Evolving Research Software towards Next-Generation High-Energy Physics Experiments

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Princeton University

17 Jan 2025 - Univ. of Hyderabad

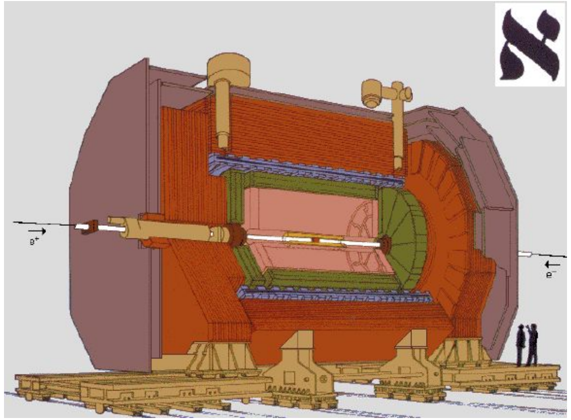
Institute for Research & Innovation in Software for High Energy Physics

Introductions…. Who am I?

I am an experimental particle physicist (Princeton Physics since 2001, but based in Geneva, Switzerland) focused on computational and data science problems in my field, along with the software/computing systems to solve them.

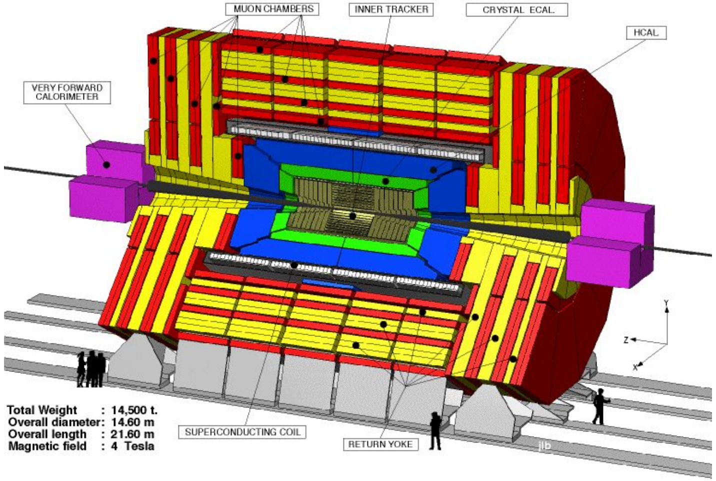
Researchers in experimental particle physics tend to introduce themselves to each other with reference to the series of experiments with which they have collaborated. So here is my own version of that:

Aleph@CERN



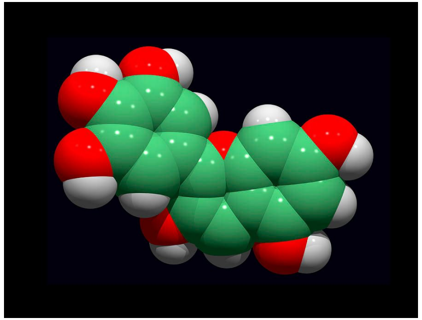
BaBar@SLAC

CMS@CERN



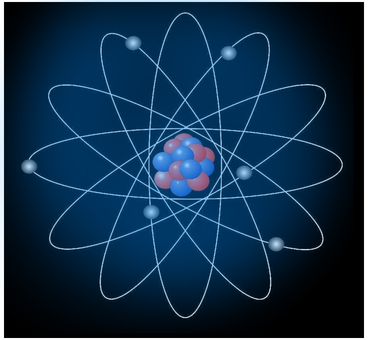
Exploring the nature of matter

Molecule
10^{-9} m = 0.000 000 001 m



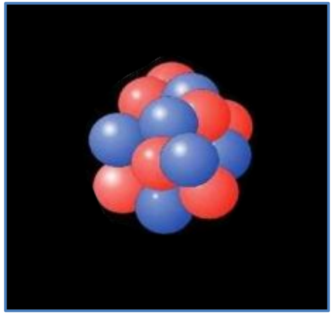
Delphinidin Molecule
(blue pigment of flowers and grapes)

Atoms
10^{-10} m = 0.000 000 000 1 m



Composed of:
Nucleus and electrons

Nucleus
10^{-14} m = 0.000 000 000 000 01 m

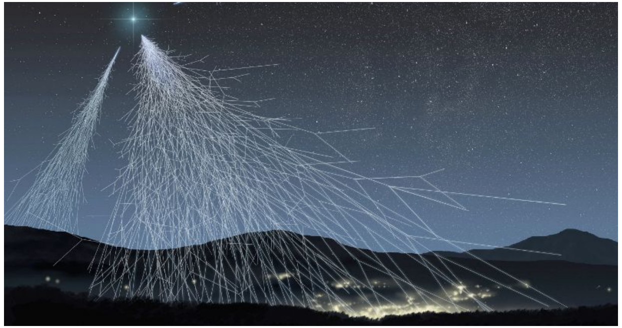


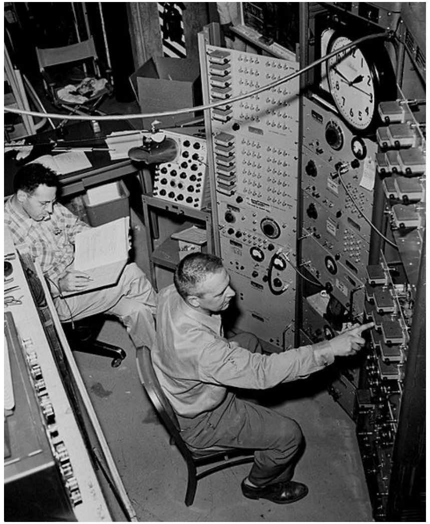
Composed of:
Protons and
neutrons

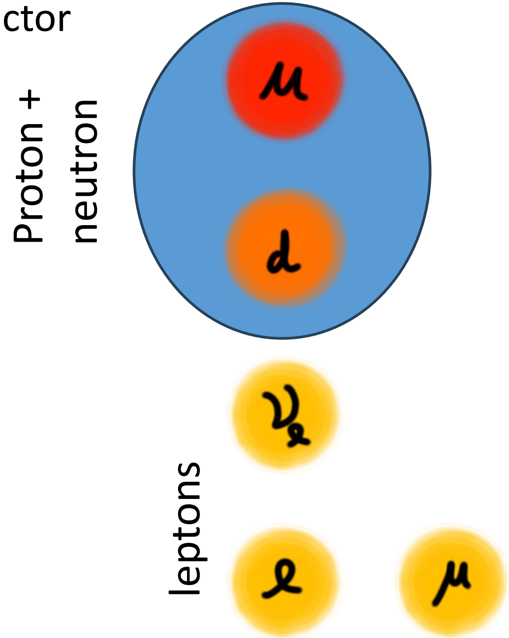
The modern era of particle physics began with the discoveries of radioactivity by Henri Becquerel in 1896, the electron by J.J. Thomson in 1897 and the atomic nucleus by Ernest Rutherford, Hans Geiger and Ernest Marsden in 1911.

Fundamental Particles of Matter

1937: Discovery of the muon (Anderson and Neddermeyer)
    a copy of the electron but with 200 times the mass ($m_\mu = 200 \times m_e$)
    -and- the positron (Anderson) in cosmic rays
1947: Charged pion discovery and Kaon discovery, 1949: neutral pion discovery
1955: Discovery of the antiproton, at the Bevatron
1956: Discovery of the neutrino (Cowan, Reines, et al), using nuclear reactor
1960s: Quark Model and Deep Inelastic Scattering Experiments (SLAC)

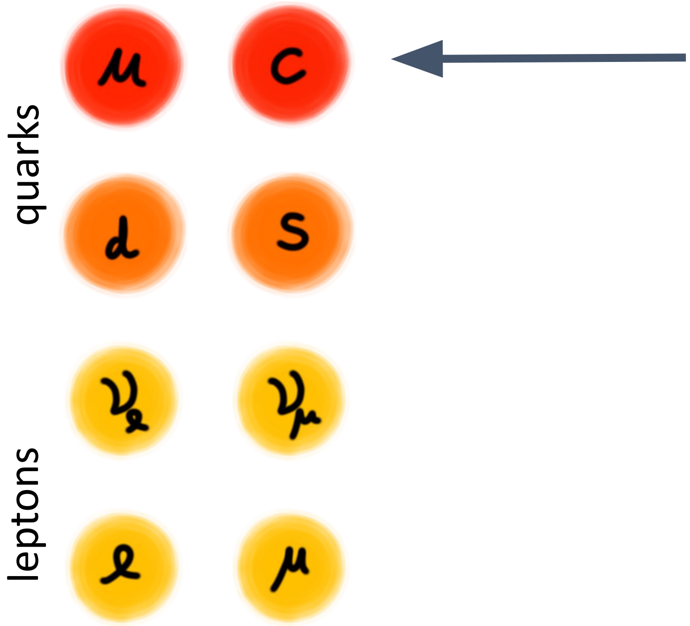






A first surprise - Muons "Who ordered that?"

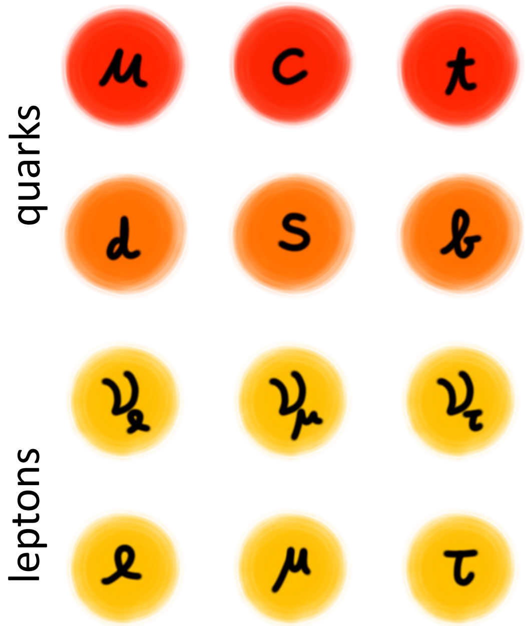
November "Charm" Revolution: Two families of fermions?



+ anti-particles
(i.e. copies of opposite charge)

Fast forward….

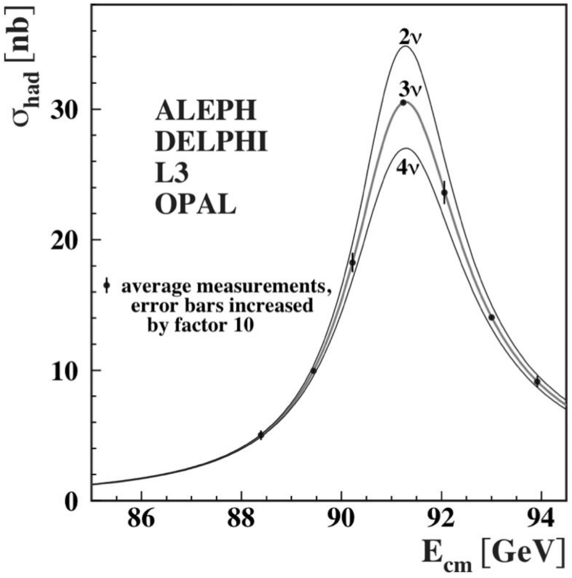
Three complete families of fermions



Electrical Charge	Spin
+2/3	1/2
-1/3	1/2
0	1/2
-1	1/2

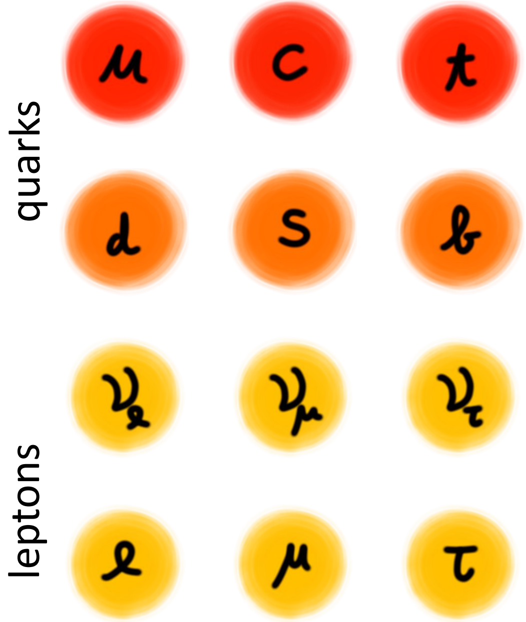
Intrinsic Angular Momentum

+ anti-particles
(i.e. copies of opposite charge)



Fundamental Particles of Matter

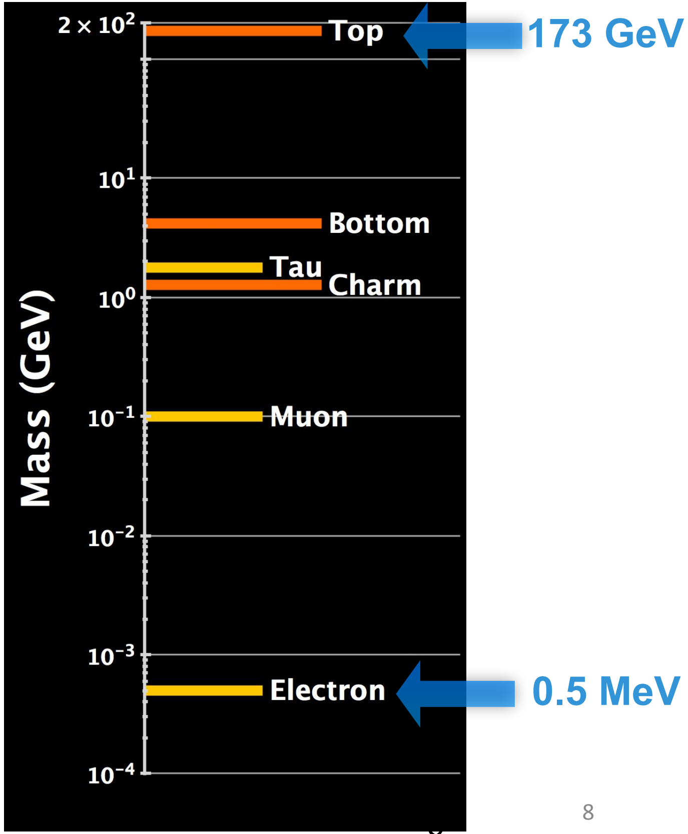
Three complete families of fermions



Electrical Charge	Spin
+2/3	1/2
-1/3	1/2
0	1/2
-1	1/2

Spin: Intrinsic Angular Momentum

+ anti-particles
(i.e. copies of opposite charge)



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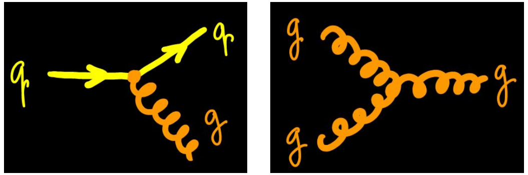
Interactions occur through exchange of bosons

0

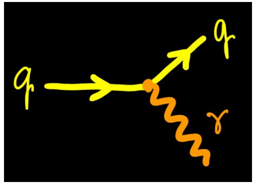
1



Strong force
(gluons)

0

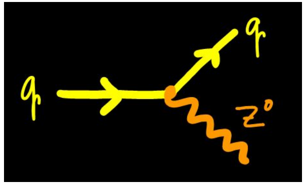
1



Electromagnetic force
(photon)

0

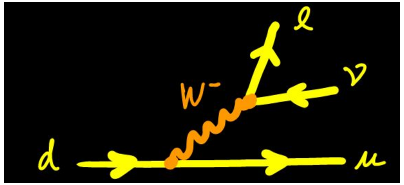
1



Weak force
(W and Z bosons)

+1 or -1

1



Charge

Spin

Beta decay:
$n \rightarrow p\, e^- \, \nu_e$

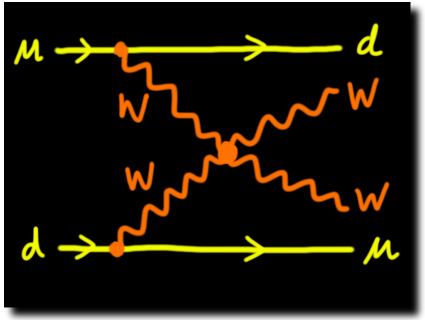
The weak nuclear force has a very small range ($10^{-18}\, m$) so its force carriers (W and Z boson) have to be massive

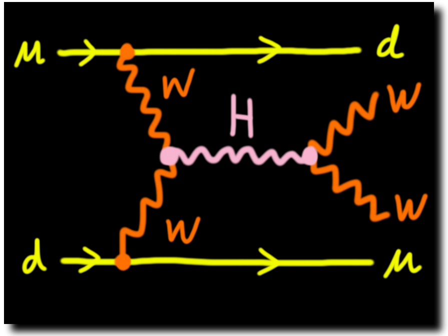
It is impossible to build a consistent theory for massive bosons like the W and Z without an additional particle.

