european social fund in the czech republic
EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT

Towards non-Gaussian nonlinearity

What is cubic nonlinarity and why do we need it?

$$\hat{H}_3 = \omega_3 \hat{x}^3$$

- Cubic Hamiltonian can be used for implementation of Hamiltonians of higher order [Lloyd and Braunstein, Phys. Rev. Lett. **82**, 1784]

$$e^{iAt}e^{iBt}e^{-iAt}e^{-iBt} = e^{-[A,B]t^2} + O(t^3)$$

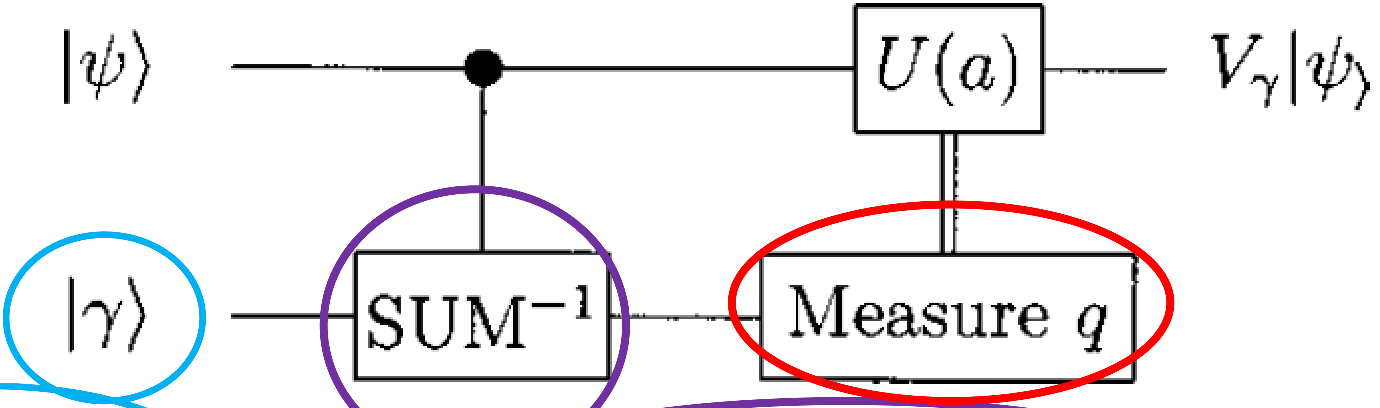
(as opposed to quadratic Hamiltonians)

$$\hat{H}_q = \sum_{i+j\leq 2} \omega_{ij}\hat{x}^i\hat{p}^j + h.c.$$

How can cubic nonlinearity be performed?

- Analogue to measurement induced squeezing
- Ancilla-and-measurement-and-feedforward:

[Gottesman *et al.* , PRA 64 012310 (2001)]



$$|\gamma\rangle = \int e^{i\chi x^3}|x\rangle dx$$

$$\int \psi(x)e^{i\chi y^3}|x, y-x\rangle dx dy$$

$$\int \psi(x)e^{i\chi(x+q)^3}|x\rangle dx = \int \psi(x)e^{i\chi(x^3+3qx^2+3q^2x+q^3)}|x\rangle dx$$

How can cubic state be generated?

$$|\gamma\rangle = \int e^{i\chi x^3}|x\rangle dx$$

- Unphysical: infinite energy

$$e^{i\chi\hat{x}^3}\hat{S}|0\rangle = \hat{S}e^{i\chi'\hat{x}^3}|0\rangle$$

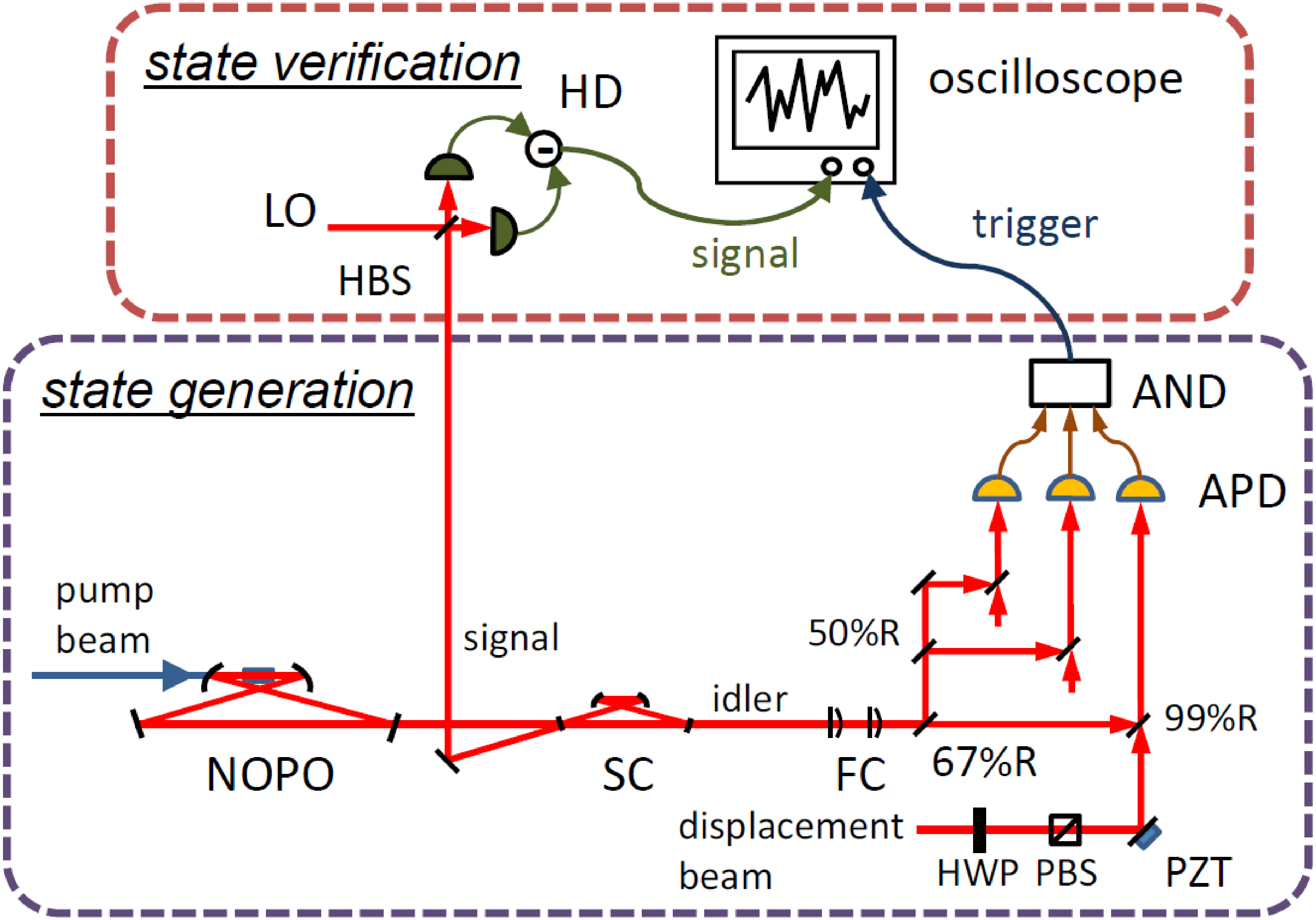
- Finite energy approximation
  - Squeezing can be disregarded, for the moment

