Quantum Optics

Luis A. Orozco
Physics Colloquium
Marshall University, April 2019
Supported by DLS APS
www.jqi.umd.edu

- M. Born and E. Wolf, *Principles of Optics* Cambridge University Press, Cambridge, 1999, 7th expanded.

- L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* Cambridge University Press, Cambridge, 1995.

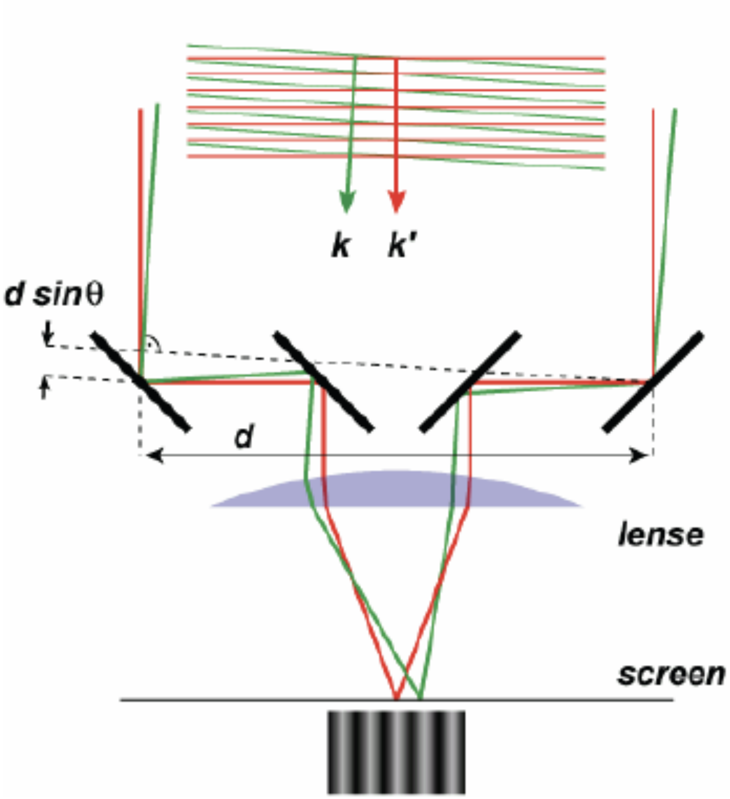
- E. Wolf, *Introduction to the Theory of Coherence and Polarization of Light* Cambridge University Press, Cambridge, 2007.

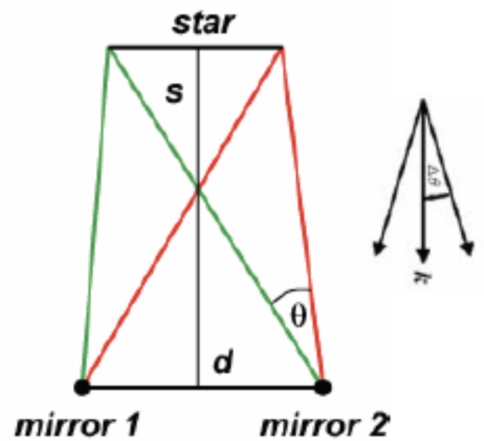
Michelson measures the diameter of a star

Michelson – Stellar Interferometer (1920)

measuring transverse spatial coherence (1st-order correlation function):

$$g^{(1)}(r_1, r_2) = \frac{\langle E(r_1)^* E(r_2)\rangle}{(\langle E(r_1)\rangle^2 \langle E(r_2)\rangle^2)^{1/2}}$$





interference pattern disappears for

$$d\,\theta_0 \simeq \lambda$$

extremely sensitive to

- *variations of atmospheric refraction index*
- *instabilities of the interferometer*

„problem“

$$I \sim \langle |E(0) + E(d)|^2 \rangle$$

$$\sim 1 + \mathrm{Re}\left(g^{(1)}(0,d)\right) \sim 1 + \cos((\mathbf{k} + \mathbf{k}')\,\mathbf{d}/2)\cos(kd\theta/2)$$

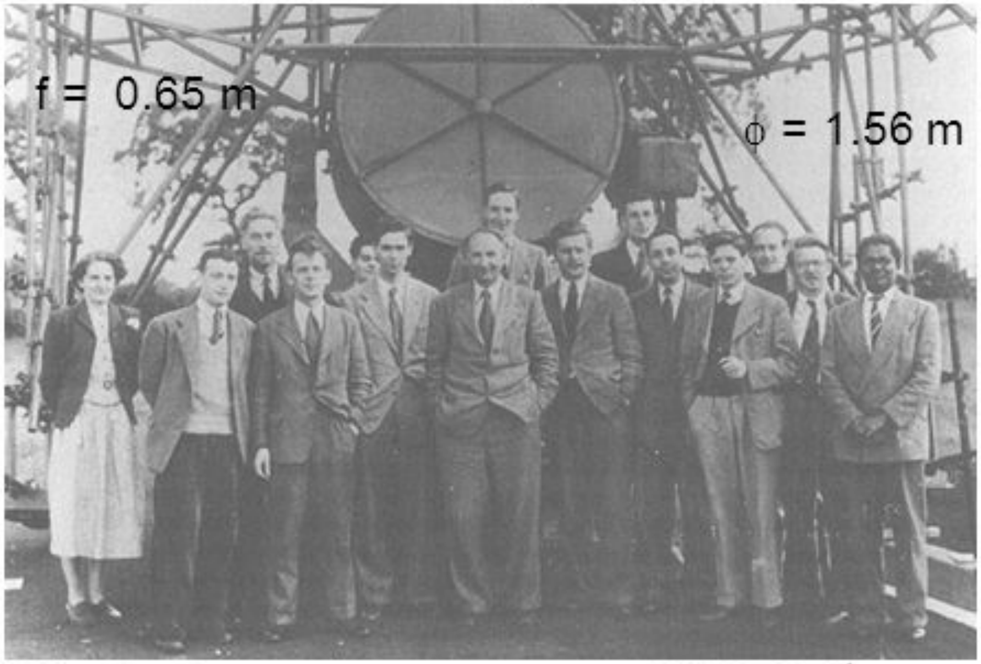
Handbury Brown and Twiss

Can we use intensity fluctuations, noise, to measure the size of a star? Yes. They were radio astronomers and had done it around 1952,

R. Hanbury Brown and R.Q. Twiss, “A New Type of Interferometer for Use in Radio Astronomy,” Phil. Mag. **46**, 663 (1954).

The Hanbury Brown Twiss stellar interferometer, Mk 1

R. Hanbury Brown & R. Q. Twiss,
A Test of a New Type of Stellar Interferometer on Sirius ,
Nature **178**, 1046-1053 (1956).



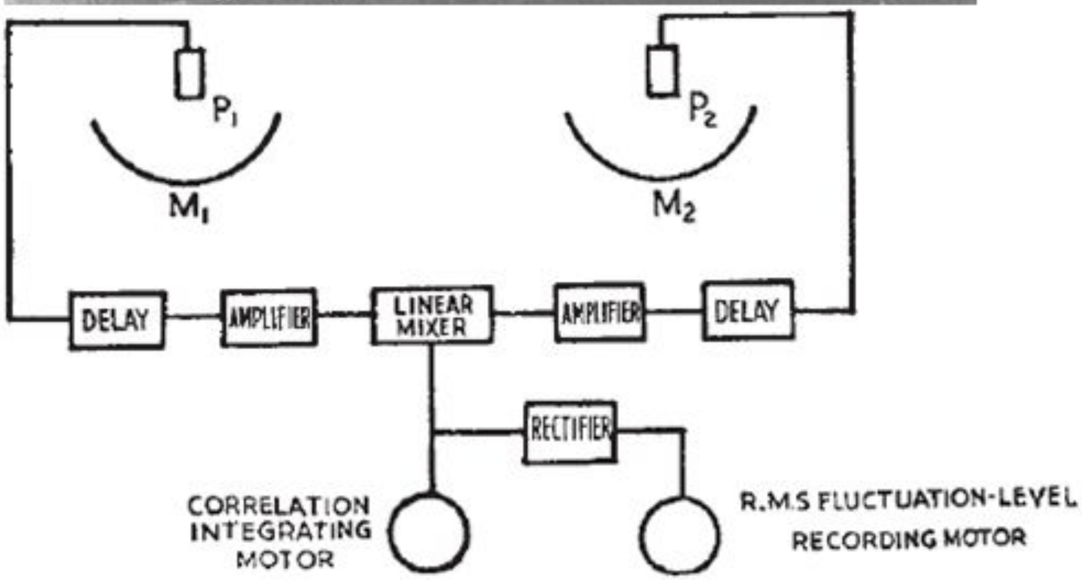


Fig. 1. Simplified diagram of the apparatus

Prediction from astrophysical theory is 0.0063”

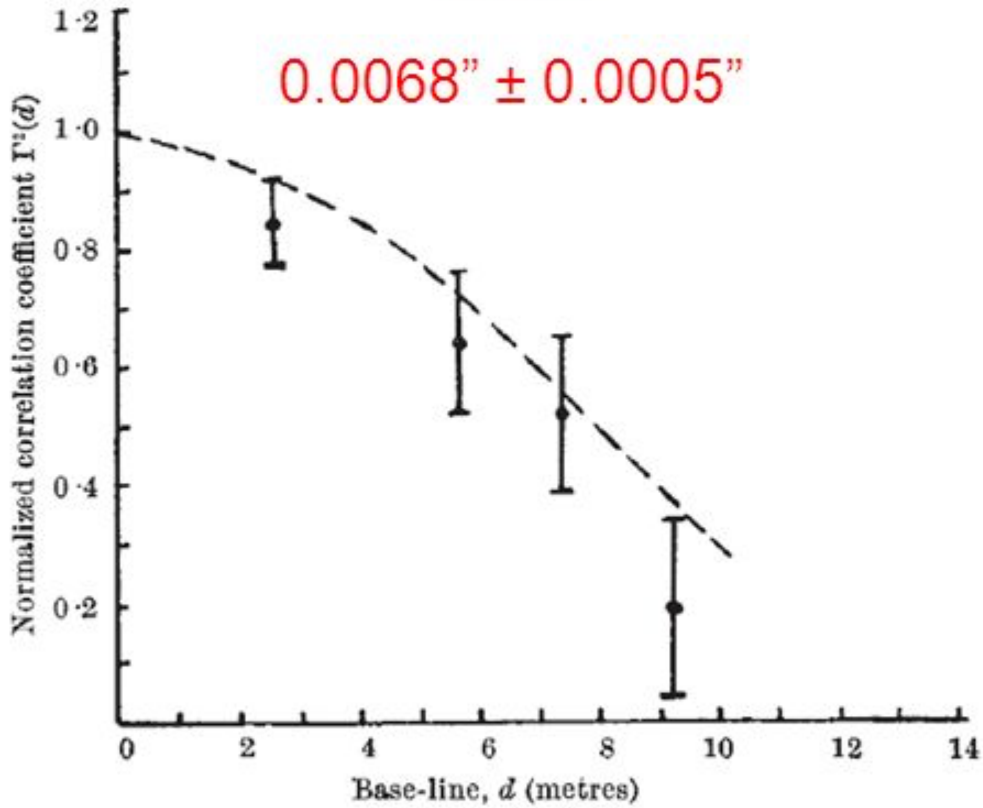
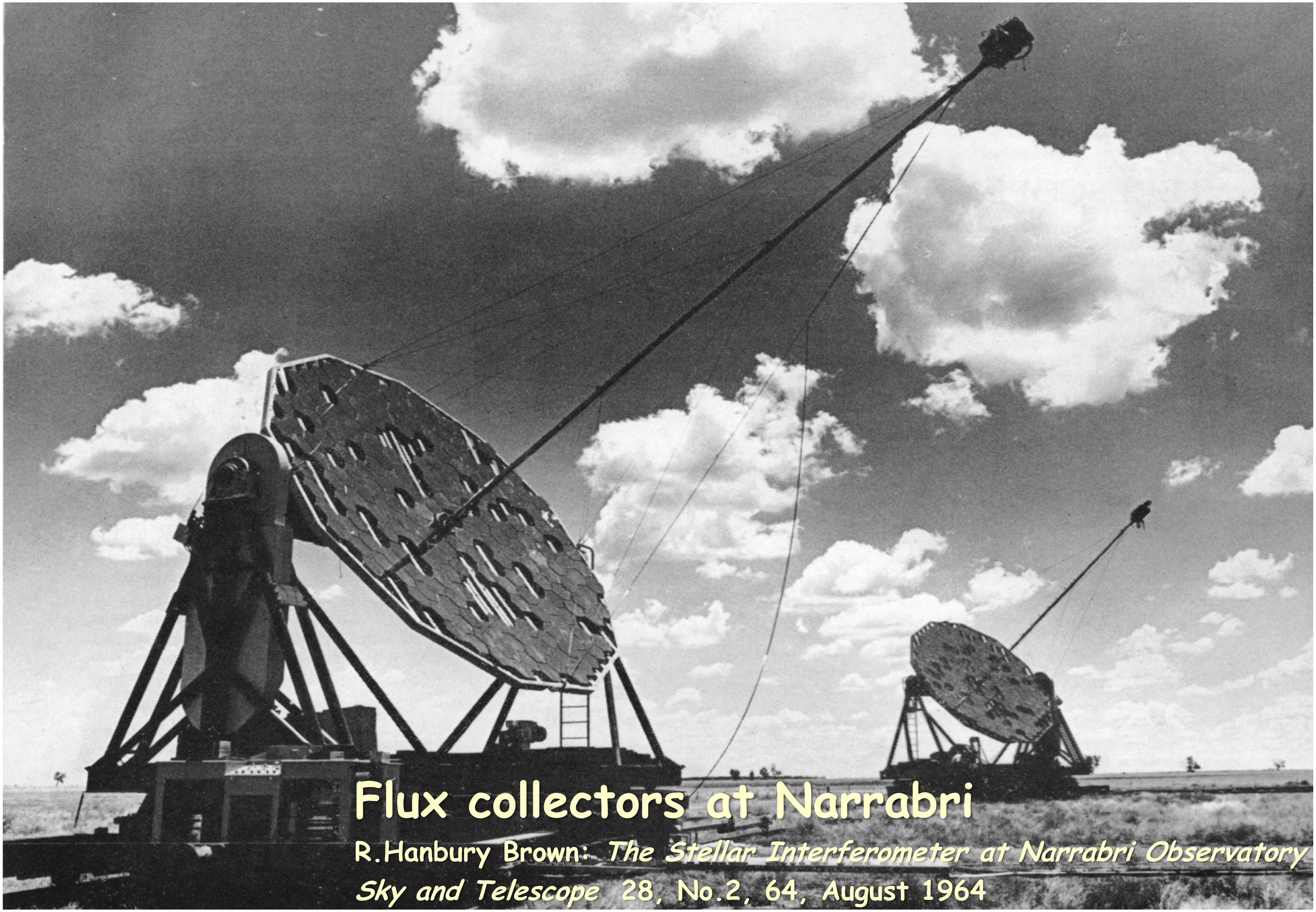


Fig. 2. Comparison between the values of the normalized correlation coefficient $\Gamma^2(d)$ observed from Sirius and the theoretical values for a star of angular diameter 0·0063″. The errors shown are the probable errors of the observations

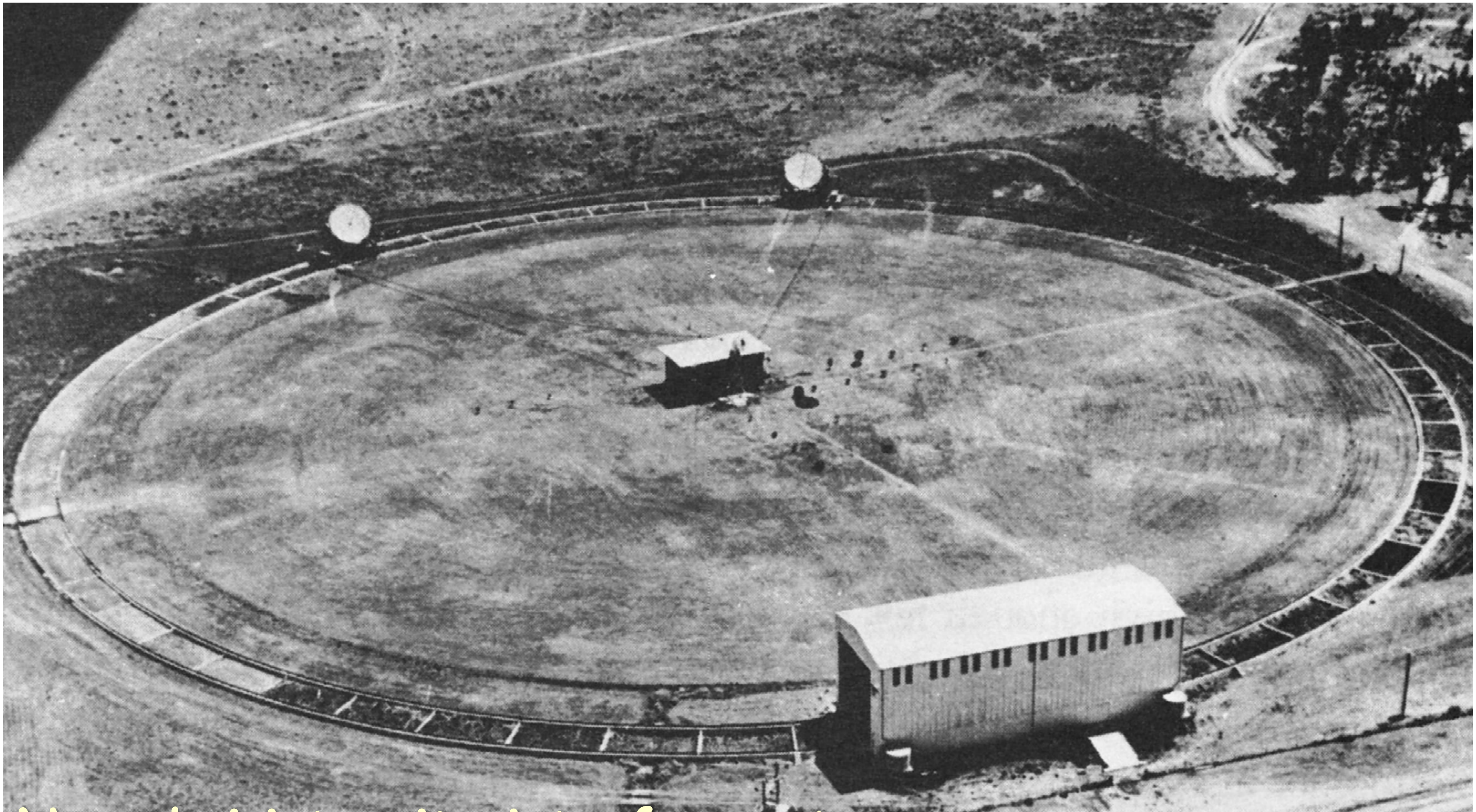
First measurement of stellar diameter in 30 years



Flux collectors at Narrabri

R.Hanbury Brown: *The Stellar Interferometer at Narrabri Observatory*

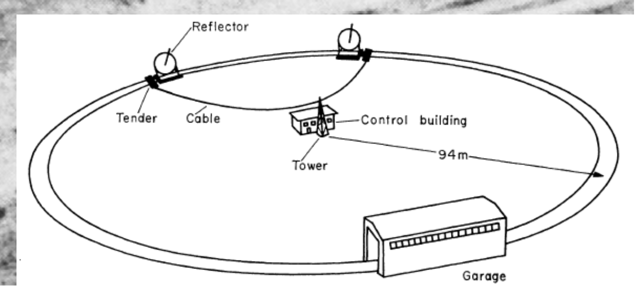
Sky and Telescope 28, No.2, 64, August 1964



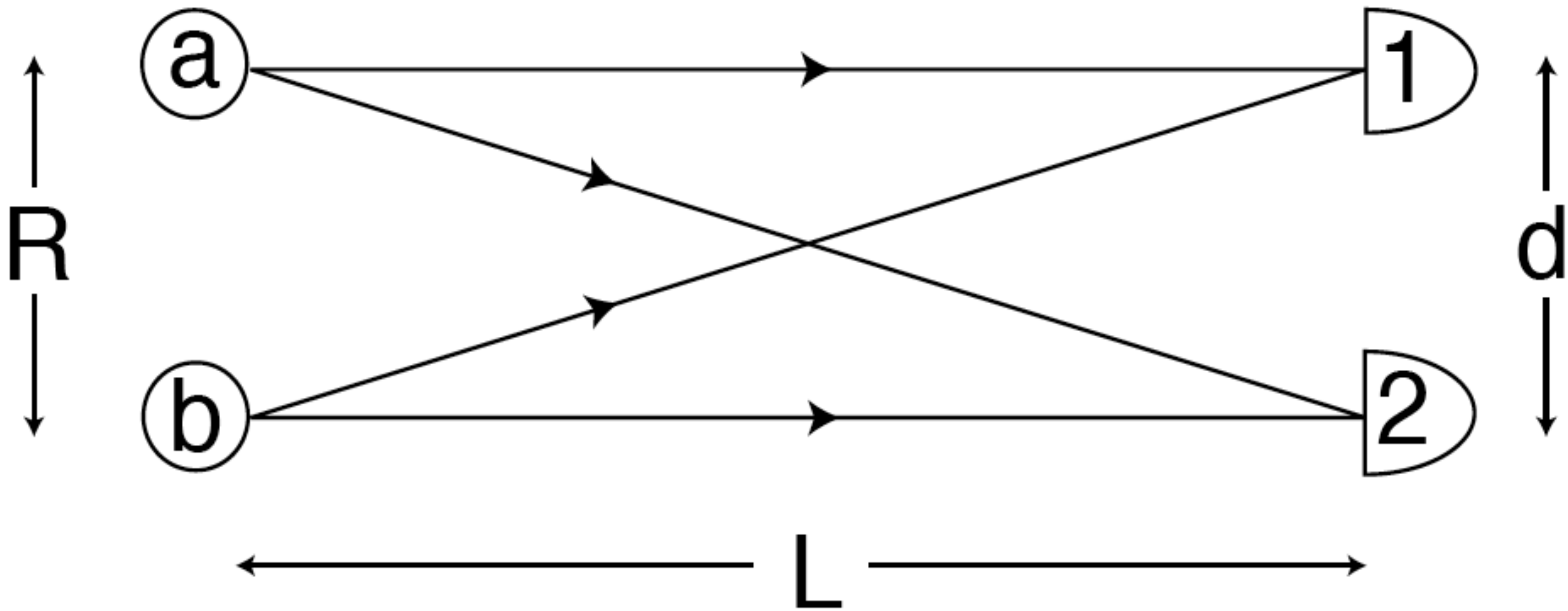
Narrabri intensity interferometer

with its circular railway track

R.Hanbury Brown: *BOFFIN. A Personal Story of the Early Days of Radar, Radio Astronomy and Quantum Optics* (1991)



The HBT controversy



The physics of Hanbury Brown–Twiss intensity interferometry: from stars to nuclear collisions.*

GORDON BAYM

Presented at the XXXVII Cracow School of Theoretical Physics, Zakopane, Poland.
May 30 - June 10, 1997.

Source a and b are within a Star. Can we measure the angular distance R/L~θ so that we could know the diameter?

Source a:

$$\alpha e^{ik|\vec{r}-\vec{r}_a|+i\phi_a}/|\vec{r}-\vec{r}_a|$$

Source b:

$$\beta e^{ik|\vec{r}-\vec{r}_b|+i\phi_b}/|\vec{r}-\vec{r}_b|$$

The amplitude at detector 1 from sources a and b is:

$$A_1 = \frac{1}{L}\left(\alpha e^{ikr_{1a}+i\phi_a} + \beta e^{ikr_{1b}+i\phi_b}\right)$$

And the intensity I_1

$$= \frac{1}{L^2}\left(|\alpha|^2 + |\beta|^2 + \alpha^* \beta e^{i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)} + \alpha\beta^* e^{-i(k(r_{1b}-r_{1a})+\phi_b-\phi_a)}\right)$$

The average over the random phases ϕ_a and ϕ_b gives zero

$$\langle I_1\rangle = \langle I_2\rangle = \frac{1}{L^2}\left(\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle\right)$$

And the product of the intensity of each of the detectors $<I_1><I_2>$ is independent of the separation of the detectors.

Multiply the two intensities and then average.

$$\langle I_1 I_2 \rangle = \langle I_1 \rangle \langle I_2 \rangle + \frac{2}{L^4}|\alpha|^2|\beta|^2 \cos\left(k(r_{1a} - r_{2a} - r_{1b} + r_{2b})\right)$$

$$= \frac{1}{L^4}\left[(|\alpha|^4 + |\beta|^4) + 2|\alpha|^2|\beta|^2(1 + \cos\left(k(r_{1a} - r_{2a} - r_{1b} + r_{2b})\right)\right].$$

$$g^{(2)} = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

$$= 1 + 2\frac{\langle|\alpha|^2\rangle\langle|\beta|^2\rangle}{(\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle)^2}\cos\left(k(r_{1a} - r_{2a} - r_{1b} + r_{2b})\right).$$

$$(L \gg R),\ k(r_{1a} - r_{2a} - r_{1b} + r_{2b}) \to k(\vec{r}_a - \vec{r}_b)\cdot(\hat{r}_2 - \hat{r}_1) = \vec{R}\cdot(\vec{k}_2 - \vec{k}_1)$$

This function changes as a function of the separation between the detectors.

$d = \lambda/\theta$ with $\theta = R/L$

Relation to the Michelson Interferometer

$$|A_1 + A_2|^2 = |A_1|^2 + |A_1|^2 + (A_1^* A_2 + A_1 A_2^*)$$

The term in parenthesis is the associated to the fringe Visibility (first order coherence) if we now take the square of the fringe visibility and average it:

$$\langle V^2 \rangle = 2\langle |A_1|^2 |A_2|^2 \rangle + \langle A_1^{*2} A_2^2 \rangle + \langle A_1^2 A_2^{*2} \rangle$$

$$\langle V^2 \rangle \rightarrow 2\langle I_1 I_2 \rangle$$

The solution of E. M. Purcell, *Nature* **178**, 1449 (1956).

Points to the work of Forrester as the frist real optical intensity correlation. A. T. Forrester, R. A. Gudmundsen and P. O. Johnson, "*Photoelectric Mixing of Incoherent Light,*" Phys. Rev. **99**, 1691 (1955).

Mentions that bosons tend to appear together

Does the calculation and relates it to the first order coherence.

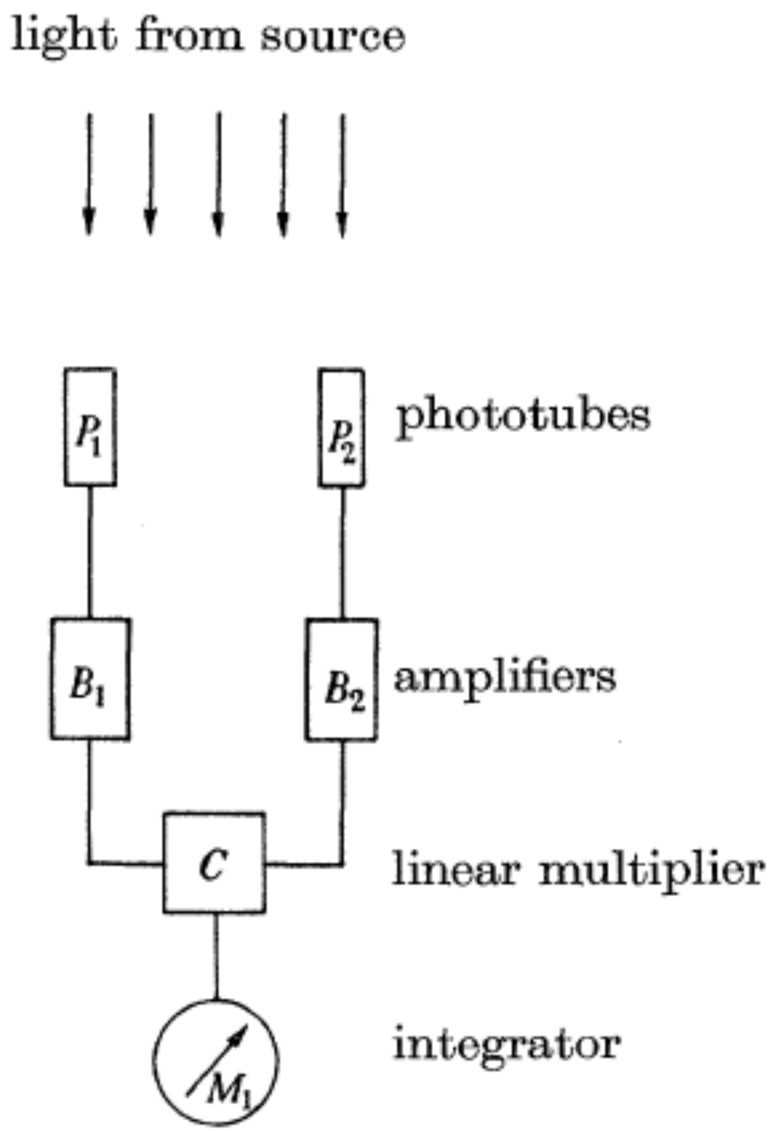


FIGURE 1. A simplified outline of an intensity interferometer.

