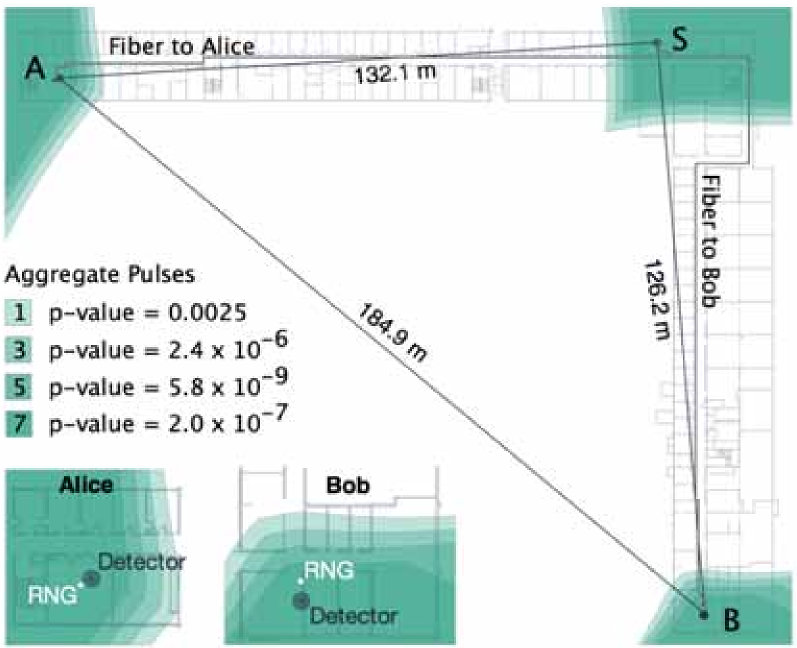
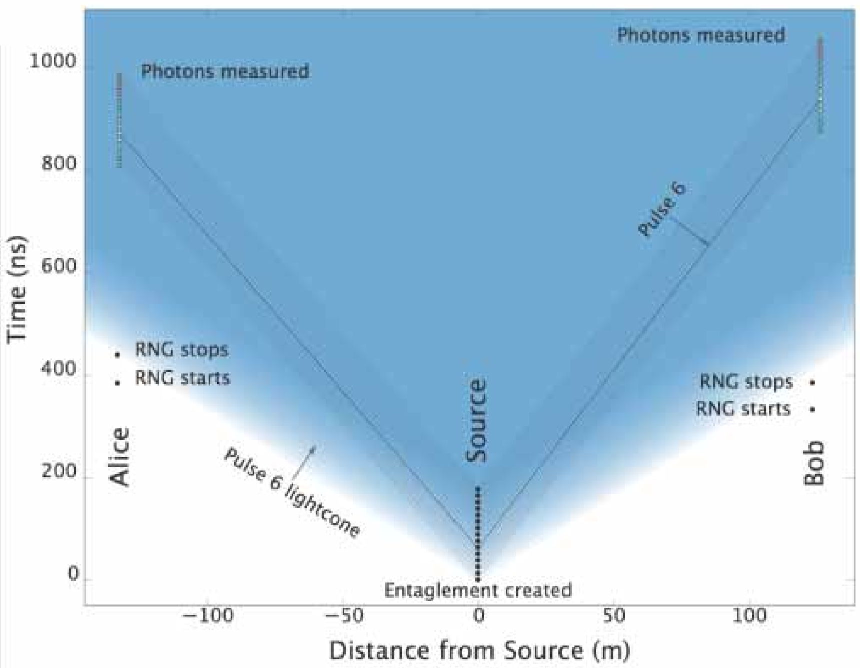




Local Realism

Einstein, Podolsky, Rosen (1935): *"If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."*

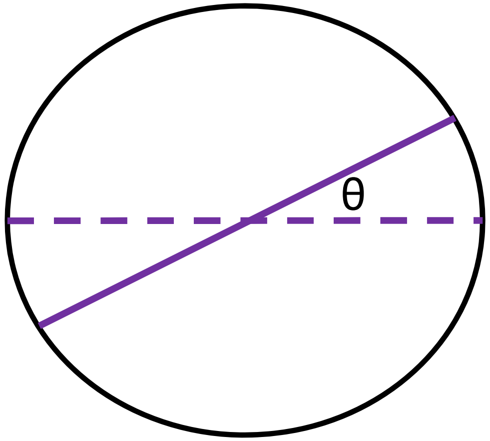
Realism: external reality exists and has definite properties whether or not we measure them

Locality: changing or measuring one system has no influence on a non-interacting system (e.g., space-like separated)

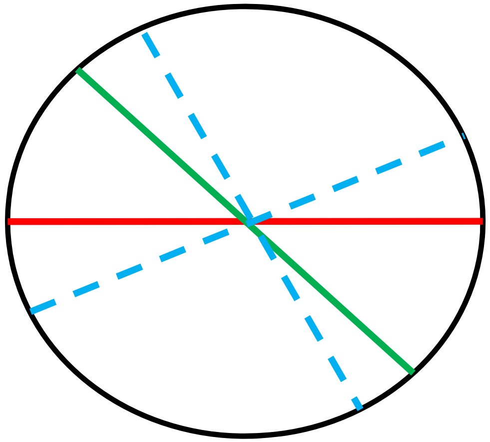
Bell (1965): QM gives different statistical predictions than any local realistic model.

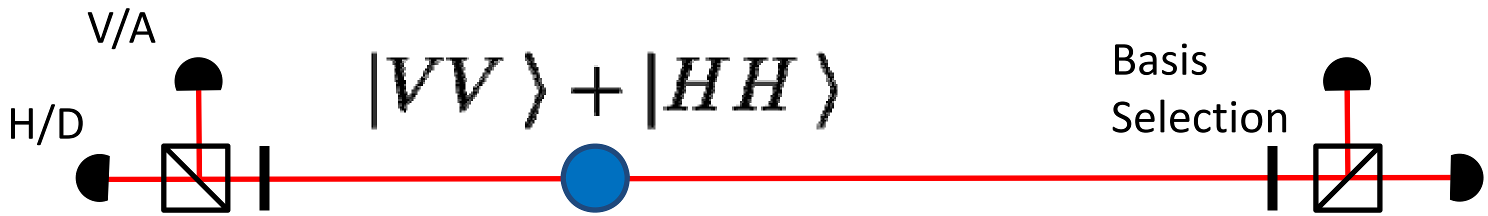
Bell Test

If measured in the θ basis, then the outcome is determined by *f*(θ) = {0,1}



Problem:





<u>CHSH Bell-inequality</u>: $|S_{LHV}| \leq 2$, $|S_{QM,\ max}| = 2\sqrt{2} = 2.828$

What is "Loophole free"?

$$P(++|ab) \leq P(+0|ab') + P(0+|a'b) + P(++|a'b')$$

$$\frac{C(++|ab)}{N(++|ab)} \leq \frac{C(+0|ab')}{N(+0|ab')} + \frac{C(0+|a'b)}{N(0+|a'b)} + \frac{C(++|a'b')}{N(++|a'b')}$$

1) ~~Locality~~
2) ~~Realism~~
3) Setting choices are independent of each other and of the photons being measured
4) measurements of locations and times of events are reliable
5) Alice's and Bob's measurement outcomes are fixed at the time taggers

A "loophole"

Can be tested (space-time separation of "detection events")

Untestable (always required to make the assumption)

Unnecessary (required only for low efficiency systems)

"Loophole free" = minimal assumptions, and all testable assumptions are bounded.

