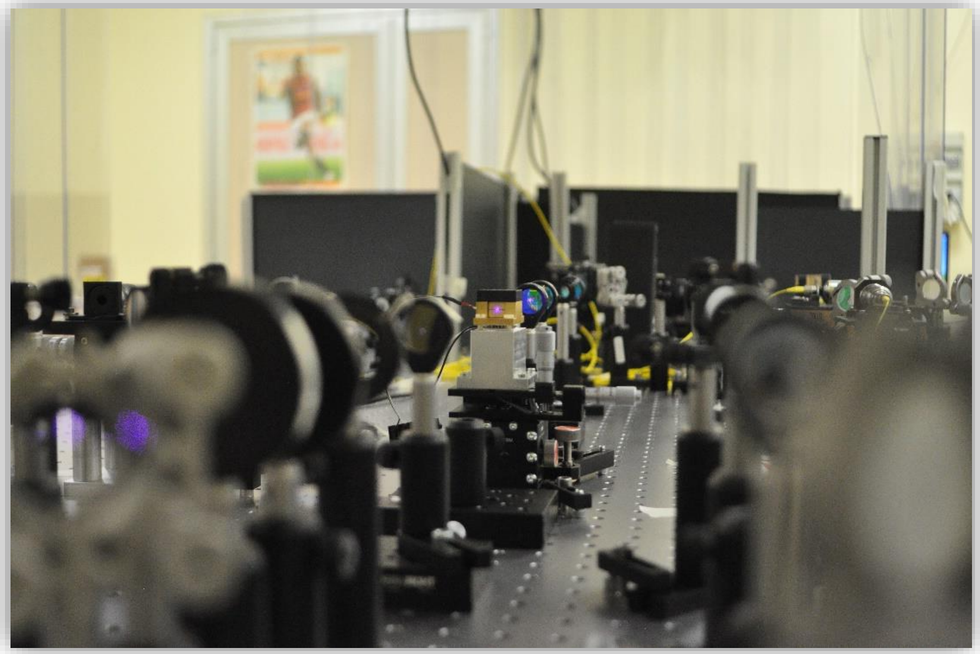
Certification of multi-photon experiments & Engineering and characterization of structured light

Taira Giordani and Alessia Suprano
Dipartimento di Fisica, Sapienza Università di Roma
www.quantumlab.it

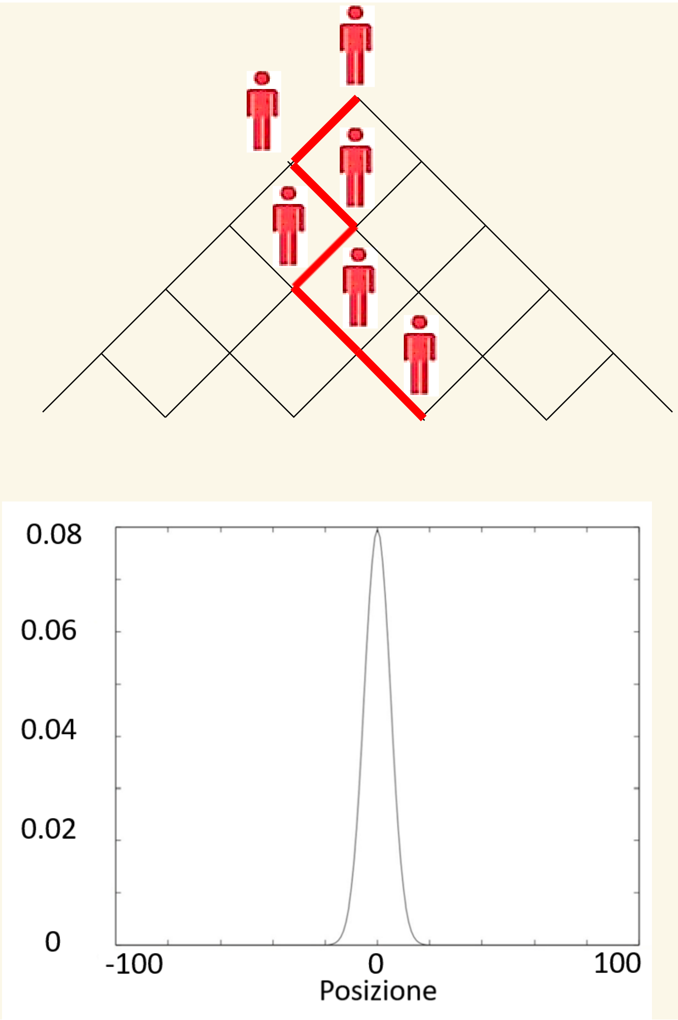
.

Quantum Technologies within INFN: status and perspectives, Padova, 21/01/2020

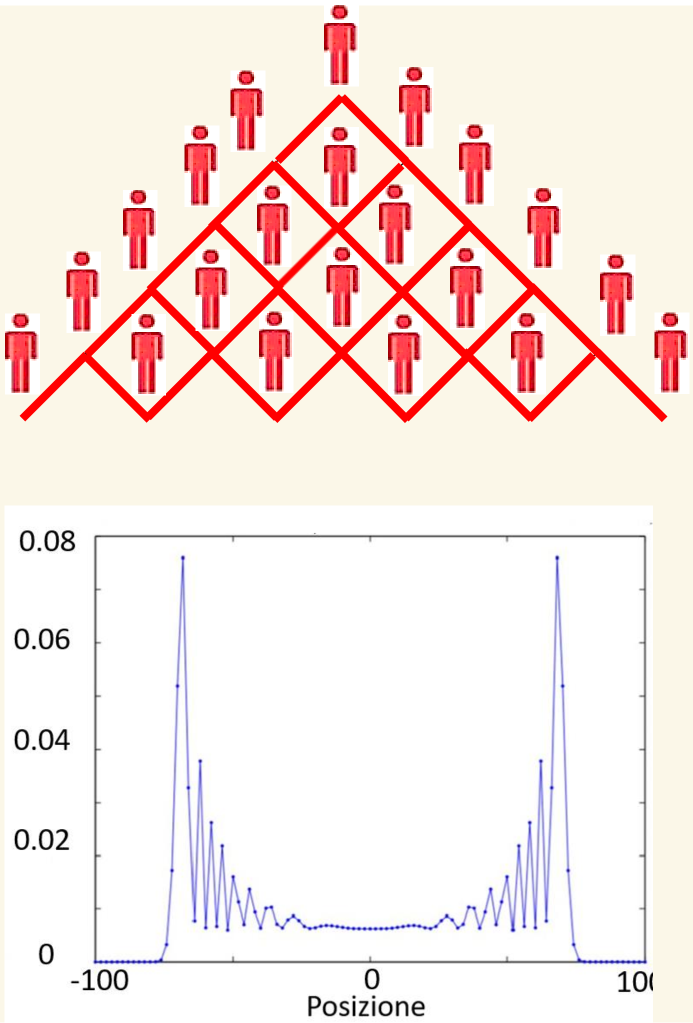


Quantum walk

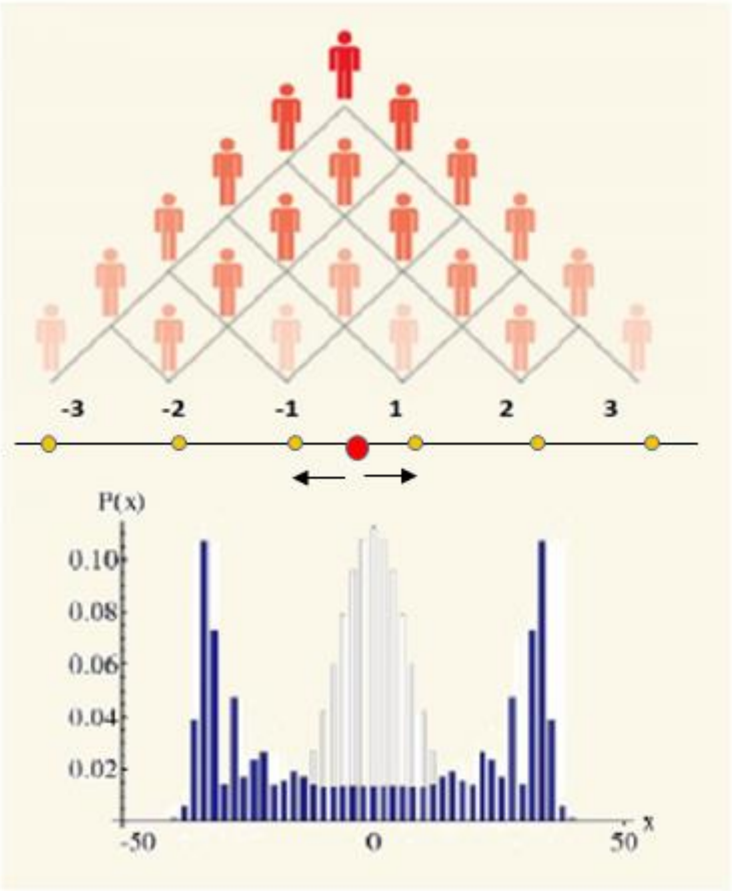
Classical random walks



Quantum random walks



1D descrete-time quantum walk



Quantum system described by:

- Walker's position $|i\rangle \in \mathcal{H}_P = \{|n\rangle : n \in \mathbb{Z}\}$
- Walker's coin $|s\rangle \in \mathcal{H}_C = \{|\uparrow\rangle, |\downarrow\rangle\}$

The evolution operator: $\hat{U} = \prod_{t=1}^{n} \hat{S}_{wc}\hat{C}_t$

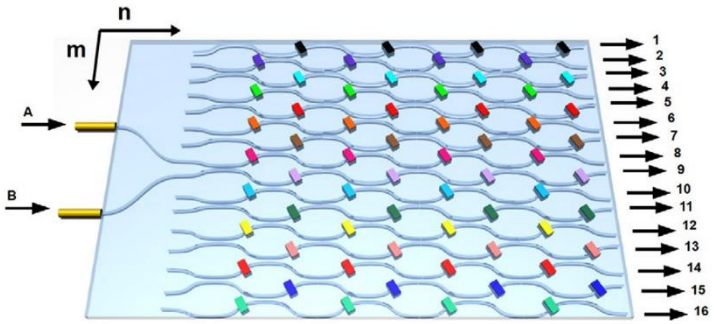
$$\hat{S} = \sum_i (|i\rangle\langle i| \otimes |\uparrow\rangle\langle\uparrow| + |i+1\rangle\langle i| \otimes |\downarrow\rangle\langle\downarrow|)$$

$$\hat{C} = \begin{pmatrix} e^{i\xi}cos\theta & sin\theta \\ -sin\theta & e^{-i\xi}cos\theta \end{pmatrix}$$

$$|\psi\rangle = \sum_i \sum_{s\in\{|\uparrow\rangle,|\downarrow\rangle\}} u_{i,s}\ |i\rangle \otimes |s\rangle$$

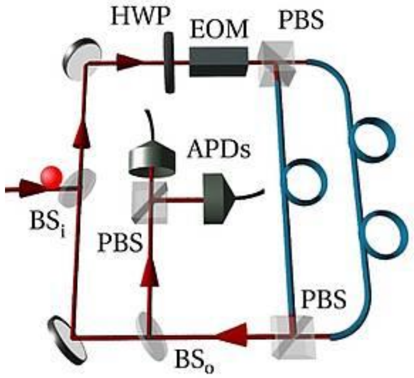
Quantum walks in photonics platforms

Integrated optical circuits



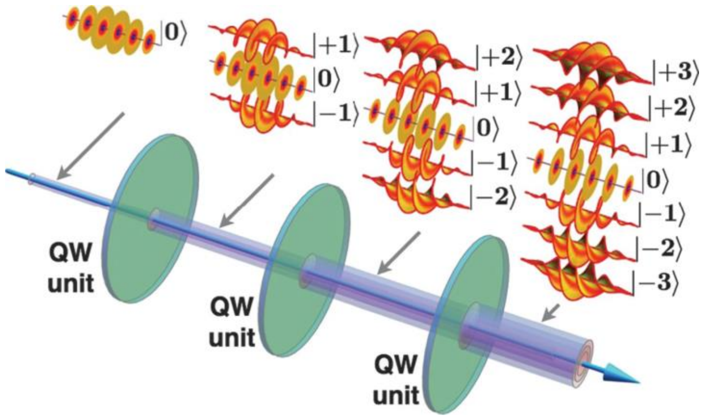
A. Crespi et al., *Nature Photonics* **7**, 322 (2013).

Fiber-loop scheme



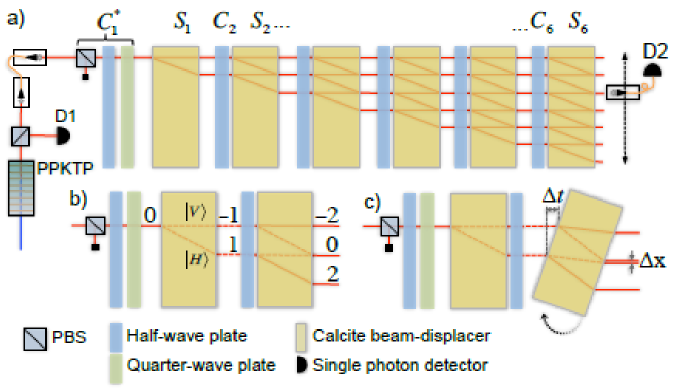
A. Schreiber et al., *Science* **336**, 55 (2012).

