

# Theoretical and Mathematical Physics

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Guido Montagna

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UNIVERSITÀ  
DI PAVIA



Istituto Nazionale di Fisica Nucleare  
Sezione di Pavia

# Hadron Structure and QCD

A. Bacchetta, B. Pasquini, M. Radici, S. Rodini et al.

# Theory and Phenomenology of Fundamental Interactions

C.M. Carloni Calame, M. Chiesa, G. Montagna, O. Nicrosini, F. Piccinini et al.

# Mathematical Methods of Field Theories

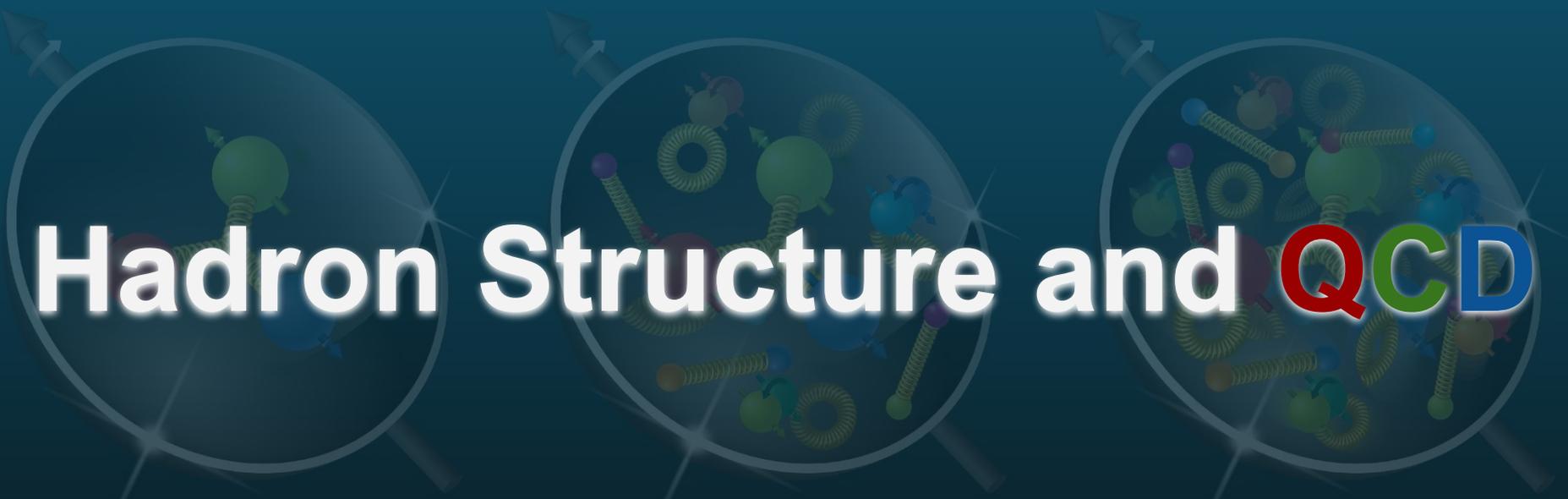
C. Dappiaggi, P. Rinaldi et al.

# Quantum Information and Quantum Foundations

A. Bisio, P. Perinotti, A. Tosini et al.

# Physics of Complex Systems and Econophysics

G. Livan, G. Montagna, O. Nicrosini et al.

The background features three overlapping circular diagrams, each containing a different representation of a hadron's internal structure. The first diagram on the left shows a simple model with a few colored spheres (quarks) and wavy lines (gluons). The middle diagram shows a more complex arrangement with more quarks and gluons. The third diagram on the right is the most detailed, showing a dense network of quarks and gluons, representing the full complexity of Quantum Chromodynamics (QCD).

# Hadron Structure and QCD

Simone Rodini

# Who are we?

A. Maestri

L. Polano

A. Schiavi

S. Rodini

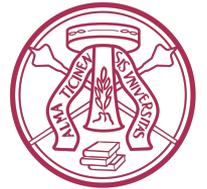
M. Radici

A. Vercesi

B. Pasquini

A. Bacchetta

A.C. Alvaro



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NINPHA



# What do we do?

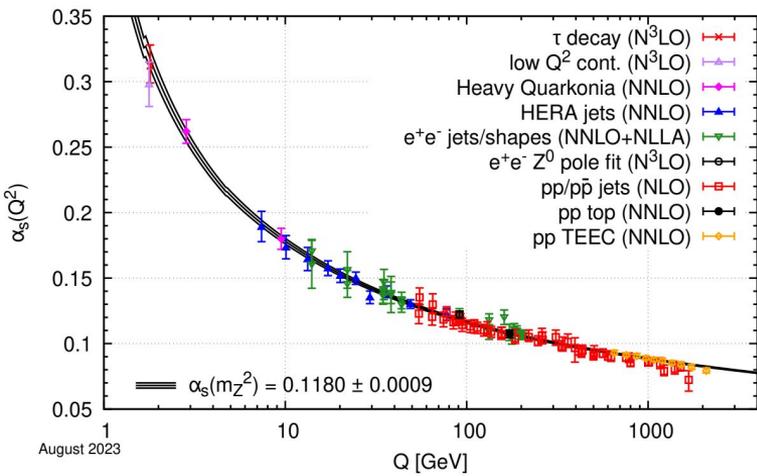
Four fundamental forces in nature

Gravitational

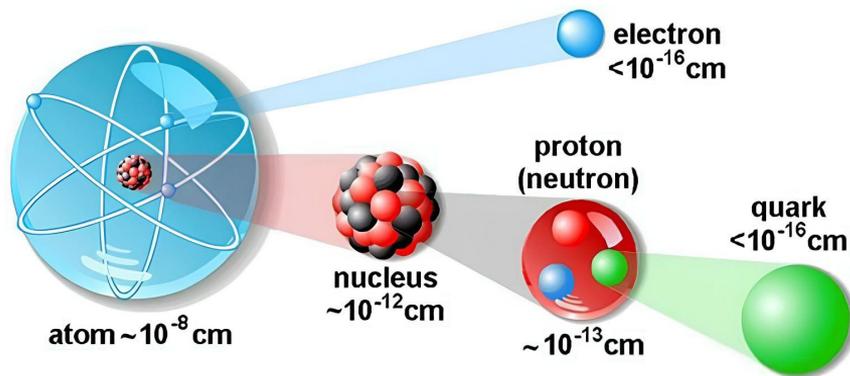
Weak

Electromagnetic

**Strong**



## Quantum Chromodynamics



From PDG:  
"Neither quarks nor gluons  
are observed as free particles"

# What do we do?

We cannot compute the proton properties in perturbation theory

Simulate the full theory

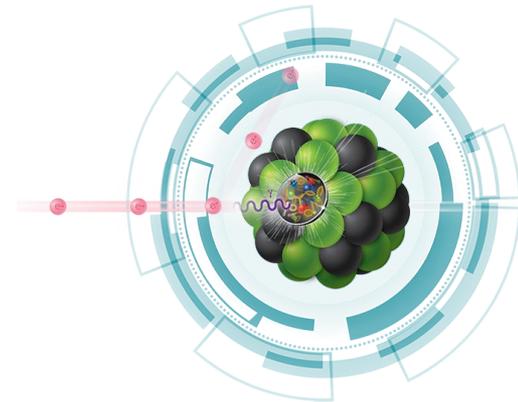
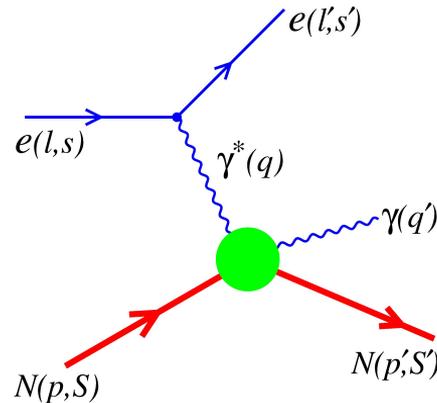
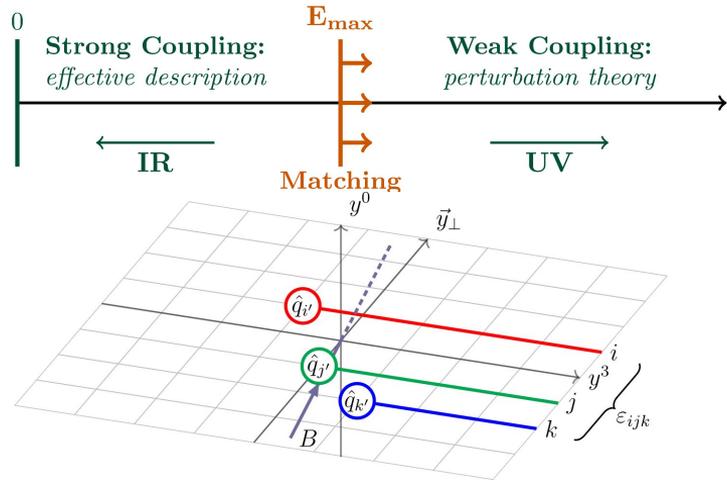
Extract proton's properties from experimental data

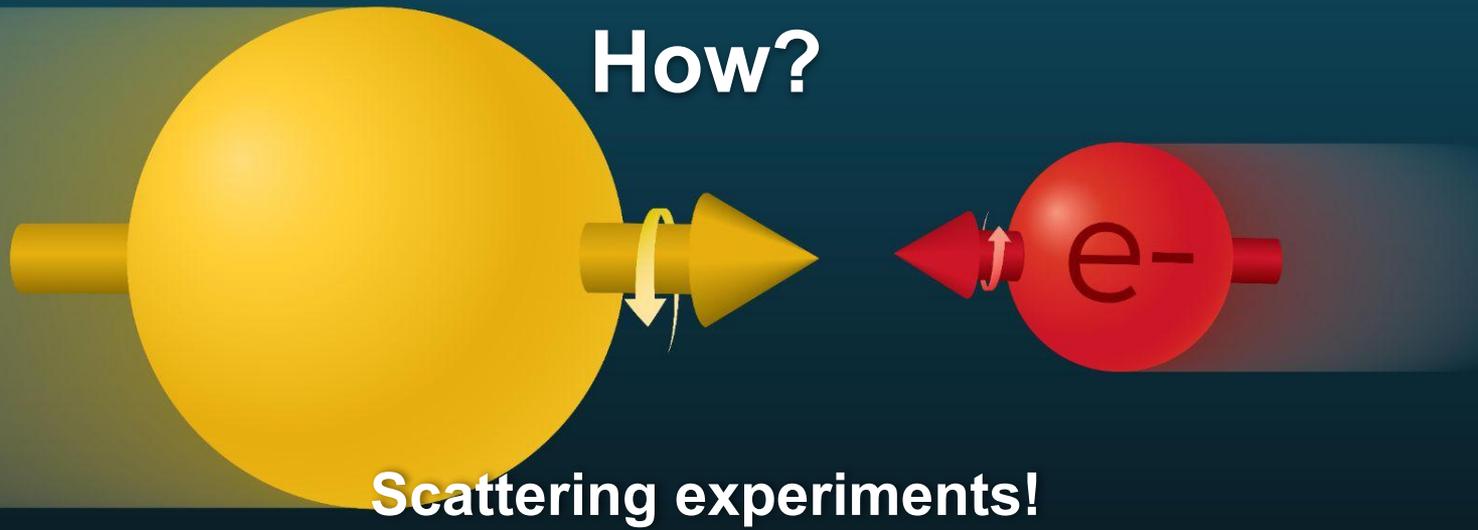
See poster of A. Maestri and A. Schiavi

See posters of

L. Polano, A. Bacchetta, M. Radici

A.C. Alvaro, B. Pasquini, S. Rodini





Low-energy

Coherent response

Global proton properties

High-energy

Incoherent response

Resolve individual constituents

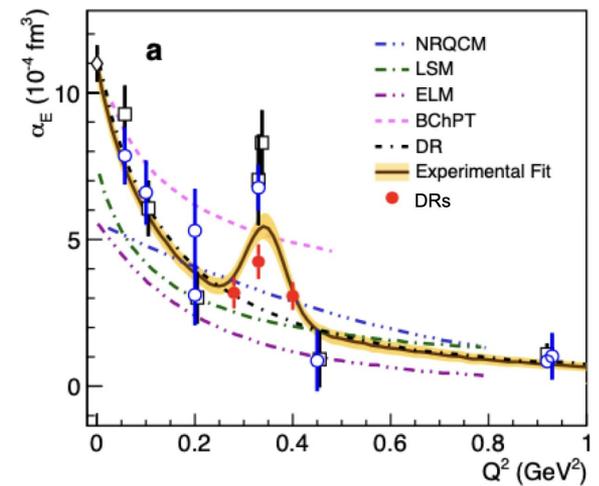
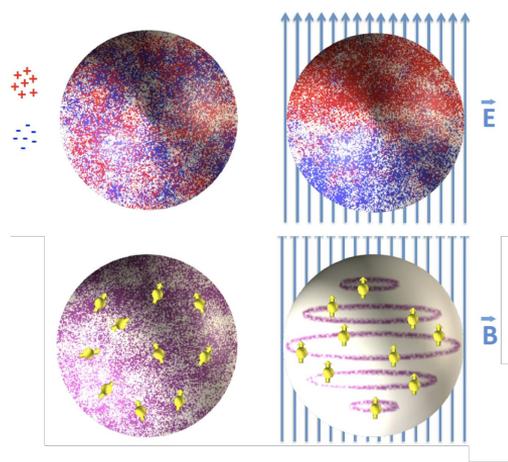
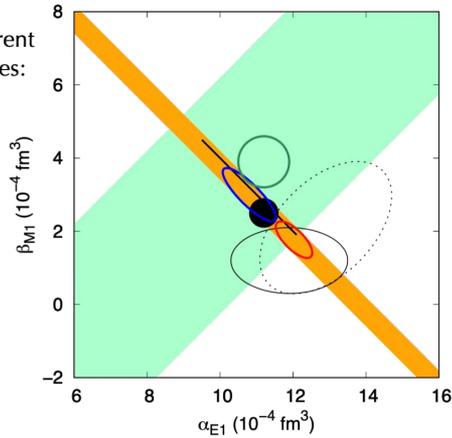
# Low energy scattering

