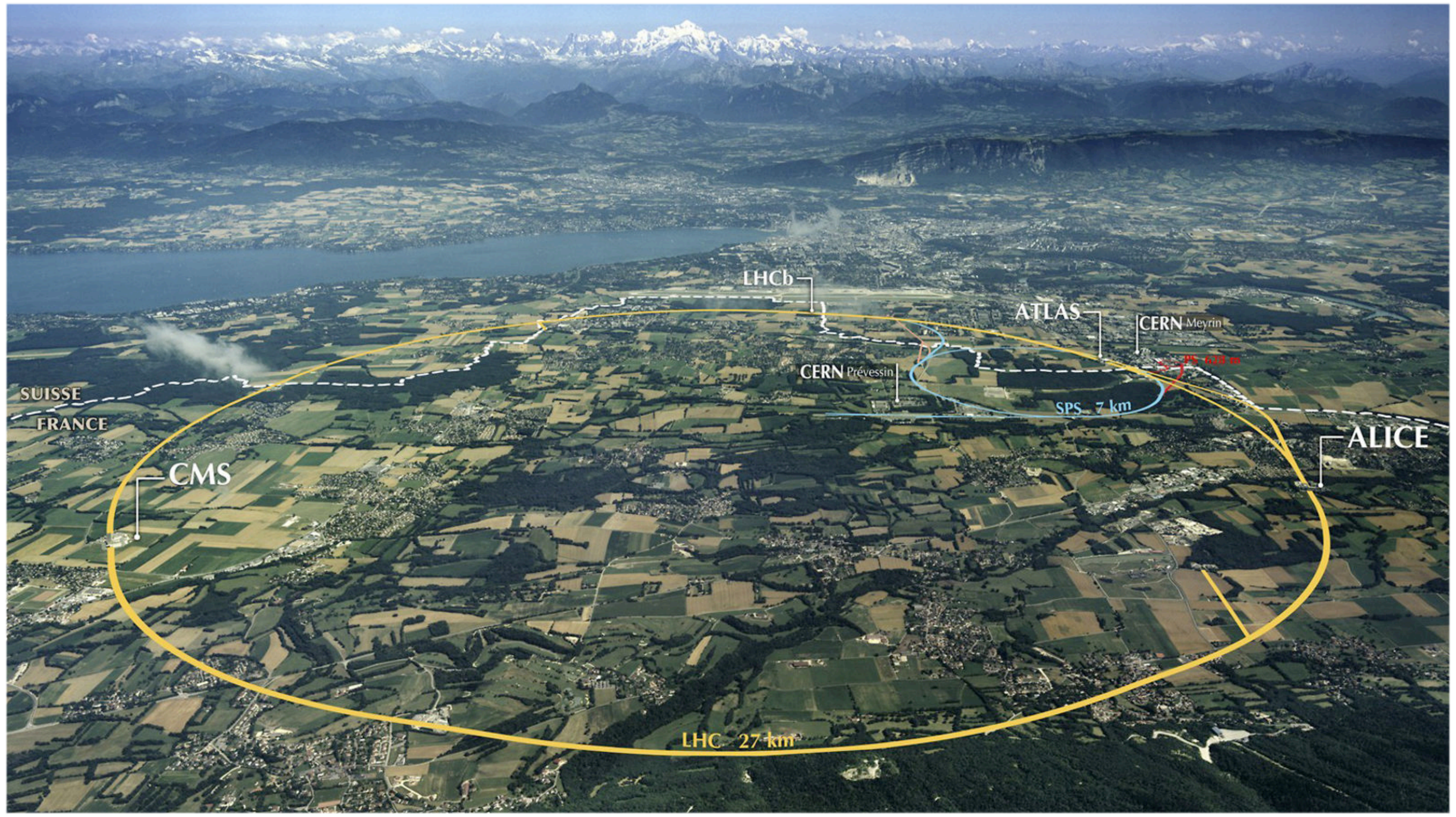
Can quantum computing help to unlock the secrets of the universe?

Heather M. Gray



https://physics.berkeley.edu/people/faculty/heather-gray

The Large Hadron Collider

Collides protons to convert mass into energy into mass

$$E = mc^2$$

A Giant Microscope?

Uncertainty Principle

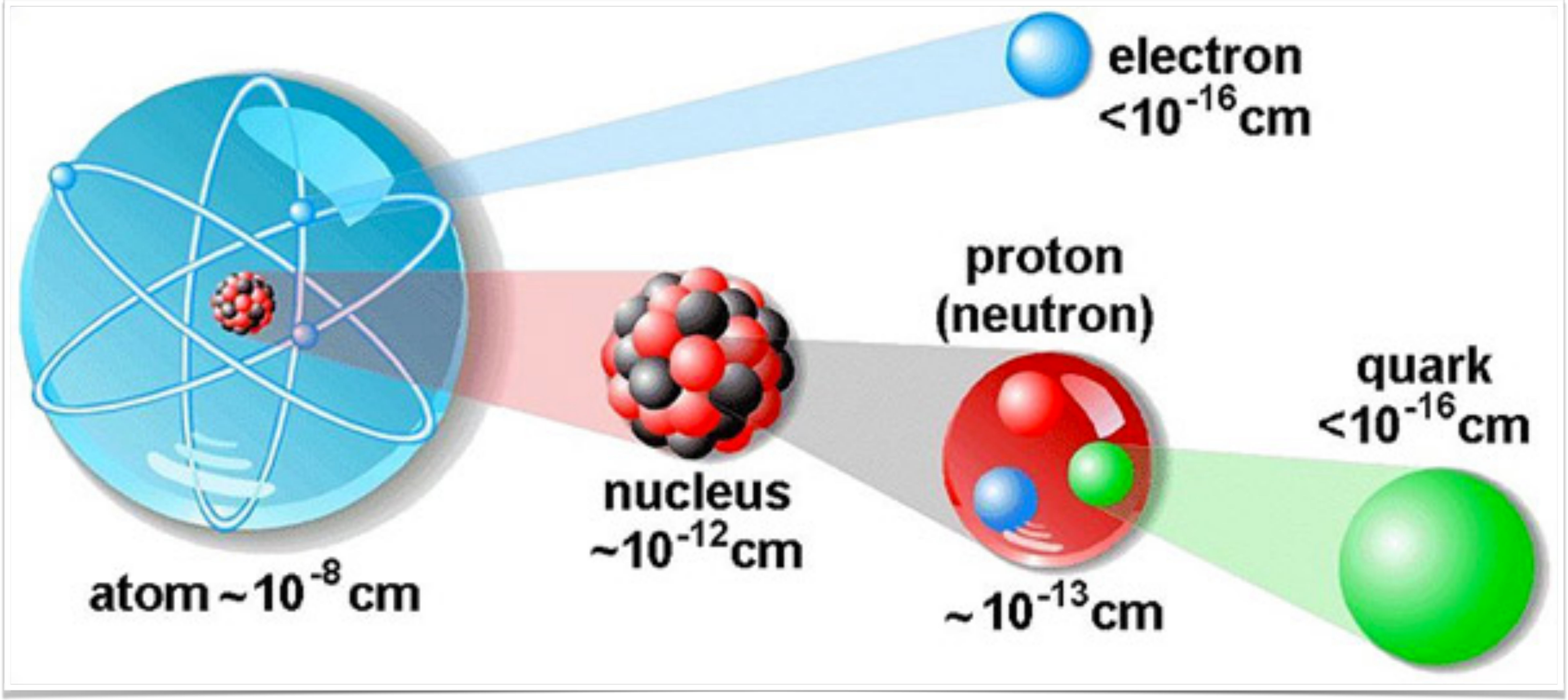
$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

distance

momentum

Protons move at 0.999999990 times the speed of light

From atom to quark



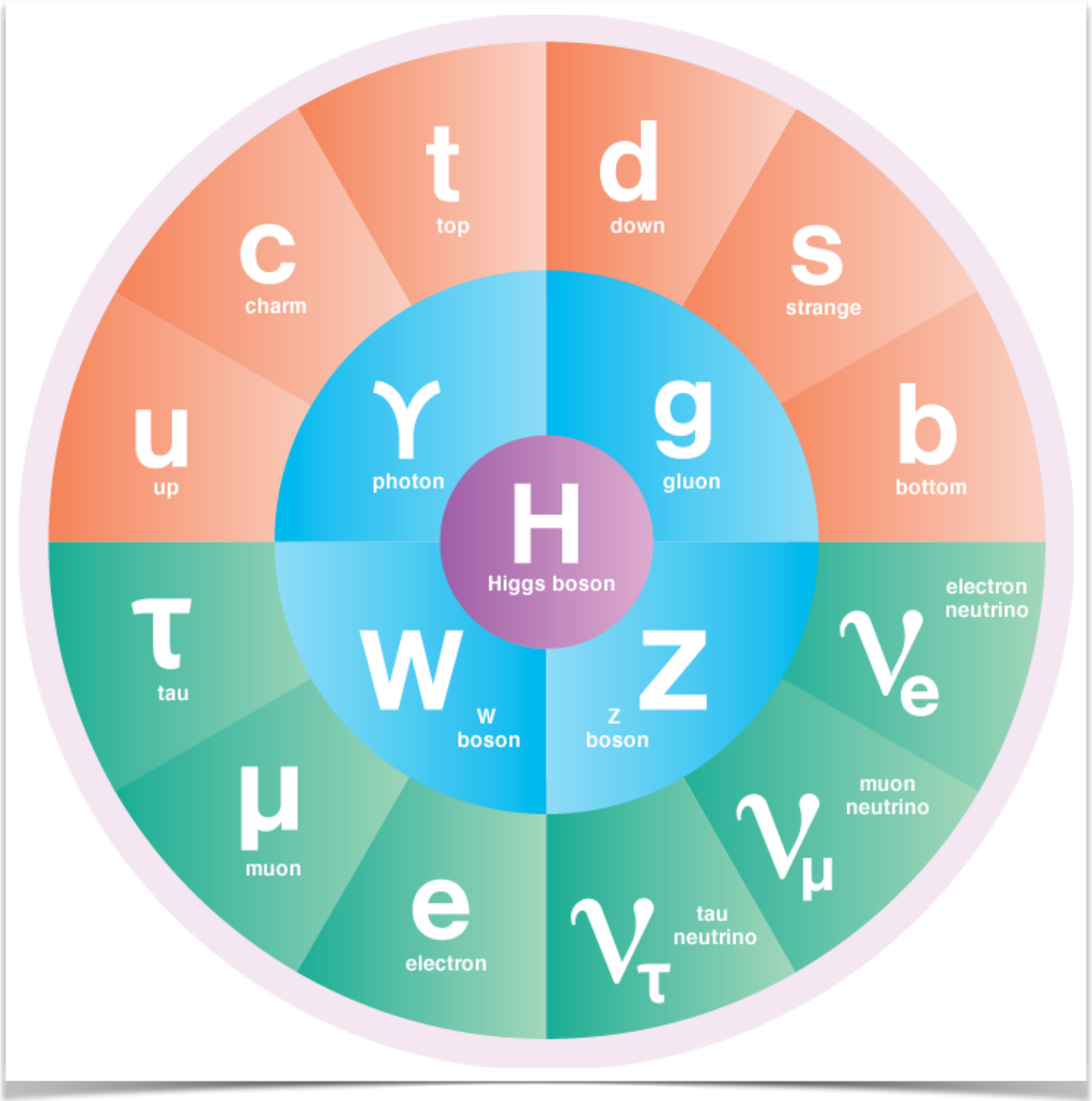
$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

