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ASFAE ASTROFÍSICA Y FÍSICA DE ALTAS ENERGÍAS

High performance and quantum computing in astrophysics and particle physics

Germán RODRIGO

Instituto de Física Corpuscular IFIC
Universitat de València - Consejo Superior de Investigaciones Científicas

4-6 Marzo 2024, Alicante

ASFAE/2022/020	RAMOS MARTÍNEZ, ALBERTO MENA, OLGA	Ondas GRavitacionales, Axiones y Materia Oscura, Lattice e Inteligencia Artificial	CSIC-IFIC	**GRAMOLA**
ASFAE/2022/009	RODRIGO GARCÍA, GERMÁN VTE. GÓNZÁLEZ ALONSO, MARTÍN	Algoritmos cuánticos en fenomenología de partículas elementales	CSIC-IFIC	**QPHENO**

Vniversitat de València · Universitat Politècnica de València · Universitas Miguel Hernández · Universitat d'Alacant Universidad de Alicante · CSIC Consejo Superior de Investigaciones Científicas

ASFAE/2022/020 - GRAMOLA: Ondas **GR**avitacionales, **A**xiones y **M**ateria **O**scura, **L**attice e Inteligencia **A**rtificial

GRAMOLA is one of the projects of the SOM group

Flavour and Origin of Matter
Sabor y Origen de la Materia

299.843 € granted . This money has been invested in:

PostDoctoral Researcher

Miguel García Folgado

New HPC Equipment

The ASFAE's research projects acknowledge the financial support from the MCIU with funding from the European Union NextGenerationEU and Generalitat Valenciana.

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List of HPC equipment purchased

Parallel Computing

10 x Working nodes:

- InfiniBand 200 Gb/s
- 2 x CPU AMD MILAN 7453 (28 cores, 2.75 GHz)
- Memory: 256 GB DDR4-3200

~ 95.000 €

Serial Computing

2 x Working nodes:

- 2 x CPU AMD GENOA 9454 (48 cores, 2.75 GHz)
- Memory: 384 GB DDR5-4800

~ 35.000 €

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ASFAE/2022/009 - QPHENO: Algoritmos cuánticos en fenomenología de partículas elementales

Germán RODRIGO (IP1)
Martín GONZÁLEZ ALONSO (IP2)

Norma Selomit RAMÍREZ URIBE (UA Sinaloa MX)
German F.R. SBORLINI (U. Salamanca)
Leandro J. CIERI
Luiz H. VALE SILVA
Jorge MARTÍNEZ DE LEJARZA
Andrés E. RENTERÍA OLIVO
David F. RENTERÍA ESTRADA
Konstantinos PYRETZIDIS
Victor BRESÓ PLA
David DÍAZ CALDERÓN
Andrea AUTIERI

new research line as part of IFIC INSTITUT DE FÍSICA CORPUSCULAR | LHCPHENO theory group

with ASFAE2022/009 | PID2020-114473GB-I00 | PROMETEO/2021/071

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ASFAE/2022/009 - QPHENO: Algoritmos cuánticos en fenomenología de partículas elementales

David Francisco
RENTERÍA ESTRADA
(now GRISOLIA - GVA)

Avanzar en el desarrollo de algoritmos cuánticos y su aplicación en física de partículas para obtener predicciones teóricas más allá del estado actual de la técnica, y explorar sus ventajas como solución a tareas de optimización, clasificación y aprendizaje automático.

Konstantinos
PYRETZIDIS

Andrés Ernesto
RENTERÍA OLIVO

MAC STUDIO - M2 ULTRA, CPU de 24 Núcleos, GPU de 60 Núcleos, Neural Engine de 32 Núcleos, RAM de 128 GB y 8 TB de almacenamiento SSD

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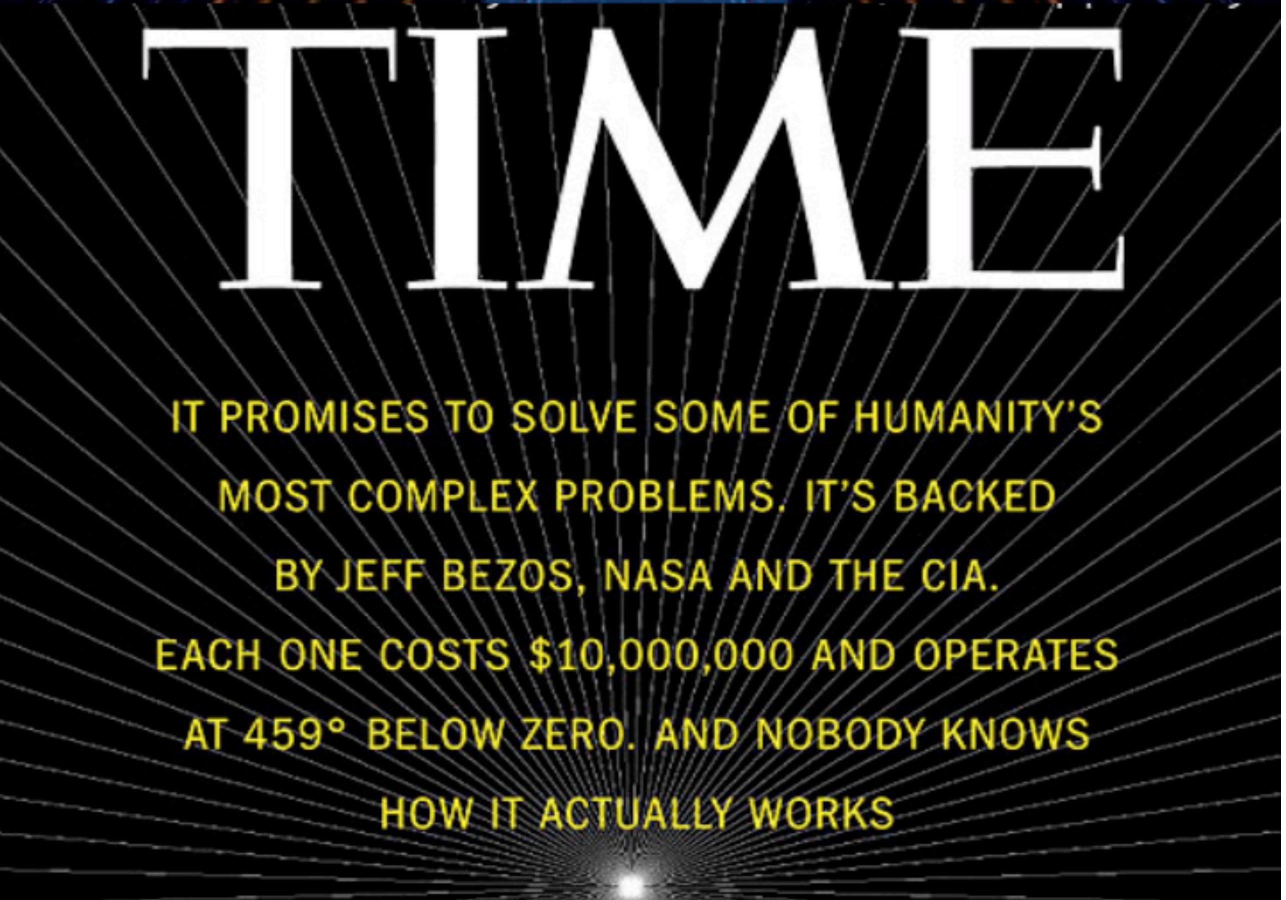
physicsworld
physicsworld.com
Volume 34 No 12 December 2021
Quantum technologies
On the cusp of a revolution


TIME
IT PROMISES TO SOLVE SOME OF HUMANITY'S
MOST COMPLEX PROBLEMS. IT'S BACKED
BY JEFF BEZOS, NASA AND THE CIA.
EACH ONE COSTS $10,000,000 AND OPERATES
AT 459° BELOW ZERO. AND NOBODY KNOWS
HOW IT ACTUALLY WORKS