Hypothesis test

- Important for any test (e.g., high energy experiments)
  - Standard deviations break down at tail ends of distributions
- Example: Test if a coin is biased towards heads
  - Null hypothesis to be tested: *coin is fair*
  - Test statistic: *Number of tosses that land heads*

```
>> length(find(randi(2,100,1) == 2))

ans =

    56
```

  - The p-value is the probability a fair coin could have produced the test statistic (or more extreme).

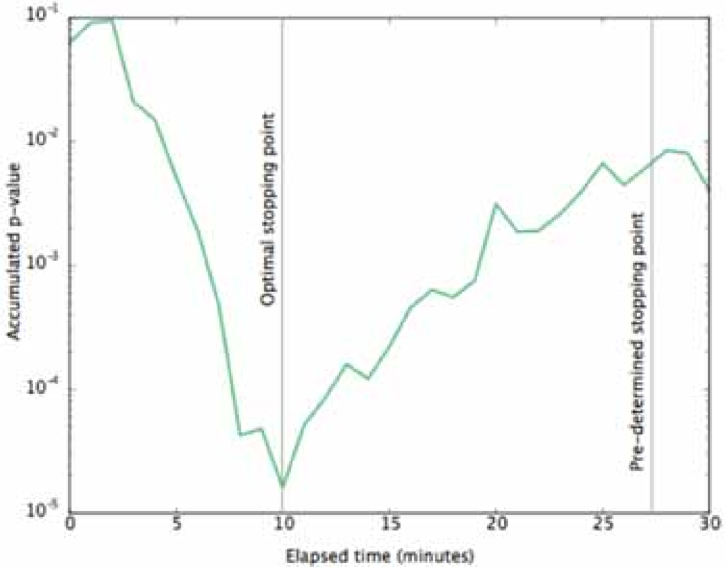
$$\sum_{k=56}^{100} \binom{100}{k} 2^{-k} 2^{-(100-k)} = 0.136$$

Is this below our threshold?
Can only draw conclusions from very small p-values.
HEP requires ~1/3,500,000

  - In our case, LR is a fair coin toss for our test statistic, so we follow same idea. But a few very key points…

Hypothesis test

$$\sum_{k=56}^{100} \binom{100}{k} 2^{-k} 2^{-(100-k)} = 0.136$$



- A few subtle points:
  - We decided to toss the coin 100 times. This must be chosen in advance!
  - Local realistic models would know the outcome given the settings and could lock in a statistical fluctuation

- We still make assumptions, we need to bound the assumptions. The p-value is no better than our confidence in assumptions.
  - In particular, we can place a bound on our no-signaling assumption. A p-value that is smaller than our confidence in no-signaling is meaningless.

Bell test

- Bell inequality: $P(++|ab) \leq P(+0|ab') + P(0+|a'b) + P(++|a'b')$

"Heads"

A "coin toss" if we see an event in this set

- Test statistic: $\{++ab, +0ab', 0+a'b, ++a'b'\}$

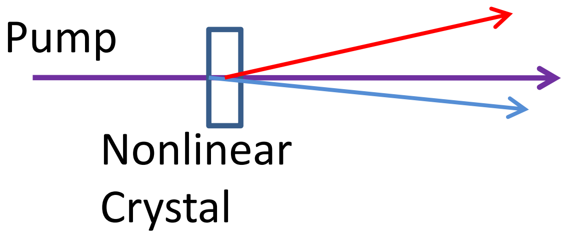
[5853 2600 2652 97]

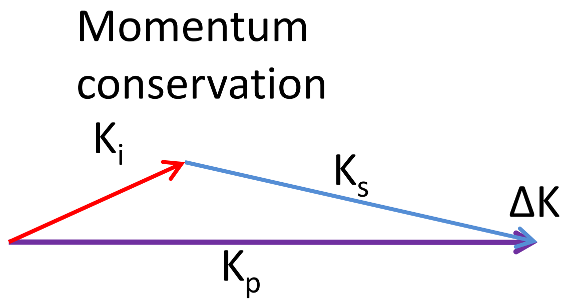
Stopping criteria: 90% of the estimated number of "coin flips" in the 30 minute data set. Use that fixed number.

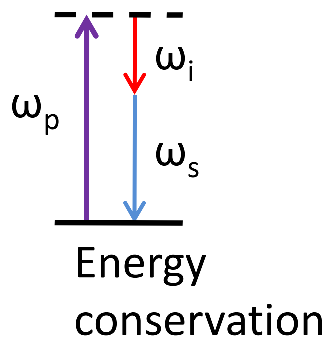
$$\sum_{k=5853}^{11202} \binom{11202}{k} 2^{-11202} = 1 \times 10^{-6}$$

The data set, on average, would have 12446 "coin flips", set stopping criteria to 0.9 x 12446 = 11202

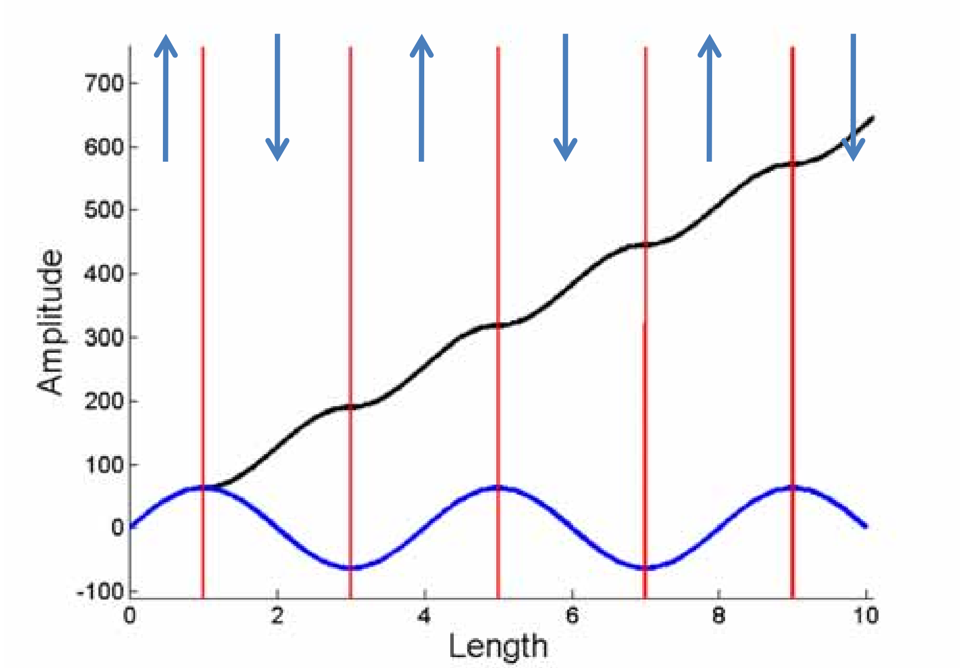
Downconversion







In our case, we use a periodically poled crystal to optimize collection efficiency and to increase count rate.