## Real Compton scattering

## Virtual Compton scattering

Extractions from different theoretical approaches:

- BChPT  
Lensky et al. [2014]
- HBChPT  
Mc Govern et al. [2013]
- sDRs  
Pasquini et al. [2019]



Pasquini, et al., Nature 611 (2022) 7935

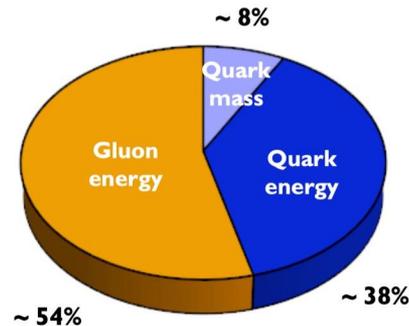
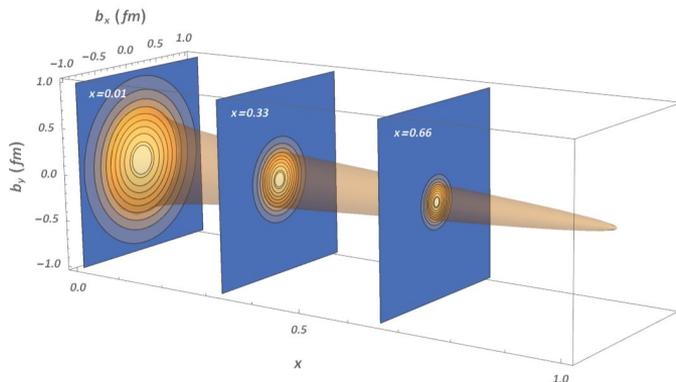
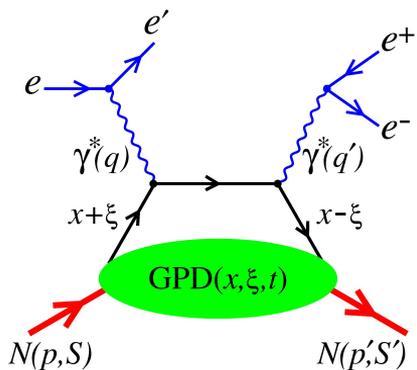
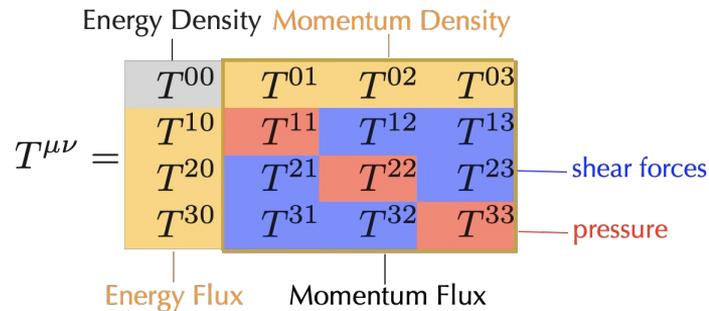
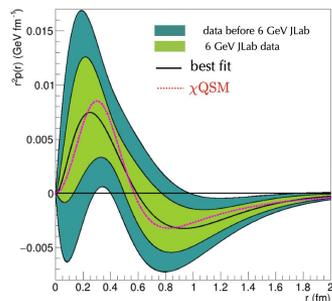
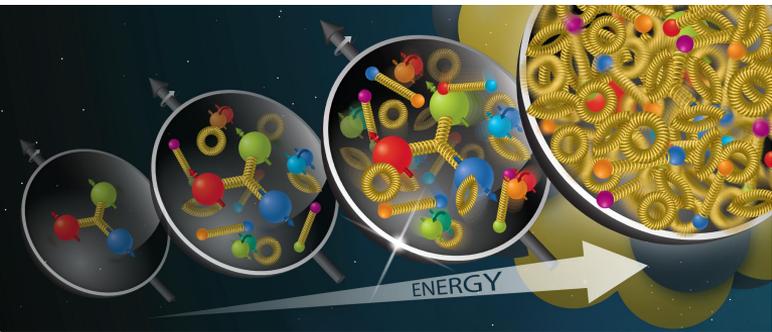
Mornacchi, Rodini, Pasquini, Pedroni, PRL 129 (2022) 102501 and in PDG 2025

Pasquini, Vanderhaeghen Ann.Rev.Nucl.Part.Sci. 68 (2018) 75-103

Pasquini, Pedroni, Sconfiatti, PRC 98 (2018) 015204 and in PDG 2019

Gorchtein, Lorcé, Pasquini, Vanderhaeghen PRL 104 (2010) 112001

# High energy scattering



Lorcé, Metz, Pasquini, Schweitzer, Encyclopedia of Particle Physics, Elsevier, 2026

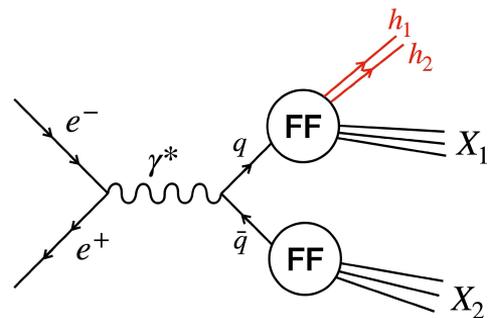
Metz, Pasquini, Rodini, PRD 102 (2021) 114042

Pasquini, Schiavi, PRD 109 (2024) 11, 114021

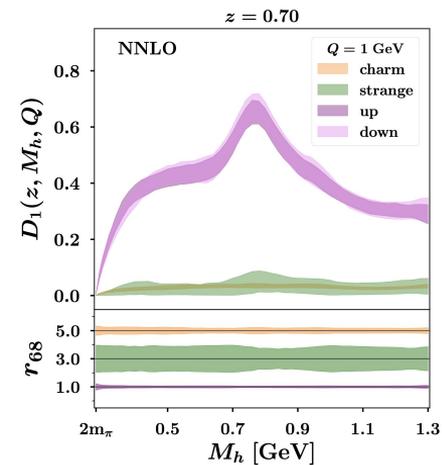
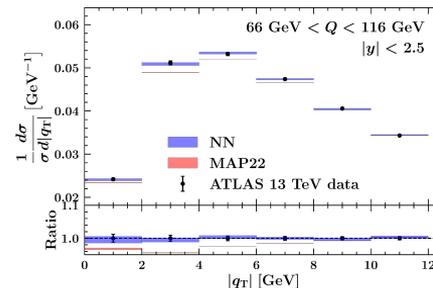
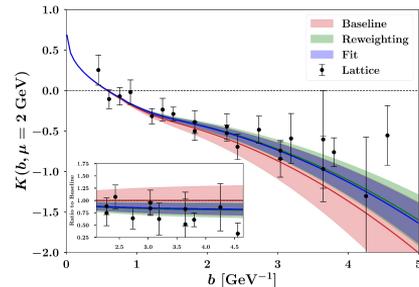
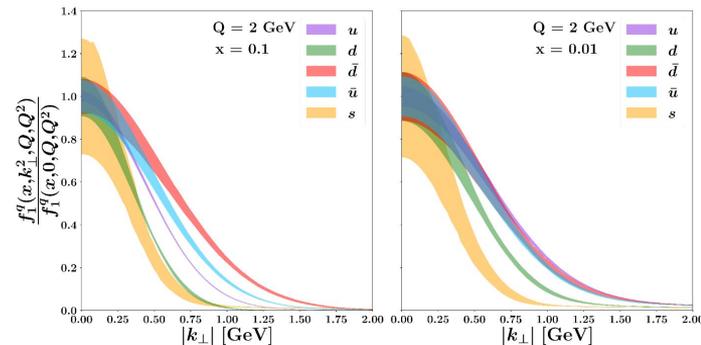
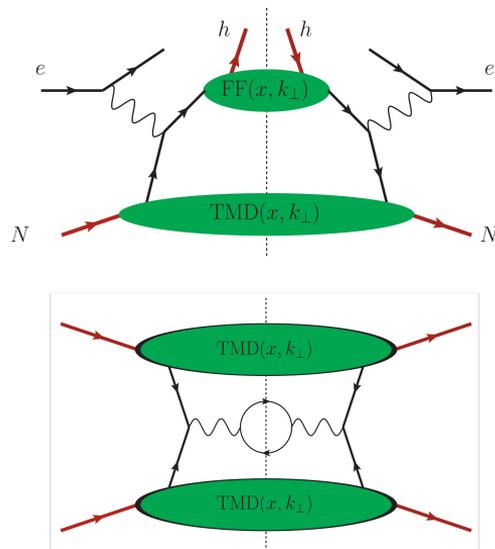
Alvaro, et al. arxiv:2512.23563

# High energy scattering

Semi-inclusive reactions,  
Where being blind helps you see



MAP collaboration, JHEP 08 (2024) 232

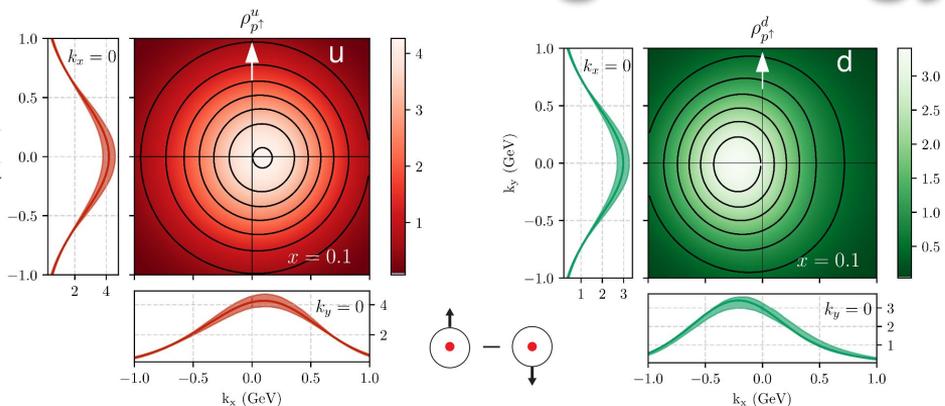


MAP collaboration, JHEP02 (2026) 051

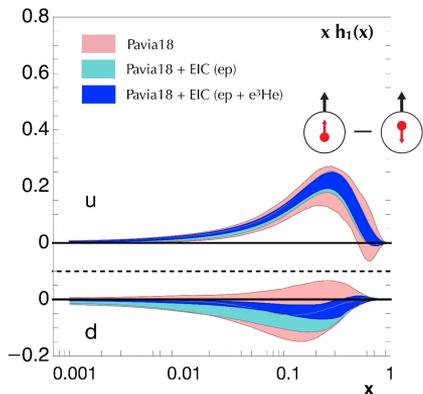
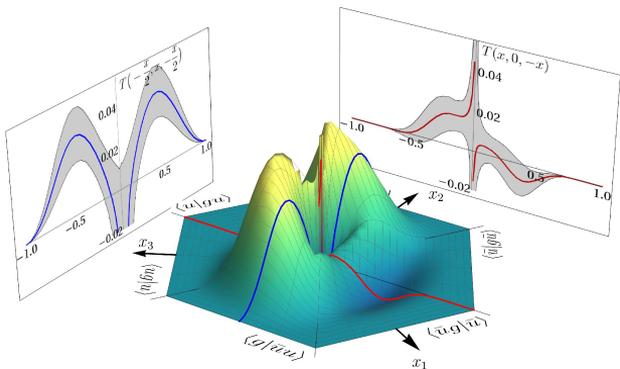
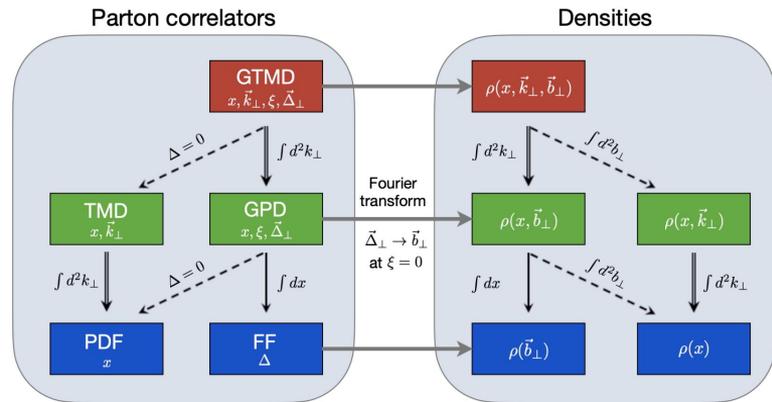
Avkhadiev, et al. arxiv:2510:26489

