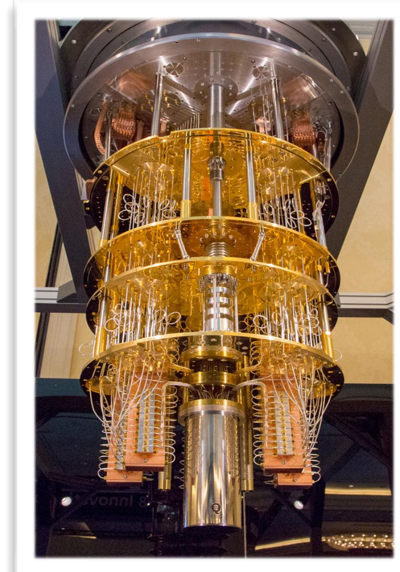

Selected recent ideas in computing and their impact on high-energy physics

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UNIVERSITY OF CALIFORNIA

BERKELEY LAB

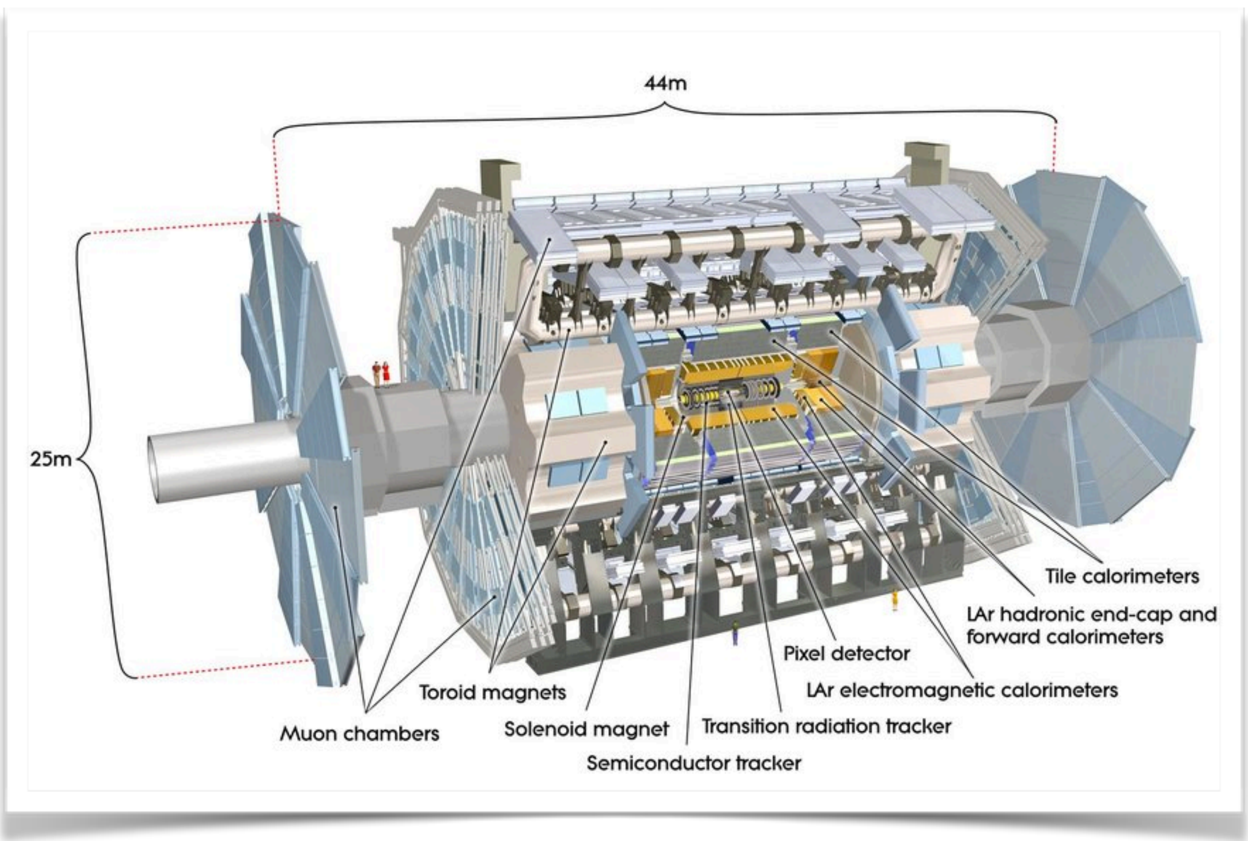
With thanks to A Bird, D. Costanzo, A. Sfyrla, JR Vlimant

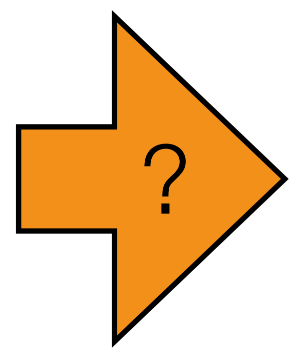
Outline

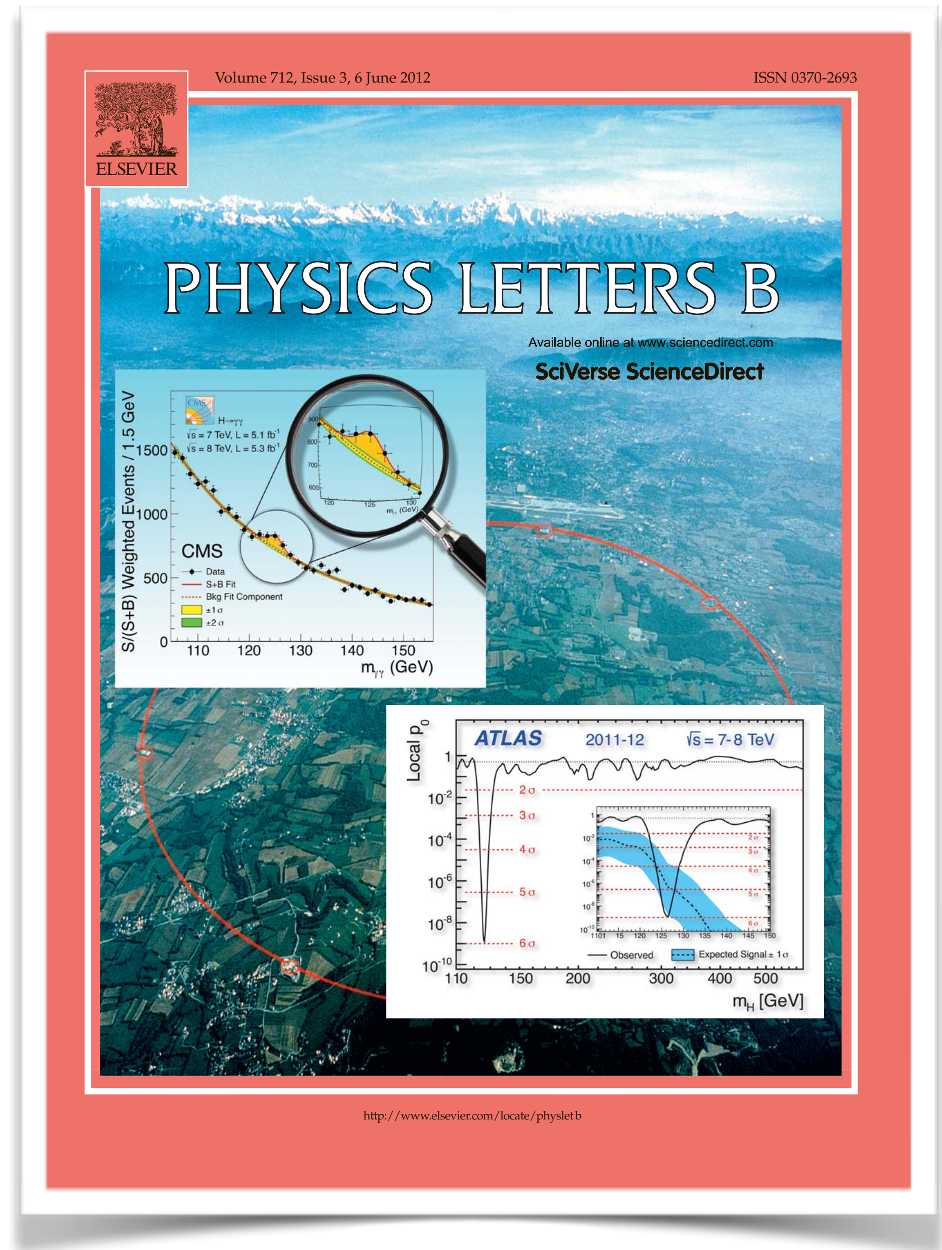
- Role of computing in high-energy physics experiments
  - Typically, use ATLAS as an example
- Recent developments in computing
  - Single core → multi-core processors
  - Machine learning
  - Quantum Computing
- Selected applications to high-energy physics

Computing in High Energy Physics

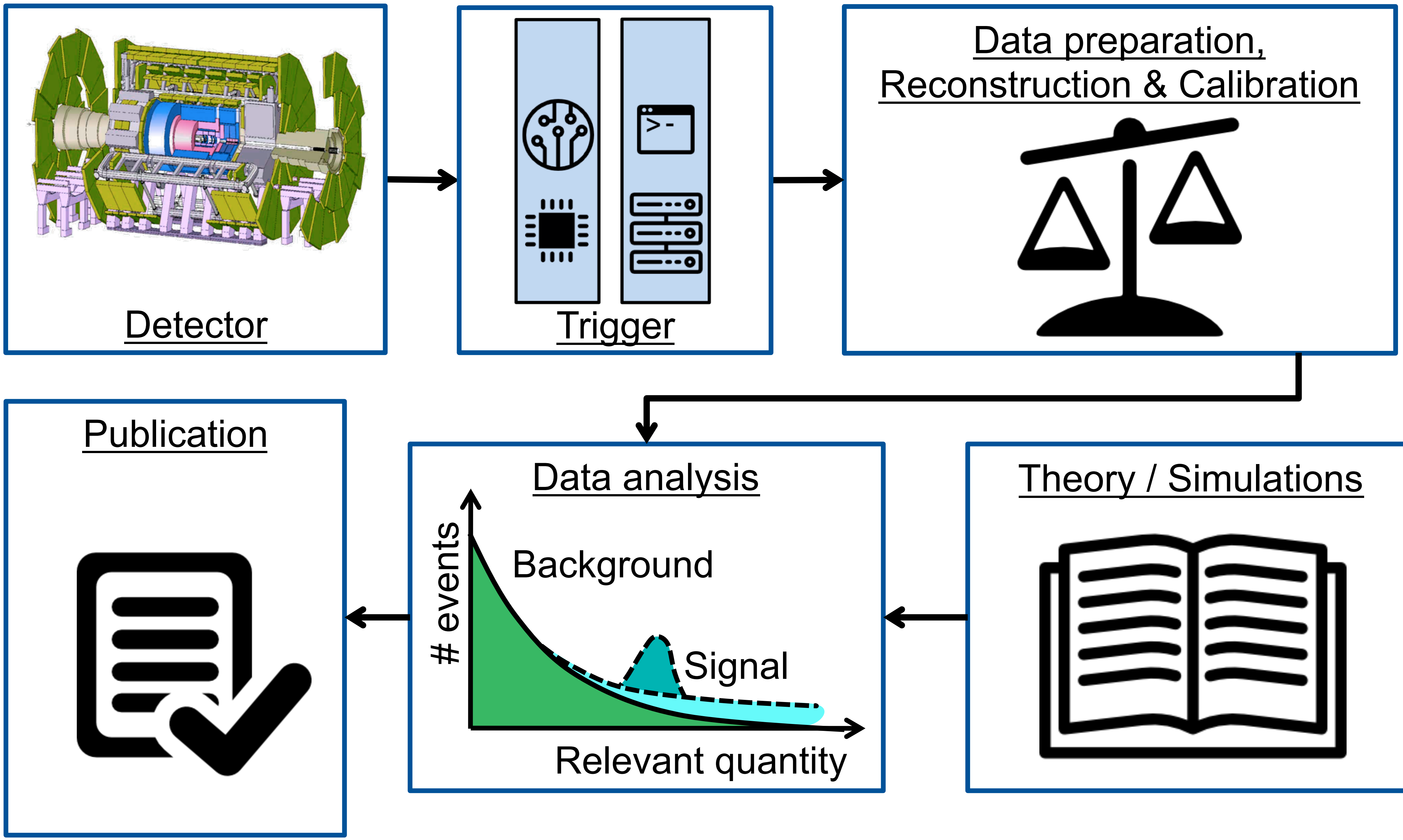
How do we get from information from particles passing through the detectors to published physics results?



