“quantum observables for high-energy physics”

The Galileo Galilei Institute
For Theoretical Physics
Centro Nazionale di Studi Avanzati dell'Istituto Nazionale di Fisica Nucleare
Arcetri, Firenze

A brief explanation for non-experts

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1920s: development of Quantum Mechanics

— Quantum Mechanics is undoubtedly correct; it has successfully passed all experimental tests

— Quantum Mechanics is undoubtedly useful; it has led to the development of transistors and all of modern electronics

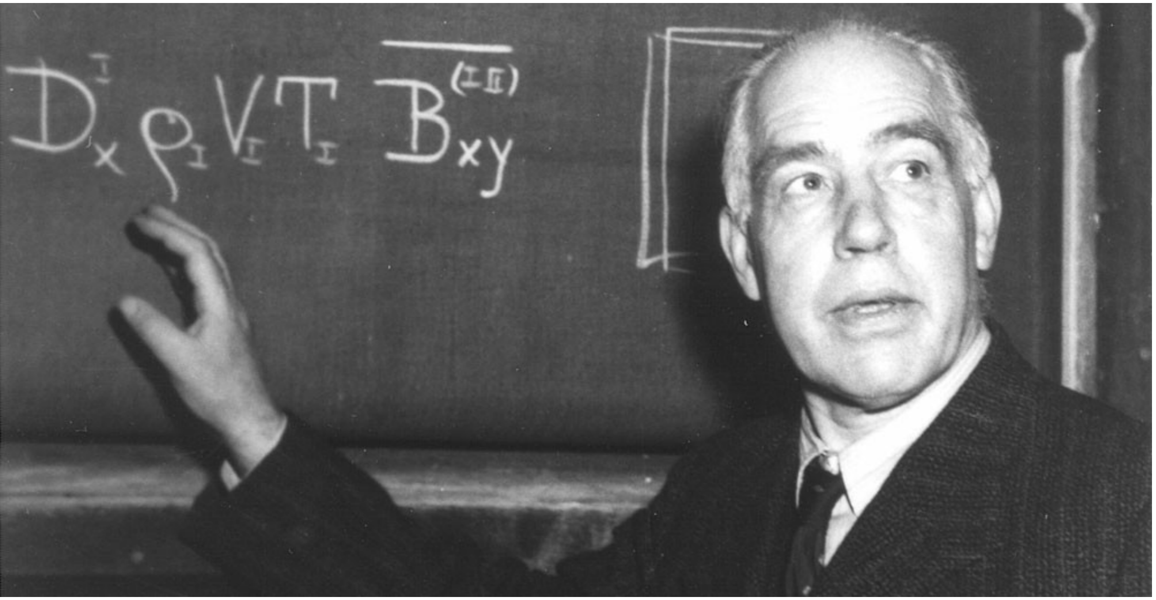
Quantum Mechanics has baffled some of the last century's best minds:
It describes objects as both waves and particles and yet they behave like neither of these. Quantum Mechanics behaves like nothing you have seen before.

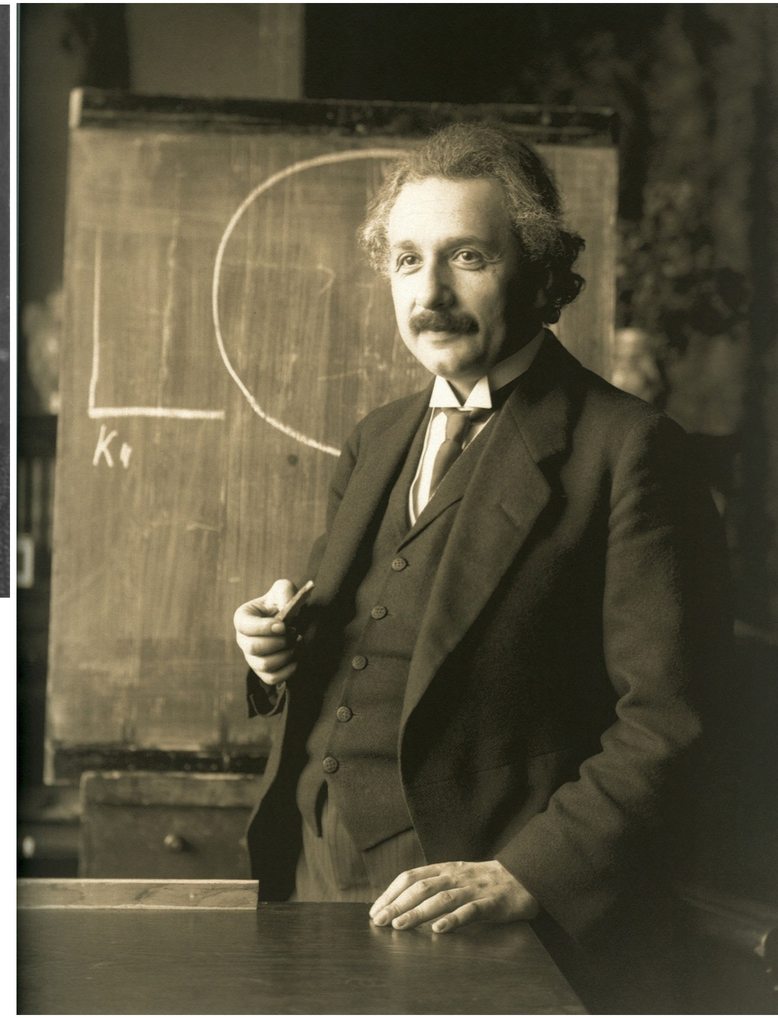
"I think I can safely say that nobody understands quantum mechanics."
– Richard Feynman

“Anyone who is not shocked by quantum theory has not understood a single word.”
– Niels Bohr

“If you are not completely confused by quantum mechanics, you do not understand it.”
– John Wheeler

Foundations of quantum mechanics





Philosophical debate among founders of quantum mechanics (and hence all of modern physics)

