Preparing Entangled Photons for Experiments in Quantum Optics

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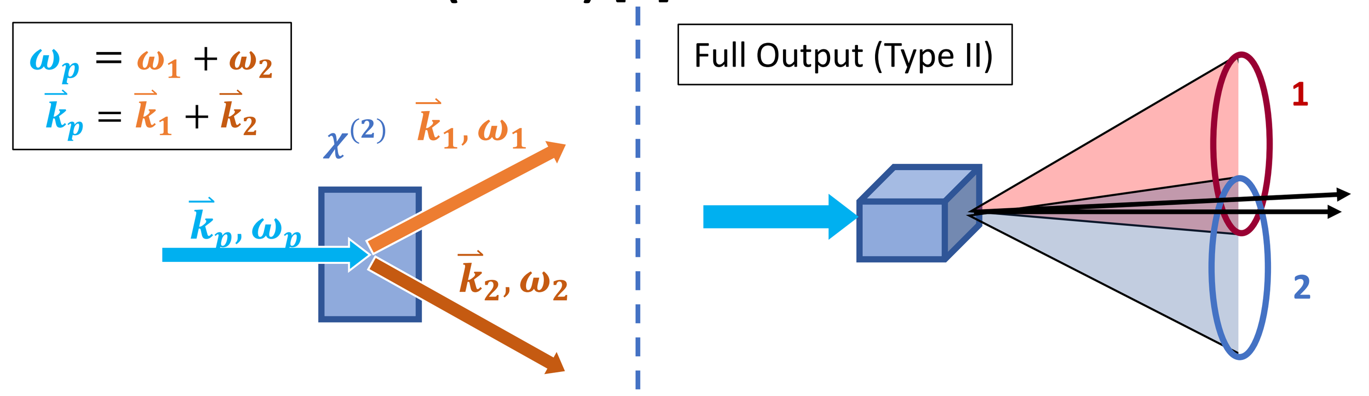
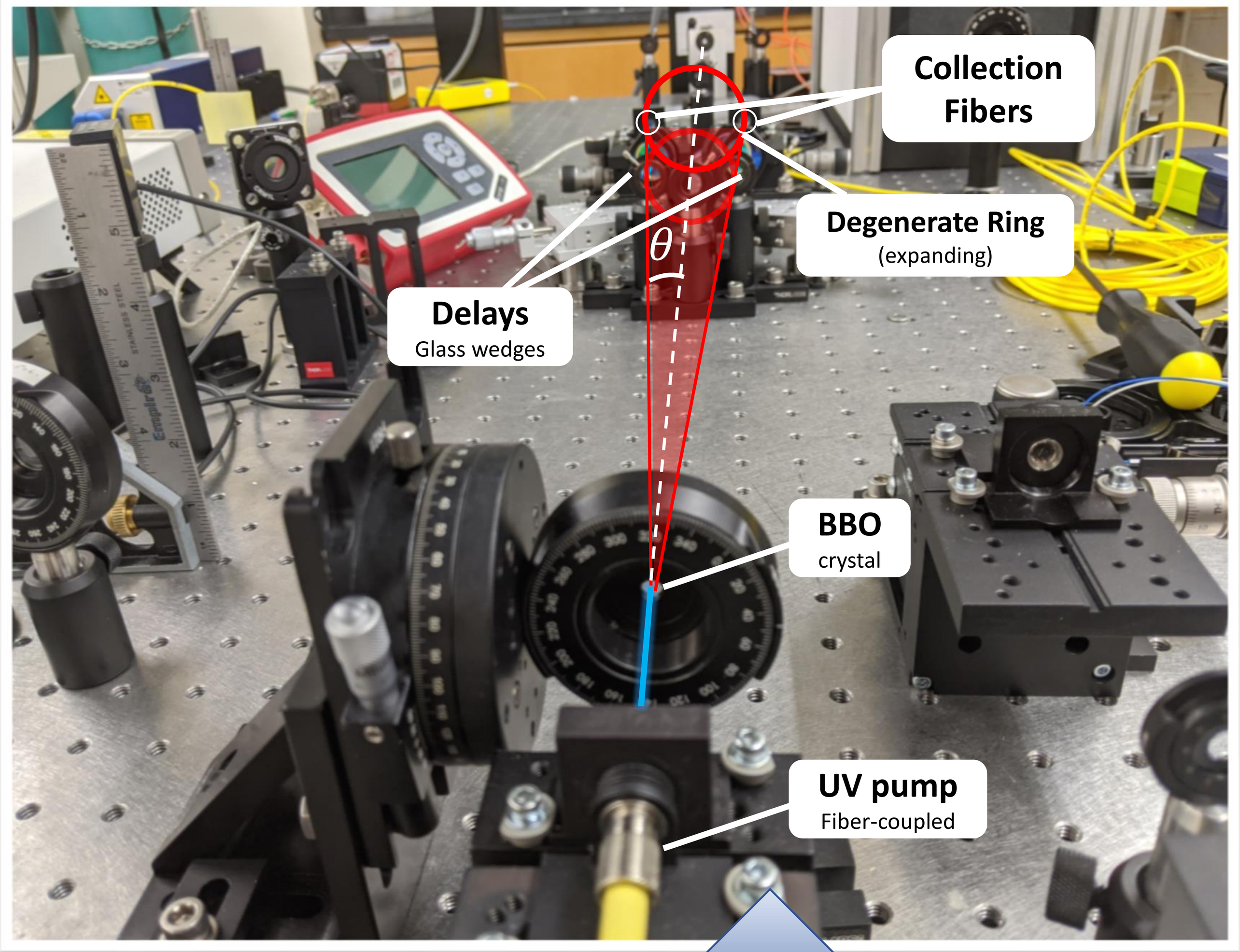
Introduction