The Higgs Boson

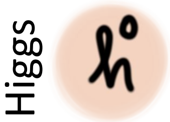
Solution proposed by several theorists in 1964

Higgs, Brout, Englert, Hagen, Guralnick and Kibble





A new fundamental particle with spin 0
(the only one in the Standard Model)
could make the theory consistent again!



	Electrical Charge	Spin
Higgs	0	0

The LHC experimental facility was built to test this theory

Higgs Particle Discovery Announcement July 4th, 2012

ICHEP, Melbourne

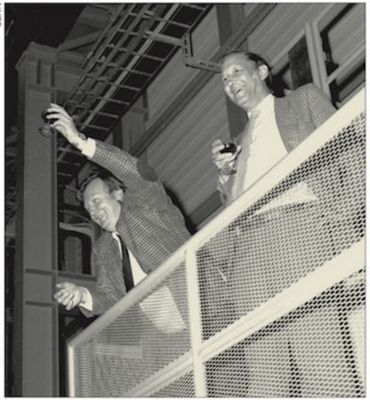
CERN, Geneva

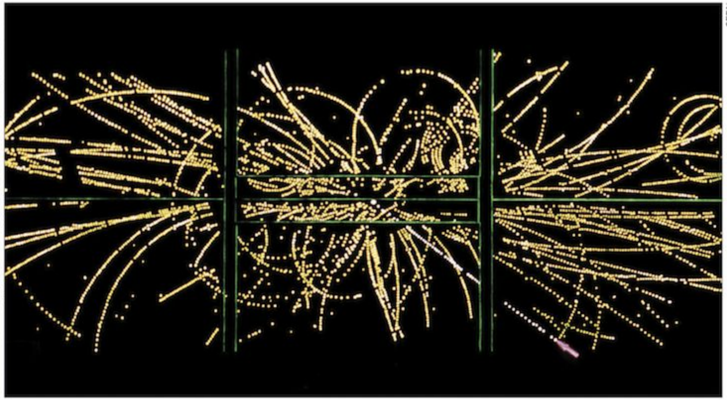
Something that looks like the Standard Model Higgs boson was discovered in 2012, Mass ~ 125 GeV

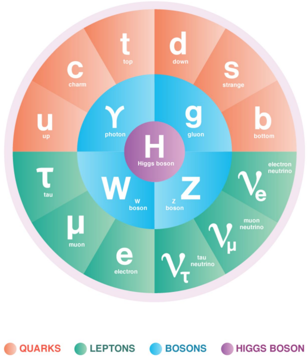
Nobel prize in physics in 2013

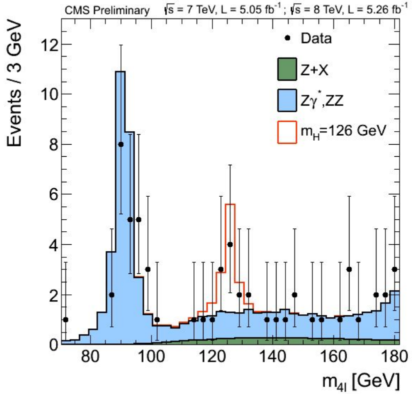
11

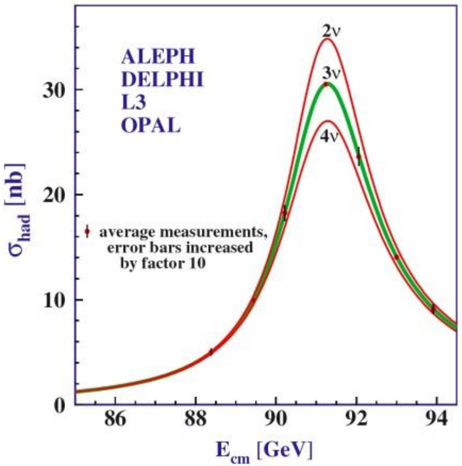
Experimental Development of the Standard Model

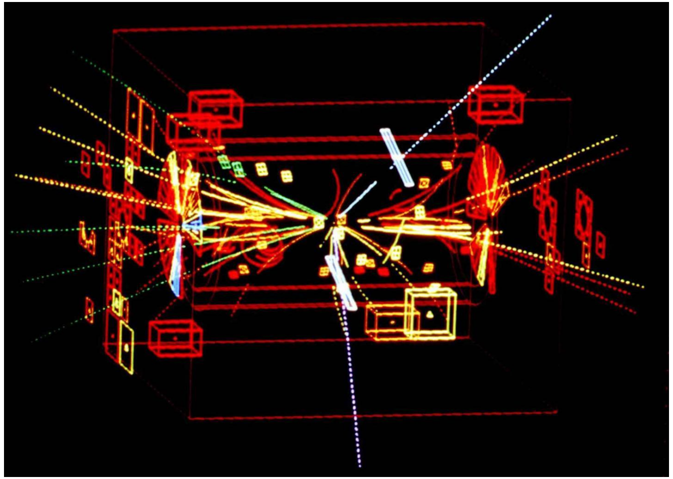


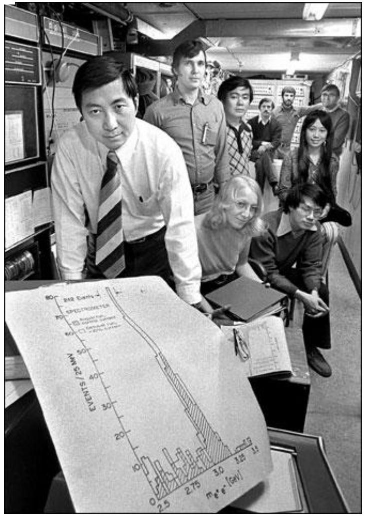






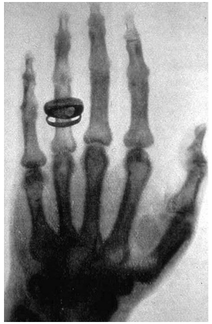


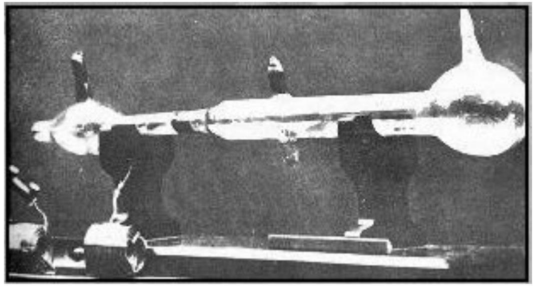




How did we get here?
(As experimentalists)

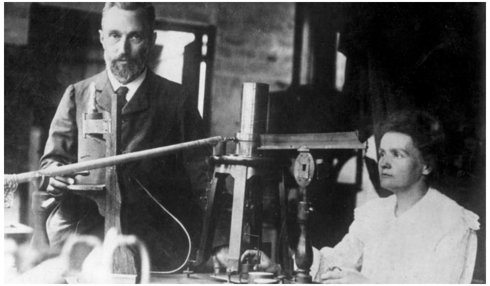
Tools ⟵⟶ Discoveries

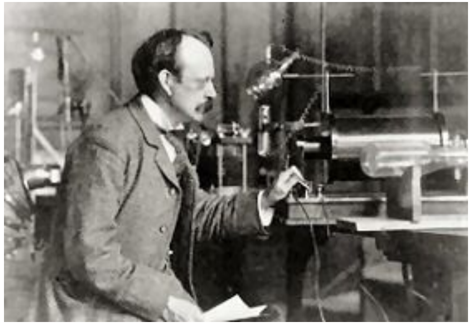




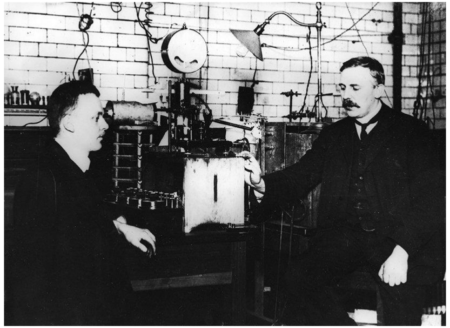
1895 - Roentgen discovers x-rays using cathode ray tubes

1896 - Bequerel accidentally discovers radioactivity in uranium, trying to explain x-rays





1898+ - Marie and Pierre Curie discover and explore radioactivity in other elements (polonium, thorium, radium)



1911 - Rutherford, Geiger, Marsden use radioactivity to explore atomic structure and discover the nucleus

Side note: Tools ⟵⟶ Discoveries

I, Pencil - Leonard Read

Connections

James Burke, the creator and host of *Connections*, explains the Haber-Bosch Process

Connections (BBC TV Series from 1979) explores this interchange over a wide range of technologies and discoveries. Perhaps a bit of a European/Western bias, but an interesting exploration of how ideas evolve. (Search in youtube, episodes are available there)

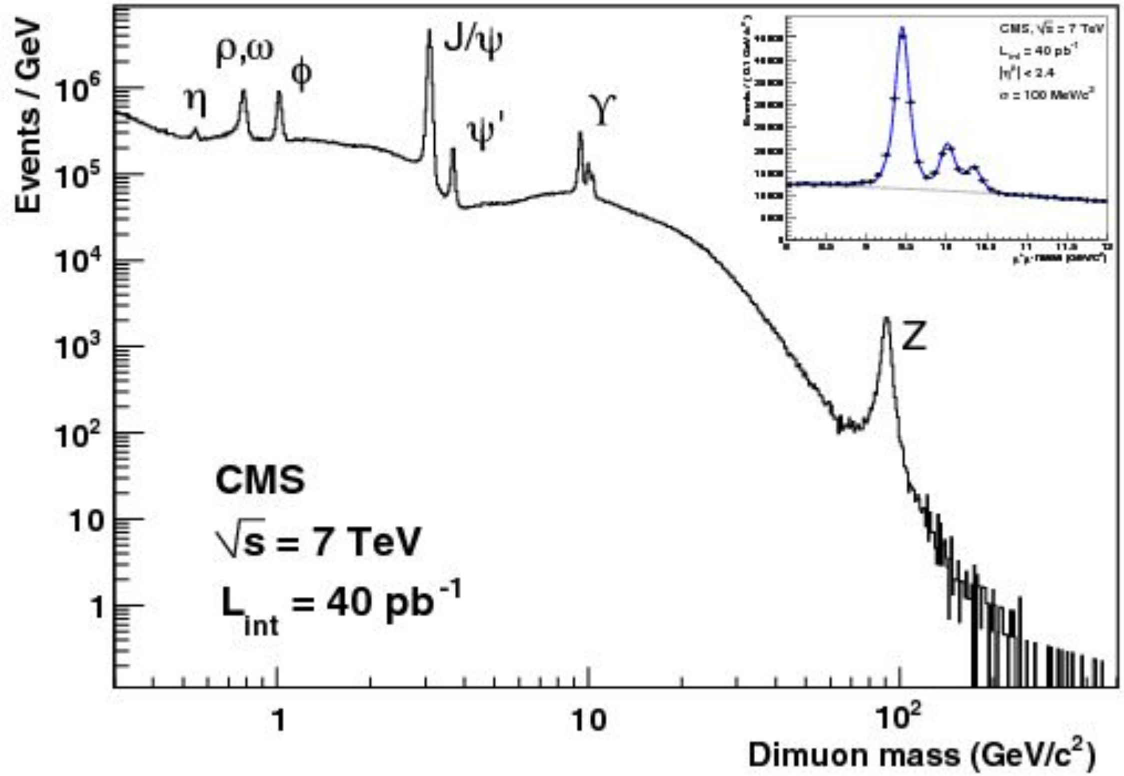
Even simple objects have a complicated technology history

Evolution in particle physics

Discovery of a particle leads to Nobel prize and full exploration of the properties of the particle.

On the subsequent experiments the particle is used for calibration or as a tool itself (e.g. in a beam).

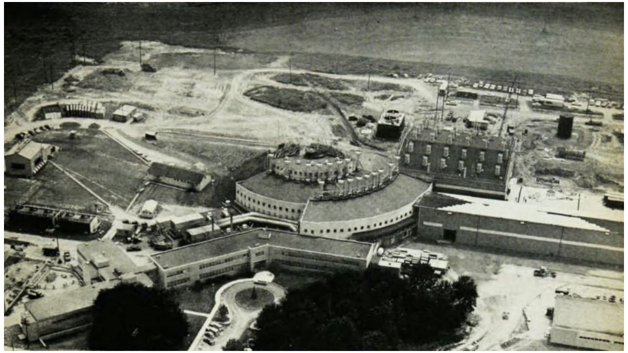
On later experiments the particle becomes a background.



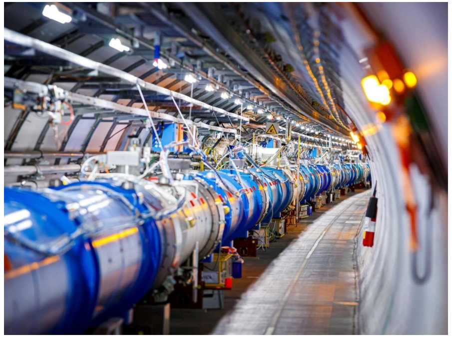
Big Science and Accelerators - larger and larger facilities

E.O. Lawrence and the cyclotron
at U.C. Berkeley

The birth of the “National Accelerator
Laboratory” in the US (now Fermilab)



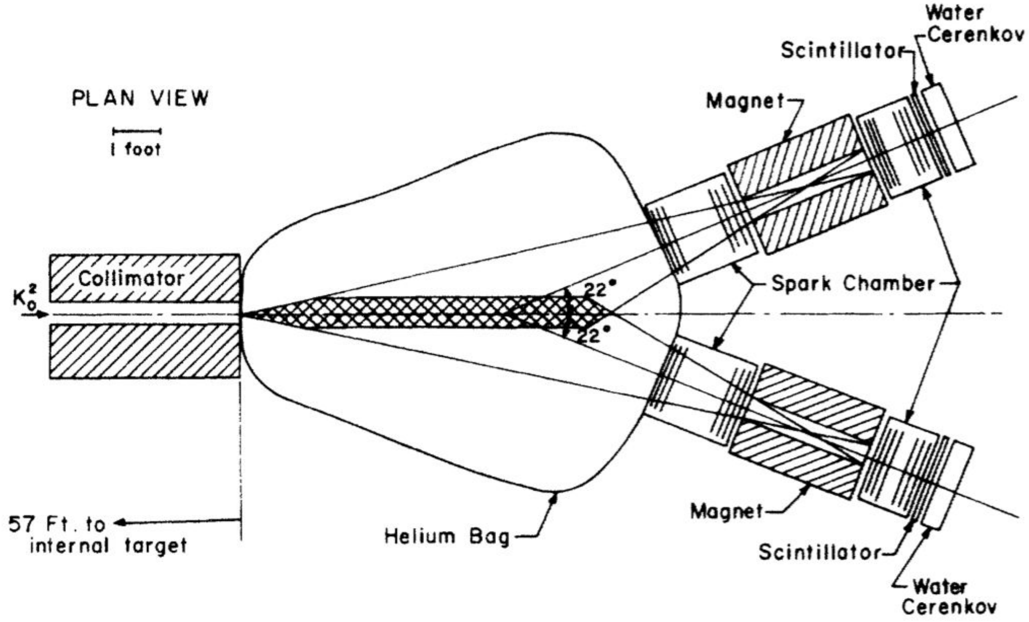
The Princeton-Pennsylvania Accelerator,
Milton White 1964 Physics Today 17(8): 27



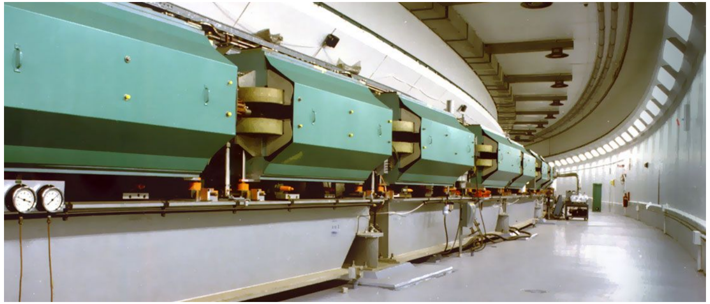
The Large Hadron Collider and
CERN first as a European laboratory
and then as a “world laboratory”

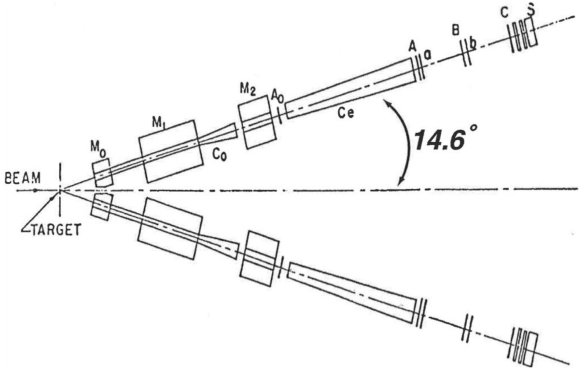
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

