QuantHEP

Quantum Computing Solutions for High-Energy Physics

Yasser Omar

contact.yasser@pqi.pt

PQI – Portuguese Quantum Institute

Instituto Superior Técnico, Universidade de Lisboa

Physics of Information and Quantum Technologies Group, CeFEMA,

PORTUGUESE
QUANTUM
INSTITUTE

TÉCNICO LISBOA

CeFEMA
Center of Physics and Engineering of Advanced Materials

QuantHEP

QuantHEP – Quantum Computing Solutions for High-Energy Physics

QuantERA project, 2020-2023

quanthep.eu

CeFEMA
Center of Physics and Engineering of Advanced Materials

INFN

State Education
Development Agency
Republic of Latvia

CERN

QUANTERA

Written in 2018, submitted in 2019, kicked-off in Lisbon in January 2020, with the goals to:

1. **Investigate the potential of quantum computation for particle tracking and event selection.**
2. **Develop the quantum simulation of events.**
3. **Promote the collaboration between the Quantum Computation / Quantum Technologies and the HEP communities.**

CeFEMA
Center of Physics and Engineering of Advanced Materials

INFN

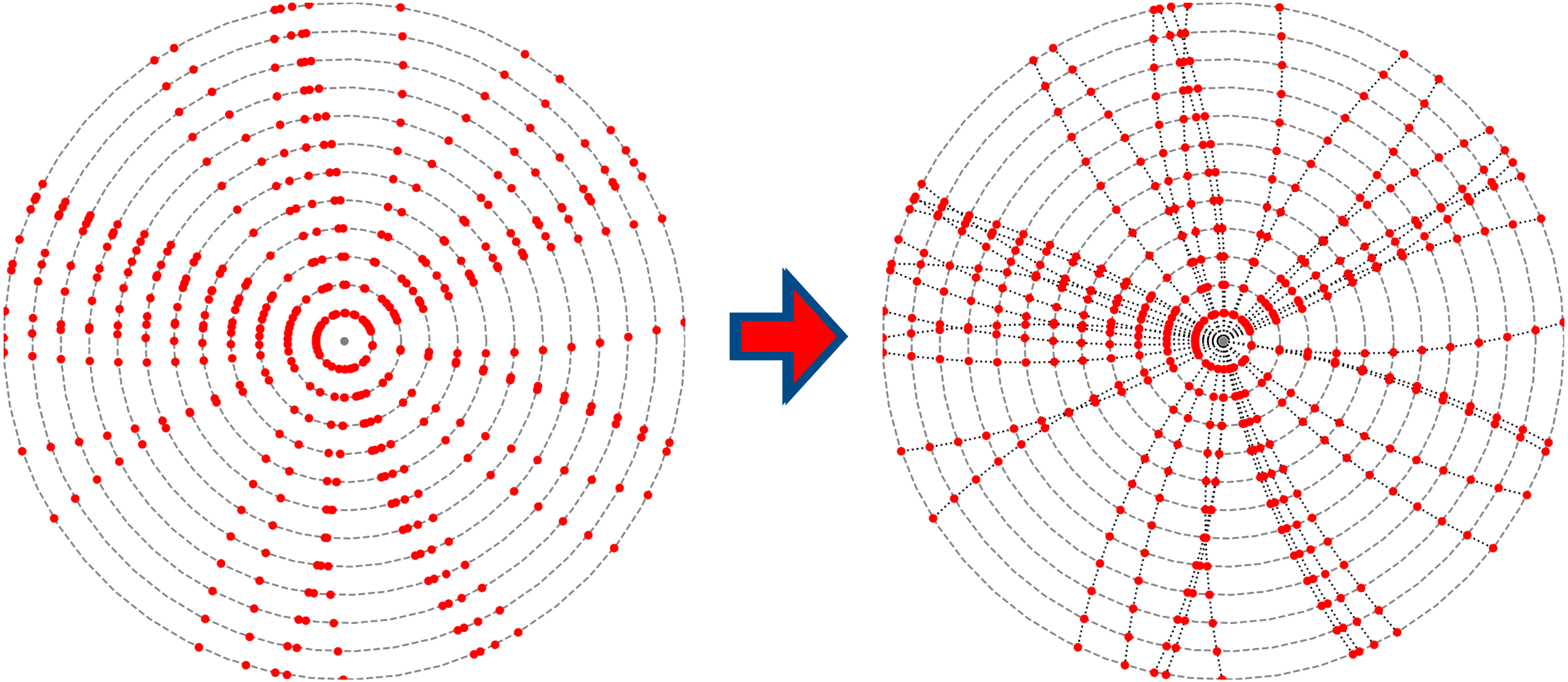
State Education
Development Agency
Republic of Latvia