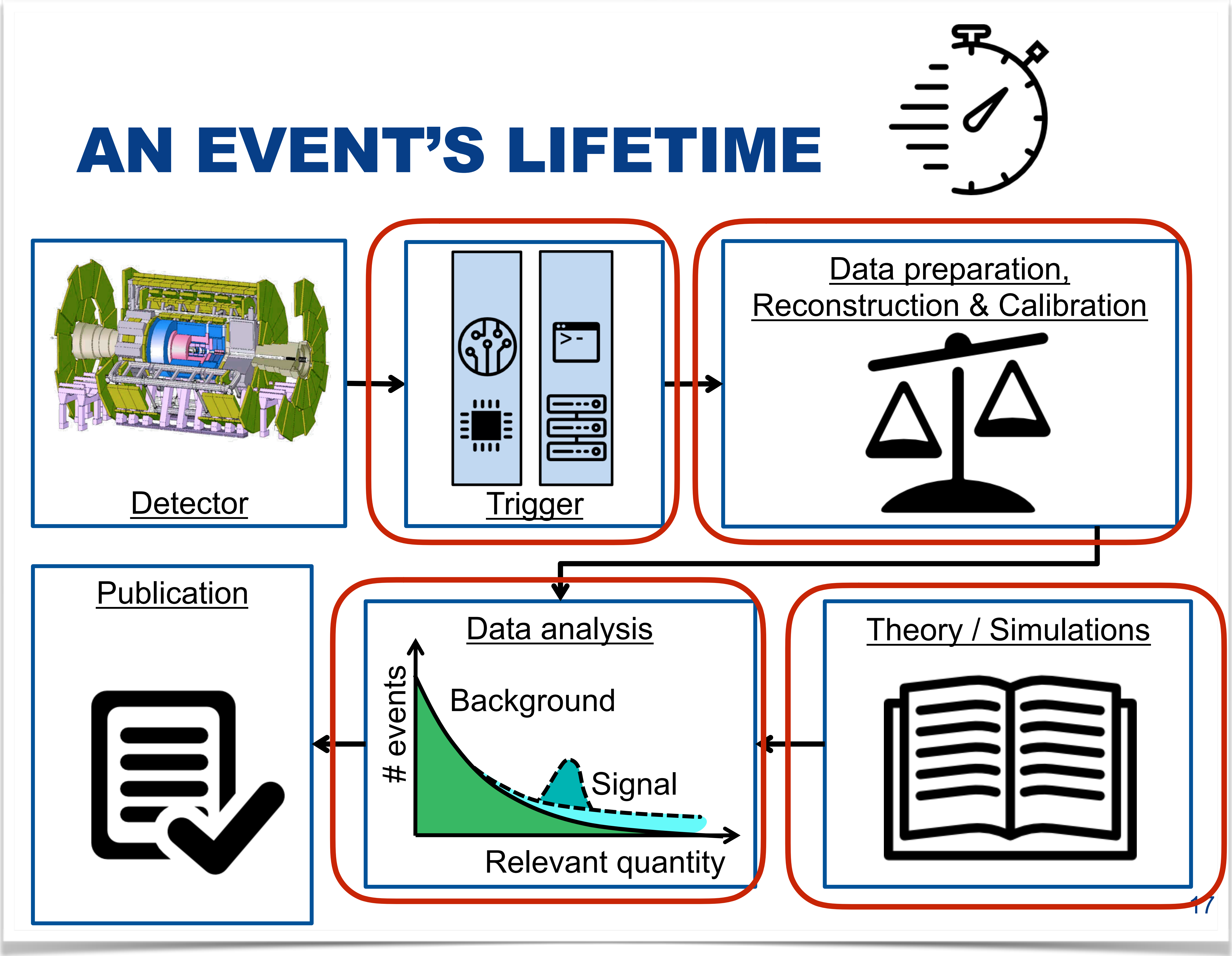




AN EVENT’S LIFETIME



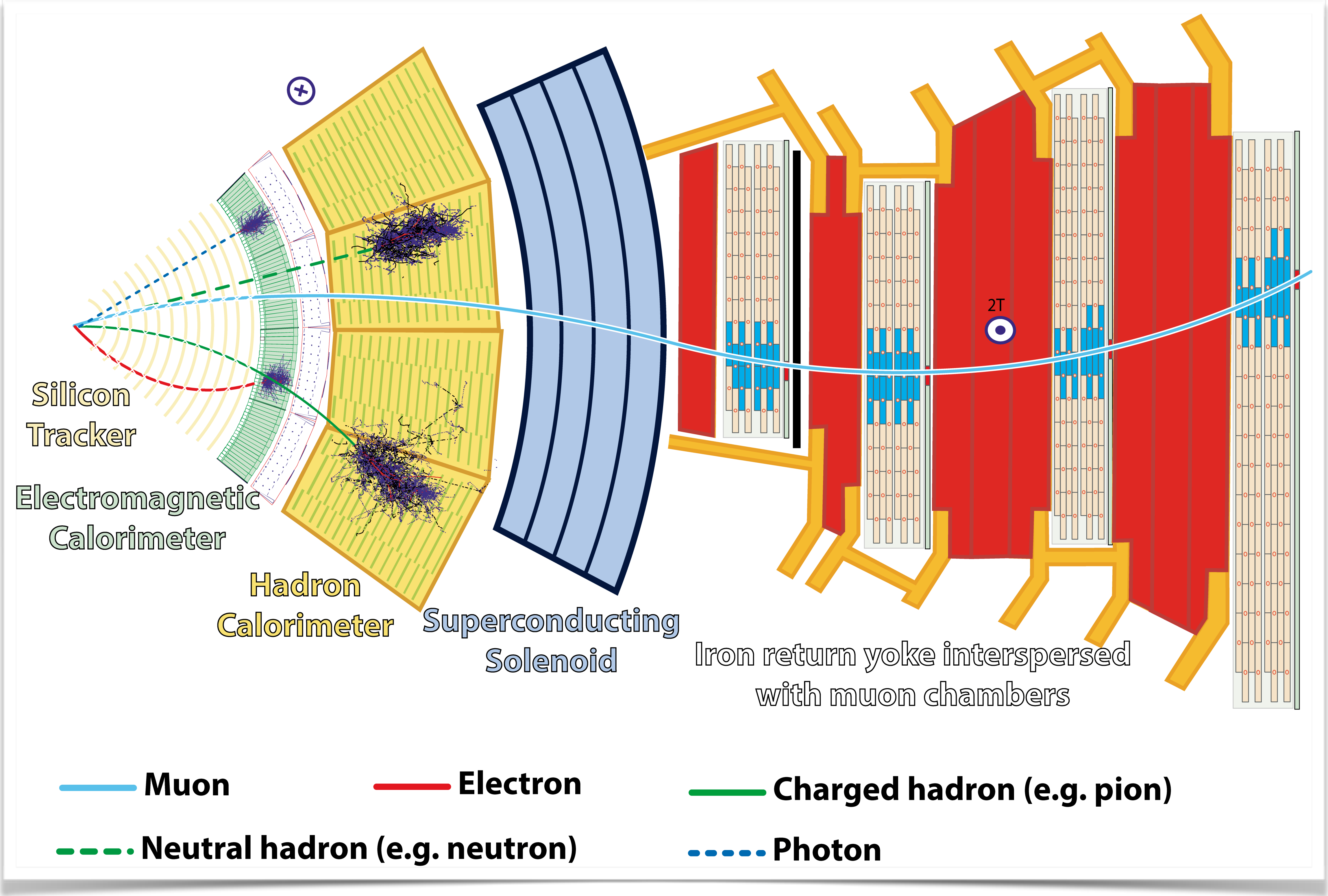
A. Sfyrla



Computing plays a key role throughout

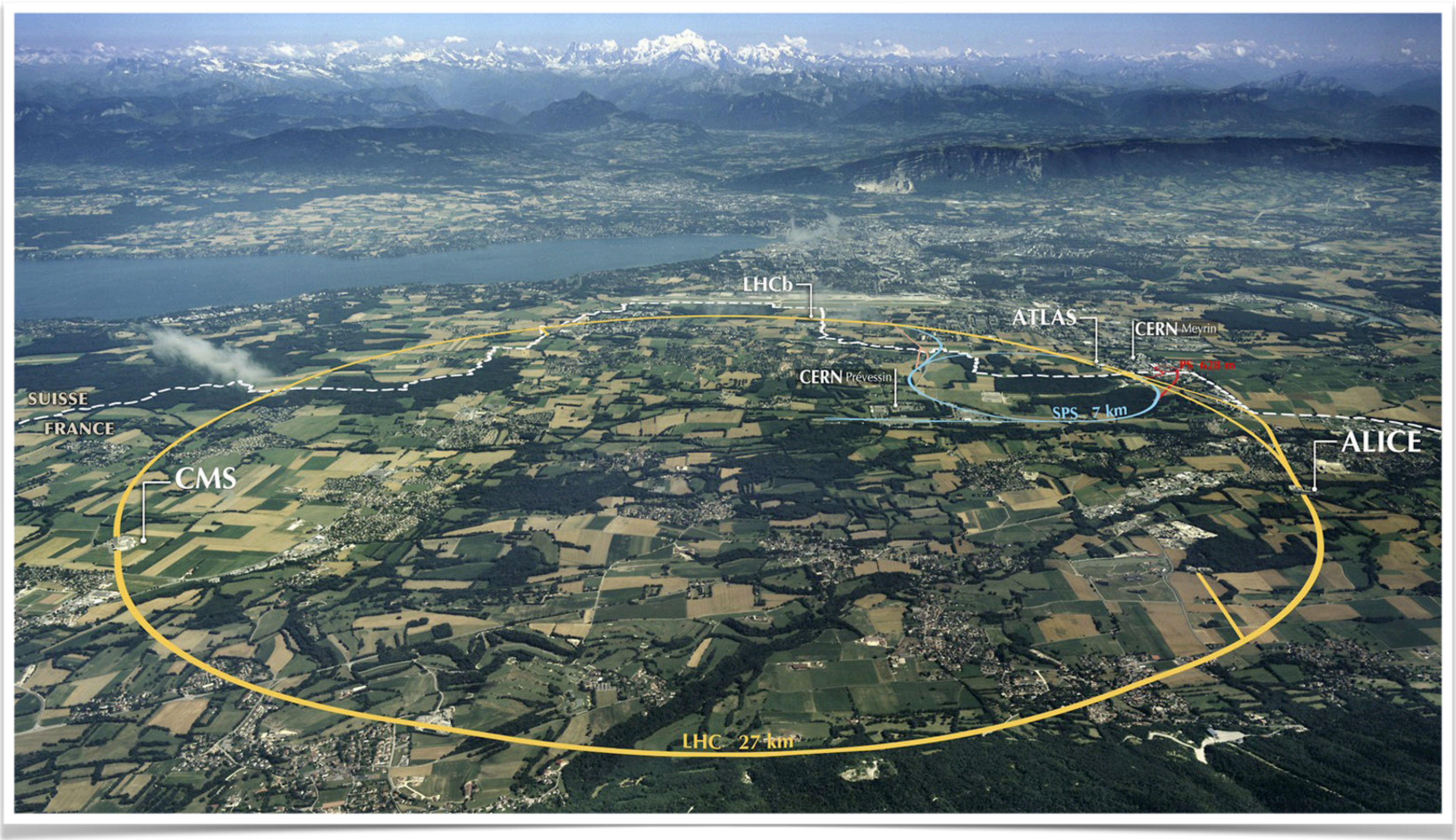
A. Sfyrla

Detecting elementary particles



Reconstruction algorithms map from detector read-out to the particles that passed through the detector

The Large Hadron Collider

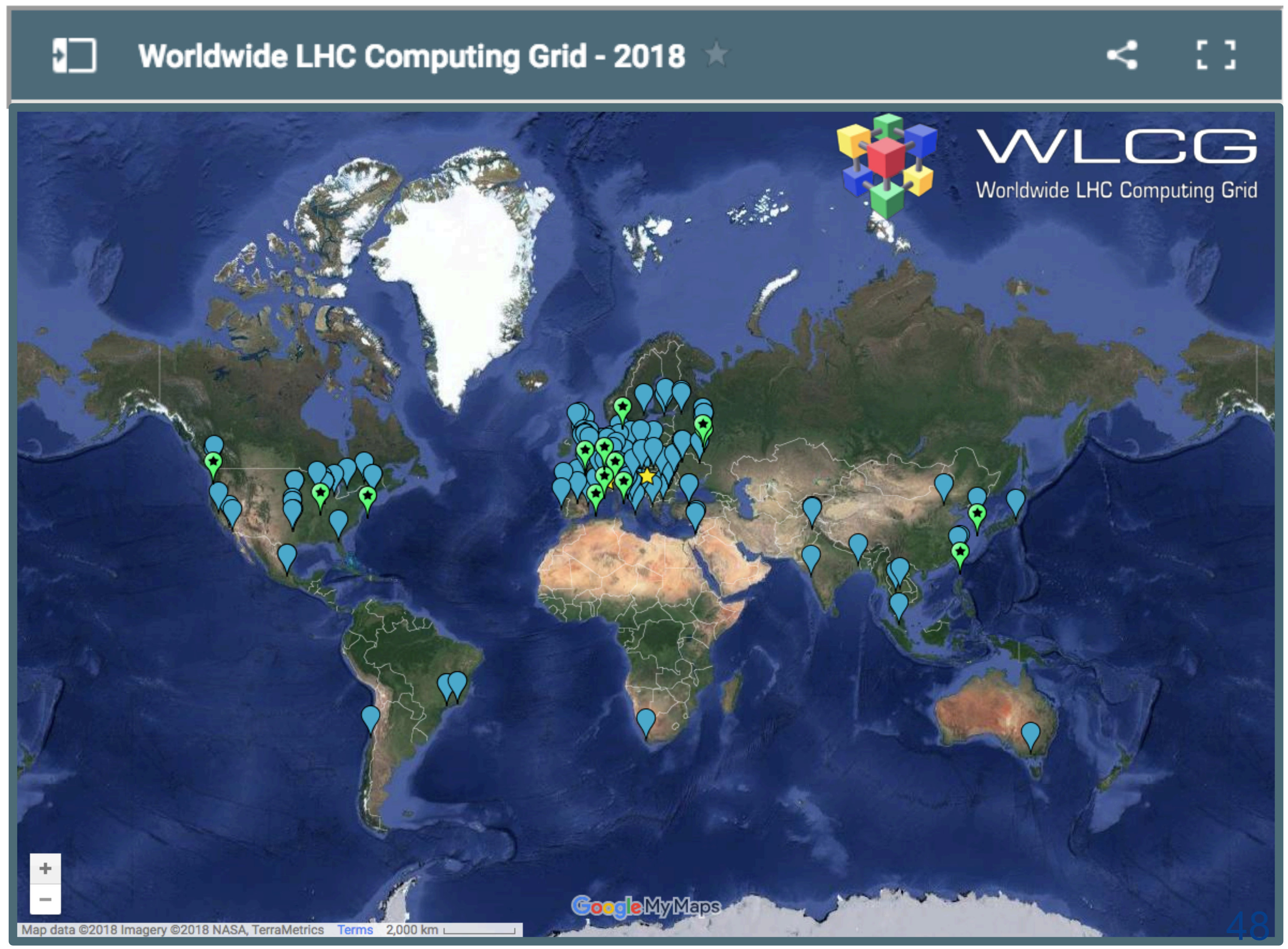


600 million collisions a second

HUGE AMOUNT OF DATA…

LHC delivered billions of recorded collision events to the LHC experiments from proton-proton and proton-lead collisions so far. This translates to many 100s PB of data recorded at CERN.

In 2018 alone, 50 PB of data were expected

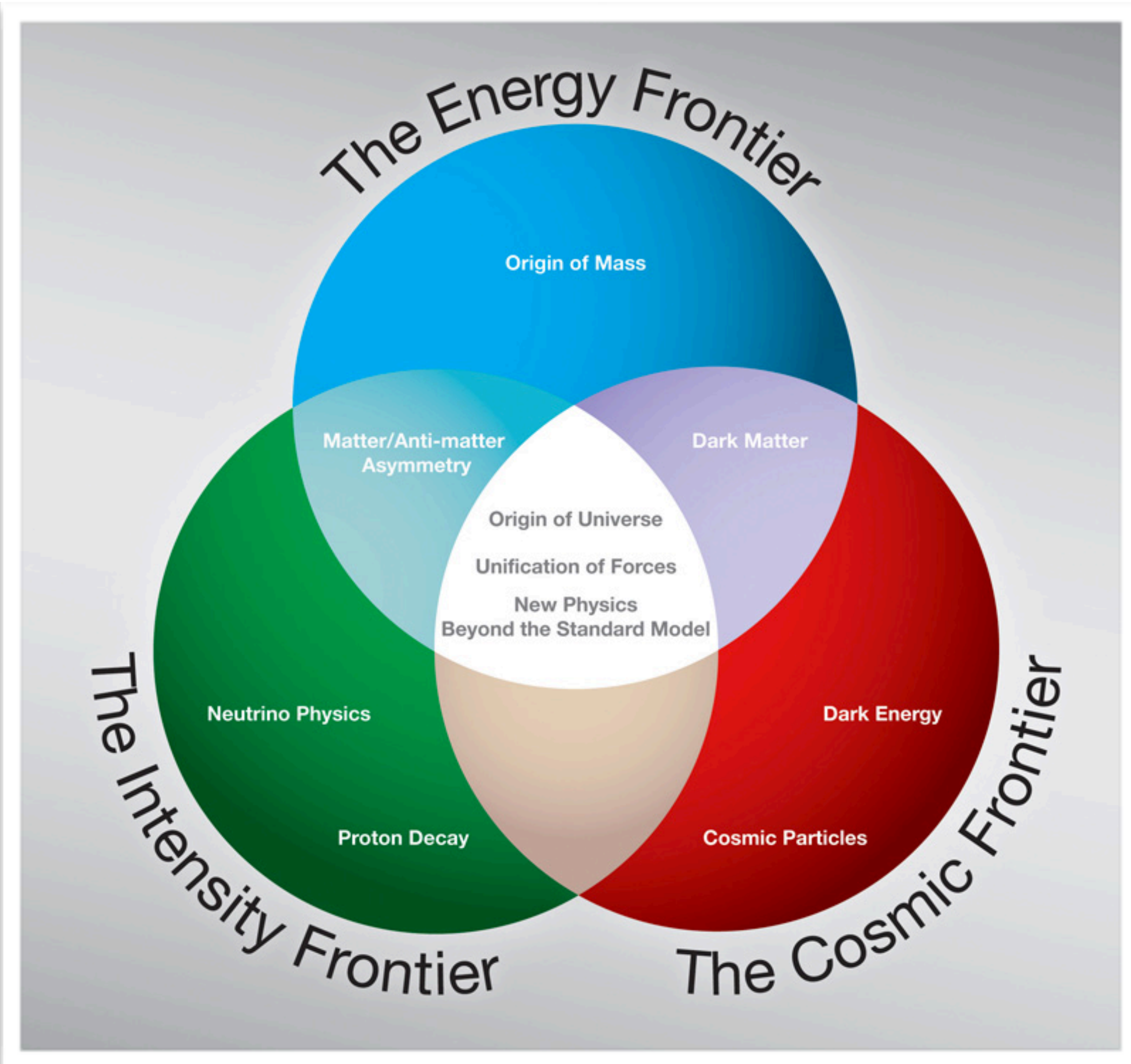


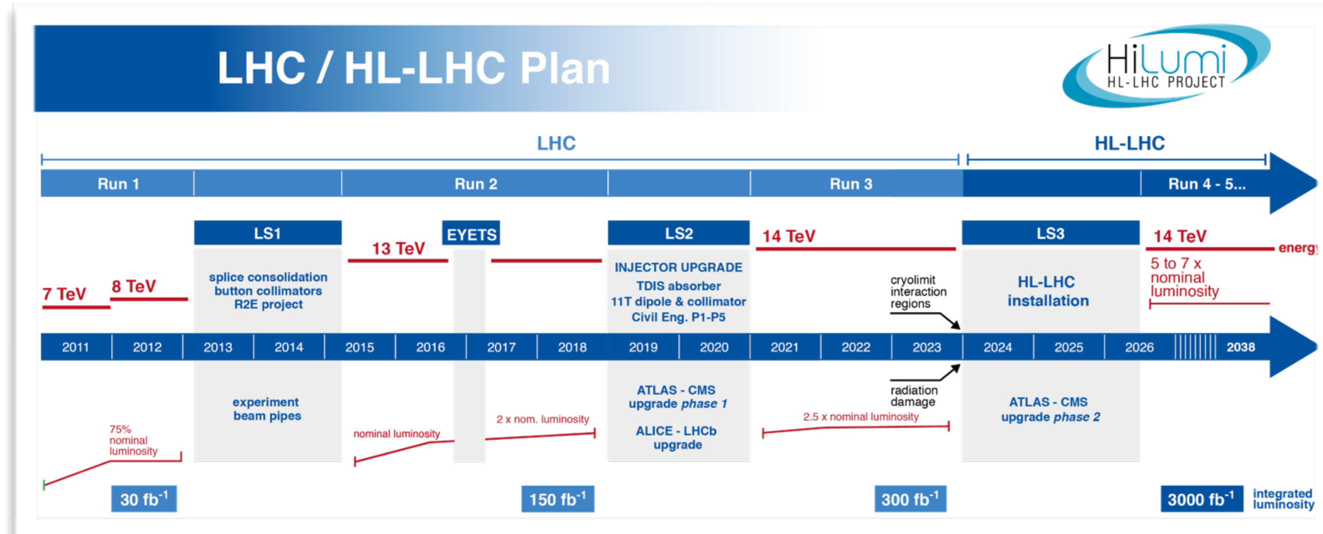
The challenge how to process and analyze the data and produce timely physics results was substantial but in the end resulted in a great success.