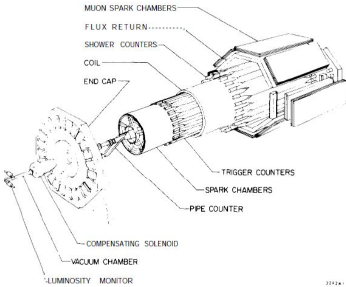


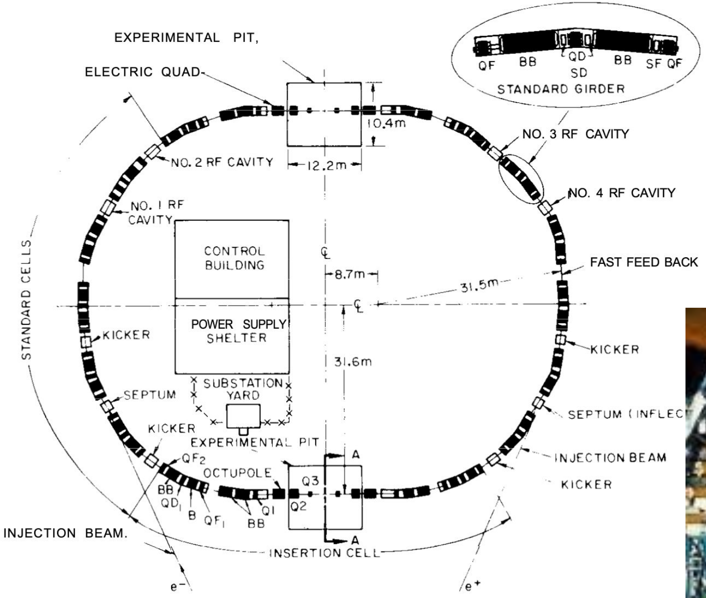
AGS at BNL delivering protons on a fixed target





Spear e+e- collider at SLAC and Mark 1 detector

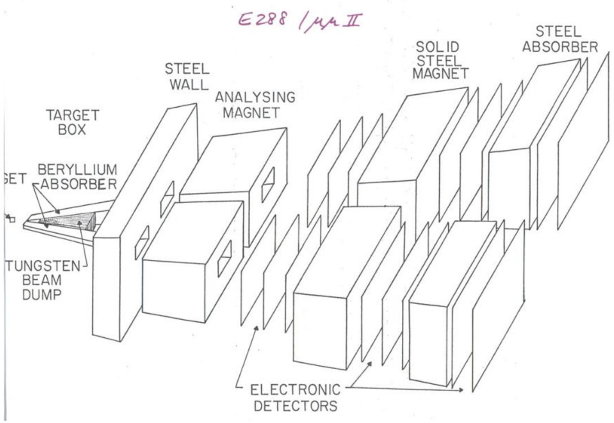




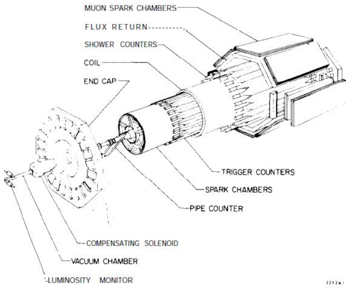
1. Schematic of the SPEAR storage ring.

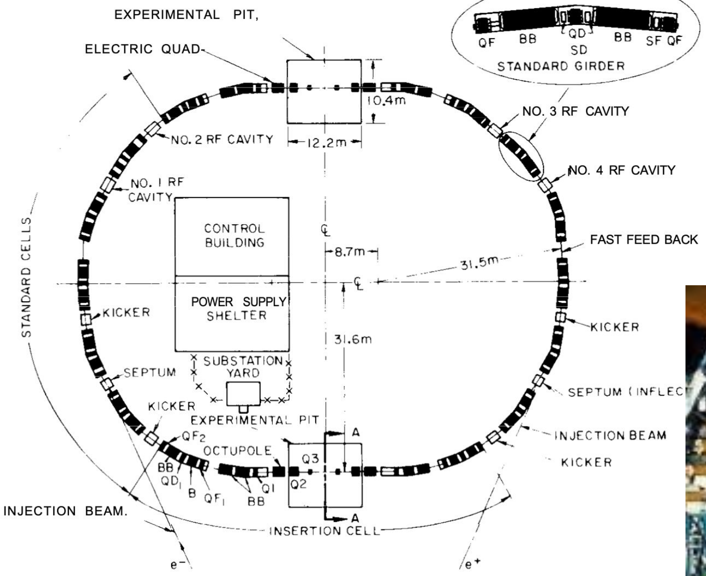
J and Psi discoveries in 1974

Protons at FNAL on a Uranium fixed target



Spear e+e- collider at SLAC and Mark 1 detector

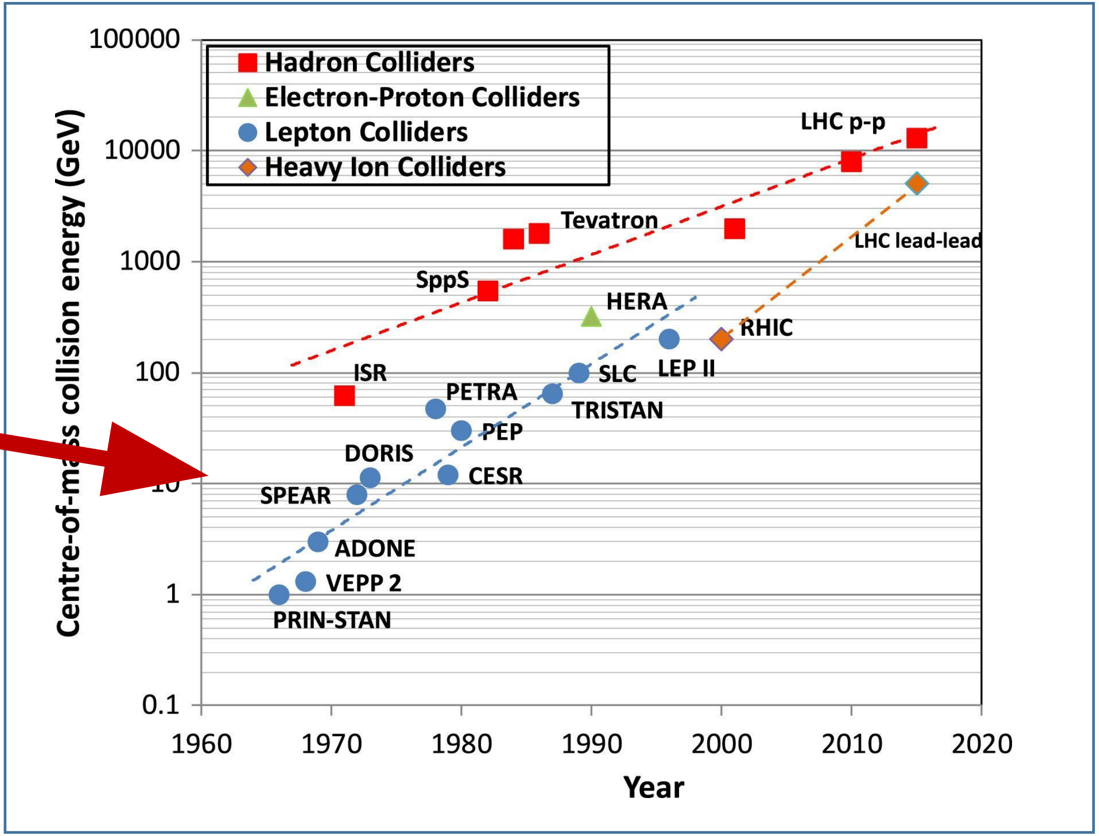




1. Schematic of the SPEAR storage ring.

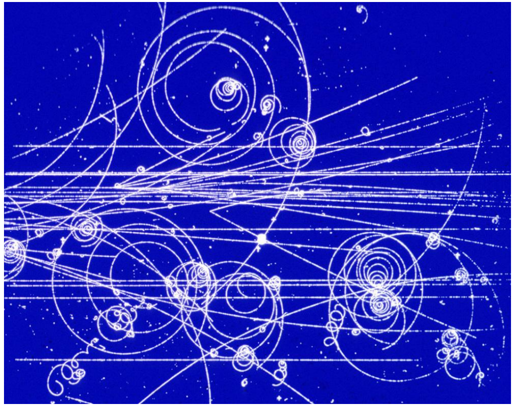
Bottom and Tau discoveries in 1977 and 1975

High Energy Physics is a facilities driven science



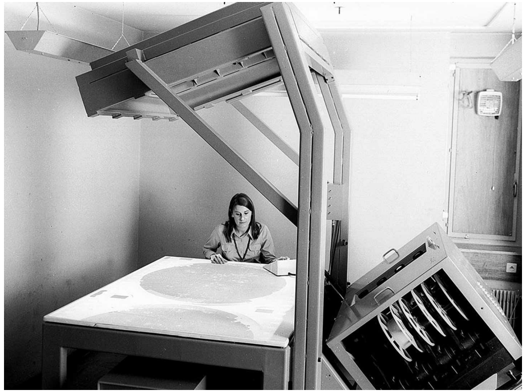
Last month:
https://indico.slac.stanford.edu/event/9040/

Instrumentation - Detectors (+ Electronics)

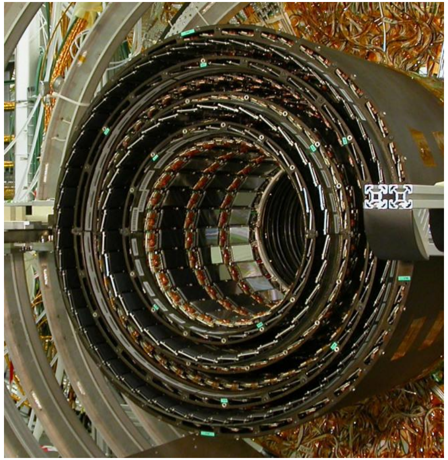


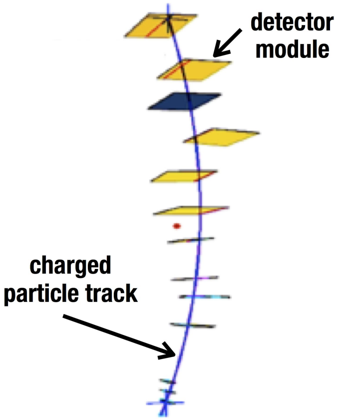
Bubble chamber photography

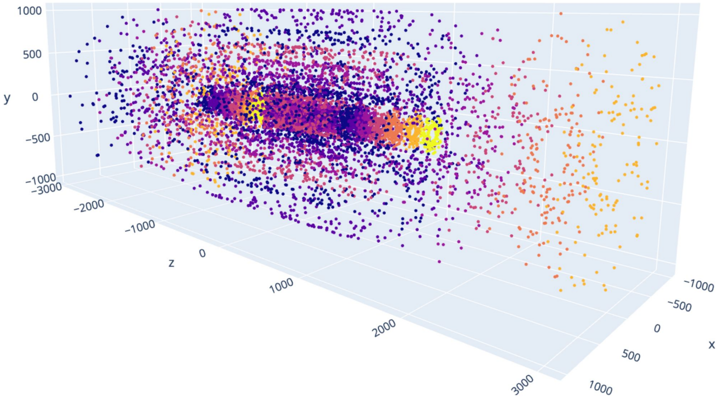
By-hand "scanning" of the photos



Modern detectors with (digital) electronic readout



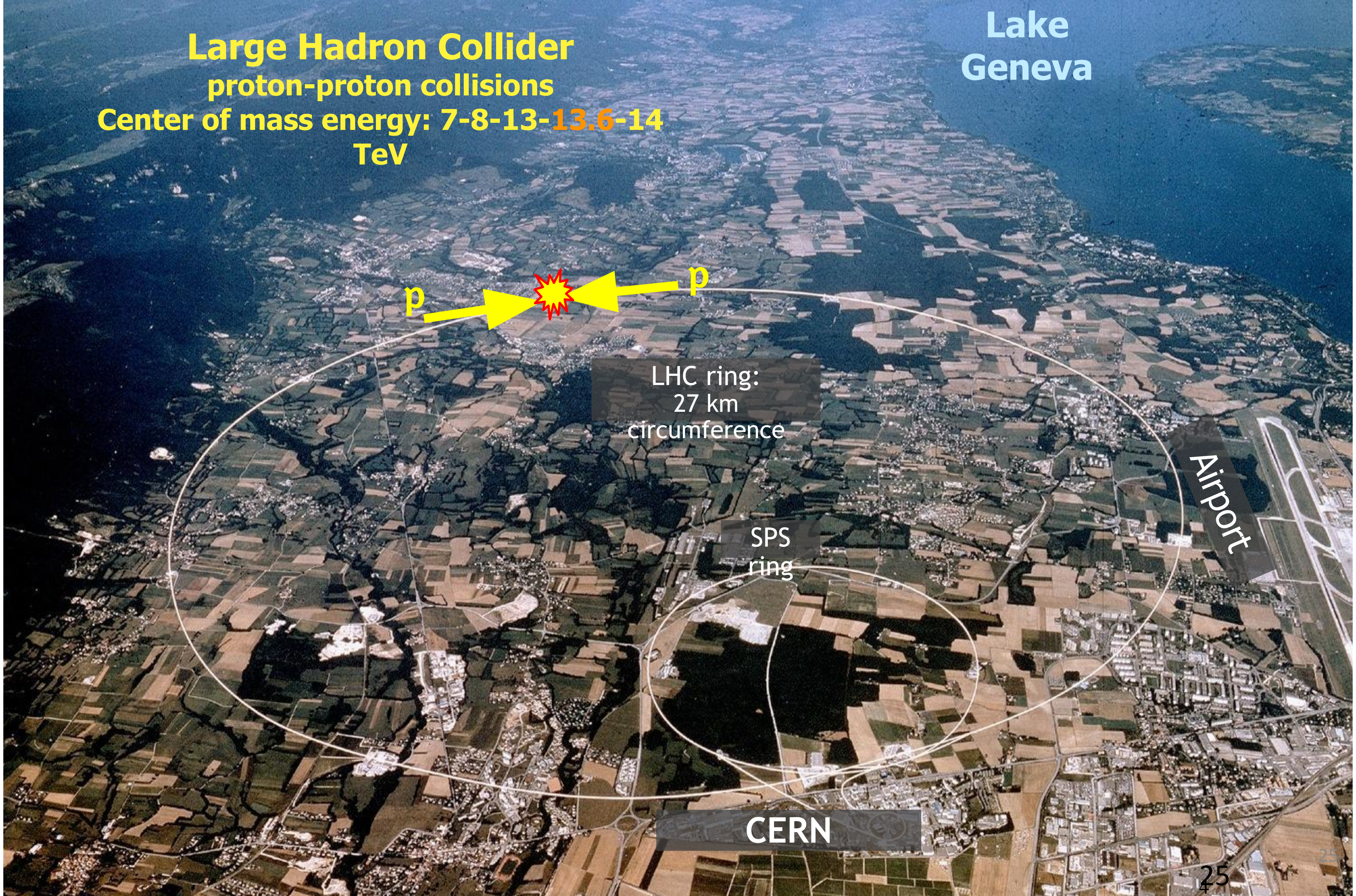




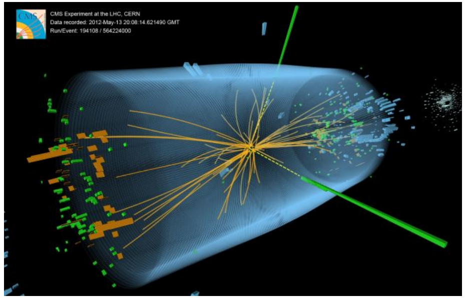
"New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained." - *Freeman Dyson*

