



# The "Information Laboratory" - AI-Native Experimental Particle Physics in the 21st Century

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1 April 2026

Rutherford Appleton Laboratory



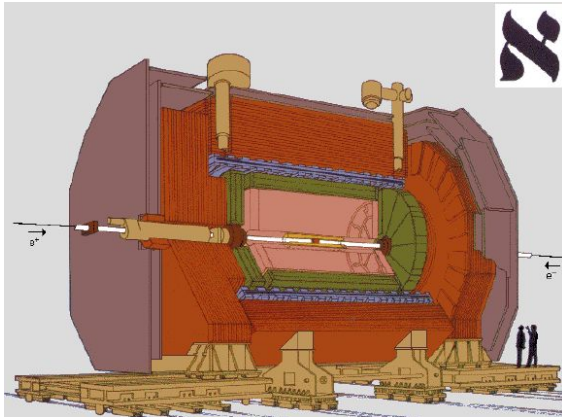
# Introductions.... Who am I?

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:

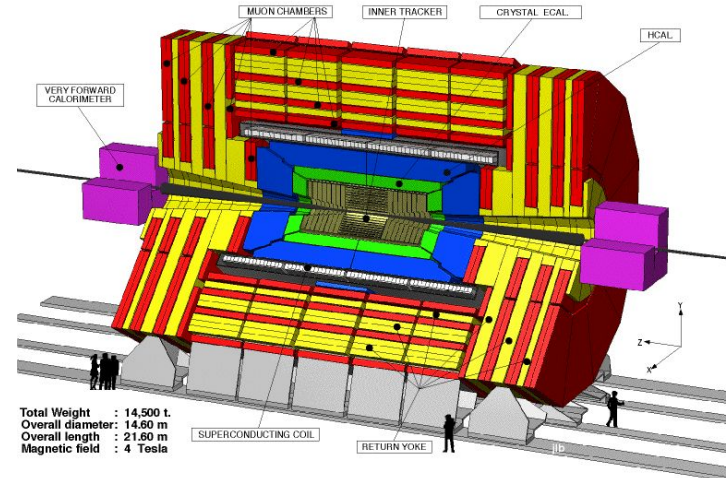
## Aleph@CERN



## BaBar@SLAC



## CMS@CERN



# BaBaR Computing Model 2 (CM2) Implementation Workshop (RAL, Jan. 2003)



(photos Stephen)

## Agenda

Photos from:

Tim Adye

Stephen Gowdy

Alvise Dorigo



# RAL CM2 Workshop (Jan. 2003)



(photo - Stephen)



What did we do to Teela Pulliam? (photo - Stephen)

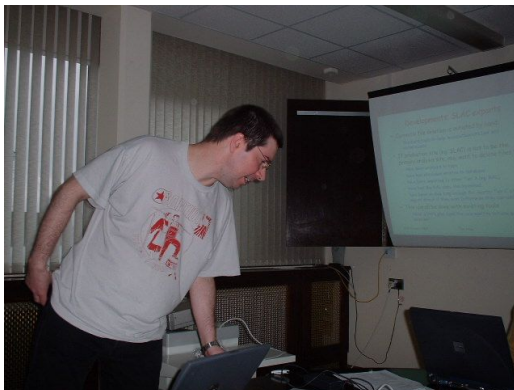
## RAL CM2 Workshop (Jan. 2003)



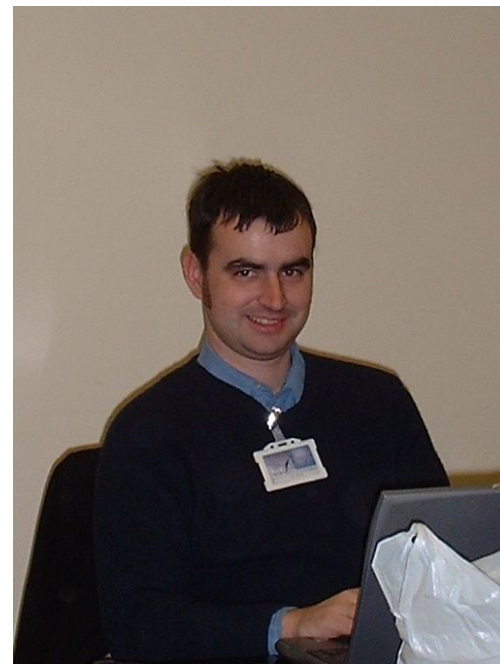
Jacek Becla and Alessandra Forti (photo - Stephen)



Adil Hasan (photo - Alvise)



Tim Adye



Stephen Gowdy (photo - Tim)

# Information Laboratory?

**Laboratory:** a place providing opportunity for experimentation, observation, or practice in a field of study - *Merriam Webster Dictionary*

**Laboratory:** Originally: a room or building for the practice of alchemy and the preparation of medicines. Later: one equipped for carrying out scientific experiments or procedures, esp. for the purposes of research, teaching, or analysis; (also) one in which chemicals or drugs are manufactured; an establishment in which such work is carried out. - *Oxford English Dictionary*

A **laboratory** is a facility that provides controlled conditions in which scientific or technological research, experiments, and measurement may be performed. - *Wikipedia*

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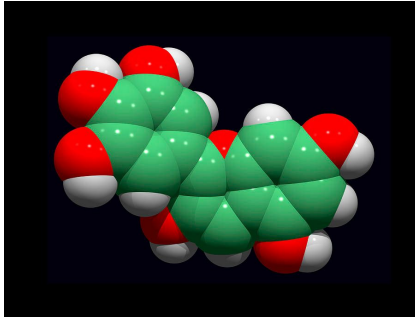
A **laboratory** is a facility that provides controlled conditions in which scientific or technological research, experiments, and measurement may be performed. - *Wikipedia*

“AI labs extend this further: the ‘experiments’ run on cloud compute, the ‘equipment’ is gradient descent and GPU clusters, and the ‘bench’ is a Jupyter notebook. The word has fully detached from its physical origins.” - *Claude, asked why we speak of “AI Labs”*

# The Quest to Understand the Nature of Matter

Molecule

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

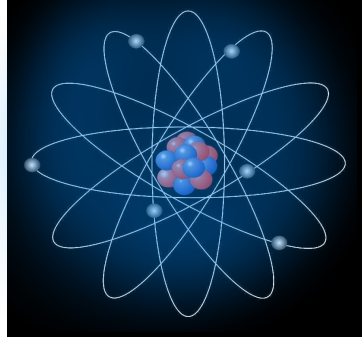


Delphinidin Molecule  
(blue pigment of flowers and grapes)



Atoms

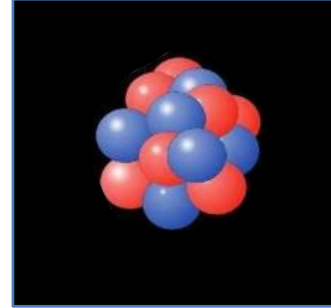
$10^{-10}$  m = 0.000 000 000 1 m



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?

**1917:** Discovery of the proton (Rutherford) using alpha particles

**1932:** Discovery of the neutron (Chadwick) using alpha particles

**1932:** Discovery of the positron (Anderson) in cosmic rays with a cloud chamber

**1937:** Discovery of the muon (Anderson and Neddermeyer) with a cloud chamber

**1947:** Charged pion discovery (Powell) and Kaon discovery (Rochester), both in cosmic rays and using photographic emulsions

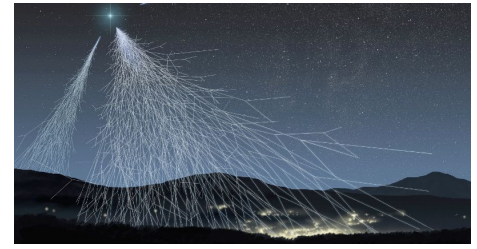
**1949:** Neutral pion discovery at the Berkeley 184 inch Cyclotron (Bjorklund et al)

**1955:** Discovery of the antiproton, at the Bevatron accelerator (in Berkeley)

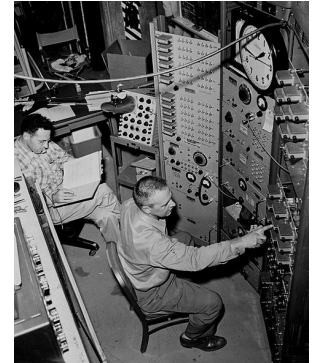
**1956:** Discovery of the neutrino (Cowan, Reines, et al), using nuclear reactor

**1950s-1960s:** Particle zoo explosion - “Had I foreseen this, I would have gone into botany” (Pauli)

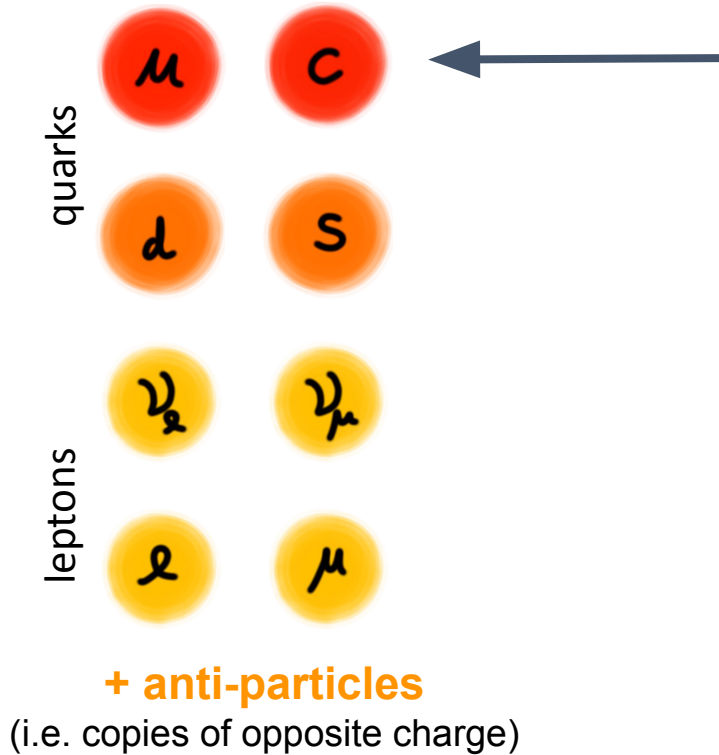
**1960s:** Quark Model and Deep Inelastic Scattering Experiments (SLAC)



**A first surprise - Muons**  
**“Who ordered that?” (Rabi)**



# November 1974 “Charm” Revolution: Two families of fermions?



## Symposium on the 50<sup>th</sup> Anniversary of the November Revolution



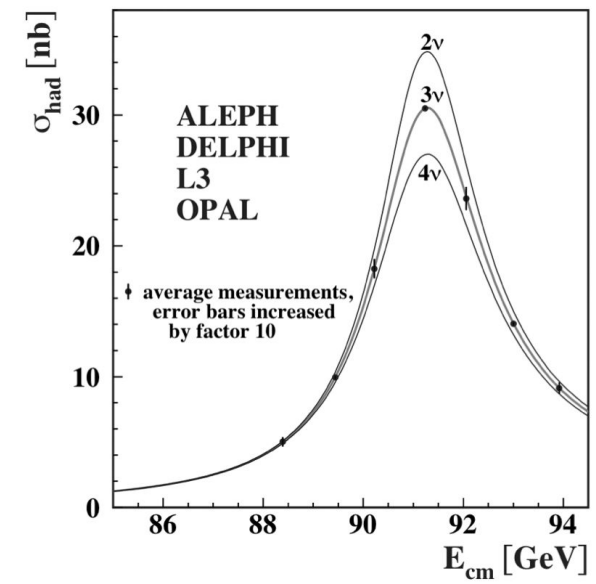
**Fast forward....**

# Three complete families of fermions

	quarks			Electrical Charge	Spin
	$u$	$c$	$t$	$+2/3$	$1/2$
	$d$	$s$	$b$	$-1/3$	$1/2$
	leptons			Electrical Charge	Spin
	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$0$	$1/2$
	$e$	$\mu$	$\tau$	$-1$	$1/2$

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

Intrinsic Angular Momentum

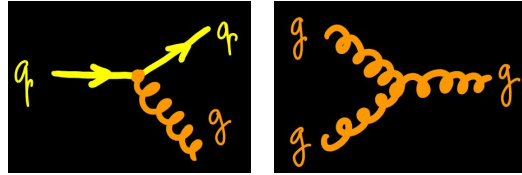


# Interactions occur through exchange of bosons



0

1

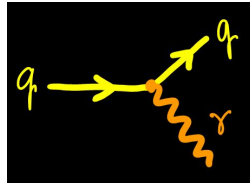


**Strong force**  
(gluons)



0

1

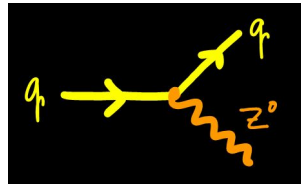


**Electromagnetic force**  
(photon)



0

1

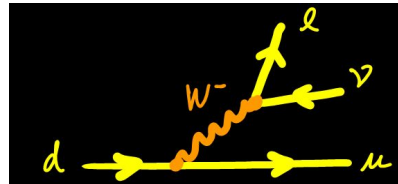


**Weak force**  
(W and Z bosons)



+1 or -1

1



Beta decay:  
 $n \rightarrow p e^- \bar{\nu}_e$

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.