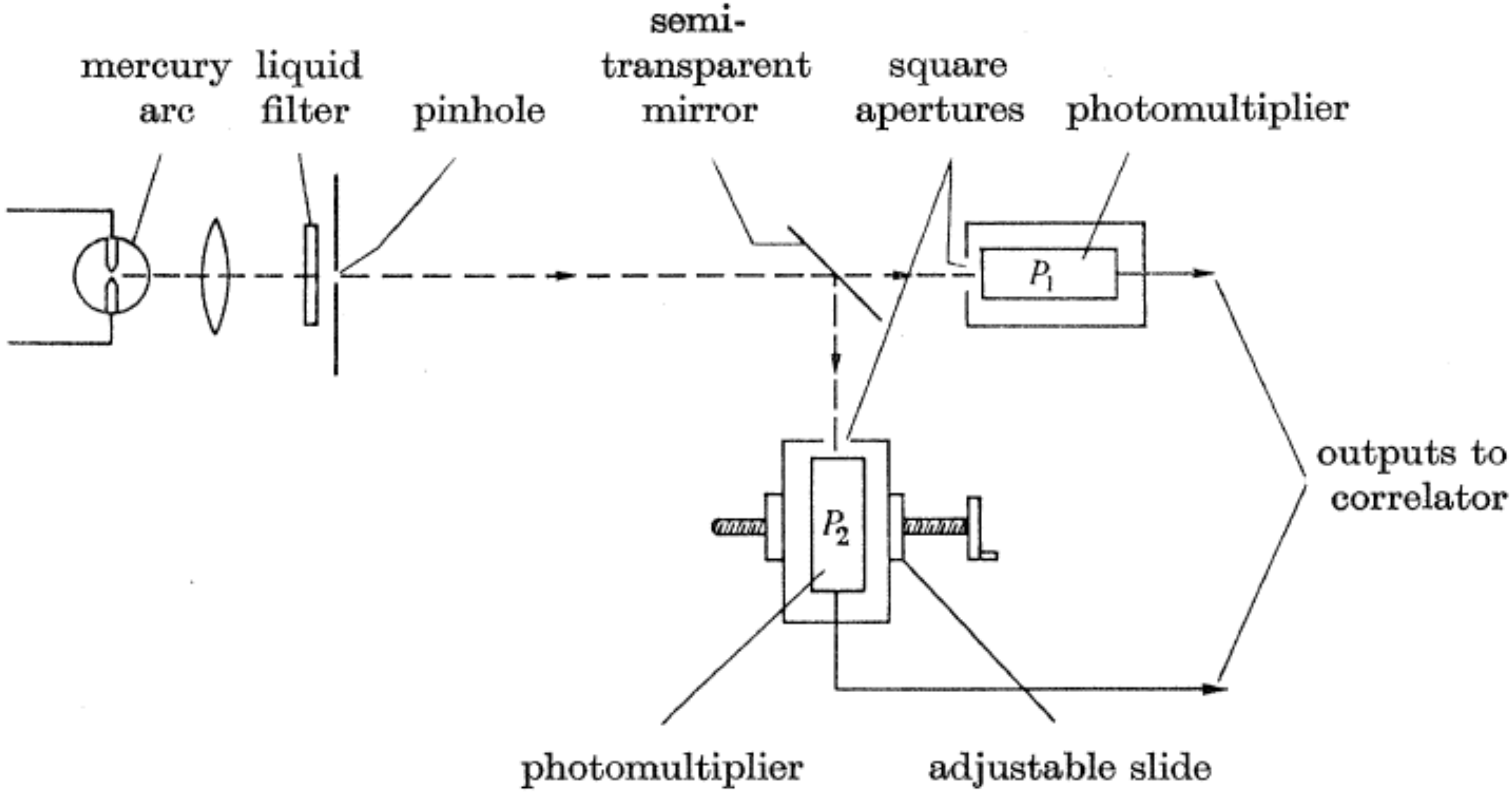
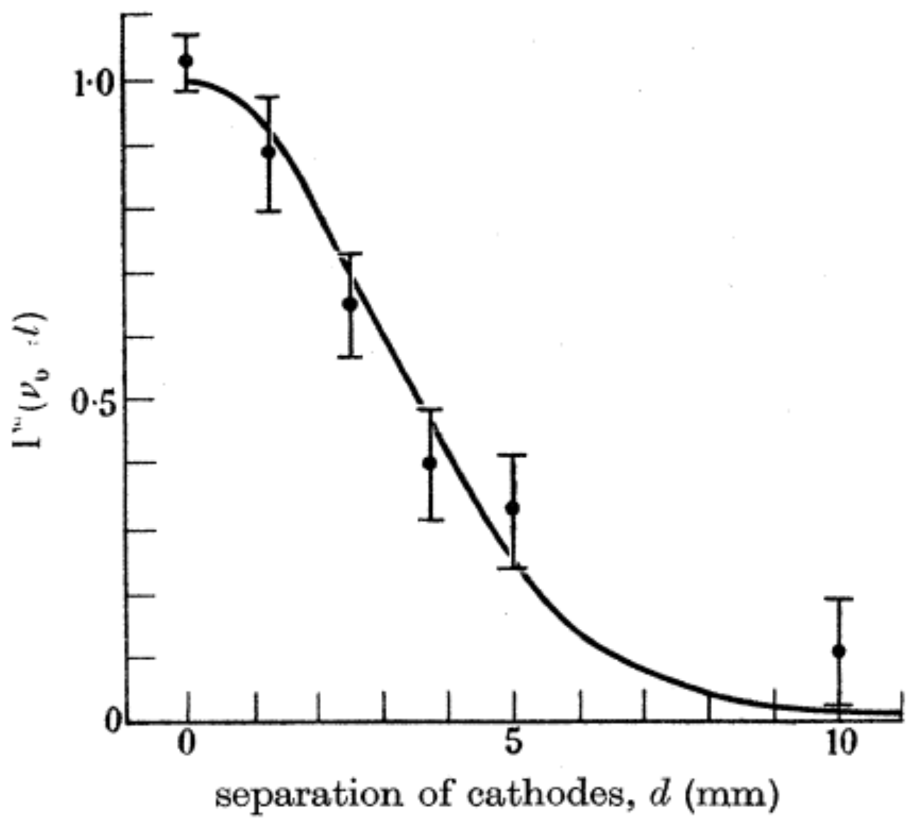


FIGURE 4. A simplified outline of the optical system.

TABLE 2. THE EXPERIMENTAL AND THEORETICAL VALUES FOR THE NORMALIZED CORRELATION FACTOR FOR DIFFERENT CATHODE SPACINGS

run no.	cathode separation (mm) d	observed correlation (r.m.s. signal to noise ratio) (S/N)	theoretical correlation assuming cathodes superimposed (r.m.s. signal to noise ratio) $(S/N)'$	experimental value of normalized correlation factor $\Gamma^2(\nu_0, d) = \frac{(S/N)}{(S/N)'}$	theoretical value of the normalized correlation factor $\Gamma^2(\nu_0, d)$
1	0	+17·55	+17·10	1·03 ± 0·04 (p.e.)	1·00
2	1·25	+ 8·25	+ 9·27	0·89 ± 0·07	0·928
3	2·50	+ 5·75	+ 8·85	0·65 ± 0·08	0·713
4	3·75	+ 3·59	+ 8·99	0·40 ± 0·07	0·461
5	5·00	+ 2·97	+ 9·00	0·33 ± 0·07	0·244
6	10·00	+ 0·90	+ 8·17	0·11 ± 0·08	0·015



Correlation measurements

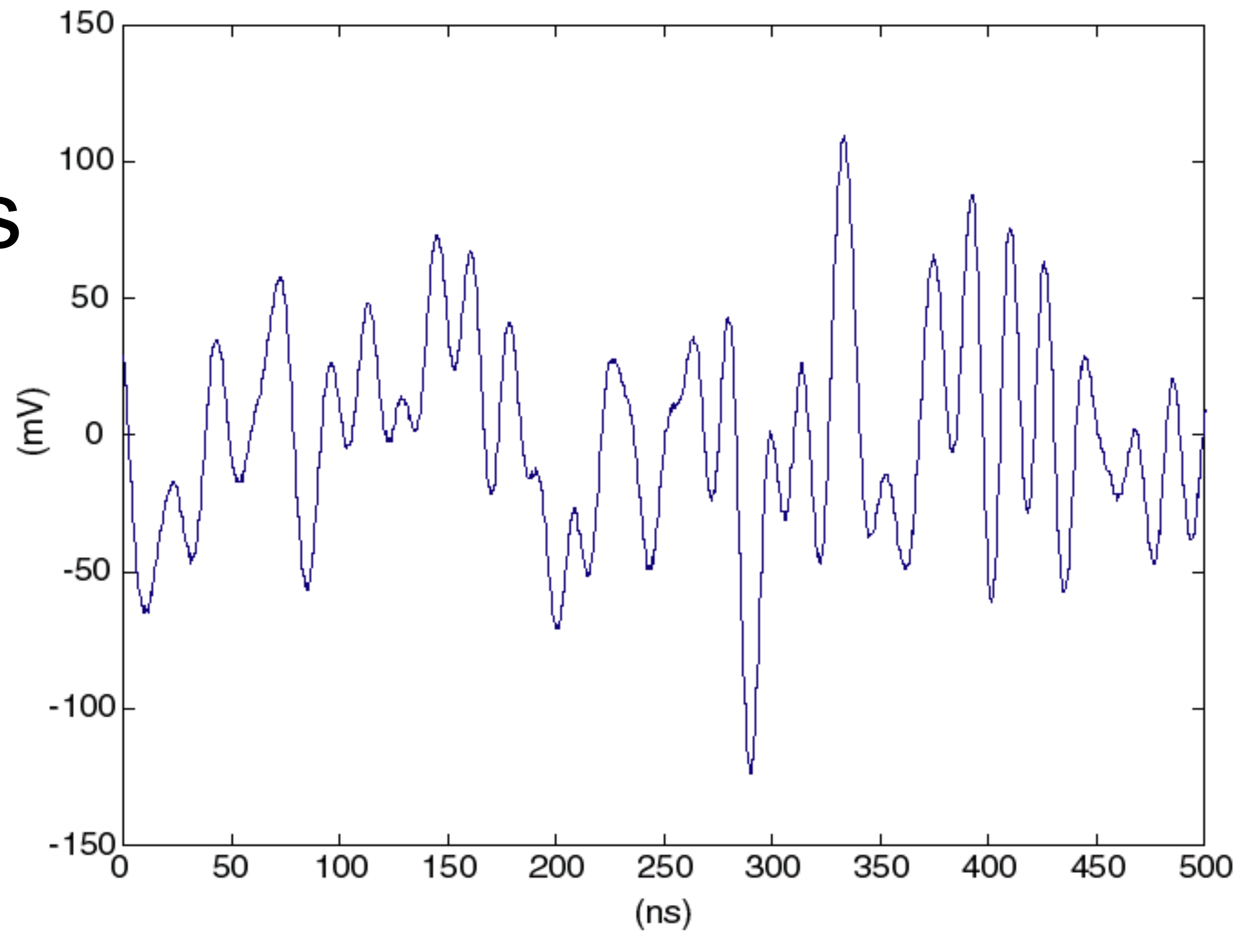
The study of optical noisy signals uses correlation functions.

$<F(t)\ F(t+\tau)>$

$<F(t)\ G(t+\tau)>$

For optical signals the variables usually are: Field and Intensity, but they can be cross correlations as well.

Photocurrent with noise:



How do we measure these functions?

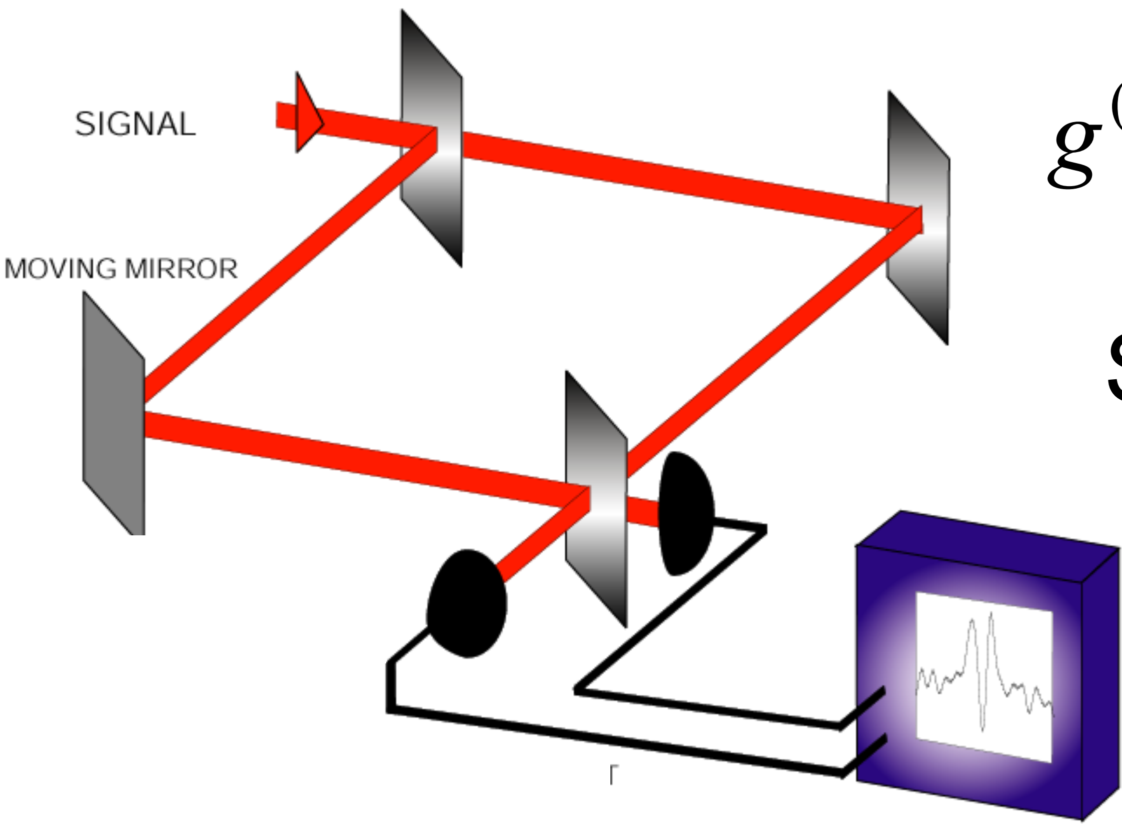
$G^{(1)}(\tau) = \langle E(t)^* E(t+\tau) \rangle$ field-field

$G^{(2)}(\tau) = \langle I(t) I(t+\tau) \rangle$ intensity-intensity

$H(\tau) = \langle I(t) E(t+\tau) \rangle$ intensity-field

- Correlation functions tell us something about fluctuations.
- The correlation functions have classical limits.
- They are related to conditional measurements. They give the probability of an event given that something has happened.

Mach Zehnder or Michelson Interferometer Field –Field Correlation



$$g^{(1)}(\tau) = \frac{\left\langle E^*(t)E(t+\tau)\right\rangle}{\left\langle I(t)\right\rangle}$$

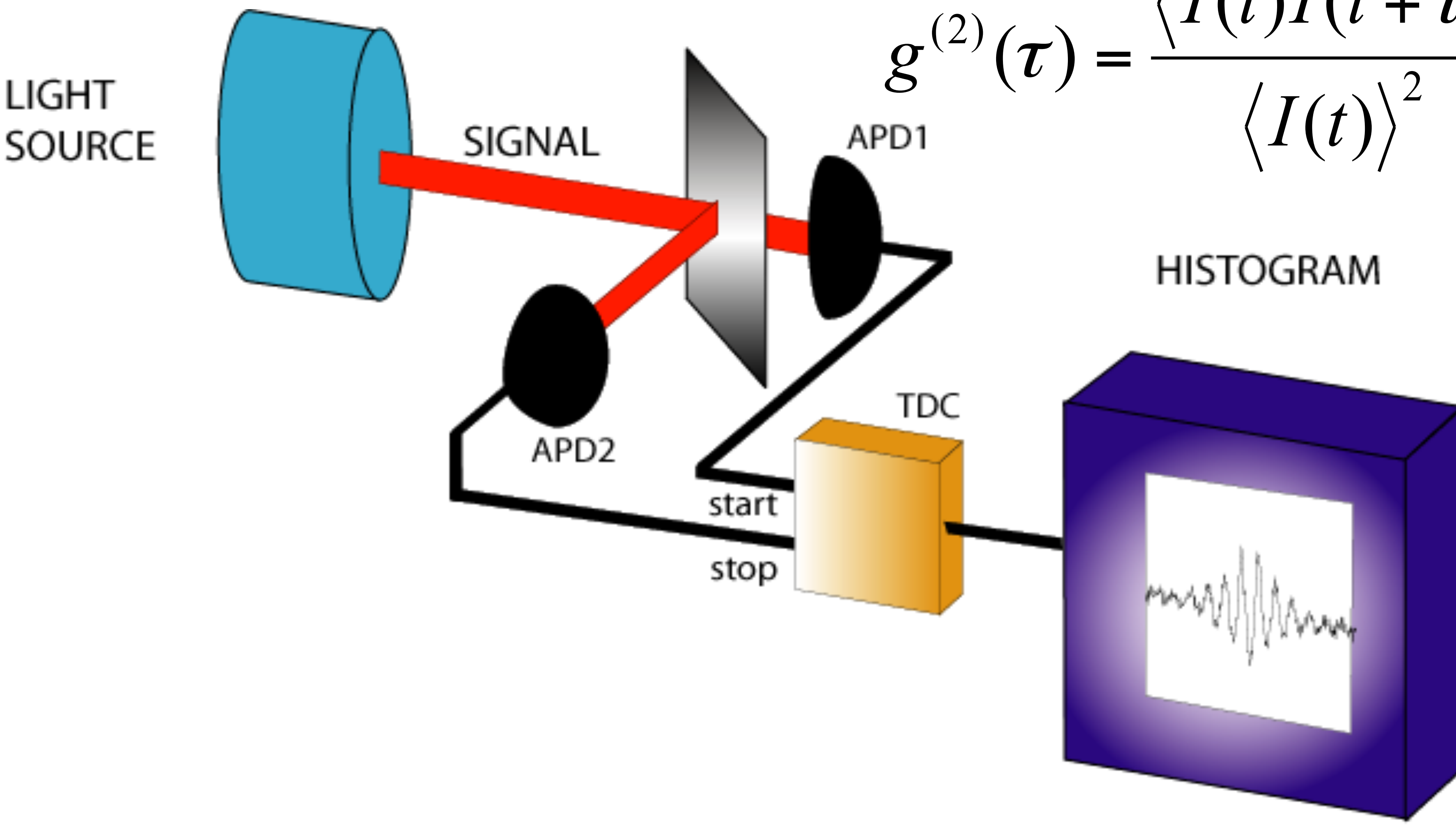
Spectrum:

$$F(\omega) = \frac{1}{2\pi}\int exp(i\omega\tau)g^{(1)}(\tau)d\tau$$

This is the basis of Fourier Spectroscopy

Hanbury Brown and Twiss; Intensity Intensity correlation

$$g^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$



Correlations of the intensity at τ=0

$$g^{(2)}(0) = \frac{\langle I(t)^2 \rangle}{\langle I(t) \rangle^2}$$

$$= \frac{\langle (I_0 + \delta(t))^2 \rangle}{\langle I_0 + \delta(t) \rangle^2}$$

$$= 1 + \frac{\langle \delta(t)^2 \rangle}{I_0^2}$$

It is proportional to the variance

Intensity correlations (bounds)

$$g^{(2)}(0) = 1 + \frac{\langle \delta(t)^2 \rangle}{I_0^2}$$

$$g^{(2)}(0) - 1 \geq 0$$

Cauchy-Schwarz

$$2I(t)I(t+\tau) \leq I^2(t) + I^2(t+\tau)$$

$$|g^{(2)}(\tau) - 1| \leq |g^{(2)}(0) - 1|$$

The correlation is maximal at equal times (τ=0) and it can not increase.

How do we measure them?

Build a “Periodogram”. The photocurrent is proportional to the intensity I(t)

$$I(t) \rightarrow I_i$$

$$I(t+\tau) \rightarrow I_j$$

$$\langle I(t)I(t+\tau)\rangle \rightarrow \sum_{i=0}^{M}\sum_{n=0}^{N} I_i I_{i+n}$$

- Discretize the time series.
- Apply the algorithm on the vector.
- Careful with the normalization.

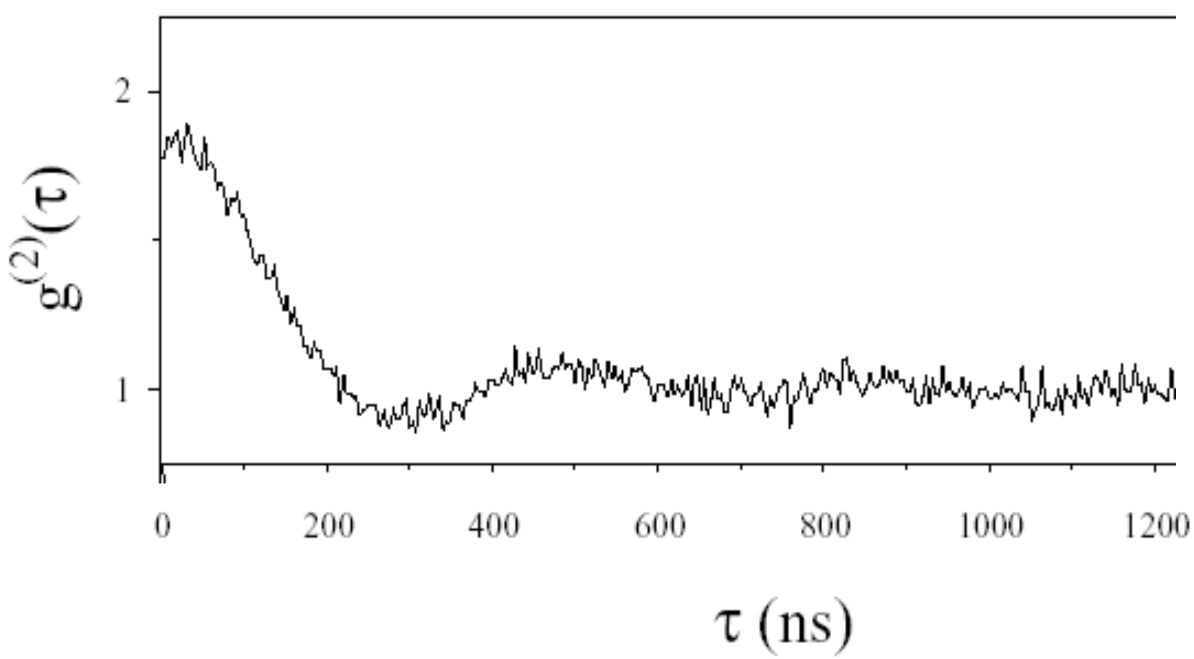
Discretize:

I_i

Multiply with displacement :

I_{i+n}

Add and average:



Another form to measure the correlation with with the waiting time distribution of the photons. The minimum size of the variance of the electromagnetic field.

- Store the time separation between two consecutive pulses (start and stop).
- Histogram the separations
- If the fluctuations are few you get after normalization $g^{(2)}(\tau)$.
- Work at low intensities (low counting rates).

Intensity (photons)

time

Use a time stamp card. Later process the data, then you can calculate all sorts of correlations.

Digitize the full signal (important to identify the nature of the event *e.g.* particle physics).

Quantum optics

- The photon is the smallest fluctuation of the intensity of the electromagnetic field, its variance.

- The photon is the quantum of energy of the electromagnetic field. With energy $\hbar\omega$ at frequency ω.

An important point about the quantum calculation $g^{(2)}(\tau)$

Quantum Correlations (Glauber):

$$g^{(2)}(\tau) = \frac{\langle T : \hat{I}(t)\hat{I}(t+\tau) :\rangle}{\langle \hat{I}(t)\rangle^2}$$

The intensity operator *I* is proportional to the number of photons, but the operators have to be normal (:) and time (*T*) ordered. All the creation operators do the left and the annihilation operators to the right (just as a photodetector works). The operators act in temporal order.

R. Glauber, *"The Quantum Theory of Optical Coherence,"* Phys. Rev. **130**, 2529 (1963).

At equal times (normal order) :

$$g^{(2)}(0) = \frac{\langle \hat{a}^\dagger \hat{a}^\dagger \hat{a} \hat{a} \rangle}{\langle \hat{a}^\dagger \hat{a} \rangle^2}.$$

Conmutator : $\hat{a}^+ \hat{a} = \hat{a}\,\hat{a}^+ - 1$

$$\left\langle \hat{a}^+ \hat{a}^+ \hat{a}\,\hat{a} \right\rangle = \left\langle \hat{a}^+ (\hat{a}\,\hat{a}^+ - 1)\,\hat{a} \right\rangle = \left\langle \hat{a}^+ \hat{a}\;\hat{a}^+ \hat{a} \right\rangle - \left\langle \hat{a}^+ \hat{a} \right\rangle$$

$$\left\langle \hat{a}^+ \hat{a}^+ \hat{a}\,\hat{a} \right\rangle = \left\langle \hat{n}^2 \right\rangle - \left\langle \hat{n} \right\rangle \quad \text{where} \quad \hat{n} = \hat{a}^+ \hat{a}$$

The correlation requires detecting two photons, so if we detect one, we have to take that into consideration in the accounting.

In terms of the variance of the photon number:

$$\sigma^2 = \langle \hat{n}^2 \rangle - \langle \hat{n} \rangle^2$$

$$g^{(2)}(0) = 1 + \frac{\sigma^2 - \langle \hat{n} \rangle}{\langle \hat{n} \rangle^2}$$

The classical result says:

$$= 1 + \frac{\langle \delta(t)^2 \rangle}{I_0^2}$$

The quantum correlation function can be zero, as the detection changes the number of photons in the field. This is related to the variance properties: is the variance larger or smaller than the mean (Poissonian, Super-Poissonian or Sub-Poissonian).

$$g^{(2)}(0) = 1 + \frac{\sigma^2 - \langle \hat{n} \rangle}{\langle \hat{n} \rangle^2}.$$

At equal times the value gives:

$g^{(2)}(0)=1$ Poissonian

$g^{(2)}(0)>1$ Super-Poissonian

$g^{(2)}(0)<1$ Sub-Poissonian

The slope at equal times:

$g^{(2)}(0)>g^{(2)}(0^{+})$ Bunched

$g^{(2)}(0)<g^{(2)}(0^{+})$ Antibunched

Classically we can not have Sub-Poissonian nor Antibunched.

Quantum Correlations (Glauber):

$$g^{(2)}(\tau) = \frac{\left\langle :\hat{I}(t)\,\hat{I}(t+\tau): \right\rangle}{\left\langle \hat{I}(t) \right\rangle^2}$$

$$g^{(2)}(\tau) = \frac{\left\langle :\hat{I}(\tau): \right\rangle_c}{\left\langle :\hat{I}: \right\rangle}$$

If we detect a photon at time *t* , $g^{(2)}(\tau)$ gives the probability of detecting a second photon after a time τ .

Correlation functions as conditional measurements in quantum optics.