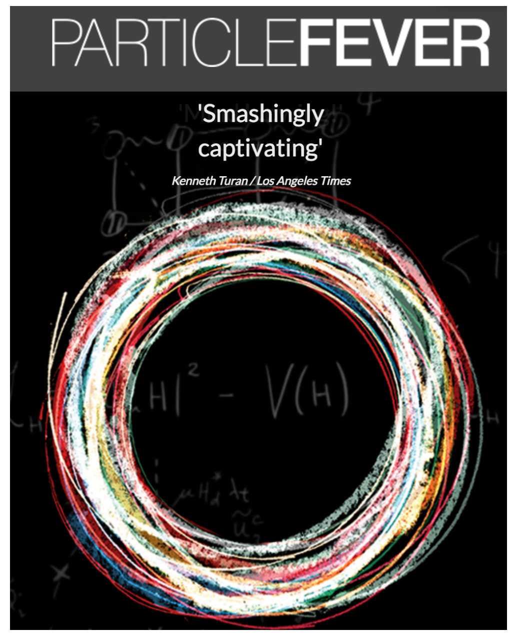
The Standard Model

Quarks

Forces

Leptons

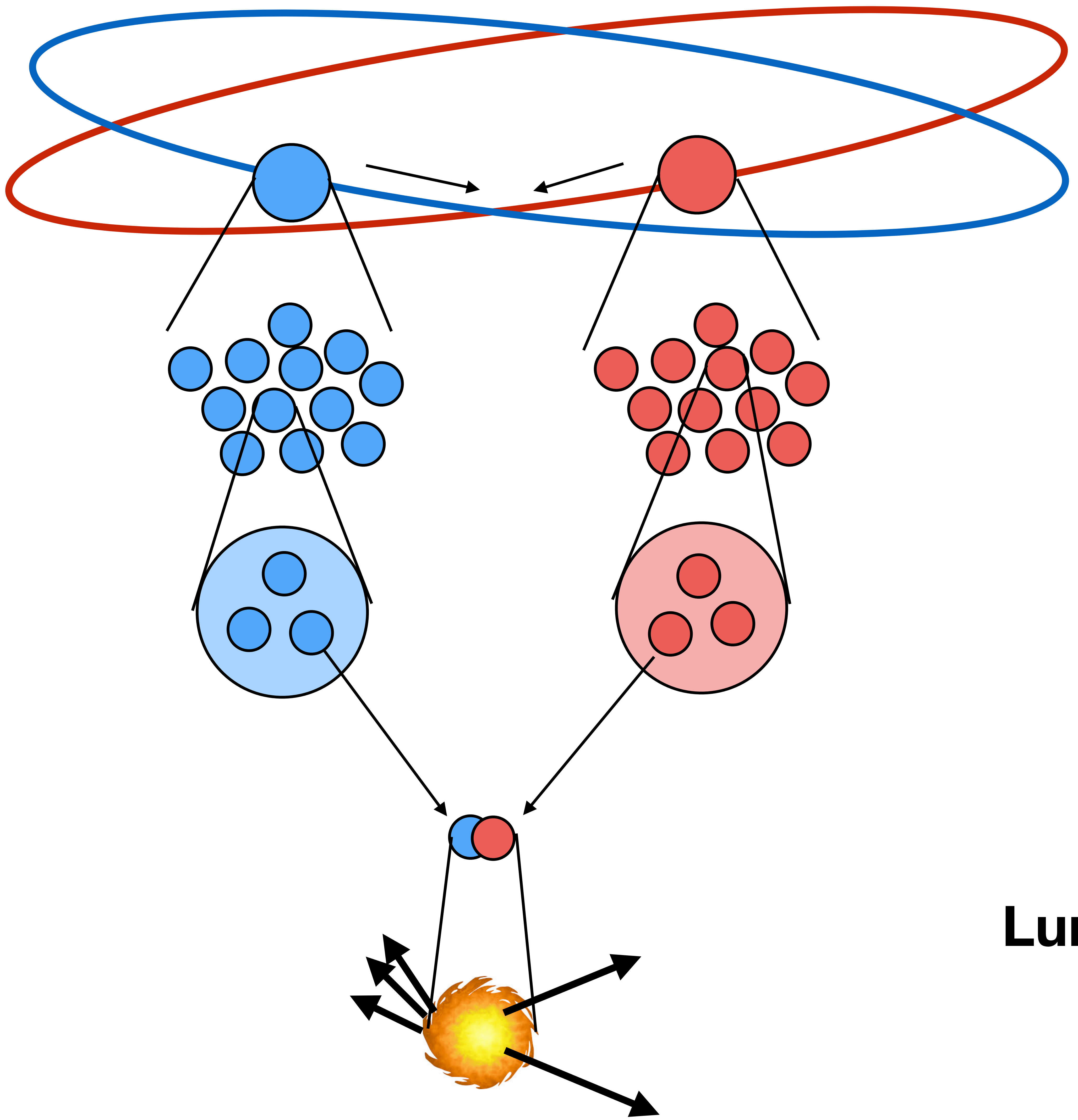




http://particlefever.com/

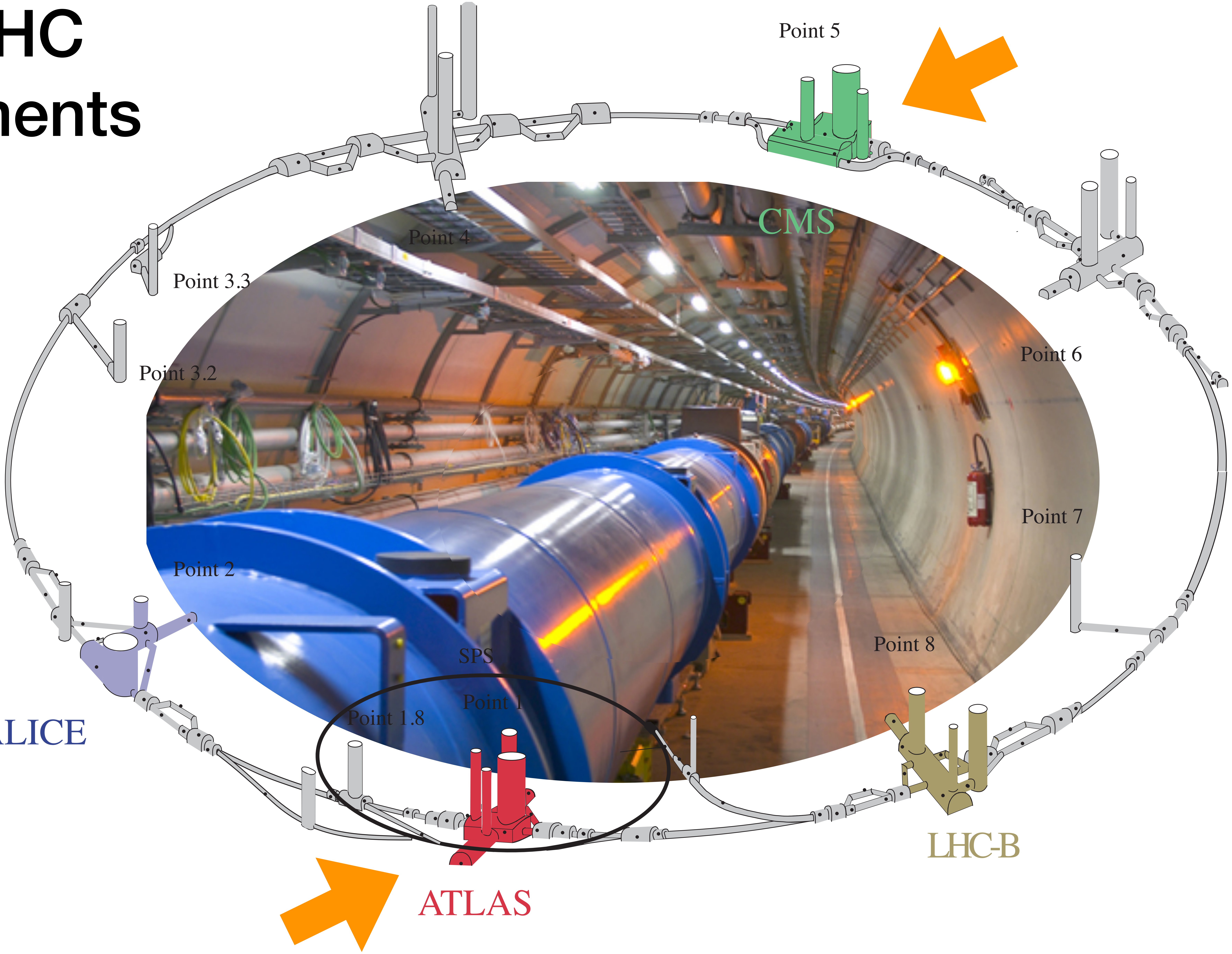
Particle Colliders

also known as:
atom smashers

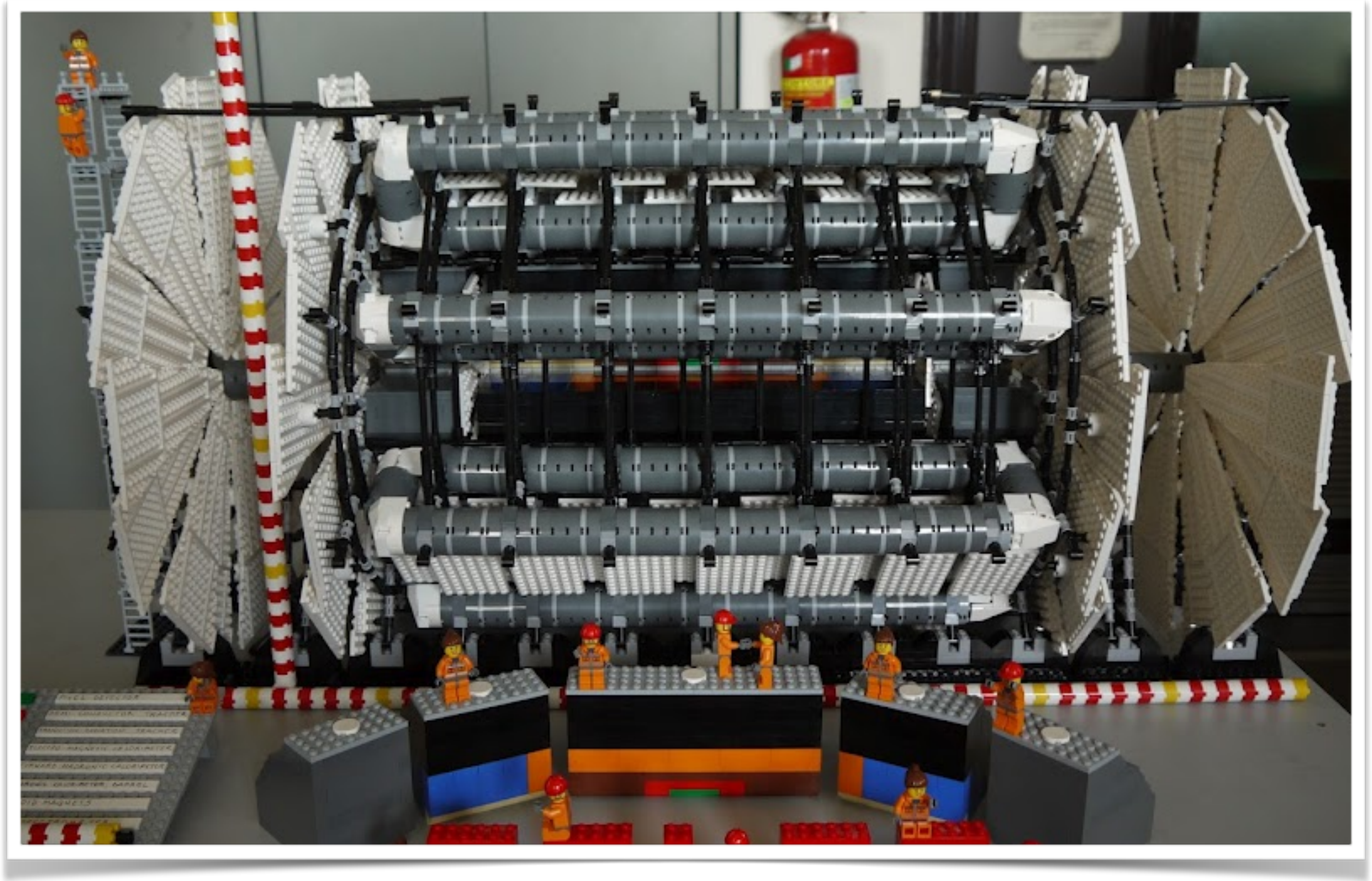


Luminosity: measure of the number of collisions i.e. how much data

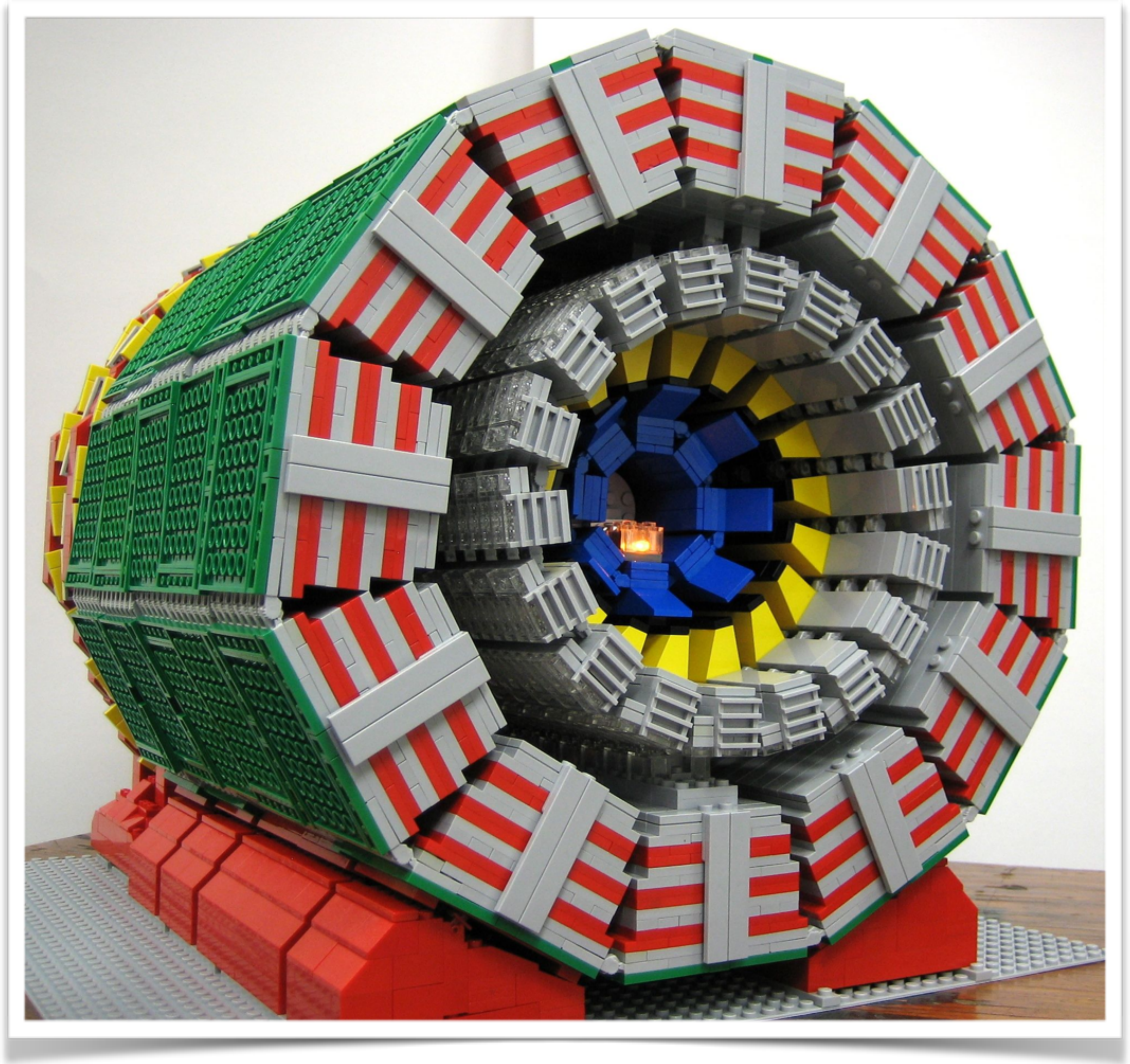
The LHC Experiments



ATLAS



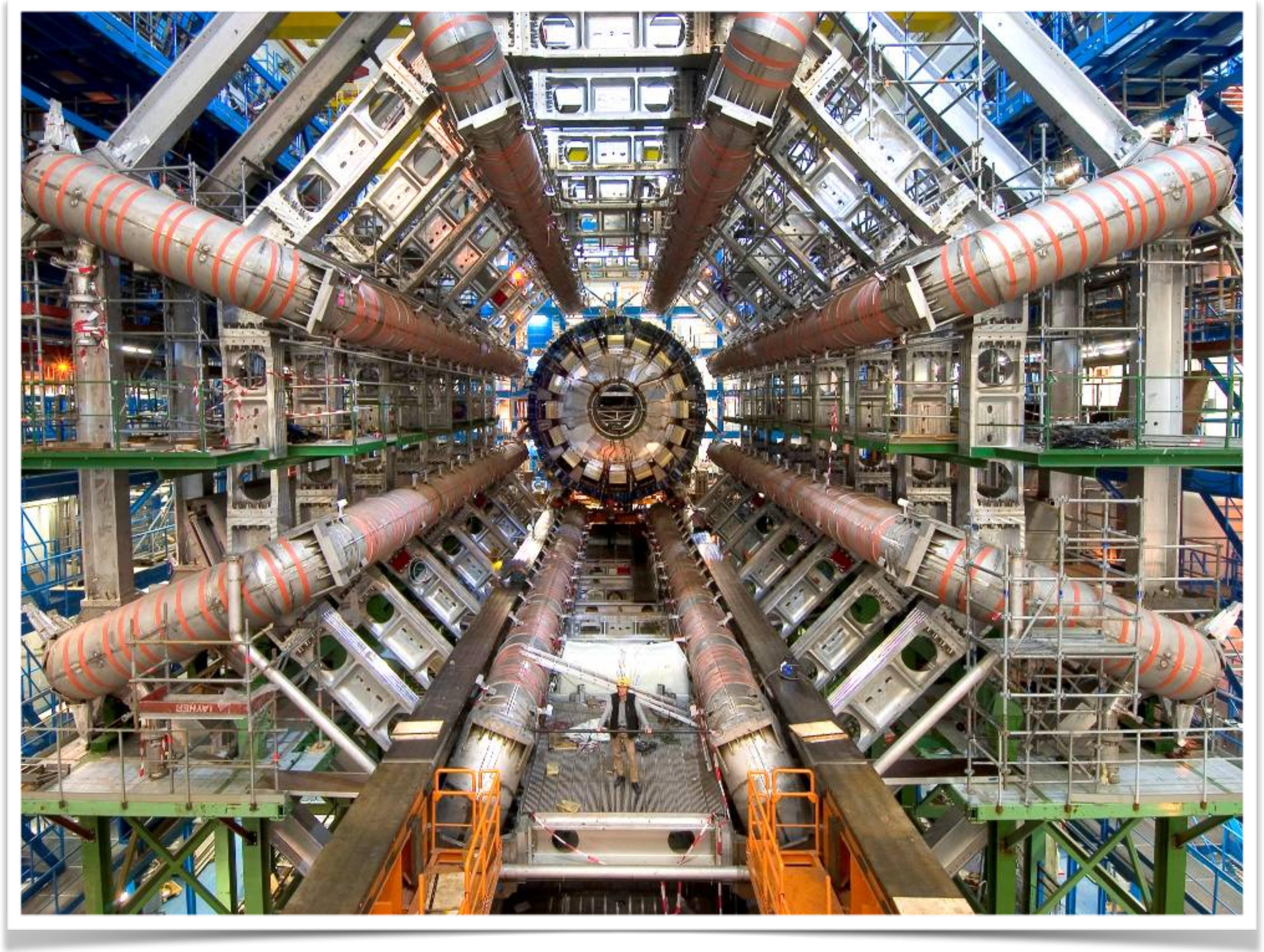
CMS



	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15

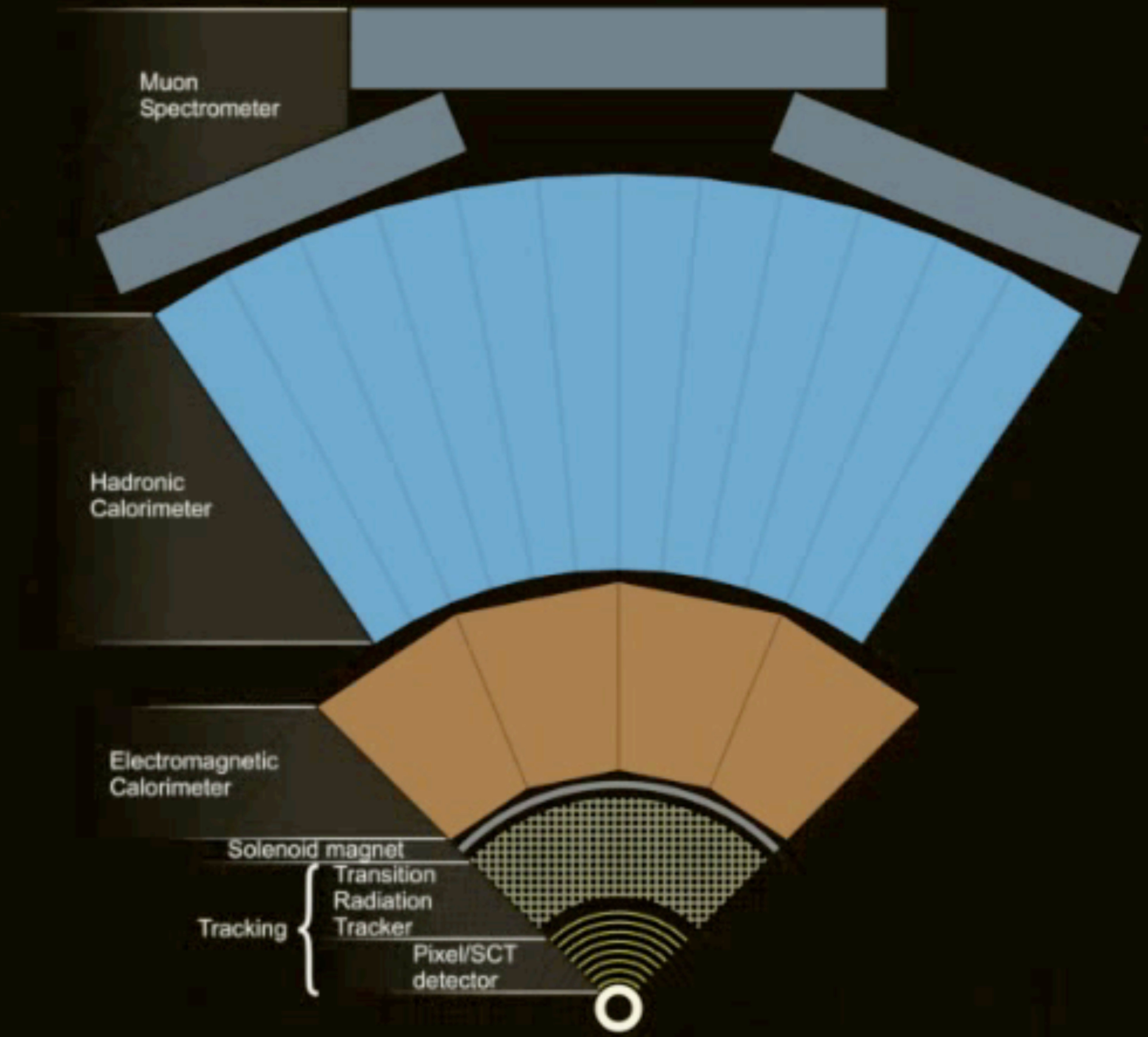
lego detector

ATLAS

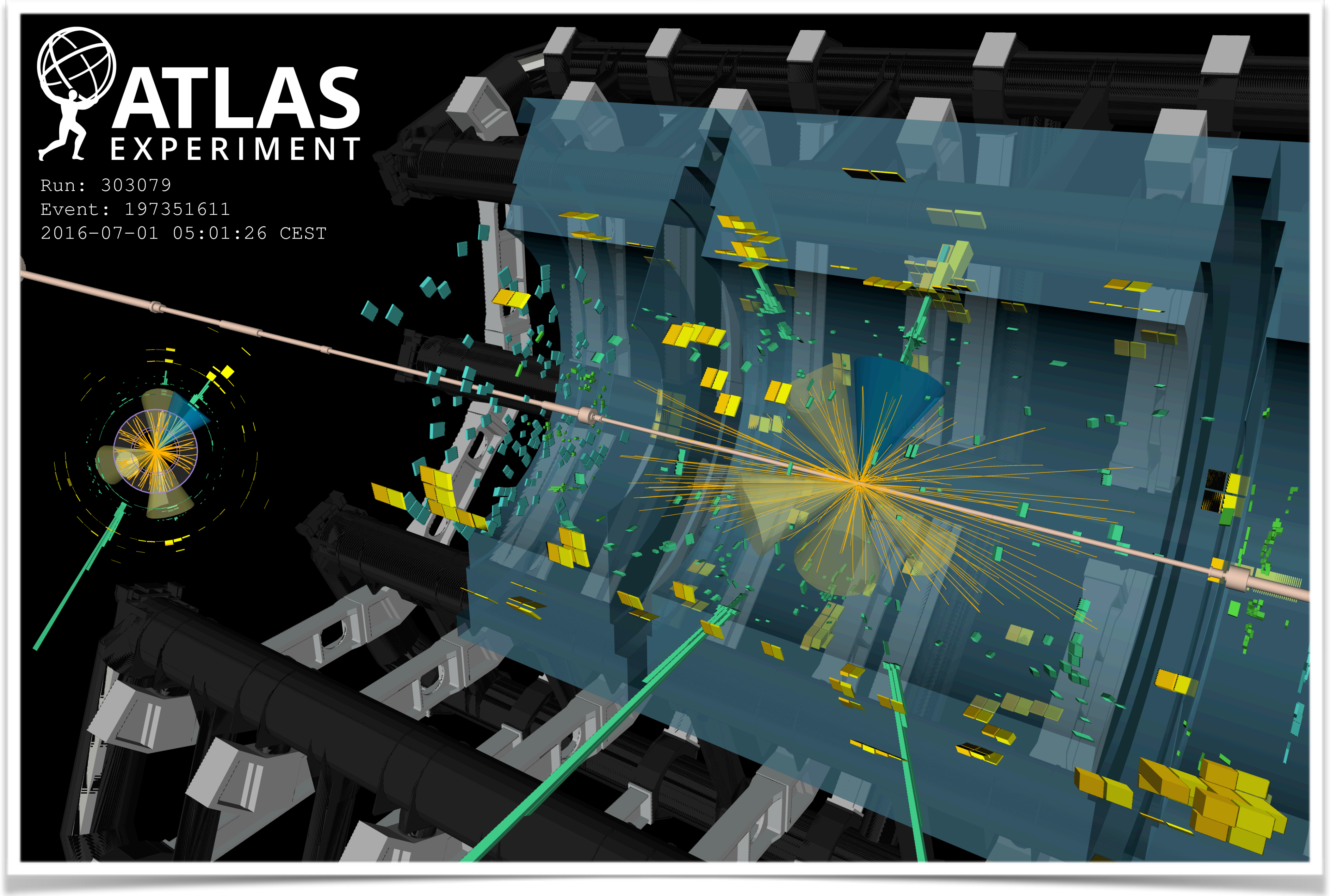


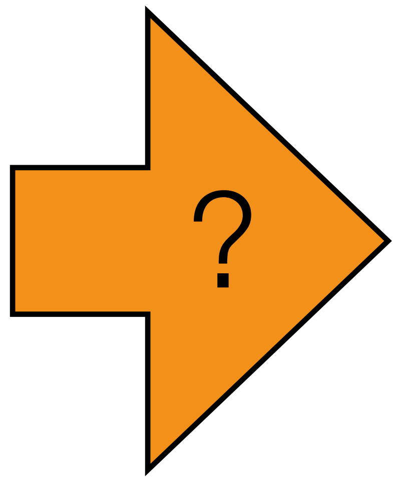
CMS

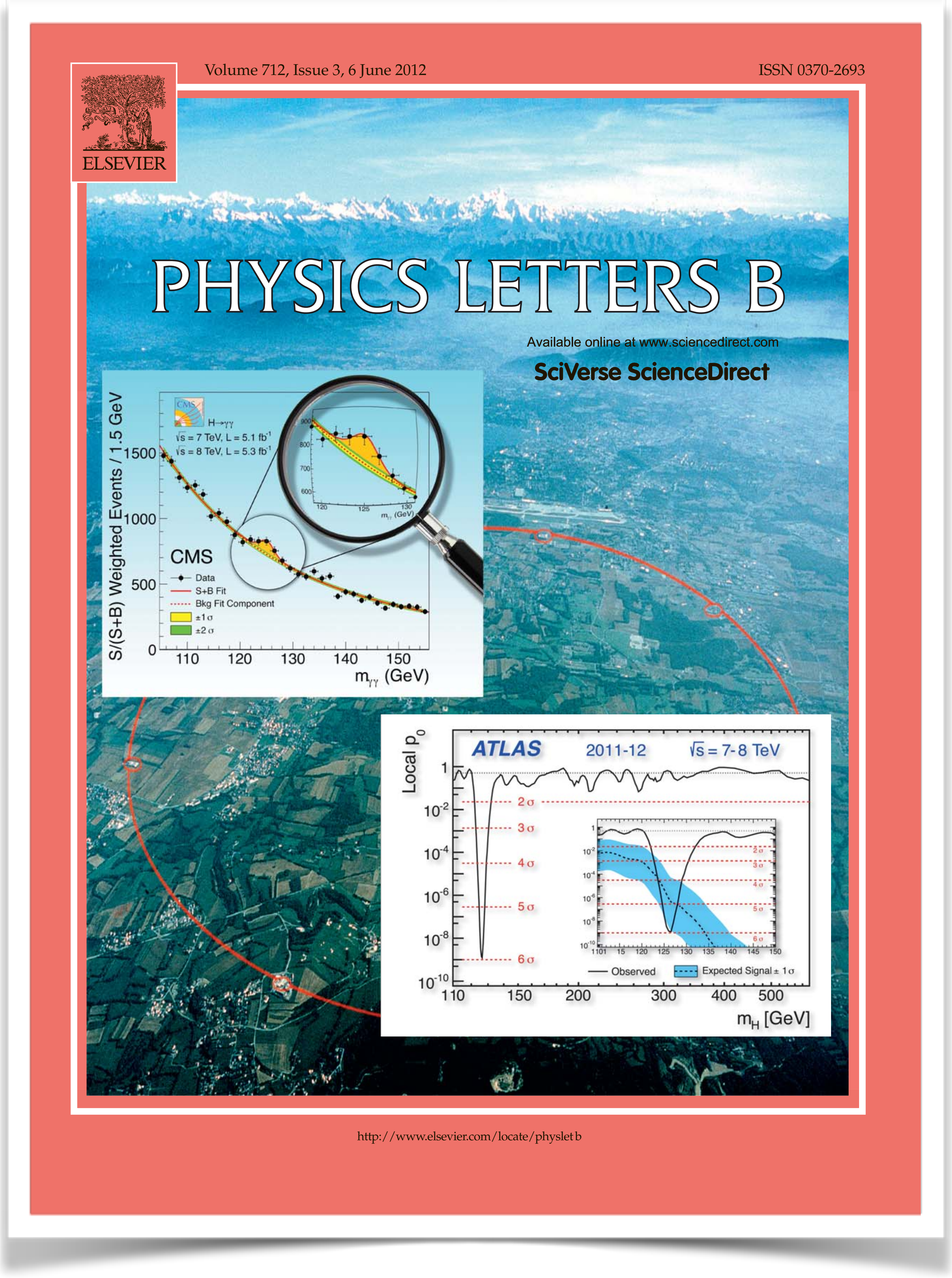
	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector

From detector to physics





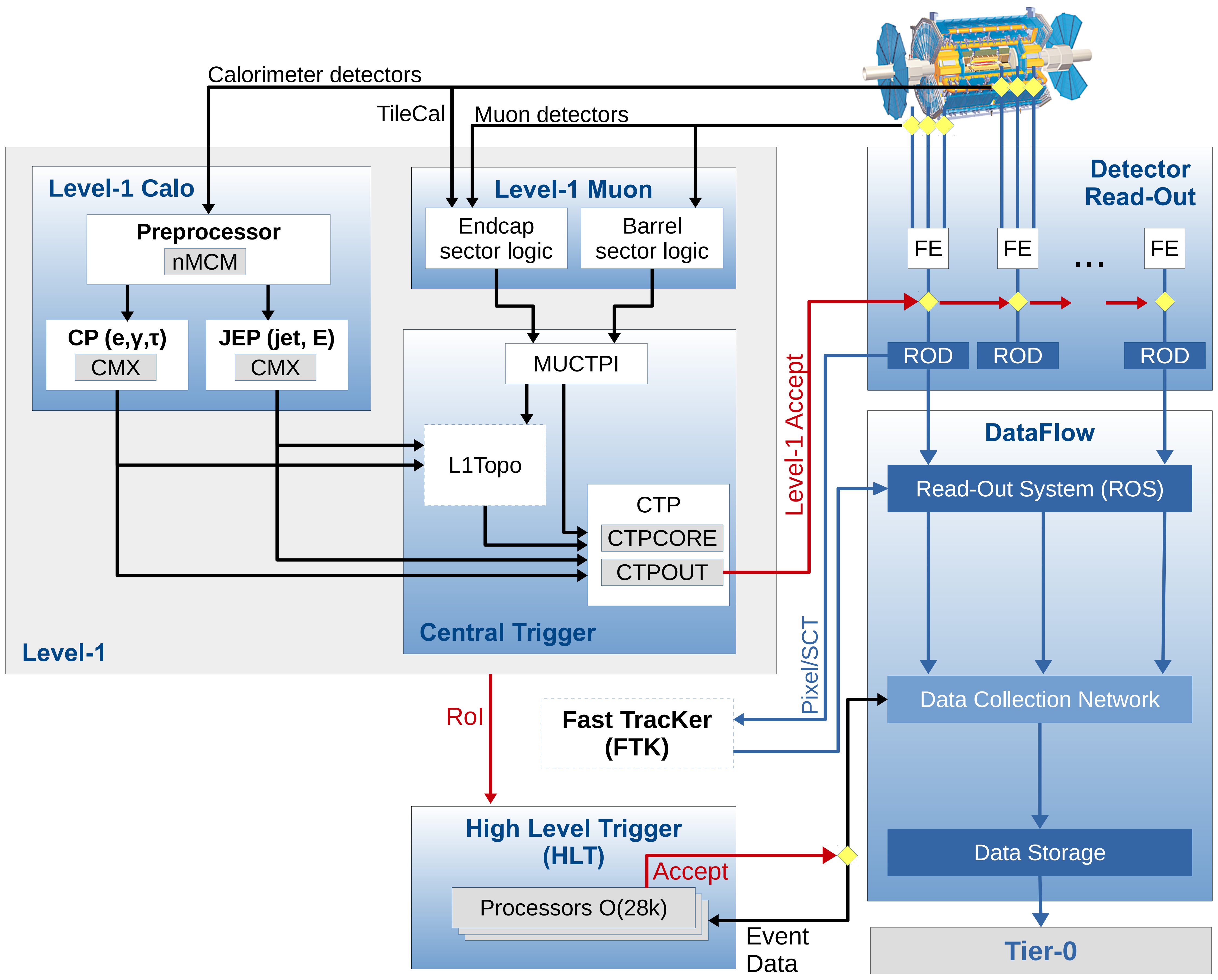


- Data Challenge:
  - 40MHz collision rate
  - ~6M seconds data-taking per year
  - ~1MB RAW event size

Zetabytes per year

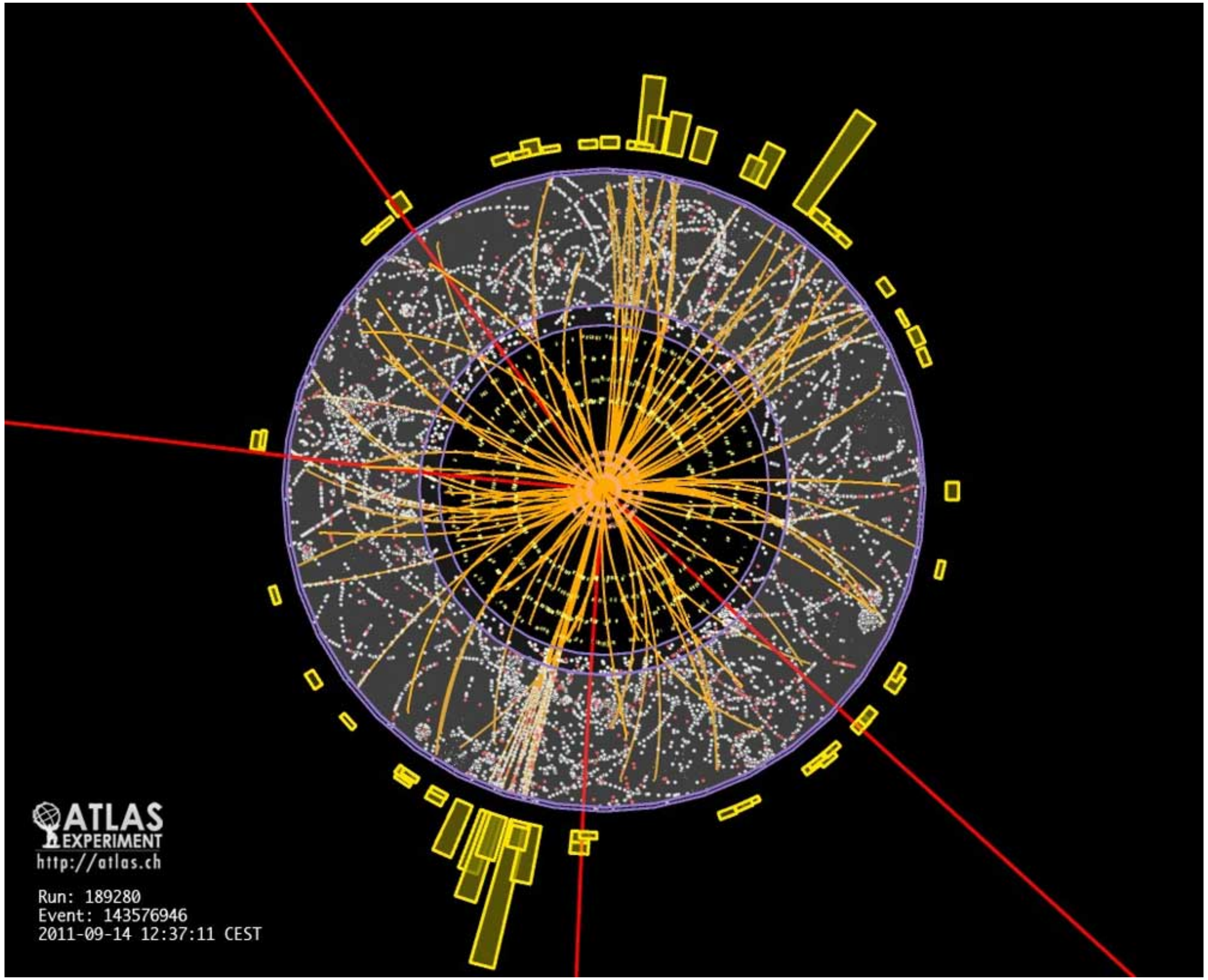
Throw away what you don’t need

- Complex trigger system to select interesting events
  - **Level 1** looks at local information to select **potentially interesting events**
    - Keep 0.2% of events
    - Decision within 2ms
  - **High Level Trigger** does incremental reconstruction to identify **genuinely interesting events**
    - Keep 1% of L1 events
    - Decision within 200ms



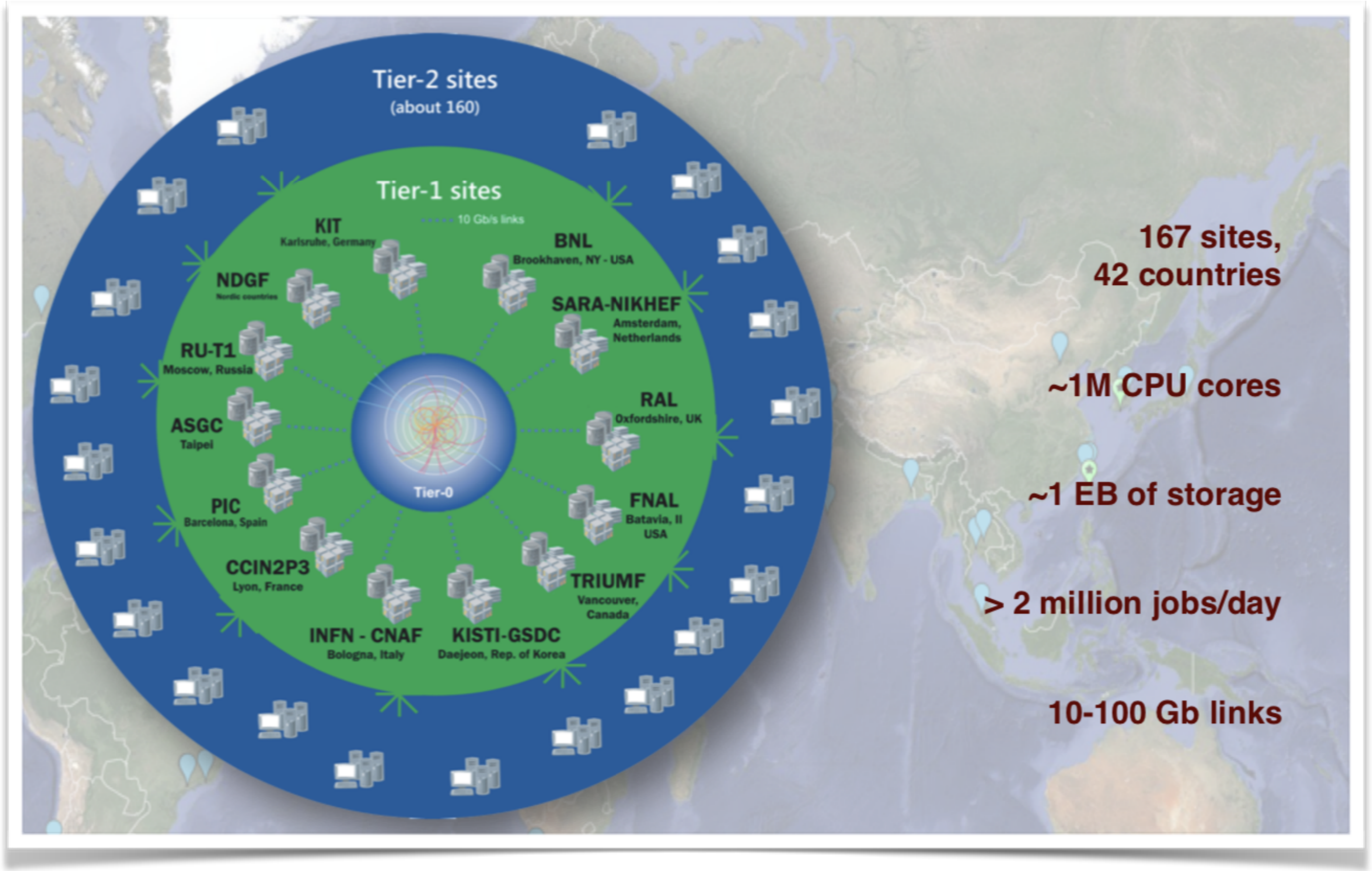
Data Processing

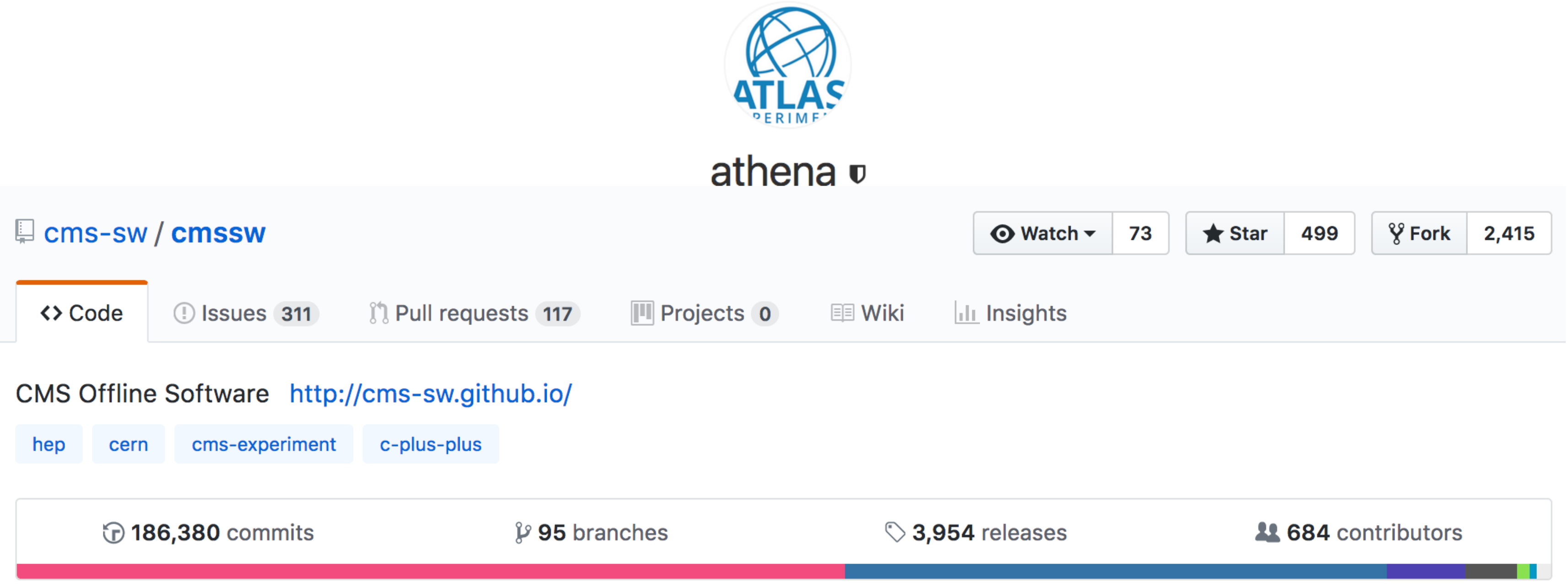
- ATLAS records **~10^{10} RAW** events a year
- **~15s** per event to reconstruct the physical particles
    - **~5000 CPU years**
- Can't do this very many times