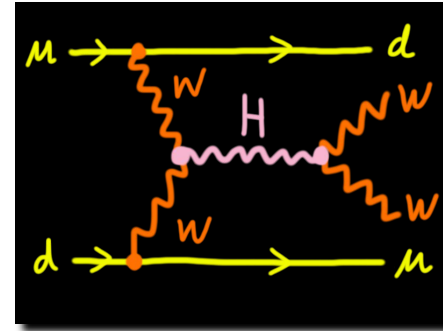
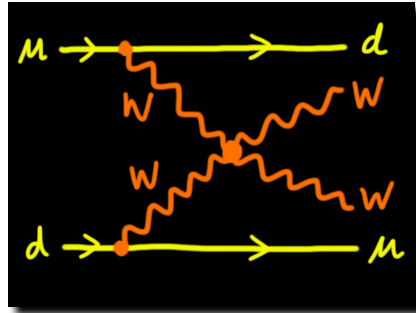
Charge

Spin

# 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!

Higgs



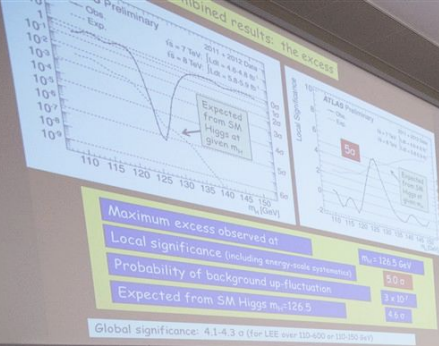
Electrical  
Charge  
0

Spin  
0

The LHC experimental facility was built to test this theory

# Higgs Particle Discovery Announcement July 4th, 2012

ICHEP,  
Melbourne



CERN, Geneva

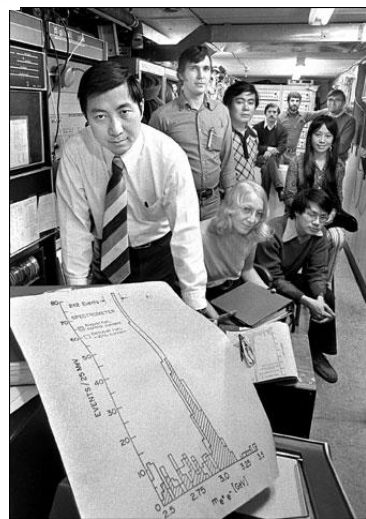
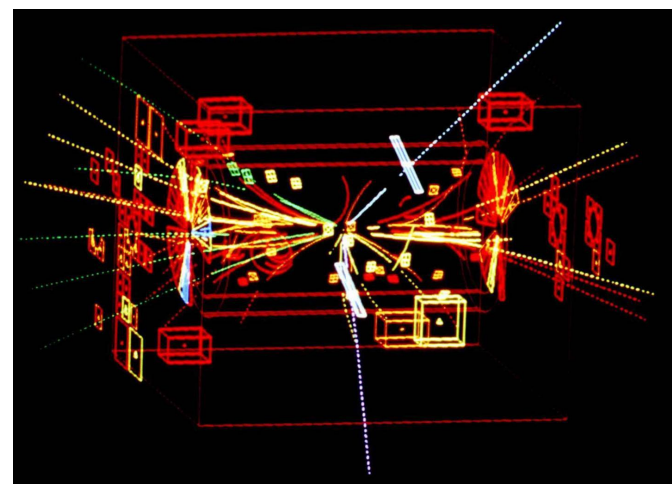
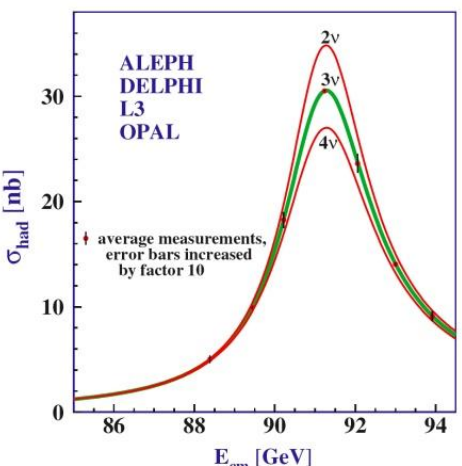
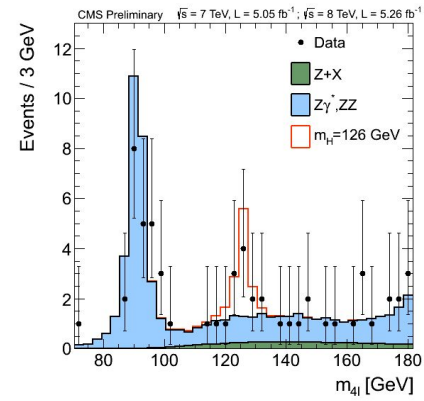
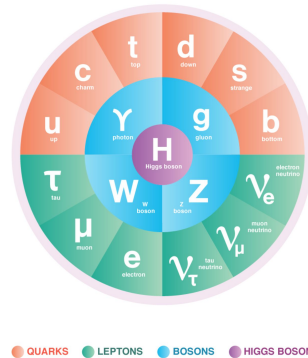
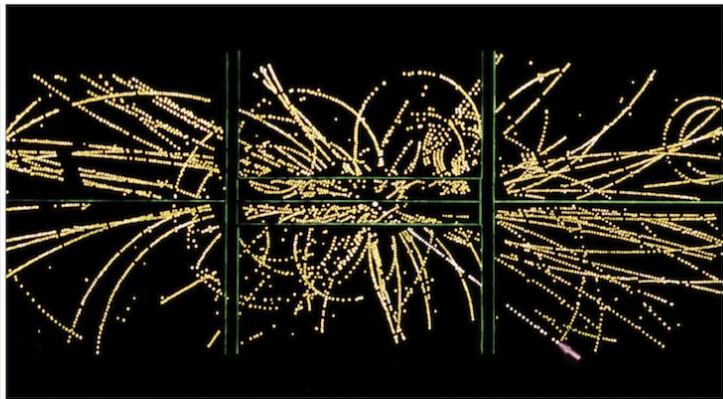
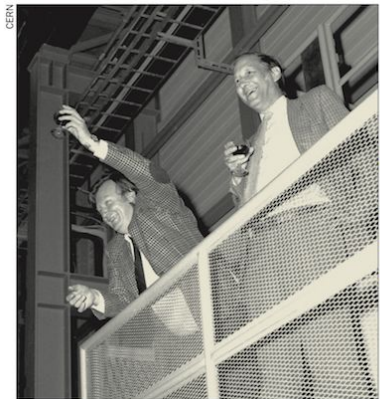


Something that looks like the Standard Model Higgs boson was discovered in 2012, Mass  $\sim 125$  GeV



Nobel prize in physics in 2013

# Experimental Development of the Standard Model

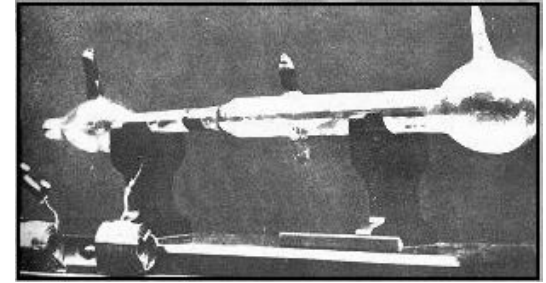


**How did we get here?  
(As experimentalists)**

**Let's talk about "facilities"**

# Tools $\longleftrightarrow$ Discoveries

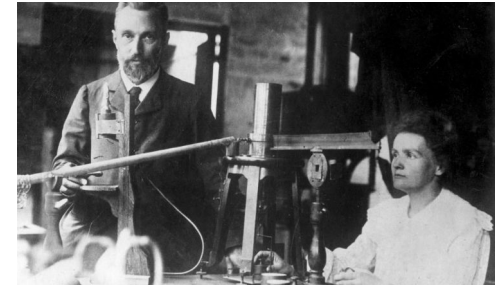
**1895** - Roentgen discovers x-rays using cathode ray tubes



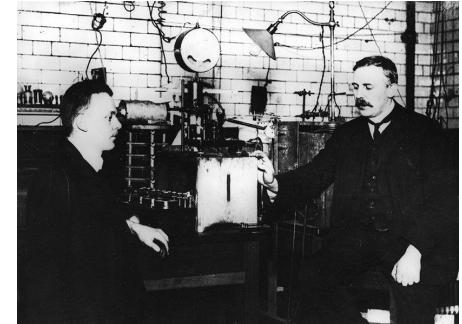
**1896** - Becquerel accidentally discovers radioactivity in uranium, trying to explain x-rays



**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



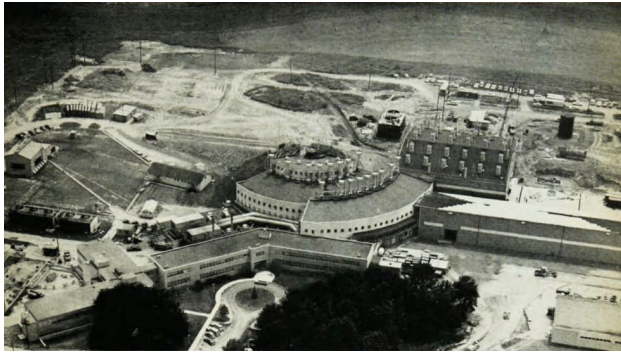
# Big Science and Accelerators - larger and larger facilities



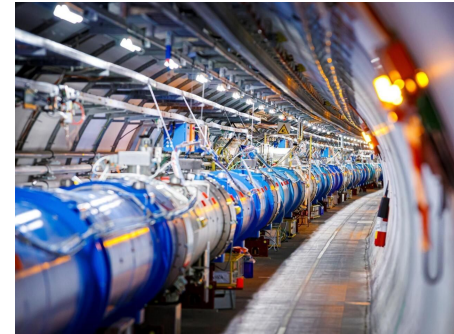
E.O. Lawrence and the cyclotron  
at U.C. Berkeley



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



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



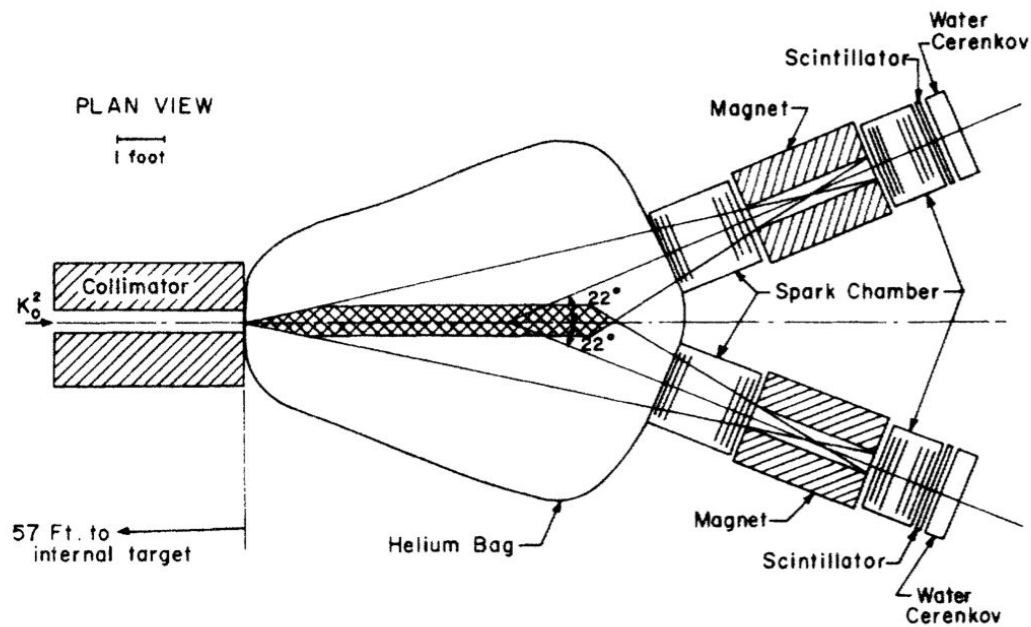
The Large Hadron Collider and  
CERN first as a European laboratory  
and then as a “world laboratory”