- The detection of the first photon gives the initial state that is going to evolve in time.
- Bayesian probabities.
- $g^{(2)}(\tau)$ Hanbury-Brown and Twiss.

Correlation functions in Optics (Wolf 1954)

- The optical correlations propagate using the wave equation for the electromagnetic field (Wolf 1954, 1955).

Quantum regression theorem

- The correlation functions can be calculated using the master equation with the appropriate initial and boundary conditions (Lax 1968).

Antibunching in Resonance Fluorescence

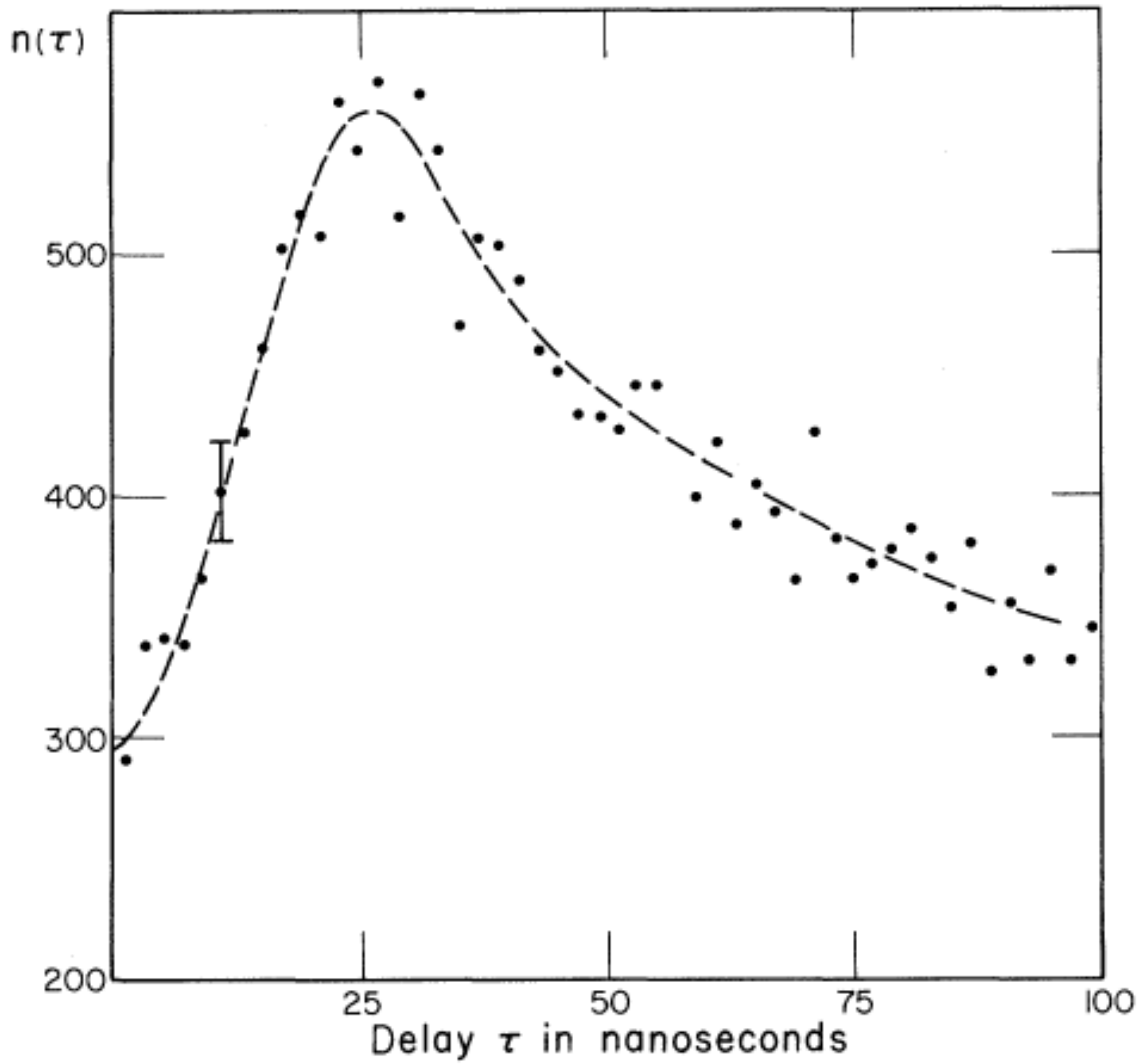
Photon Antibunching in Resonance Fluorescence

H. J. Kimble,[(a)] M. Dagenais, and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 22 July 1977)

The phenomenon of antibunching of photoelectric counts has been observed in resonance fluorescence experiments in which sodium atoms are continuously excited by a dye-laser beam. It is pointed out that, unlike photoelectric bunching, which can be given a semiclassical interpretation, antibunching is understandable only in terms of a quantized electromagnetic field. The measurement also provides rather direct evidence for an atom undergoing a quantum jump.



n(τ)
500
400
300
200
25
50
75
100
Delay τ in nanoseconds

An example of Intensity Intensity Correlations in cavity QED

Optical Cavity QED

Quantum electrodynamics for pedestrians. No need for renormalization. One or a finite number of modes from the cavity.

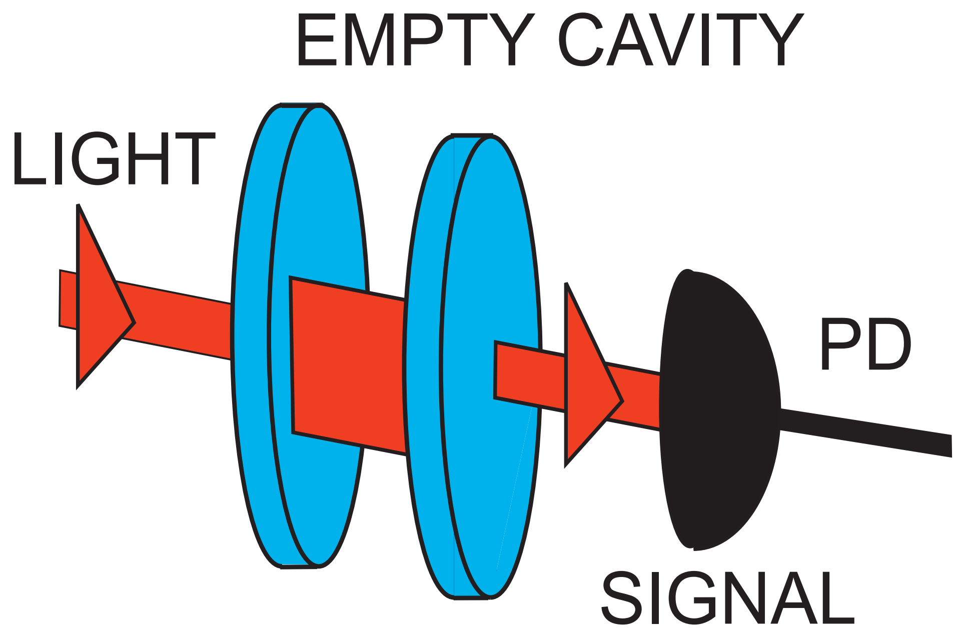
ATOMS + CAVITY MODE

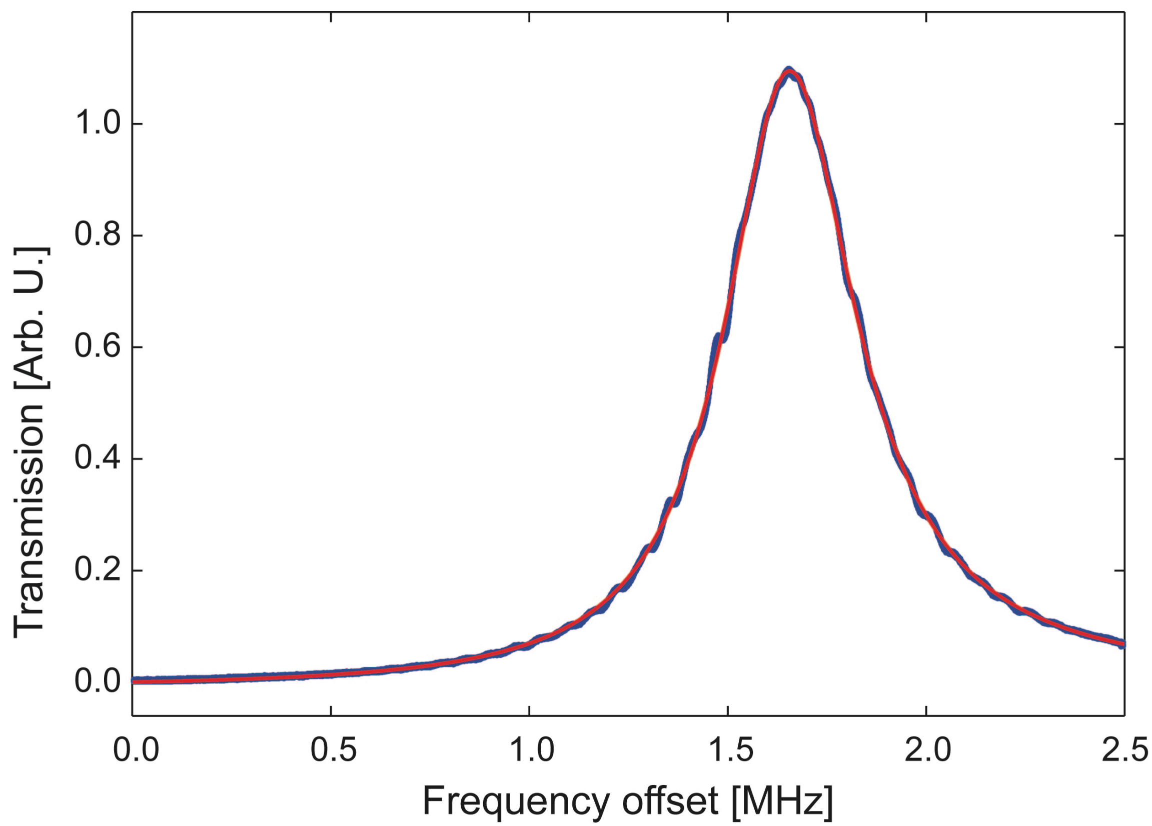
Dipolar coupling between the atom and the mode of the cavity:

$$g = \frac{d \cdot E_v}{\hbar}$$

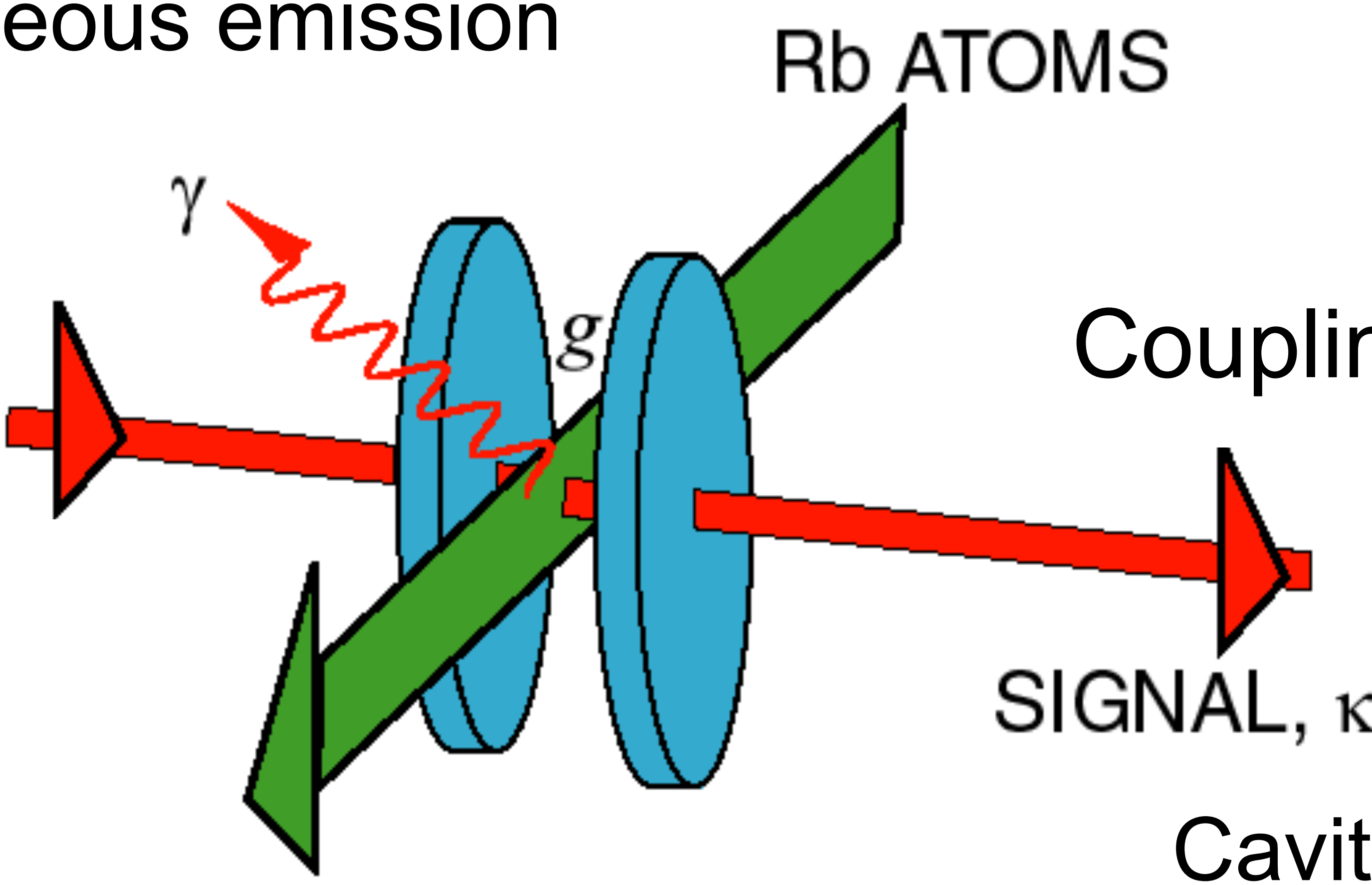
El electric field associated with one photon on average in the cavity with volume: V_{eff} is:

$$E_v = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V_{eff}}}$$


EMPTY CAVITY
LIGHT
PD
SIGNAL


Transmission [Arb. U.]
Frequency offset [MHz]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5

Spontaneous emission



Coupling

Cavity decay

Cooperativity for one atom: C_1

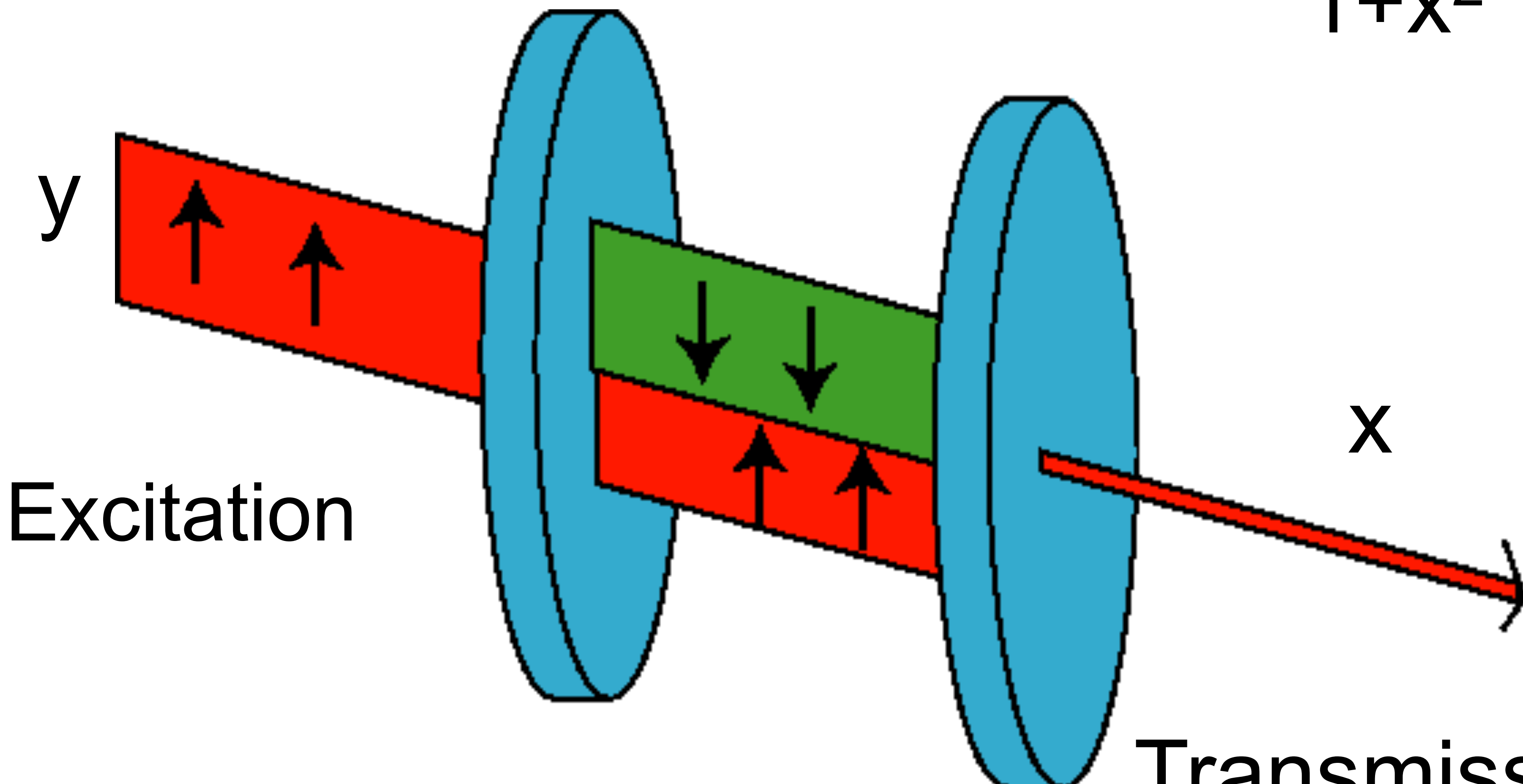
$$C_1 = \frac{g^2}{\kappa\gamma} \qquad C = C_1 N$$

Cooperativity for N atoms: C

$$g \approx \kappa \approx \gamma$$

Steady State

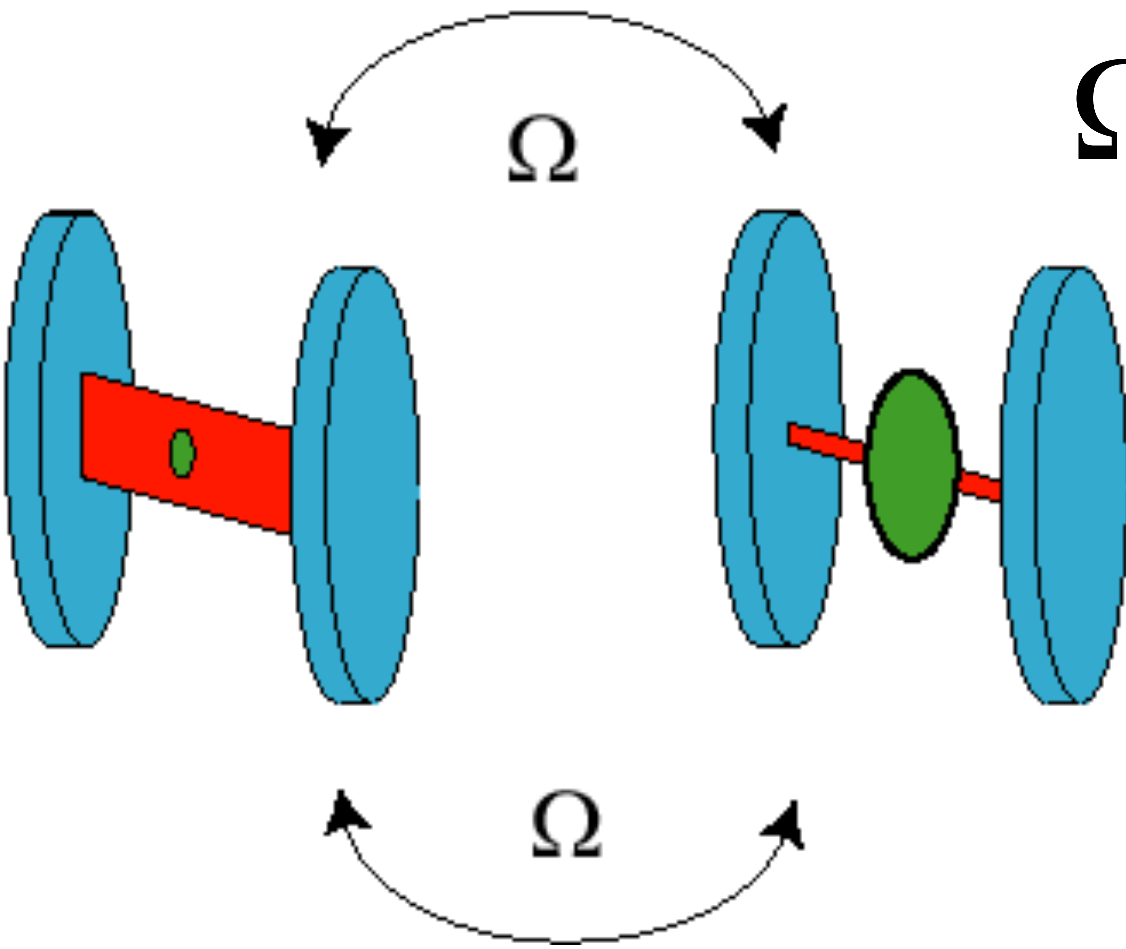
Atomic polarization: $\dfrac{-2Cx}{1+x^2}$



Transmission
$x/y = 1/(1+2C)$

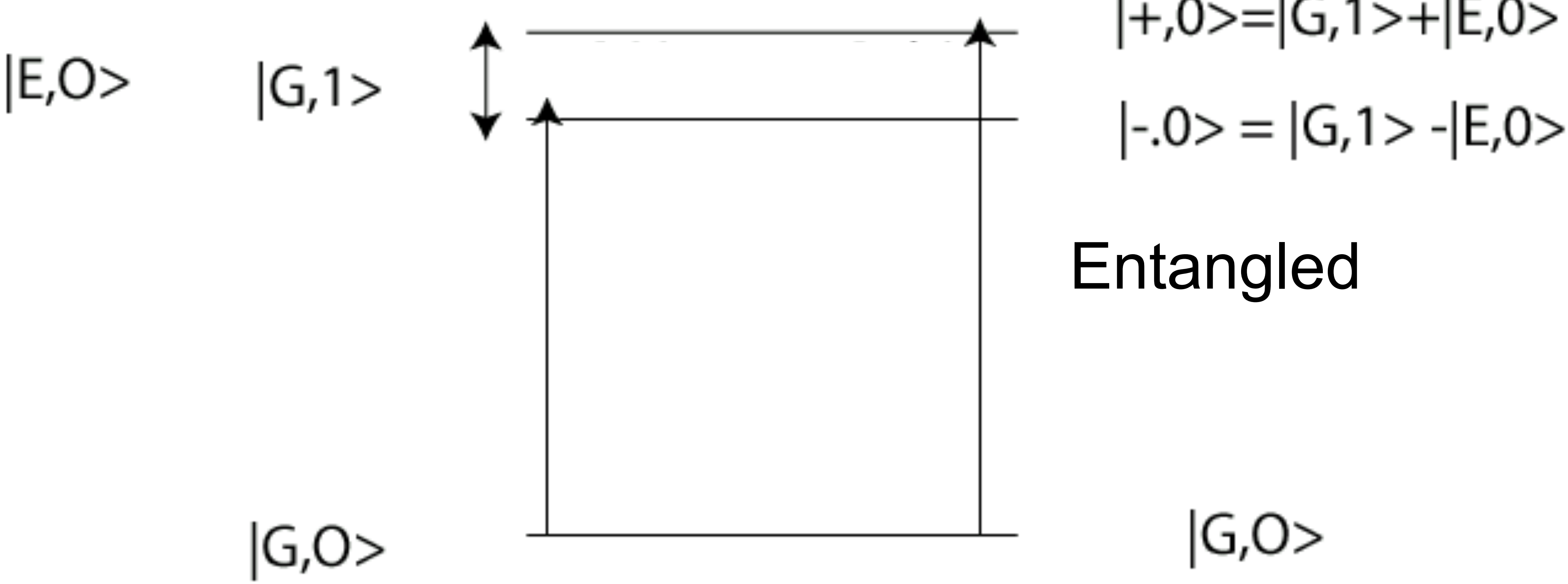
Jaynes Cummings Dynamics
Rabi Oscillations

