Statistics of Heralded Single Photon Sources in Spontaneous Parametric Downconversion

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Outline

- Single Photon Sources (SPS)
- Heralded Single Photon Sources (HSPS) and Spontaneous Parametric Downconversion (SPDC)
- Statistics of classical and non-classical sources of light

- Observation of sub-Poissonian statistics in SPDC - HSPS
- Study of second order correlation function

Single Photon Sources

- **Why Single Photon Sources?**

- Photon qubits : light-speed, loss-less, easy to manipulate
- Quantum Cryptography protocols demand Single Photon Sources
- generation of truly random numbers

- **Single Photon Sources**

- elementary excitation state of Em field, monochromatic, on-demand – Quantum dots, Single atoms/ions, Color centres etc.
- 100% one photon, 0% multiple photons – Experimental challenge
- weak coherent pulses – but still not non-classical

  Solution : Heralded SPS!

Heralded Single Photon Sources

- **Interaction with Non linear media**

- Intense electric field causes redistribution of atoms, leaving them polarized

$$P_i = \varepsilon_0 \, (\chi_{ij}^{(1)} E_j + \chi_{ijk}^{(2)} E_j E_k + \chi_{ijkl}^{(3)} E_j E_k E_l + \; \ldots)$$

Heralded Single Photon Sources

- **Interaction with Non linear media**

- Two pump photons (ω) annihilate to give an output photon of 2ω

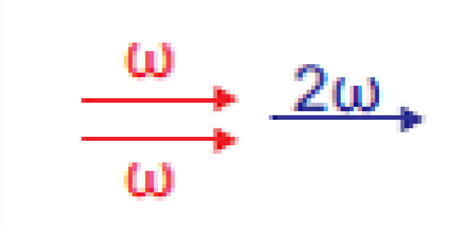
$$P_i = \varepsilon_0 \, (\chi_{ij}^{(1)} E_j + \chi_{ijk}^{(2)} E_j E_k)$$

for a pump field, $E = A\cos(\omega t)$

$$P = \varepsilon_0 \, (\chi^{(1)} A\cos(\omega t) + \frac{1}{2}\chi^{(2)} A^2 (1 + \cos(2\omega t)))$$

pump photon

upconverted photons



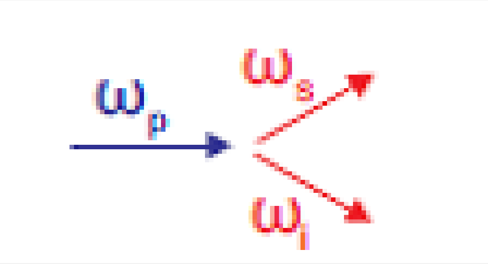
- Second Harmonic Generation

from ω to 2ω

Heralded Single Photon Sources

- **Spontaneous Parametric Down Conversion**

- Pumping a crystal with $\chi^{(2)}$ nonlinearity generates a pair of signal and idler photons
- destruction of one photon (2ω) into two photons (ω).



- Down Conversion

OBSERVATION OF SIMULTANEITY IN PARAMETRIC PRODUCTION OF OPTICAL PHOTON PAIRS

David C. Burnham and Donald L. Weinberg
National Aeronautics and Space Administration Electronics Research Center, Cambridge, Massachusetts 02142
(Received 12 May 1970)

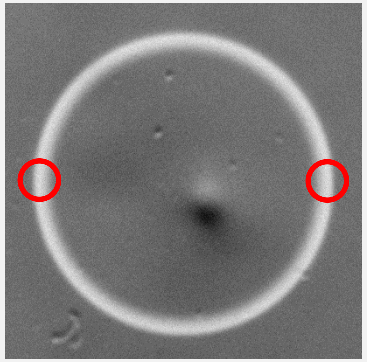
The quantum mechanical description of parametric fluorescence is the splitting of a single photon into two photons. This description has been verified by observing coincidences between photons emitted by an ammonium dihydrogen phosphate crystal pumped by a 325-nm He-Cd laser. The coincidence rate R_C decreases to the calculated accidental rate [$<0.03R_C$(max)], unless the two detectors are arranged to satisfy energy and momentum conservation and have equal time delays.