hype
physicsworld.com
12 December 2021
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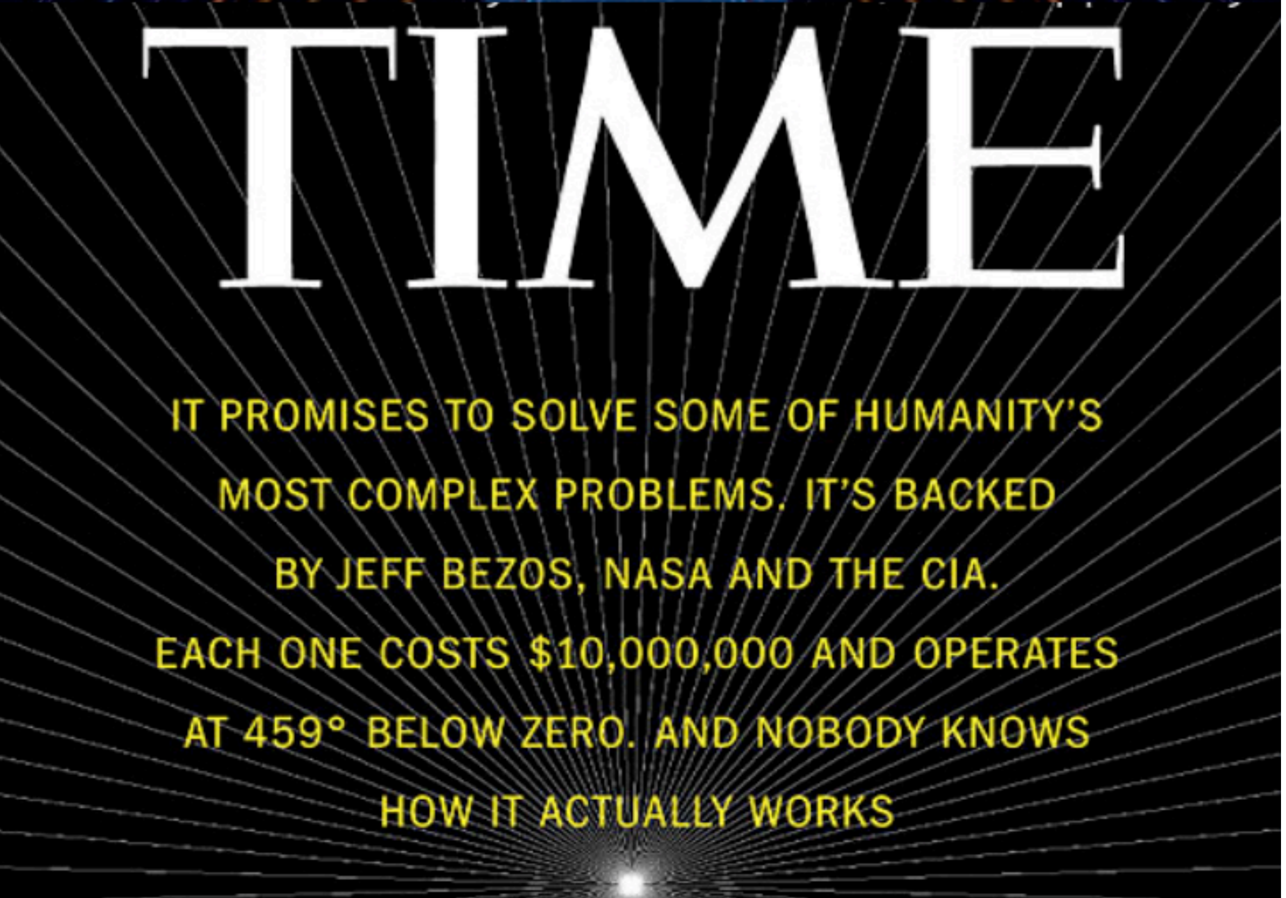
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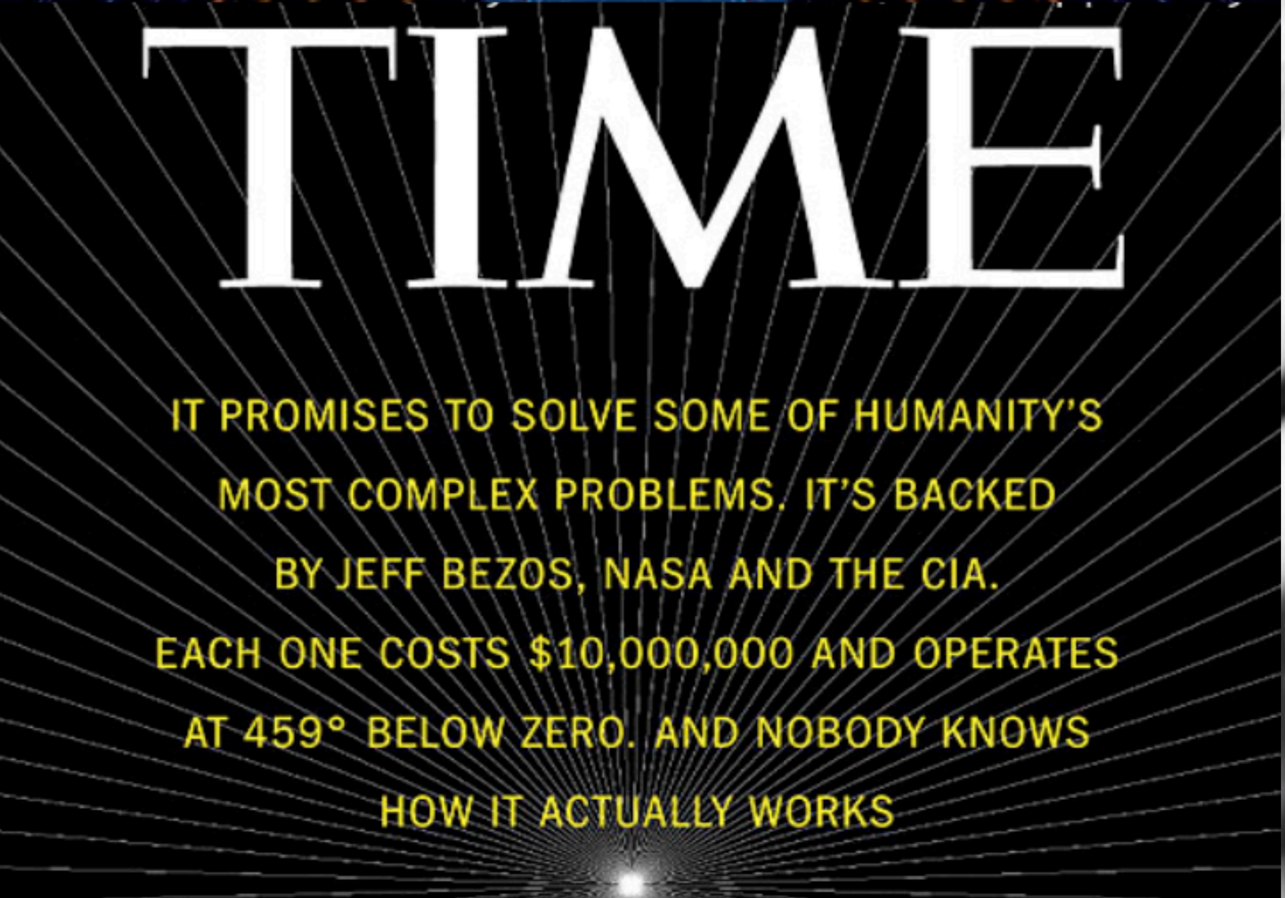
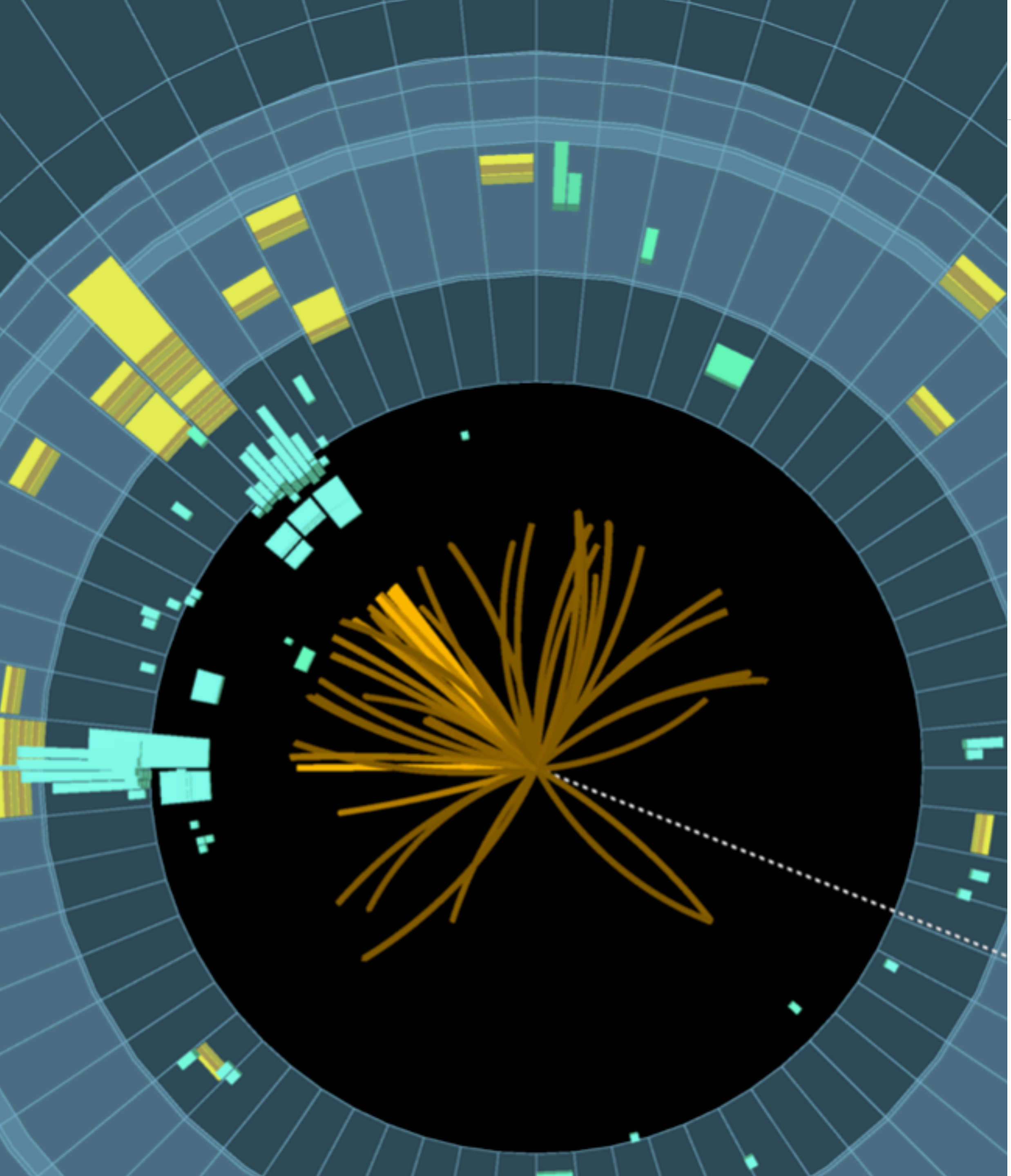
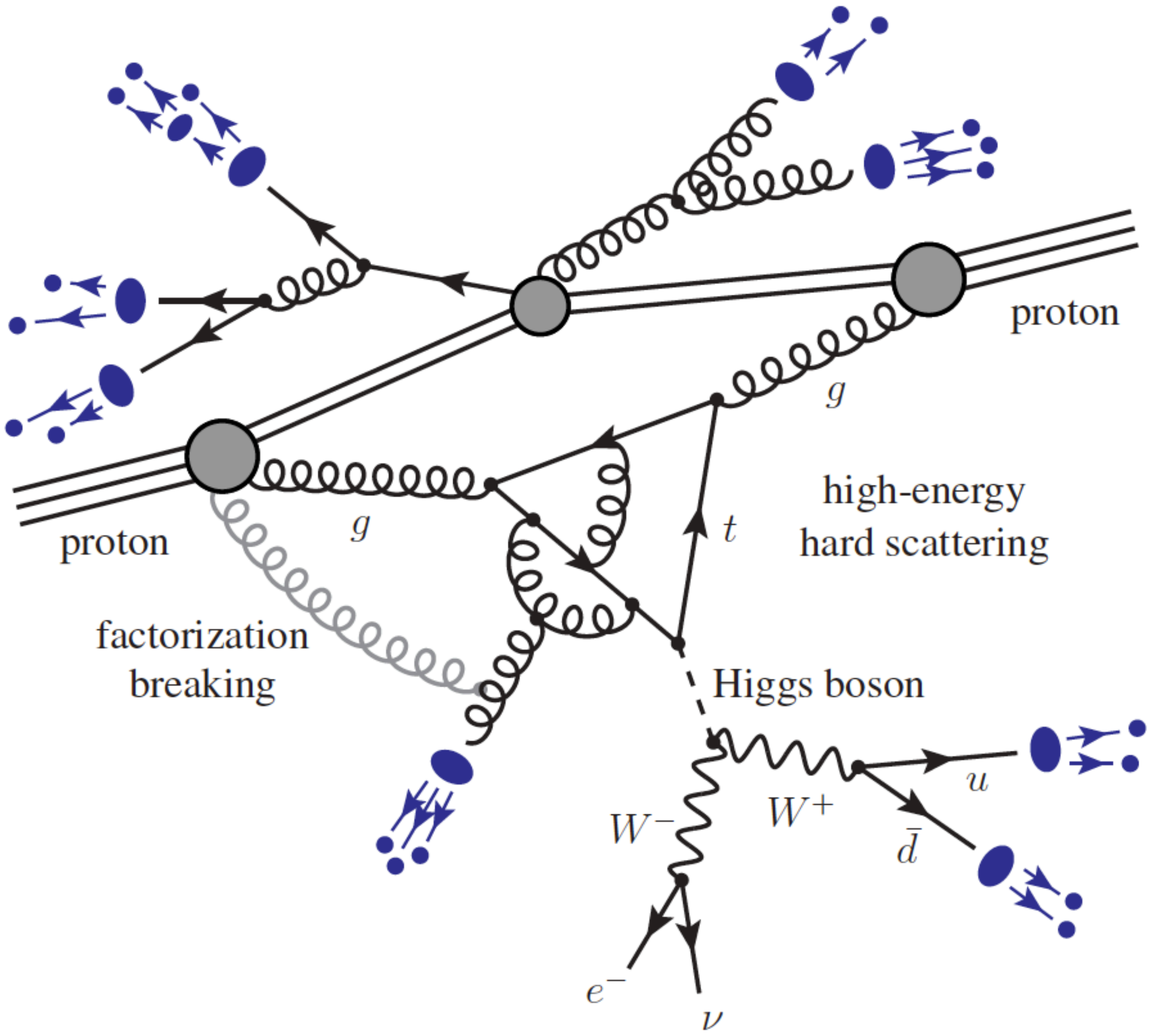
hype

