Magdalena Stobińska
MPL
Max Planck Institute for the Science of Light
Erlangen-Nürnberg University

Macroscopic quantum states of light generated by quantum cloners

Motivation

Fundamental interest:

quantum-classical border

loophole-free Bell tests

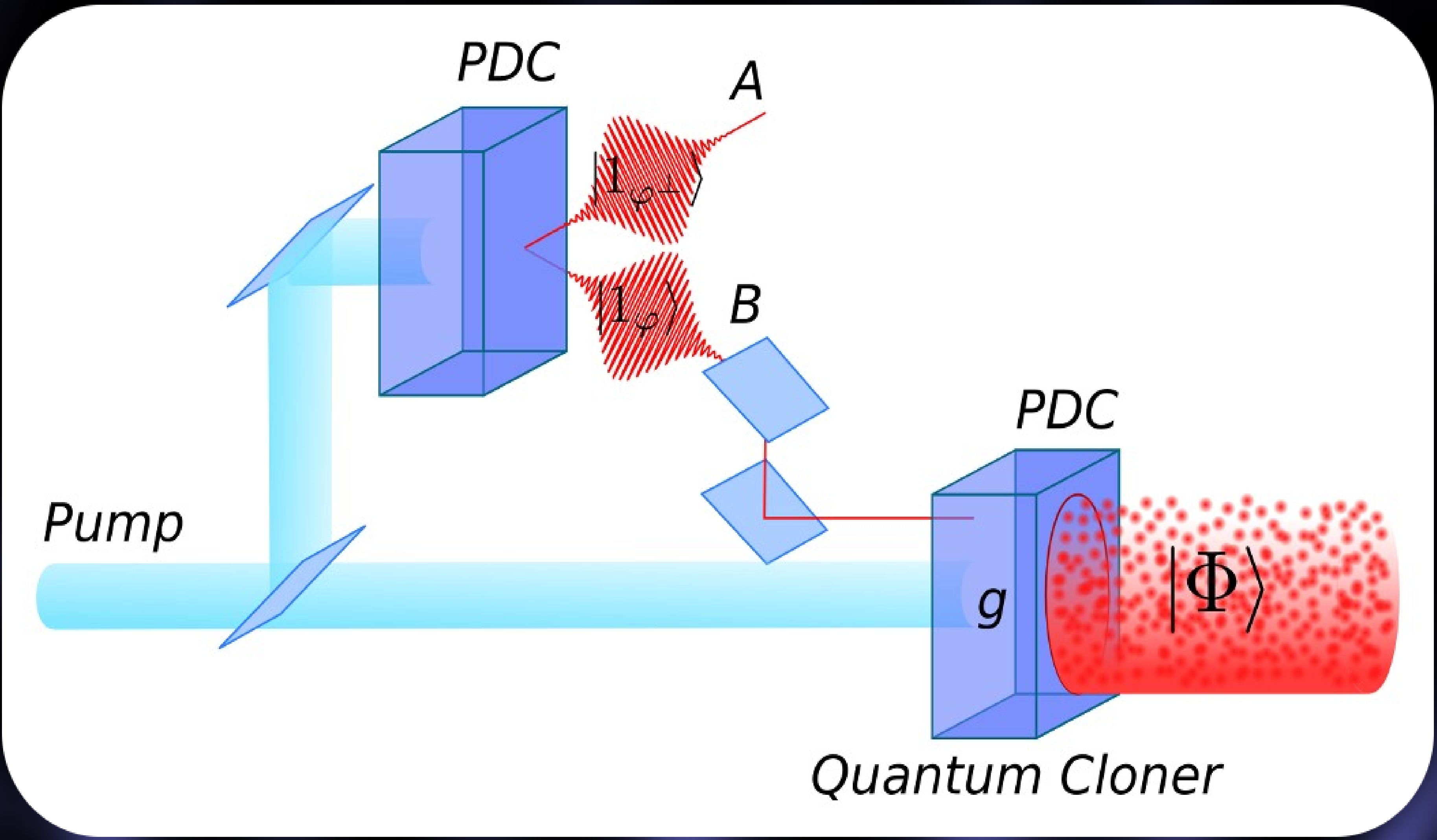
Macroscopic nature makes them always detectable with classical detectors

Applications:

quantum metrology (super-resolution)

quantum information technology (efficient coupling between light and matter)

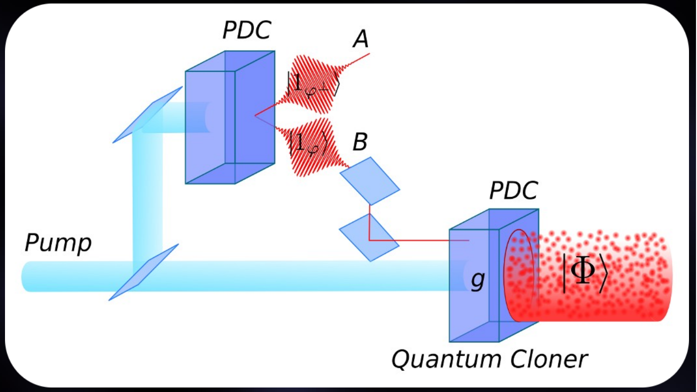
Multiphoton Polarization Entanglement



Population on average $4sh^2g$ of photons

F. De Martini et al, PRL **100**, 253601 (2008)

Multiphoton Polarization Entanglement



Equatorial states of polarization

$$|1_\varphi\rangle = 1/\sqrt{2}(|1_H, 0_V\rangle + e^{i\varphi}|0_H, 1_V\rangle)$$

$$|1_{\varphi^\perp}\rangle = 1/\sqrt{2}(|1_H, 0_V\rangle - e^{i\varphi}|0_H, 1_V\rangle)$$

PDC singlet

$$1/\sqrt{2}(|1_\varphi\rangle_A |1_{\varphi^\perp}\rangle_B - |1_{\varphi^\perp}\rangle_A |1_\varphi\rangle_B)$$

Quantum amplification

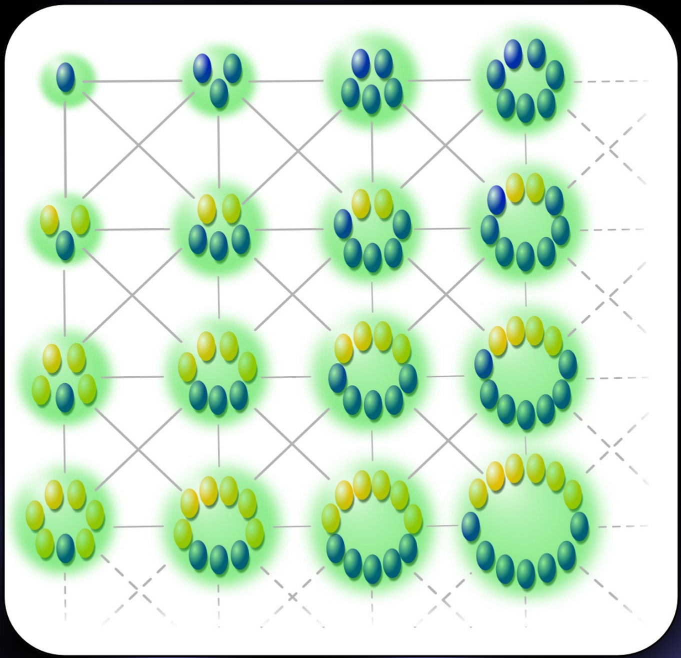
$$|1_\varphi\rangle \rightarrow |\Phi\rangle \quad |1_{\varphi^\perp}\rangle \rightarrow |\Phi_\perp\rangle$$

Macroscopic Quantum Properties

Polarization and photon number properties

$|\Phi\rangle$

$(1,3,5,...)$ photons in φ
$(0,2,4,...)$ photons in $\varphi^{\perp}$



$\bar{m}_{\varphi} = 3m+1$
$\bar{m}_{\varphi^{\perp}} = m$

$|\Phi_{\perp}\rangle$

$(1,3,5,...)$ photons in $\varphi^{\perp}$
$(0,2,4,...)$ photons in φ

$\bar{m}_{\varphi^{\perp}} = 3m+1$
$\bar{m}_{\varphi} = m$

Population $\bar{m} = 10^5$ for $g = 6$

Macroscopic Singlets – Schrödinger Cats

"Micro-macro" singlet

$$1/\sqrt{2}\left(|1_{\varphi}\rangle_A|\Phi_{\perp}\rangle_B - |1_{\varphi^{\perp}}\rangle_A|\Phi\rangle_B\right)$$