ILLINOIS

spdcalc.org

Crystal Options

KTP ref 1

Type 2: e -> e + o

Calculate theta

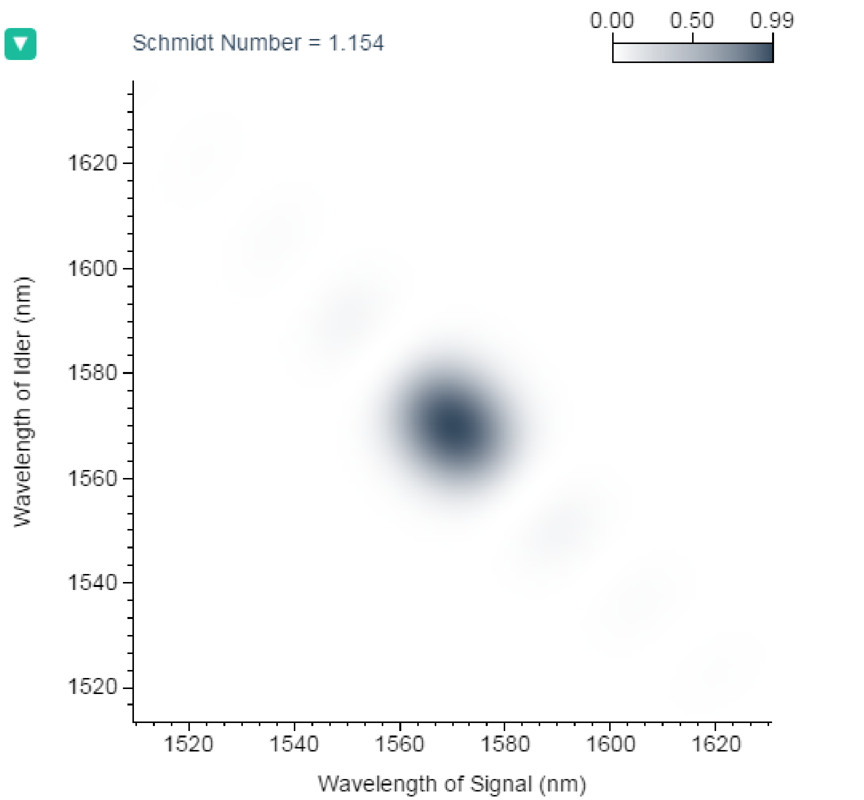
Theta (deg)	90.00
Phi (deg)	0
Length (um)	2000.00
Temperature	20