MAP collaboration, PRL 135 (2025) 2, 021904

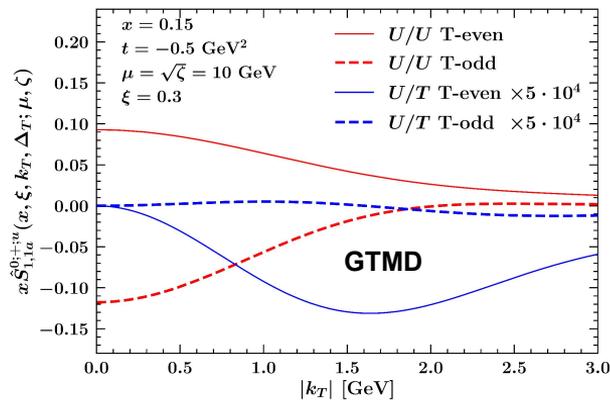
# High energy scattering



Bacchetta, Delcarro, Pisano, Radici, PLB 827 (2022) 136961



Radici, Bacchetta, PRL 120 (2018) 19, 192001



Bertone, et al. JHEP 05 (2025) 183

Vladimirov, Portela, Rodini, arxiv:2511:04294

# Additional informations

## Collaborations

- M.A.P. Collaboration
- Madrid , Mainz, Tübingen University
- BNL (US), DESY (DE), JeffersonLab (US), IRFU CEA (FR)

## Current fundings

- INFN project NINPHA, local coordinator M. Radici
- PRIN2022 “ProtoTaste”, P.I. A. Bacchetta
- COST Action SHARP

## Prominent roles

- A. Bacchetta:
  - convener of the EICUG Theory Working Group
  - PAC member SPS CERN
  - Member of Int. Spin Phys. Committee
- B. Pasquini:
  - Chair of ECT\* Scientific Board
  - member of IAC, CFNS (Stony Brook-US)
  - Co-Director of ILCAC
  - PAC member of MAMI and MESA (Mainz)
- M. Radici:
  - Past Chair (till 2025) EIC User Group
  - member of ePIC Coll. Council
  - PAC member of JeffersonLab

# Teoria e Fenomenologia delle Interazioni Fondamentali

Mauro Chiesa

# Theory & Phenomenology of Fundamental Interactions: QFT@COLLIDERS

## PhD students



M. Ghilardi



F.P. Ucci

## PostDocs & Collaborators



F. Belloni

E. Budassi

C.L. Del Pio

A. Gurgone

## Staff



C.M. Carloni Calame

Responsabile locale  
Coordinatore GRIV PV



M. Chiesa



G. Montagna



M. Moretti



O. Nicosini INFN PV Director

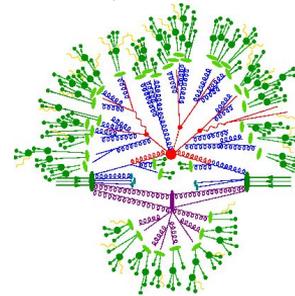


F. Piccinini GGI Director, FI

# Theory

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi}\not{\partial}\psi + h.c. \\ & + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\ & + \frac{1}{2} \phi^\dagger \phi^2 - V(\phi) \end{aligned}$$

Provide precise theory predictions & Monte Carlo event generators

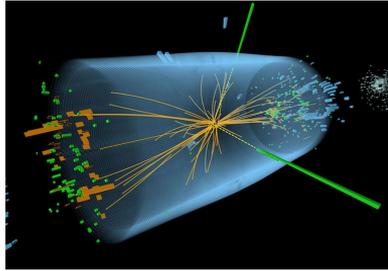


# Monte Carlo

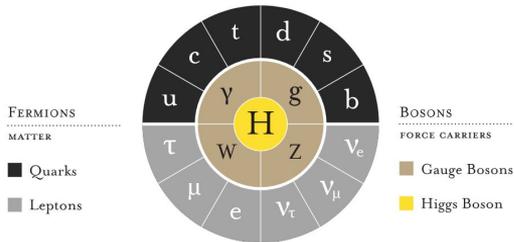
Perform sensitivity studies, assess theory uncertainties affecting measurements

Explore the impact of experimental results on the theory

# Experiment



The  
Standard Model  
of PARTICLE PHYSICS



# A journey through frontiers

## Intensity frontier



Flavour factories,  
Muon g-2, MUonE

## Energy frontier



Precision Electroweak  
Physics at O(10) TeV  
proton-proton colliders

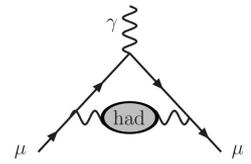
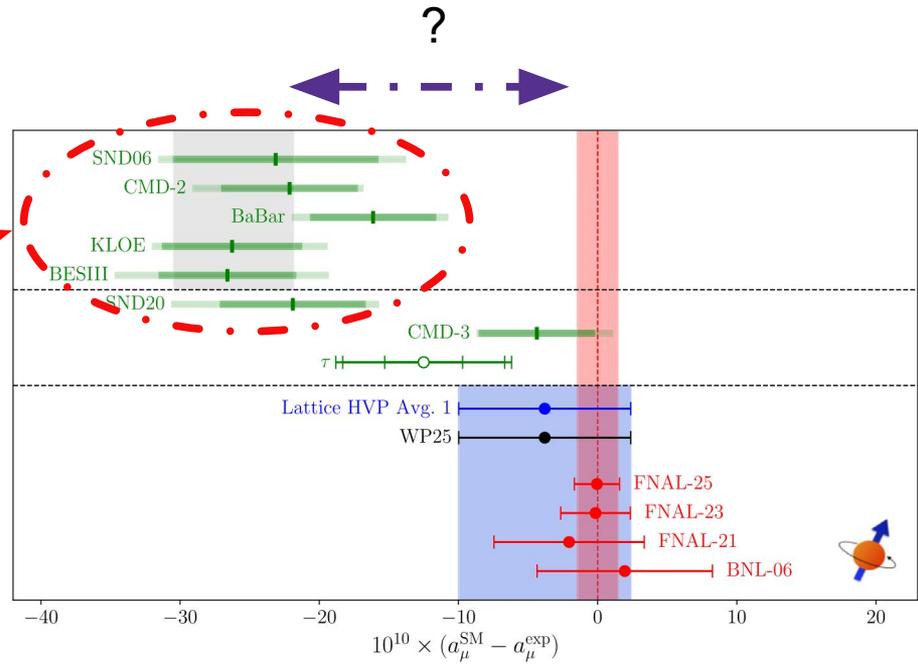
## Imagination(?) frontier



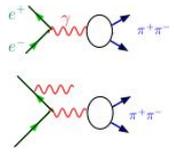
SM tests at energy  
scales never reached  
before

# Resolving the tension in muon anomaly $a_\mu = (g-2)/2$ determination

Different strategies to compute  $H_{(adronic)} V_{(acuum)} P_{(olarization)}$



Need for more precise tools for  $F_\pi(q^2)$



Monte Carlo generator for

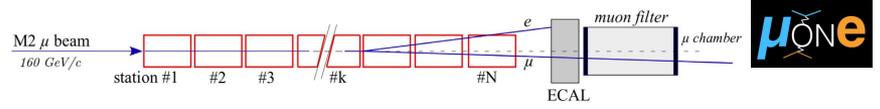
$$e^+e^- \rightarrow \pi^+\pi^-$$

$$e^+e^- \rightarrow \pi^+\pi^-\gamma$$

@NLO+parton shower in BabaYaga@NLO

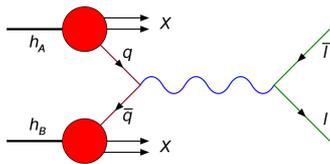
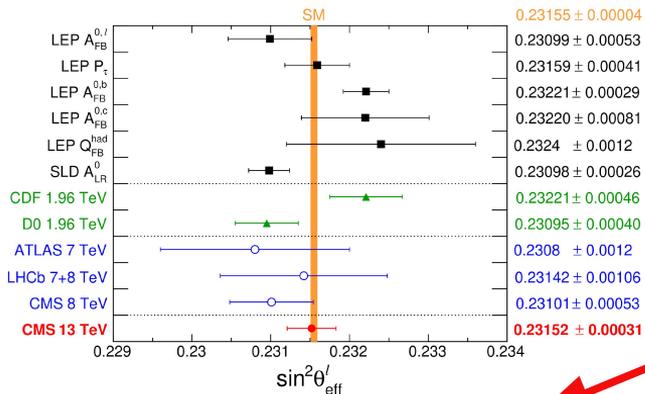
poster #28 by M. Ghilardi

Alternative approach: HPV from the hadronic running of  $\alpha_{QED}(Q^2 < 0)$  measured from elastic  $\mu$ -e scattering



poster #39 by E. Budassi

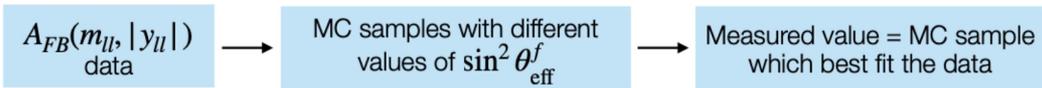
# Precision electroweak physics at the LHC pp collider



High-precision MC templates are mandatory

Authors of NLO EW+NLO QCD+PS event generators for:

- Neutral current Drell-Yan
- Charged current Drell-Yan
- Diboson production
- Vector boson scattering



Exploratory work toward a new generation of MC tools:

DY  
@NLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS



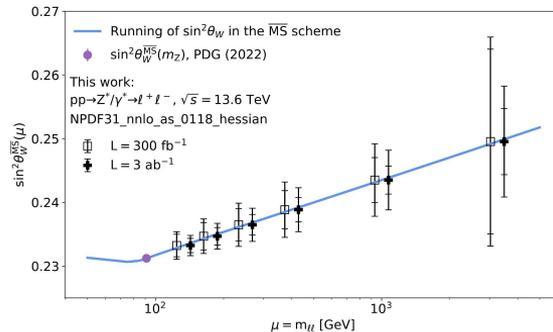
DY+jet @NLO<sub>QCD</sub>+NLO<sub>EW</sub>+PS

DY  
@N(N)LO<sub>QCD</sub>+NLO<sub>EW</sub>+PS

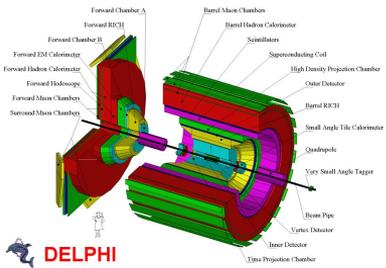
poster #29 by F. Belloni

Assessment of the theory uncertainties on precision EW measurements

study of the sensitivity on  $\sin\theta_W(\mu^2)$  at the TEV scale

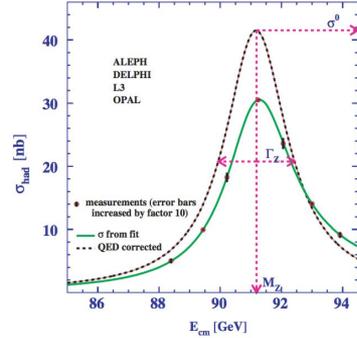


poster #42 by MC



$$L = \frac{\sigma_{\text{had}}}{\sigma_{\text{had}}}$$

luminosity



The luminosity uncertainty is a limiting factor for the precision achievable at a collider

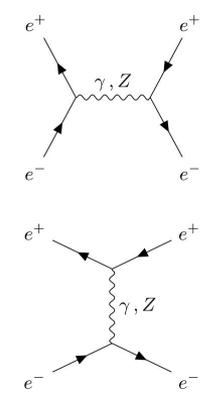
The physics program at FCC-ee requires:

$$\Delta L / L \leq 10^{-4} \quad \text{at the Z peak}$$

$$\Delta L / L \leq 10^{-3} \quad \text{above the WW threshold}$$

$$\Delta N_{\text{events}} \quad \& \quad \Delta L \quad \rightarrow \quad \Delta \sigma$$

At e+e- colliders, the luminosity is measured from Bhabha scattering



$$L = \frac{N_{\text{events}}}{\sigma_{\text{predicted}}}$$

High statistics

High precision calculations in the SM, small theory uncertainties

What about contamination from physics yet to be discovered?