"Macro-macro" singlet

$$1/\sqrt{2}\left(|\Phi\rangle_A|\Phi_{\perp}\rangle_B - |\Phi_{\perp}\rangle_A|\Phi\rangle_B\right)$$

Singlets are useful if $|\Phi\rangle$ and $|\Phi_{\perp}\rangle$ are distinguishable

Photon Number Distribution: detector point of view

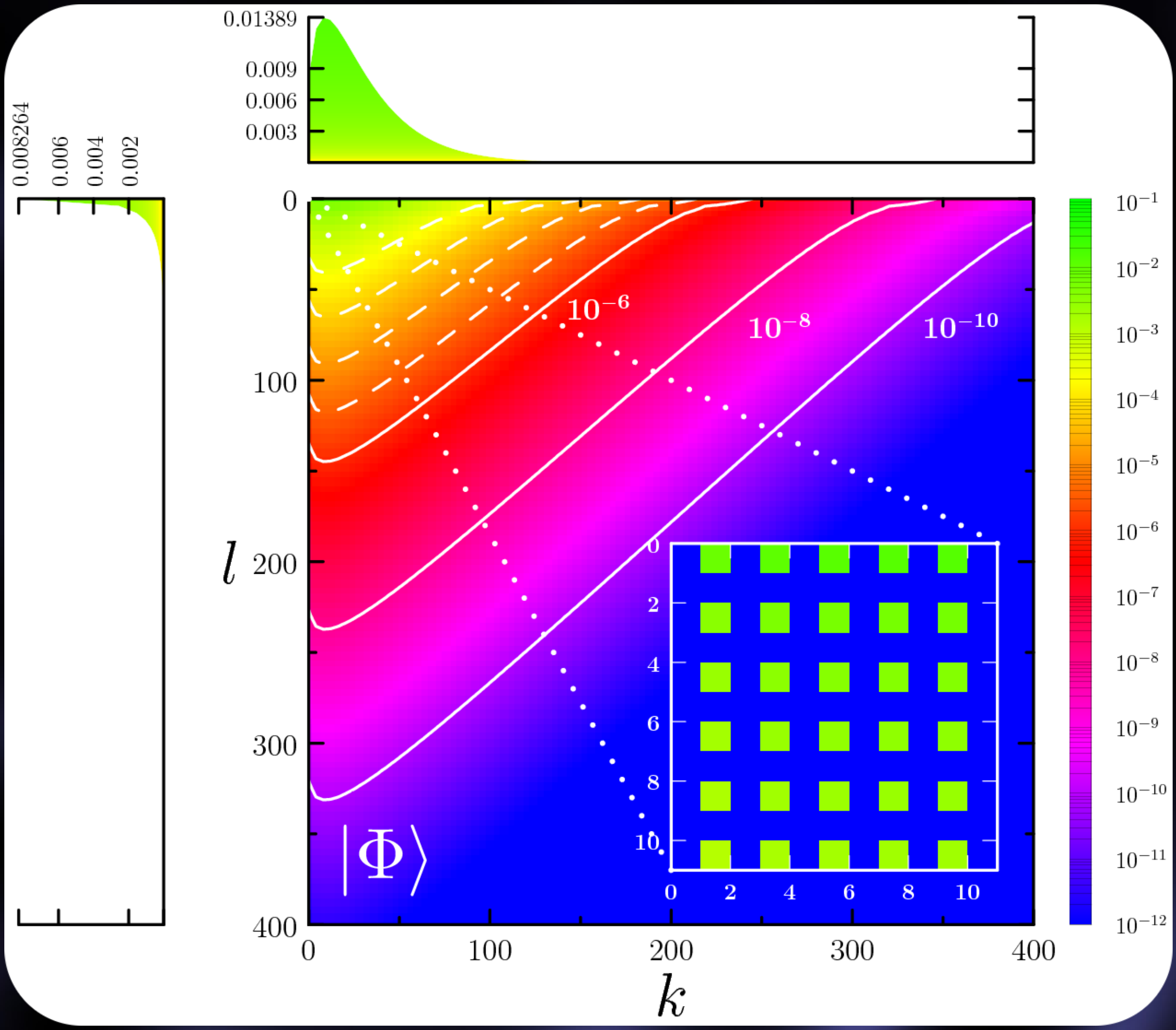
Effective overlap ~10^{-1}

Photon distributions are continuous

$$p_{\Phi}(k,l) = |\langle k,l|\Phi\rangle|^2$$
$$p_{\Phi^{\perp}}(k,l) = p_{\Phi}(l,k)$$

Distinguishability

$$v = 0.64$$



How to improve distinguishability of macroscopic states?

Filtering – Quantum State Engineering

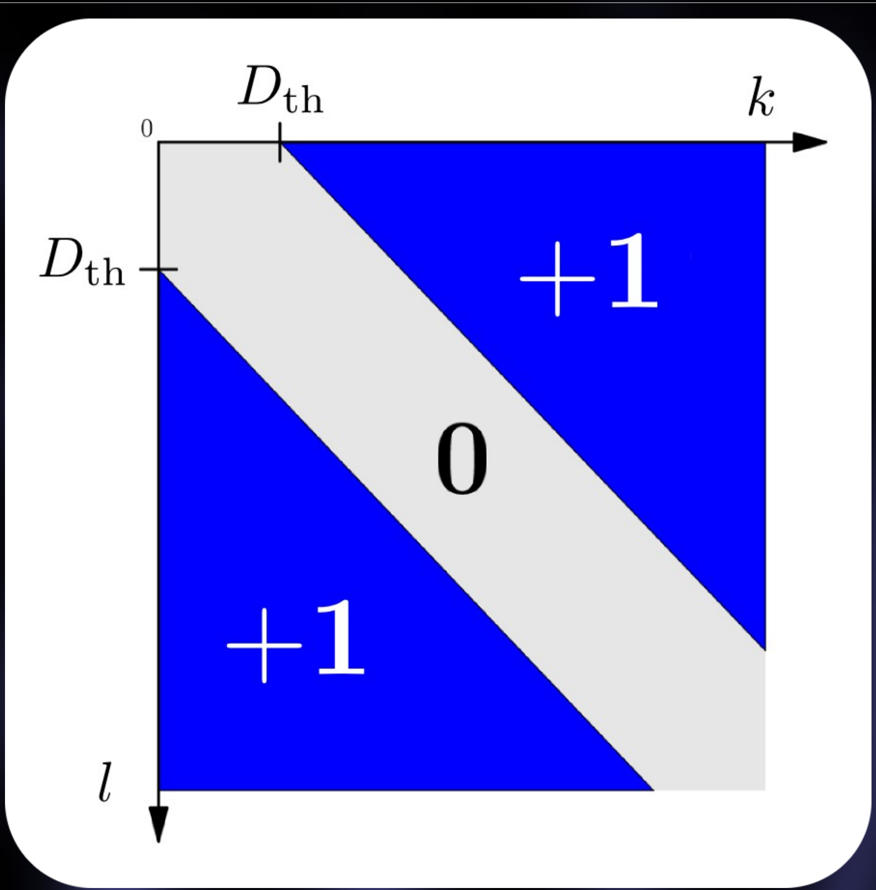
POVM (positive operator valued measure) describe measurement induced quantum operations

- preserve quantum macroscopic character
- significantly improve distinguishability with inefficient detection
- are crucial for any quantum protocol, Bell inequality violation, quantum cryptography and quantum metrology

Modulus Difference Filter

Quantum scissors

$$\mathcal{P}_{D_{th}} = \sum_{\substack{k,l=0 \\ |k-l|\geq D_{\mathrm{th}}}}^{\infty} |k,l\rangle\langle k,l|$$



