QC@INFN

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Istituto Nazionale di Fisica Nucleare
Sezione di Ferrara

Workshop CCR
Paestum 26 maggio 2022

Outline

- A (short) overview of INFN efforts in QIS/QT
- ICSC Spoke 10
- Using IBM Q resources through CERN
  - A couple of examples
- Conclusions

Early studies

- Efforts emerged at INFN over the past years, in a bottom-up approach
- CSN4 “iniziative speciali”, e.g.
  - Foundational studies, theory of measure, entanglement (BELL)
  - Quantum Systems: entanglement, simulations, information (QUANTUM)
- CSN5:
  - technological developments (single photon detectors; detectors for dark matter searches; atomic interferometry for gravity)
  - Quantum simulations (theories with “sign problem”)
  - More recently: thematic calls
    - DARTWARS: Build and test Travelling Wave Parametric Amplifies to read tiny signals close to the quantum limit with reasonable amplification rate and as large as possible bandwidth
    - QUANTEP: Learn to develop and operate “universal” quantum gates using Linear Optic Quantum Computation technology.

Quantera

- A leading European network of 39 public Research Funding Organisations (RFOs) from 31 countries supporting excellent Research and Innovation in Quantum Technologies (QT)
- INFN joined Quantera as one of the Italian funding members in 2018
- 2019 call: 5/15 INFN proposals accepted (total: 12/85 proposal accepted)
  - Qu3D - Quantum 3D Imaging at high speed and high resolution, Milena D'Angelo (BA)
  - QuICHE - Quantum Information and Communication with High-dimensional Encoding, Chiara Machiavello (PV)
  - QuantHEP - Quantum Computing Solutions for High-Energy Physics, Simone Montangero (PD)
  - SECRET - SECuRe quantum communication based on Energy-Time/time-bin entanglement, Giuseppe Vallone (PD)
  - PACE-IN - Photon-Atom Cooperative Effects at Interfaces, Paolo Facchi (BA)

Quantera-2

- 2021 call: 39 projects awarded funding, 2 with INFN participation
- **SQUEIS**: Squeezing-Enhanced Inertial Sensing (G. Tino, FI)
  - establish new frontiers in atom interferometry by devising and applying quantum-enhancement techniques based on squeezing to state-of-the-art applications in gravimetry, gradiometry and inertial sensing.
  - tunable atom-atom interaction in quantum gases, as well as non-demolition measurements via the coupling of atoms and light
- **T-NiSQ**: Tensor Networks in Simulation of Quantum matter (S. Montangero, PD)
  - systematically develop quantum-inspired algorithms to benchmark, certify and validate quantum devices
  - Tensor networks play a central role
  - Develop benchmarking tools for high-dimensional quantum systems in the presence of noise and test them in state-of-the-art quantum simulations and computations.
  - Advance our understanding of dynamical and strong- correlation effects in quantum matter also beyond the NISQ era

SQMS

SQMS - mission

- ***The mission of the SQMS is to achieve transformational advances in the major cross-cutting challenge of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing.***
  - The main QIS problem the Center will attack is coherence, the lifetime of quantum states.
  - We will attack the coherence of scalable 2D devices with strengths in materials and low loss RF superconductivity, and the scalability of record coherence 3D devices with strengths in large high Q RF cry-systems integration.
  - In quantum computing we will build alpha prototypes of 2D and 3D quantum information processors with revolutionary capabilities.
  - In quantum sensing we will purse fundamental physics questions by leveraging SRF cavity-based quantum technologies.

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

SQMS

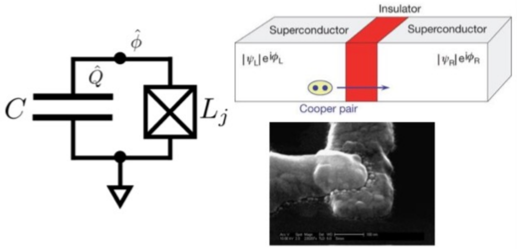
Anna Grassellino (FNAL)

2D and 3D quantum devices

- Our qubits use superconducting technologies - coherence is a critical feature!
- SQMS Jargon
  - "2D": arrays of superconducting transmons (mostly built by Rigetti Computing)
  - "3D": superconducting transmons coupled to a resonator cavity (particularly SRF cavities)