Einstein (and common sense):
Particles have properties

Bohr (and quantum mechanics):
Quantum probabilities are all there is to know

1935: Einstein-Podolsky-Rosen thought experiment

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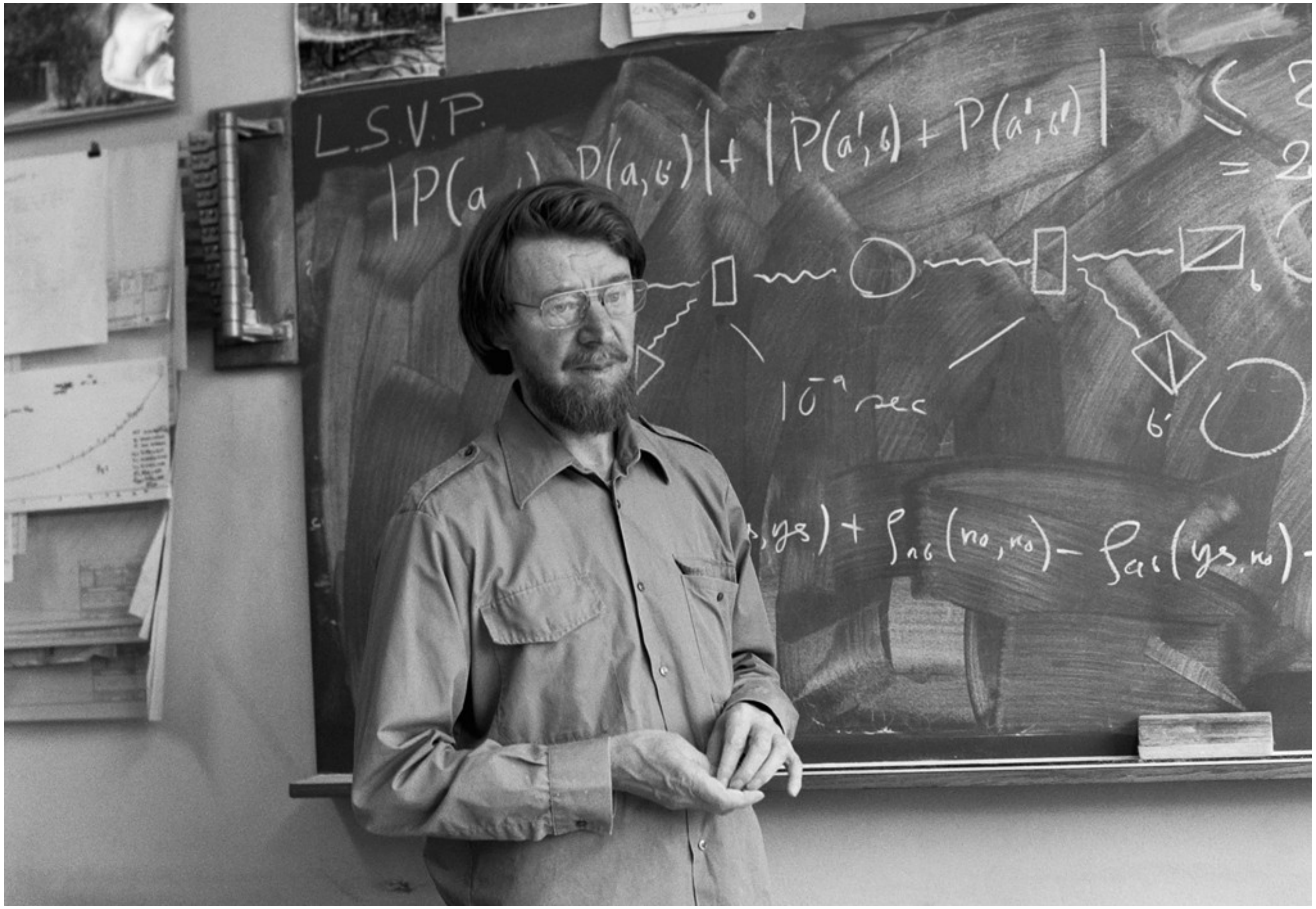
Einstein vs. Bohr...

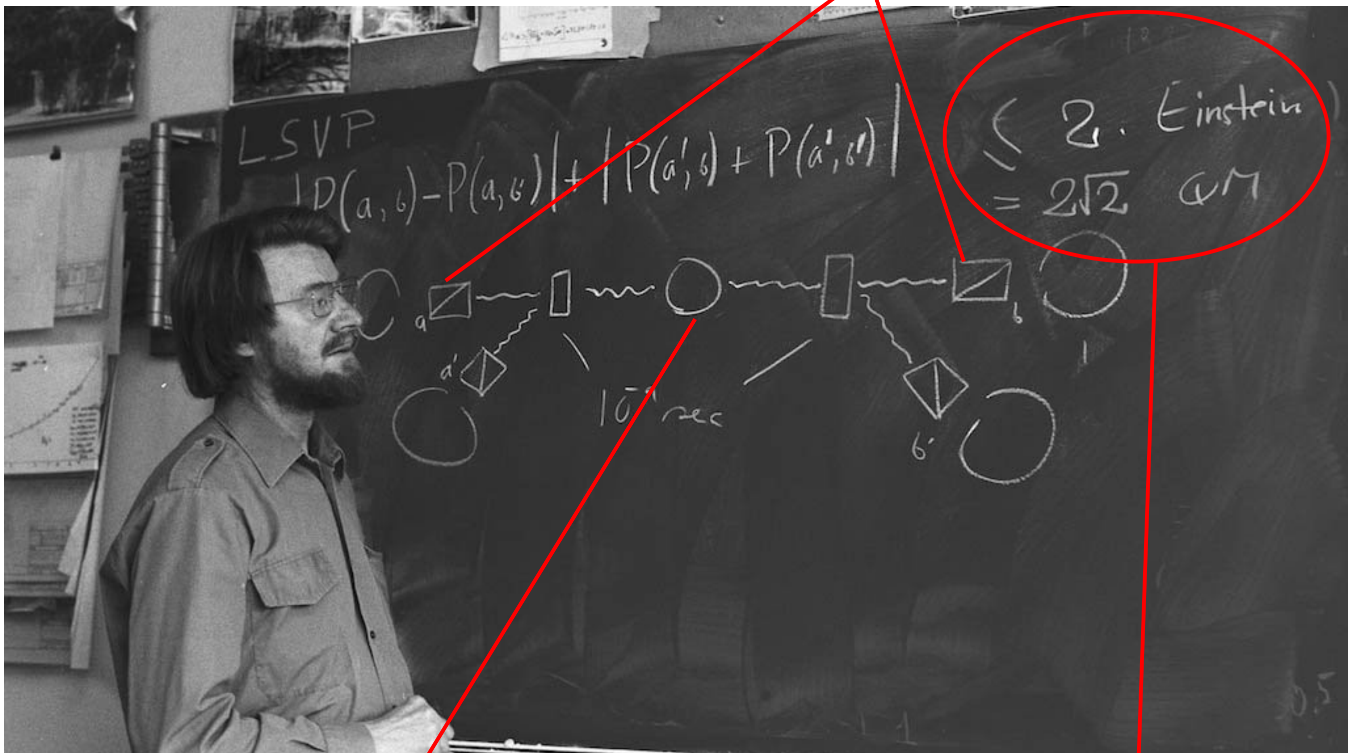
Quantum information



1964: John Bell at CERN sharpened the formulation of the Einstein Podolsky Rosen experiment in terms of Bell inequalities

