Experimental detection of strongly non-classical states of light

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Outline of the talk

I. Quantum non-Gaussian states

II. Witness of quantum non-Gaussian states

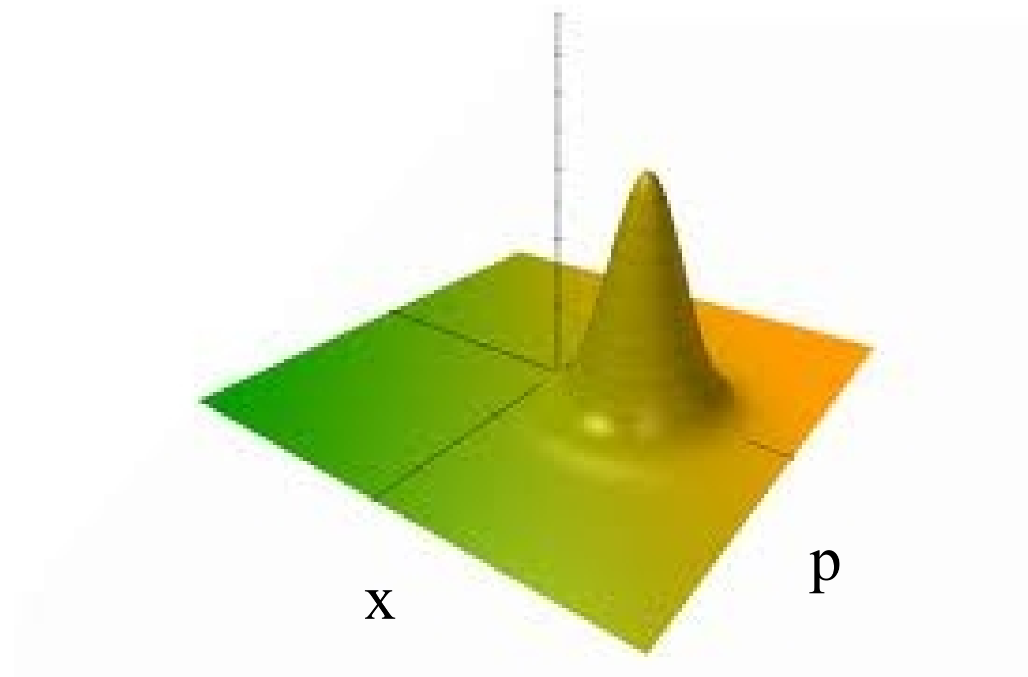
III. Application to conditionally generated heralded single-photon state

IV. Application to noisy photon subtracted squeezed vacuum state

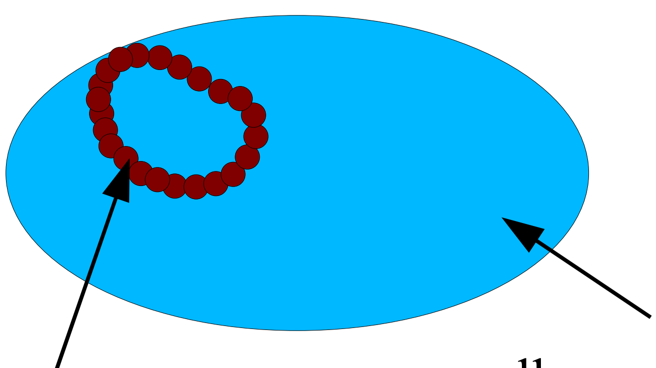
Gaussian states and their mixtures

Gaussian states

- Possess Gaussian Wigner function
- Thermal, coherent and squeezed states
- Admit simple analytical desription
- Can be easily generated experimentally
- Crucial resource in CV QIP
- Do not form convex set



$$[x, p] = i$$



$$W(x, p) = \frac{ab}{\pi} e^{-a^2(x-x_0)^2 - b^2(p-p_0)^2}$$

Gaussian states and their mixtures

Gaussian states

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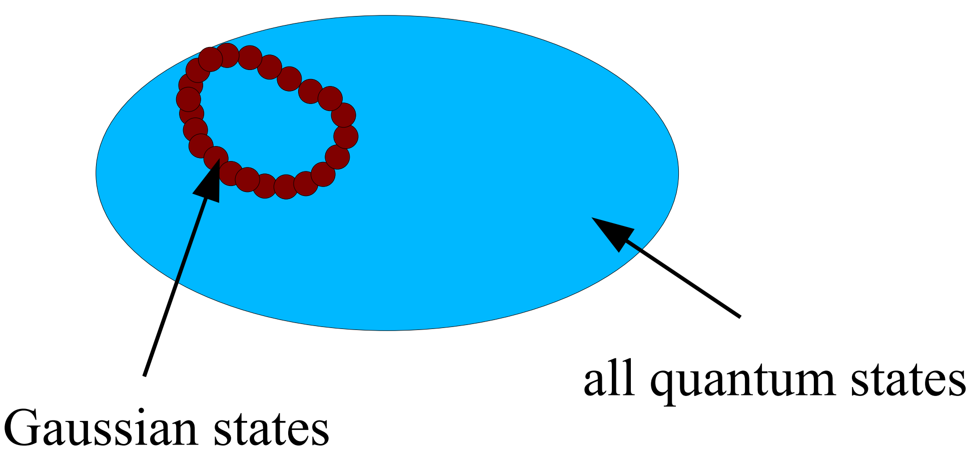


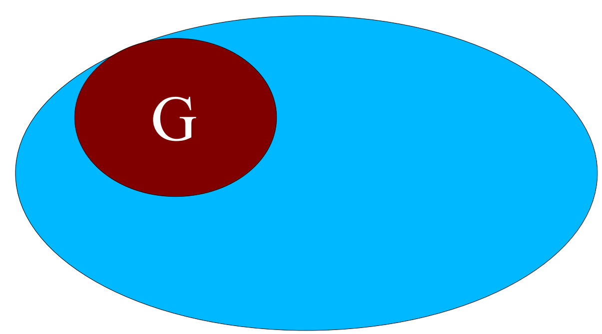
Mixtures of Gaussian states

Set **G** of ll states of the form

$$\rho = \int P(\lambda)\rho_G(\lambda)\mathrm{d}\lambda$$

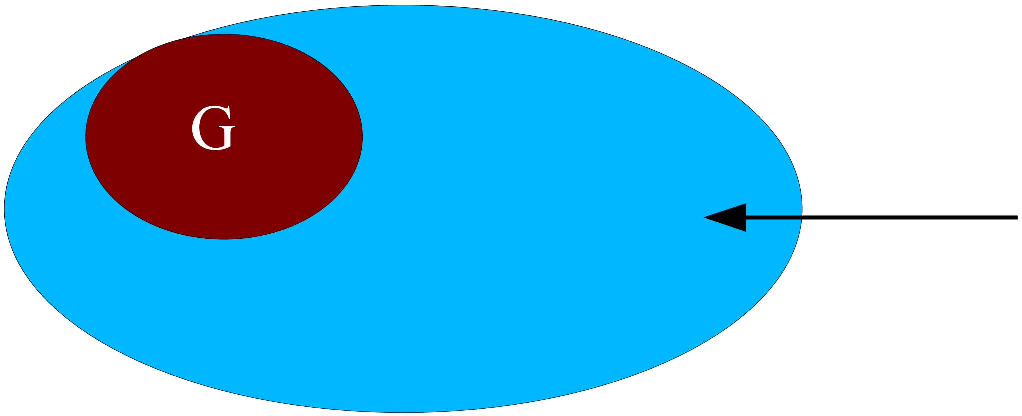
$$\int P(\lambda)\mathrm{d}\lambda = 1 \qquad P(\lambda) \geq 0$$