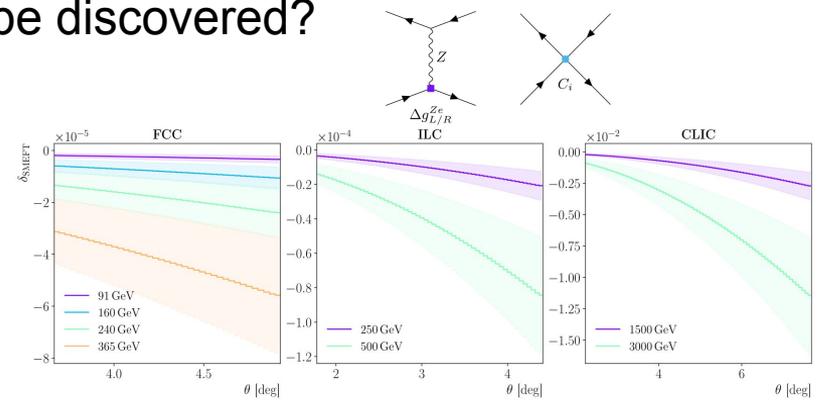
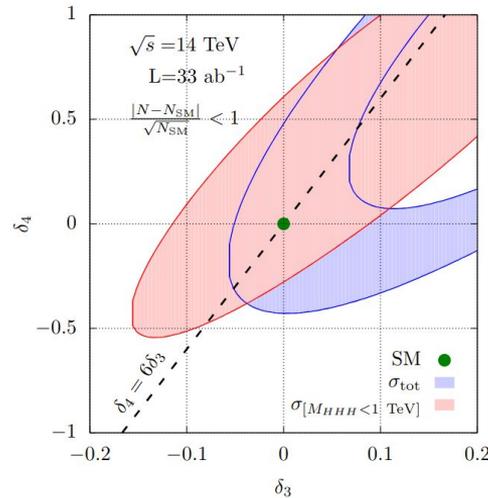
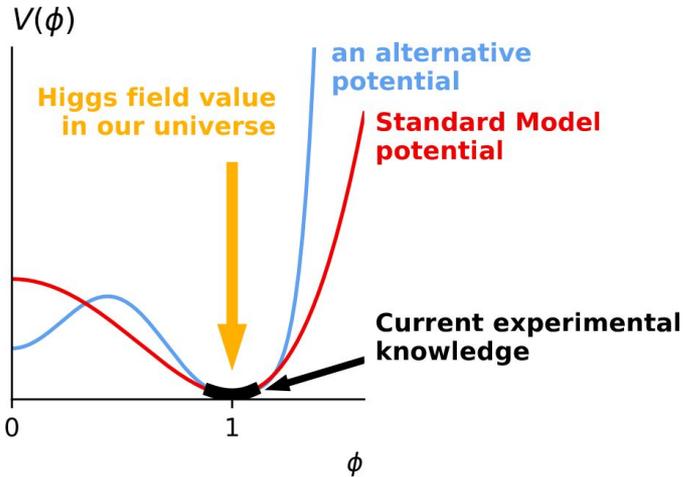
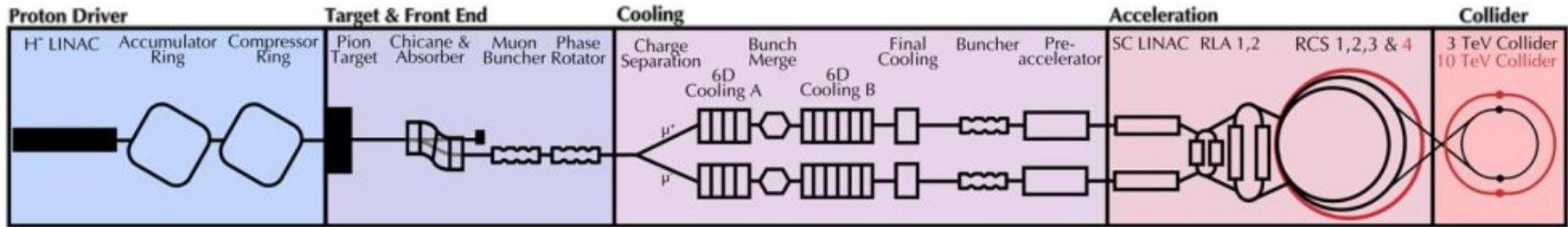


FIG. 4. SMEFT deviation to the SABS differential cross section as a function of the electron scattering angle in the same setup of Table III

See poster #27 by F.P. Ucci for details



Higgs self-couplings related to the shape of the Higgs potential

Contributing to the community studies on the physics case of the high-energy muon collider



# Collaborations & funding



QFT@Colliders



Universität  
Zürich<sup>UZH</sup>



20225X52RA  
20229KEFAM



# Fisica Matematica

Paolo Rinaldi

# People

- Claudio Dappiaggi (PO)
- Paolo Rinaldi (RTT)
- Beatrice Costeri, Andrea Parpinel, Raman Deep Singh (PhD Students )

# Research topics: mathematical aspects of QFT

- Quantum field theory on curved spacetimes
- Algebraic quantum field theory
- Stochastic partial differential equations and stochastic quantization

# Quantum field theory on curved spacetimes

- Classical gravity (GR) + quantum matter (QFT)
- Usual formulation of QFT on Minkowski strongly relies on Poincaré symmetries and momentum representation
- A different paradigm is needed on curved spacetimes ➡ **Algebraic QFT**
- Applications: black hole physics, cosmology, semi-classical analysis...
- Recent interest: boundaries effects in QFT



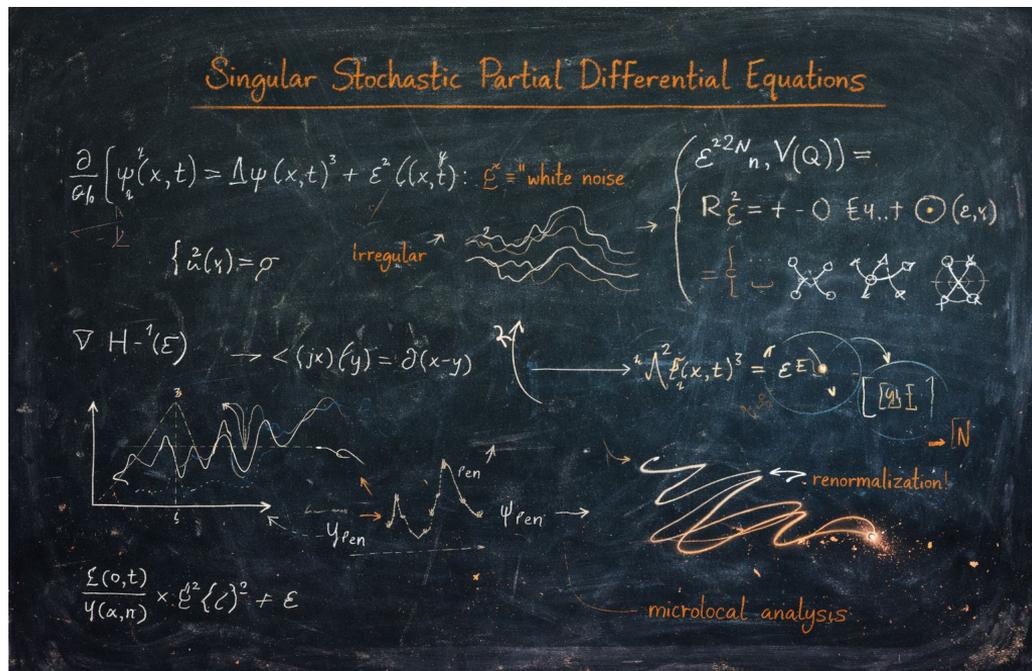
# Algebraic Quantum Field Theory (AQFT)

- Mathematical formulation of QFTs
- algebra of observables + state + GNS theorem = Hilbert space formalism of QFT
- Particular emphasis on interacting theories:
  - 1) renormalization as an extension procedure for distributions
  - 2) mathematical background for perturbation theory and renormalization group flow

# (Singular) Stochastic Partial Differential Equations

$$\Phi^3 \text{ Equation: } \partial_t \phi = \Delta \phi - \phi^3 + \xi$$

- Irregular nature of the **white noise**  $\Rightarrow$  solution theory calls for **renormalization**, just like interacting QFT!
- Recent progress: we proposed a novel framework to construct perturbatively a renormalized solution to a large class of singular SPDEs
- Based on **microlocal analysis** and the tools of perturbative AQFT



# Stochastic Quantisation

$$\Phi^3 \text{ Equation: } \partial_t \phi = \Delta \phi - \phi^3 + \xi$$

- Program started formally by Parisi & Wu in 1981
- Goal: **non-perturbative** construction of the Feynman path integral measure of an interacting quantum field theory
- Constructed as Wick rotation of the equilibrium limit of the above dynamics **(through renormalization!)**

Stochastic Quantisation

- Parisi & Wu, 1981\*

= Program: non-perturbative of an interacting QFT  
= Constructed as Wick rotation of the equilibrium limit.

Goal: Perturbative Construction

= envy  
= equilibration

equilibrium

Feynman's Path Integral Measure.

$$x = \int_{\mathcal{X}} \mathcal{D}_2 \mathcal{E}^{-S\phi} \cdot \varphi(x_1, x_2) = \int_{\mathcal{X}} \mathcal{D}_2 \mathcal{E}^{-S\phi} \cdot \varphi(x_1, x_2) = \mathcal{J}(x_2), \dots \varphi(x_2)$$

The diagram on the chalkboard illustrates the stochastic quantization process. It starts with a stochastic differential equation (SDE) for a field  $\phi(x, t)$  driven by white noise  $\xi(x, t)$ . The SDE is written as  $\frac{\partial \phi(x, t)}{\partial t} = \frac{\delta S[\phi]}{\delta \phi(x, t)} + \eta(x, t)$ , where  $\eta$  is white noise. This leads to a dynamic system  $\dot{\phi}(x, t) = -\delta S[\phi](x, t) + \eta(x, t)$ . The diagram shows a plot of  $\phi(x, t)$  versus  $t$  with a noisy trajectory. An arrow labeled 'dynamics' points to a plot of  $\phi(x, t)$  versus  $x$  showing a noisy equilibrium state. An arrow labeled 'equilibrium' points to a plot of  $\phi(x, t)$  versus  $x$  showing a smooth equilibrium state. An arrow labeled 'Goal: Perturbative Construction' points to the Feynman path integral measure  $\int_{\mathcal{X}} \mathcal{D}_2 \mathcal{E}^{-S\phi} \cdot \varphi(x_1, x_2)$ . The diagram also includes a note 'Feynman's Path Integral Measure' and a final equation  $x = \int_{\mathcal{X}} \mathcal{D}_2 \mathcal{E}^{-S\phi} \cdot \varphi(x_1, x_2) = \mathcal{J}(x_2), \dots \varphi(x_2)$ .