LHC Computing

- Use **1M CPU cores** every hour of every day
- Store **1000PB** of **data**
- Make **100PB** of **data transfers** per year

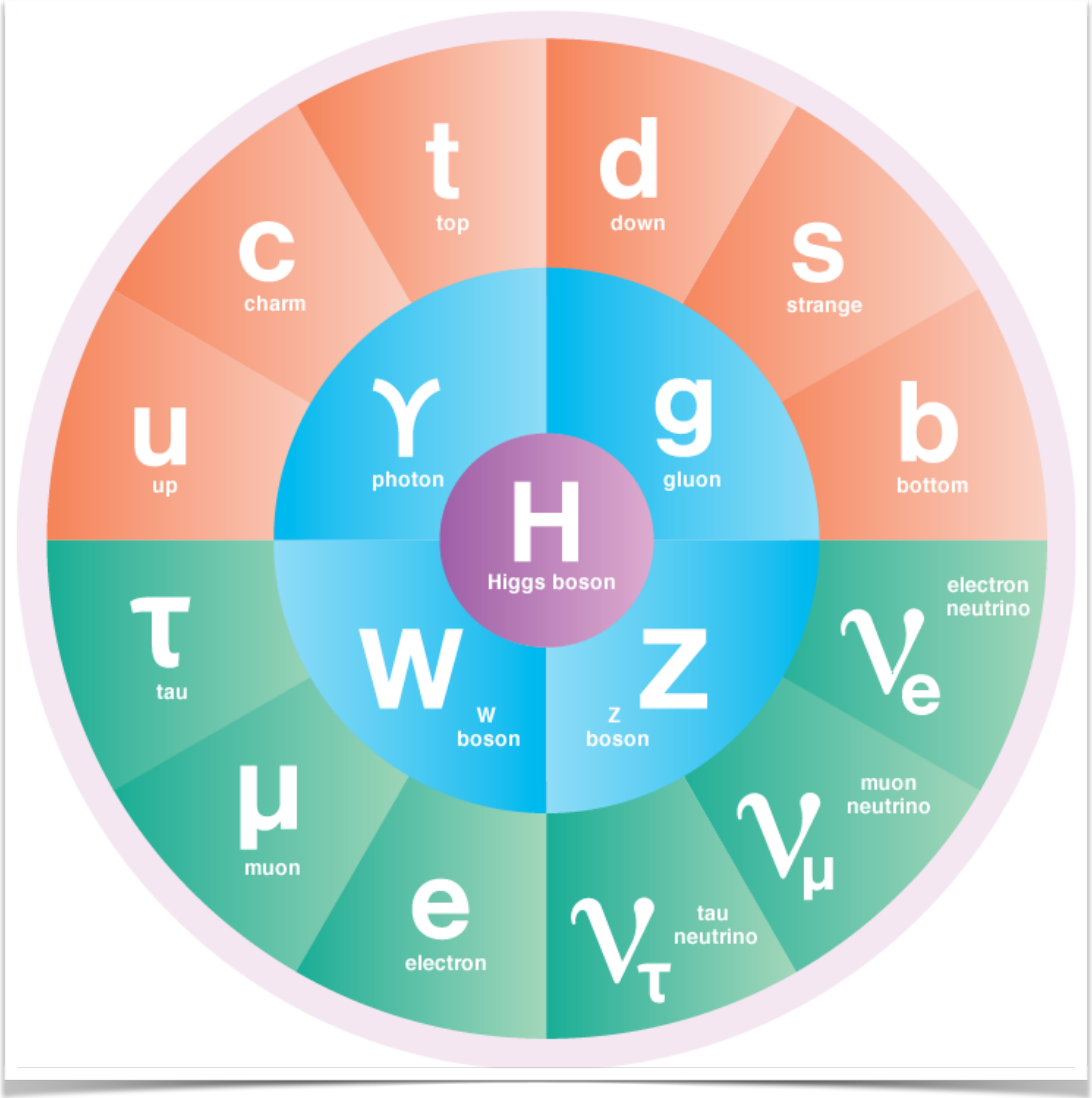




Why?

We have an extraordinarily successful description of nature:

The Standard Model



But … questions remained

- What is the origin of particle masses ?
- What is dark matter ?
- Why is there so much more matter than antimatter in the universe?
- What happened in the first few moments of the universe ?
- Are there other forces ?

The LHC is looking for answers to all these questions

But ... questions remained

- What is the origin of particle masses ?
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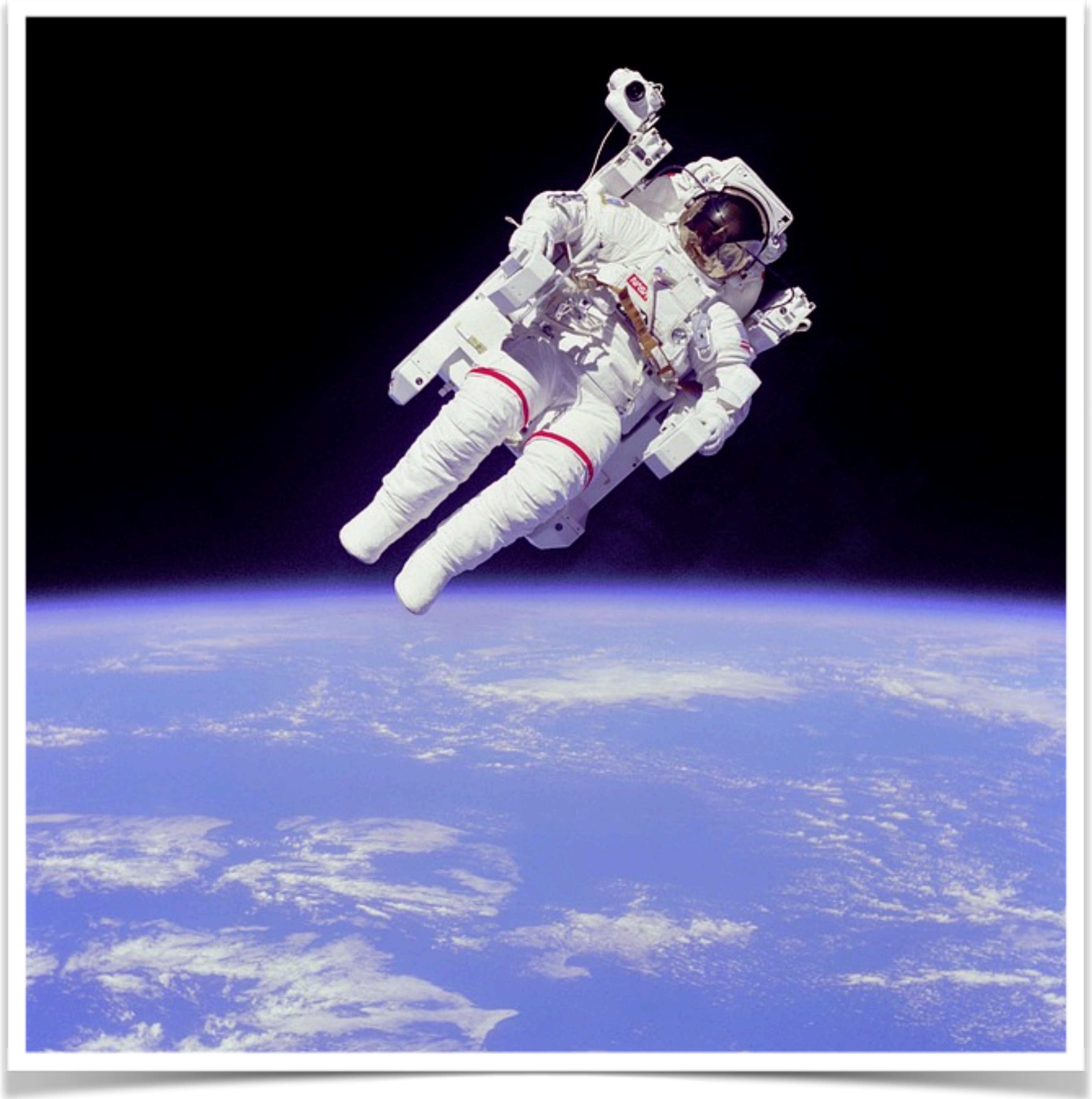
The LHC is looking for answers to all these questions

The Standard Model equations would work perfectly if all particles were massless

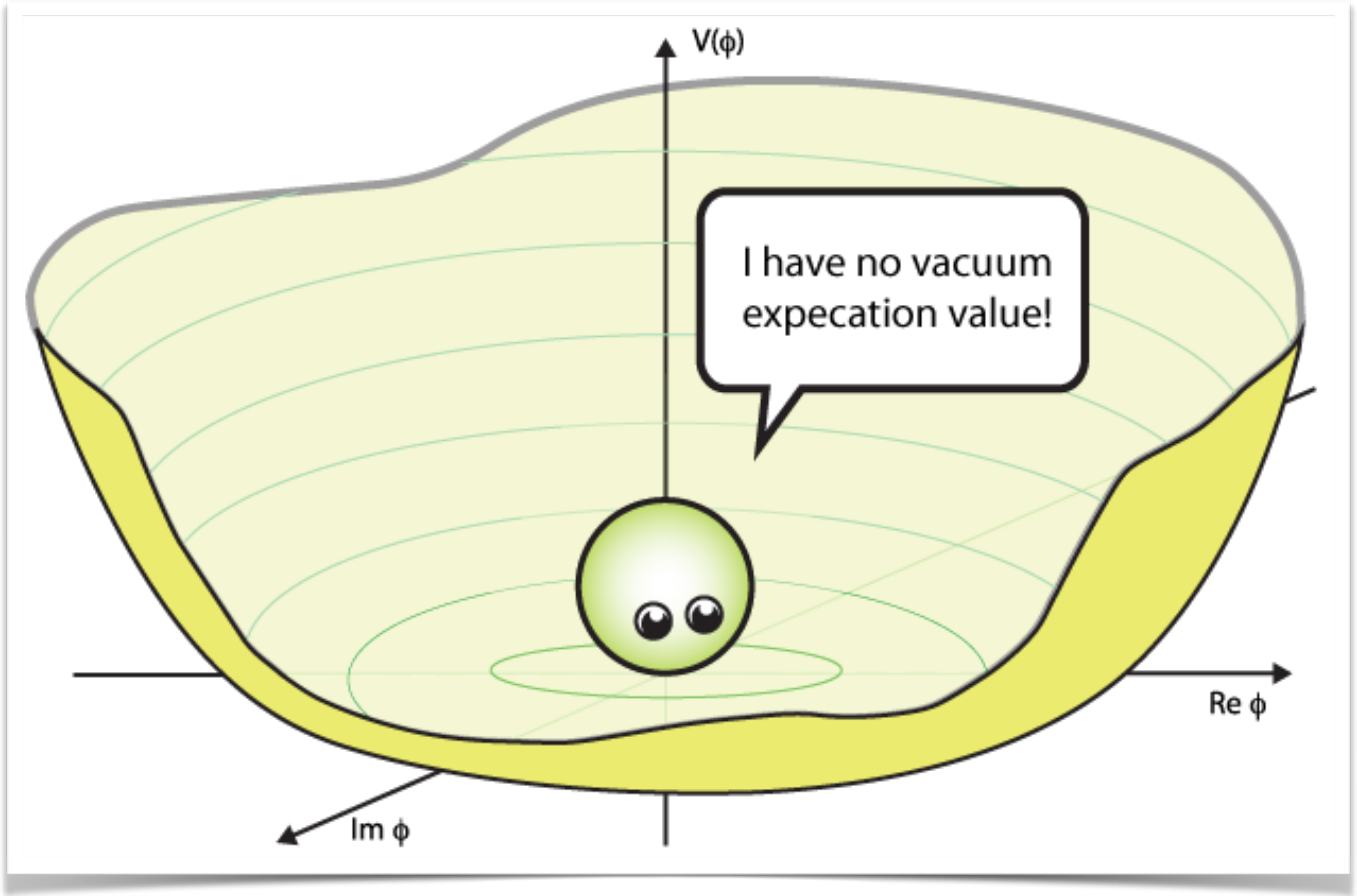


… but experiments told us otherwise

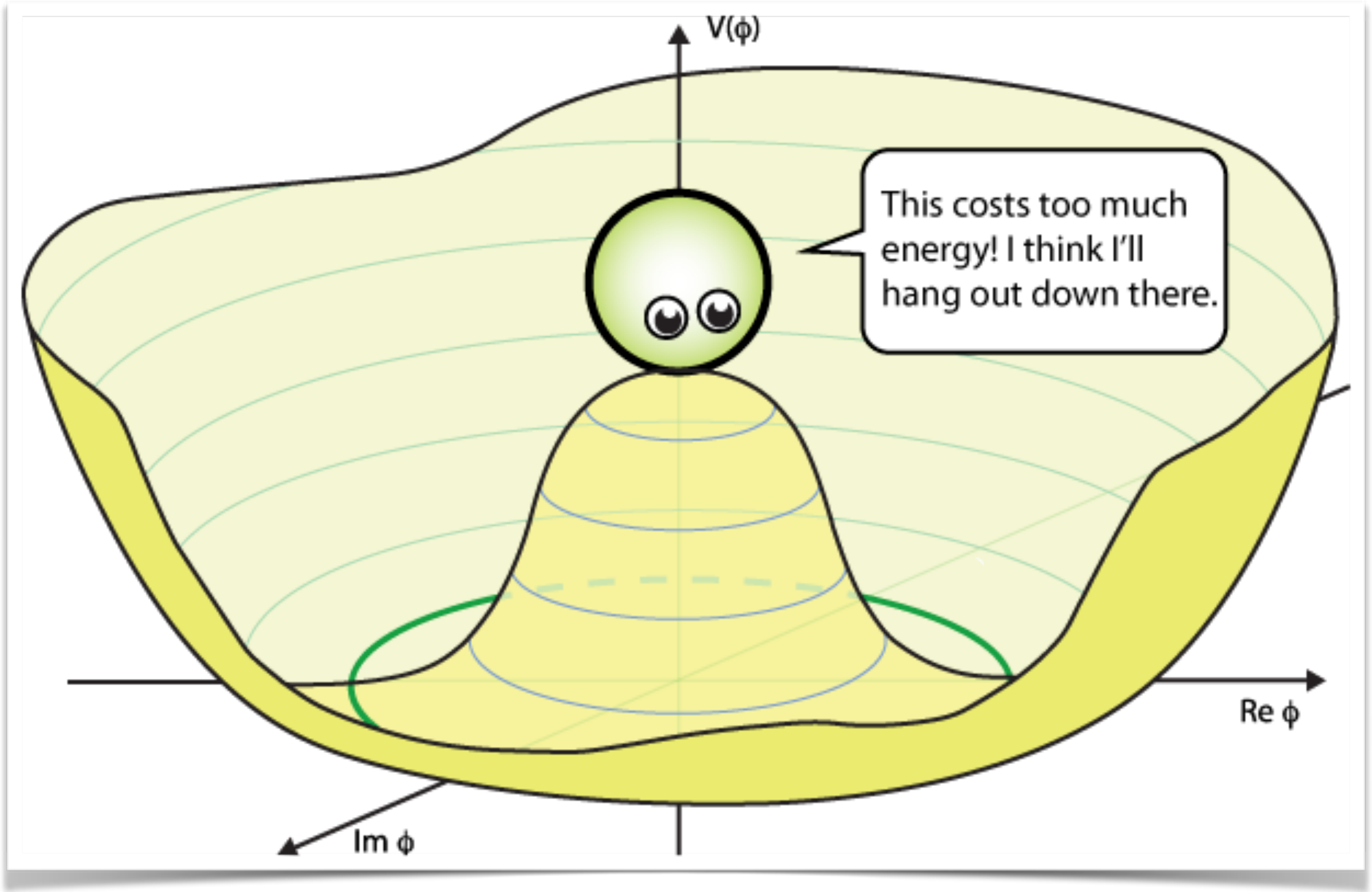
The Higgs Boson

a mathematical trick

Early universe



Today

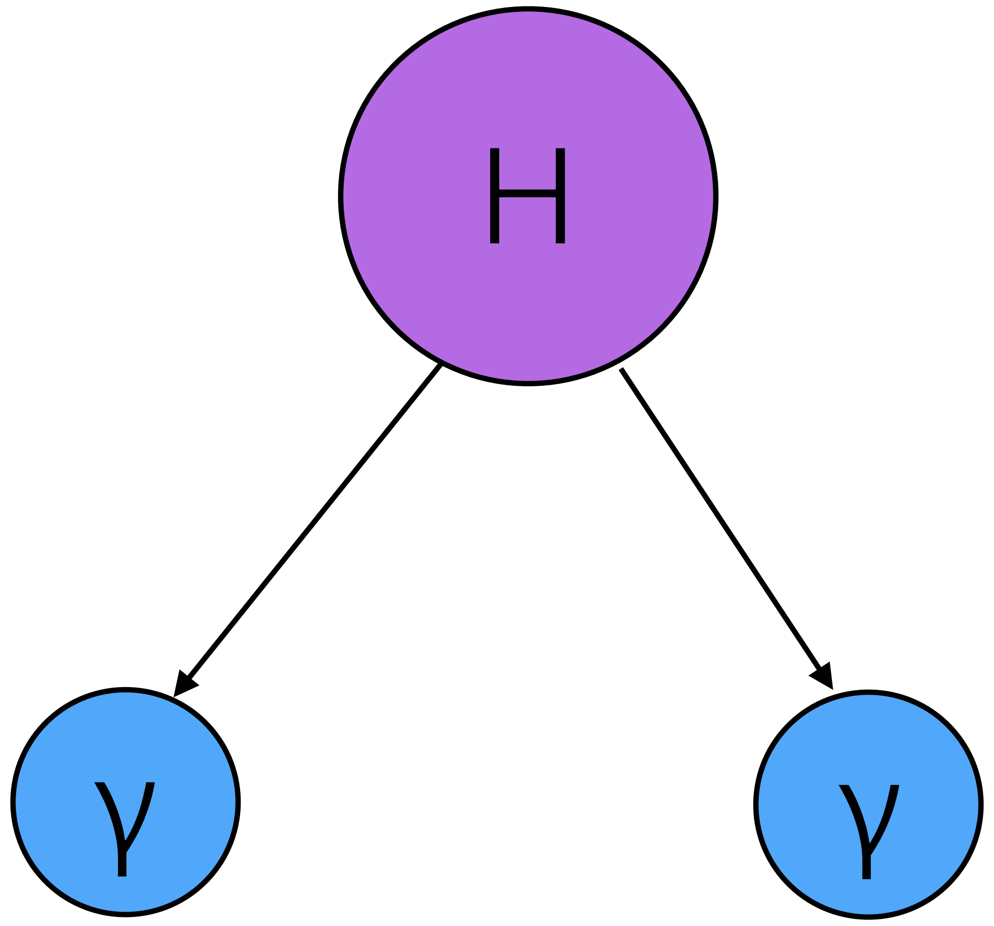


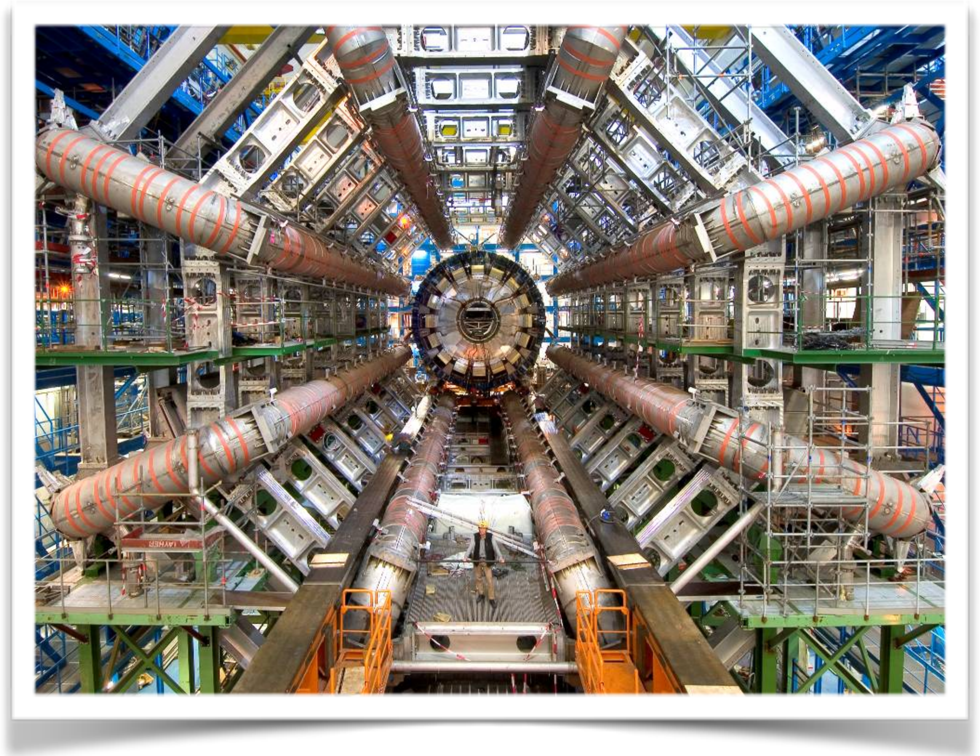
First predicted almost 60 years ago!