and fear







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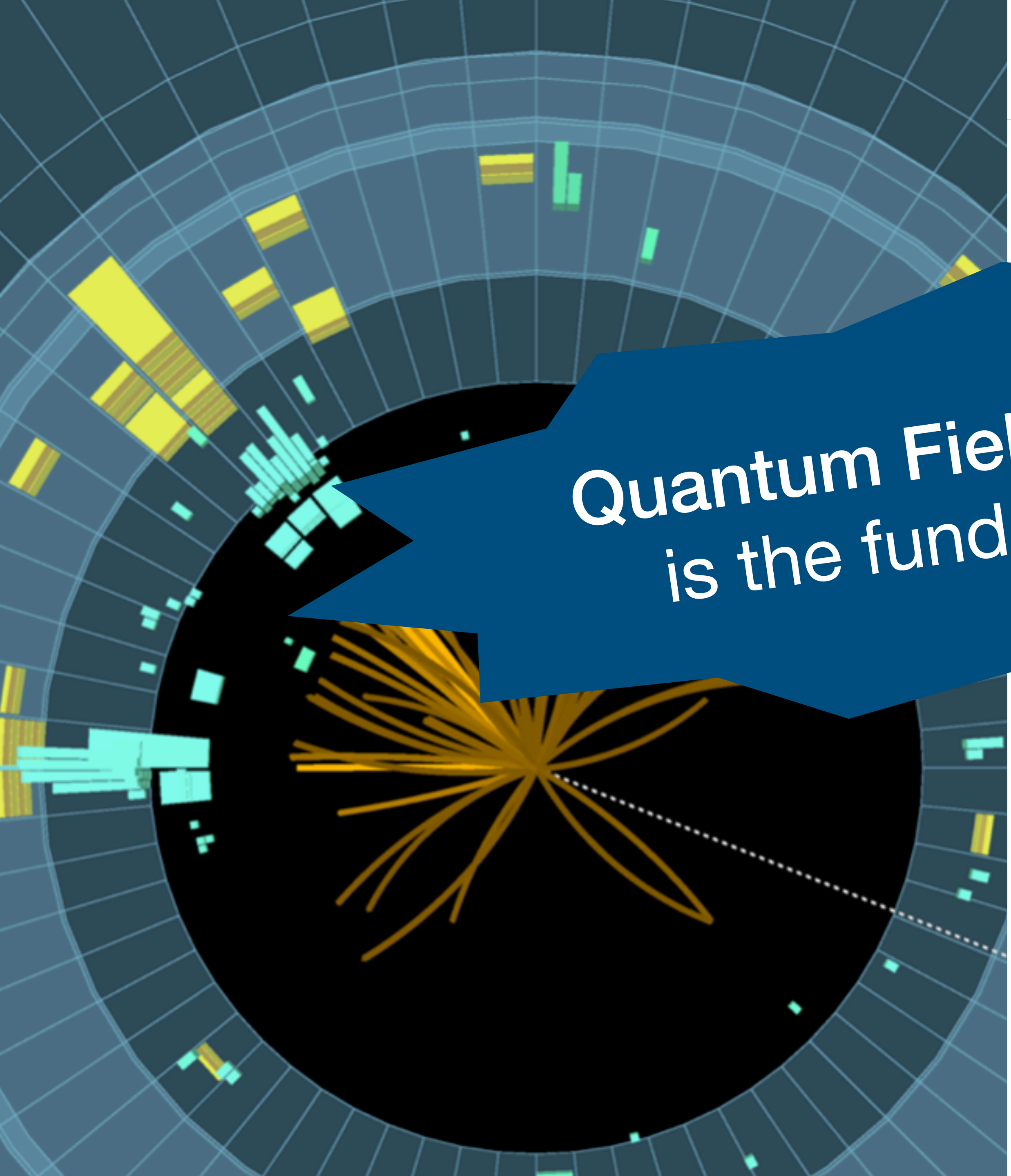