Heralded Single Photon Sources

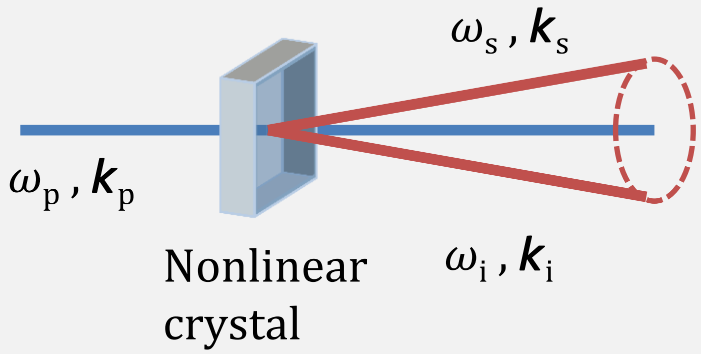
- **More on Spontaneous Parametric Down Conversion**

interaction Hamiltonian should take the form,

$\hat{H}_{int} \sim \chi^{(2)}\, \hat{a}_p \hat{a}^{\dagger}_s \hat{a}^{\dagger}_i$ + h.c.



Type-I BiBO



$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$

$\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$

Phase Matching Condition

Photon Statistics

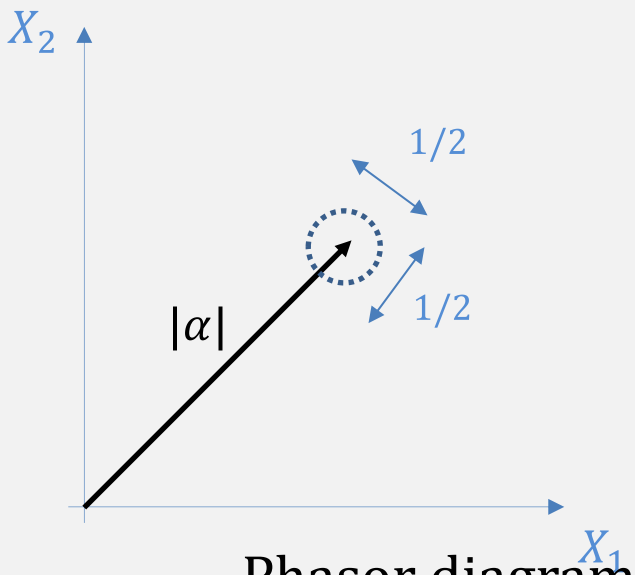
Electromagnetic field as a quantum harmonic oscillator.

Coherent State,

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

variance

$$(\Delta n)^2 = \langle\alpha|(\hat{n} - \bar{n})^2|\alpha\rangle = \bar{n}$$ - Poissonian



Phasor diagram

The Mandel Q-paramter,

$$Q \equiv \frac{\left\langle(\hat{a}^\dagger\hat{a}^\dagger\hat{a}\,\hat{a} - \langle\,\hat{a}^\dagger\hat{a}\rangle^2)\right\rangle}{\langle\hat{a}^\dagger\hat{a}\rangle} = \frac{\langle(\Delta n)^2\rangle}{\langle n\rangle} - 1 = \frac{\sigma^2}{\mu} - 1$$