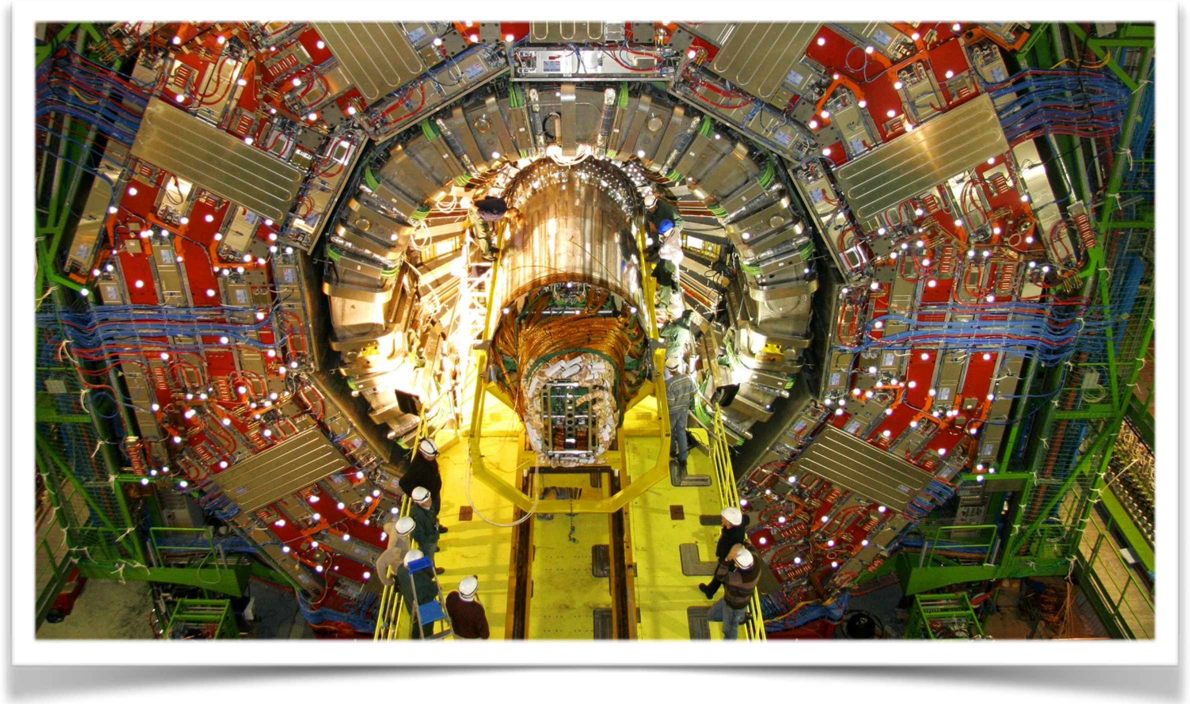
Seeing particles, e.g. the Higgs

Highly unstable elementary particle!
Lifetime is only 1.6×10^{-22} s

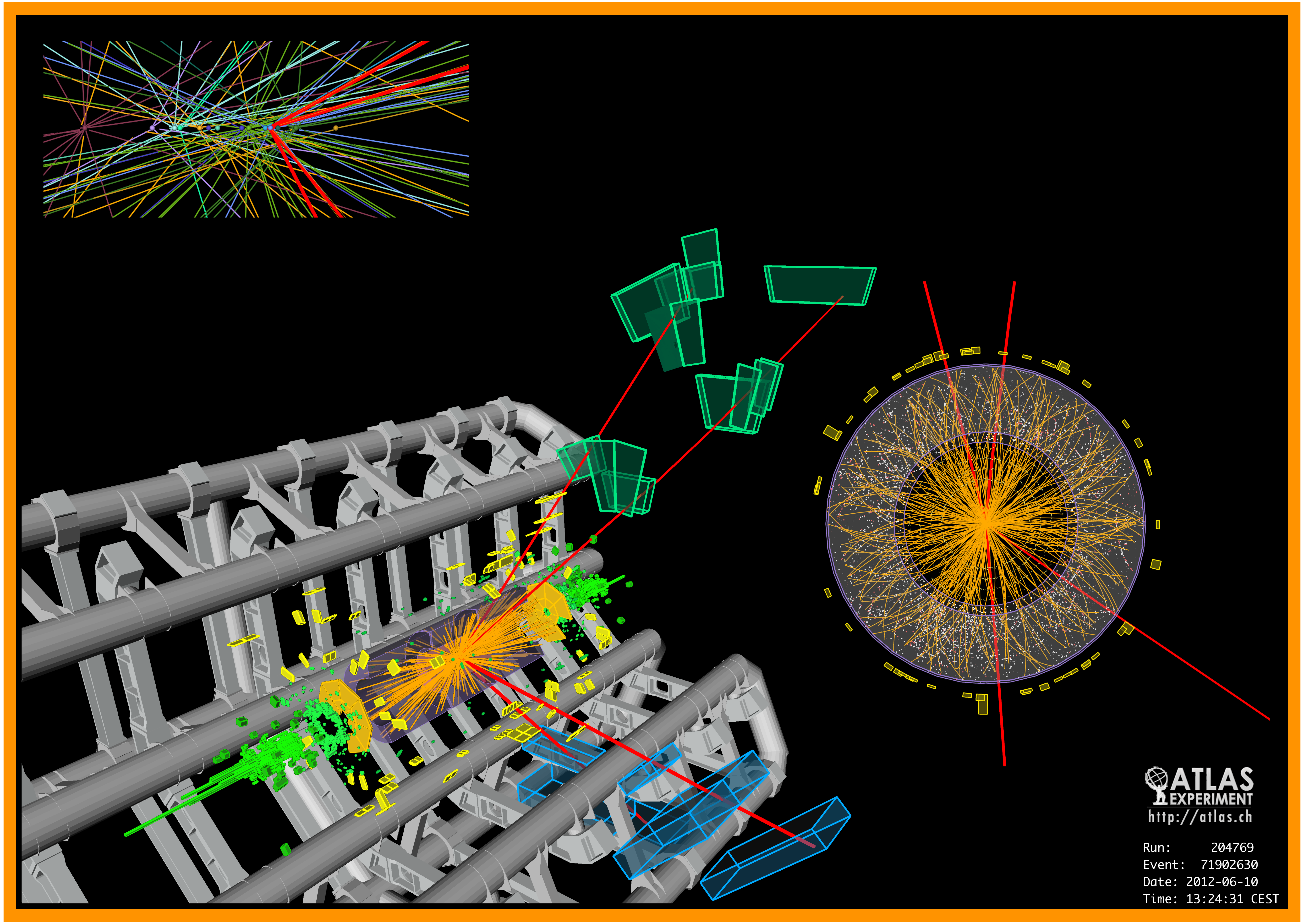
Example: Higgs decay to two photons



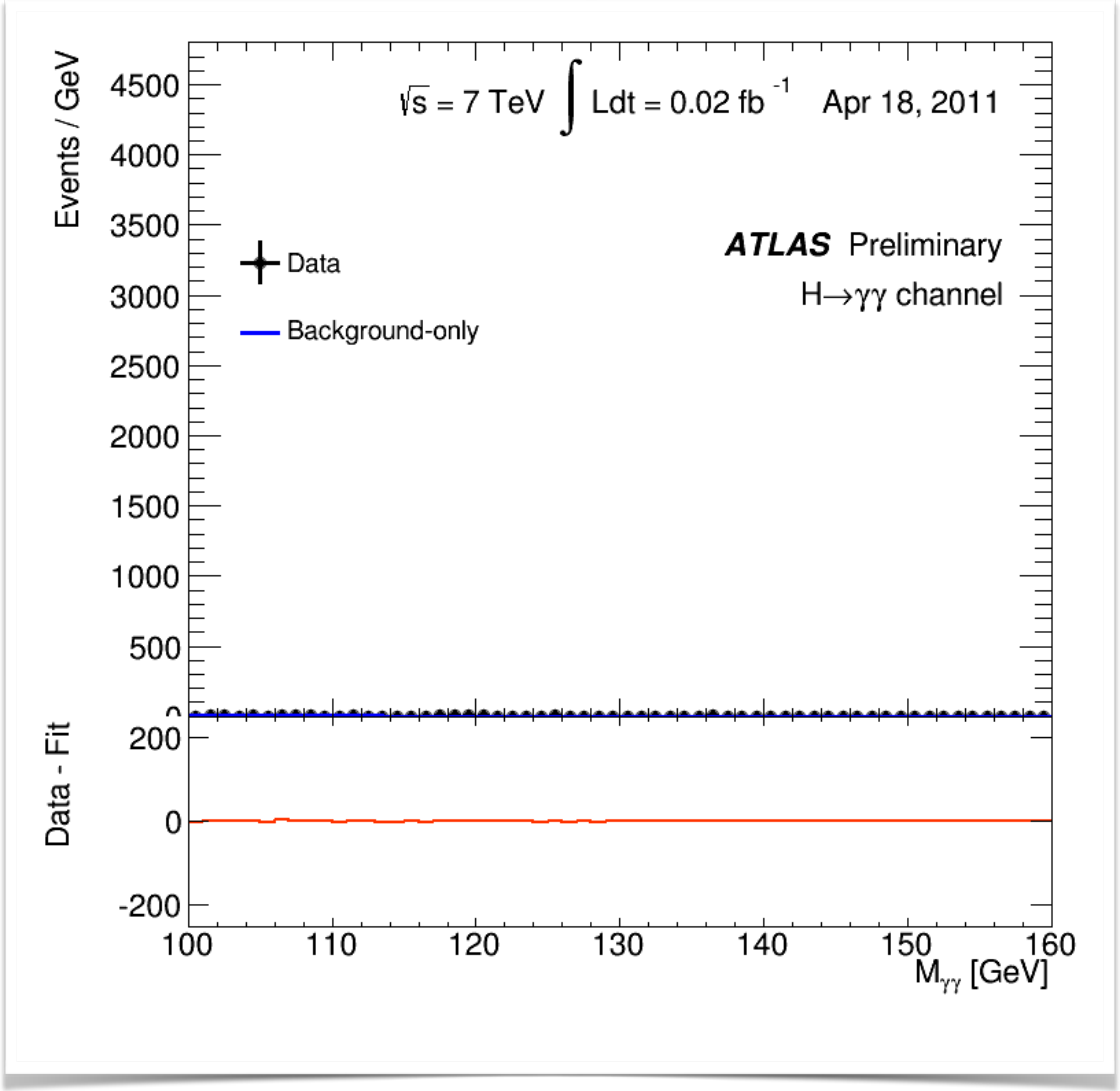




See Higgs by studying its remnants:
the particles it decay to

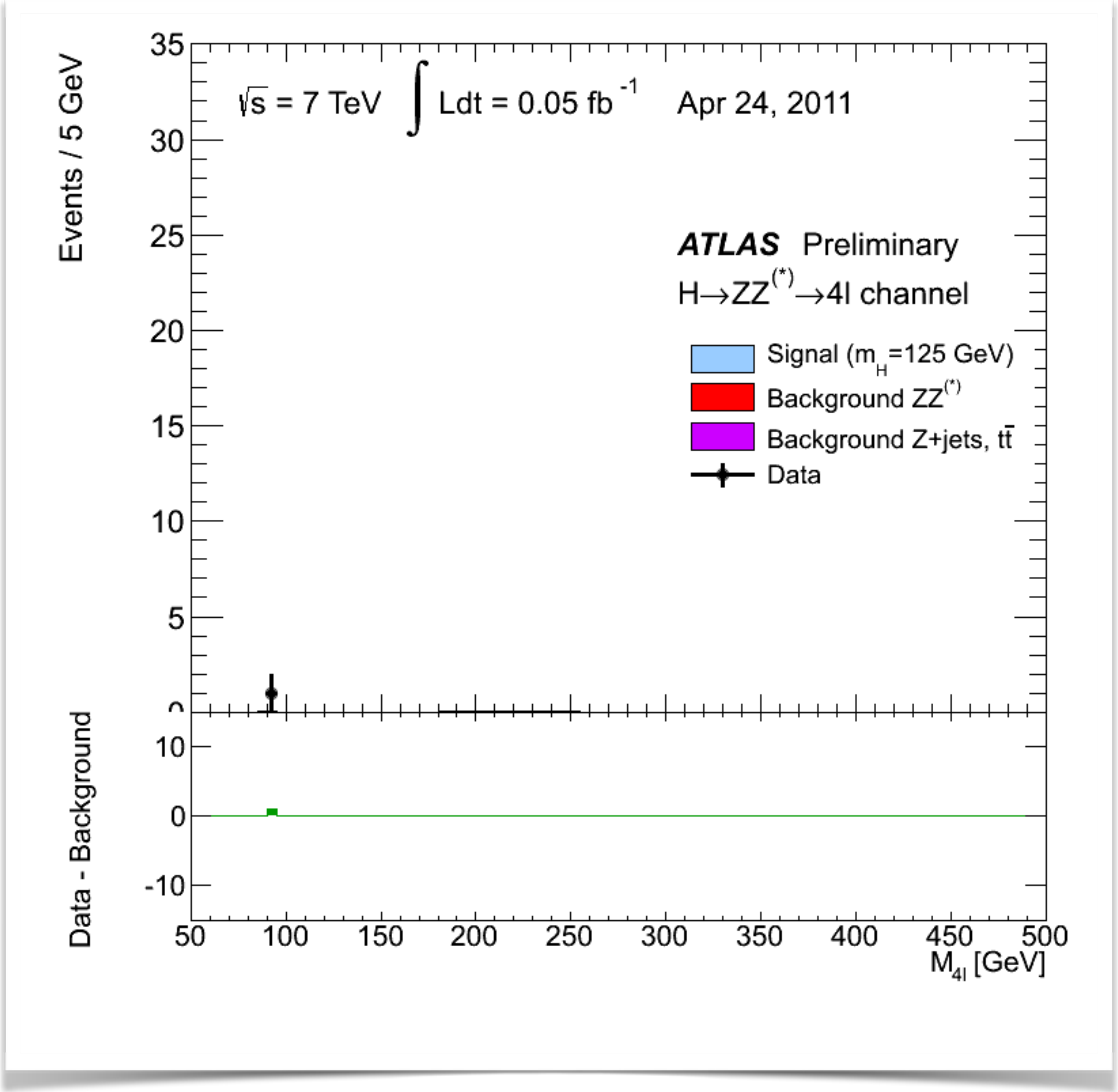

ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

Higgs to two photons ($H \to \gamma\gamma$)



4 July 2012

Higgs to 4 leptons (H→ZZ*→llll)



4 July 2012

4 July 2012: Higgs (In)dependence Day

LEP/LIBRARY

ps

LEP Note 440
11.4.1983

PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER

S. Myers and W. Schnell

1. Introduction

This analysis was stimulated by news from the United States where very large $p\bar{p}$ and pp colliders are actively being studied at the moment. Indeed, a first look at the basic performance limitations of possible $p\bar{p}$ or pp rings in the LEP tunnel seems overdue, however far off in the future a possible start of such a p-LEP project may yet be in time. What we shall discuss is, in fact, rather obvious, but such a discussion has, to the best of our knowledge, not been presented so far.

We shall not address any detailed design questions but shall give basic equations and make a few plausible assumptions for the purpose of illustration. Thus, we shall assume throughout that the maximum energy per beam is 8 TeV (corresponding to a little over 9 T bending field in very advanced superconducting magnets) and that injection is at 0.4 TeV. The ring circumference is, of course that of LEP, namely 26,659 m. It should be clear from this requirement of "Ten Tesla Magnets" alone that such a project is not for the near future and that it should not be attempted before the technology is ready.

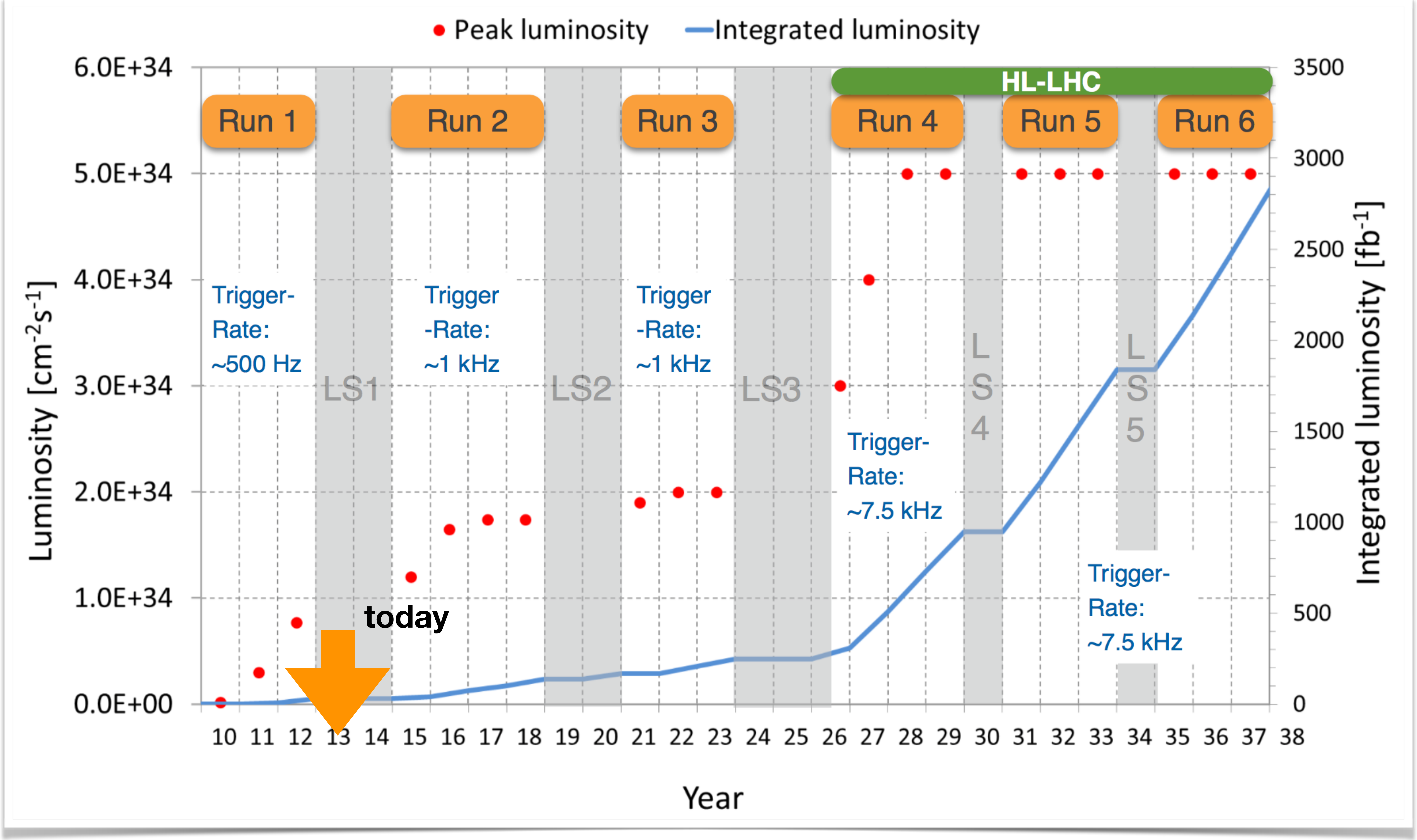
Duration of projects /planning stability:
First LHC workshop 1984 !

Nobel Prize in Physics
2013
to
Peter Higgs
François Englert

More questions to be solved

- What is the origin of particle masses ? ✓
- What is dark matter ?
- Why is there so much more matter than antimatter in the universe?
- What happened in the first few moments of the universe ?
- Are there other forces ?

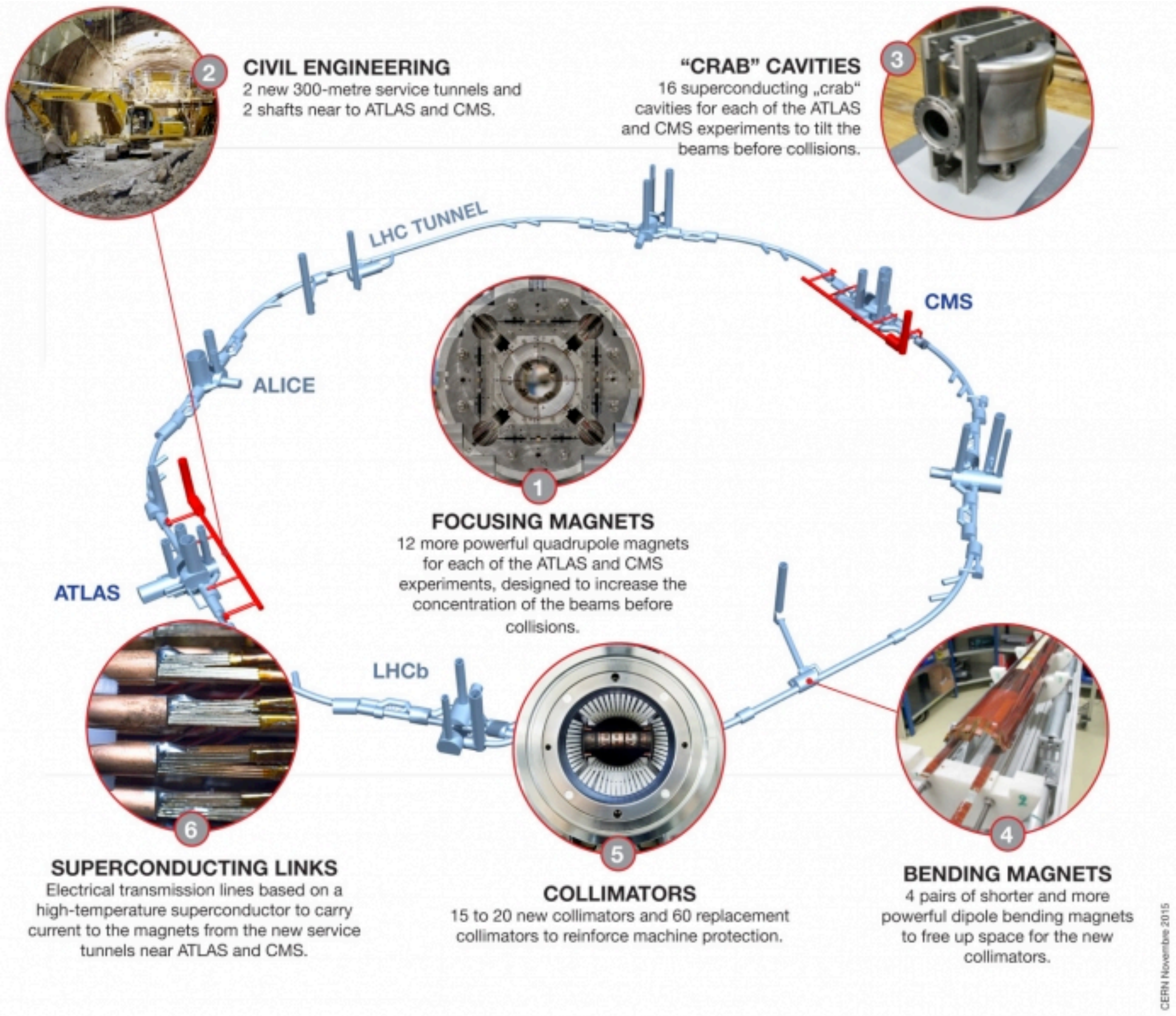
Solution: More data



Only have 5% of the total data expected from the LHC

Major accelerator upgrade:
The High-Luminosity LHC (HL-LHC)

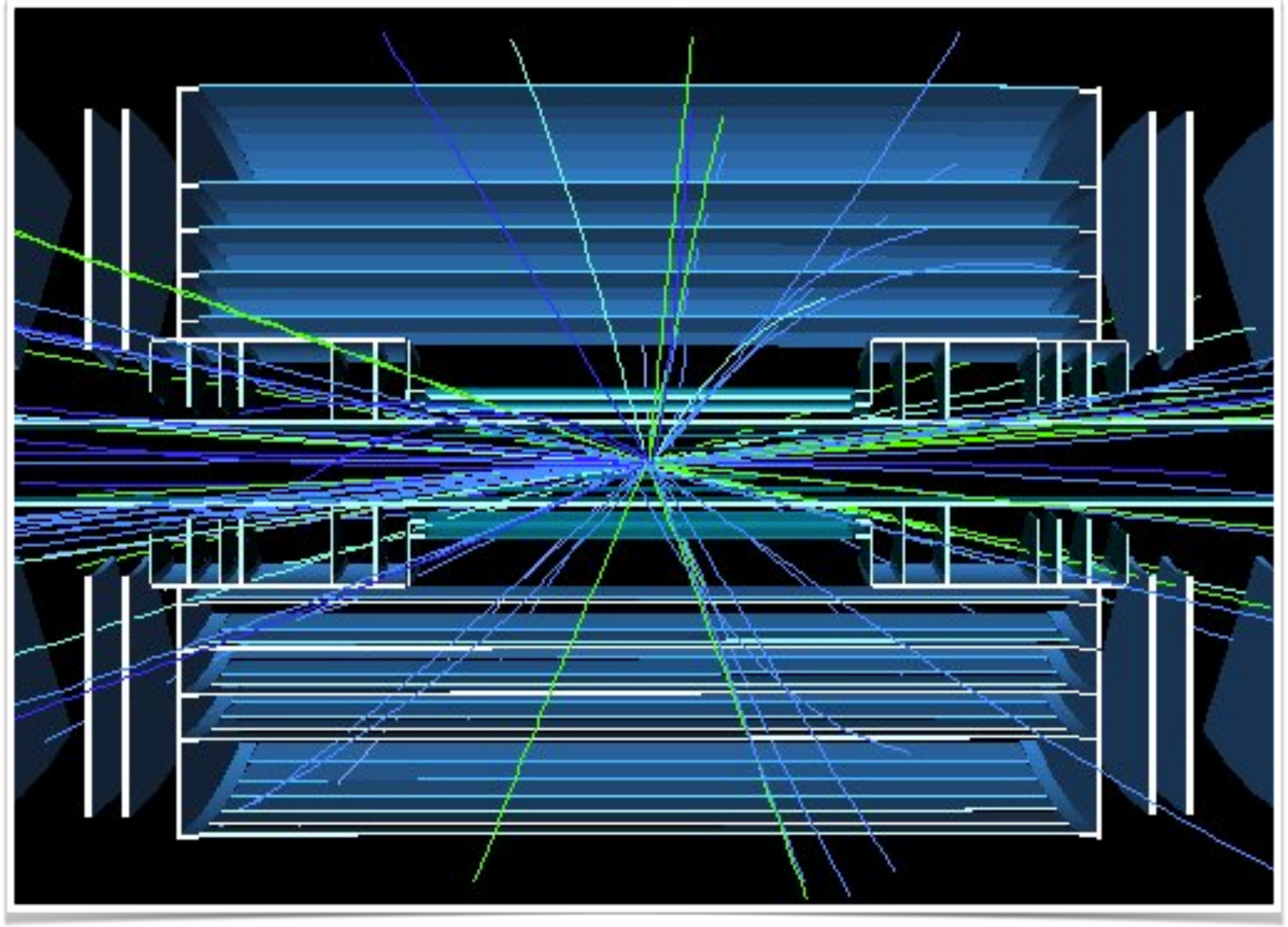
HiLumi HL-LHC PROJECT



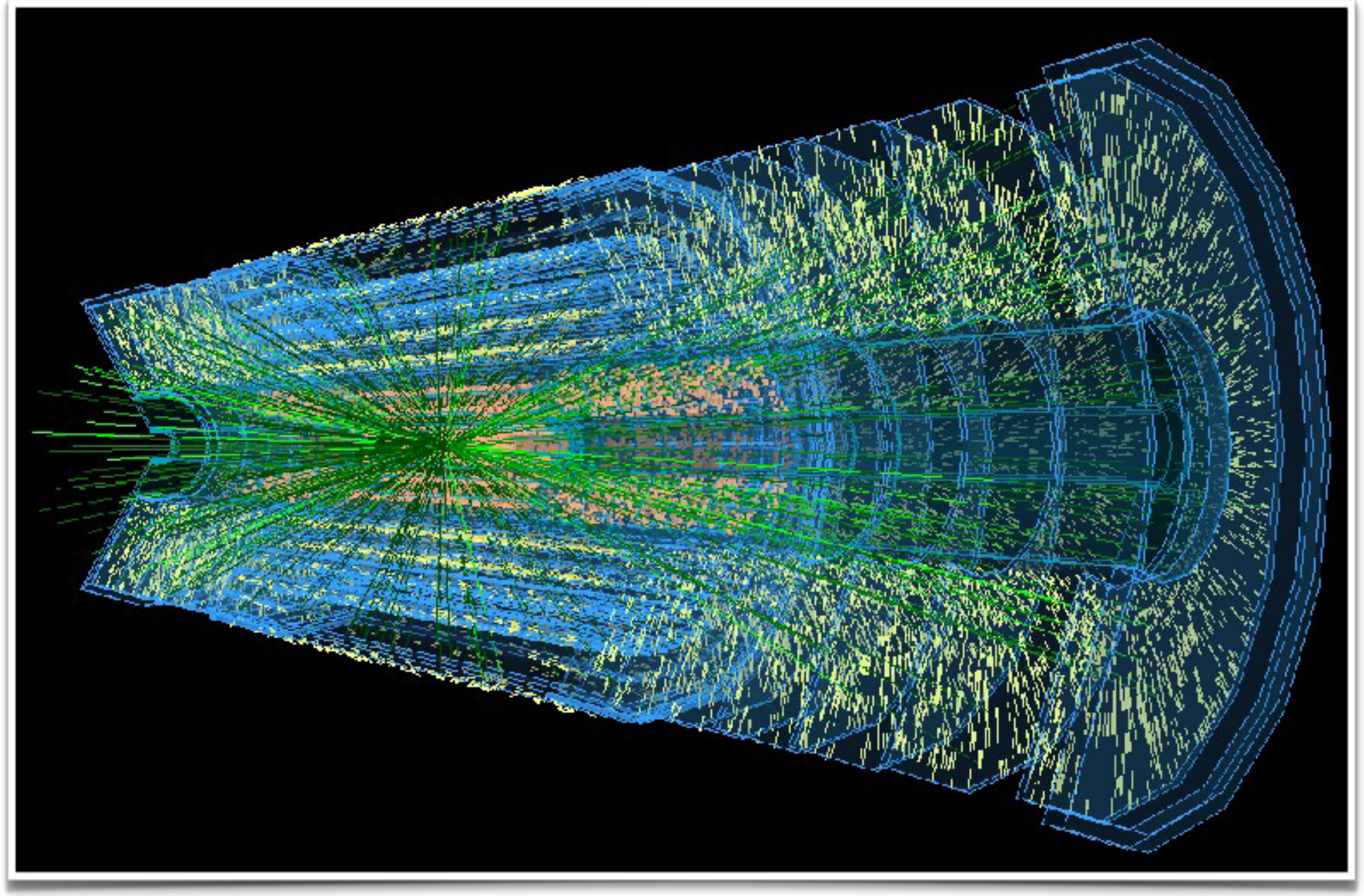
Great for physics … but a challenge for computing