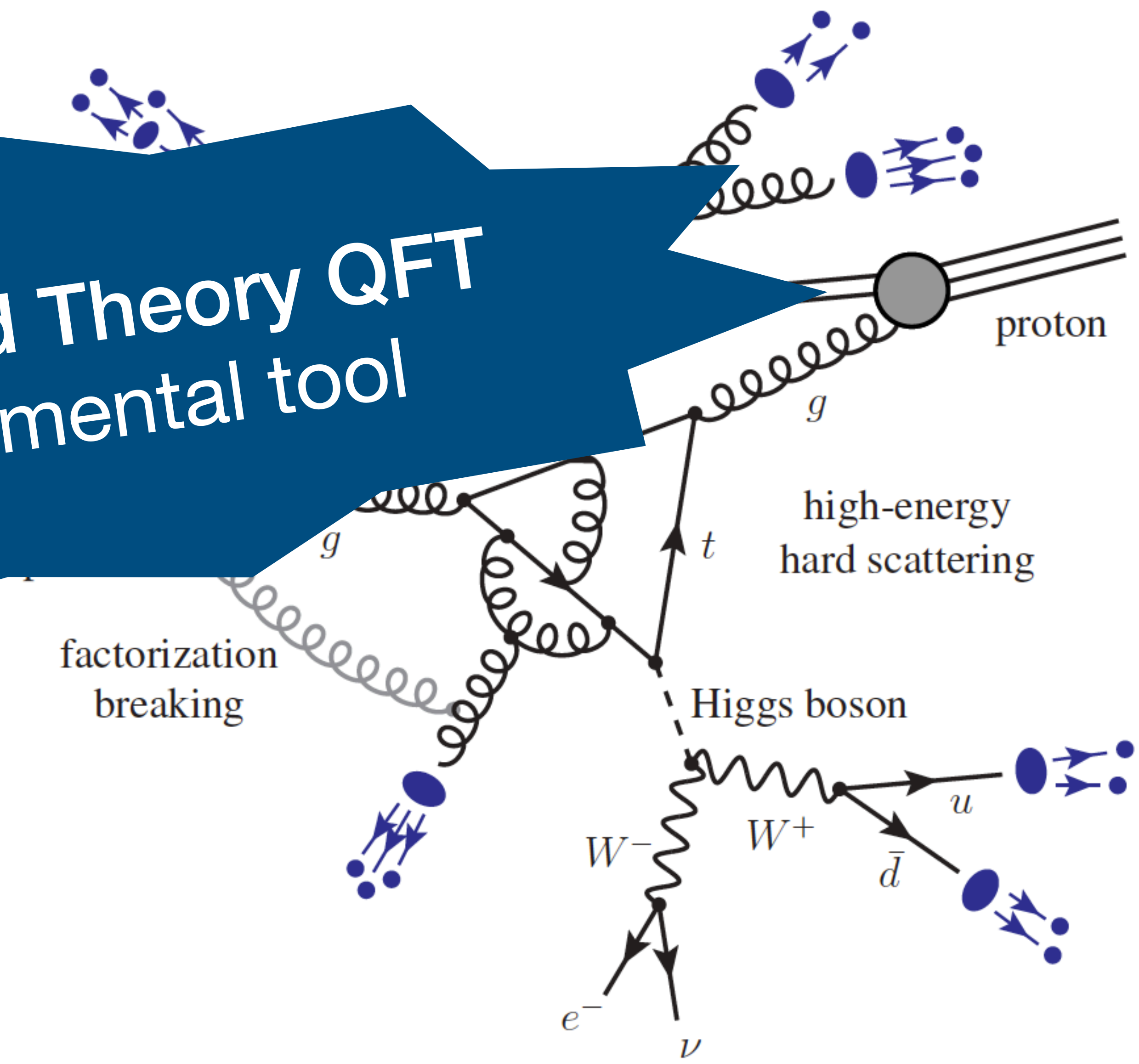
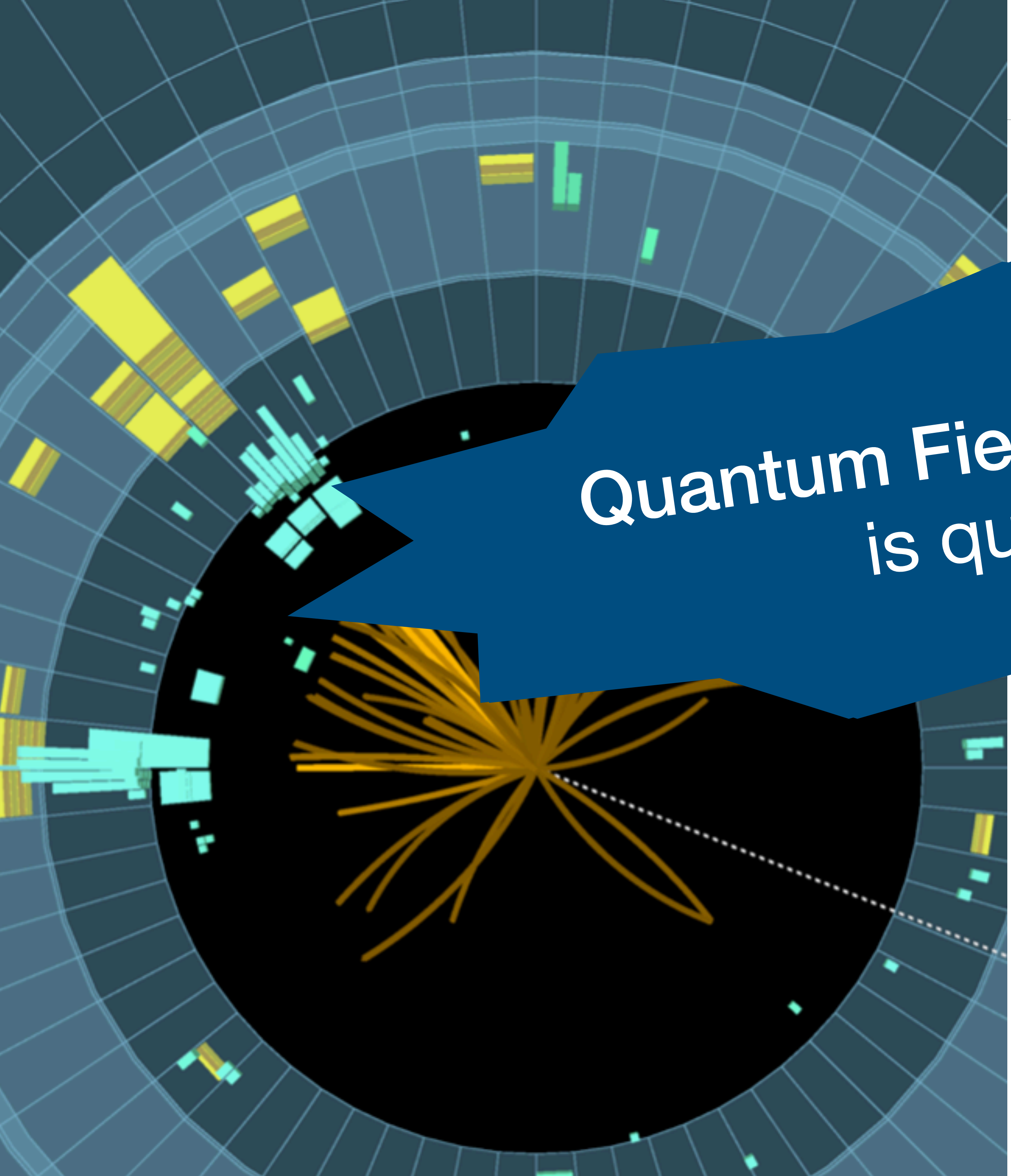
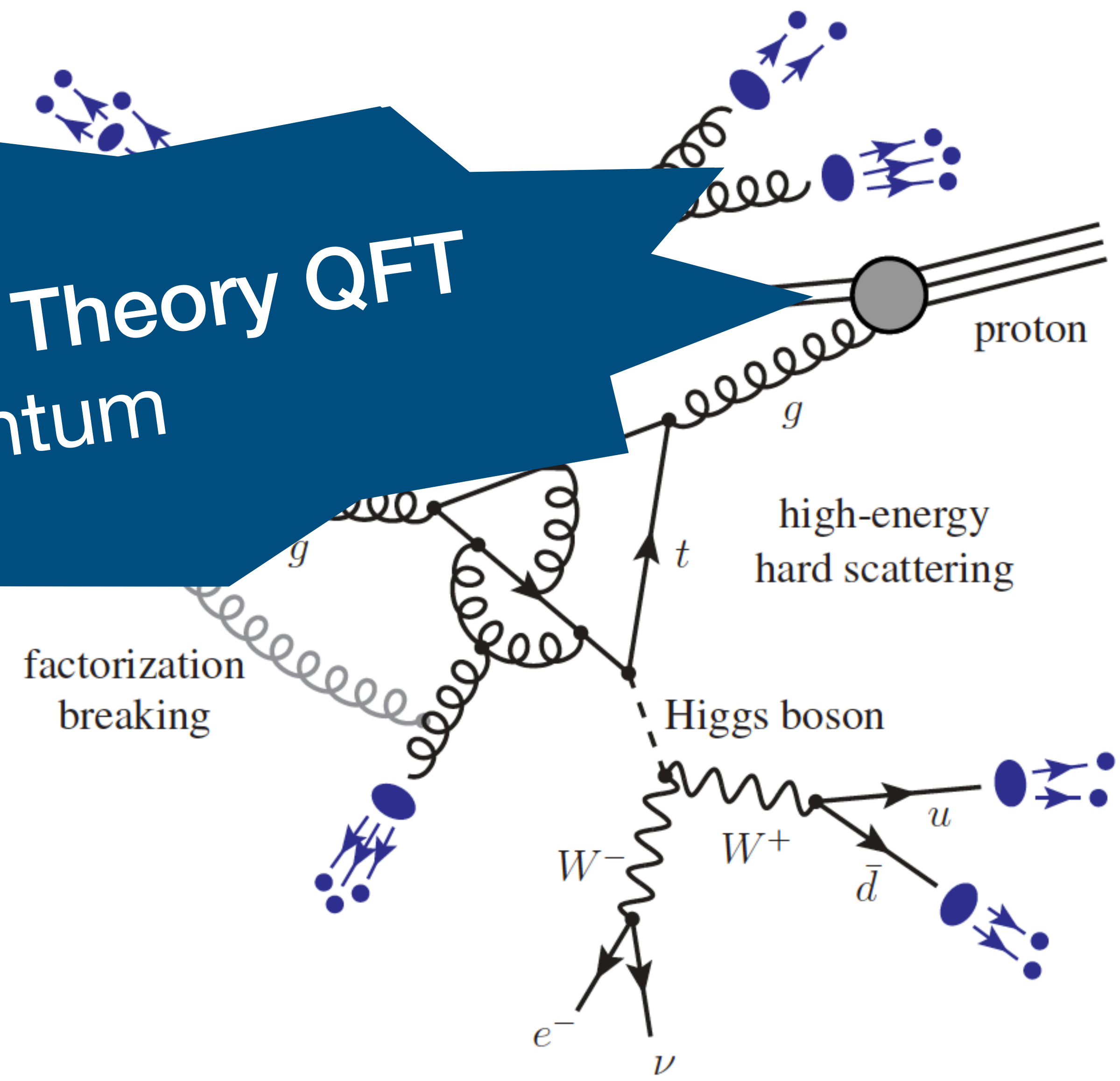