$$(1+i\chi\hat{x}^3)|0\rangle$$

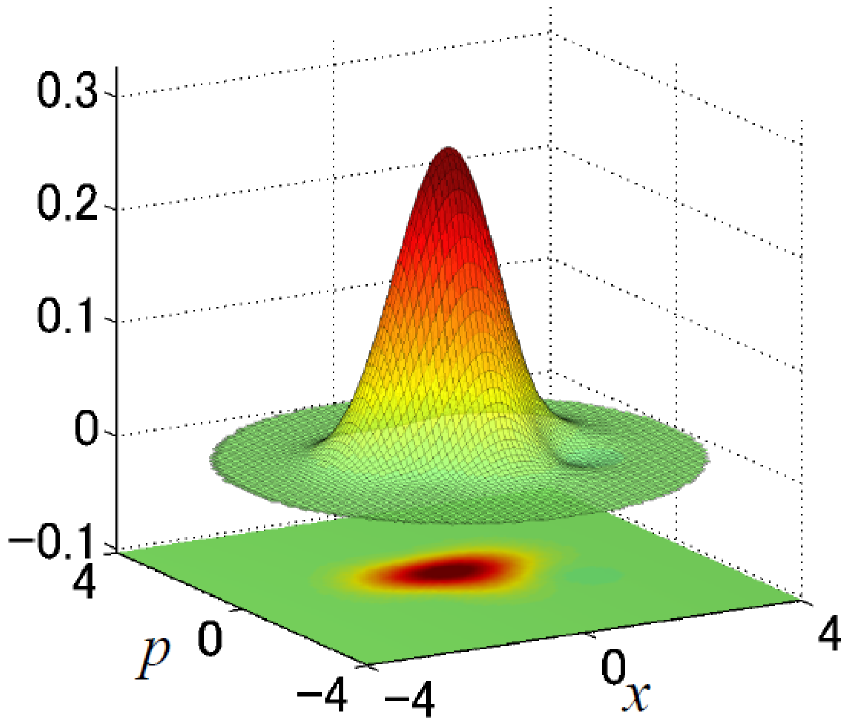
- Weak cubic nonlinearity approximation

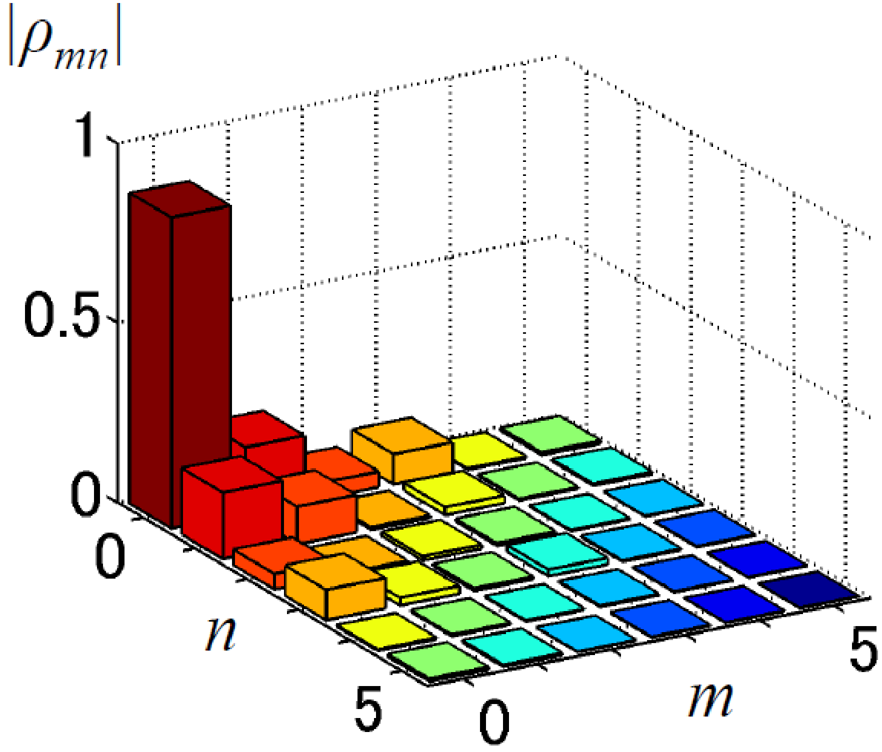
$$|0\rangle + i\frac{\chi\sqrt{3}}{2\sqrt{2}}\left(\sqrt{3}|1\rangle + \sqrt{2}|3\rangle\right)$$