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

1. LC circuit with Josephson junction



"Transmon" qubits

J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

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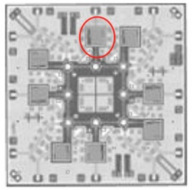
2. Resonators (cavities)

2D



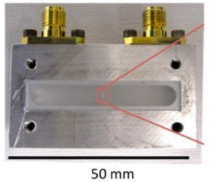
Rigetti 8-qubit processor

Q ~ 10^5

$T_{coherence}$ ~ 0.000001 s

M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

3D



3D transmon

Q ~ 10^8

$T_{coherence}$ ~ 0.001 s

H. Paik et al, Phys. Rev. Lett. 107, 240501 (2011)

Fermilab SRF resonators

Q > 10^{10}

$T_{coherence}$ > 1 s

A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

SQMS

Processor Metrics	Leading Systems	Center Prototypes (3 yr)		Center Device Goals (5 yr)	
		2D-Alpha (estimate)	SRF-Alpha (estimate)	SQMS-2D (estimate)	SQMS-3D (estimate)
Number of qubits	53	128	>100	256	>200
Connectivity graph (qubit:neighbors)	1:4	1:3	1:10	1:3	1:200
Qubit T_1 lifetime, us (median)	70	200	400,000	400	1,000,000
Gate time, ns (median)	20	50	2000	40	100
Coherence/gate time ratio	1,000	4,000	20,000	10,000	100,000,000
Single qubit gate fidelity (%)	99.85	99.6	99.5	99.95	99.95
Two qubit gate fidelity (%)	99.65	99.2	99.5	99.9%	99.95
Achievable circuit depth (1/error)	300	100	200	1,000	2,000

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

INFN@SQMS

- GGI, LNGS, LNL, Ferrara, Firenze, Padova, Pavia, Roma I

- theory at the fundational / metrological level
- theory and algorithms for quantum applications
- measure and mitigate the negative impact of radioactive background
- contribute/improve our expertise in superconducting cavities
- couple transmons and (B-friendly) cavities
- make LNGS a national test/characterization facility for Quantum devices
- Ph.D. schools/workshops/conferences at GGI (and elsewhere)
- help young people enter this field

ICSC

- See also Claudio’s presentation

Spoke 10 - Quantum Computing

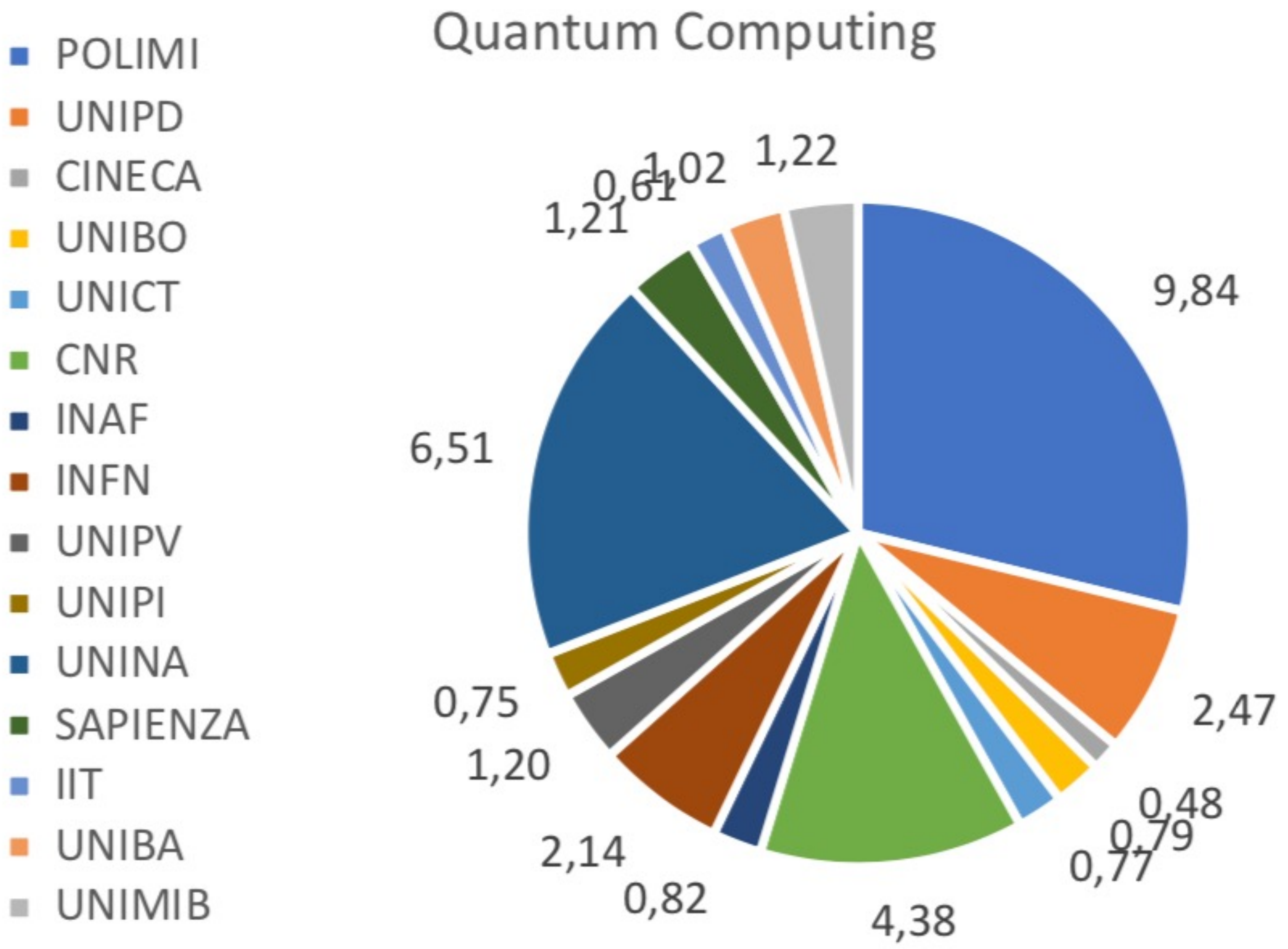
Goals:

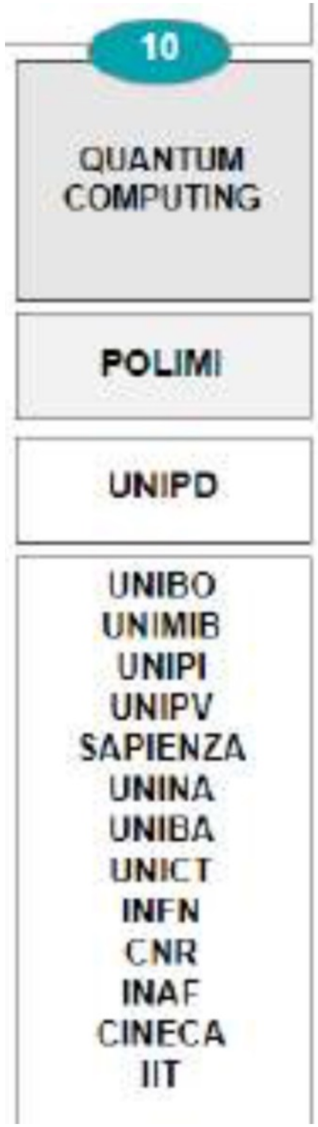
- Exploitation of QC to solve complex problems in the field of optimization, simulation and machine learning.
- Identify quantum algorithms characterized by a speedup, even limited, if compared with the corresponding classical algorithm.
- Use the quantum approach to perform calculations on state-of-the-art classical computers (quantum-inspired algorithms, emulators, tensor network computations)
  - To gain significant benefits in terms of algorithms efficiency without using a quantum hardware.
- This will lead to a hybrid systems configuration, that will integrate quantum and classical high-performance computing in order to solve complex problems in a sustainable time.

Activities: development and application of

- high-level quantum software for general purpose problems and for scientific and industrial applications;
- libraries and development frameworks to access quantum accelerators;
- low-level software for the physical operation of specific quantum computers;
- software for benchmarking and verification of the quantum computations, optimization of algorithms and compilation;