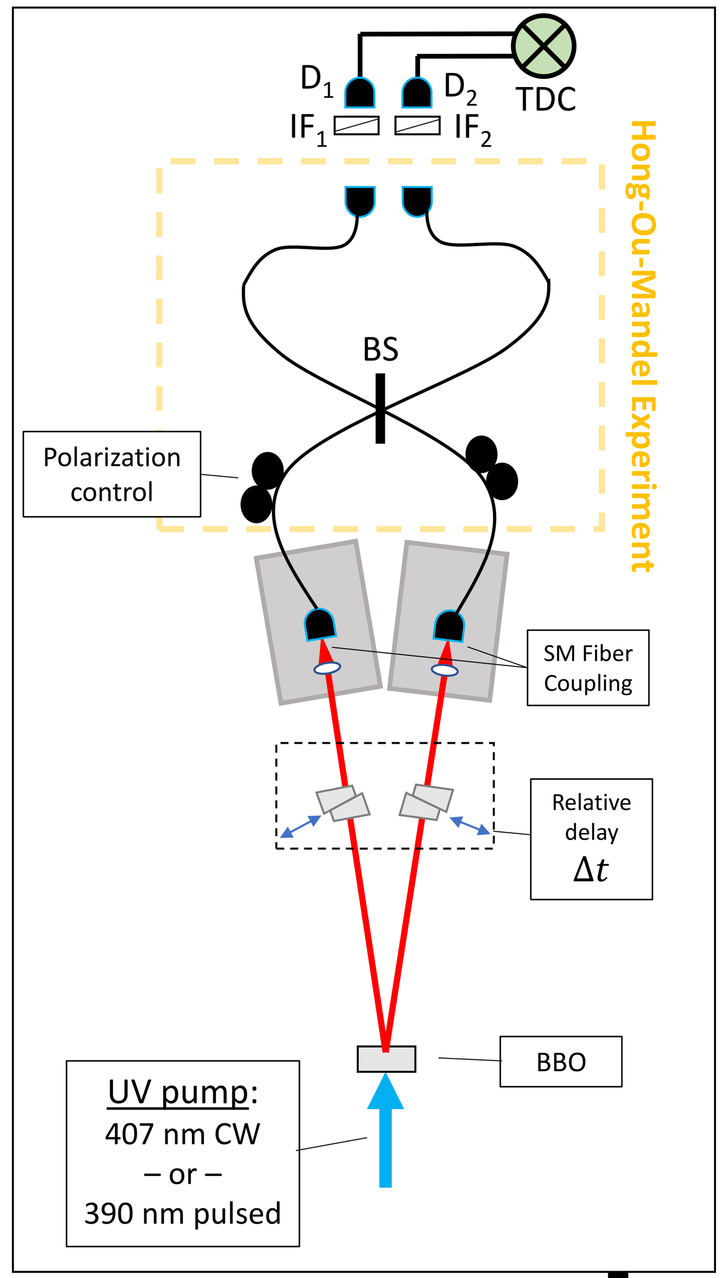
Entangled photon pairs are a fundamental resource for quantum optics & information research. To produce them in the lab, we use ***Spontaneous Parametric Down-Conversion*** **(SPDC)** [1].