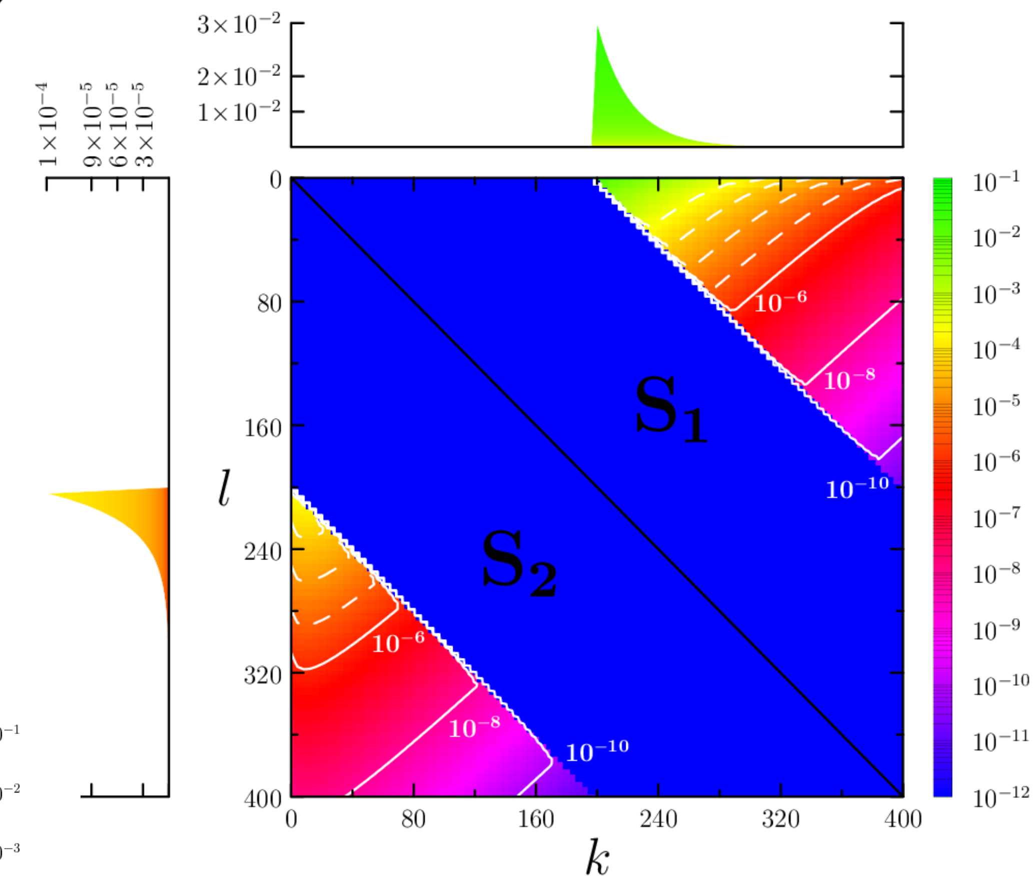
POVM measurement

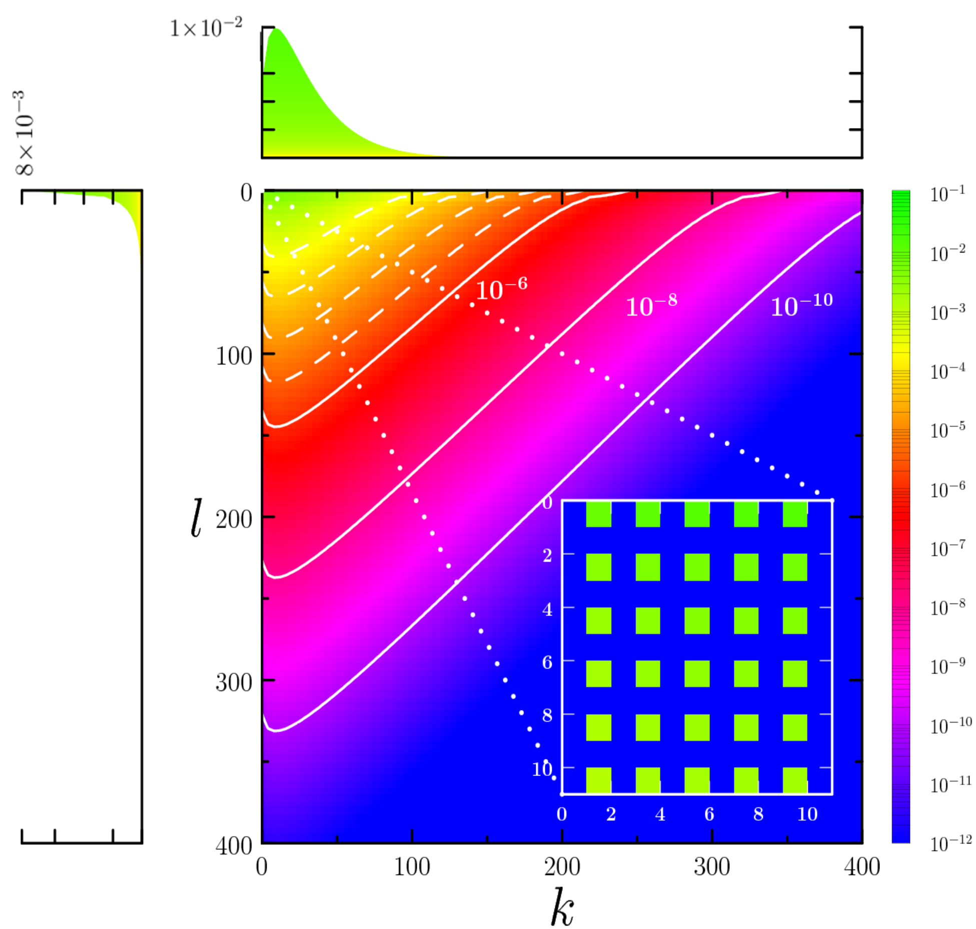
MDF filters both macroqubits fairly

MDF has binary output (exact value of the modulus is not measured)

engineering of quantum superposition without collapsing on a particular Fock state