Angular momentum of light



F. Cardano et al., *Science Advances* **1**, e1500087 (2015).

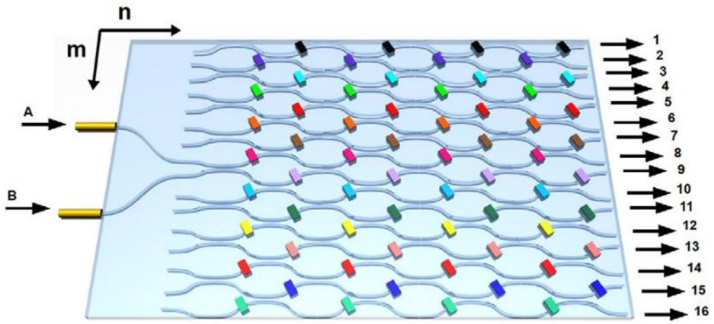
Bulk interferometric scheme

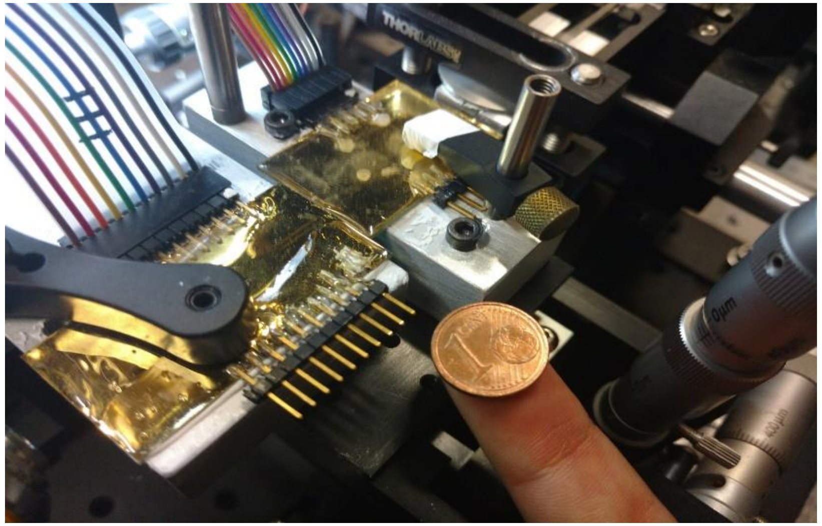


M. A. Broome et al., *Phys. Rev. Lett.* **104**, 153602 (2010).

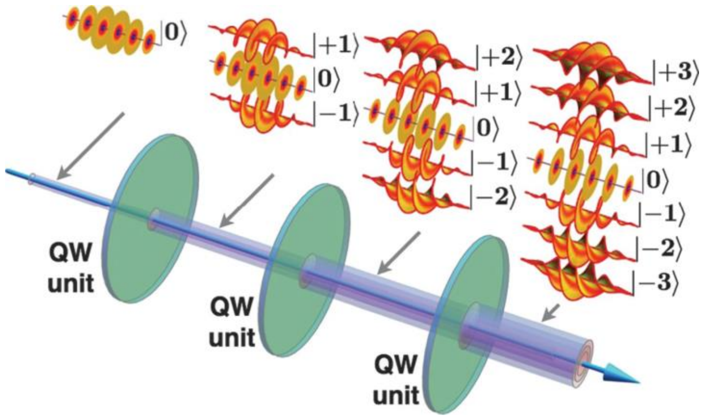
Our photonic platforms

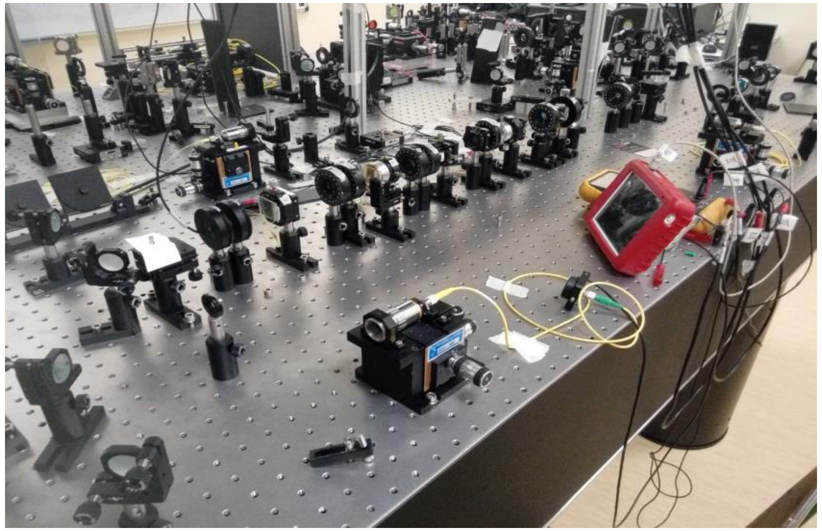
Integrated optical circuits



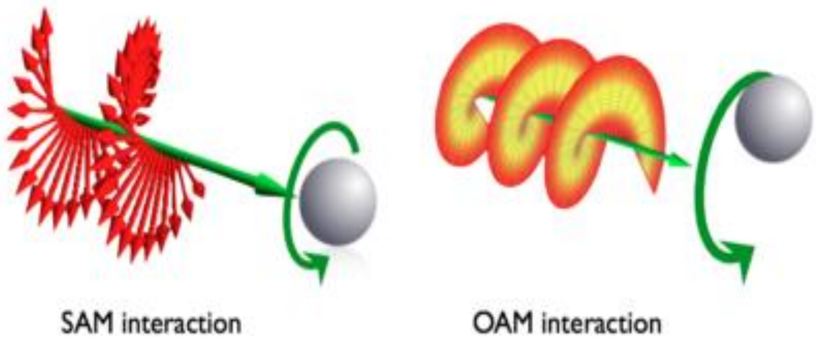


Angular momentum of light





Angular momentum of light

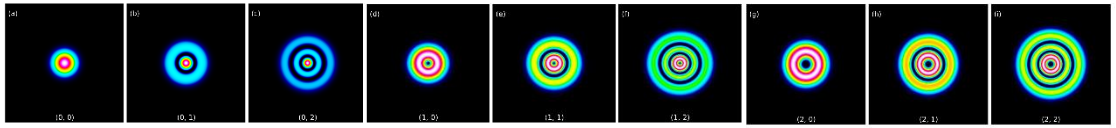


Orbital Angular Momentum (OAM):

$$E(r,\varphi) = E_0 e^{im\varphi}$$

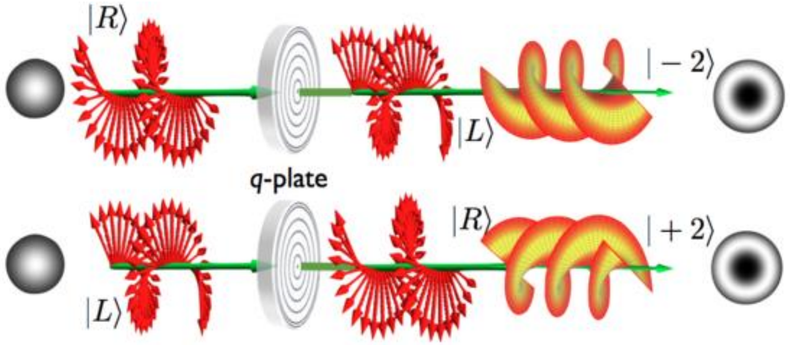
↓

Laguerre-Gauss modes

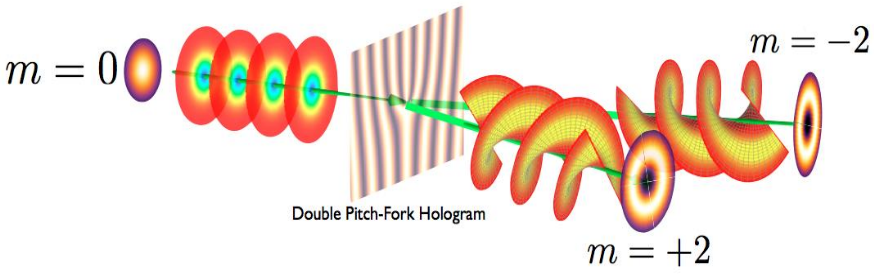


OAM manipulation

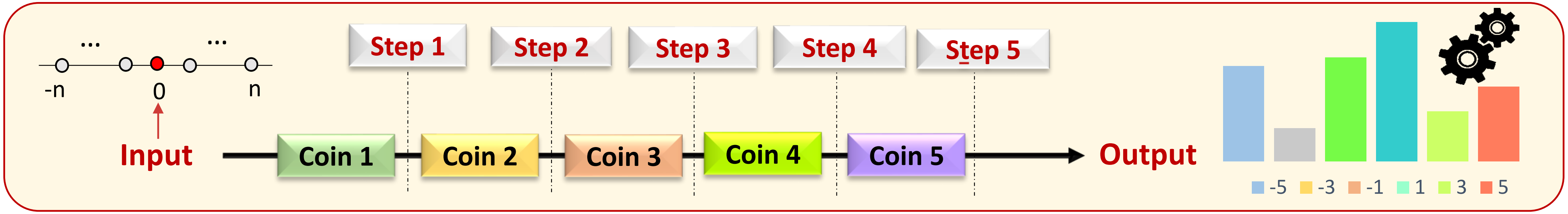
with inhomogeneous birefringent media: coupling between SAM and OAM



with holograms: generation of arbitrary beam shapes, including OAM eigenstates.

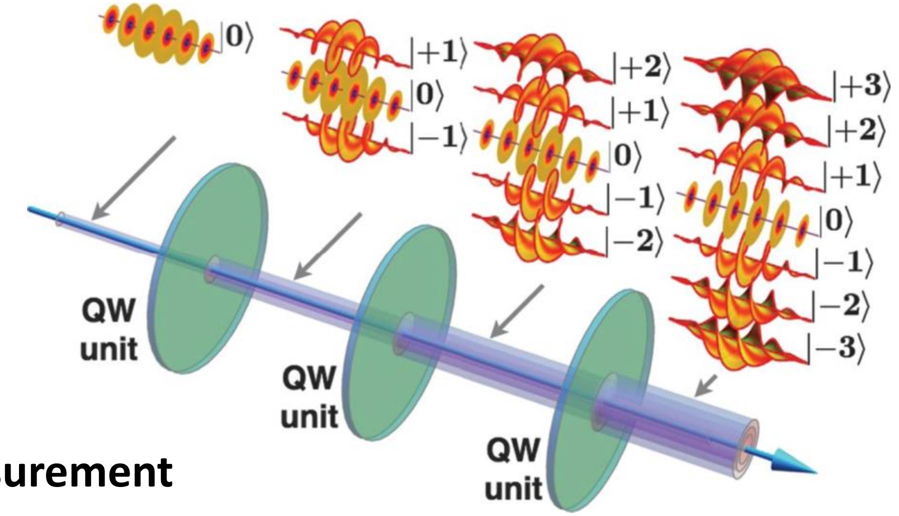


Quantum state engineering



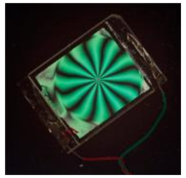
The idea: exploiting discrete-time quantum walks on a line to engineer qudit states in dimension $n + 1$.

The platform: The position of the walker is encoded in the OAM eigenstates $\{m\}$ while the coin degree of freedom in the polarization $\{R, L\}$