Budget





INFN:
Technology:Algorithms = 75:25

Work packages/tasks

Quantum Computing

WP1. Software **Leader: INFN**	WP2. Mapping, compilation and quantum computing emulation. **Leader: CINECA**	WP3. Firmware and hardware platforms **Leaders: CNR, CT**
Development and application of high-level quantum software for algorithms solving general purpose problems, scientific and industrial applications.	Development of software for compilation, benchmarking, verification emulation of quantum computers and algorithms.	Development of low-level software for the physical operation of quantum computers. Development of the quantum computer hardware chain in its four most promising forms: ions, atoms, photons and superconductors.
T1.1 New algorithms PV, BO, IIT, CT, CINECA, CNR, PI, RM1, BA, Polimi, PD **T1.2 Applications and use cases** IIT, BO, CINECA, CNR, INAF, INFN, PV, PI, BA, MIB, Polimi, PD	**T2.1 Mapping and compilation** BO, CNR, PI, Polimi **T2.2 Emulation** CINECA, INAF, BA, PD	**T3.1 Photonic** (RM1, CNR, MIB, PV, NA) **T3.2 SC circuits** (NA, INFN, MIB, CNR, CT) **T3.3 Atoms** (CNR, PD); **T3.4 Ions** (PD, CNR); **T3.5 Models and firmware** (CT, Polimi, BA, PD, MIB, CNR, PI)

Work packages/tasks

Quantum Computing

WP1. Software

T1.1 New algorithms
PV, BO, IIT, CT, CINECA, CNR, PI, RM1, BA, Polimi, PD

T1.2 Applications and use cases
IIT, BO, CINECA, CNR, INAF, INFN, PV, PI, BA, MIB, Polimi, PD

M1.1 (M12): Designing quantum algorithms
M1.2 (M24): Development and validation of quantum algorithms and applications
M1.3 (M36): Benchmarking quantum-accelerated applications against classical applications

WP2. Mapping, compilation and quantum computing emulation.

T2.1 Mapping and compilation
BO, CNR, PI, Polimi

T2.2 Emulation
CINECA, INAF, BA, PD

M2.1 (M12): Classic emulator with 100+ qbits
M2.2 (M36): Test quantum supremacy in industrial setting
M2.3 (M36): tools and methodologies for design automation and mapping

WP3. Firmware and hardware platforms

T3.1 Photonic (RM1, CNR, MIB, PV, NA)
T3.2 SC circuits (NA, INFN, MIB, CNR, CT)
T3.3 Atoms (CNR, PD); **T3.4 Ions** (PD, CNR);
T3.5 Models and firmware (CT, Polimi, BA, PD, MIB, CNR, PI)

M3.1 (M24): Two platforms with 5+ qbits
M3.2 (M36): Photonic sampling machine with 5+ photons and 24+ modes
M3.2 (M36): Supporting tools for hardware platforms

INFN involvement in WP1

- **Applied quantum algorithms:** exploit the potential of Quantum Computing to change the paradigm of classification and reconstruction algorithms used in fundamental physics research
  - tackle classification problems within the framework of Quantum Machine Learning
  - study correlations among the features of a dataset, by measuring the entanglement correlations between qubits, and therefore extracting information on the underlying physics
  - quantum algorithms can be employed to efficiently reconstruct physics objects, such as charged particle tracks, specifically to reduce combinatorial background during the initial seeding stage

Who

- Ferrara and Padova INFN units will focus on algorithms related to track reconstruction and event classification for the analysis of data collected at HEP experiments
- Roma1 INFN unit involved in the Virgo/Ligo collaborations will develop quantum algorithms – including matched filtering, pattern recognition methods, and machine learning – to dramatically boost the sensitivity of GW searches.

Using IBM Q resources through CERN

- An agreement between INFN and CERN was recently signed for priority usage of IBM Q resources
  - Started on May 15th, for two years
- A number of projects have been defined