CERN

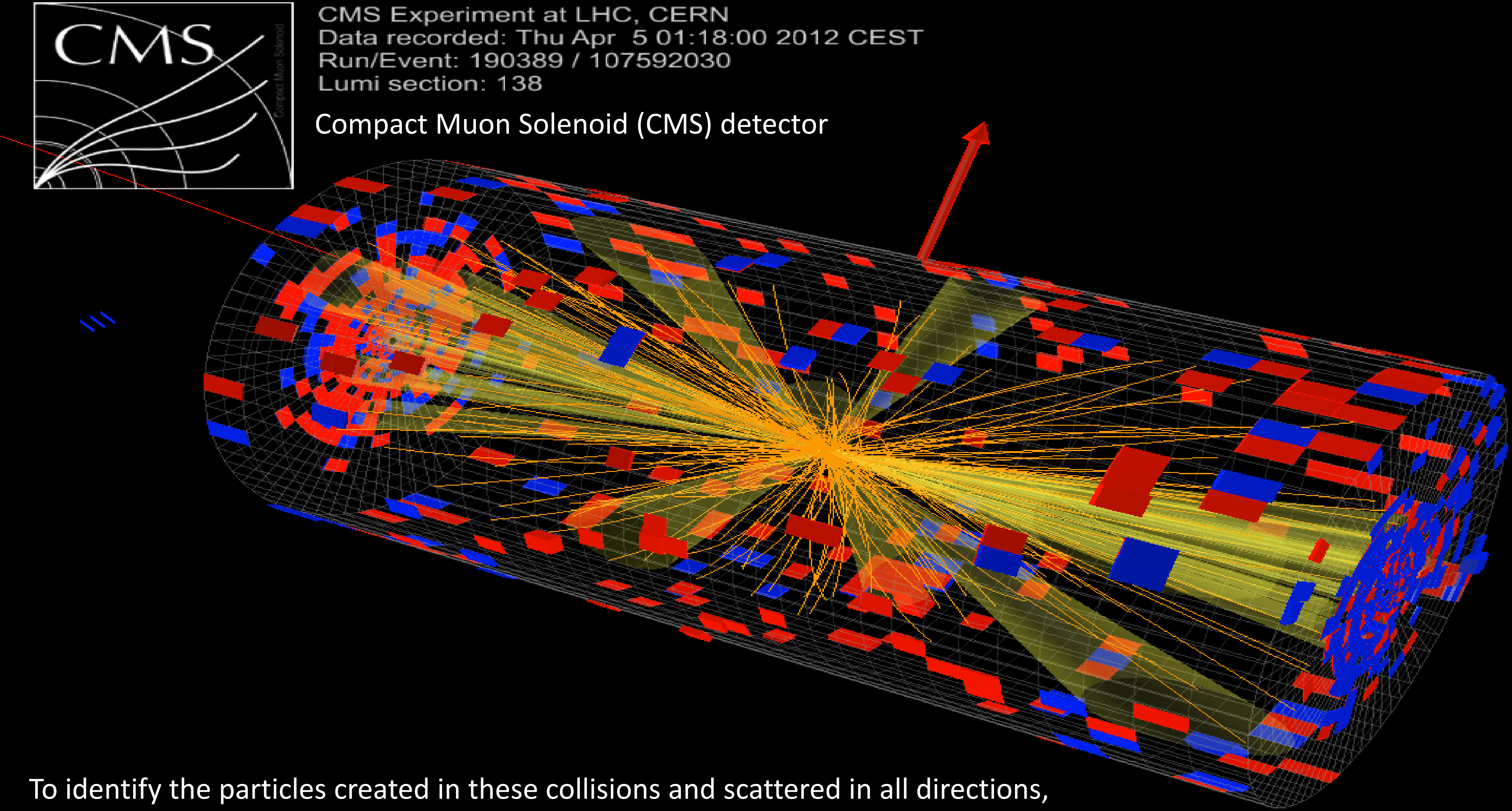
QUANTERA

The problem of particle tracking

The Tracking Problem

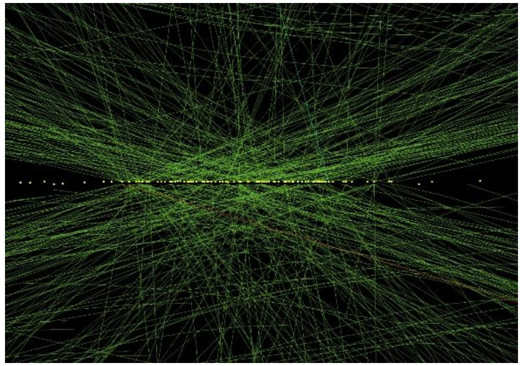


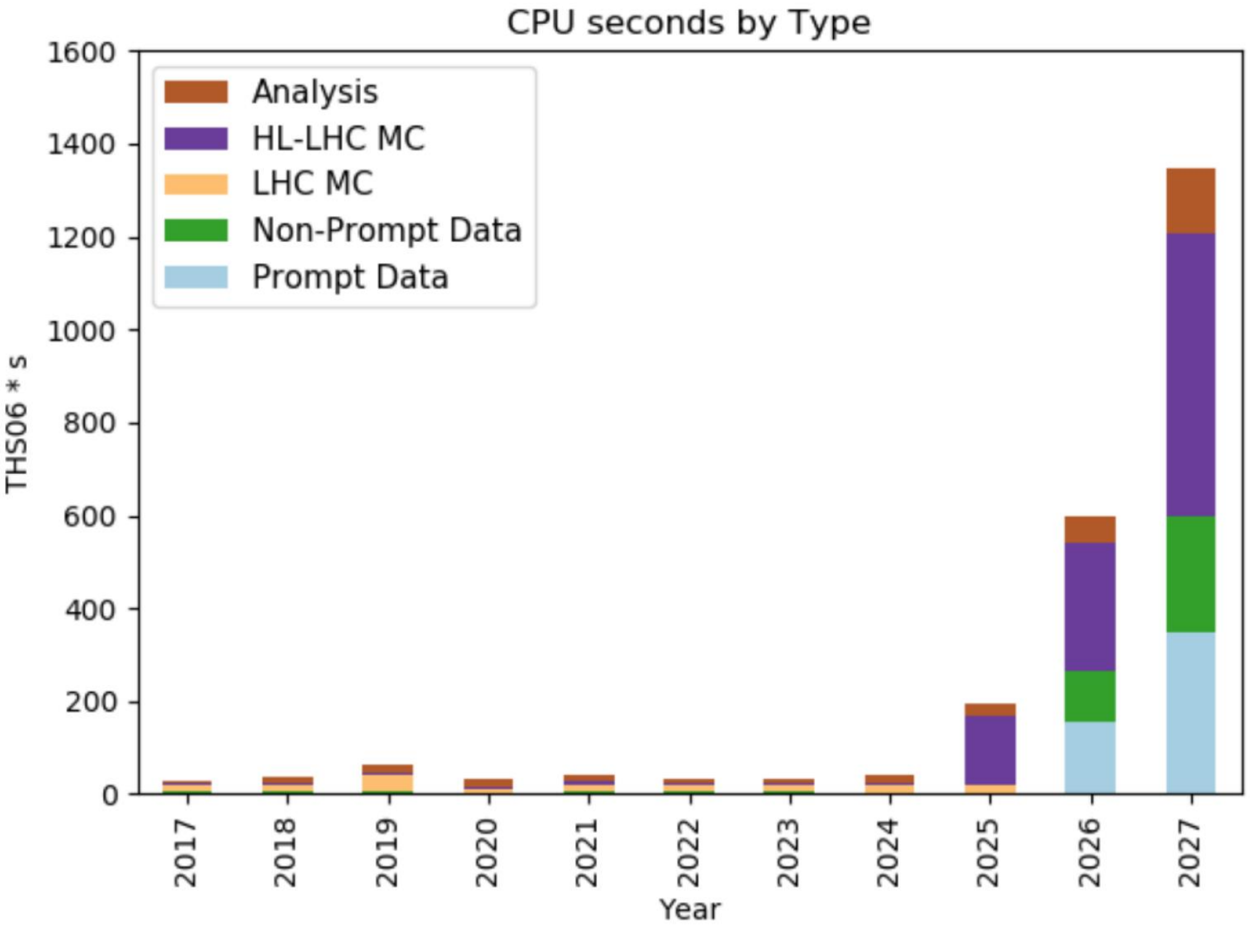
Compact Muon Solenoid (CMS) detector

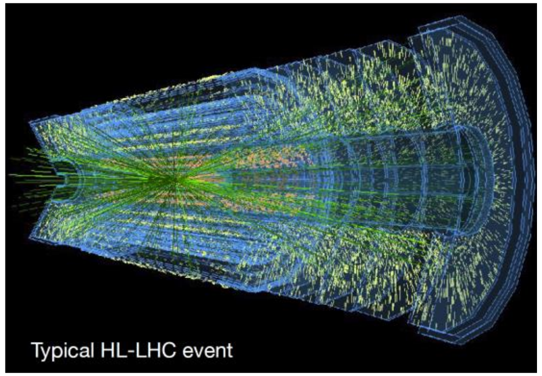


To identify the particles created in these collisions and scattered in all directions, we need to reconstruct their trajectories: tracking.

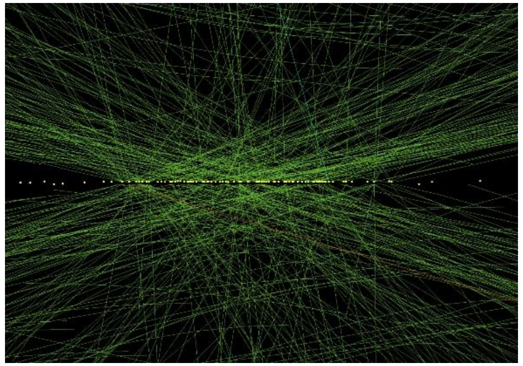
Tracking: a challenging computational problem

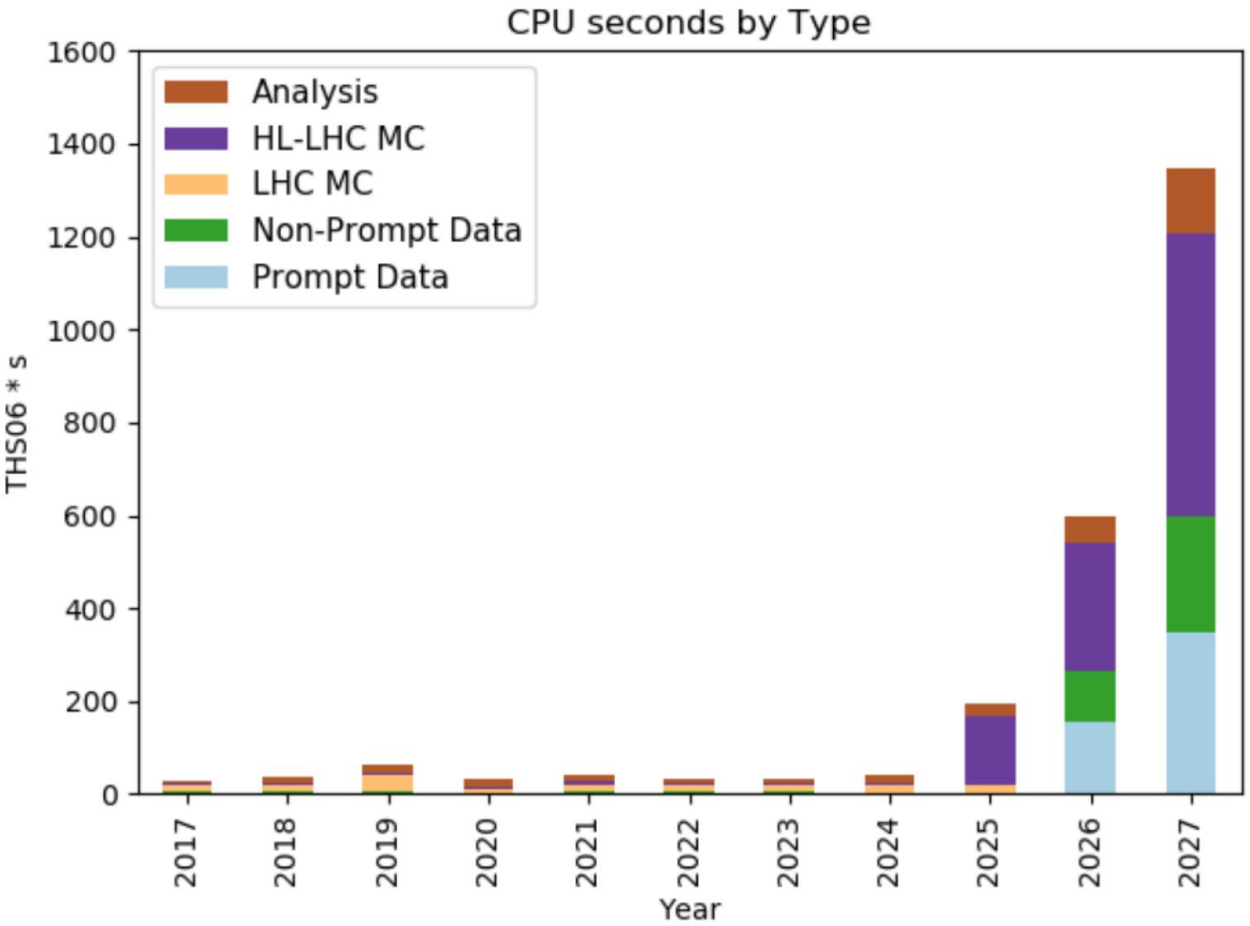


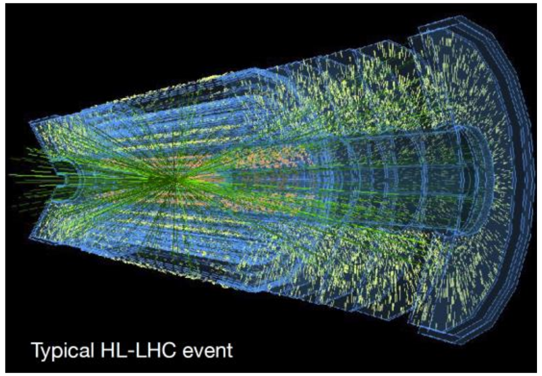




Tracking: a challenging computational problem







If computational performance does not meet the increasing demand, in HL-LHC or in the 100 TeV potential FCC, an immense amount of data will have to be discarded, significantly reducing the chances of observing rare events!

How hard is particle tracking?

Global vs. Local Methods

Global methods of pattern recognition have the common property to treat all hit information in an equal and unbiased way.

Essentially, they are clustering algorithms in some feature space.

Local methods reconstruct tracks one by one.

The algorithm that we describes is an typical example of this class.

Global vs. Local Methods

Global methods of pattern recognition have the common property to treat all hit information in an equal and unbiased way.