Exchange of excitation for *N* atoms:



$$\Omega \approx g\sqrt{N}$$

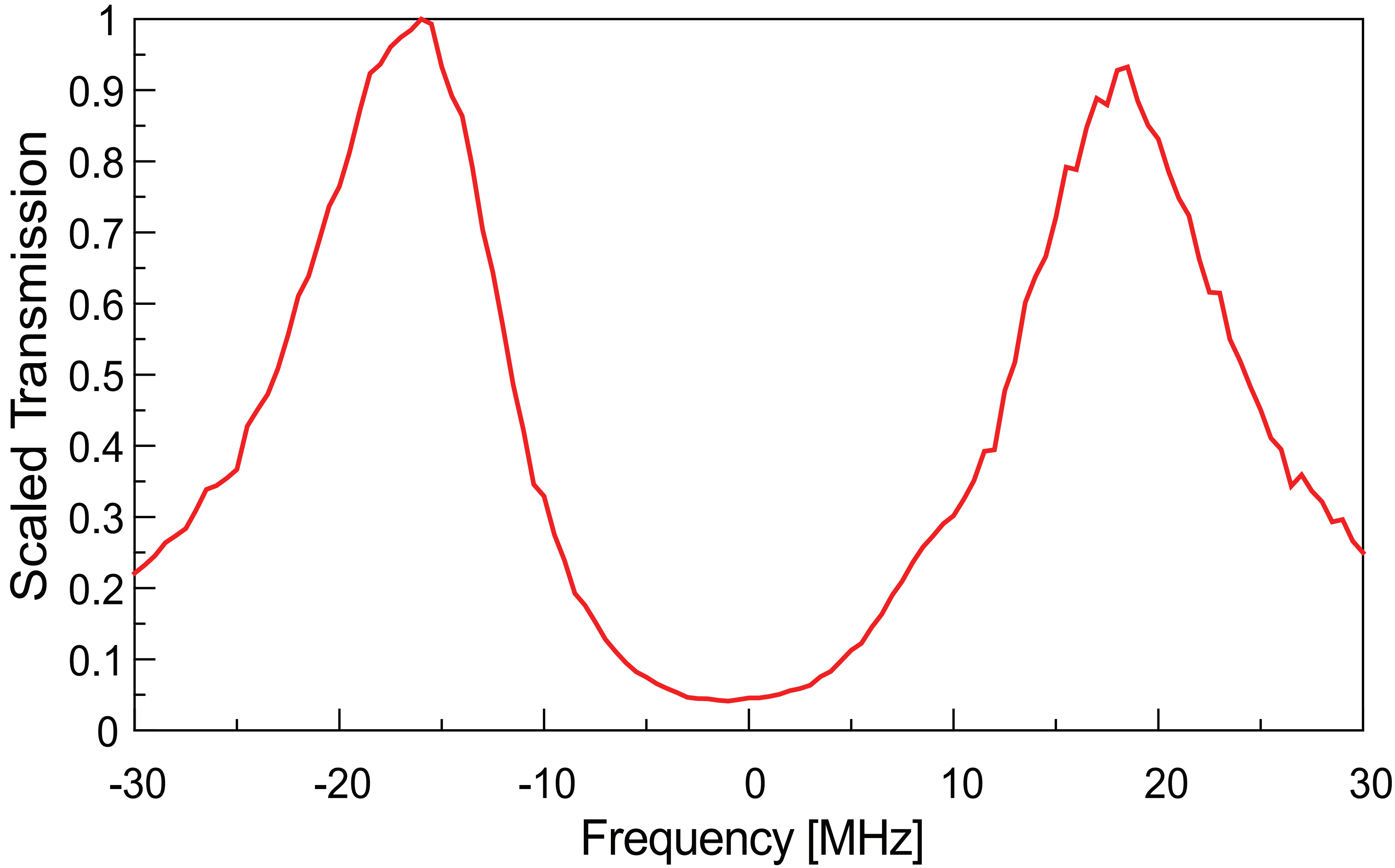
2g Vacuum Rabi Splitting

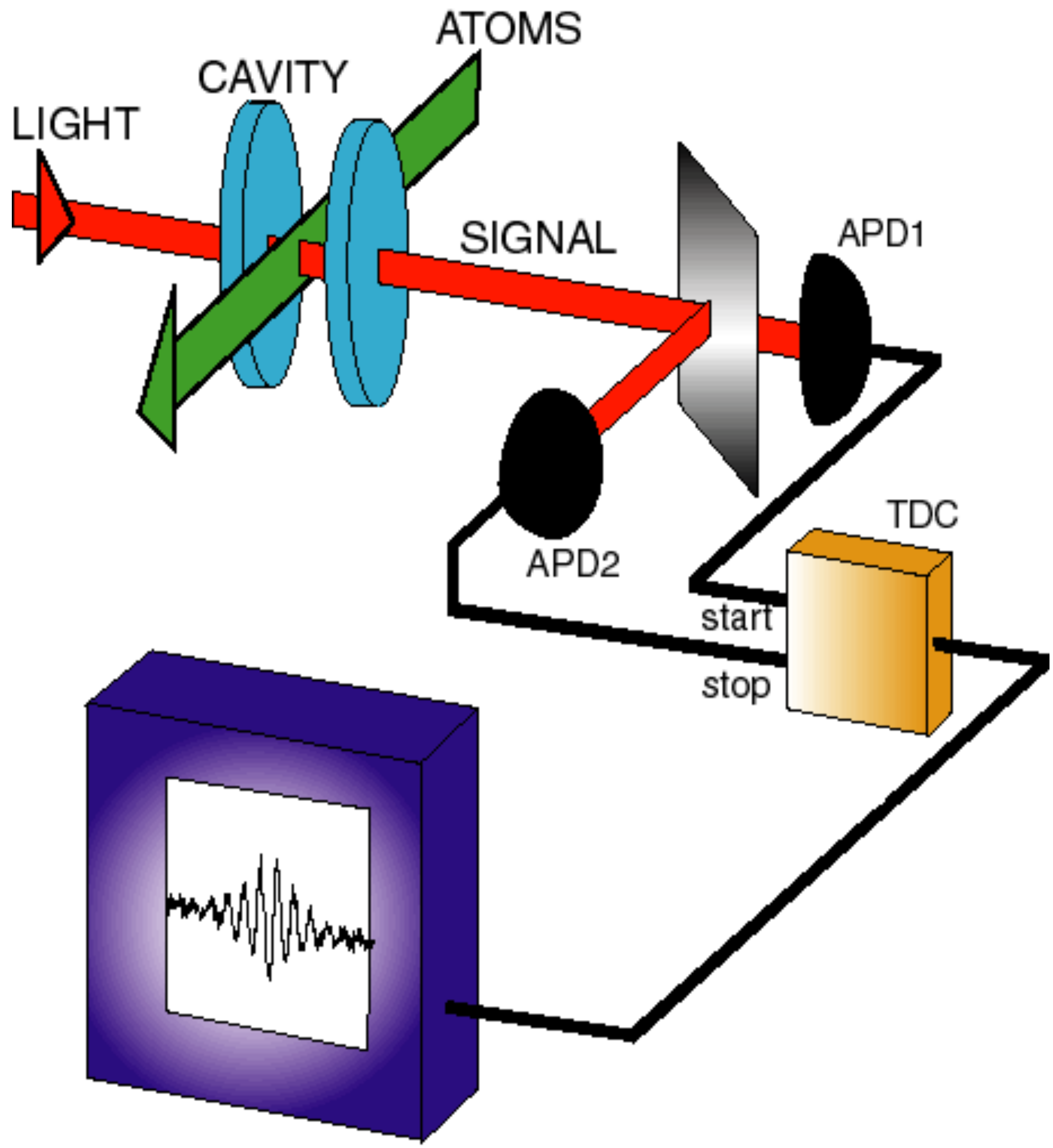


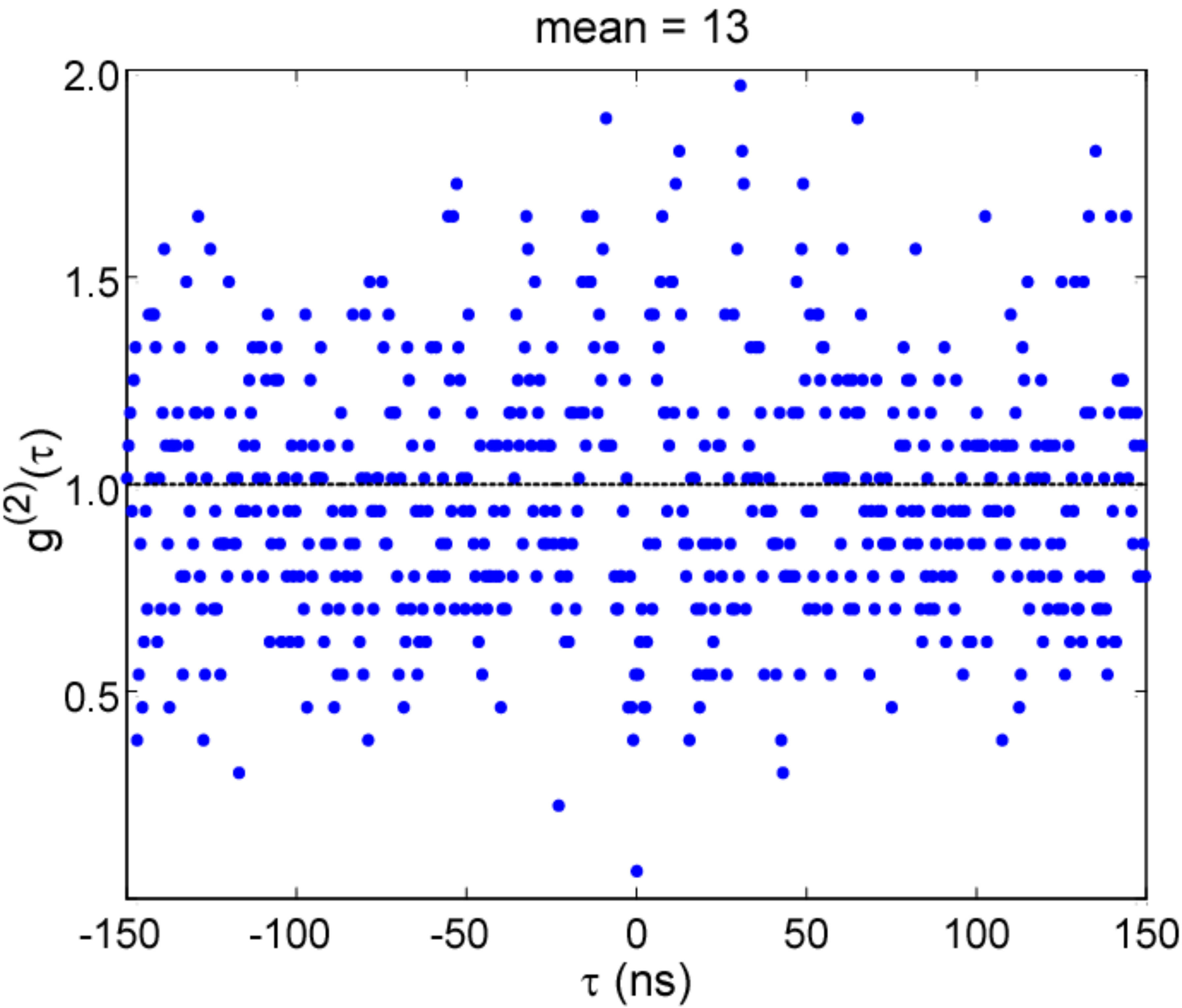
Not coupled

Two normal modes

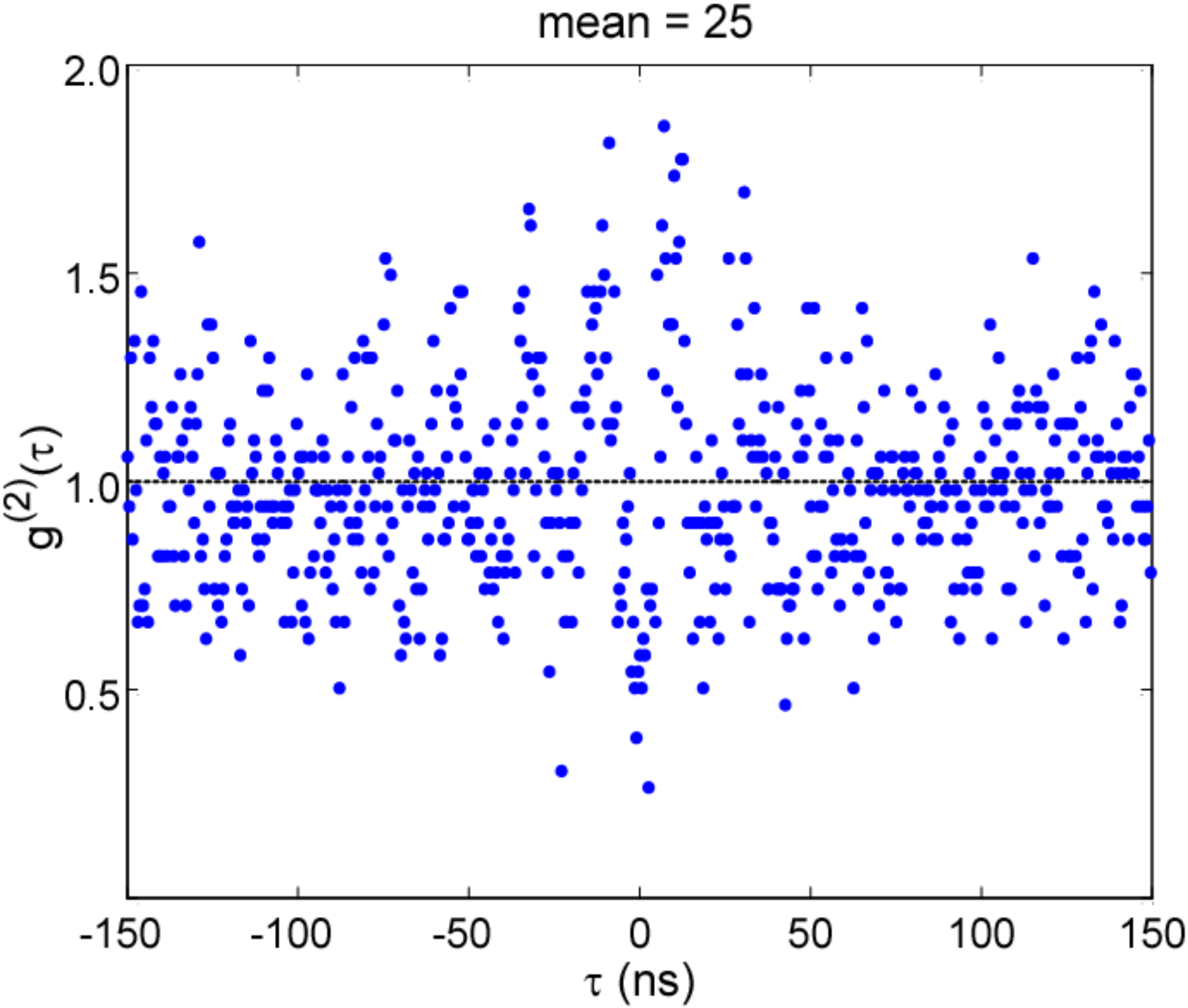
Transmission doublet different from the Fabry Perot resonance

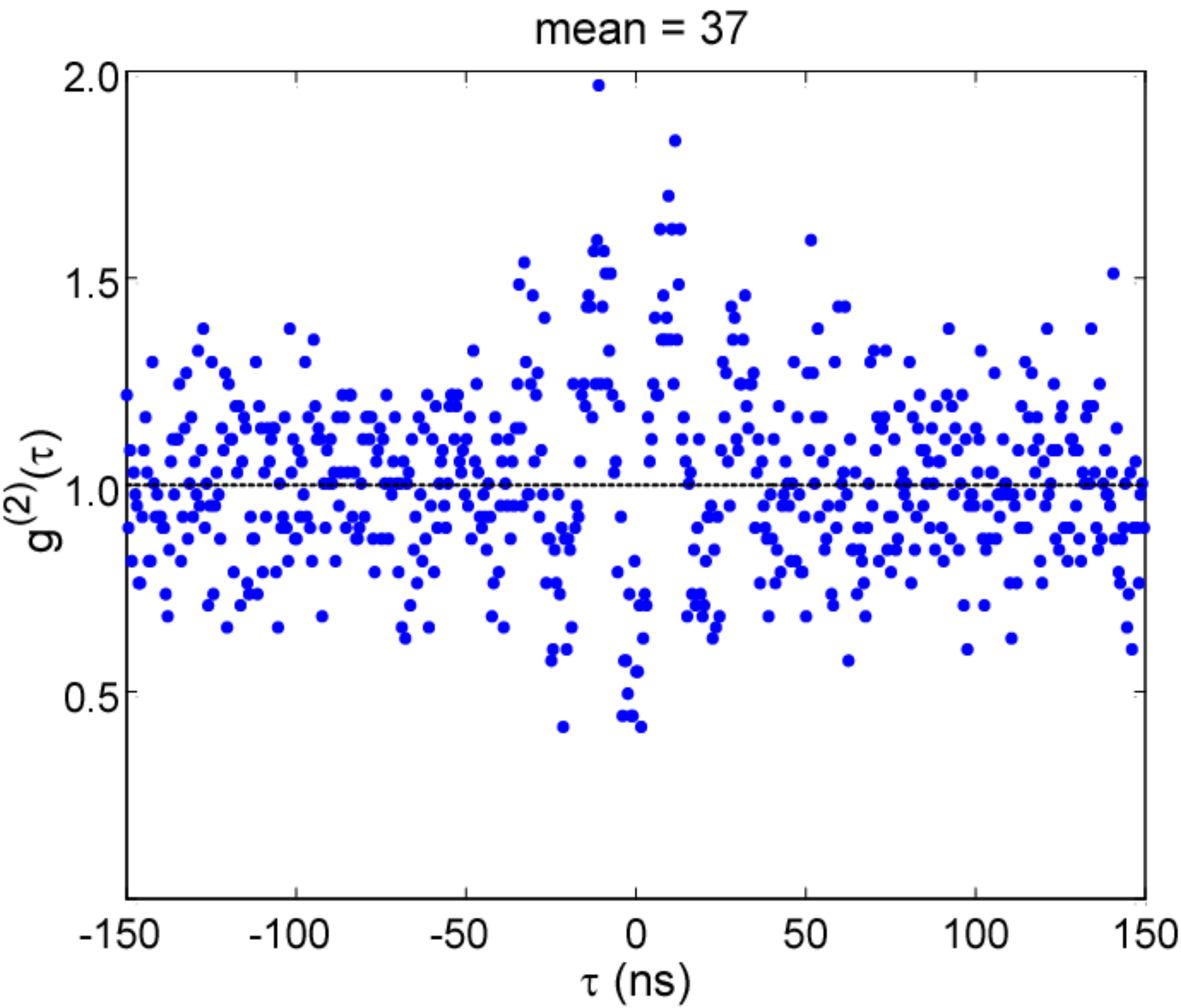



ATOMS
CAVITY
LIGHT
SIGNAL
APD1
APD2
TDC
start
stop

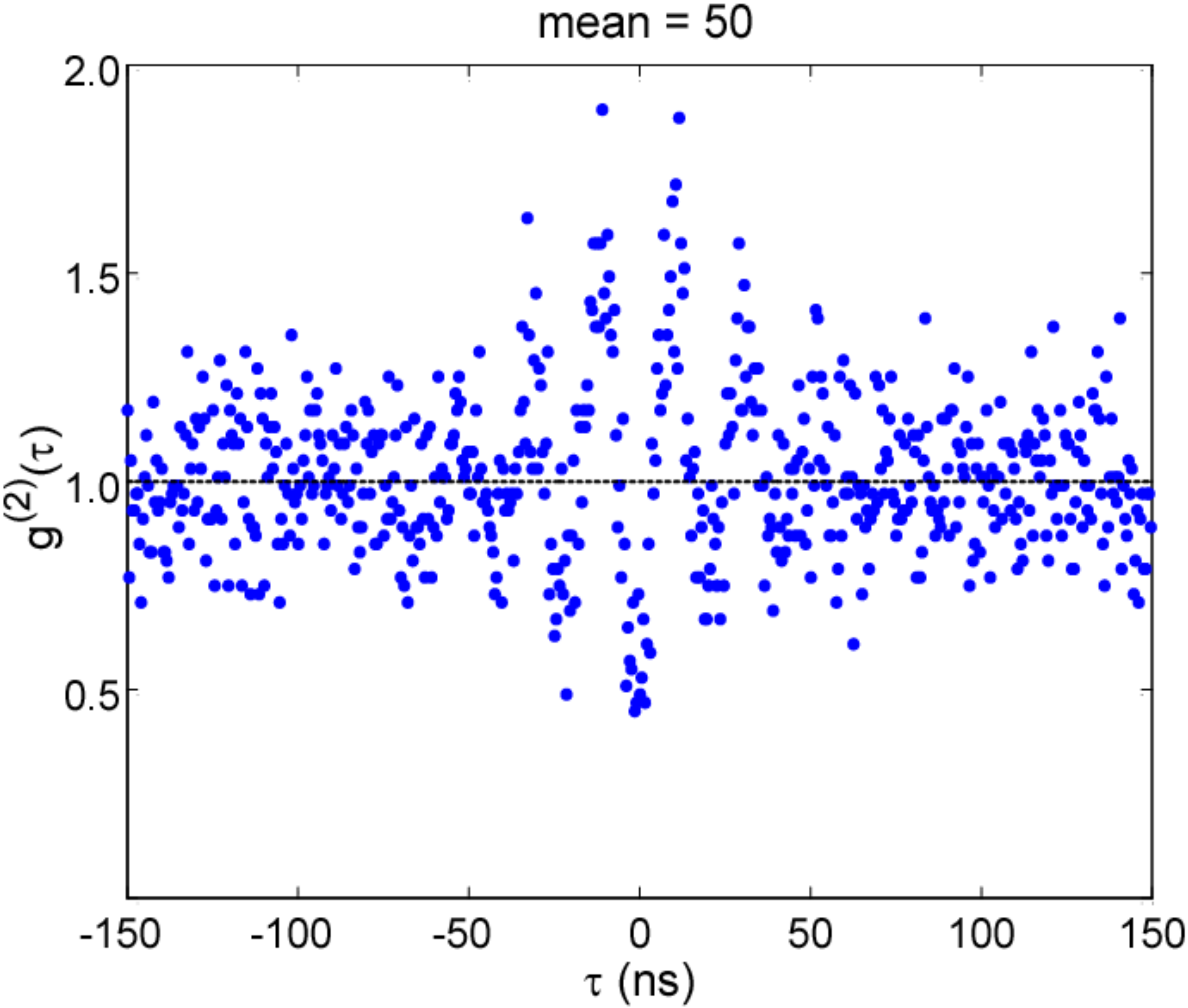


mean = 13
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

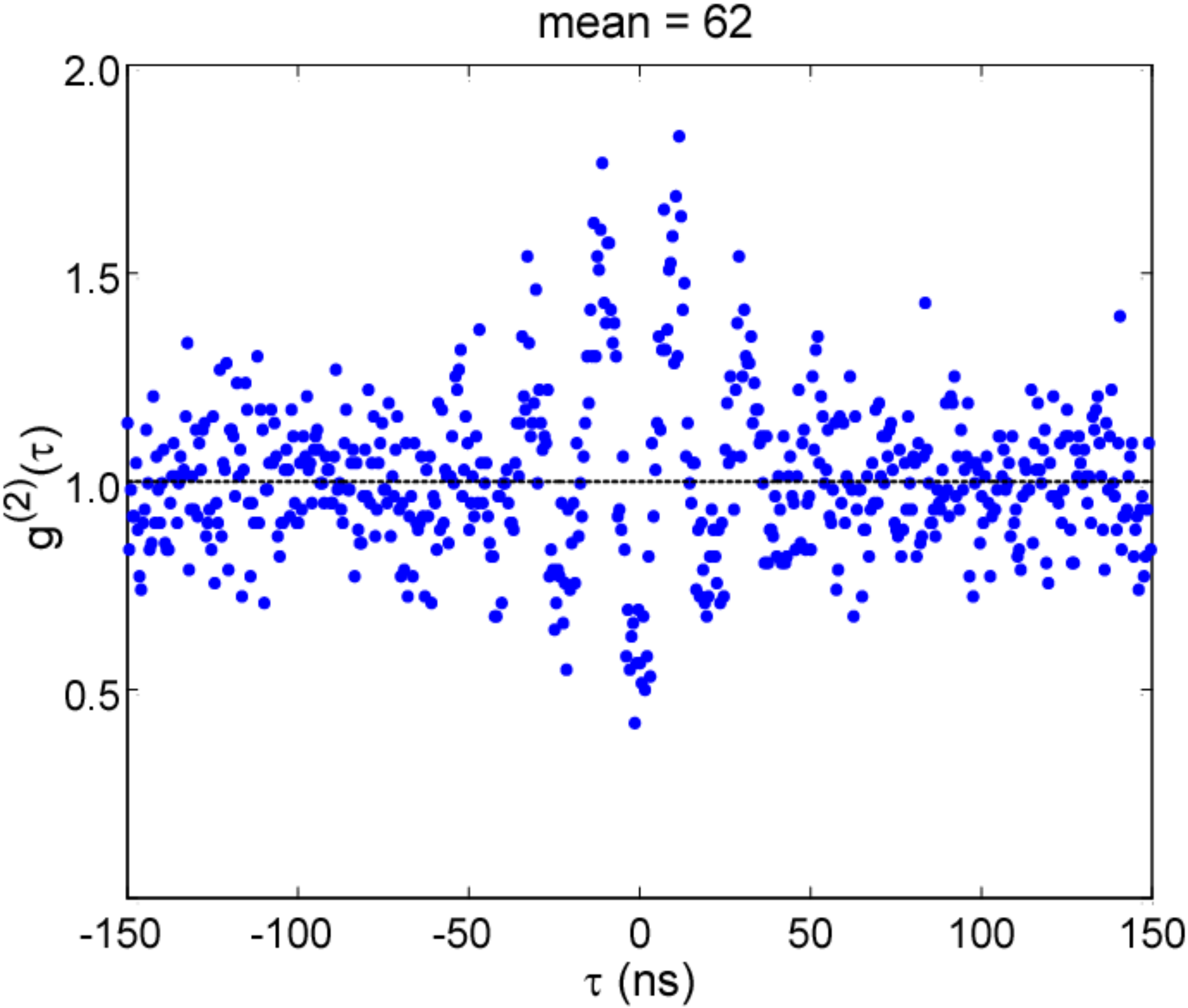

mean = 25
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)



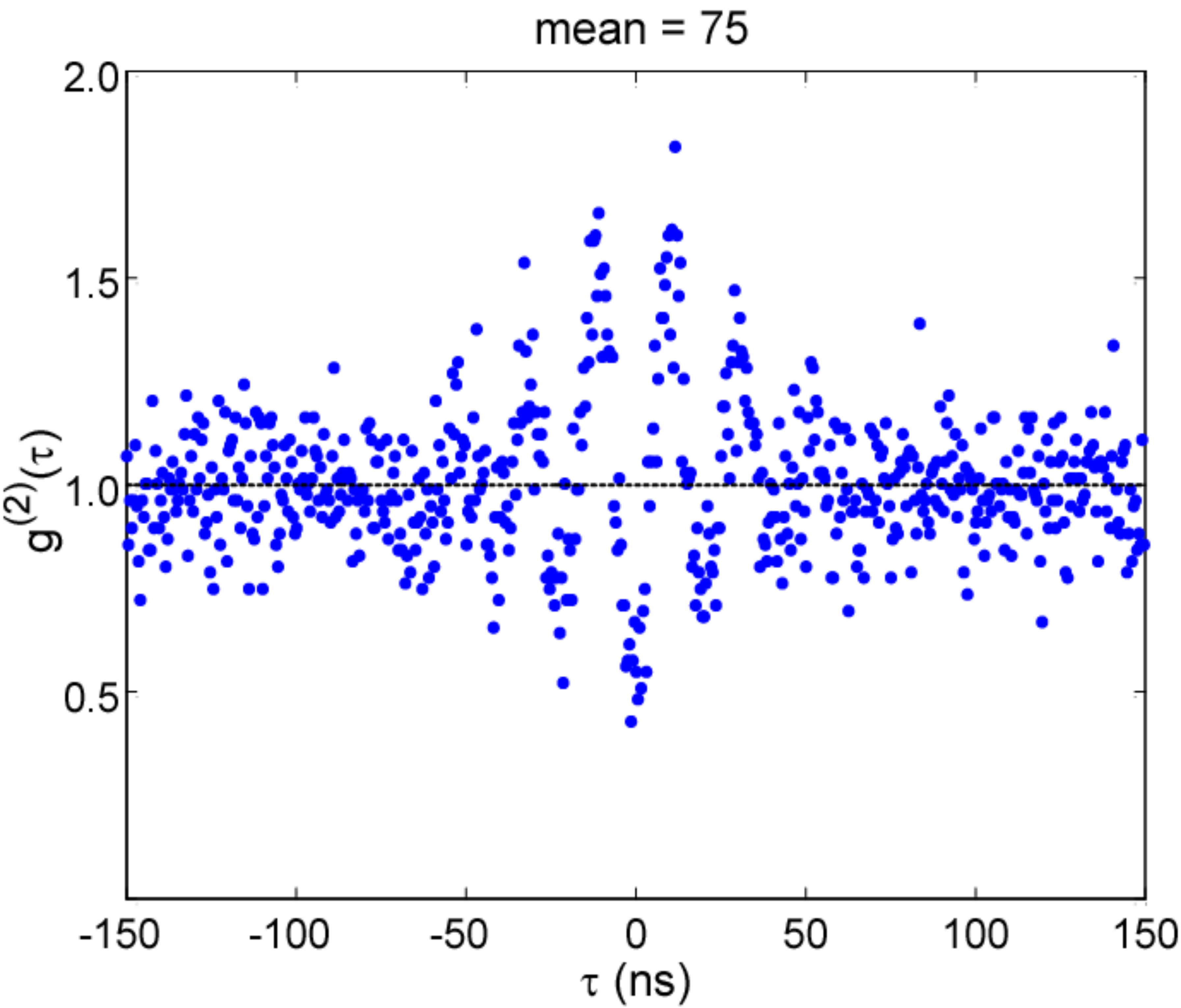
mean = 37
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