HL-LHC Events

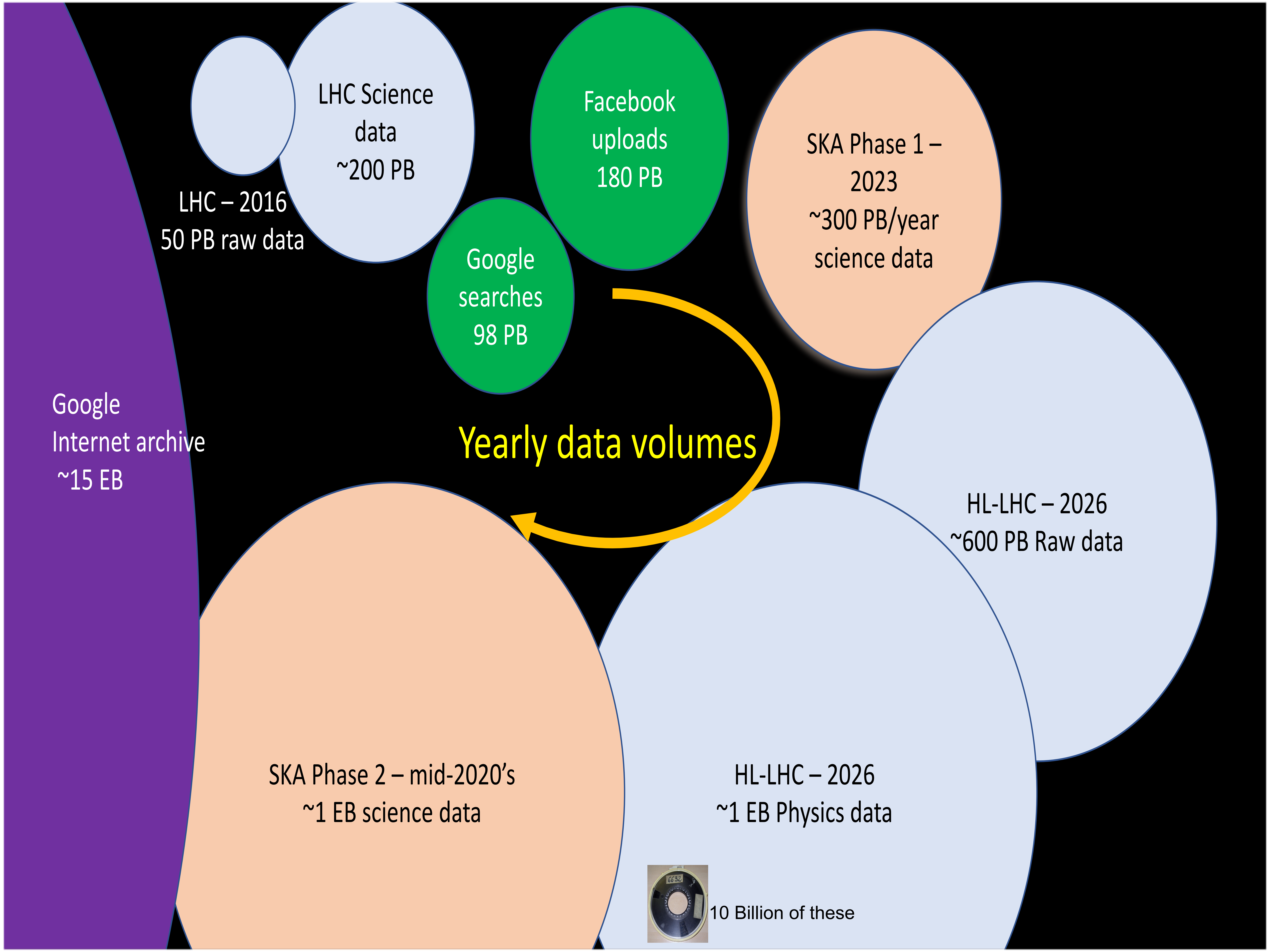
First data



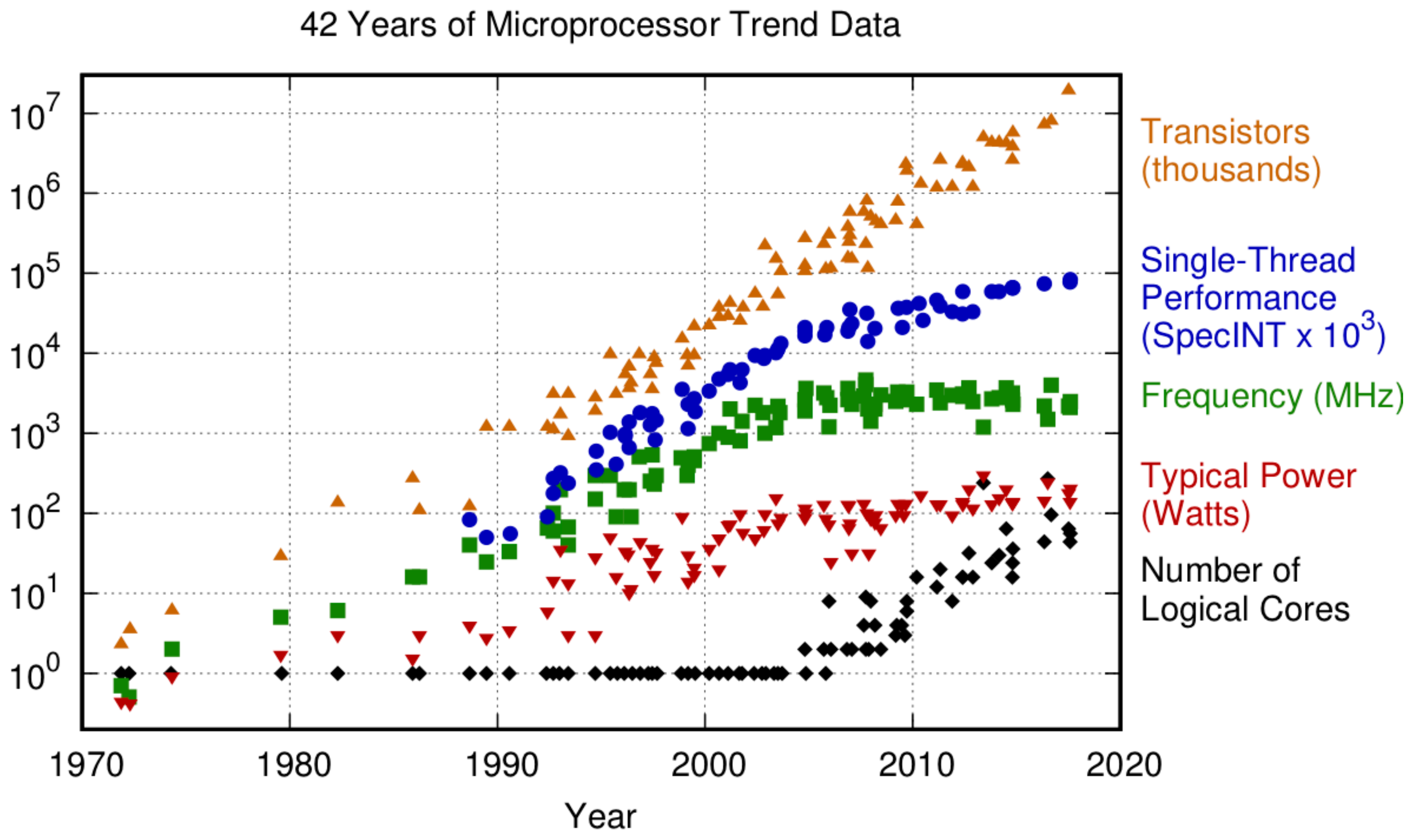
HL-LHC



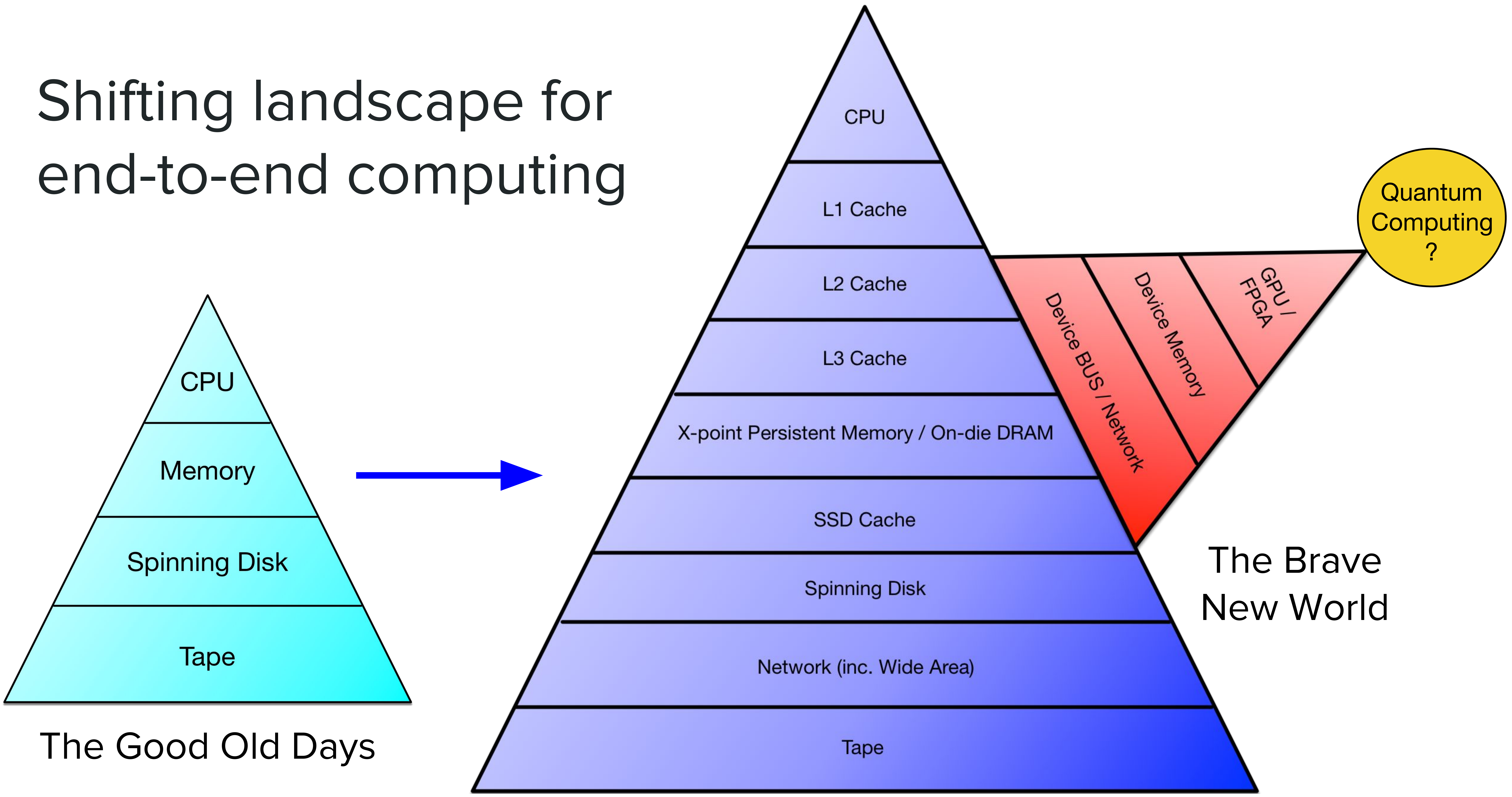
Combinatoric explosion that naively scales as n!


LHC Science data ~200 PB
LHC – 2016 50 PB raw data
Facebook uploads 180 PB
SKA Phase 1 – 2023 ~300 PB/year science data
Google searches 98 PB
Google Internet archive ~15 EB
Yearly data volumes
HL-LHC – 2026 ~600 PB Raw data
SKA Phase 2 – mid-2020's ~1 EB science data
HL-LHC – 2026 ~1 EB Physics data
10 Billion of these

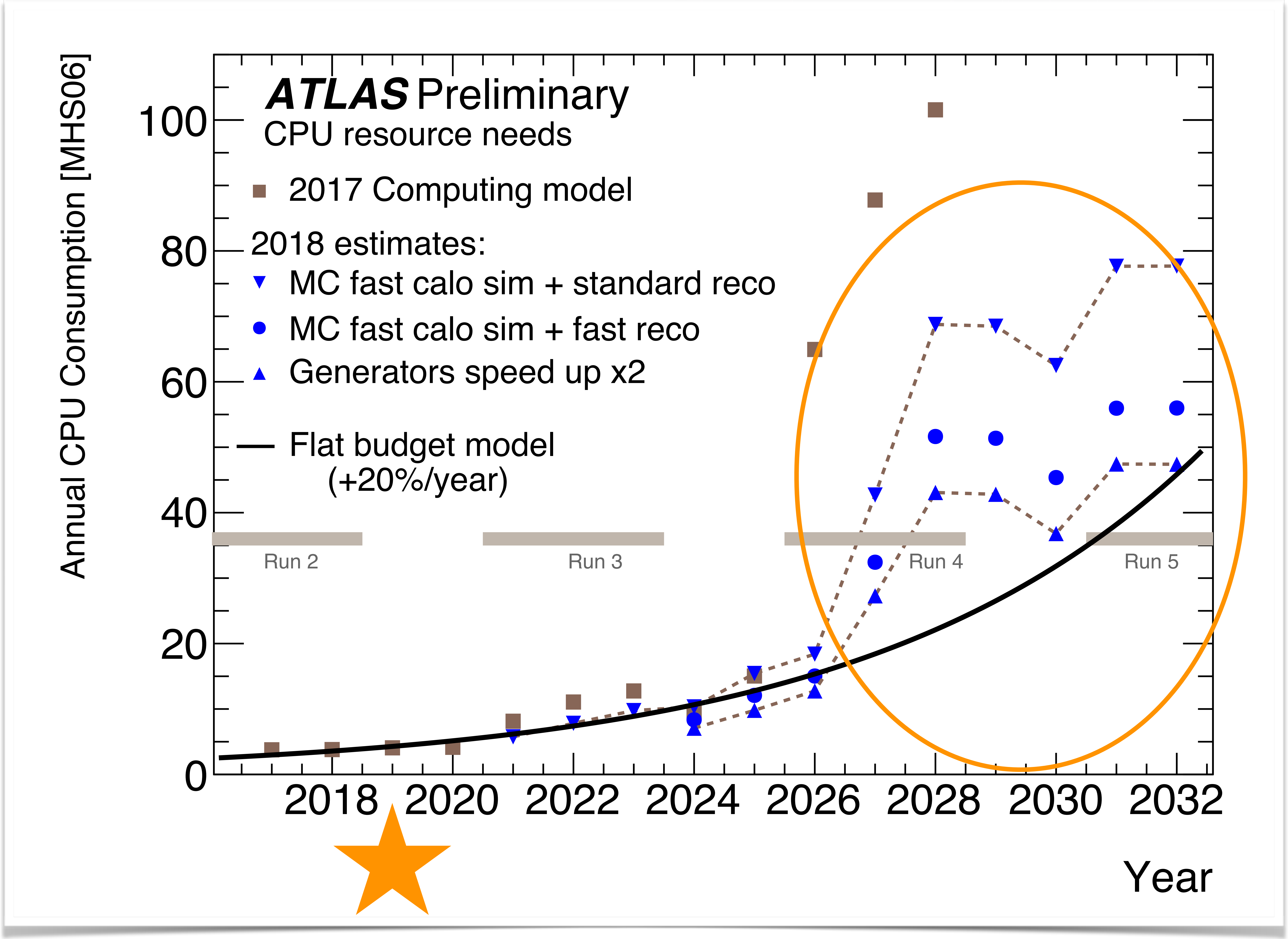
Technology Challenges



Shifting landscape for end-to-end computing



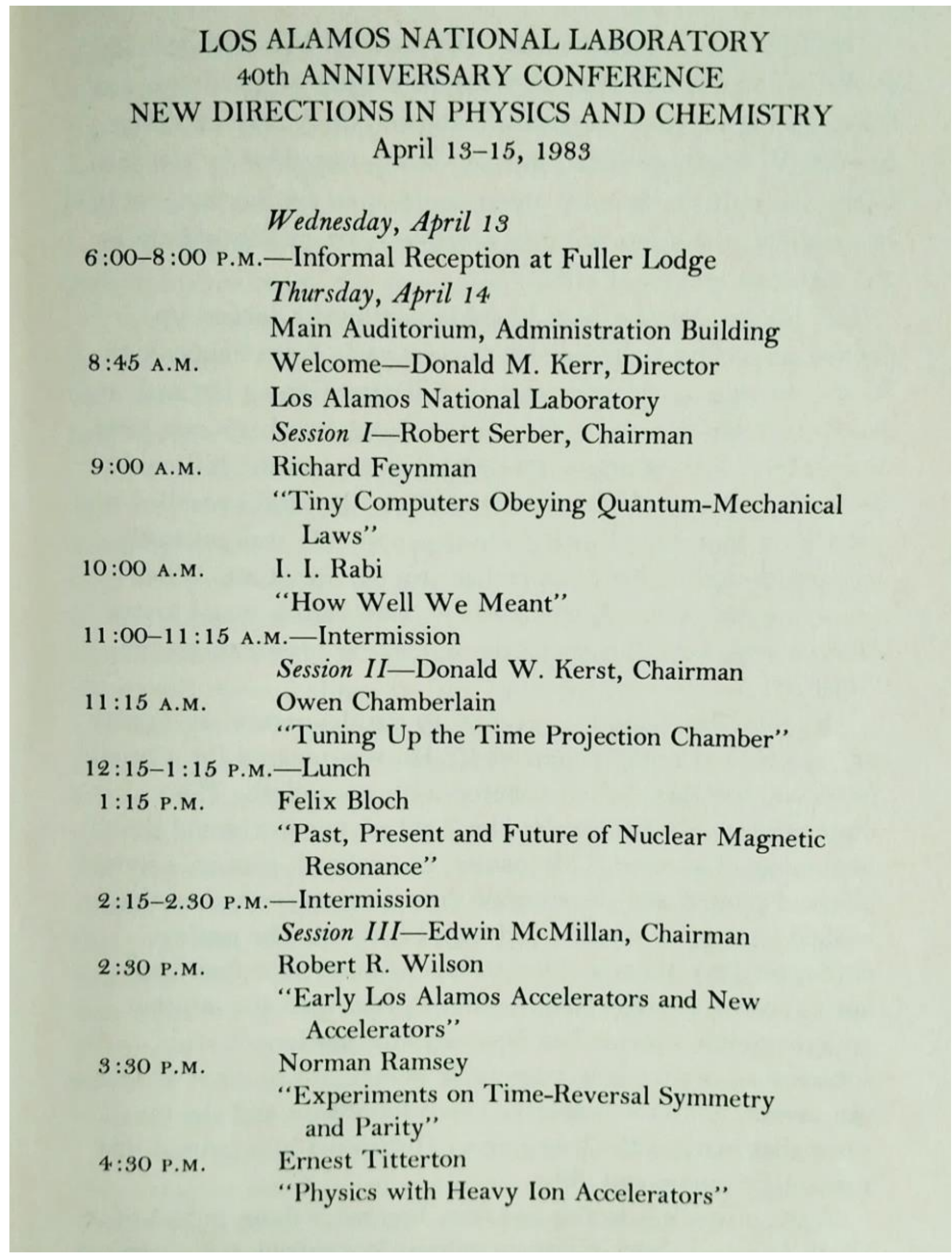
The HL-LHC Computing Problem



Can quantum computing play a role?

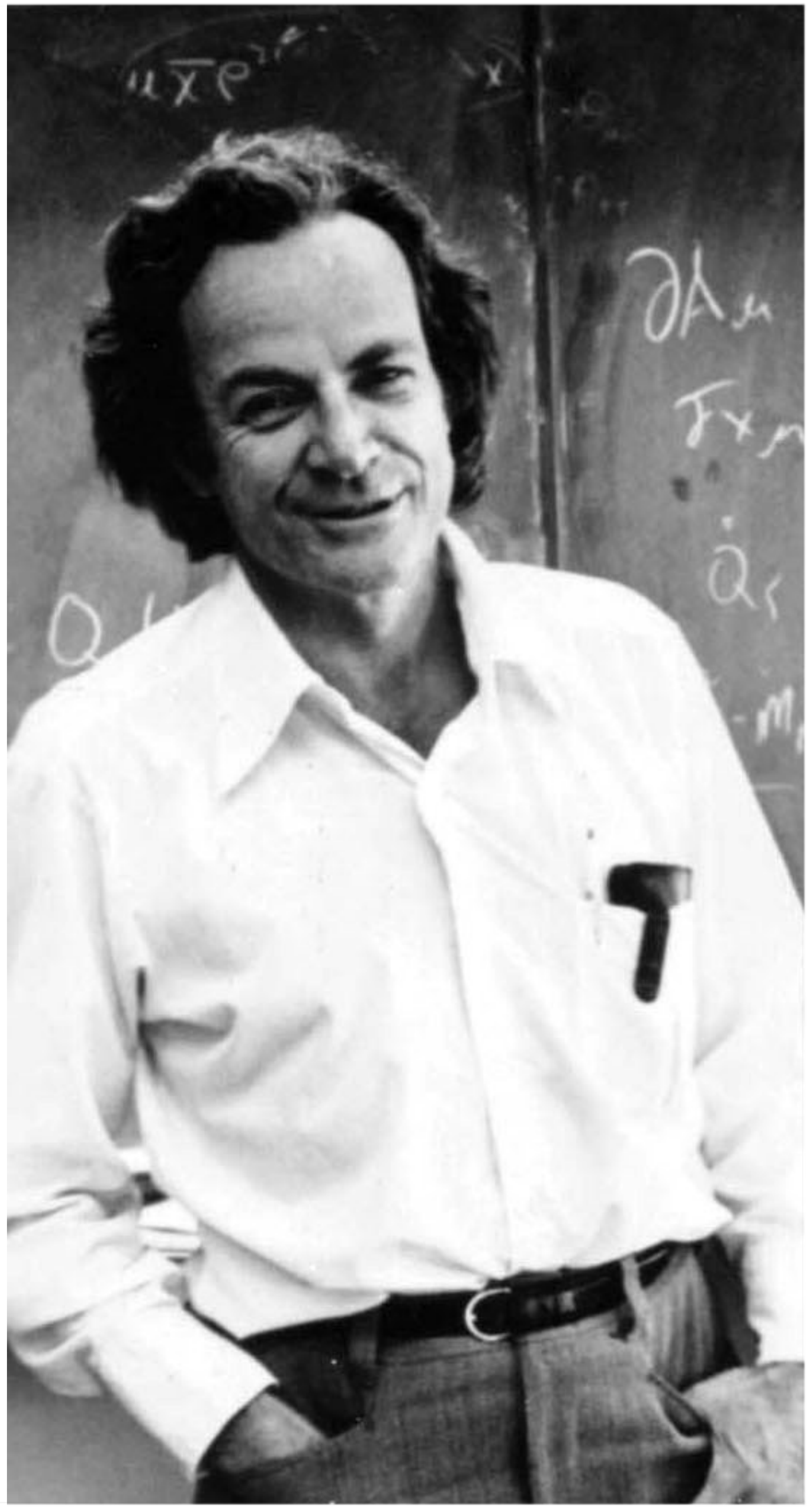
Initial ideas of quantum computing

"Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws."



LOS ALAMOS NATIONAL LABORATORY
40th ANNIVERSARY CONFERENCE
NEW DIRECTIONS IN PHYSICS AND CHEMISTRY
April 13–15, 1983

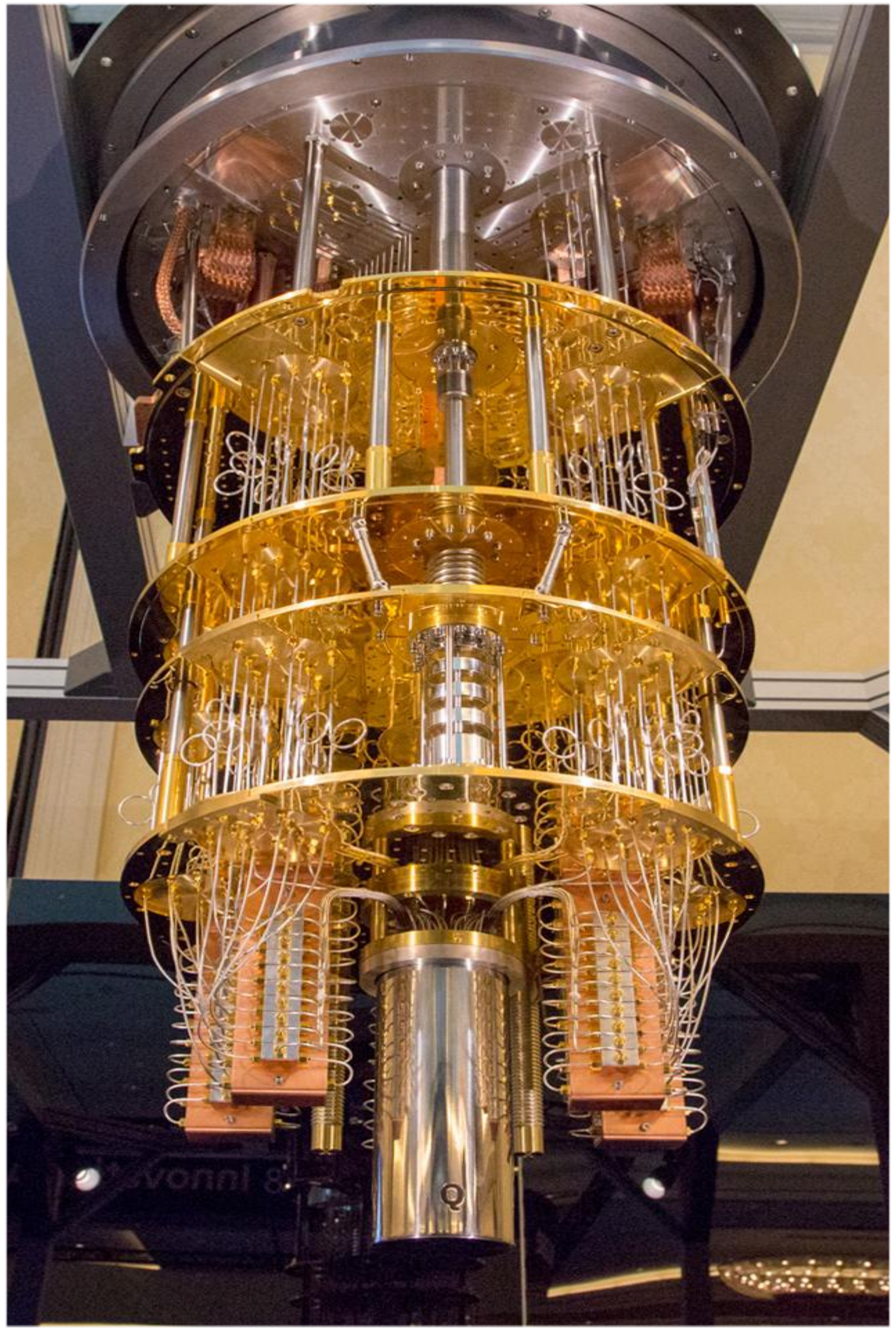
Wednesday, April 13
6:00–8:00 P.M.—Informal Reception at Fuller Lodge
Thursday, April 14
Main Auditorium, Administration Building
8:45 A.M. Welcome—Donald M. Kerr, Director
Los Alamos National Laboratory
Session I—Robert Serber, Chairman
9:00 A.M. Richard Feynman
"Tiny Computers Obeying Quantum-Mechanical Laws"
10:00 A.M. I. I. Rabi
"How Well We Meant"
11:00–11:15 A.M.—Intermission
Session II—Donald W. Kerst, Chairman
11:15 A.M. Owen Chamberlain
"Tuning Up the Time Projection Chamber"
12:15–1:15 P.M.—Lunch
1:15 P.M. Felix Bloch
"Past, Present and Future of Nuclear Magnetic Resonance"
2:15–2:30 P.M.—Intermission
Session III—Edwin McMillan, Chairman
2:30 P.M. Robert R. Wilson
"Early Los Alamos Accelerators and New Accelerators"
3:30 P.M. Norman Ramsey
"Experiments on Time-Reversal Symmetry and Parity"
4:30 P.M. Ernest Titterton
"Physics with Heavy Ion Accelerators"