$\rho_G(\lambda)$ … Gaussian state parameterized by λ



G is a convex set

Quantum non-Gaussian states



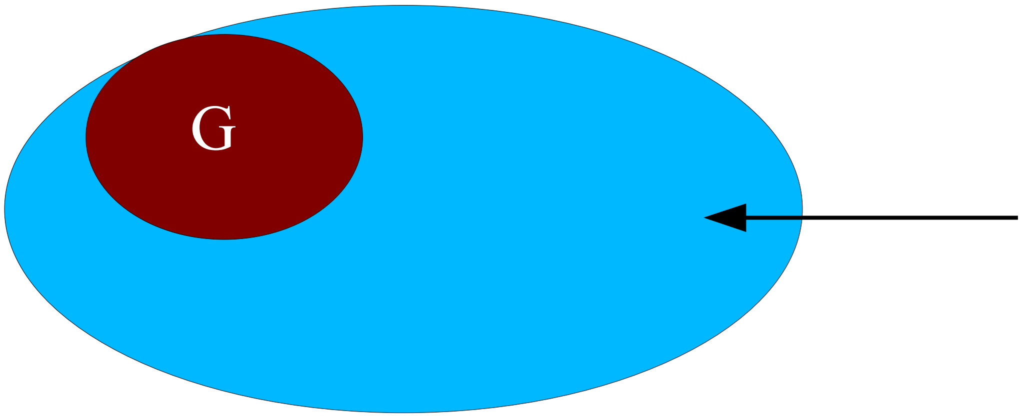
$$\rho \neq \int P(\lambda)\rho_G(\lambda)\,\mathrm{d}\lambda$$

$$P(\lambda) \geq 0$$

- Defined as states that do not belong to **G**

R. Filip and L. Mišta, Jr., Phys. Rev. Lett. **106**, 200401 (2011).

Quantum non-Gaussian states



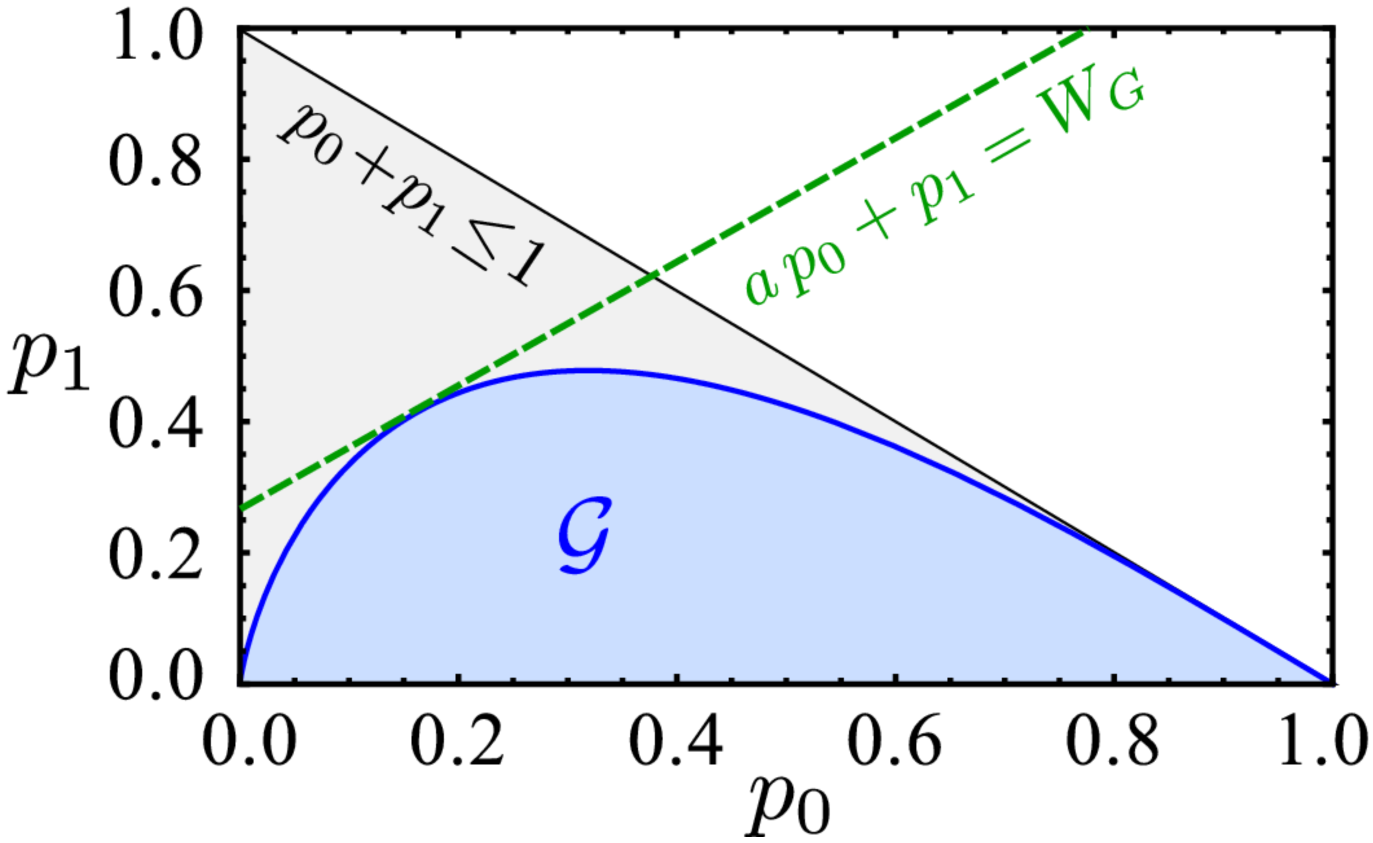
$$\rho \neq \int P(\lambda)\rho_G(\lambda)\,\mathrm{d}\lambda$$

$$P(\lambda) \geq 0$$

- Defined as states that do not belong to **G**
- Quantum non-Gaussian states cannot be generated from vacuum by passive linear optics, squeezing, and classical mixing
- Some higher-order nonlinearity must be involved in their generation
- Quantum non-Gaussian states can exhibit positive Wigner function