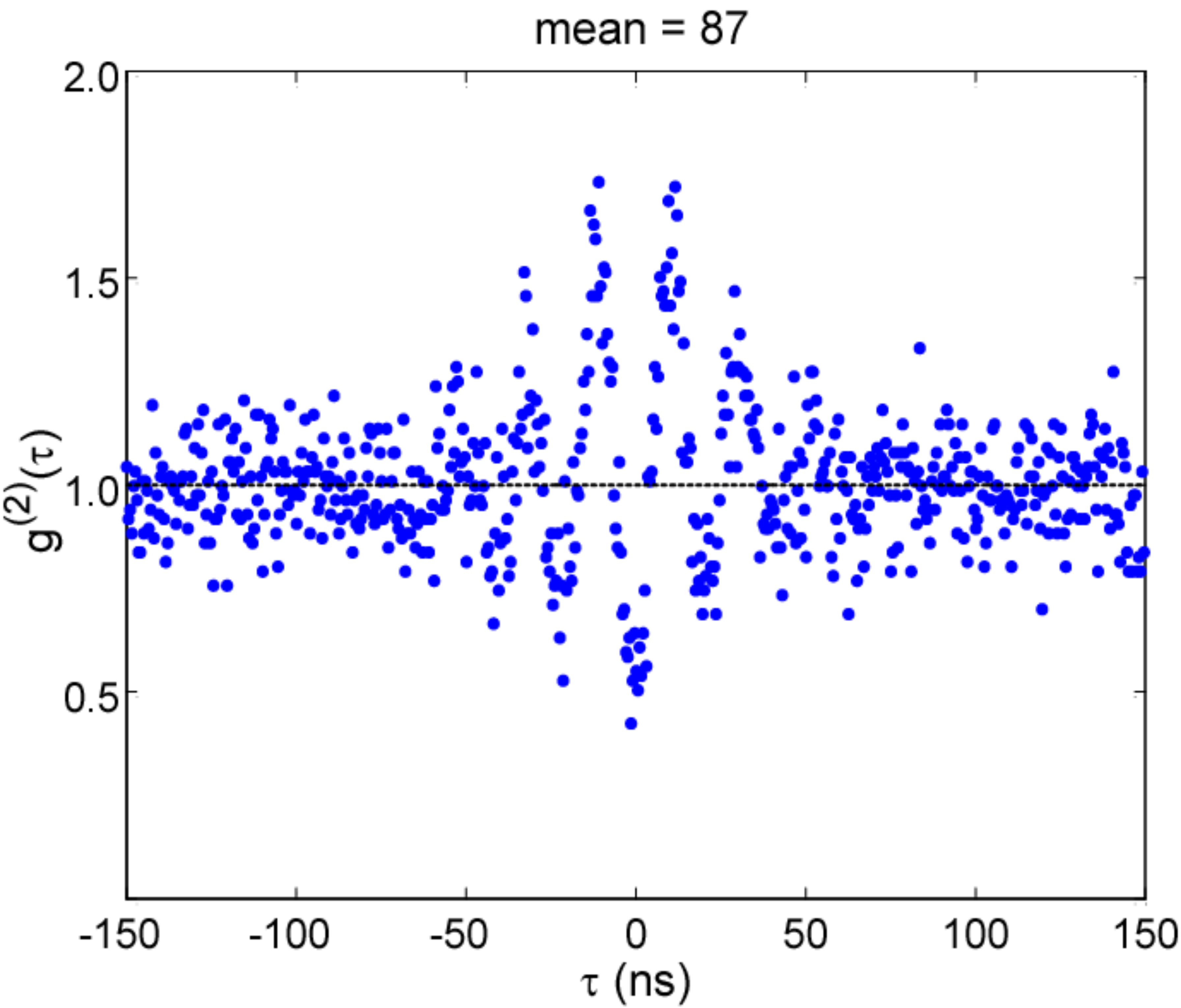


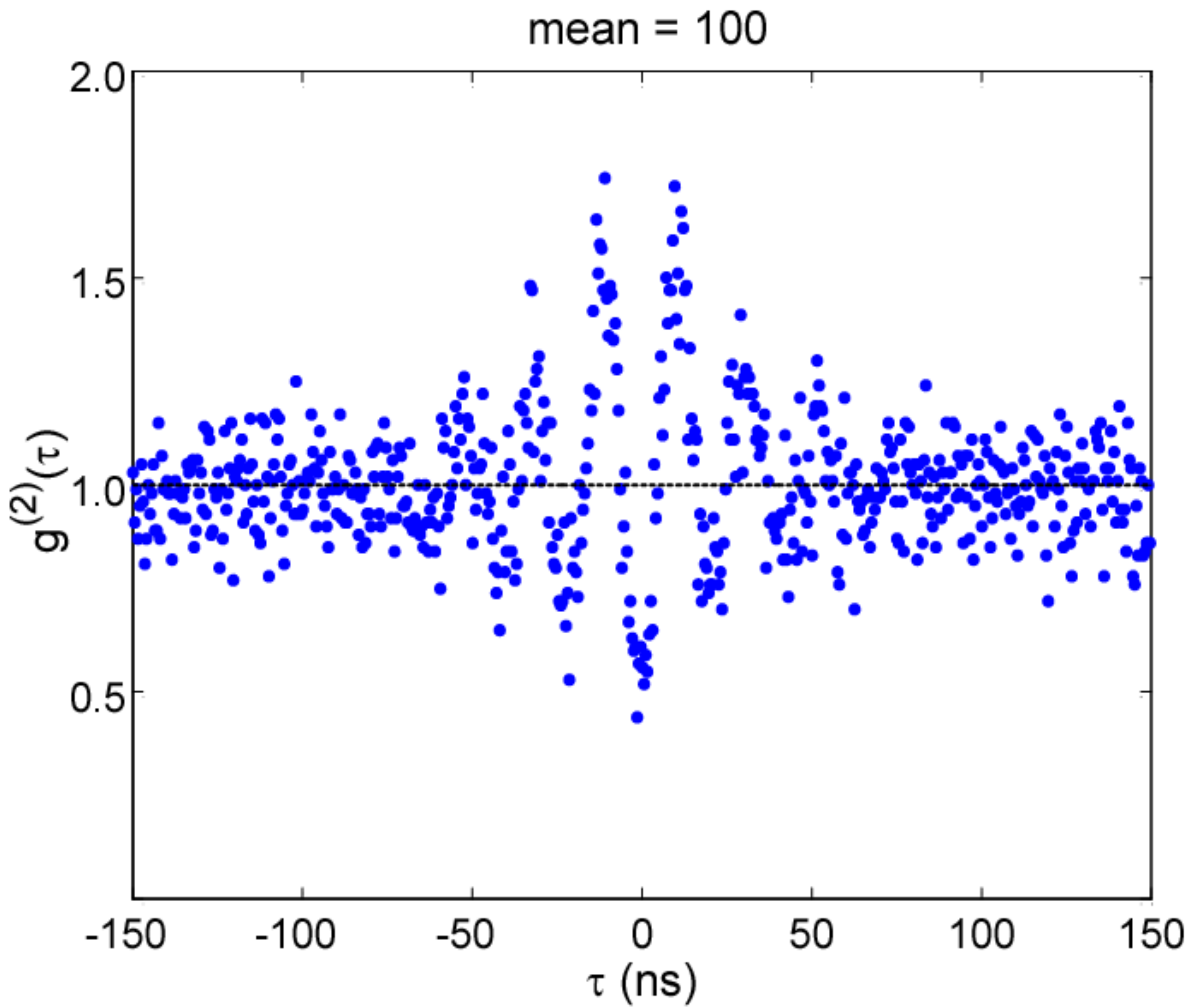
mean = 50
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

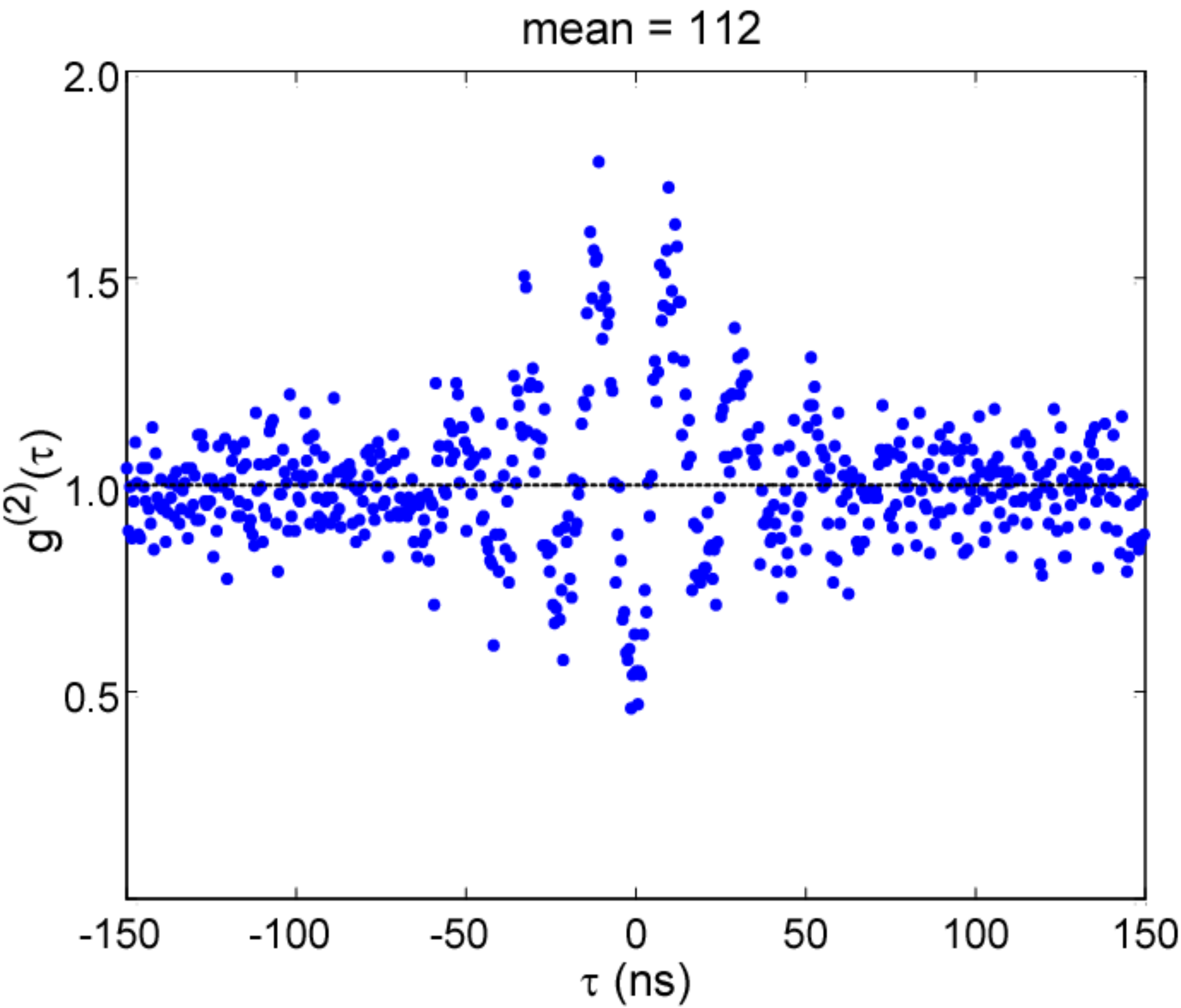


mean = 62
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

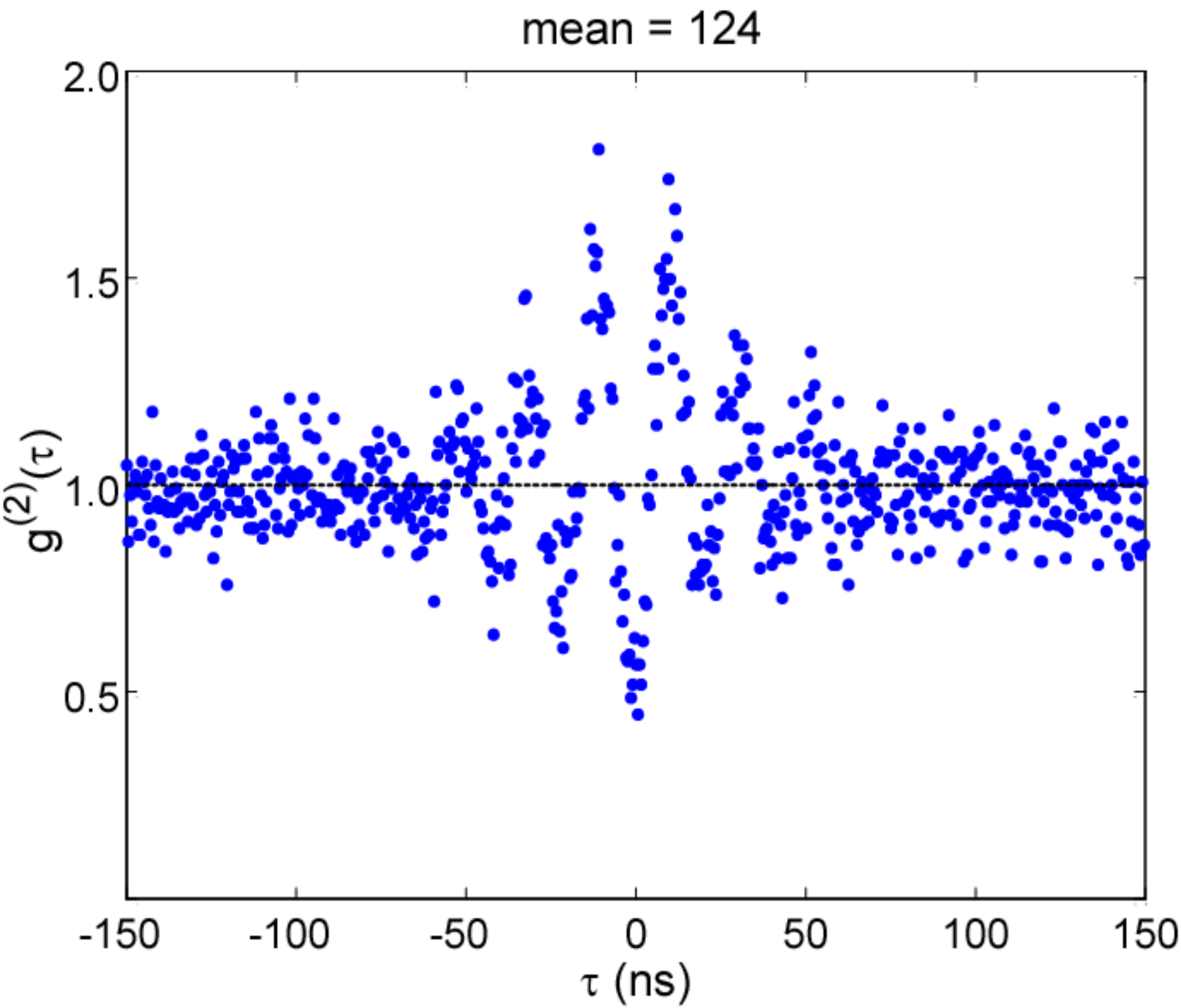

mean = 75
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

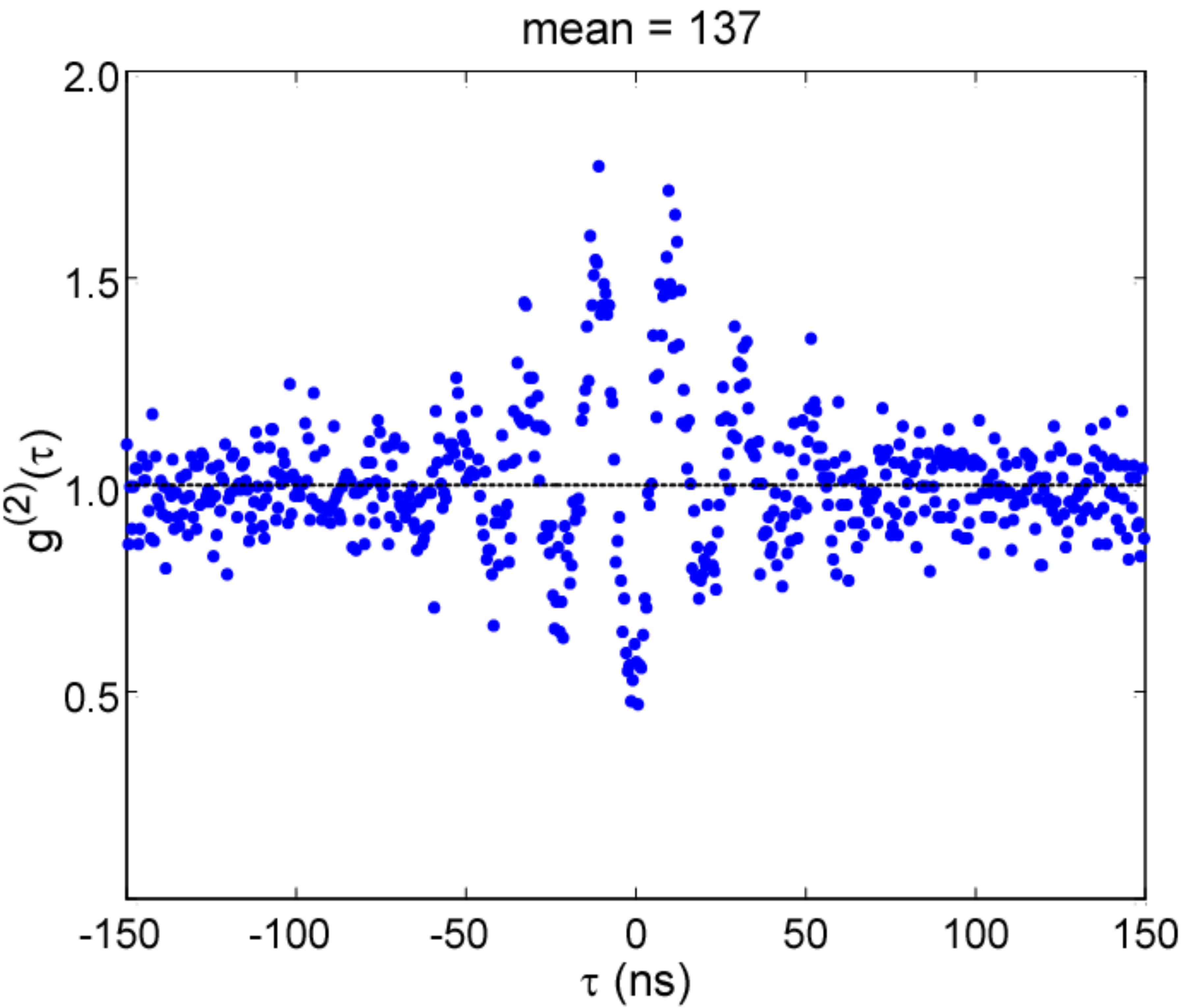

mean = 87
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)


mean = 100
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

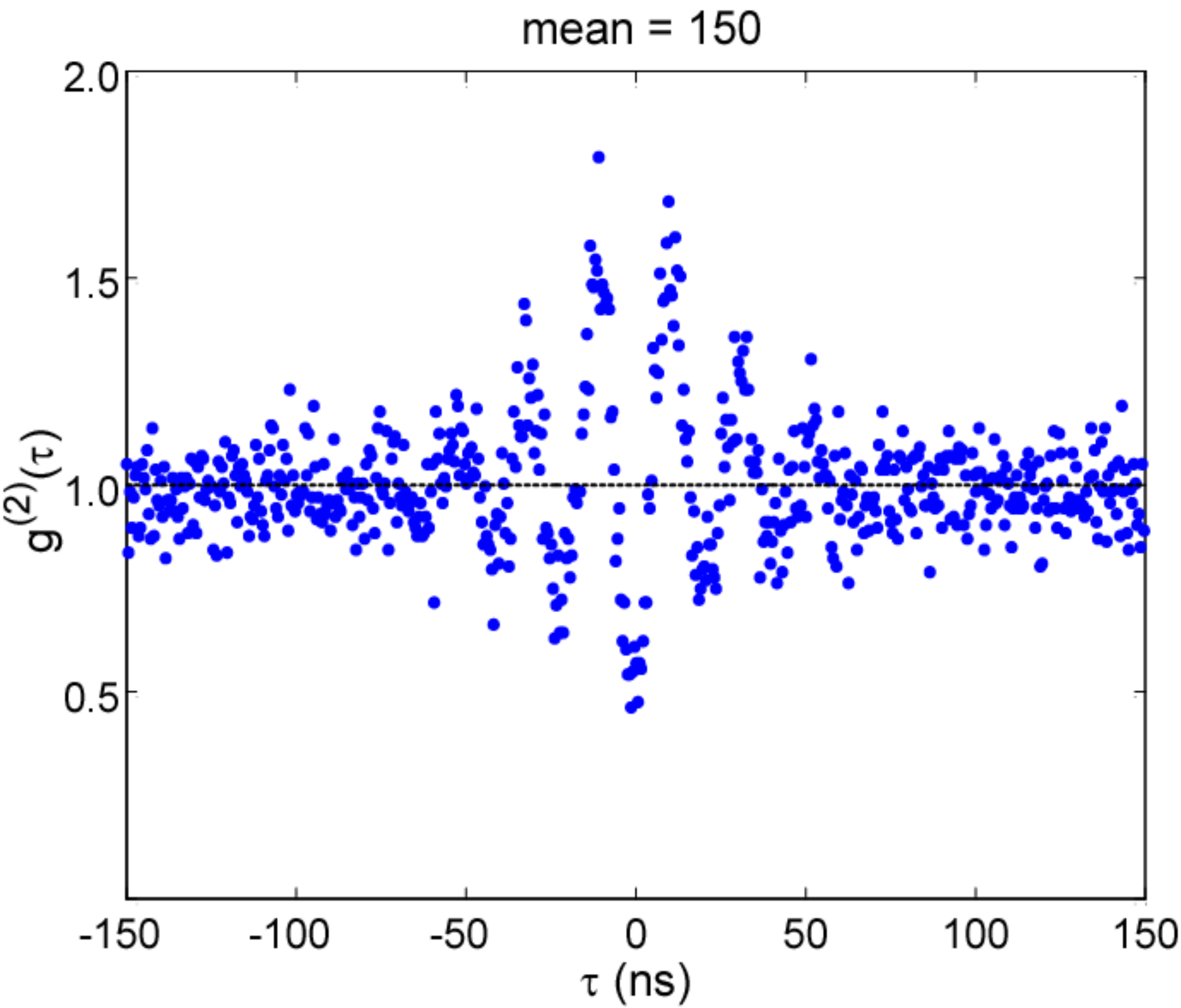


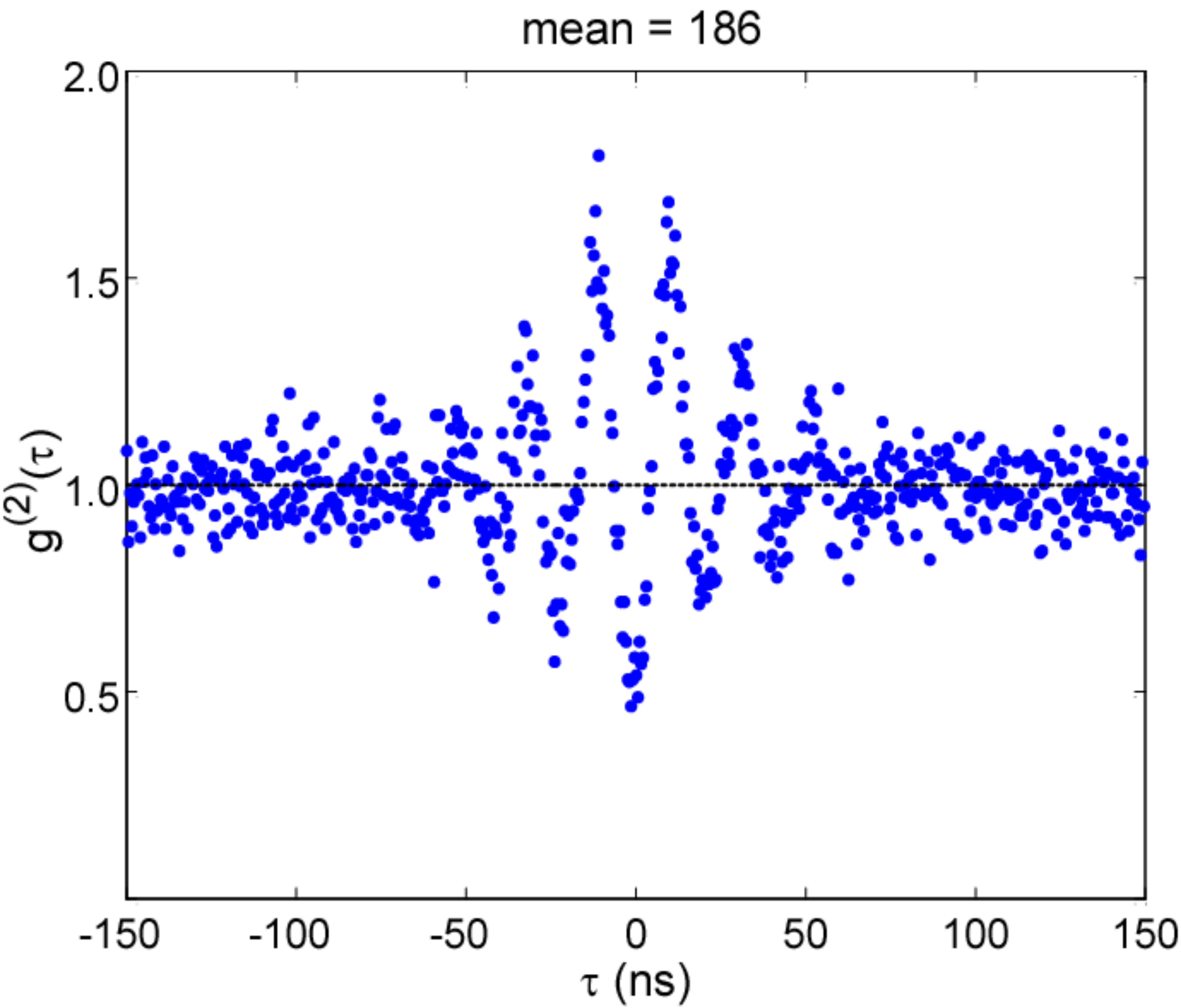
mean = 112
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

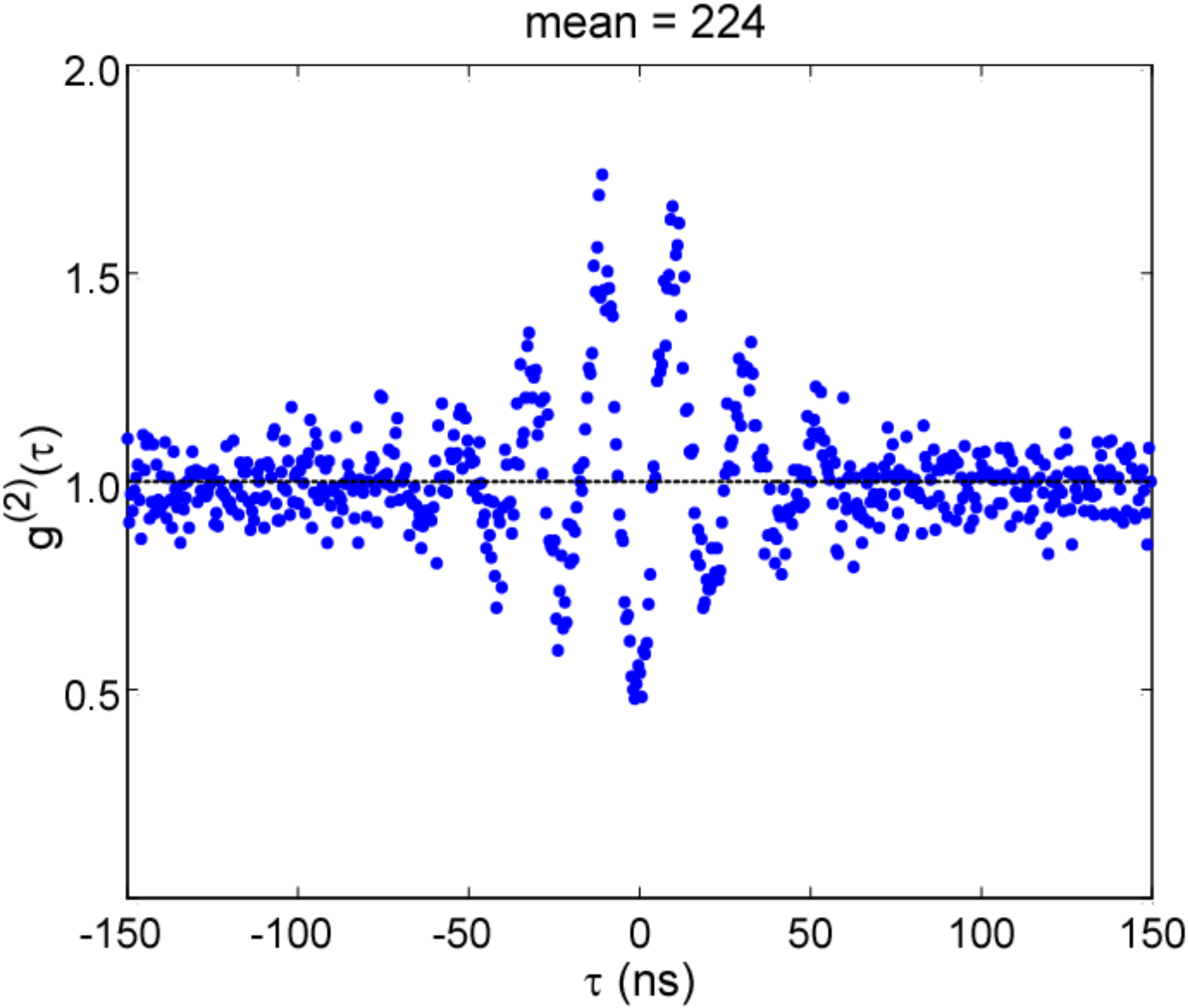

mean = 124
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)