Essentially, they are clustering algorithms in some feature space.

Local methods reconstruct tracks one by one.

The algorithm that we describes is an typical example of this class.

Combinatorial Track Finder

The CMS Collaboration,
Description and performance of track and primary-vertex reconstruction with the CMS tracker,
Journal of Instrumentation **9**, 10009 (2014).

- **Seed generation:** Start with initial estimates of the track parameters (seeds).
- **Track finding:** Propagate tracks from layer to layer with Combinatorial Kalman Filter. Stop when outermost layers are reached.
- **Track cleaning:** Eliminate tracks corresponding to same particle.
- **Track fitting:** Smooth the trajectories.
- **Track selection:** Select based on quality criteria.

Combinatorial Track Finder

The CMS Collaboration,
Description and performance of track and primary-vertex reconstruction with the CMS tracker,
Journal of Instrumentation **9**, 10009 (2014).

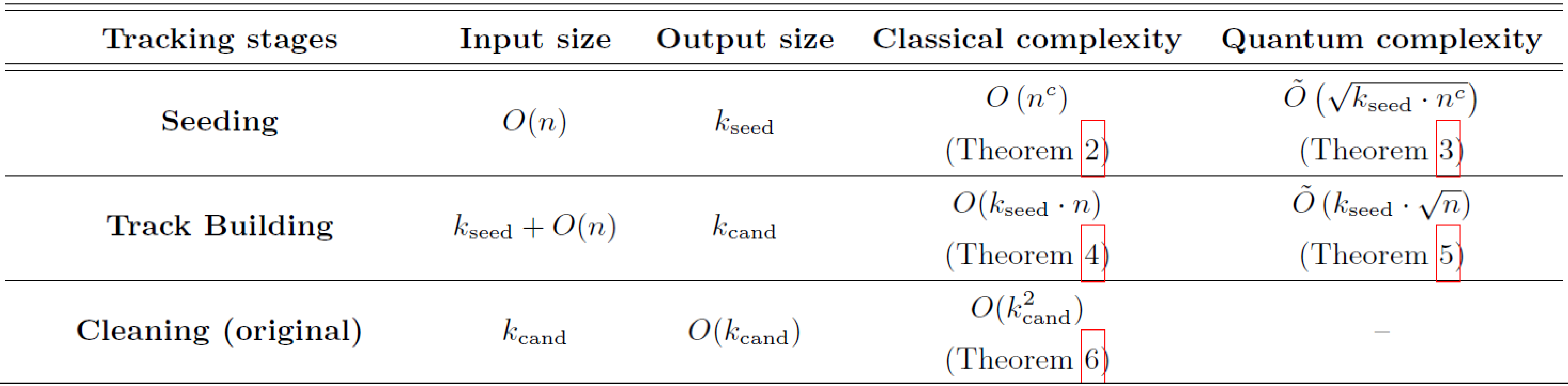
- **Seed generation:** Start with initial estimates of the track parameters (seeds).
- **Track finding:** Propagate tracks from layer to layer with Combinatorial Kalman Filter. Stop when outermost layers are reached.
- **Track cleaning:** Eliminate tracks corresponding to same particle.
- **Track fitting:** Smooth the trajectories.
- **Track selection:** Select based on quality criteria.

We want to develop a computational complexity analysis of this algorithm, and namely of these 5 stages, to:

- Establish formally how efficient this algorithm is.
- Investigate if it is optimal, or if it can be improved…
- … including with quantum computation.

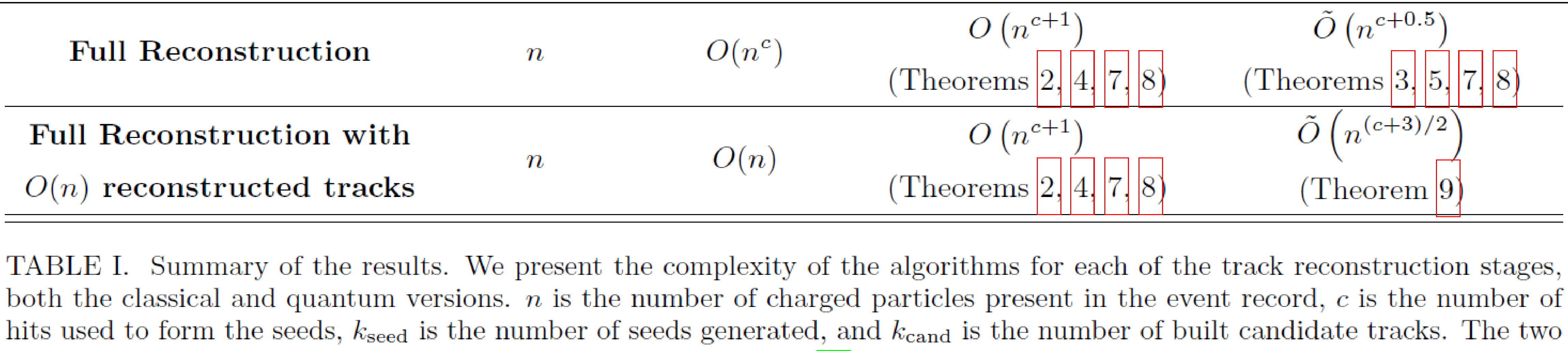
Tracking stages	**Input size**	**Output size**	**Classical complexity**	**Quantum complexity**
Seeding	$O(n)$	k_{seed}	$O\left(n^c\right)$ (Theorem 2)	$\tilde{O}\left(\sqrt{k_{\text{seed}}} \cdot n^c\right)$ (Theorem 3)
Track Building	$k_{\text{seed}} + O(n)$	k_{cand}	$O(k_{\text{seed}} \cdot n)$ (Theorem 4)	$\tilde{O}\left(k_{\text{seed}} \cdot \sqrt{n}\right)$ (Theorem 5)
Cleaning (original)	k_{cand}	$O(k_{\text{cand}})$	$O(k_{\text{cand}}^2)$ (Theorem 6)	–
Cleaning (improved)	k_{cand}	$O(k_{\text{cand}})$	$\tilde{O}(k_{\text{cand}})$ (Theorem 7)	–
Selection	$O(k_{\text{cand}})$	$O(k_{\text{cand}})$	$O(k_{\text{cand}})$ (Theorem 8)	–
Full Reconstruction	n	$O(n^c)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{c+0.5}\right)$ (Theorems 3, 5, 7, 8)
Full Reconstruction with $O(n)$ reconstructed tracks	n	$O(n)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{(c+3)/2}\right)$ (Theorem 9)

TABLE I. Summary of the results. We present the complexity of the algorithms for each of the track reconstruction stages, both the classical and quantum versions. n is the number of charged particles present in the event record, c is the number of hits used to form the seeds, k_{seed} is the number of seeds generated, and k_{cand} is the number of built candidate tracks. The two



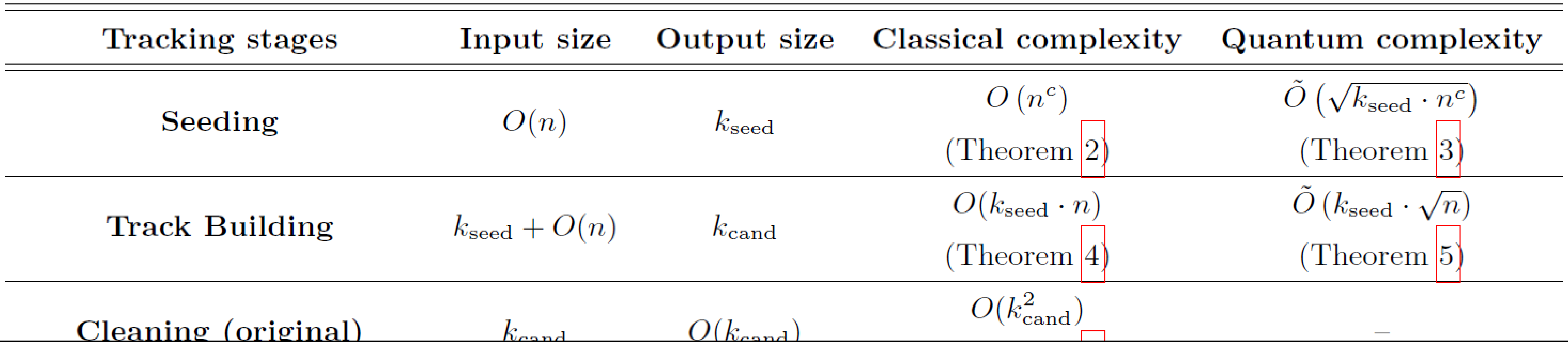
Tracking stages	Input size	Output size	Classical complexity	Quantum complexity
Seeding	$O(n)$	k_{seed}	$O\left(n^c\right)$ (Theorem 2)	$\tilde{O}\left(\sqrt{k_{\text{seed}}} \cdot n^c\right)$ (Theorem 3)
Track Building	$k_{\text{seed}} + O(n)$	k_{cand}	$O(k_{\text{seed}} \cdot n)$ (Theorem 4)	$\tilde{O}\left(k_{\text{seed}} \cdot \sqrt{n}\right)$ (Theorem 5)
Cleaning (original)	k_{cand}	$O(k_{\text{cand}})$	$O(k_{\text{cand}}^2)$ (Theorem 6)	–

Paraphrasing the Monty Python:
Every speed-up is special, every speed-up is sacred!