Photon Statistics

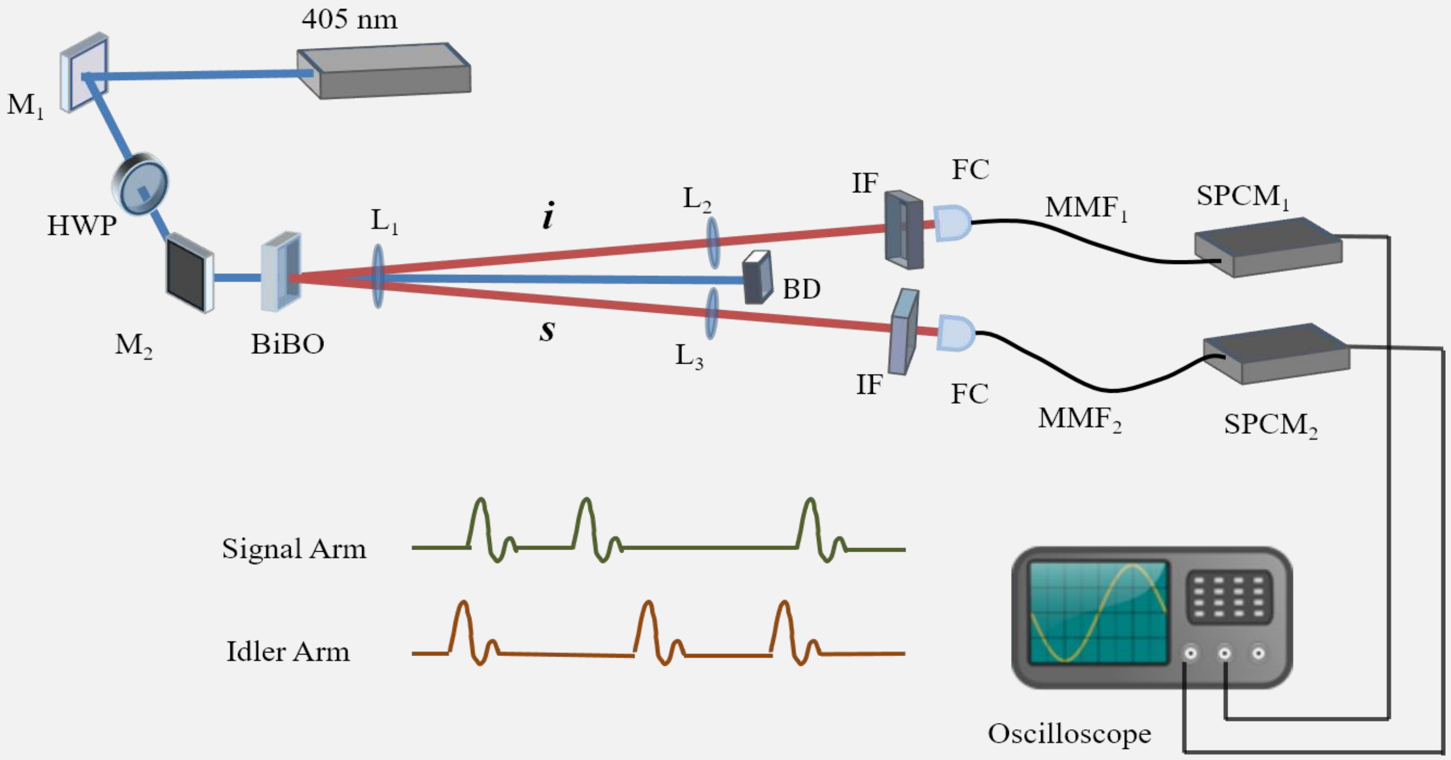
Type of Statistics	Examples	I (t)	Variance and Mean
Super-Poissonian	Thermal, Chaotic, or Incoherent	Time varying	$\sigma^2 > \mu$
Poissonian	Coherent light	constant	$\sigma^2 = \mu$
Sub-Poissonian	Non-classical	constant	$\sigma^2 < \mu$

Sub-Poissonian statistics is a clear signature of non-classical nature of our source

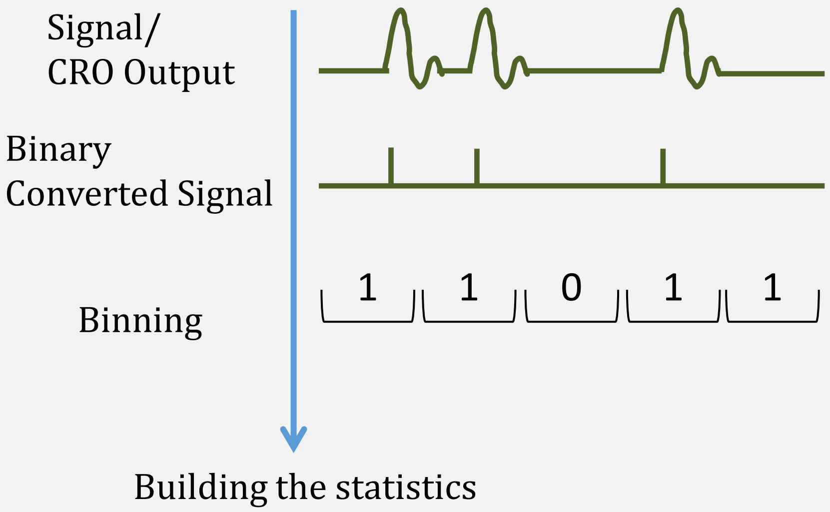
Building Number Statistics Using an Oscilloscope

The pair of photons generated in SPDC are coupled for maximum efficiency in signal (*s*) and idler (*i*) and the detection output is recorded using an oscilloscope.

- 405 nm -> two 810 nm
- coincidence window (τ_c =1 ns) and interference filters help in selecting out the corresponding pairs.
- Lenses and Fiber Couplers are used to efficiently couple these photons to MultiMode Fibres.

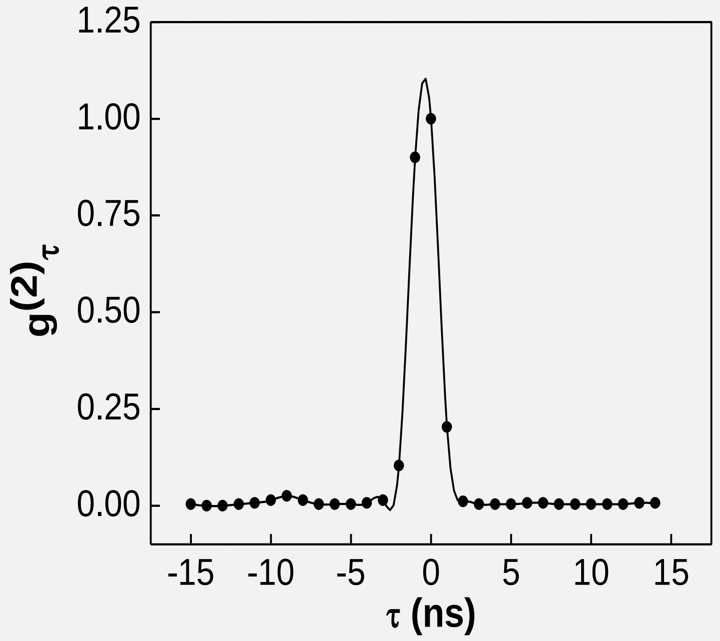


Building Number Statistics Using an Oscilloscope



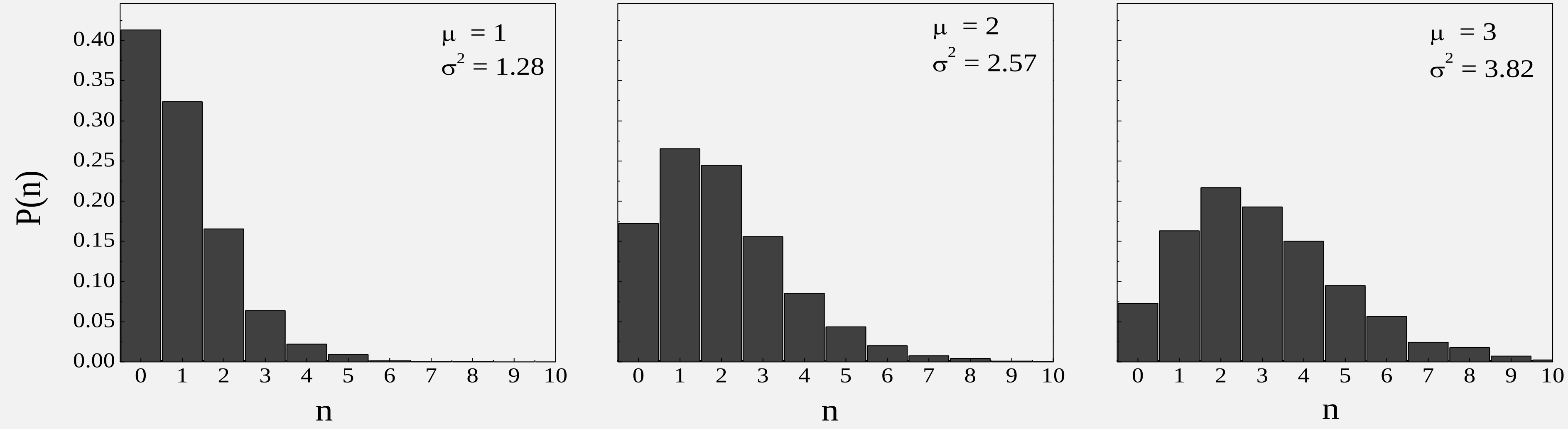
Bin size is varied in order to accommodate different average number of photons per bin.

The two-fold correlation between arms *i* and *s*, confirms that the twin photons are reaching the detectors simultaneously.

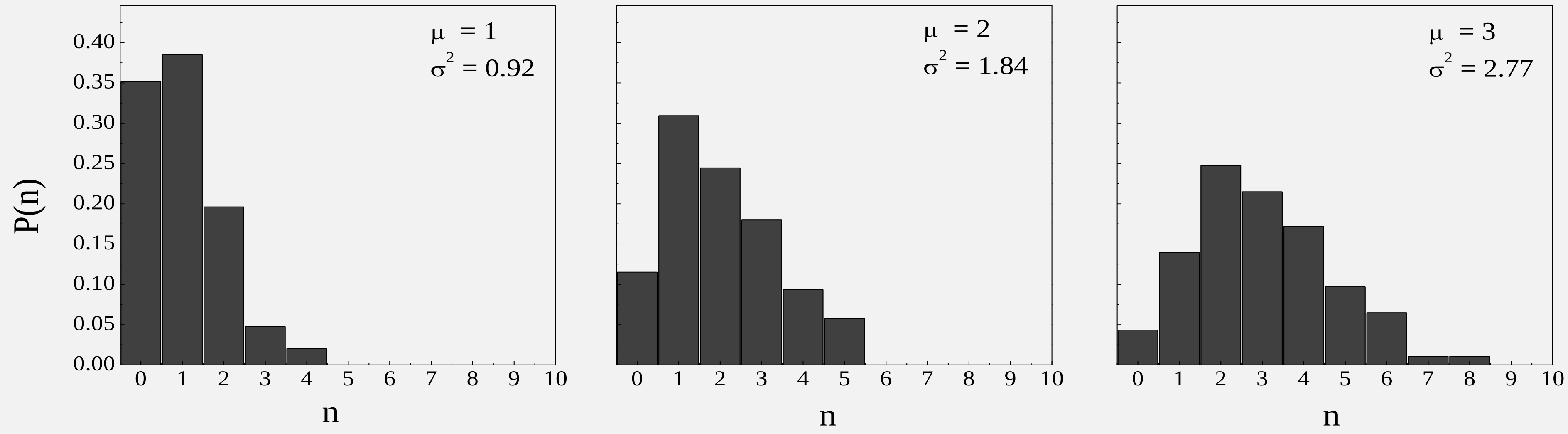


Building Number Statistics Using an Oscilloscope

Thermal light, Q = 0.28



Heralded single photon source, Q = -0.08



Building Number Statistics Using an Oscilloscope

- The number distribution for the parametric fluorescence from an individual arm shows super-Poissonian statistics with $Q = 0.28$.
- The heralded counts follow sub-Poissonian distribution with a significantly negative value for Mandel Q-parameter $(Q = -0.08)$.
- The number distributions follow the same statistics for different values of average photon numbers.

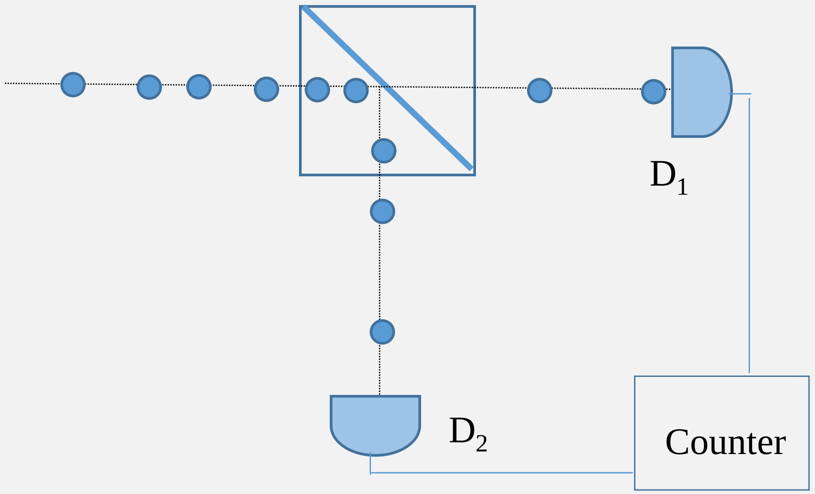
HBT and Second Order Correlation Function, $g^{(2)}_{(\tau)}$

classical second order correlation function,

$$g^{(2)}_{(\tau)} = \frac{\langle E^*(t)E^*(t+\tau)E(t+\tau)E(t)\rangle}{|\langle E^*(t)E(t)\rangle|^2}$$