Pump Options

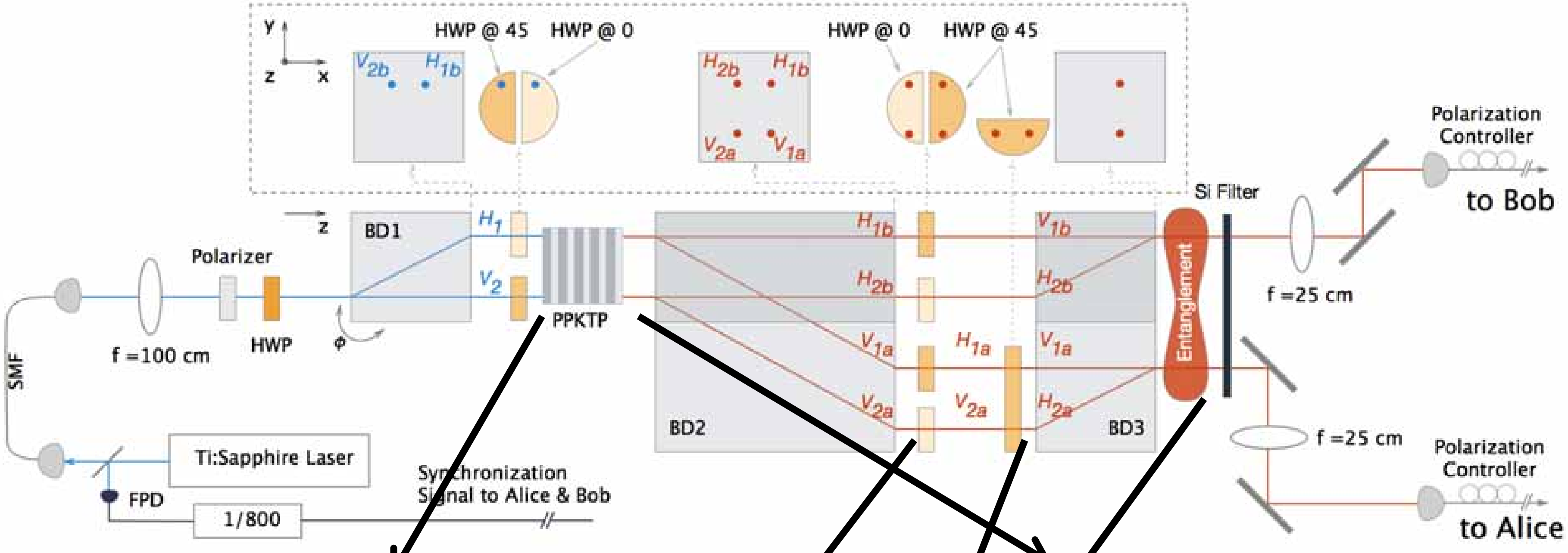
Signal Options

Periodic Poling

Joint spectral intensity



Source



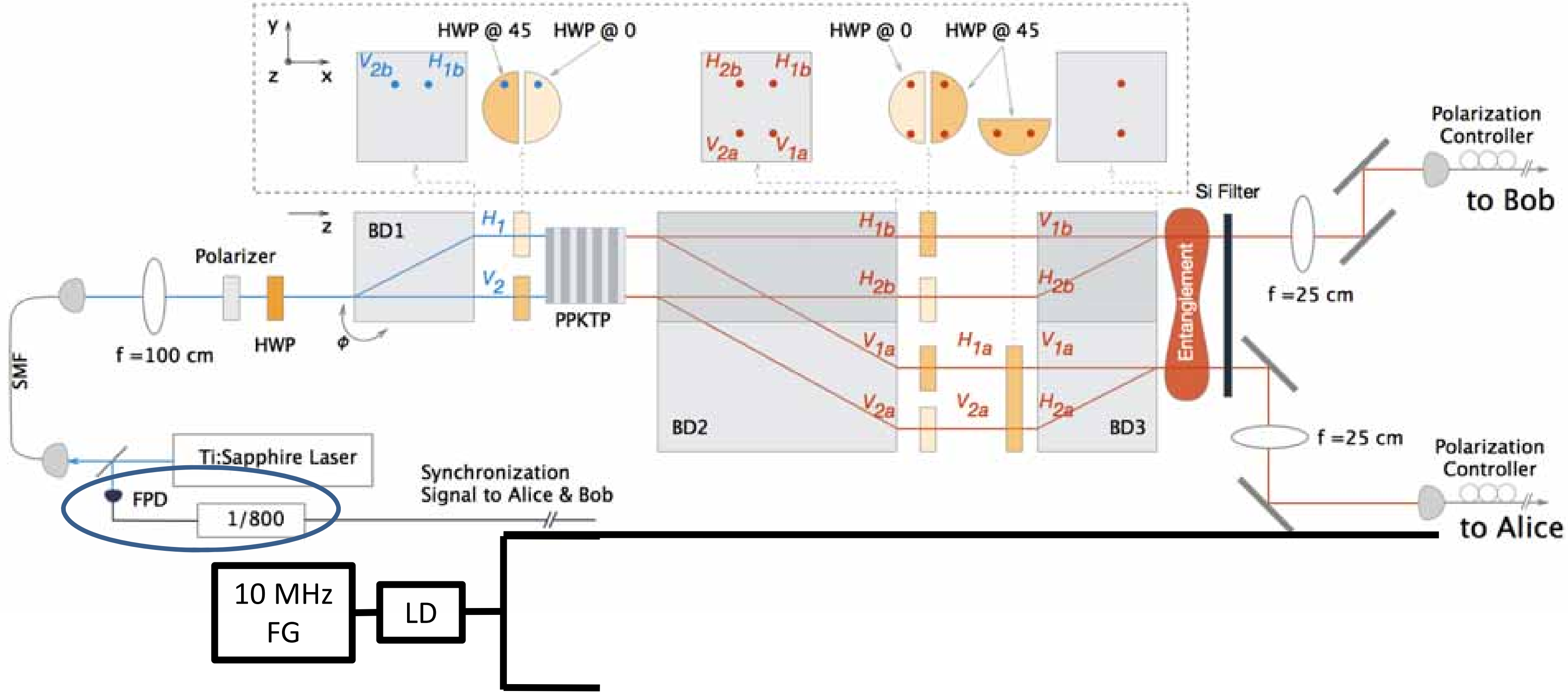
$$|H, L\rangle + e^{i\phi}|H, R\rangle \qquad |HV, L\rangle + e^{i\phi}|HV, R\rangle$$