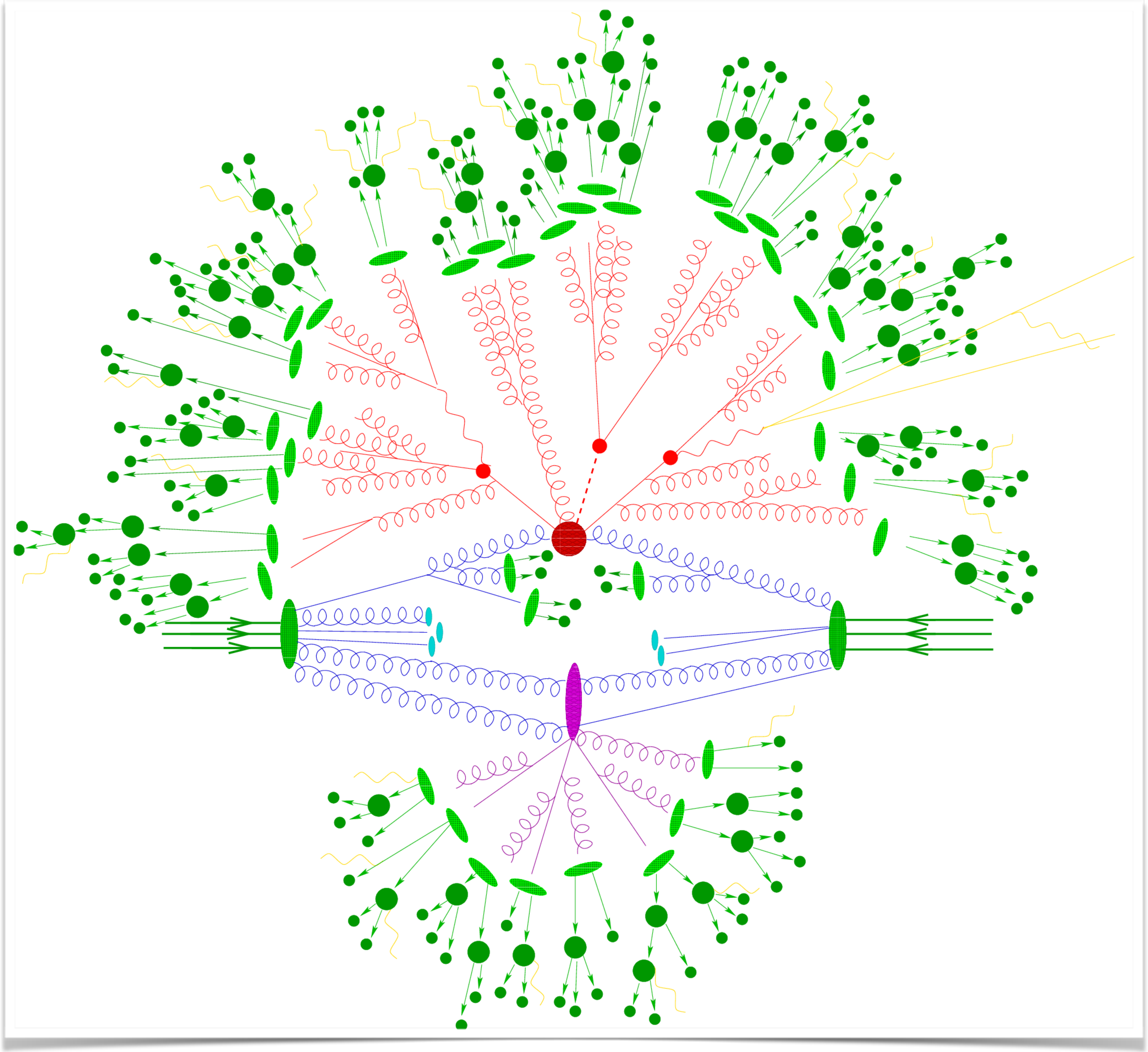
RICHARD FEYNMAN (1982)

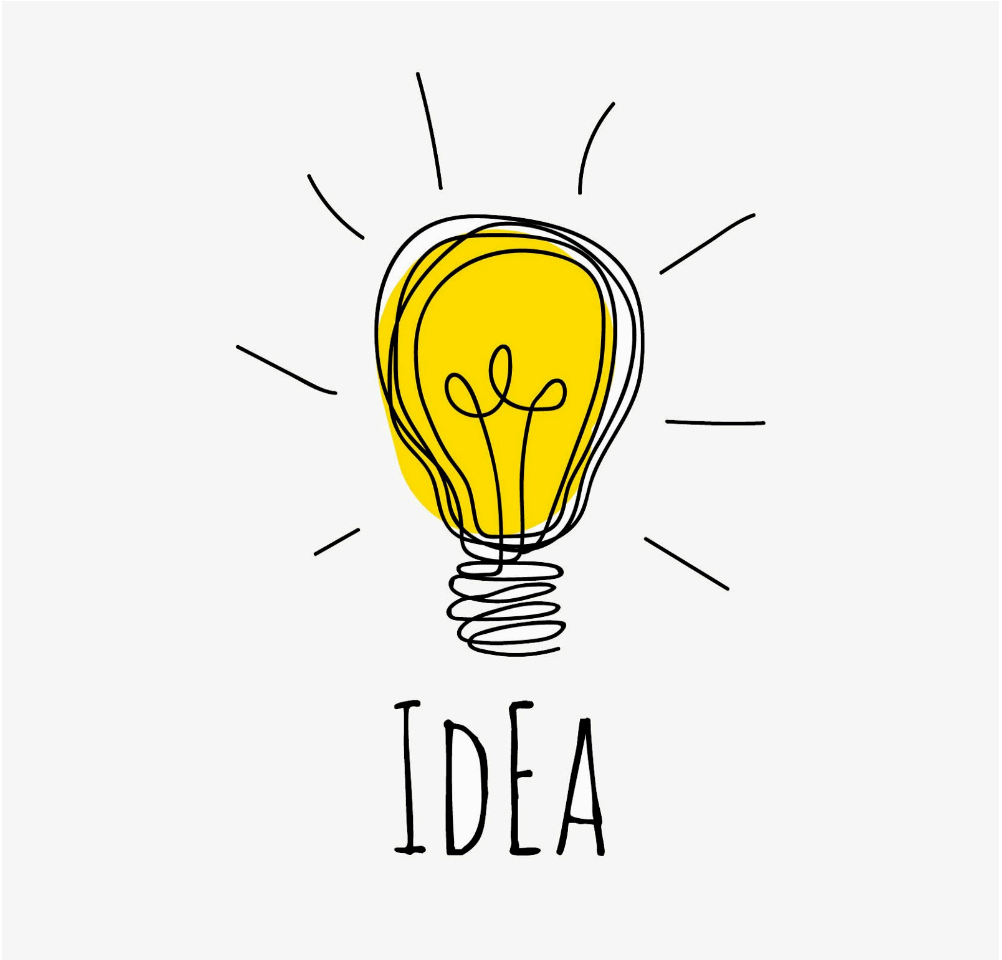
Almost 40 years later

IBM 20Q Tokyo chip



D Wave 2000Q

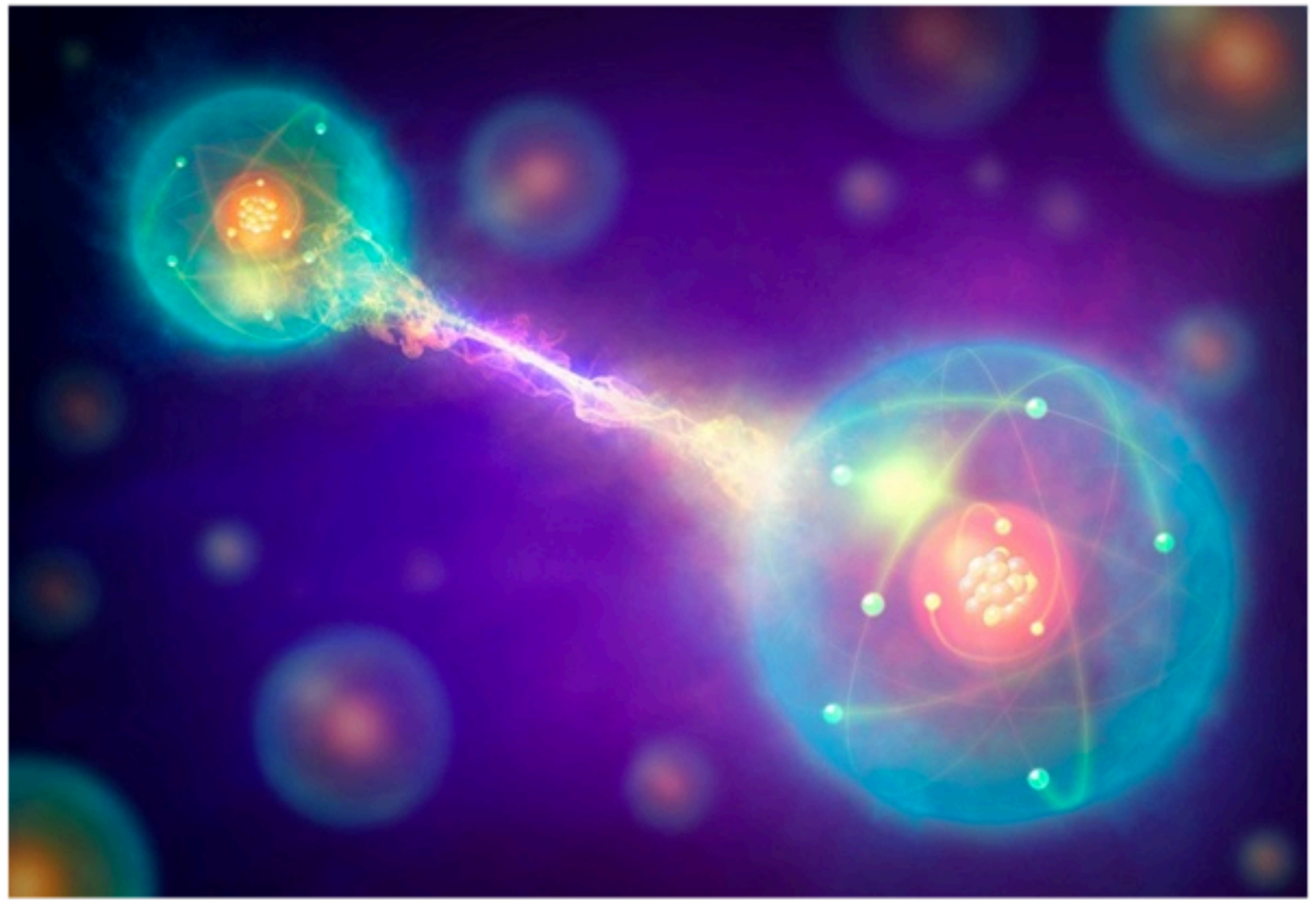




Simulating Correlations

Currently simulate events assuming the evolution of each particle is independent

Entanglement



- Particles obey quantum mechanics
- Correlations exist between them
- Idea: exploit entanglement between qubits on a quantum computer to improve the description of the parton shower

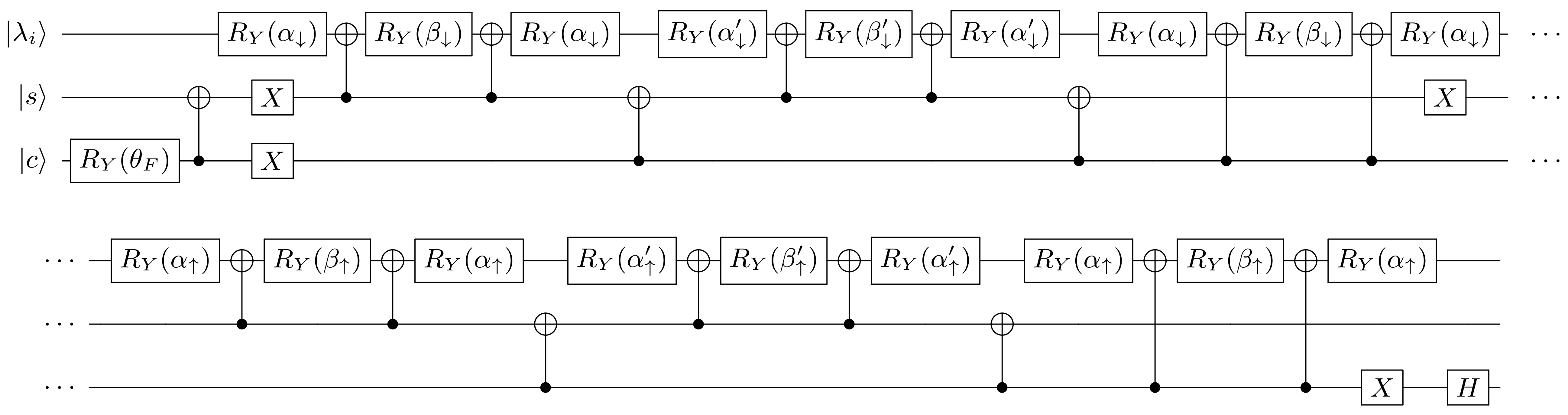
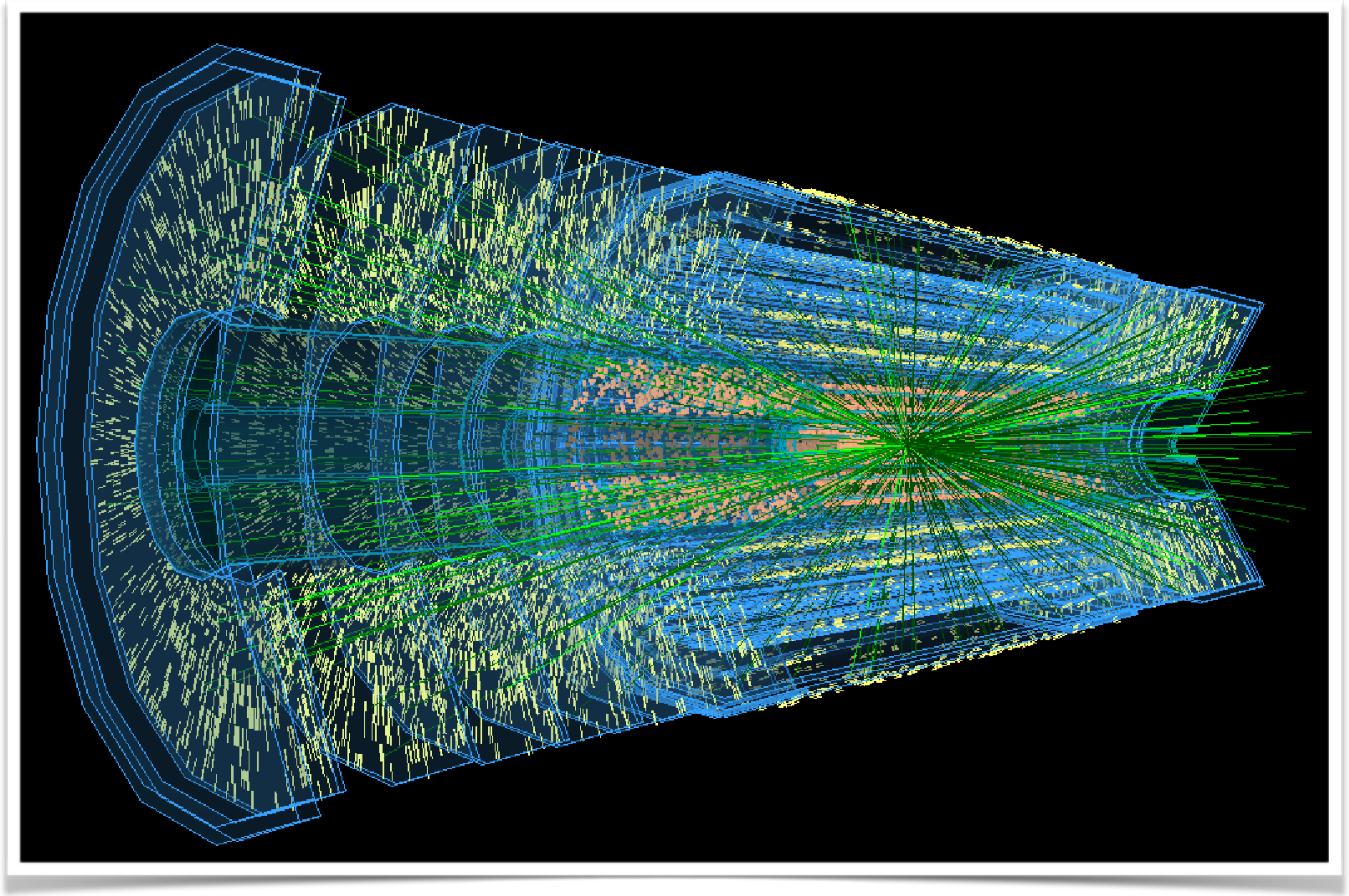
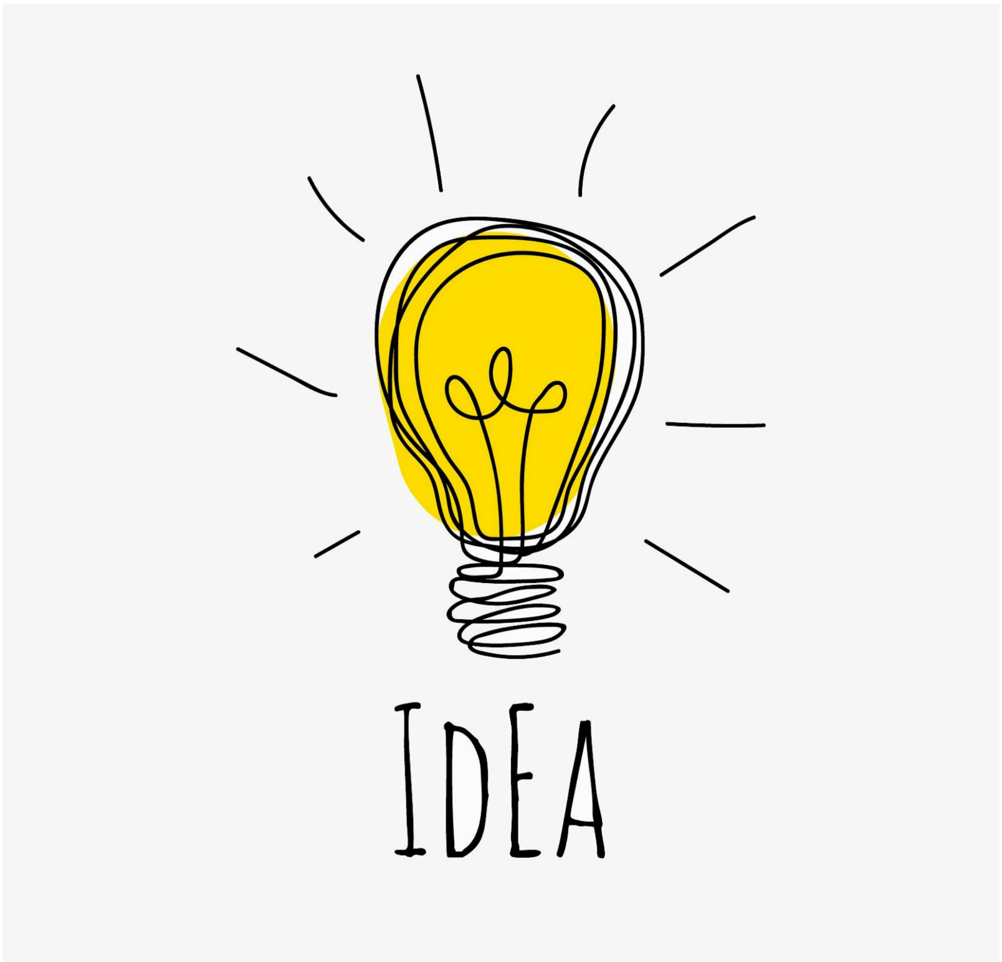
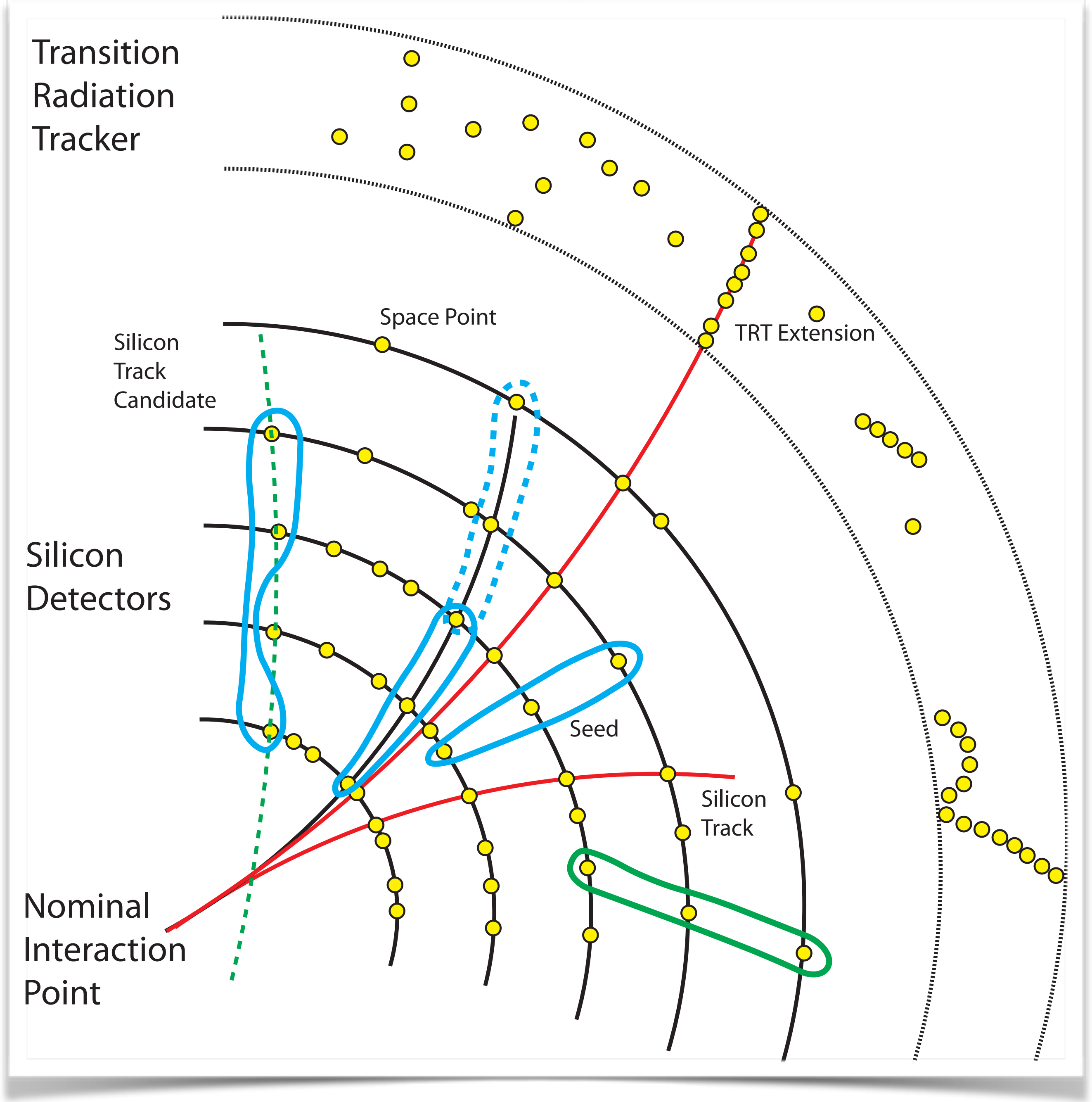


FIG. 8. The complete quantum circuit for a single step after the decomposition into only single qubit and CNOT gates. The angles labeled with ↓ and ↑ correspond to the decomposition of $U_{A,\downarrow}$ and $U_{A,\uparrow}$ respectively. Note that $\alpha'_{\downarrow,\uparrow} = -\alpha_{\downarrow,\uparrow}$ and $\beta'_{\downarrow,\uparrow} = -\beta_{\downarrow,\uparrow}$