EVIDENCE FOR THE  $2\pi$  DECAY OF THE  $K_2^0$  MESON\*†

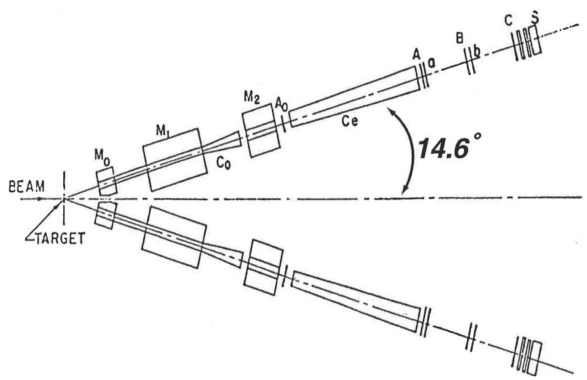
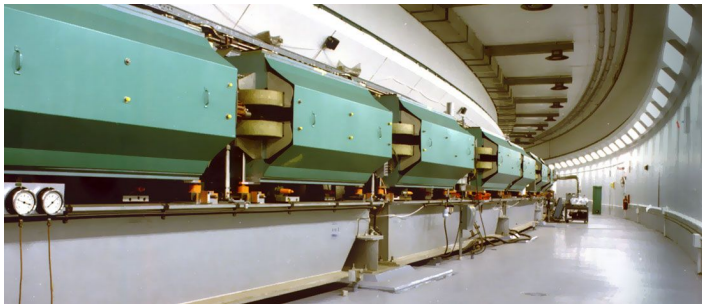
J. H. Christenson, J. W. Cronin,† V. L. Fitch,† and R. Turlay§

Princeton University, Princeton, New Jersey

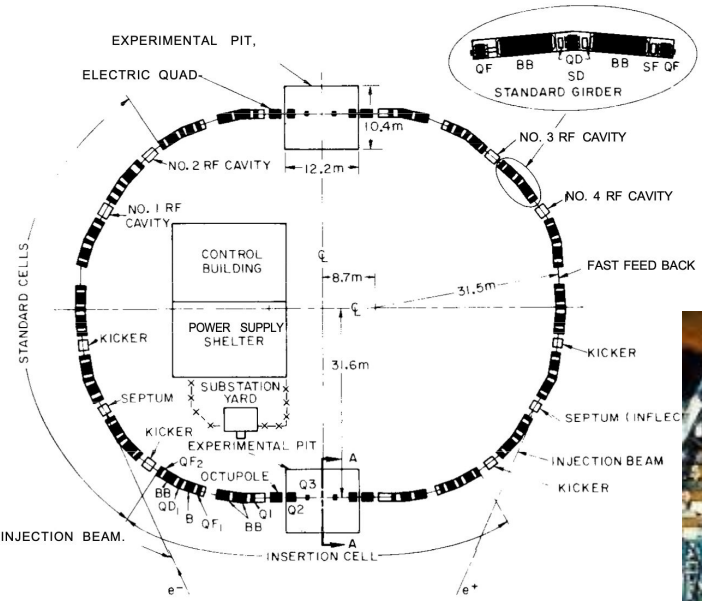
(Received 10 July 1964)



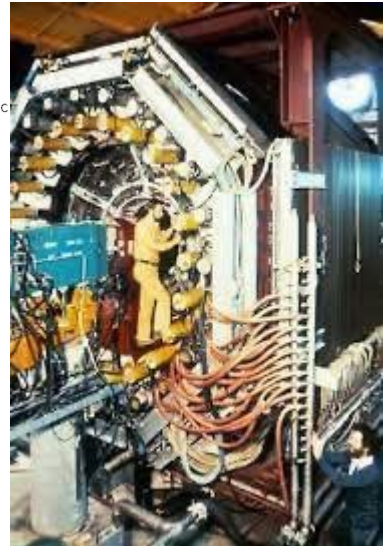
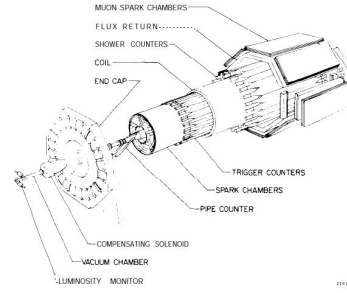
AGS at BNL delivering protons on a fixed target



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



1. Schematic of the SPEAR storage ring.

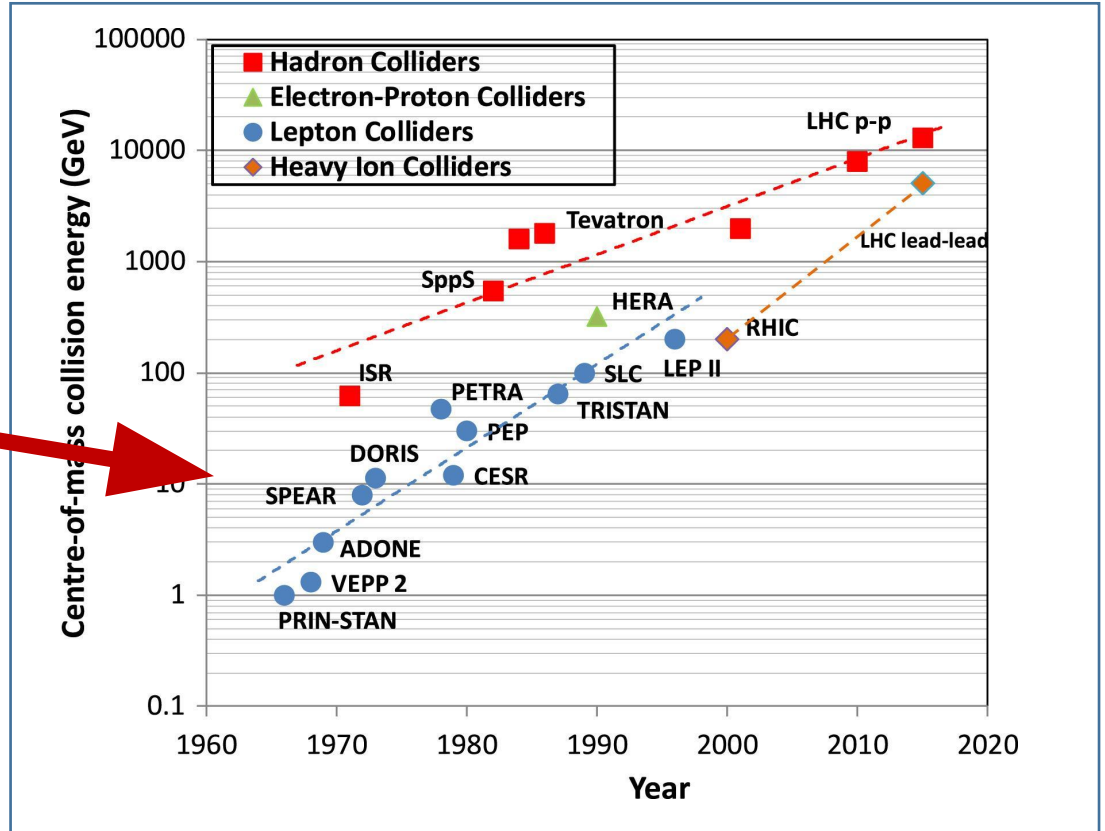
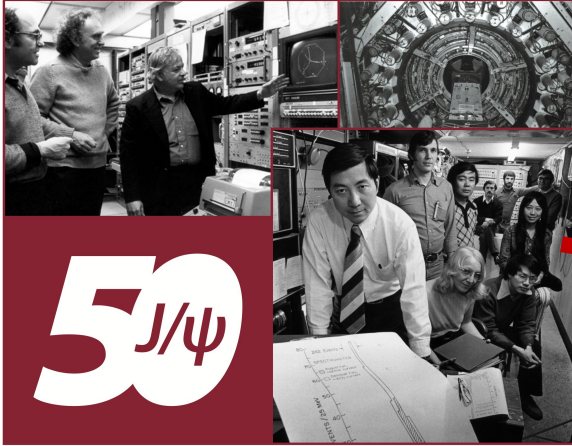


J and Psi discoveries in 1974



# High Energy Physics is a facilities driven science

Symposium on the 50<sup>th</sup> Anniversary  
of the November Revolution



<https://indico.slac.stanford.edu/event/9040/>

# HEP Laboratories CERN

## CERN's New Accelerator: Germans Insist on a Site in Germany

*London.* Western Europe has entered upon its own replay of the 1963 pork-barrel politicking that enveloped the high-energy accelerator that the U.S. Atomic Energy Commission (AEC) was forced to locate in Batavia, Illinois. And, to the chagrin of advocates of European cooperation in big science and technology, it is happening at the European Center for Nuclear Research (CERN), which has long stood out as a model of smooth-running, unselfish multinational endeavor.

The Batavia machine, it will be recalled, was designed at Berkeley's Lawrence Radiation Laboratory, with all involved assuming that it would be built in the vicinity of the design group, which was the pattern that had prevailed with all previous accelerators. However, midwestern legislators, scientists, and an assortment of allies drawn from industry and higher education rebelled at the prospect of R & D-rich California receiving still another major federal facility. Citing the alleged paucity of such govern-

clear that, if the machine does not go to Germany, German money will not go to the machine. Without Germany's 36 percent contribution to the \$340-million venture, the project will be dead, since the original designs were redrawn to a stripped down, economy level after Britain dropped out for financial reasons in 1968.

Germany's demand for the machine turns out, upon examination, to be based on fairly plausible grounds. The fact is that, because of her wealth, she puts the most money into Europe's cooperative endeavors but, because of her past, very little of this contribution ends up on German soil. Barred during the occupation from conducting research related to atomic energy, rocketry, electronics, and various other fields, the Germans kept alive in these areas by becoming great international cooperators, even at the cost of their money and talent going abroad. When the occupation restrictions were lifted, many institutions and patterns of cooperation were



ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE  
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

### CONVENTION

FOR THE ESTABLISHMENT OF A EUROPEAN ORGANIZATION  
FOR NUCLEAR RESEARCH

PARIS, 14<sup>th</sup> JULY, 1953

As amended

CERN was a collaborative decision taken in Europe in 1953, but key decisions that eventually made CERN a world laboratory for particle physics also came later, e.g. the SPS site choice in 1971 to build on the existing laboratory infrastructure.

#### Site of the CERN SPS Machine

It was finally decided to locate the SPS machine adjacent to the existing laboratory of CERN. This enabled the CERN 28 GeV proton synchrotron to be used as the injector for the new machine, and the existing West Experimental Area, together with the large bubble chambers and spectrometers, to be used as its first experimental area. The use of these existing facilities of CERN, and the infrastructure and services of the laboratory, reduced the original cost of the project by a factor of two, and considerably speeded up the construction of the new machine.

# HEP Laboratories FNAL and SSC

The US has struggled more with the competing regional politics of multiple large laboratories and large projects, e.g. as seen with the SSC history. See also [“The Site Context for Fermilab” \(Physics Today \(Jan 1989\)\)](#).