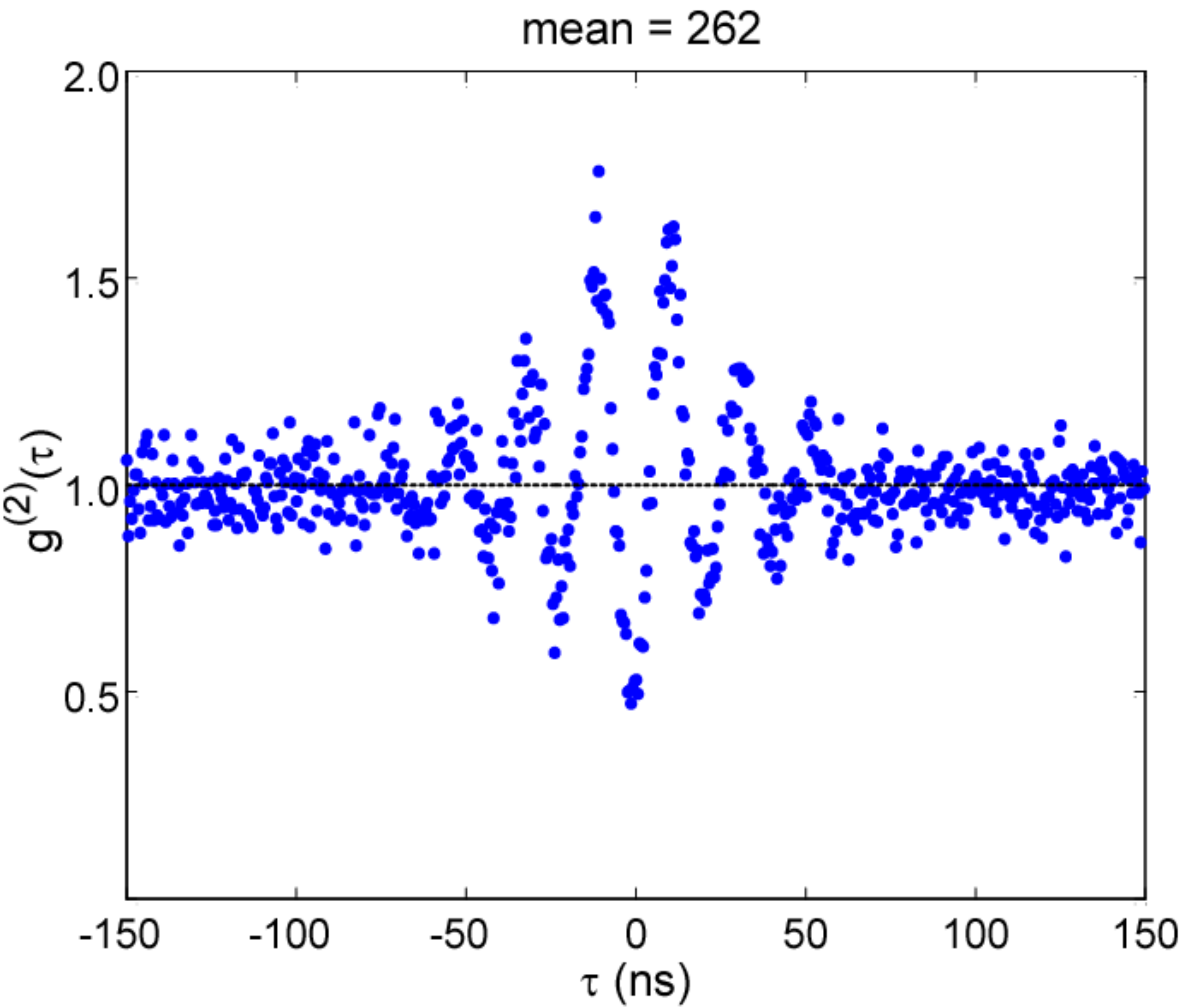
mean = 137
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)


mean = 150
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

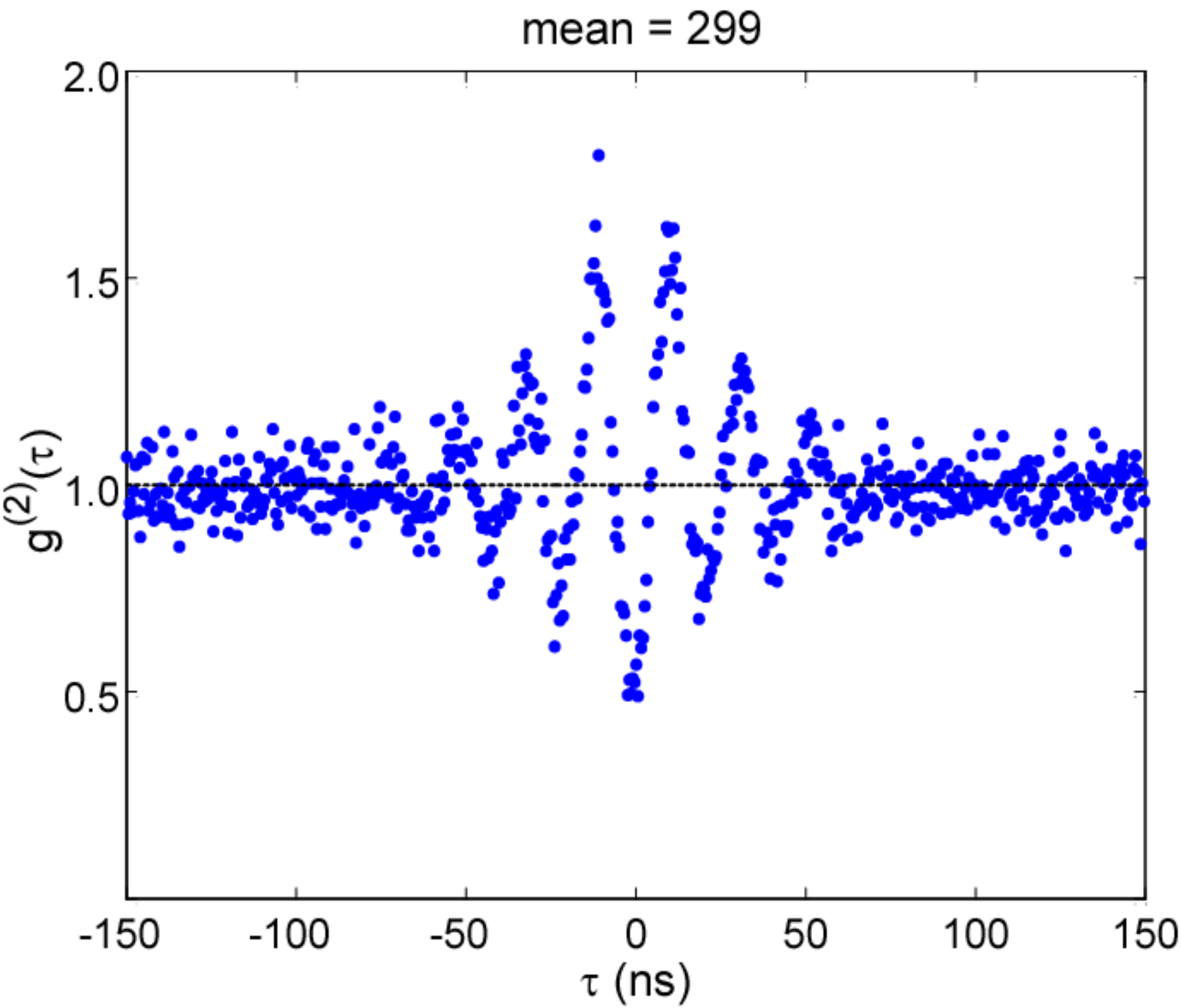

mean = 186
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

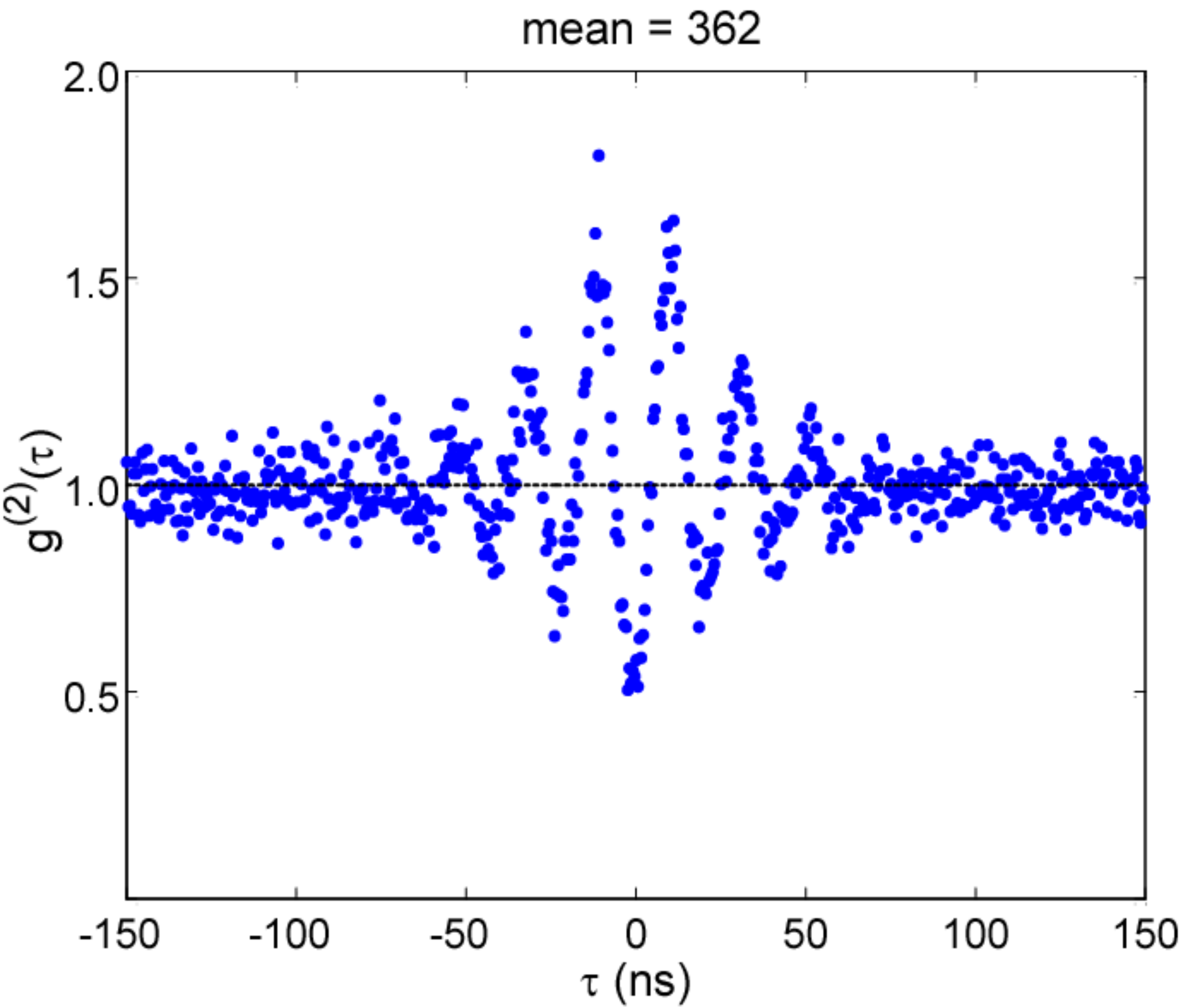


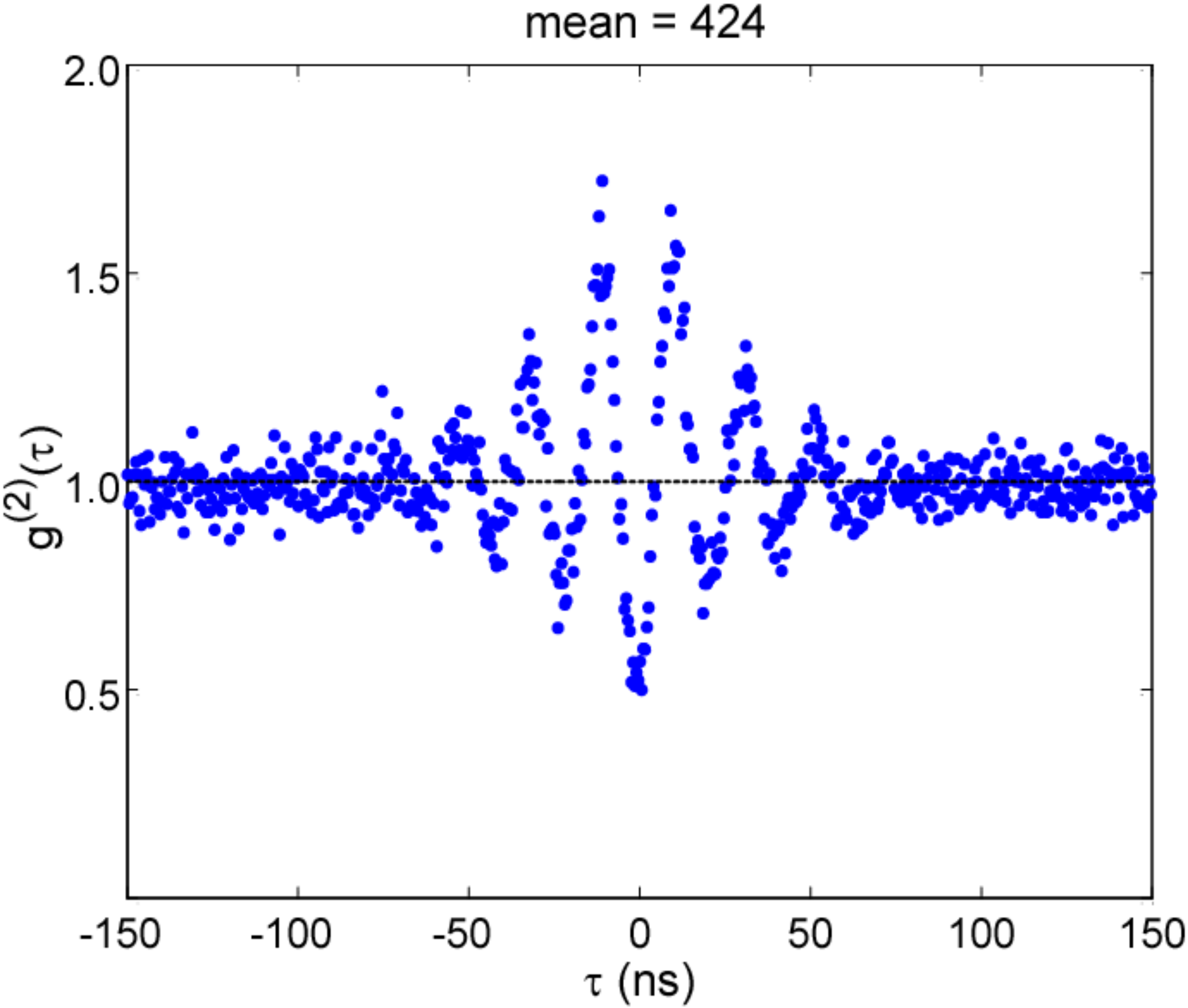
mean = 224
2.0
1.5
1.0
0.5
g^(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)



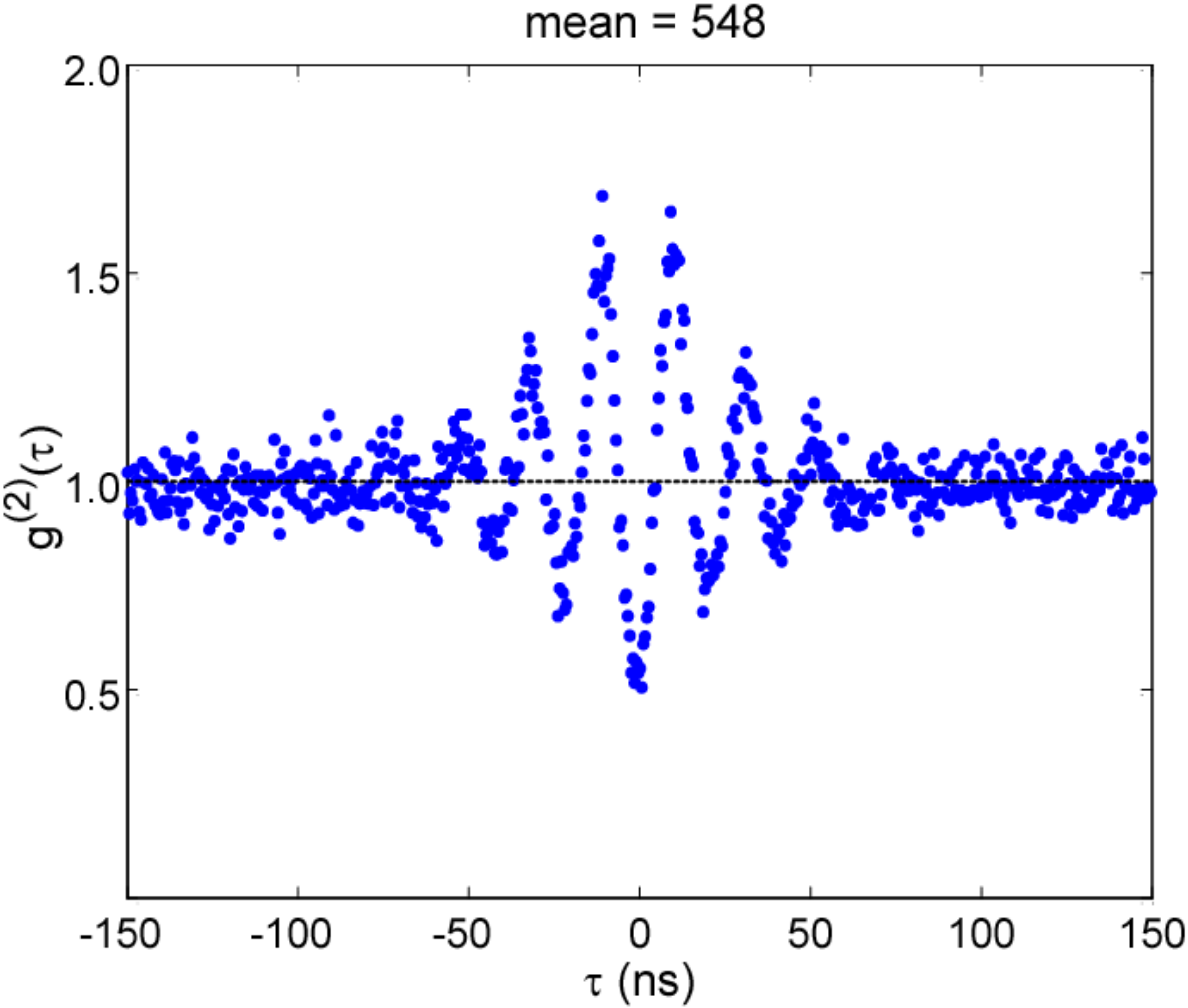
mean = 262
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

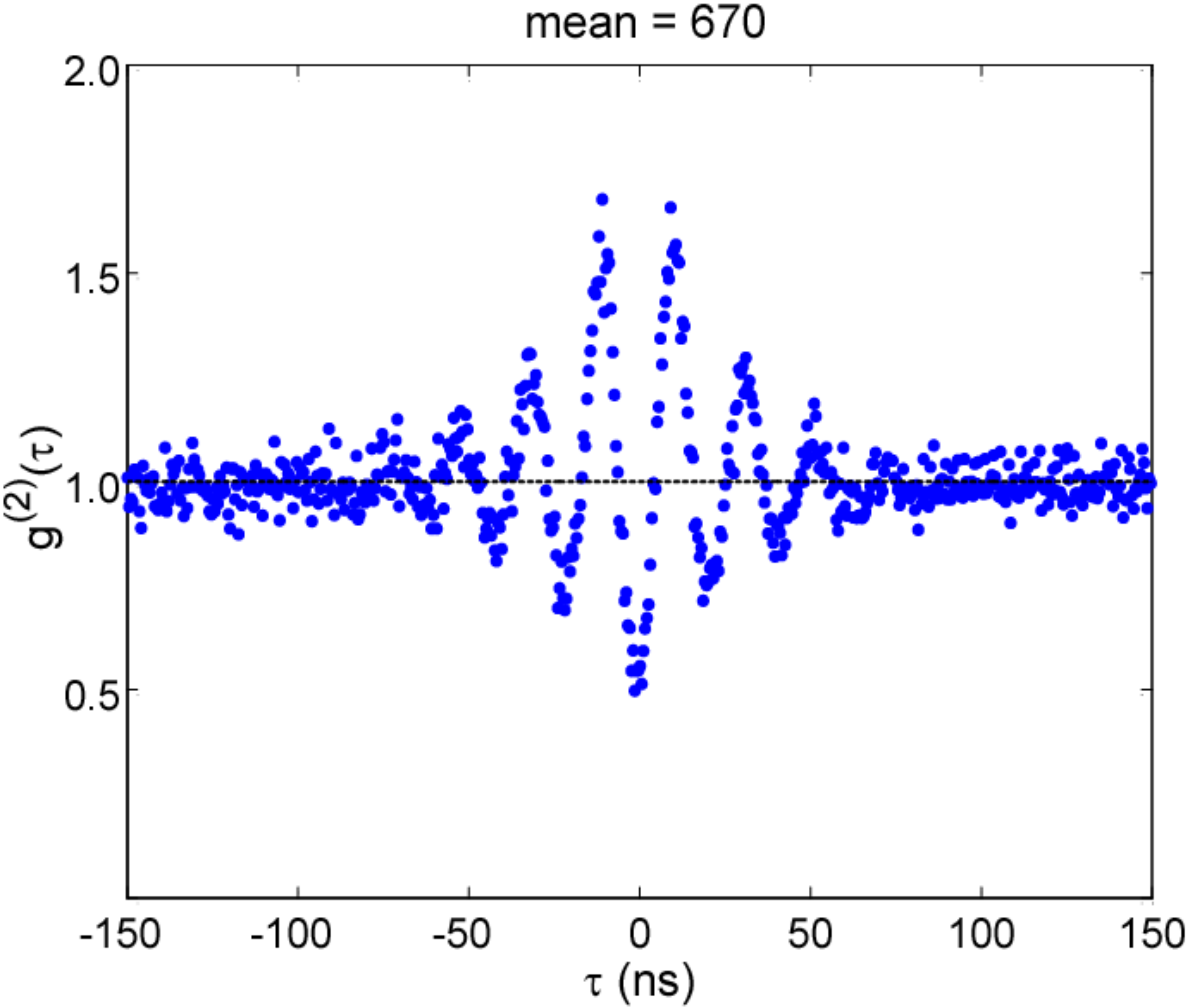

mean = 299
2.0
1.5
1.0
0.5
g(2)(τ)
-150
-100
-50
0
50
100
150
τ (ns)

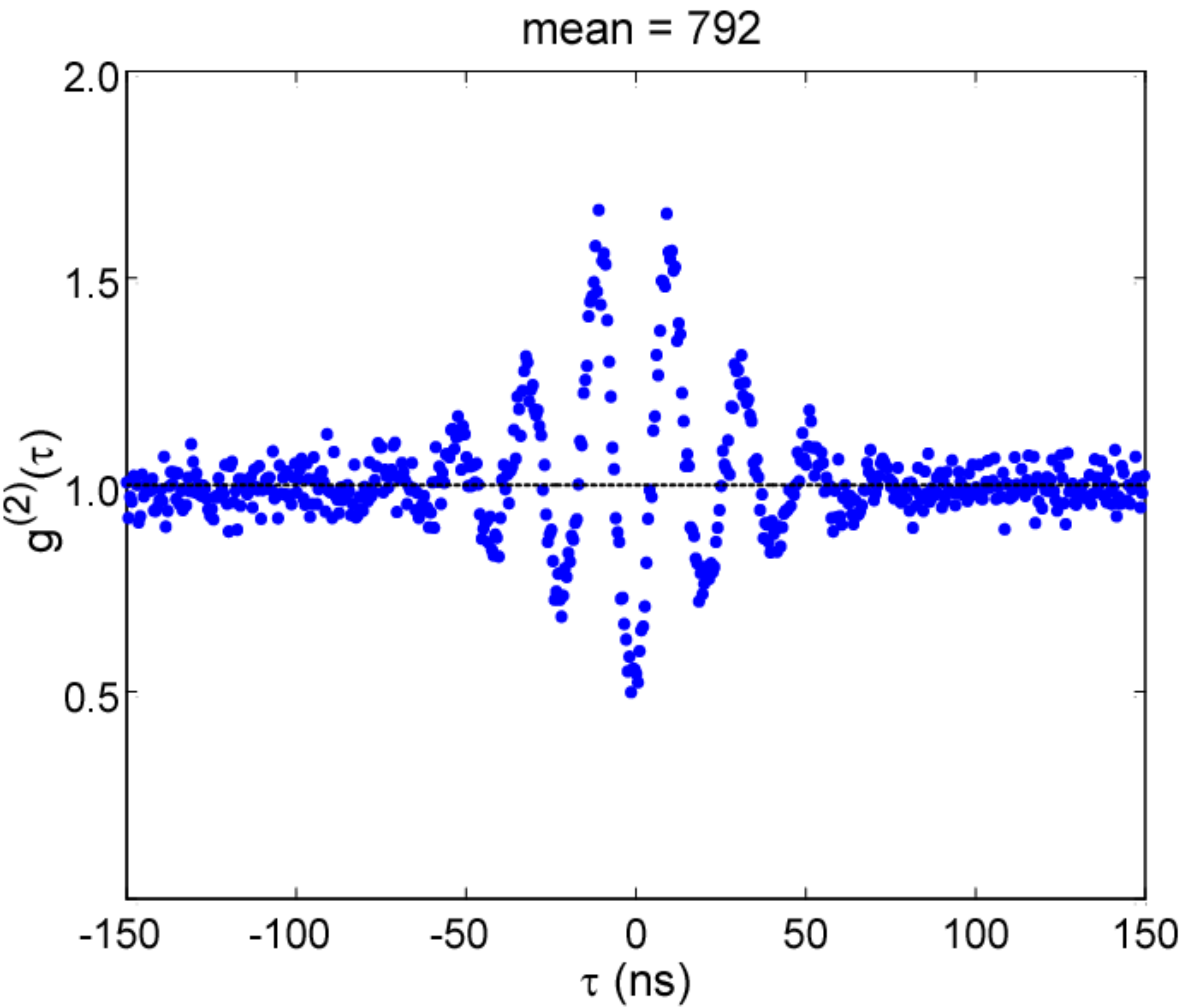

mean = 362
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)