Full Reconstruction	n	$O(n^c)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{c+0.5}\right)$ (Theorems 3, 5, 7, 8)
Full Reconstruction with $O(n)$ reconstructed tracks	n	$O(n)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{(c+3)/2}\right)$ (Theorem 9)

TABLE I. Summary of the results. We present the complexity of the algorithms for each of the track reconstruction stages, both the classical and quantum versions. n is the number of charged particles present in the event record, c is the number of hits used to form the seeds, k_{seed} is the number of seeds generated, and k_{cand} is the number of built candidate tracks. The two

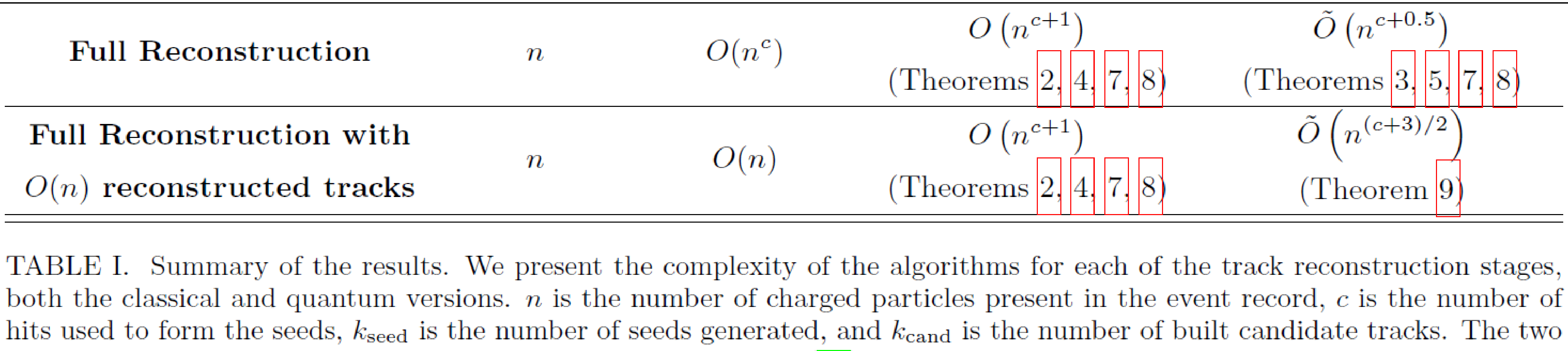


Tracking stages	Input size	Output size	Classical complexity	Quantum complexity
Seeding	$O(n)$	k_{seed}	$O\left(n^c\right)$ (Theorem 2)	$\tilde{O}\left(\sqrt{k_{\text{seed}}} \cdot n^c\right)$ (Theorem 3)
Track Building	$k_{\text{seed}} + O(n)$	k_{cand}	$O(k_{\text{seed}} \cdot n)$ (Theorem 4)	$\tilde{O}\left(k_{\text{seed}} \cdot \sqrt{n}\right)$ (Theorem 5)
Cleaning (original)	k_{cand}	$O(k_{\text{cand}})$	$O(k_{\text{cand}}^2)$	–

D. Magano, A. Kumar, M. Kālis, A. Locāns, A. Glos, S. Pratapsi, G. Quinta, M. Dimitrijevs,
A. Rivošs, P. Bargassa, J. Seixas, A. Ambainis, Y. Omar

Quantum speedup for track reconstruction in particle accelerators

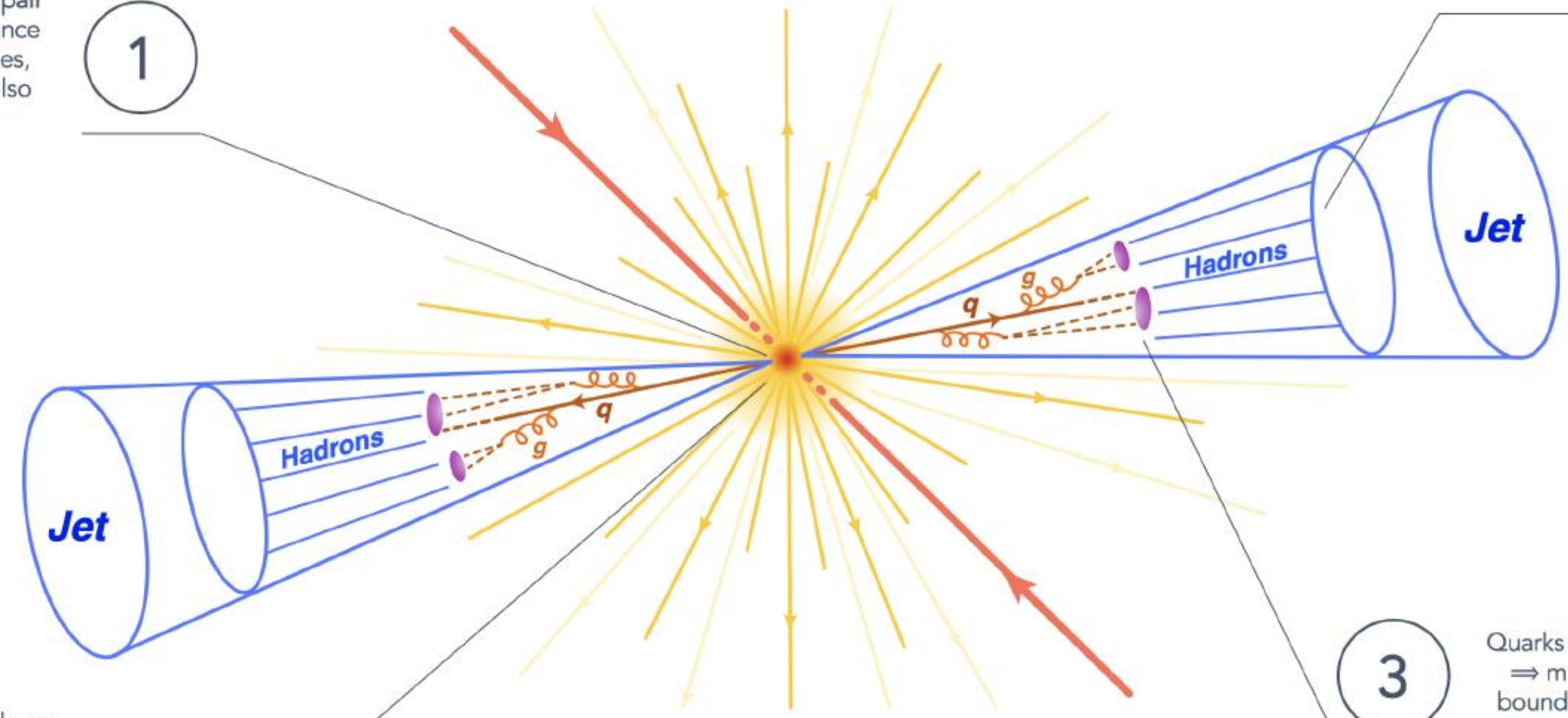
Physical Review D **105**, 076012 (2022).



Full Reconstruction	n	$O(n^c)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{c+0.5}\right)$ (Theorems 3, 5, 7, 8)
Full Reconstruction with $O(n)$ reconstructed tracks	n	$O(n)$	$O\left(n^{c+1}\right)$ (Theorems 2, 4, 7, 8)	$\tilde{O}\left(n^{(c+3)/2}\right)$ (Theorem 9)

TABLE I. Summary of the results. We present the complexity of the algorithms for each of the track reconstruction stages, both the classical and quantum versions. n is the number of charged particles present in the event record, c is the number of hits used to form the seeds, k_{seed} is the number of seeds generated, and k_{cand} is the number of built candidate tracks. The two

Jet Clustering



① When a **quark-antiquark pair** is produced, as the distance between quarks increases, the separation energy also increases.

② For a sufficiently **large distance**, the energy will be enough for a **new**, more favorable **pair** to be produced.

③ Quarks obey color-confinement ⟹ must evolve to colorless bound states – **hadronisation**.

④ The hadrons and subsequent final stable particles tend to travel all in the same direction, forming **collimated sprays of particles - jets**.

Adiabatic Quantum Algorithm for Multijet Clustering

- A novel quantum annealing binary clustering algorithm
- Outperforms the Thrust algorithm
- Can be extended to any number of jets

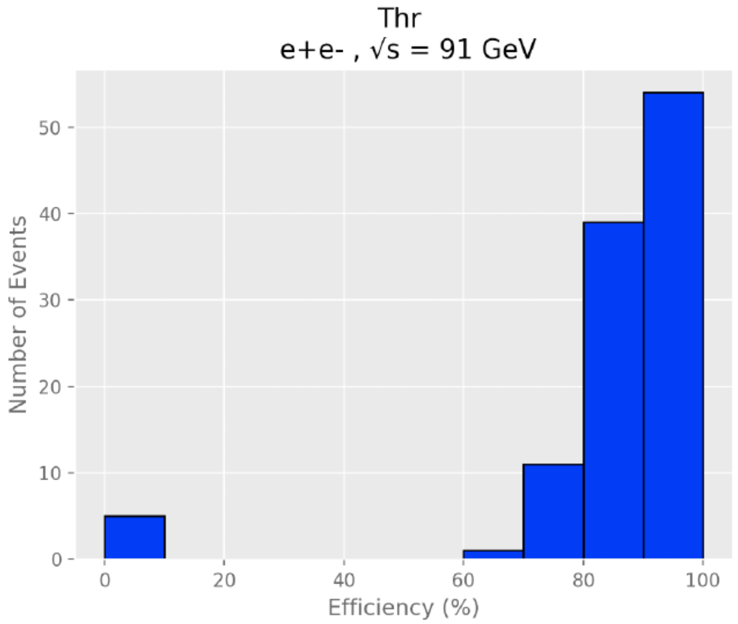


Figure 2: Histogram of the obtained efficiency for the Thrust-based algorithm by Wei *et al.* [3], ϵ_{Thr}.