Bell-style experiments

Two well-separated & independent detectors



Measurement result decides which interpretation is correct

Source of quantum-correlated “entangled” photons

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Experimental quantum information

1970s-now: Aspect, Clauser, Zeilinger and many others designed and performed experiments that can test Bell inequalities

The result: Bohr was right, Einstein and common sense were wrong

A triumph of emprical science: settle a philosophical debate with an experiment

2022 Nobel prize “for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

© Nobel Prize Outreach. Photo: Stefan Bladh
Alain Aspect
Prize share: 1/3

© Nobel Prize Outreach. Photo: Stefan Bladh
John F. Clauser
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Anton Zeilinger
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Quantum information

Since the 1970s, experiments with photons have evolved to close all “loopholes” in the Bell test

Theorists have developed new ways to evade bounds: super-determinism etc.

A lot of development to characterize entangled systems: quantum tomography, from qubits to qutrits and…

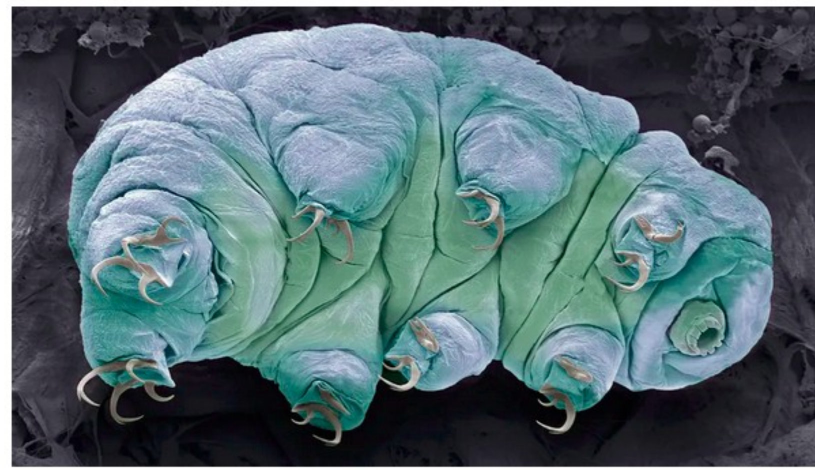
Experiments have explored many other quantum-entangled systems

Animals

Frozen tardigrade becomes first 'quantum entangled' animal in history, researchers claim

News By Brandon Specktor published December 20, 2021

Some experts are skeptical that the frozen moss piglet really entered a quantum state.



(Image credit: STEVE GSCHMEISSNER/SCIENCE PHOTO LIBRARY/Getty Images)

Tardigrades — those microscopic, plump-bodied critters lovingly known as "moss piglets" — have been put through the ringer for science. The amazingly durable creatures have been shot out of guns, bathed in boiling-hot water, exposed to intense ultraviolet radiation and even (accidentally) crash-landed on the moon, all to test the limits of their impressive "tun" state — a survival mechanism wherein tardigrades curl up into shrunken, dehydrated balls and

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High-energy collisions allow for precise study of fundamental particles and their interactions