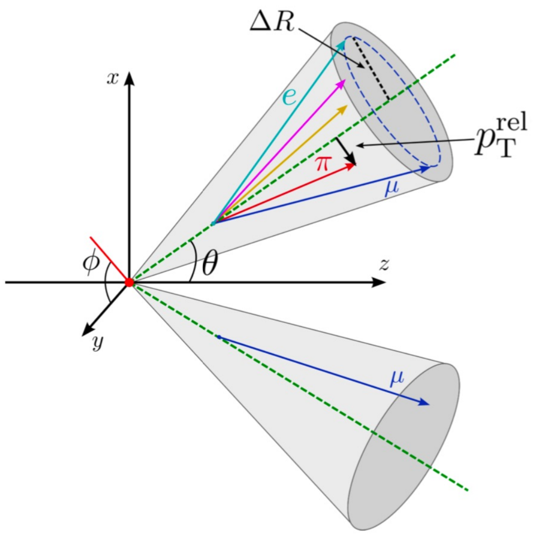
Name	Qubits	QV	CLOPS	Status	Total pending jobs
ibm_washington Exploratory	127	64	850	Online - Queue paused	237
ibmq_brooklyn Exploratory	65	32	1.5K	Online	102
ibmq_kolkata Exploratory	27	128	2K	Online - Queue paused	70
ibmq_montreal	27	128	2K	Online	767
ibmq_mumbai Exploratory	27	128	1.8K	Online - Queue paused	684
ibm_cairo	27	64	2.4K	Online	320
ibm_auckland Exploratory	27	64	2.4K	Online - Queue paused	240
ibm_hanoi	27	64	2.3K	Online	324
ibmq_toronto	27	32	1.8K	Online	180
ibm_peekskill Exploratory	27	-	-	Online	0
ibmq_guadalupe	16	32	2.4K	Online	100
ibm_perth	7	32	2.9K	Online	39
ibm_lagos	7	32	2.7K	Online	52
ibm_nairobi	7	32	2.6K	Online	0
ibmq_jakarta	7	16	2.4K	Online	116
ibmq_manila	5	32	2.8K	Online	143
ibmq_bogota	5	32	2.3K	Online	89
ibmq_santiago	5	32	-	Online	123
ibmq_quito	5	16	2.5K	Online	66
ibmq_belem	5	16	2.5K	Online	30
ibmq_lima	5	8	2.7K	Online	125
ibmq_armonk	1	1	-	Online	0