Physics Nobel Prizes → Tools open doors to new research avenues

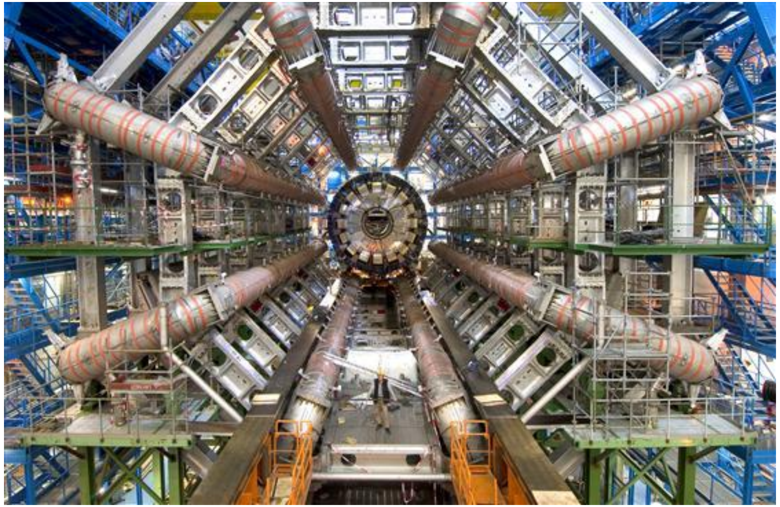
- **2024** (Hopfield, Hinton) - foundational discoveries and inventions that enable machine learning with artificial neural networks
- **2023** (Agostini, Krausz, L'Huillier) - development of experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter
- **2018** (Ashkin) - invention of optical tweezers and their application to biological systems
- **2018** (Mourou, Strickland) - invention of a method of generating high-intensity ultra-short optical pulses
- **2014** (Isamu, Hiroshi, Nakamura) - invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources
- **2012** (Haroche, Winelar) - development of methods that enable measuring and manipulation of individual quantum systems
- **2009** (Boyle, Smith) - invention of the CCD sensor, an imaging semiconductor circuit
- **2009** (Kao) - achievements concerning the transmission of light in fibres for optical communication
- **2005** (Glauber) - contributions to the field of optics
- **2005** (Hall, Hänsch) - contributions to the development of laser spectroscopy
- **2000** (Kilby) - development of the integrated circuit (microchip)
- **2000** (Alferov, Kroemer) - development of fast semiconductors for use in microelectronics
- **1997** (Chu, Cohen-Tannoudji, Phillips) - process of trapping atoms with laser cooling
- **1992** (Charpak) - invention of a detector that traces subatomic particles
- **1989** (Dehmelt, Paul) - development of methods to isolate atoms and subatomic particles for study
- **1989** (Ramsey) - development of the atomic clock


Large Hadron Collider
proton-proton collisions
Center of mass energy: 7-8-13-13.6-14
TeV
Lake
Geneva
p
p
LHC ring:
27 km
circumference
Airport
SPS
ring
CERN

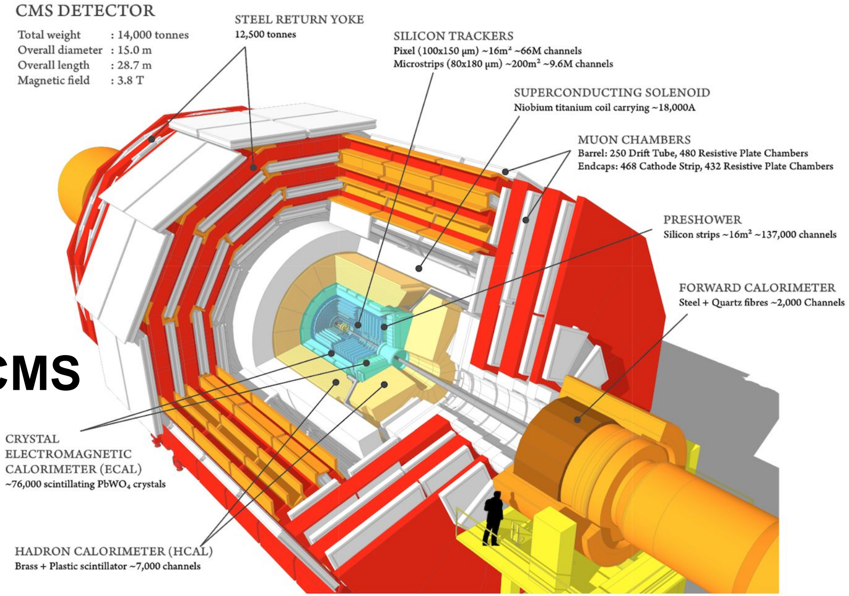
Large Hadron Collider Experiments Are Massive Data Generators



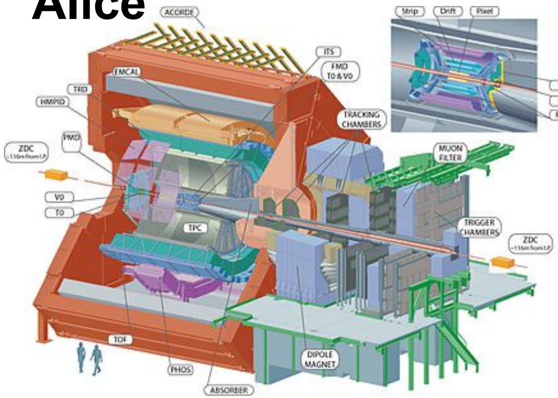
Atlas

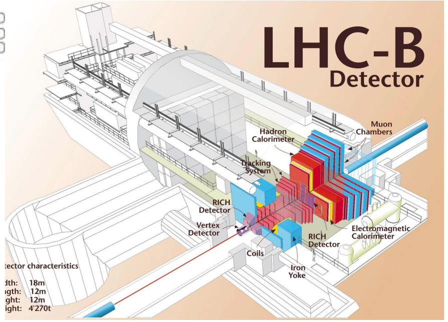


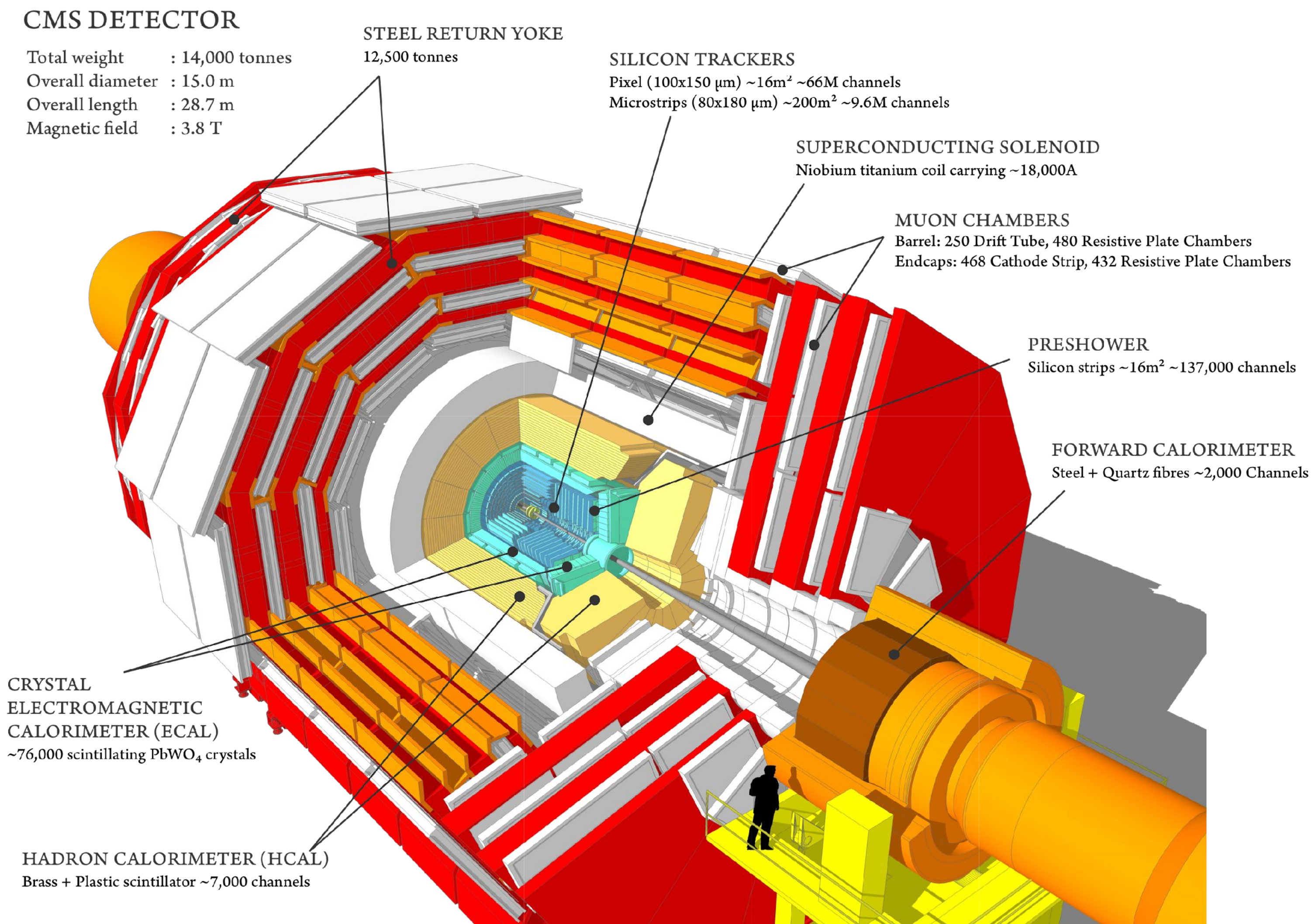
CMS



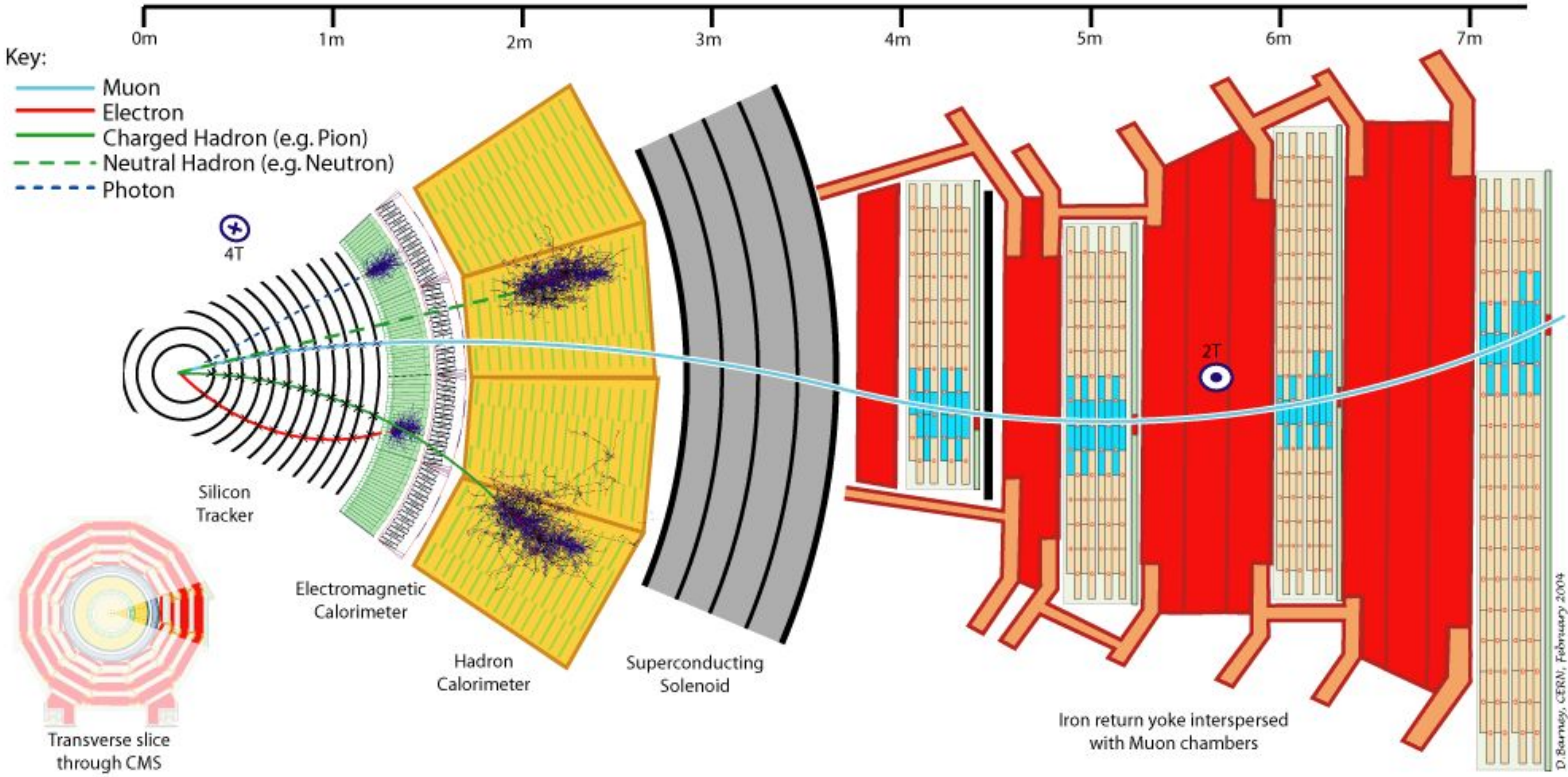
Alice







CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

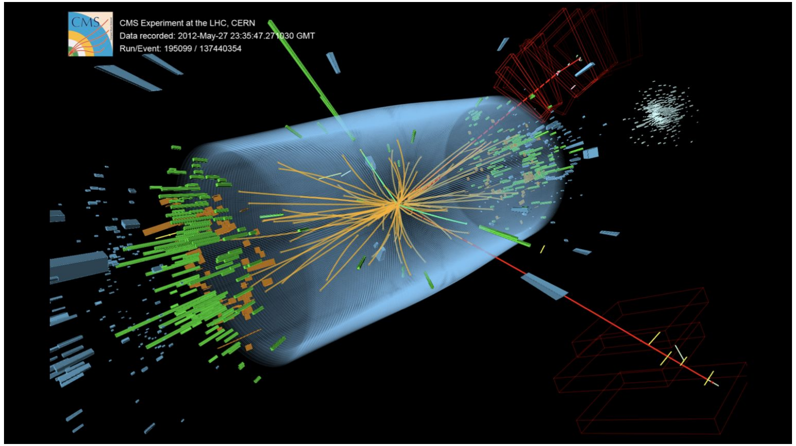
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

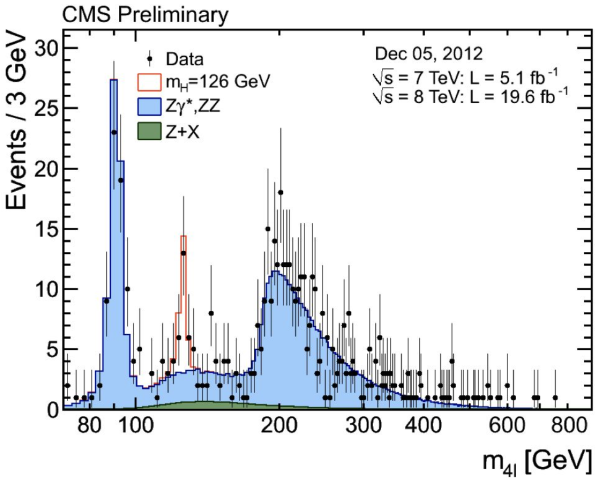
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.