# Collaborations

-  Genova, Roma-Tor Vergata, Trento, Milano-Statale
-  York, Oxford
-  Leipzig, Regensburg, Potsdam, Würzburg
-  Lausanne - EPFL, Geneve
-  Paris - Sorbonne, Grenoble, Tours
-  McGill



# Quantum Information and Quantum Foundations

Alessandro Bisio

# Beachcombers on the wilder shores of Quantum Physics...

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POWERED BY

**QUit**  
quantum information  
theory group

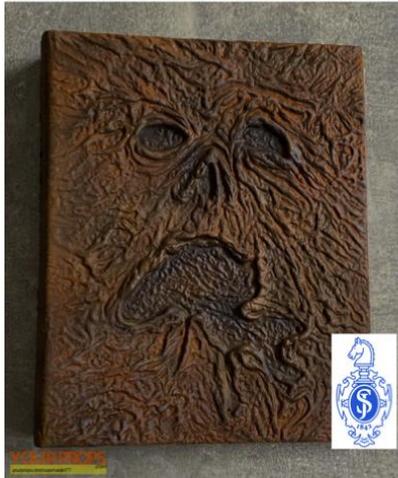
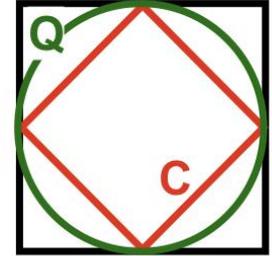


# Quantum Foundations in the light of Quantum Information

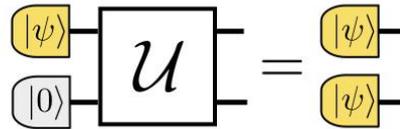
Quantum systems are the carriers of information.

The mathematical structure of quantum theory is the handbook that tells us **what operations are allowed** and what are the **ultimate performance limits**.

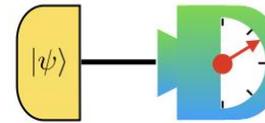
Qubit



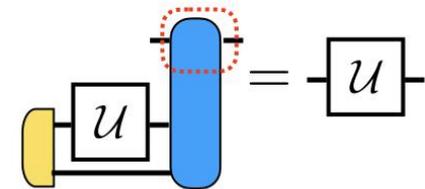
No cloning



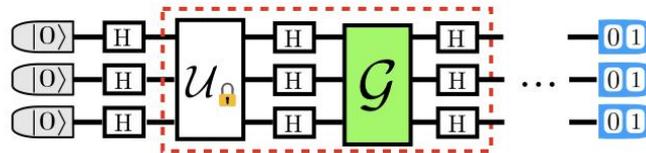
No perfect state detector



No programming



Search algorithm



$$T_G = O(\sqrt{N})$$



# Operational Probabilistic Theories (OPTs)

---

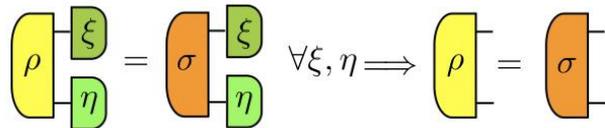
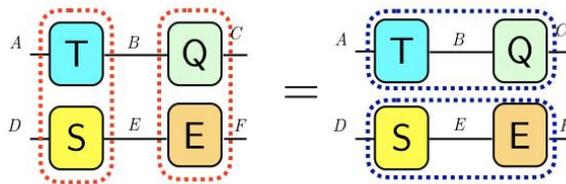
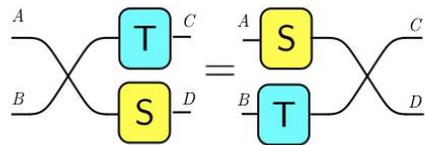
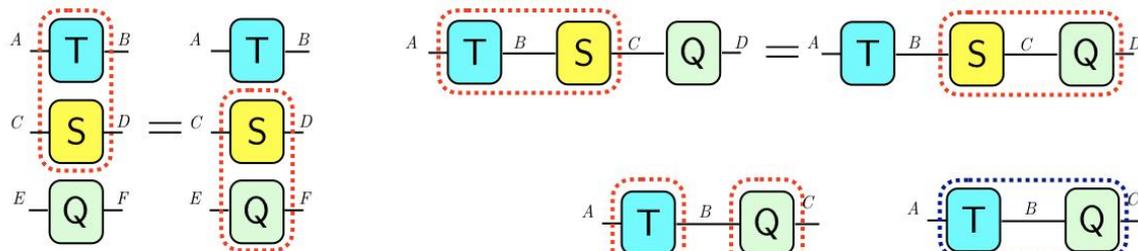
What is special about quantum theory as opposed to classical theory?

Can we derive the mathematics of quantum theory from **information-theoretic properties**?

# Operational Probabilistic Theories (OPTs)

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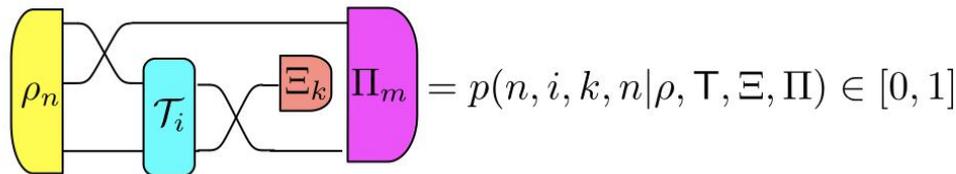
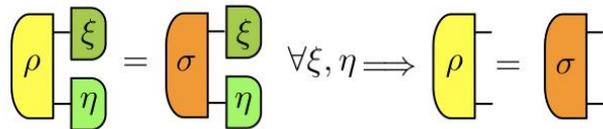
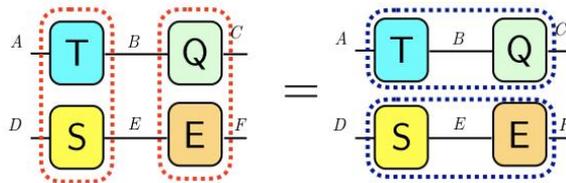
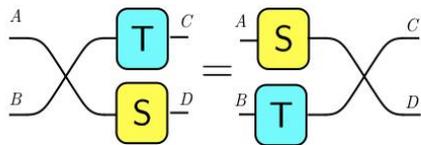
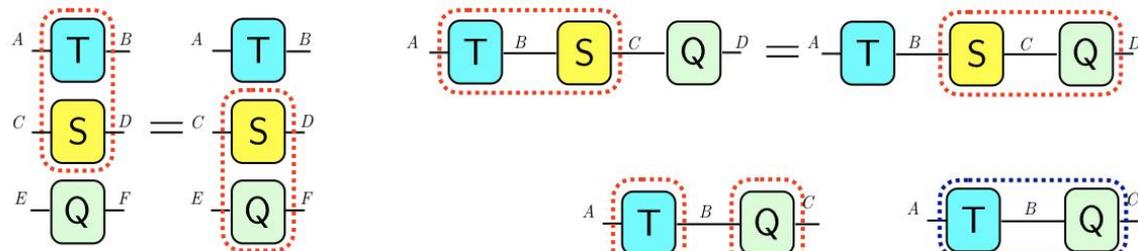
**OPT**

**Diagrammatic Language**

# Operational Probabilistic Theories (OPTs)

What is special about quantum theory as opposed to classical theory?

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**OPT**

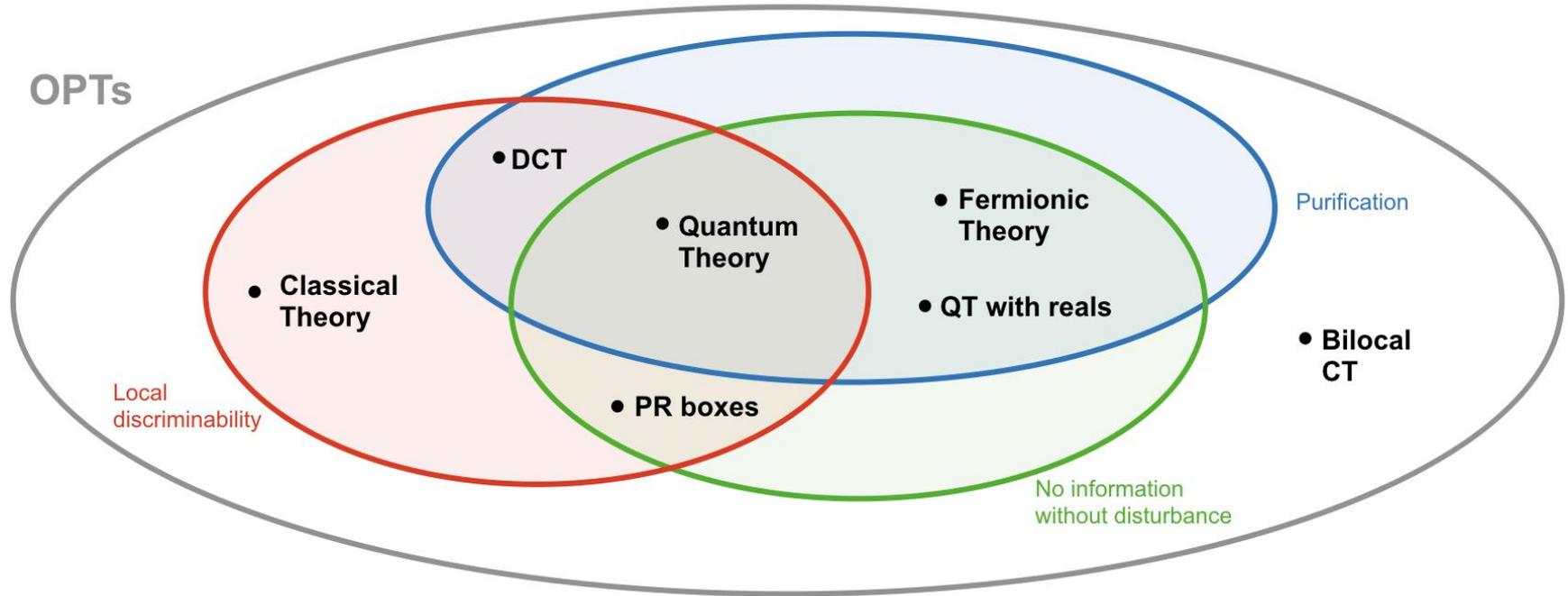
**Diagrammatic Language**

+

**Probabilistic structure**

$$p(n, i, k, n | \rho, T, \Xi, \Pi) \in [0, 1]$$

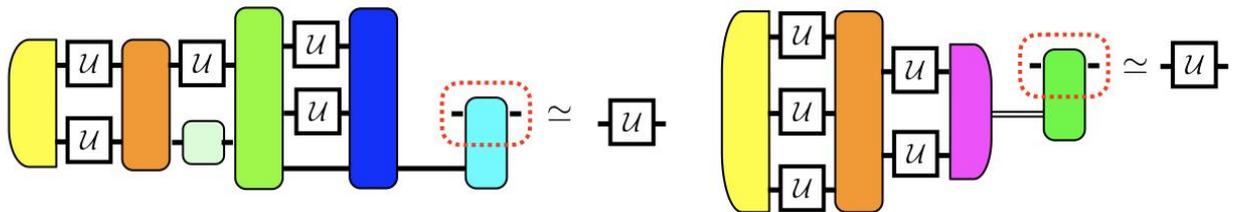
# Operational Probabilistic Theories (OPTs)



**Applications:** Information processing in more general frameworks:  
**Fermionic** theory, theories with fundamental or effective **constraints**  
(superselection, energy conservation, intrinsic level of noise...)

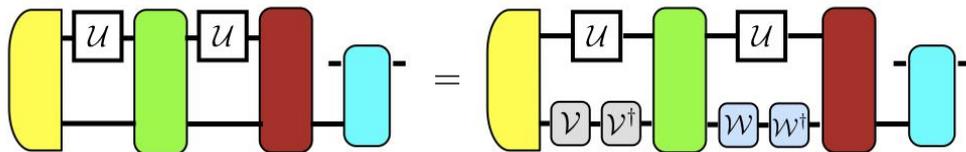
# Higher-Order Quantum Theory

What is the best **storage-and-retrieval** strategy which is allowed by Quantum Theory?



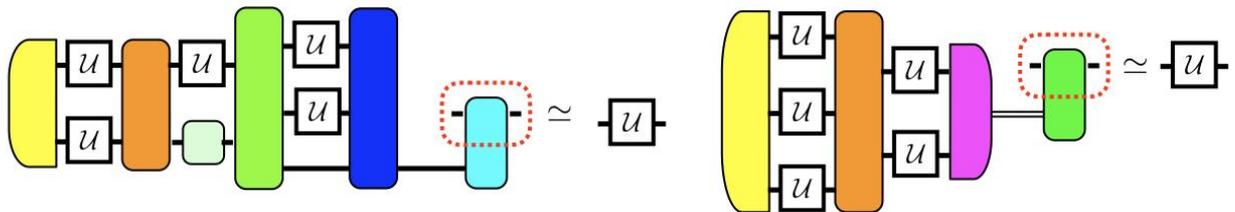
There are **several architectures**.