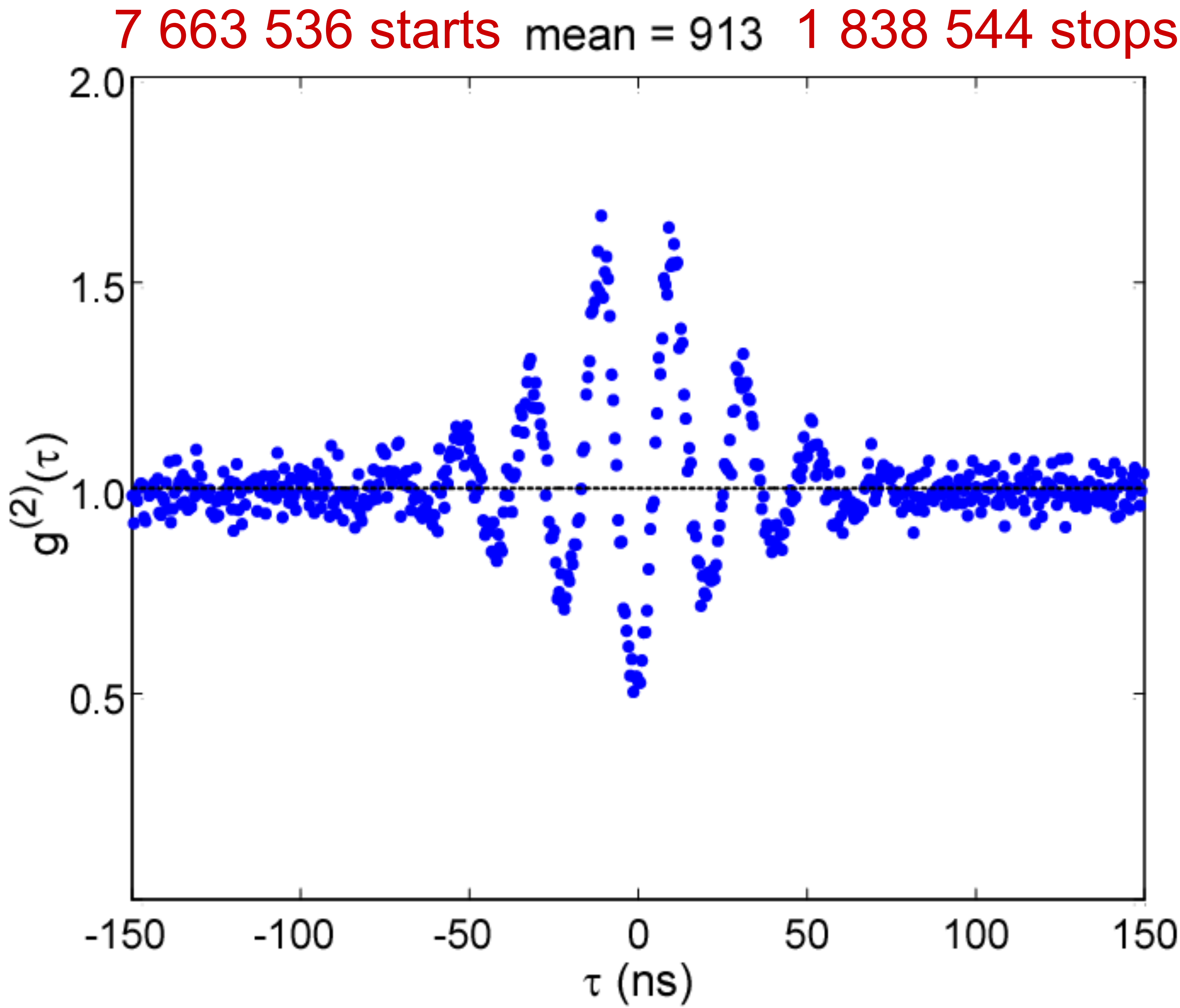


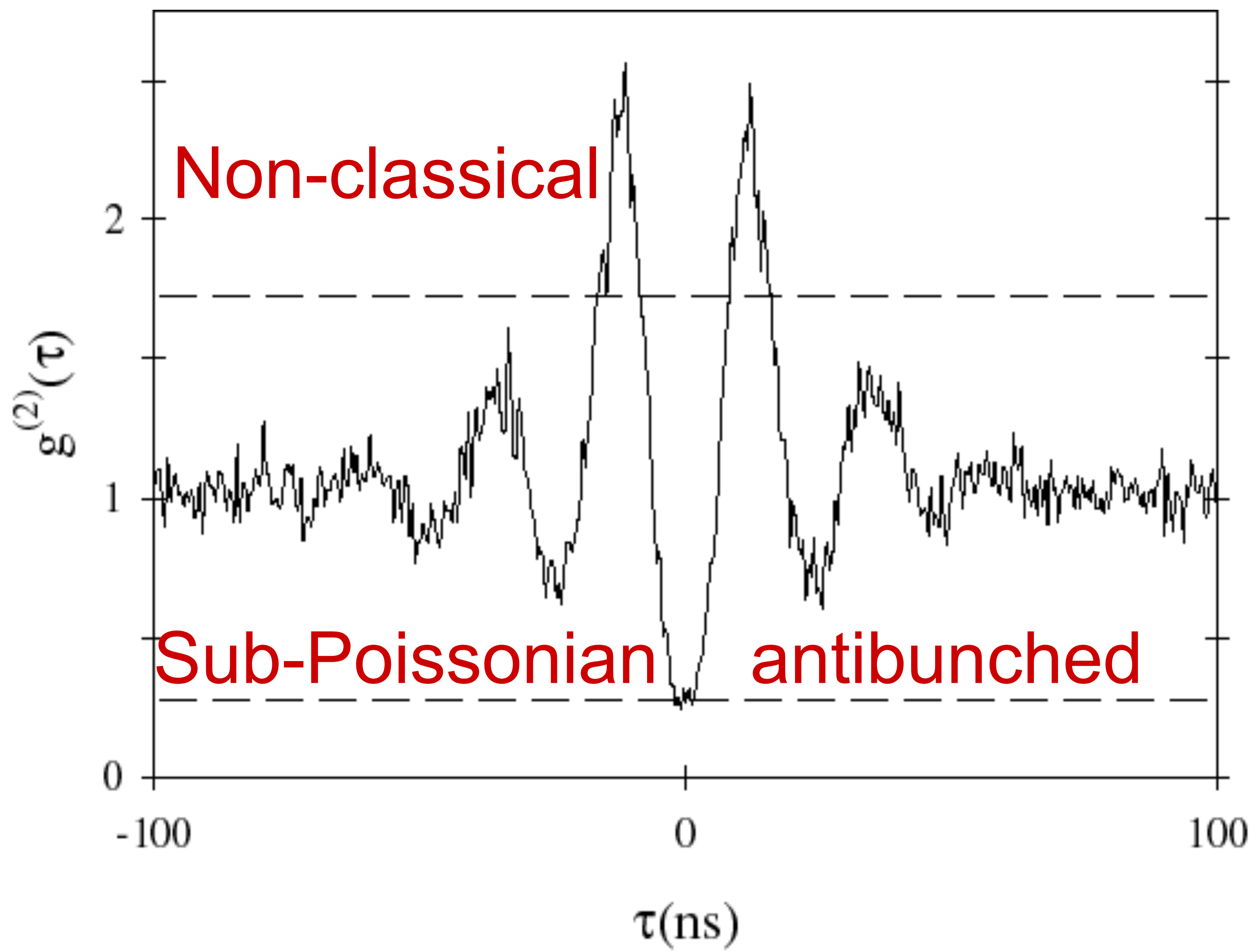
mean = 424
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)


mean = 548
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)


mean = 670
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)


mean = 792
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)


7 663 536 starts
mean = 913
1 838 544 stops
2.0
1.5
1.0
0.5
$g^{(2)}(\tau)$
-150
-100
-50
0
50
100
150
τ (ns)



Classically $g^{(2)}(0) > g^{(2)}(\tau)$ and also $|g^{(2)}(0)-1| > |g^{(2)}(\tau)-1|$

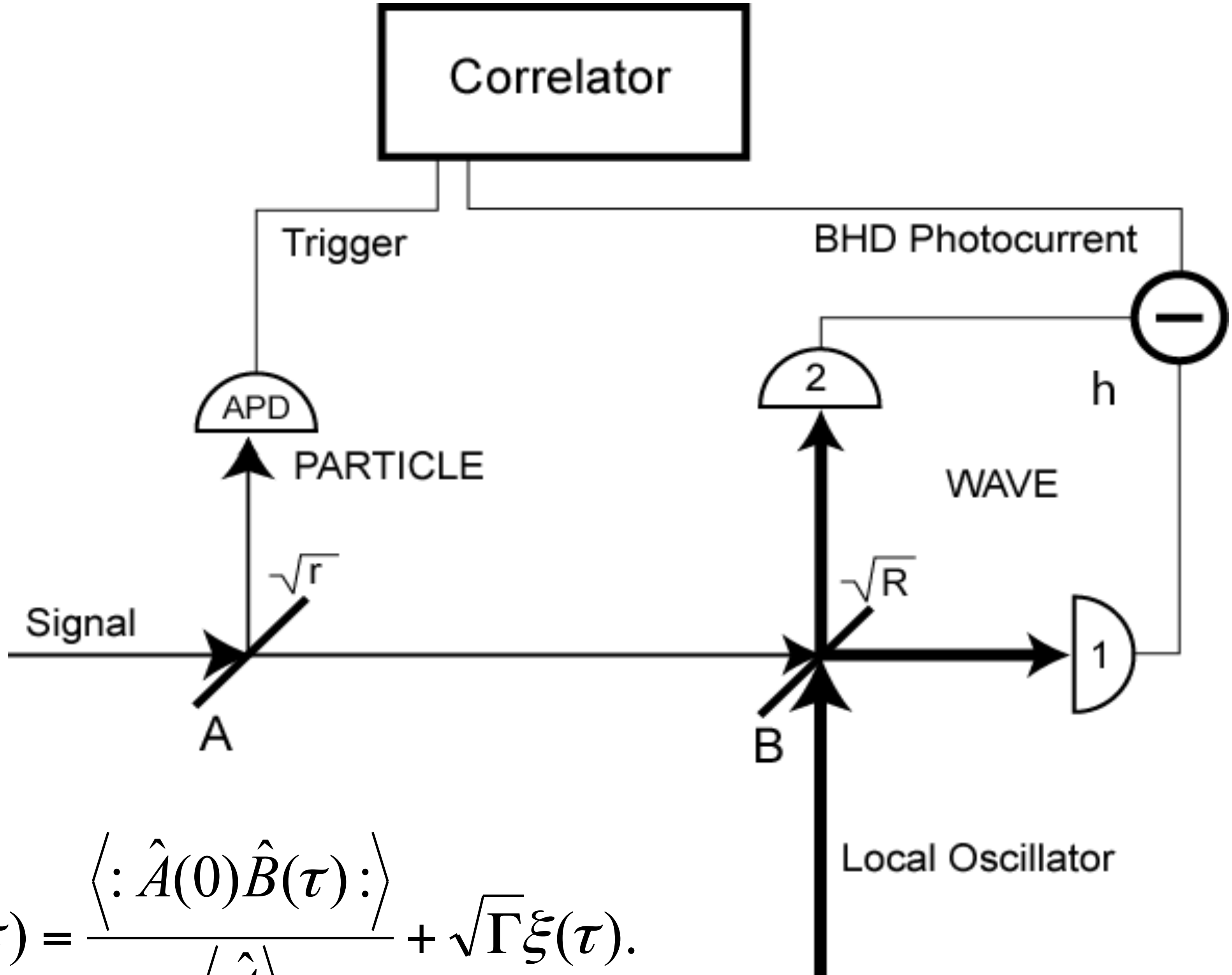
How to correlate fields and intensities?

H. J. Carmichael, G. T. Foster, L. A. Orozco, J. E. Reiner, and P. R. Rice " Intensity-Field Correlations of Non-Classical Light ". Progress in Optics, Vol. 46, 355-403, Edited by E. Wolf Elsevier, Amsterdam 2004.

Detection of the field: Homodyne.

Conditional Measurement: Only measure when we know there is a photon.

The Intensity-Field correlator.



$$\mathrm{H}(\tau) = \frac{\left\langle : \hat{A}(0)\hat{B}(\tau) : \right\rangle}{\left\langle \hat{A} \right\rangle} + \sqrt{\Gamma}\xi(\tau).$$

Condition on a Click

Measure the correlation function of the Intensity and the Field:

$<I(t)\, E(t+\tau)>$

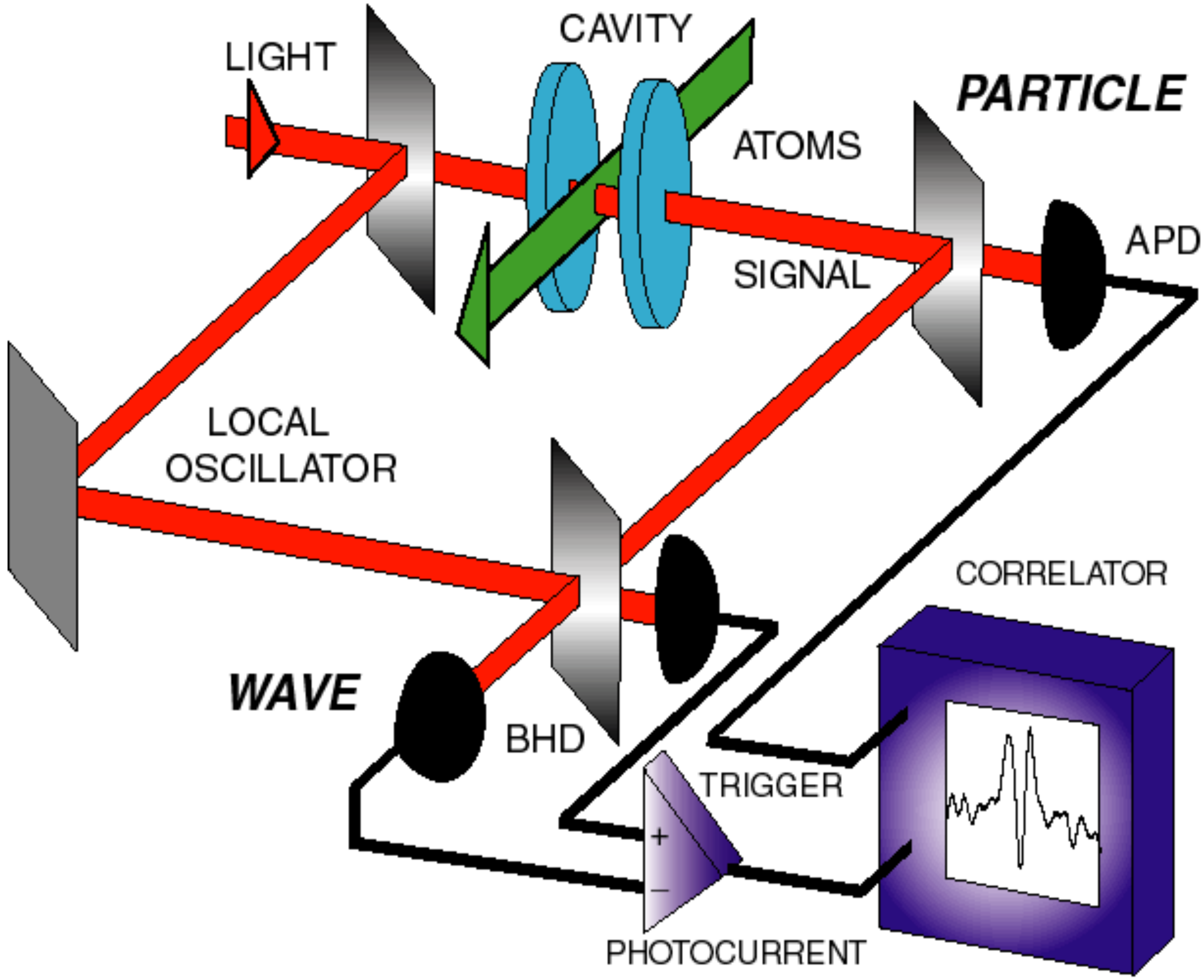
Normalized form:

$h_\theta(\tau) = <E(\tau)>_c / <E>$

From Cauchy Schwartz inequalities:

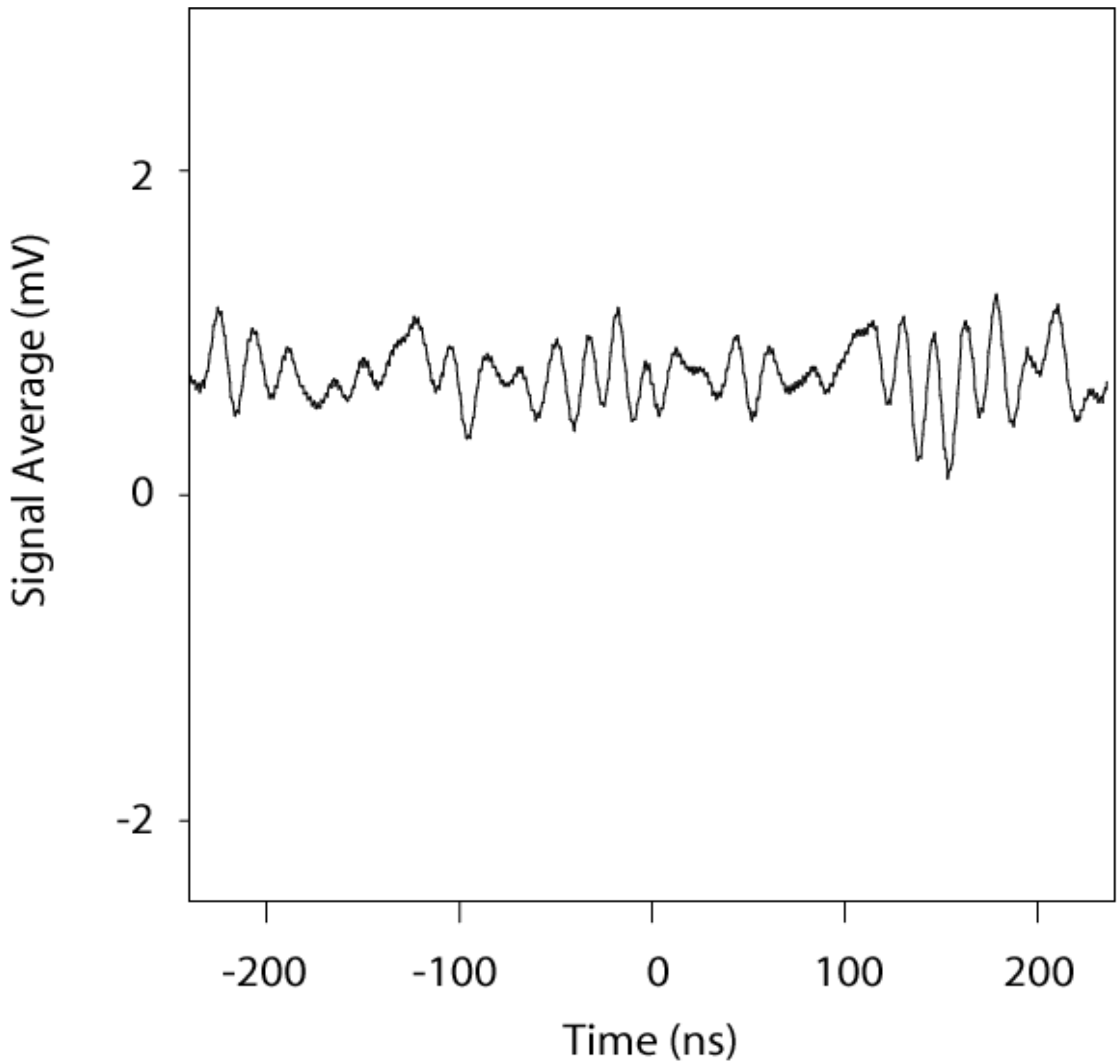
$$0 \leq \bar{h}_0(0) - 1 \leq 2$$

$$\left|\bar{h}_0(\tau) - 1\right| \leq \left|\bar{h}_0(0) - 1\right|$$

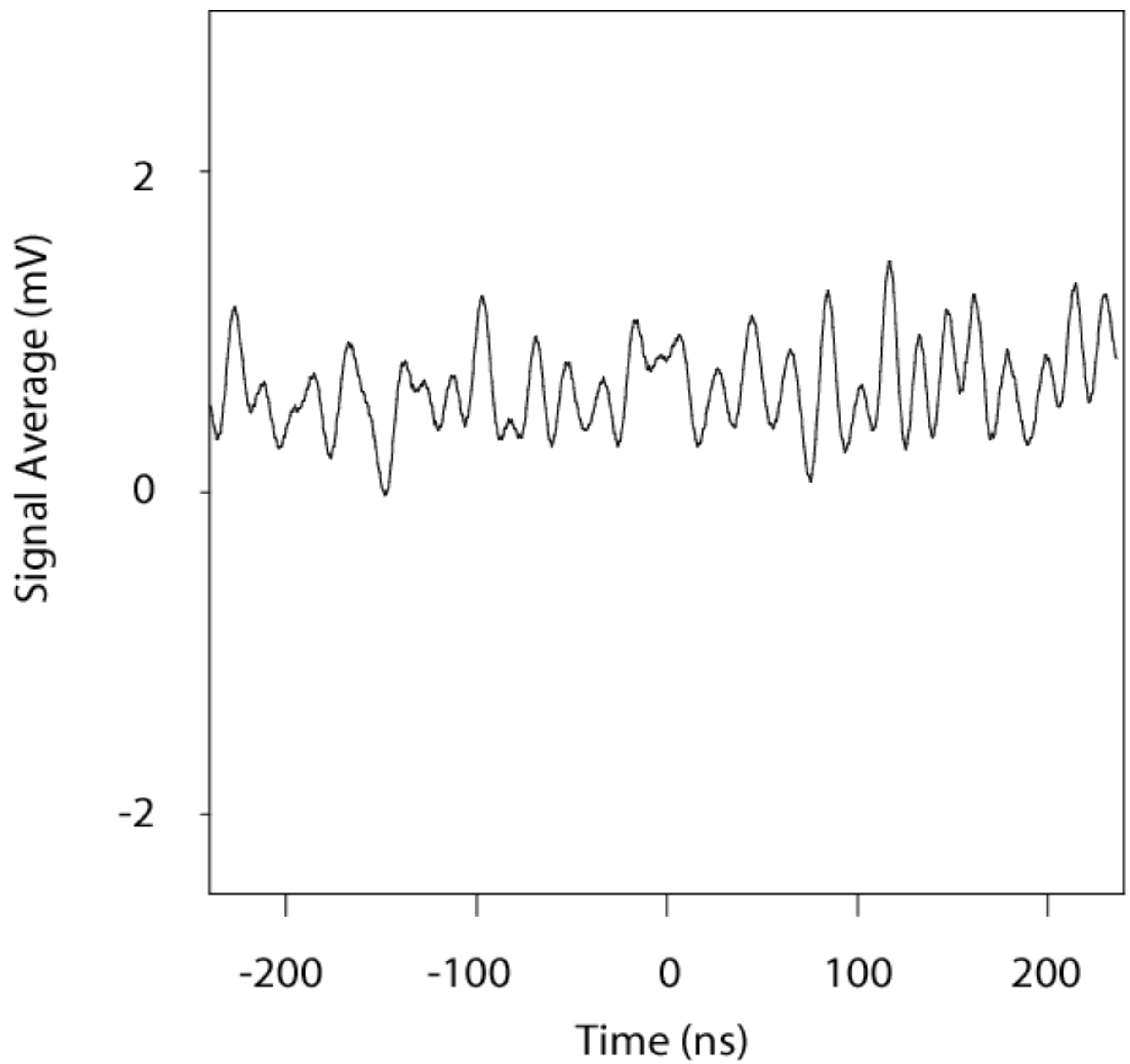


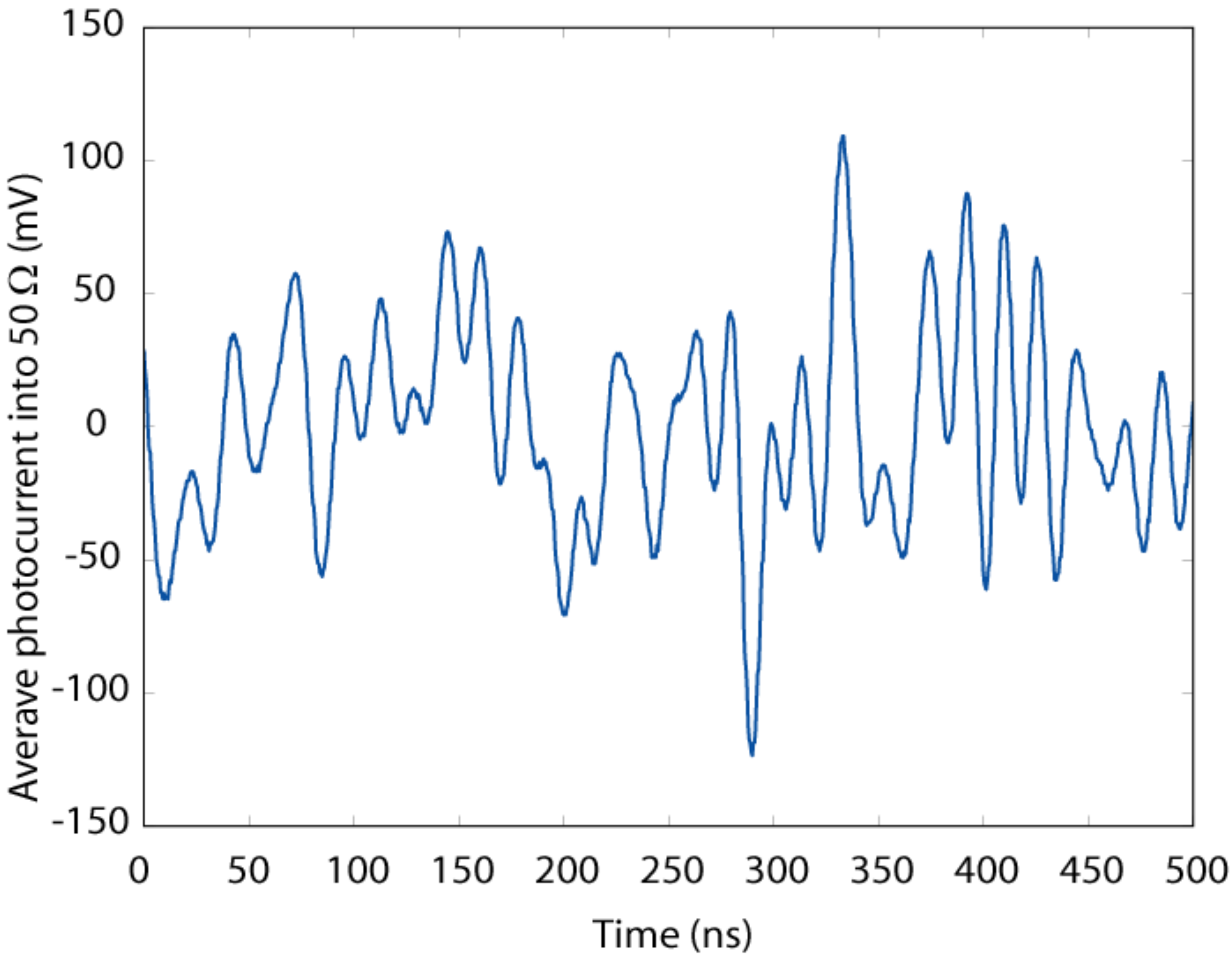
LIGHT
CAVITY
ATOMS
PARTICLE
APD
SIGNAL
LOCAL
OSCILLATOR
CORRELATOR
WAVE
BHD
TRIGGER
+
–
PHOTOCURRENT

Photocurrent average with random conditioning

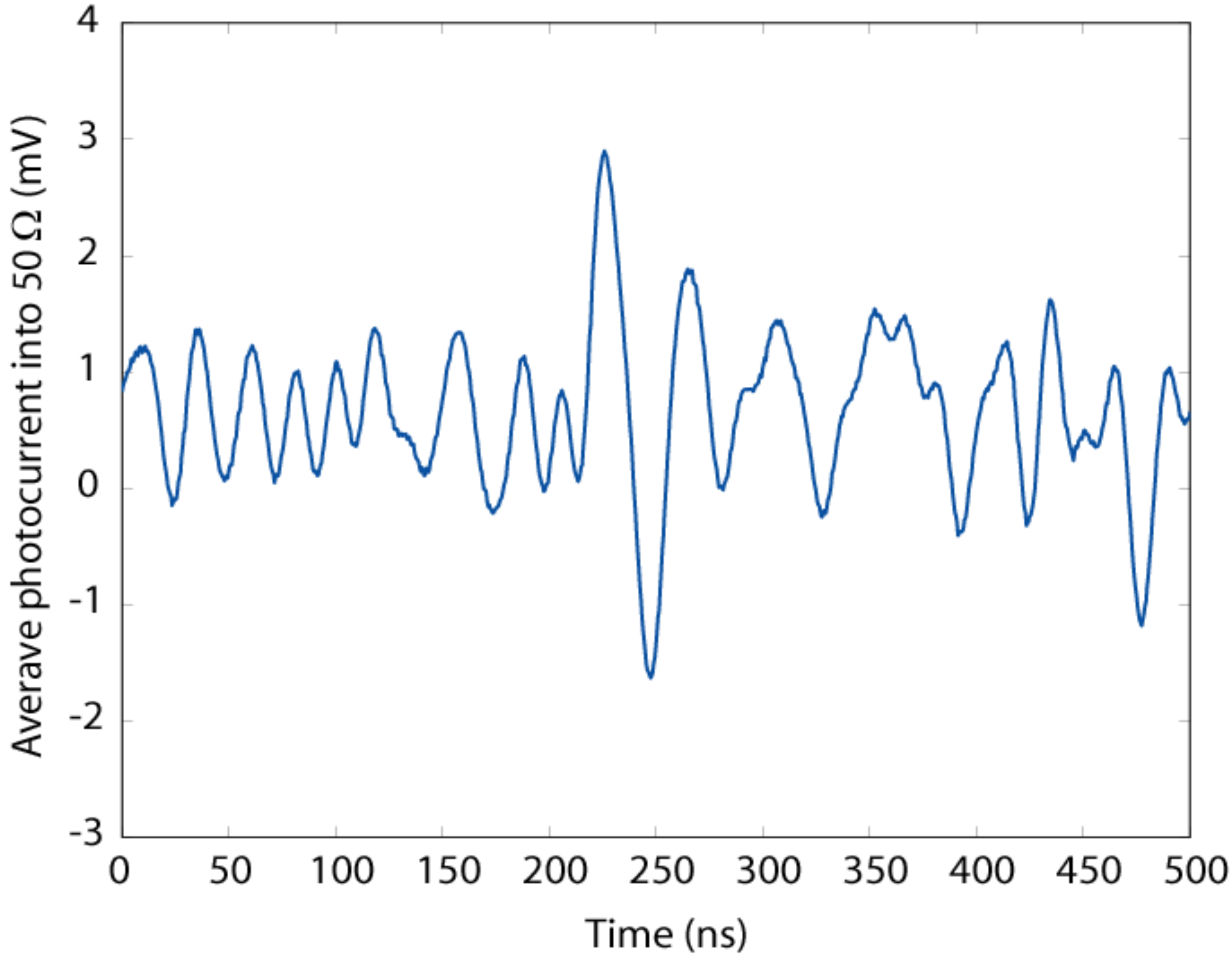


Conditional photocurrent with no atoms in the cavity.