- Can be engineered on the single photon level


state verification
HD
oscilloscope
LO
HBS
signal
trigger
state generation
AND
APD
pump
beam
signal
50%R
idler
99%R
NOPO
SC
FC
67%R
displacement
beam
HWP
PBS
PZT

The experimentally generated state



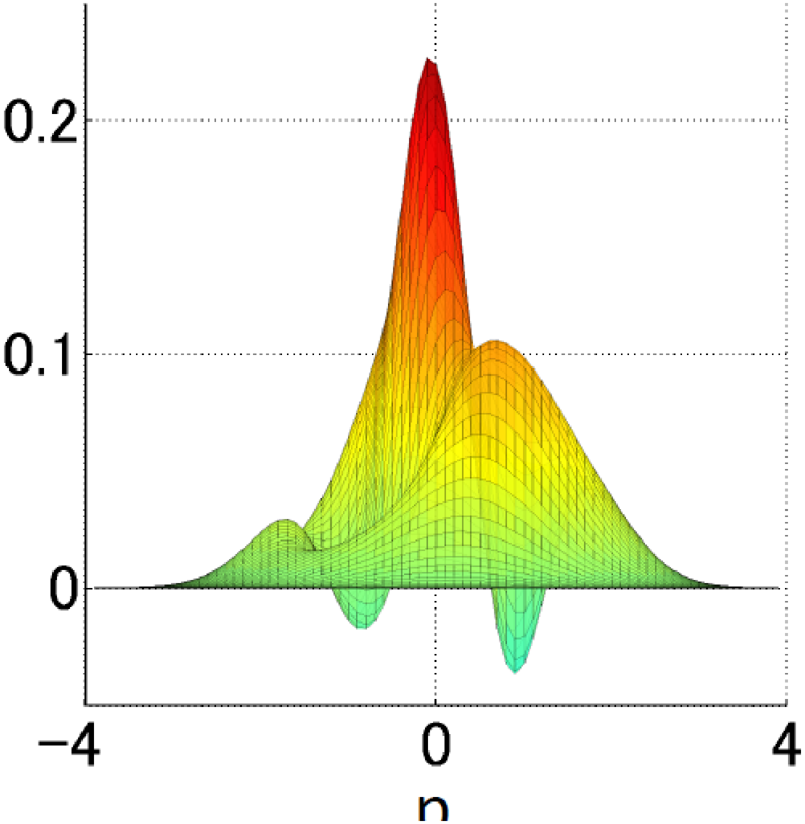


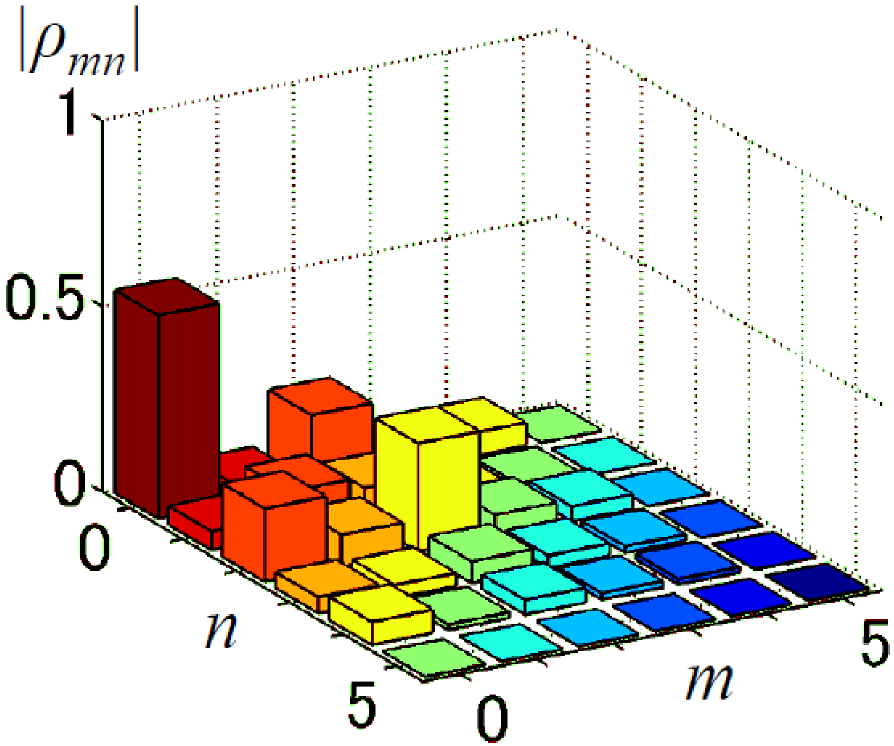
$$|0\rangle + i\frac{\chi\sqrt{3}}{2\sqrt{2}}\left(\sqrt{3}|1\rangle + \sqrt{2}|3\rangle\right)$$

$$F = 0.89$$

$$F_{|0\rangle} = 0.98$$

Single photon subtraction on data





$$\sqrt{3}|0\rangle + \sqrt{6}|2\rangle$$

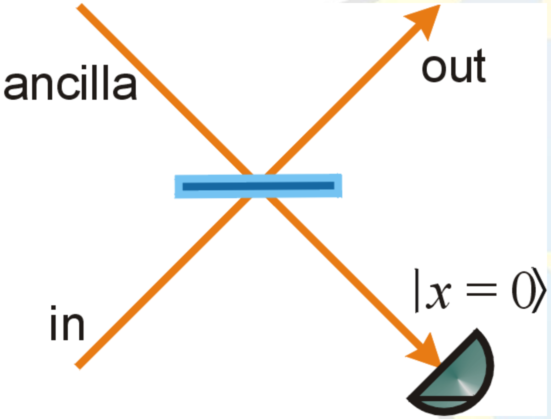
Analysis of cubic behavior

- The state is non-classical
  - It could correspond to the ideal state + noise
  - But does it posses cubic nonlinearity?