Quantum Field Theory QFT is the fundamental tool



Quantum Field Theory QFT is quantum



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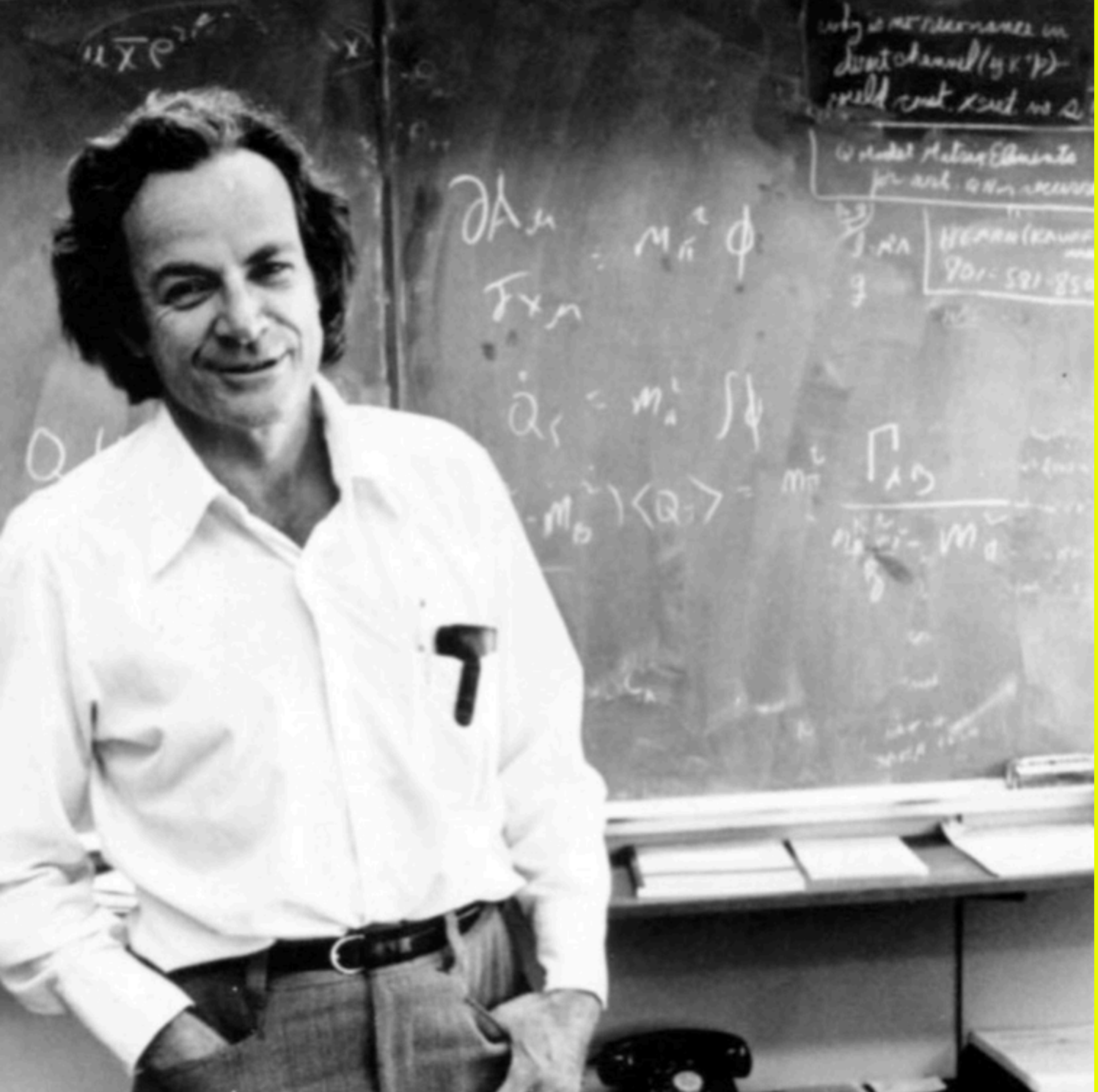
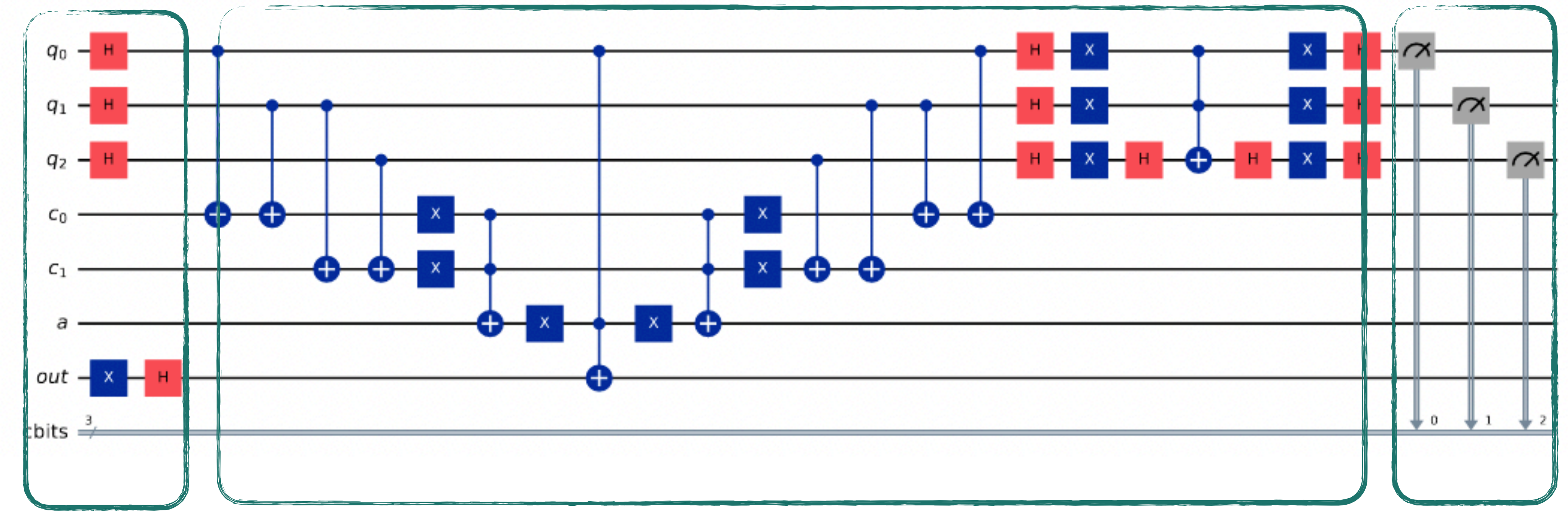


"Nature isn't classical, dammit, and if you want to make a simulation of nature, you better make it quantum"