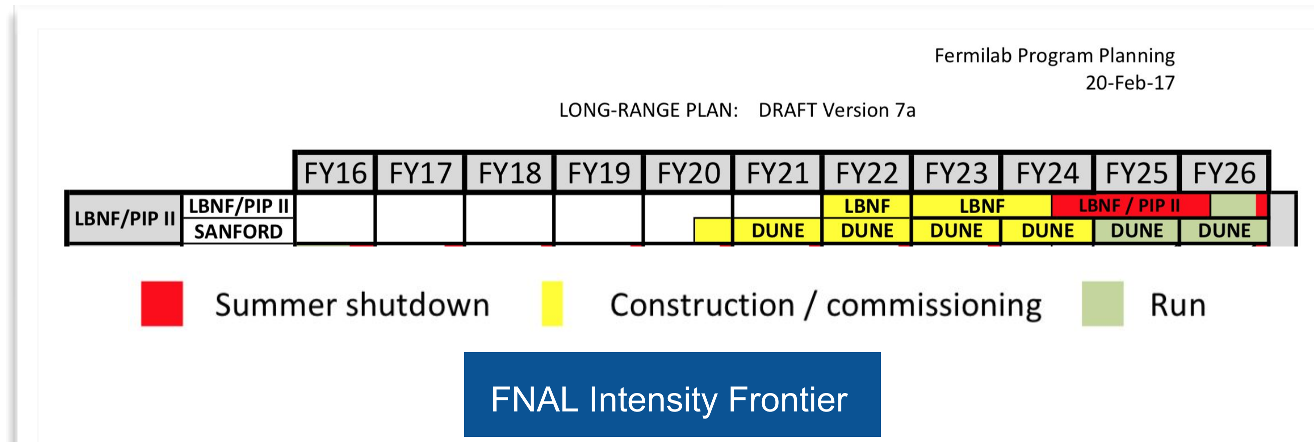
http://wlcg-public.web.cern.ch/

Future Challenges

Upgraded experiments planned on all frontiers

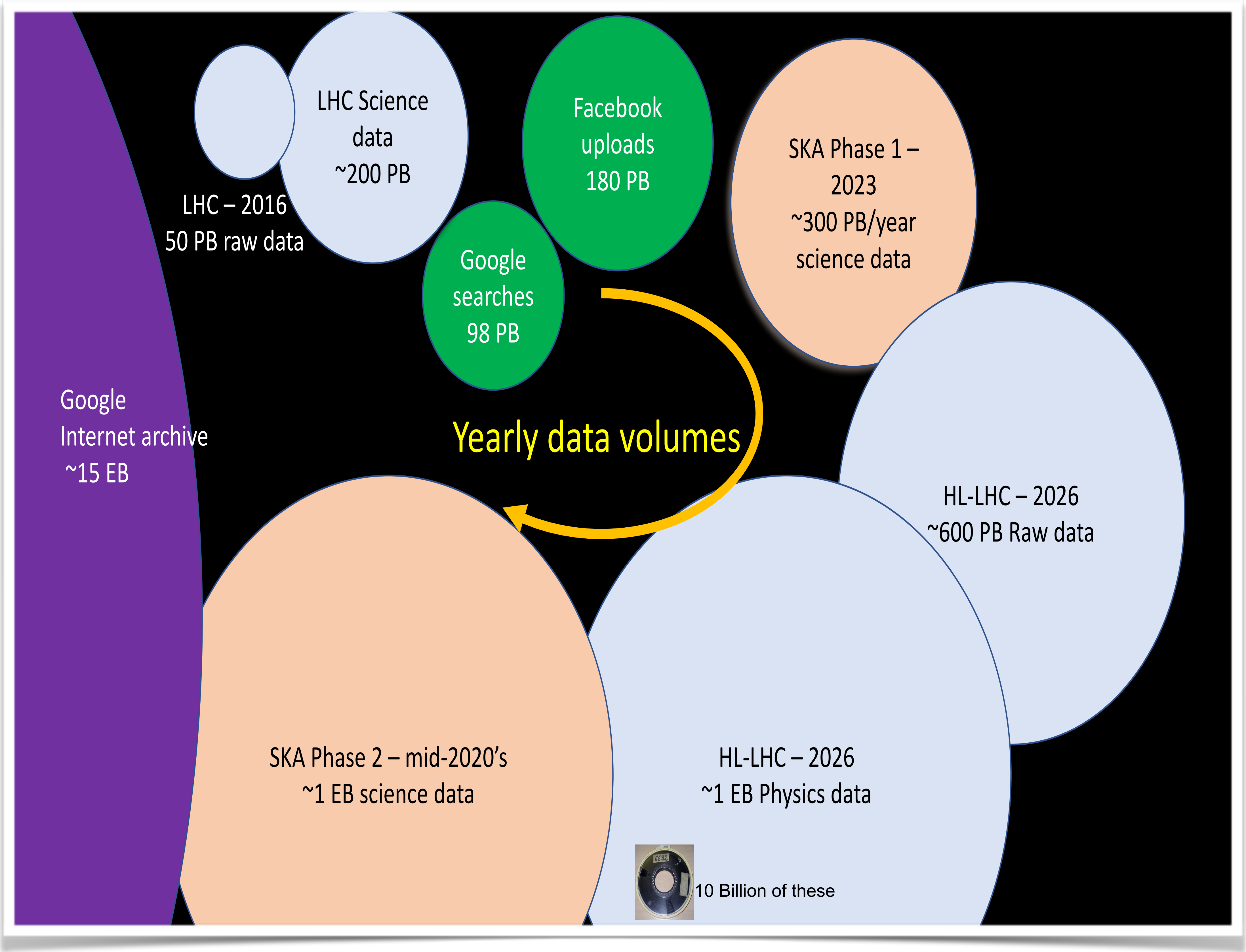






Upgrades typically produce even more data

Big Data: Now and in the Future

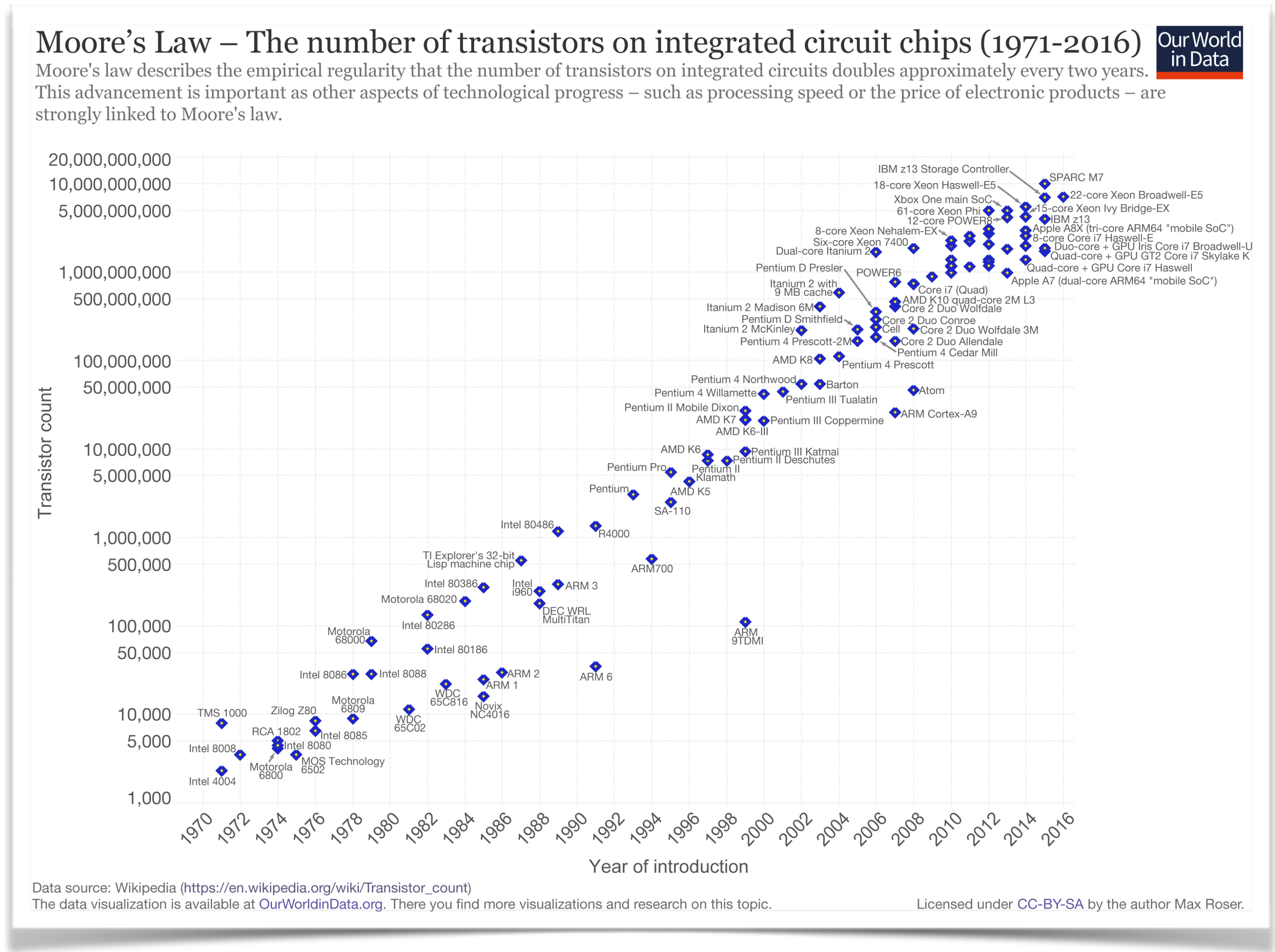


wired, I. Bird, D. Costanzo

Moore’s Law

Number of transistors on integrated circuits doubles every two years

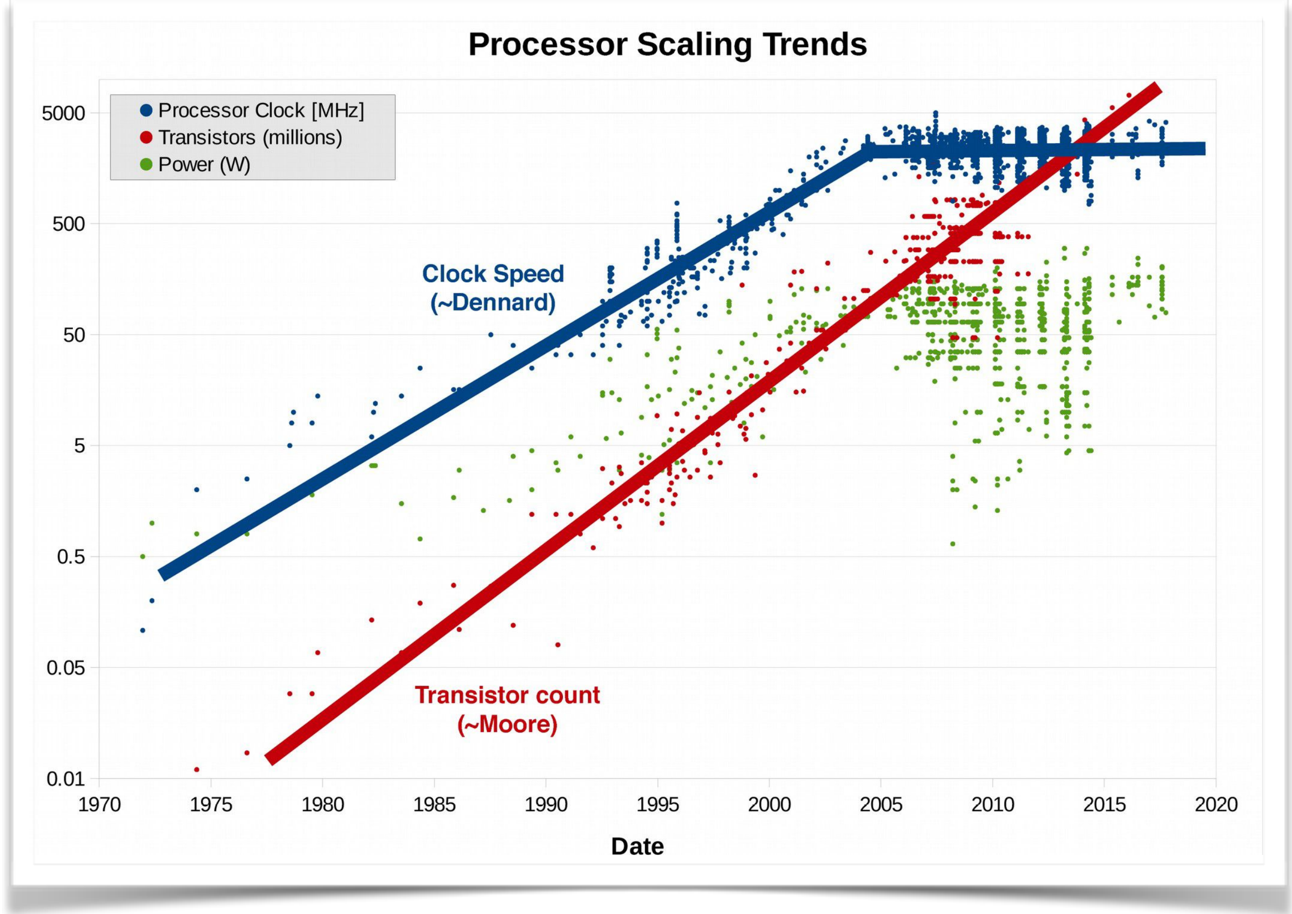
We’ve been relying on this: amount of **computing power** one can purchase **increases** even with a fixed budget

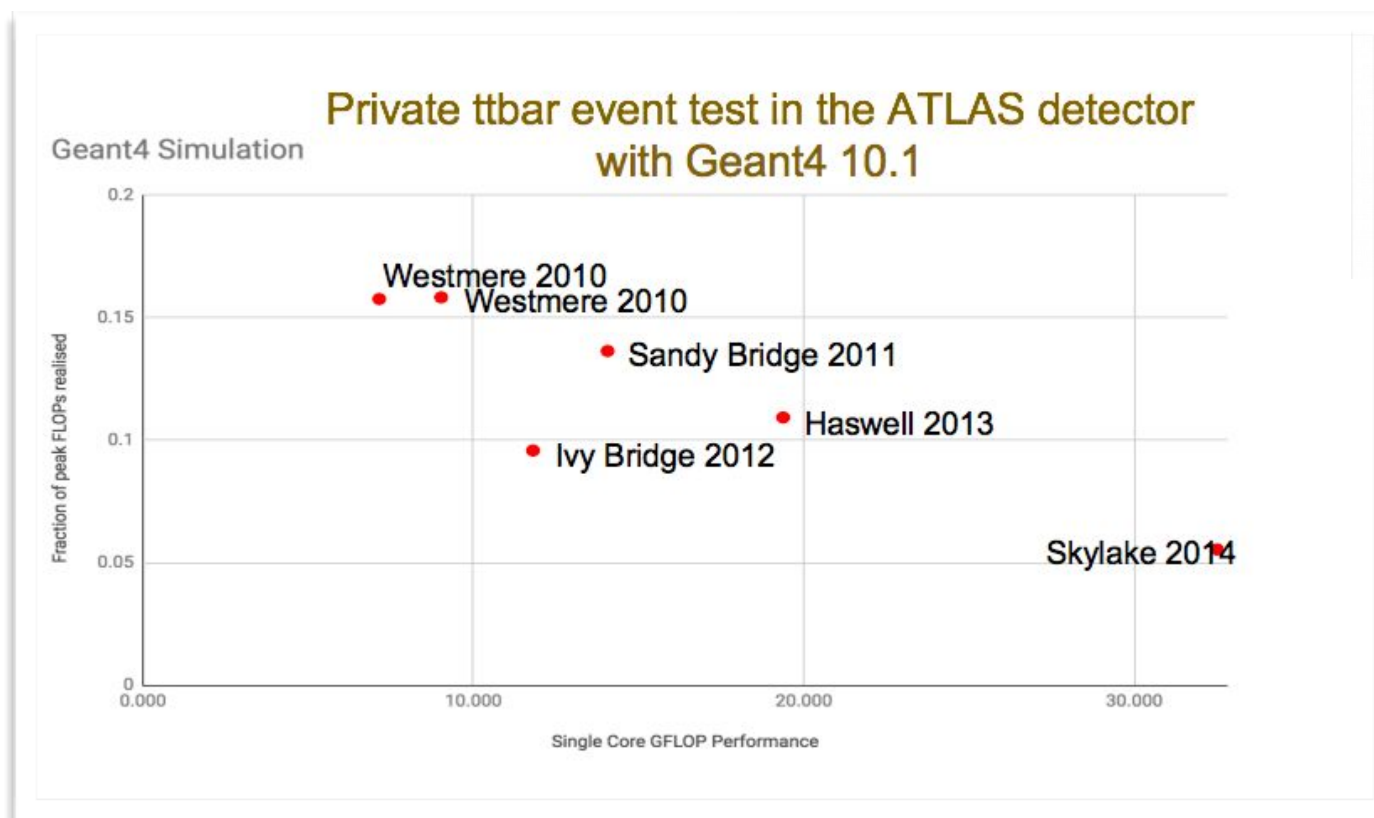


Not expected to continue indefinitely: approaching the size of atoms

Changing Technologies

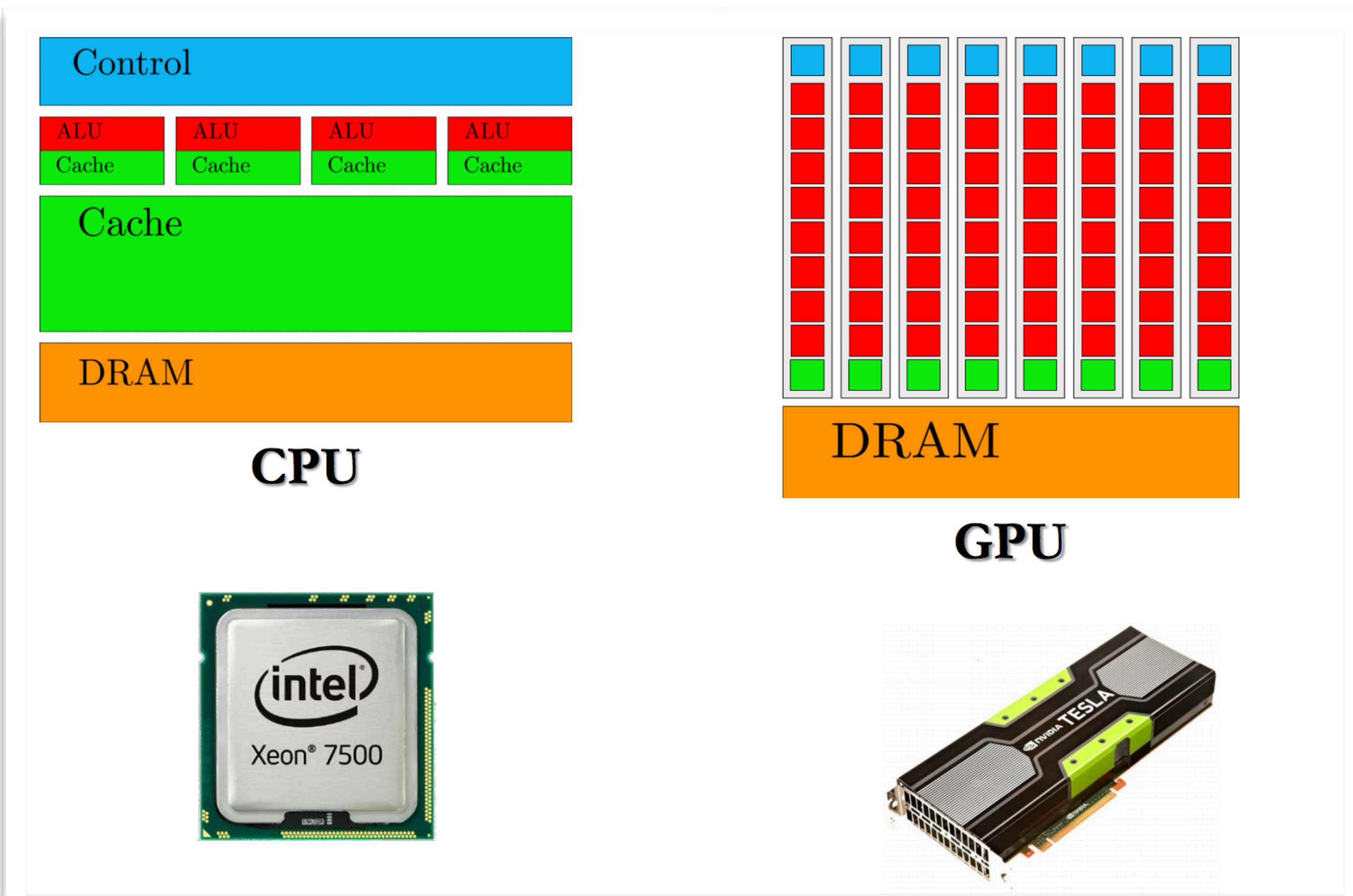
- Recently, trend has been towards increasing number of processors rather than increasing speed of each individual processor
  - Reflects that we're hitting limits in what is possible in terms of speed
- Take a typical ATLAS event and look at the speed of an individual processor on some of the modern machines
  - Decreasing on newer machines



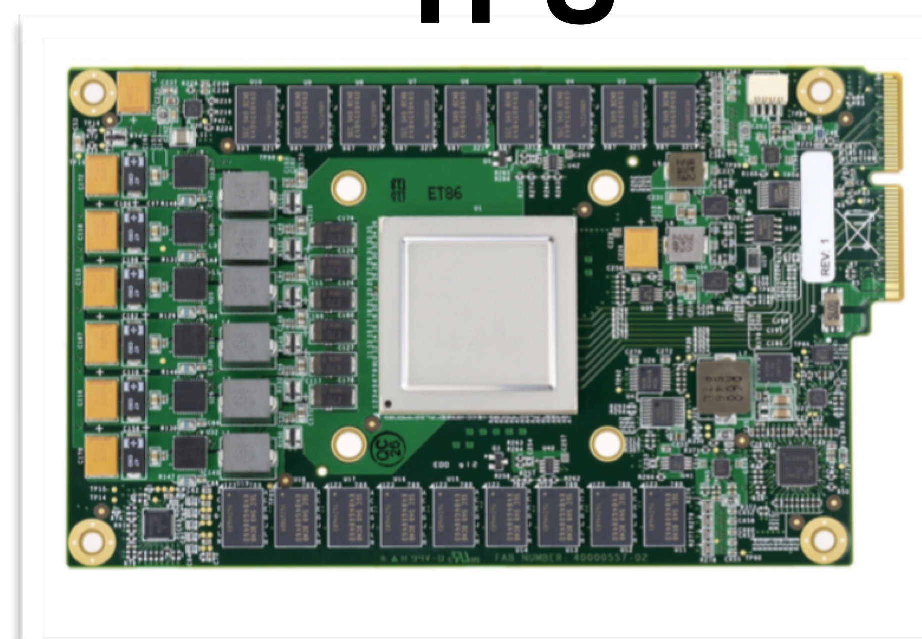


Accelerators

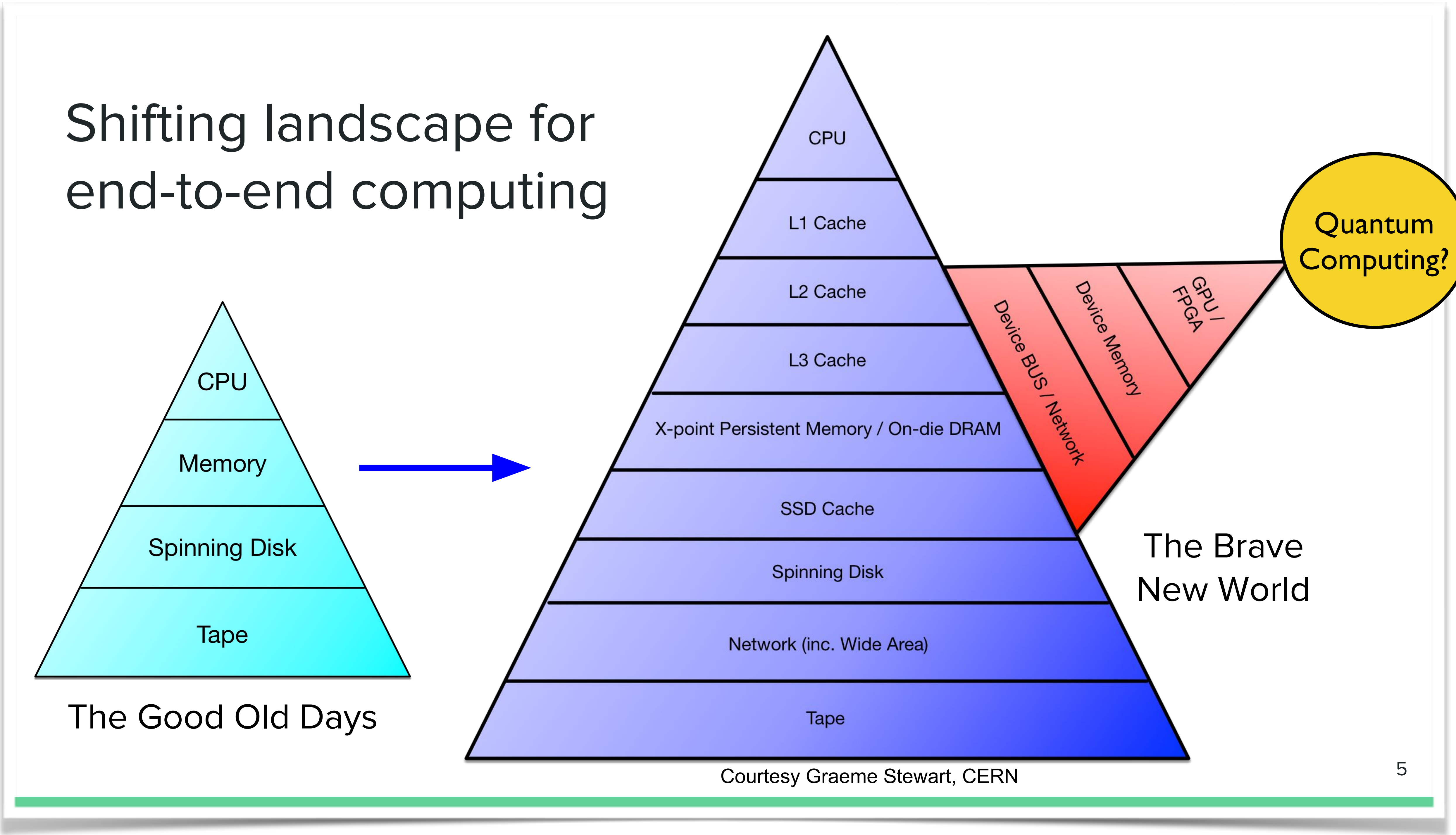
- GPU = Graphics processing unit
- FPGA = Field programmable gate array
- Inexpensive, large processing power, but limited instruction set
- More recently: new computer architectures largely focussed on machine learning have started to appear, e.g. google's TPU = tensor processing unit