QW unit =

Shift



Q-plates

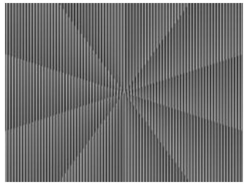
+

Coin

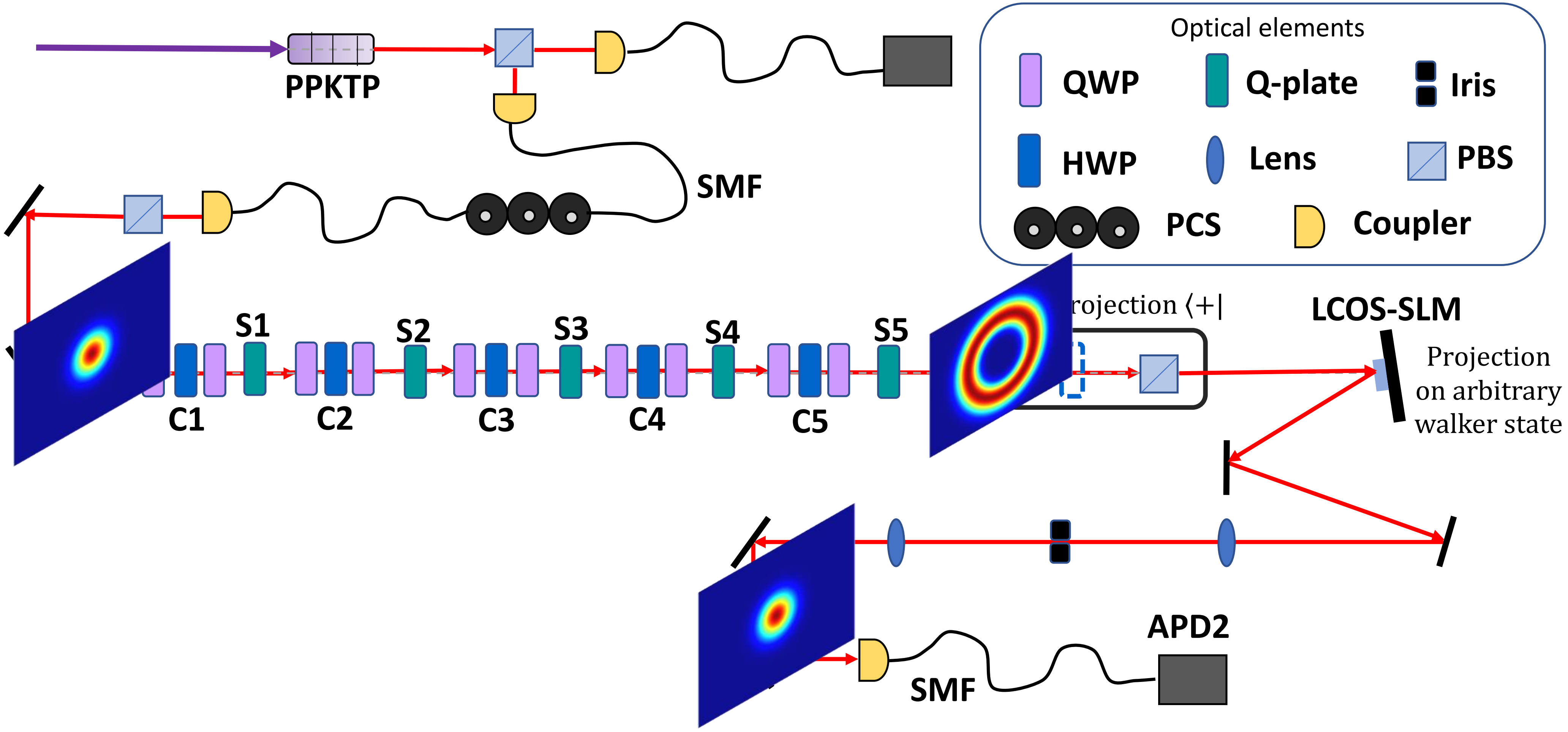
Waveplates

Measurement

+

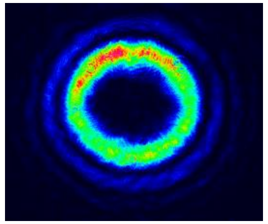


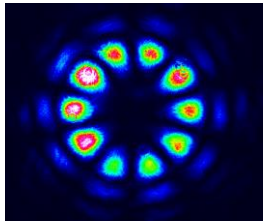
Experimental quantum state engineering

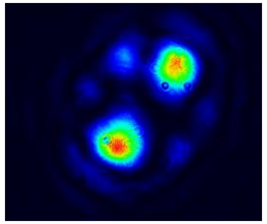


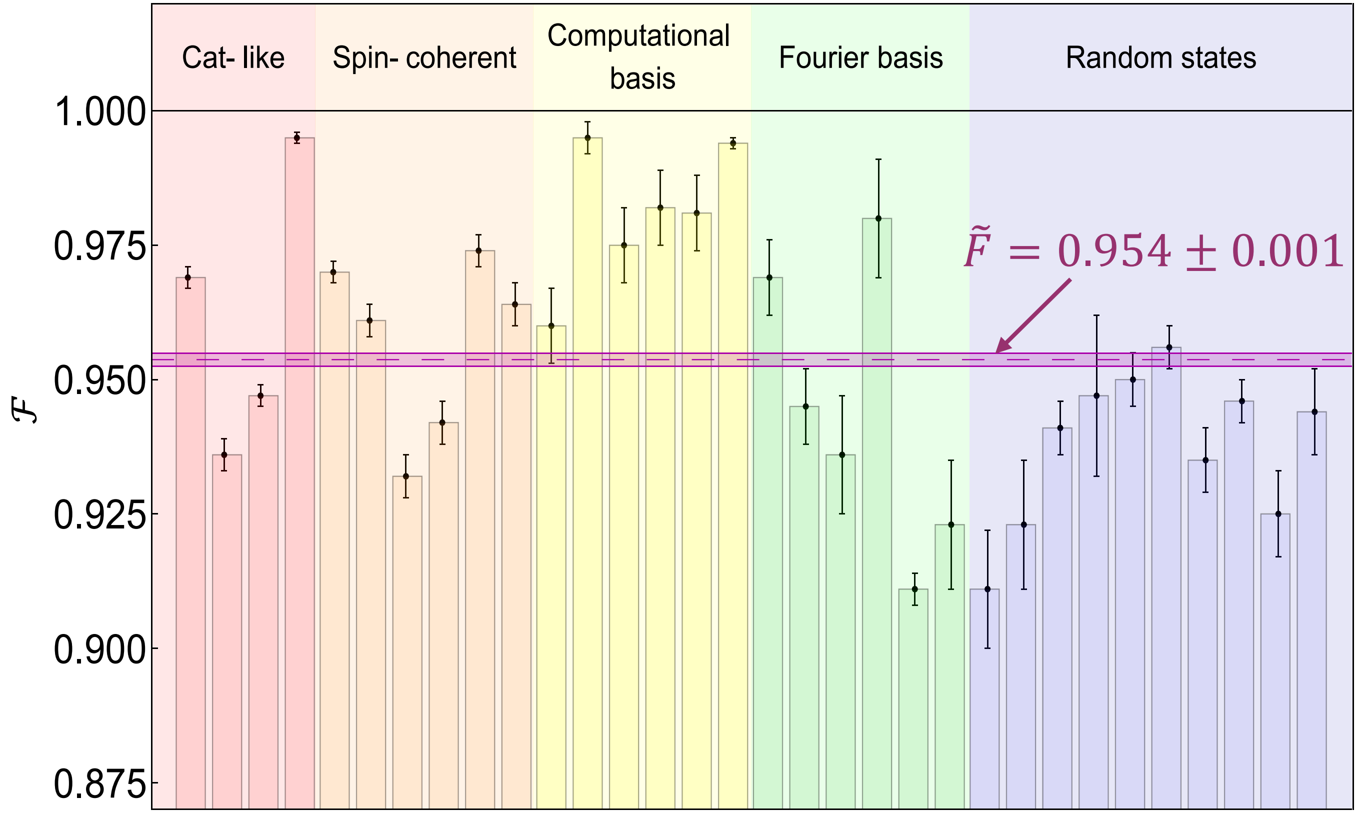
T. Giordani, E. Polino, S. Emiliani, A. Suprano, L. Innocenti, H. Majury, L. Marrucci, M. Paternostro, A. Ferraro, N. Spagnolo, and F. Sciarrino, Phys. Rev. Lett. 122, 020503 (2019).

Quantum state engineering: results







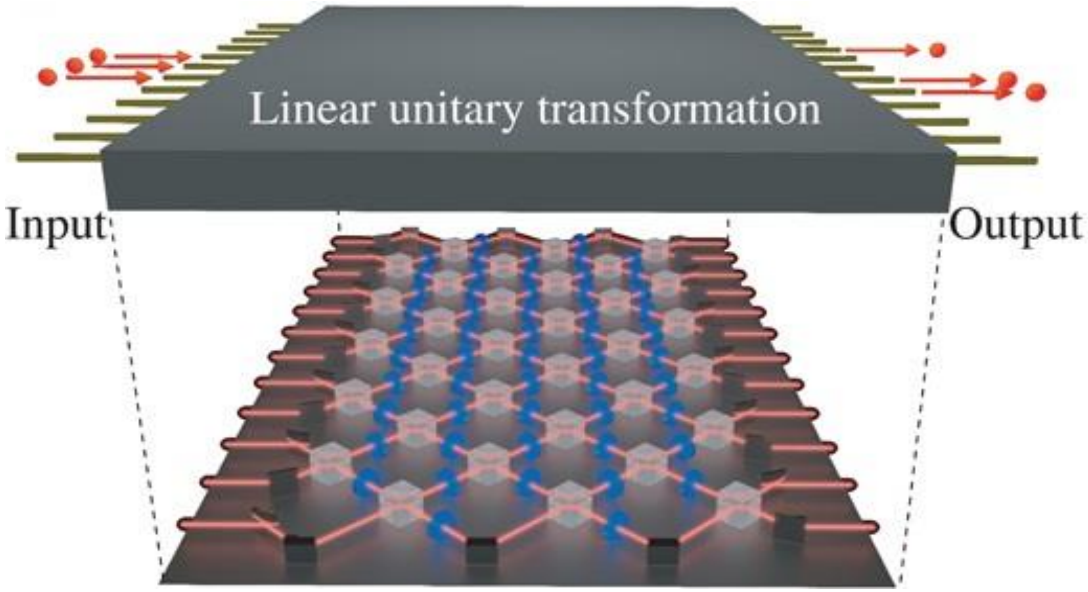


- We have successfully implemented a 5-step quantum walk and a quantum state engineering protocols
- These results reinforce the idea that numerical optimization complementing quantum dynamics of a sufficient degree of complexity is effective for high-dimensional state engineering.
- Such toolbox paves the way to a large range of applications in the context of quantum programmable dynamics

L. Innocenti et al., *Phys. Rev. A* **96**, 062326 (2017).
T. Giordani et al., Phys. Rev. Lett. 122, 020503 (2019)

Multi-particle regime

- A platform for simulating non-interacting bosonic systems evolving in random network
- Boson Sampling: a non-universal model of quantum computation based on n indistinguishable photons, m-mode passive optical interferometer and single photon detection

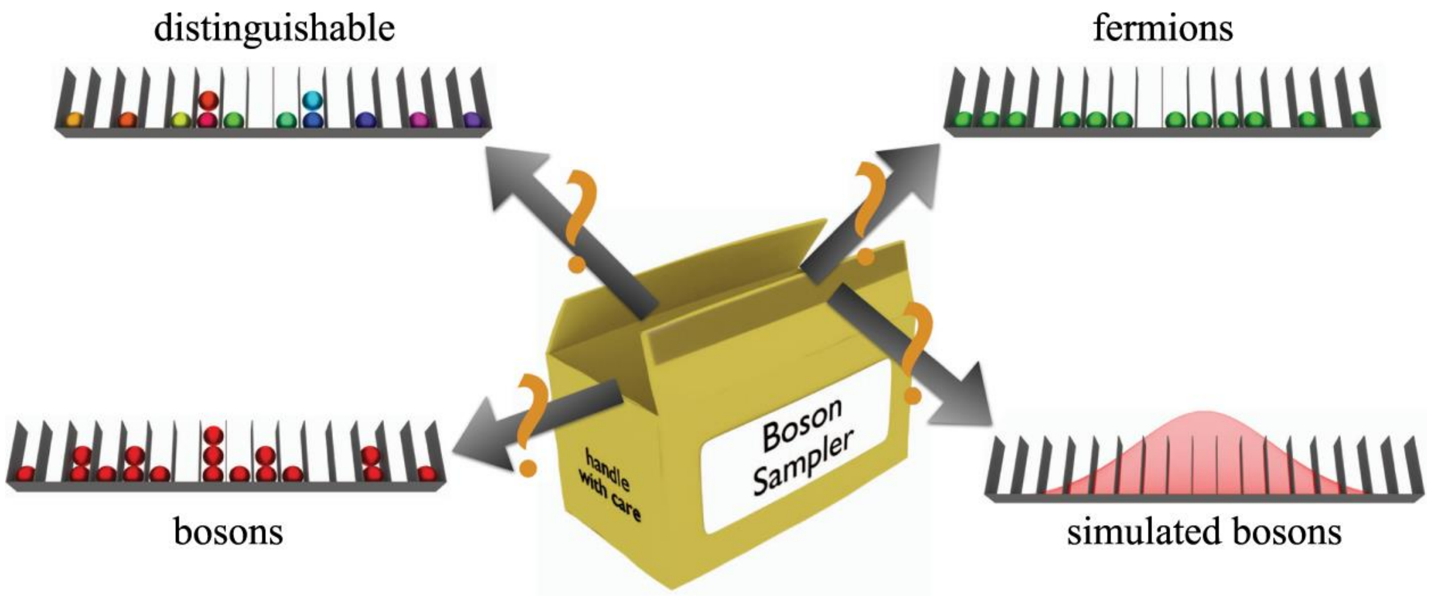


$$|j_1,\ldots,j_m\rangle \dashrightarrow \sum_{S} \frac{\mathrm{Per}(U_s)}{\sqrt{j_1^{(s)}!\ldots j_m^{(s)}!}} \left|j_1^{(s)},\ldots,j_m^{(s)}\right\rangle$$

$$\mathrm{Per}(U_s) = \sum_{\sigma\in S_n}\prod_{i=1}^{n}(U_s)_{i\sigma(i)} = \begin{pmatrix} u_{1\,1} & u_{1\,2} & \ldots & u_{1\,m} \\ u_{2\,1} & u_{2\,2} & \ldots & u_{11} \\ \vdots & \vdots & \ldots & \vdots \\ & & \ldots & \\ u_{m-1\,1} & u_{m-1\,2} & \ldots & u_{m-1\,m} \\ u_{m\,1} & u_{m\,2} & \ldots & u_{m\,m} \end{pmatrix}$$

$$= u_{21}u_{m2} + u_{m\,1}u_{22}$$

Validation of multi-photon interference



Statistical properties of the output state of a Boson Sampler

Physical properties of Bosonic systems

M. Walschaers et al., New J. Phys. **18** 032001 (2016)

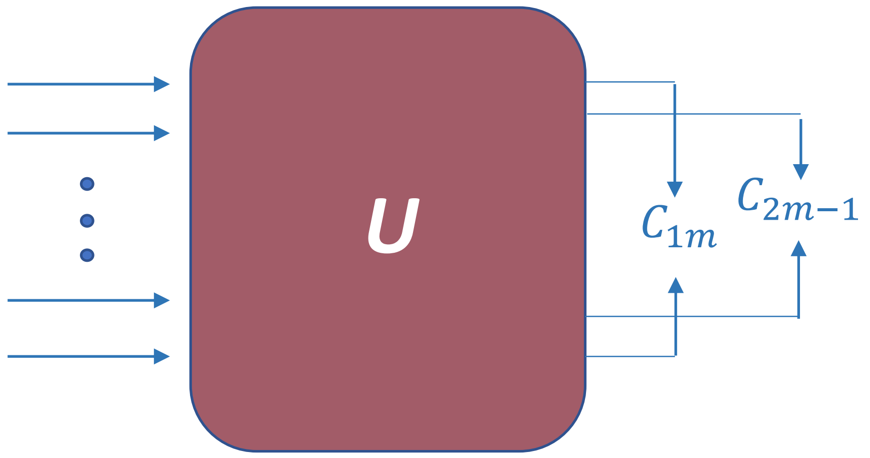
T. Giordani et al, Nat. Phot. **12** 173–178 (2018)