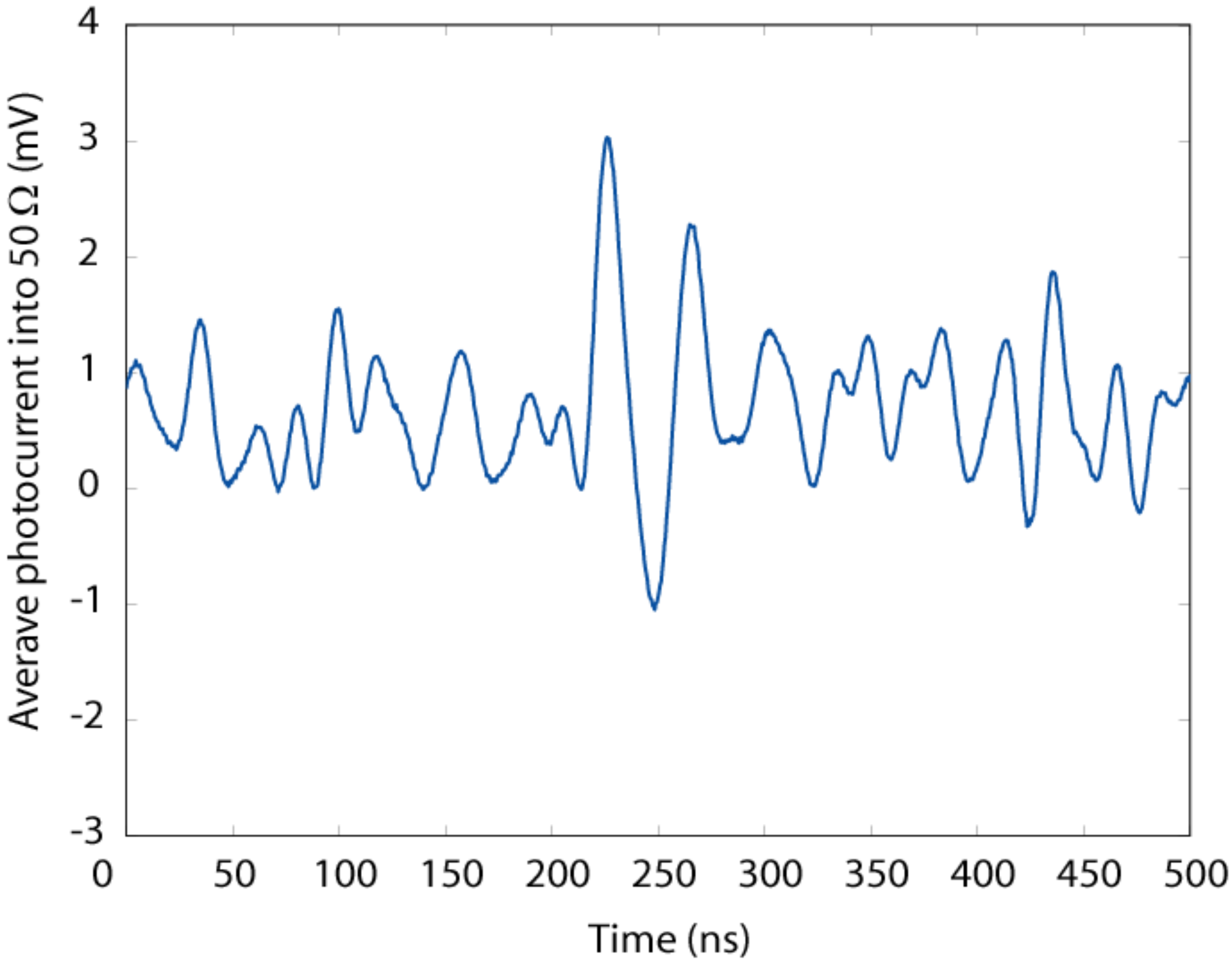




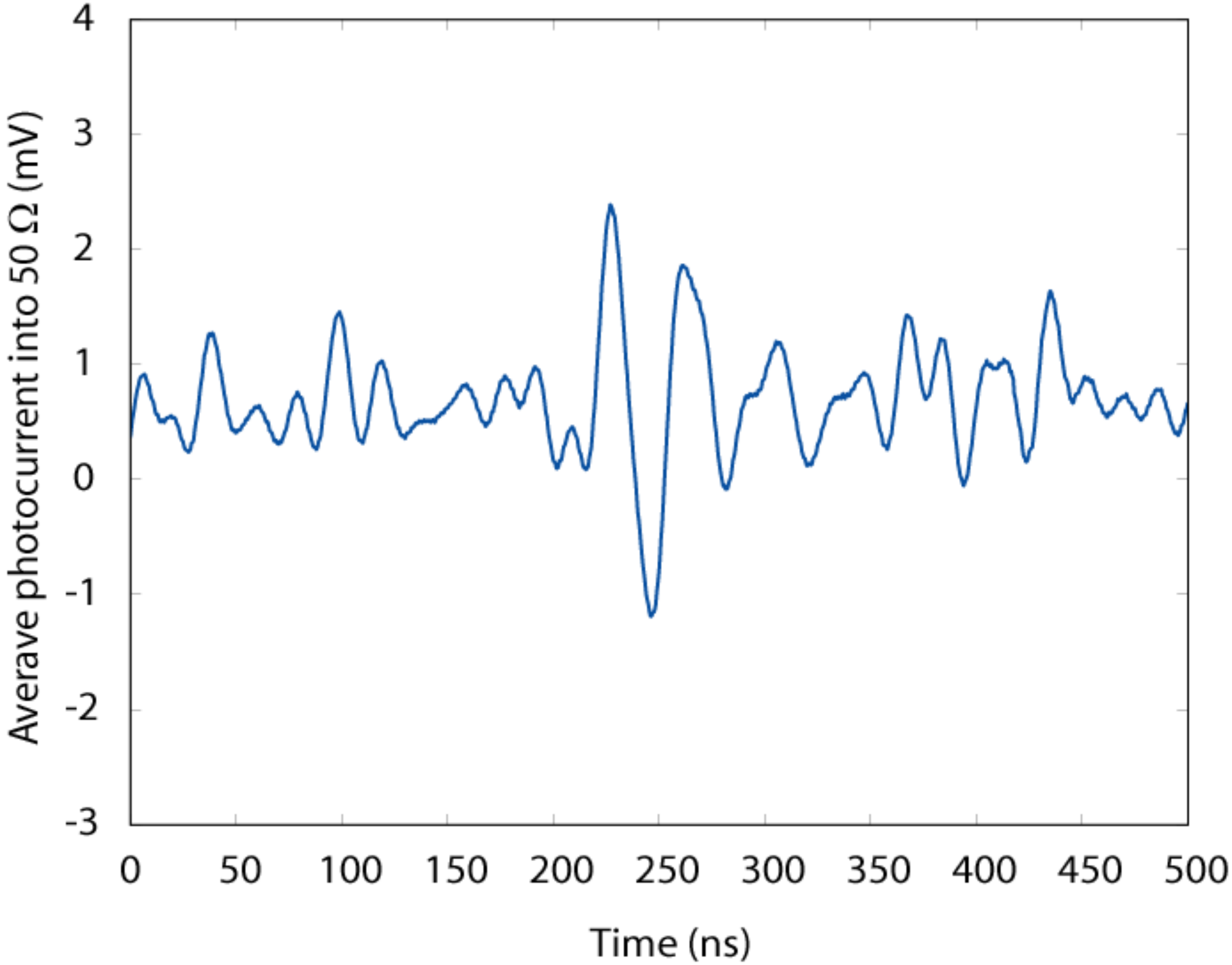
After 1 average



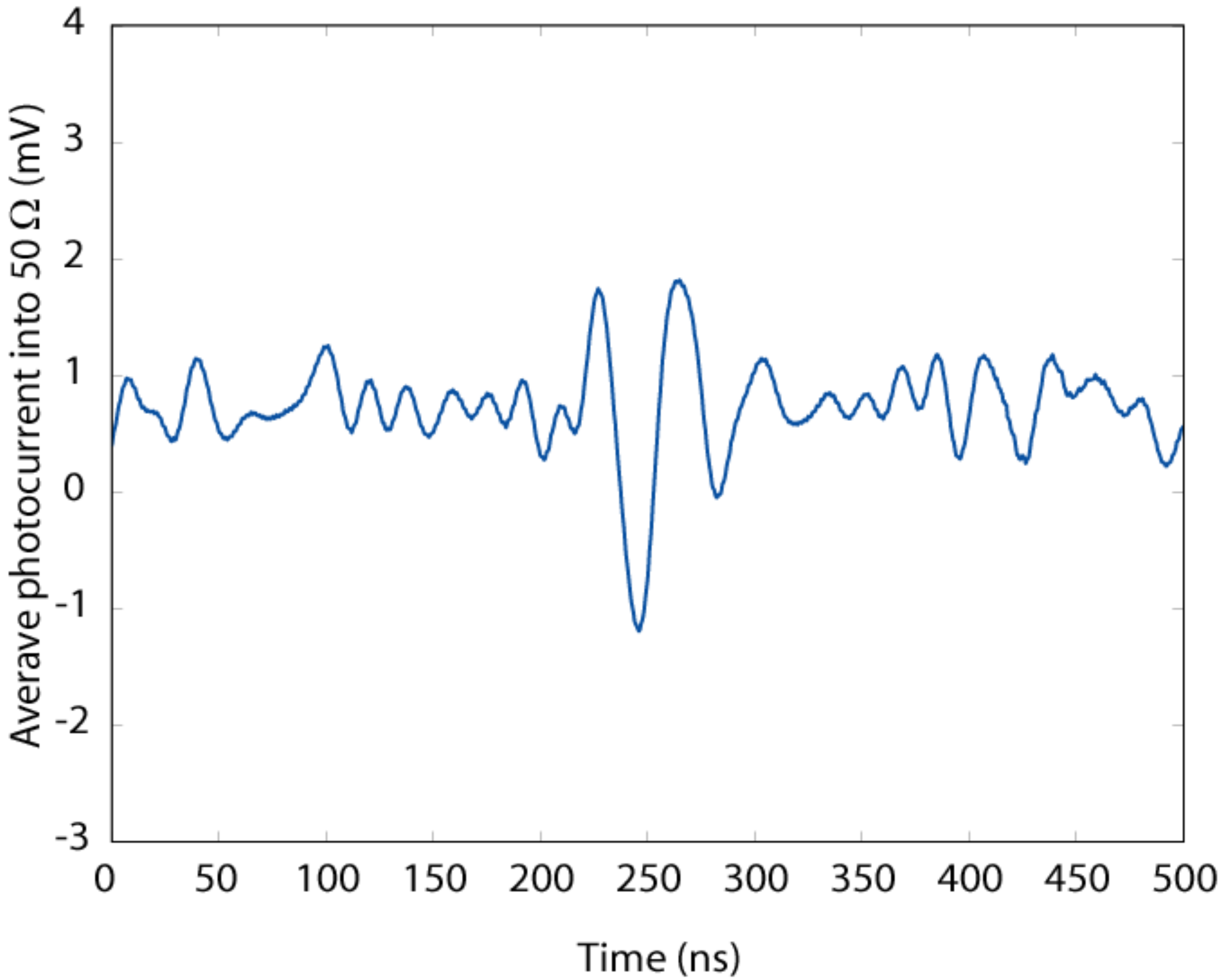
After 6,000 averages



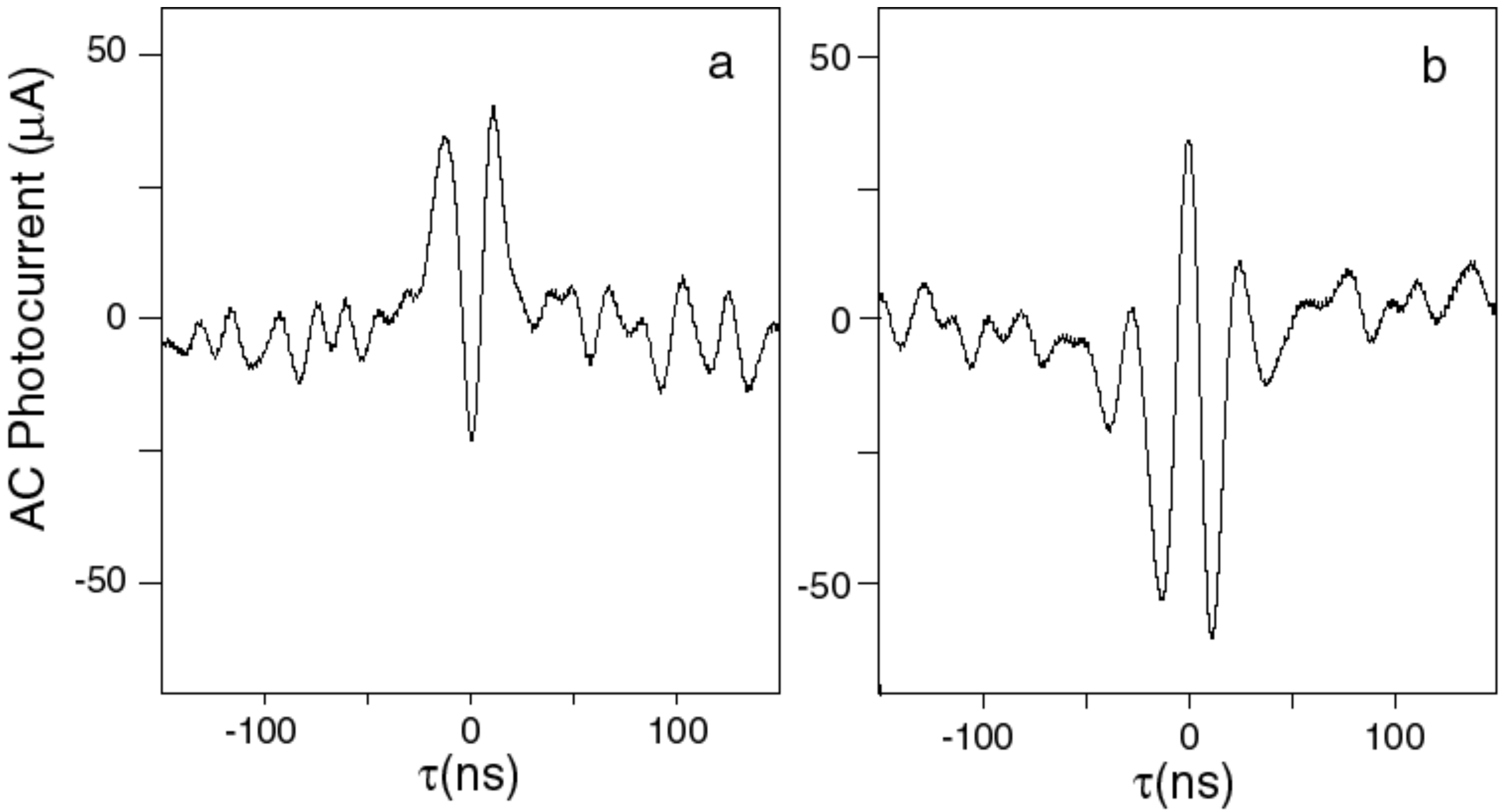
After 10,000 averages



After 30,000 averages

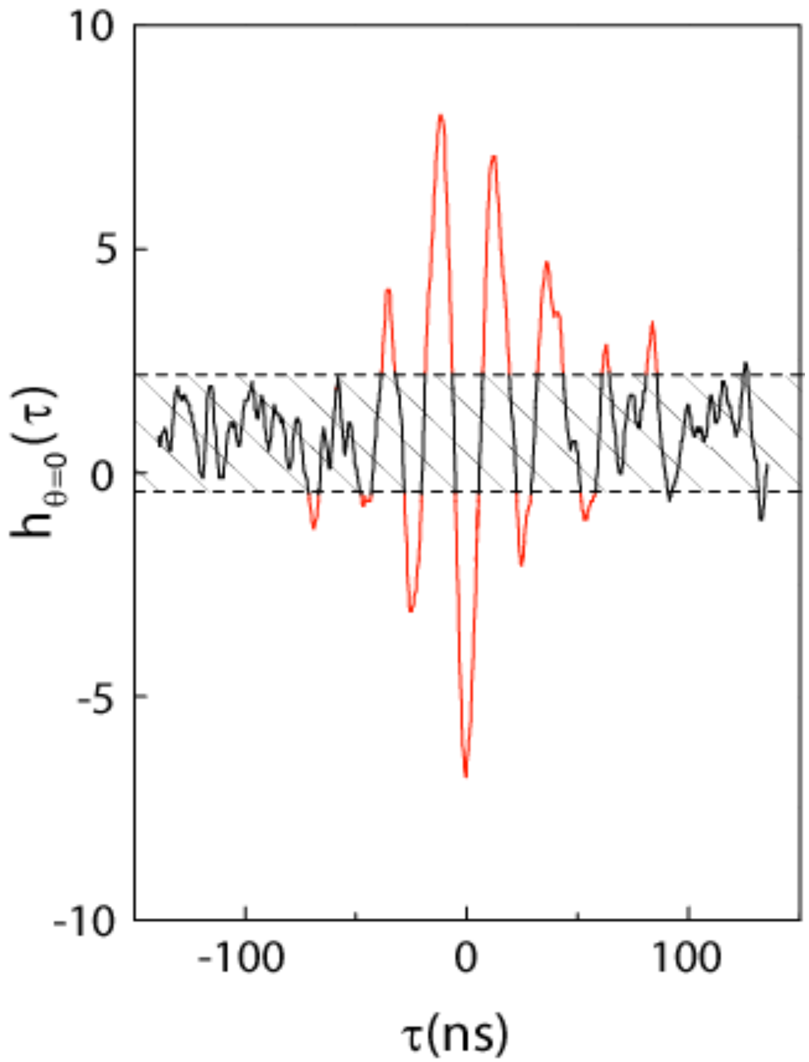


After 65,000 averages



Flip the phase of the Mach-Zehnder by 146°

Monte Carlo simulations for weak excitation:



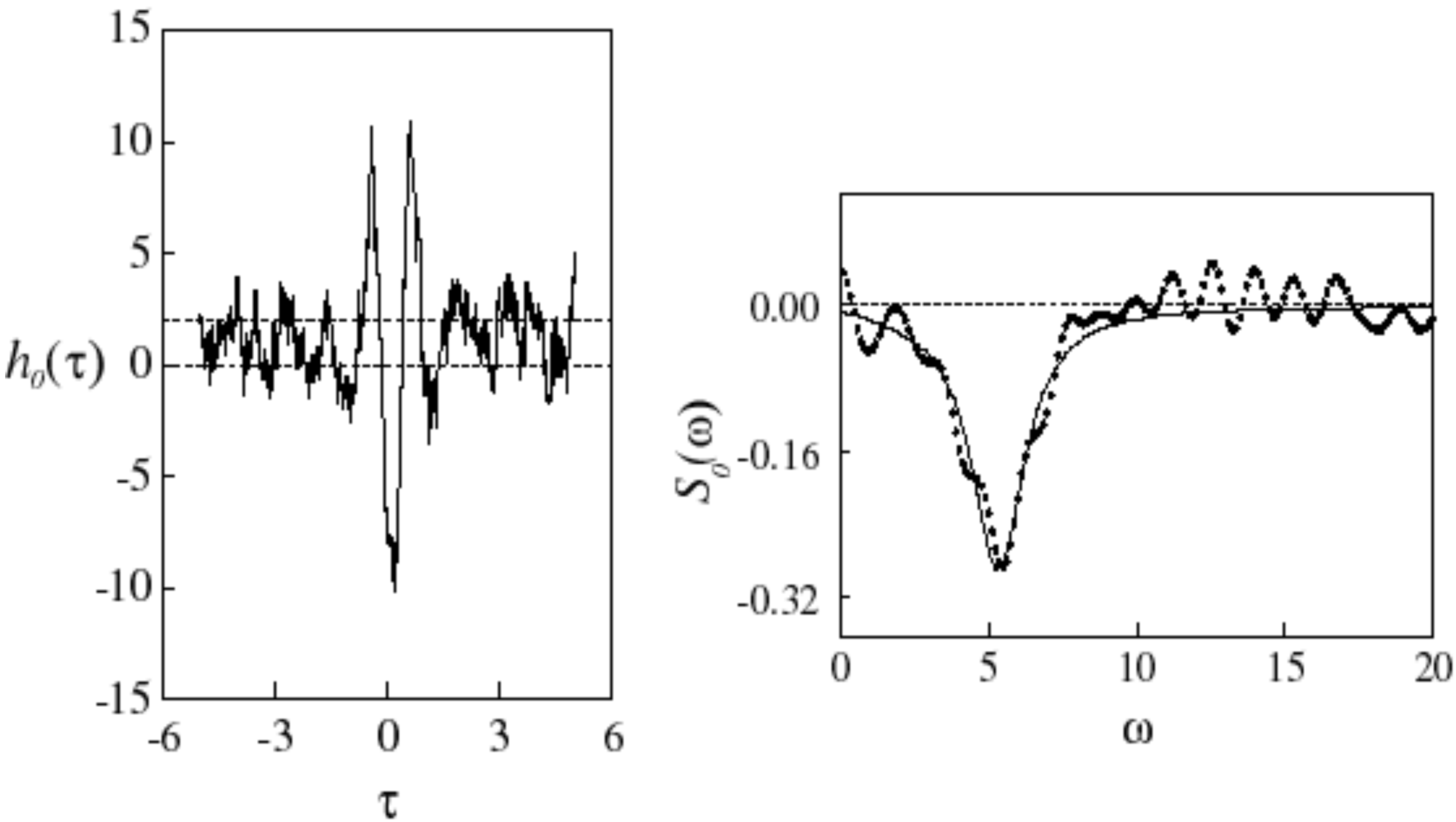
Atomic beam N=11

The fluctuations of the electromagnetic field are measured by the spectrum of squeezing. Look at the noise spectrum of the photocurrent.

$$S(\nu,0^\circ) = 4F\int_0^\infty \cos(2\pi\nu\tau)[\overline{h}_0(\tau)-1]d\tau,$$

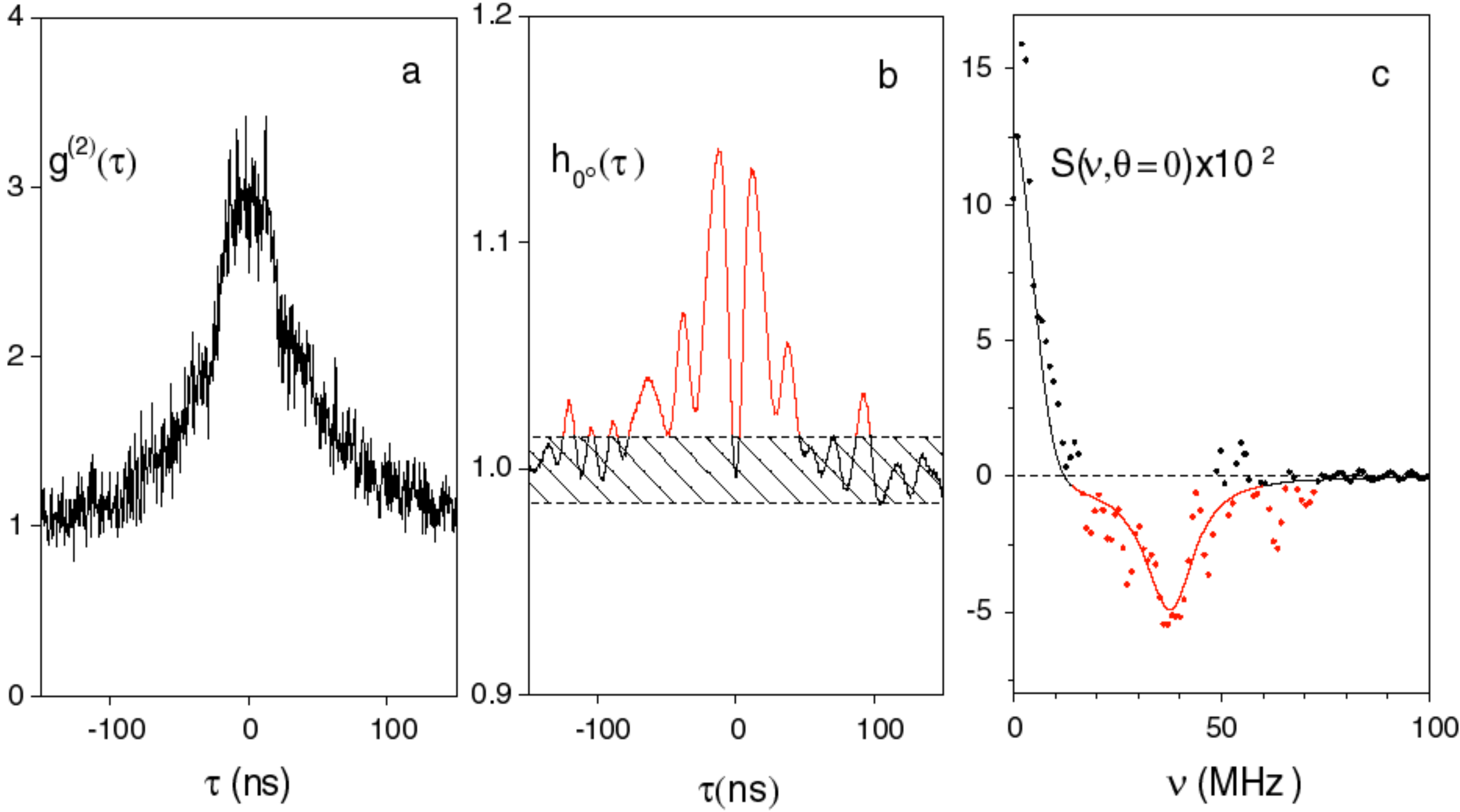
F is the photon flux into the correlator.

Monte Carlo simulations of the wave-particle correlation and the spectrum of squeezing in the low intensity limit for an atomic beam.



It has upper and a lower classical bounds

Classical $g^{(2)}$ Non-classical h Squeezing



N=13; 1.2n_0

With quantum optics we can measure and then manipulate the fluctuations of the field (Squeezing) and the intensity.

Improve the S/N ratio in LIGO, in telecomunications, etc.

Thanks