TPU

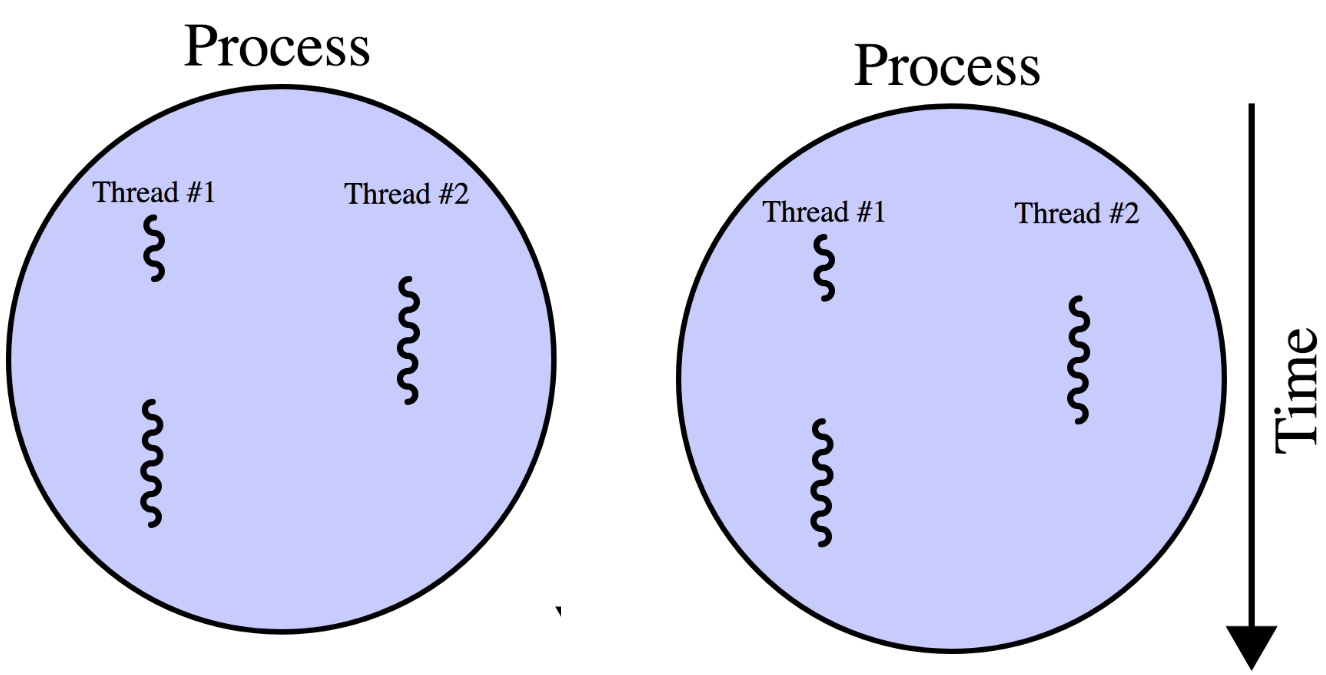


Computing is becoming more complex



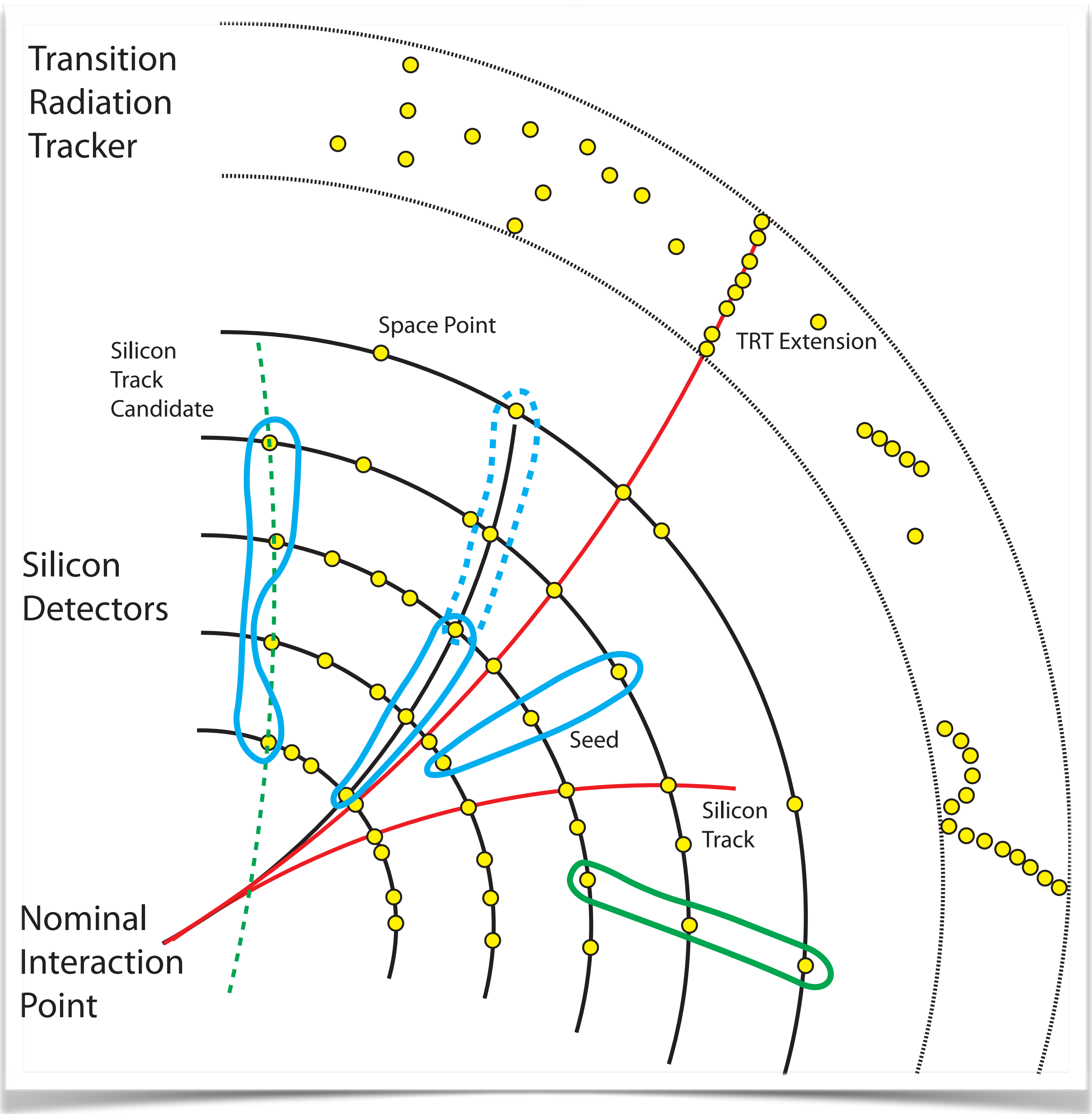
Parallelism

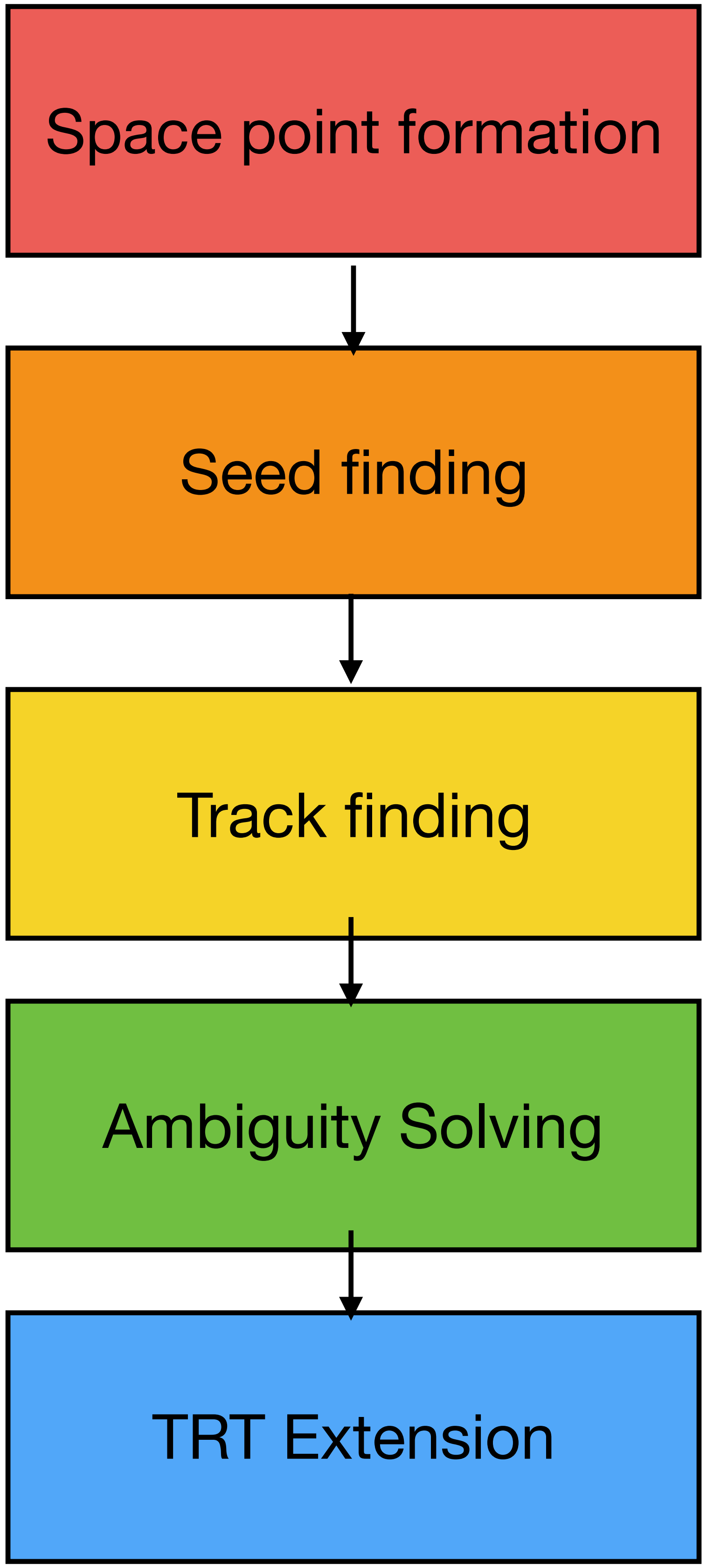
- One technique to exploit these new hardware devices is moving away from the idea of processing each event sequentially
  - Multiple events in parallel (each in a separate process)
  - Divide an individual events into separate threads
- This is difficult to achieve
  - Different threads and processes need to operate independently without impacting each other
- How to share data between processes?



Example: Track Reconstruction Algorithms

- Reconstructing the passages of charged particles through the detector takes the largest fraction of CPU time

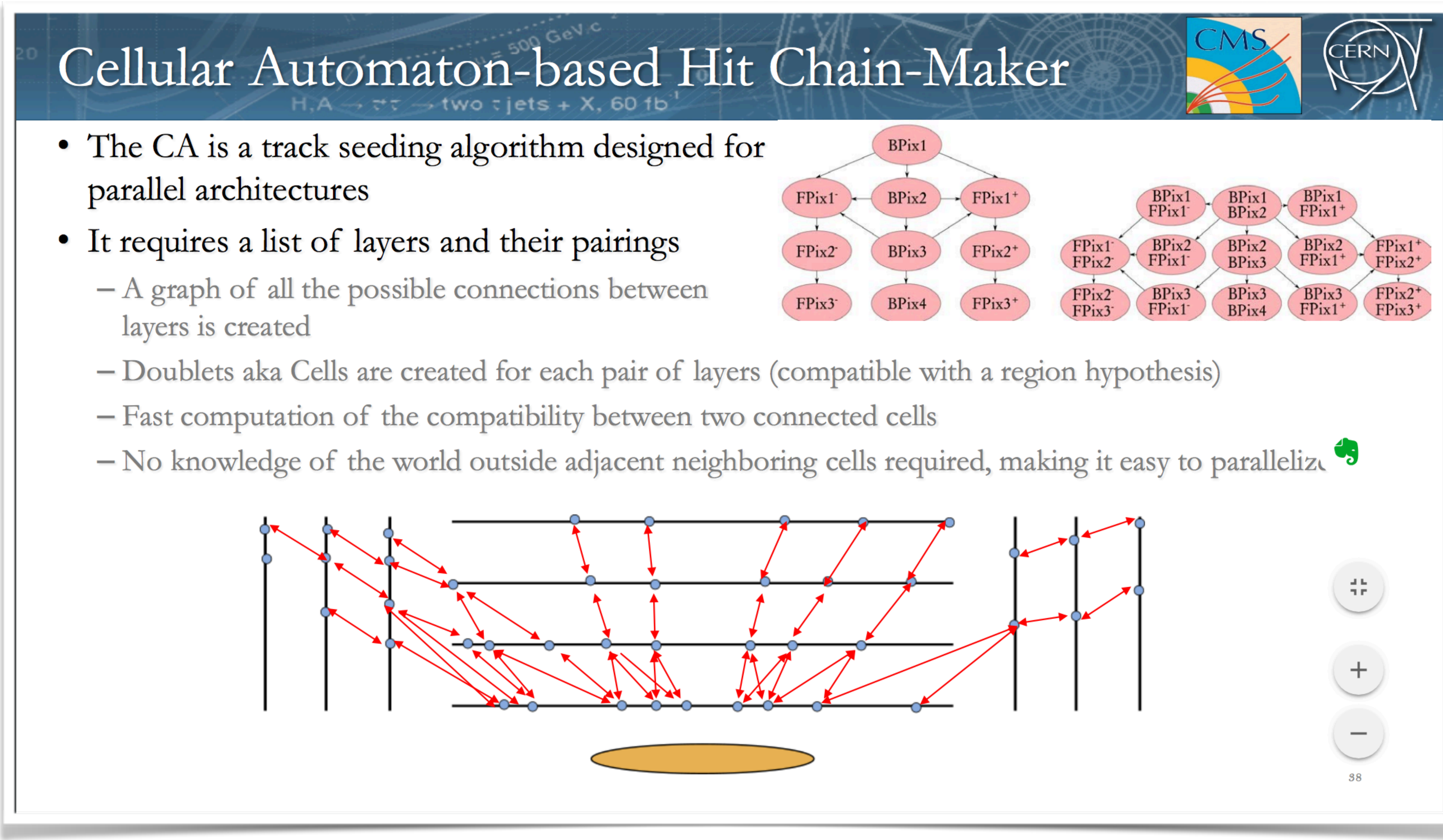




ATLAS-CONF-2010-072

Track Seeding → Cellular Automaton

Exploiting parallelism efficiently requires rethinking our algorithms



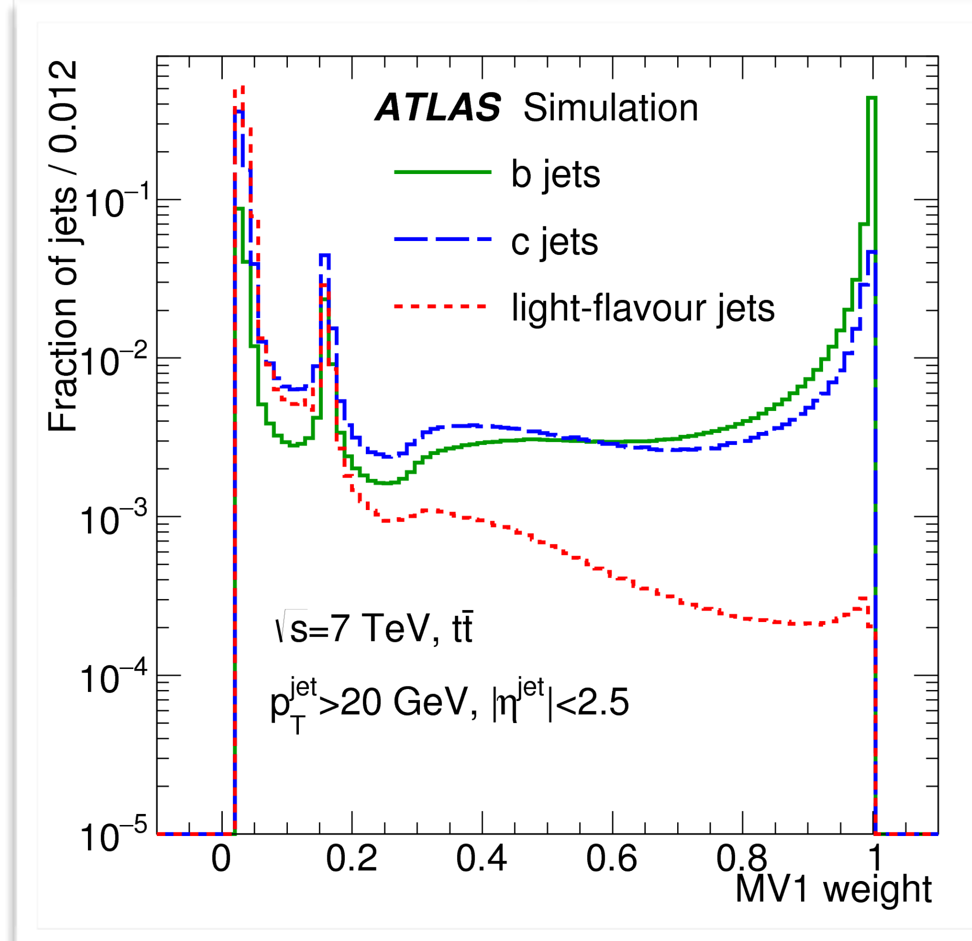
F. Pantaleo

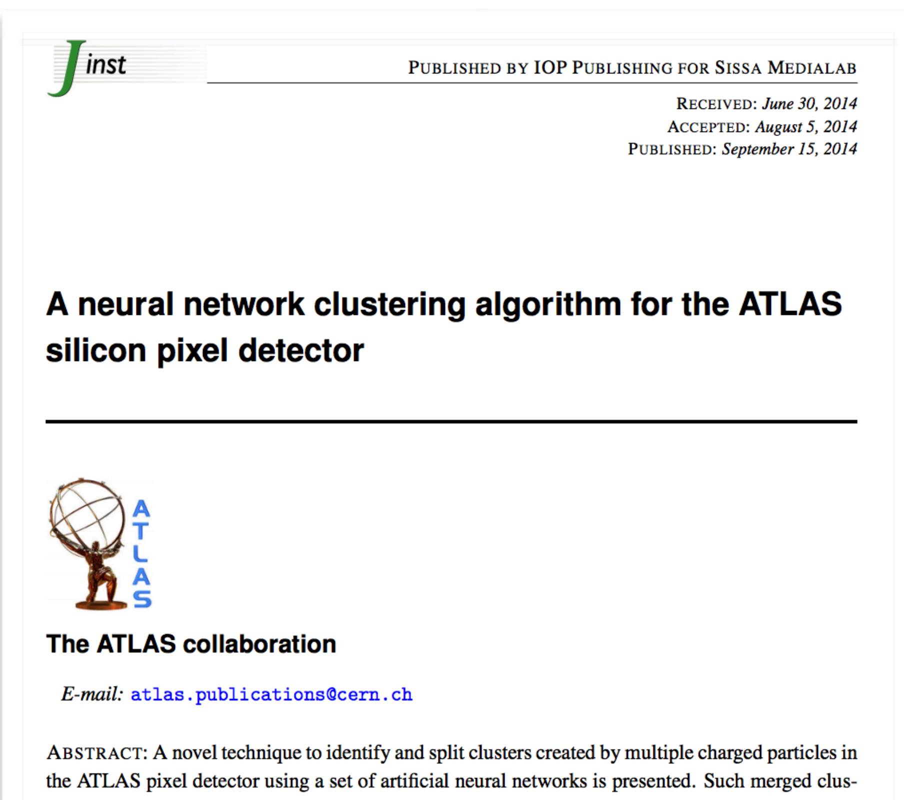
Artificial intelligence/machine learning

- In a nutshell: get the computer to learn without explicit programming
- **Machine learning** currently used throughout high-energy physics and most efforts can be characterised into one of two areas
- **Object classification**
  - Is the reconstructed object the one that I want or is it background ?
  - These developments tend to be more general than a signal analysis and can be used throughout the physics program
- **Event classification**
  - Are the properties of the reconstructed objects in the event consistent with signal or background?
  - Various types of machine learning have been used
  - Most often boosted decision trees (BDTs), also quite often neural networks (NNs)
- AI/ML is an extremely active field both in computer science and in industry