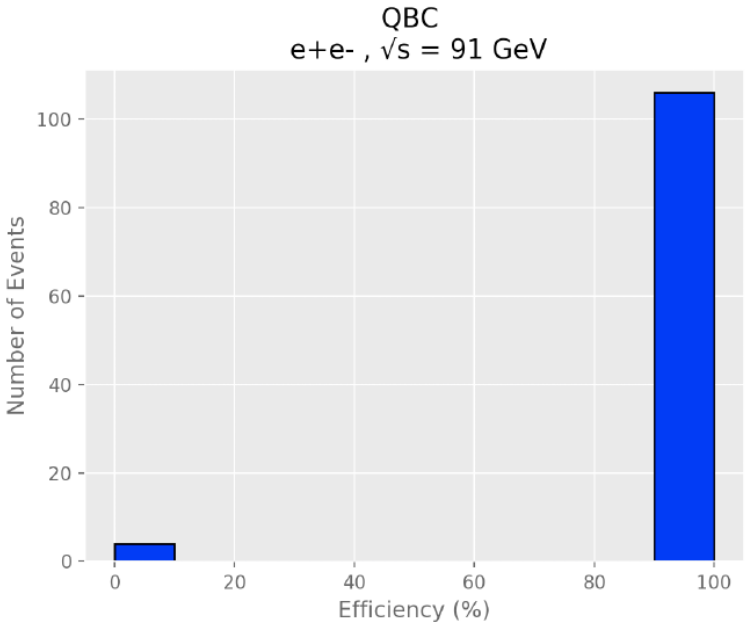


Figure 1: Histogram of the obtained efficiency for the proposed quantum binary clustering algorithm, ϵ_{QBC}.

Diogo Pires, Yasser Omar, João Seixas

Adiabatic Quantum Algorithm for Multijet Clustering in High Energy Physics

arXiv:2012.14514 (2020)

A Digital Quantum Algorithm for Jet Clustering

- The first digital quantum algorithm to tackle jet clustering. Based on quantum k-means.
- Comparable, yet generally lower complexity relative to the classical state-of-the-art k_t clustering algorithm.

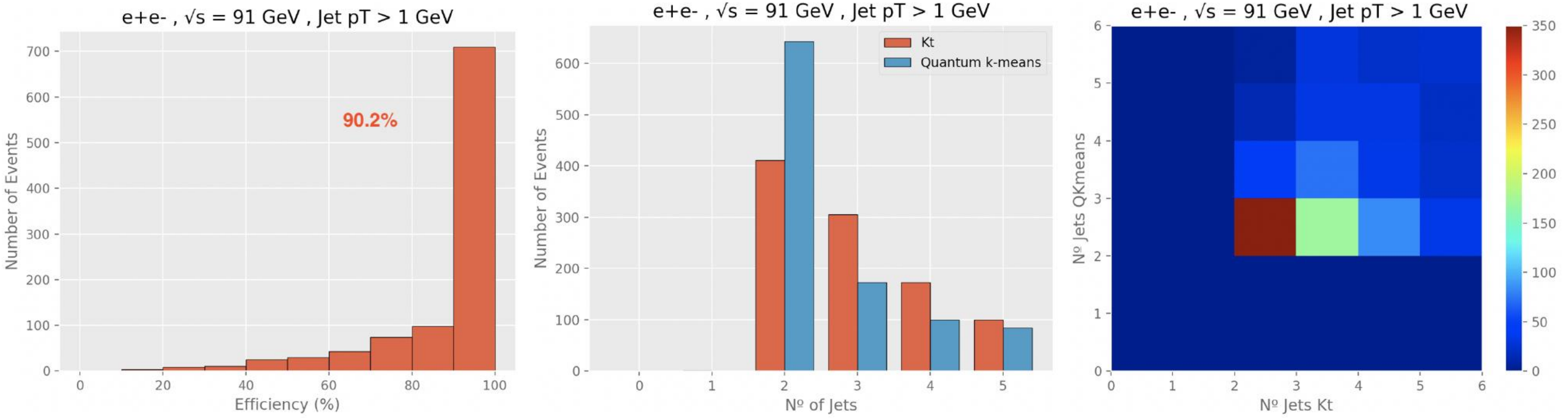


Figure 7. Histograms of the obtained efficiencies ε (on the left), number of found meaningful jets K (middle), and heatmap of the number of jets found by the proposed algorithm against those found by the k_t benchmark for a jet p_T cutoff of 1 GeV.

Diogo Pires, Pedrame Bargassa, João Seixas, Yasser Omar

A Digital Quantum Algorithm for Jet Clustering in High-Energy Physics

arXiv:2101.05618 (2021)

QuantHEP

Quantum algorithm for the classification of supersymmetric top quark events

Motivation: Improve approach based on zoomed Quantum Annealing (QA) for classification of stop events

- Run on Chimera graph of D-Wave
- Put QA on equal footing vs classical Machine Learning (ML) tool:
  - based on same variables to build a strong classifier R
  - prepare data w Principal Component Analysis before feeding to QA
- Explore many sets of variables & augmentation schemes

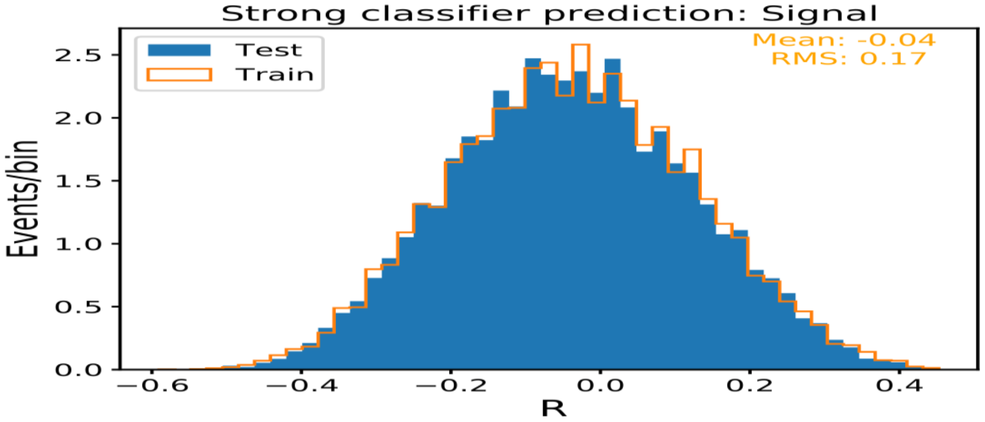


Figure of Merit including stat. & sys. uncertainties: more complete than Efficiency(S) vs Efficiency(B):

BDT: 1.44 ± 0.06 **QA: 1.57 ± 0.24**

Promising: QA performs at least as well as classical Machine Learning

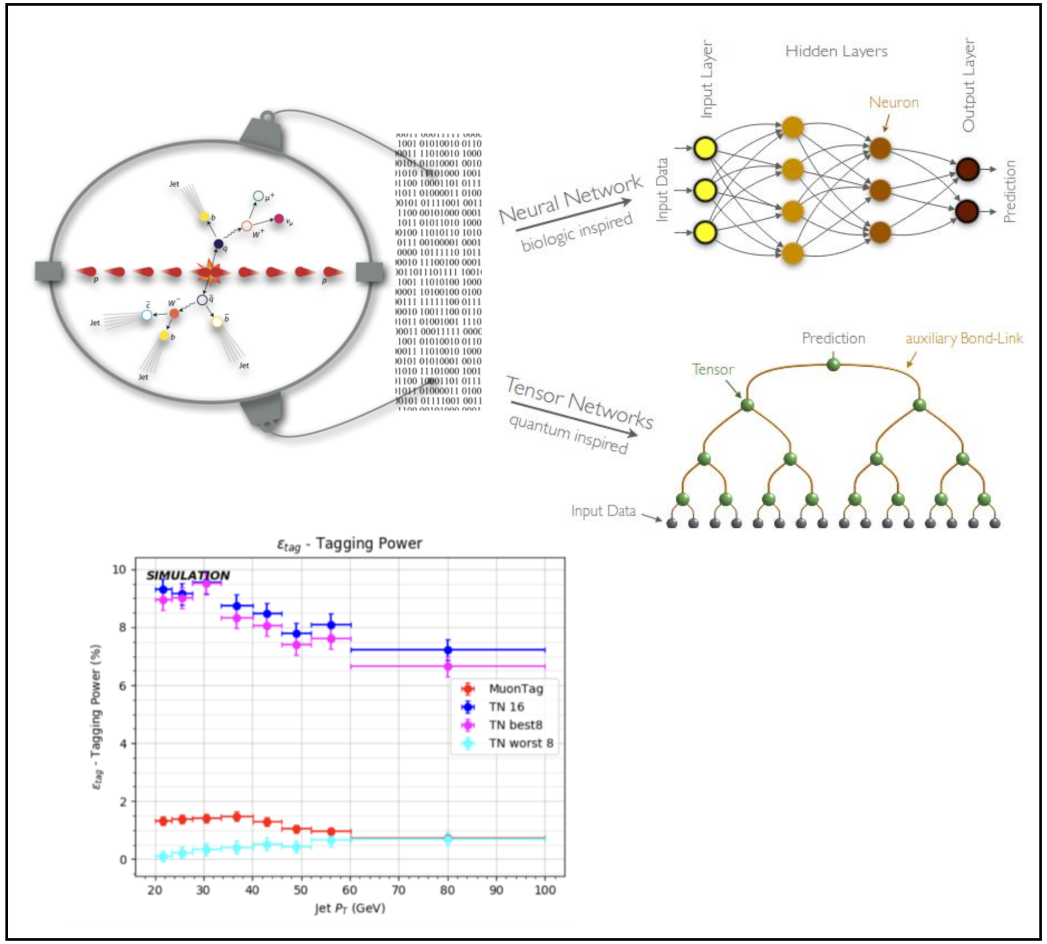
P. Bargassa, T. Cabos, A. Oudot, T. Hessel, S. Cavinato, Physical Review D **104**, 096004 (2021)

Tensor Network Machine Learning: LHCb data analysis

Goal/Motivation: generalization and application of quantum-inspired tensor network algorithms to a very challenging machine-learning problem in high-energy physics: the analysis and classification of data produced by the Large Hadron Collider at CERN.