Filtering $\bar{m} = 10$

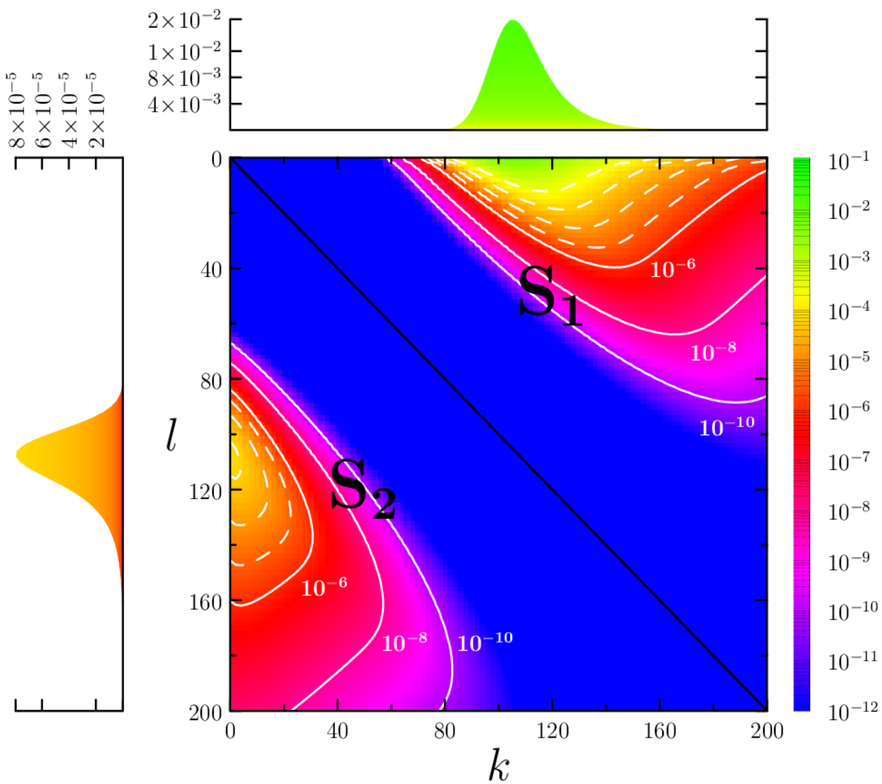




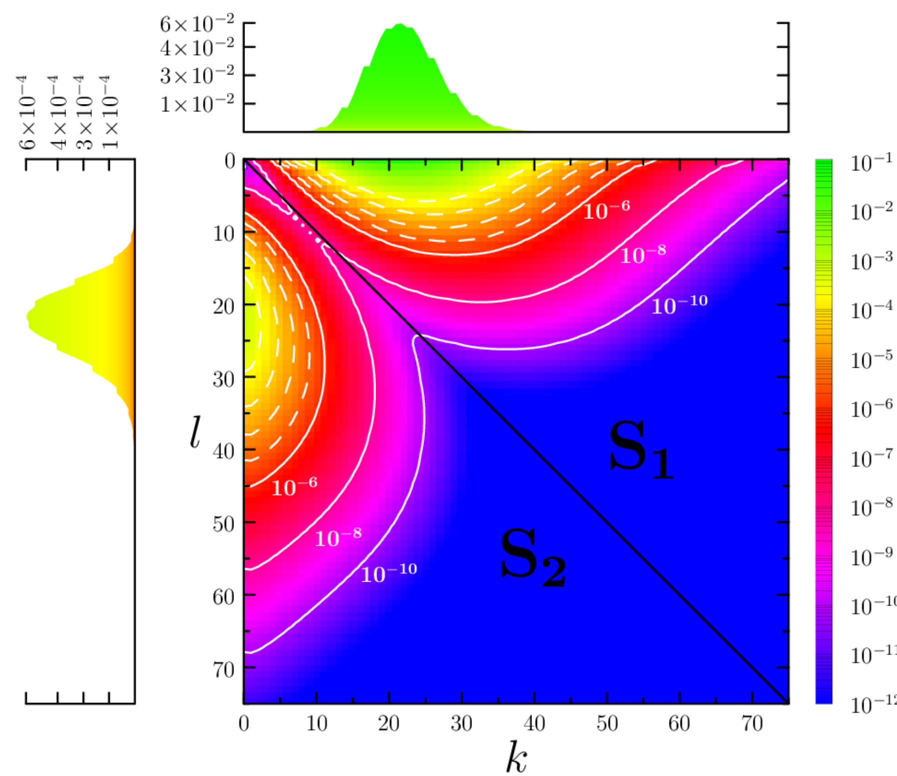
Filtering in Presence of Losses

$\bar{m} = 10$

50%



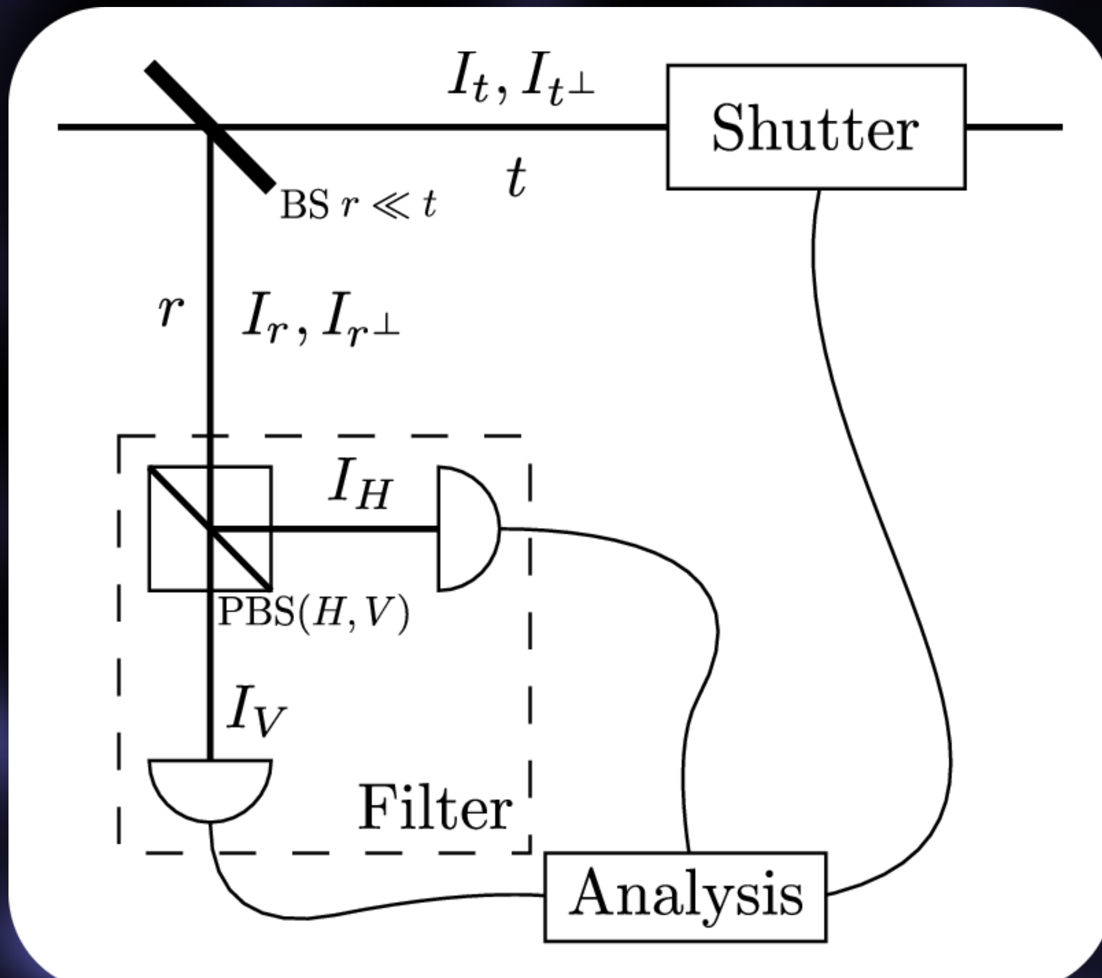
90%

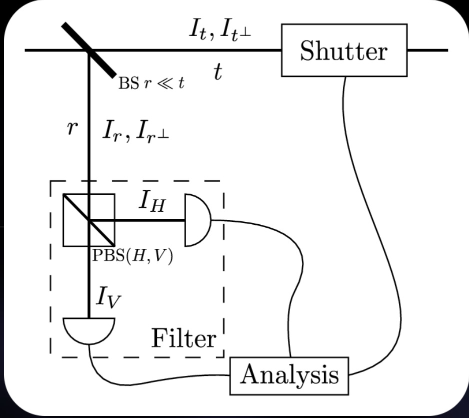


Distinguishability improvement is noticible for detectors measuring ± 150 photons

Physical Implementation of Modulus Difference Filter

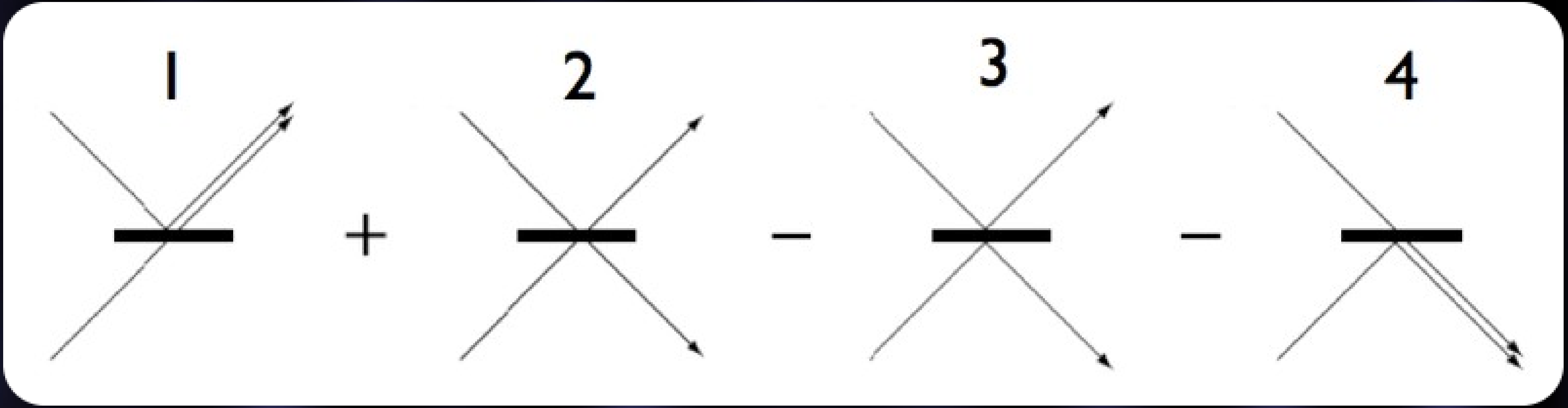
"Tap" measurement, feed forward technique,
and Hong-Ou-Mandel effect