R. Filip and L. Mišta, Jr., Phys. Rev. Lett. **106**, 200401 (2011).

Witness of quantum non-Gaussian character

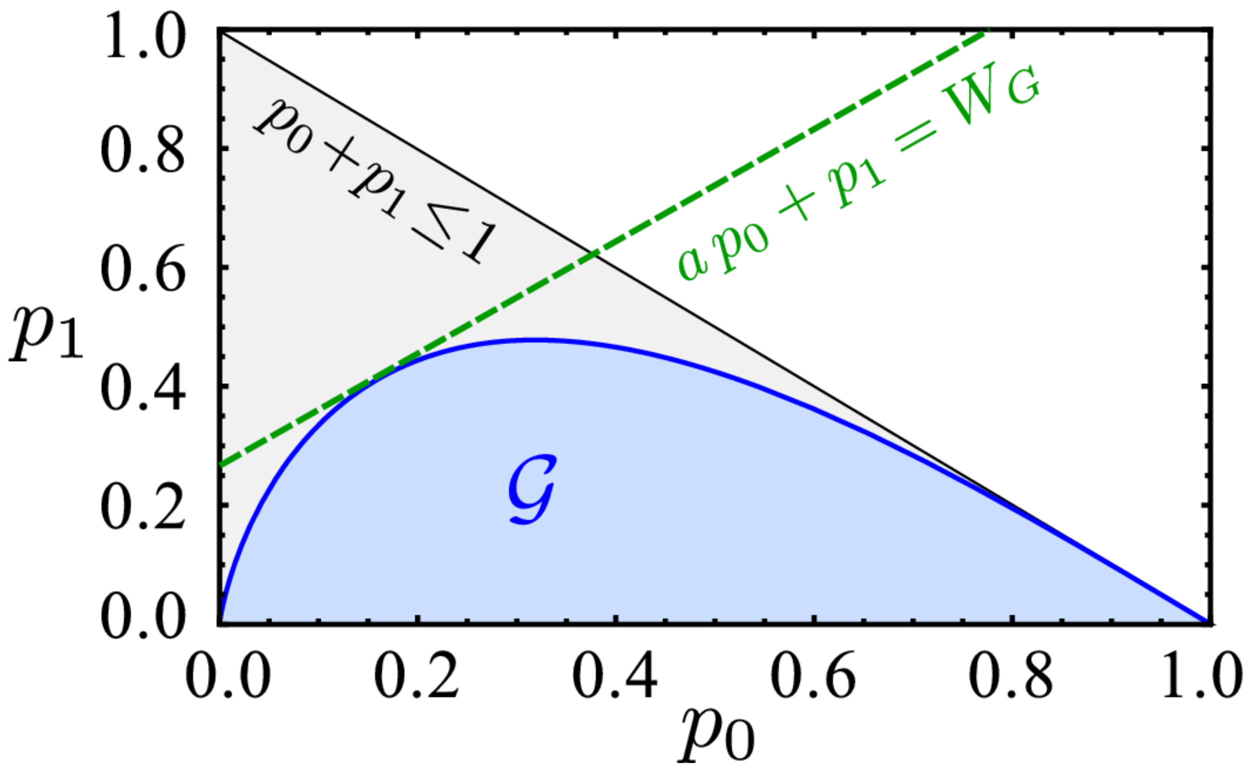


- Based on probabilities of vacuum and single-photon states
- If p_1 exceeds certain bound for fixed p_0 then the state is quantum non-Gaussian

R. Filip and L. Mišta, Jr., Phys. Rev. Lett. **106**, 200401 (2011).

M. Ježek, I. Straka, M. Mičuda, M. Dušek, J. Fiurášek, and R. Filip, Phys. Rev. Lett. **107**, 213602 (2011).

Witness of quantum non-Gaussian character

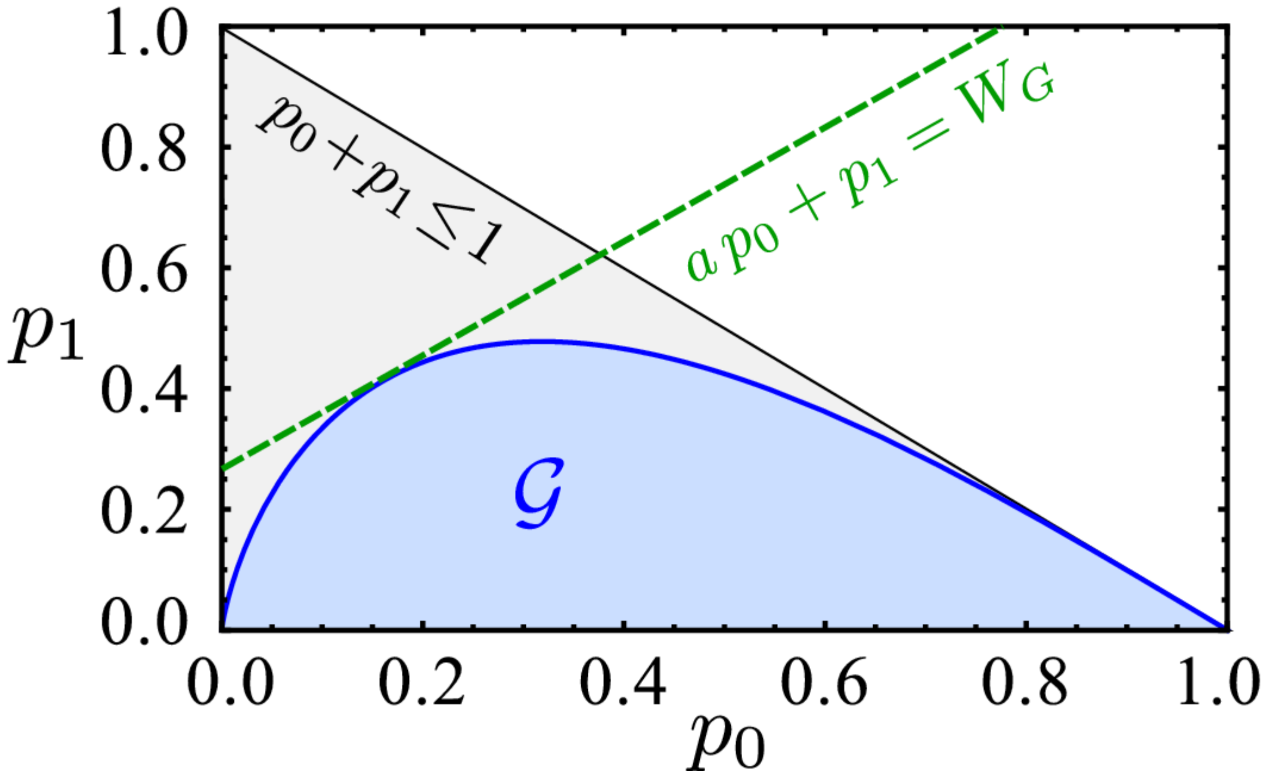


Analytical parametric description of the Gaussian boundary

– obtained by maximization of p_1 for a fixed p_0 over pure squeezed coherent states

$$p_0=\frac{e^{-d^2[1-\tanh(r)]}}{\cosh(r)} \qquad p_1=\frac{d^2 e^{-d^2[1-\tanh(r)]}}{\cosh^3(r)} \qquad d^2=\frac{e^{4r}-1}{4}$$