Touschek and his team in front of AdA

Scooping up discoveries since the 1950s

1950s and 60s: SLAC: quark model

1962: : muon neutrino

1974: SLAC+BNL: charm quark

1975: SLAC: tau lepton

1977: FermiLab: bottom quark

1979: Petra DESY: gluon

1980s: $Sp\bar{p}S$ 546/630 GeV: W & Z bosons

1995: Tevatron $p\bar{p}$ 1.8 TeV: top quark

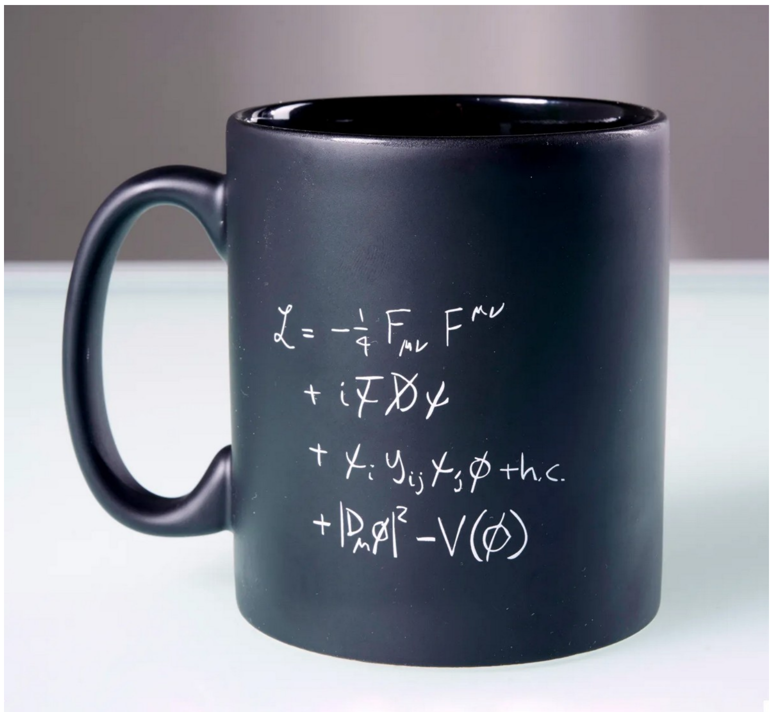
2000: DONUT : tau neutrino

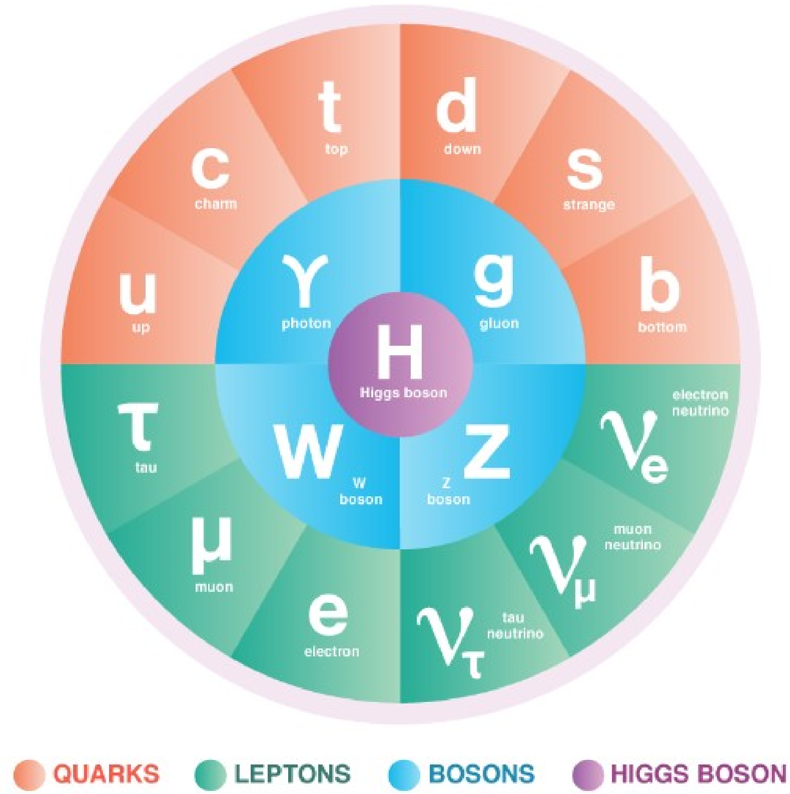
2012: LHC pp 8 TeV: Higgs boson

2018: LHC pp 13 TeV: Higgs couplings to fermions

1960s: developing the Standard Model of particle physics

— a quantum field theory, firmly rooted in quantum mechanics
— an accurate description of the constituents of matter and their interactions
— not yet the “theory of everything”, but not bad for an equation that fits on a mug…





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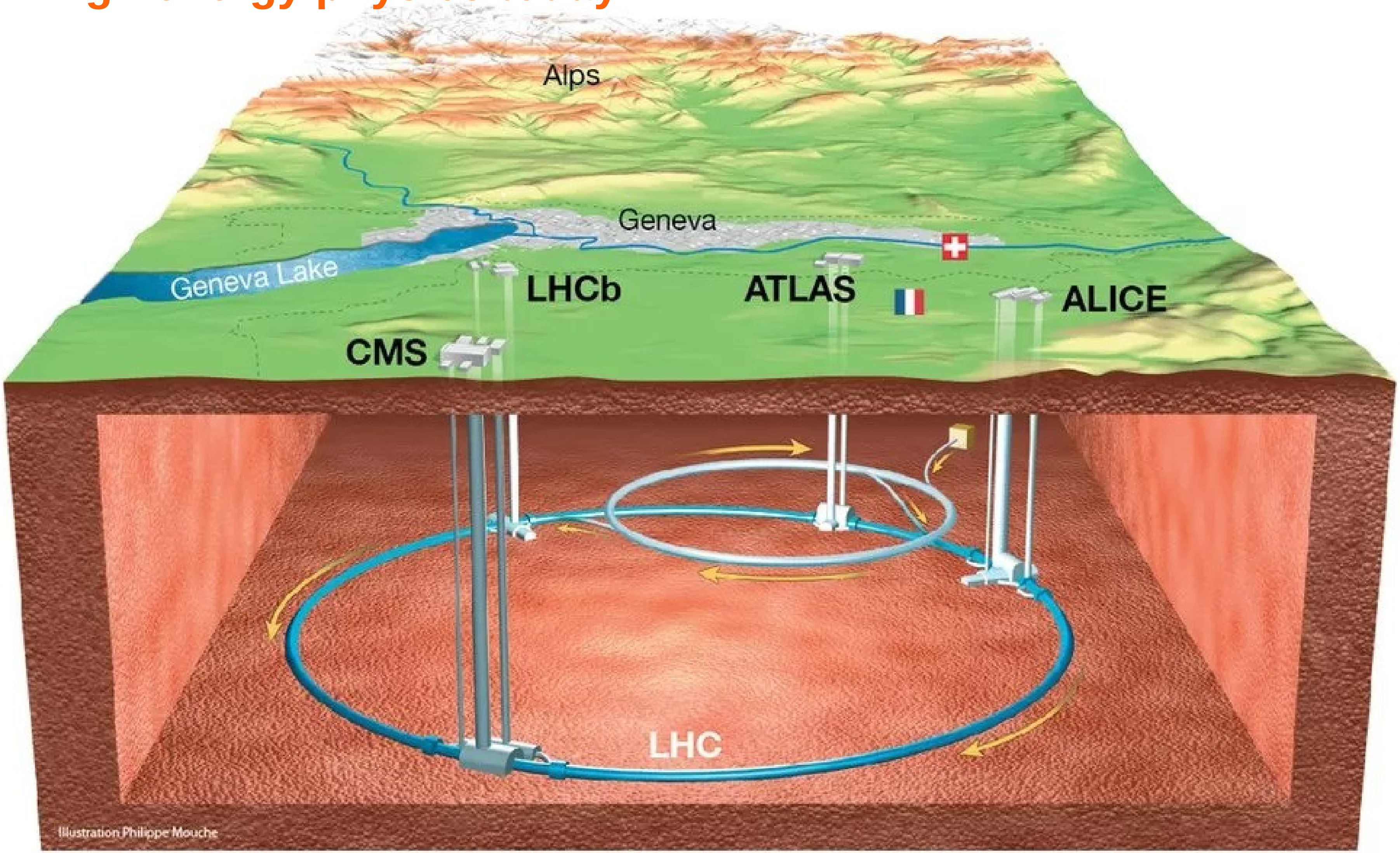
High energy physics today