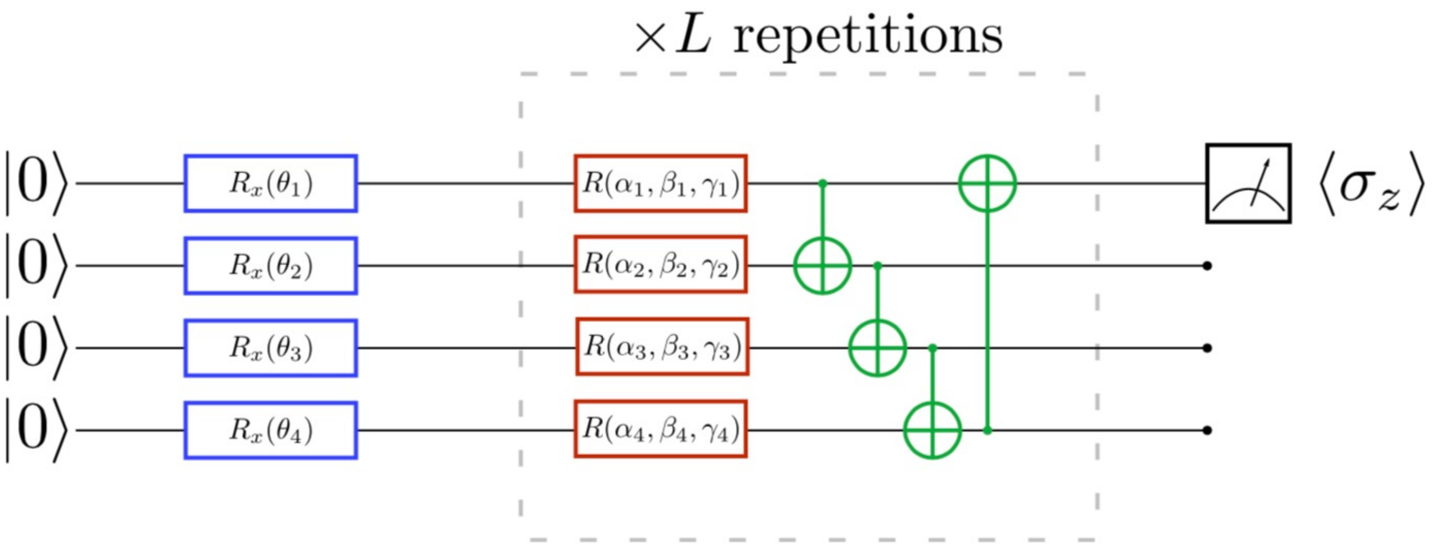
Using IBM Q resources through CERN

- Hamiltonian evolution of the dynamics of QCD-inspired field theory models
  P. Facchi (BA), S. Montangero (PD), E. Ercolessi (BO)
- Circumventing the sign problem for LQCD-simulations
  M. D'Elia (PI)
- Quantum Machine Learning for Event Classification and Event Simulation in Nuclear Physics, High-Energy Physics and Gravitational Wave experiments
  L. Sestini (PD), P. Astone, C. Palomba and S. Giagu (Roma1)
- Quantum simulation of the Nucleon-Nucleon potential,
  F. Pederiva (TIFPA)
- Quantum simulations of collective neutrino oscillations
  A. Roggero (TIFPA)
- Quantum graph networks for particle track reconstruction
  D. Bonacorsi (BO), C. Bozzi (FE), A. Rizzi (PI)
- Exploring Quantum Computing
  F. Schifano (FE)

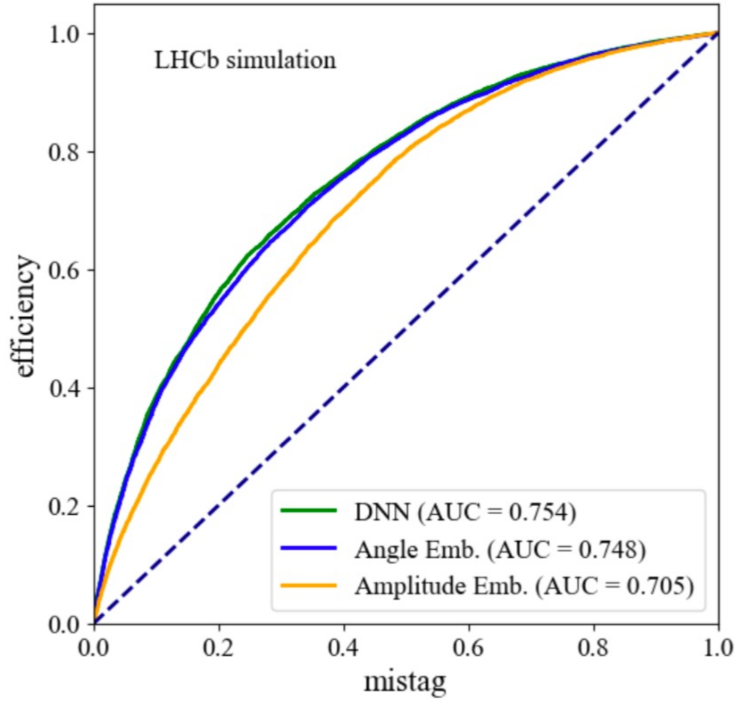
QML for b-jet identification at LHCb

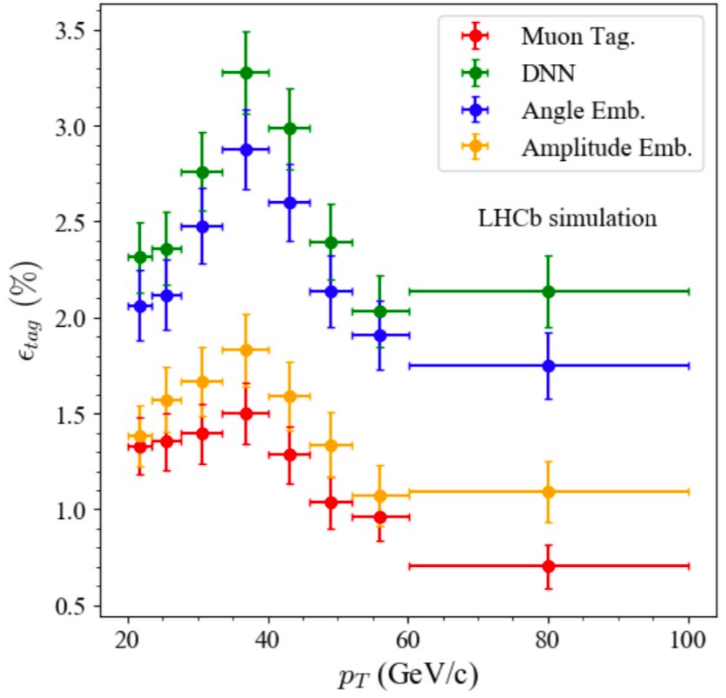
- The goal: identify jets produced by the hadronization of b quarks and tag whether they were originated by a b or anti-b
- The tool: a QML approach based on a Variational Quantum Classifier