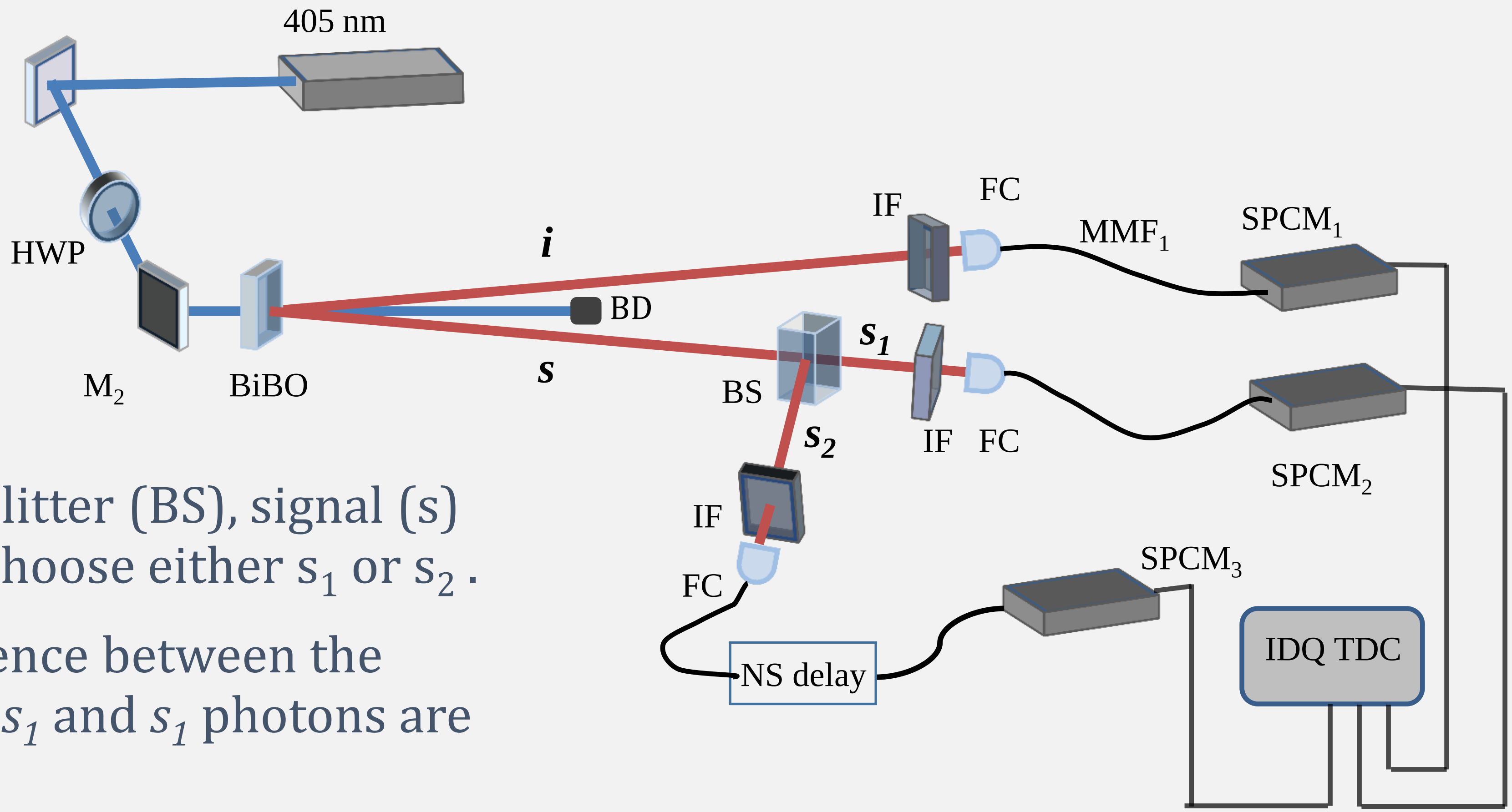
for photons, $$g^{(2)}_{(\tau)} = \frac{\langle n_1(t)\ n_2(t+\tau)\rangle}{\langle n_1(t)\rangle\langle n_2(t+\tau)\rangle}$$

