Title: TBA

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Abstract:

Experimental measurements of bounds on higher-order interferences

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Experimental measurements of bounds
on higher-order interference

Motivation

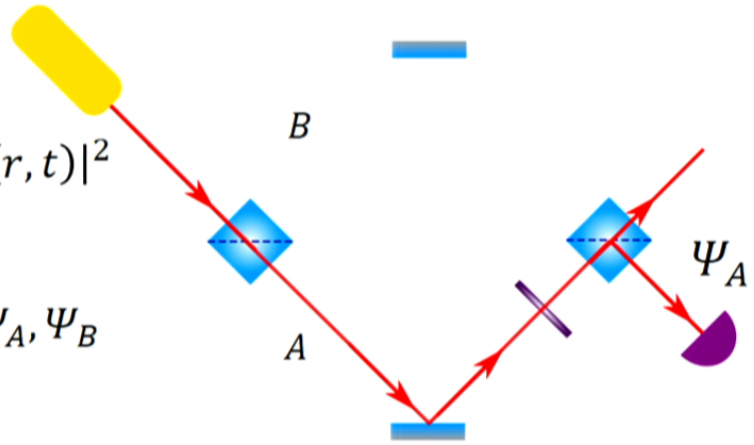
- Quantum mechanics is based on axioms
  - Are they correct?
    - Only experimental test possible

- Incompatibility of quantum mechanics and gravitation
  - Generalization for unification
  - Axioms could be violated

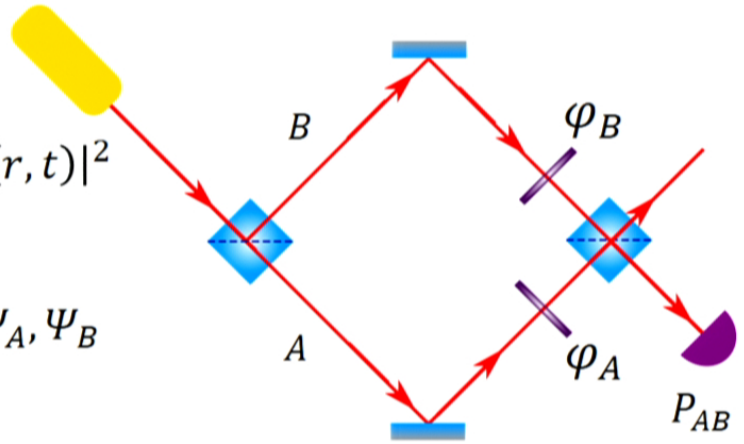
R. D. Sorkin, Mod. Phys. Lett. A **9**, 3119-3128 (1994)

Born's rule in a Mach Zehnder Interferometer

- $P(r,t) = \Psi^*(r,t)\Psi(r,t) = |\Psi(r,t)|^2$
- Superposition of two states: Ψ_A, Ψ_B



Born's rule in a Mach Zehnder Interferometer



- $P(r,t) = \Psi^*(r,t)\Psi(r,t) = |\Psi(r,t)|^2$
- Superposition of two states: Ψ_A, Ψ_B
- $P_{AB} = |\Psi_A + \Psi_B|^2 = \underbrace{|\Psi_A|^2}_{P_A} + \underbrace{|\Psi_B|^2}_{P_B} + \underbrace{\Psi_A^*\Psi_B + \Psi_A\Psi_B^*}_{I_{AB}}$
- Interference term:

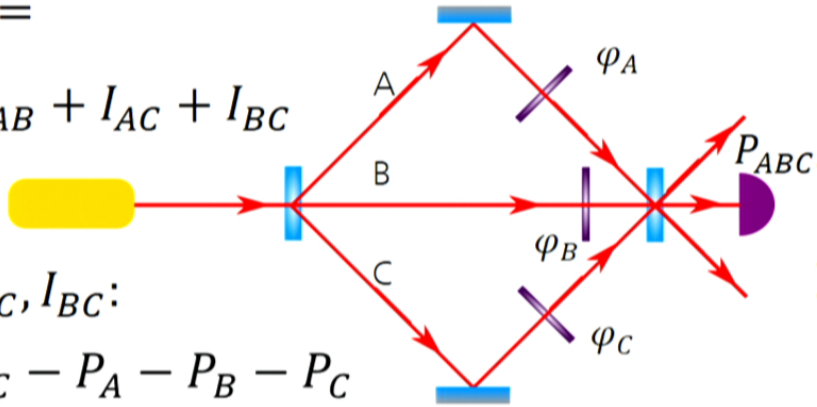
$$I_{AB} = P_{AB} - P_A - P_B \neq 0$$

depending on the phasedifference $\varphi_A - \varphi_B$

For three paths we get:

- $P_{ABC} = |\Psi_A + \Psi_B + \Psi_C|^2 =$

$$P_A + P_B + P_C + I_{AB} + I_{AC} + I_{BC}$$



- use definitions for I_{AB}, I_{AC}, I_{BC}:

$$P_{ABC} = P_{AB} + P_{AC} + P_{BC} - P_A - P_B - P_C$$

- According to conventional theory there is no higher order interference term I_{ABC}:

$$I_{ABC} = P_{ABC} - P_{AB} - P_{AC} - P_{BC} + P_A + P_B + P_C = 0$$

R. D. Sorkin, Mod. Phys. Lett. A **9**, 3119-3128 (1994)

In the experiment

- Not so easy to measure probabilities directly
  - $P \propto p$ (intensity on PD/counts on single photon detector)
  - p_0 background/dark counts

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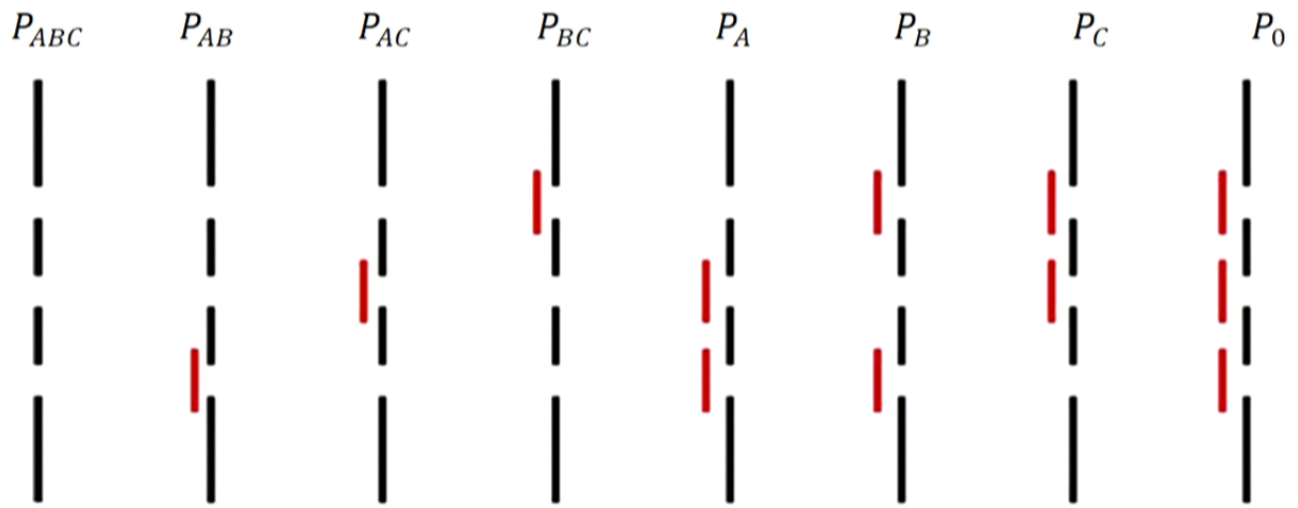
$$I_{ABC} \propto \epsilon_3 = p_{ABC} - p_{AB} - p_{AC} - p_{BC} + p_A + p_B + p_C - p_0 \stackrel{!}{=} 0$$



Dakić et al., New J. Phys. **16** (2014) 023028

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$$I_{ABC} \propto \epsilon_3 = p_{ABC} - p_{AB} - p_{AC} - p_{BC} + p_A + p_B + p_C - p_0 \stackrel{!}{=} 0$$

- Normalization to compare results

$$\kappa_3 = \frac{\epsilon_3}{\delta_3}$$

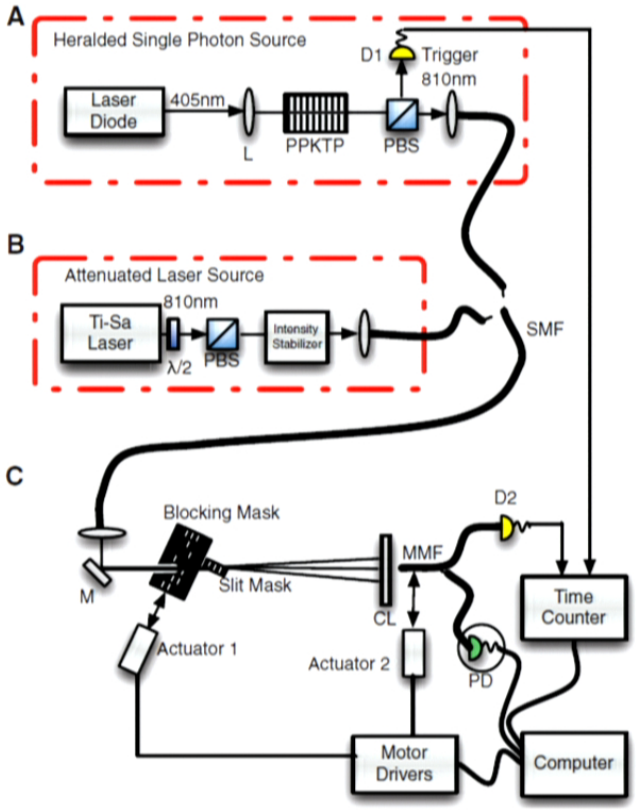
- δ_3: sum of the absolute values of two-path interference terms

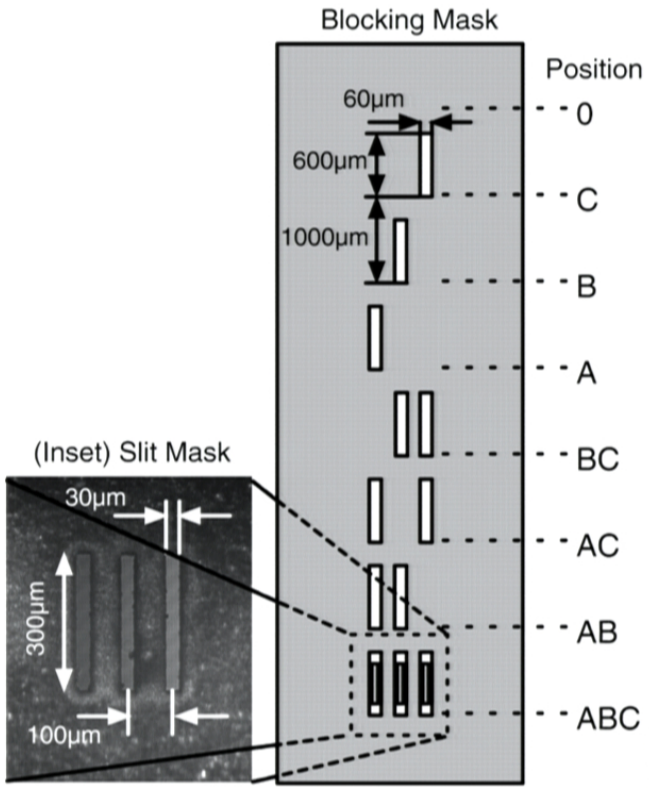
$$\delta_3 = |I_{AB}| + |I_{AC}| + |I_{BC}|$$

U. Sinha et al., Science **329**, 418-421 (2010)

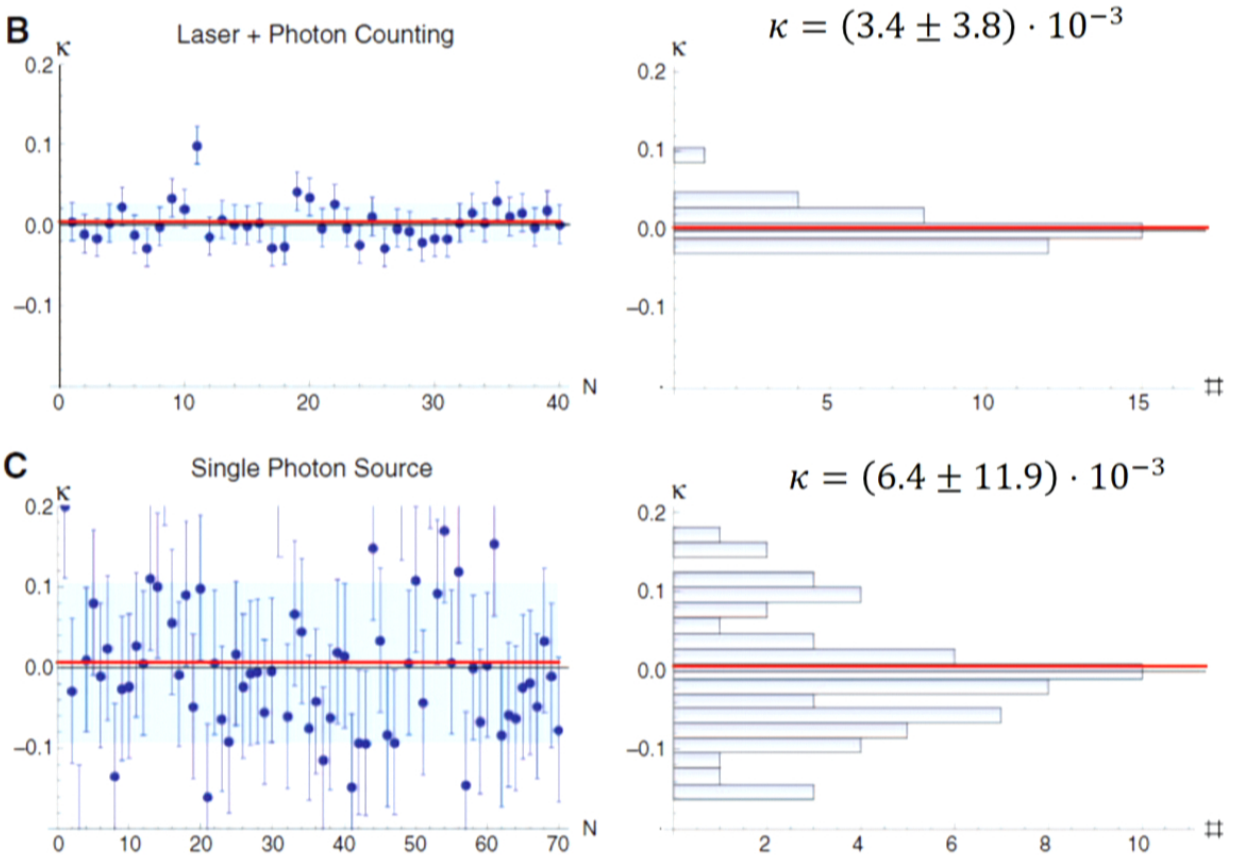
First experimental realization

By U. Sinha et al., Science 329, 418-421 (2010)