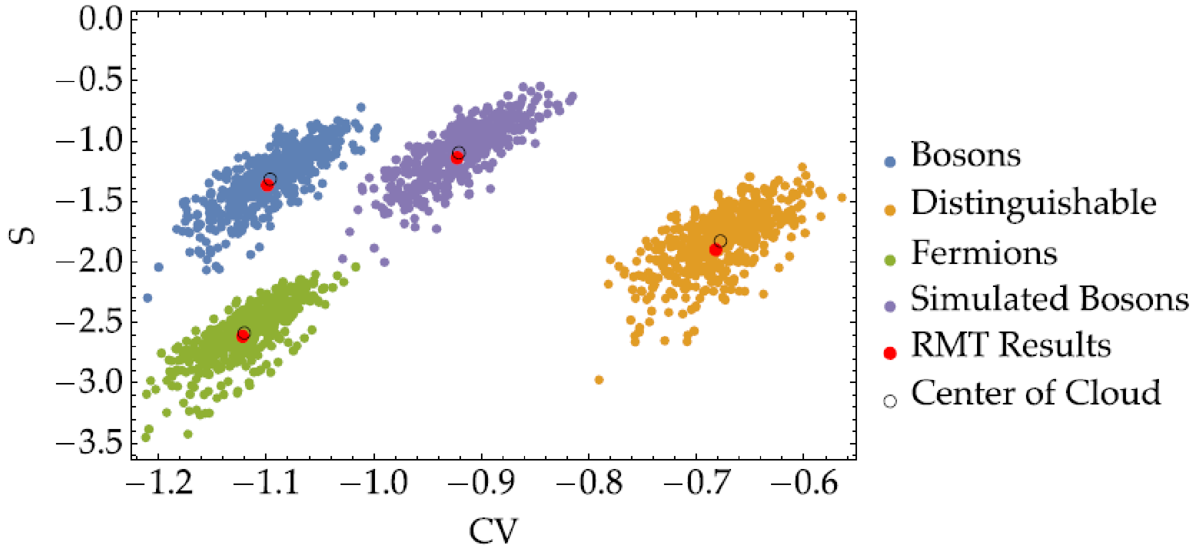
D. J. Brod et al., Phys. Rev. Lett. **122** 063602 (2019)

T. Giordani et al., arxiv preprint arXiv:1907.01325

Statistical benchmarking

Discerning genuine quantum interference through first statistical moments of two-mode correlation functions





n: number of photons m: number of modes

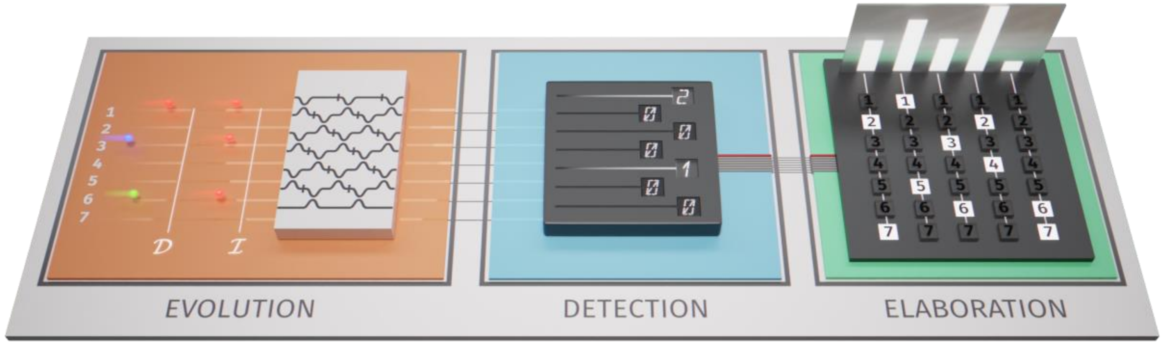
C-dataset: $C_{ij} = \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle$ i, j output ports

First moments: NM= $\frac{m^2}{n}\overline{C_{ij}}$ CV= $\frac{\sigma_{C_{ij}}}{\overline{C_{ij}}}$ S= $skewness$

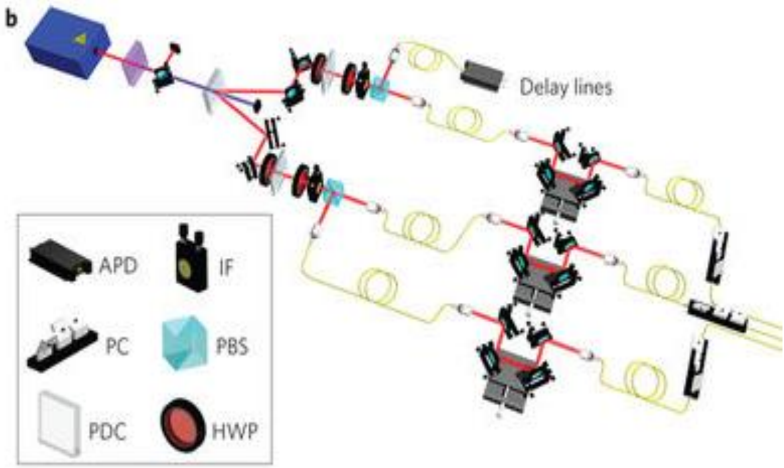
M. Walschaers et al., Statistical benchmark for BosonSampling, New J. Phys. **18** (2016) 032001

Experimental implementation

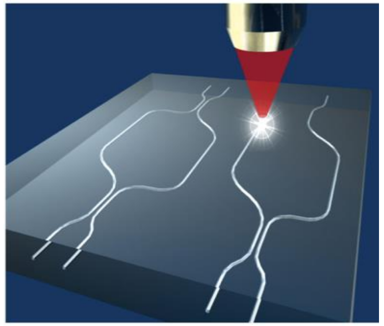
Goal: discriminating dynamics of distinguishable (D) and indistinguishable (I) particles in a proof of principle experiment n=3 m=7



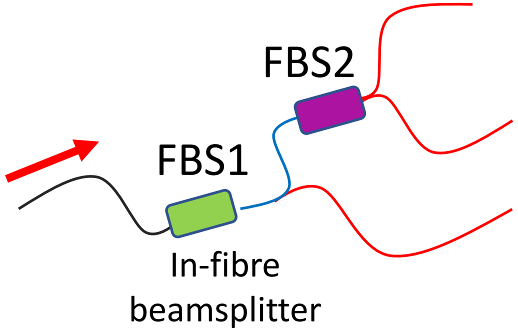
Single-photon source: two pairs generation



Integrated device: femtosecond laser writing



Approximated photon-number-resolving detection

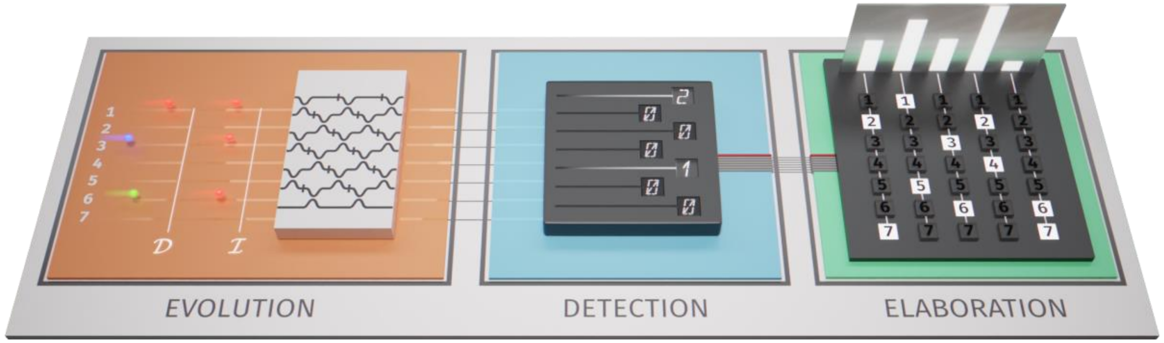


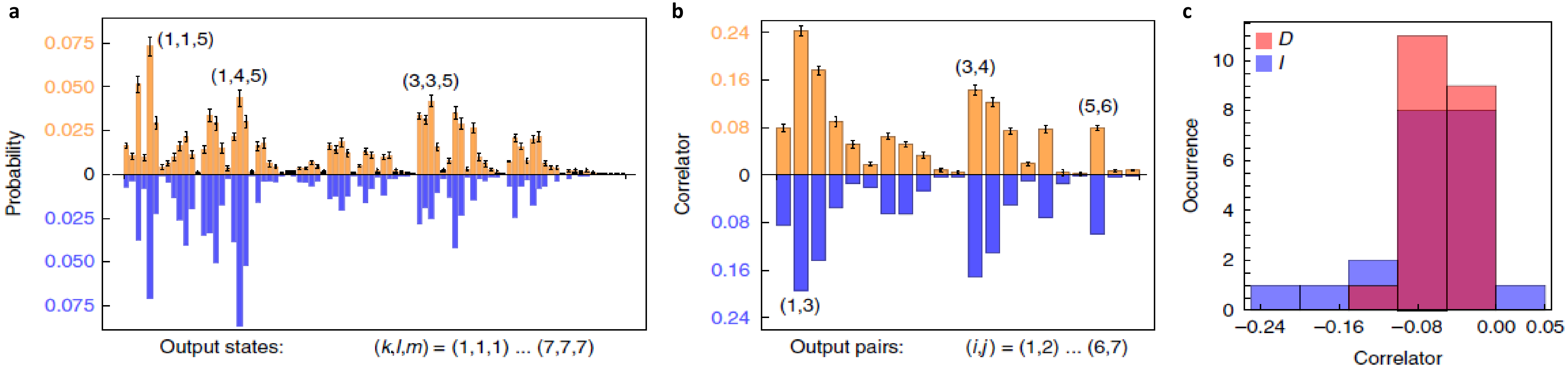
T. Giordani, F. Flamini, M. Pompili, N. Viggianiello, N. Spagnolo, A. Crespi, R. Osellame, N. Wiebe, M. Walschaers, A. Buchleitner, and F. Sciarrino, Experimental statistical signature of many-body quantum interference, Nat. Phot. **12** 173–178 (2018)

Experimental Results

Goal: discriminating dynamics of distinguishable (D) and indistinguishable (I) particles in a proof of principle experiment

n=3 m=7





1. Collecting 3-photons events

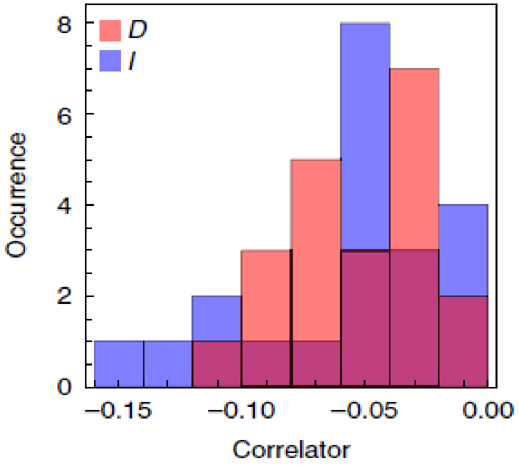
2. Compute C-dataset

3. Obtain correlator's distribution

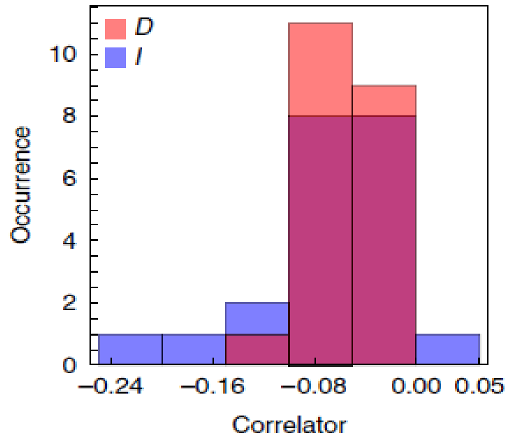
T. Giordani et al., Experimental statistical signature of many-body quantum interference, Nat. Phot. **12** 173–178 (2018)