ML in the Higgs Program

- Higgs coupling to bottom quarks
  - b-jet tagging
  - Event classification
- Higgs coupling to top quarks
  - Object and event classification
  - Multinomial BDT





Jinst

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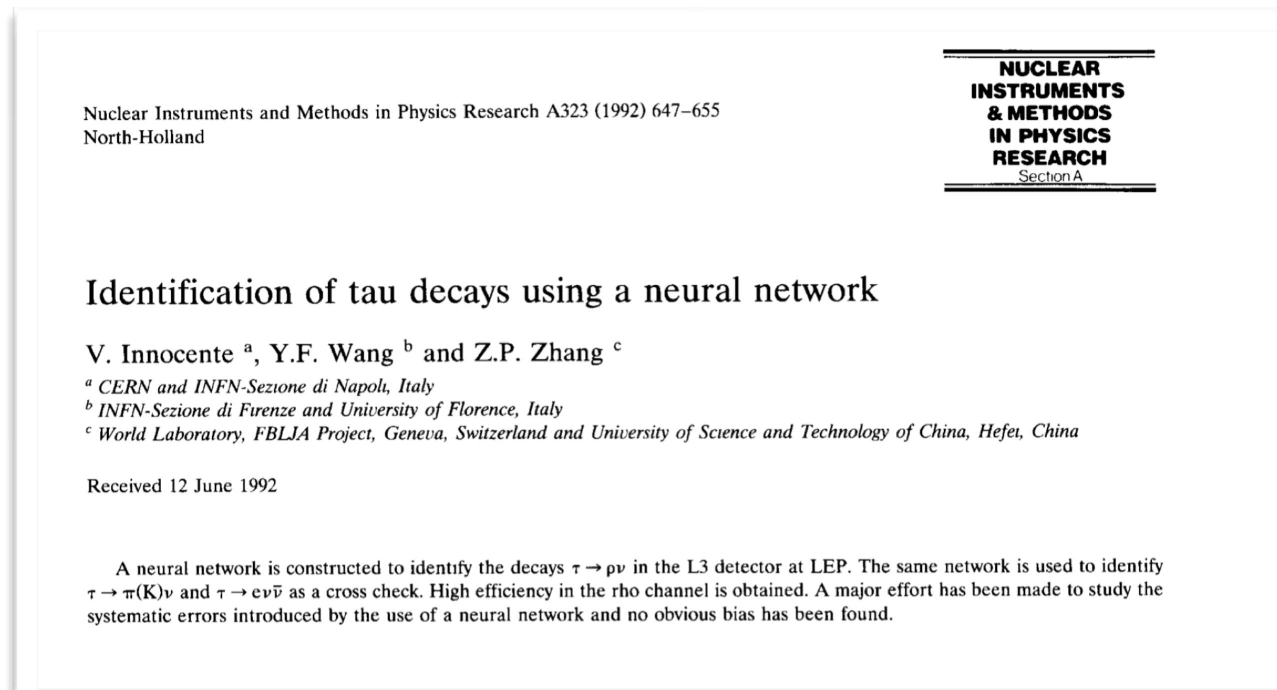
ACCEPTED: *August 5, 2014*
PUBLISHED: *September 15, 2014*

A neural network clustering algorithm for the ATLAS silicon pixel detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A novel technique to identify and split clusters created by multiple charged particles in the ATLAS pixel detector using a set of artificial neural networks is presented. Such merged clus-



Nuclear Instruments and Methods in Physics Research A323 (1992) 647–655
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Identification of tau decays using a neural network

V. Innocente [a], Y.F. Wang [b] and Z.P. Zhang [c]

[a] *CERN and INFN-Sezione di Napoli, Italy*
[b] *INFN-Sezione di Firenze and University of Florence, Italy*
[c] *World Laboratory, FBLJA Project, Geneva, Switzerland and University of Science and Technology of China, Hefei, China*

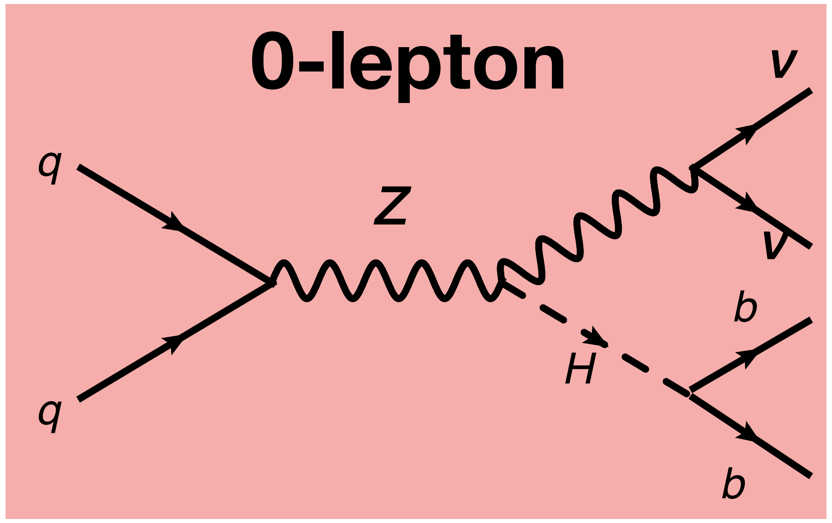
Received 12 June 1992

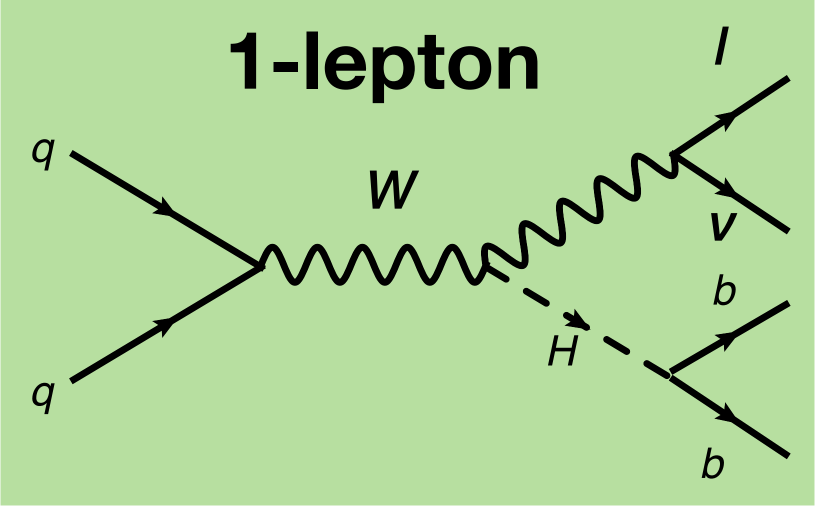
A neural network is constructed to identify the decays $\tau \to \rho\nu$ in the L3 detector at LEP. The same network is used to identify $\tau \to \pi(K)\nu$ and $\tau \to e\nu\bar{\nu}$ as a cross check. High efficiency in the rho channel is obtained. A major effort has been made to study the systematic errors introduced by the use of a neural network and no obvious bias has been found.

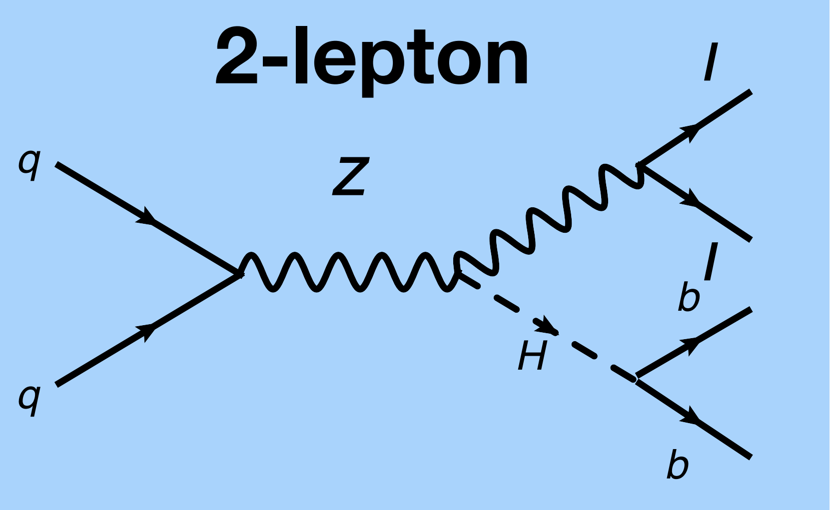
H→bb

JHEP 12 (2017) 024
JHEP 01 (2015) 069
HIGG-2018-04

- Largest branching ratio (58%), large backgrounds
- Production modes studied VBF, VH, ttH, (ggF)
  - ggF is swamped by large QCD dijet production
- Most powerful channel is VH (V=W, Z)
- Three channels
  - 0-lepton: Z(νν)H(bb)
  - 1-lepton: W(lν)H(b)
  - 2-lepton: Z(ll)H(bb)
- Events contain two b-jets and 0-2 leptons



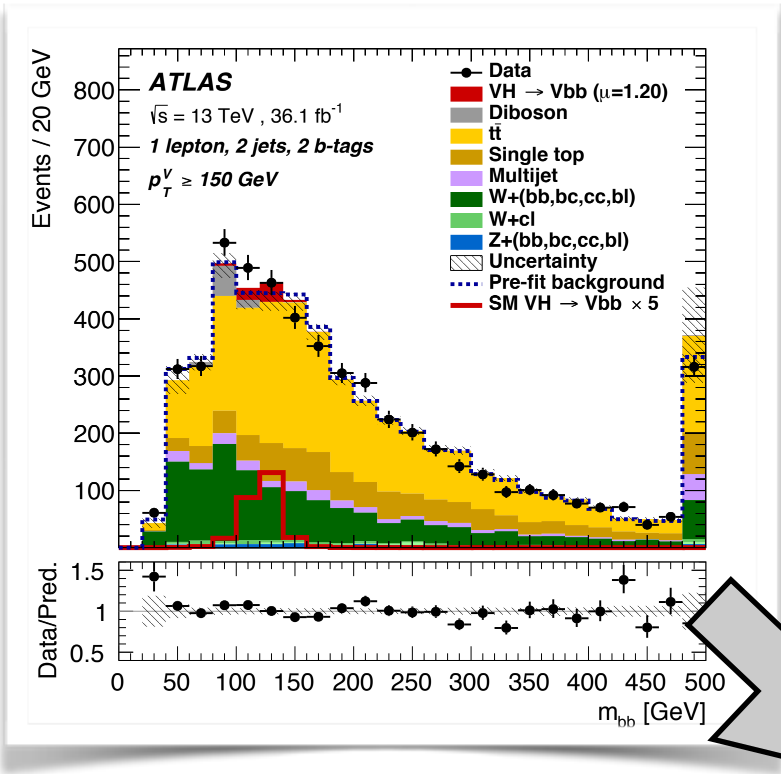


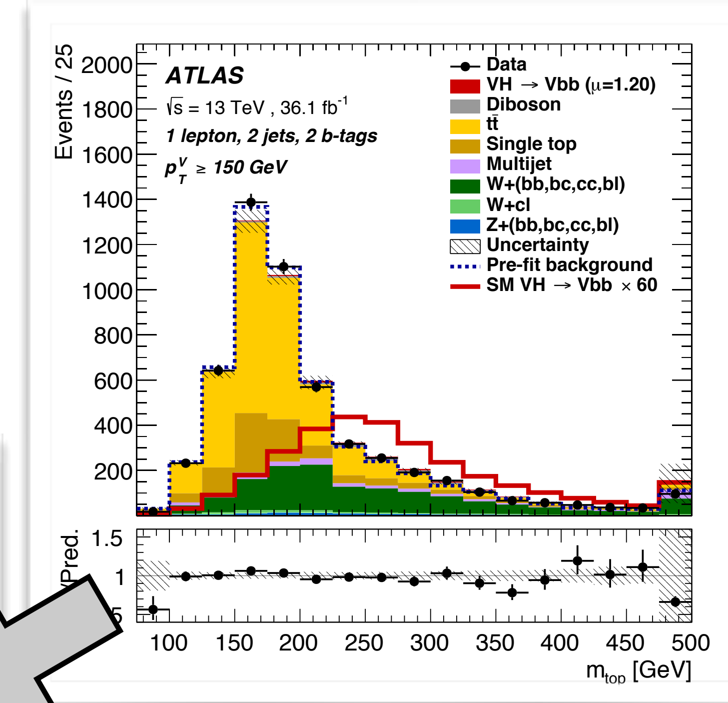


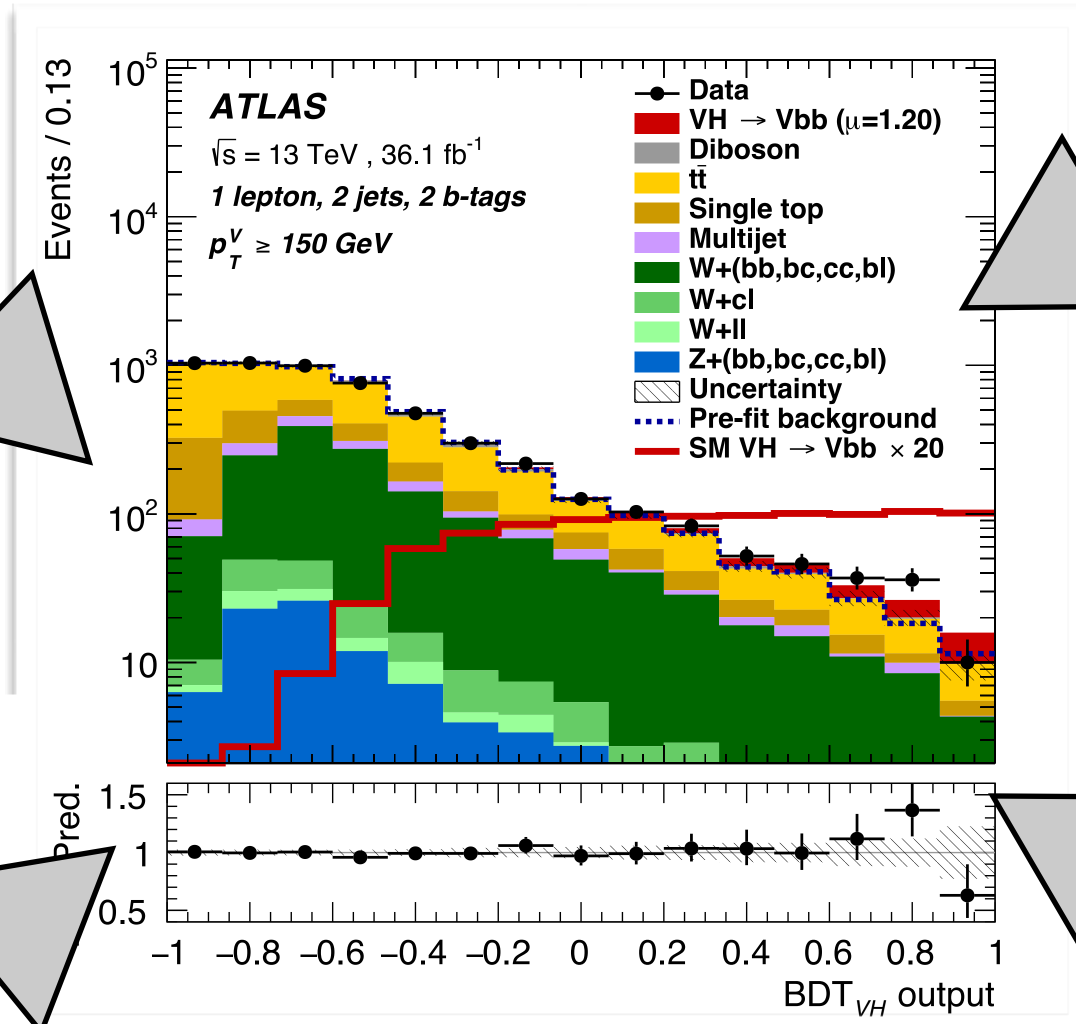
BDT construction

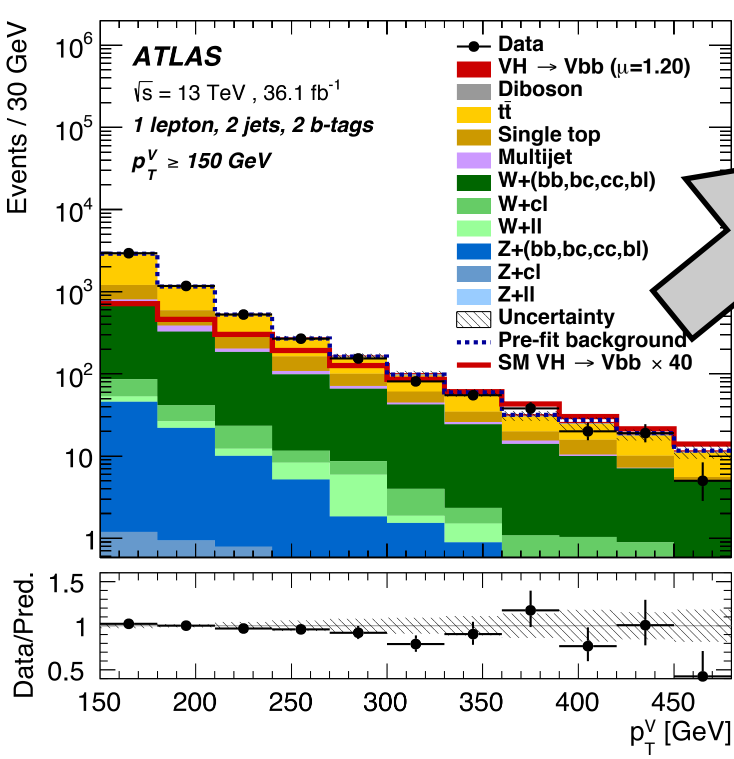
HIGG-2016-29

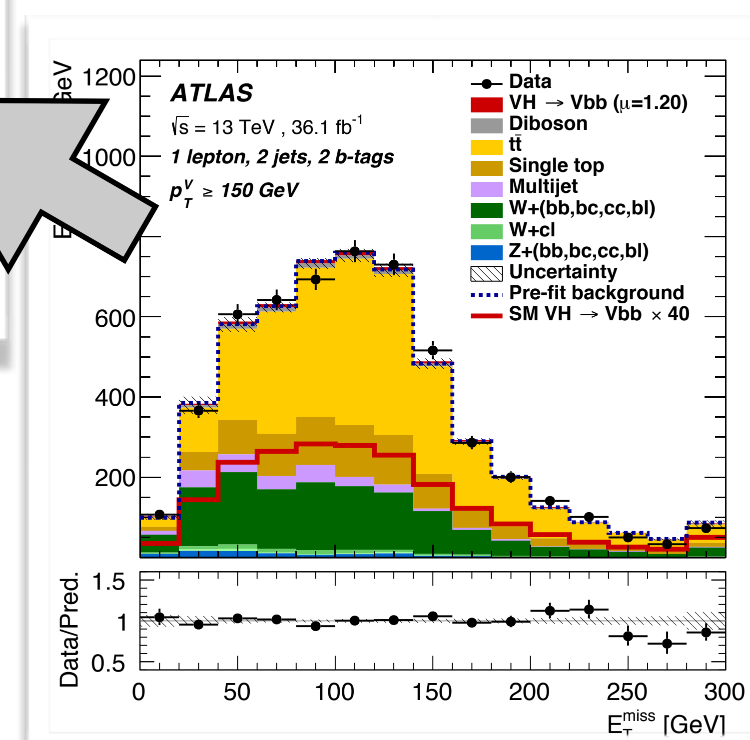
(previous analysis version)