Witness of quantum non-Gaussian character

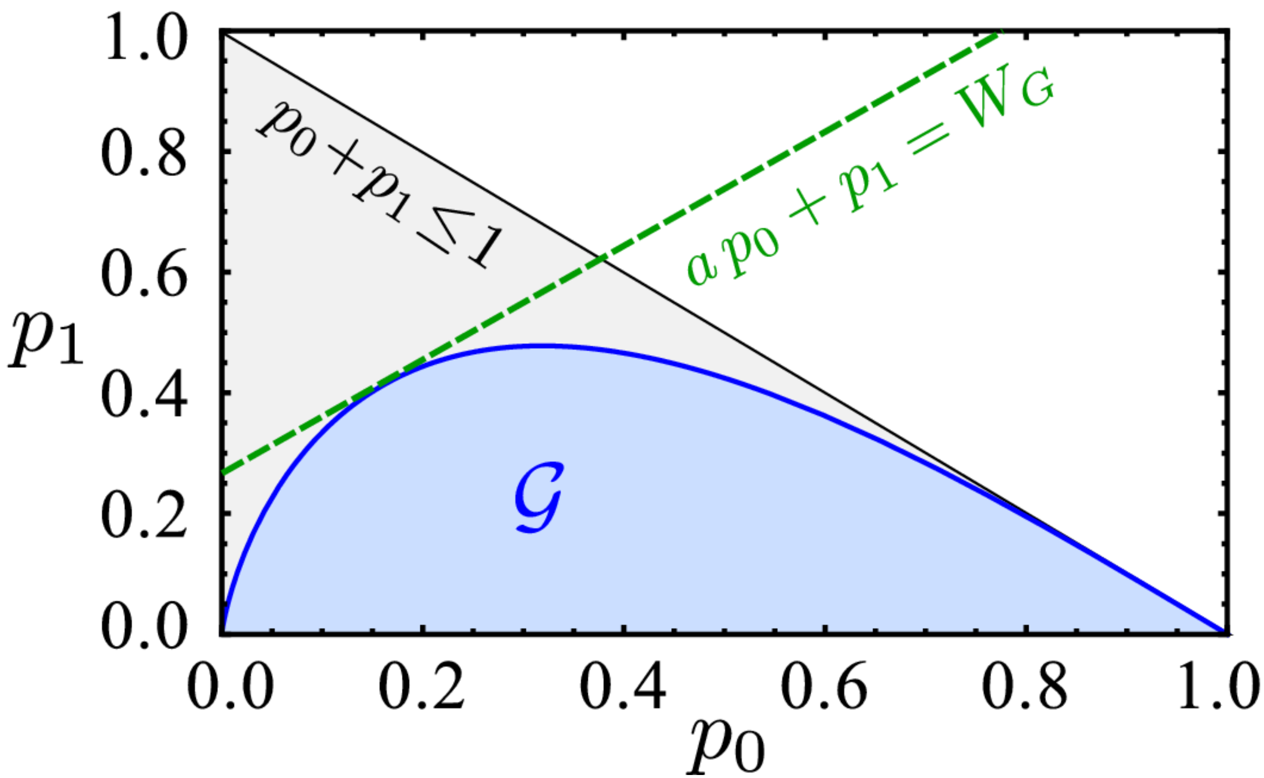


$$W = ap_0 + p_1 \qquad a < 1$$

$$W_G = \max_G (ap_0 + p_1)$$

The state is quantum non-Gaussian if $\quad W > W_G$

Witness of quantum non-Gaussian character



$$W = ap_0 + p_1 \qquad a < 1$$

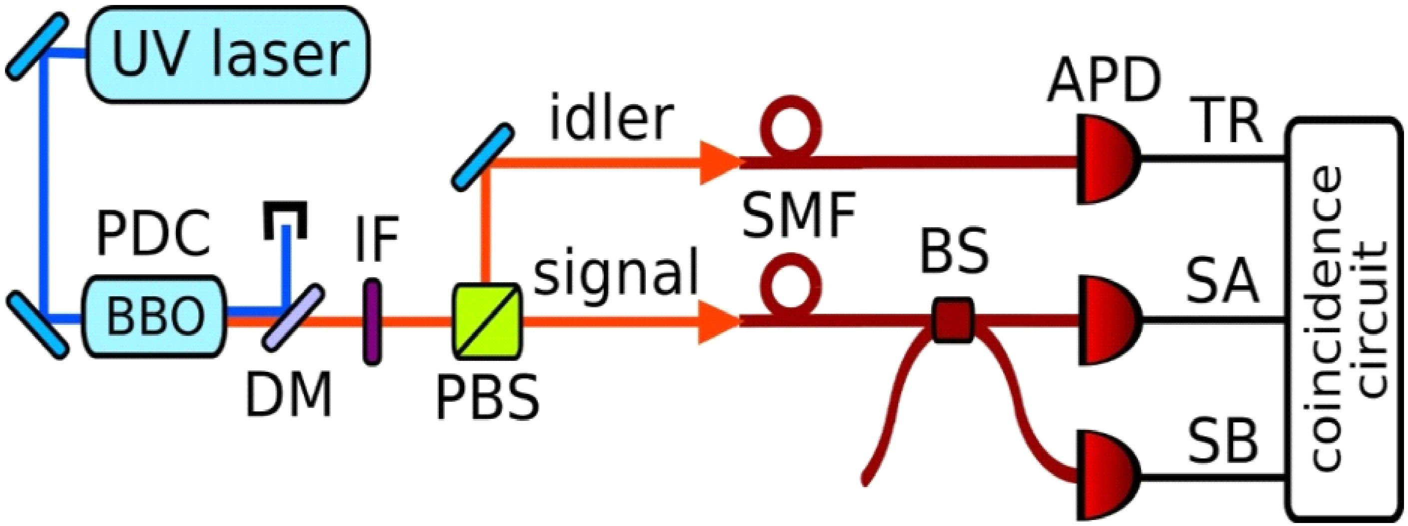
$$W_G = \max_G (ap_0 + p_1)$$

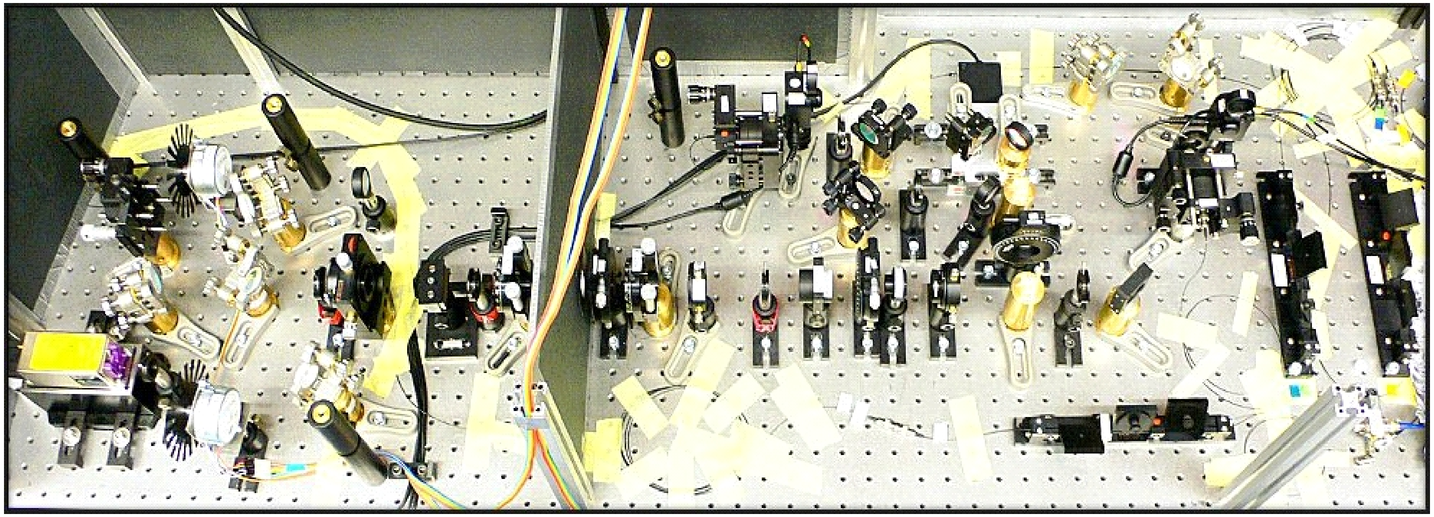
The state is quantum non-Gaussian if $W > W_G$