Inside a nonlinear crystal, a high-energy pump photon essentially decays into two lower-energy photons, conserving energy and momentum (***phase-matching conditions***). The output is *entangled* in multiple degrees of freedom: time & frequency, space & momentum. We can calculate its precise shape from the phase-matching equations, and derive results like those below.

Correlated parts of the Type-I ring are focused into single-mode (SM) fibers, then directed through interference filters (IF) and finally single-photon detectors D_1 & D_2. A pair registers as a ***coincident count,*** measured by the time-to-digital converter (TDC). We measure rates on the order of 100 pairs/sec per mW of pump power, with 10 nm of bandwidth.





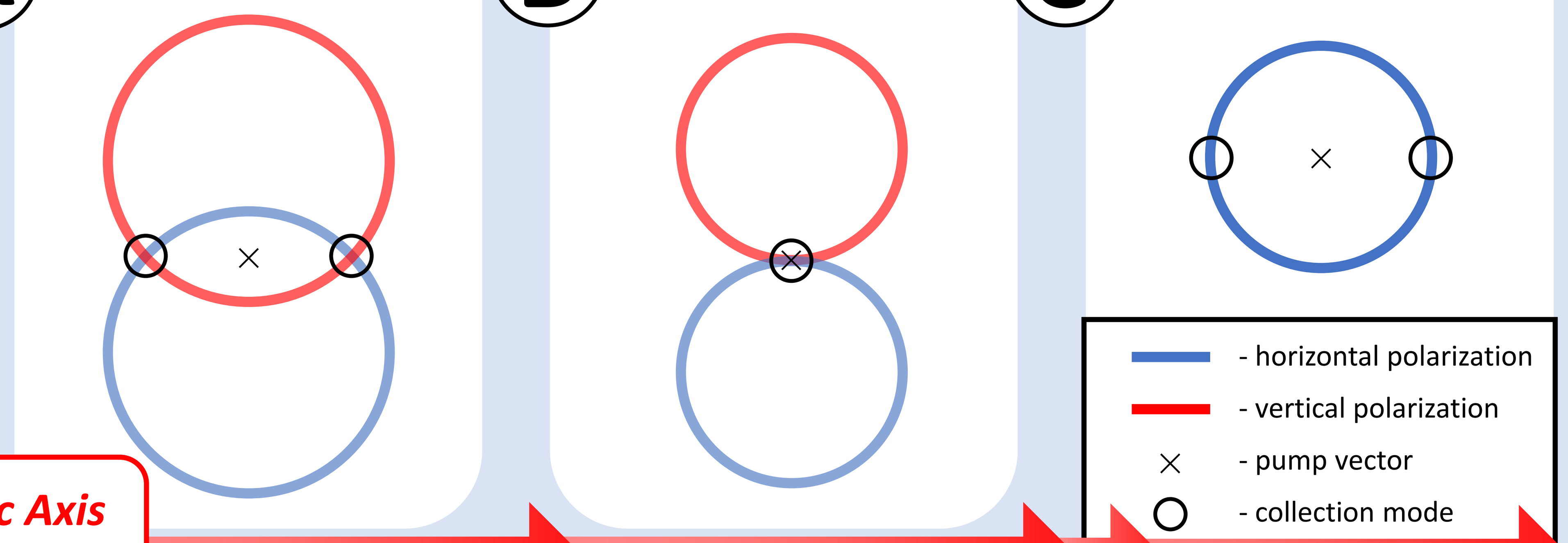
(λ, θ)

SPDC Output

A ***"Kwiat" Cones*** (Type II)

B ***Collinear*** (Type II)

C ***Non-collinear*** (Type I)