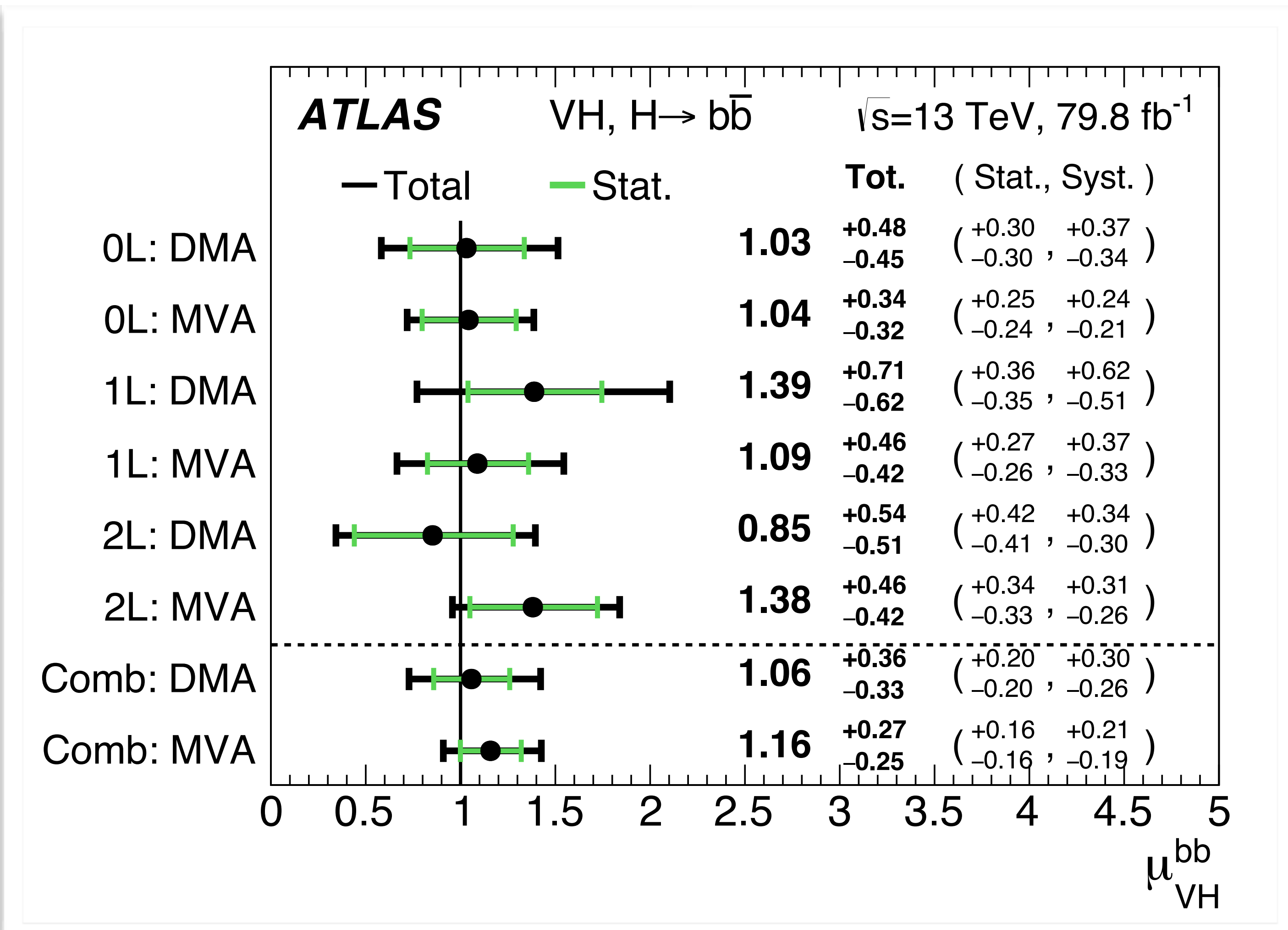


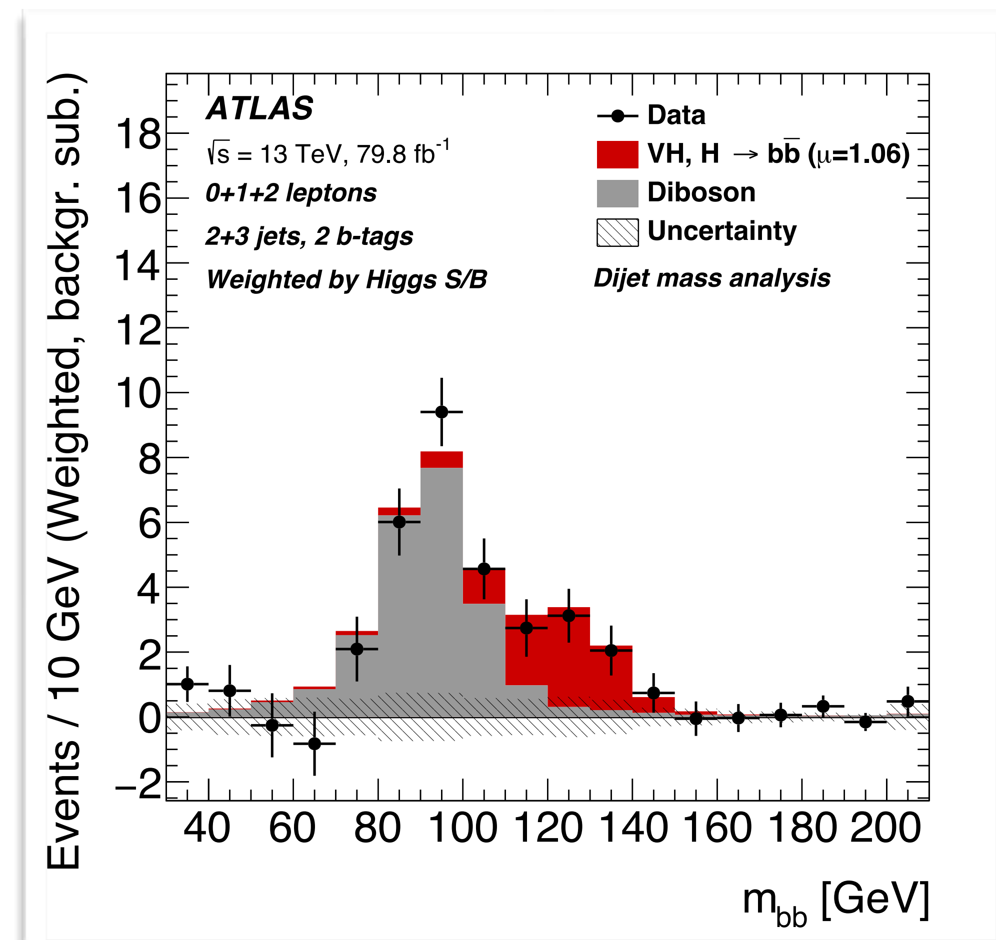
Cut-based vs MVA

HIGG-2018-04

DMA = dijet-mass analysis
3.6σ observed
3.5σ expected

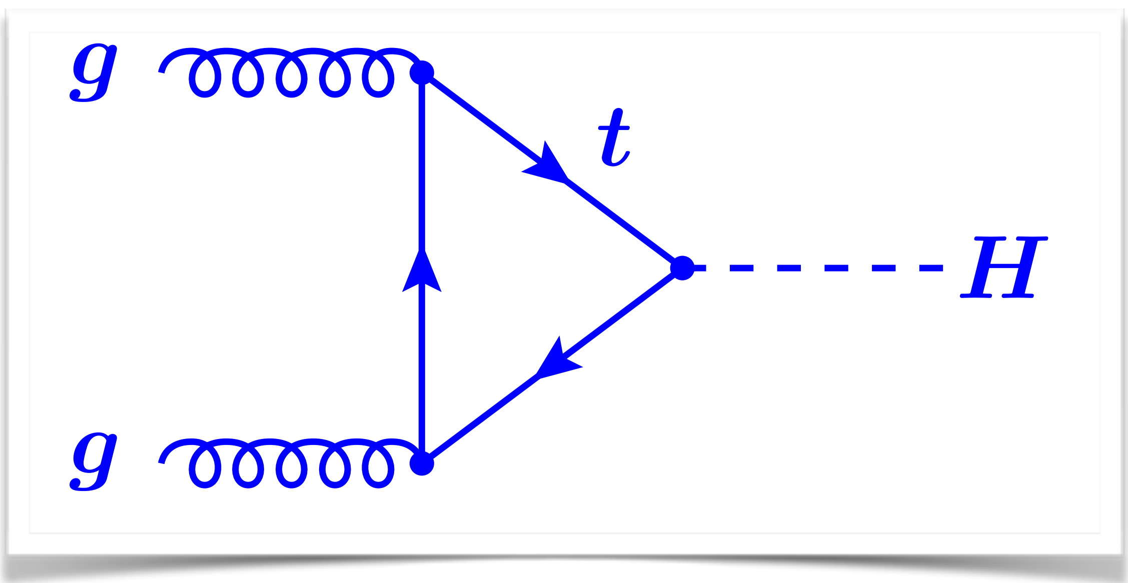
MVA = multivariate analysis
4.9σ observed
4.3σ expected

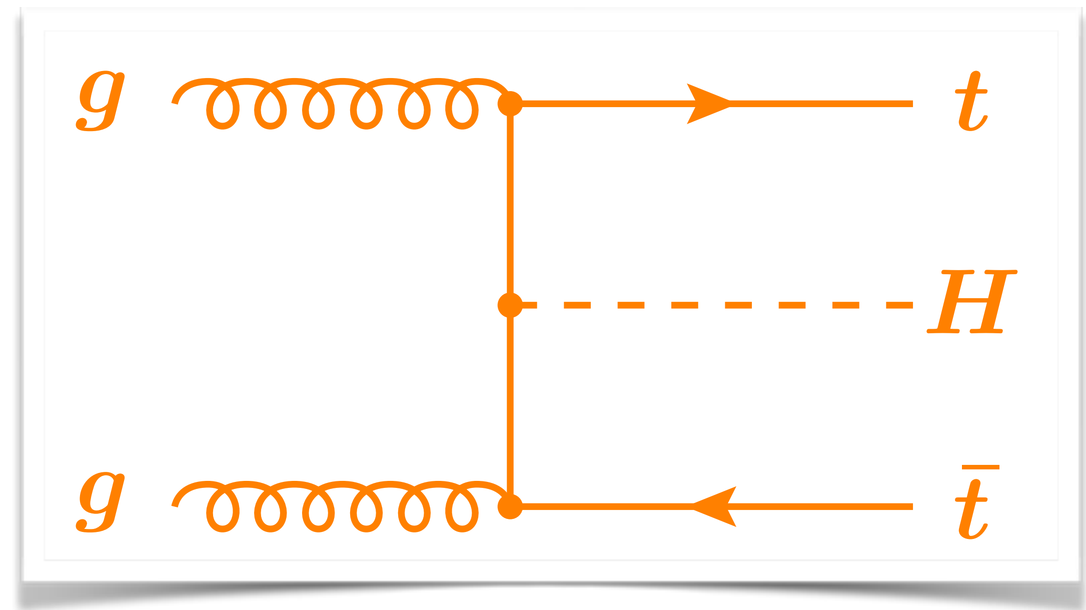




ttH: Directly probe the coupling of the Higgs to top quarks

ggF was the production mode used for the Higgs discovery



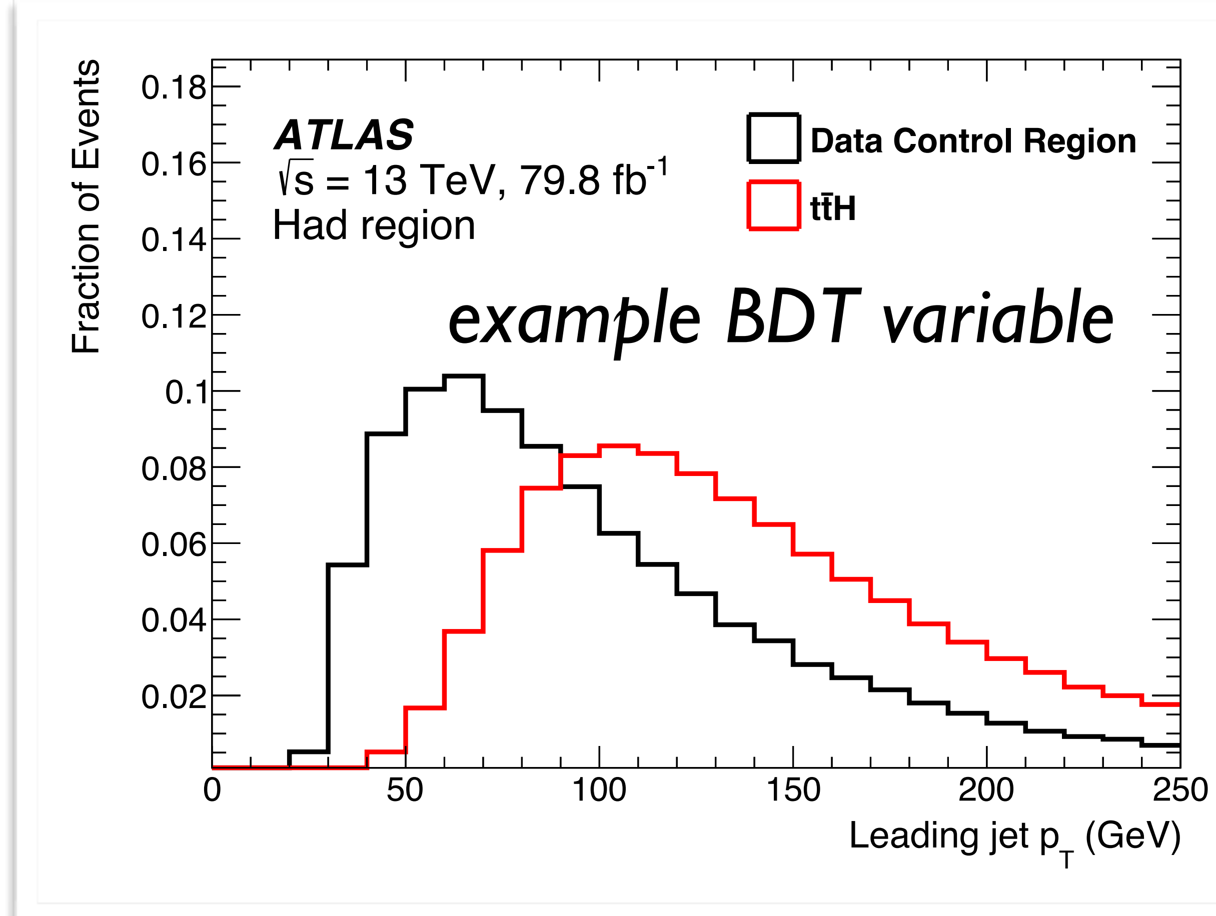


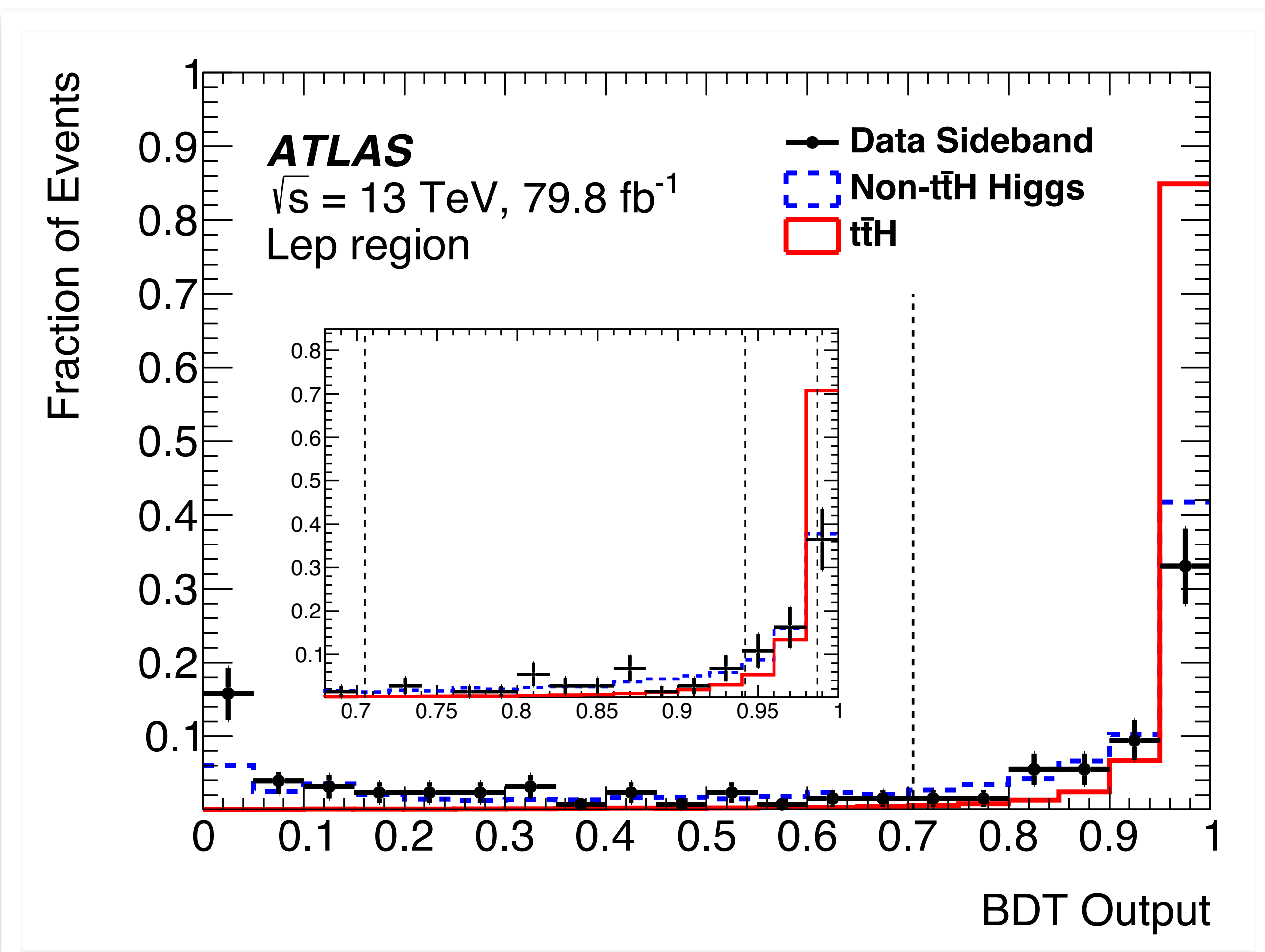
But … we can’t see inside the loops
Could contain some new particle other than the top quark
With ttH production, we can observe the top quark directly

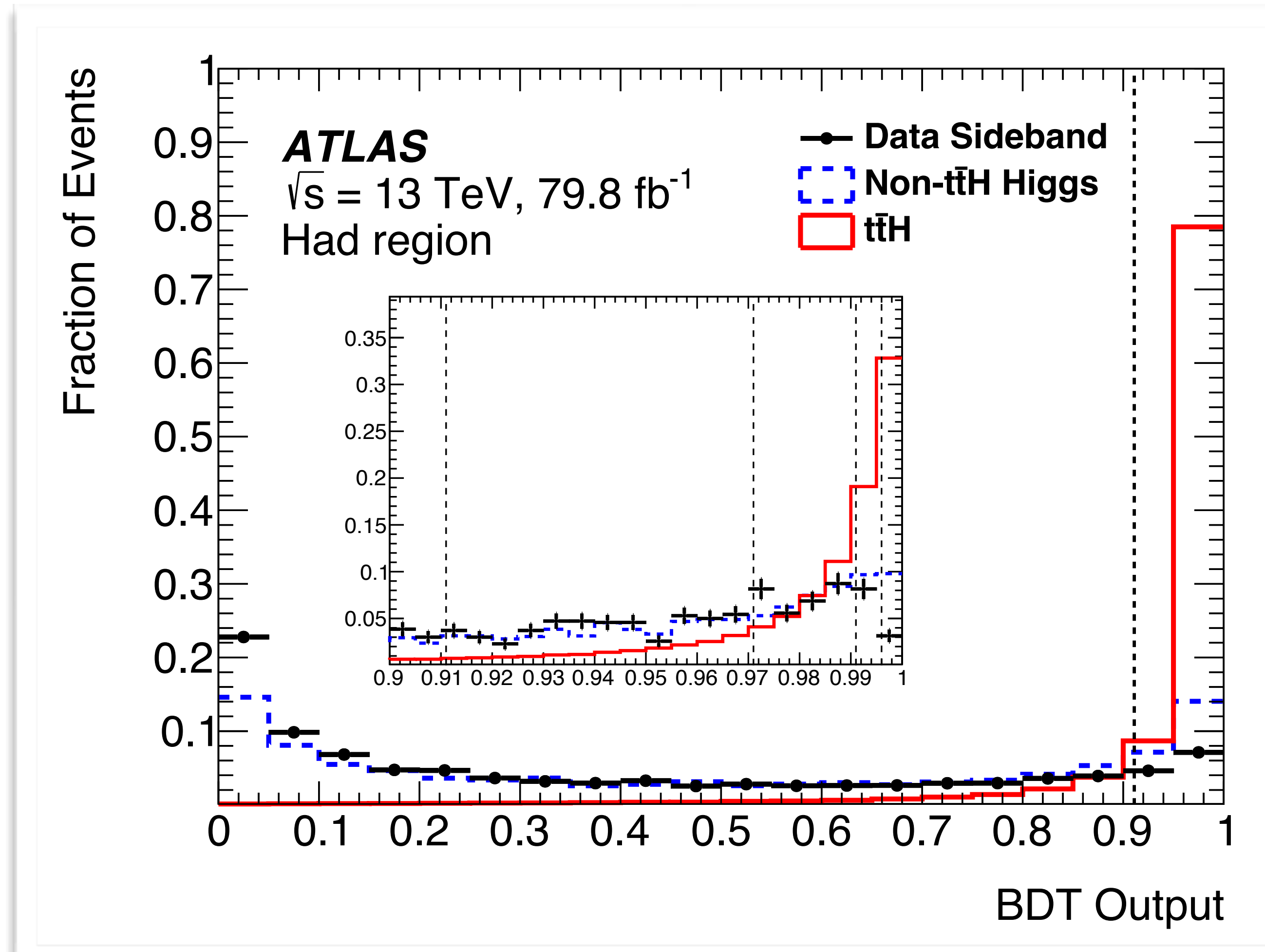
Briefly mention two channels: Higgs to diphoton and Higgs to leptons