Classification of experimental data

Input A

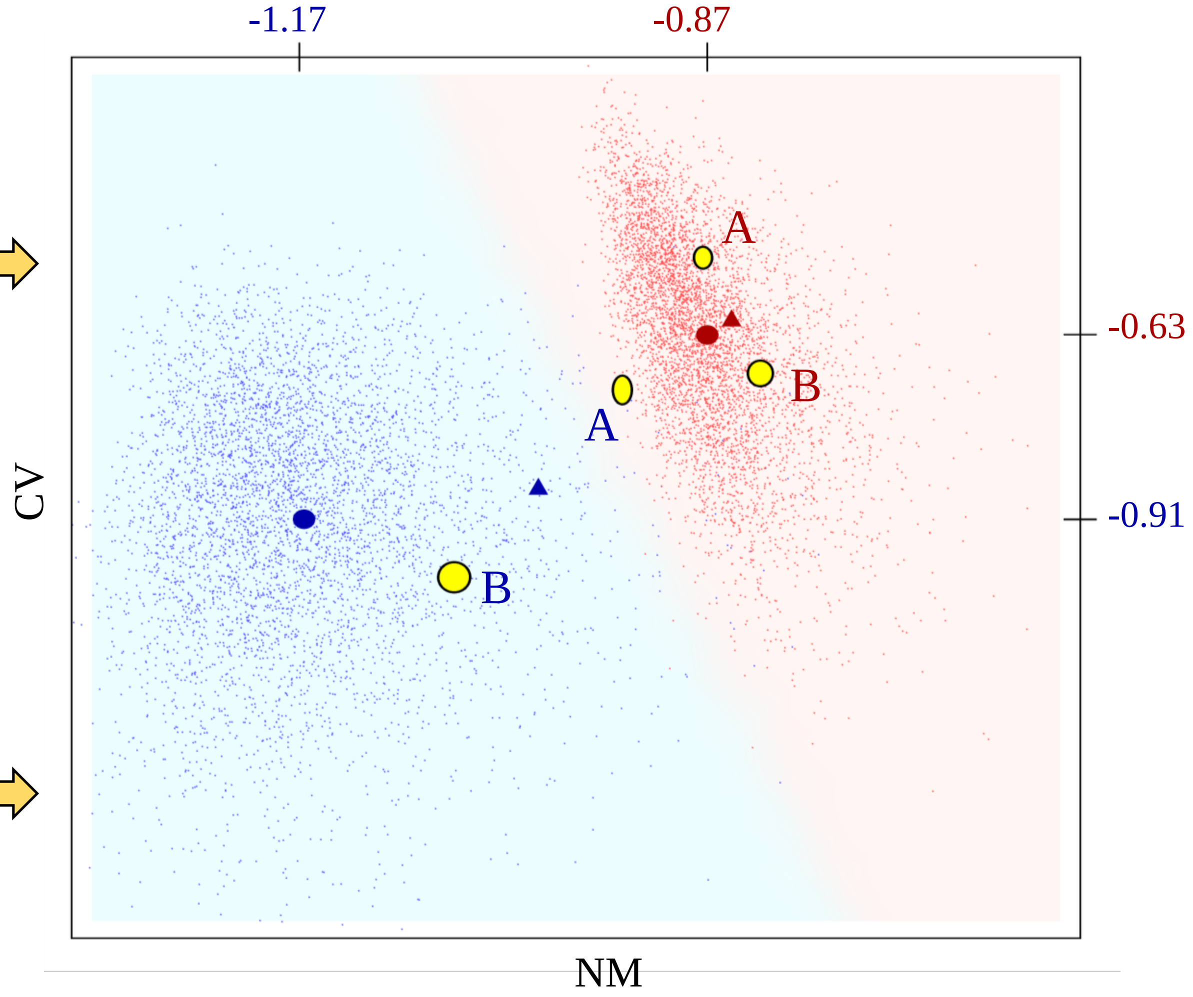


Input B



Computing first moments

Computing first moments



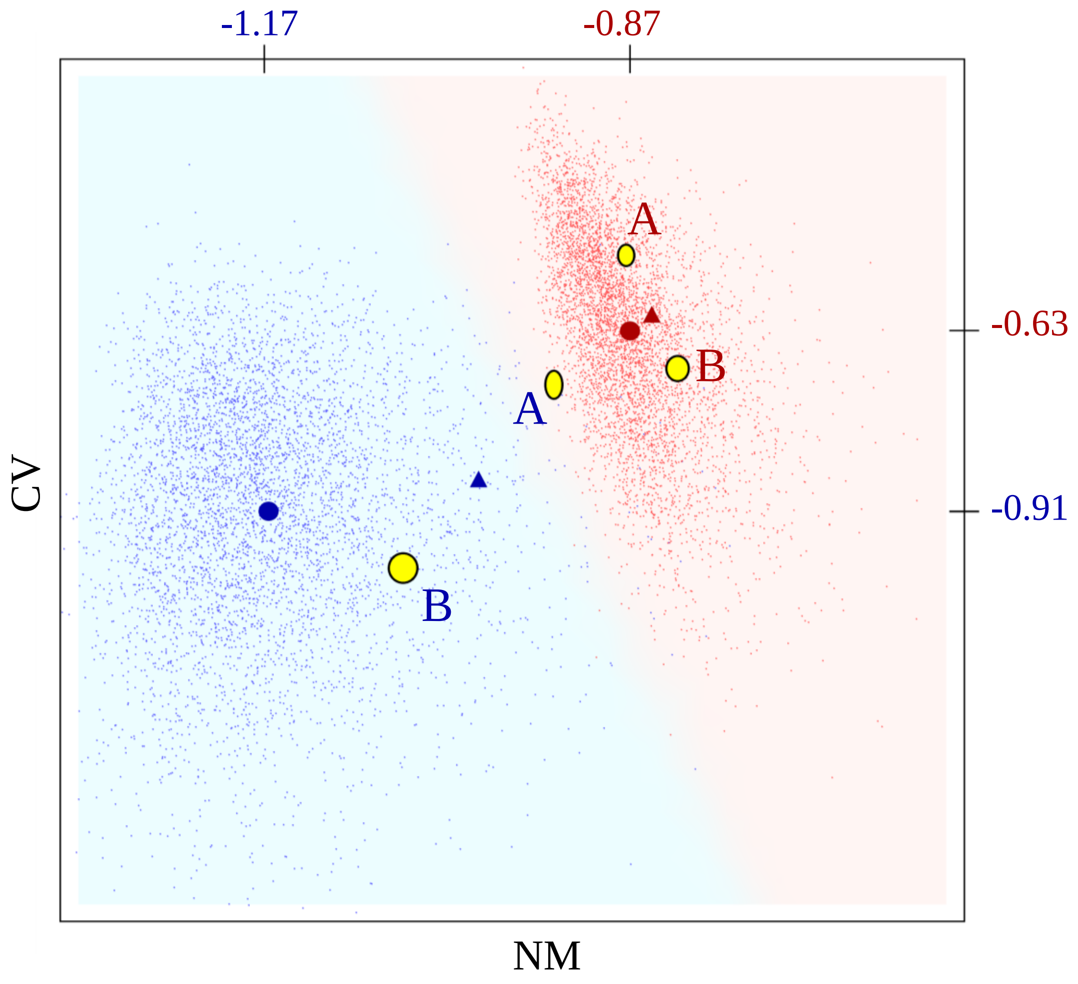
T. Giordani et al., Experimental statistical signature of many-body quantum interference, Nat. Phot. **12** 173–178 (2018)

Classification of experimental data

1. Two hypotheses
- D (distinguishable)
- I (Indistinguishable)

2. Training set
- Set of points in NM-CV plane for different Haar-random matrices

3. Test different classifiers
- Support-vector machine
- K-nearest neighbors
- Random forest

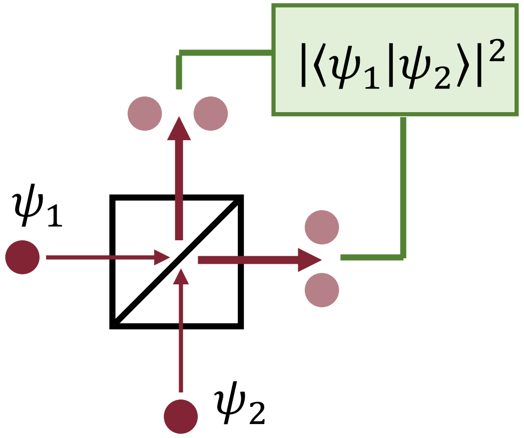


T. Giordani et al., Experimental statistical signature of many-body quantum interference, Nat. Phot. **12** 173–178 (2018)

Perspectives: multi-photon indistinguishability test

Ingredients

- HOM test
    - *Overlap estimation*

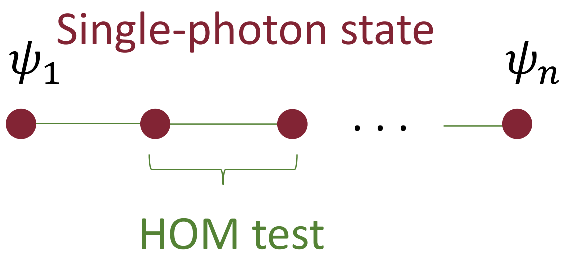


- Multi-photon states

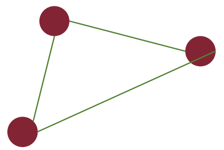
$$\rho = \rho_1 \otimes \rho_2 \dots \otimes \rho_n \qquad \rho = c_0\, \rho^{ind} + \sum_s c_s\, \rho_s^{\perp}$$

Multi-photon indistinguability test

- Linear graph representation



- Circular graph representation



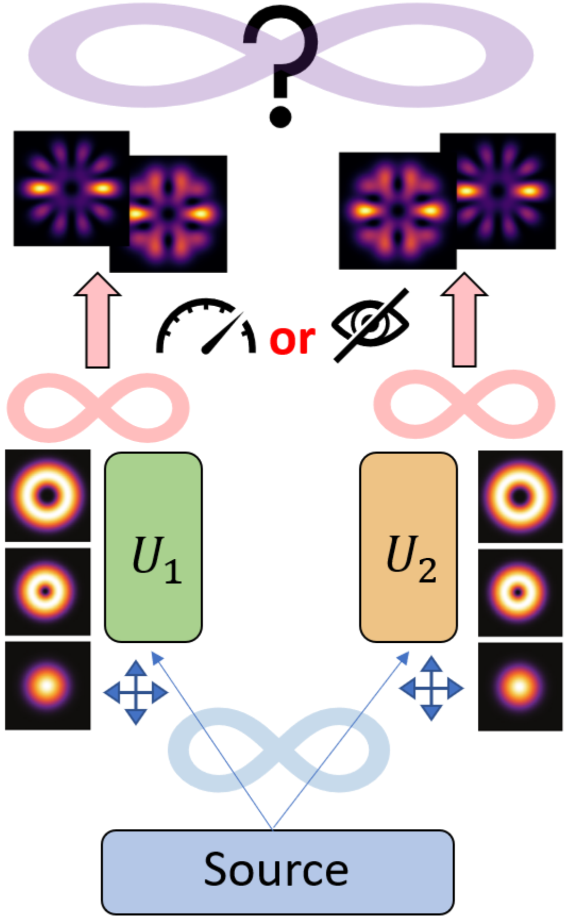
- Quantification of c_0
- Coherence and dimension witnesses

D. J. Brod et al., Witnessing Genuine Multiphoton Indistinguishability, Phys. Rev. Lett. **122** 063602 (2019)
T. Giordani et al., Experimental quantification of genuine four-photon indistinguishability, arxiv preprint arXiv:1907.01325

Perspectives: quantum walks with structured light

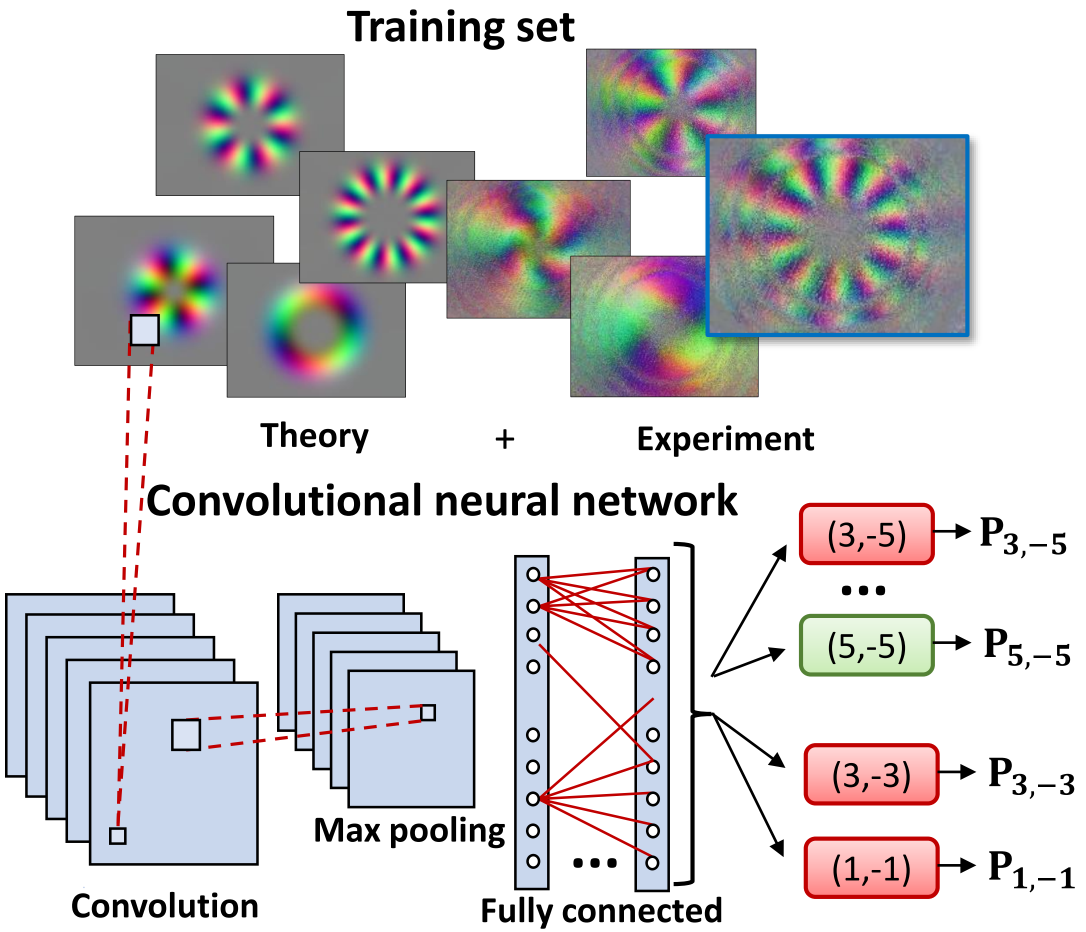
In the quantum regime

- Quantum state engineering of entangled qudits



...and with classical light

- Characterization of structured light via machine learning-based method



Our collaborators

QUEEN'S UNIVERSITY BELFAST

M. Paternostro
A. Ferraro
L. Innocenti
H. Majury

Università degli Studi di Napoli Federico II

L. Marrucci

Consiglio Nazionale delle Ricerche

R. Osellame
A. Crespi

Microsoft

N. Wiebe

UNI FREIBURG

A. Buchleitner
M. Walshaers

uff

D. J. Brod
E. Galvão

Thank you!