Key results:

- study of efficient protocols for encoding machine learning problems in tree tensor network (TTN) architectures;
- classification of the charge of b-quarks (i.e. b or $\bar{b}$) produced in proton–proton collisions at LHC with TTN algorithms;
- analysis of the performances of TTN algorithms and comparison with standard neural-network approach.



Paper reference: **npj Quantum Inf 7, 111 (2021)**

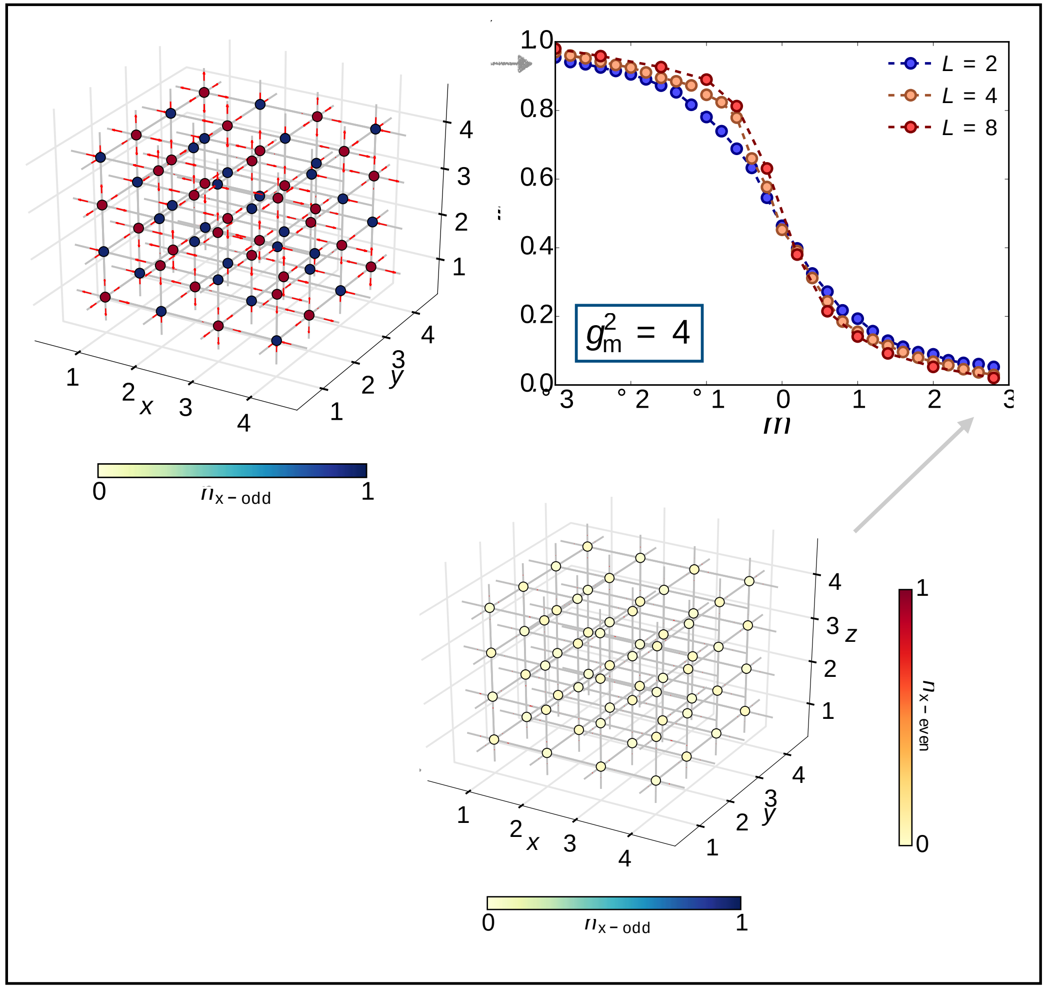
(3+1)D Quantum Electrodynamics at finite density with Tensor Networks

Goal/Motivation: generalization of sign-problem-free tensor network methods to high-dimensional lattice gauge theories (LGTs).

Key results:

- extension of high-performance tensor network algorithms to (3+1)D LGTs;
- study of the low-energy phase diagram of Quantum Electrodynamics (QED) at zero and finite charge density;
- analysis of the confinement properties of the QED model at weak and strong coupling;
- study of non-perturbative charge-screening effects.

Paper reference: **Nature Communications 12, 3600 (2021)**



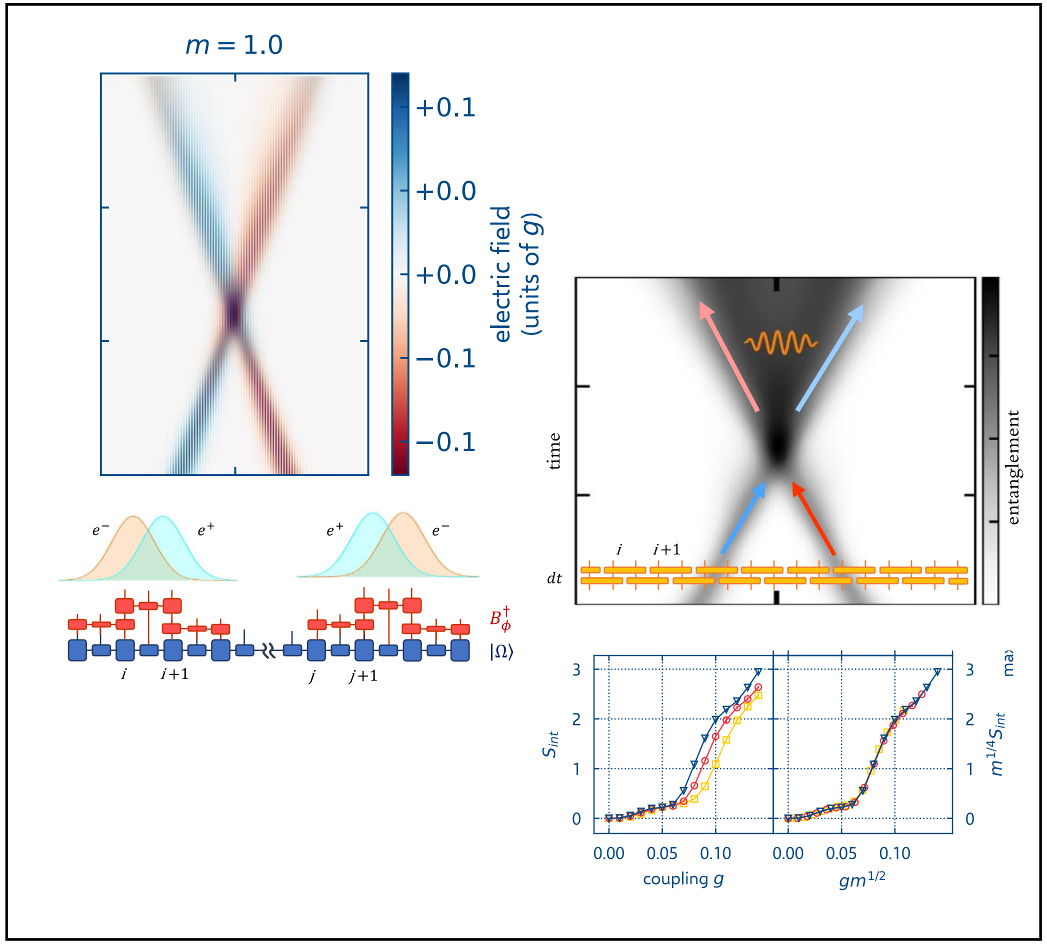
QuantHEP

Tensor Networks for scattering dynamics in (1+1)D QED

Goal/Motivation: development of tensor network protocols for preparing initial meson wave packets with given momentum and position, and simulation of the real-time dynamics of scattering events in lattice gauge theories.

Key results:

- analysis of efficient strategies for encoding meson wave packets on tensor network algorithms;
- simulation of the real-time dynamics of two initially separated colliding mesons in (1+1)D Quantum Electrodynamics.
- measurement of scattering amplitudes and entanglement generated by the scattering process;
- identification of two different regimes for the asymptotic entanglement.



Paper reference: **Phys. Rev. D 104, 114501 (2021)**

QuantHEP

Leptonic CP violation and neutrino entanglement

- We show how a minimization of quantum entanglement between the oscillating flavors of a neutrino leads to a unique prediction for the CP-violation phase in the neutrino sector without assuming extra symmetries in the Standard Model.