- Fidelity is of no use
- We need to look for alternative figures of merit

Inducing cubic operation

- Virtual application of the gate



$$\psi_{\text{out}}(x) \approx \psi_{\text{in}}(x)\psi_{\text{ancilla}}(x)$$

$$\hat{x} \to \hat{x} \quad \hat{p} \to \hat{p} + 3\chi\hat{x}^2$$

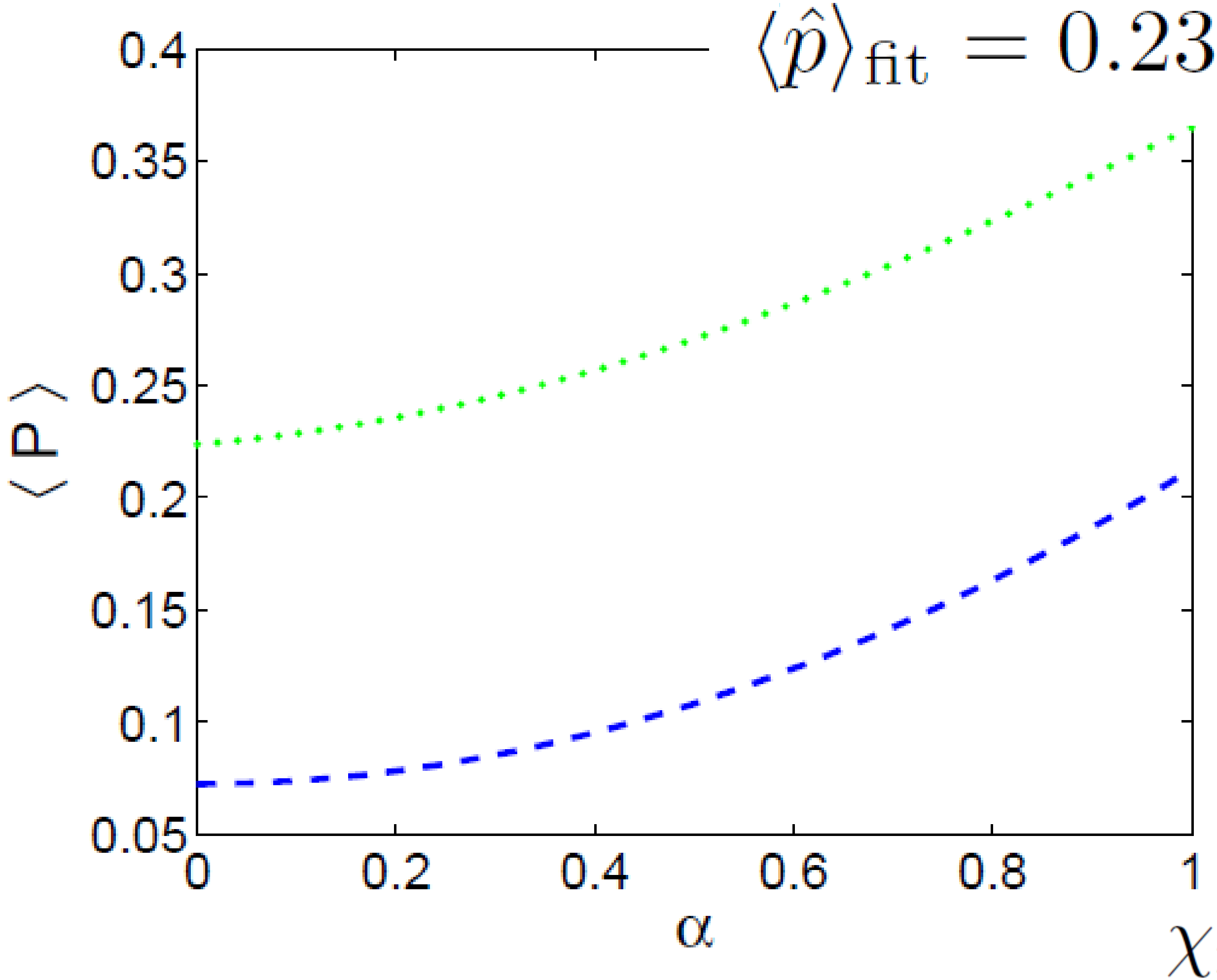
- For a set of coherent states $|\alpha\rangle$:

$$\langle p\rangle \to \langle p\rangle + 3\chi(2\alpha^2 + 1/2)$$

Inducing nonlinearity

$$\langle p \rangle \to \langle p \rangle + 3\chi(2\alpha^2 + 1/2)$$

$$\langle \hat{p} \rangle_{\mathrm{fit}} = 0.23 + 0.14\alpha^2$$

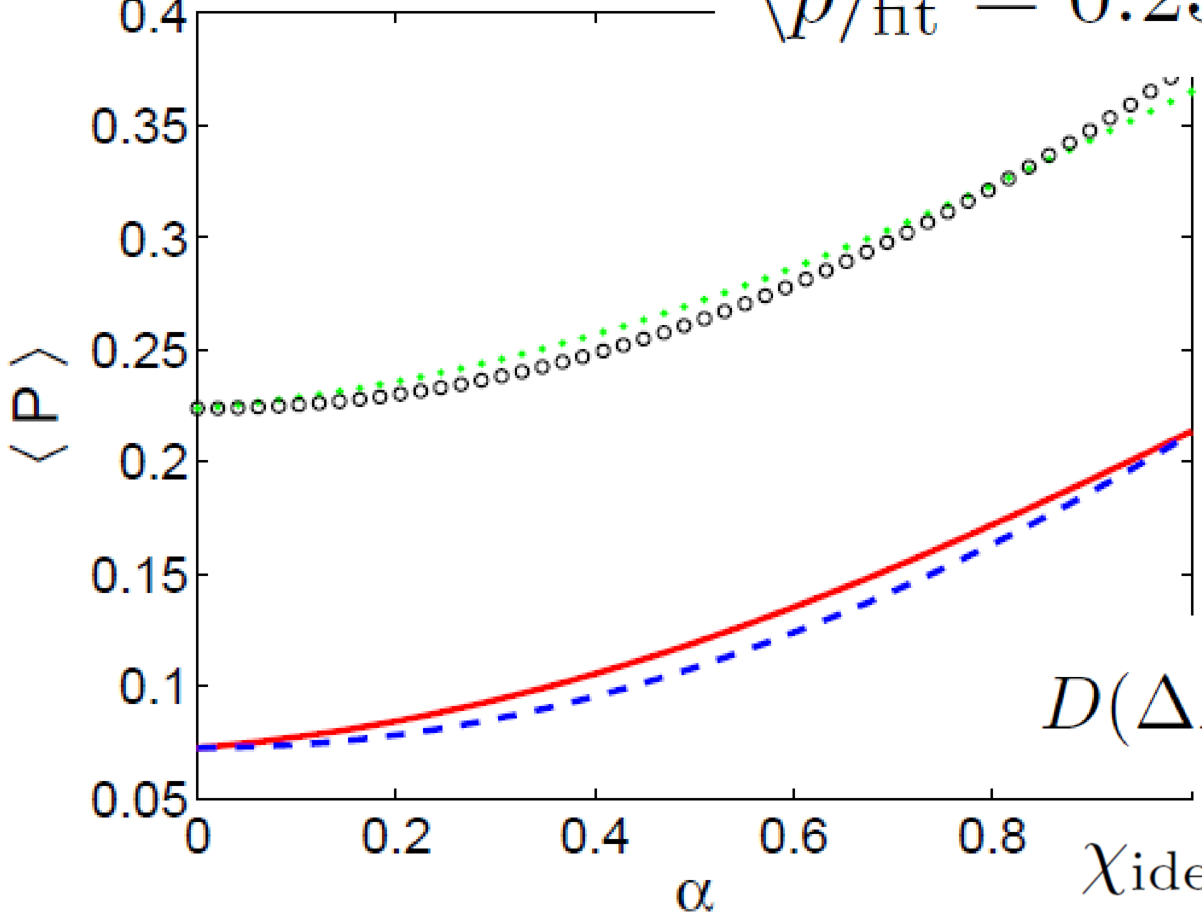


$$\chi_{\mathrm{ideal}} = 0.09$$

Inducing nonlinearity

$$\langle p \rangle \rightarrow \langle p \rangle + 3\chi(2\alpha^2 + 1/2)$$

$$\langle \hat{p} \rangle_{\text{fit}} = 0.23 + 0.14\alpha^2$$



$$D(\Delta P) = 0.16$$

$$\chi_{\text{ideal}} = 0.09$$

Observing cubic nonlinearity directly

- Density matrix in position representation

$$\rho(x, x') = \langle x|\hat{\rho}|x\rangle$$

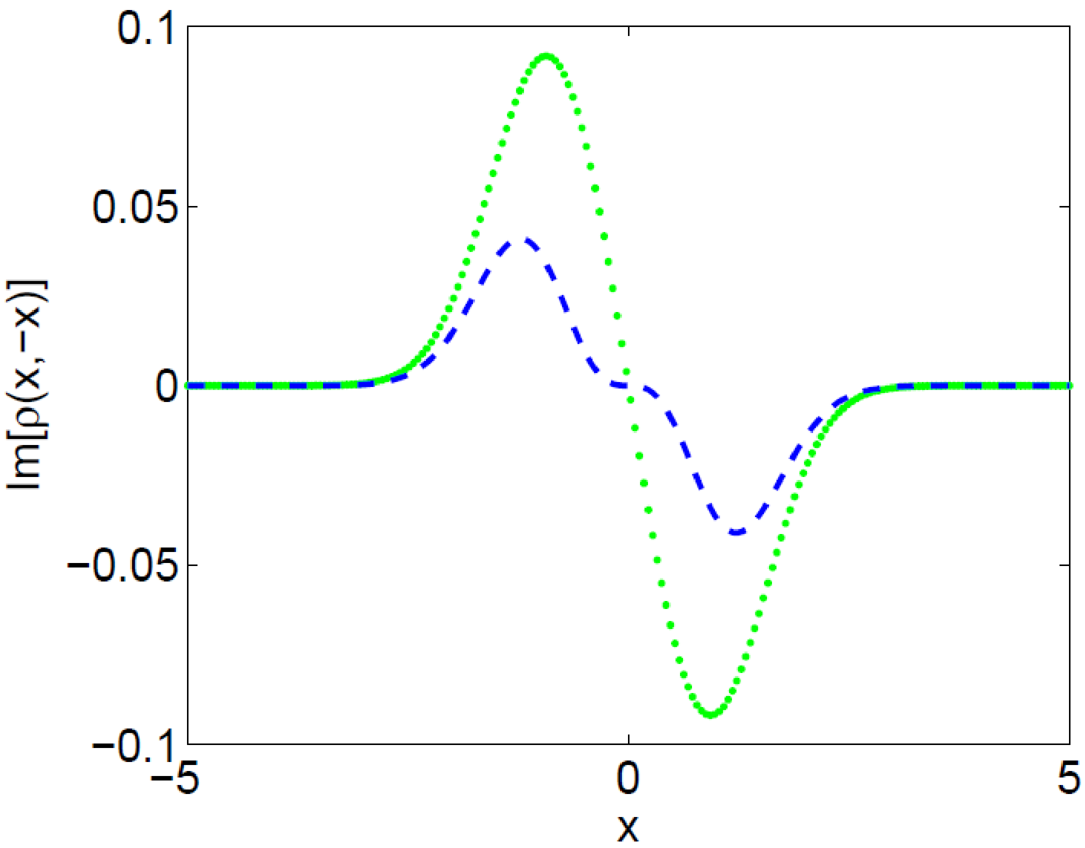
- Looking at the main anti-diagonal:

$$\rho_{id}(x, -x) = \langle x|(1 + i\chi\hat{x}^3)|0\rangle\langle 0|(1 - i\chi\hat{x}^3)| - x\rangle$$

$$= e^{-x^2}(1 - \chi^2 x^6 + 2i\chi x^3)$$

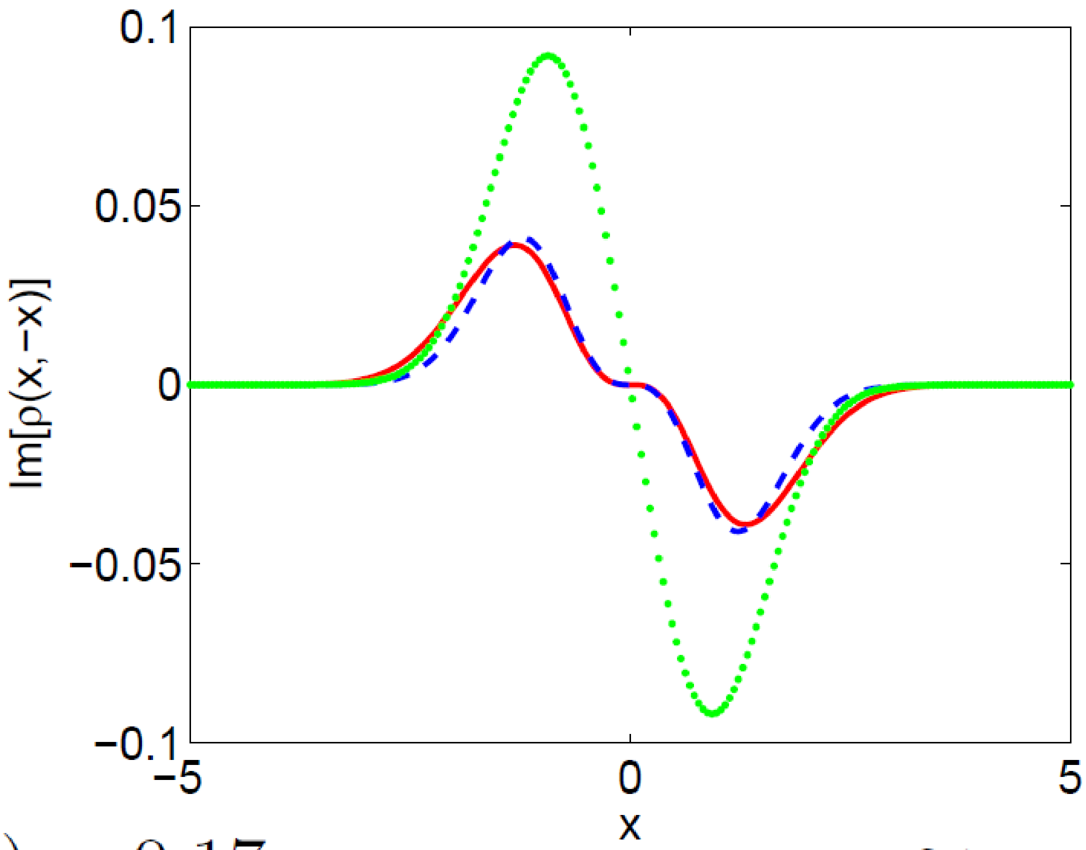
  – Cubic nonlinearity is visible in the imaginary part

Density matrix in position representation



$$\chi_{\text{ideal}} = 0.09$$

Density matrix in position representation



$D(\Delta P) = 0.17$

$\chi_{\mathrm{ideal}} = 0.09$

Summary

- Quantum nonlinearity can be engineered photon-by-photon
- We have experimentally prepared a quantum state, which is the first step in this direction
  - It is a a specific superposition of 0, 1 and 3 photons
  - It is not perfect, but two independent figures of merit confirmed its properties as:
    - Cubic state with $\chi = 0.09$ displaced in P roughly by 0.16

Meanwhile at Queen’s University Belfast

QTEQ

QUANTUM TECHNOLOGY at QUEEN’S

In collaboration with:

- Mauro Paternostro
- Gerard McKeown
- Laura Mazzola
- Carlo di Franco
- Gabriel Torlai

PHYSICAL REVIEW A **87**, 052112 (2013)

Violation of Bell's inequalities with preamplified homodyne detection

G. Torlai,[1,2] G. McKeown,[2] P. Marek,[3] R. Filip,[3] H. Jeong,[4,5] M. Paternostro,[2] and G. De Chiara[2]

[1]*Department of Physics, Ludwig Maximilians Universität, Schellingstraße 4 80799, Munich, Germany*

[2]*Centre for Theoretical Atomic, Molecular and Optical Physics, School of Mathematics and Physics, Queen's University, Belfast BT7 1NN, United Kingdom*

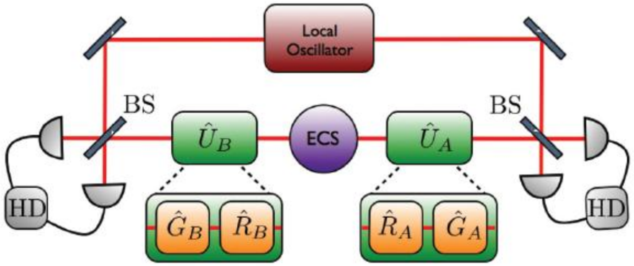
[3]*Department of Optics, Palacký University, 17. listopadu 1192/12, 77207 Olomouc, Czech Republic*