$$g^{(2)}_{(0)} = \frac{\left\langle(\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}\right\rangle}{\langle\hat{a}^\dagger\hat{a}\rangle\langle\hat{a}^\dagger\hat{a}\rangle} = 1 + \frac{\langle(\Delta\hat{n})^2\rangle - \langle\hat{n}\rangle}{\langle\hat{n}\rangle^2}$$



- for coherent sources, $g^{(2)}_{(\tau)} = 1$ $g^{(2)}_{(0)} = 1$
- for thermal sources, $g^{(2)}_{(\tau)} > 1$ $g^{(2)}_{(0)} = 2$
- for single photon sources, $g^{(2)}_{(\tau)} < 1$ $g^{(2)}_{(0)} = 0$

Second Order Correlation Function, $g^{(2)}(\tau)$



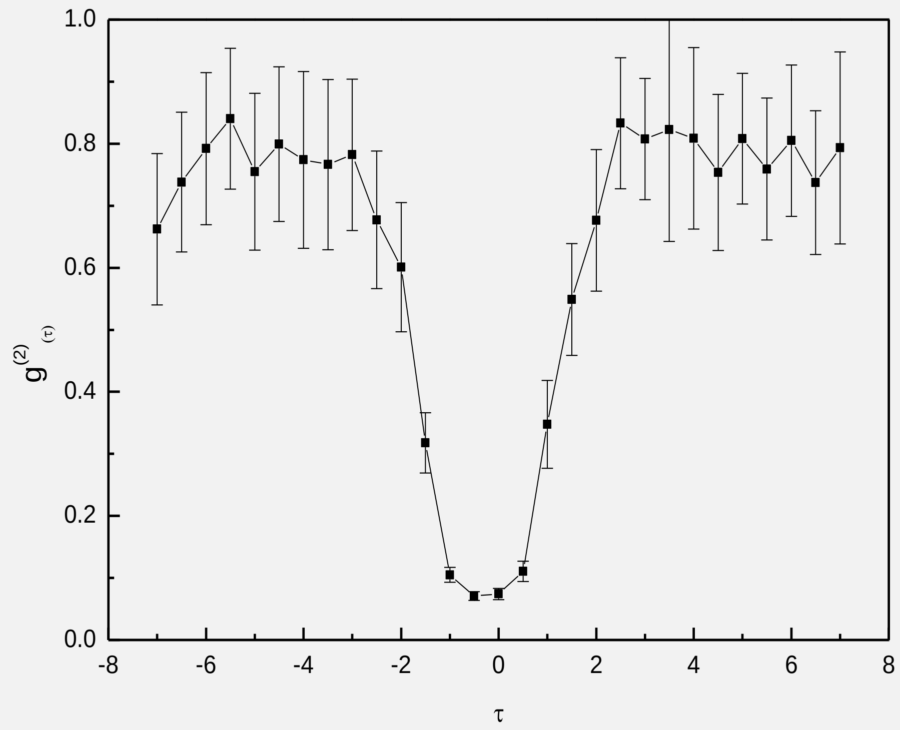
- at the beamsplitter (BS), signal (s) photons will choose either s_1 or s_2 .
- triple coincidence between the detection of i, s_1 and s_1 photons are recorded.
- $g^{(2)}{}_{(i,s1,s2)} = \frac{C_{i,s1,s2}}{C_{i,s1} C_{i,s2}} * R$