- Richard P. Feynman

QUANTUM CIRCUITS



initialisation and superposition

Unitary transformations through logic quantum gates (H, NOT, CNOT, …)

measurement

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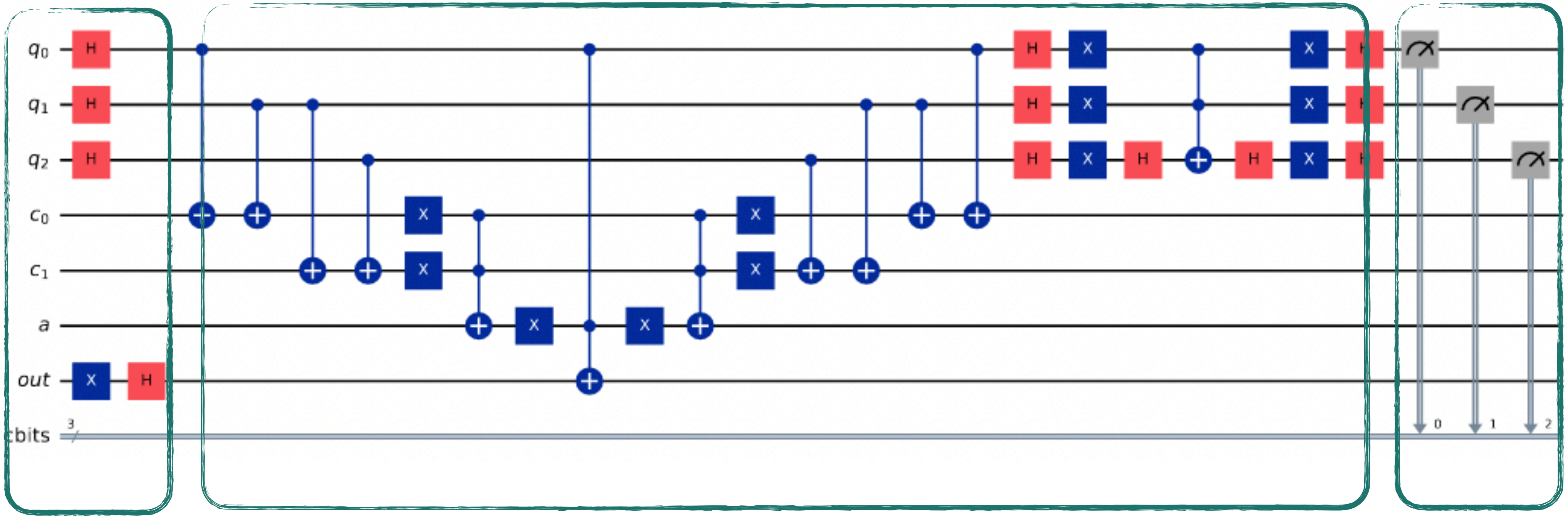
QUANTUM CIRCUITS



initialisation and superposition

Unitary transformations through logic quantum gates (H, NOT, CNOT, …)

measurement

- Quantum computing ≠ **parallelisation:** the superposition colapse after each measurement
- Most suitable for complex problems with scarce input data (for now)

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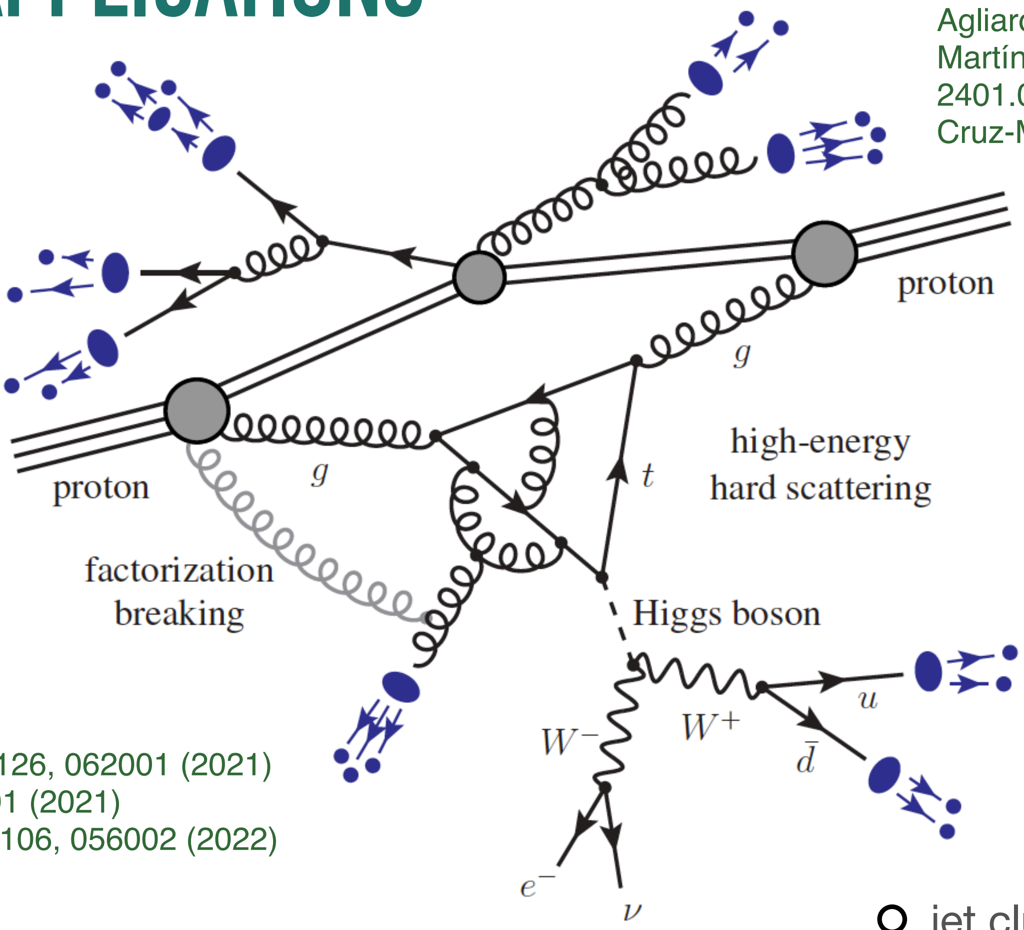
RECENT QUANTUM APPLICATIONS



- Monte Carlo integration:

Herbert, Q6, 823 (2022)
Agliardi, Grossi, Pellen, Prati, PLB 832, 137228 (2022)
Martínez de Lejarza, Grossi, Cieri, GR, 2305.01686, 2401.03023
Cruz-Martínez, Robbiati, Carraza, 2308.05657

- track reconstruction:

Mangano et al., PRD 105, 076012 (2022)
Duckett, Facini, Jastrzebski, Malik, Scanlon, Rettie, 2212.07279
Schwägerl, Issever, Jansen, Khoo, Kühn, Tüysüz, Weber, 2303.13249

- tree-level helicity amplitudes:

Bepari, Malik, Spannowsky, Williams, PRD103, 076020 (2021)

- multiloop scattering amplitudes:

Ramírez, Rentería, GR, Sborlini, Vale Silva, JHEP 2205, 100 (2022)
Clemente, Crippa, Jansen, Ramírez, Rentería, GR, Sborlini, Vale Silva, 2210.13240

- parton densities:

Pérez-Salinas, Cruz-Martínez, Alhajri, Carrazza, PRD 103, 034027 (2021)

- parton showers:

Bauer, de Jong, Nachman, Provasoli, PRL 126, 062001 (2021)
Bauer, Freytsis, Nachman, PRL 127, 212001 (2021)
Bepari, Malik, Spannowsky, Williams, PRD 106, 056002 (2022)

- jets in a medium:

Barata, Du, Li, Qian, Salgado, PRD 106, 074013 (2022)
Barata, Salgado, EPJC 81, 862 (2021)

- quantum machine learning:

Guan, Perdue, Pesah, Schuld, Terashi, Vallecorsa, Vlimant, MLST 2, 011003 (2021)
Wu et al., JPG 48, 125003 (2021)
Felser, Trenti, Sestini, Gianelle, Zuliani, Lucchesi, Montangero, npjQI 7, 111 (2021)

- jet clustering:

Wei, Naik, Harrow, Thaler, PRD 101, 094015 (2020)
Pires, Bargassa, Seixas, Omar, 2101.05618
Pires, Omar, Seixas, PLB 843, 138000 (2023)
Martinez de Lejarza, Cieri, GR, PRD 106, 036021 (2022)

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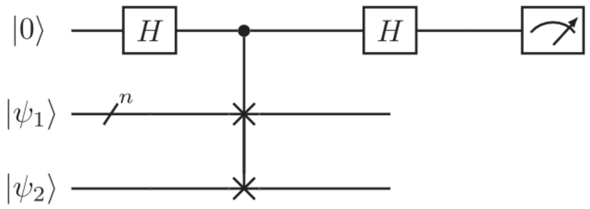
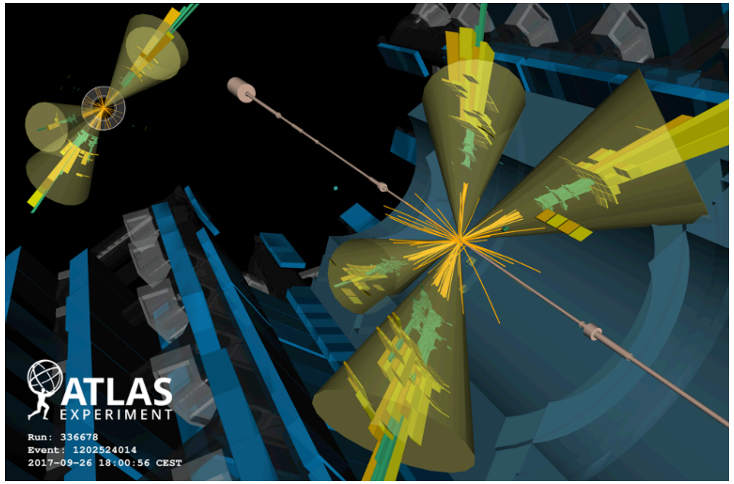
Martínez de Lejarza, Cieri, Rodrigo, PRD 106, 036021 (2022)