$$(|H, LT\rangle|V, LB\rangle) + e^{i\phi}(|H, RT\rangle|V, RB\rangle)$$

$$(|H, LT\rangle|H, LB\rangle) + e^{i\phi}(|V, RT\rangle|V, RB\rangle)$$

$$(|H, T\rangle|H, B\rangle) + e^{i\phi}(|V, T\rangle|V, B\rangle)$$

Source



$$\cos(16^\circ)|HH\rangle + \sin(16^\circ)|VV\rangle$$

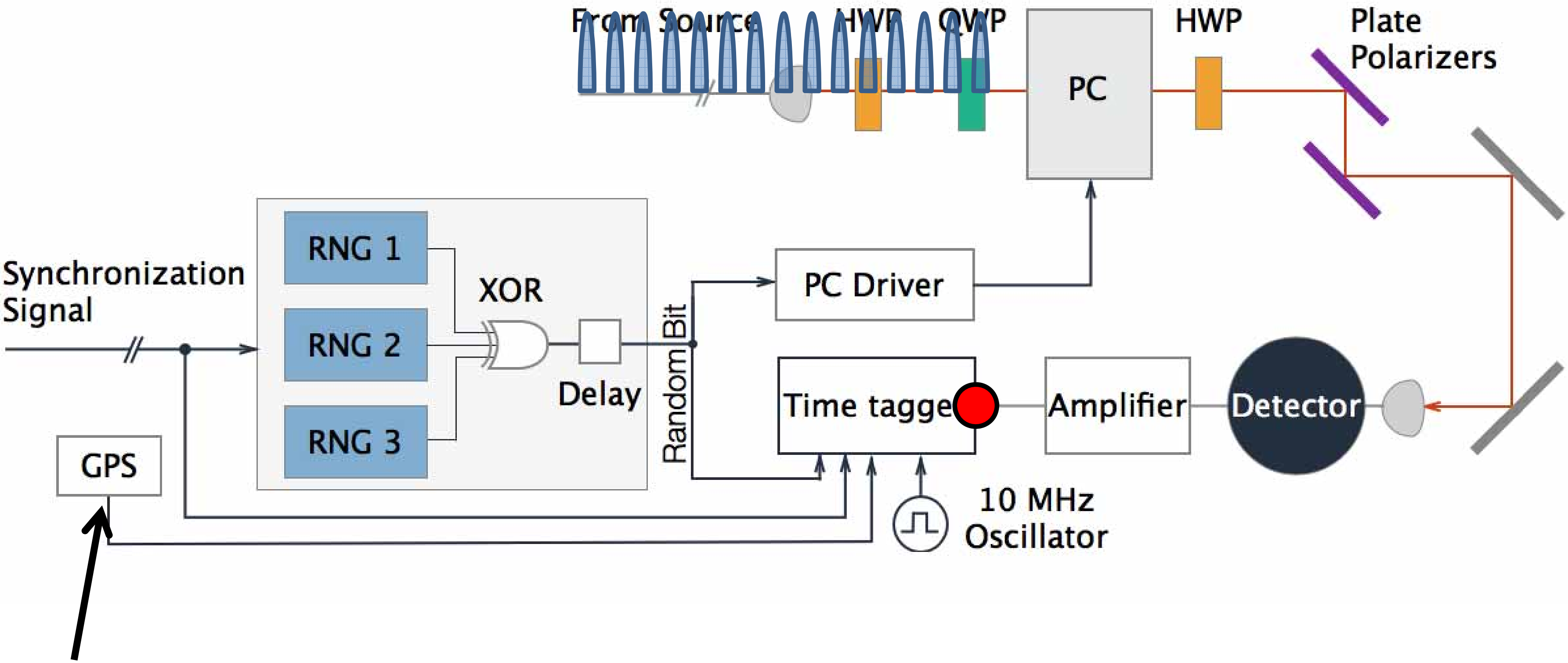
0.961 0.276

Detection

a = 4.2º, a’ = -25.9º

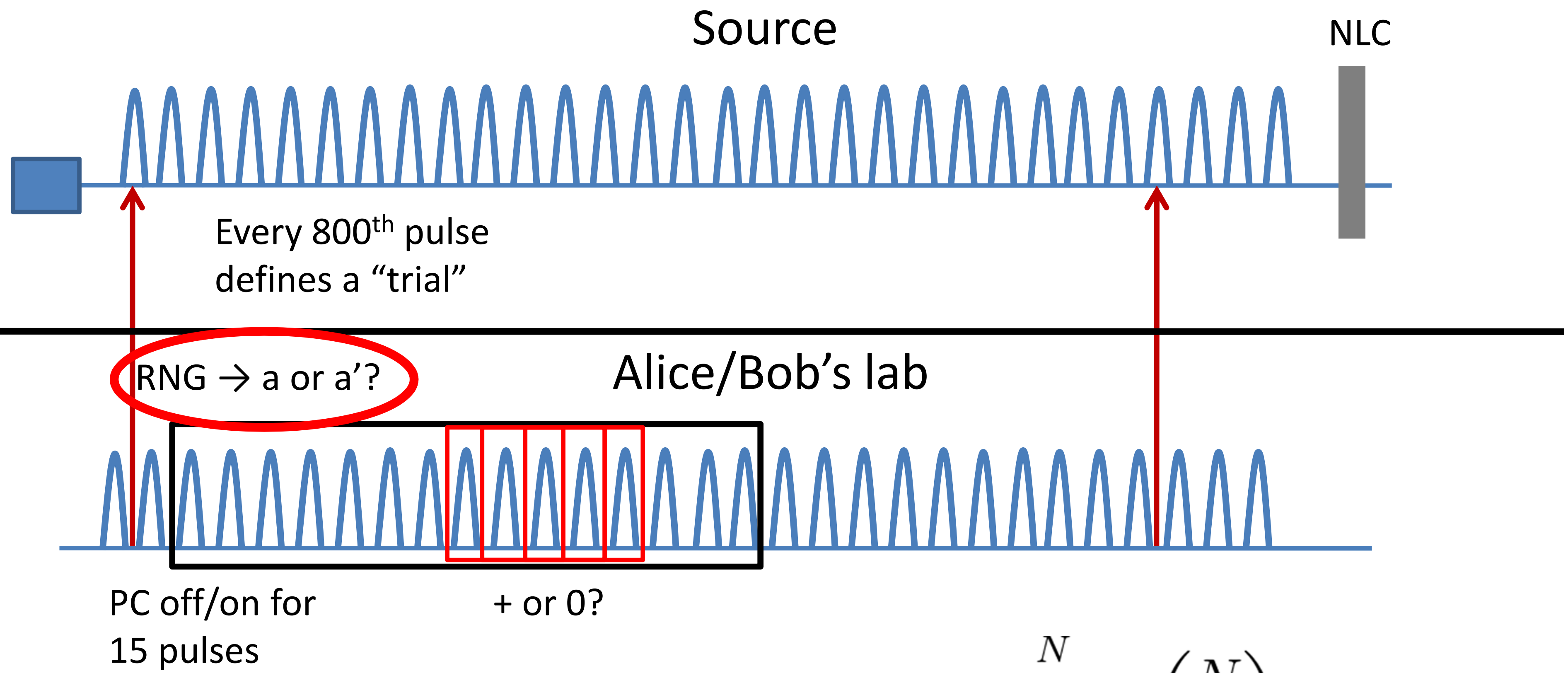
b = -4.2º, b’ = 25.9º

200 ns “on” time
at λ/6 voltage



1 Hz sync clock

What we call 0/+ events



$$\{++ab, +0ab', 0+a'b, ++a'b'\} \longrightarrow \sum_{k=N_{++ab}}^{N} \binom{N}{k} 2^{-N} = p_v$$

RNG sources

- We XOR 3 RNG distinct sources
  - 2 QRNG sources
    - Photon-Sampling Random Number Generator
      - Is there a photon in an attenuated coherent state?
    - Phase-Diffusion Random Number Generator
      - What is the phase between a laser now and a re-seeded laser?
  - Cultural numbers
    - Both Alice and Bob have a string based on movies and shows (e.g., Star Trek, Saved by the Bell, Back to the Future, Dr. Who)
    - What is more likely: QRNG are correlated to entangled photons, or shows from the 1990's are correlated to entangled photons?
    - Does not use the same power grid that the laser, crystal, QRNG, detectors all rely on, for example.
  - The total RNG relies on all 3 QRNG, if one disagrees with the cultural numbers, then the QRNG secures it, and vice versa.

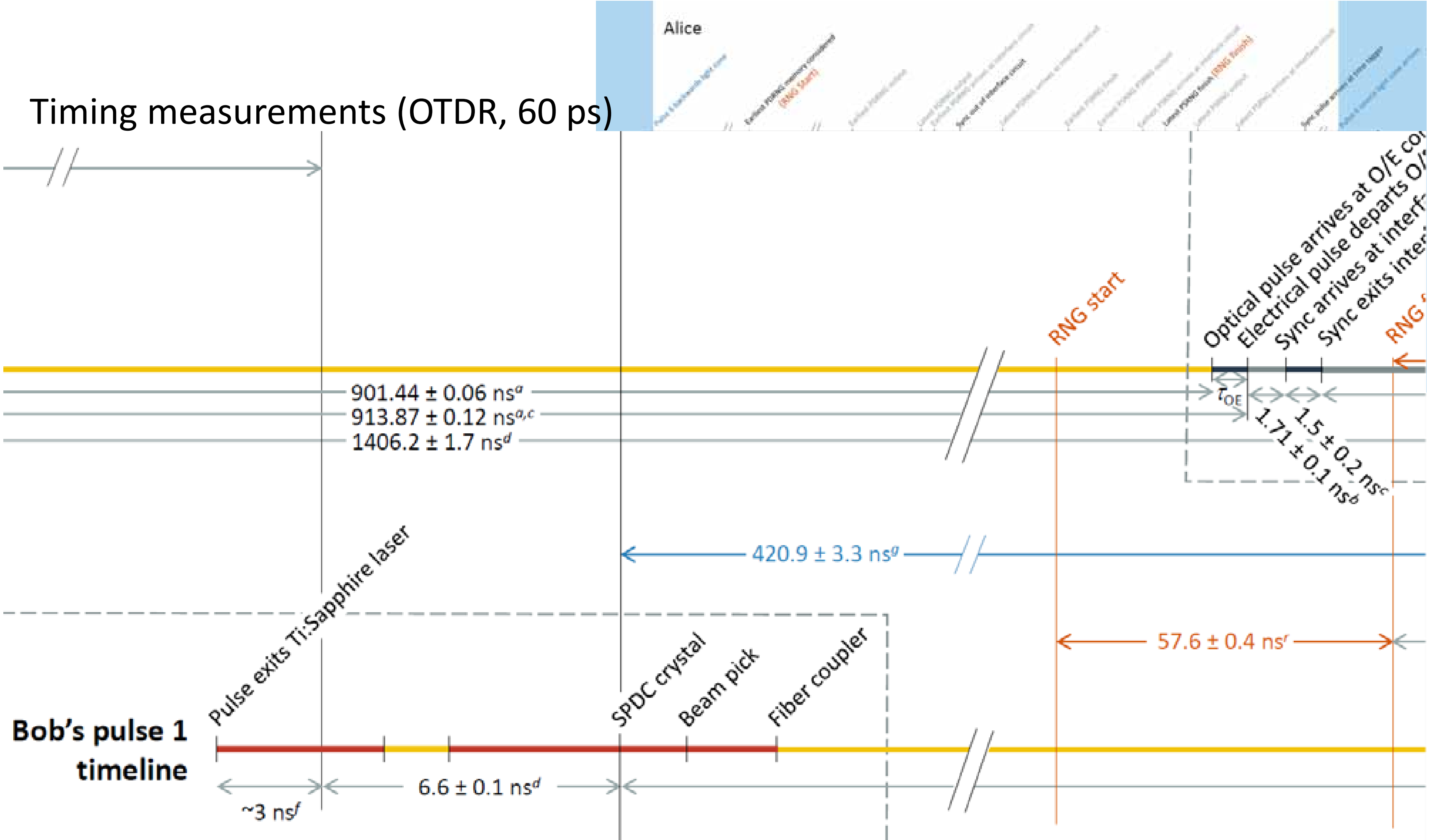
S. Pironio, "Random 'choices' and the locality loophole", arXiv:1510.00248 [quant-ph] (2015).