Channel Definition

- BDTs are trained using ttH signal and background from data control regions
- Mostly kinematic variables for jets and photons (p_T, η, φ) also b-tagging, MET
- Define 7 categories over two channels

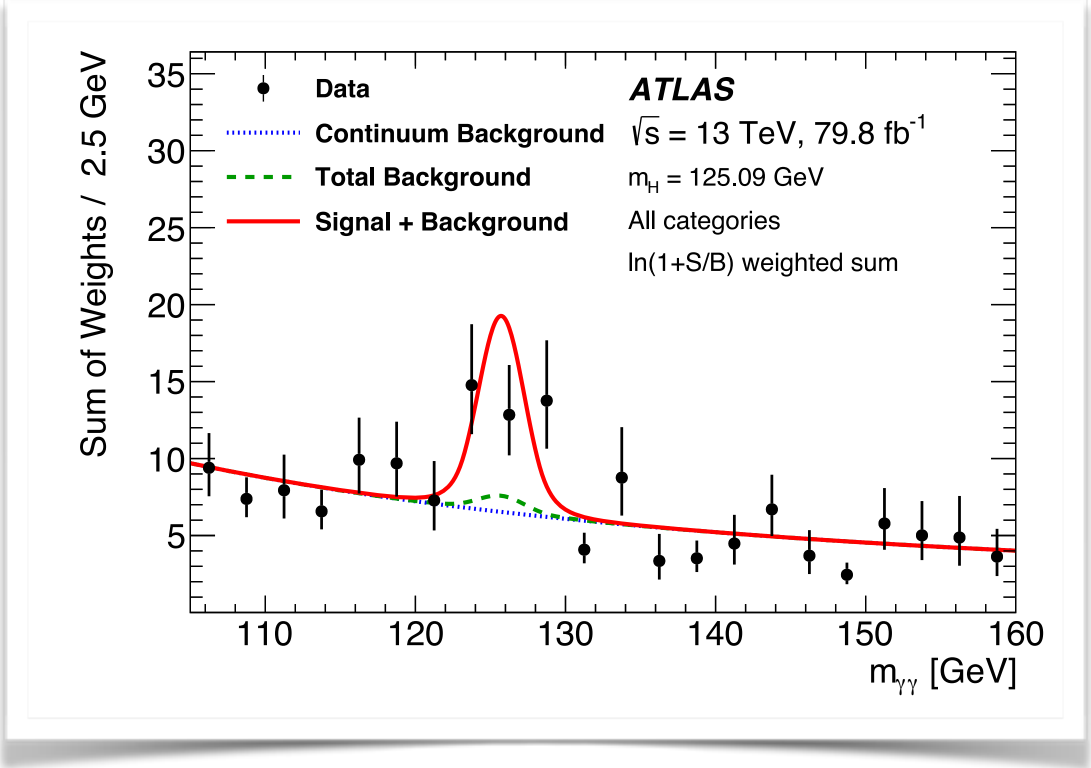






Results

- Peak in diphoton mass distribution at 125 GeV
- A fit over the seven categories yields 36±12 ttH(γγ) events
- 50% sensitivity improvement compared to the previous ATLAS publication with the same luminosity (largely due to BDT)



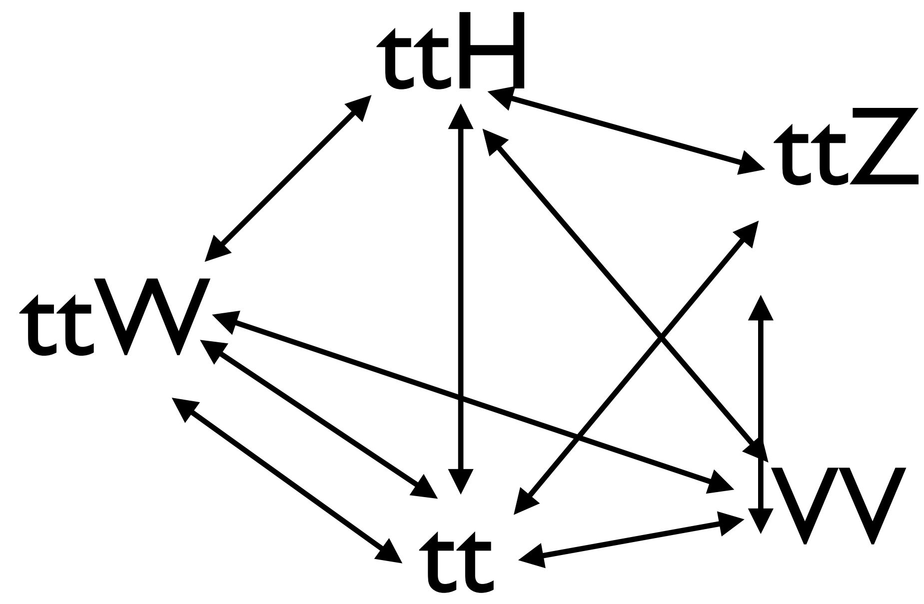
Significance

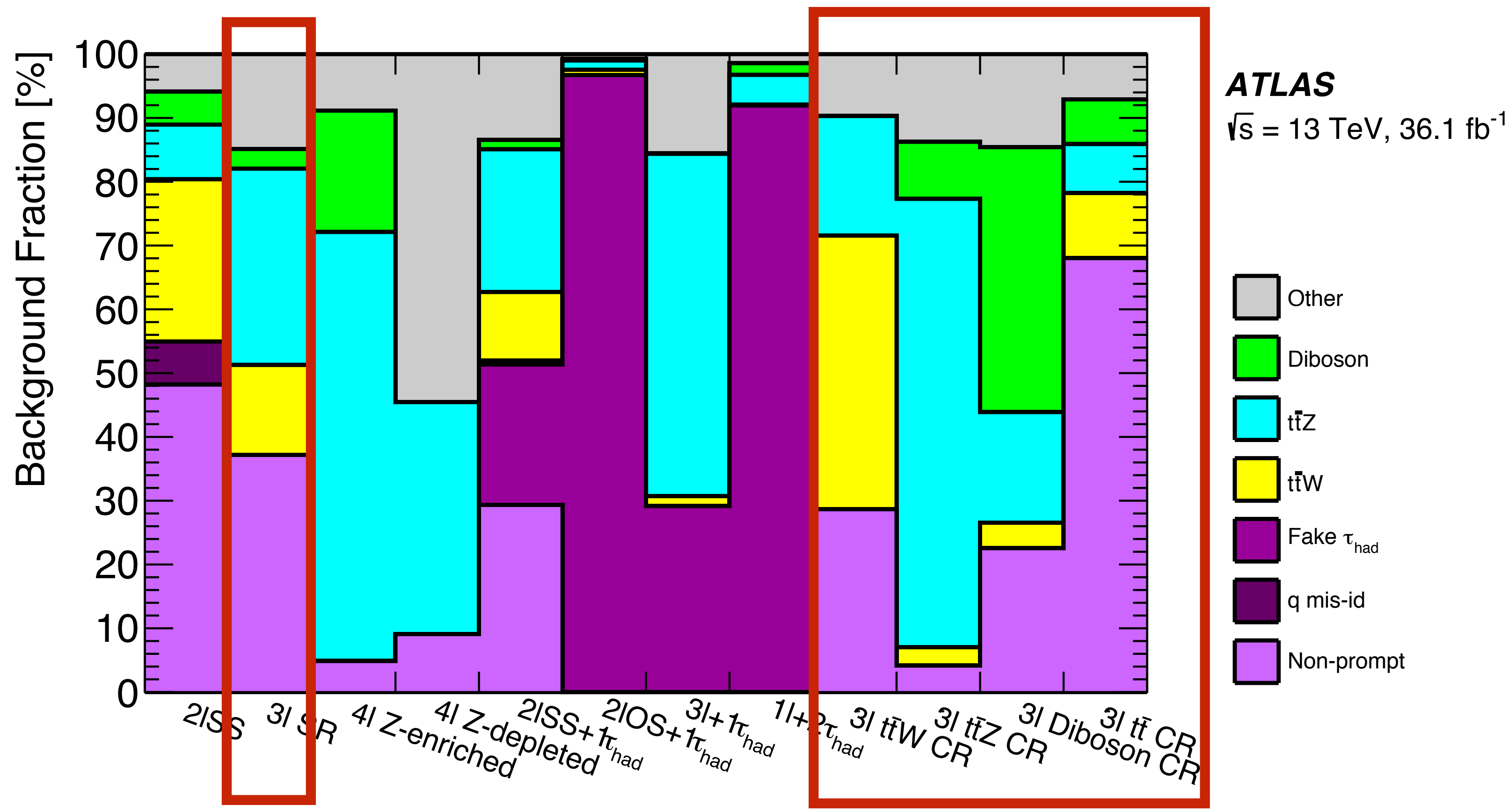
	Observed	Expected
Had	3.8σ	2.7σ
Lep	1.9σ	2.5σ
Comb	4.1σ	3.7σ

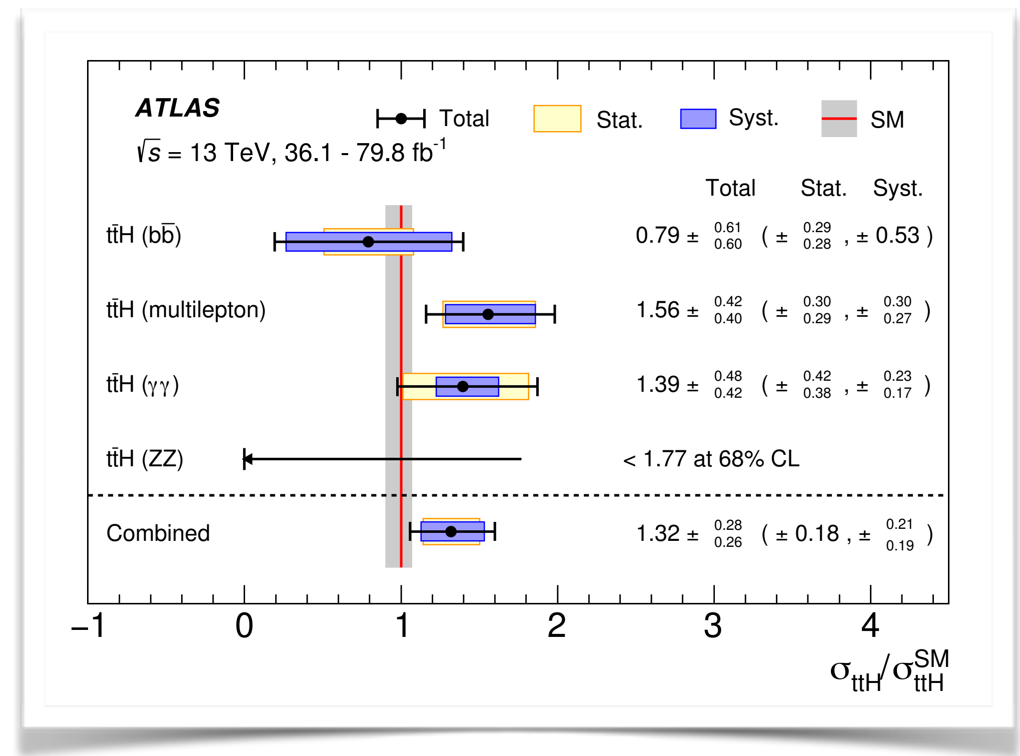
Multinomial BDT for Top-Higgs Interaction

Train 5D BDT in the 3l channel

Extract signal and define control regions simultaneously







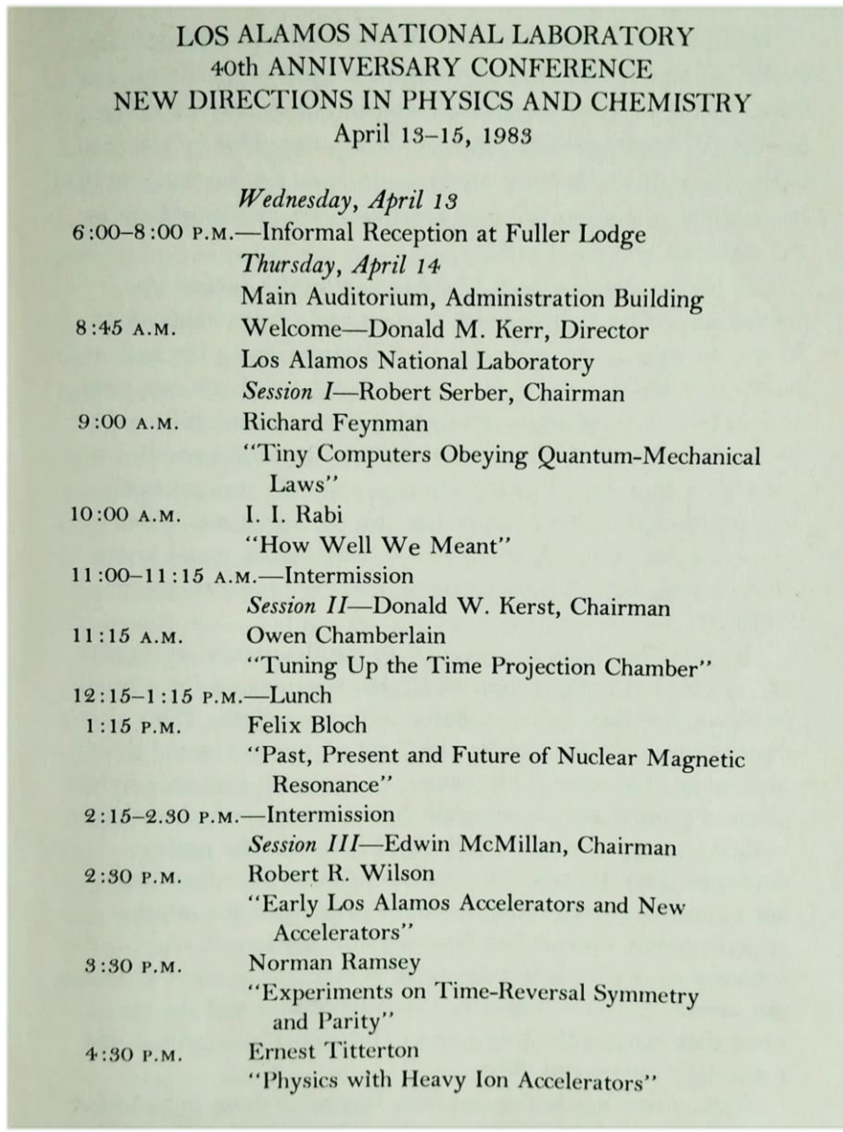
Observed significance:6.3σ

Expected significance: 5.1σ

Direct observation of the coupling of the Higgs to top quarks

Quantum computing is not a new idea

"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

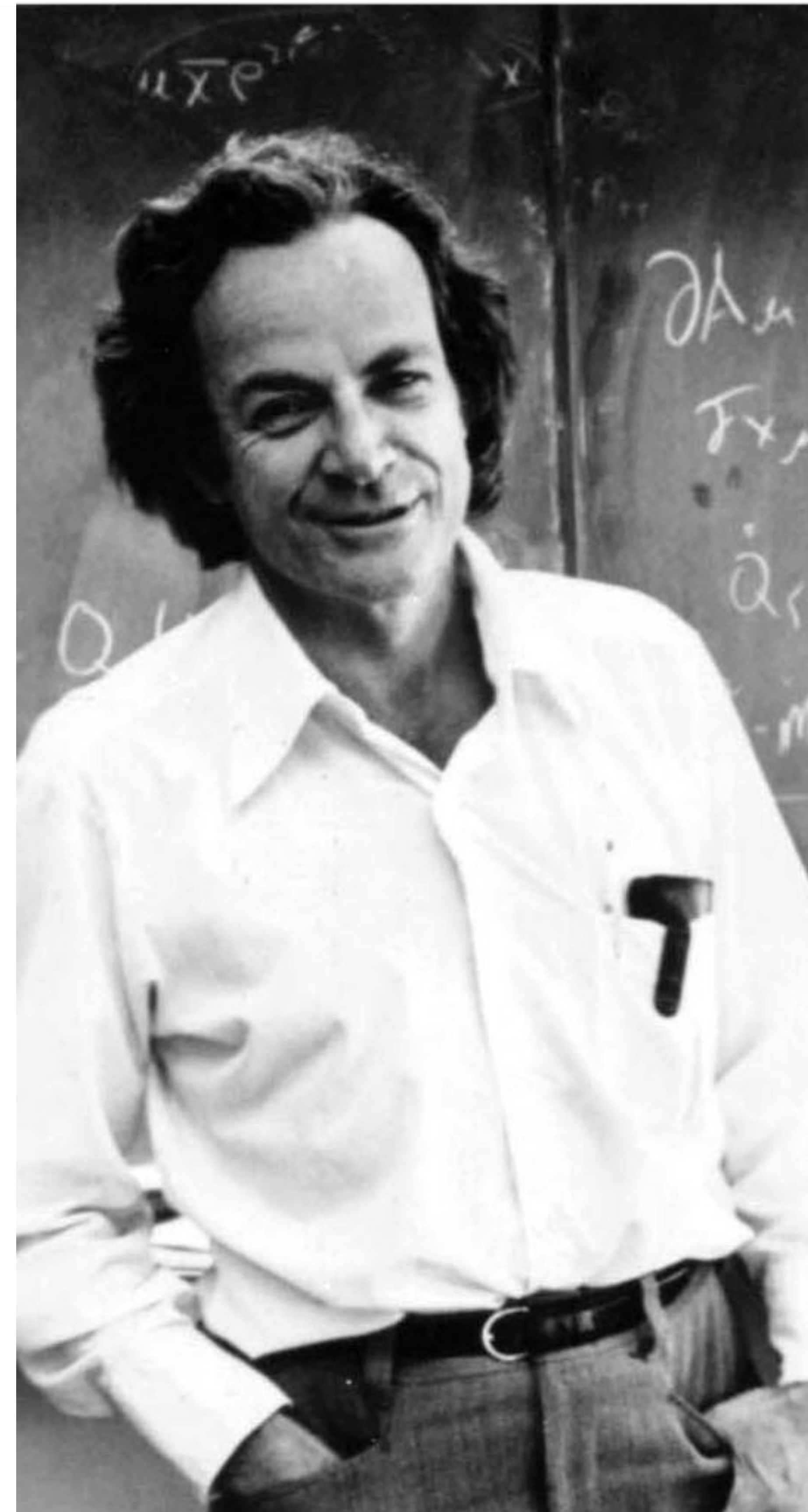
6:00–8:00 P.M.—Informal Reception at Fuller Lodge

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"