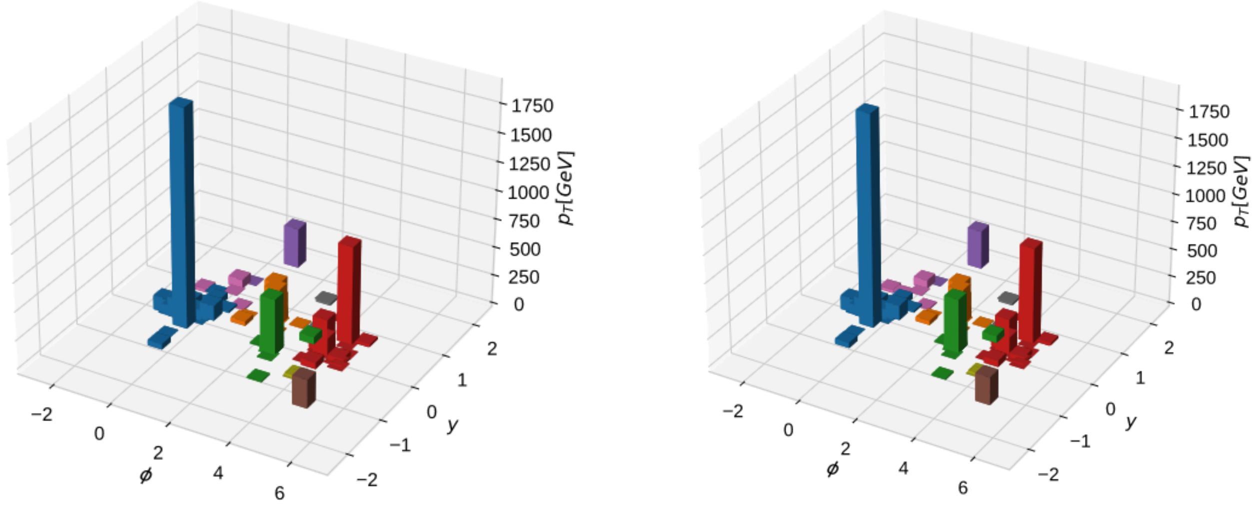
JET CLUSTERING AT THE LHC

- Three clustering algorithms: K-means, Affinity Propagation, k_T-jet
- Hierarchical classical clustering (e.g. k_T-jet) requires to find the absolute minimum distance at each intermediate steep: very costly computationally
- Mininum-distance in a quantum algorithm is probabilistic and less expensive: **clustering ordering** relaxed
- Bare anti-k_T has complexity $\mathcal{O}(N^3)$, reduced to $\mathcal{O}(N\log(N))$ by using geometrical nearest neighbour and optimization with Voronoi diagrams. Bare quantum version is $\mathcal{O}(N^2\log(N))$ without any optimization



SwapTest to calculate distances





(a) Classical anti-k_T, $p=-1$, $R=1$.

(b) Quantum anti-k_T, $p=-1$, $R=1$, $\epsilon_c=0.99$.

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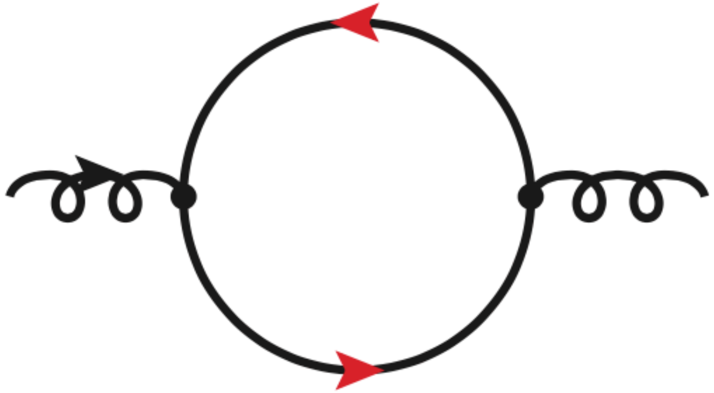
Ramírez, Rentería, Rodrigo, Sborlini, Vale Silva, JHEP 2205, 100
Clemente, Crippa, Jansen, Ramírez, Rentería, Rodrigo, Sborlini, Vale Silva, PRD 108, 096035 (2023)

CAUSALITY IN FEYNMAN LOOP INTEGRALS



- Feynman propagators describe a quantum superposition of propagation in both directions

$$G_F(q_i) = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle \right)$$

- A Feynman diagram is a superposition of 2^n states

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Ramírez, Rentería, Rodrigo, Sborlini, Vale Silva, JHEP 2205, 100
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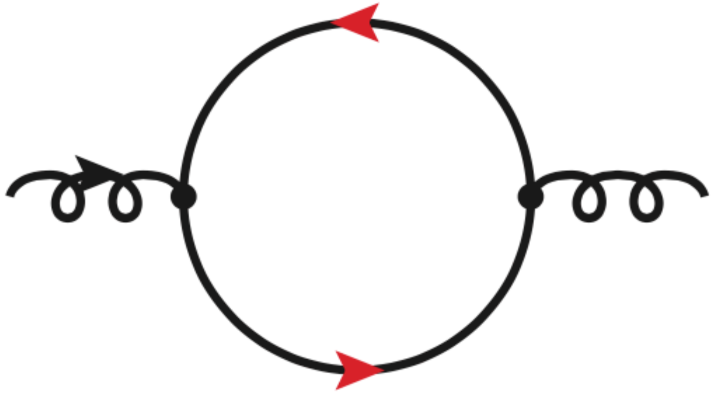

- Feynman propagators describe a quantum superposition of propagation in both directions

$$G_F(q_i) = \frac{1}{\sqrt{2}} \left(|0\rangle + |1\rangle \right)$$

- A Feynman diagram is a superposition of 2^n states

- If the emitted particle returns to the starting point: it **travels back in time** and thus **breaks causality** ≡ cyclic configurations are forbidden

- Causal configurations of Feynman diagrams are **directed acyclic graphs (DAG)** in graph theory

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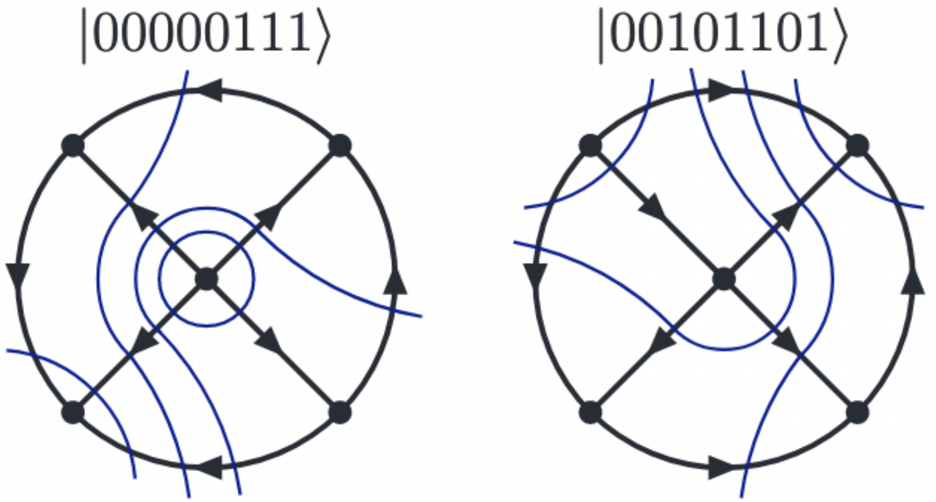
Ramírez, Rentería, Rodrigo, Sborlini, Vale Silva, JHEP 2205, 100
Clemente, Crippa, Jansen, Ramírez, Rentería, Rodrigo, Sborlini, Vale Silva, PRD 108, 096035 (2023)

CAUSALITY IN FEYNMAN LOOP INTEGRALS

Grover's algorithm
Amplitude amplification



CTIC centro tecnológico

DESY.