Position/timing measurements

- Multiple measurements all consistent
  - OTDR 
  - Timetagger
  - Manual distance measurements
  - GPS measurements
- Final position uncertainty = 1 m (3.3 ns)
  - Limited by position of the detector in the cryostat (we cannot see it, therefore we only say it is in the cryostat)

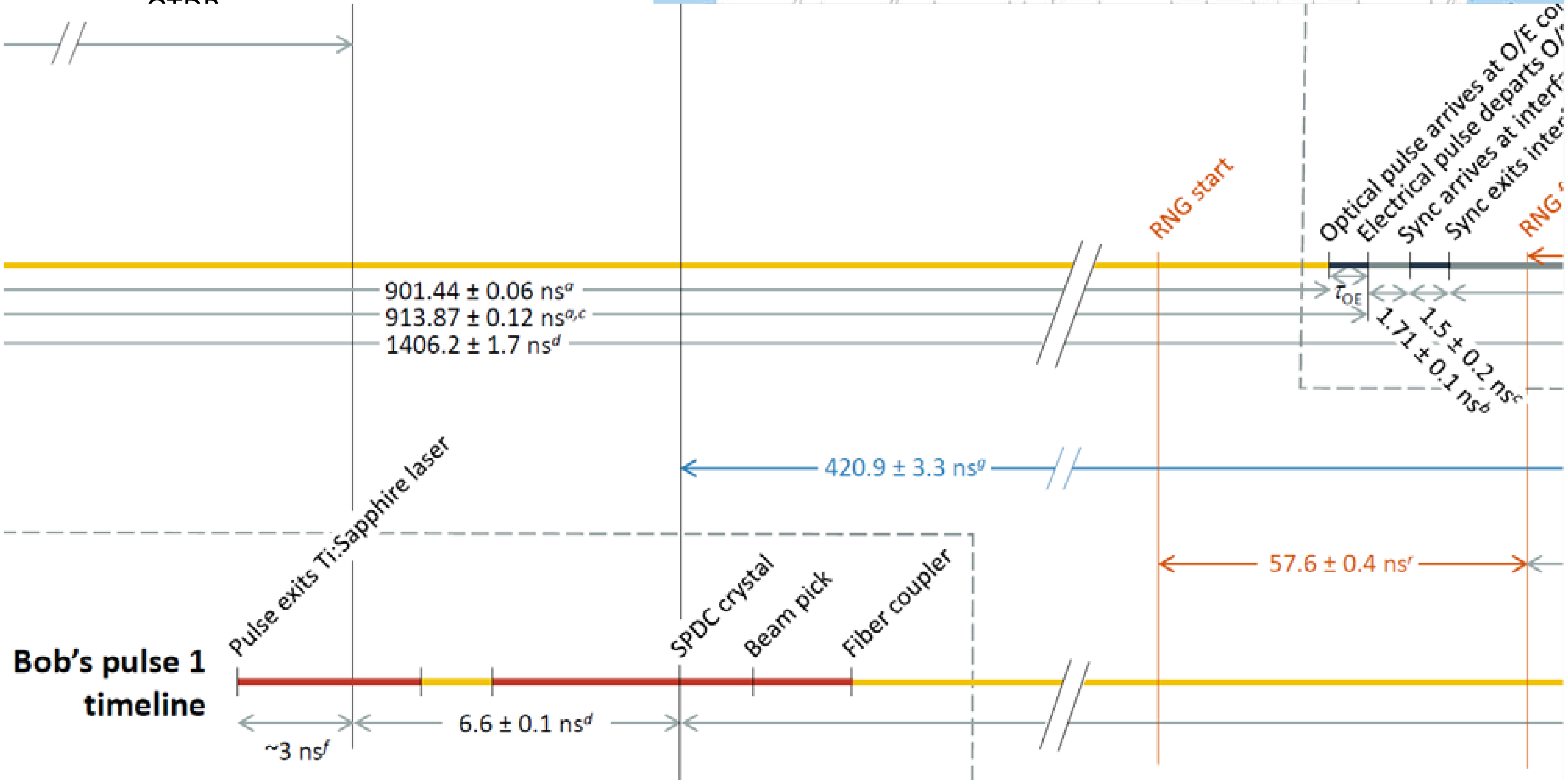
Position/timing measurements

Timing measurements (OTDR, 60 ps)



Position/timing measurements

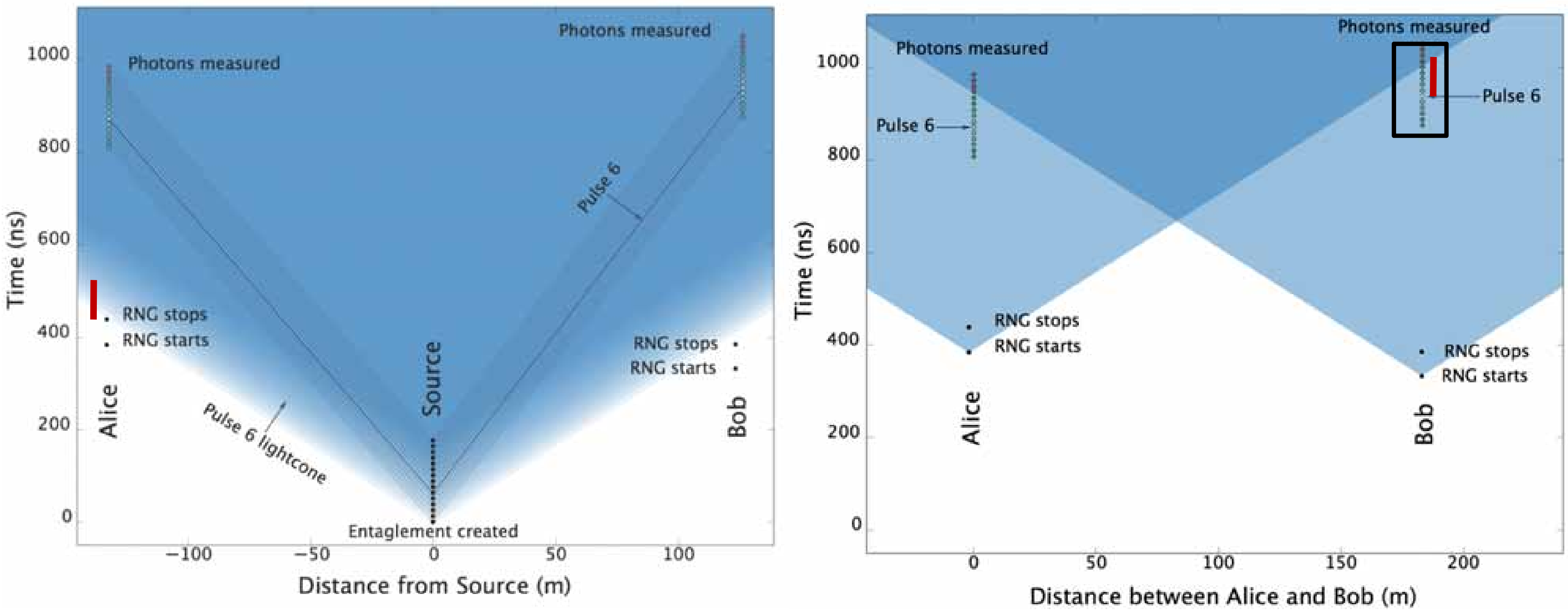
- Multiple measurements all consistent
  - Manual distance measurements
  - GPS measurements
  - OTDR