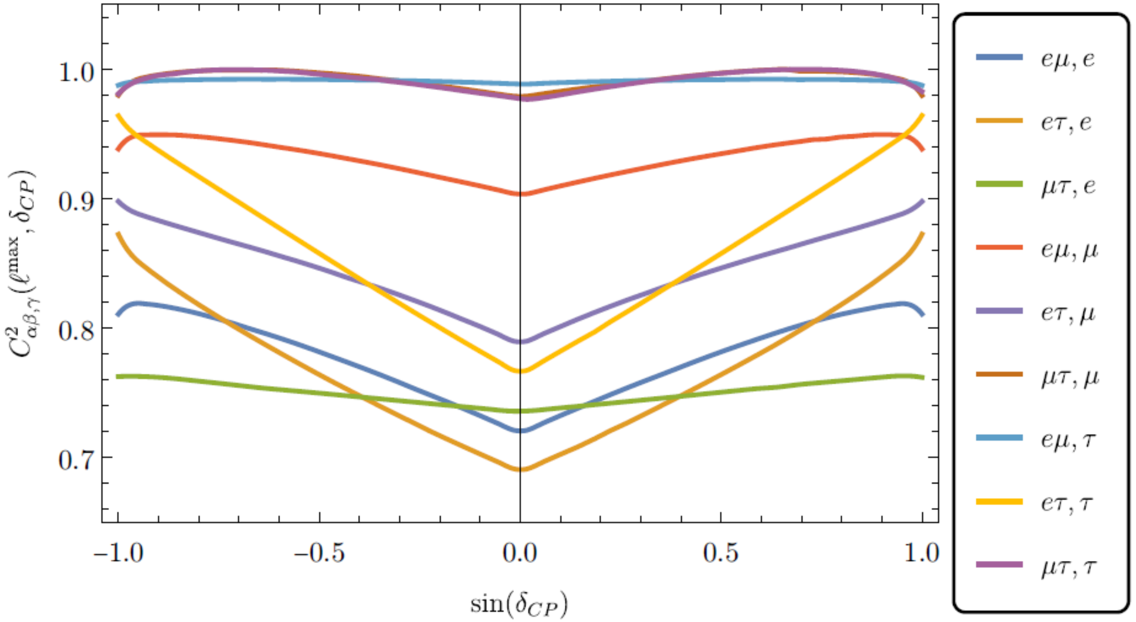
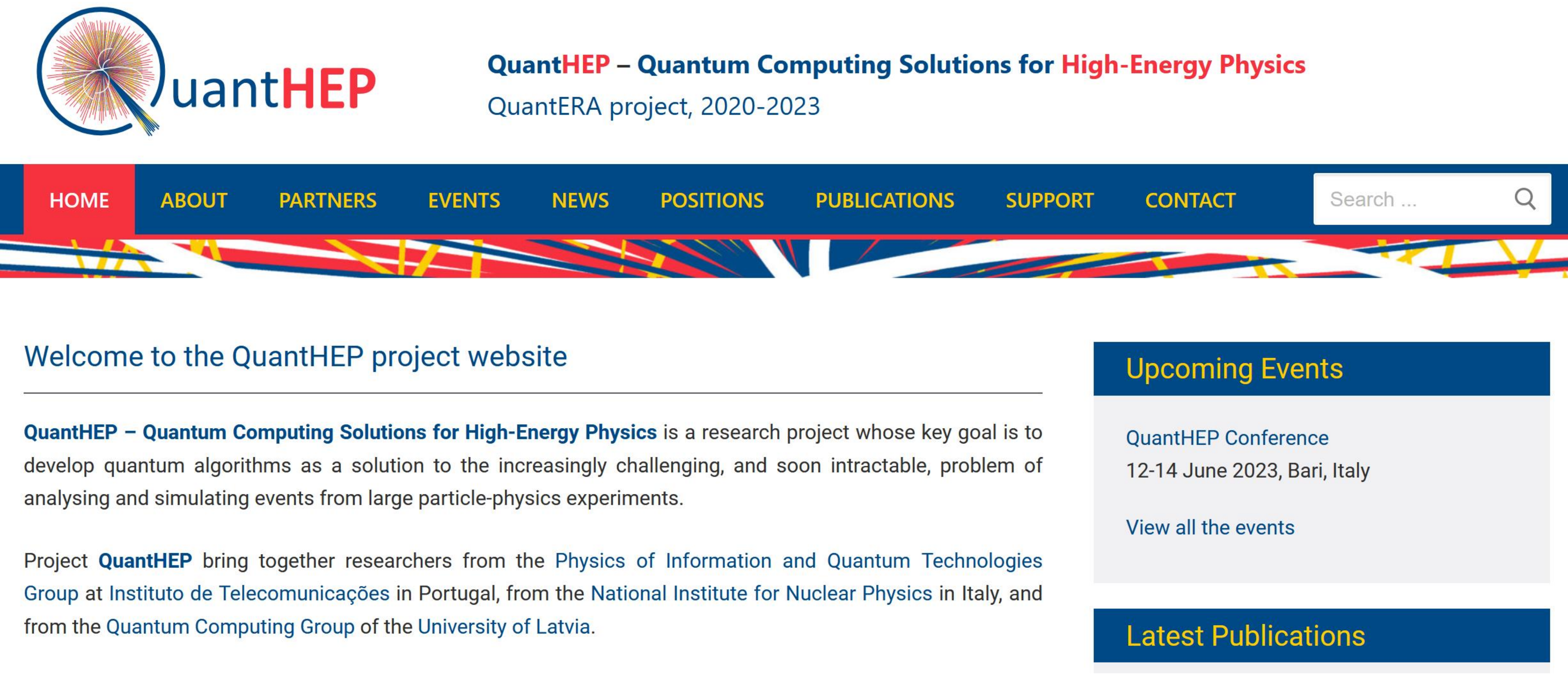


Figure 3. The concurrences between all possible pairs of neutrino flavors, for all initial neutrino flavors possibilities. It is found numerically that the global minimum of all these functions is achieved for the electron/tau neutrino flavor case, starting with an initial electron neutrino. All free parameters apart from δ_{CP} are fixed according to the most recent experimental data [19].

Gonçalo M. Quinta, Alexandre Sousa, Yasser Omar

Predicting leptonic CP violation via minimization of neutrino entanglement

arXiv:2207.03303 (2022)



QuantHEP – Quantum Computing Solutions for High-Energy Physics

QuantERA project, 2020-2023

Welcome to the QuantHEP project website

QuantHEP – Quantum Computing Solutions for High-Energy Physics is a research project whose key goal is to develop quantum algorithms as a solution to the increasingly challenging, and soon intractable, problem of analysing and simulating events from large particle-physics experiments.

Project **QuantHEP** bring together researchers from the Physics of Information and Quantum Technologies Group at Instituto de Telecomunicações in Portugal, from the National Institute for Nuclear Physics in Italy, and from the Quantum Computing Group of the University of Latvia.

Upcoming Events

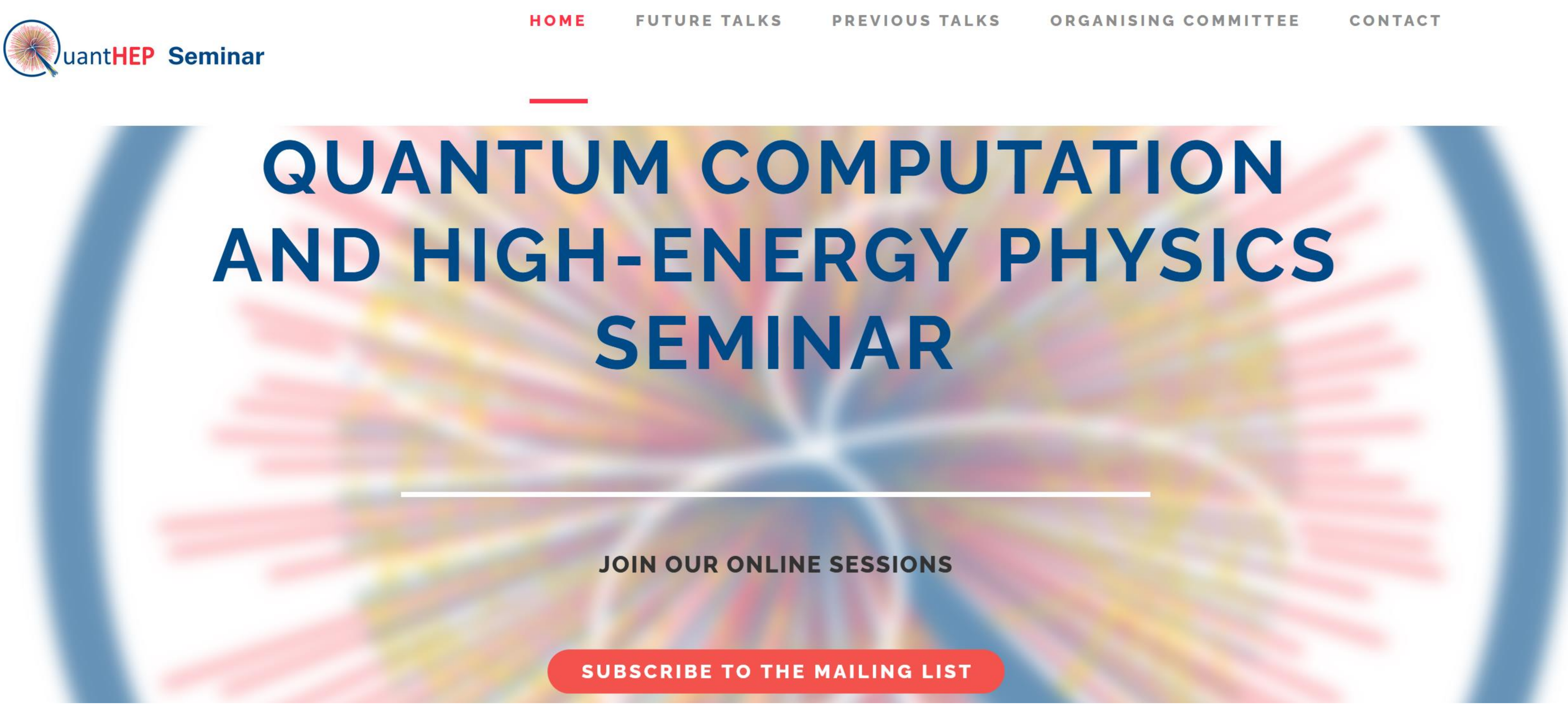
QuantHEP Conference
12-14 June 2023, Bari, Italy