CMS has ~4300 Scientists, Engineers and technicians
(including 800 PhD students) from 41 Countries and 179 institutes

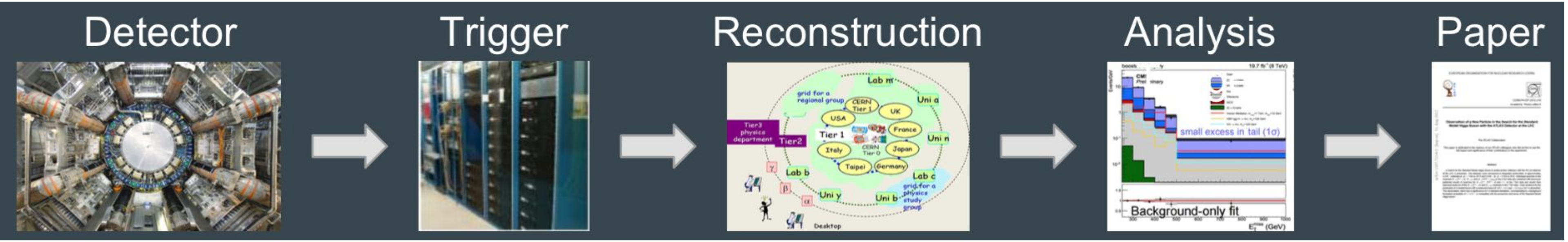
Just as with facilities, HEP scientists rely on large computing infrastructures to do their science





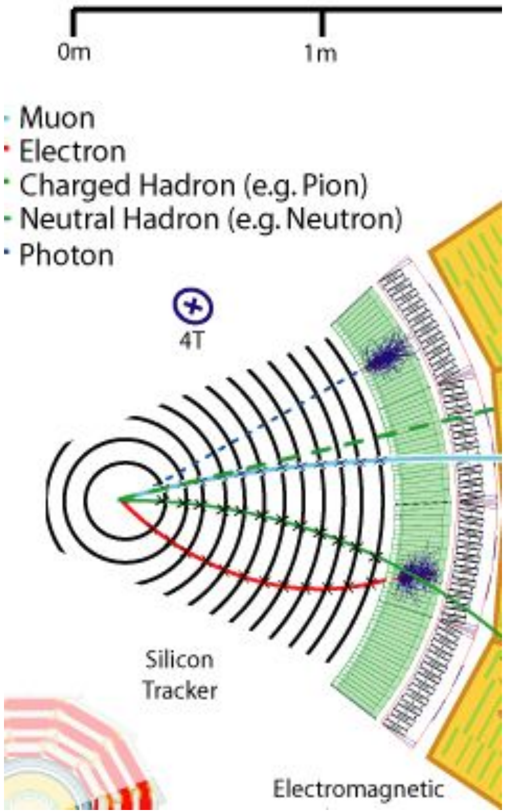
Large scale software
and computing
infrastructures

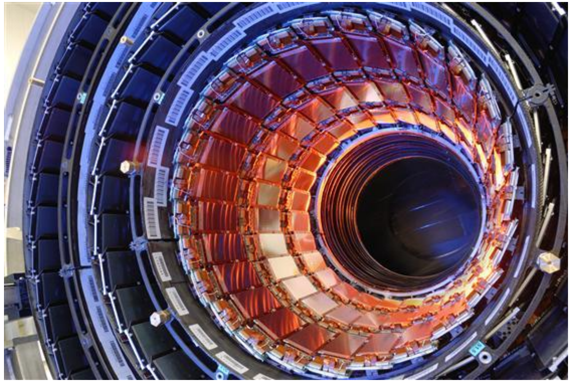
Our software takes data from collisions to physics results

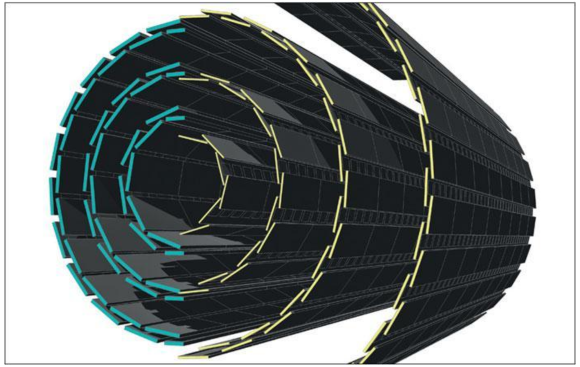


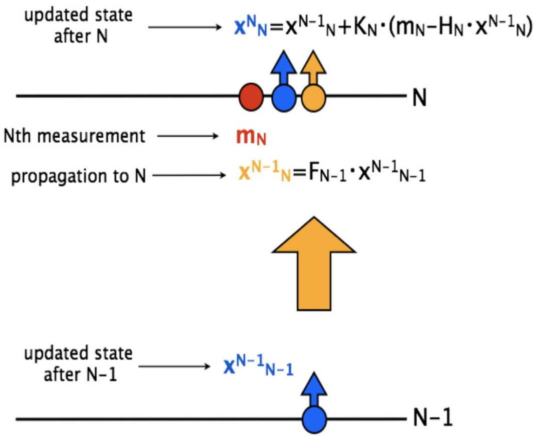
- Detector data collected at the rate of 60 TB/second must be reduced to ~5 GB/second in real time
- Pattern recognition algorithms find particle trajectories from the detector data (“reconstruction”)
- In parallel, Monte Carlo methods are used to create simulations of how different physics processes appear in our detector
- Collisions are categorized by examining reconstructed particles for signs of specific physics processes (eg, Higgs decays) (“Analysis”)

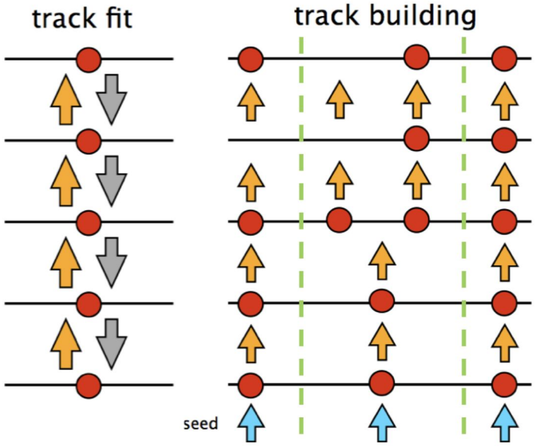
Reconstruction applications process RAW data into “physics objects” for analysis



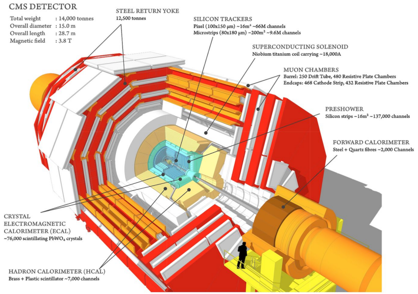








Tracking particles through CMS



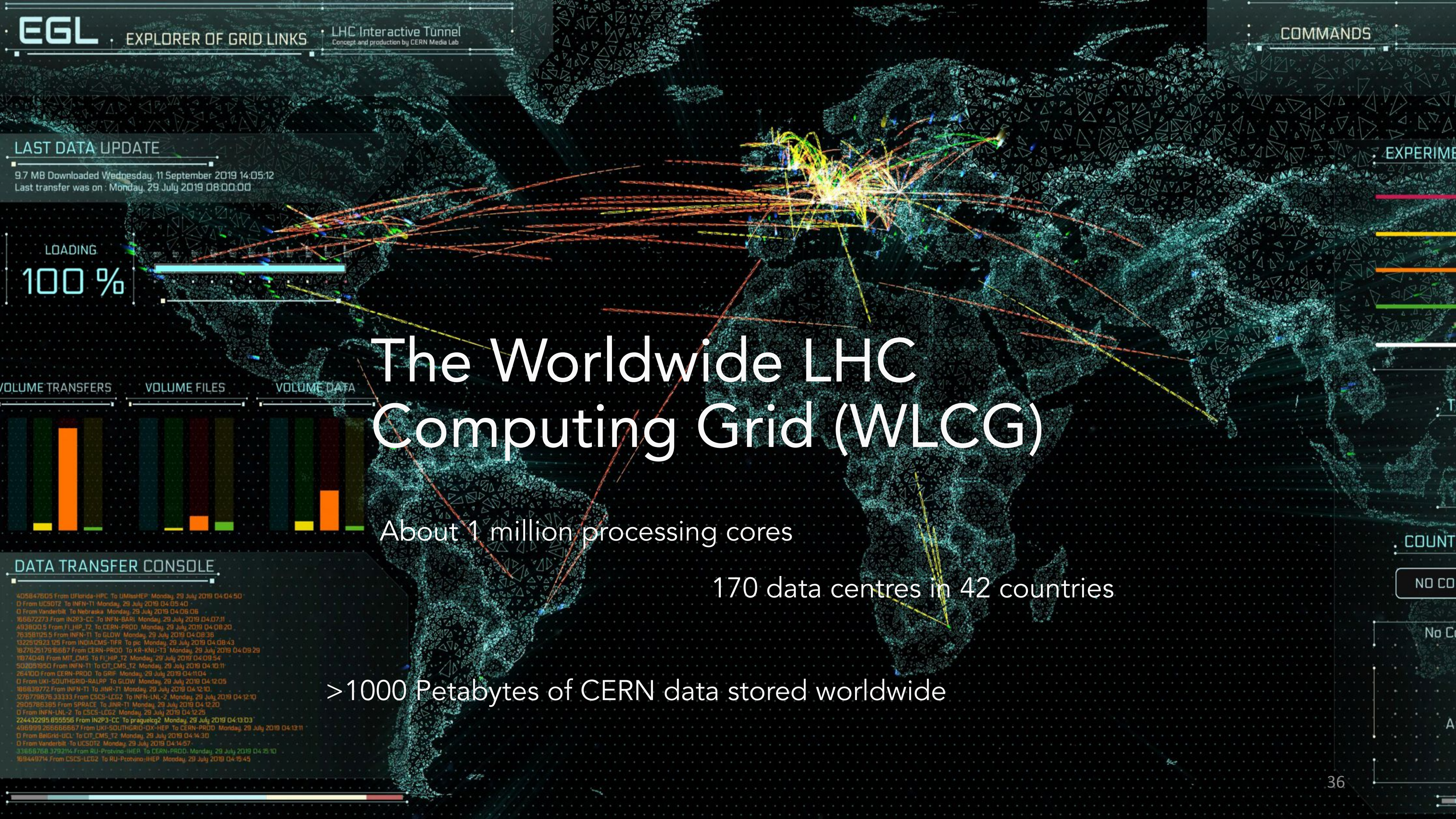
	LHC events per year (/10^9)	Tracks per year (/10^{15})	Time for processing (Latency)
L1 Trigger (FPGA-based)	240000	1000	~10 us
"High Level" Trigger	6000	40	Seconds
Offline Processing	60	0.5	Days – can be redone if needed
Analysis	60	0.5	Years -- redone many times

The Worldwide LHC Computing Grid (WLCG)

About 1 million processing cores

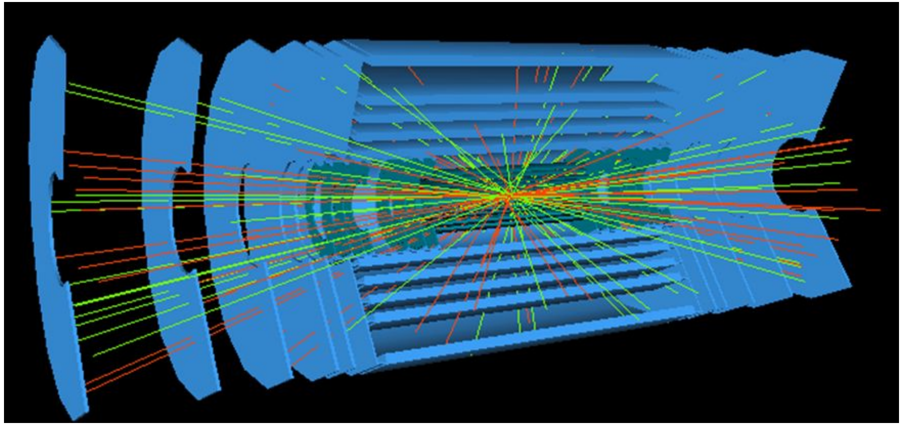
170 data centres in 42 countries

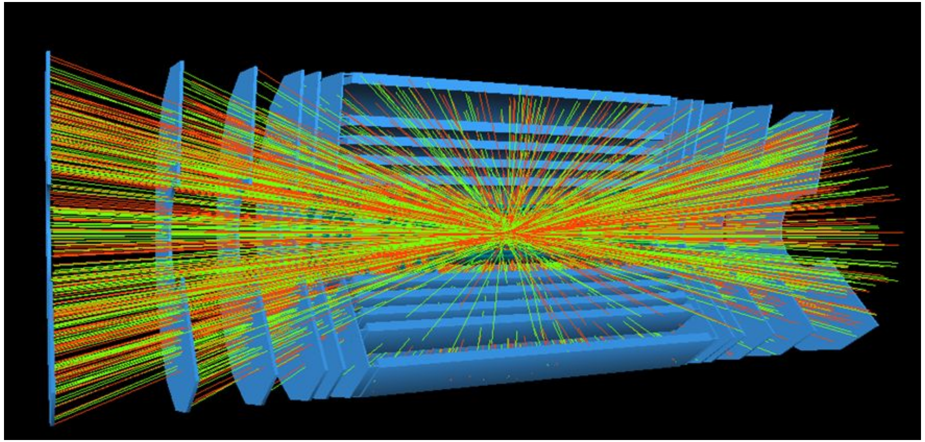
>1000 Petabytes of CERN data stored worldwide



What are the big challenges?

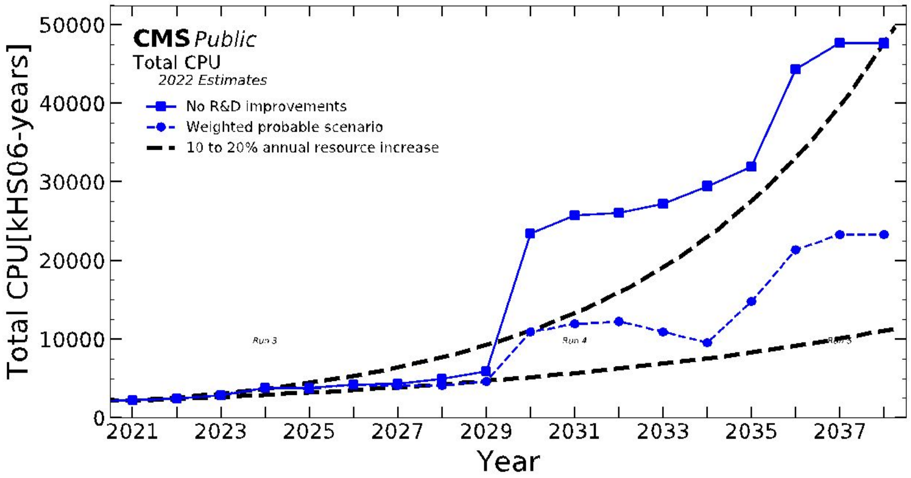
Challenge of next-generation, higher-luminosity or higher-intensity experiments

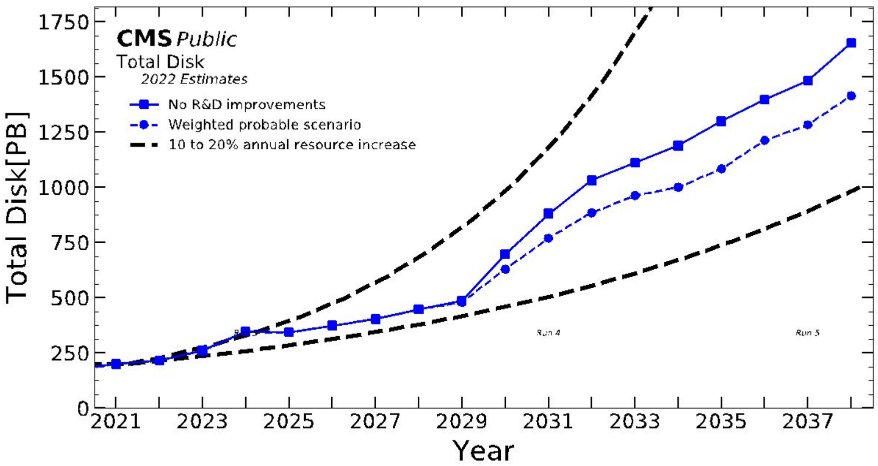




- HL-LHC expects to deliver 200 simultaneous interactions per bunch crossing. 5x more than today.
- More capable detectors are being built to facilitate finding ”needles” in this much bigger “haystack”
- Similarly, the analyst community must develop new and more capable approaches to prepare for much higher event rates, higher event complexity, and more detailed detector information.

Future experiments pose even larger computing challenges





- A naive extrapolation from today's computing model and techniques, even after assuming Moore's Law increases in capabilities, is insufficient to meet the expected resource needs for HL-LHC
  - Technology evolution for processors and storage is an additional challenge
  - New ideas and methods are needed, and software is the key ingredient

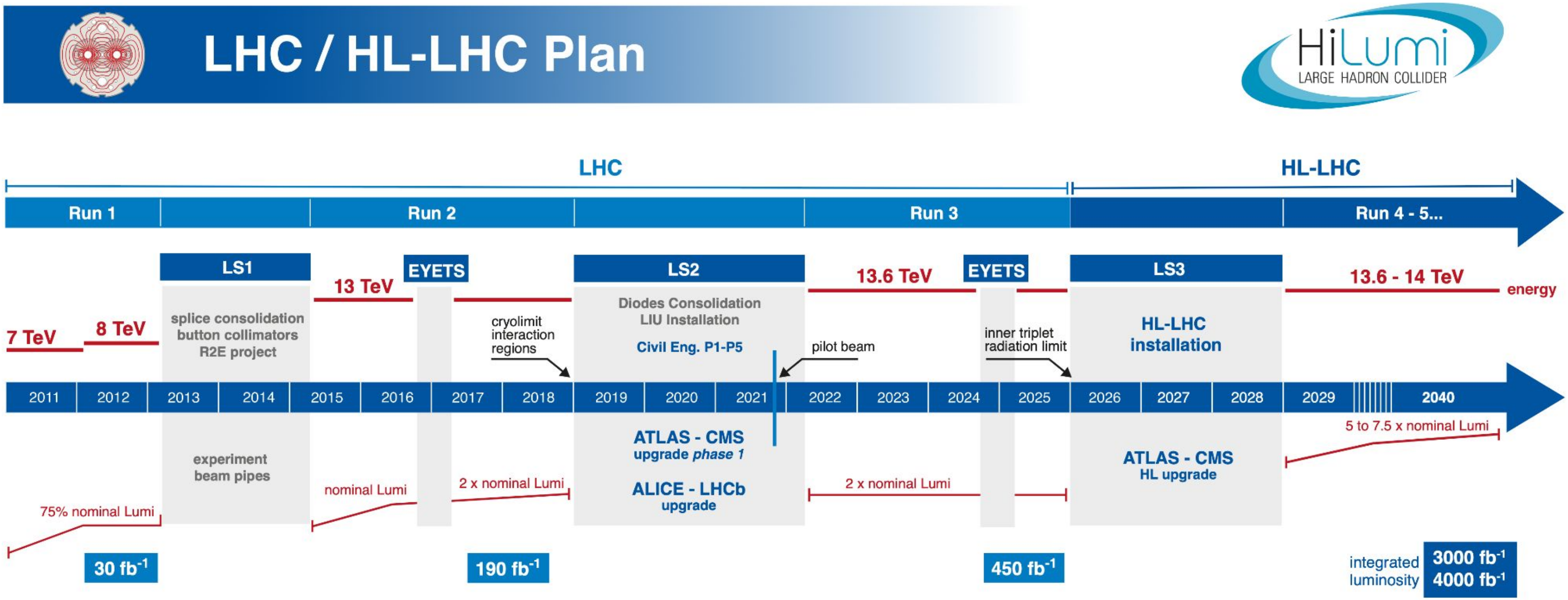
Human time is critical: Optimizing analysis is about more than just about pure resources