Spacetime Diagrams

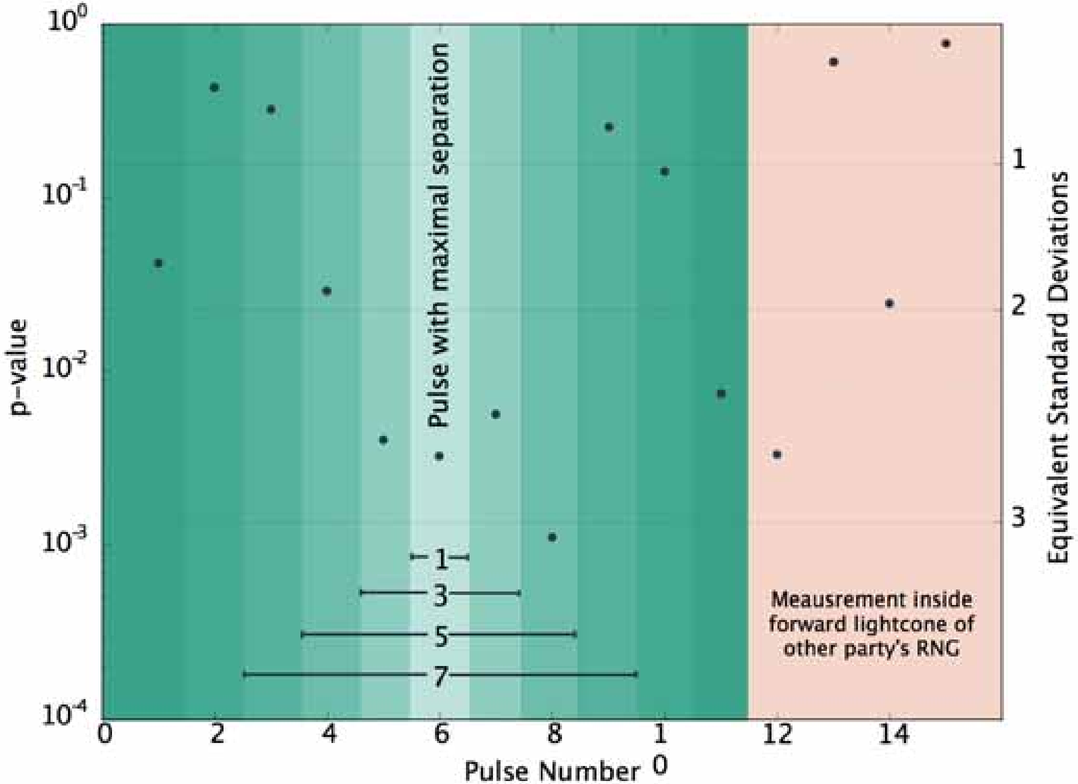
Of the 15 pulses, the optimal spacetime separation is pulse 6. We center all data analysis around pulse 6.

Pulse separation = 12.5 ns, position uncertainty = 3.3 ns



Data

- We took a total of 6 data sets.
  - The p-values displayed account for data set selection
  - Other data sets still have small p-values.
- The data set presented is for 30 minutes of data (our stopping criteria means we use approximately 27 minutes)



Large distribution of p-values is due to Pockels cell voltage fluctuations during the 200 ns active time (7 pulse data is worse than 5 pulse data!)

Data with spacetime confidence

All locations can simultaneously move inside the uncertainty bubble.