SAPIENZA Università di Roma

E. Polino,
F. Acanfora
C. Esposito
N. Viggianiello

F. Hoch
M. Romano
F. Flamini
G. Carvacho
N. Spagnolo
F. Sciarrino

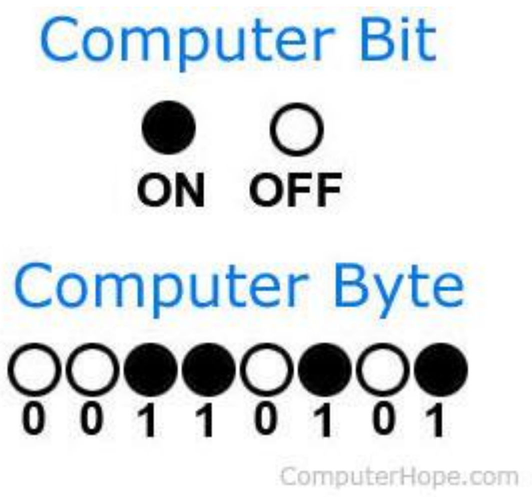
QUANTUM LAB
Quantum Information Lab
Dipartimento di Fisica, Università di Roma La Sapienza

QUCHIP
Quantum Simulation on a Photonic Chip

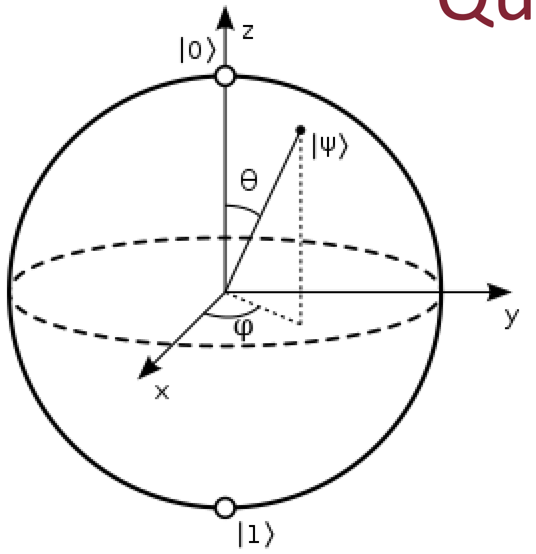
erc
PHOSPhOR
Advanced Grant from
European Research Council
Established by the European Commission

Quantum Information

Bit



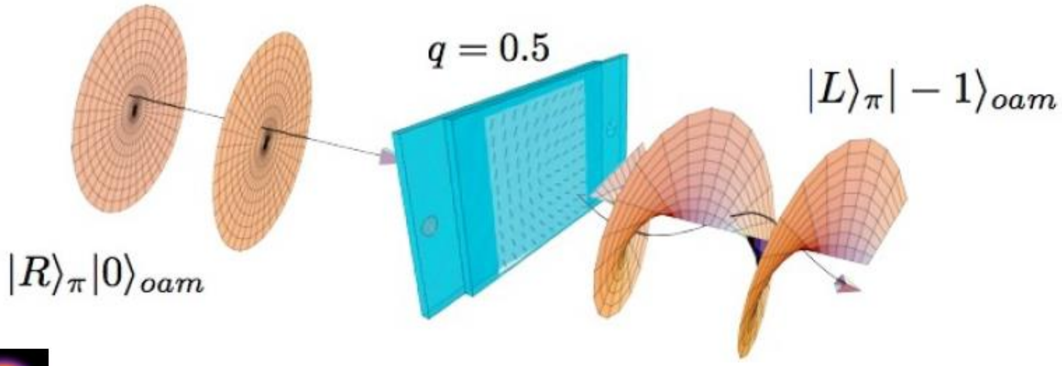
Qubit

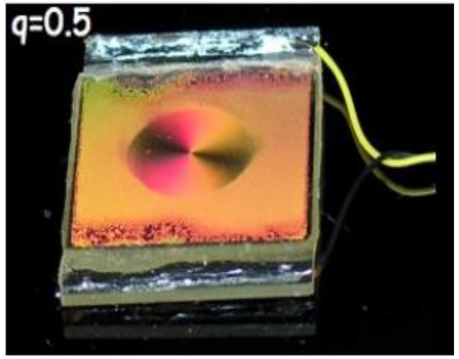


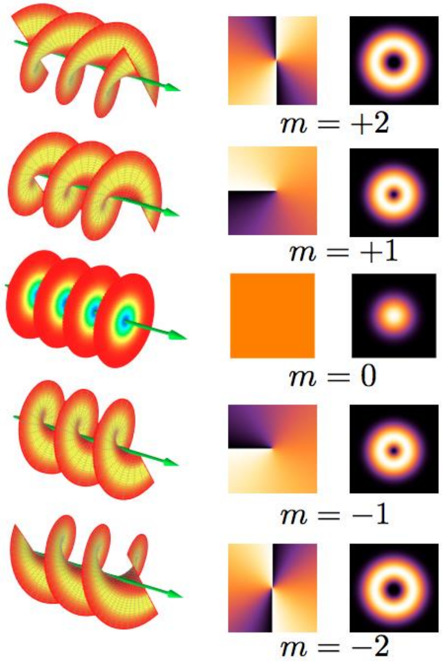
- **Quantum computation:**
  - Shor algorithm for prime factorization (1994)
  - Grover search algorithm (1996)
  - …
- **Quantum cryptography and communication**
- **Quantum simulation**

A. W. Harrow and A. Montanaro, Quantum computational supremacy, Nature **549**, 203-2019 (2017)

OAM manipulation: Q-plates







$$\alpha(r,\varphi) = \varphi q + \alpha_0$$

$$Q_\delta^{\alpha_0}|L,m\rangle = \cos\left(\frac{\delta}{2}\right)|L,m\rangle - i\sin\left(\frac{\delta}{2}\right)e^{i2\alpha_0}|R,m+2q\rangle$$

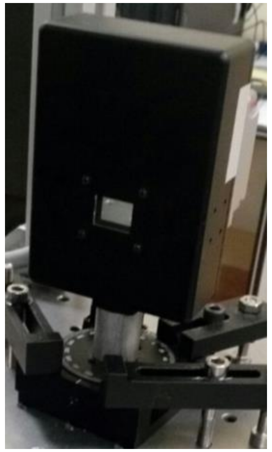
$$Q_\delta^{\alpha_0}|R,m\rangle = \cos\left(\frac{\delta}{2}\right)|R,m\rangle - i\sin\left(\frac{\delta}{2}\right)e^{-i2\alpha_0}|L,m-2q\rangle$$

L. Marrucci et al., Phys. Rev. Lett. **96**, 163905 (2006).

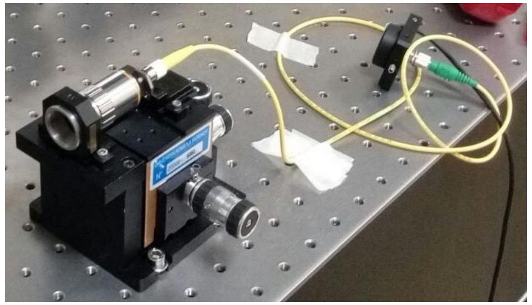
OAM manipulation: SLM

Spatial Light Modulator

(SLM)



+

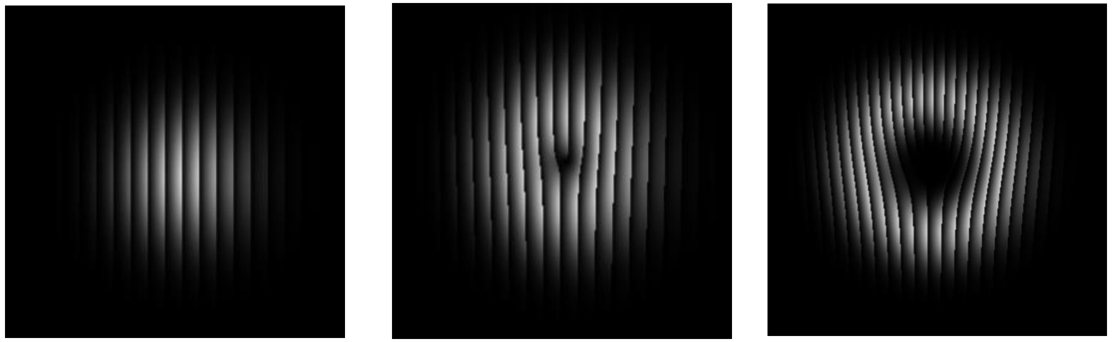


Coupling in single mode fiber (SMF)

$$\Psi(m,n) = \mathcal{M}(m,n)\mathrm{Mod}\left(\Phi(m,n) - \pi\mathcal{M}(m,n) + \frac{2\pi m}{\Lambda}, 2\pi\right)$$

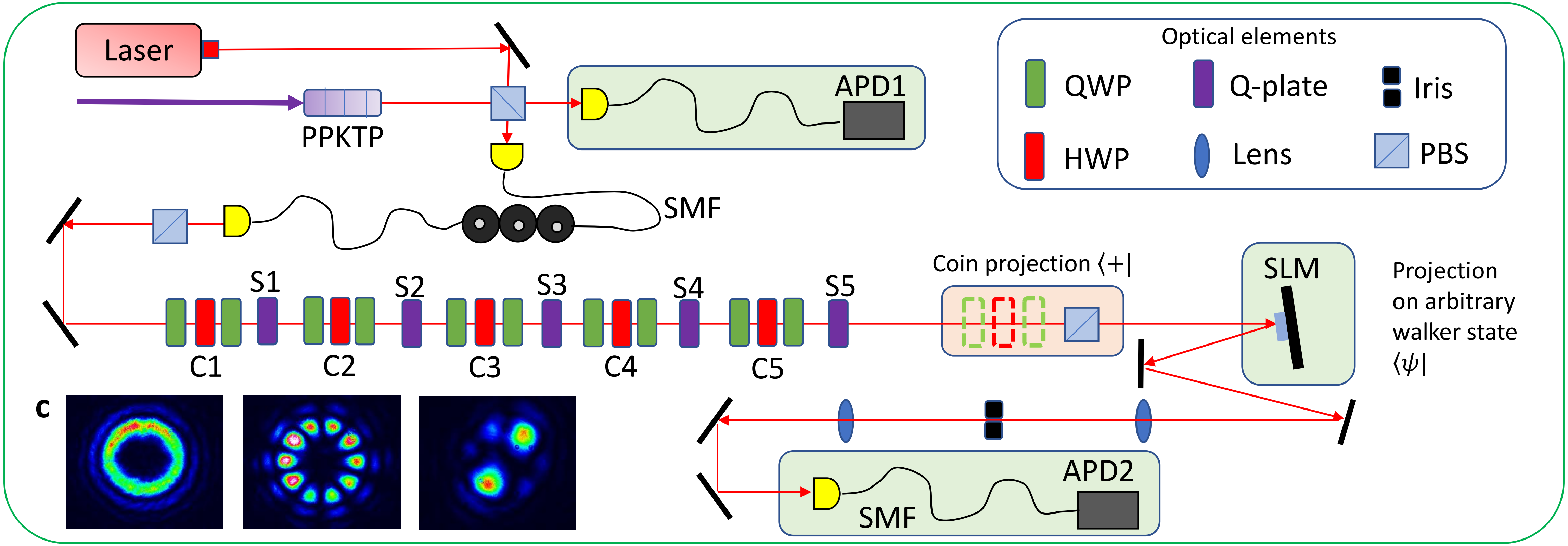
$$\psi(x,y)^{m,n} = A(x,y)^{m,n} e^{i\,\phi(x,y)^{m,n}}$$

$$M(m,n) = 1 + \frac{1}{\pi} sinc^{-1}(A)$$



A. Mair et al., Nature **412**, 313-316 (2001)
E. Bolduc *et al.*, *Optics Letters* **38**, 18 (2013)

Experimental quantum state engineering



T. Giordani, E. Polino, S. Emiliani, A. Suprano, L. Innocenti, H. Majury, L. Marrucci, M. Paternostro, A. Ferraro, N. Spagnolo, and F. Sciarrino, Experimental engineering of arbitrary qudit states with discrete-time quantum walks," (2018), preprint at arXiv: quant-ph/1808.08875 (2018)

Numerical optimization method

$$\hat{S}_{wc} = \sum_{k=1}^{n} |k\rangle\langle k|_w \otimes |\uparrow\rangle\langle\uparrow|_c + |k+1\rangle\langle k|_w \otimes |\downarrow\rangle\langle\downarrow|_w$$

$$\hat{C}_t = \begin{pmatrix} e^{i\xi t}\cos\theta_t & e^{i\zeta t}\sin\theta_t \\ -e^{-i\zeta t}\sin\theta_t & e^{-i\xi t}\cos\theta_t \end{pmatrix}$$

Initial state: $|\psi^{(0)}\rangle = |1\rangle \otimes (u_{1,\uparrow}^{(0)}|1,\uparrow\rangle + u_{1,\downarrow}^{(0)}\,|1,\downarrow\rangle)$

Condition after n steps of the Quantum Walk:

- $\langle 1,\downarrow|\psi^{(n)}\rangle = \langle n+1,\uparrow|\psi^{(n)}\rangle = 0$
- $\boldsymbol{v}_1^{(n)\dagger}\boldsymbol{v}_n^{(n)} = 0$ $\qquad \boldsymbol{v}_k^{(n)} = \begin{pmatrix} u_{k,\uparrow}^{(n)} \\ u_{k+1,\downarrow}^{(n)} \end{pmatrix}$
- $\sum_{k=1}^{s} \boldsymbol{v}_k^{(n)\dagger}\boldsymbol{v}_{n-s+k}^{(n)} = 0 \qquad s = 1,2,\dots,n-1$

Innocenti et al., Phys. Rev. A 96:062326 (2017)

Numerical optimization method

$$N\left(u_{k,\uparrow}+u_{k,\downarrow}\right)=u_k$$

$$|\psi\rangle = N(u_1|1,\uparrow\rangle + u_{n+1}|n+1,\downarrow\rangle + \sum_{k=2}^{n}[(u_k - d_k)|k,\uparrow\rangle + d_k|k,\downarrow\rangle]$$