	LHC (Run 1&2)	HL-LHC (Run 4+)
Analysis Dataset size	10 TB	1,000 TB
Target Scan Turnaround time	Weeks	Hours
Analysis team size (physicists)	5-10	< 5
Primary analysis resource	Laptop	Analysis Facility

LHC analysis:
- Search & Precision Physics
- Simple ML techniques (BDT)
- Reproducibility in its infancy

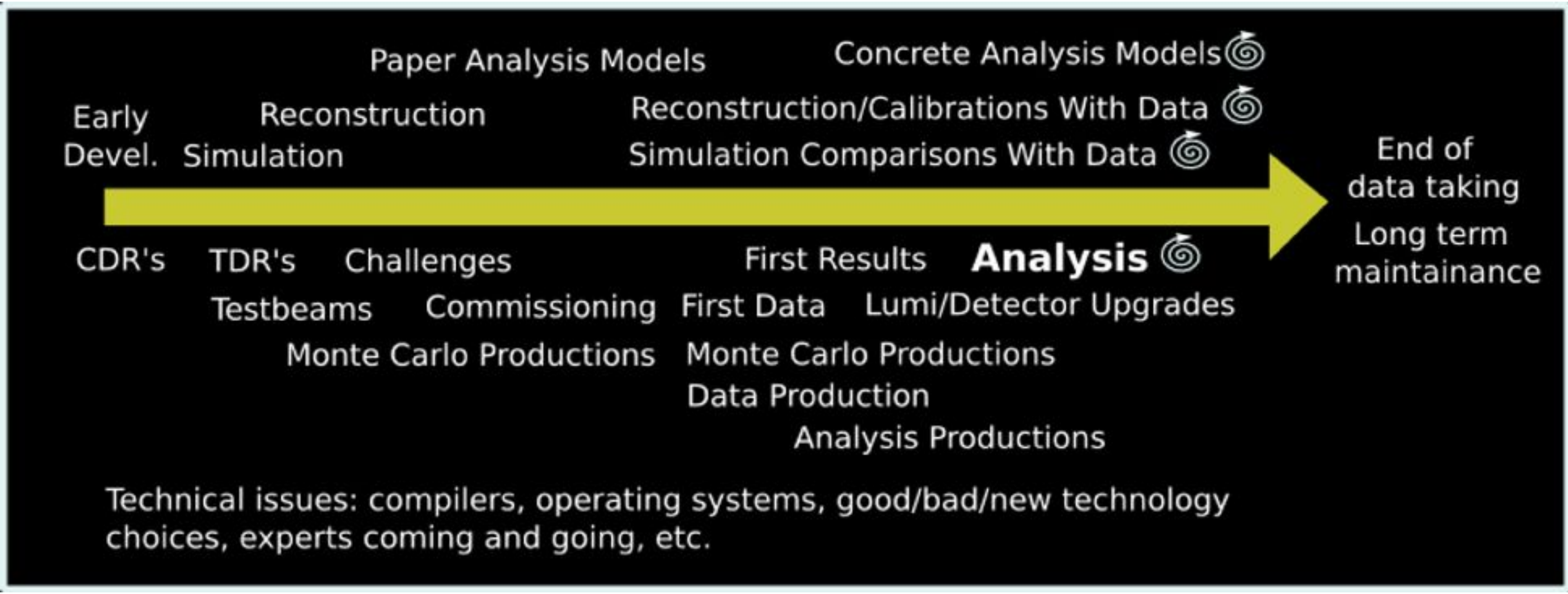
HL-LHC analysis:
- Very High Precision Physics
- Modern ML (Deep Learning)
- Reproducible and Open Data

Experimental timescales span decades

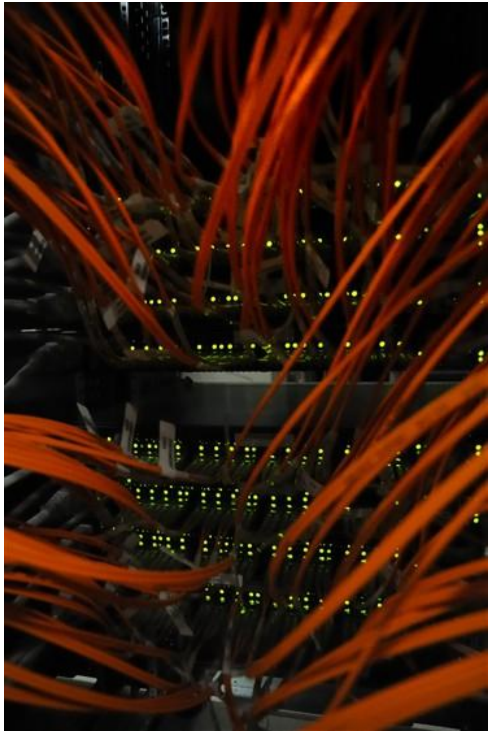


Experiment designs start far before data taking. CMS was formed in 1992 (more than 30 years ago!), expects to run through 2040 and do data analysis for years after that

HEP software lifecycle



Cyberinfrastructure?

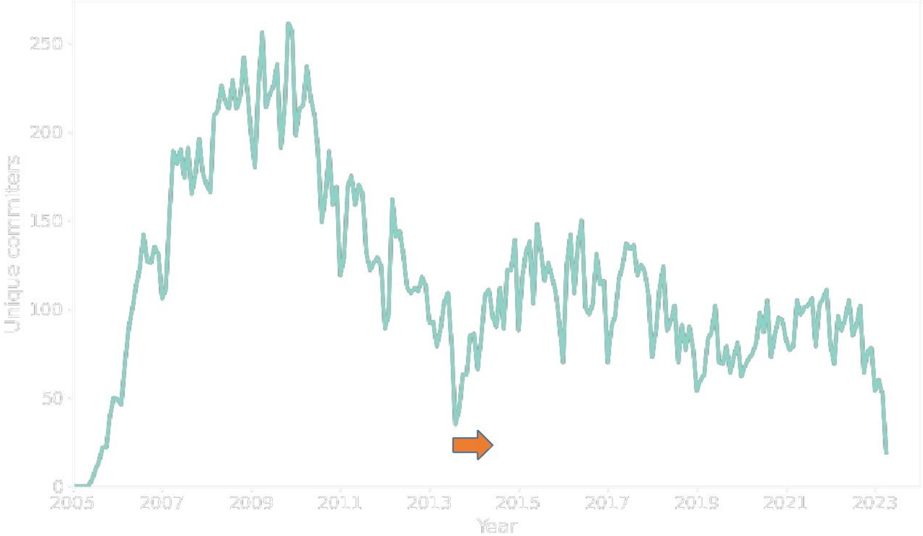


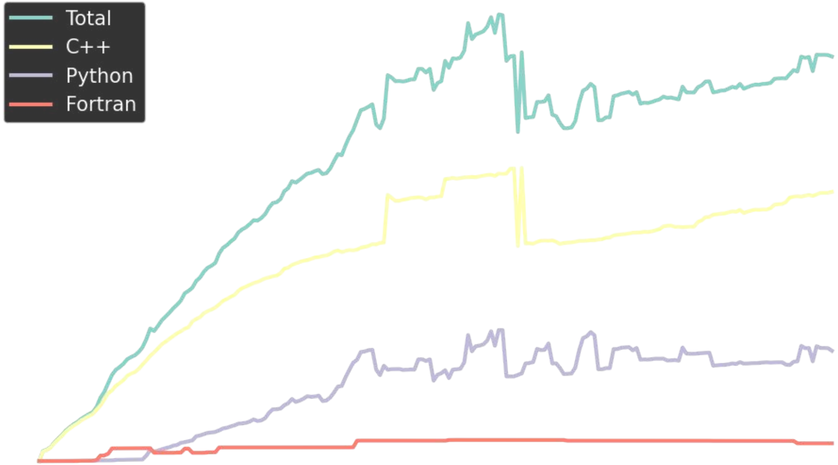
Conceptual motivations behind the HEP Software Foundation

Computer hardware is a consumable. Software is the actual "cyberinfrastructure" in the long run.

More importantly software is also an *intellectual product* of our research, not just a tool.

Large scale collaborative software development in HEP





Many developers, typically a handful of true experts

Millions of lines of code for CMS - And this excludes most data analysis code, event generators, detector simulation codes, and others…

Community Structures Reflect Our Community Evolution/Needs

WLCG
Worldwide LHC Computing Grid

The **Worldwide LHC Computing Grid (WLCG)** project is a global collaboration of around 170 computing centres in more than 40 countries, linking up national and international grid infrastructures. The mission of the WLCG project is to provide global computing resources ... **[2000's and 2010's era]**

HSF
HEP Software Foundation

The **HEP Software Foundation** facilitates cooperation and common efforts in High Energy Physics software and computing internationally. **[2010's and 2020's era]**

WLCG/HSF 2024 (13-17 May) - https://indico.cern.ch/event/1369601/


About Connect Activities Fellows Jobs

Institute for Research and Innovation in Software for High Energy Physics (IRIS-HEP)

Computational and data science research to enable discoveries in fundamental physics

IRIS-HEP is a software institute funded by the National Science Foundation. It aims to develop the state-of-the-art software cyberinfrastructure required for the challenges of data intensive scientific research at the High Luminosity Large Hadron Collider (HL-LHC) at CERN, and other planned HEP experiments of the 2020's. These facilities are discovery machines which aim to understand the fundamental building blocks of nature and their interactions. Full Overview

News and Featured Stories:

IRIS-HEP Receives $25M Funding for Another Five Years of Research

"IRIS-HEP received funding from the Office of Advanced Cyberinfrastructure and the Physics Division at the National Science Foundation for five years."

Read more

Out of harm's way: Physics research program supports Ukrainian students displaced by war

"Ukrainia students escape the war and pursue research at the Large Hadron Collider (LHC), under supervision from Princeton University faculty."

Read more

Upcoming Events:

- May 24, 2024 — CERN — IRIS-HEP / AGC Demo Day #5
- Jun 20–21, 2024 — Princeton University — USCMS/IRIS-HEP Software Training
- Jul 8–14, 2024 — Tacoma, Washington — Scientific Computing with Python (SciPy) 2024
- Jul 18–19, 2024 — University of Washington — USATLAS/IRIS-HEP Software Training
- Jul 22–26, 2024 — Princeton University — CoDaS-HEP 2024 - Computational and Data Science Training for High Energy Physics
- Aug 26–30, 2024 — Aachen, Germany — PyHEP.dev 2024 - "Python in HEP" Developer's Workshop
- Sep 4–6, 2024 — University of Washington — IRIS-HEP Institute Retreat
- Sep 23–25, 2024 — Valencia (Spain) — Fourth MODE Workshop on Differentiable Programming for Experiment Design

View all past events

http://iris-hep.org

Conceived as a **"software upgrade"** project and guided initially by the "Community White Paper" roadmap developed in 2016-2017: it involves 21 universities, spanning ATLAS, CMS and LHCb.

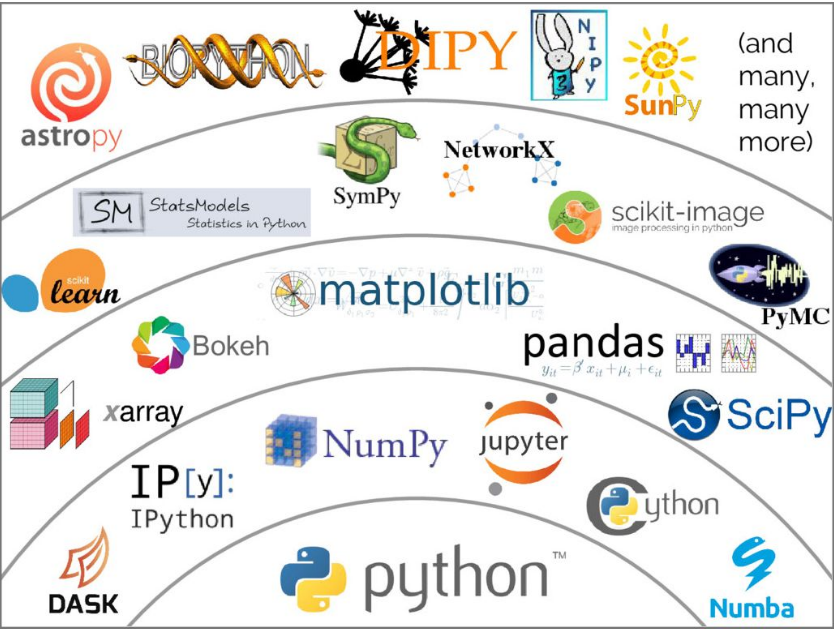
IRIS-HEP is supported by the U.S. National Science Foundation through the **Office of Advanced CyberInfrastructure** in the Directorate for Computer and Information Science and Engineering and the **Division of Physics** in the Directorate for Mathematical and Physical Sciences.

10-year project: Originally funded in 2018 as OAC-1836650 and renewed in 2023 through 2028 as PHY-2323298.

Example outcomes

Leveraging data science for HEP analysis

Scientific Python / PyData vision/ecosystem



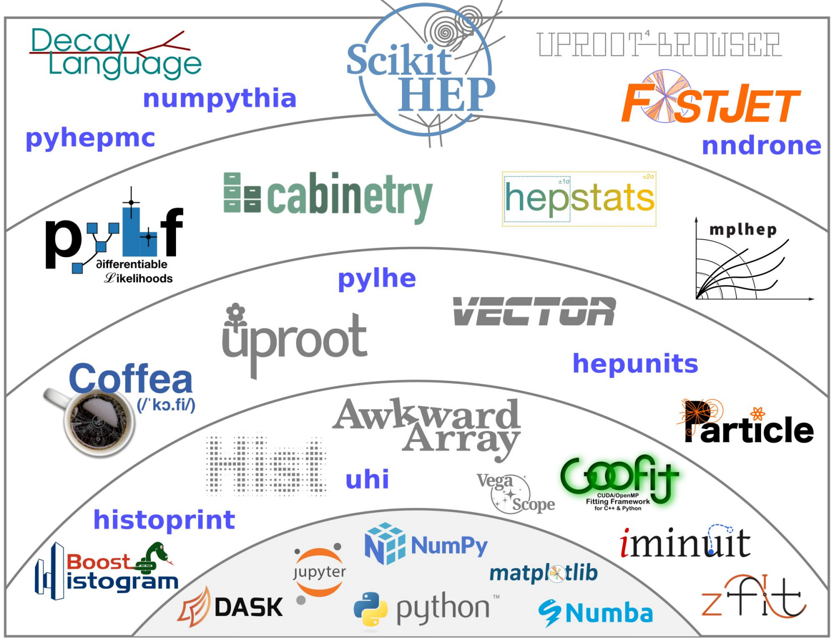
Application Specific

Domain Specific

Technique specific

Foundational

Developing HEP data analysis ecosystem



Awkward Array – numpy for HEP data

```
array = ak.Array([
    [{"x": 1.1, "y": [1]}, {"x": 2.2, "y": [1, 2]}, {"x": 3.3, "y": [1, 2, 3]}],
    [],
    [{"x": 4.4, "y": [1, 2, 3, 4]}, {"x": 5.5, "y": [1, 2, 3, 4, 5]}]
])
```

```
output = []
for sublist in python_objects:
    tmp1 = []
    for record in sublist:
        tmp2 = []
        for number in record["y"][1:]:
            tmp2.append(np.square(number))
        tmp1.append(tmp2)
    output.append(tmp1)
```

2.3 minutes to run (22 GB footprint)

```
output = np.square(array["y", ..., 1:])
```