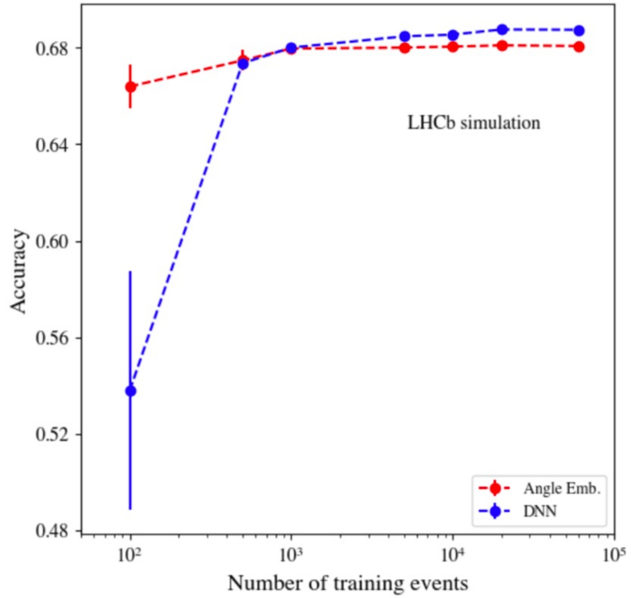


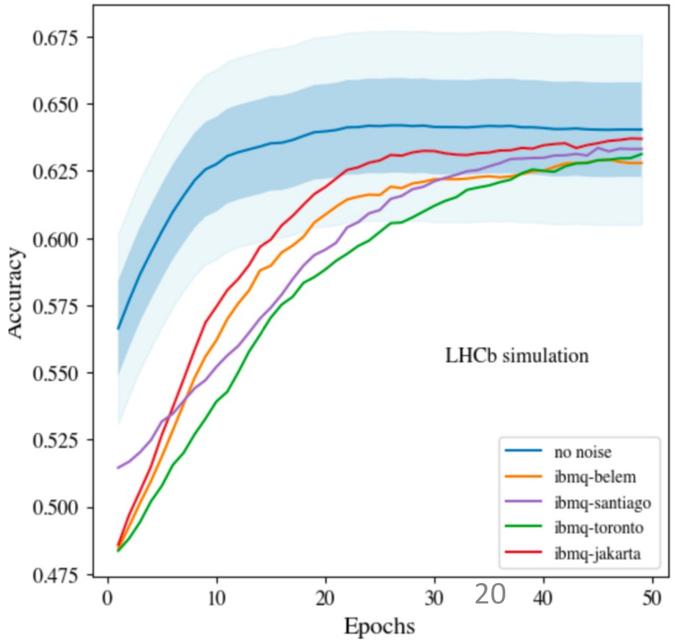


QML for b-jet identification at LHCb





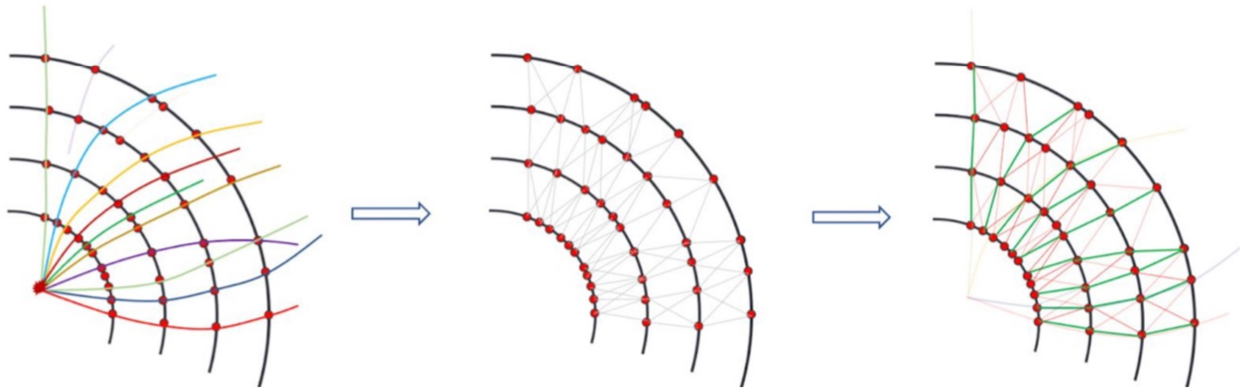




- Similar performance wrt DNN, plateau reached with less training events
- noisy devices imply increase in number of training epochs