There are **redundancies** in the description



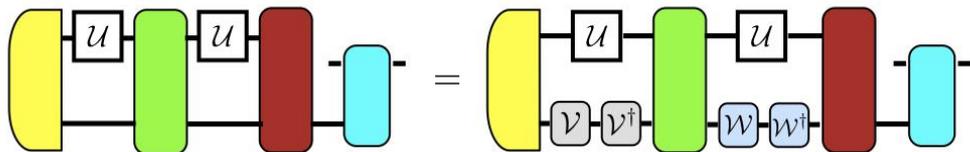
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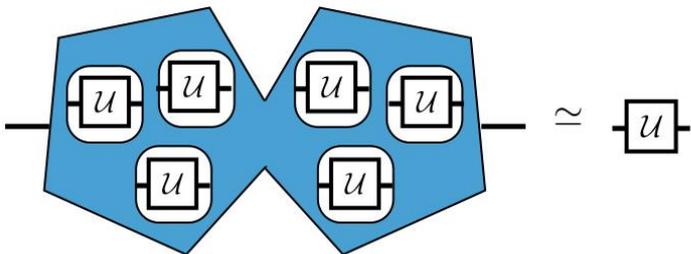


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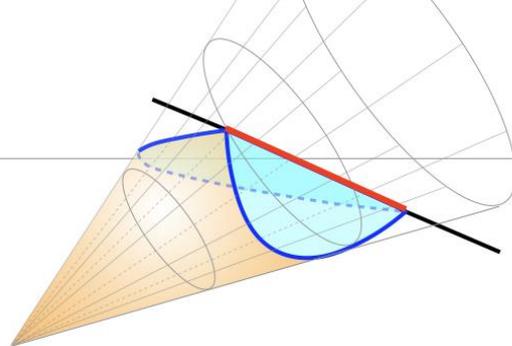


## Higher-Order Quantum Maps

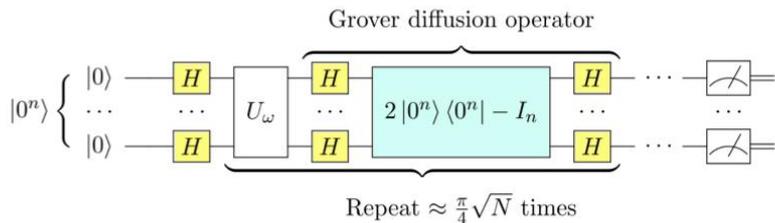


The most general **admissible** map from some type of process to another type of process

# Higher-Order Quantum Theory

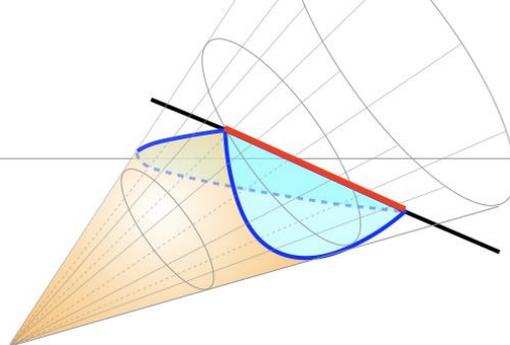


Higher-Order Maps provide a **non redundant** description of any information processing task.

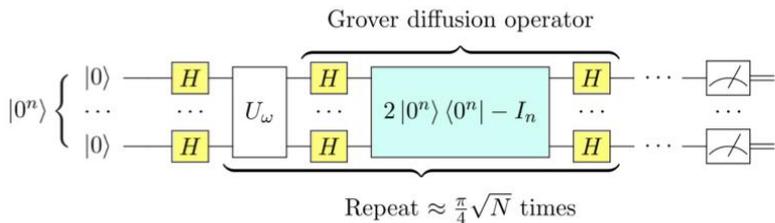


This is crucial when **transformations**, rather than states, **are the carriers of information.**

# Higher-Order Quantum Theory

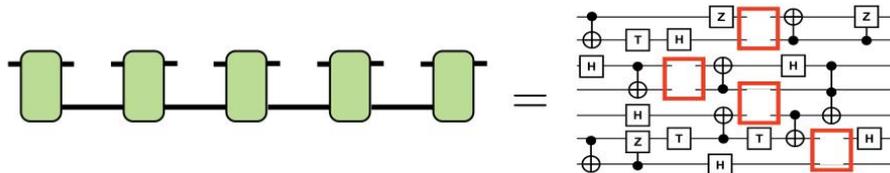


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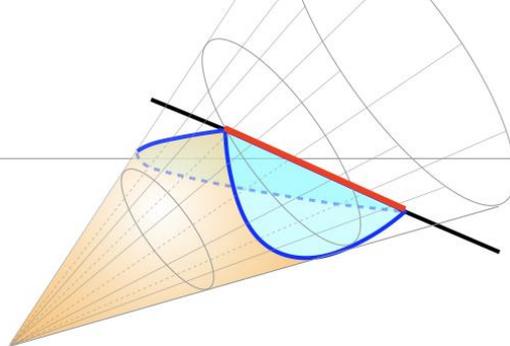


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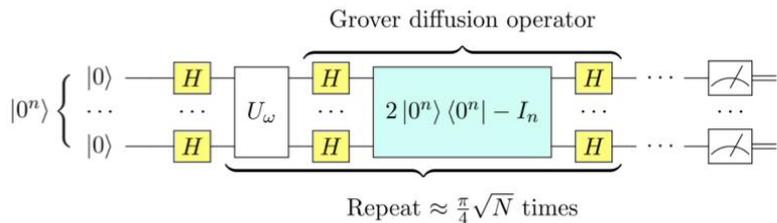
Some Higher-Order Quantum Maps admits a **realization** as quantum circuit with open slots...



# Higher-Order Quantum Theory

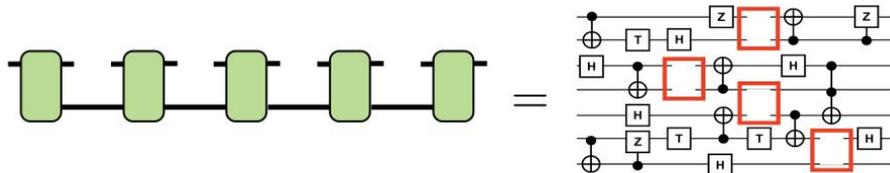


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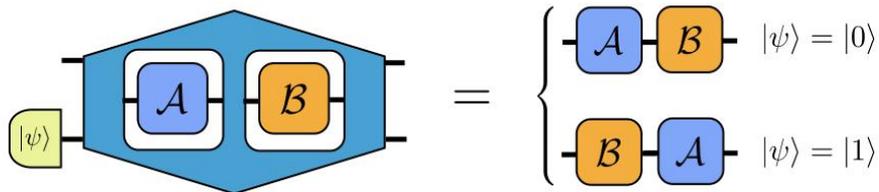


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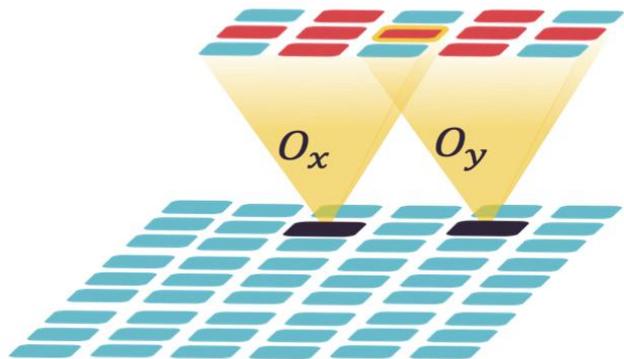
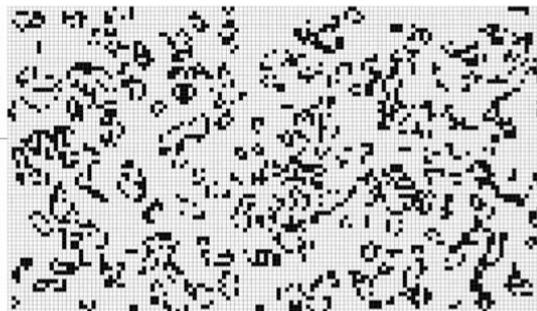
...but some do not.



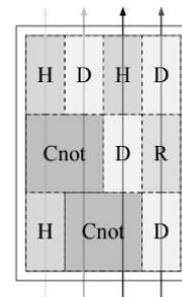
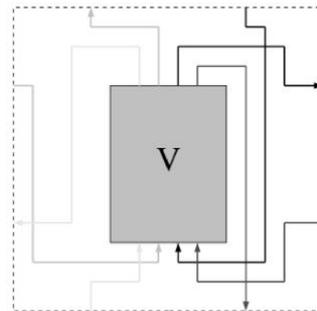
**Indefinite causal structure:** the cause-effect order of the resources is not fixed.

# Quantum Cellular Automata

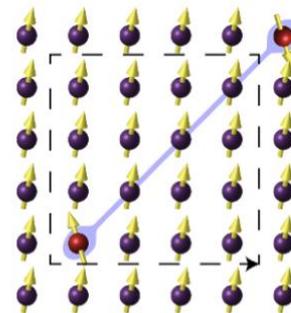
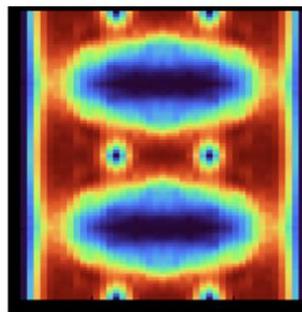
A (Quantum/Classical) Cellular Automaton is a lattice of (Quantum/Classical) physical systems which evolves according to a **local update rule**.



It is a computational model which is equivalent to the (Quantum/Classical) Turing Machine



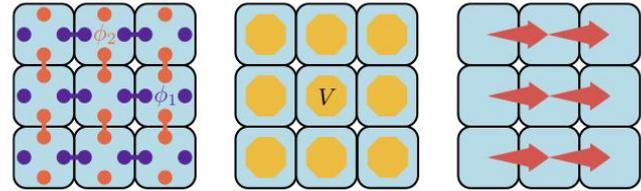
Studying Quantum Dynamics with tools of quantum information theory and Quantum Simulations



# Quantum Cellular Automata

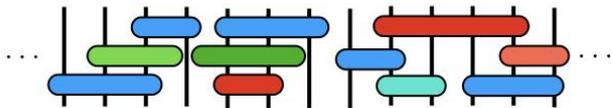
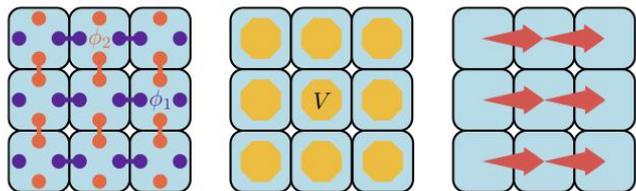
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**Classification** of Quantum Cellular Automata:  
what are the **simplest admissible** dynamics?



# Quantum Cellular Automata

**Classification** of Quantum Cellular Automata:  
what are the **simplest admissible** dynamics?

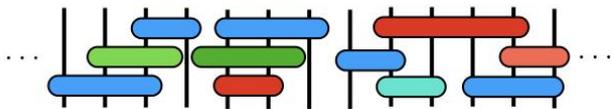
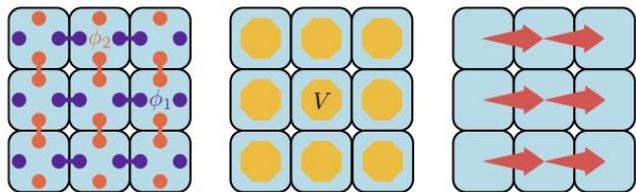


A **Finite-Depth Quantum Circuit (FDQC)**  
is a QCA. But not all the QCA are FDQC.  
When a QCA is a FDQC?



# Quantum Cellular Automata

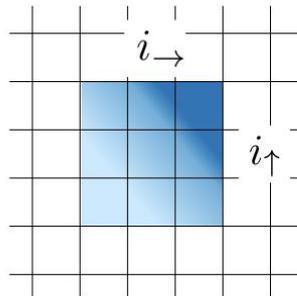
**Classification** of Quantum Cellular Automata:  
what are the **simplest admissible** dynamics?



A **Finite-Depth Quantum Circuit (FDQC)**  
is a QCA. But not all the QCA are FDQC.  
When a QCA is a FDQC?