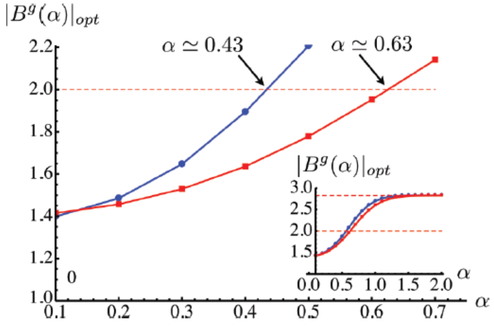
[4]*Center for Macroscopic Quantum Control, Department of Physics and Astronomy, Seoul National University, Seoul, 151-742, Korea*

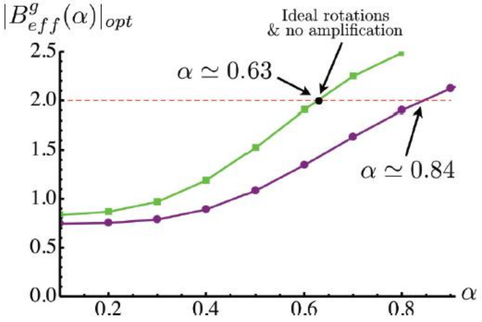
[5]*Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, University of Queensland, Brisbane, Queensland 4072, Australia*

(Received 18 January 2013; published 10 May 2013)

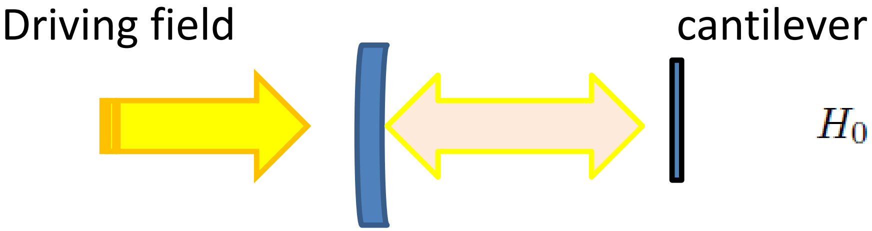
We show that the use of probabilistic noiseless amplification in entangled coherent state-based schemes for the test of quantum nonlocality provides substantial advantages. The threshold amplitude to falsify a Bell-CHSH nonlocality test, in fact, is significantly reduced when amplification is embedded into the test itself. Such a beneficial effect holds also in the presence of detection inefficiency. Our study helps in affirming noiseless amplification as a valuable tool for coherent information processing and the generation of strongly nonclassical states of bosonic systems.



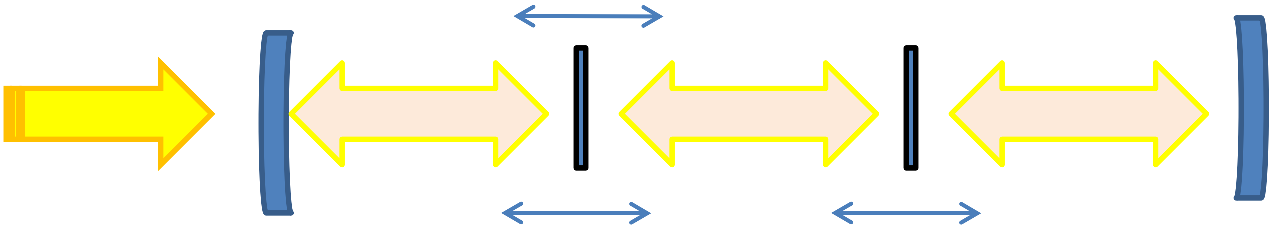




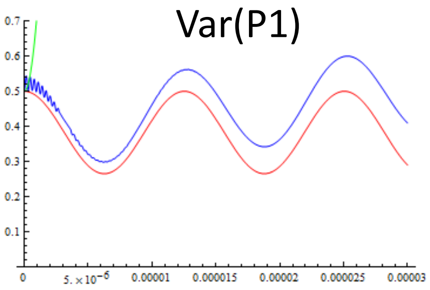
Controlled dynamics of a mechanical oscilator

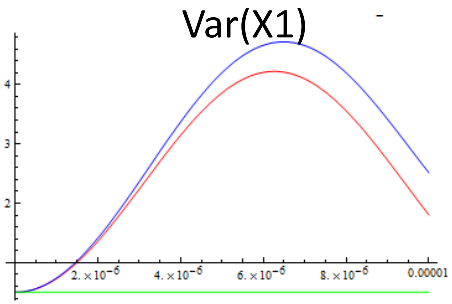


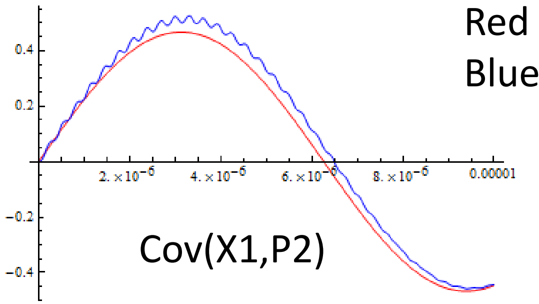
$$H_0 = \frac{p^2}{2m} + \frac{1}{2} m \omega_m^2 q^2 + \hbar(\omega_c - \omega_L) a^\dagger a + i\hbar\epsilon(a^\dagger - a)$$



- Interaction between two cantilevers mediated by light
- We are searching for regime allowing a well defined interaction
- Preliminary results - two mode quadrature variances:


Var(P1)

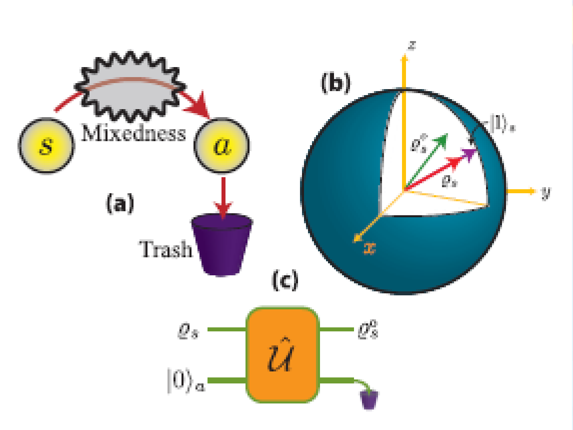

Var(X1)