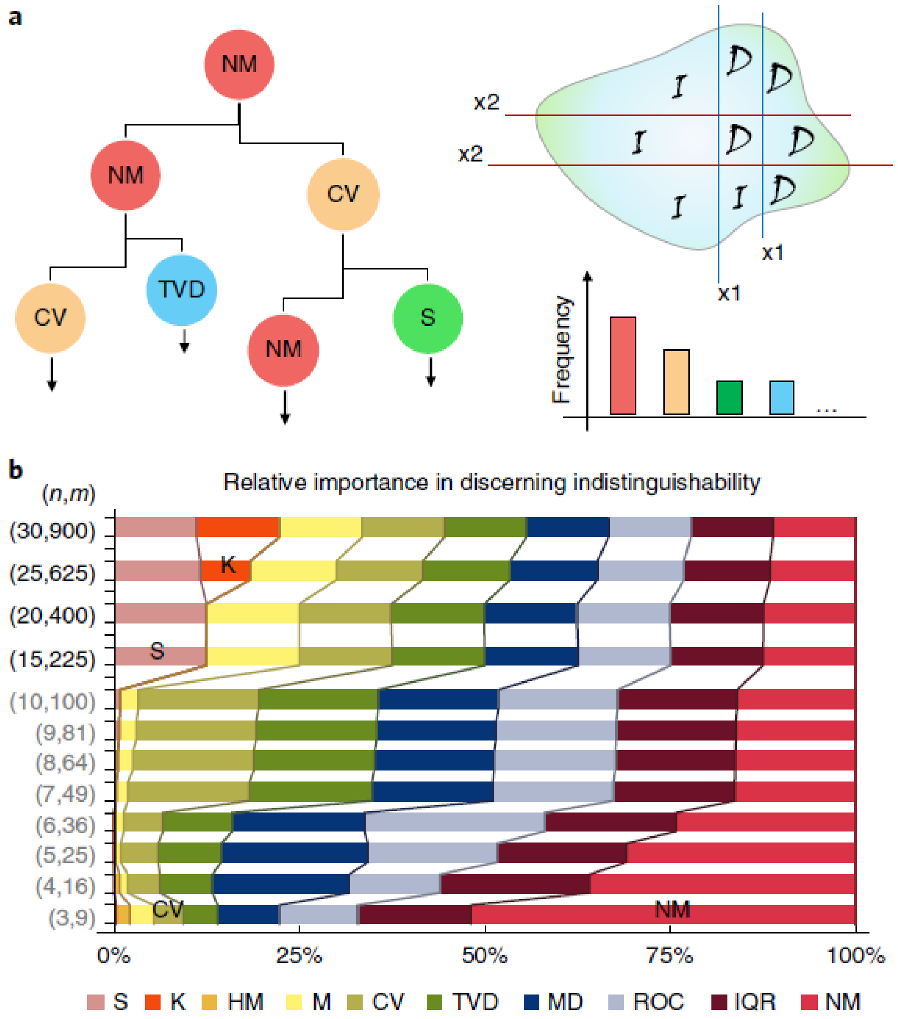
$$\Big\downarrow \quad |+\rangle_c\langle+|$$

$$\sum_{k=1}^{s}(u_k-d_k)^*(u_{n-s+k}-d_{n-s+k})+d_{k+1}^*\,d_{n-s+k+1}=0$$

$$\forall\, s=1,\ldots,n-1 \qquad d_1=0 \quad d_{n+1}=u_{n+1}$$

Innocenti et al., Phys. Rev. A 96:062326 (2017)

Perspectives: machine learning



Is it possible to individuate other properties of C-dataset for validating Boson Sampling?

Random forest classifier

Training with different features

- Total variation distance
- Kurtosis
- Harmonic mean
- … others

T. Giordani et al., Experimental statistical signature of many-body quantum interference, Nat. Phot. **12** 173–178 (2018)

Preliminary results: 4-photon states

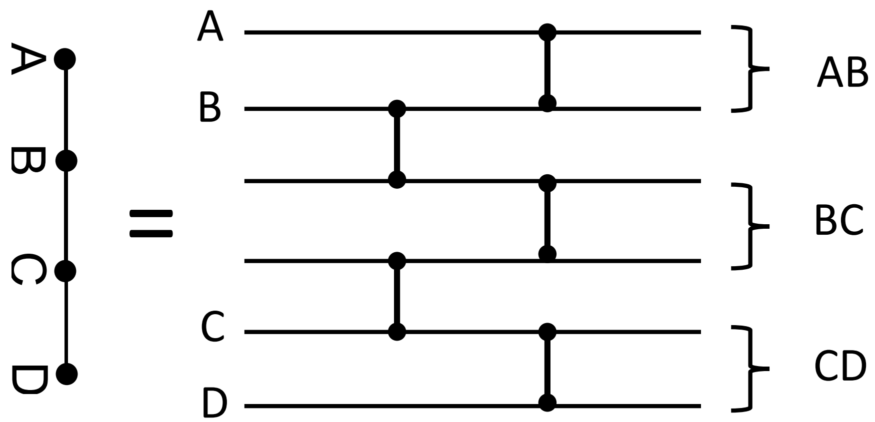
T. Giordani
C. Esposito
N. Viggianiello
M. Romano
F. Hoch
F. Flamini
G. Carvacho
N. Spagnolo
F. Sciarrino

SAPIENZA UNIVERSITÀ DI ROMA

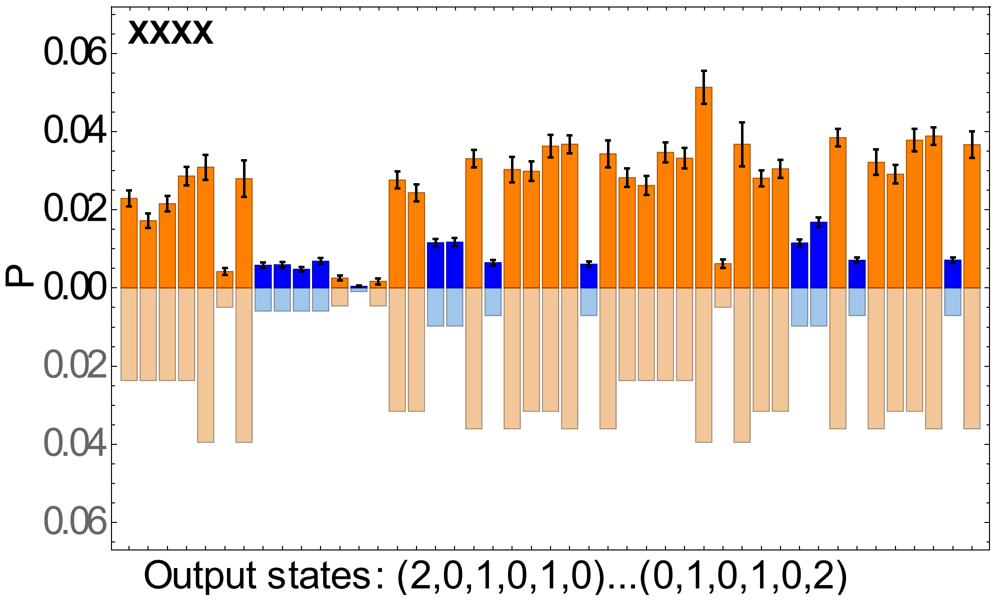
SCUOLA NORMALE SUPERIORE

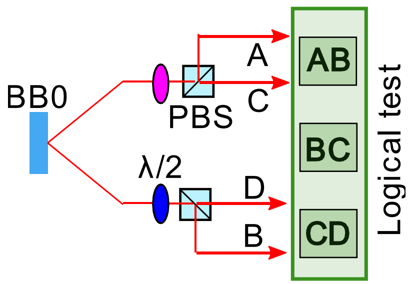
D. J. Brod
E. Galvão

uff

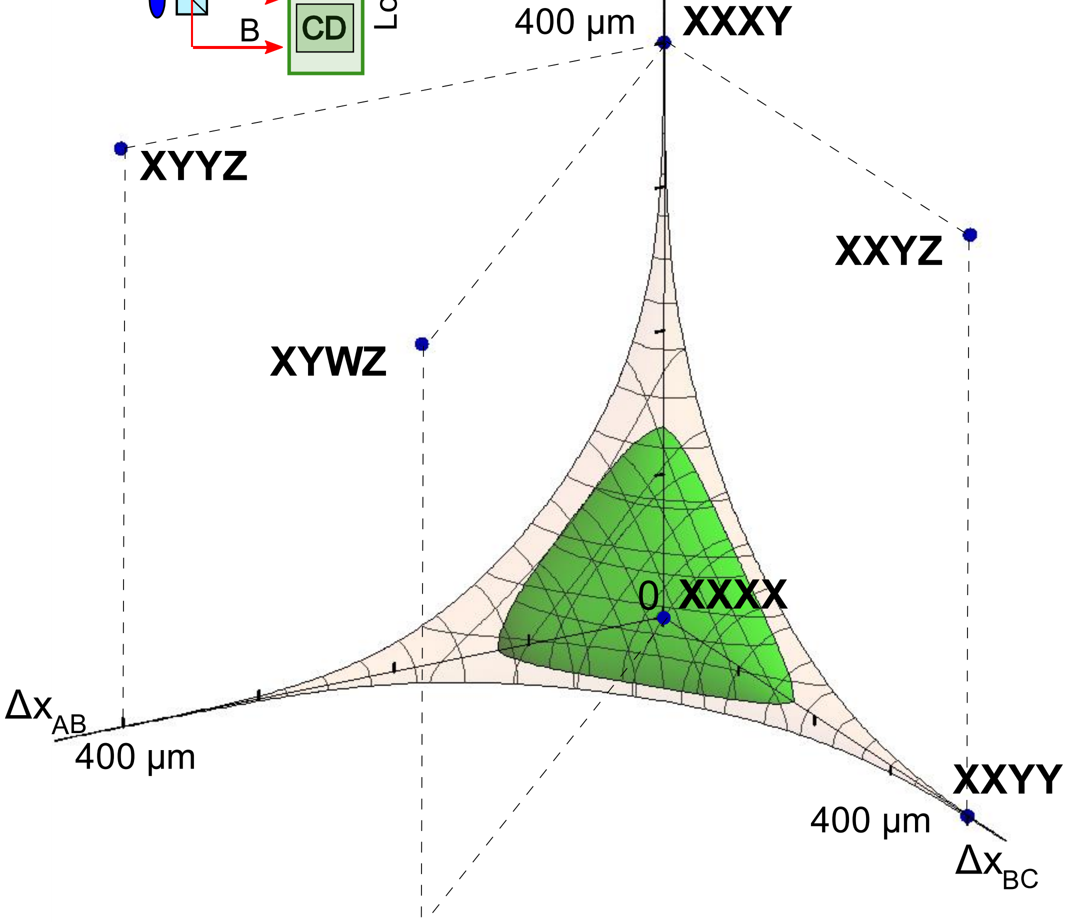


$$W = 0.889 \pm 0.002$$





$$W \geq \frac{5}{6}$$

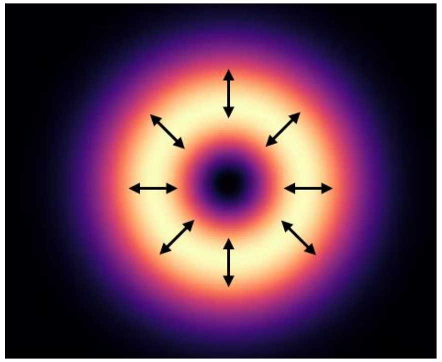


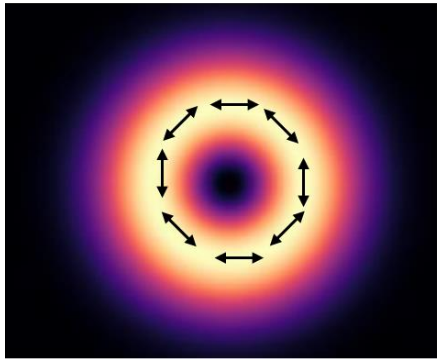
Vector Vortex Beam

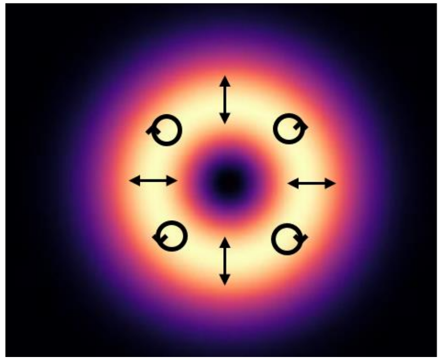
A vector vortex beam (VVB) is a mode in which the polarization is not uniform in the transverse plane, making it interesting for the correlation between SAM and OAM.

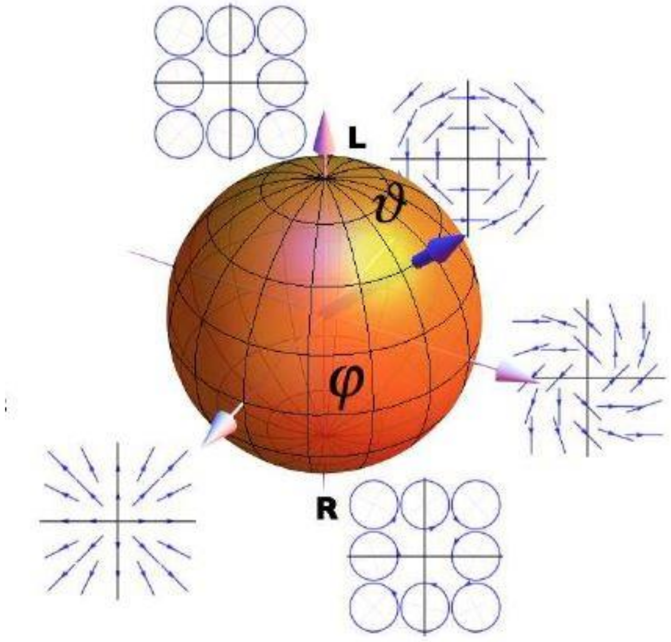
Coherent superposition of Laguerre-Gauss modes (LG) → Experimental generation with our Quantum Walk

$$E_{m1,m2,p} = \overline{e}_L \cos\left(\frac{\theta}{2}\right) LG_{m1,p} + \overline{e}_R\, e^{i\varphi} \sin\left(\frac{\theta}{2}\right) LG_{m2,p}$$