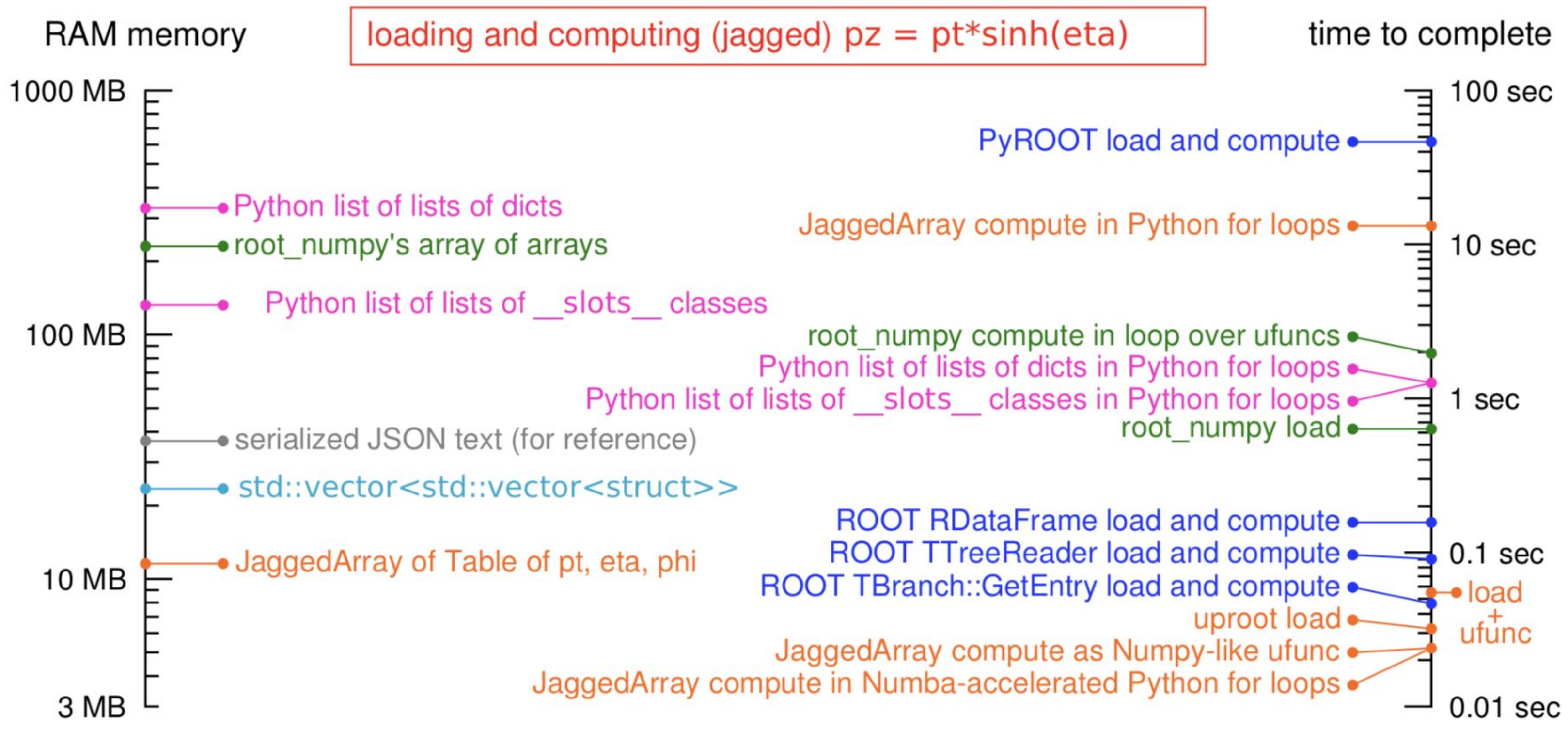
```
[
    [[], [4], [4, 9]],
    [],
    [[4, 9, 16], [4, 9, 16, 25]]
]
```

4.6 seconds to run (2.1 GB footprint)

(single-threaded on a 2.2 GHz processor with a dataset 10 million times larger than the one shown)

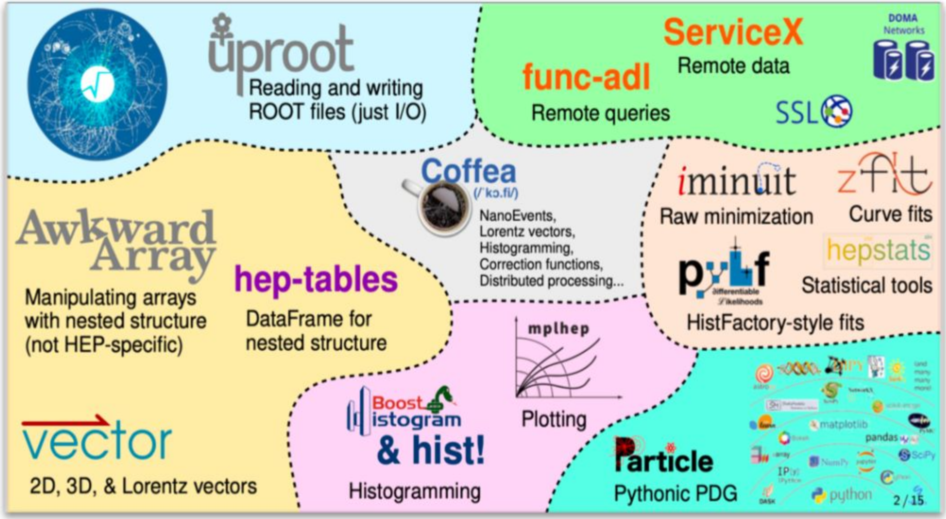
- General tool for manipulating JSON-like structures in a NumPy-like way
- Motivated by problems in HEP which commonly include irregular, “jagged” data

Exciting results are possible: Orders of magnitude speed ups

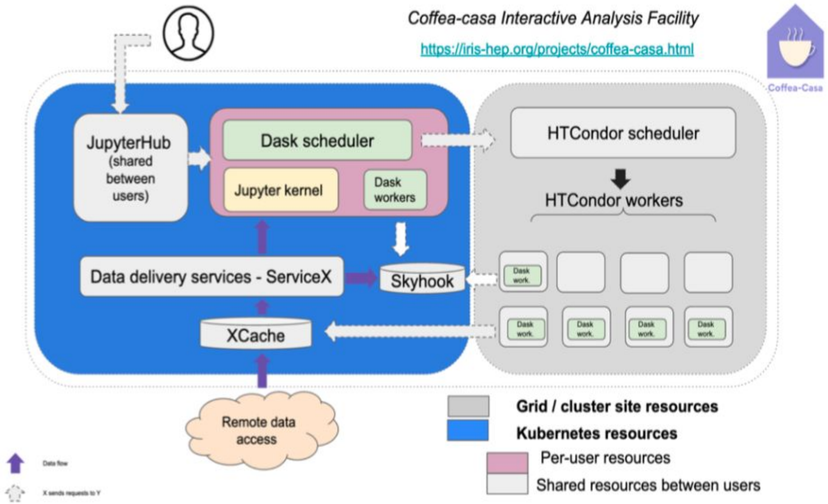


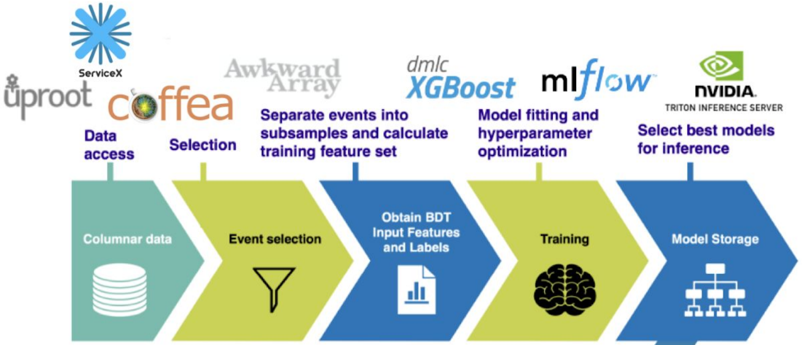
What comes next? Analysis tool chains and facilities rather than just tools

Analysis Tools



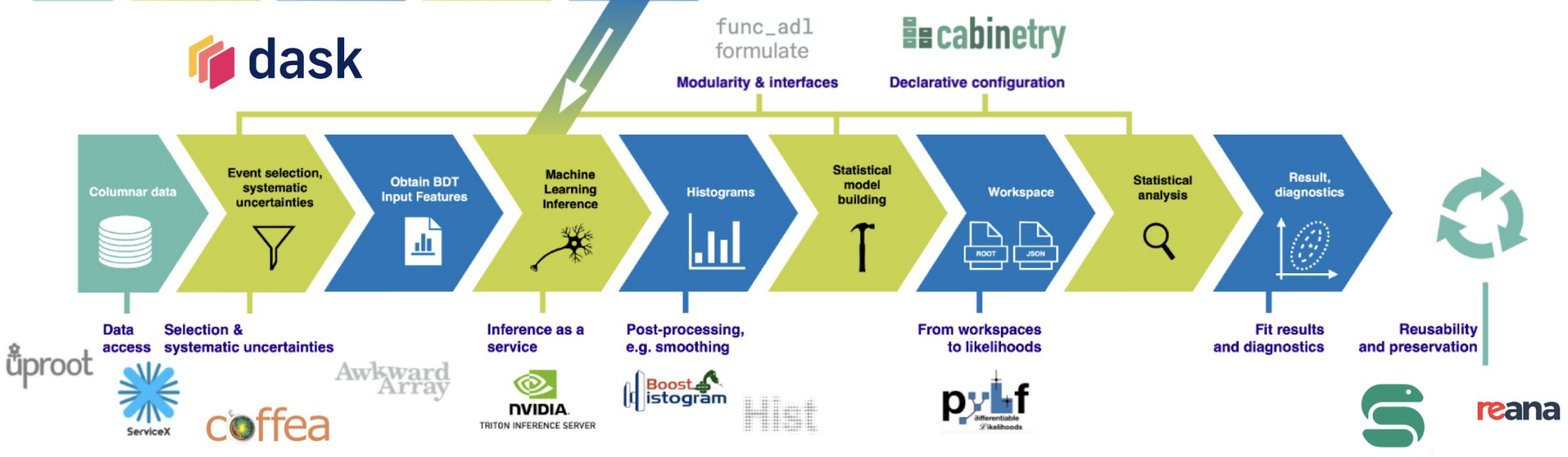
Analysis Facilities



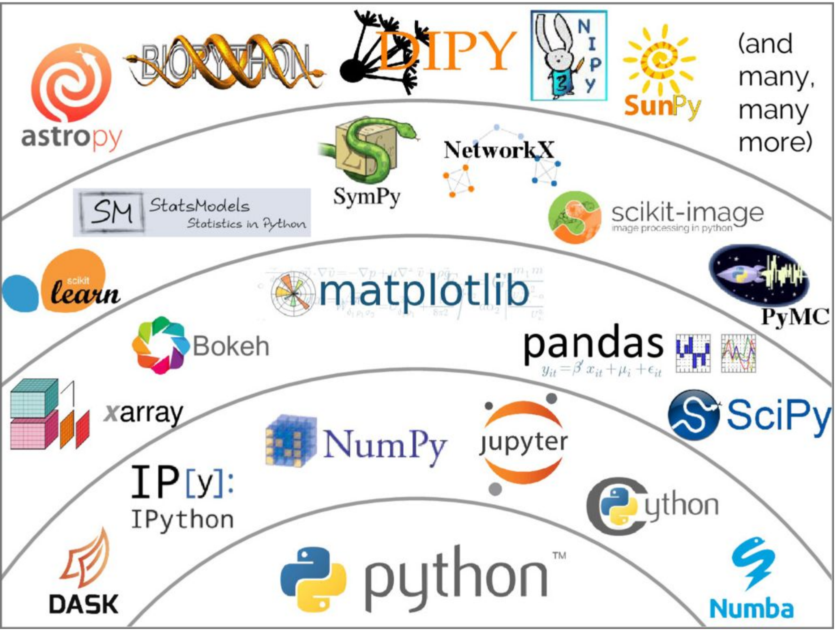


The **IRIS-HEP reference implementation** employs the **Scikit-HEP/ PyHEP ecosystem** and serves as **ideal environment** to test our **latest R&D**.

find it all on GitHub and https://agc.readthedocs.io/



Leveraging data science for HEP analysis

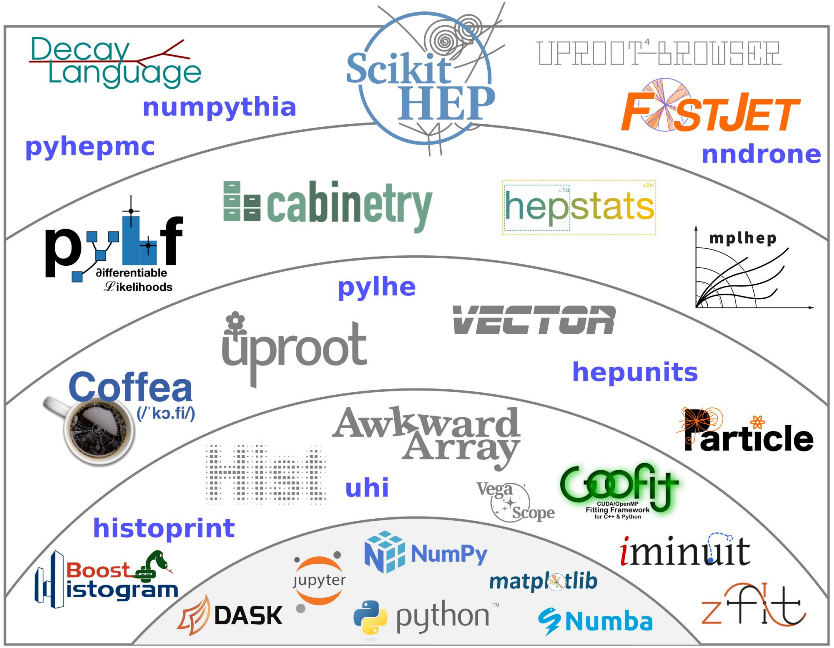


Application Specific

Domain Specific

Technique specific

Foundational



PyHEP development

HSF | Activities | Meetings | Communication | Projects & Support | About

PyHEP - Python in HEP

The PyHEP working group brings together a community of developers and users of Python in Particle Physics, with the aim of improving the sharing of knowledge and expertise. It embraces the broad community, from HEP to the Astroparticle and Intensity Frontier communities.

Conveners

- Eduardo Rodrigues (LHCb, University of Liverpool)
- Jim Pivarski (CMS and IRIS-HEP, Princeton)
- Matthew Feickert (ATLAS and IRIS-HEP, University of Wisconsin-Madison)
- Nikolai Hartmann (Belle II, LMU Munich)

All coordinators can be reached at hsf-pyhep-organisation@googlegroups.com.

Getting Involved

Everyone is welcome to join the community and participate, contribute, to the organised meetings and by means of the following communication channels:

- Gitter channel PyHEP for any informal exchanges.
- GitHub repository of resources, e.g., Python libraries of interest to Particle Physics.
- PyHEP Workshop Twitter handle: @PyHEPConf

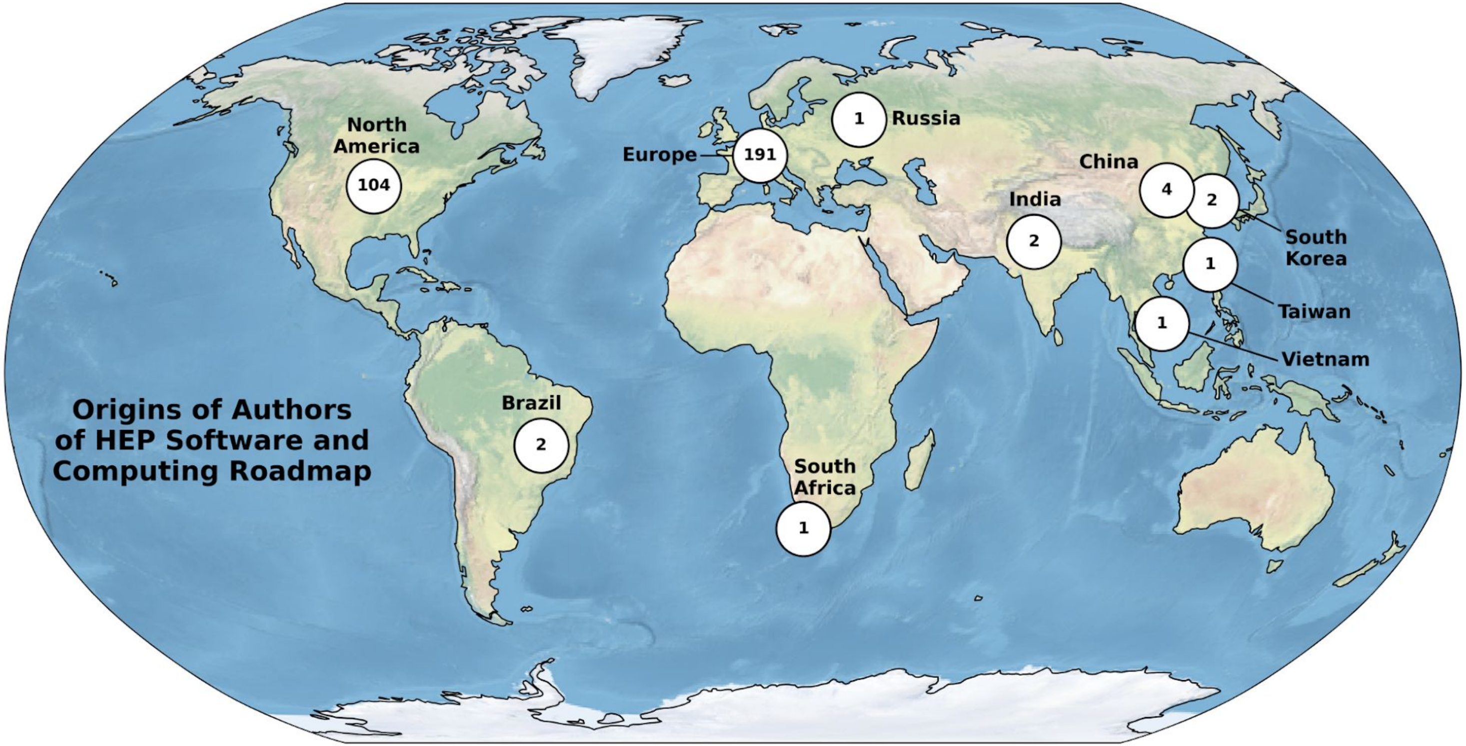
Extra Gitter channels have been created by and for the benefit of the community:

- PyHEP-newcomers for newcomers support (very low entry threshold).