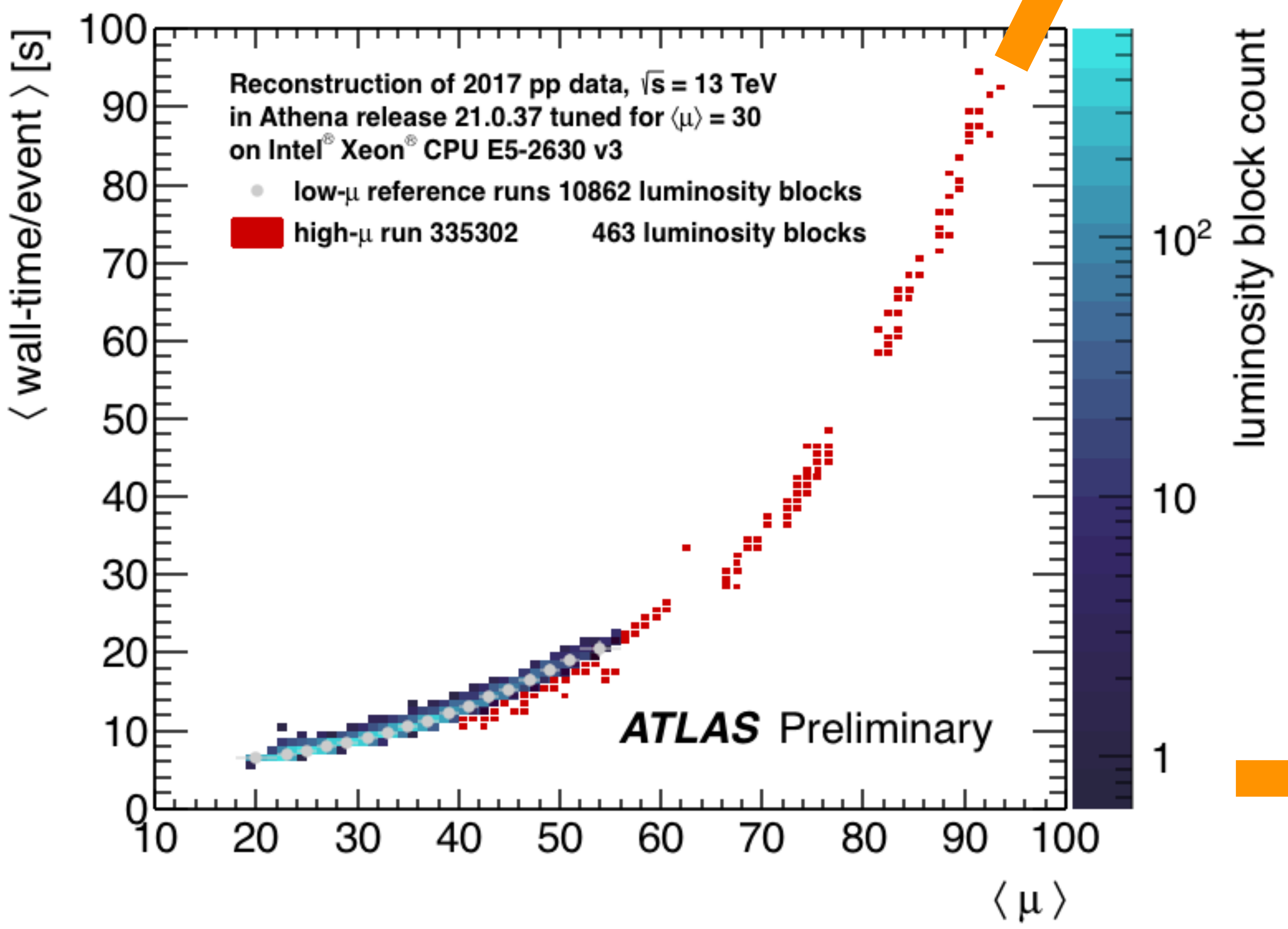
arXiv:1901.08148







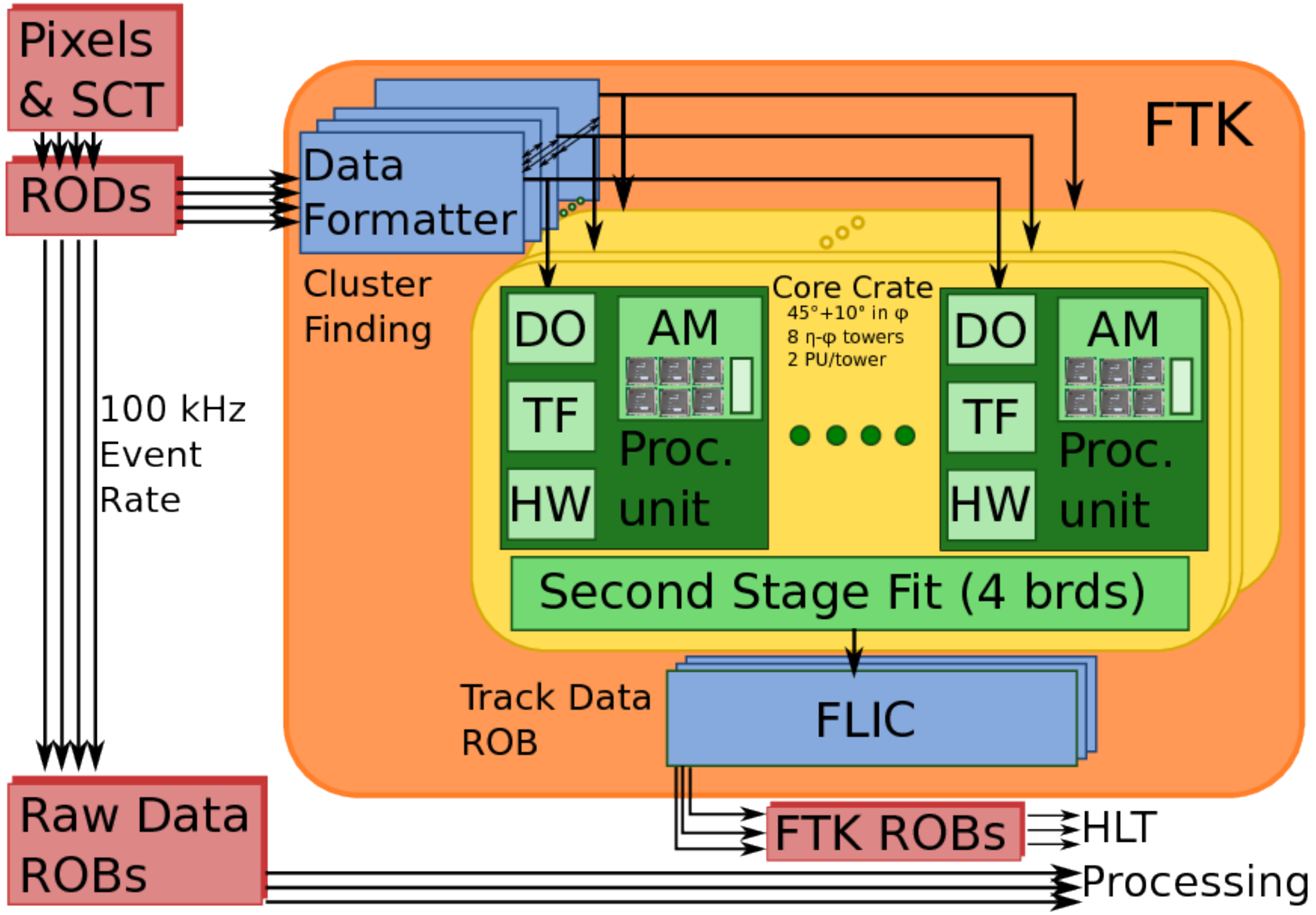
Reconstructing Tracks



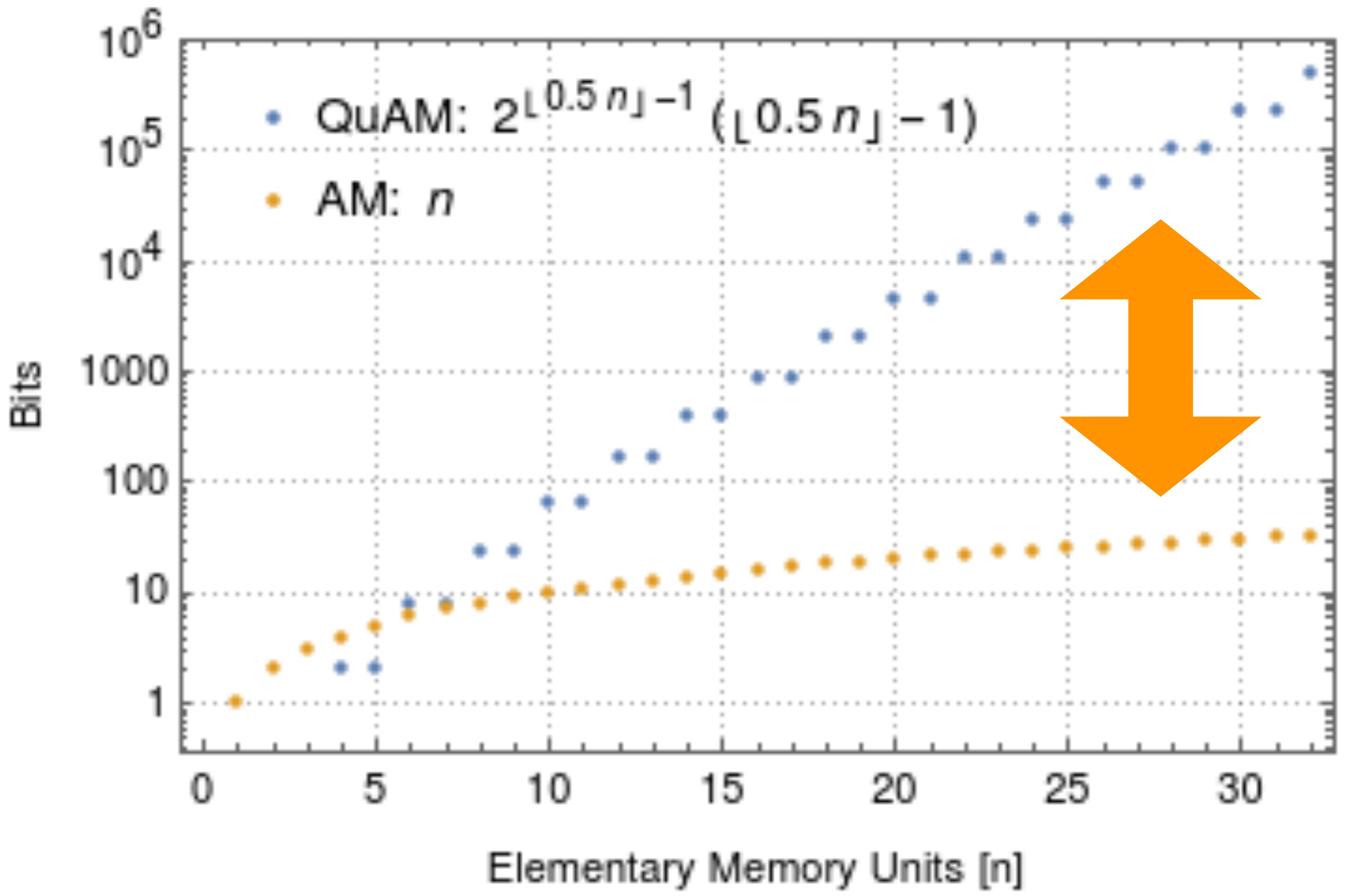
Track reconstruction is expected to have the largest CPU burden at the HL-LHC

HL-LHC: μ= 140-200

Different Algorithms: Associative Memory



Quantum associative memory has potential for exponential storage capacity

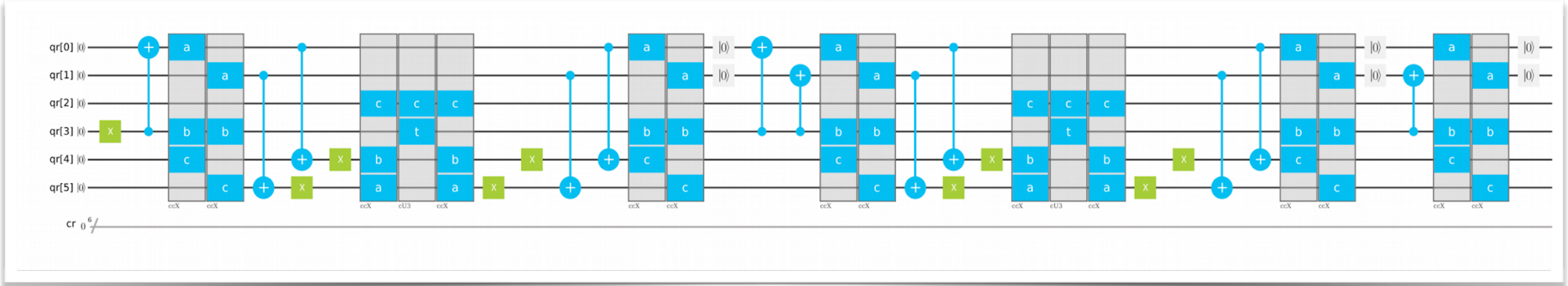


arXiv:1902.00498

QuAM Demonstration on IBM-Q

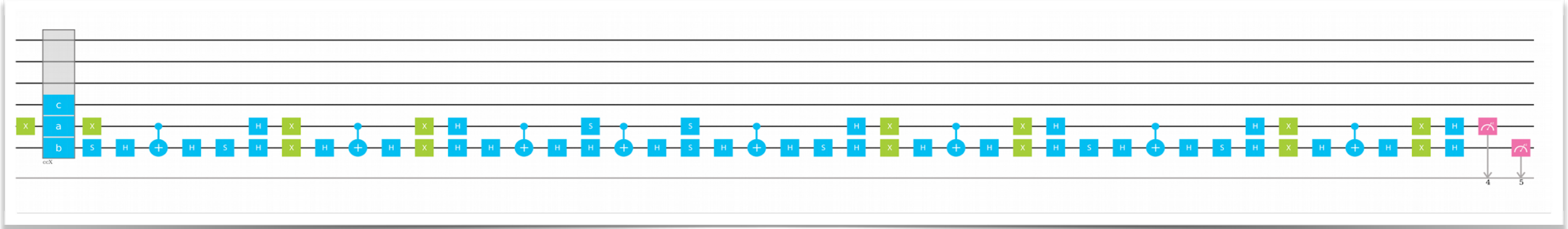
QuAM storage circuit generator

Ex.: complete circuit for retrieving one 2-bit pattern



QuAM retrieval circuit generator

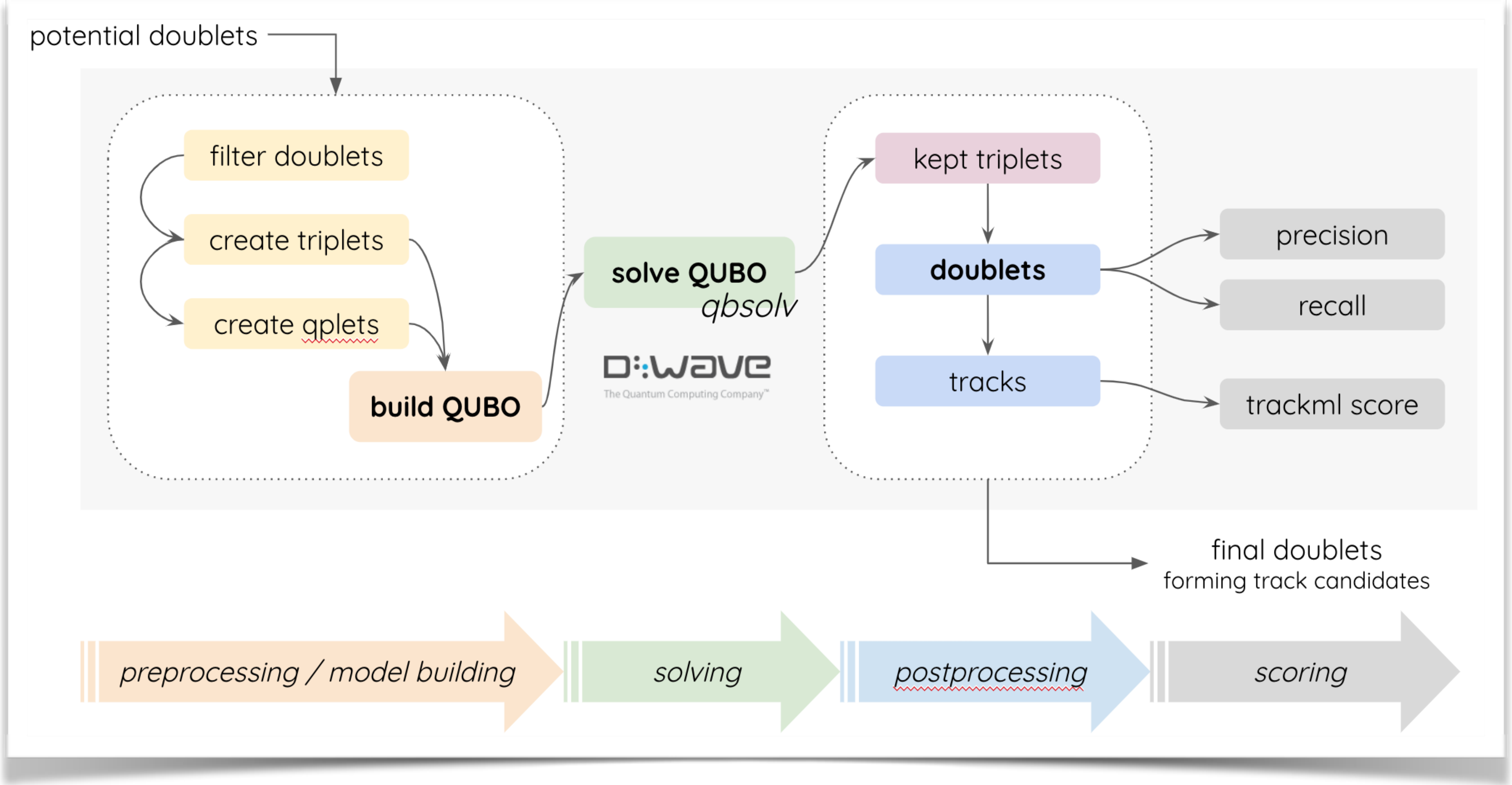
Ex.: complete circuit for retrieving one 2-bit pattern

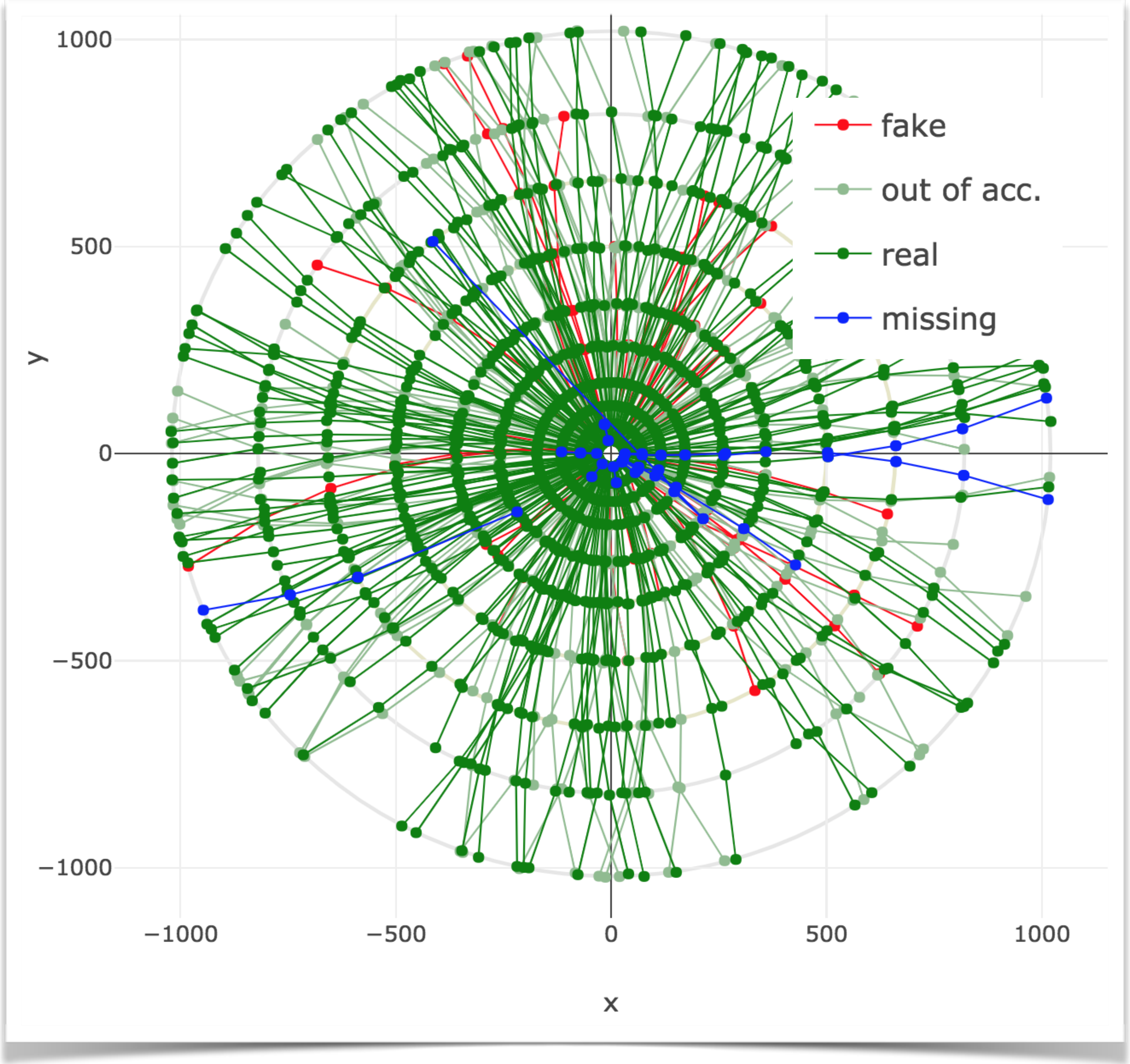


arXiv:1902.00498

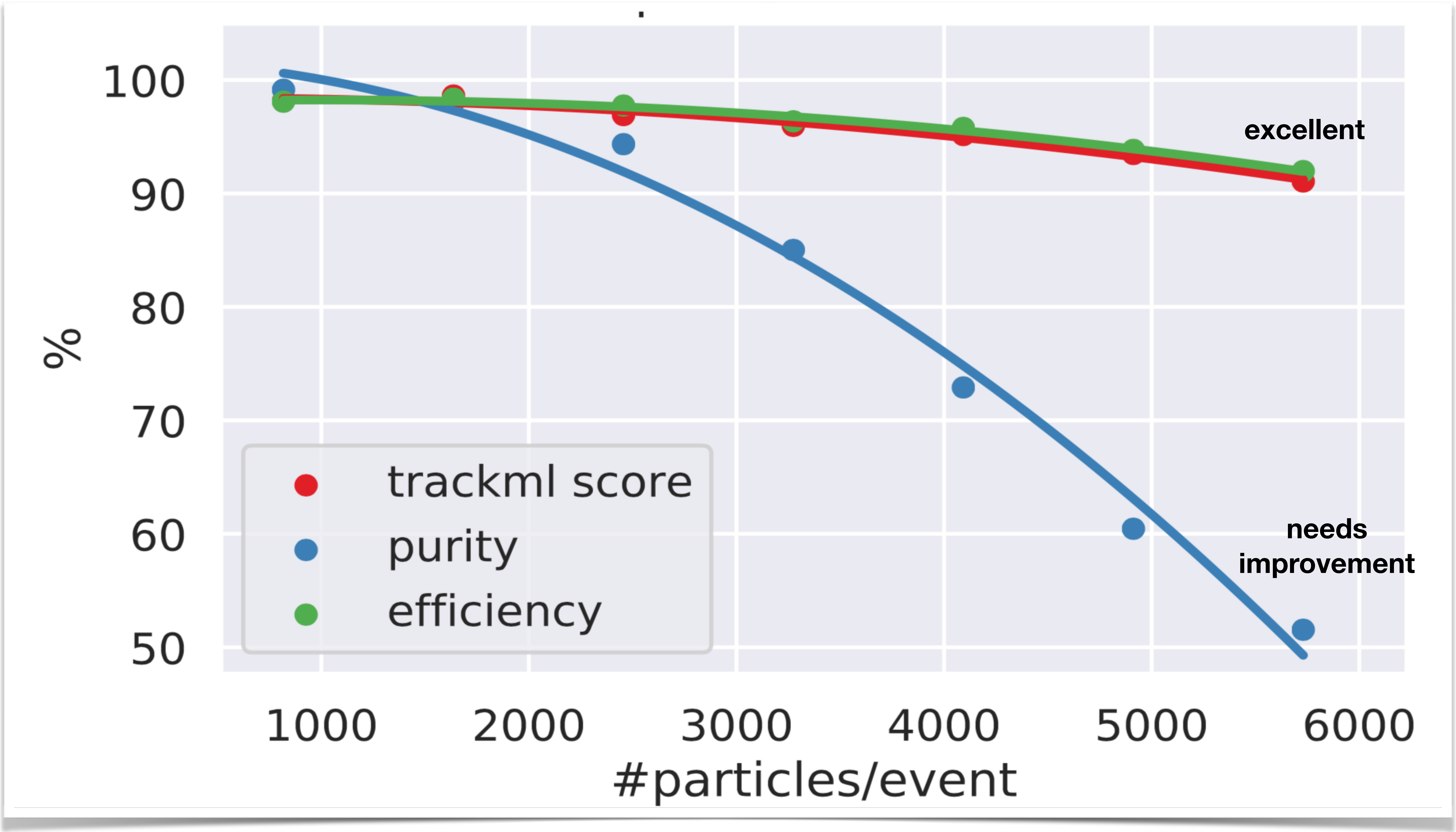
Different Algorithms: Quantum Annealing

- Reformulate track reconstruction as an energy minimisation problem
  - Solve using the D-Wave quantum annealer
- Solution time not expected to scale with number of tracks