## AT LAST, CONGRESS AGREES TO BUILD SSC, AFTER TEXAS-TYPE WHEELING AND DEALING

The political barriers that stood in the way of the Superconducting Super Collider were overcome at last on 7 September. That morning a House-Senate conference committee assembled in a small room adorned with bucolic murals on the Senate side of the Capitol and agreed to allocate the down payment for what will certainly be one of the technological wonders of the 21st century—a mammoth accelerator operating underground in a 53-mile racetrack-shaped tunnel, where two counter-circulating beams of protons will collide at 40 TeV in the center of mass. Of the \$225 million the committee cleared for the SSC in the fiscal year beginning 1 October, \$135 million will go for the first year of construction. That is \$25 million more than the House voted in June to start building the machine, but \$25 million less than the Bush Administration sought.

Congressional support for the SSC was much stronger than any of its scientific proponents dared hope. The House vote on 28 June came after an emotional 1-hour 20-minute debate in which critics argued that it was a “quark-barrel” project that would drain funds away from more important priorities for science and society. But at the end the House paid little heed to such gloomy warnings and voted decisively 331 to 89 against a

site was chosen. He and many other members believed that a project so expensive and esoteric would have little appeal on Capitol Hill. Just because he is so influential as a power broker, Bevill was lobbied by President Bush, Southern colleagues, and university presidents and scientists. Roy Schwitters, the Harvard physicist who has been the SSC’s director since January, called on Bevill with other prominent physicists to convince him that the project was the right choice for the country at the right time. Even while embattled in an ethics scandal, Jim Wright, then House Speaker, lobbied Bevill and other lawmakers to vote for building the SSC in his home state of Texas.

### Within the ‘All-American’ bill

When Bevill finally agreed to back SSC construction, the action did not go unnoticed. Bevill is the key figure in unlocking pet projects for many members through energy and water appropriations legislation, known on Capitol Hill as the “All-American” bill because it often seems that every district in the country needs a new water project or research grant. This year the bill includes more than \$200 million for 40 new water projects that were not requested by the Administration but were proposed by individual members of Congress, usually as

committee. His cosponsors were Eckart and another Democrat, Howard Wolpe of Michigan, and Republican Sherwood Boehlert of upstate New York. They attacked the merits of the project, the cost, even the decision to locate it in Texas. Eckart called it “more pork for the plains of Texas.” Obey argued: “All we ask is that we stop making spending promises we can’t pay for... It’s one of the largest public works projects in the history of this country.”

Hyperbole also pervaded the rhetoric of the supercollider’s defenders. “If we can be successful with the SSC,” said Robert A. Roe, the New Jersey Democrat who heads the House Committee on Science, Space and Technology, “we can revolutionize knowledge in the world.” Roe spoke of investing in the technology of the future and protecting the nation’s scientific preeminence. Only a week before, at a meeting to devise strategy for the impending floor vote, Roe had threatened to oppose the SSC unless more money was restored for a New Jersey project—magnetic fusion research at the Princeton University Plasma Physics Laboratory. Roe’s resistance was averted by some last-minute maneuvering by Jim Chapman, the Texas Democrat who Wright had placed on the appropriations committee to steer the SSC through

## CONGRESS CANCELS SSC AND ALLOCATES HIGH BUDGETS FOR TECHNOLOGY IN 1994

When fiscal 1994 began on 1 October, Congress still had not appropriated funds for any of the R&D agencies; in the weeks that followed, a series of bills, each known as a “continuing resolution” had to be passed for the government to operate at no more than fiscal 1993 budget levels. But by the end of October, all the R&D budgets were in place except for those in Defense and Interior. The results, on balance, were only sort of good. Unarguably the worst result was the decision on the Superconducting Super Collider—virtually a death knell for high-energy physics in the US.

While many of the research agencies received increases, varying from a paltry 2% for NASA to a prodigious 35% for the National Institute of Standards and Technology, the allocations were almost always less than the Administration had requested (see table). What’s worse, some important basic science projects were abruptly canceled—among these, the SSC, almost 20% completed under the gentle rolling prairie around Waxahachie, Texas, and the second of two Advanced X-ray Astrophysics Facilities, a single spectrometer mission bearing the appellation AXAF-S that Senate appropriators “reluctantly” considered less than cost-effective.

### Tragedy of the SSC

In delaying the SSC, Congress allo-

troweak symmetry and to reveal the ultimate origin of particle masses. Without the SSC those scientific problems may remain unsolved—at least until another proton collider is built, most probably the Large Hadron Collider that is now proposed for an existing underground tunnel at CERN, the large European accelerator center outside Geneva. Still, without an SSC, the continued vitality of the US high-energy program is in grave peril. To answer whether the 60-year history of American contributions to particle physics is approaching an end and to examine the options available to the community, Energy Secretary Hazel R. O’Leary directed her High-Energy Physics Advisory Panel to describe the field’s future a decade hence. HEPAP was asked explicitly to weigh the possibility of international collaboration with CERN. The panel’s schedule calls for submitting an initial report by 28 February and a final report by 30 April.

The fatal blow dealt the SSC in the House is usually attributed to its ascending cost, now estimated at nearly \$11 billion, in a period when Congress is emphasizing deficit reduction and balanced budgets. To be sure, the SSC was a prominent target in a time of scarcity, though allegations of mismanagement didn’t win friends in Congress (see PHYSICS TODAY, August, page 43). The project’s

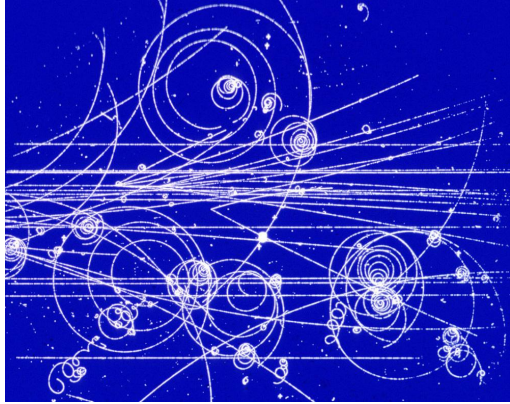
cal 1994, the research budgets fared better than might be expected. Ironically, the \$640 million allocated for the SSC’s funeral is the largest amount the project ever received from Congress.

The final budgets included a few surprises: The largest big-ticket item, NASA’s space station, squeaked through the appropriations process in the House by one vote, after a great deal of jawboning by the White House and by the lobbyists for the aerospace industry who made the arguments for retaining jobs and maintaining foreign commitments. In the end, the station got the full \$2.1 billion that the Administration had asked for.

### DOE’s two new projects

Though it lost the SSC, the Energy Department gained two new projects: \$36 million was allocated to begin work on the asymmetric B-meson accelerator at the Stanford Linear Accelerator Center and \$17 million of the requested \$39 million was appropriated to continue designing the Advanced Neutron Source, which would be constructed at the Oak Ridge National Laboratory. Although the House-Senate conference report accompanying DOE’s bill proposes that ground for the ANS will be broken in 1995, the facility’s \$2.7 billion price tag is bound to provoke the nipping scrutiny by the department and Congress that contributed

# Left uncovered here, but not to be forgotten: Detectors (+ Electronics)

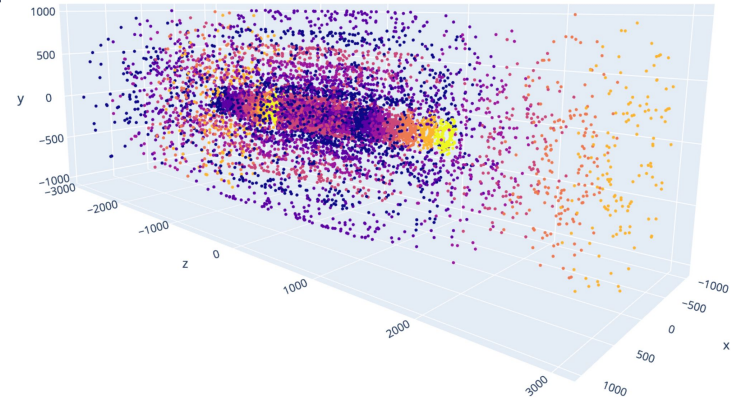
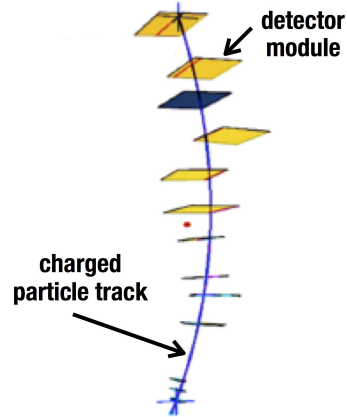
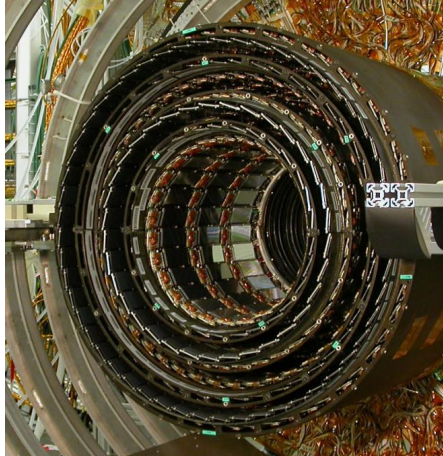


Bubble chamber  
photography

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

# Experimental Observation of a Heavy Particle $J^\dagger$

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,  
J. Leong, T. McCorrison, 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  $p + \text{Be} \rightarrow e^+ + e^- + x$  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

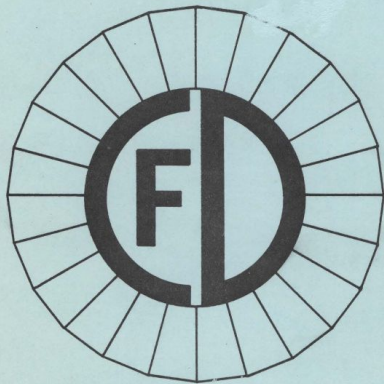
G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,  
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,  
J. Wiss, and J. E. Zipse

*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  $e^+e^- \rightarrow \text{hadrons}$ ,  $e^+e^-$ , and possibly  $\mu^+\mu^-$  at a center-of-mass energy of  $3.105 \pm 0.003$  GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

DESIGN REPORT  
FOR THE  
FERMILAB COLLIDER DETECTOR FACILITY  
(CDF)  
AUGUST, 1981



August, 1981

DESIGN REPORT

For the Fermilab Collider Detector Facility (CDF)

Argonne National Laboratory - D. Ayres, R. Diebold, E. May, B. Musgrave, L. Nodulman, J. Sauer, R. Wagner, A.B. Wicklund

University of Chicago - H. Frisch, C. Grosso-Pilcher, M. Shochet

Fermi National Accelerator Laboratory - M. Atac, F. Bedeschi, A. Brenner, T. Collins, T. Droege, J. Elias, J. Freeman, I. Gaines, J. Grimson, D. Gross, D. Hanssen, H. Jensen, R. Kadel, H. Kautzky, R. Kephart, M. Ono, R. Thatcher, D. Theriot, A. Tollestrup, R. Yamada, J. Yoh

Laboratori Nazionali dell' INFN - Frascati - S. Bertolucci, M. Cordelli, P. Giromini, P. Sermoneta

Harvard University - G. Brandenburg, R. Schwitters

University of Illinois - G. Ascoli, B. Eisenstein, L. Holloway, U. Kruse

KEK - S. Inaba, M. Mishina, K. Ogawa, F. Takasaki, Y. Watase

Lawrence Berkeley Laboratory - W. Carithers, W. Chinowsky, R. Kelly, K. Shinsky

University of Pisa - G. Bellettini, R. Bertani, L. Bosio, C. Bradaschia, R. DelFabbro, E. Focardi, M.A. Giorgi, A. Menzione, L. Ristori, A. Scribano, G. Tonelli

Purdue University - V. Barnes, R.S. Christian, C. Davis, A.F. Garfinkel, A. Laasanen

Texas A & M - P. McIntyre, T. Meyer, R. Webb

Tsukuba University - Y. Asano, S. Kim, K. Kondo, S. Miyashita, H. Miyata, S. Mori, I. Nakano, Y. Takaiwa, K. Takikawa, Y. Yasu

University of Wisconsin - D. Cline, R. Loveless, R. Morse, L. Pondrom, D. Reeder, J. Rhoades, M. Sheaff

**August, 1981**

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8. High level computer complex: These computers run the whole system. The complex will contain one or more powerful 32-bit processors together with additional CPU's to act as front ends. Its jobs include data logging onto magnetic tape, overall performance monitoring, overall system control, event analysis, event display, data base management, etc.