This witness can detect quantum non-Gaussian states with positive Wigner function, e.g.:

$$\rho = (1-p)|0\rangle\langle 0| + p|1\rangle\langle 1|$$

Heralded single photon state





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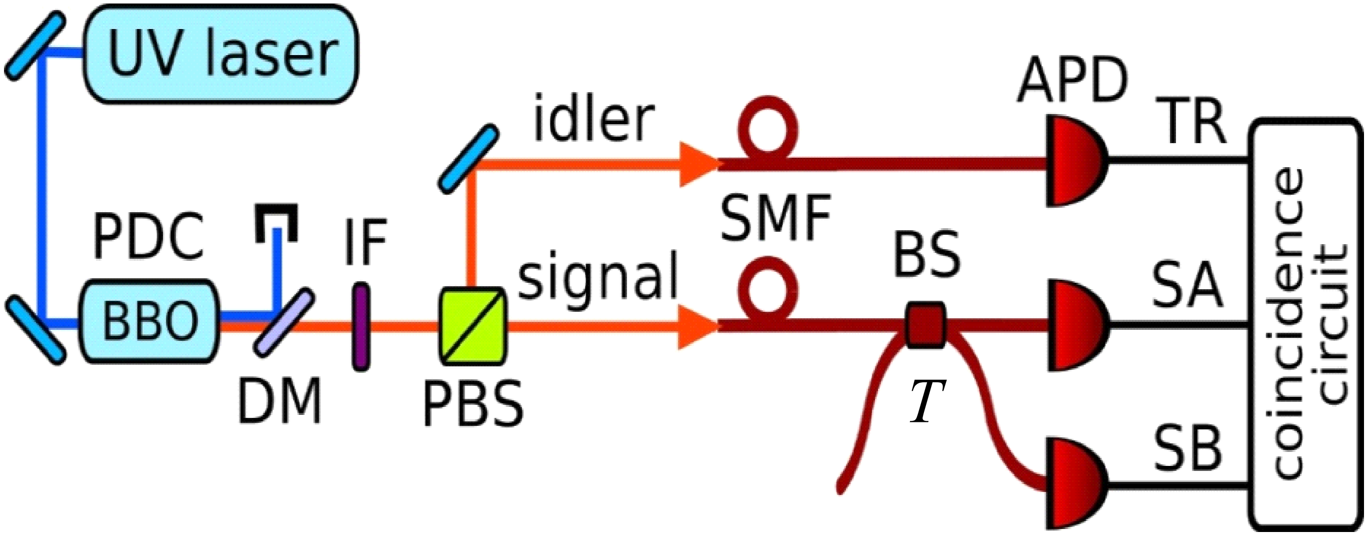
Estimation of p_0 and p_1 from coincidence rates



R0 - rate of trigger detector TR

R1 – two-fold coincindence rate TR&SA+TR&SB

R2 – three-fold coincindence rate TR&SA&SB

$$p_0 = 1 - \frac{R_1 + R_2}{R_0}$$

$$p_1 = \frac{R_1}{R_0} - \frac{T^2 + (1 - T^2)}{2T(1-T)} \frac{R_2}{R_0}$$

This estimator provides a lower bound on p_1.

Experimental results

TABLE I: Estimated probabilities p_0 and p_1, and the corresponding witness ΔW are shown for several different pump powers P and IF widths w (– denotes no filter).

P [mW]	w [nm]	p_0	p_1	ΔW [$\times 10^{-6}$]
50	2	0.9124	0.0875	412 ± 1
50	10	0.8589	0.1410	1666 ± 3
20	10	0.8425	0.1574	2370 ± 2
50	–	0.7095	0.2901	14252 ± 17
5	–	0.7296	0.2704	11825 ± 15

$$\Delta W = W - W_G$$

Quantum non-Gaussianity certified by many standard deviations

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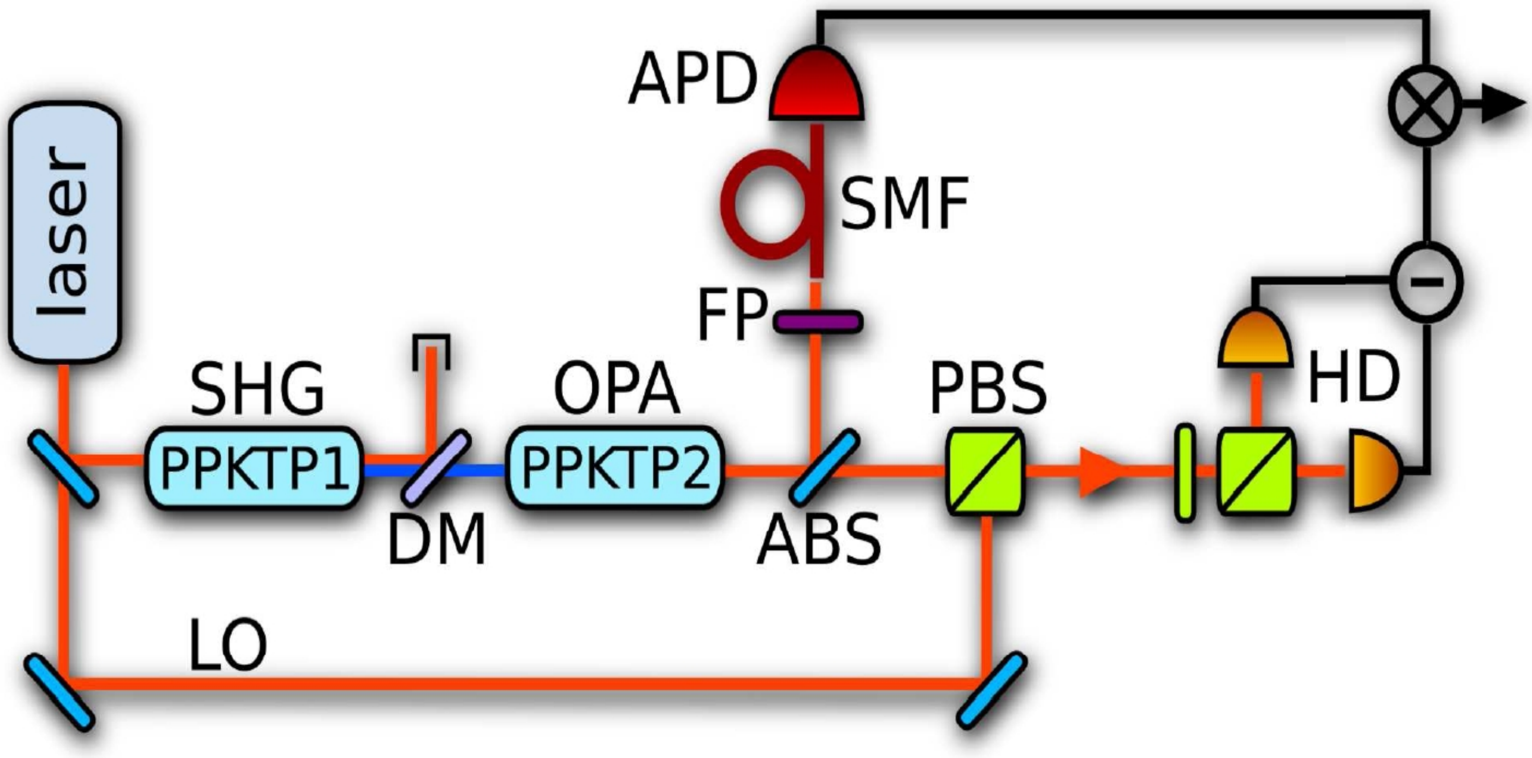
Photon subtracted squeezed vacuum state