Hong-Ou-Mandel Effect

Interference of two non-zero Fock states on BS



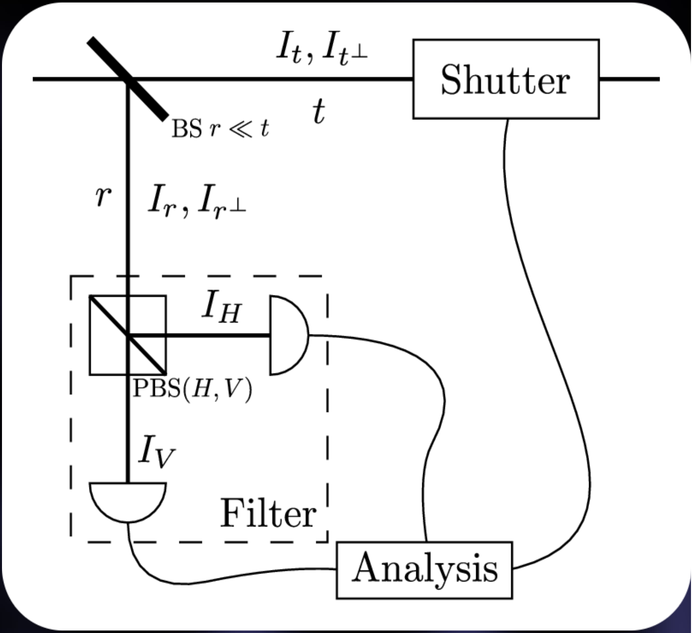
$$|1,1\rangle = a^\dagger b^\dagger |0,0\rangle \rightarrow \frac{1}{2}\left(c^\dagger + d^\dagger\right)\left(c^\dagger - d^\dagger\right)|0,0\rangle$$

$$= \frac{1}{2}\left({c^\dagger}^2 - {d^\dagger}^2\right)|0,0\rangle = \frac{|2,0\rangle - |0,2\rangle}{\sqrt{2}}$$

Multiphoton Hong-Ou-Mandel Effect

PBS and output: $(H,\,V)$ basis

Input: $(H+e^{i\varphi}V,\,H-e^{i\varphi}V)$ basis



Detected state

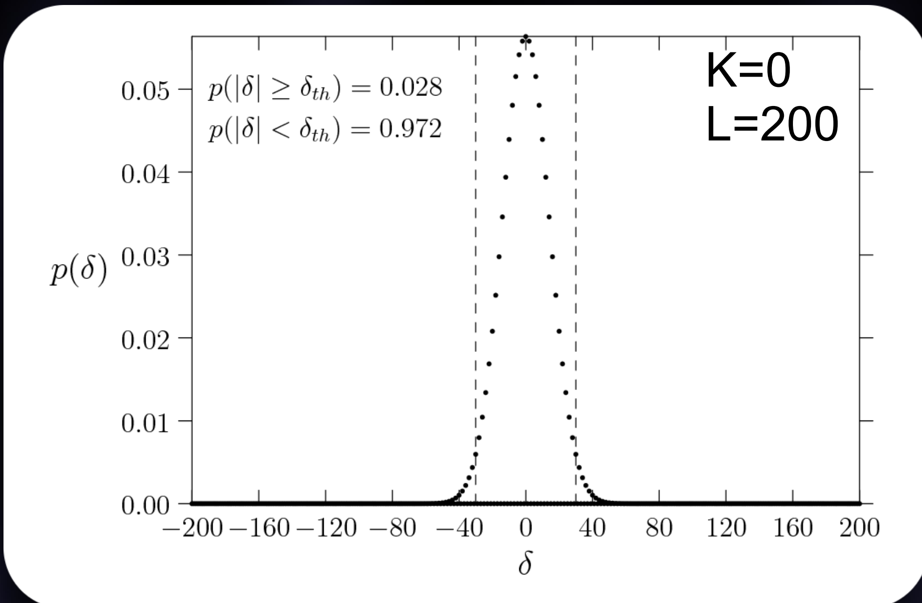
$$|K,L\rangle_{HV} \qquad \sigma = K+L$$

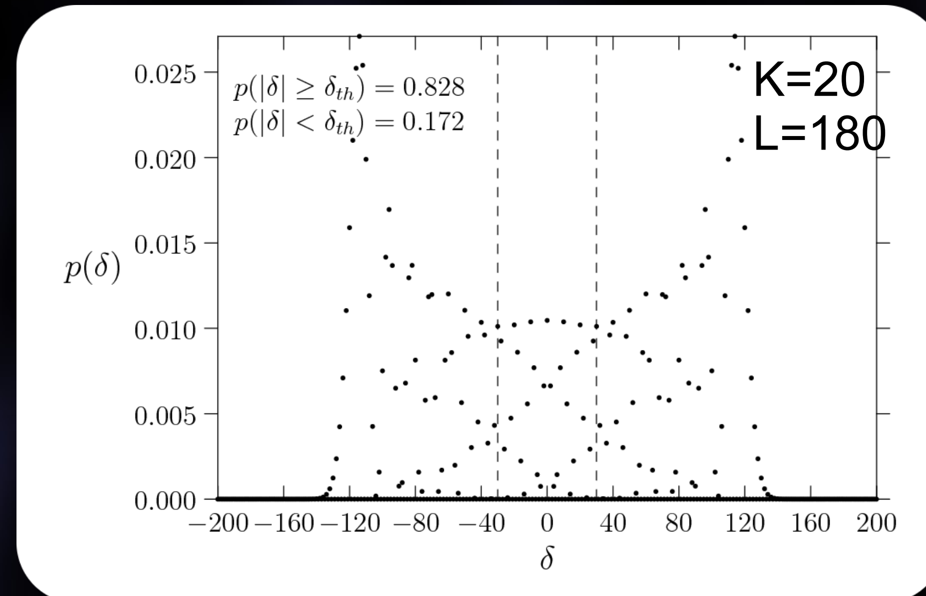
The input state is given by BS operation

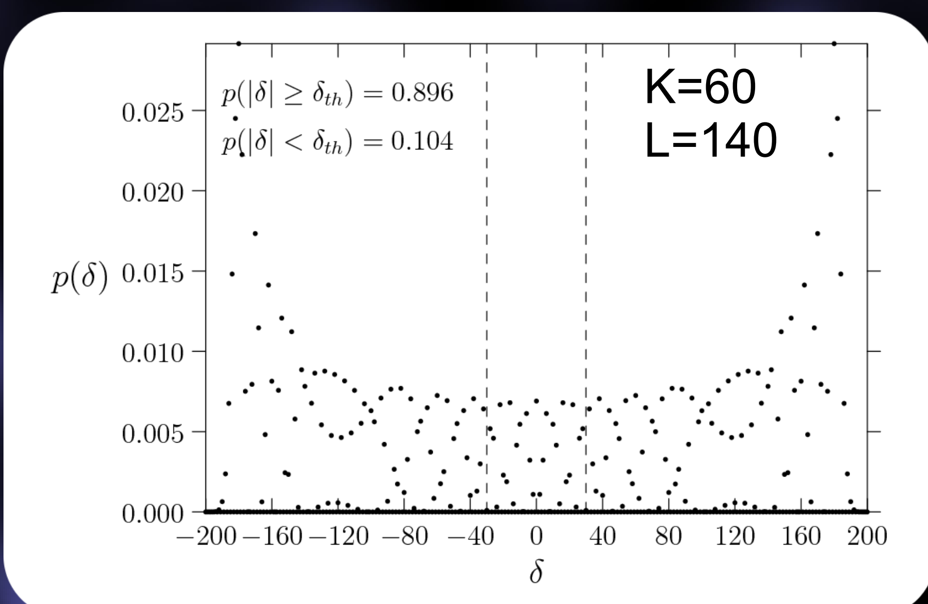
$$|\Psi\rangle_{in} = \mathcal{N}\sum_{\delta=-\sigma}^{\sigma} A^{\sigma}\left(\frac{\sigma+\delta}{2},\frac{\sigma-\delta}{2}\right)\left|\frac{\sigma+\delta}{2},\frac{\sigma-\delta}{2}\right\rangle_{r,r^\perp}$$