$C_{i,s}$ – *coincidence counts between i & s*

R – *pair production rate*

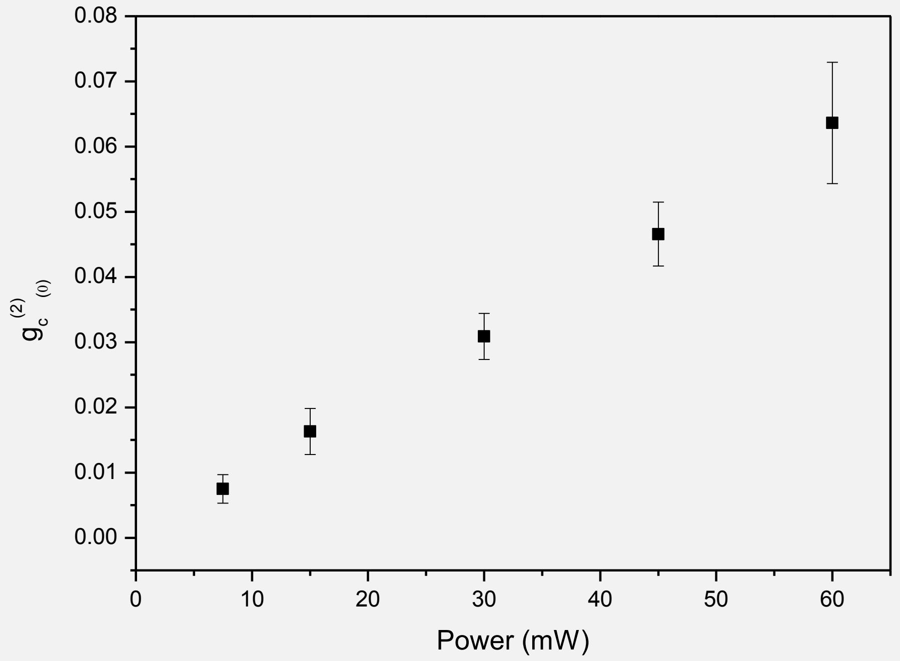
Second Order Correlation Function, $g^{(2)}_{(\tau)}$

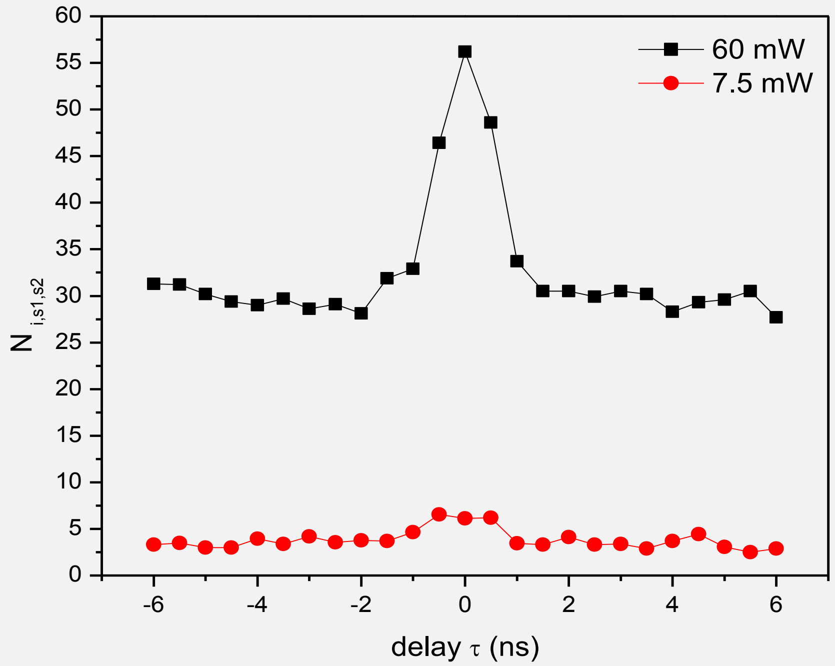
- Second order correlation function, $g^{(2)}_{(\tau)}$ is determined for *signal (s)* photons conditioned by the detection of *idler (i)* photons.
- $g^{(2)}_{(\tau)}$ for the heralded single photon source shows the expected HBT dip at zero delay.
- $g^{(2)}_{(o)} = 0.07$



anti-bunching has been confirmed, and quality of the single photon nature of the heralded source is determined.

Second Order Correlation Function, $g^{(2)}_{(\tau)}$





- $g^{(2)}_{(o)}$ improves from 0.064 to 0.0075 by reducing the power
- as a result of reduced number of multiphoton emissions

THANK YOU