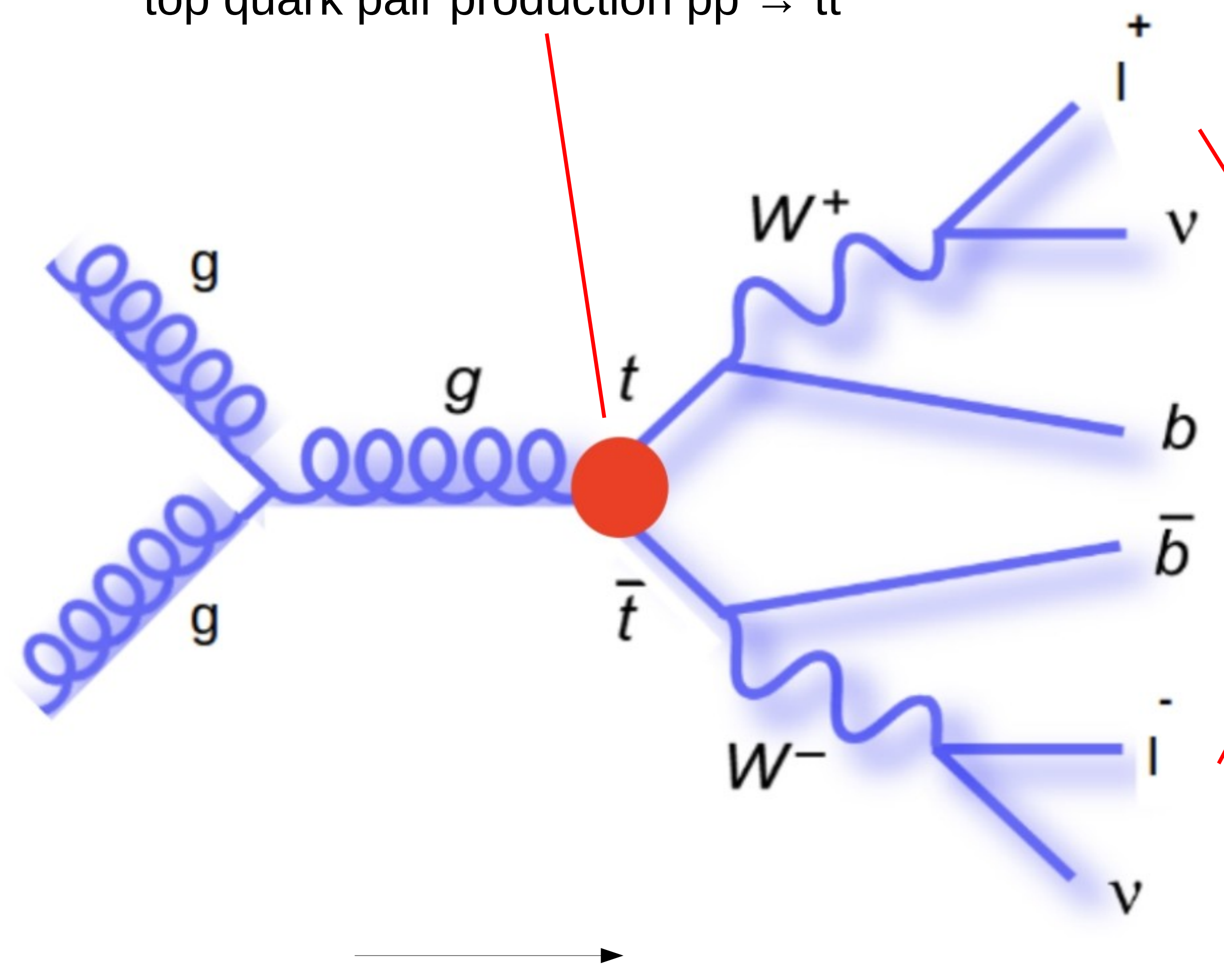


LHC: proton-proton collisions at the highest possible energy: 13.6 TeV in run 3
ATLAS + CMS: general-purpose experiments (the Higgs boson + …)

High energy collisions: top quark pair production

Afik & de Nova, EPJ Plus 136 (2021) + many more

Source of entangled particles:
top quark pair production $pp \to t\bar{t}$



Two detectors:
top quark decay
$t \to Wb$, $W \to l^{\pm}\nu$

Feynman diagram for LHC "reaction": time runs from left to right; gluons in protons collide and form a top-anti-top pair; the top quarks decay via $t \to Wb$, W's decay to a lepton and neutrino via $W \to l^{\pm}\nu$

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Quantum entanglement in top quark pair production

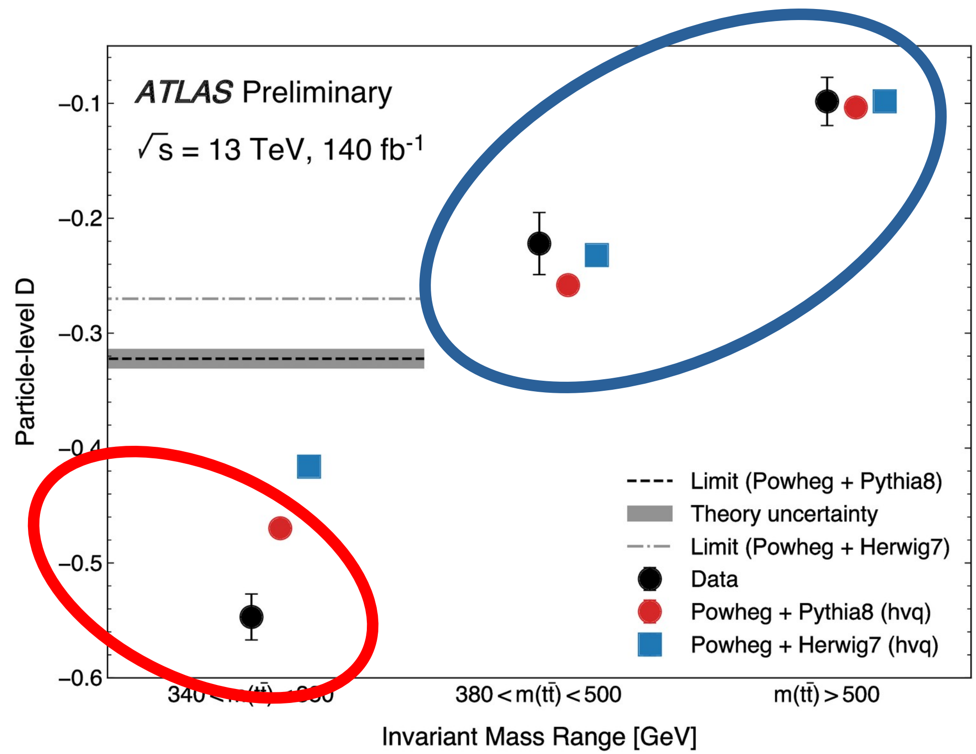
Read more about this!