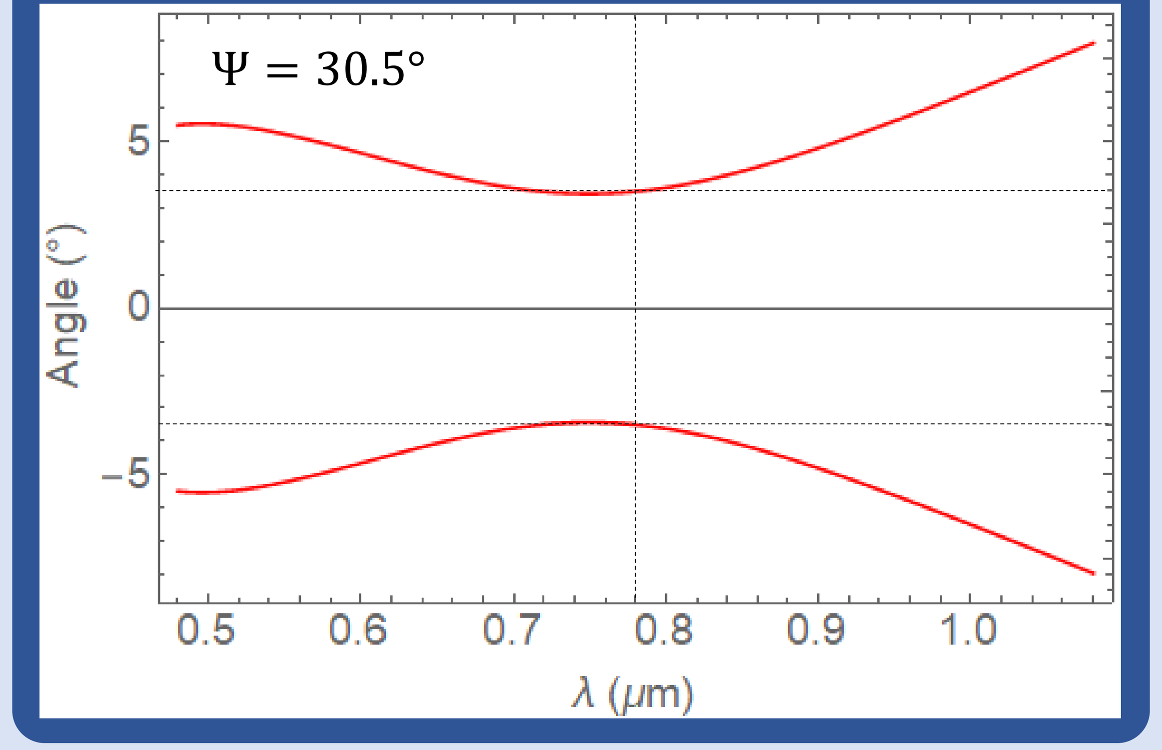


Optic Axis Angle: $\Psi = 44°$ → $\Psi = 43.5°$ → $\Psi = 30°$

Phase-matching types: ***Type I*** **-** output photons have the <u>same</u> polarization
Type II **-** they have <u>orthogonal</u> polarization

BBO can be used for either, depending on crystal orientation (OA angle). Output cross-sections are shown above for ***degenerate*** SPDC (V-polarized 390 nm pump). Type-II pairs (Fig. A & B) are also entangled in polarization.

Non-collinear Type I Tuning Curve

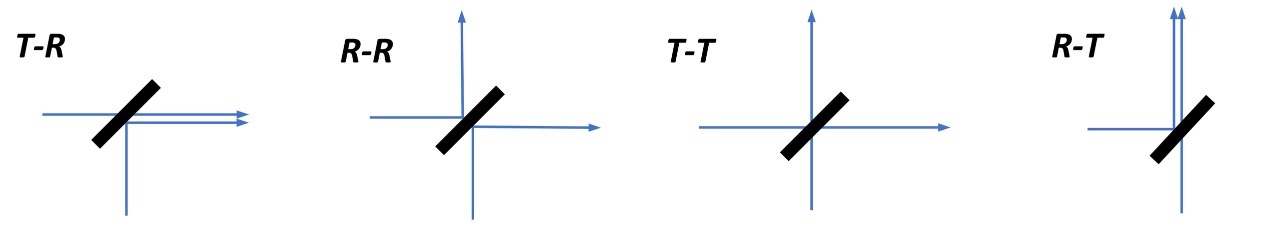


A ***tuning curve*** shows output angle as a function of wavelength. Degenerate pairs ($\lambda = 780$ nm) exit symmetrically ($\theta = \pm 3.5°$). If we are interested in non-degenerate pairs, the above plot says they mostly lie outside the Type-I degenerate ring (Fig. C).