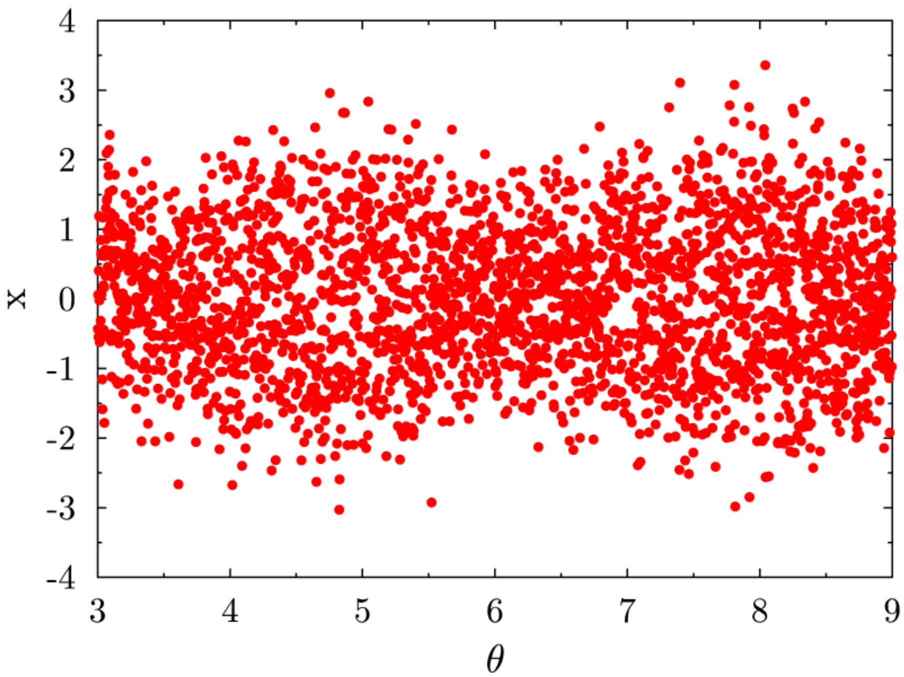


- The state is prepared by conditionally subtracting a single photon from picosecond pulsed squeezed vacuum state
- The state is then probed by homodyne detection

A. Tipsmark, R. Dong, A. Laghaout, P. Marek, M. Ježek, and U.L. Andersen, Phys. Rev. A **84**, 050301(R) (2011).

M. Ježek, A. Tipsmark, R. Dong, J. Fiurášek, L. Mišta, Jr. R. Filip, and U.L. Andersen, arXiv:1206.7057 (2012).

Estimation of p_n from homodyne data



Measured quadrature distributions

$$w(x_\theta;\theta)$$

U. Leonhardt, H. Paul, and G.M. DAriano, Phys. Rev. A **52**, 4899 (1995).

U. Leonhardt, M. Munroe, T. Kiss, Th. Richter, and M.G. Raymer, Opt. Commun. **127**, 144 (1995).

Th. Richter, Phys. Rev. A **61**, 063819 (2000).

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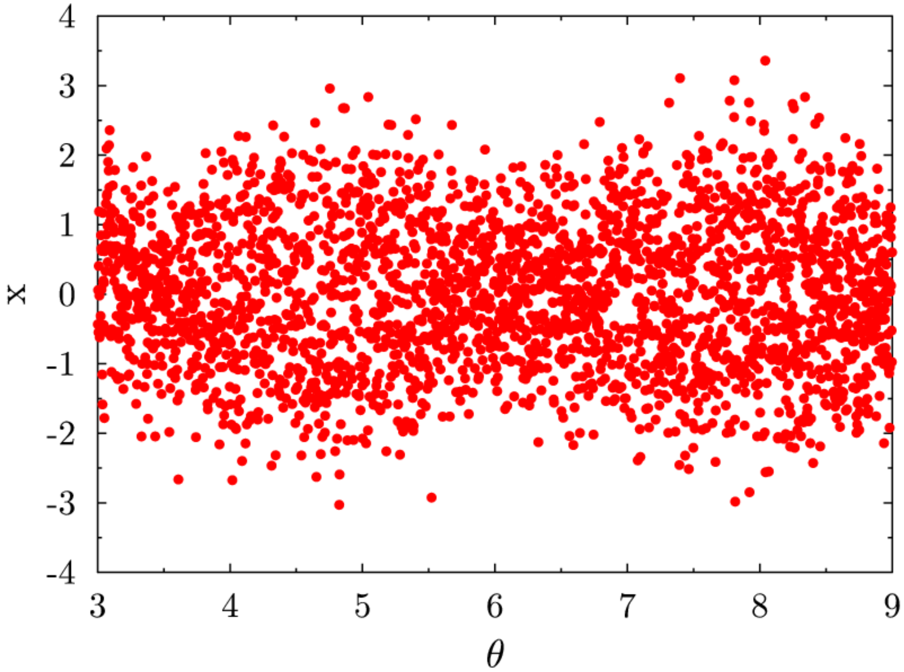
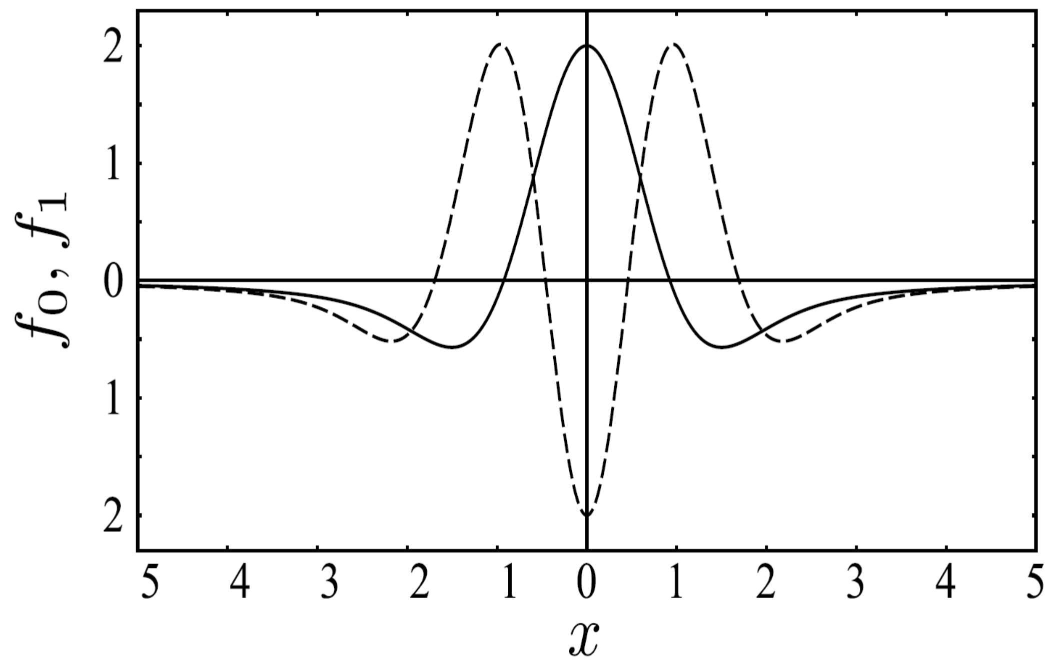