https://atlas.cern/Updates/Briefing/Top-Entanglement

Collect top quark data,
separate in three regions,
measure "entangled-o-meter" D

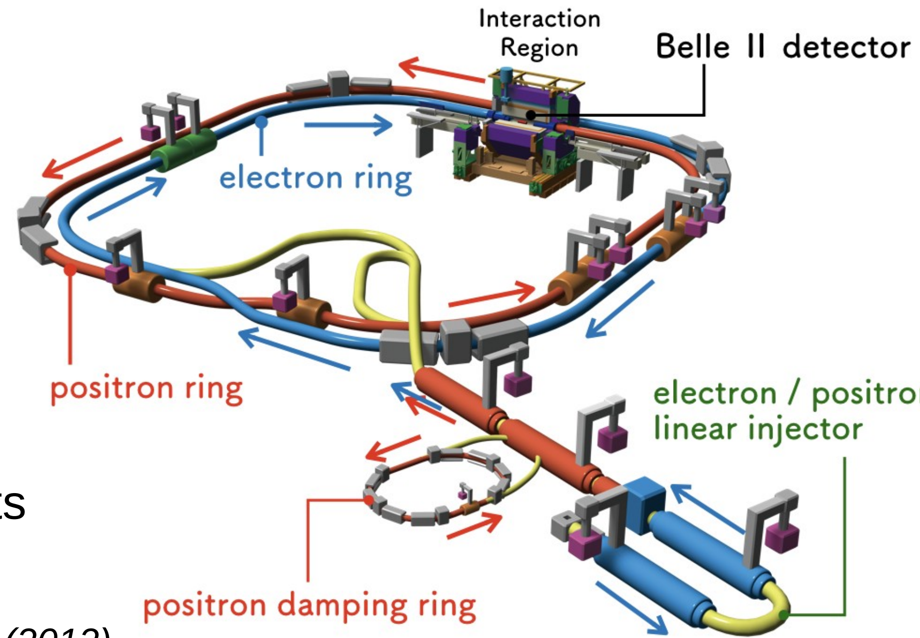
D ≠ 0: top quark spins are correlated.
Confirms something we have known since 2012.

D < –1/3: top quarks are "entangled"
This is new and exciting!



Looking forward to a CMS result

B-factories, Higgs factories...



B-factories: entangled B/$\bar{B}$ systems

LHCb: b-quark production at the LHC
SuperKEKB: $e^+e^- \to \Upsilon \to b\bar{b}$
Babar (SLAC) and Belle (KEK) experiments

Bell inequality, Go et al. (Belle), PRL99 (2007)
T-violation: Bernabeu et al., JHEP 08, Babar, PRL109 (2012)
$B^0 \to J/\psi K^*$ LHCb, Fabbrichesi et al., arXiv:2305.04982


European strategy update

3 High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

Higgs factory:

A new electron-positron collider to study Higgs, top and the electroweak sector

Higgs initial state: $H \to ZZ$
Polarized beams (linear colliders + CEPC)

One new answer and many new questions

High-energy colliders are "quantum information laboratories"

***Q**uantum information experiments in a unique high-energy environment and with unique self-analyzing particle decays.*

One new answer, many new questions

***N**eed expertise from both disciplines and from experimentalists and theorists.*
Handing over to Fabio Maltoni to formulate the mandate of the workshop.

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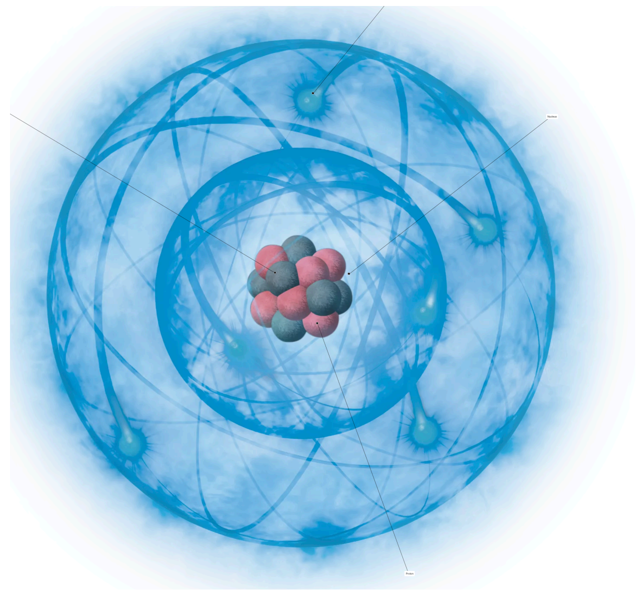
Why this workshop?
Why now?
Why here?
How?

Why this workshop?

Quantum information/computing/technology : push quantum into the macroscopic world



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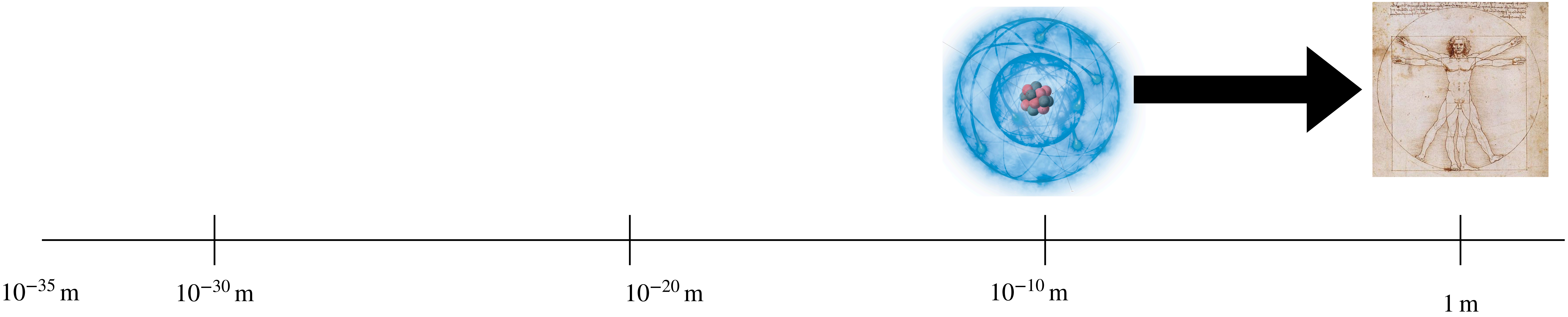
Quantum computers, quantum communications, quantum devices,…

Why this workshop?

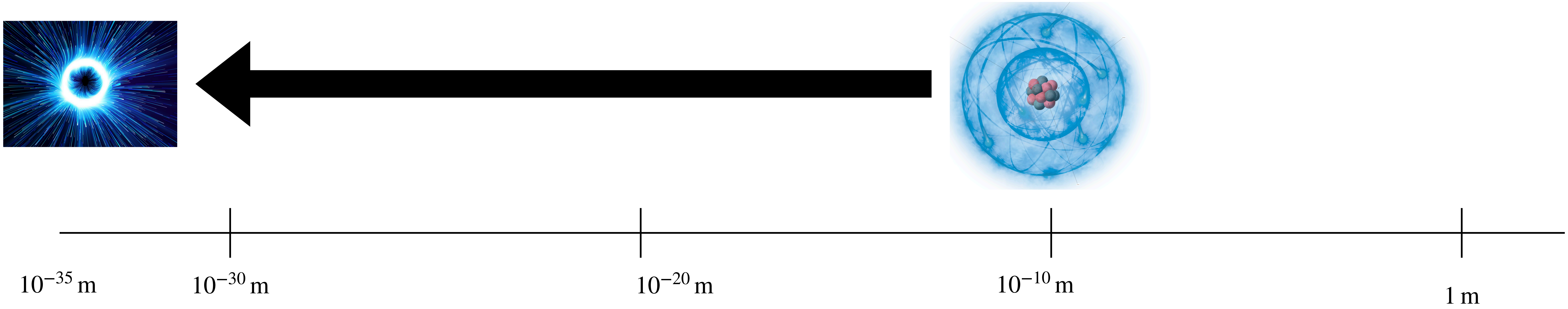
Quantum information/computing/technology : push quantum into the macroscopic world



Quantum computers, quantum communications, quantum devices,…

Why this workshop?

Quantum information paradox (gravity+quantum mechanics):

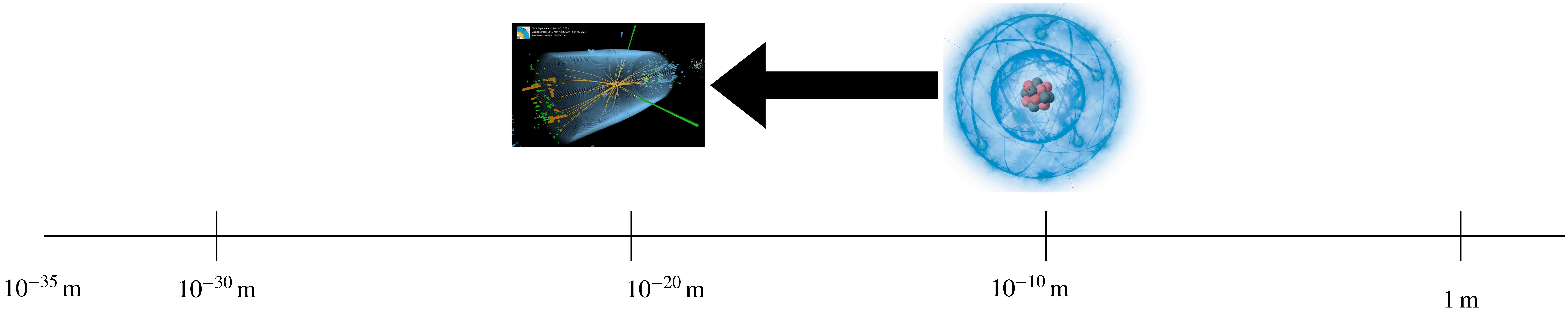


It from Qubit:

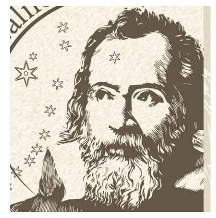
- Does spacetime emerge from entanglement?
- Do black holes have interiors?
- Does the universe exist outside our horizon?
- **What is the information-theoretic structure of quantum field theories?**
- Can quantum computers simulate all physical phenomena?
- How does quantum information flow in time?

Why this workshop?

What can we learn on Fundamental Interactions from quantum information ideas/methods/techniques/results?



*Io stimo più il trovar un vero, benché di cosa leggiera, che 'l disputar lungamente delle massime questioni senza conseguir verità nissuna.