View all the events

Latest Publications

quanthep.eu

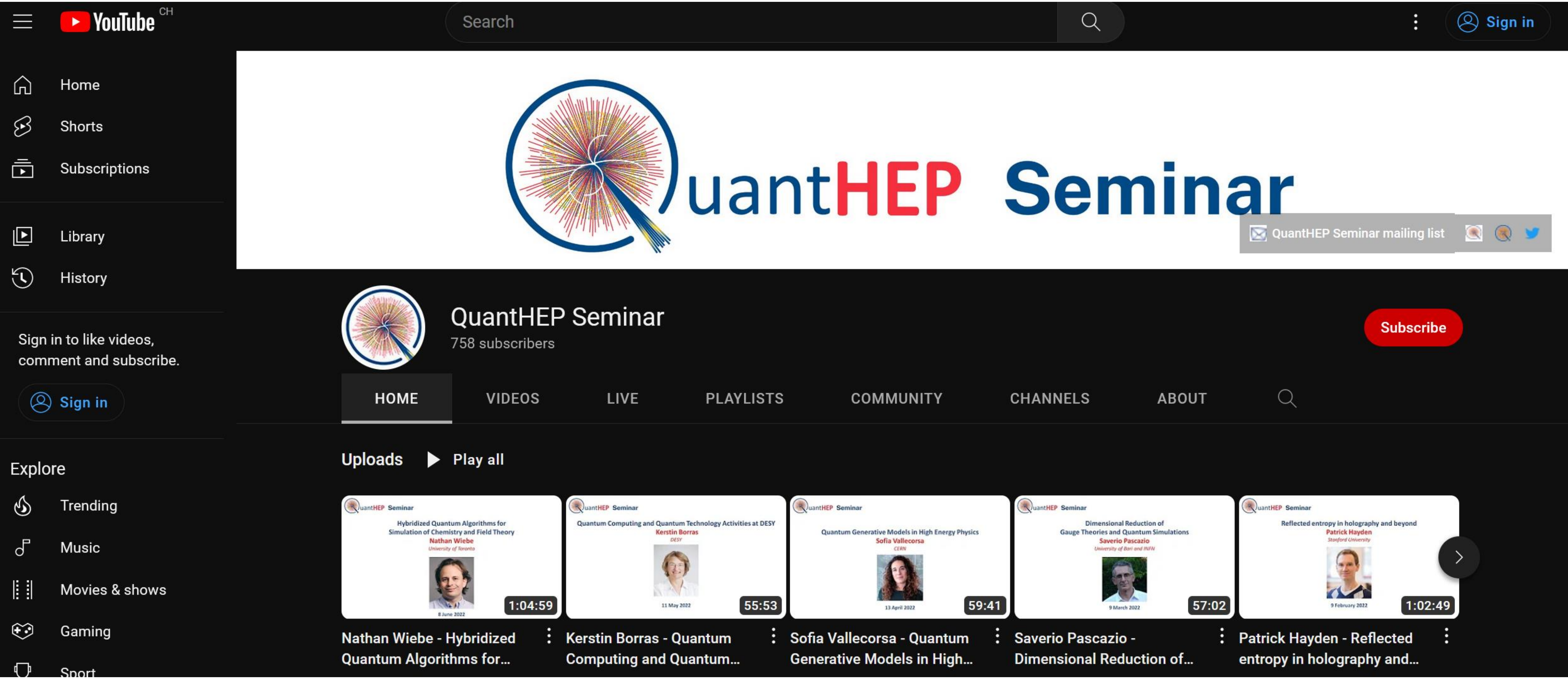
@QuantHEP



QUANTUM COMPUTATION AND HIGH-ENERGY PHYSICS SEMINAR

JOIN OUR ONLINE SESSIONS

quanthep-seminar.org



Sign in to like videos, comment and subscribe.

QuantHEP Seminar

758 subscribers

QuantHEP Seminar — Hybridized Quantum Algorithms for Simulation of Chemistry and Field Theory — Nathan Wiebe — University of Toronto — 8 June 2022

Nathan Wiebe - Hybridized Quantum Algorithms for...

QuantHEP Seminar — Quantum Computing and Quantum Technology Activities at DESY — Kerstin Borras — DESY — 11 May 2022

Kerstin Borras - Quantum Computing and Quantum...

QuantHEP Seminar — Quantum Generative Models in High Energy Physics — Sofia Vallecorsa — CERN — 13 April 2022

Sofia Vallecorsa - Quantum Generative Models in High...

QuantHEP Seminar — Dimensional Reduction of Gauge Theories and Quantum Simulations — Saverio Pascazio — University of Bari and INFN — 9 March 2022

Saverio Pascazio - Dimensional Reduction of...

QuantHEP Seminar — Reflected entropy in holography and beyond — Patrick Hayden — Stanford University — 9 February 2022

Patrick Hayden - Reflected entropy in holography and...

www.youtube.com/c/QuantHEPSeminar

QuantHEP Conference 2023

12-14 June 2023, in Bari, Italy

A regular conference for the QT and HEP communities to meet, discuss the latest results and future directions, as well as get training in QT & HEP.

Physics of Information & Quantum Technologies Group

We gratefully acknowledge the support from:

John Templeton Foundation

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

MARIE CURIE ACTIONS

"la Caixa" Foundation

cost

European Science Foundation

SEVENTH FRAMEWORK PROGRAMME

HORIZON 2020

QUANTUM FLAGSHIP

QUANTERA

Physics of Information & Quantum Technologies Group

We currently have 3 new Post-doc positions and 3 new PhD Student positions available. Apply now:

www.phys-info.org

QuantHEP

Quantum Computing Solutions for High-Energy Physics

Yasser Omar

contact.yasser@pqi.pt

PQI – Portuguese Quantum Institute

Instituto Superior Técnico, Universidade de Lisboa

Physics of Information and Quantum Technologies Group, CeFEMA,

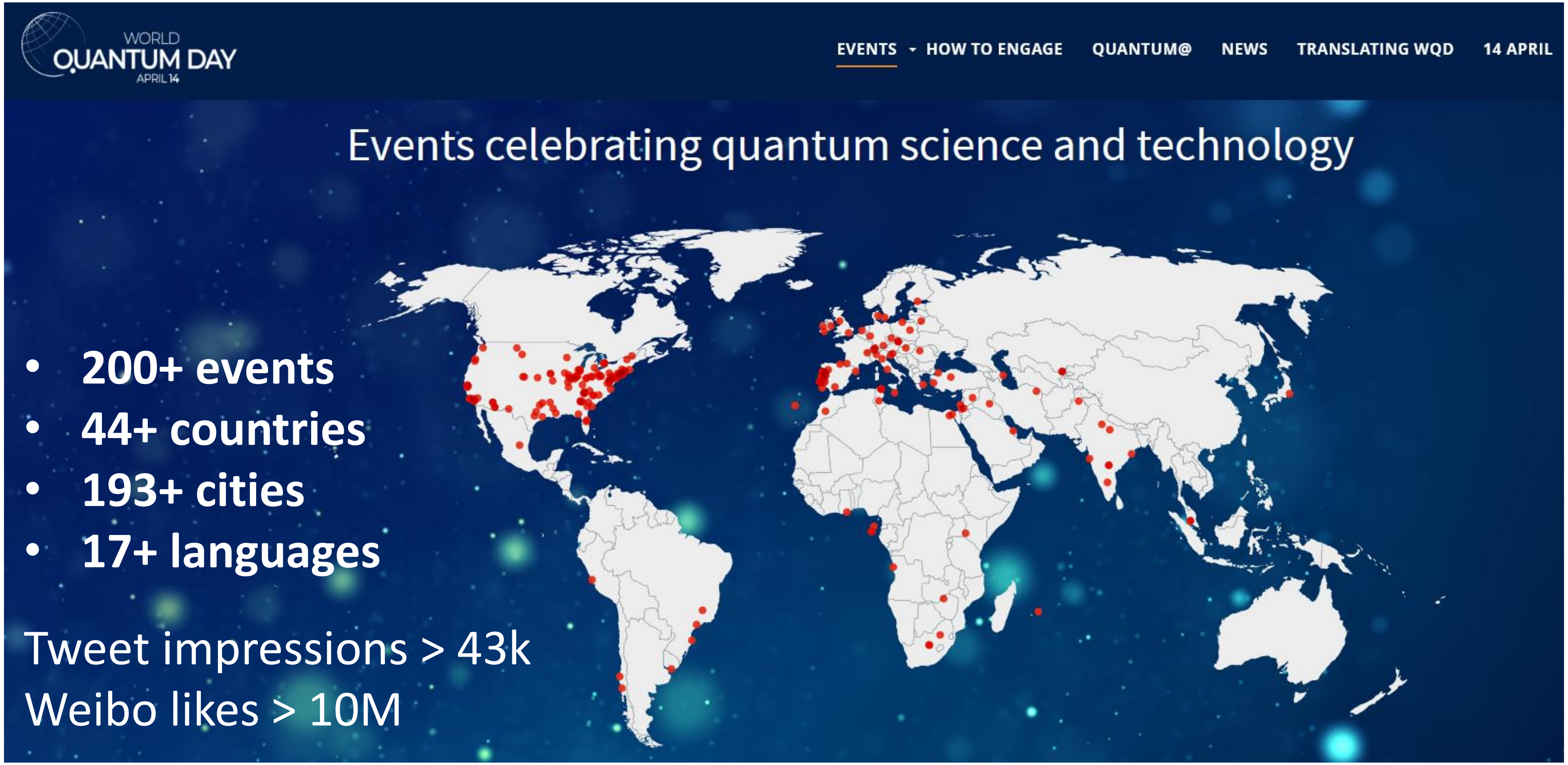
PORTUGUESE
QUANTUM
INSTITUTE

TÉCNICO LISBOA

CeFEMA
Center of Physics and Engineering of Advanced Materials

WORLD
QUANTUM DAY
APRIL 14

- 200+ events covering Africa, the Americas, Asia, and Europe!
- Launched Quantum@School and Quantum@Museum projects.
- Join QuCATS in celebrating the World Quantum Day in 2023!
- 14 April: European Quantum Day?



Events celebrating quantum science and technology

- 200+ events
- 44+ countries
- 193+ cities
- 17+ languages

Tweet impressions > 43k
Weibo likes > 10M

worldquantumday.org

@WorldQuantumDay