As many as possible of these components will be assembled from commercially available CPUs and standard software so that our limited resources can be focused on the pieces of the problem that cannot be solved with commercially available equipment.

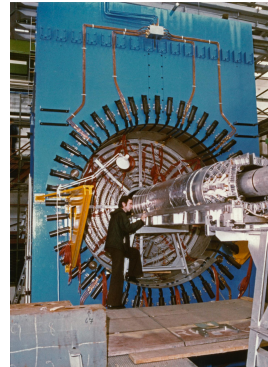
### 9.3 SETTLED ISSUES

Several important decisions have already been made about the implementation of certain pieces of the data acquisition system. These are:

1. VAX: The high level CPU will be a VAX.
2. FASTBUS: The various processors in the system will be linked via the FASTBUS, and most data transfers in the system will be block transfers from one FASTBUS memory to another.
3. Front End Modules: There is an overall requirement on the Front-End Modules that they deliver their data into FASTBUS memories within 0.5-1.0 milliseconds.

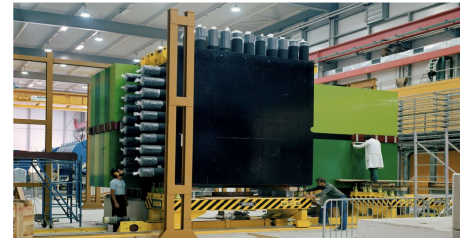
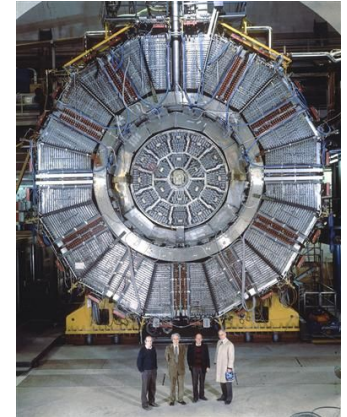
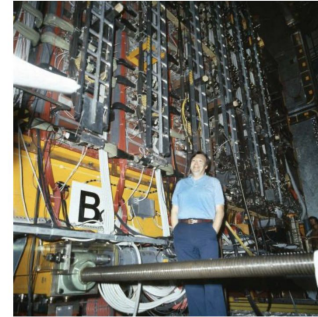
## CDF CDR

And there was a similar evolution towards collider detectors, larger (international) collaborations at PETRA with 4 fixed experiments, UA1 and UA2 at the SppS, at LEP with 4 fixed experiments. And also non-collider collaborations such as EMC were building long running (evolving) facilities.



29 JUNE 1978

### UA1 experiment approved





## Technical Design Report

### The *BaBar* Collaboration

March, 1995

March, 1995

11

## Computing

There are a number of computing challenges for the proposed *BaBar* detector. The data rates are high for an  $e^+e^-$  collider, and there is a large quantity of useful data which must be stored and analyzed. Convenient interactive access must be available for the efficient extraction of physics results. In addition, the wide geographical distribution of the collaboration implies significant issues for remote access to the data and code, collaboration communication, and for remote computing.

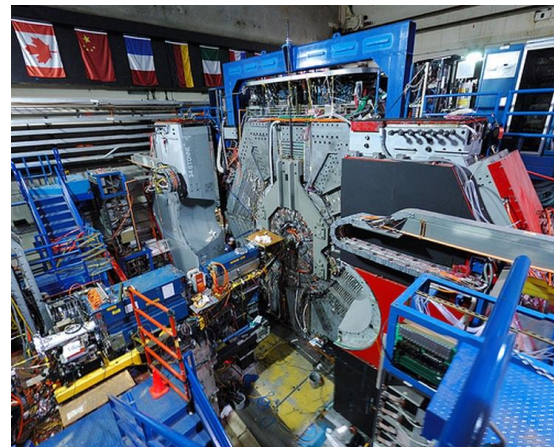
The *BaBar* Computing System, as defined here, includes several aspects: (1) the online data acquisition, control, and monitoring hardware and software; (2) the offline computing hardware—CPUs (“farm” and desktop), storage, X servers, and networking—whether local to SLAC or at remote locations; (3) the software environment in which the computing work is done; and (4) the code itself used by the collaboration. All of these are important items for *BaBar* computing, although parts of these, including most of (2), are properly considered institutional infrastructure.

The next section reviews the computing requirements, and Section 11.2 gives an overview of the proposed computing system. Following these are more detailed discussions of the computing model, software environment, online system, reconstruction and analysis framework, computing support plan, integration issues, system responsibilities and management, and cost and schedule.

### 11.1 Requirements

In this section, the basic computing requirements for *BaBar* are summarized. These are divided into operational requirements and technical requirements. Operational requirements are broad capabilities that must be present in order for the system to respond adequately to the environment within which it must operate. Technical requirements are specific capabilities that the system must exhibit in order to meet the operational requirements, for example, the CPU power and bandwidth. Estimates are given for the early years of the experiment. It is recognized that the requirements may increase as the experiment progresses; hence, a general further requirement exists that the system be scalable to meet future needs.

50 pages on Computing

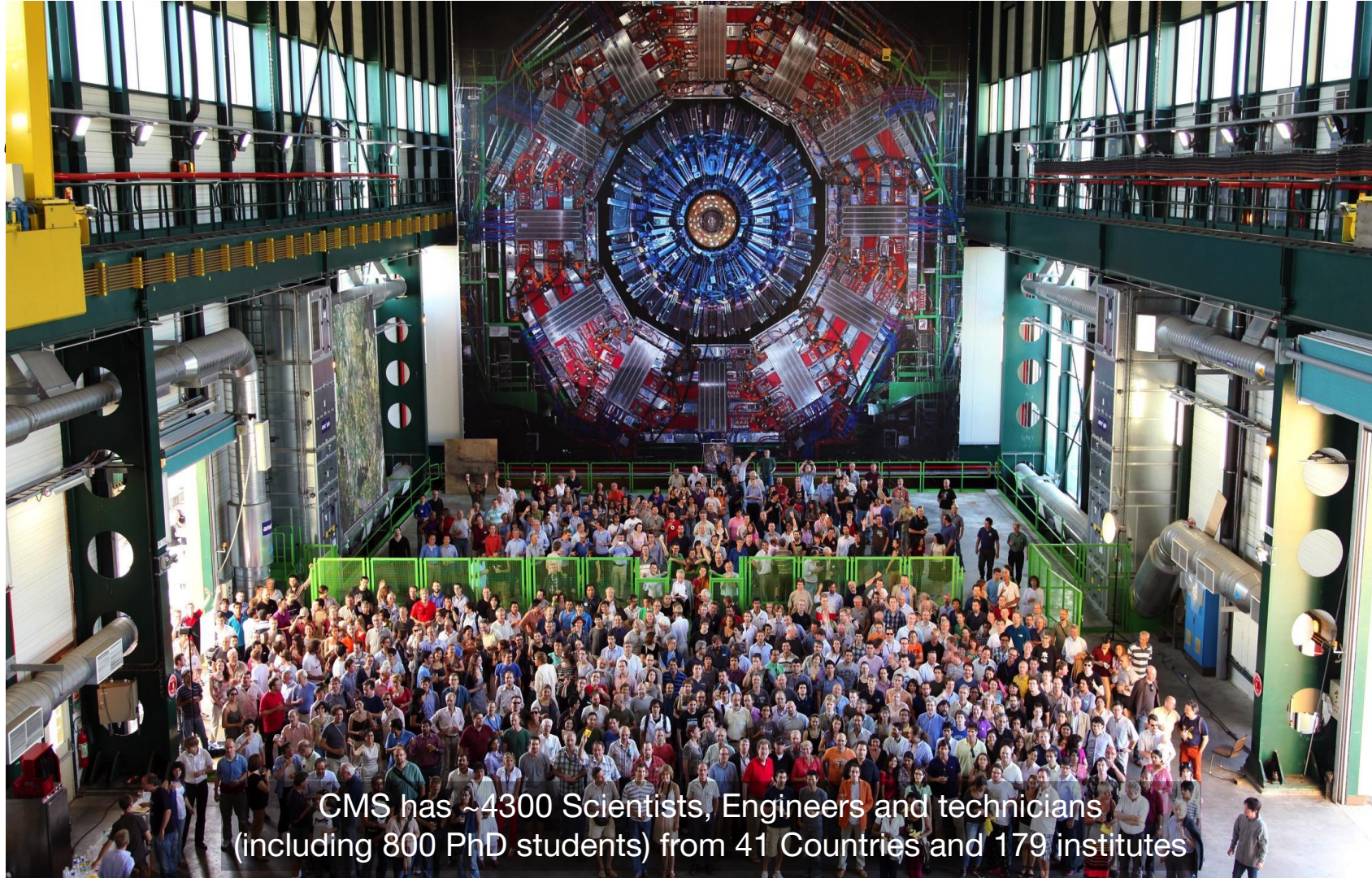


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TECHNICAL DESIGN REPORT FOR THE *BaBar* DETECTOR

BaBar TDR  
March 1995

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

# 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  $\mu\text{m}$ )  $\sim 16\text{m}^2 \sim 66\text{M}$  channels  
Microstrips (80x180  $\mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

SUPERCONDUCTING SOLENOID  
Niobium titanium coil carrying  $\sim 18,000\text{A}$

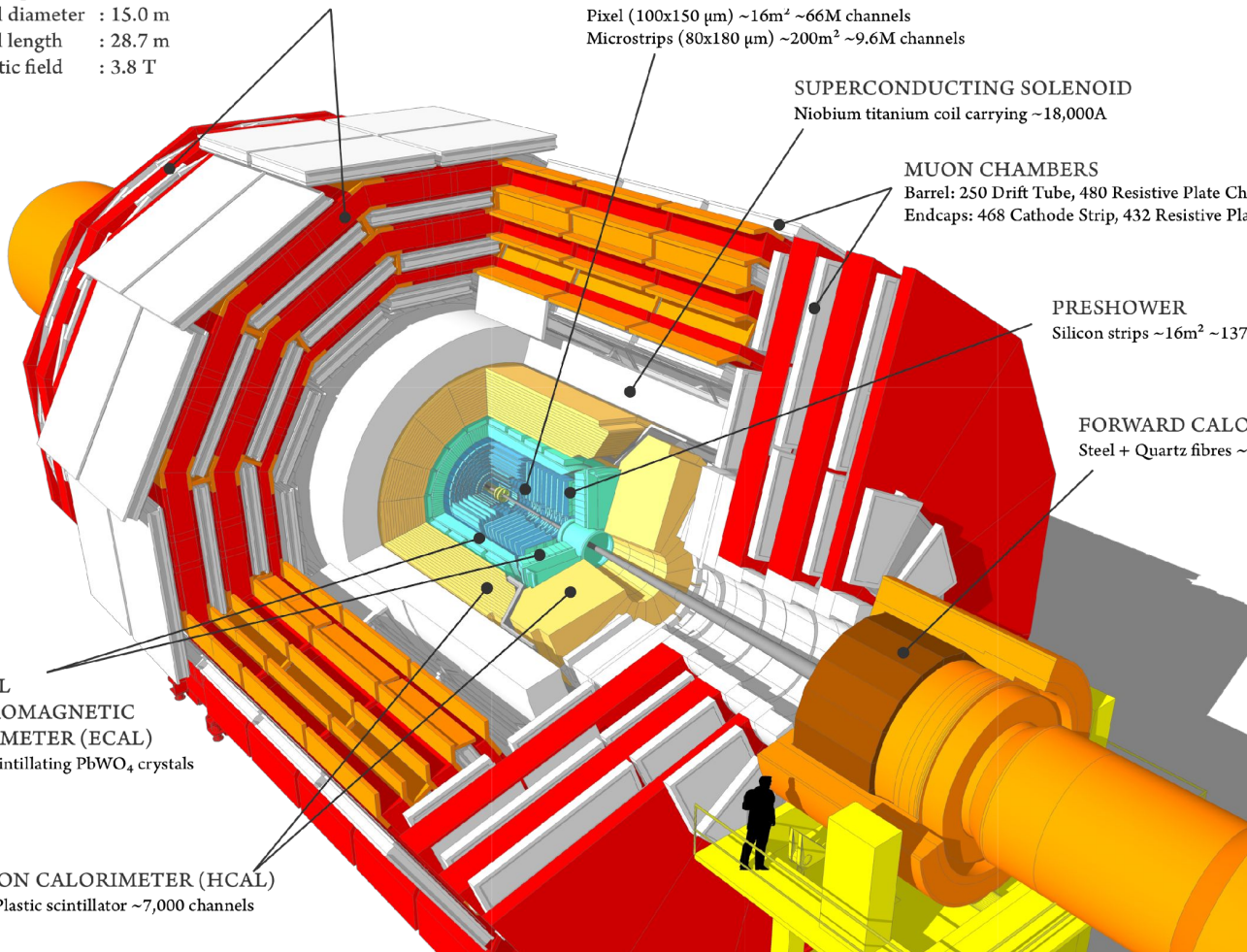
MUON CHAMBERS  
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