The HSF-India Project

http://research-software-collaborations.org/

However, nearly all authors of the HSF Community Roadmap were from institutions in Europe and the US



Facilitating international research software: The “HSF-India” project

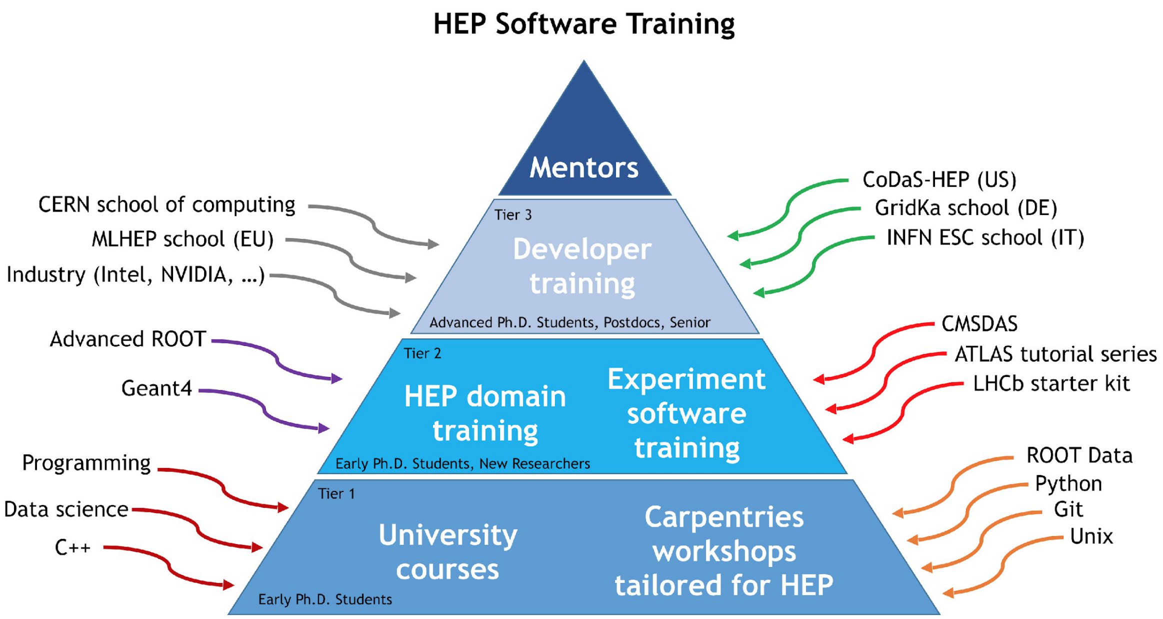
- Given the growing complexity of our scientific data and collaborations, building and fostering collaborations are increasingly important to raise the collective productivity of our research community.
- HSF-India project aims to build international research software collaborations between US, European, and India based researchers to reach the science goals of experimental particle, nuclear and astroparticle research.

  Intended as a long-term investment in international team science with a broad research scope

Rather than directly fund a specific research activities, much of our funding is to facilitate research collaborations

- Training in research software skills
- Bidirectional research exchanges
- Student programs

Bootstrap collaboration through software training



- A vision for training in HEP: researchers progress (vertically) from basic skills training, through user training in existing software to training in skills needed to develop new research software.

We have run software workshops in Mumbai (TIFR), Bhubaneswar (NISER), Delhi (University of Delhi), Kolkata (VECC) and now U.Hyderabad

- Regionally organized, primarily targeting MS/PhD level students.
- Mix of lectures and hands-on exercises
- Mix of local and US instructors
- Jupyter notebook based materials derived from/patterned after HSF training courses

Scientific Python

Marshmallow Challenge

We want to organize these events regionally to make it easier for interested students to attend

Current and upcoming events

https://indico.cern.ch/event/1394564/

HSF-India workshop in IISC Bangalore - 16-22 June 2025 (Indico link forthcoming)

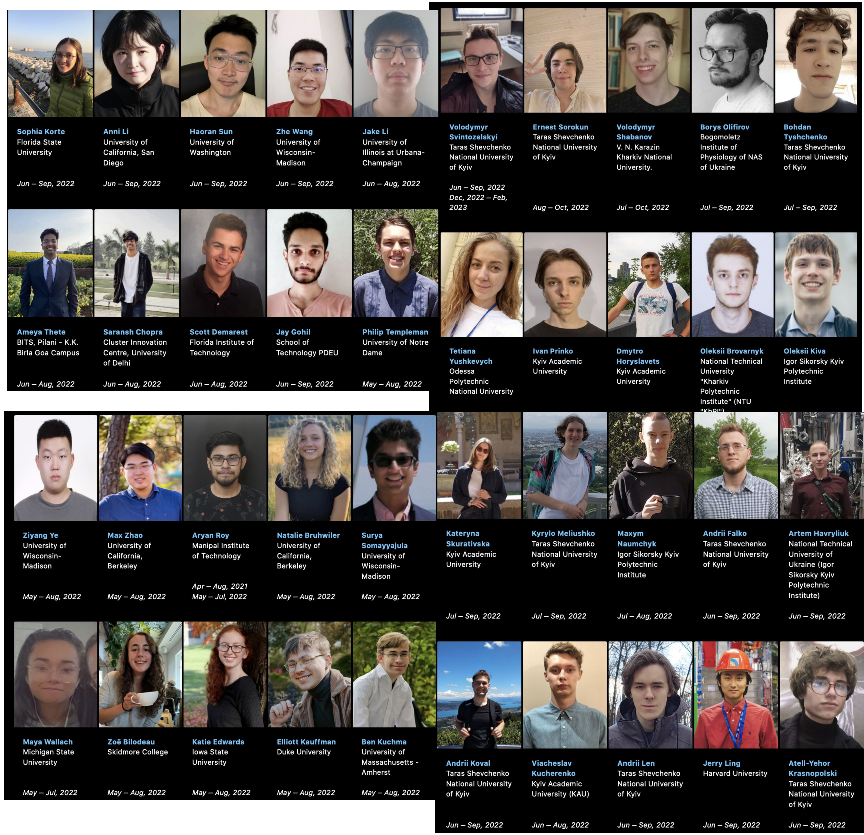
CMSDAS IIT Hyderabad - 23-27 June 2025 (perhaps a collaboration with HSF-India)

We are exploring additional possibilities for “hackathon” events to further build skills, as well as Physics/CS collaborations.

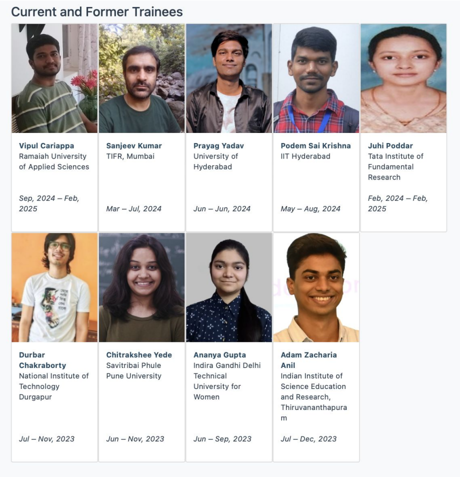
3-6 month project Fellows Program

- **Project focused** aiming to bring students into contact with “mentors” to work on a specific, pre-defined project, allowing them to grow their software skills and experience working in large projects
- These short term projects that build **longer term collaborations** in research software and foster **scientific career progression**
- Our program is open for applications for either full time (eg, during semester breaks) or part time expressions of interest

Also IRIS-HEP Fellows: https://iris-hep.org/fellows.html



[HSF-India Research Software Trainees](#)



Bidirectional Research Exchange Program

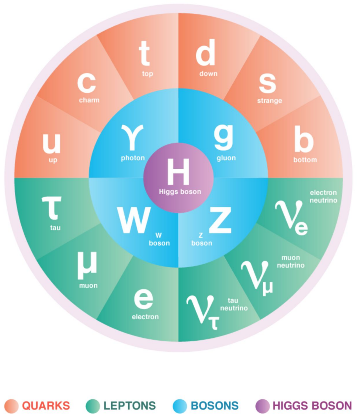
We also have funding for “research exchanges” that support travel costs for 1-3 months. These are meant for very senior PhD students and more senior researchers that have already

Who can we support?

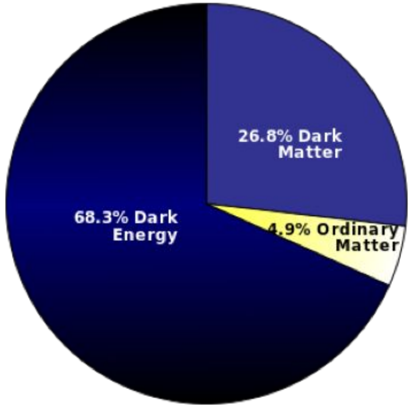
- Researchers affiliated to a US university/lab exchange based in India
- Researchers affiliated to an university/lab in India exchange based in US or CERN to work with a US affiliated group

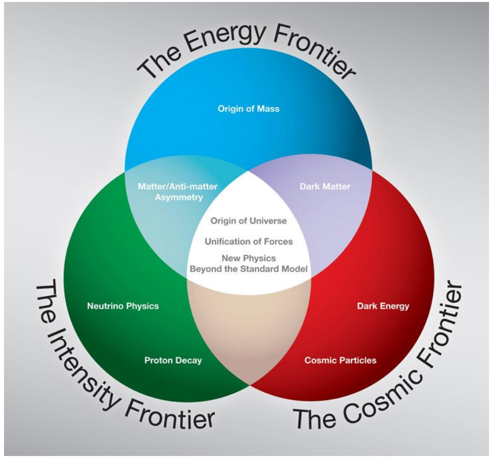
We are looking for either project/host ideas or those interested in doing an exchange. If you have ideas for projects that interest you, we can help identify matches with US researchers

Science Drivers - Beyond the Standard Model of Particle Physics



While the Standard Model of Particle Physics describes, often with incredible precision, the vast majority of experimental observations, it is known to be incomplete. It does not (for example) include gravity, and it does not explain neutrino masses, the matter-antimatter asymmetry or dark matter/energy.

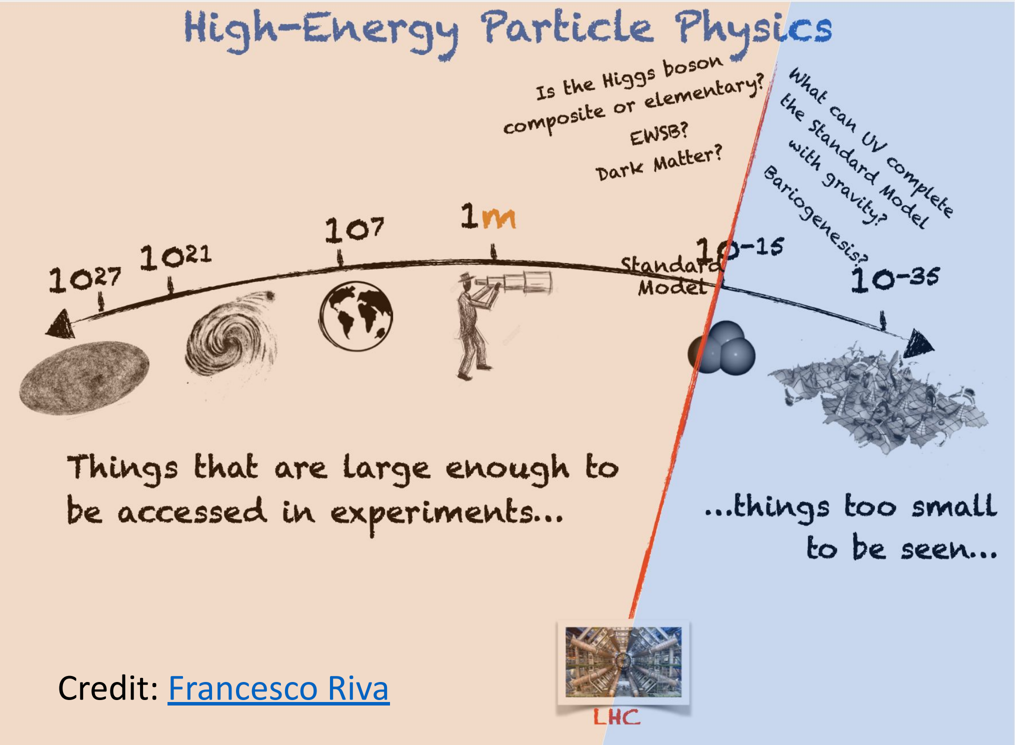




From "Building for Discovery - Strategic Plan for U.S. Particle Physics in the Global Context" - Report of the Particle Physics Project Prioritization Panel (P5):

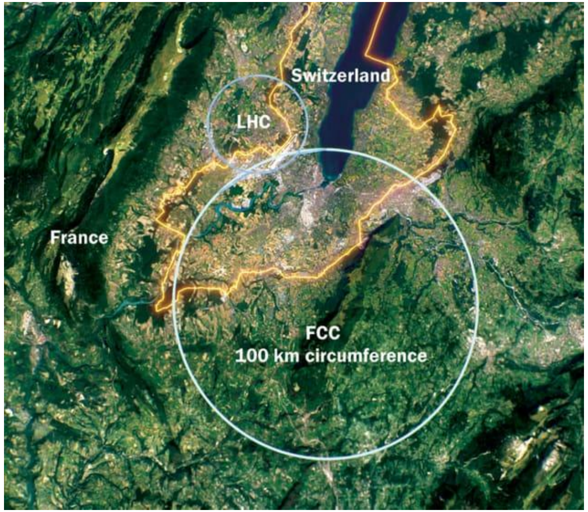
1) Use the Higgs boson as a new tool for discovery
2) Pursue the physics associated with neutrino mass
3) Identify the new physics of dark matter
4) Understand cosmic acceleration: dark energy and inflation
5) Explore the unknown: new particles, interactions, and physical principles

We know that physics beyond our current model exists. However, we do not yet know the energy scale to probe.



Credit: [Francesco Riva]

Next-generation colliders will bring precision science with Higgs



CERN feasibility study of next generation e+e- and hadron collider

Conclusion and Opportunities

- Experimental science is enabled by tools innovation, which become facilities enabling further science. Our science has been driven by accelerator and detector innovation.

- As facilities get larger, scientific collaborations are created to build and exploit those facilities. These large international collaborations of scientists allow experimental endeavors to exploit regional strengths.

- Just as with other aspects of our science, software teams that are inherently international are most likely to develop performant, highly usable, and sustainable **research software ecosystems**, which are a new kind of "facility" and an *intellectual product* of our research.

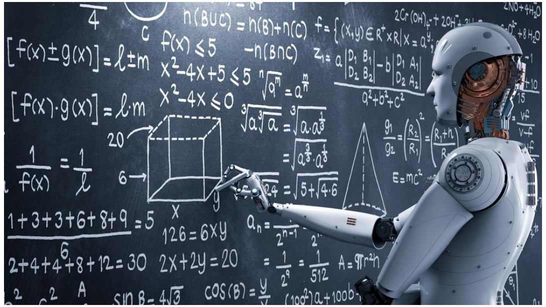
- HSF-India is a project which aims to further catalyze global collaboration in research software in Physics.

    - http://research-software-collaborations.org

And the Future for HEP?

The **Worldwide LHC Computing Grid (WLCG)** project is a global collaboration of around 170 computing centres in more than 40 countries, linking up national and international grid infrastructures. The mission of the WLCG project is to provide global computing resources ... **[2000's and 2010's era]**

The **HEP Software Foundation** facilitates cooperation and common efforts in High Energy Physics software and computing internationally. **[2010's and 2020's era]**



What collaborative research efforts will the rest of the 2020's and the 2030's produce for the future "facilities" for the HEP community?