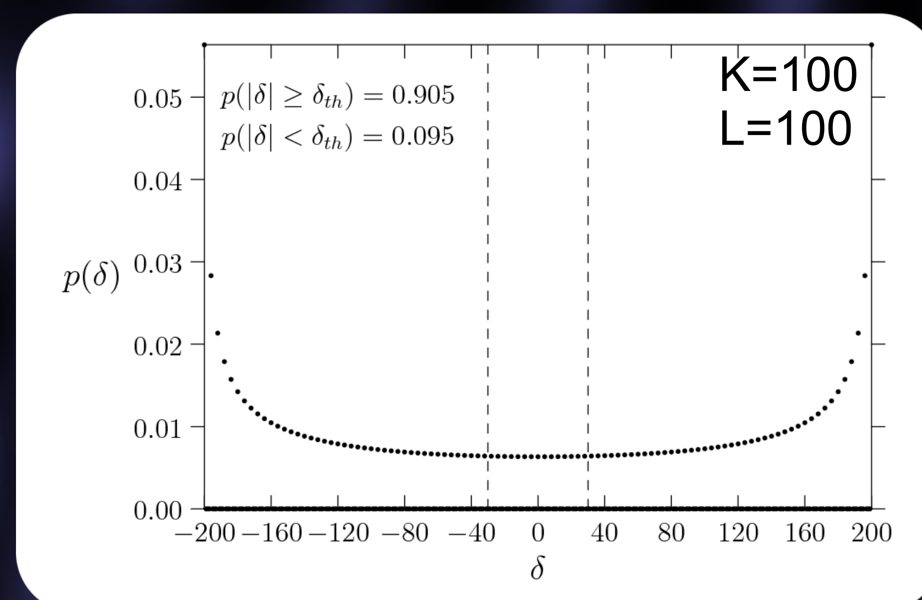
Multiphoton Hong-Ou-Mandel Effect

$\sigma = 200$



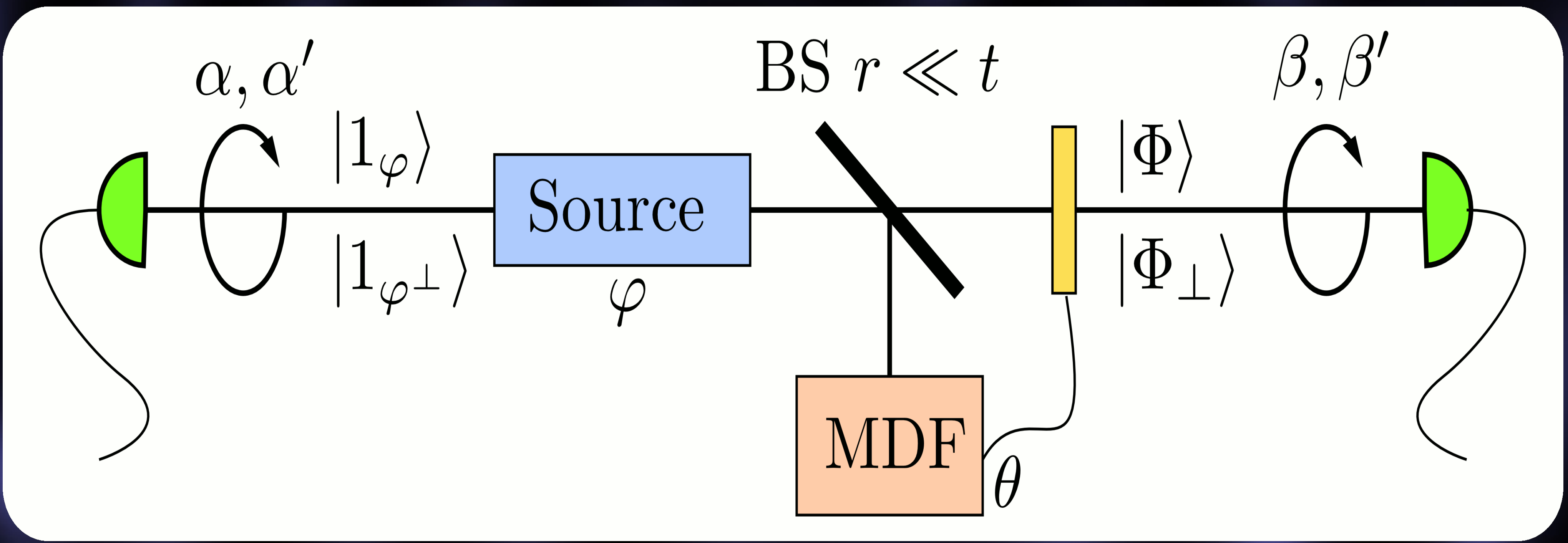




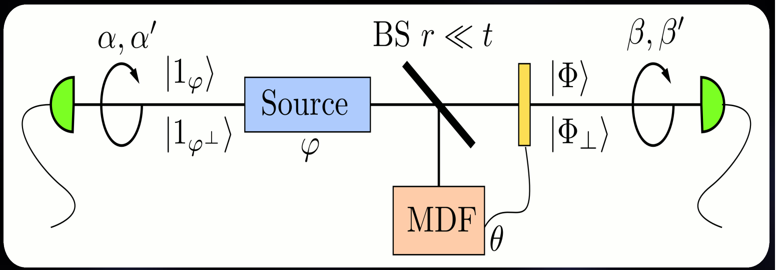


Bell Inequality Test for Micro-Macro Singlet with Preselection

$$1/\sqrt{2}\left(|1_\varphi\rangle_A|\Phi_\perp\rangle_B - |1_{\varphi^\perp}\rangle_A|\Phi\rangle_B\right)$$



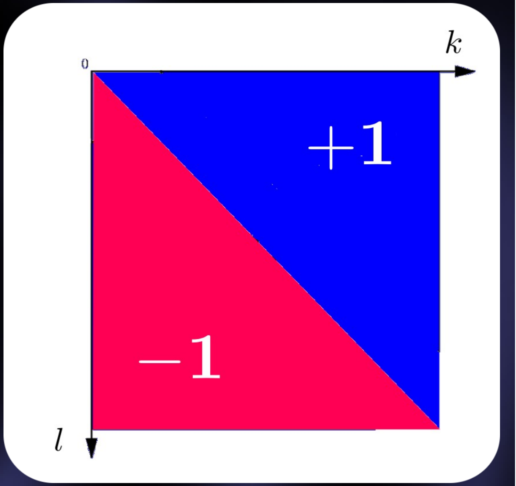
Bell Inequality Test for Micro-Macro Singlet with Preselection



Observables

$$\mathcal{O}^{(m)} = |1_\alpha\rangle\langle 1_\alpha| - |1_{\alpha^\perp}\rangle\langle 1_{\alpha^\perp}|$$

$$\mathcal{O}^{(M)} = \left(\sum_{\substack{k,l=0 \\ k-l\geq 0}}^{\infty} - \sum_{\substack{k,l=0 \\ k-l<0}}^{\infty} \right) |k,l\rangle\langle k,l|$$



Correlation function

$$E(\alpha,\beta) = \langle \mathcal{O}^{(m)} \otimes \mathcal{O}^{(M)} \rangle$$

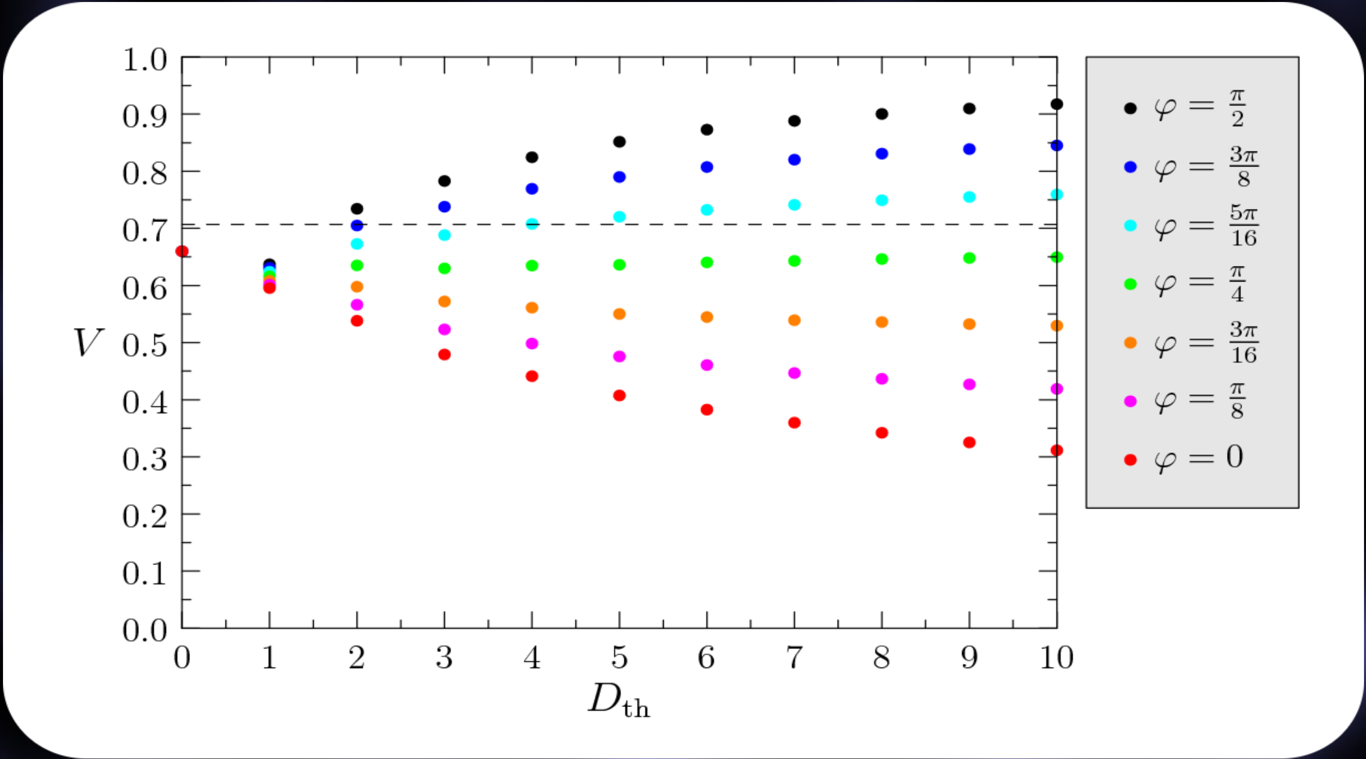
CHSH-Bell inequality

$$B = E(\alpha,\beta) + E(\alpha',\beta) + E(\alpha,\beta') - E(\alpha',\beta')$$

Filtering in Orthogonal Basis

Difference operator is not rotationally invariant

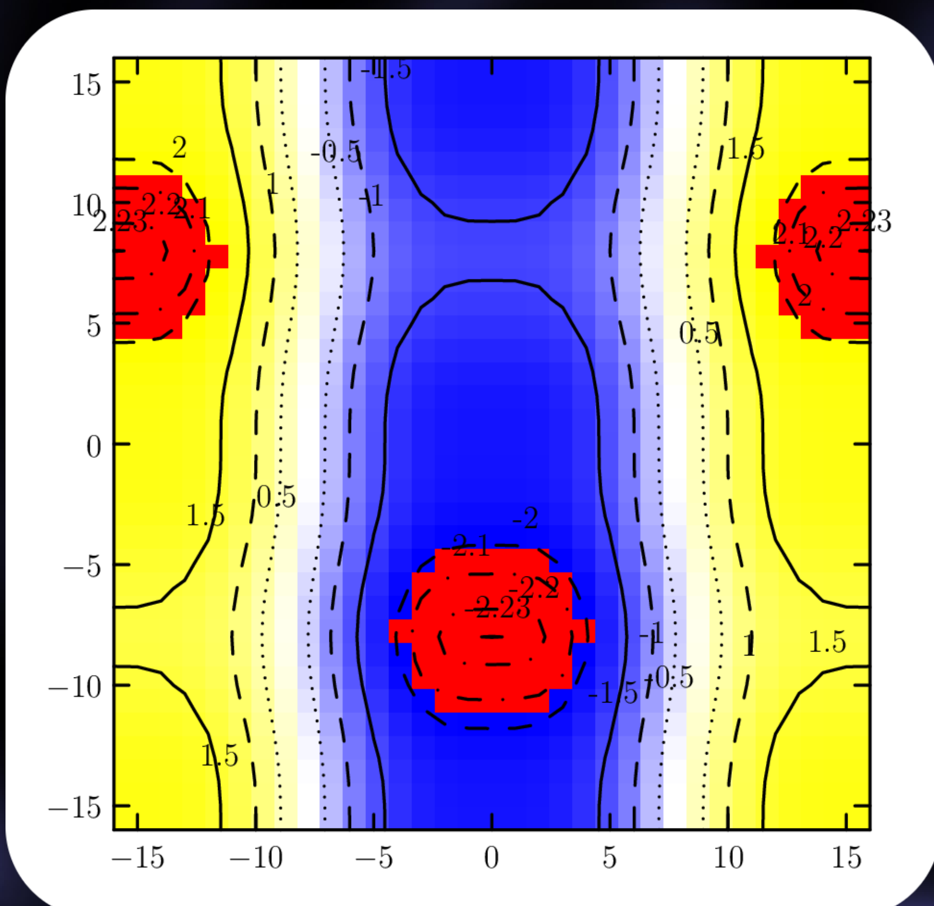
If distinguishability increases in the source basis $\varphi = \pi/2$, it decreases in the orthogonal basis $\varphi = 0$



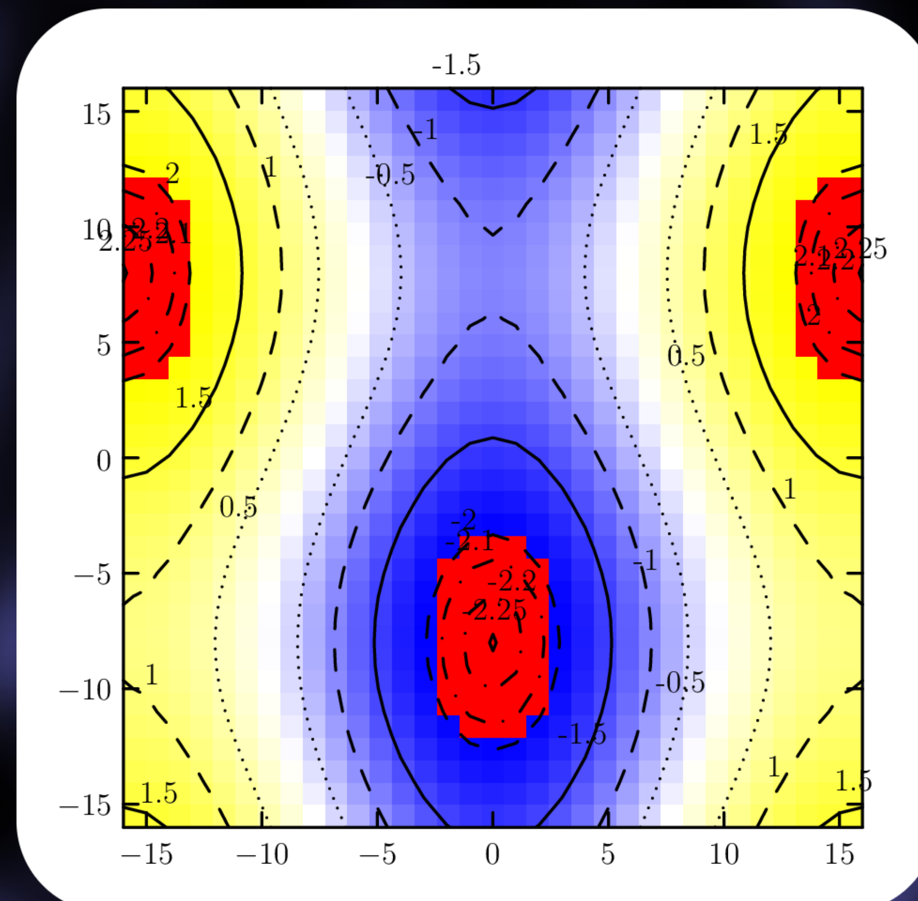
For every preselection basis θ there are rotations α, β for which $B > 2$

Bell Inequality Violation g = 0.05, $D_{th} = 1$

Analytical result



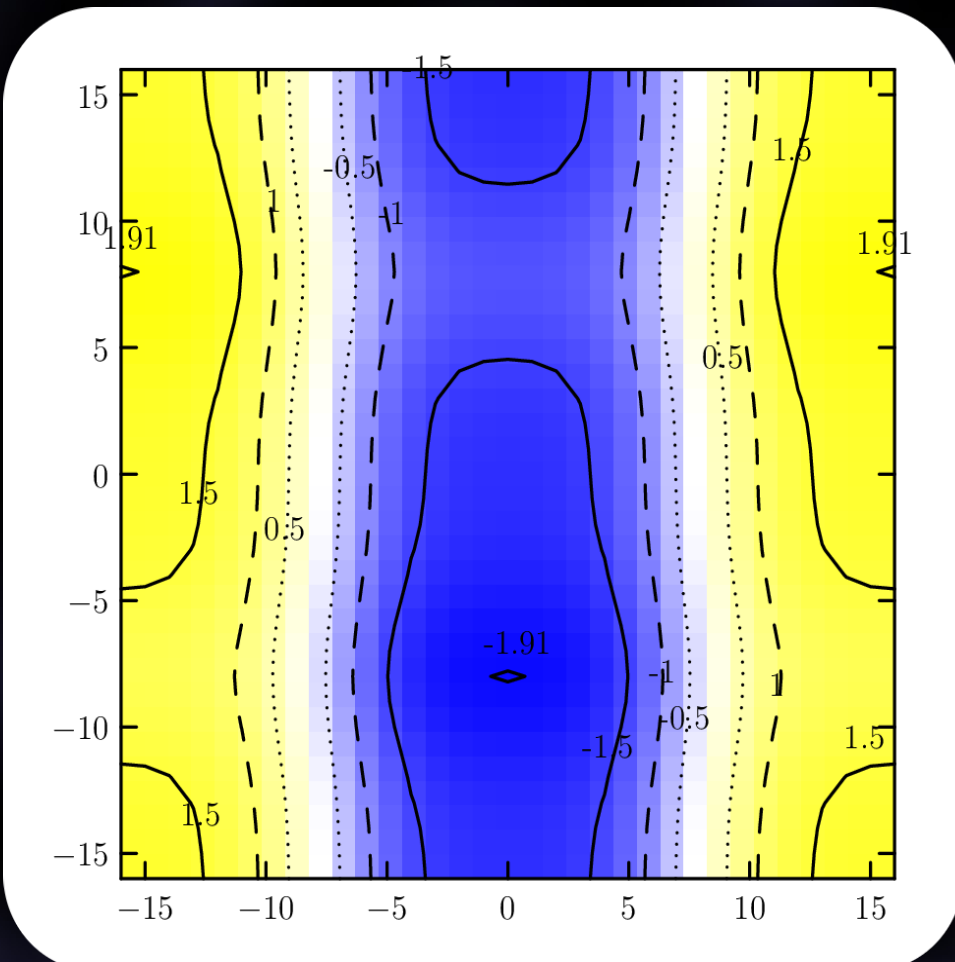
Numerical result



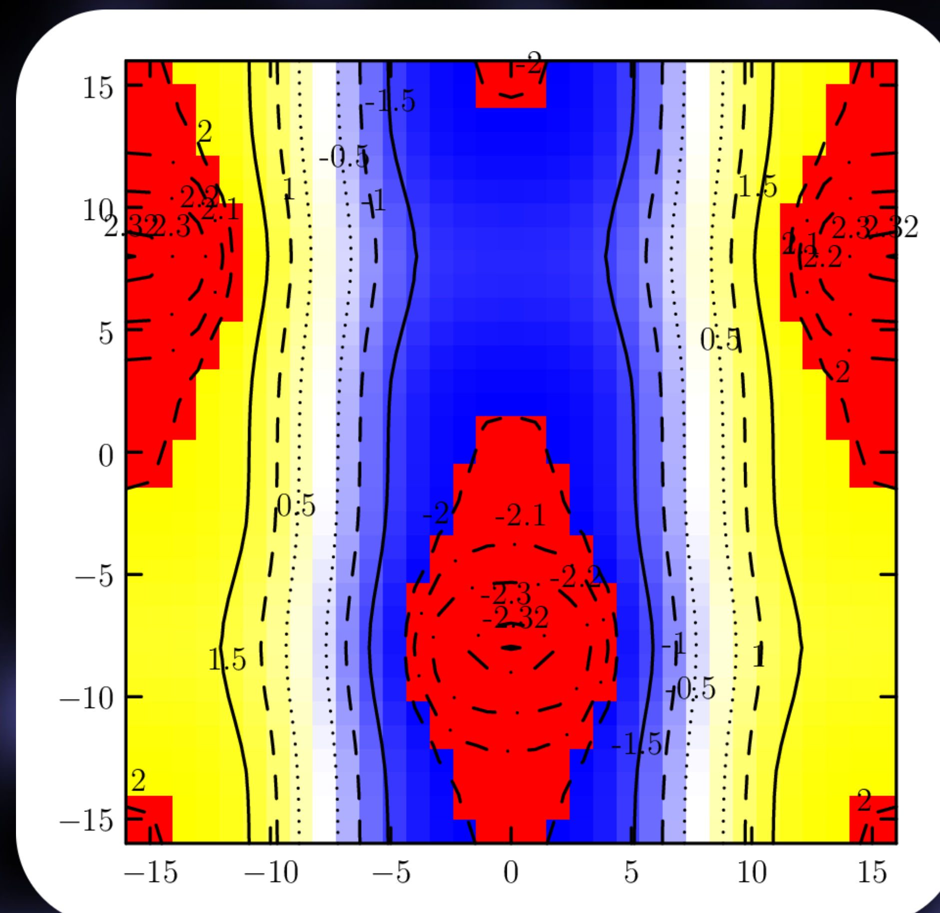
Maximal value of B is independent of preselection basis θ

Numerical Results g = 1.1 (7 photons on average)

$$D_{th} = 7, \ B = \pm 1.91$$



$$D_{th} = 9, \ B = \pm 2.32$$



Conclusions

We proposed Modulus Intensity Difference filter

- POVM measurement (preserves quantum superposition)
- Based on Hong-Ou-Mandel effect
- Works for super-Poissonian input statistics

Applied to quantum macroscopic states of light

- Increases distinguishability, also in presence of high losses
- Increases sensitivity of phase estimation
- Hope for a loophole-free Bell inequality test

Our Team

Falk Töppel

Adam Buraczewski

In collaboration with

N. Gisin
P. Sekatski
M. Chekhova
M. Żukowski

arXiv:1108.4906

Thank You!