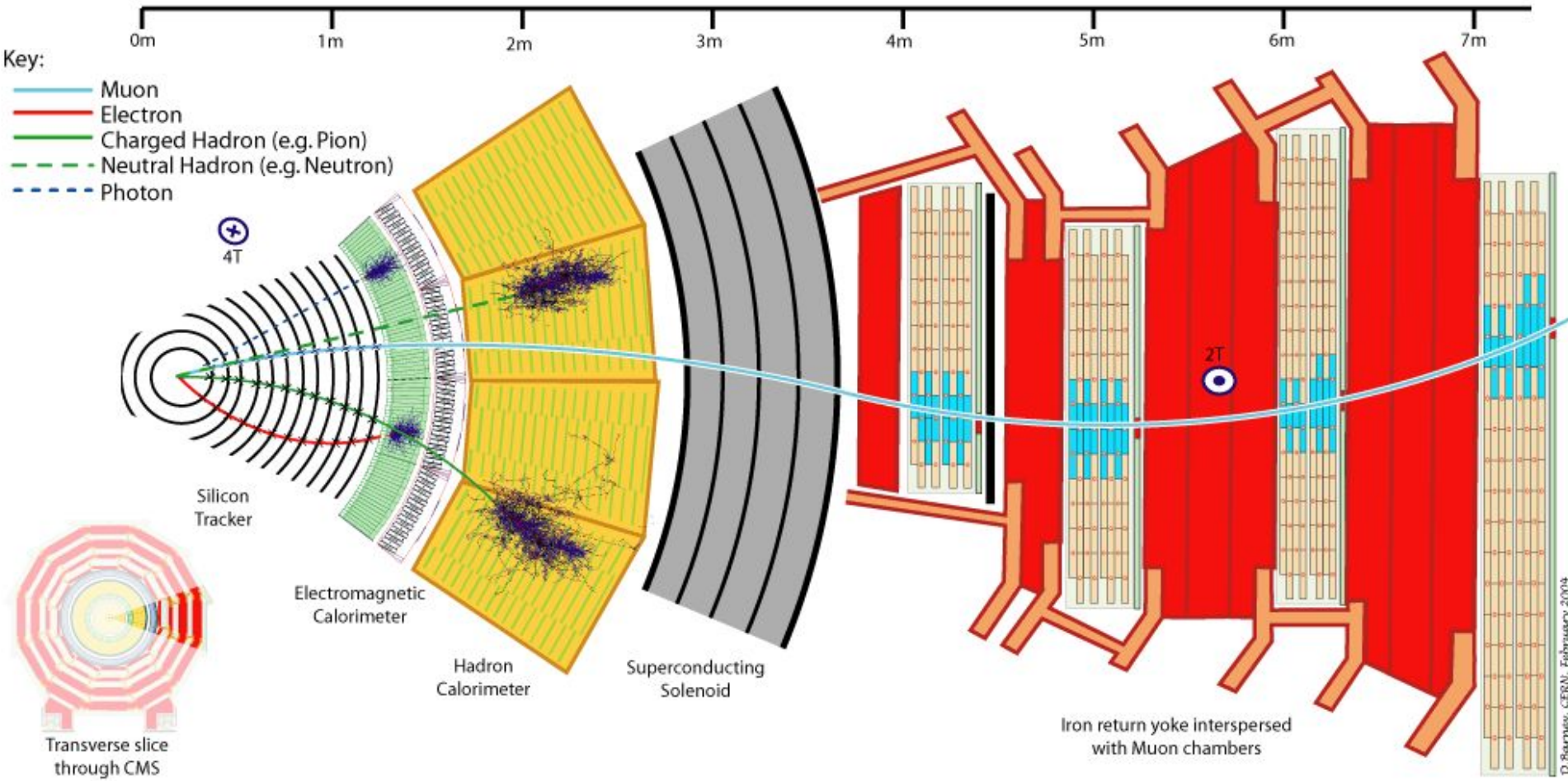
PRESHOWER  
Silicon strips  $\sim 16\text{m}^2 \sim 137,000$  channels

FORWARD CALORIMETER  
Steel + Quartz fibres  $\sim 2,000$  Channels

CRYSTAL  
ELECTROMAGNETIC  
CALORIMETER (ECAL)  
 $\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

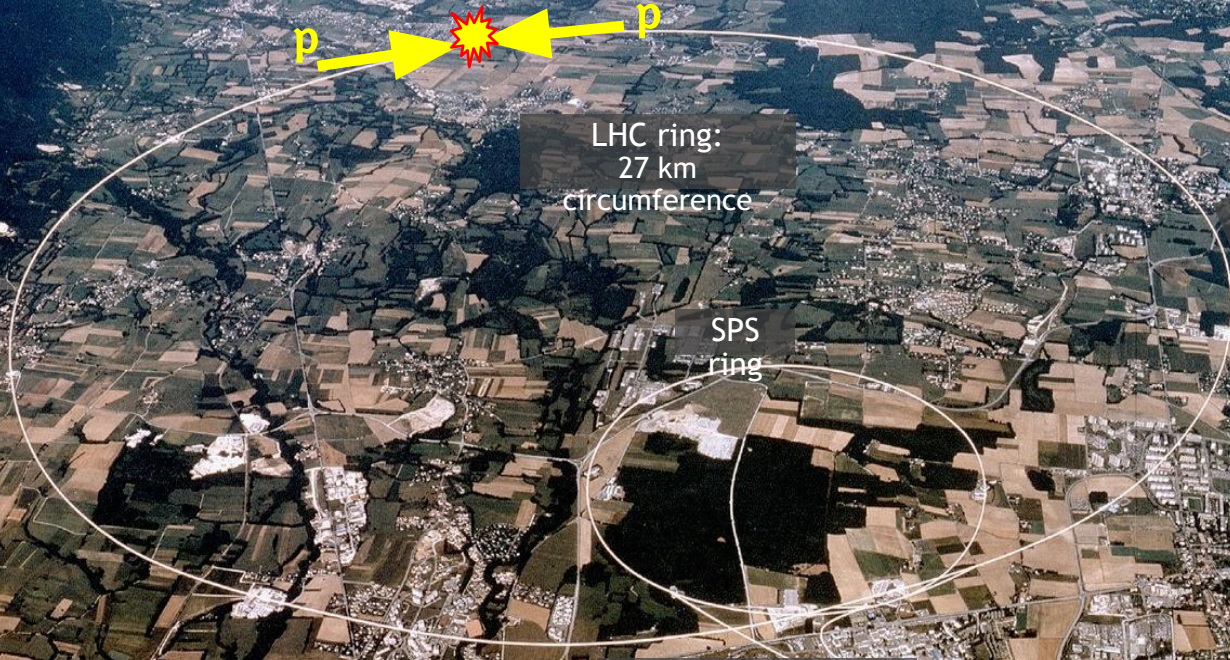
HADRON CALORIMETER (HCAL)  
Brass + Plastic scintillator  $\sim 7,000$  channels





**Large Hadron Collider**  
proton-proton collisions  
Center of mass energy: 7-8-13-13.6-14  
TeV

Lake  
Geneva



LHC ring:  
27 km  
circumference

SPS  
ring

Airport

CERN



# Computing in High Energy Physics



## COMPUTING IN HIGH ENERGY PHYSICS

June 25-28, 1985 - Amsterdam (Netherlands)

Organized by the National Institute for Nuclear Physics and High Energy Physics, section H (NIKHEF-H) and the Computer Science Dept. (FVI), University of Amsterdam

### FINAL PROGRAM AND GENERAL INFORMATION

- \* Program
- \* Exhibition
- \* General Information
- \* List of Participants per 06-21-1985

## Computing in High Energy Physics Conference Series

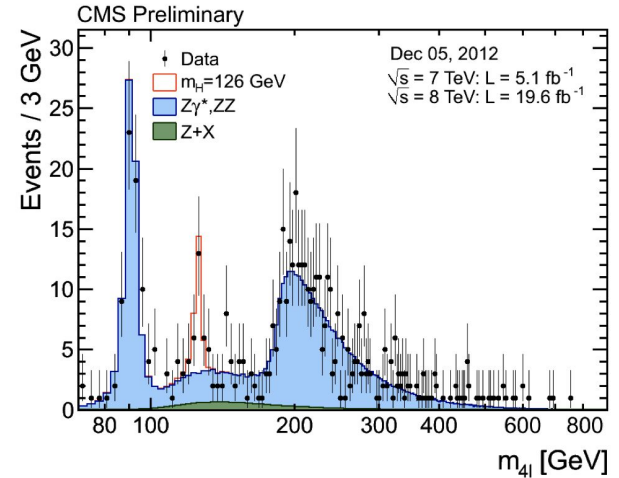
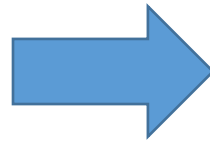
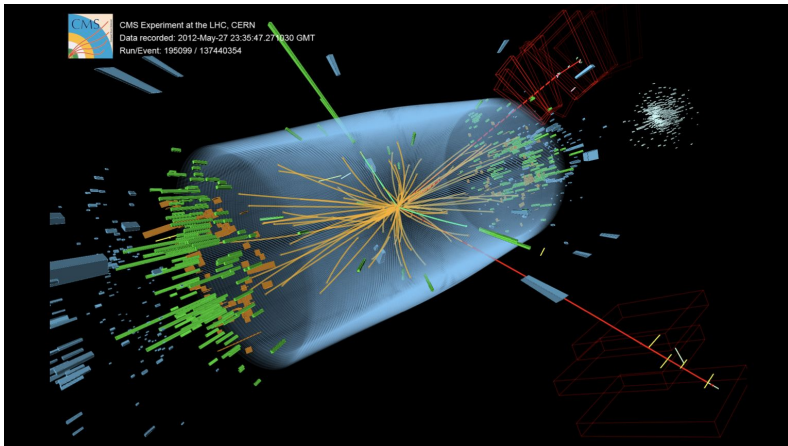
Every 18 months since 1985.

Initial conference was heavily focused on topics highly connected to computing hardware, data acquisition and networking. (I am not going to do justice to these the involvement of HEP in the development of computing in this talk due to lack of time, but it was an important part of the history.)

Software became an ever present topic as things involved.