In **1D** and **2D** quantum information behaves as  
an **incompressible** fluid. QCA are classified  
by their flow rate.



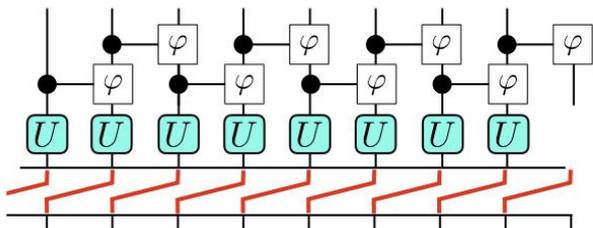
$\alpha$  is a circuit



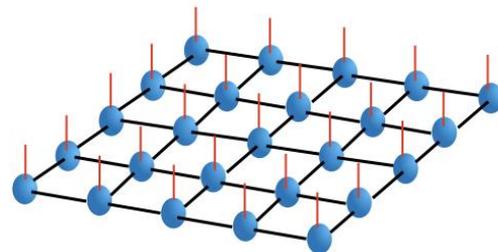
$$i_{\rightarrow}(\alpha) = i_{\downarrow}(\alpha) = 0$$

# Quantum Cellular Automata

What is the (quantum) **computational power** of a QCA?

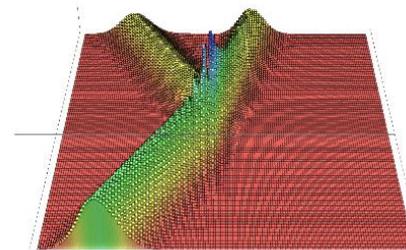
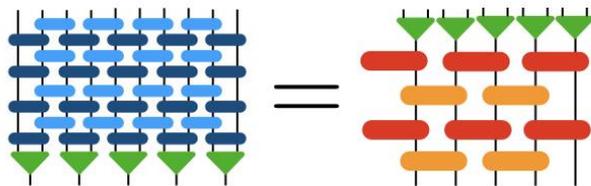
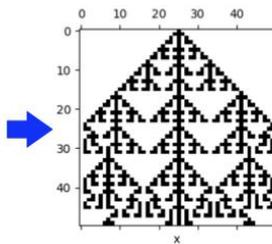
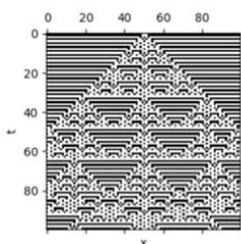


When a given QCA is Quantum Turing **complete**?



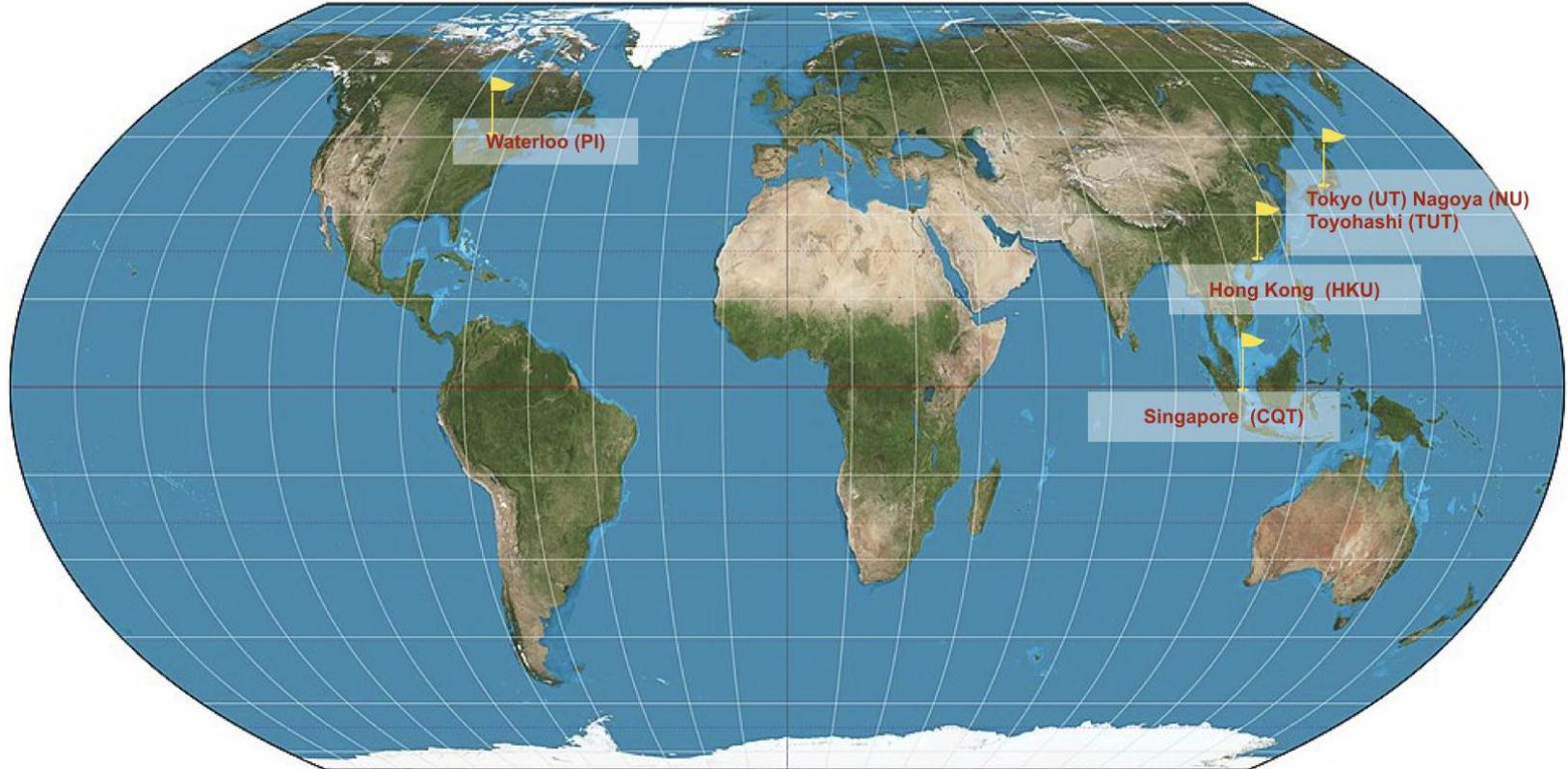
How hard is it to **classically** simulate a QCA?

What is the large scale dynamics of a QCA?

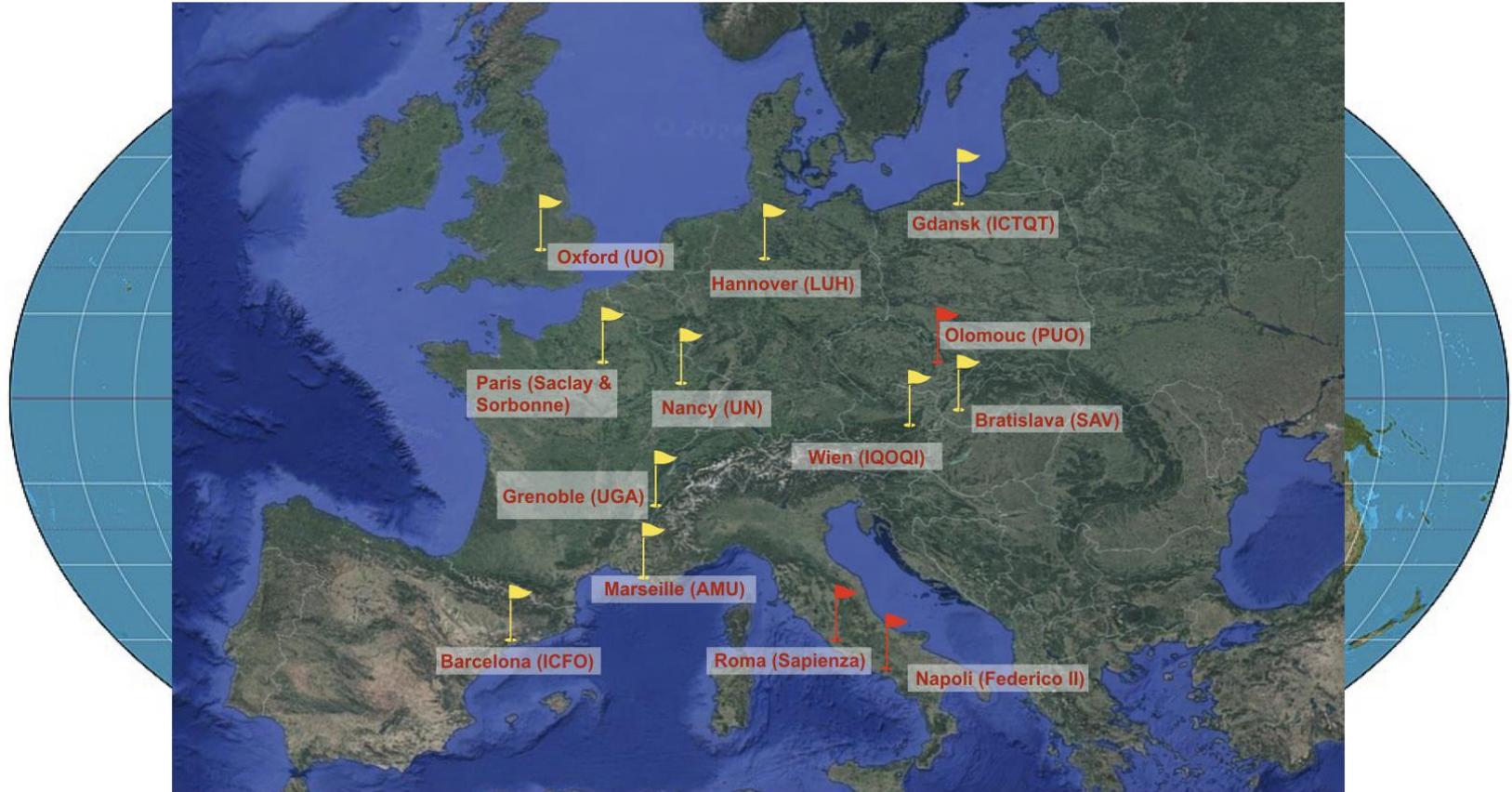


# A collective endeavor

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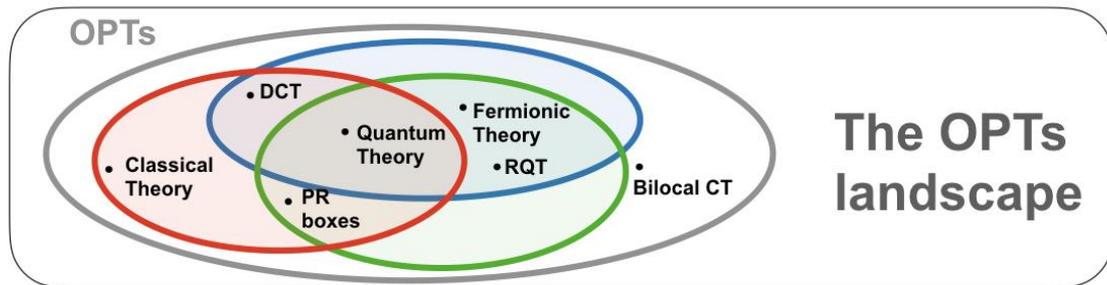


# A collective endeavor

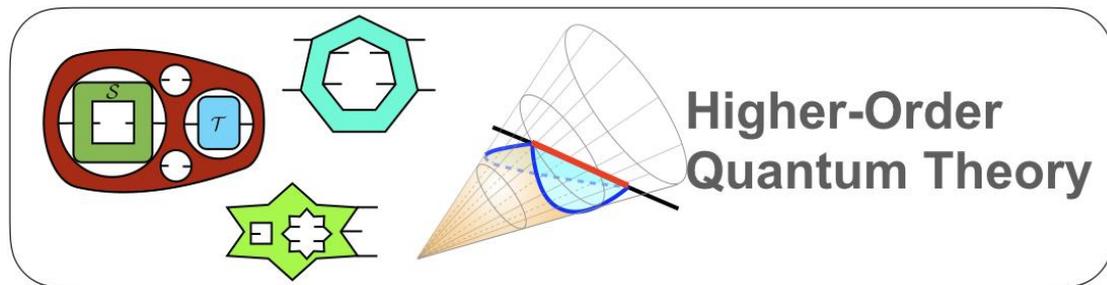


# Summary

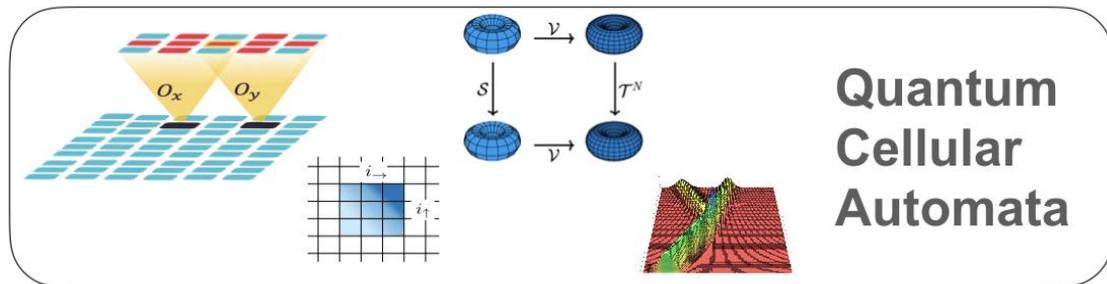
- What is special about Quantum Theory?