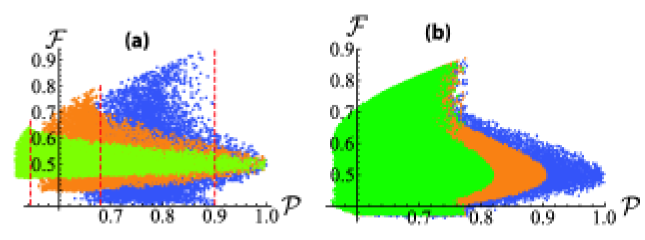

Cov(X1,P2)

Red – approximation
Blue – full theory

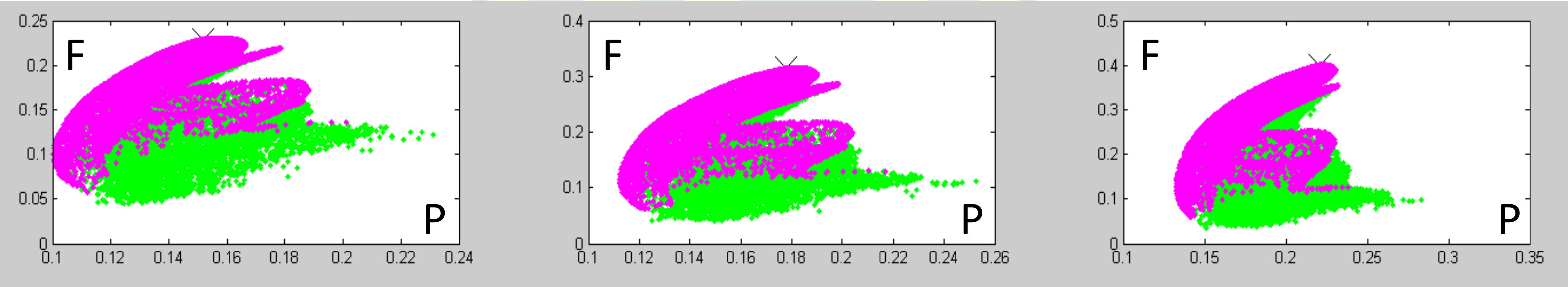
Limits on deterministic purification of quantum states

- During purification, purity and fidelity of qubits can not be increased simultaneously [Scientific Reports 3, 1387 (2013)]





- This is not universally true for CV systems:

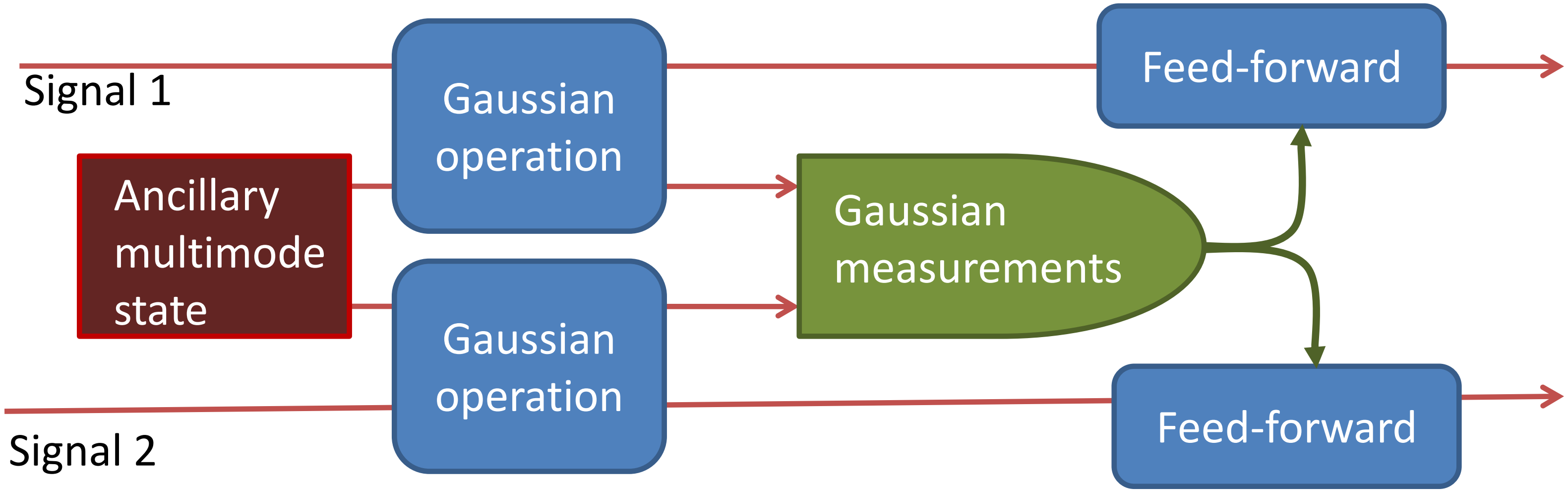


- The question is: What are the actual conditions?

Imperial College London

- Collaboration with:
- Myungshik Kim
- Catherine Hughes
- Marco Genoni

Engineering of Multi-mode non-Gaussian Hamiltonians



For non-Gaussian Hamiltonian $H = x_1^2 x_2$ this is fairly straightforward and the only non-trivial part lies in generating the desired ancillary state.

We will propose feasible methods of doing so.

Thank you
for your attention!

esf european social fund in the czech republic
EUROPEAN UNION
MŠMT MINISTRY OF EDUCATION, YOUTH AND SPORTS
2007–13 OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT