Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Abbe Center of Photonics | JENA
Friedrich-Schiller-Universität

BioQantSense

Funded by the European Union

Quantum approaches to polarization-based sensing

Vira BESAGA, Dr.-Ing.

vira.besaga@uni-jena.de

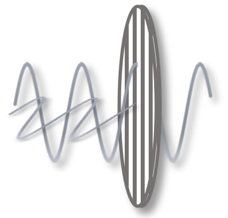
18 March 2025

18th Photonics Workshop | Kopaonik, Serbia

https://www.iap.uni-jena.de/nano-quantum-optics

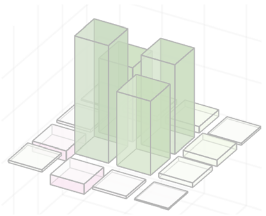
Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Outline



Why sensing with polarization?

Polarization based probing with Bell states

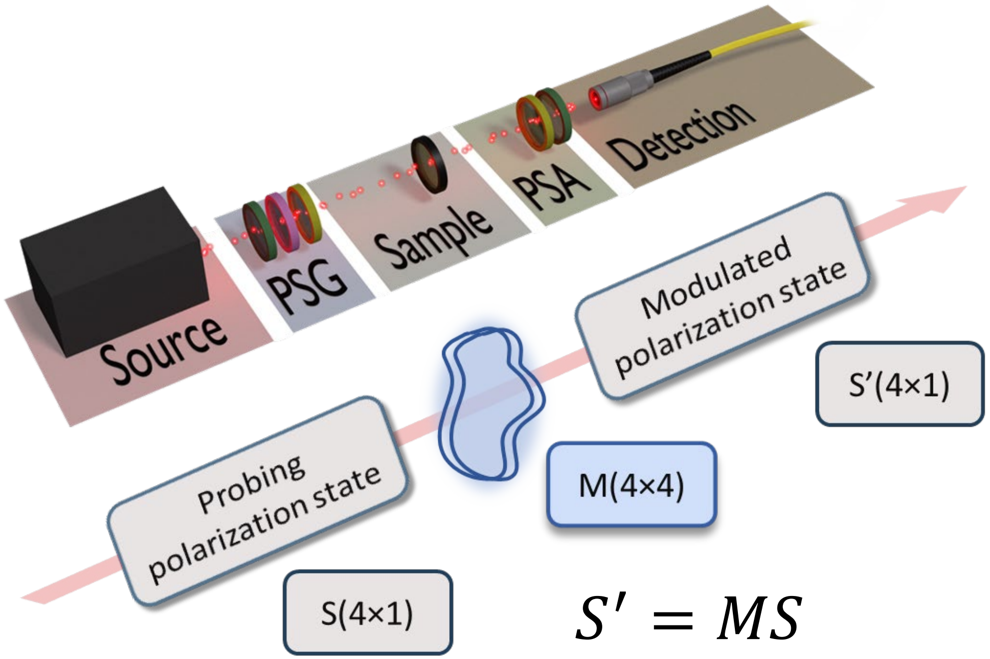


Showcase: scattering samples

Framework for classification with just two measurements per sample

Polarization as a rich information channel

Institute of Applied Physics
Friedrich-Schiller-Universität Jena



$$S' = MS$$

T	-LE	-LE'	CE
-LE	D	CR	-LR'
-LE'	-CR	D'	LR
CE	LR'	-LR	Dc

T - tranmittance/reflectance
LE - linear extinction
CE - circular extinction
LR - linear retardance
CR - circular retardance
D - depolarization

Polarization response → specimen's properties:

- birefringence
- polarization selectivity in reflection/transmission
- chemical composition

Applications:

- optical biomedical diagnostics
- control of nonlinear phenomena
- technical characterization
- remote sensing
- quantum communication, computing, and metrology

→ acknowledged methods of **Stokes and Mueller polarimetry**

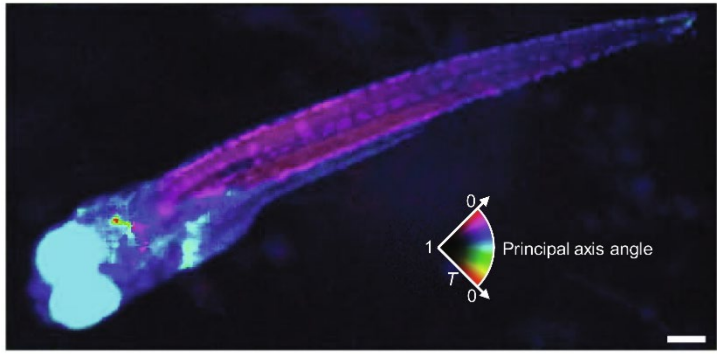
[J. Opt. Soc. Am. A 33, 1396-1408 (2016)
Light: Sci. Appl. 10, 194 (2021).]

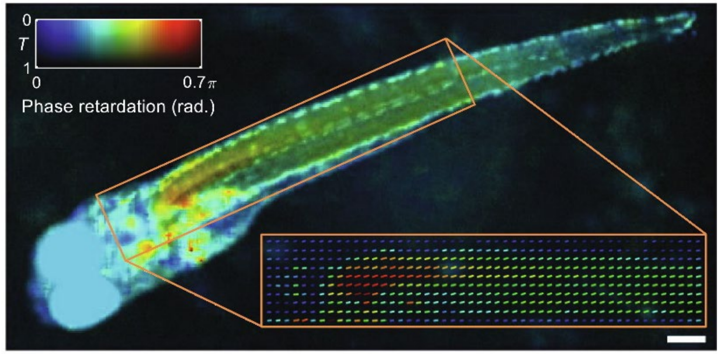
Active research towards quantum-empowered polarimetry

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

- Theoretical framework, incl. with entangled photons
- quantum holography via polarization-entanglement
- ghost polarimetry using classical light & with correlated photon pairs

A. Z. Goldberg, Phys. Rev. Research 2, 023038 (2020).
S. Magnitskiy, et al., Opt. Lett. 45, 3641-3644 (2020).
H. Defienne, et al., Nat. Phys. 17, 591-597 (2021).
V. Sukharenko, et al., Opt. Lett. 46, 2799-2802 (2021).
M. Kaur, et al., Sci. Rep. 11, 23636 (2021).
R. Camphausen, et al., Sci. Adv. 7, eabj2155 (2021).
S. Restuccia, et al., Phys. Rev. A 106, 062601 (2022).
S. Magnitskiy, et al., Opt. Lett. 47, 754-757 (2022).
A. Saxena, et al., Sci. Rep. 12, 21105 (2022).
A. Pedram, et al, arXiv:2304.08258 [quant-ph] (2023).
D. Agapov, D., Jetp Lett. (2024).
...





Birefringence of Zebra fish, sample scanning

[Adapted from Y. Zhang et al., Sci. Adv. 10, eadk1495 (2024)]

- Most recent: Birefringence imaging and realization of an ellipsometer

Y. Zhang et al., Sci. Adv.10,eadk1495(2024)
Meng-Yu Xie, arXiv:2402.17401 [quant-ph] (2024)

News from our lab: looking for practical realizations/applications

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

So far, integral sensing, spatial resolution by sample scanning possible

- Polarization-based probing of subtle samples
- Detection of microorganisms in water
- Nonlocal quantum differentiation of polarization objects
- Nonlocality-enhanced precision in parameter estimation
- Quantitative sensing towards diagnostics
- Sensing with NOON states
- Error-compensated sensing

Ongoing

News from our lab: the less measurements – the better

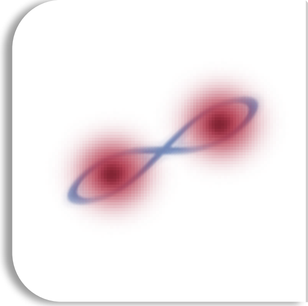
Institute of Applied Physics
Friedrich-Schiller-Universität Jena

So far, integral sensing, spatial resolution by sample scanning possible

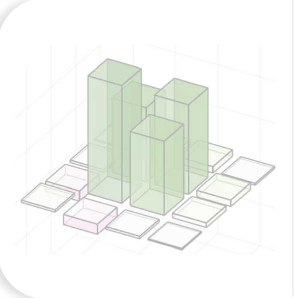
- Polarization-based probing of subtle samples
- Detection of microorganisms in water
- Nonlocal quantum differentiation of polarization objects
- Nonlocality-enhanced precision in parameter estimation
- Quantitative sensing towards diagnostics
- Sensing with NOON states
- Error-compensated sensing

Outline

Why sensing with polarization?



Polarization based probing with Bell states

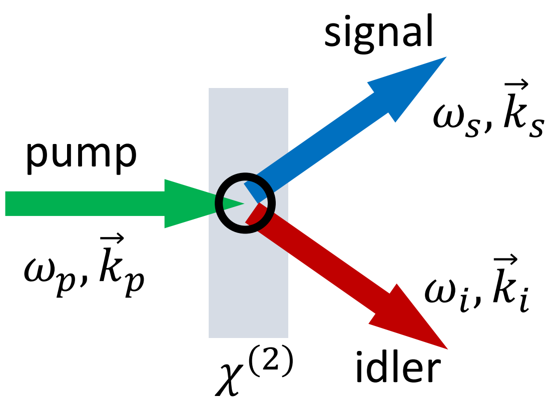


Showcase: scattering samples

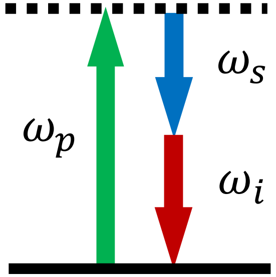
Framework for classification with just two measurements per sample

Probing state preparation: SPDC in bulk crystals

A correlated photon pair or a biphoton state



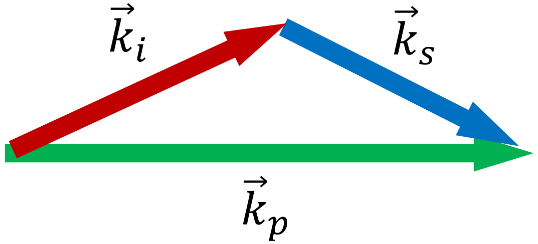
energy conservation



$$\omega_p = \omega_s + \omega_i$$

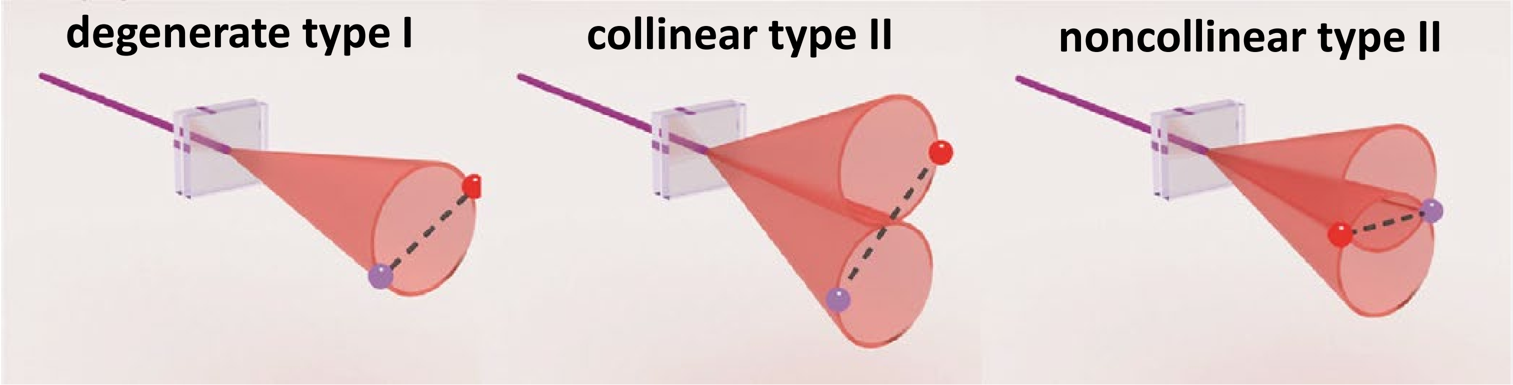
limits attainable combinations of frequencies

phase matching



$$\vec{k}_p(\omega_p) = \vec{k}_s(\omega_s) + \vec{k}_i(\omega_i)$$

defines generated combinations and their directions
→ controlled by nonlinear structure



[Adapted from Zhang, C. et al., Adv. Quantum Technol., 4: 2000132 (2021).]

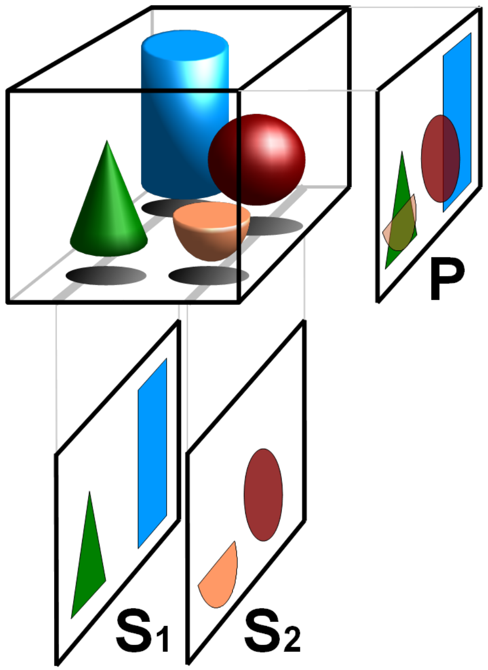
Polarization entangled photons, e.g.:

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H_S V_I\rangle + |V_S H_I\rangle)$$

Signal acquisition: quantum state tomography

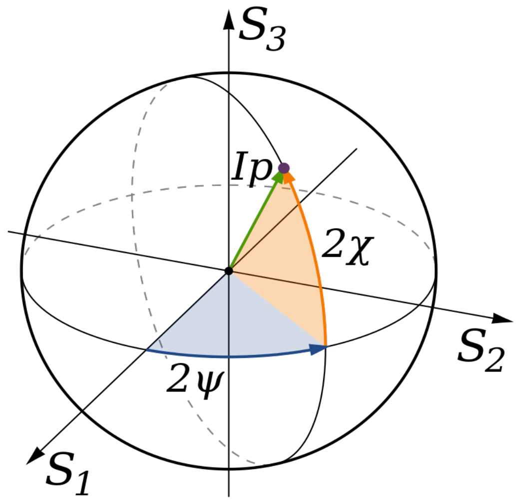
Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Projective 2D images to reconstruct the 3D shape

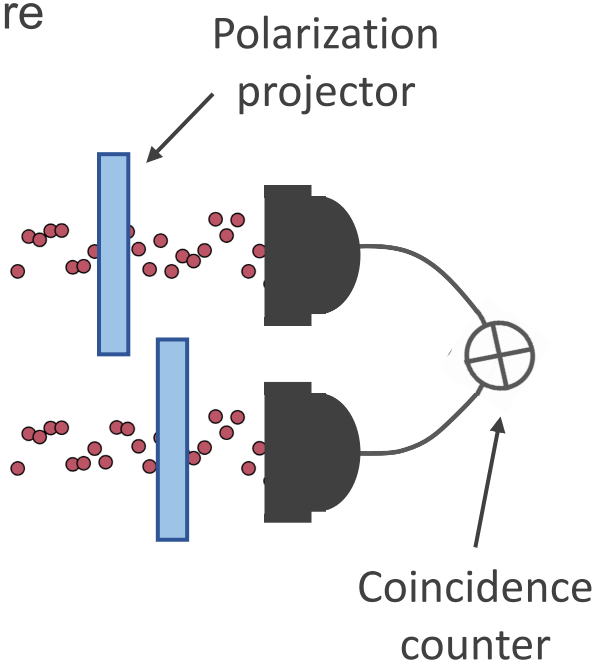


[https://en.wikipedia.org]

Projective measurements at multiple bases to reconstruct the quantum state ~ Stokes parameters for Poincare sphere



[https://en.wikipedia.org]

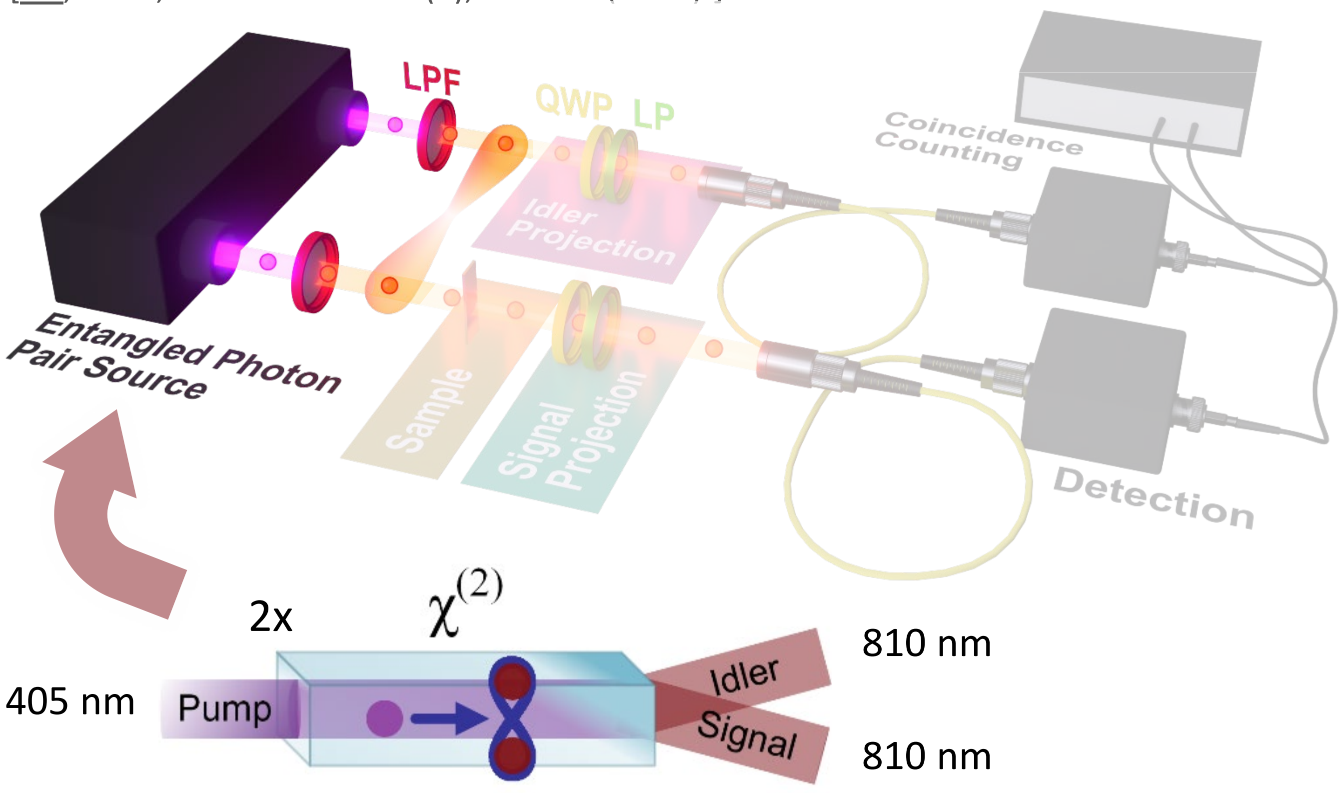


Photons detected with both detectors simultaneously (within a small time window for a predefined delay line accounting for channel paths)

Experimental arrangement

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

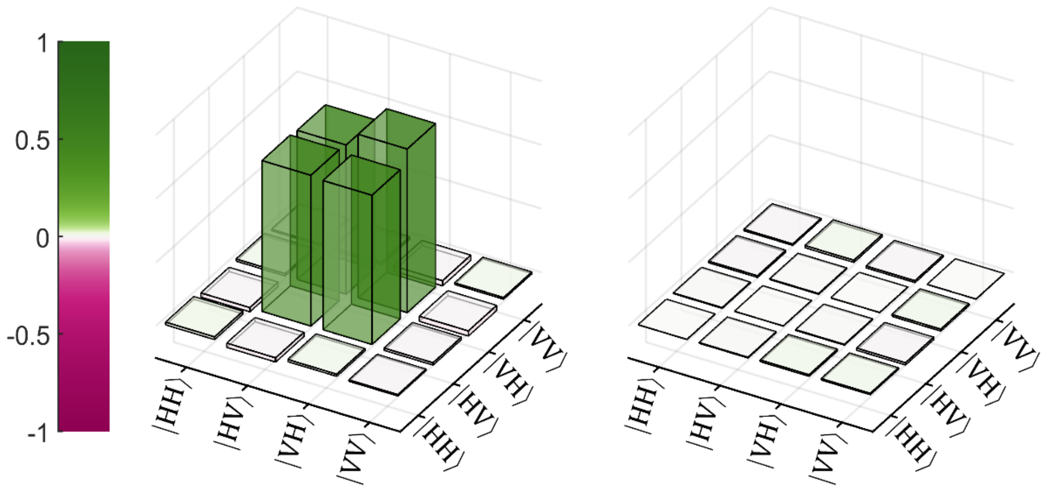
[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



- Quantum State Tomography, incl. maximum likelihood estimation algorithm
- Entanglement in polarization (S: signal, I: idler):

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|H_S V_I\rangle + |V_S H_I\rangle)$$

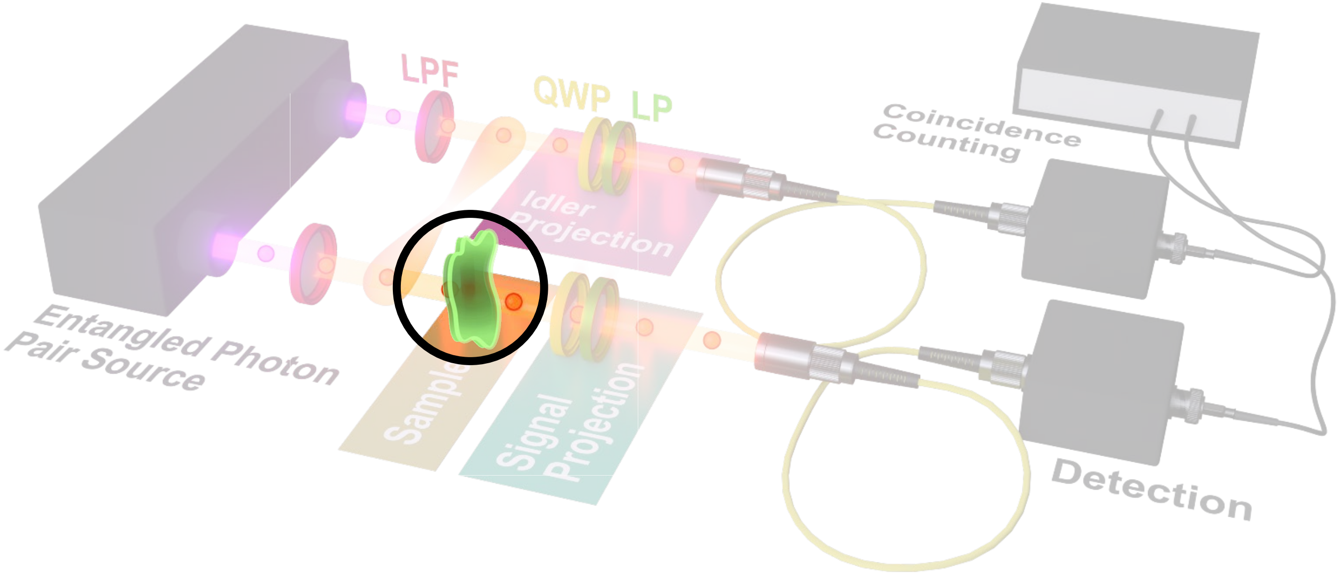
Fidelity 0.96; Concurrence 0.94



- Spontaneous parametric down-conversion (SPDC)
- 2 nonlinear crystals (ppKTP), type-II phase-matching
- Interferometer on beam displacers

Undesired state degradation → sensing instead!

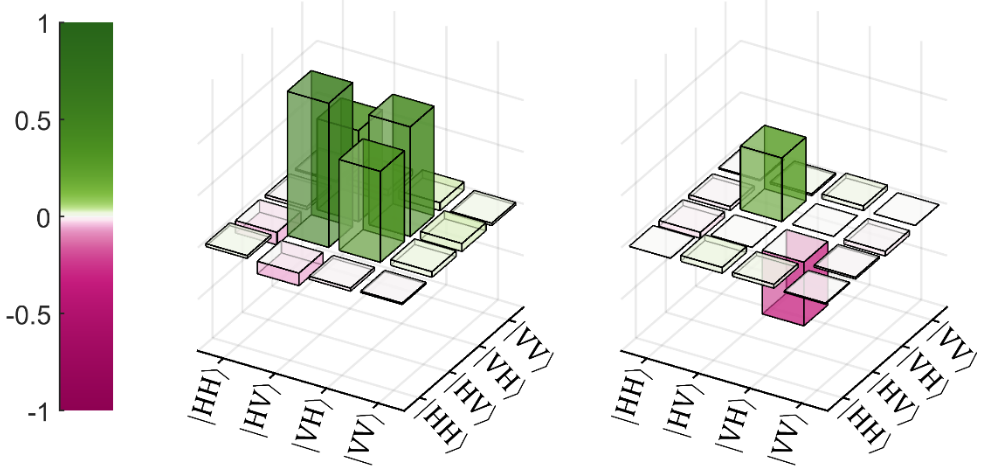
[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



- Why not using this for sensing?
- Not necessarily full Mueller matrix is of interest
- Detection/discrimination as a target

- Apparent and not new: state changes due to complex/scattering obstacle for one of the partner photons
- So far: goal to revive or overcome entanglement loss → quantum communication

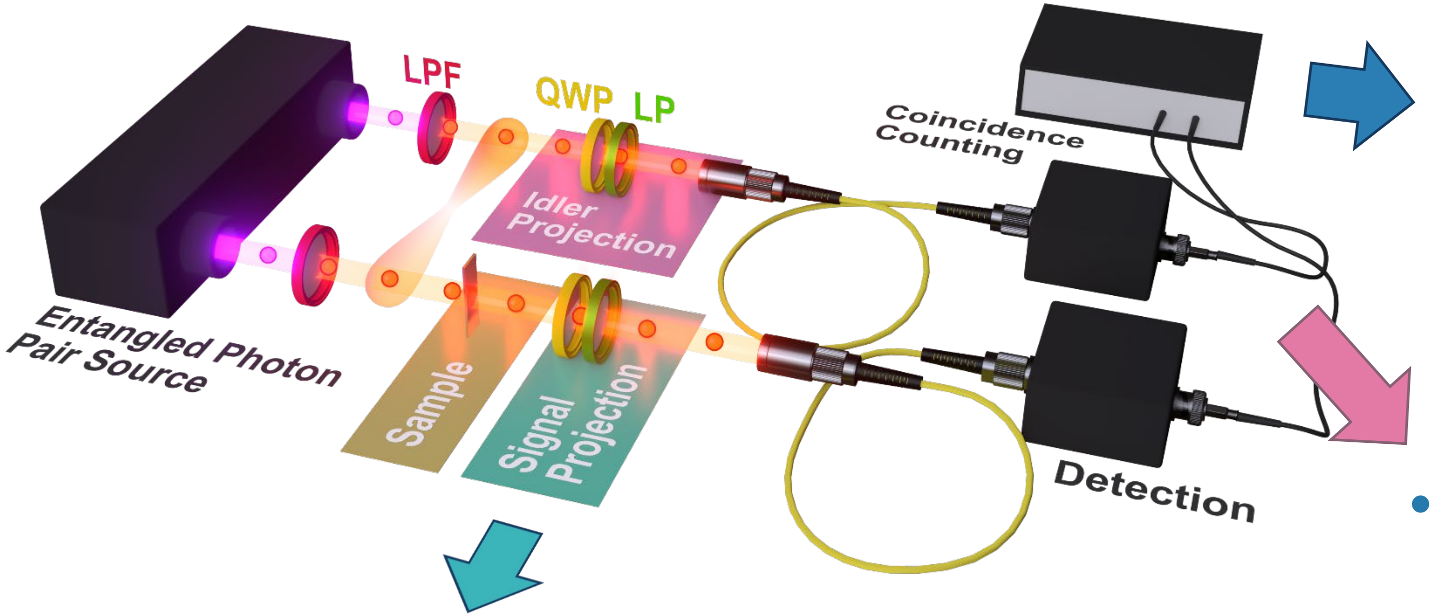
[E.g., Nat. Phys. 16, 1112–1116 (2020) and Nat. Phys. 19, 562–568 (2023).]



Remote state preparation as the basis

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



- The probability for recording a coincidence for the signal and idler pair:

$$P_n = \mathrm{tr}\left[\left(\mathrm{p}_n^i\right)\frac{\rho_r}{\mathrm{tr}(\rho_r)}\left(\mathrm{p}_n^i\right)^\dagger\right]$$

- Before being detected, signal photon undergoes polarization transformation:

$$T_s = \mathrm{p}^s M_s$$

with sample's Mueller matrix M_s

- At the moment of signal photon detection, the idler photon becomes:

$$\rho_r = \mathrm{tr_P}\left[(T_s \otimes 1)\rho_0 (T_s \otimes 1)^\dagger\right]$$

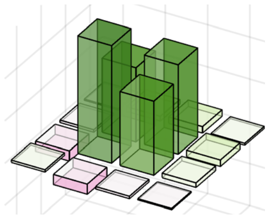
with initial probing state ρ_0

[Vega et al., Phys. Rev. Applied 16, 064032 (2021)]

Outline

Why sensing with polarization?

Polarization based probing with Bell states



Showcase: scattering samples

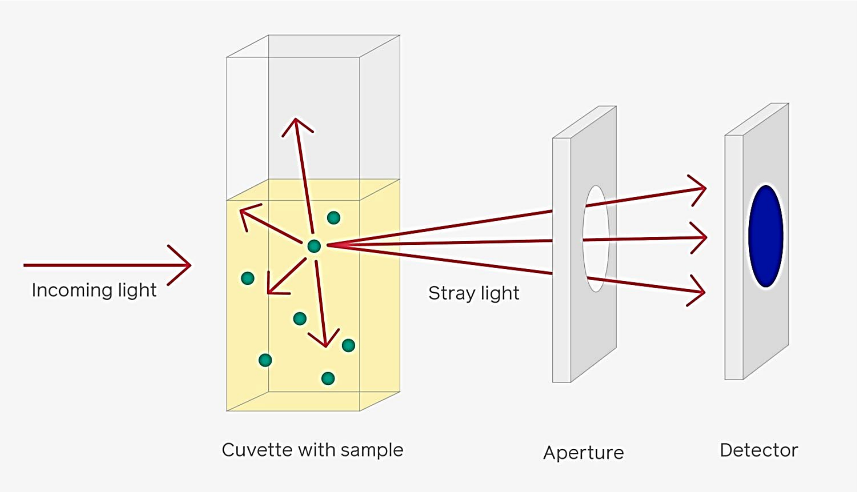
Framework for classification with just two measurements per sample

Probing of scattering samples

Scattering, or more generally turbid, media:

- suspensions: PM (particulate matter) polluted air, microbiologically polluted water, aerosols, etc.
- bacterial cultures
- biological tissues
- etc.

Transmission/scattering for bacterial culture density monitoring (example of OD600 measurement)



[https://byonoy.com/]

Relevant fields:

- Environmental monitoring: air and water quality
- free-space communication by optical means
- biomedical diagnostics
- etc.

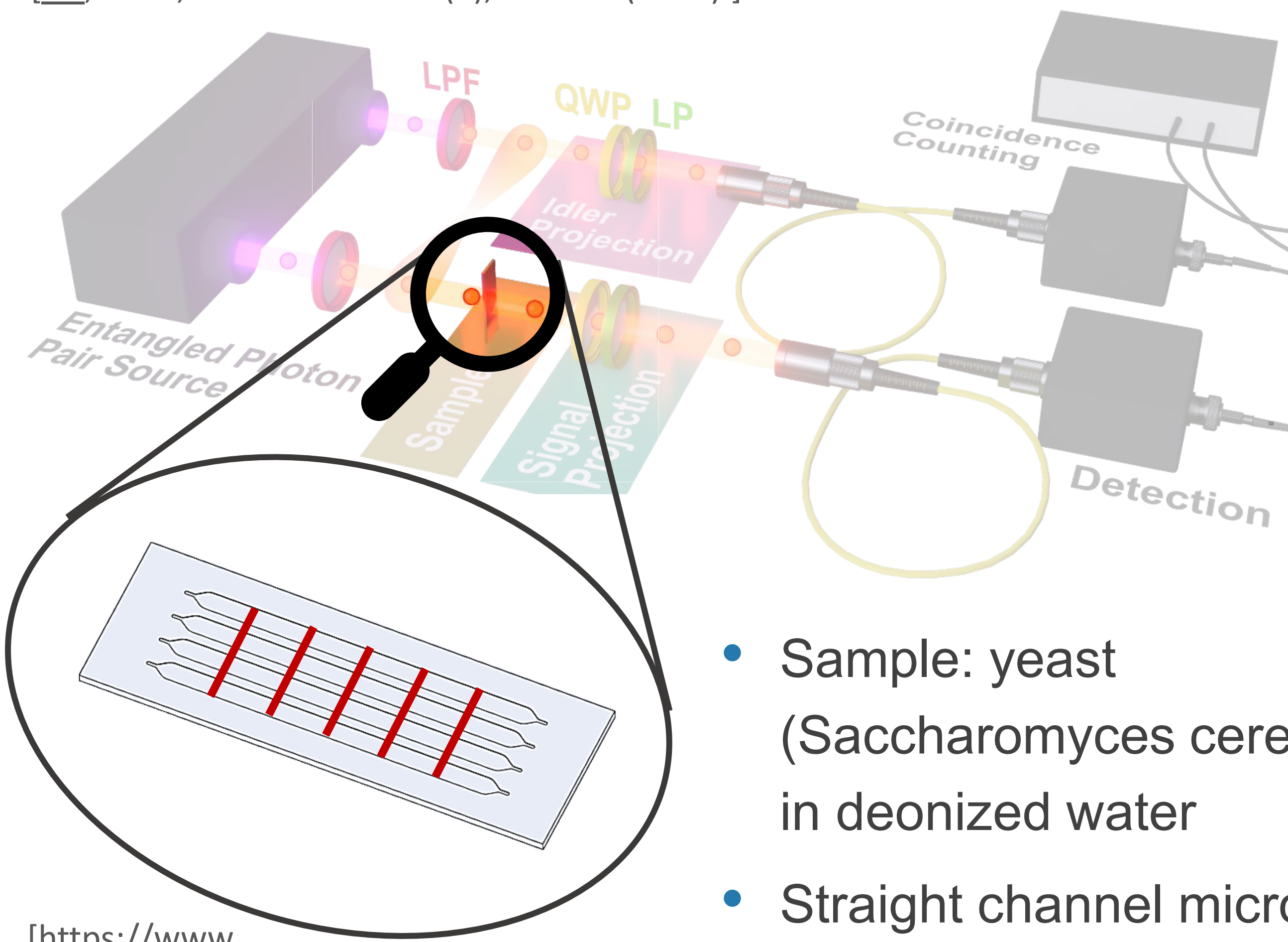
Our approach:
monitoring entangled state change due to scattering of one of the partner photons

[**VB**, et al., arXiv:2411.06134 (2024).
L. Zhang, **VB**, et al., J. Biophoton., e202400018 (2024).
VB, et al., Proc. SPIE 12993, 129930A (2024).]

Detection of yeast cells in diluted solutions

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

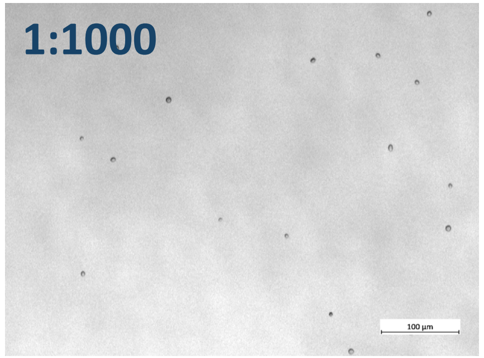
[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



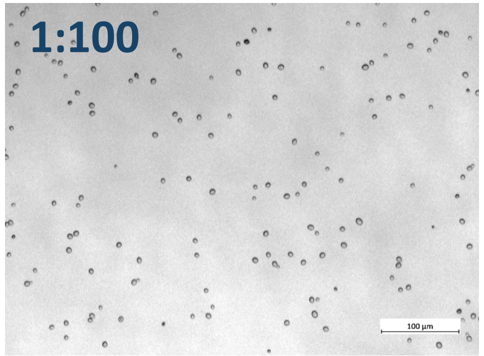
[https://www.
microfluidic-chipshop.com]

- Sample: yeast (Saccharomyces cerevisiae) in deonized water
- Straight channel microfluidic glass chip:
  lid of 250 µm thickness

- 4 channels, each:
  3.1 mm wide, 30 µm deep, 58.5 mm long
- Initial solution of 250 mg S. cerevisiae in 1 ml H_2O diluted 1:10, 1:100 and 1:1000
- Resultant tested concentrations:
  25 mg/ml, 2.5 mg/ml, and 250 µg/ml



250 µg/ml



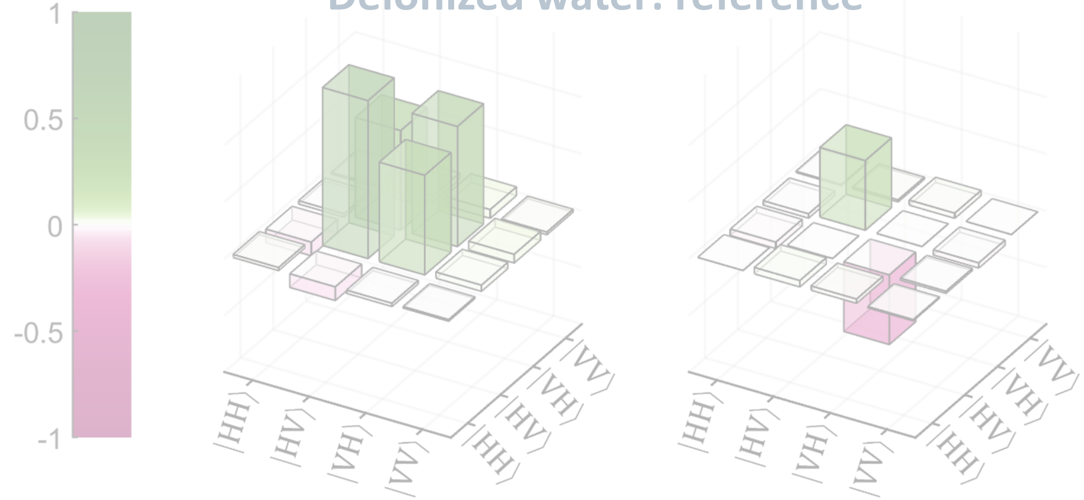
2.5 mg/ml

Representative microscopic images, 10x

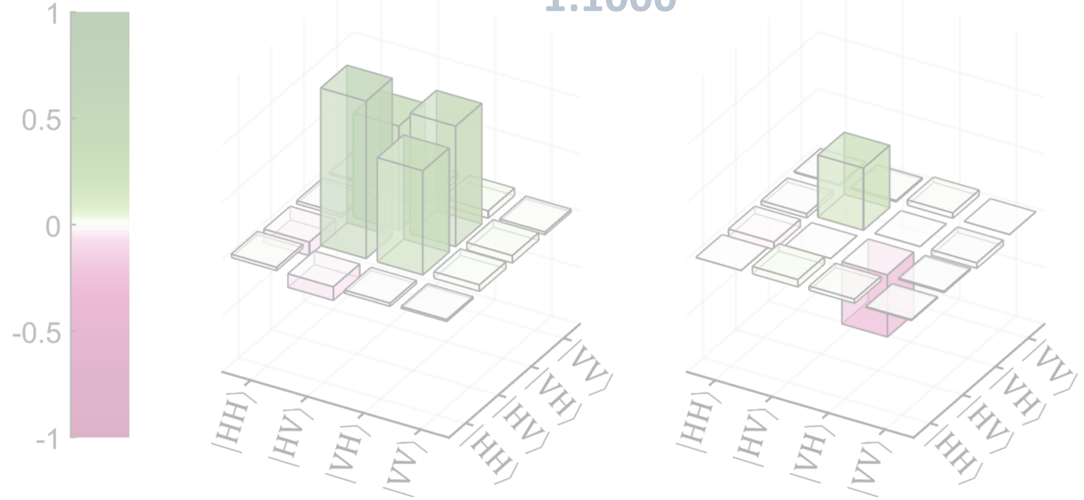
Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Sensitive to less than 100 cells in the volume

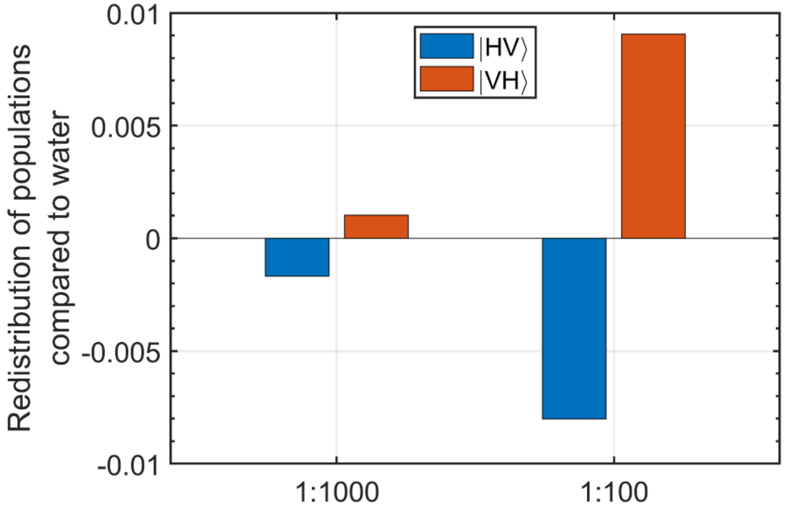
Deionized water: reference



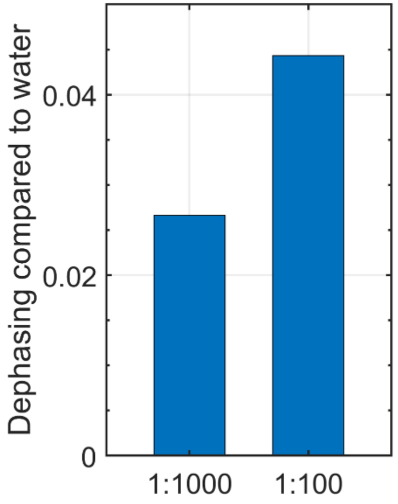
1:1000



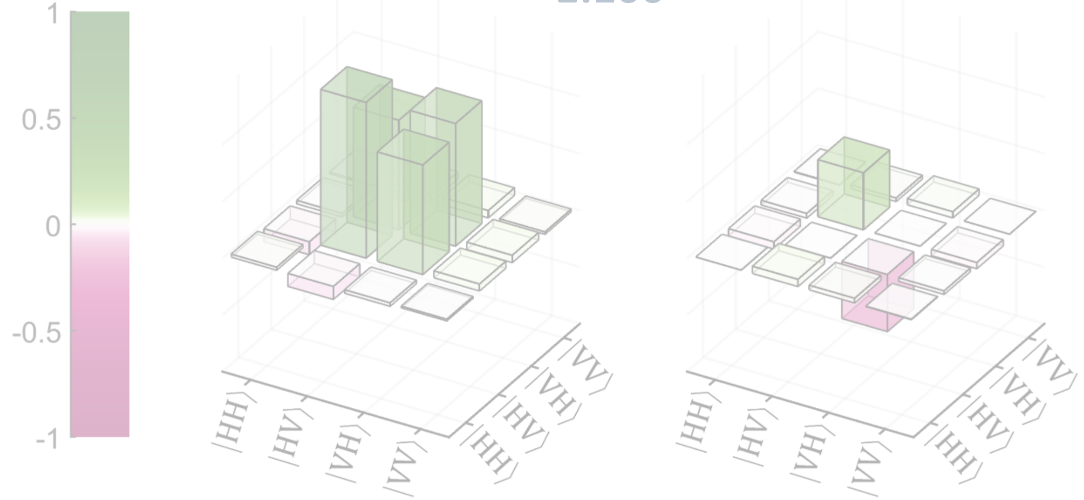
Change in real part



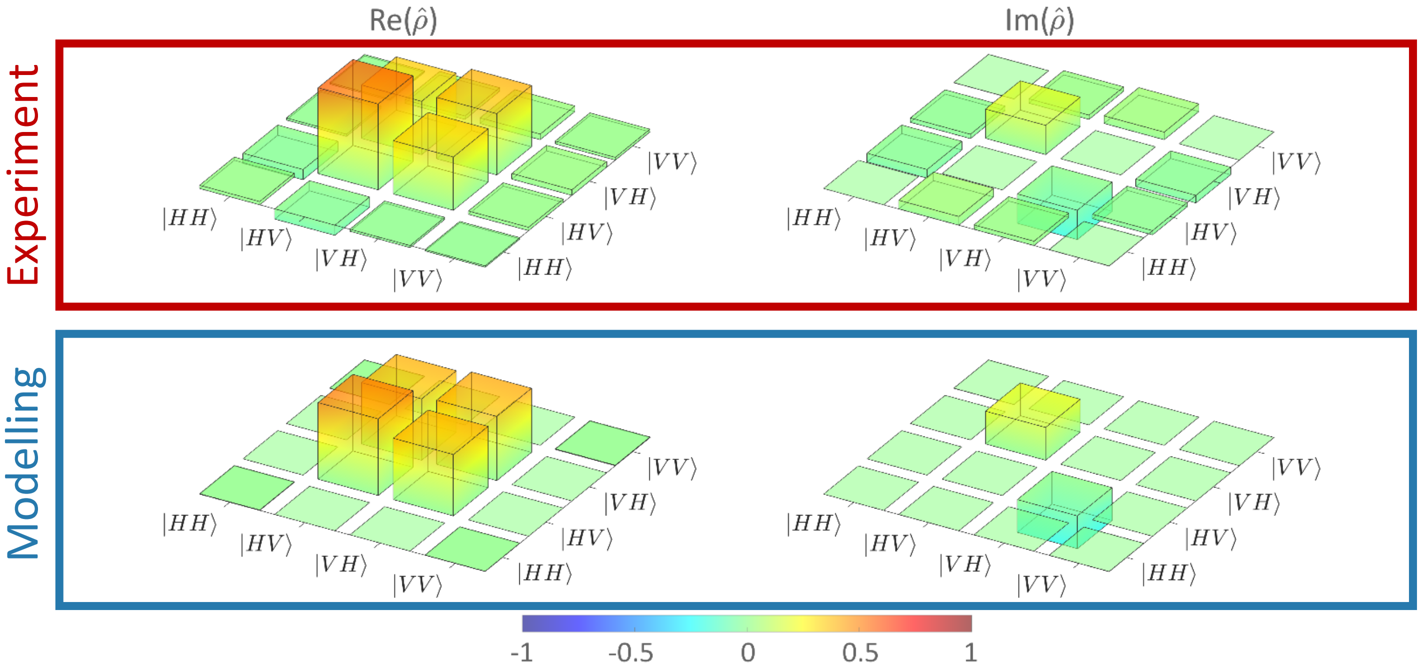
Absolute change in imag. part



1:100



Evolution of the state in tissue phantoms



Representative output for a sample with 0.1 mm^{-1} absorption coefficient, 0.65 scattering anisotropy factor, and 4.55 $^{-1}$ scattering coefficient

Test samples:

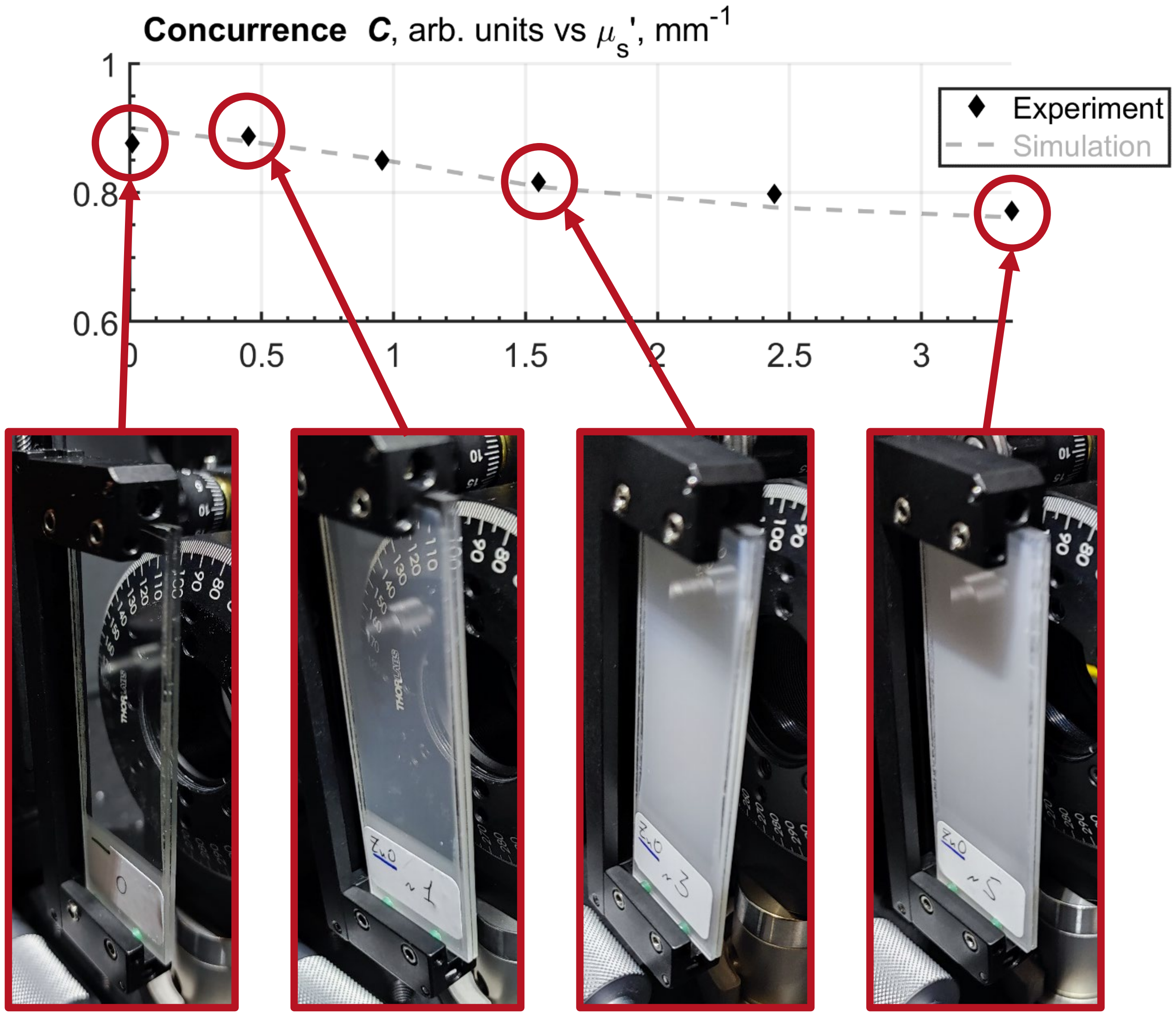
- tissue phantoms of different density of scattering centers (ZnO nanoparticles): thin films between glass microslides
- reference sample: polymer matrix without scattering nanoparticles
- integral sensing with collimated beam

State evolution:

- signs of dephasing and redistribution of populations of the basis states
- close correlation between modelling and measurement

[**VB**, et al., arXiv:2411.06134 (2024).
VB, et al., Optica Sensing Congress, QTh1G.6 (2024).]

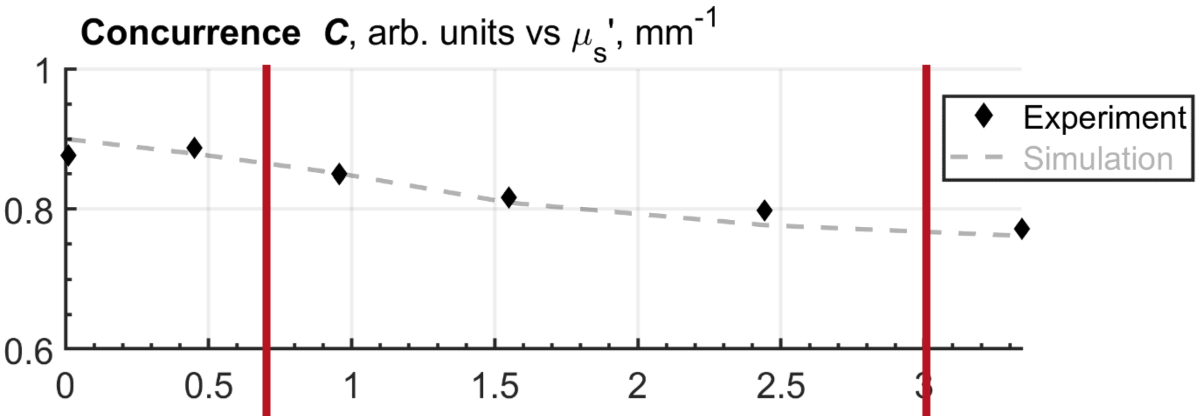
Potential of quantitative diagnostics



- Clear dependence on scattering properties of the sample
- Successful measurement till scattering coefficient of approx. 8.00 mm^{-1}
- $\mu_s' = \mu_s(1-g)$ is the reduced scattering coefficient accounting for scattering anisotropy

[**VB**, et al., arXiv:2411.06134 (2024).
VB, et al., Optica Sensing Congress, QTh1G.6 (2024).]

Broad applicability



Different atmos-pheric conditions ←

Real biomedical samples →

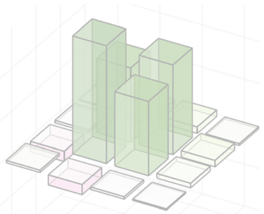
- Clear dependence on scattering properties of the sample
- Successful measurement till scattering coefficient of approx. 8.00 mm^{-1}
- $\mu_s' = \mu_s(1-g)$ is the reduced scattering coefficient accounting for scattering anisotropy

[**VB**, et al., arXiv:2411.06134 (2024).
VB, et al., Optica Sensing Congress, QTh1G.6 (2024).]

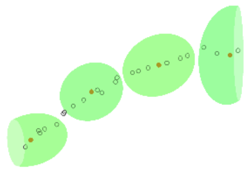
Outline

Why sensing with polarization?

Polarization based probing with Bell states



Showcase: scattering samples

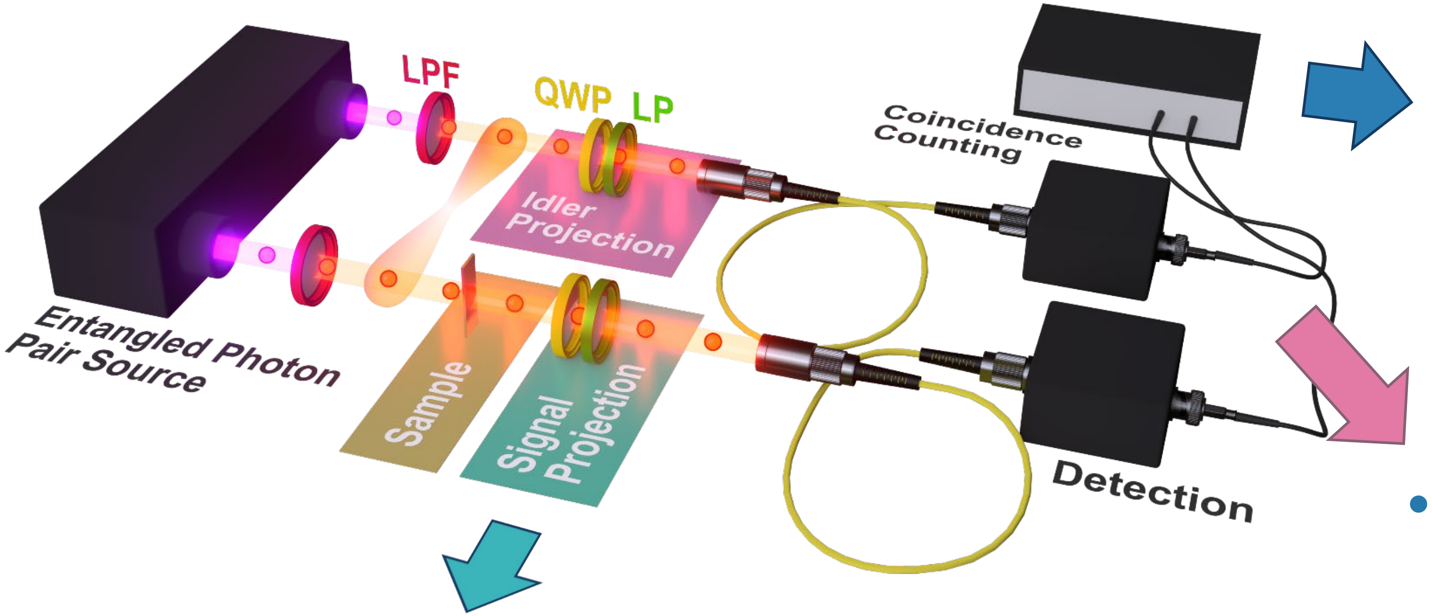


Framework for classification with just two measurements per sample

Non-local polarization-based sample differentiation

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



- The probability for recording a coincidence for the signal and idler pair:

$$P_n = \mathrm{tr}\left[\left(\mathrm{p}_n^i\right)\frac{\rho_r}{\mathrm{tr}(\rho_r)}\left(\mathrm{p}_n^i\right)^\dagger\right]$$

- At the moment of signal photon detection, the idler photon becomes:

$$\rho_r = \mathrm{tr}_\mathrm{P}\left[(T_s \otimes 1)\rho_0(T_s \otimes 1)^\dagger\right]$$

with initial probing state ρ_0

- Before being detected, signal photon undergoes polarization transformation:

$$T_s = \mathrm{p}^s M_s$$

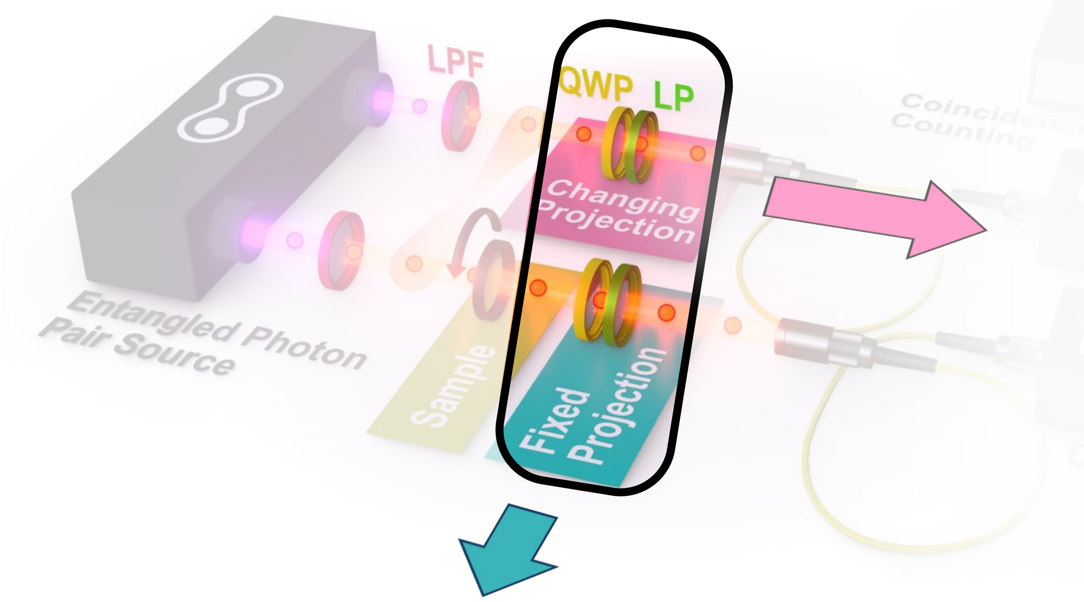
with sample's Mueller matrix M_s

[Vega et al., Phys. Rev. Applied 16, 064032 (2021)]

Single fixed projection for a predefined set of samples

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



Alternated polarization projections
at remote idler channel allow for that probabilities P_n form unique combinations for every sample
→ measured number of coincidences $N_n \propto P_n$ become relative "coordinates"

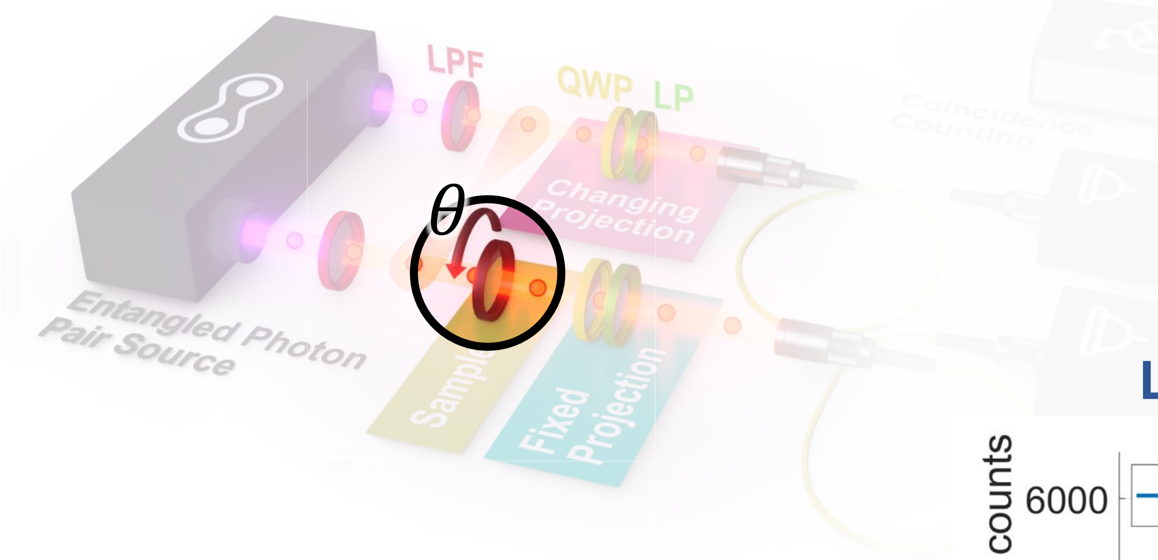
Fixed polarization projection
ensures that for all samples in the considered set, the reduced state ρ_r **is different**, which is not generally the case

Different ρ_r are the different states on the Poincaré sphere that are then projected to different points in in the virtual space of coincidences

Test sample set with slightly different Mueller matrices

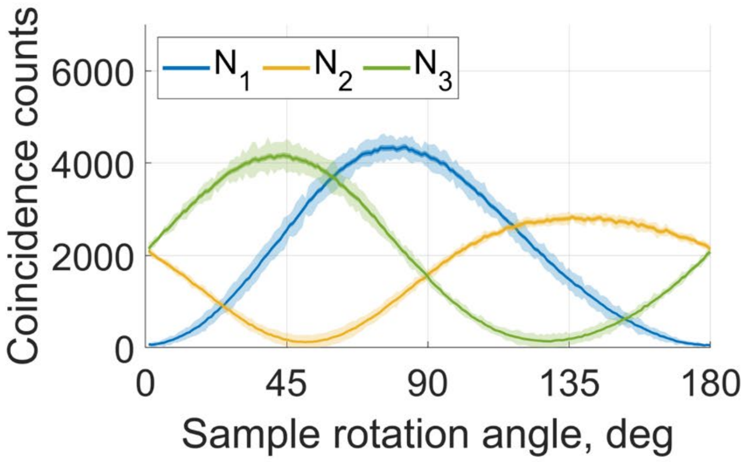
Institute of Applied Physics
Friedrich-Schiller-Universität Jena

[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]

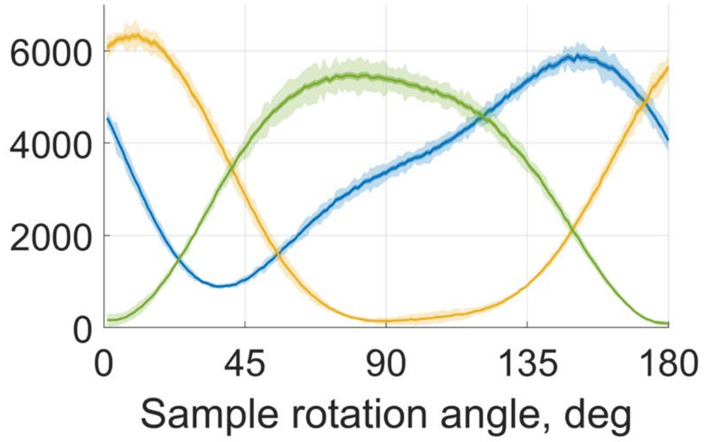


Representative measurement outcome when three projections are applied in the idler arm

Linear polarizer



Quarter-wave plate



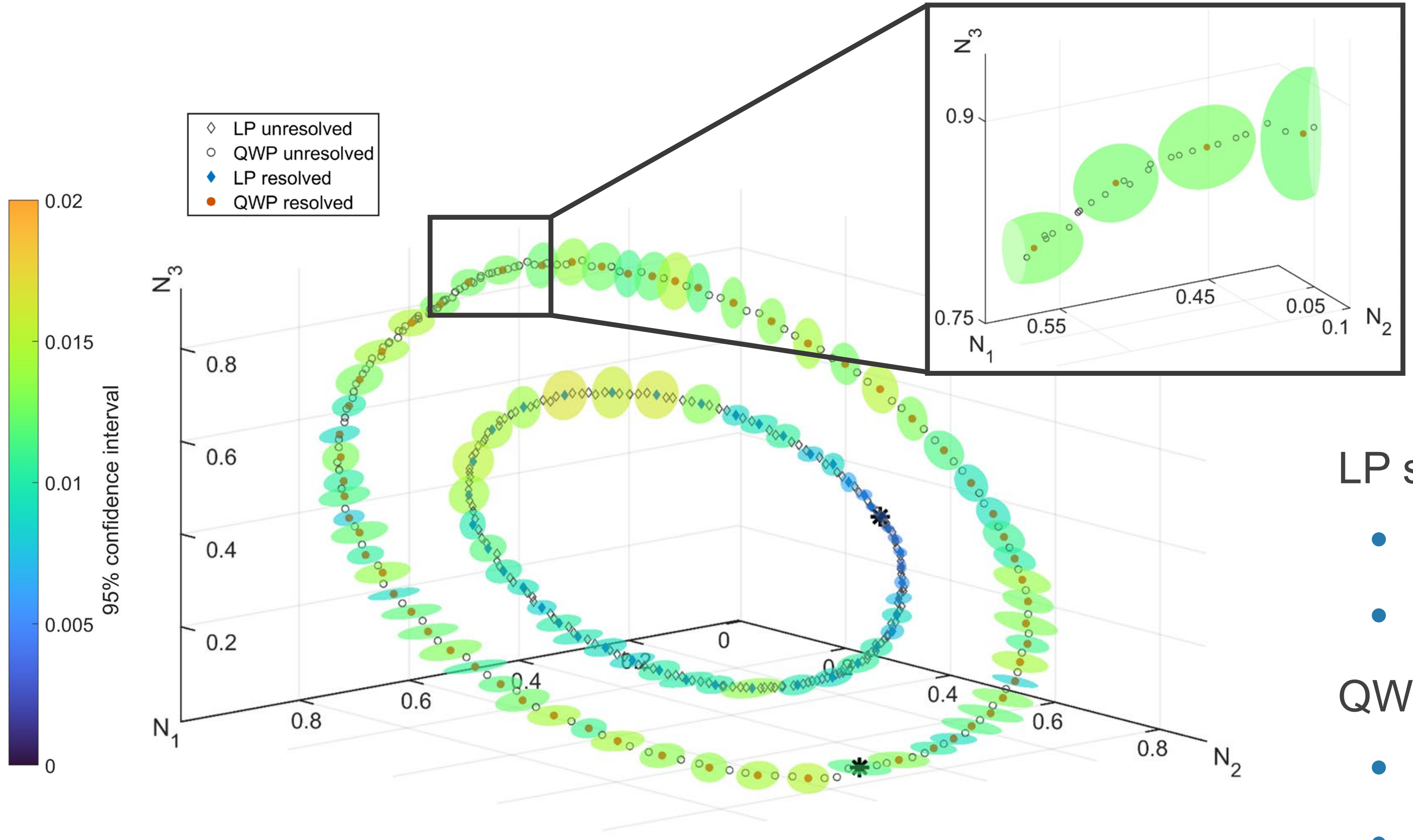
- Sample: LP and QWP at different orientations of principal optical axis, 1° step