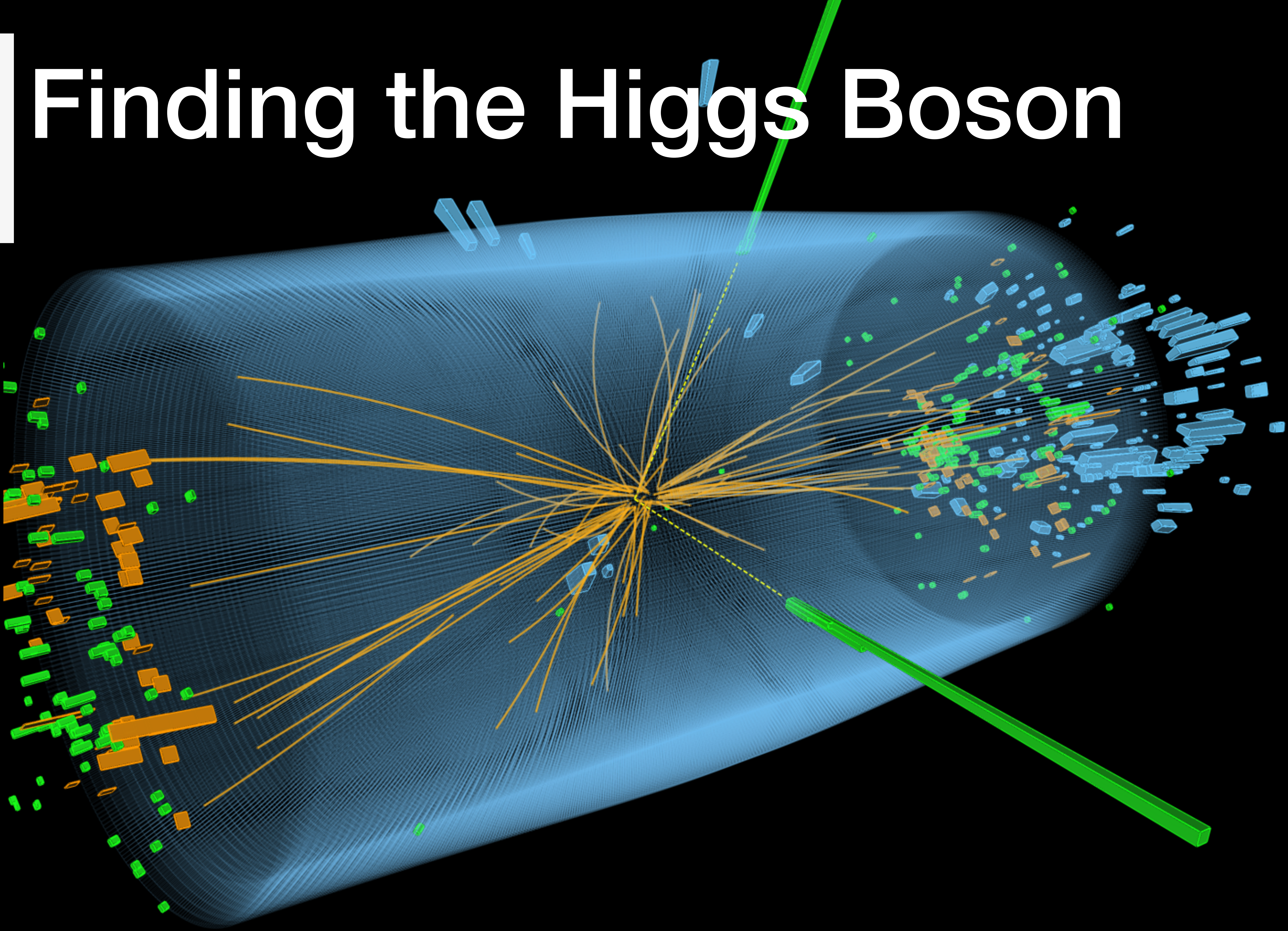


arXiv:1902.08324

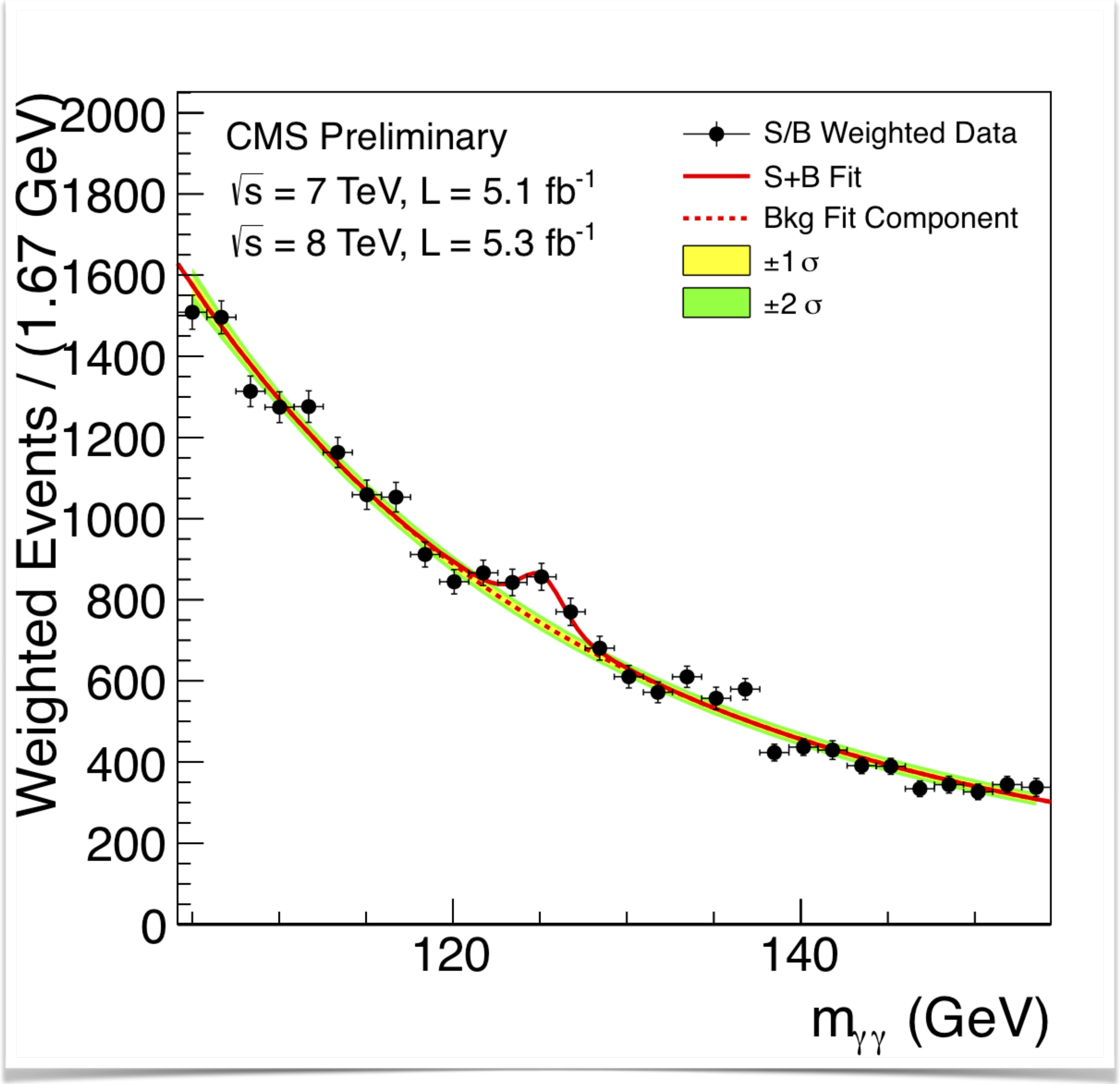


arXiv:1902.08324

Finding the Higgs Boson



Finding the Higgs Boson



doi:10.1038/nature24047

Solving a Higgs optimization problem with quantum annealing for machine learning

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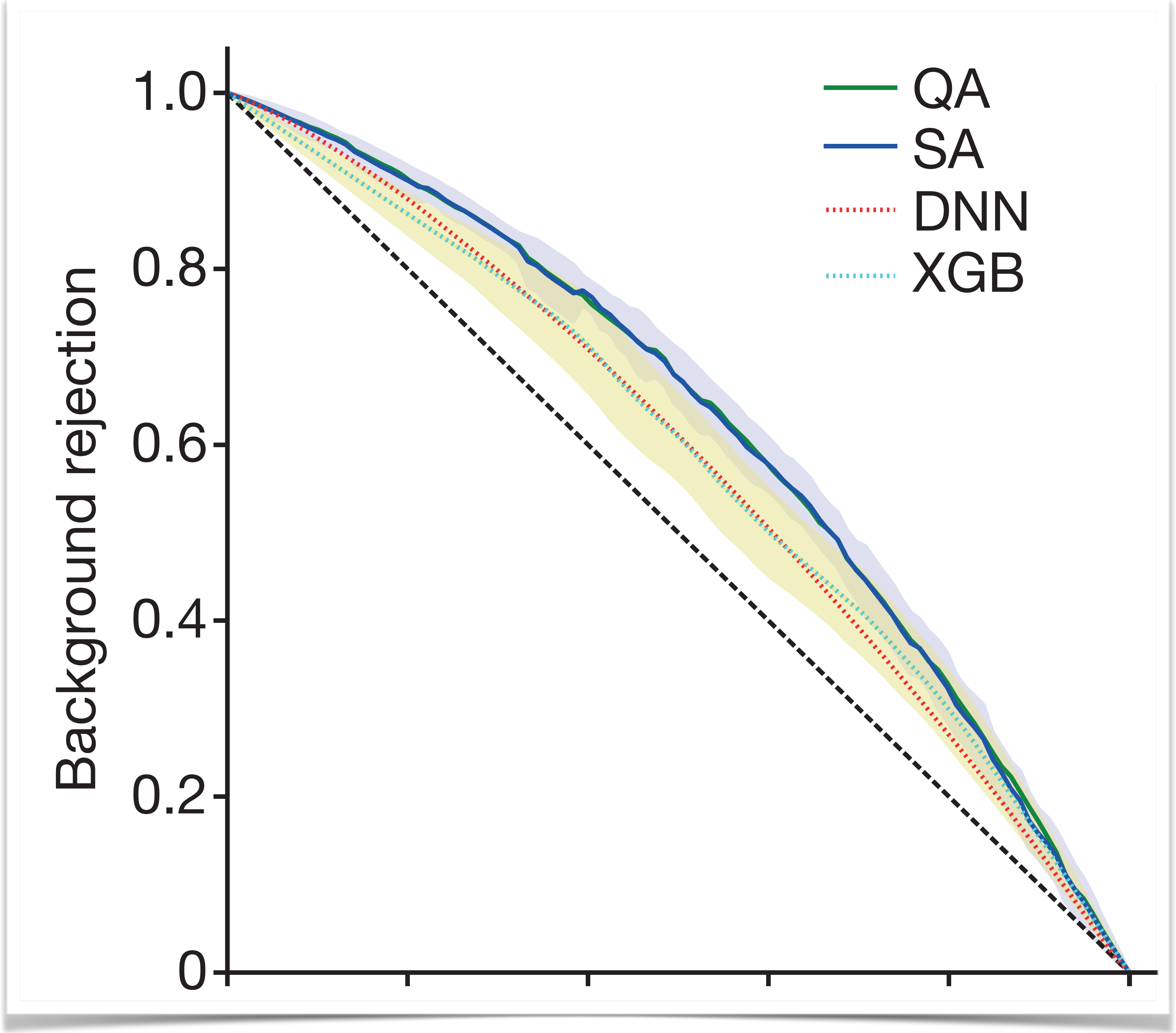

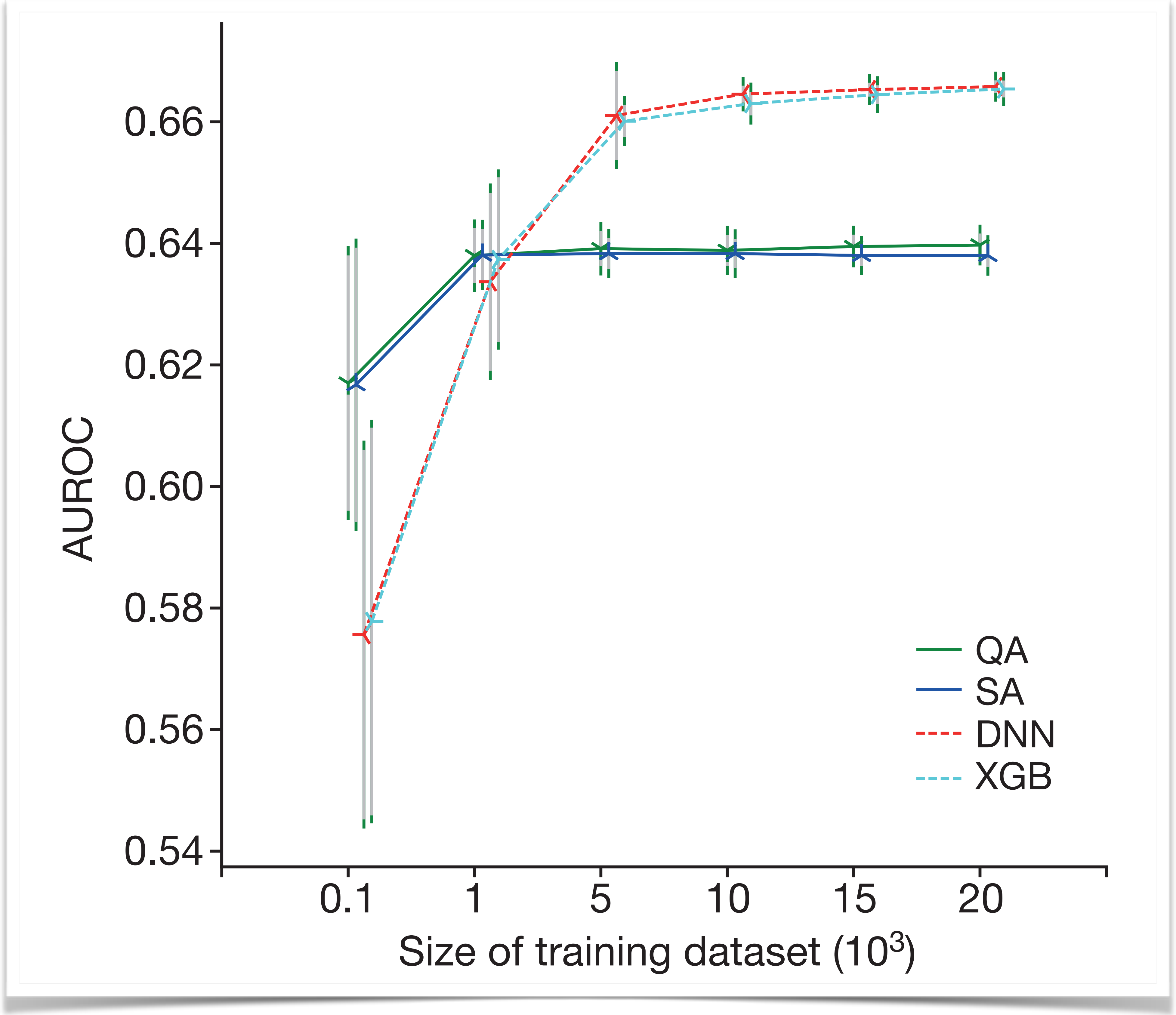

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Conclusion

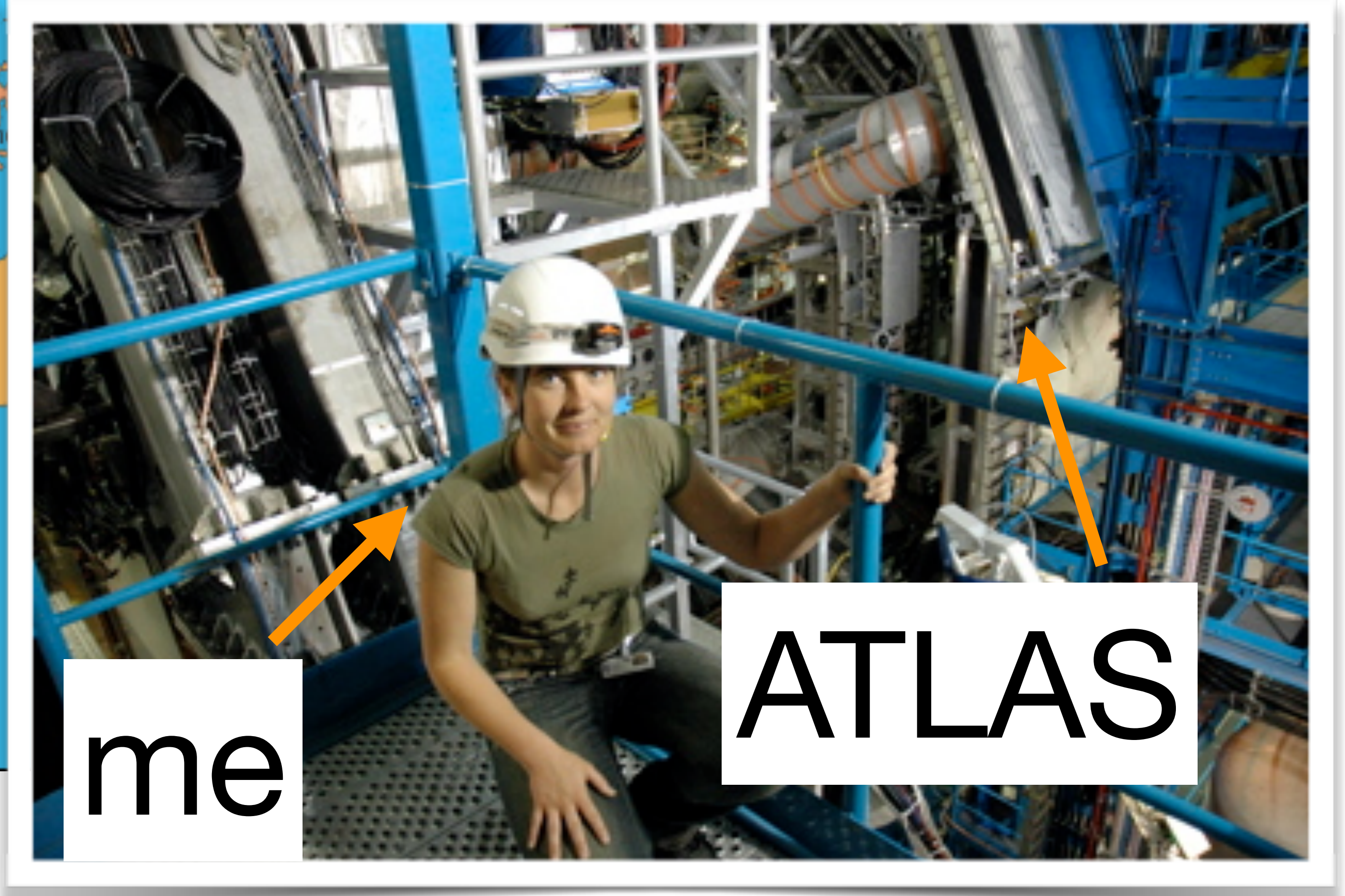
- The first ten years of the LHC have been highly successful
  - Highlight was the exciting discovery of a new particle: the Higgs boson
- The upcoming HL-LHC could provide answers to many outstanding questions in physics
  - Significant computing challenge ahead to process the data needed for physics analysis
- Many new ideas and paradigms are being actively explored
  - Can quantum computing play a role?

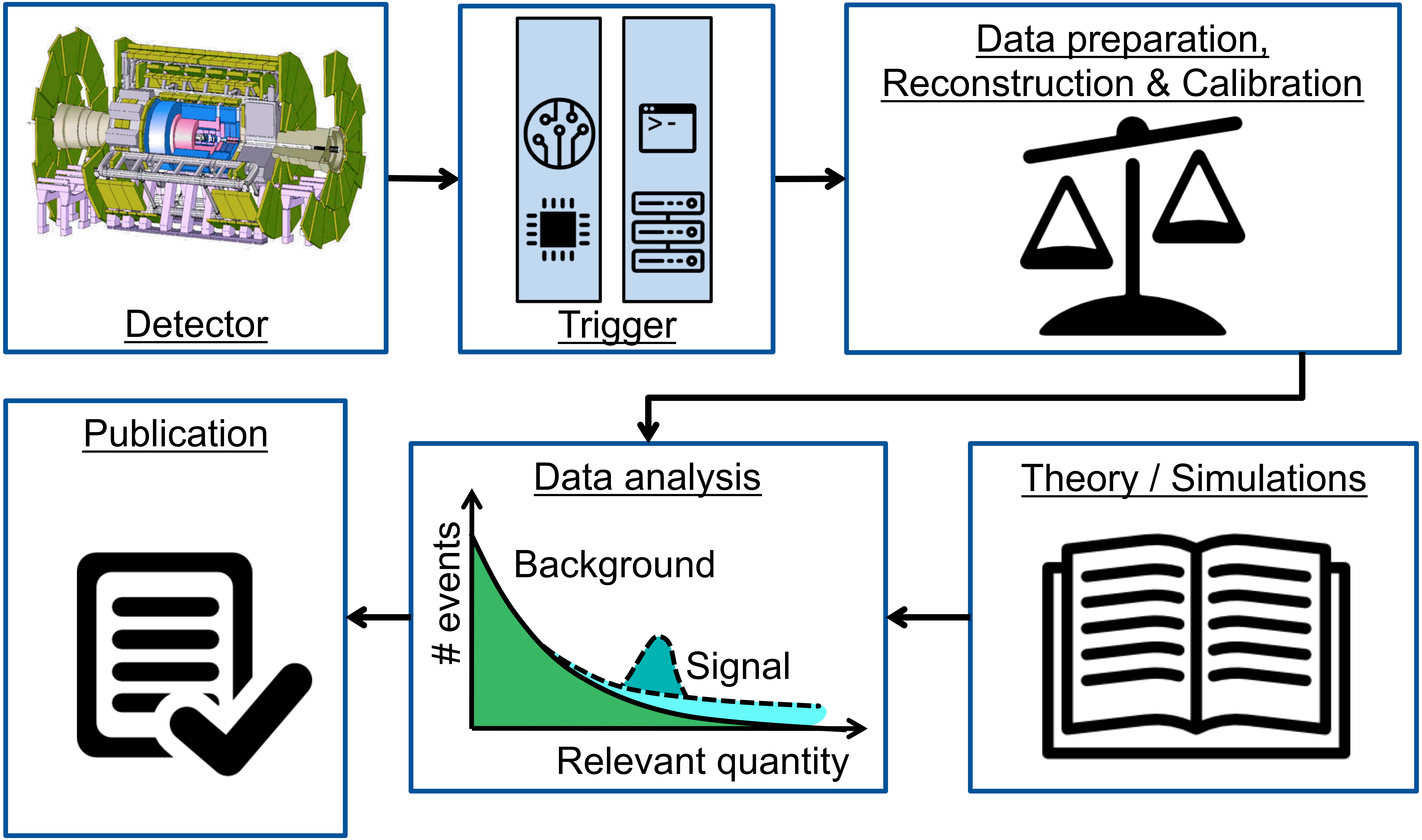
Thank you!

Many thanks to CERN, the ATLAS & CMS experiments, I. Bird, A. Hoecker,vL. Linder, S. Montangero, I. Shapoval, G. Stewart, A. Sfyrla, K. Rupp, J.-R. Vlimant for material used in this presentation

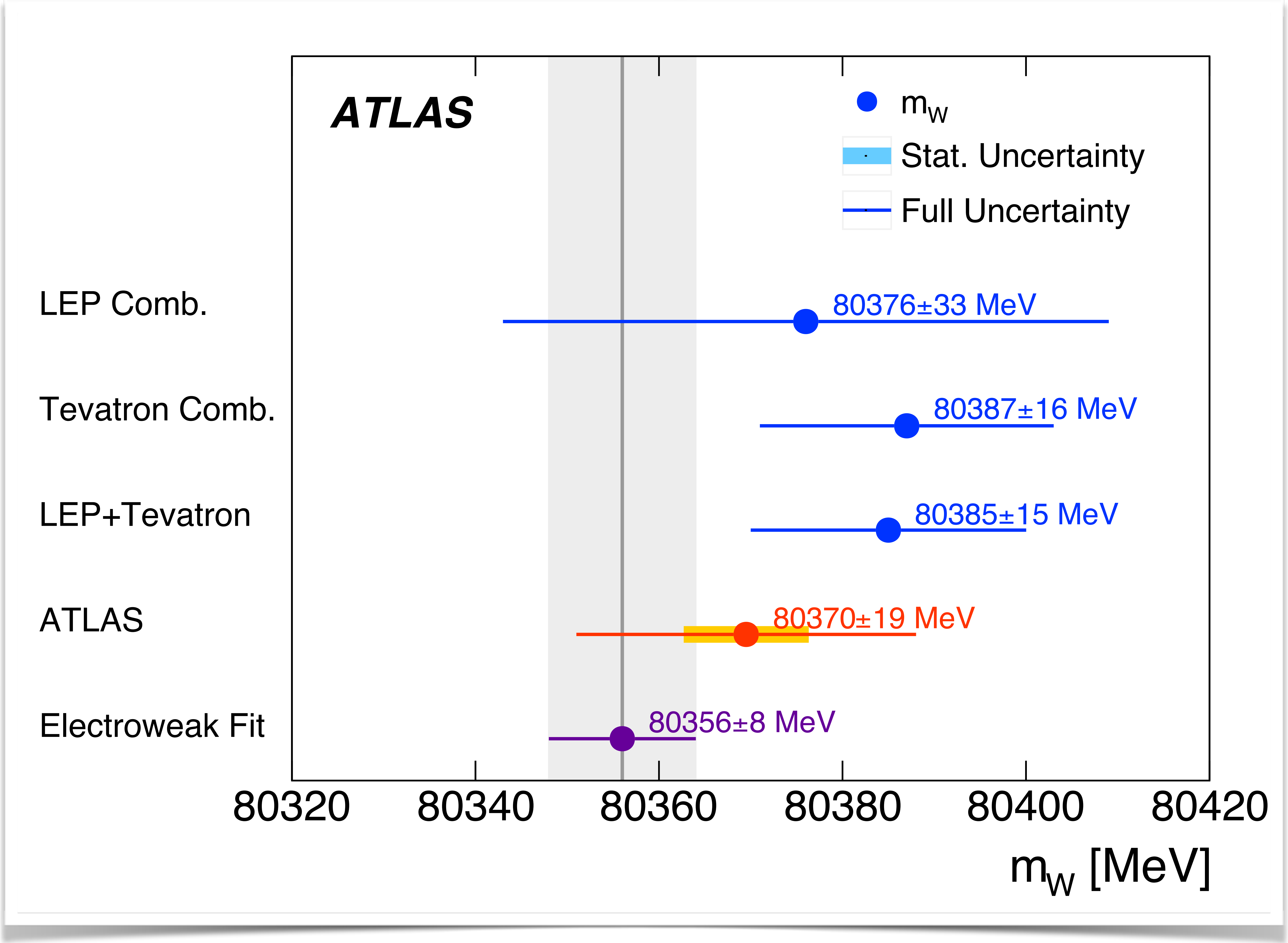
Who am I? Assistant Professor of Physics at UC Berkeley

What do I do? Study the Higgs Boson as a member of the ATLAS experiment



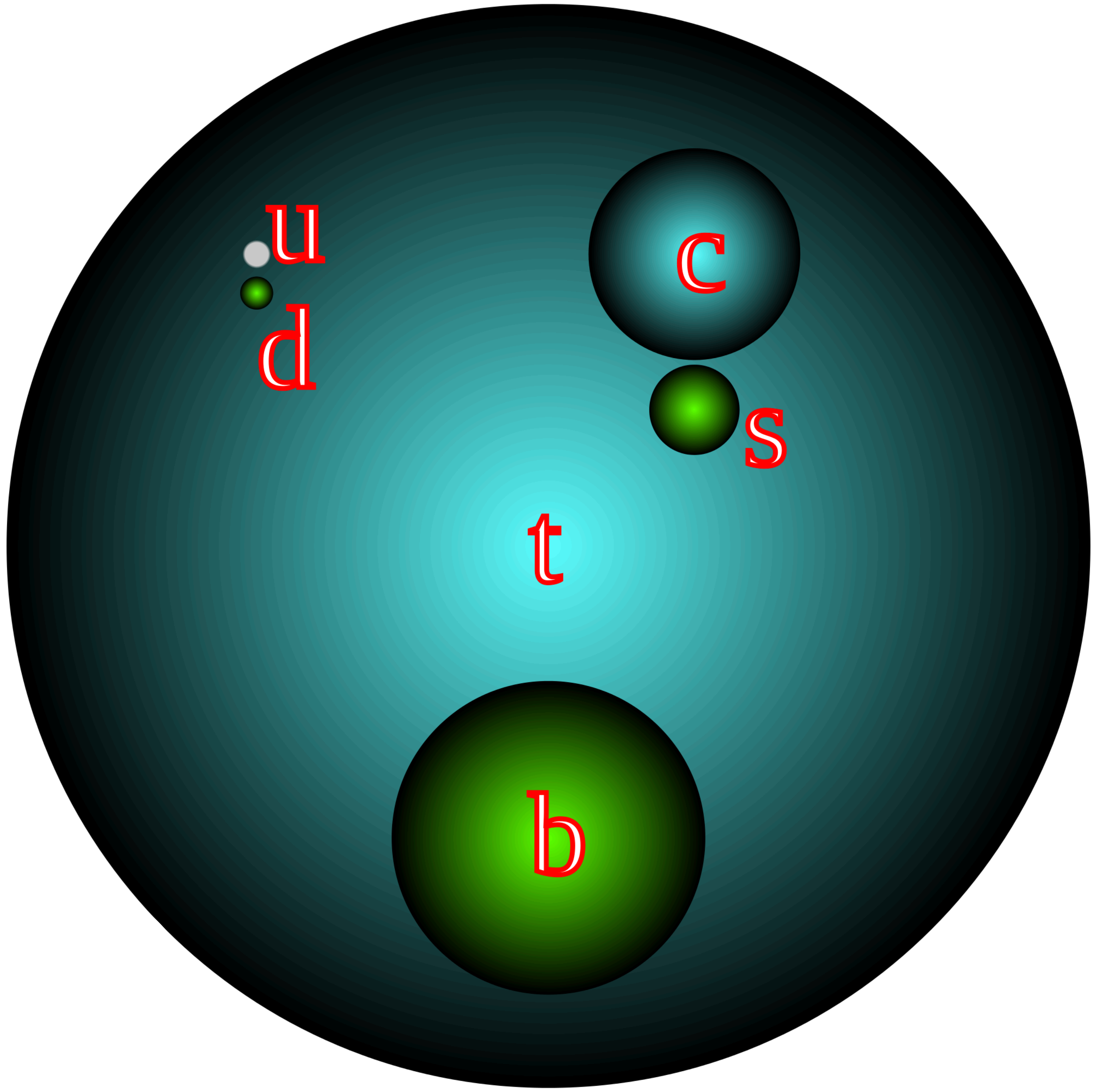

Detector
Trigger
Data preparation,
Reconstruction & Calibration
Publication
Data analysis
events
Background
Signal
Relevant quantity
Theory / Simulations

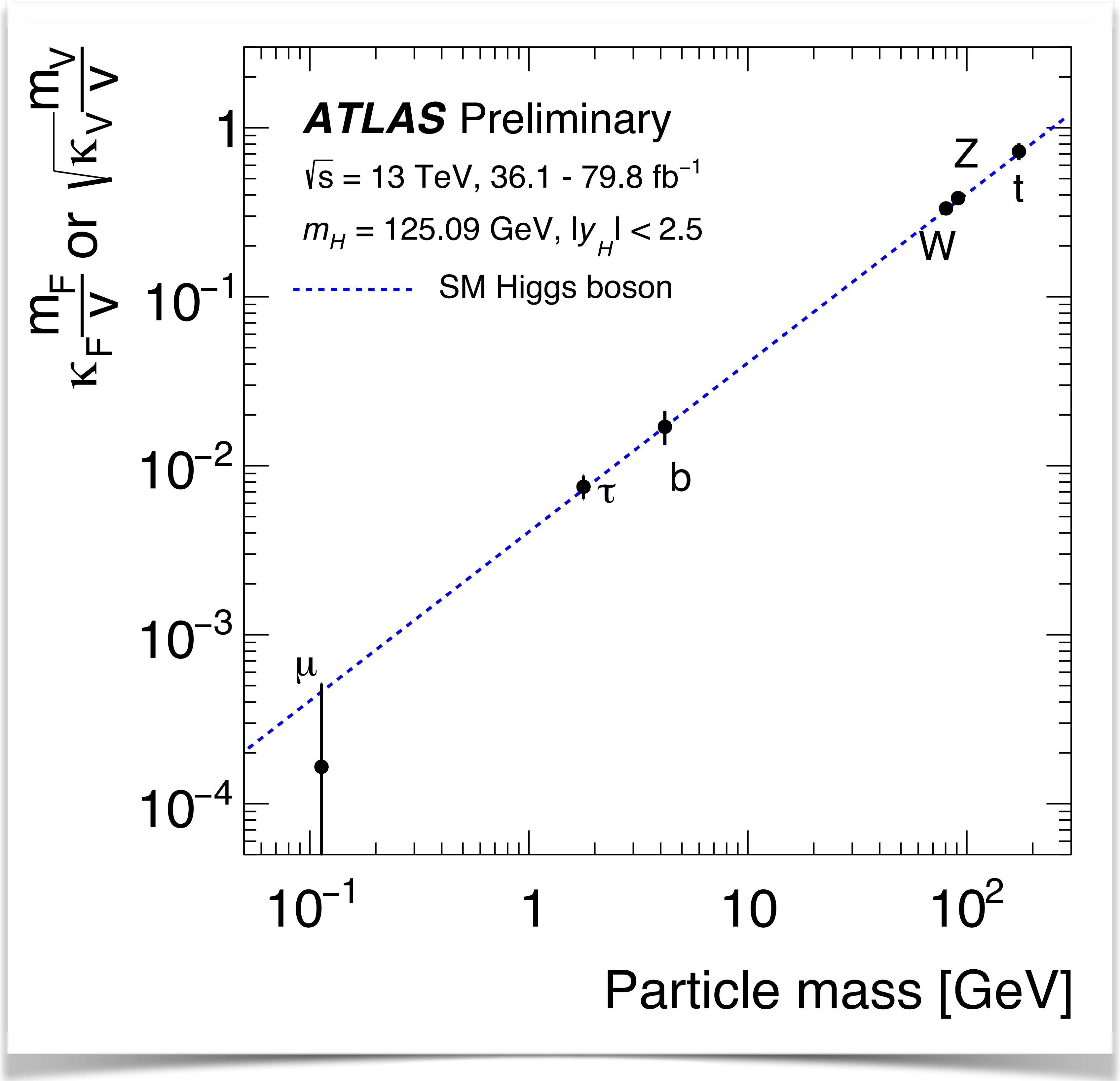
The W Boson has mass !



as does the Z boson

Many particles in the SM have mass





ATLAS-CONF-2018-031

Reminder: Potential Energy