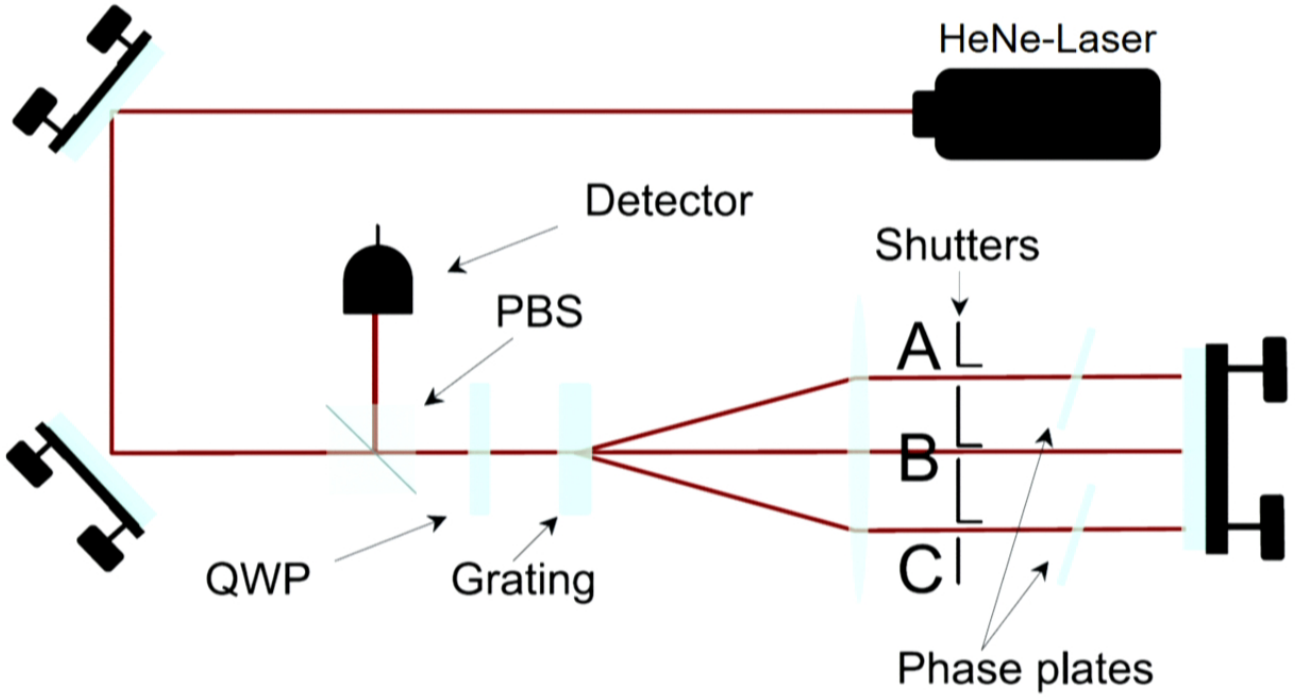


First results



U. Sinha et al., Science **329**, 418-421 (2010)

From slit setup to interferometric measurement



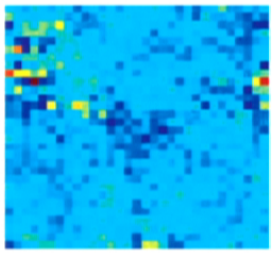
I. Söllner et al., Found. Phys. **42**, 742-751 (2012)

Other Experiments

- Spatial light modulators/orbital angular momentum:

  Hickmann et al., Europhysics Letters **96**, 64006 (2011).

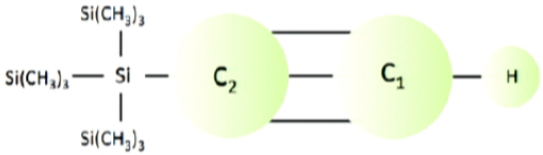
  $$\kappa \leq (4 \pm 30) \cdot 10^{-3}$$



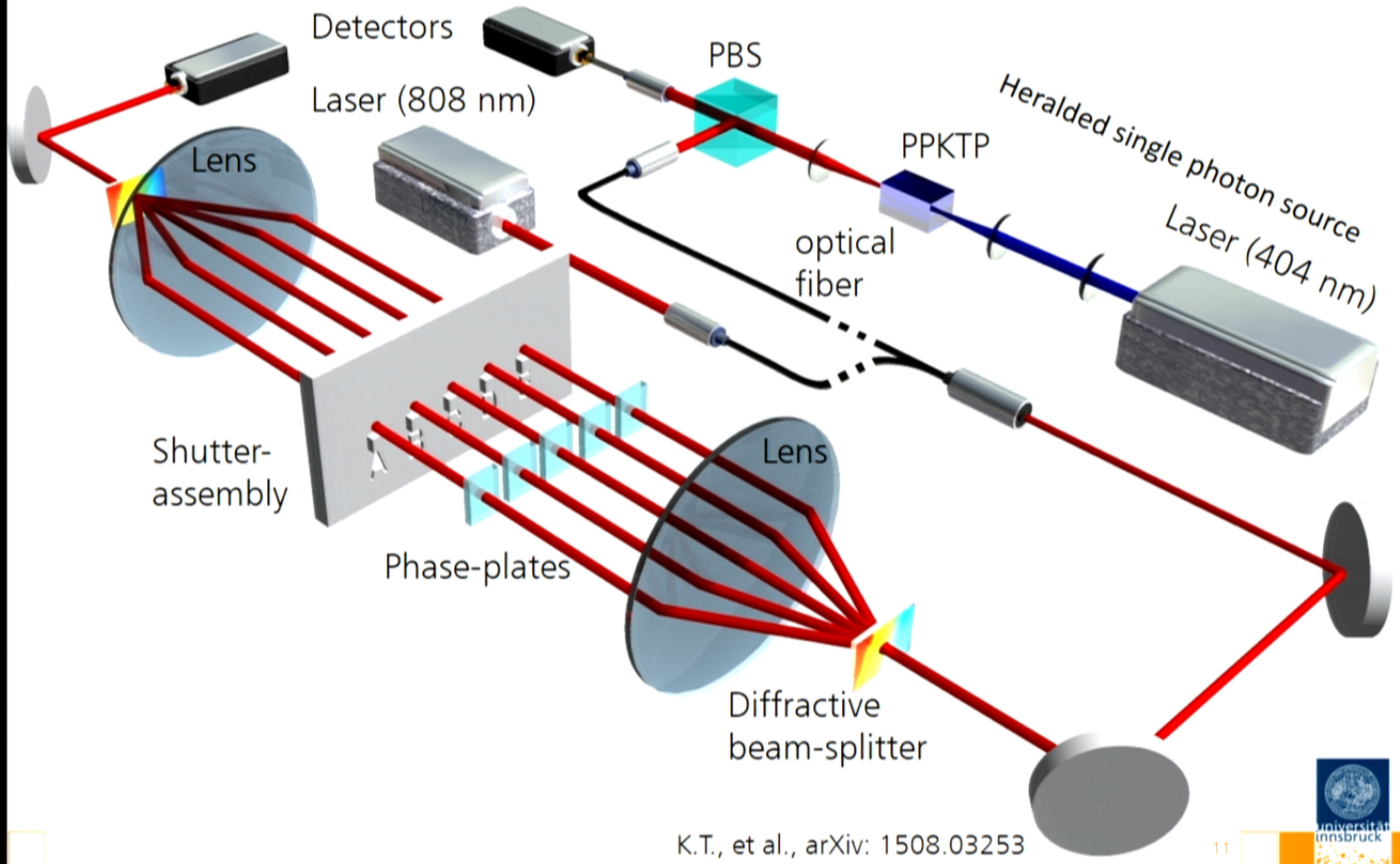
- Nuclear Magnetic Resonance on three-qubit molecule (spin ½ quantum register):

  Park, Moussa, Laflamme, New Journal of Physics 14, 113025 (2012).

  $$\kappa \leq (1 \pm 3) \cdot 10^{-3}$$



Our experimental setup



K.T., et al., arXiv: 1508.03253

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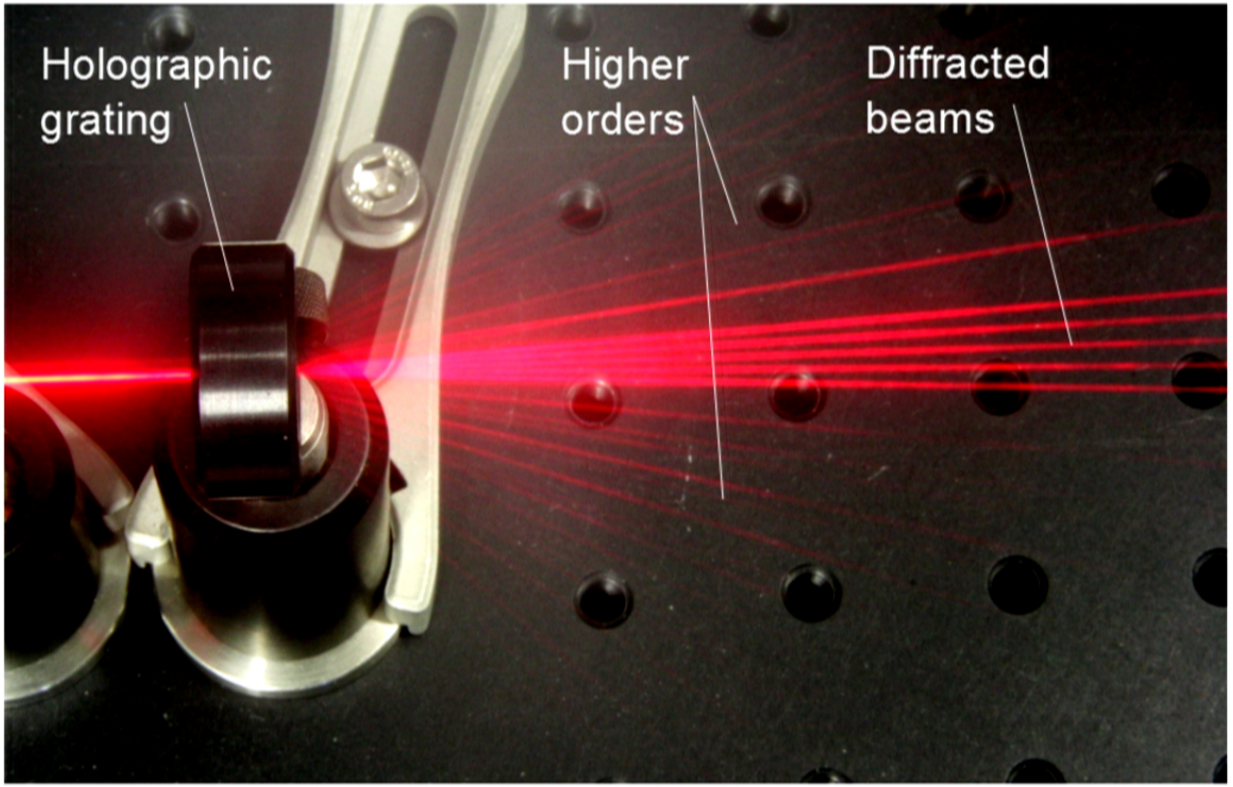

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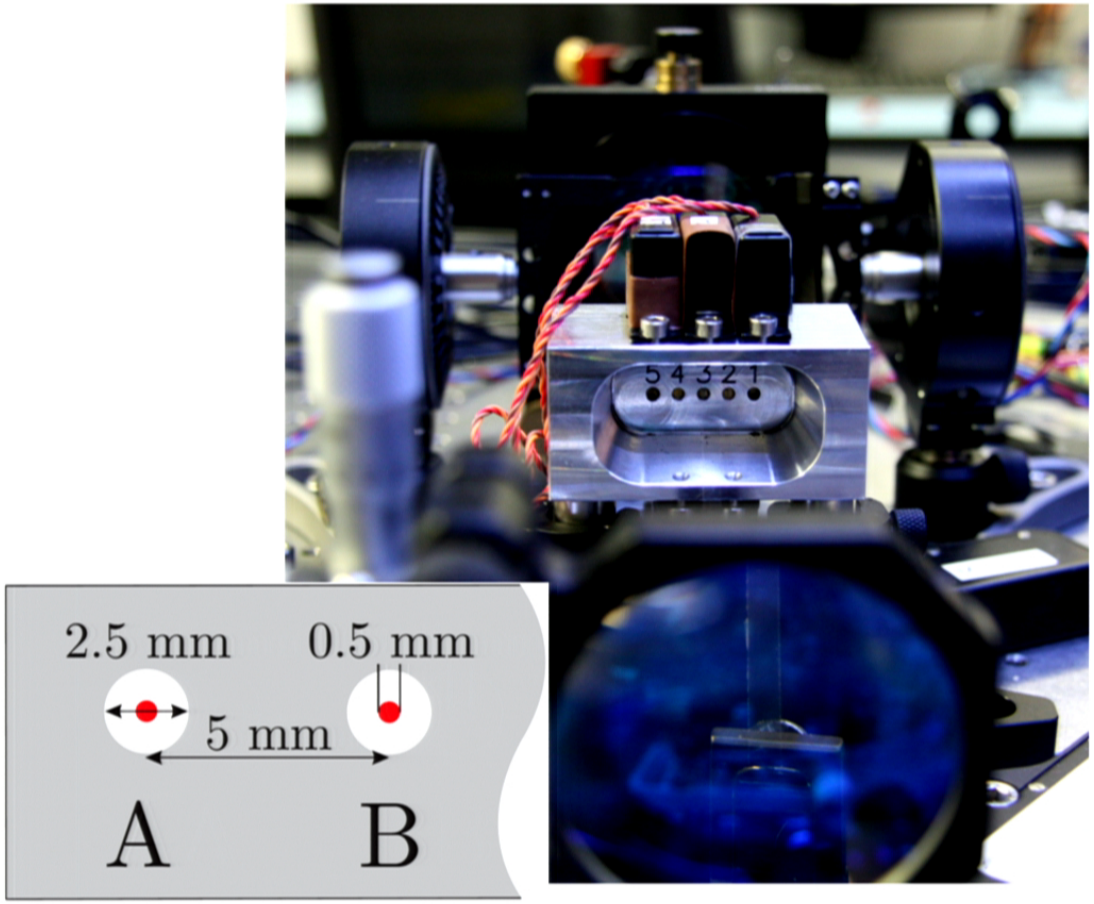

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Experimental setup

3 different measurement regimes possible:

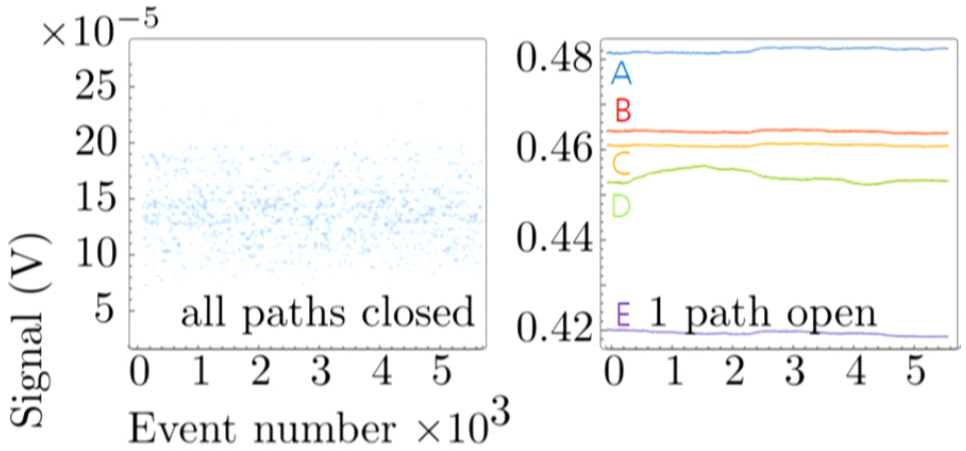
- Classical (C): with laser and photoreceiver
- Semi-classical (SC): with unheralded single photons and single photon detector
- Quantum (Q): with heralded single photons and single photon detector

Why more than three paths?

- Reduce systematics
  - Contains five 4-path, ten 3-path, and ten 2-path sub-interferometers
- Measure 4 and 5 path terms directly
- Born's rule modification
  - Power series: $P = |\psi|^2 + c_4|\psi|^4 + c_6|\psi|^6 + \cdots$
  - Modified exponent: $P = |\psi|^p$
- Test explicit models
  - nonlinear extensions of Born's rule
  - Density cube model

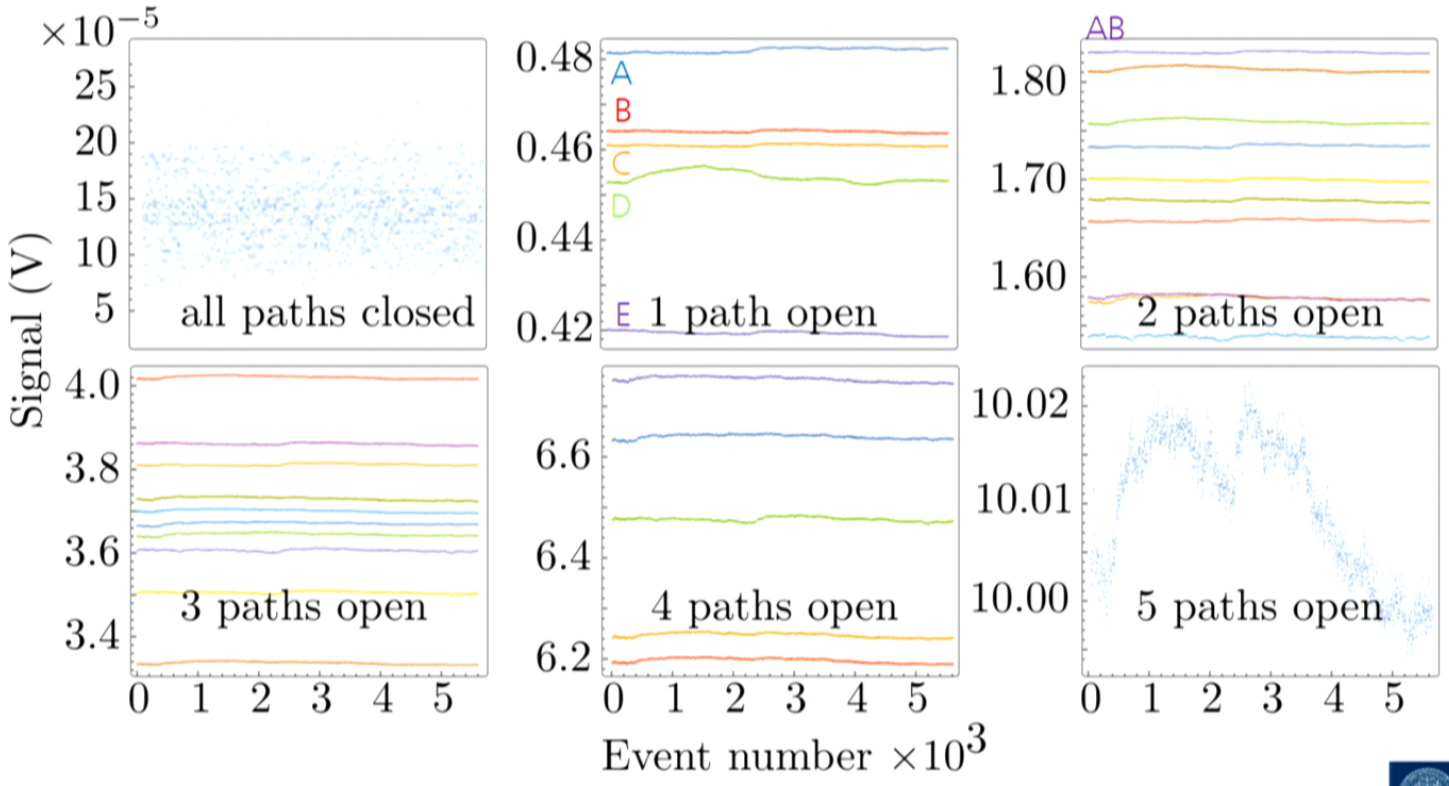
B. Dakic, et al., New J. Phys. 16, 023028 (2014)

Measurement – Classical



K.T., et al., arXiv: 1508.03253

Measurement – Classical



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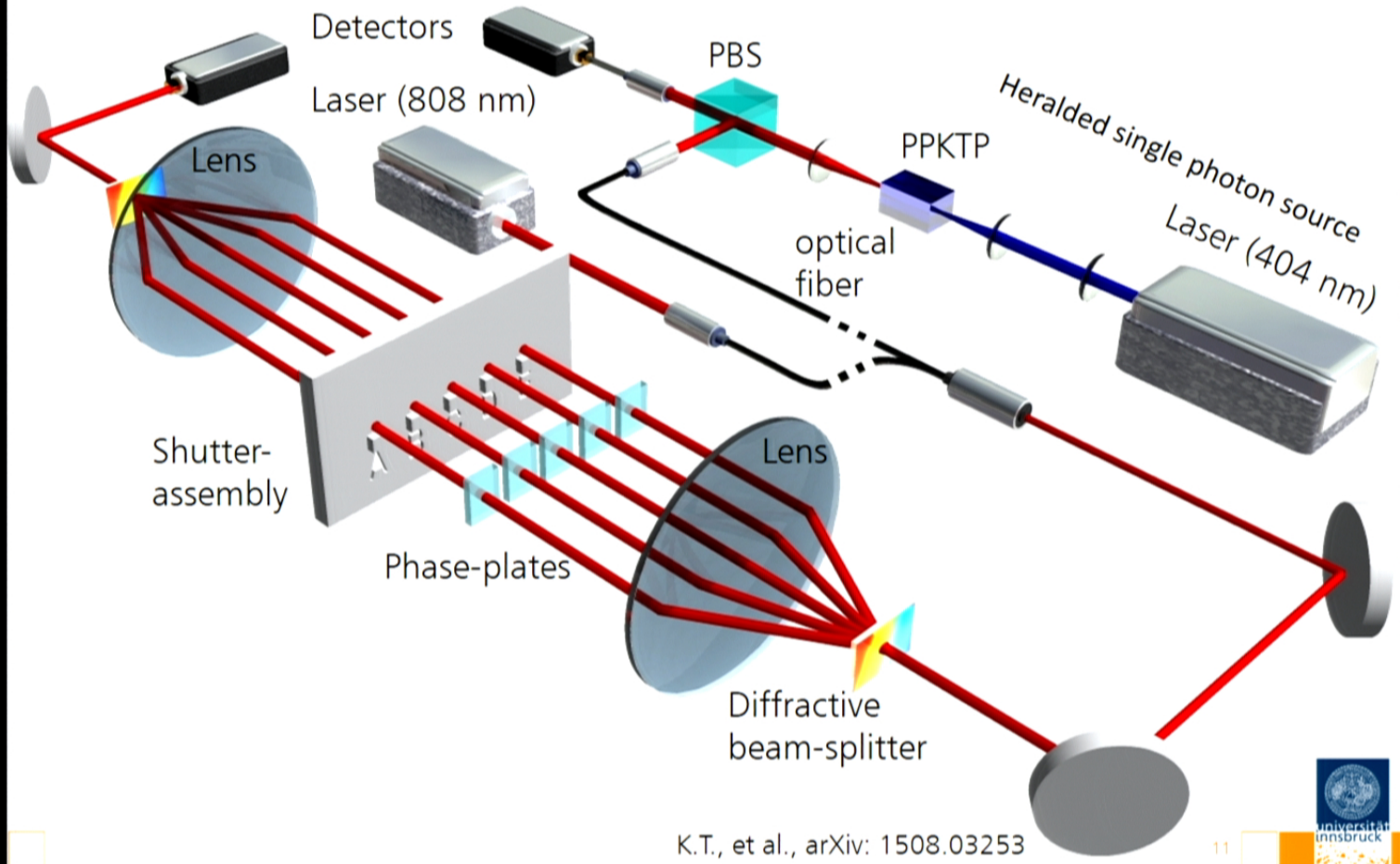
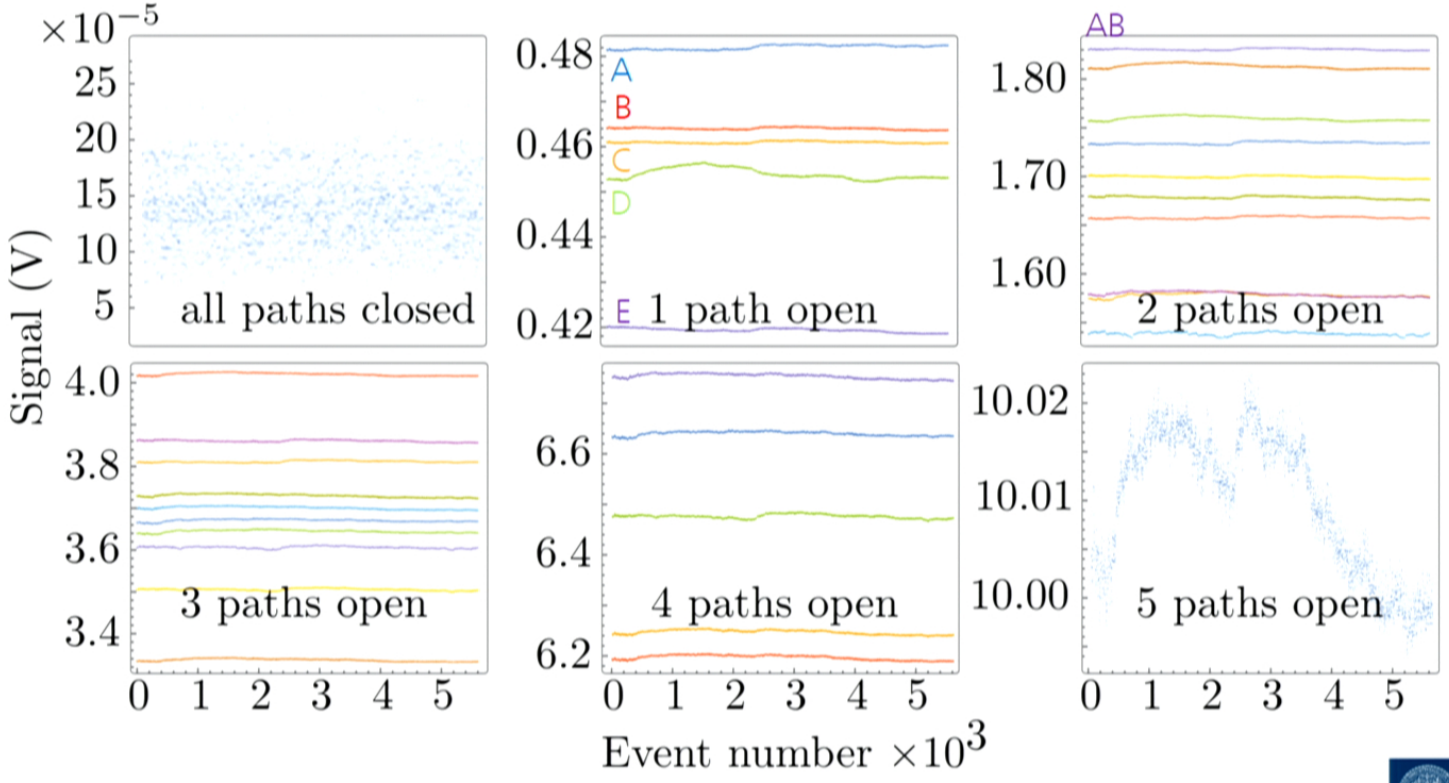


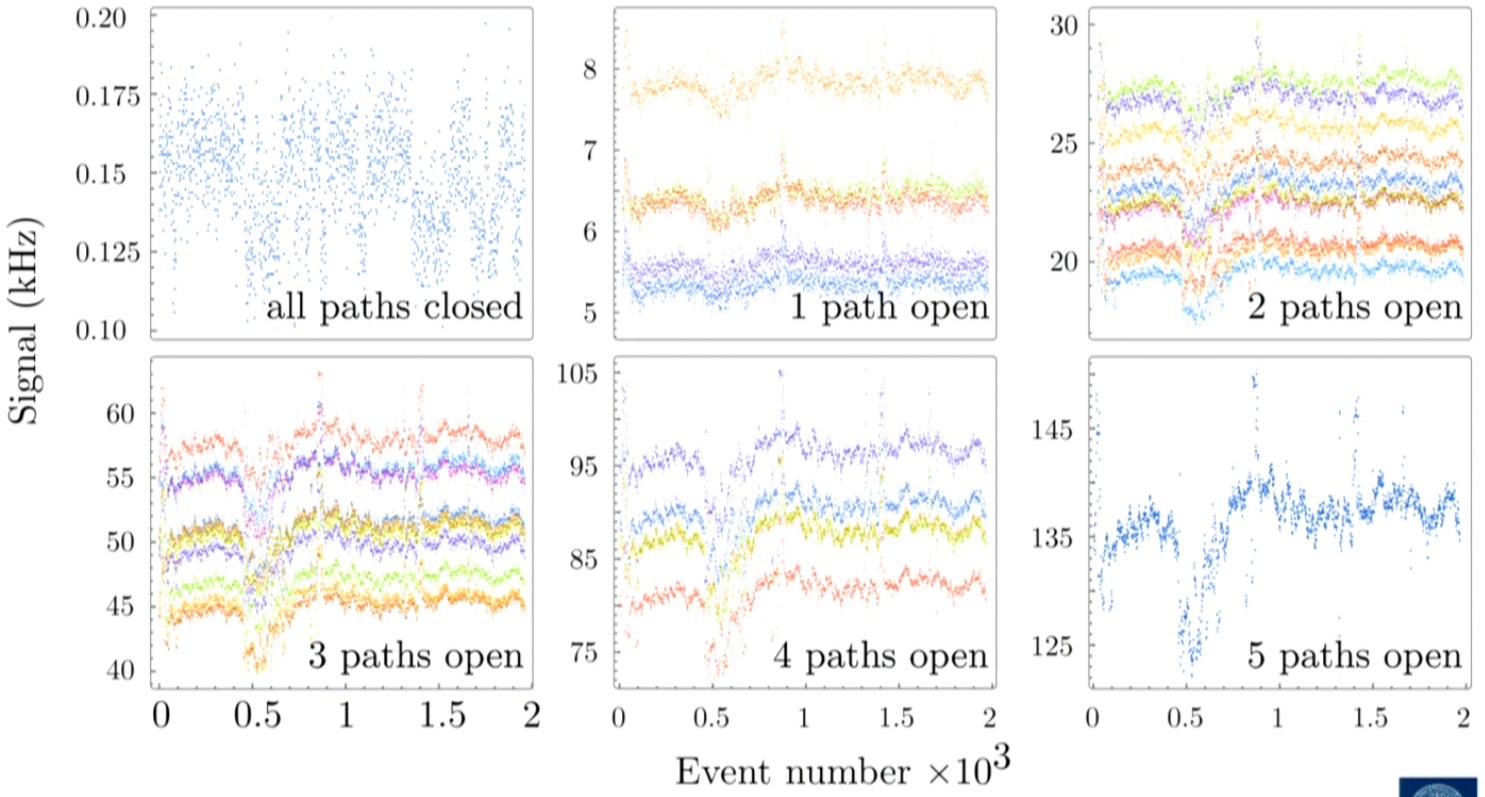
K.T., et al., arXiv: 1508.03253

Measurement – Classical



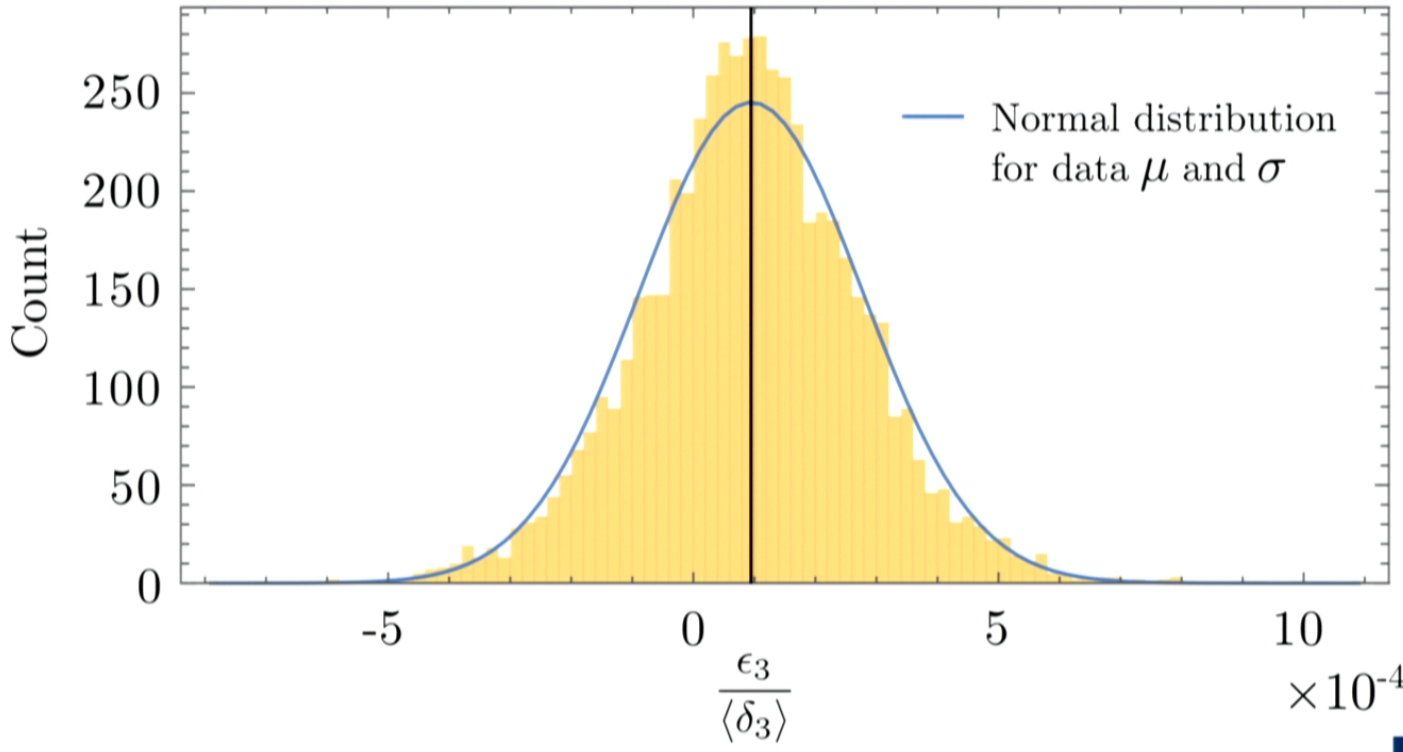
K.T., et al., arXiv: 1508.03253

Measurement – Semi classical



K.T., et al., arXiv: 1508.03253

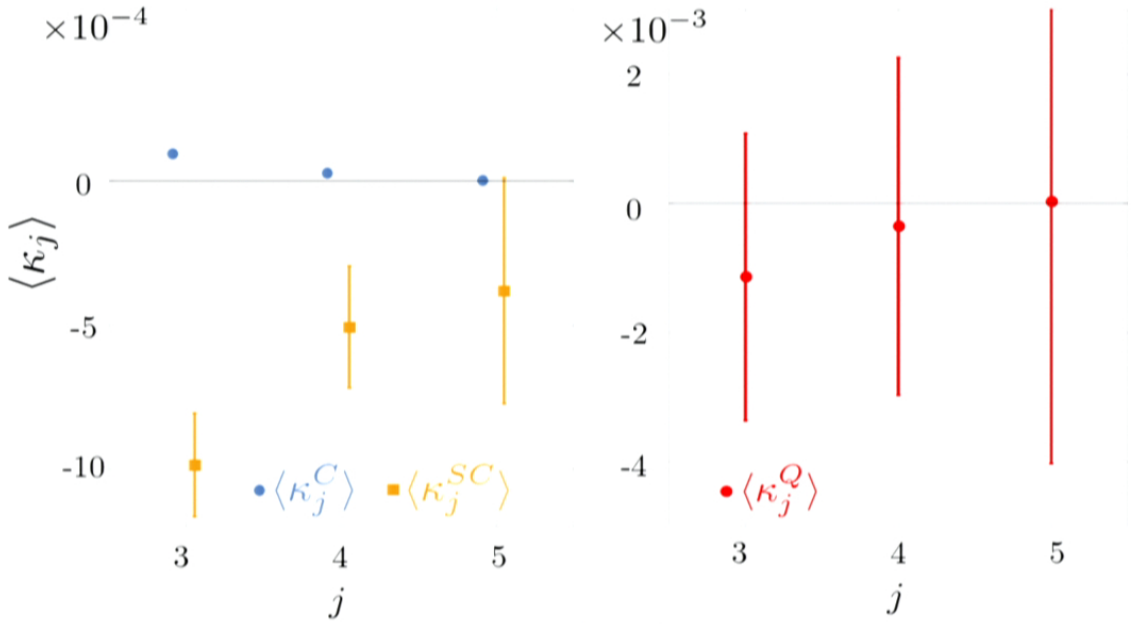
Calculating higher order interferences
Classical measurement for combination ABC



K.T., et al., arXiv: 1508.03253

Calculating higher order interferences

	$\langle \kappa_3 \rangle$	$\langle \kappa_4 \rangle$	$\langle \kappa_5 \rangle$
classical ($\times 10^{-5}$)	9.7 ± 0.1	2.7 ± 0.2	0.3 ± 0.3
semi-classical ($\times 10^{-4}$)	-9.9 ± 1.8	-5.1 ± 2.1	-3.8 ± 3.9
quantum ($\times 10^{-3}$)	-1.1 ± 1.6	0.3 ± 1.8	-2.6 ± 2.9



K.T., et al., arXiv: 1508.03253

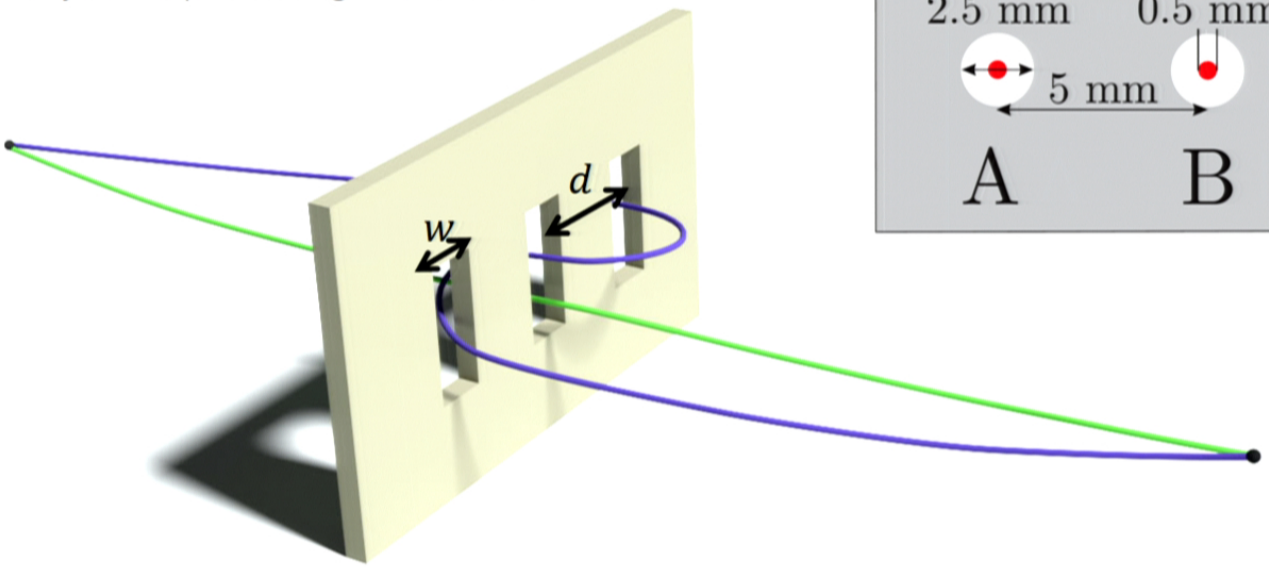
Possible sources of errors

- Random errors:
  - Countrate fluctuations of the source
  - Detector/electronic noise
  - Phase fluctuations

} Average out for many measurements (gives broader distribution/ larger error)

Nonclassical Paths

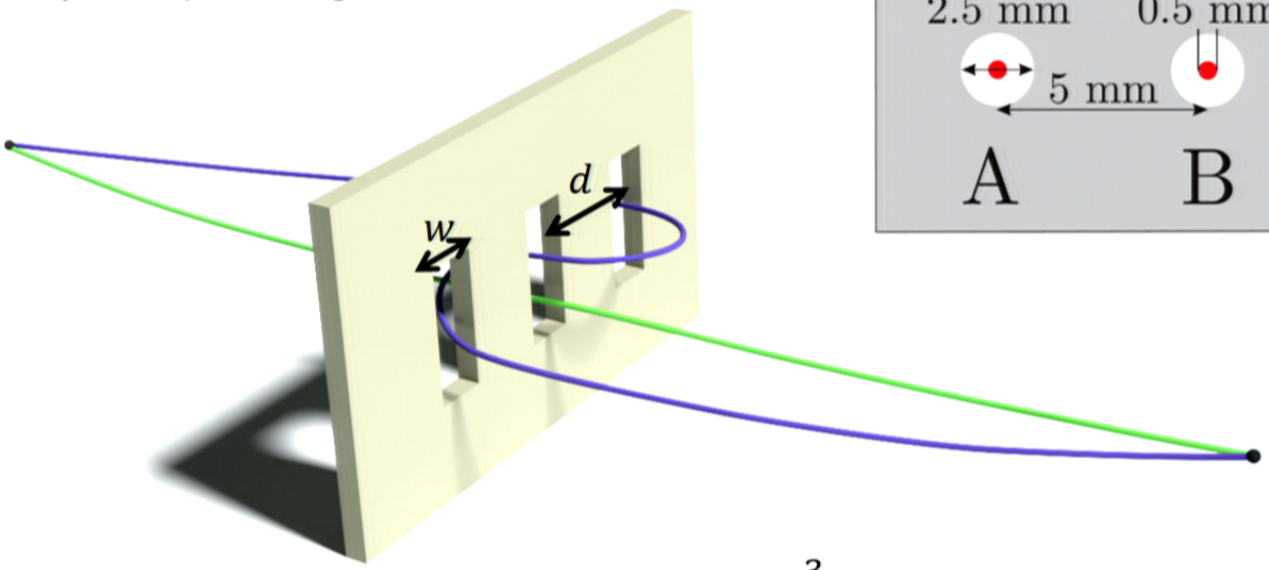
Feynman path integral formalism



R. Sawant et al., Phys. Rev. Lett. **113**, 120406 (2014)

Nonclassical Paths

Feynman path integral formalism

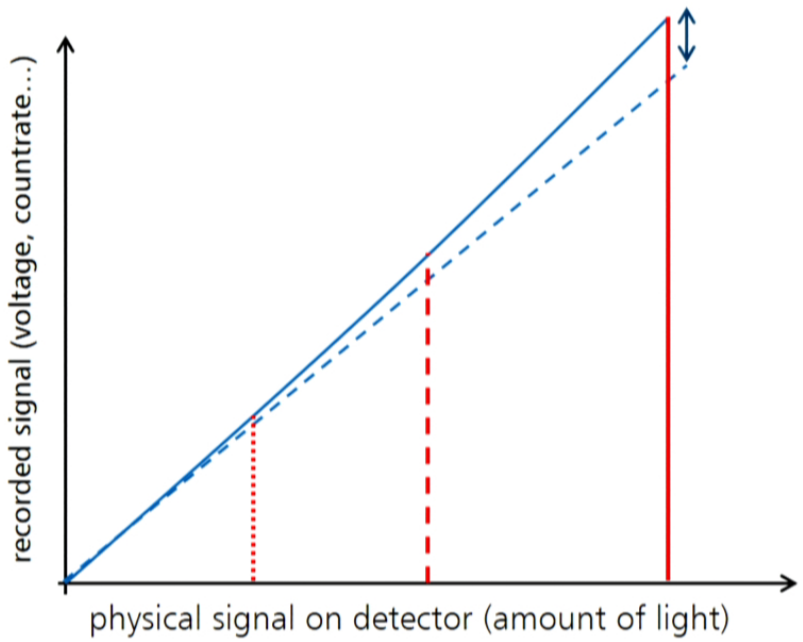


$$\kappa_{max} \approx 0.03 \frac{\lambda^{\frac{3}{2}}}{d^{\frac{1}{2}} w} = 1.2 \cdot 10^{-7}$$

R. Sawant et al., Phys. Rev. Lett. **113**, 120406 (2014)

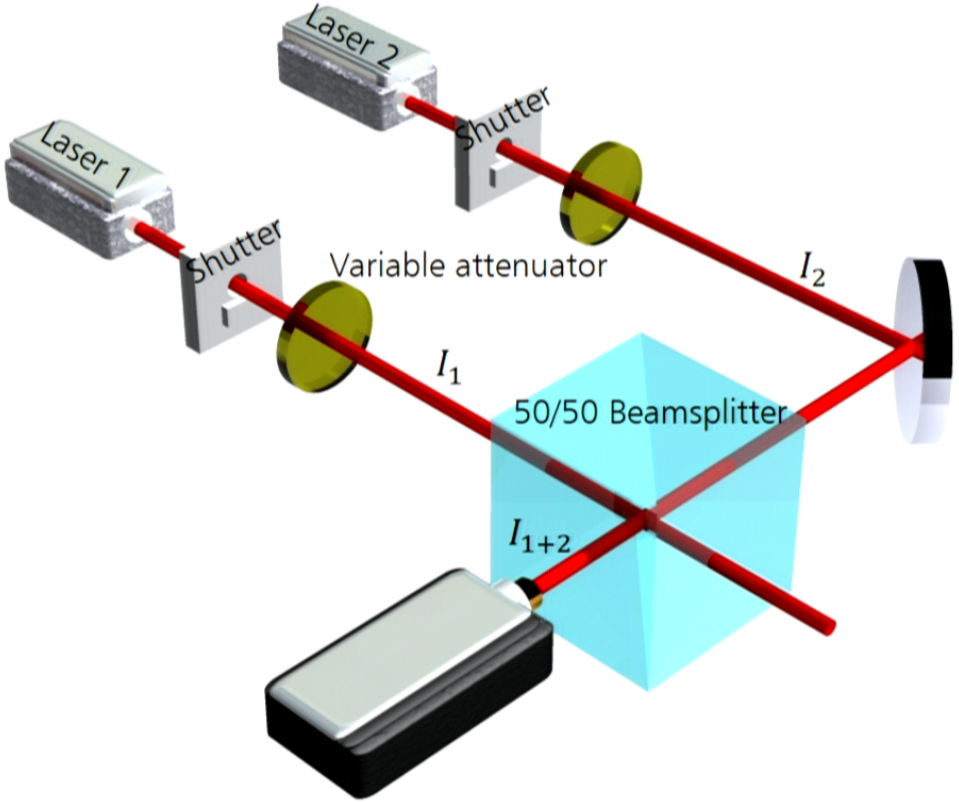
Detector nonlinearity

- Terms are affected differently → Bias on higher-order interference



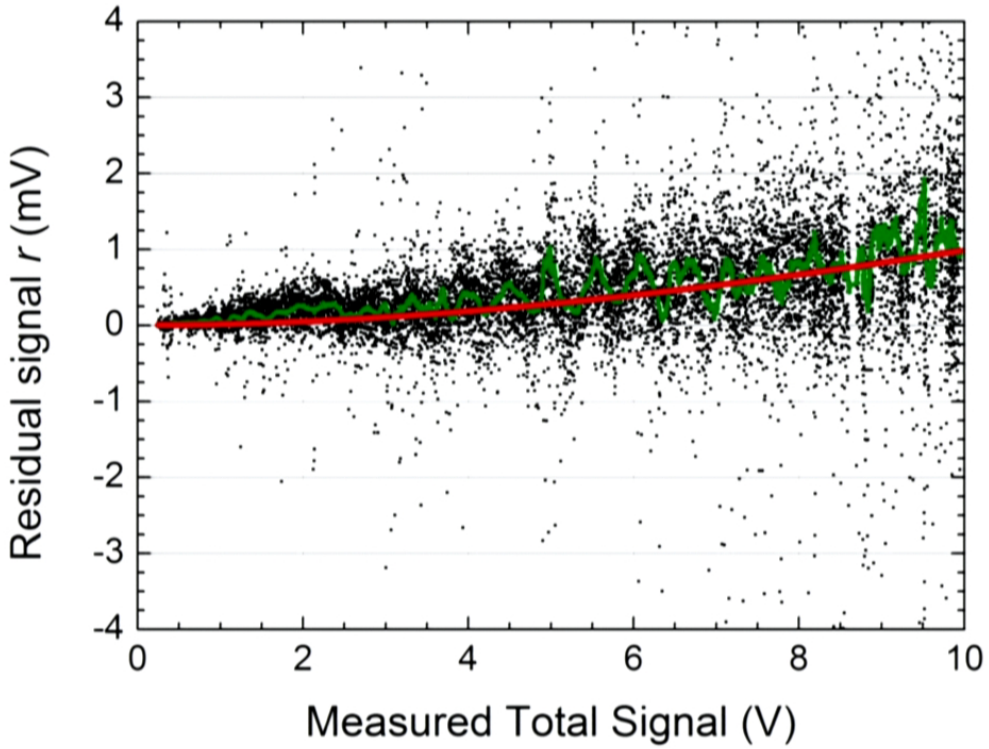
$$\epsilon_{ABC} = p_{ABC} - p_{AB} - p_{AC} - p_{BC} + p_A + p_B + p_C$$

Nonlinearity Measurement
Superposition Method



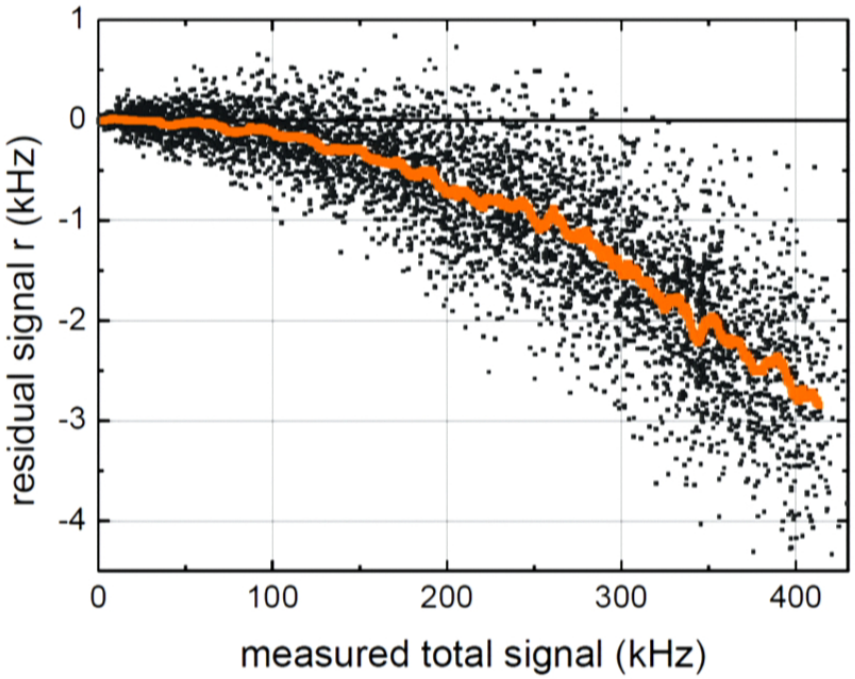
T. K. et al., Rev. Sci. Instr. **85**, 063102 (2014)

Residual signal of our photoreceiver/voltmeter



T. K. et al., Rev. Sci. Instr. **85**, 063102 (2014)

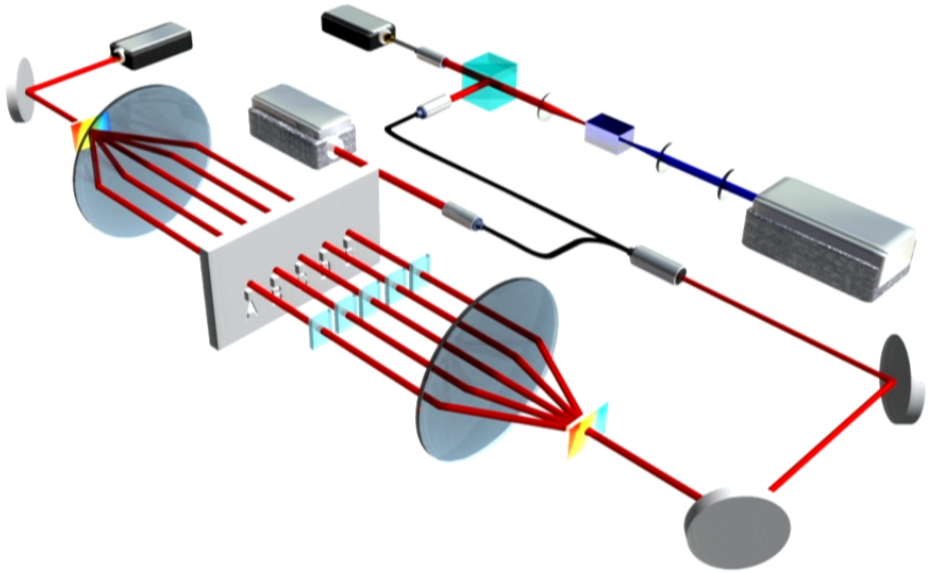
Residual signal of our single photon detector



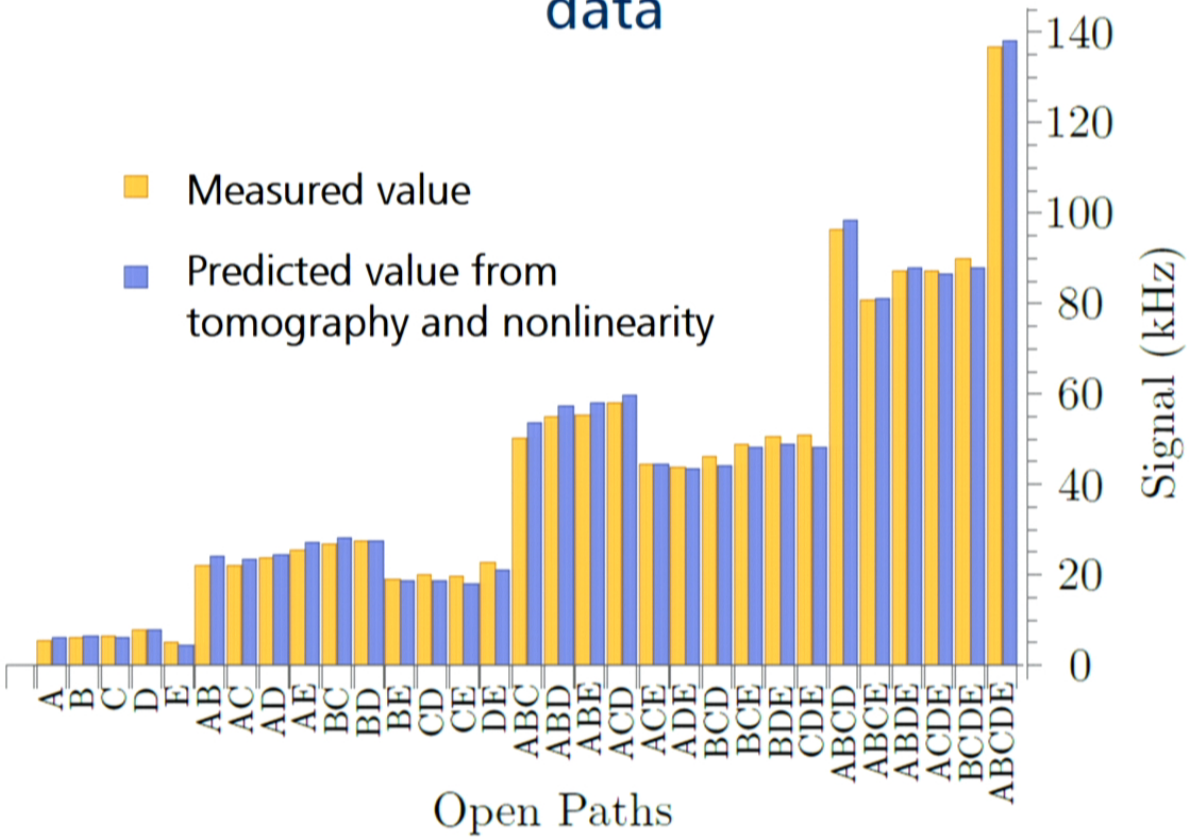
T. K. et al., Rev. Sci. Instr. **85**, 063102 (2014)

Reconstruction of the 5-dimensional qudit state describing our interferometer

Numerical reconstruction from 46 different single- and two-path measurements with defined phases via direct reconstruction



Comparison between measured and simulated data



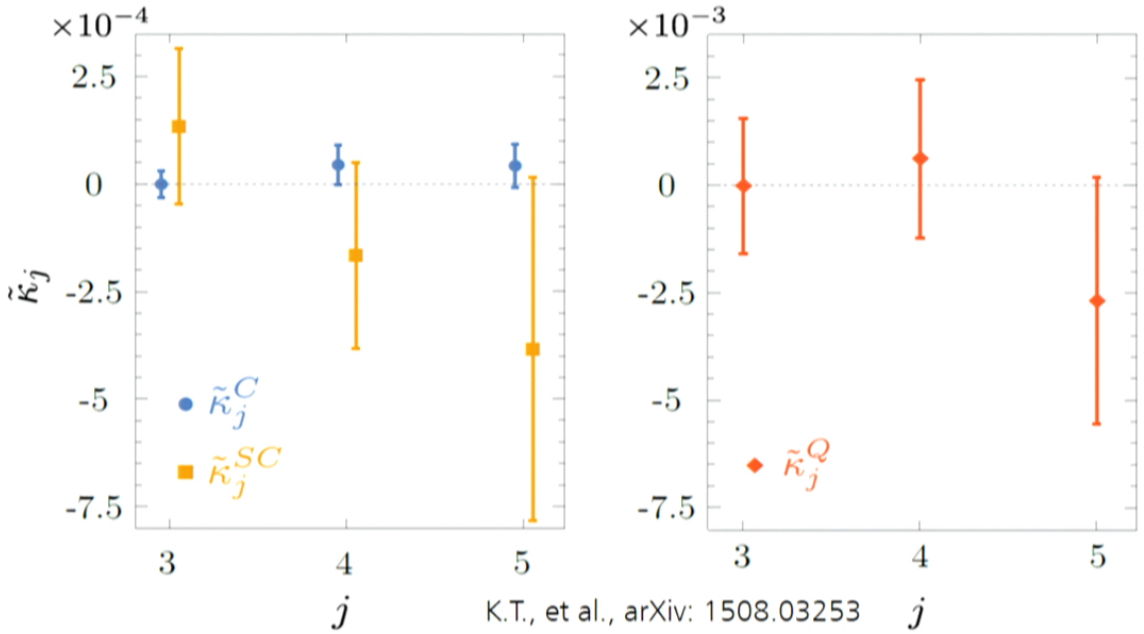
=> Calculate κ_{th} from predicted data

K.T., et al., arXiv: 1508.03253

Corrected results

$$\tilde{\kappa} = \langle \kappa \rangle - \kappa_{th}$$

	$\tilde{\kappa}_3$	$\tilde{\kappa}_4$	$\tilde{\kappa}_5$
classical ($\times 10^{-5}$)	0.0 ± 3.1	4.7 ± 4.4	4.2 ± 5.1
semi-classical ($\times 10^{-4}$)	1.3 ± 1.8	-1.6 ± 2.1	-3.8 ± 4.0
quantum ($\times 10^{-3}$)	0.0 ± 1.6	0.6 ± 1.8	-2.7 ± 2.9



K.T., et al., arXiv: 1508.03253

Results

- No higher order interferences found, only upper bound
- Improvement of two orders of magnitude
- First measurement of κ_4, κ_5
- Main sources of error
  - Nonlinearity
  - Counting error

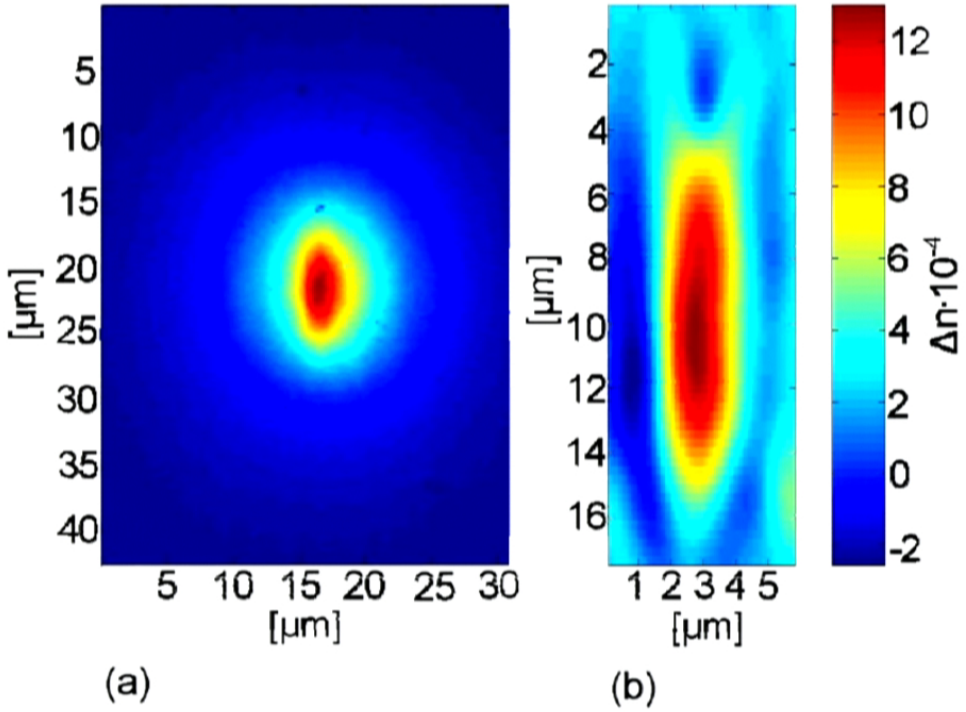
Other concept of multi-path interferometer

- Smaller -> better phase stability
- Perfect mode overlap (required for other experiment: Peres test against hyper-complex quantum mechanics)
- Integrated optical setup as an option

Peres, Phys. Rev. Lett. **42** (1979), 683

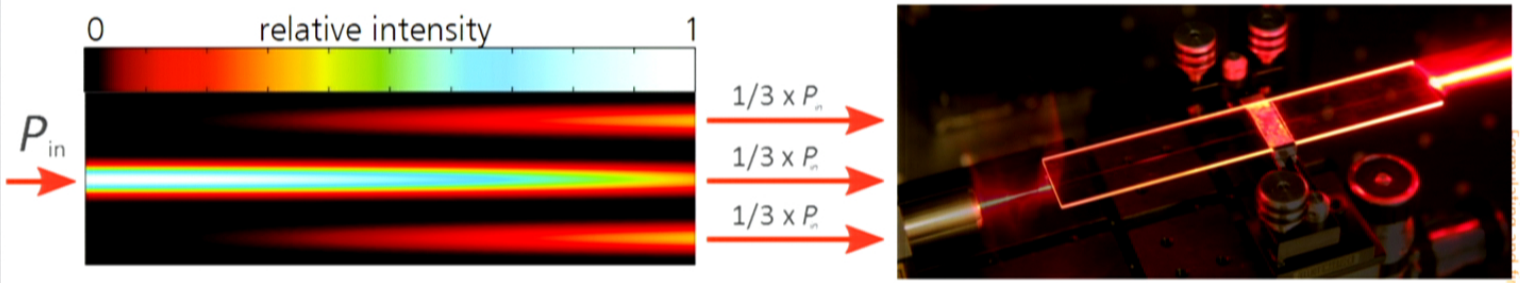
Integrated optics

Collaboration with A. Szameit/University of Jena



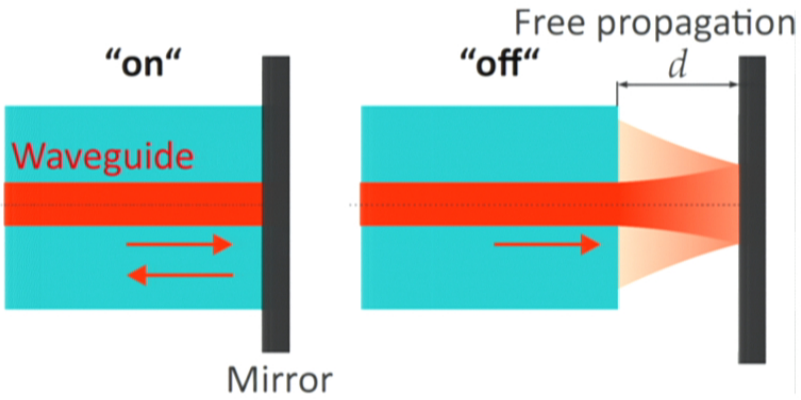
D. Blömer et al., Opt. Express **14**, 2151-2157 (2006)

Waveguide beamsplitter



Keil, et al., arXiv:1606.01068

Realization of “shutters“



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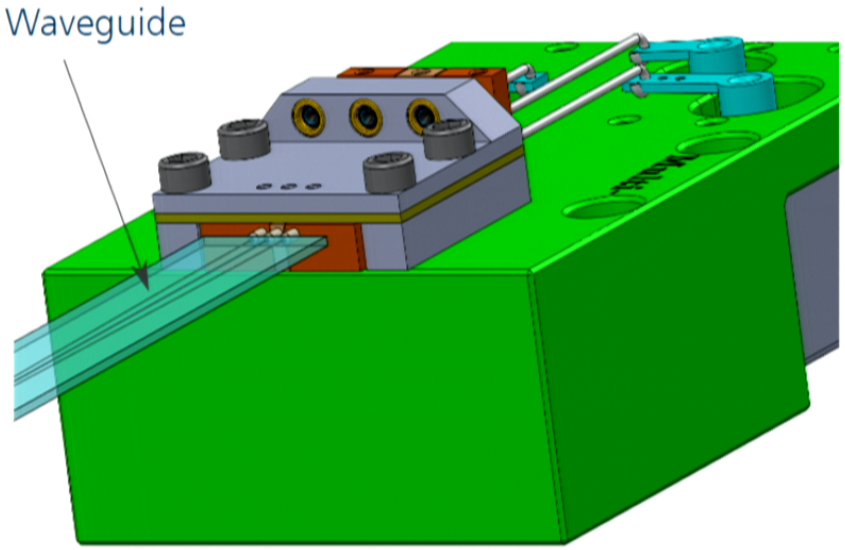
Experimental Setup



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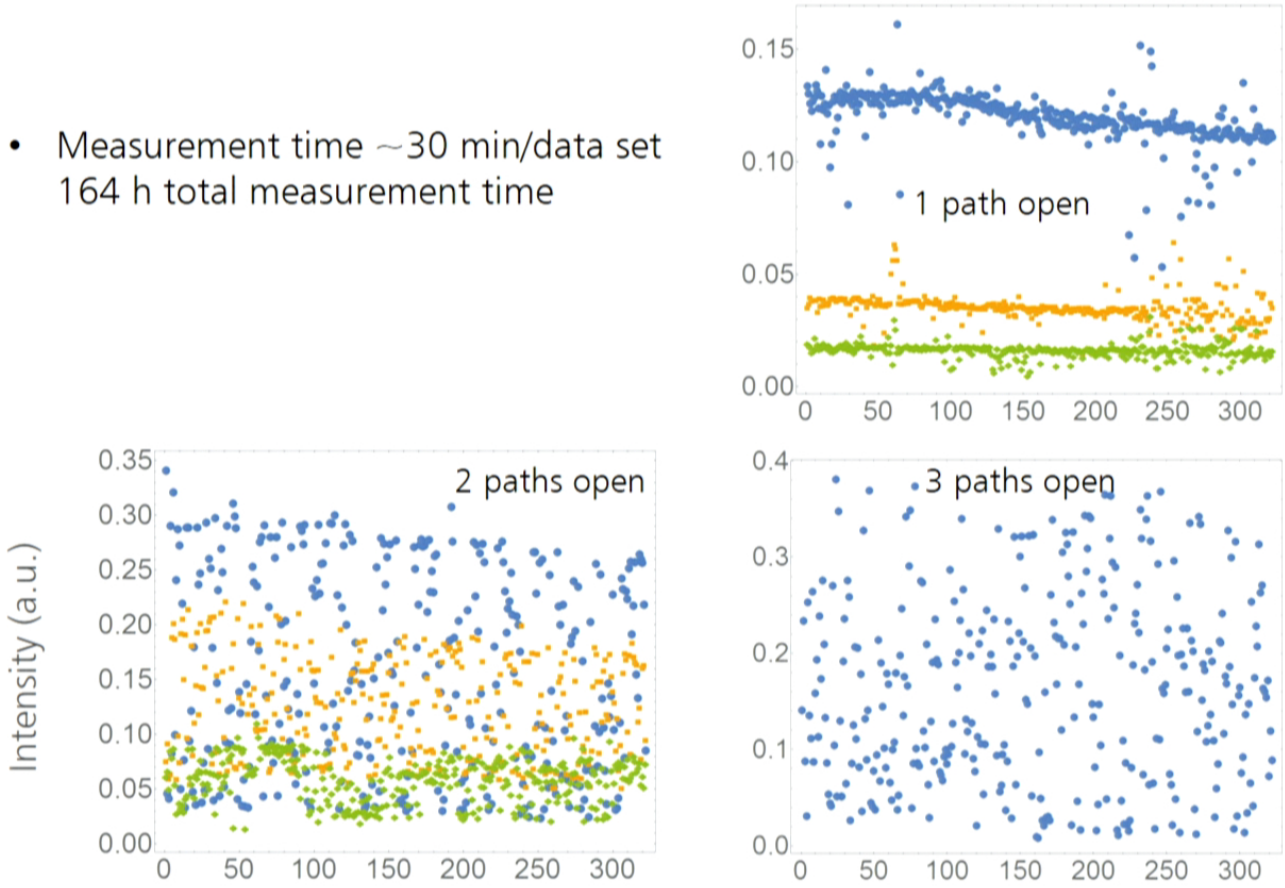
Measurement results

- Measurement time ~30 min/data set
  164 h total measurement time



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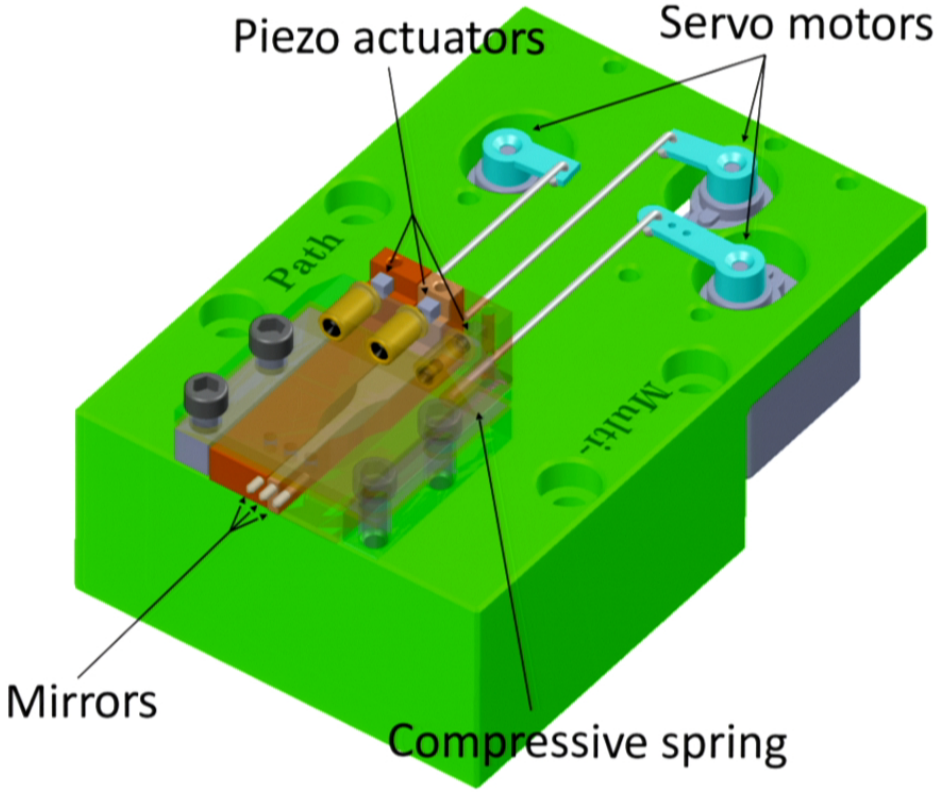

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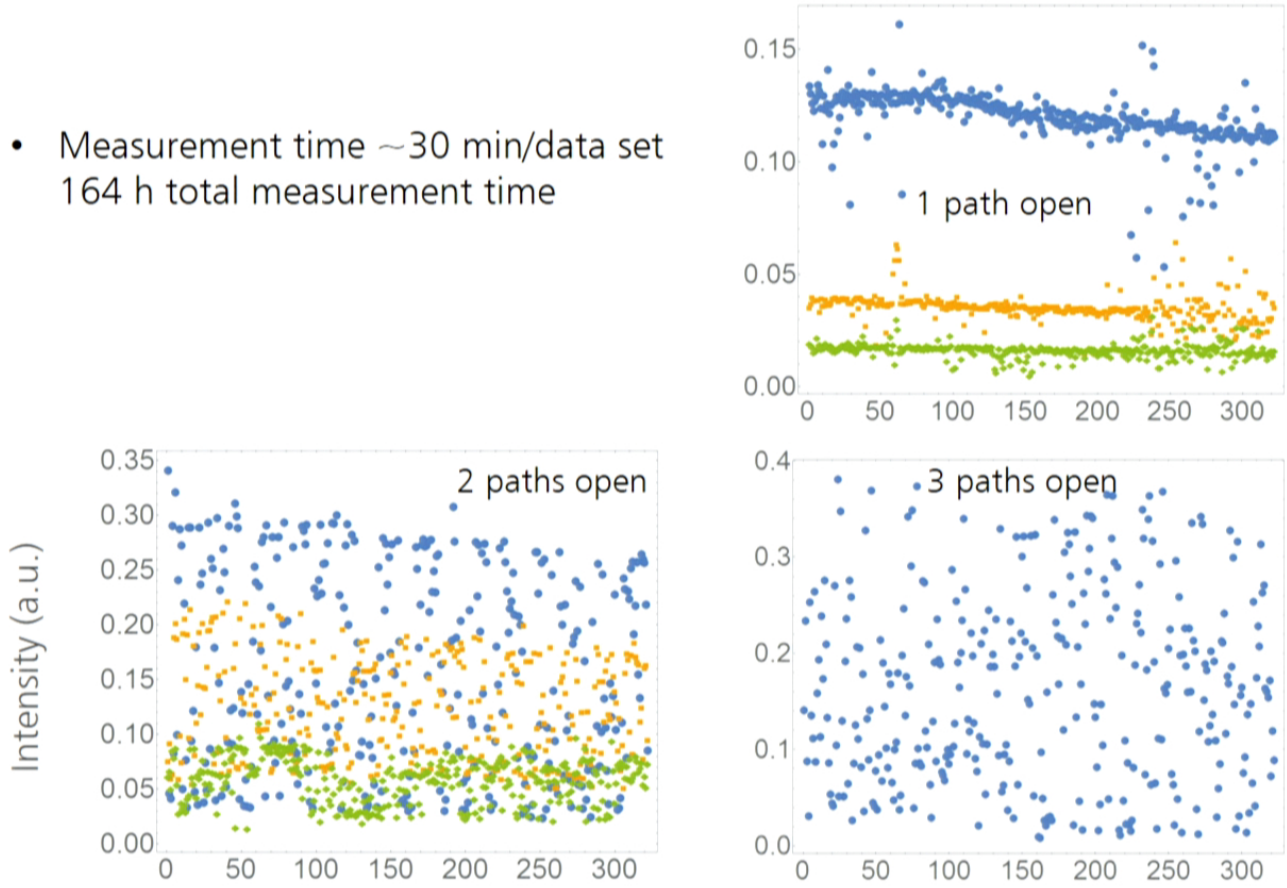

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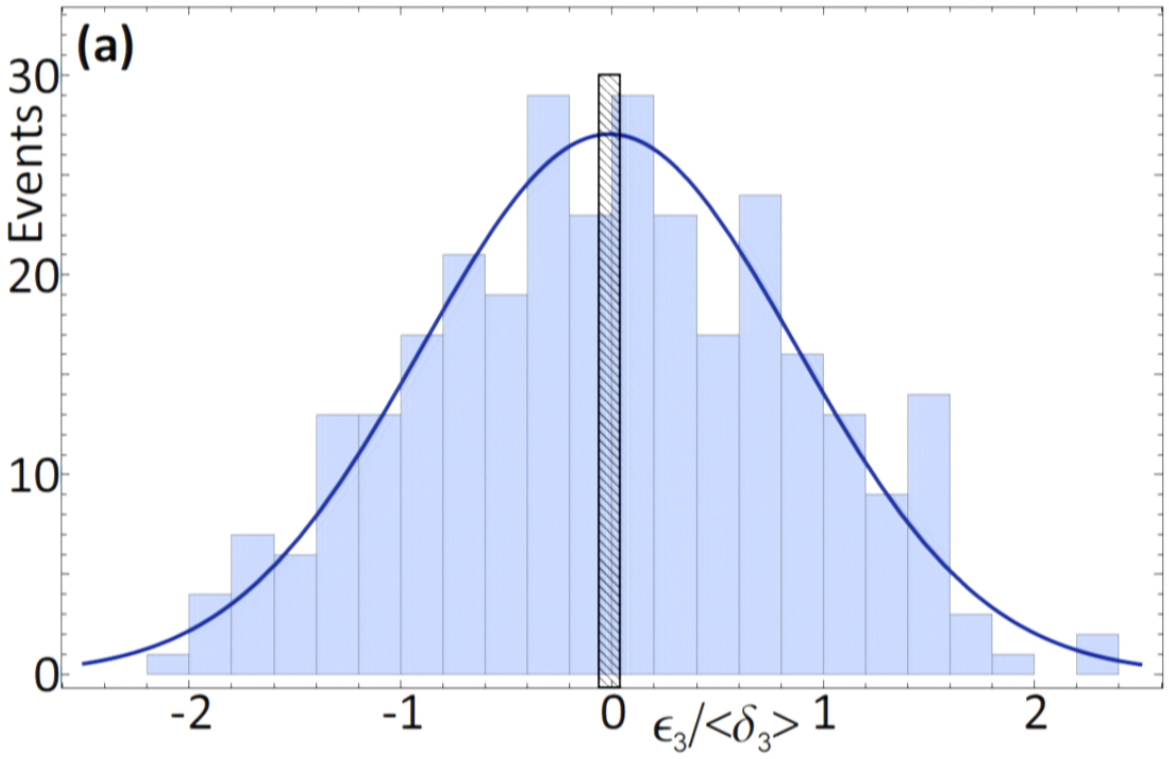
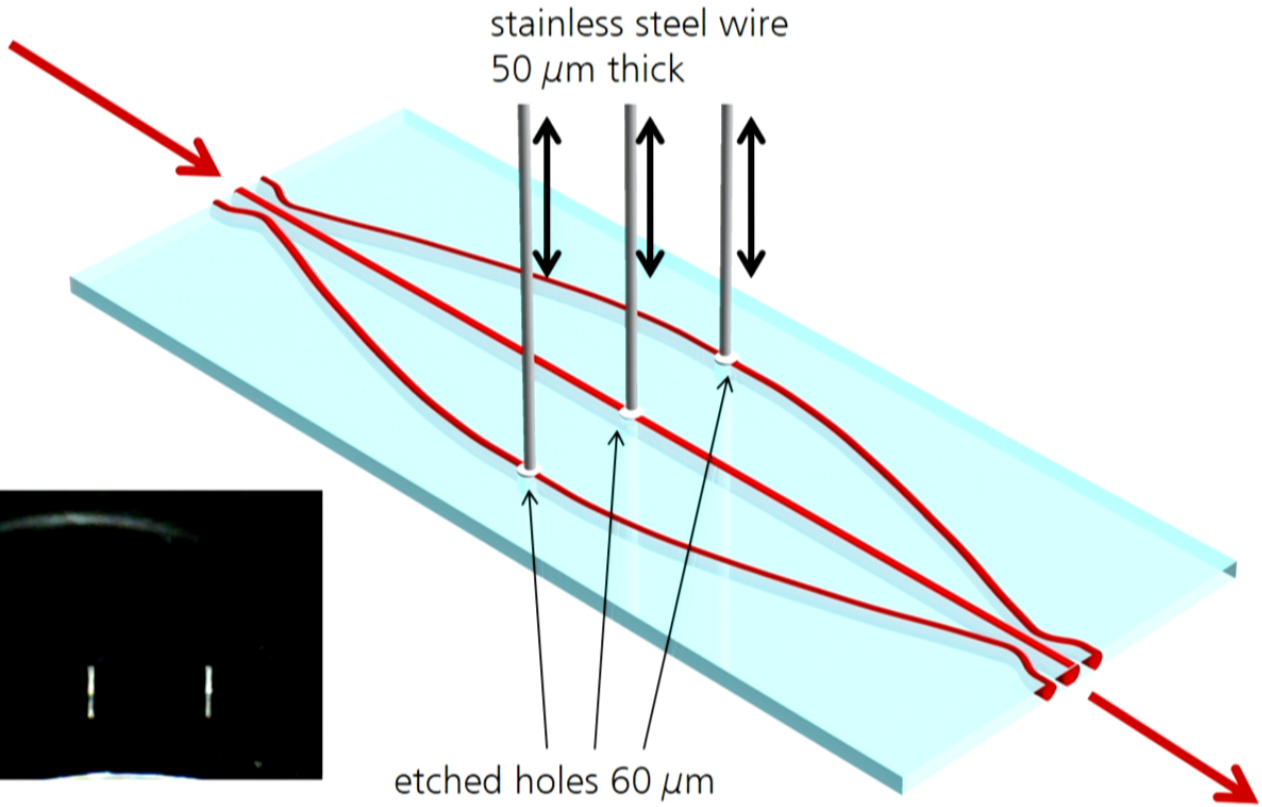
Measurement results



$$\langle \kappa_3 \rangle = (-1 \pm 5) \cdot 10^{-2}$$

Keil, et al., arXiv:1606.01068

Work in progress: modified setup – advanced design



Collaboration/Funding

Vienna

Jena

European Research Council

FWF Der Wissenschaftsfonds.

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Bundesministerium für Bildung und Forschung

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Thank You for your Attention

Peres criterion

Three scatterers:

Scattering phase $\gamma = (\sigma_{12} - \sigma_1 - \sigma_2)/2\sqrt{\sigma_1\,\sigma_2}$

$$\alpha = (\sigma_{23} - \sigma_2 - \sigma_3)/2\sqrt{\sigma_2\,\sigma_3}$$

$$\beta = (\sigma_{31} - \sigma_3 - \sigma_1)/2\sqrt{\sigma_3\,\sigma_1}$$

$$F(\alpha, \beta, \gamma) = \alpha^2 + \beta^2 + \gamma^2 - 2\alpha\beta\gamma$$

Peres, Phys. Rev. Lett. 42 (1979), 683.

Peres criterion

Three scatterers:

Scattering phase $\gamma = (\sigma_{12} - \sigma_1 - \sigma_2)/2\sqrt{\sigma_1\,\sigma_2}$

$$\alpha = (\sigma_{23} - \sigma_2 - \sigma_3)/2\sqrt{\sigma_2\,\sigma_3}$$

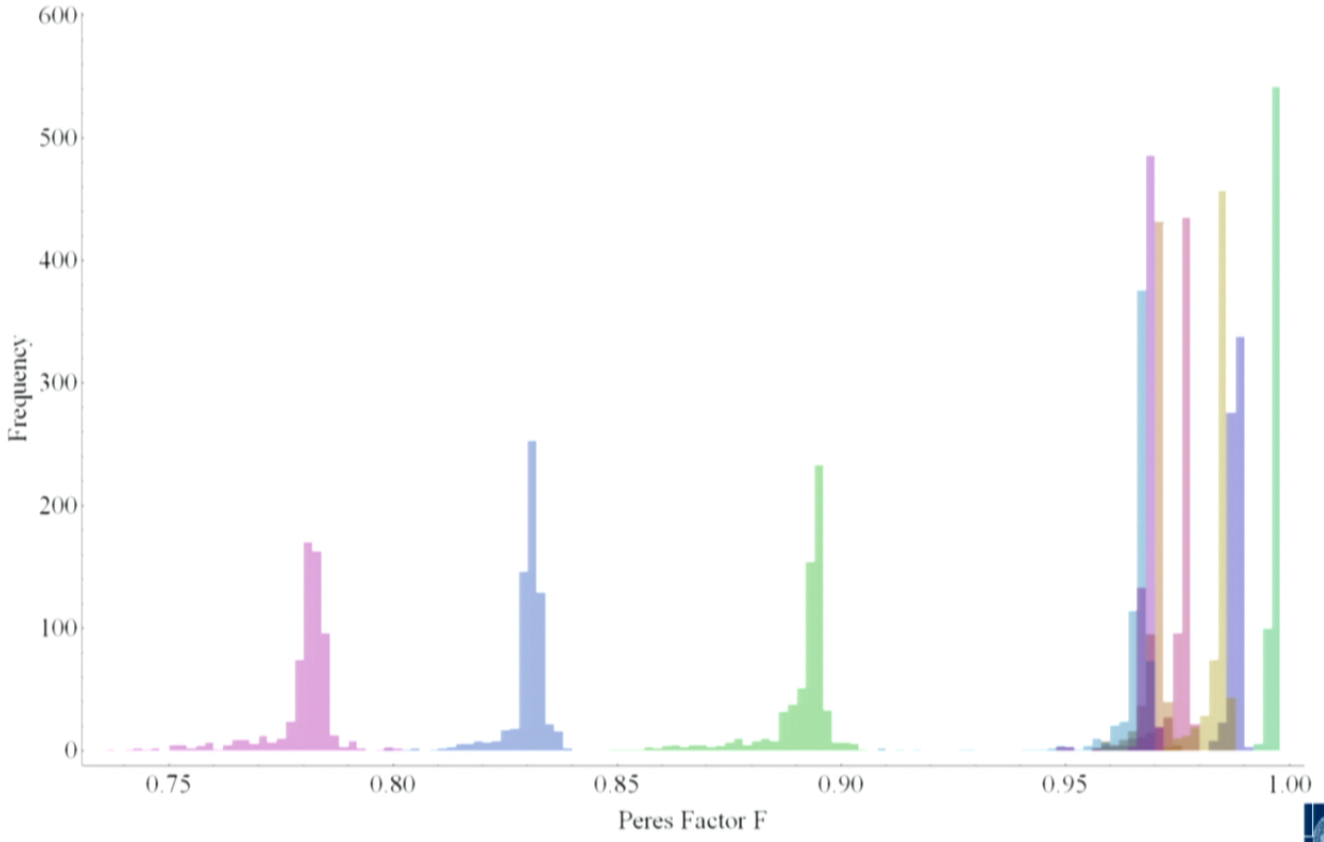
$$\beta = (\sigma_{31} - \sigma_3 - \sigma_1)/2\sqrt{\sigma_3\,\sigma_1}$$

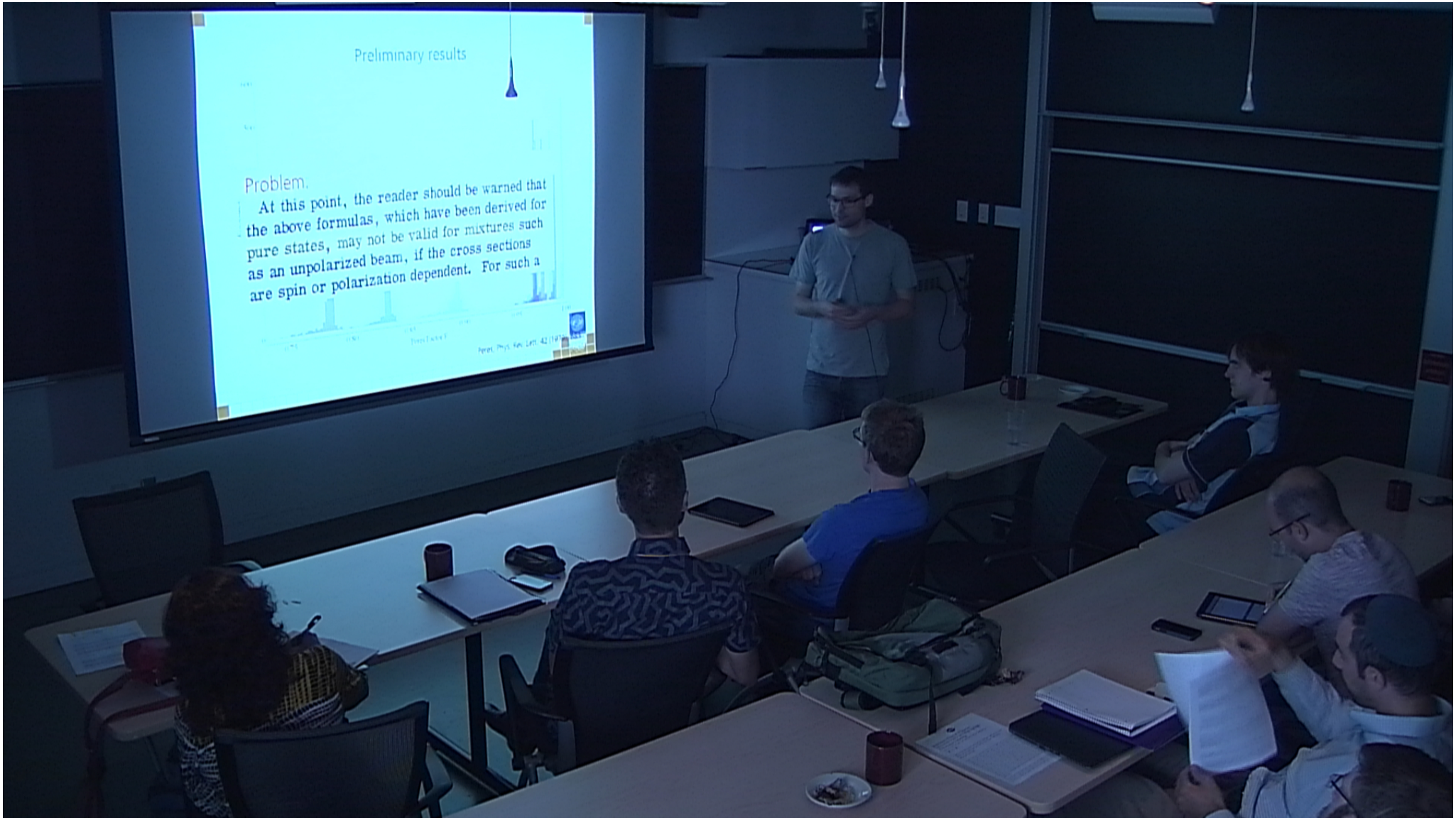
$$F(\alpha, \beta, \gamma) = \alpha^2 + \beta^2 + \gamma^2 - 2\alpha\beta\gamma$$

For $F(\alpha, \beta, \gamma) = 1$ complex quantum theory
For $0 < F(\alpha, \beta, \gamma) < 1$ quaternionic quantum theory
For $F(\alpha, \beta, \gamma) > 1$ superposition principle is violated

Peres, Phys. Rev. Lett. 42 (1979), 683.

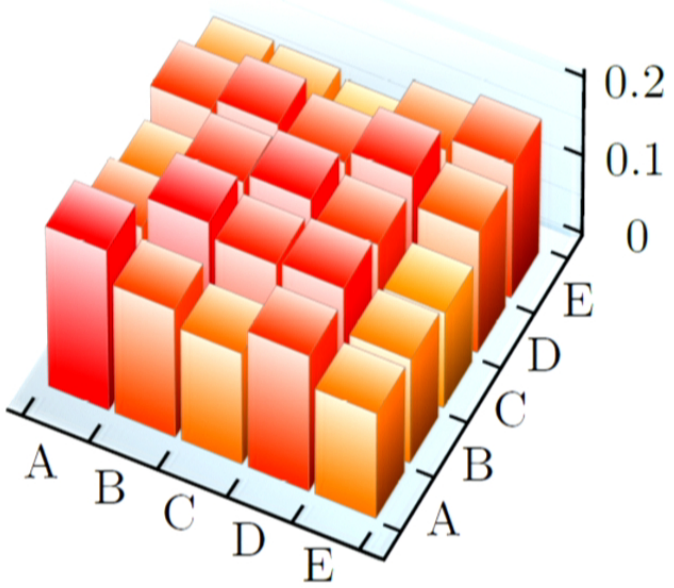
Preliminary results



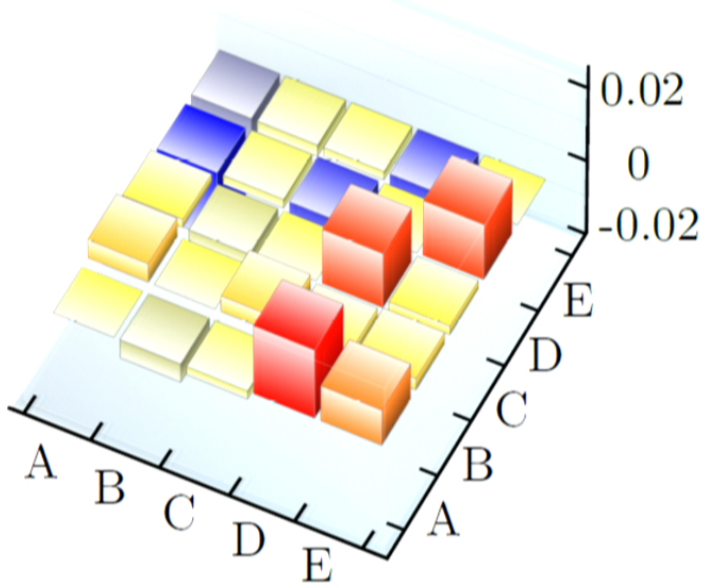

Preliminary results
Problem.
At this point, the reader should be warned that the above formulas, which have been derived for pure states, may not be valid for mixtures such as an unpolarized beam, if the cross sections are spin or polarization dependent. For such a

Reconstruction of the 5-dimensional qudit state describing our interferometer

$\mathrm{Re}\,(\rho)$



$\mathrm{Im}\,(\rho)$



$\mathrm{tr}\,\rho^2 = 0.74$

K.T., et al., arXiv: 1508.03253