$$M_s = R(\theta)M_{LP,QWP}R(-\theta)$$

with $R(\theta)$ for rotation.

Proof-of-concept with 3 coincidence measurements

Institute of Applied Physics
Friedrich-Schiller-Universität Jena



In total 102 samples, with 2° angular resolution for a large range of angles for both LP and QWP

LP subset:

- 42 samples distinguished
- 4° median step, max: 8°

QWP subset:

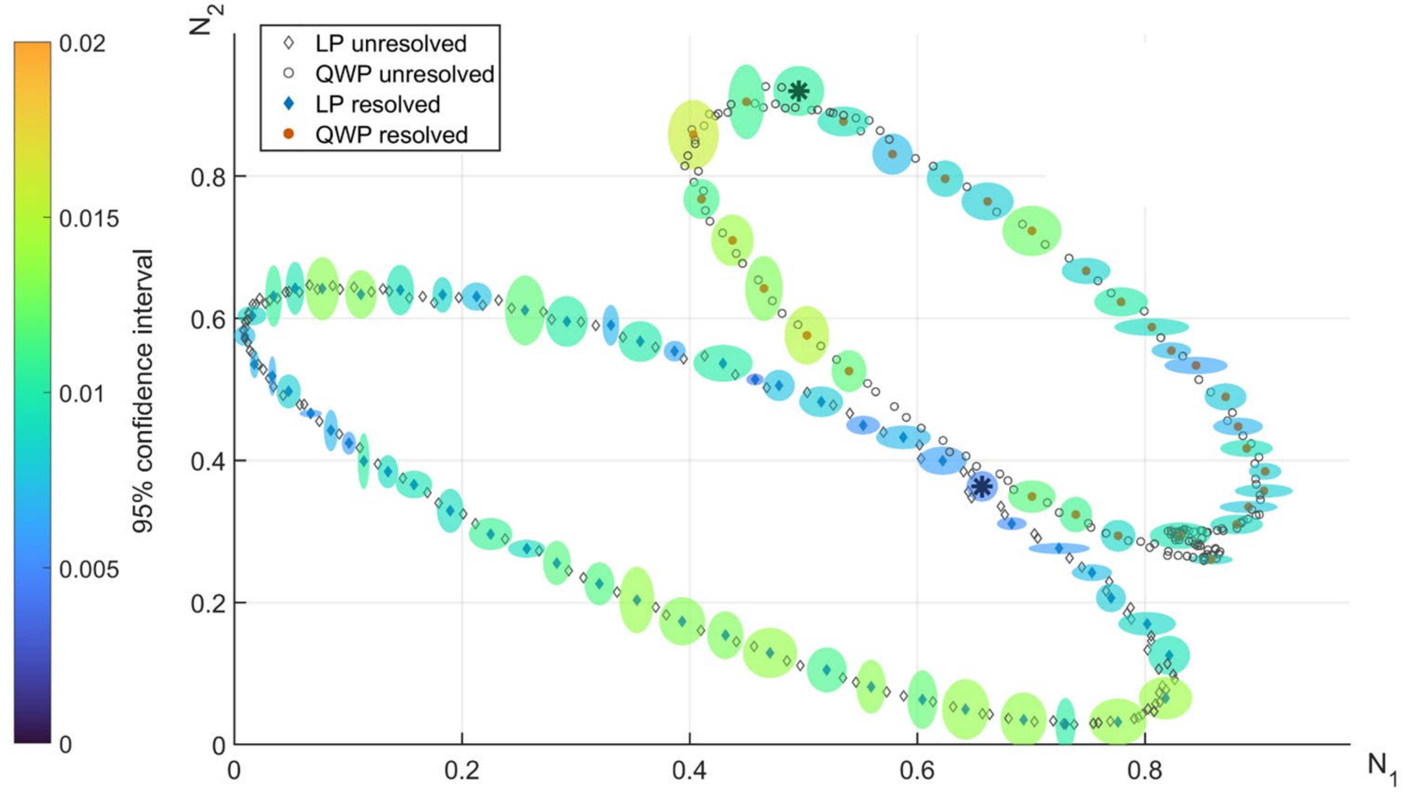
- 60 samples
- 2° median step, max 9°

[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]

Possible also with just two projections

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Just two projections in the idler channel:



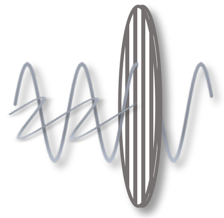
In total **84** samples with 2° angular resolution could be successfully distinguished

> than typical sample set size for practical applications

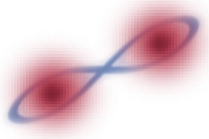
Twice less measurements than needed for single qubit tomography!

[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]

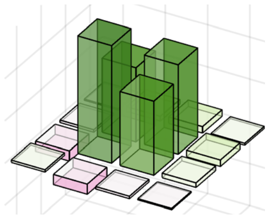
Outline



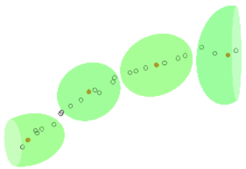
Why sensing with polarization?



Polarization based probing with Bell states



Showcase: scattering samples



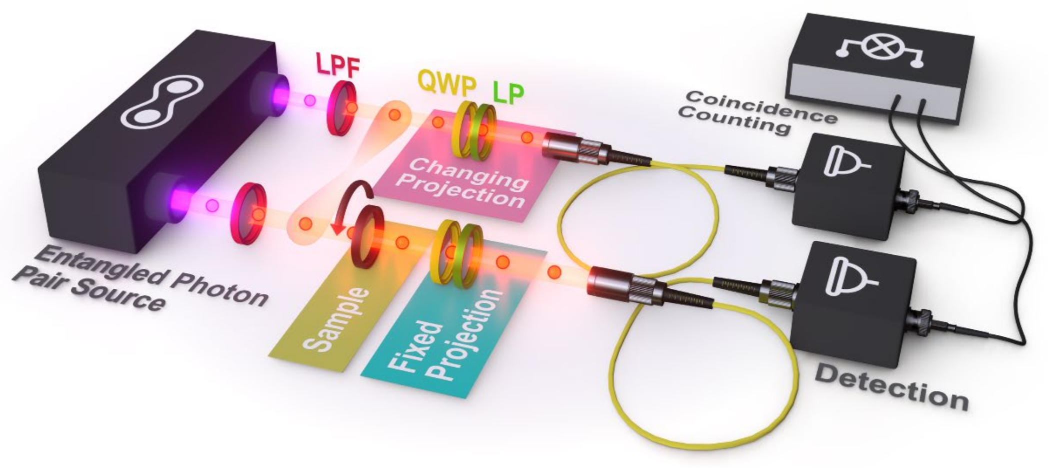
Framework for classification with just two measurements per sample

Conclusions & outlook

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

- Demonstration of applicability of polarization-entangled photons for practical sensing: tissue phantoms, microorganisms in water @ less than 100 cells in the measured volume, cell cultures
- Experimental demonstration of nonlocal differentiation between polarization objects with just two polarization projections in the remote optical channel: more than 80 samples with subtle differences in polarization response (2° step in orientation of optical axis) → framework for classification
- **Potential for biomedical diagnostics, remote sensing, and other classification/detection tasks**

[VB, et al., APL Photonics 9 (4), 041301 (2024)]



Contact me @

Visit our group

Acknowledgements

Colleagues and collaborators (also beyond the presented results)

@ Nano & Quantum Optics group
- Prof. Dr. Thomas Pertsch
- Dr. Frank Setzpfandt
- Luosha Zhang

@ FSU Jena
- Prof. Dr. Fabian Steinlechner
- Dr. Thomas Siefke
- Prof. Dr. Stefan Heinemann
- Dr. Philipp Rühl

@ IPHT Jena
- Dr. Tobias Meyer-Zedler

@ UKJ: Dr. rer. nat. Anna Mühlig

QuantIm4Life

Bundesministerium für Bildung und Forschung

Friedrich-Schiller-Universität Jena

ProChance career

Internationally:
- Prof. Igor Meglinski, Aston Uni, Birmingham
- Prof. Alexander Bykov, Uni Oulu
- Dr. Ivan Lopushenko, Uni Oulu
- Prof. Andrey Sukhorukov, ANU Canberra
- Prof. Özgür E. Müstecaplıoğlu, Koç Univeristy

Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Thank you for your attention!