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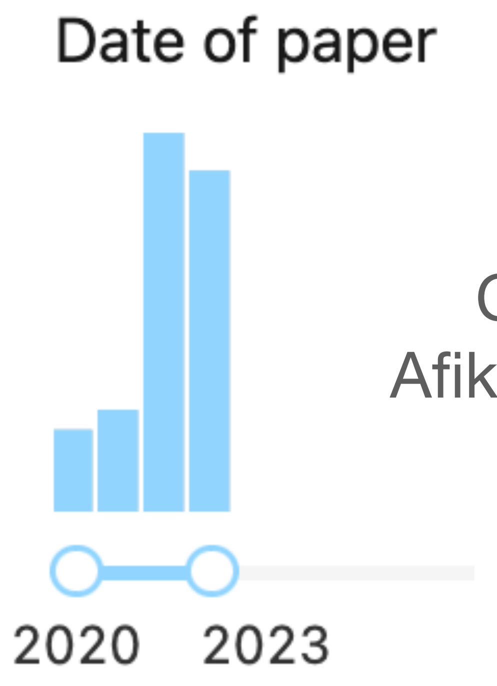
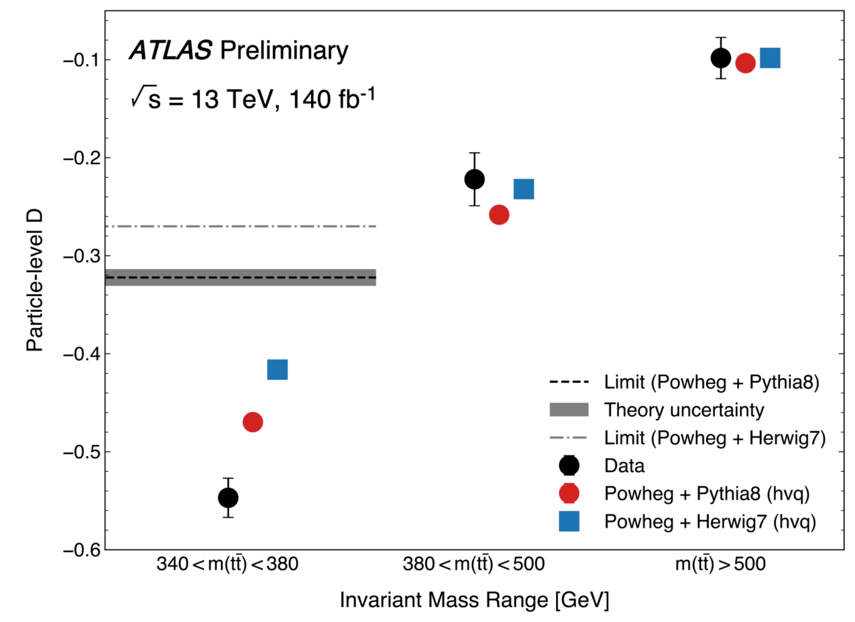
Why now?

What can we learn on Fundamental Interactions from quantum information ideas/methods/techniques/results?

- An impressive rise of interest in the HEP community in the last one or two years, accelerating.
- Very interesting and promising results
- New ideas
- Broadening of the interest to more formal as well as pheno aspects
- First experimental result appeared!



Citations to the Afik & de Nova paper



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Why here?

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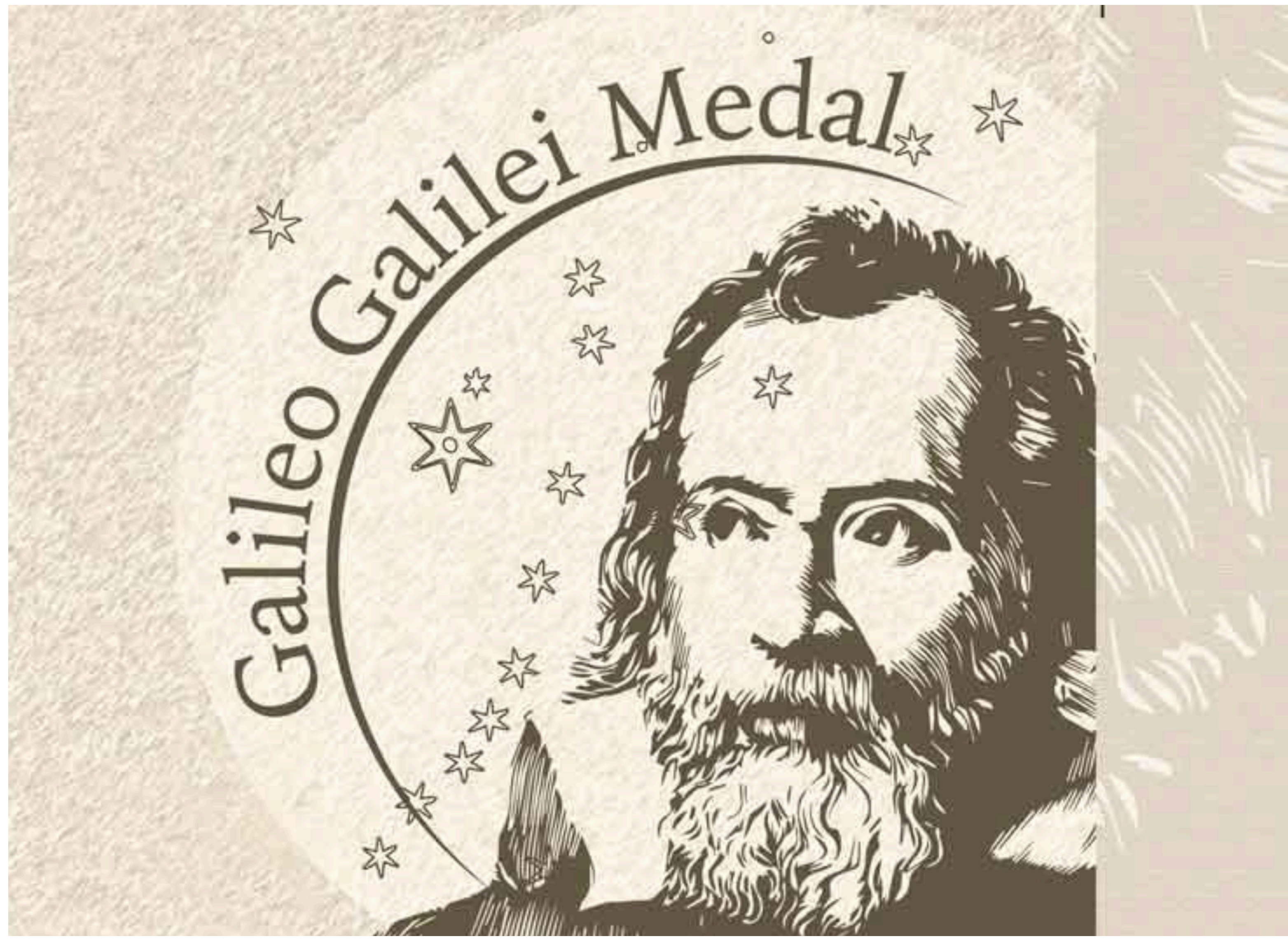

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How?

A multi-pronged approach:

- **Discuss** the most recent results and ideas through presentations and informal meetings
- **Learn** QI from lectures given by renown experts in the field
- **Get updated** on the developments of Quantum Technologies in HEP
- **Get inspired** on what how to contribute/participate and what to do next!
- **Enjoy!**