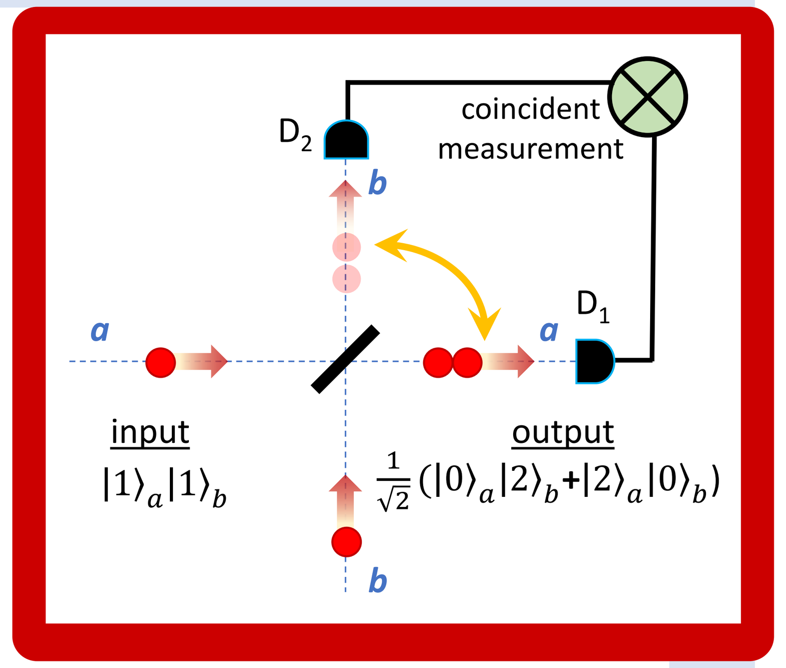
Two-photon Interference

Let's put our photon pairs to the test!

What happens when two single photons enter a 50/50 beam-splitter? We might expect one of 4 outcomes (*T*: transmitted, *R*: reflected)…



…with equal probability. But instead, we observe photons "bunching" together, always exiting the same way! How?



This is not "bunching," but destructive interference between ***indistinguishable alternatives*** to a detection event [2]. We can see this in a simple Fock-state model: *T-R* and *R-T* amplitudes cancel!

$$|1\rangle_a|1\rangle_b = \hat{a}^\dagger\hat{b}^\dagger|0\rangle_a|0\rangle_b \xrightarrow{BS} \frac{1}{2}(\hat{a}^\dagger + i\hat{b}^\dagger)(i\hat{a}^\dagger + \hat{b}^\dagger)|0\rangle_a|0\rangle_b$$
$$= \frac{1}{2}[i(\hat{a}^\dagger)^2 + \hat{a}^\dagger\hat{b}^\dagger - \hat{b}^\dagger\hat{a}^\dagger + i(\hat{b}^\dagger)^2]|0\rangle_a|0\rangle_b$$

Zero!

The interfering terms both result in a ***coincident count.*** If detectors fire simulataneously, we have no ***distinguishing information*** between these possibilities (T-R or R-T). Distinguishability destroys interference, and could come from differences in frequency, polarization, timing (relative delay), etc.

Experiment:

We vary the relative delay between the photons by Δt, and count coincidences R_c.

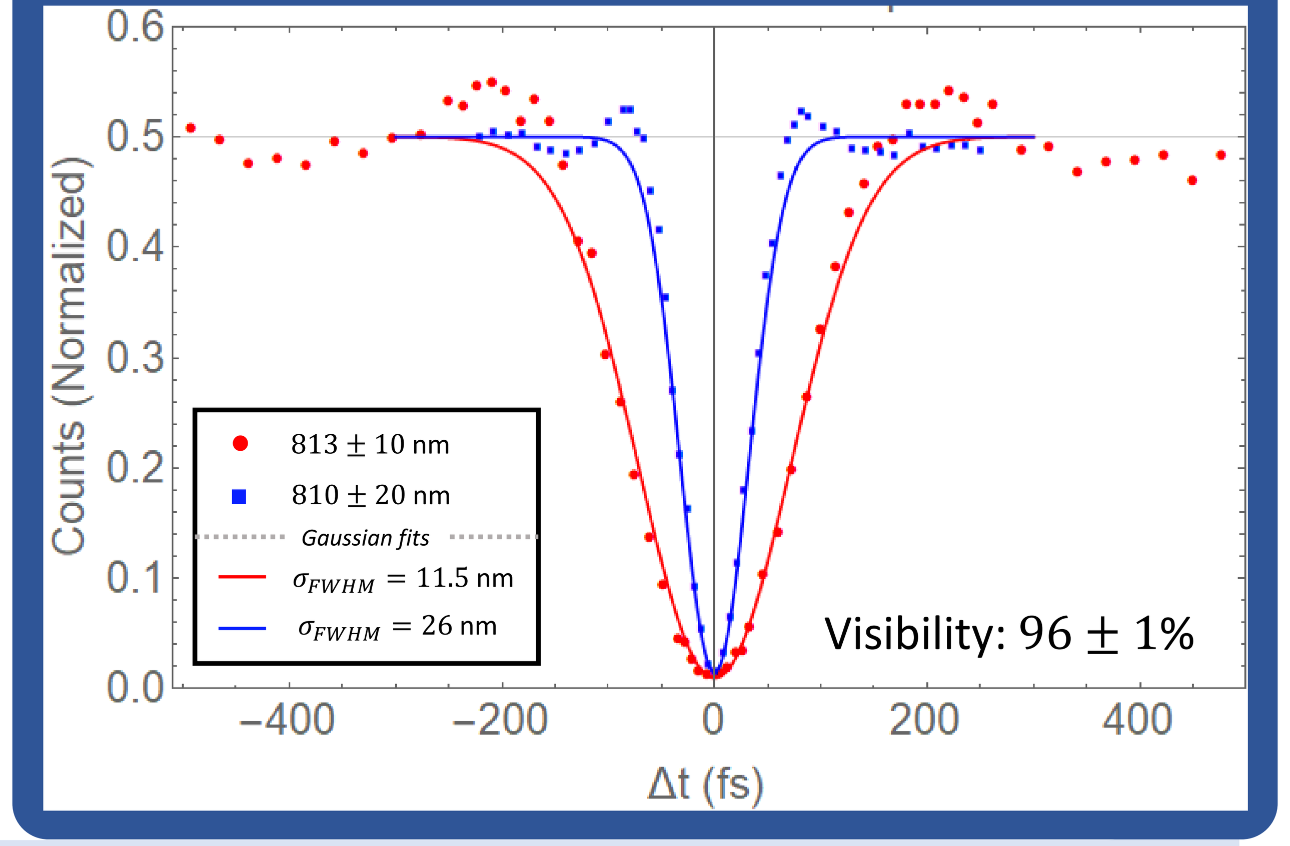
$\lvert\Delta t\rvert$	decreases	⬇
indistinguishability	increases	⬆
R_c	decreases	⬇

The shape of this "dip" depends on the filter bandwidth σ. For gaussian filters [3]:

$$R_c \propto 1 - e^{-(\sigma\Delta t)^2/2}$$

At the right, deviations between data and fits can be attributed to non-gaussian filters.

Hong-Ou-Mandel "Dip" - 407 nm CW pump



References

[1] Yanhua Shih, "Entangled Biphoton Source – Propoerty and Preparation," Rep. Prog. Phys. 66 1009 (2003)

[2] T. B. Pittman, D. V. Strekalov, A. Migdall, M. H. Rubin, A. V. Sergienko, and Y. H. Shih, "Can two-photon interference be considered the interference of two photons?" Phys. Rev. Lett. **77**, 1917 (1996)

[3] C. K. Hong, Z. Y. Ou, and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference," Phys. Rev. Lett. **59**, 2044 (1987)