Track reconstruction with QGNN

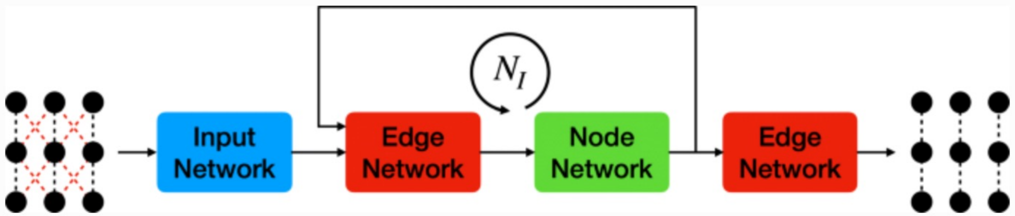
- The goal of track reconstruction:
  - Given set of hits in a detector from particles, assign label(s) to each hit.
  - Perfect classification: All hits from a particle (*and only those hits*) share the same label
- Represent an event with a graph
  - Treat each hit as a node
  - A node can have features (e.g. position, energy deposit, etc.)
  - Nodes can be connected by edges, that represent the possibility of belonging to the same track



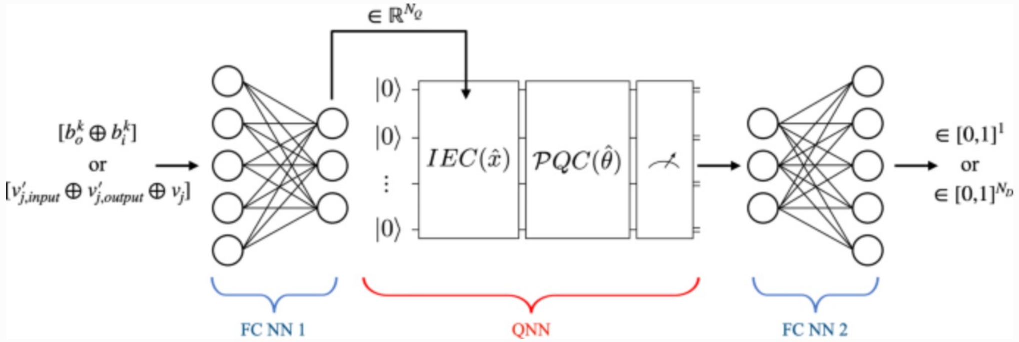
Use ML and/or graph techniques to segment or cluster the nodes to match particle tracks, e.g.

Graph Neural Networks (GNNs)
Quantum GNN

Track reconstruction with QGNN



Schematic of the QGNN architecture. The pre-processed graph is fed to an Input Network, which increases the dimension of the node features. Then, the graph's features are updated with the Edge and Node Networks iteratively, number of iterations (N_I) times. Finally, the same Edge Network is used one more time to extract the edge features of the graph that predicts the track segments. There is only one Edge Network in the pipeline, two Edge Networks are drawn only for visual purposes. The pipeline is adapted from Farrell et al. (2018)



The Hybrid Neural Network (HNN) architecture. The input is first fed into a classical fully connected Neural Network (FC NN) layer with sigmoid activation. Then, its output is encoded in the QNN with the information encoding circuit (IEC). Next, the parametrized quantum circuit (PQC) applies transformations on the encoded states. The output of QNN is obtained as expectation values for each qubit that is measured. A final FC NN layer with sigmoid activation is used to combine the results of different qubit measurements. The same HNN architecture is used in Edge (upper input and output dimension) and Node Networks (lower input and output dimension) with different parameters. The input and output dimension sizes change according to the network type. Details of the dimensions of each layer are given in Table 1

Conclusion

- The vast majority of INFN efforts is concentrated on quantum technologies, some on quantum simulations
- Trying to push on Algorithmic Quantum Computing by
  - Building groups experimenting on algorithms, programming methodologies, libraries, interfaces with traditional systems
  - Actively participating in the ICSC endeavour
  - Giving access to simulators and real machines
- A Quantum Computing Working Group is being setup within the new INFN Computing Organization (C3SN)
  - Composition and mandate under discussion
- A QC@INFN workshop is being organised