Variational Quantum Eigensolver
Minimization of a Hamiltonian

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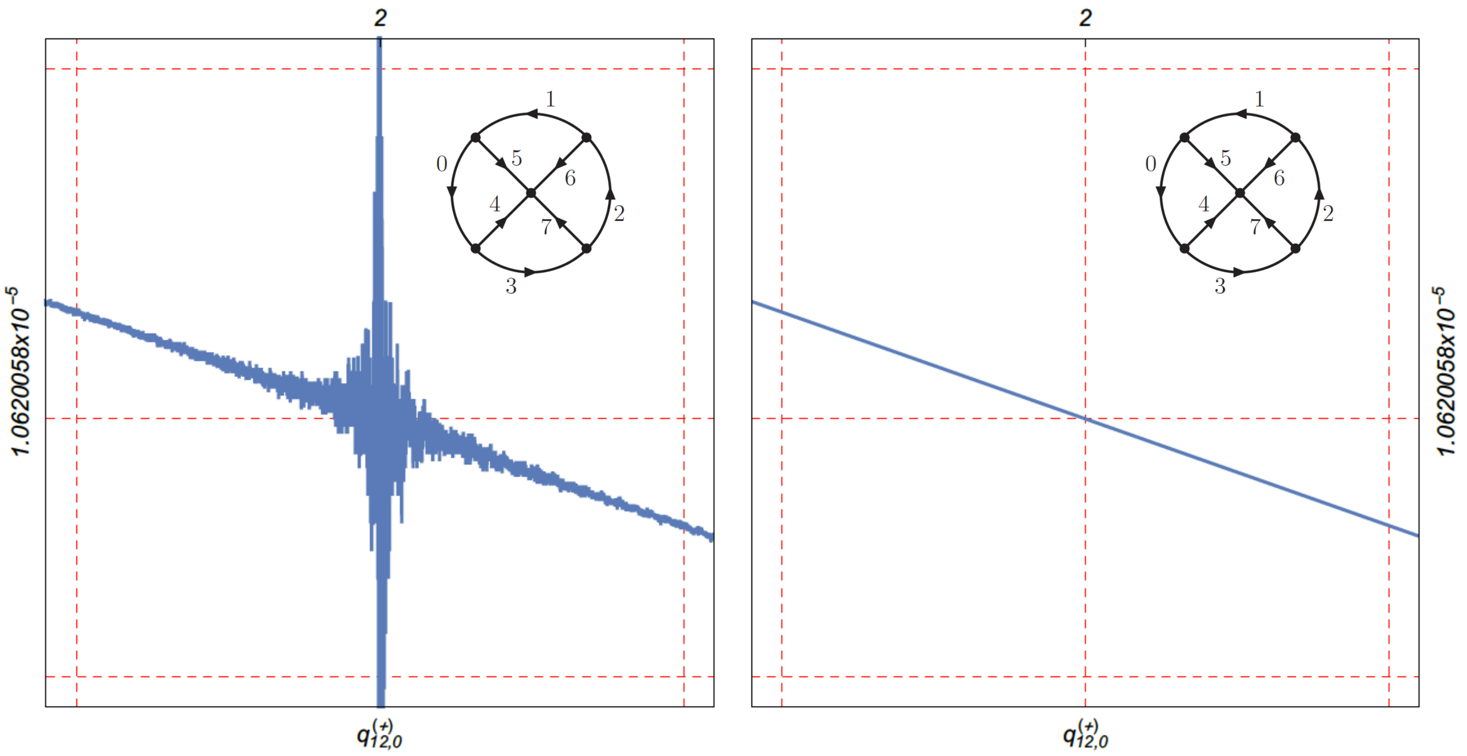
Aguilera, Driencourt, Hernández, Plenter, Ramírez, Rentería, Rodrigo, Sborlini, Torres, Tracz, PRL 124, 211602 (2020)

JHEP **1912**, 063 | JHEP **2101**, 069 | JHEP **2102**, 112 | JHEP **2104**, 129

NUMERICAL STABILITY OF CAUSAL LTD

- integrands in the Feynman representation have singularities that are nonphysical ≡ not related to the optical theorem
- LTD leads to **manifestly causal representations** (free of non-causal singularities): more stable numerically



- **Integrand numerical instabilities** across a noncausal threshold
- manifestly causal LTD representation

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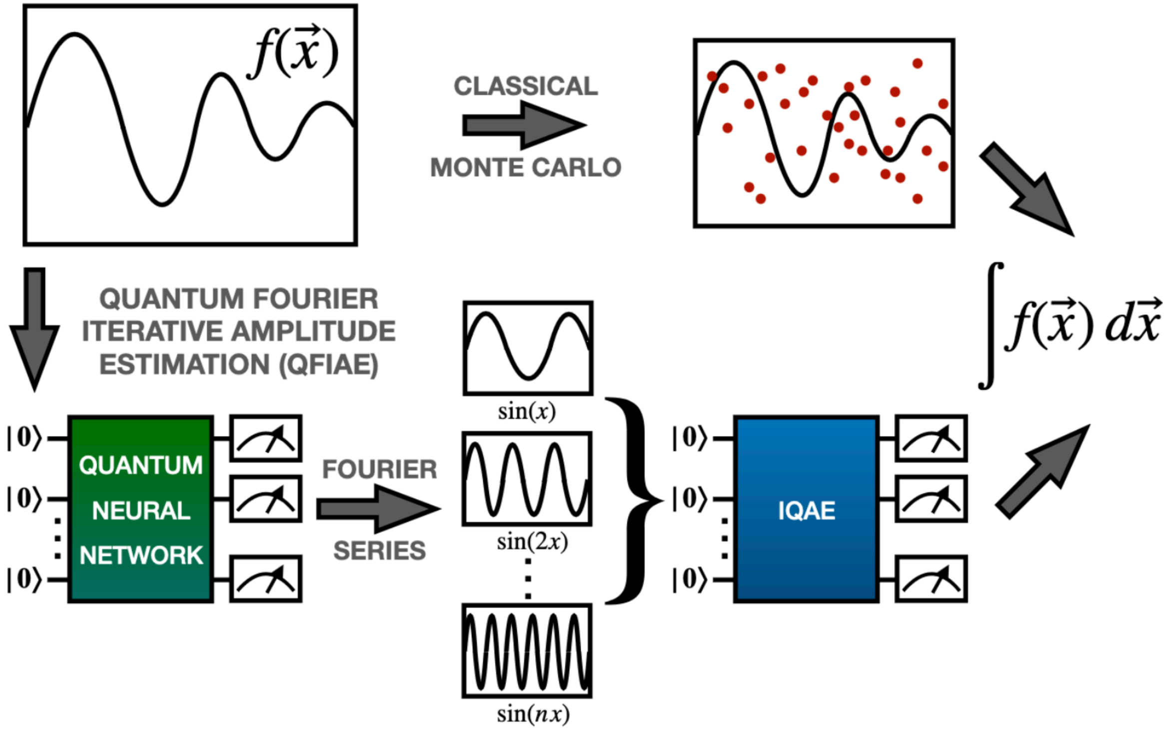
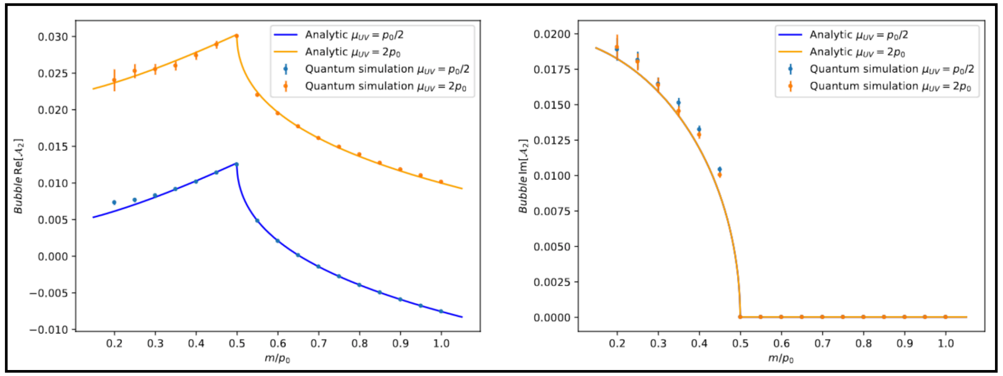
Martínez de Lejarza, Grossi, Cieri, Rodrigo, IEEE QCE2023 [2305.01686]
Martínez de Lejarza, Cieri, Grossi, Vallecorsa, Rodrigo, 2401.03023

QUANTUM FOURIER ITERATIVE AMPLITUDE ESTIMATION (QFIAE)



Fourier	IQAE	$\mathcal{A}_1^{(1,\mathrm{R})}(m;\mu_{\mathrm{UV}})$ $m=5, \mu_{\mathrm{UV}}=m/2$	$\mathcal{A}_1^{(1,\mathrm{R})}(m;\mu_{\mathrm{UV}})$ $m=5, \mu_{\mathrm{UV}}=2m$
S	S	−0.101(3)	−0.254(9)
S	Q	−0.108(4)	−0.270(12)
Q	S	−0.105(2)	−0.252(6)
Q	Q	−0.106(3)	−0.270(9)
Analytical		−0.1007	−0.2554



- Quantum Machine Learning + Grover's amplification
- Fourier series using a **Quantum Neural Network (QNN)**
- Integrates each component using Iterative Quantum Amplitude Estimation (IQAE), a variant of Grover's algorithm

CERN | QUANTUM TECHNOLOGY INITIATIVE

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CONCLUSIONS

- **Theory and experiment** in astrophysics and particle physics demand for increasing computing resources
- Brute force approaches may not suffice and are not planet friendly (e.g. current theoretical predictions at colliders require months of CPU time at large-scale clusters)
- Developing new methods, algorithms and technologies are both a challenge and interesting

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