Measured quadrature distributions

Pattern functions

$$w(x_\theta;\theta)$$

$$p_n = \frac{1}{\pi}\int_0^\pi \int_{-\infty}^{\infty} w(x_\theta;\theta)\, f_n(x_\theta)\, \mathrm{d}x_\theta\, \mathrm{d}\theta$$

U. Leonhardt, H. Paul, and G.M. DAriano, Phys. Rev. A **52**, 4899 (1995).

U. Leonhardt, M. Munroe, T. Kiss, Th. Richter, and M.G. Raymer, Opt. Commun. **127**, 144 (1995).

Th. Richter, Phys. Rev. A **61**, 063819 (2000).

Generalized witness

Based on probabilities of squeezed vacuum and single photon states

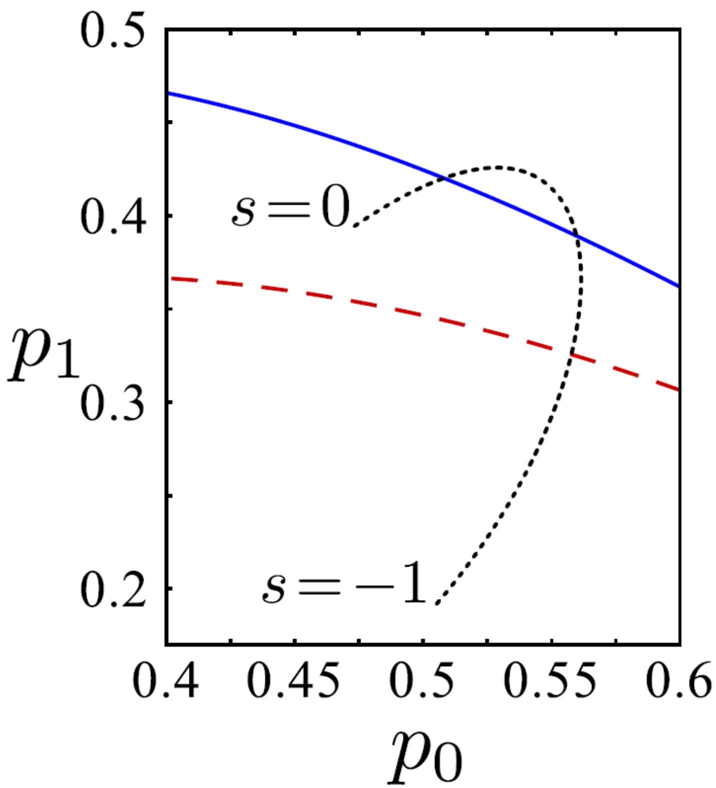
$$W(s) = a p_0(s) + p_1(s) \qquad p_n(s) = \langle n | S(s) \rho S^{\dagger}(s) | n \rangle$$

Generalized witness

Based on probabilities of squeezed vacuum and single photon states

$$W(s) = a p_0(s) + p_1(s) \qquad p_n(s) = \langle n | S(s) \rho S^{\otimes}(s) | n \rangle$$

More powerful than the original witness



Squeezing transformation:

$$x \rightarrow x e^{-s}$$

$$p \rightarrow p e^{s}$$

Generalized witness

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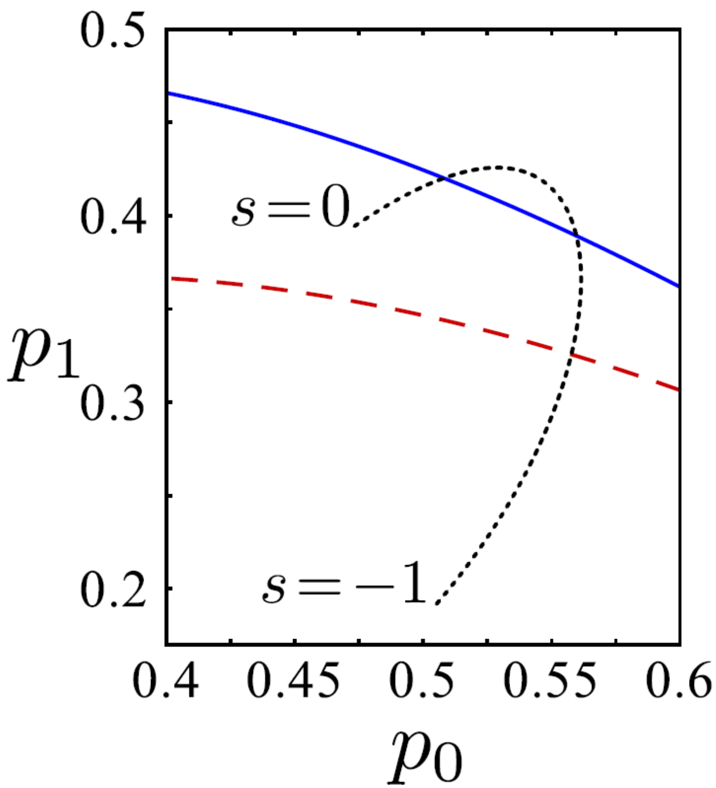
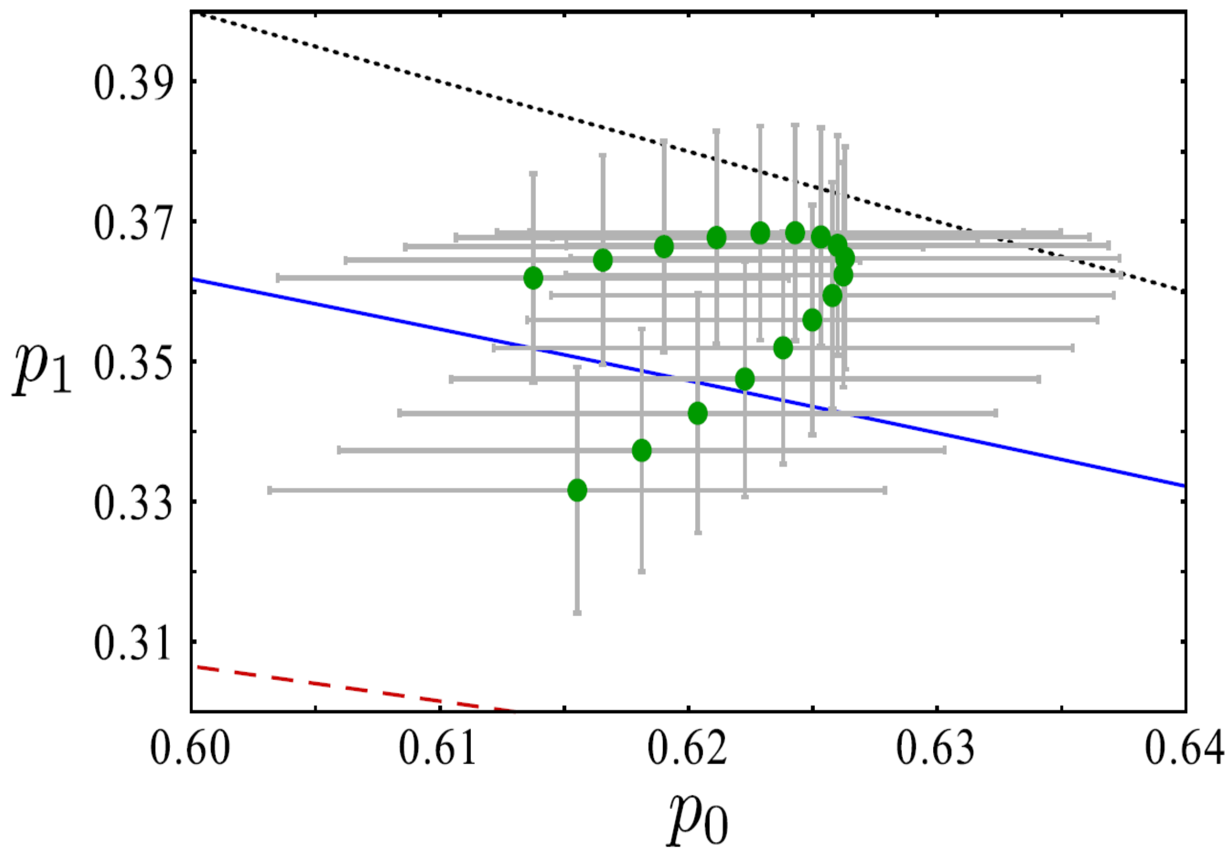