<http://www.chep2013.org/assets/doc/CHEP1985-final-program.pdf>

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



Large scale software  
and computing  
infrastructures



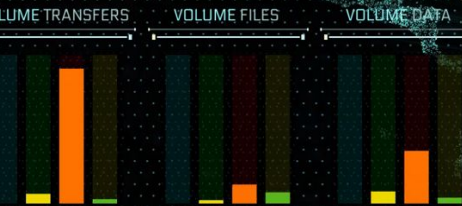
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LAST DATA UPDATE

9.7 MB Downloaded Wednesday, 11 September 2019 14:05:12  
Last transfer was on: Monday, 29 July 2019 08:00:00

LOADING  
100 %



DATA TRANSFER CONSOLE

425847625 From BFlorida-HEP To UMaineHEP Monday, 29 July 2019 04:04:50  
 0 From UCSD072 To INFN-T1 Monday, 29 July 2019 04:05:40  
 0 From Vanderbilt To Indonesia Monday, 29 July 2019 04:06:06  
 153672273 From NS3-CC To INFN-BARI Monday, 29 July 2019 04:07:01  
 4930015 From FI-HP\_T2 To CERN-PROD Monday, 29 July 2019 04:08:20  
 763851025 From INFN-T1 To GLWV Monday, 29 July 2019 04:08:36  
 132292923 05 From INDIA-CMS-TIFR To pc Monday, 29 July 2019 04:08:43  
 102057038567 From CERN-PROD To INFN-T1 Monday, 29 July 2019 04:09:29  
 1074048 From MIT\_CMS\_18 FI-HP\_T2 Monday, 29 July 2019 04:09:54  
 502059550 From INFN-T1 To CTI-CMS\_T2 Monday, 29 July 2019 04:10:11  
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 3207280733333 From CERN-LIGO To INFN-ANZ Monday, 29 July 2019 04:12:20  
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 0 From INFN-UK\_3 To CERN-LEP Monday, 29 July 2019 04:12:25  
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 0 From Vanderbilt To UCSD072 Monday, 29 July 2019 04:14:57  
 33855768 373204 From RU-Prisma-HEP To CERN-PROD Monday, 29 July 2019 04:15:10  
 18644974 From CERN-LIGO To RU-Proton-HEP Monday, 29 July 2019 04:15:45

# The Worldwide LHC Computing Grid (WLCG)

About 1 million processing cores

170 data centres in 42 countries

> 1000 Petabytes of CERN data stored worldwide

# 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.

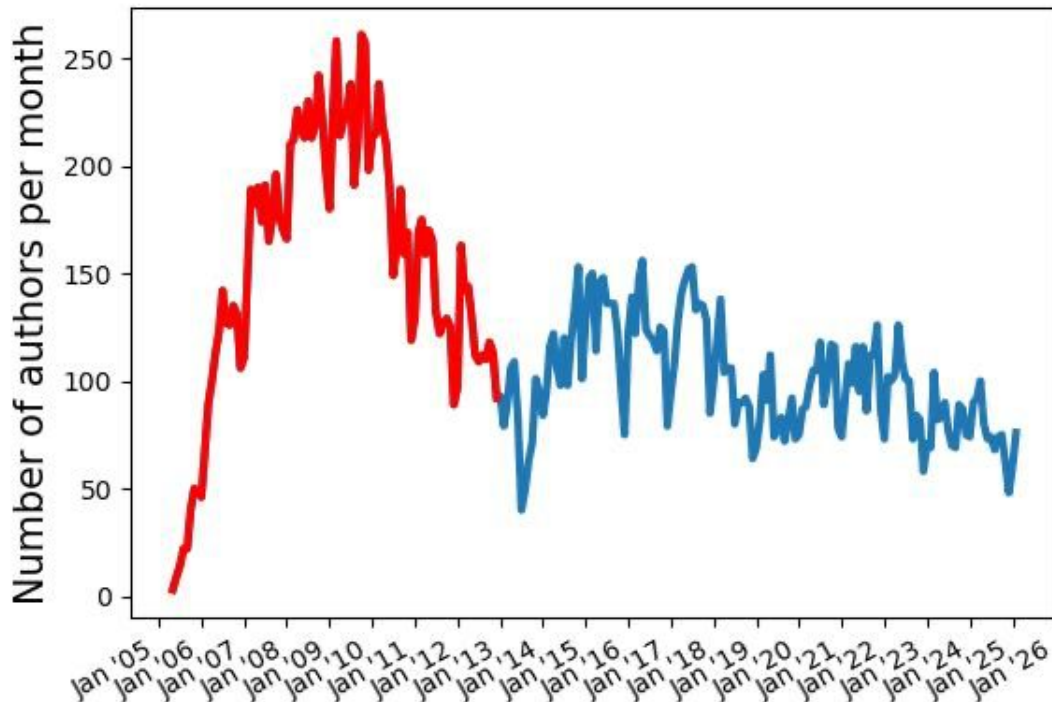


# Large scale collaborative software development in HEP - CMSSW Example

In addition to software codes useful for many experiments, each experiment usually has its own customized software, often with millions of lines of code.

For example, CMS has “CMSSW”:  
<https://github.com/cms-sw/cmssw>

These are also highly collaborative software development projects, with many physicist developers contributing along with (typically) a handful of core experts/professionals.



# Software in High Energy Physics



CERN-DD 78-2 c<sub>1</sub>

R. Brun  
R. Hagelberg  
M. Hansroul  
J.C. Lassalle

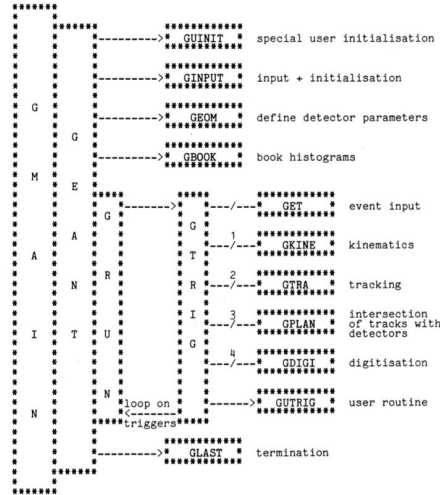
CERN - DATA HANDLING DIVISION  
DD/78/2  
January 1978

[Redacted]

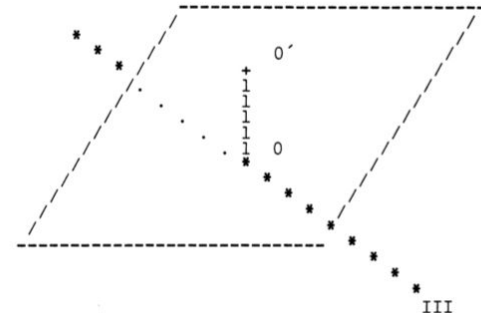
CM-P00059731

SIMULATION PROGRAM  
FOR  
PARTICLE PHYSICS EXPERIMENTS

USER GUIDE  
AND  
REFERENCE MANUAL



# MC Simulation of the "passage of particles through matter"

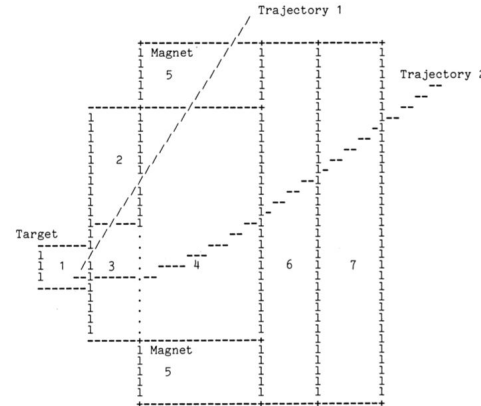
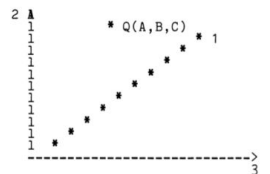


### 2.3 REFERENCE SYSTEM

The master reference system is determined according to the way the user represents the kinematical quantities. Consequently this system will also be referred to as the user system.

If the axes are labelled 1,2,3, then the point Q(A,B,C) is represented by

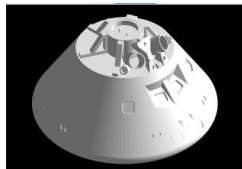
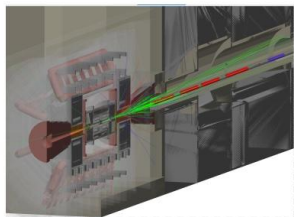
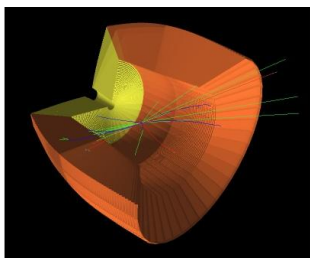
- A on axis 1
- B on axis 2
- C on axis 3



The media, the magnetic field, and some of the detector parameters are defined in this system.

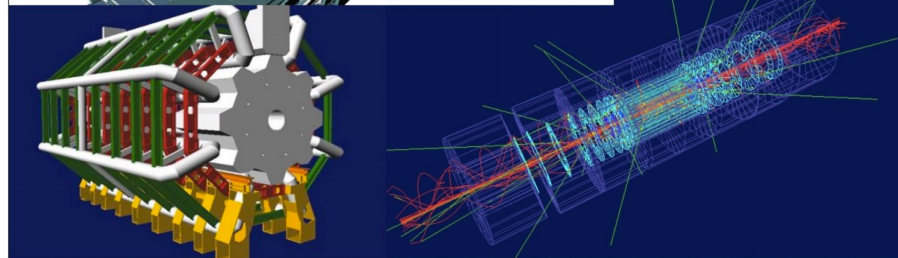
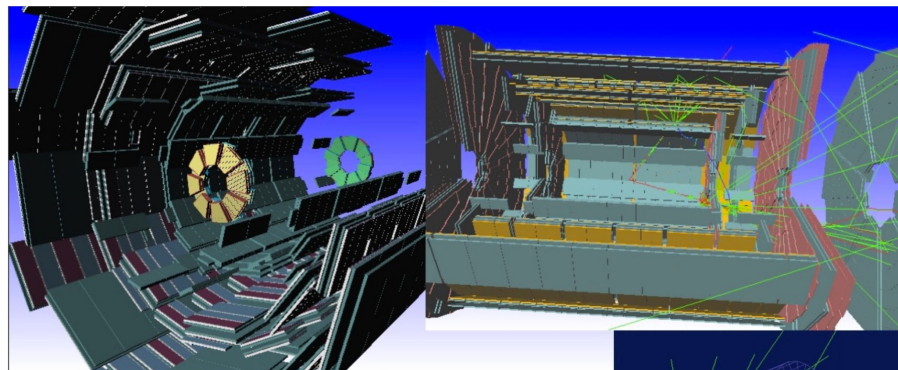
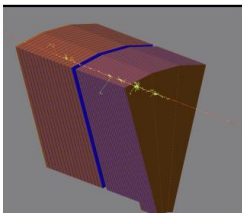
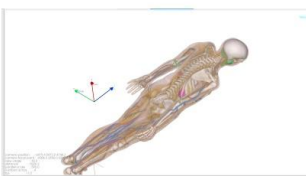
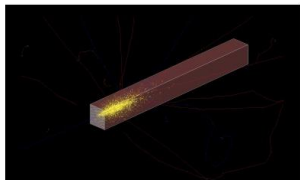
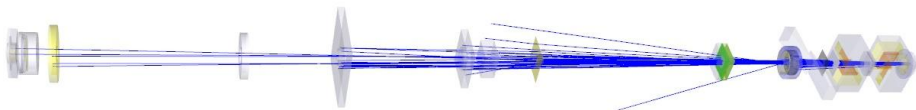
# GEometry ANd Tracking (GEANT) Software

## FORTRAN

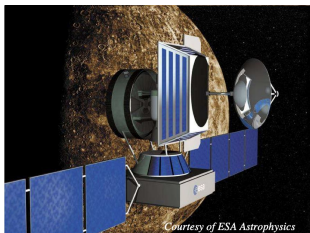
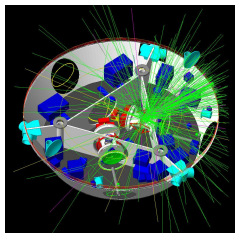
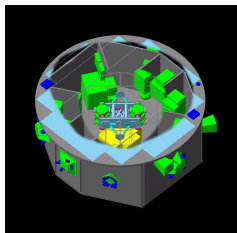


MC Simulation

C++ 1995-



Many applications beyond particle physics

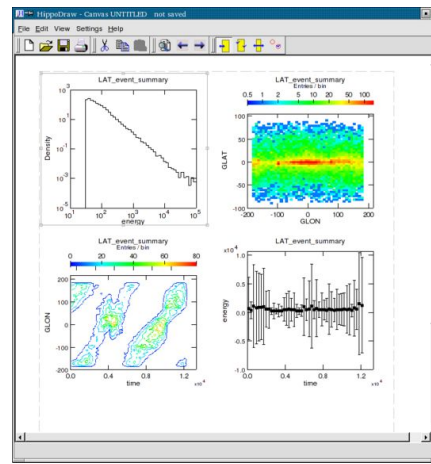


LISA Pathfinder

Bepi Colombo



# Visualization and Data Analysis



1990s



Hippodraw



Histo-Scope & NPlot

Histo-Scope is a tool to select and display histograms, n-tuples, and scalar values from a program as data is being created or analyzed. Using Histo-Scope, physicists can interactively "browse" through the large quantities of statistical data that their analysis and data acquisition programs gather as they run. It is intended to complement existing physics applications, providing immediate access to data while a program is running, as well as new interactive methods for viewing data.