spacetime overhead

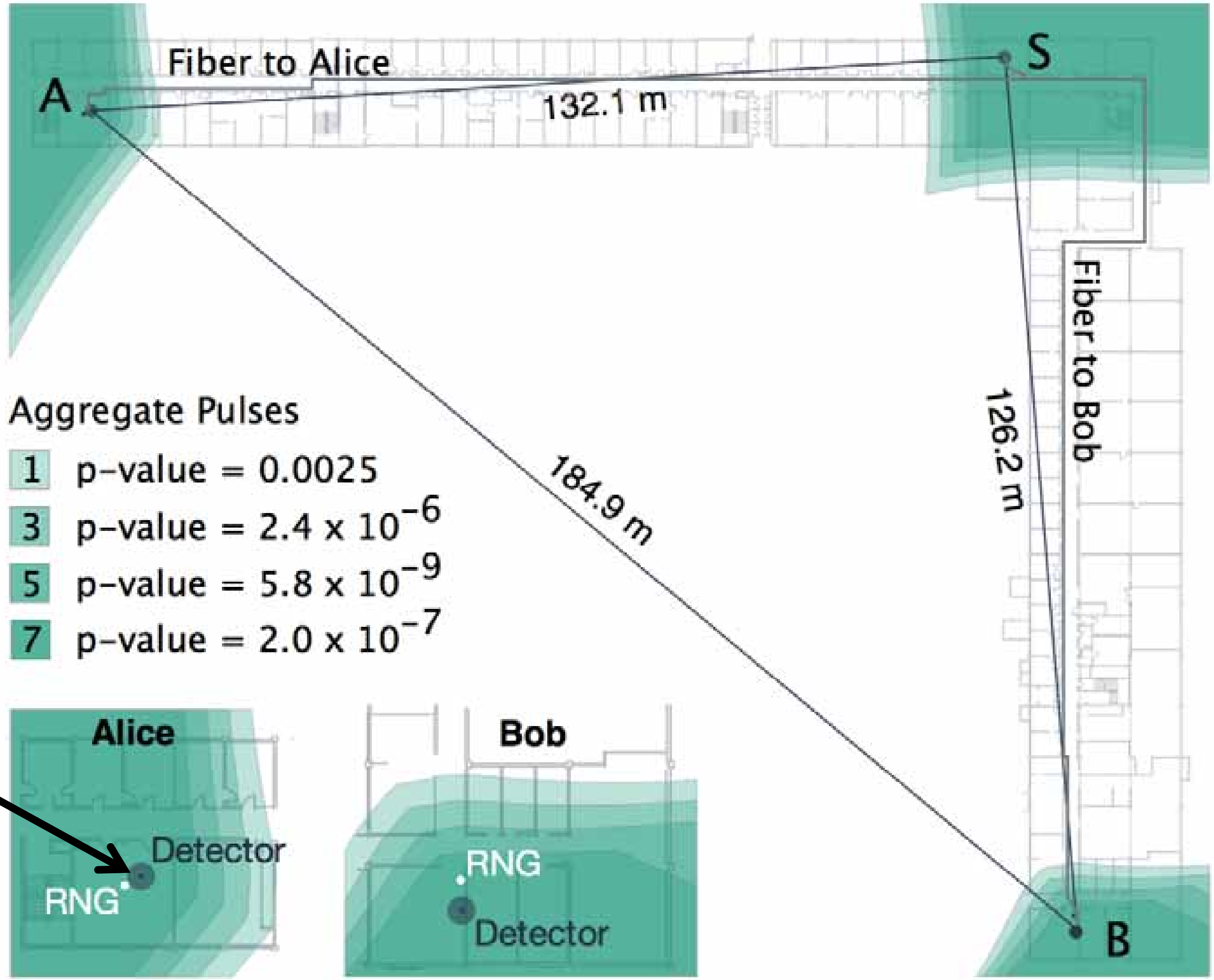
9.2m

7.3m

5.4m

3.5m

(±1m)

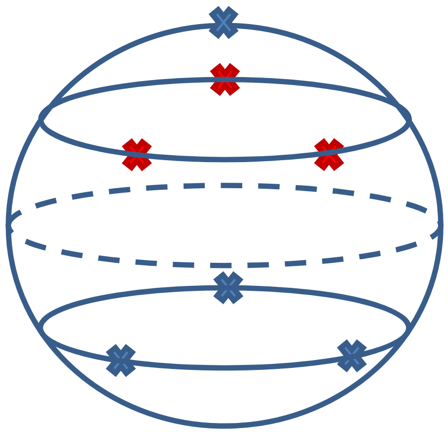


Conclusion

- "Loophole free" is minimizing assumptions, and testing those that can be tested
- Hypothesis testing should be used in future experiments
- Multiple RNG devices are used since RNG is a weak point in Bell tests
- P-values of 0.0025, $2.4x10^{-6}$, $5.8x10^{-9}$,$2.0x10^{-7}$ with spacetime separation 9.2m, 7.3m, 5.4m, 3.5m (±1m)
- Hard experiment, lucky to have 3 results
- Can't do randomness extraction yet (not enough data), but soon…
- Not the end of experimental Bell tests, so much more! (e.g., see the poster on our arXiv paper: B. G. Christensen, Y.-C. Liang, N. Brunner, N. Gisin, P. G. Kwiat, "Exploring the limits of quantum nonlocality with entangled photons", arXiv:1506.01649 [quant-ph] (2015).

QM exists in a complex Hilbert Space?

- Can we use a Bell inequality that has a bound if we only use 2-dimensions of the Poincare sphere?



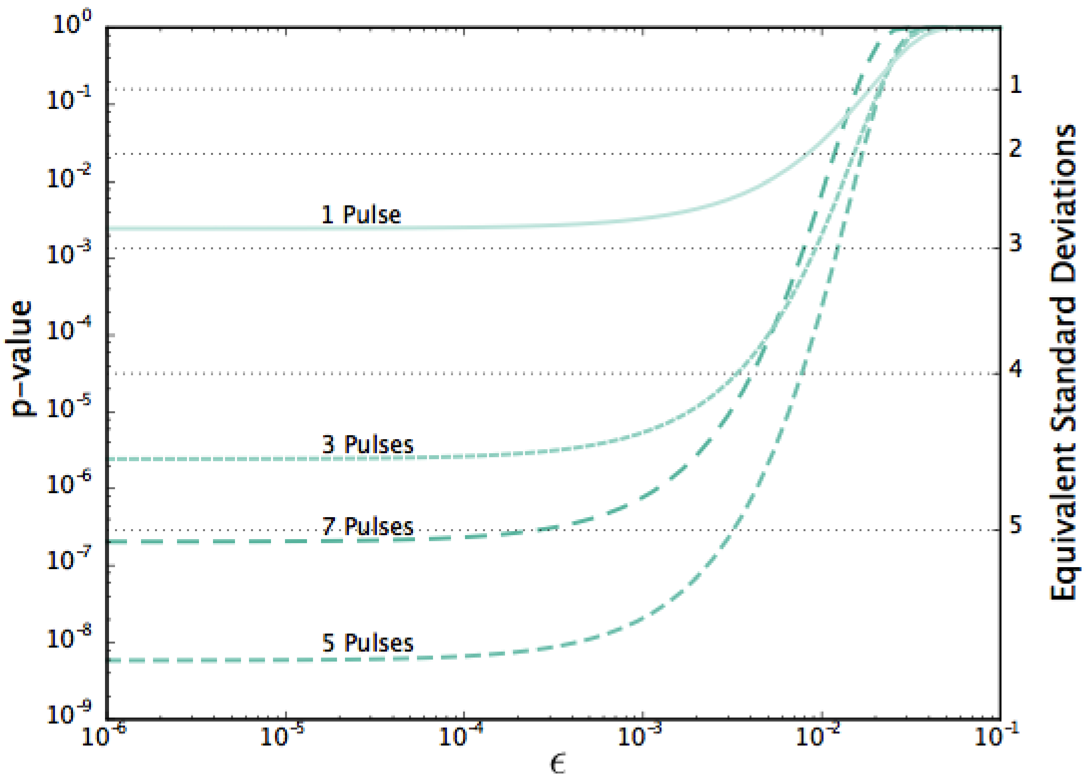
Alice's three vectors are mutually orthogonal
Bob's four vectors are the vertices of a tetrahedron

The Elegant Bell Inequality

$$\begin{aligned}&E(a_1,b_1)+E(a_2,b_1)+E(a_3,b_1)\\&E(a_1,b_2)-E(a_2,b_2)-E(a_3,b_2)\\&-E(a_1,b_3)+E(a_2,b_3)-E(a_3,b_3)\\&-E(a_1,b_4)-E(a_2,b_4)+E(a_3,b_4)\end{aligned} \leq 6$$

N. Gisin, Bell inequalities: many questions, a few answers. arXiv:0702021 [quant-ph] (2007).

RNG Bias



p−value
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
ϵ
1 Pulse
3 Pulses
7 Pulses
5 Pulses
1
2
3
4
5
Equivalent Standard Deviations