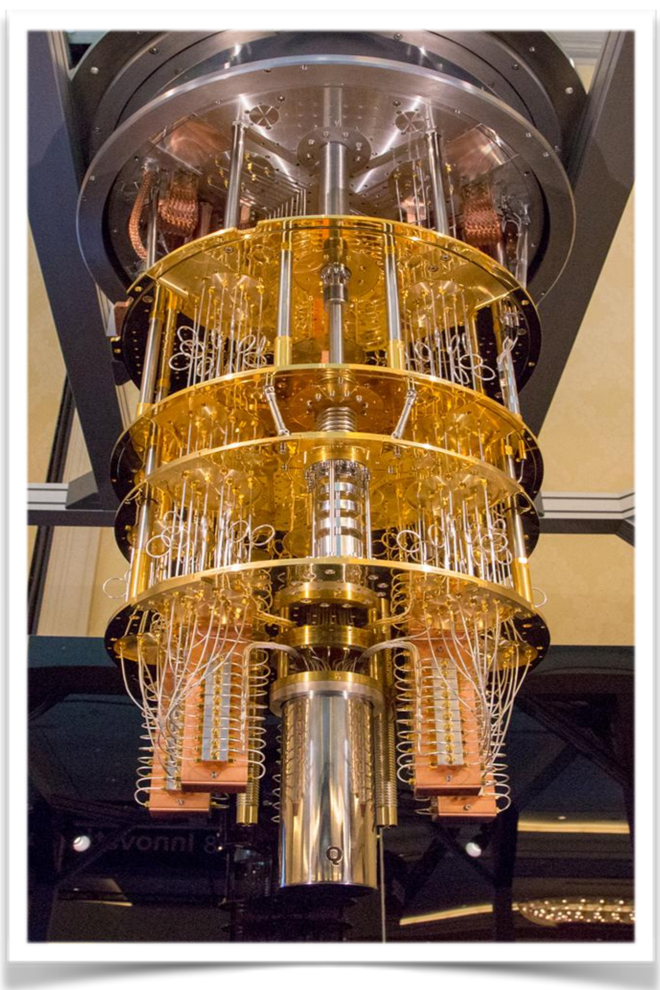
RICHARD FEYNMAN (1982)



Rise of Quantum Computing

- Considerable progress in recent years: rapidly rising number of qubits
- Current state of the art quantum computers fall into two main categories
  - Quantum annealers, e.g. D-Wave (2000 qubits)
  - Universal quantum computers, e.g. IBM Q (20 quits)
- All quantum computers are not equal: challenges include connectivity and noise (error handling)

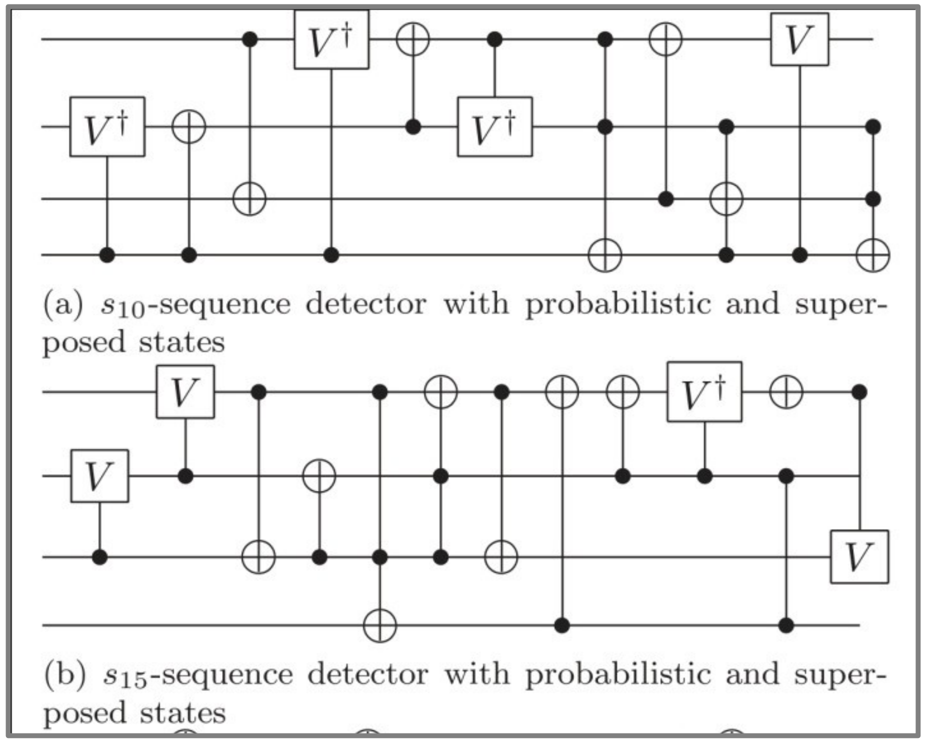
IBM 20Q Tokyo chip

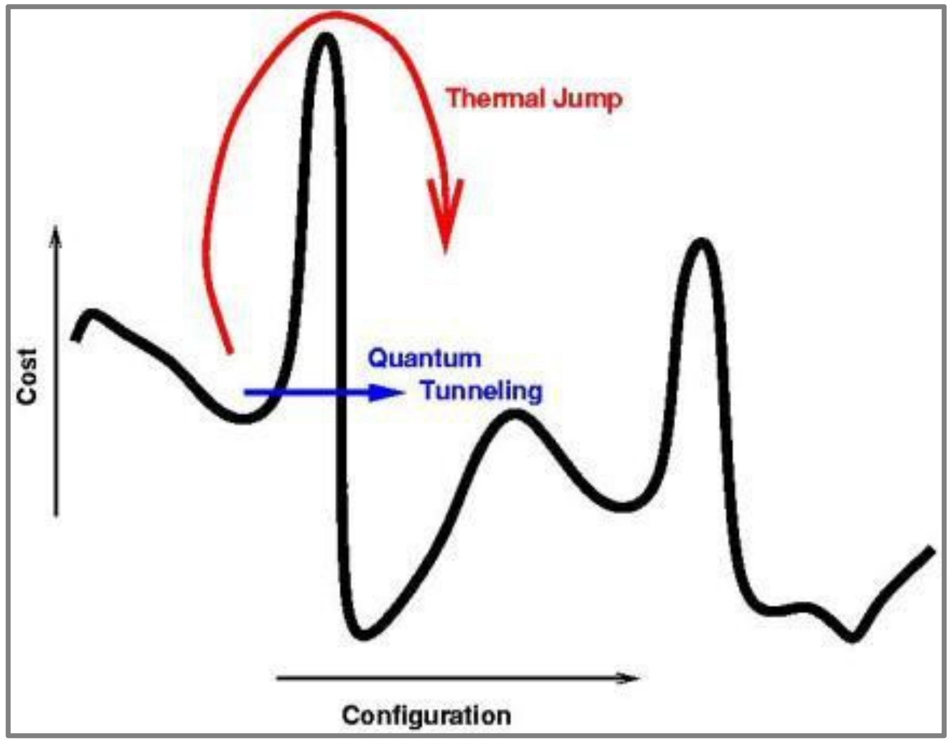


D Wave

arXiv:1801.00862.pdf

Qubits and qubits



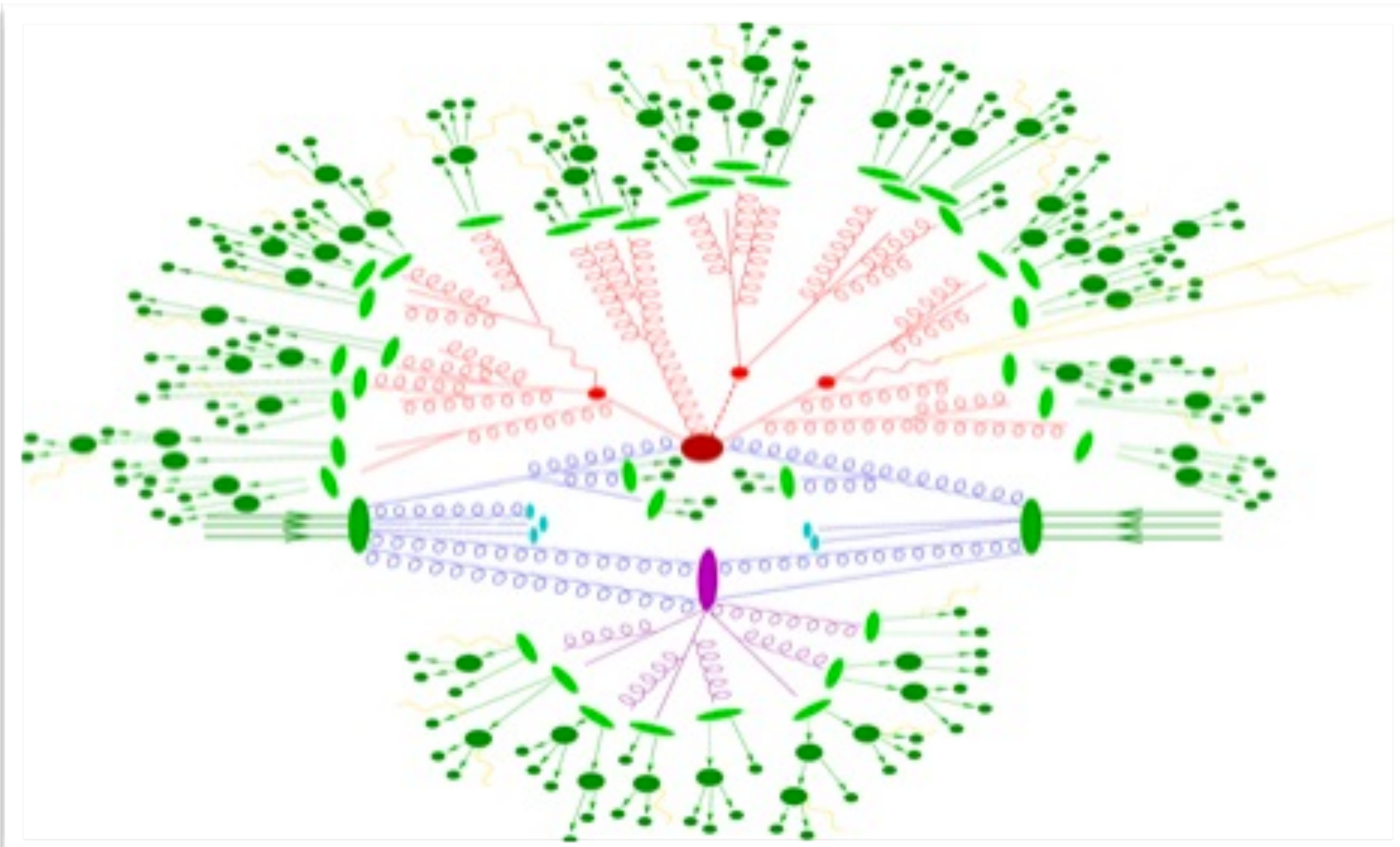


<u>Quantum Circuits</u>
Series of quantum gates operating on a set of quantum states.

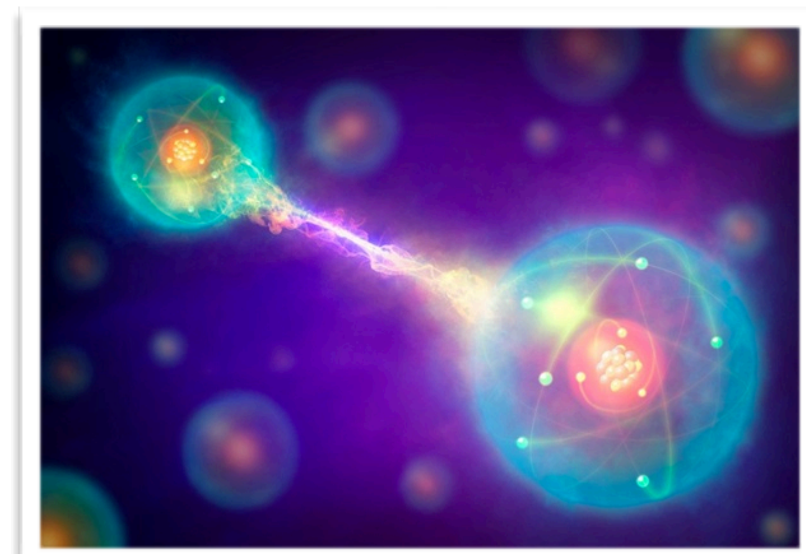
<u>Quantum Annealing</u>
Evolution of a quantum system to a low T Gibbs state
That's D-Wave !

Slide courtesy of J.R. Vlimant

Event generation with quantum computers



Current MC generators neglect the correlations between particles in the parton shower

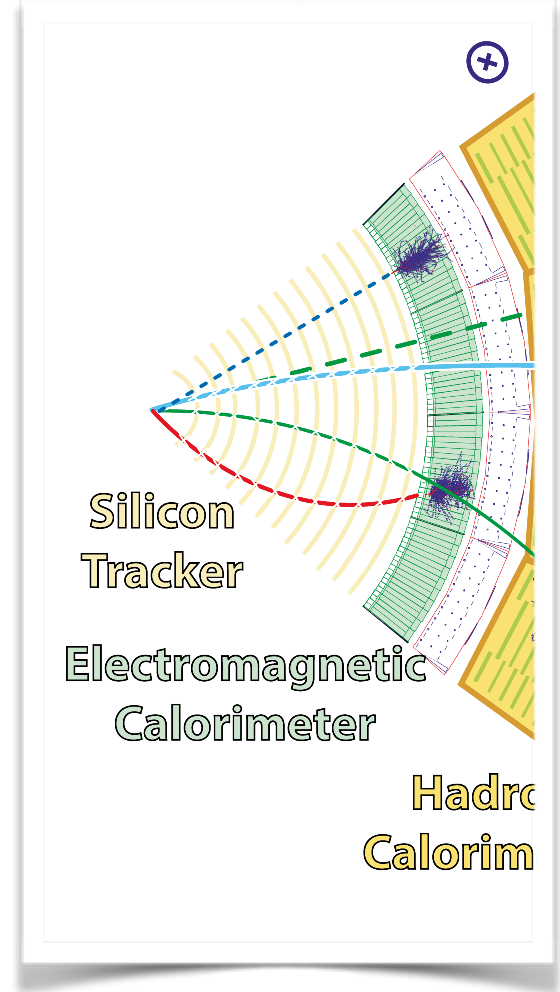


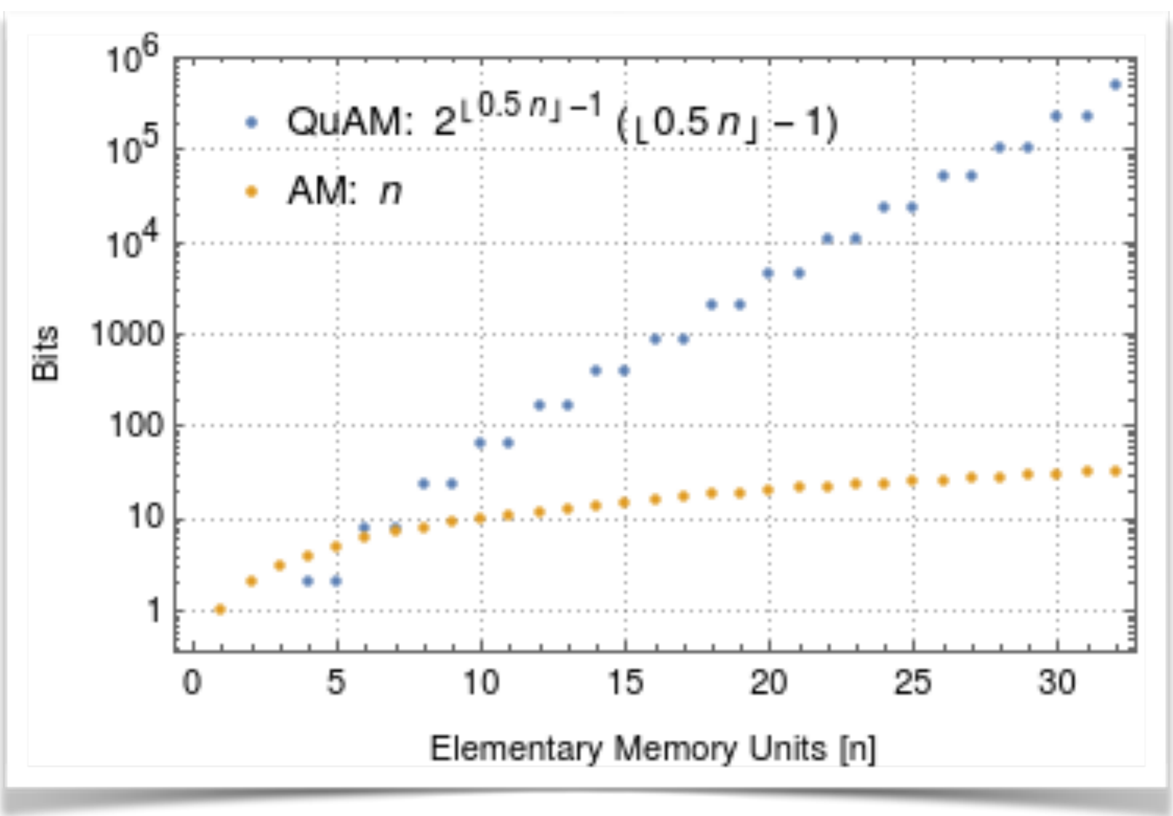
- Particles are quantum mechanical objects
- Correlations exist between them
- Idea: exploit entanglement between qubits on a quantum computer to improve the description of the parton shower

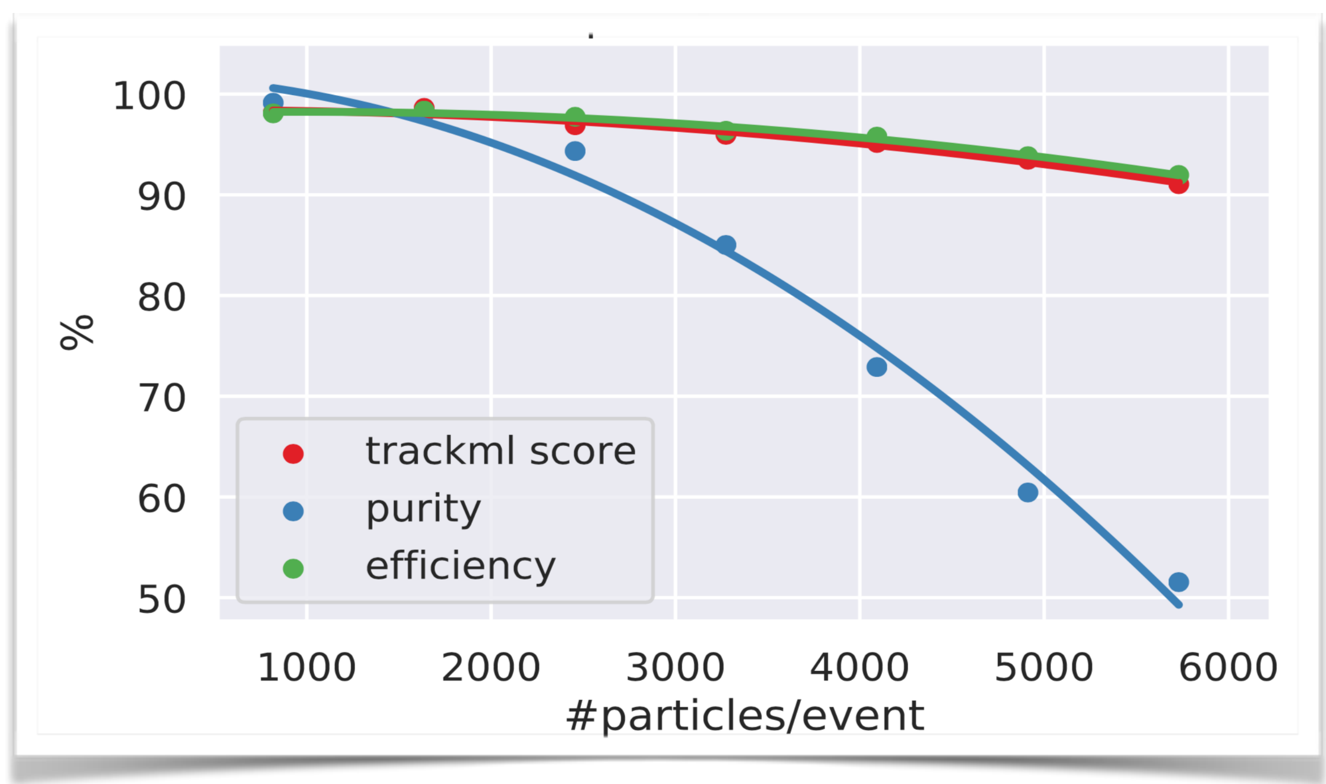
arXiv:1901.08148

Track Reconstruction

- How could quantum computers be used for track reconstruction?
- Associative memory: potential for exponential storage
- Quantum annealing: algorithmic execution time independent of particle multiplicity







Conclusion

- Brief introduction to the central role of computing in high-energy physics
- Overview of some recent developments in computing
  - Challenge and opportunities for high-energy physics
- Illustrated this with a few selected examples
  - Parallelisation for track reconstruction
  - Machine learning in Higgs analyses
  - Quantum computing for event generation and tracking
- But most of all I hope I stimulated your thinking … the world of computing is changing rapidly and there are probably many other ways we can benefit
  - New ideas are needed!

Back up