- Transformations as the carriers of information



- Quantum Dynamics in the light of Quantum Information



# Complex Systems & Econophysics

Giacomo Livan

# Complex Systems & Econophysics group

A collection of a large number of units that **interact locally** — in the absence of explicit coordination — giving rise to an **emergent macroscopic behavior** that is generally hard to describe or predict based on the behavior of the individual units.

*“More is different”* — P. W. Anderson (Science, 1972)

What we do, in a nutshell:  
**cross-disciplinary applications of Statistical  
Mechanics**

# Complex Systems & Econophysics group

- Giacomo Livan, Guido Montagna (UniPV & INFN)
- Oreste Nicosini (INFN)



Federica De Domenico  
Graduated Feb. 2026

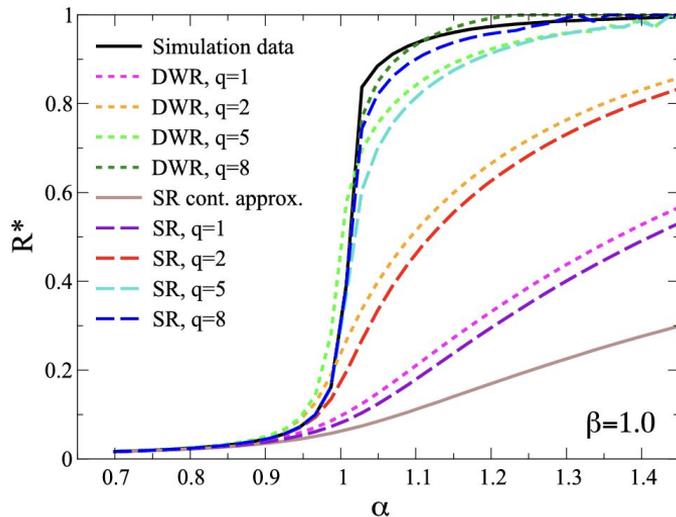
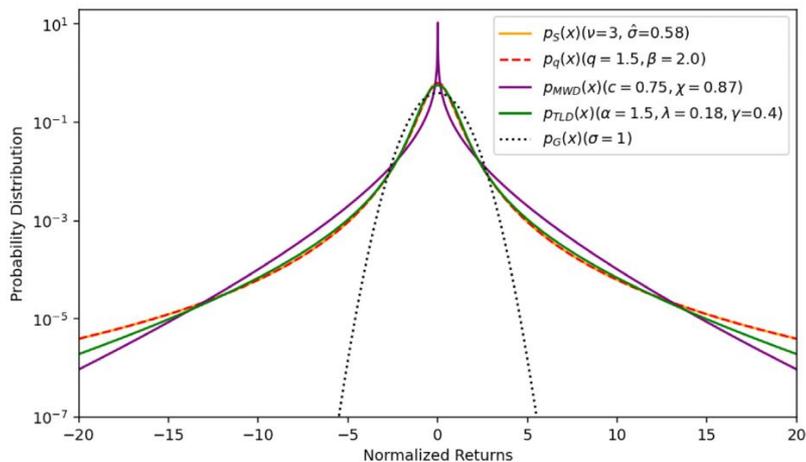


Giacomo Frigerio  
Complex Systems PhD programme  
@ UniCT



Federico Quetti  
Comp. Math. PhD programme  
@ UniPV

# Econophysics



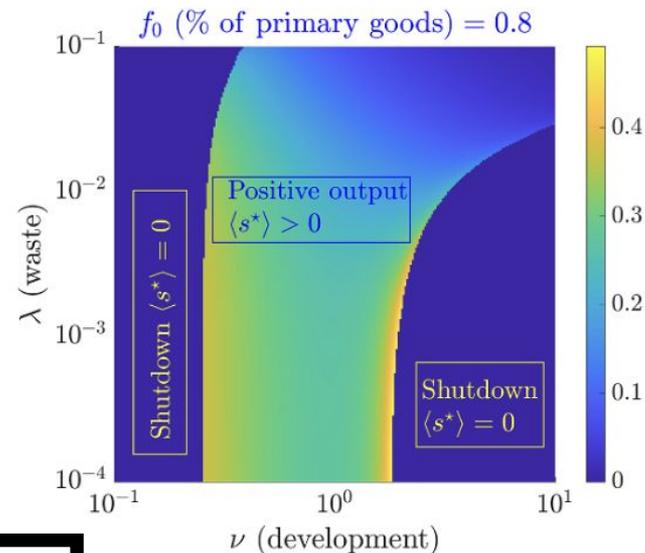
- Capturing statistical regularities and “stylized facts” in financial markets
- Analysis of shocks and systemic risk in financial networks

F. De Domenico, G. L., G. Montagna, O. Nicosini,  
*Physica A* (2023)

G. Ricciardi, G. Montagna, G. Caldarelli, G. Cimini,  
*Physica A* (2023)

# Complex socio-economic systems

- Economic complexity (macroeconomic shifts as phase transitions)
- Opinion dynamics, diffusion of (mis)information in complex networks
- Evolutionary game theory, evolution of cooperation



F. Marcuccini, G. L., *J. Stat Mech.* (2025)

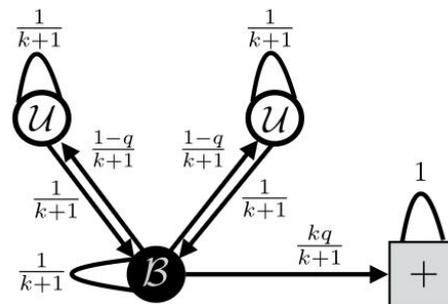
F. De Domenico, F. Caccioli, G. L., *J. Phys. Complexity* (2025)

F. De Domenico, F. Caccioli, G. L., G. Montagna, O. Nicosini, *RSOS* (2024)

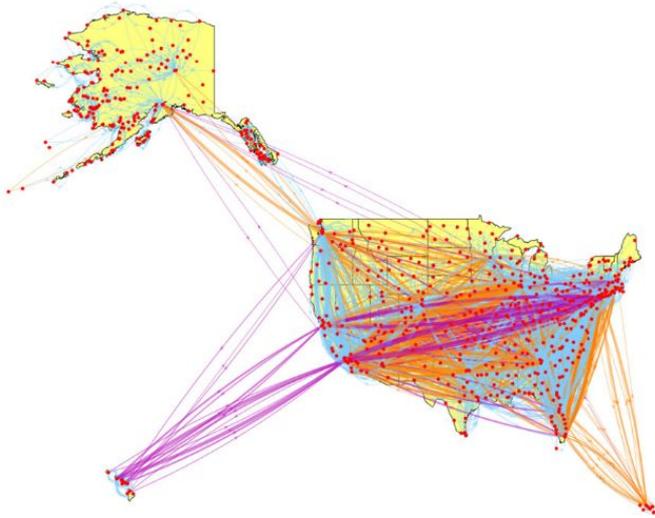
D. Riazi, G.L., *Physica A* (2024); *Advances in Complex Systems* (2025)

O. Sikder, R. E. Smith, P. Vivo, G. L., *Sci. Rep.* (2020)

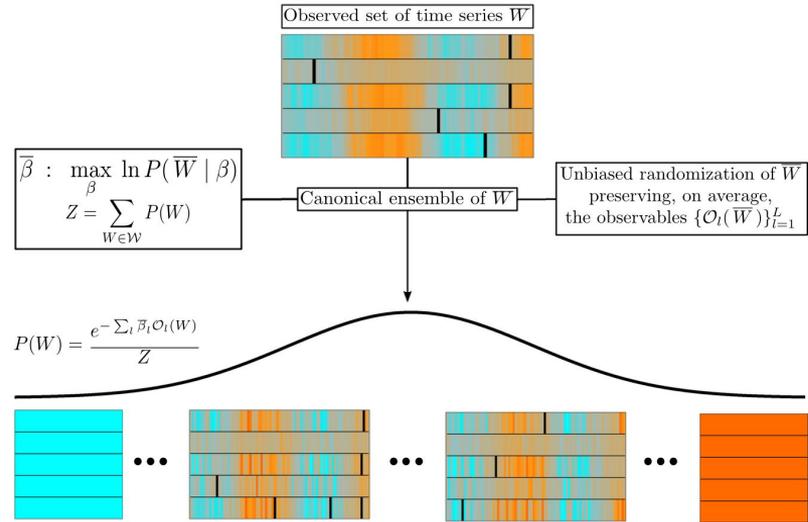
G. L., *RSOS* (2019)



# Signal vs noise in complex systems



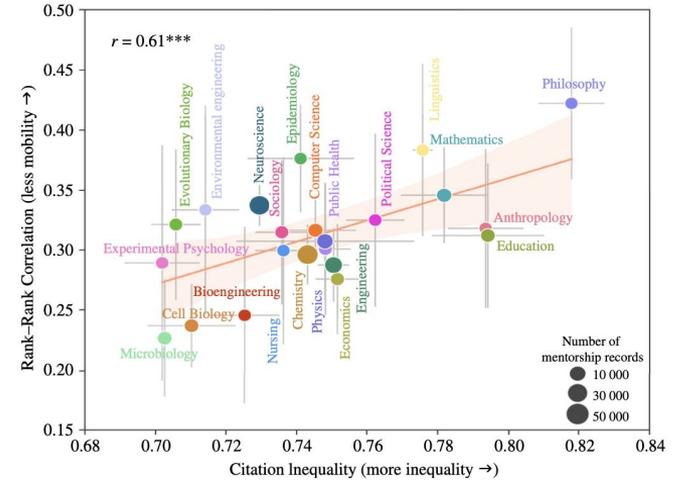
- Network filtering
- Generation of synthetic time series with realistic statistical properties
- Emergence of Zipf's law



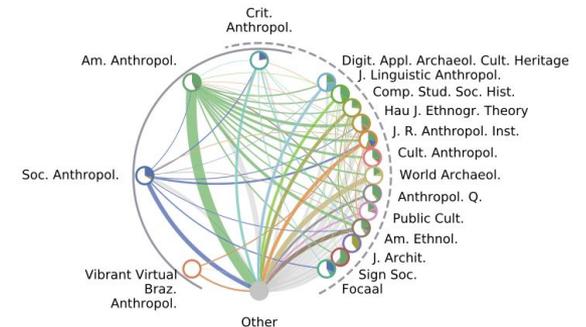
D. Cugini, A. Timpanaro, G. L., G. Guarnieri, *J. Stat. Mech.* (2025)  
S. Tilly, G. L., *Expert Systems with Applications* (2021)  
R. Marcaccioli, G. L., *Phys. Rev. E* (2020)  
R. Marcaccioli, G. L., *Nature Communications* (2019)

# Science of Science

- Data-driven analysis of scientific publications and careers
- Detecting “citation cartels”
- Academic Great Gatsby curve
- 2020 Eugene Garfield Award



M. S. Mariani et al., *Nature Communications* (2024)  
Y. Sun, F. Caccioli, G. L., *J. Royal Society Interface* (2024)  
Y. Sun, X. Li, F. Caccioli, G. L., *PNAS* (2023)  
S. Kojaku, G. L., N. Masuda, *Sci. Rep.* (2021)  
W. Li, T. Aste, F. Caccioli, G. L., *Nature Communications* (2019)



# Our collaborators



- China: Southern University, Southeast University
- USA: Indiana University, Michigan, University
- Austria: Complexity Science Hub
- Bank of England
- Central banks in South America

Giacomo Bormetti  
Dip. Economia UniPV



UNIVERSITÀ  
degli STUDI  
di CATANIA



Università  
degli Studi  
di Palermo