Pattern functions for $p_n(s)$

$$f_n(x_\theta;\theta;s) = \frac{1}{g^2} f_n\left(\frac{x_\theta}{g}\right)$$

$$g = \sqrt{e^{2s}\cos^2(\theta) + e^{-2s}\sin^2(\theta)}$$

Results



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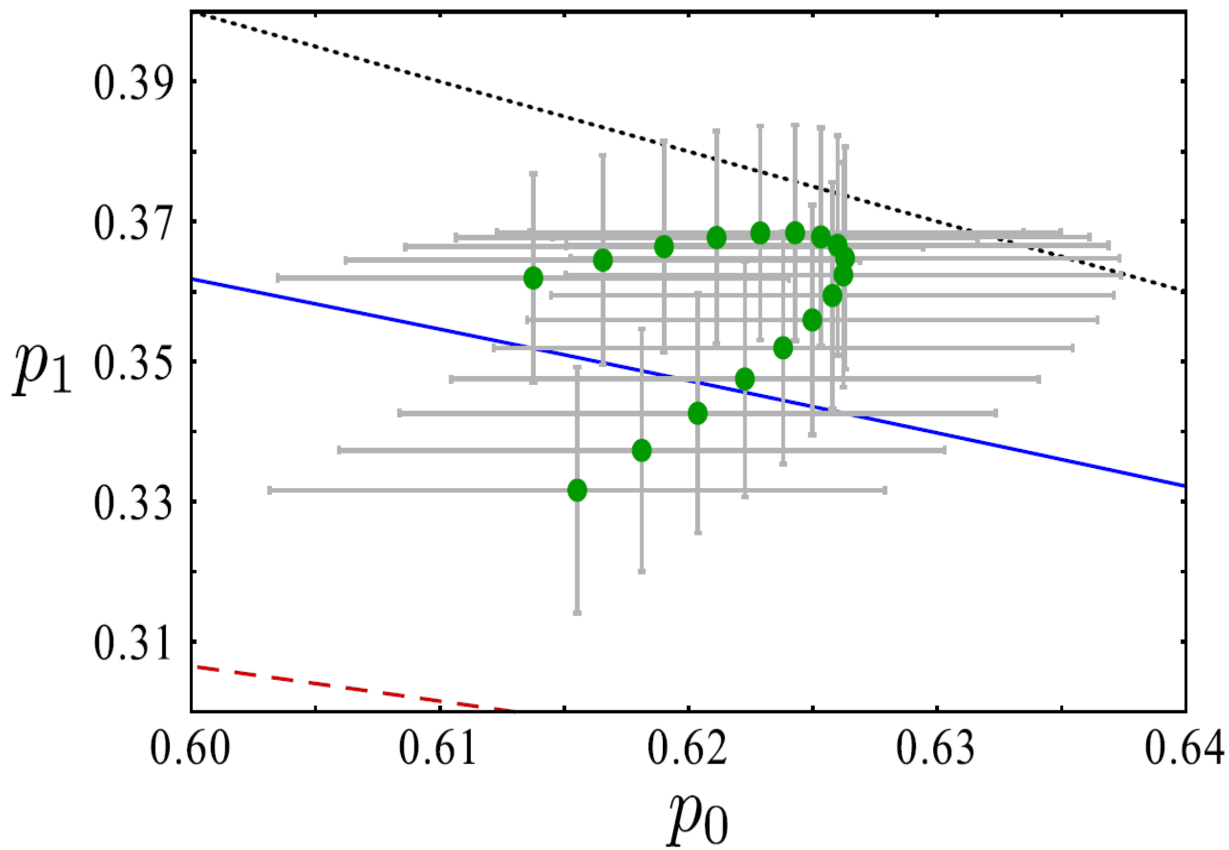

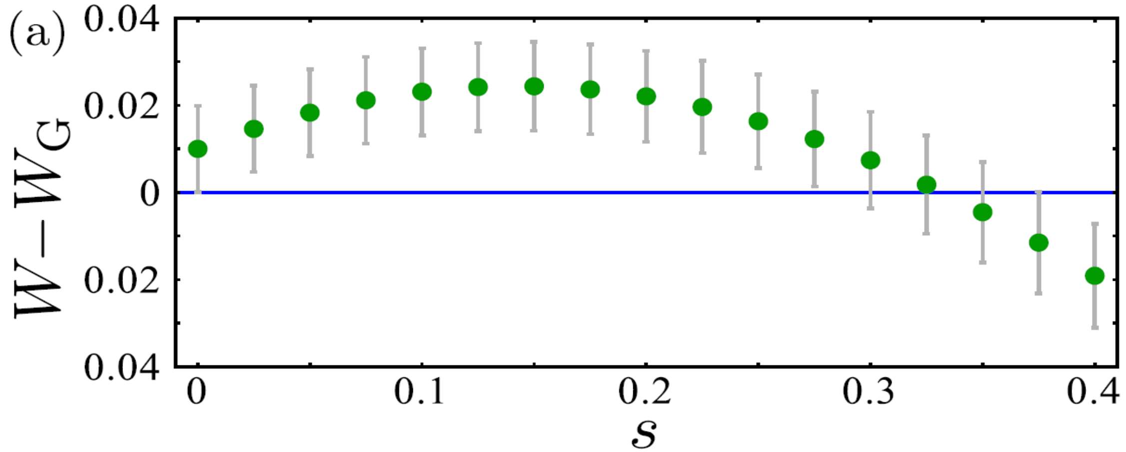

$$\Delta W(s_{opt}) = 0.024 \pm 0.010$$

Thank you for your attention!