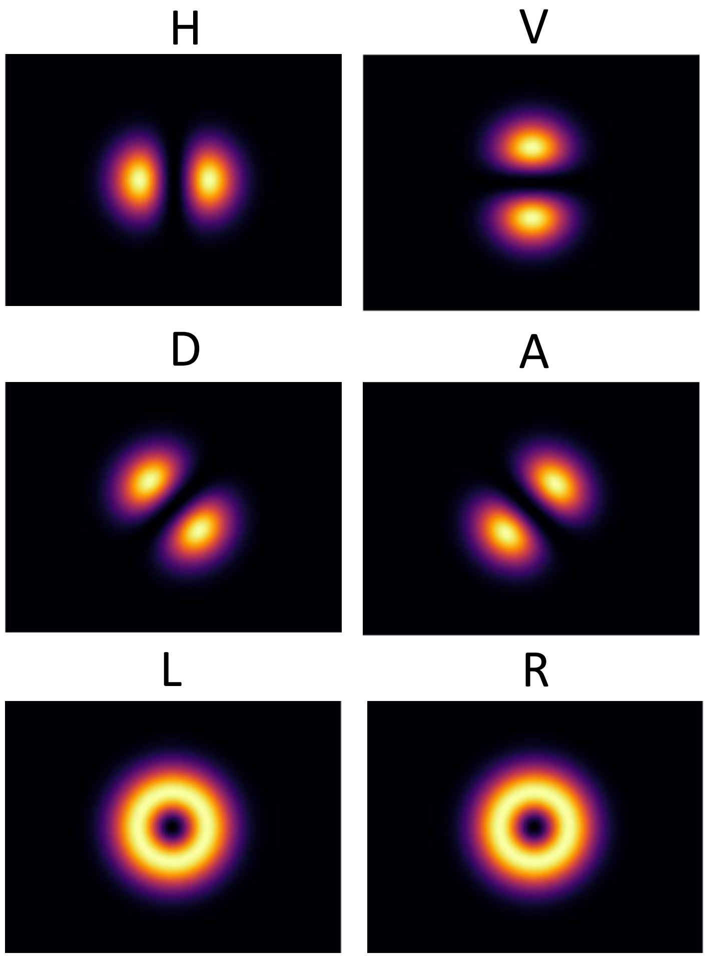




G. Milione et all. *Phys. Rev. Lett.* 107, 053601 (2011)

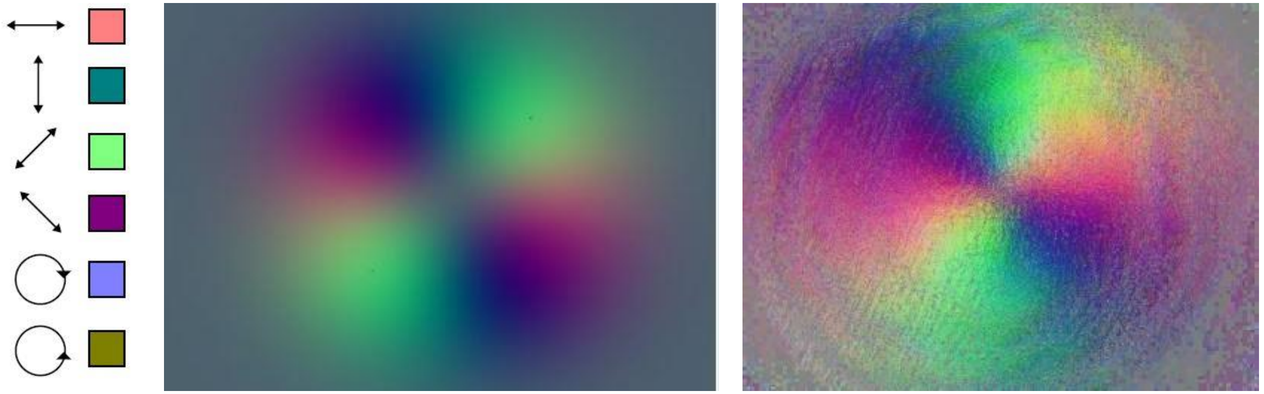
Vector Vortex Beam

Goal: classification of experimental vector vortex beam engineered with our protocol using a Machine Learning technique



RGB codification:

$$\{S_1, S_2, S_3\} \longrightarrow \{Red, Green, Blue\}$$

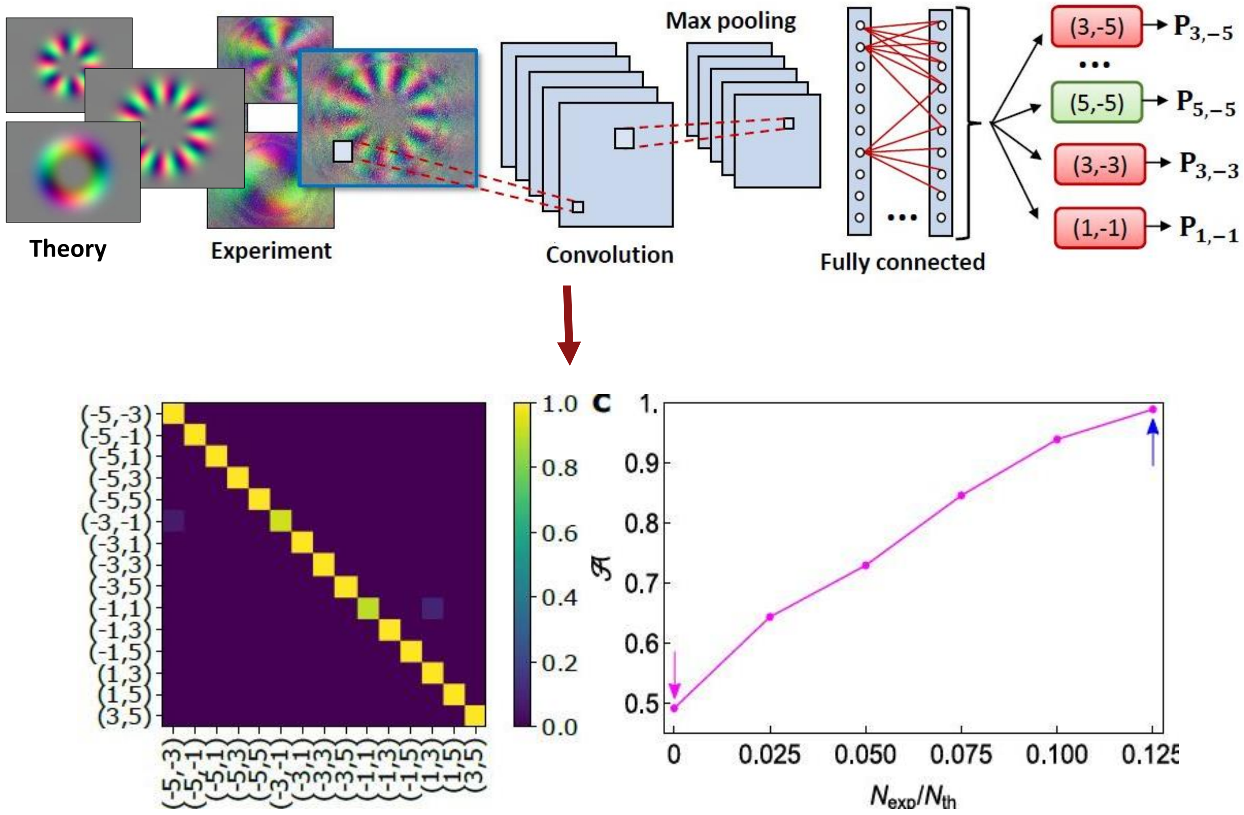


T. Giordani, A. Suprano, E. Polino, F. Acanfora, N. Spagnolo, F. Sciarrino, L. Innocenti, M. Paternostro, A. Ferraro et all. *In preparation*.

Preliminary result

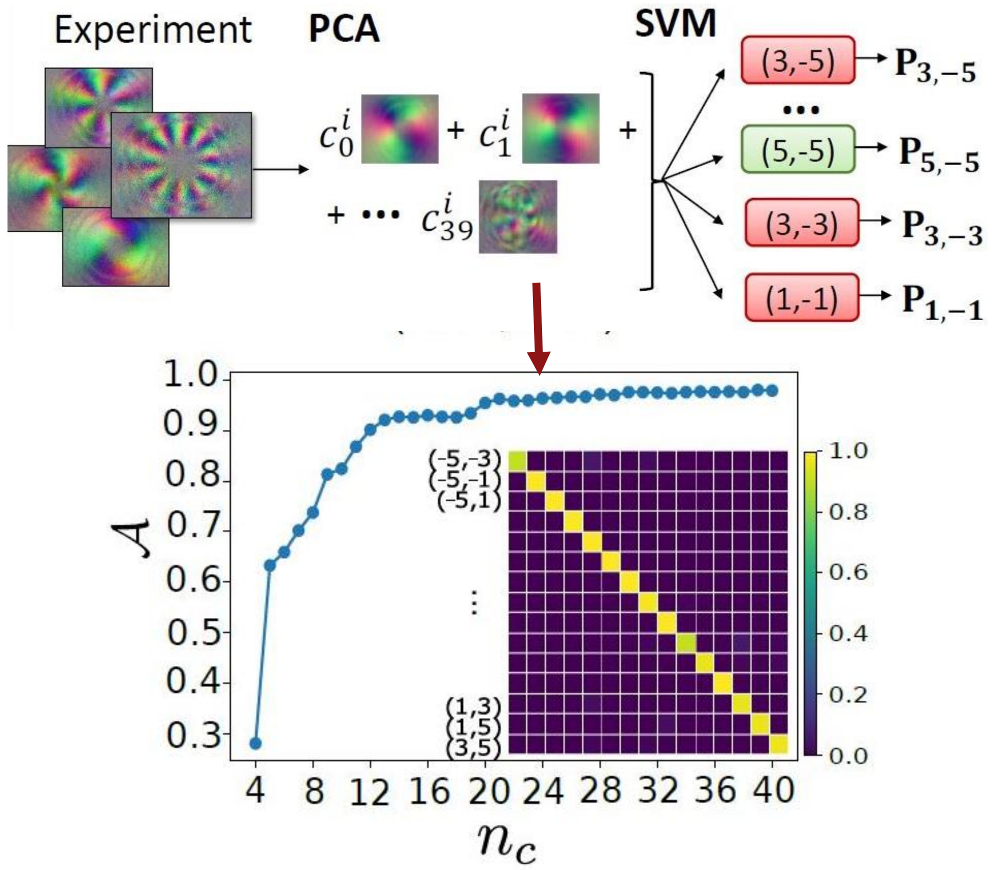
Classification of 15 balanced superposition of different OAM eigenvalues: $\frac{|m\rangle + e^{i\varphi}|n\rangle}{\sqrt{2}}$

Convolutional Neural Network



Accuracy: 99%

Principal Component Analysis

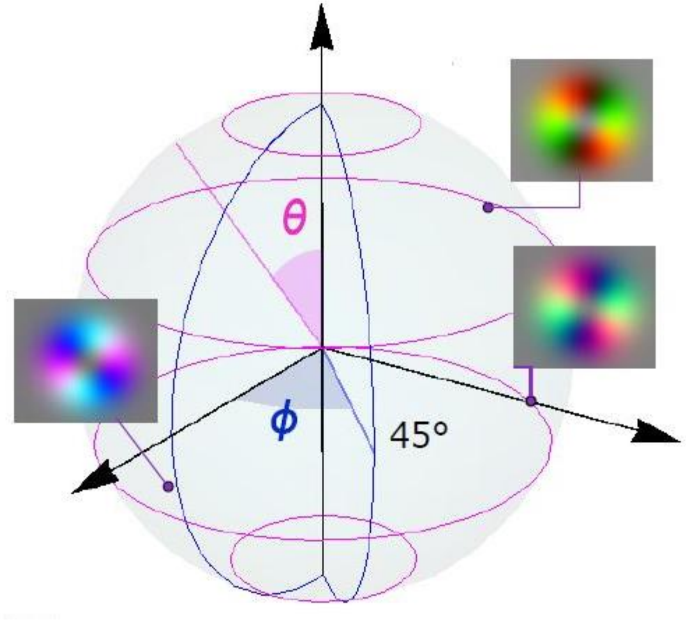


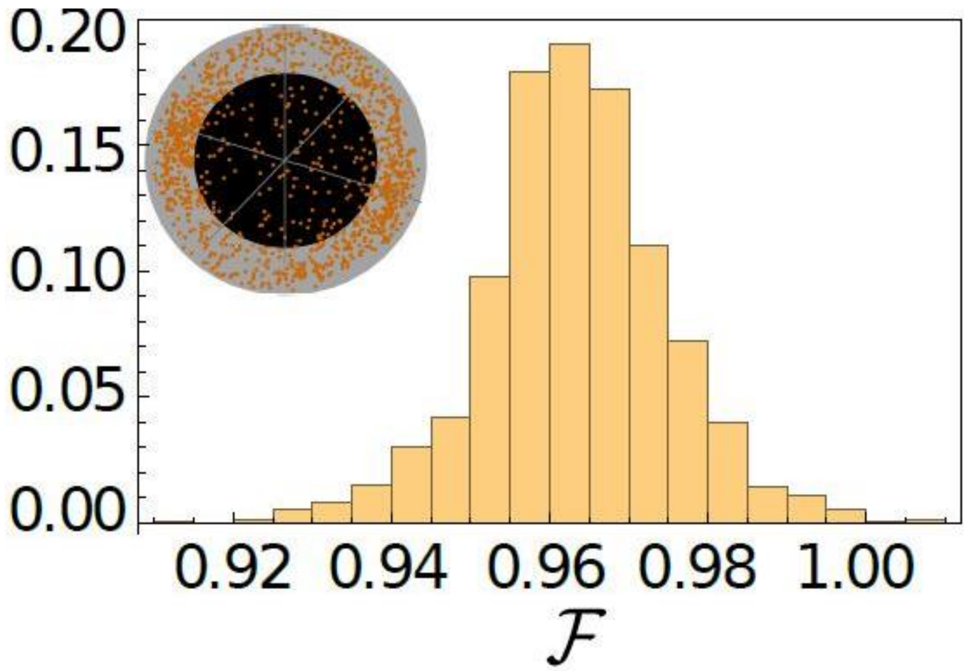
Accuracy: 98%

T. Giordani, A. Suprano, E. Polino, F. Acanfora, N. Spagnolo, F. Sciarrino, L. Innocenti, M. Paternostro, A. Ferraro et all. *In preparation*.

Preliminary result: Principal Component Analysis

Reconstruction of revelant input states: $\frac{cos\left(\frac{\theta}{2}\right)|1\rangle + e^{i\varphi}sin\left(\frac{\theta}{2}\right)|-1\rangle}{\sqrt{2}}$





Mean Fidelity: 96%

T. Giordani, A. Suprano, E. Polino, F. Acanfora, N. Spagnolo, F. Sciarrino, L. Innocenti, M. Paternostro, A. Ferraro et all. *In preparation*.