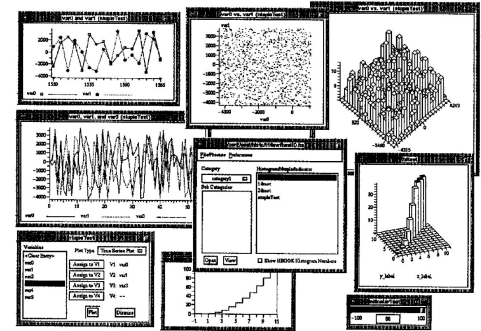
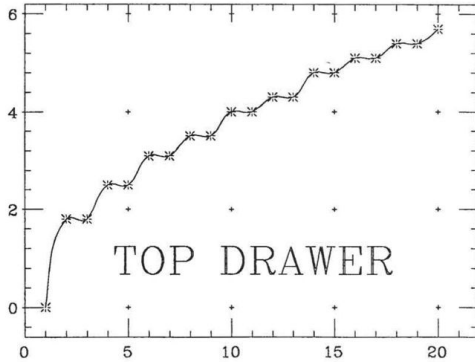


Figure 1. Viewing Data with Histo-Scope

1992(?) - [unclear]

SLAC COMPUTATION GROUP  
Stanford, California

CGTM No. 178  
Revised August 1978;  
Revised November 1980;  
Revised April 1987



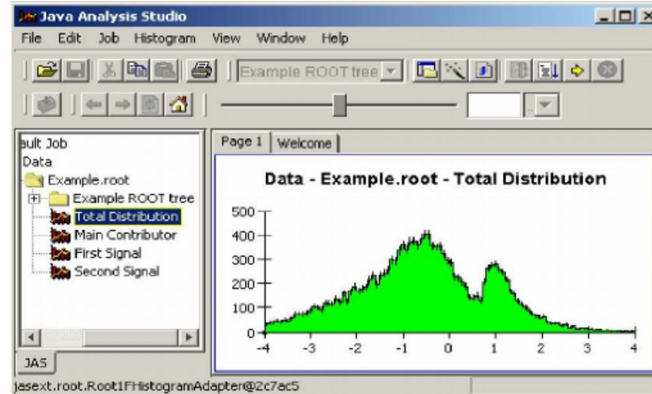
Roger B. Chaffee  
Computation Research Group  
Stanford Linear Accelerator Center

Revised April 1987 by  
Bill Johnson and Joey Wells  
SLAC Computing Services

1970s

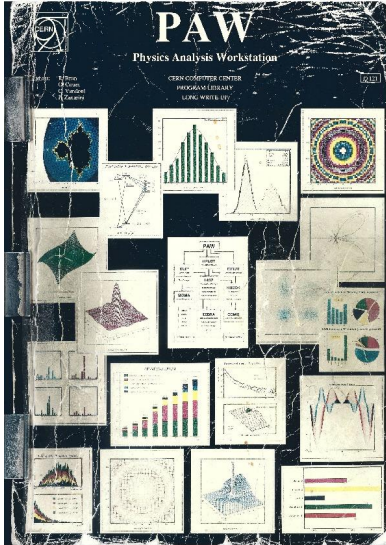


Top Drawer

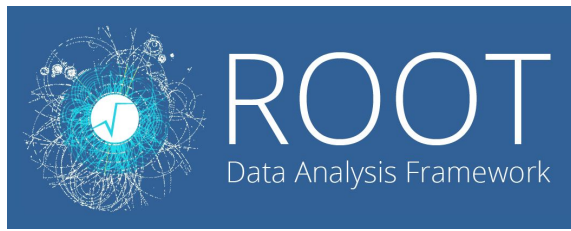


Java Analysis Studio (JAS)

# Visualization and Data Analysis



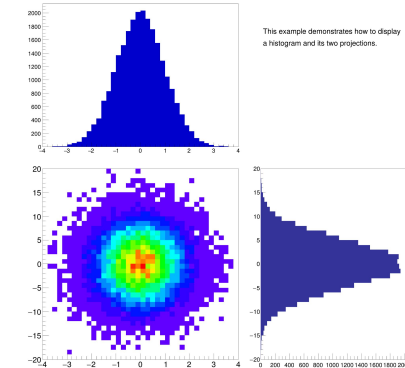
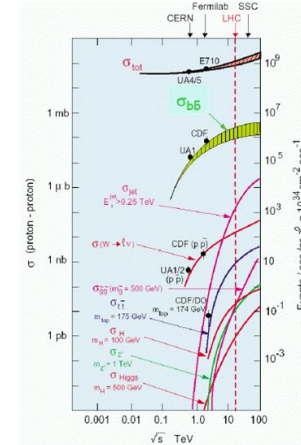
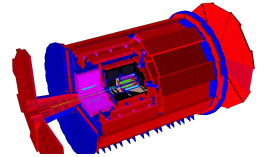
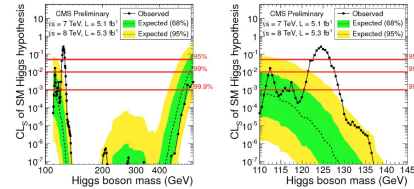
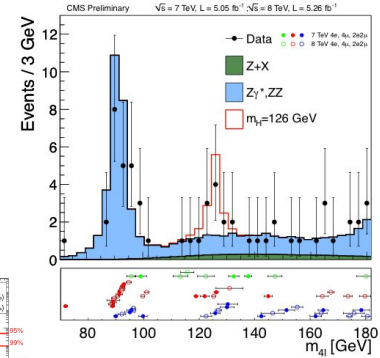
1984 -  
early  
2000s  
FORTRAN



C++ 1995-

## ROOT Manual - Functional parts

- Histograms
- Graphs
- Graphics
- Fitting
- Dataframes
- Trees
- RooFit
- Machine learning with ROOT
- Python interface
- Mathematical libraries
- Physics vectors
- Geometry
- I/O Concepts
- I/O of custom classes
- Signal/Slot communication
- JSROOT
- How to embed ROOT in a GUI
- The C++ interpreter Cling



# Data Organization, Management and Access

CDF Note No. 156



YBOS

PROGRAMMERS REFERENCE MANUAL

Version 4.00

18 May 1995

David Quarrie  
Brian Troemel

CDF Computing Group  
Fermilab MS318  
Batavia IL 60510  
Tel: (312) 840-3975

DECnet Address: BOHOST::QUARRIE  
BOHOST::TROEMEL  
BITNET Address: "QUARRIE@FNALB0"  
"TROEMEL@FNALB0"

ALEPH 86-62  
F. Ranjard  
14.5.1986

Distr.: SOFTWR

———DRAFT———

## The BOS System

Dynamic memory management

FORTRAN77 Version

Volker Blobel  
II. Institut für Experimentalphysik  
Universität Hamburg  
Luruper Chaussee 149  
2000 Hamburg 50

April 1, 1986

### Abstract

BOS is a program system for the dynamic management of data areas and for the input/output of sets of data areas. The system supports a modular structure of the application program and portability for both the software and the data sets. The main application is in the data analysis of high-energy-physics experiments. This manual describes the use of the FORTRAN77 version.

(And ZEBRA at CERN, etc.)

### 1 PREFACE

YBOS is based on two previous memory management systems, BOS and ZBOOK, developed at DESY and CERN, respectively. Version 1.00 was designed and implemented by:-

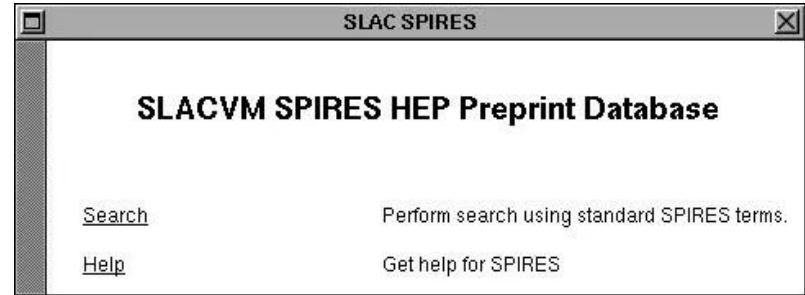
V. Blobel  
II. Institute fuer Experimentalphysik  
University of Hamburg  
Notkestrasse 85  
2000 HAMBURG 52  
WEST GERMANY

This Reference Manual describes the CDF implementation of YBOS which has been modified to run on a VAX or IBM and has several extensions added.

# Communications and Information Management

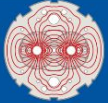
SLAC

SPIRES

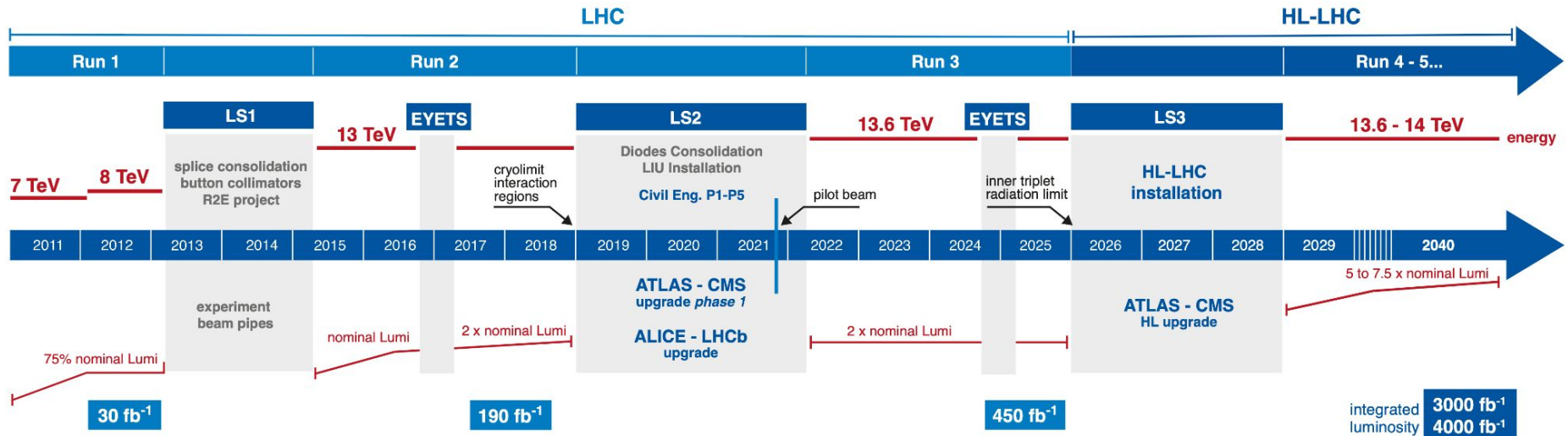


“World Wide Web”  
http server/protocol with html  
document formatting protocol  
1989-

# Experimental timescales span decades



## LHC / HL-LHC Plan



Experiment designs start far before data taking. CMS was formed in 1992 (more than 30 years ago!), expects to run through 2040 with continued data analysis beyond that date.

# Community Structures Reflect Our Community Evolution/Needs



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]**



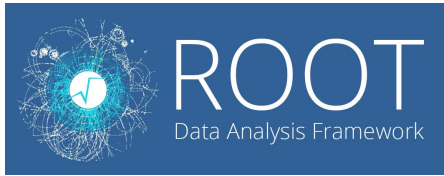
The **HEP Software Foundation** facilitates cooperation and common efforts in High Energy Physics software and computing internationally. **[2010's and 2020's era]**

**WLCG/HSF Workshop 2025**

5–9 May 2025  
IJCLab, Paris  
Europe/Paris timezone

WLCG/HSF 2025 (5-9 May) - <https://indico.cern.ch/event/1484669/>

# Building different types of collaborations



## Collaborate With Us

We warmly welcome your contribution to ROOT!

There are two ways in which you can contribute:

- Many community contributors.**
- Large CERN team, with many smaller partnerships at other institutions.**



## Collaboration

[Geant4 team and documents](#)

(As of 2003)

GEANT4 Collaboration

S. Agostinelli<sup>ae</sup>, J. Allison<sup>as,\*</sup>, K. Amako<sup>e</sup>, J. Apostolakis<sup>a</sup>,  
 H. Araujo<sup>aj</sup>, P. Arce<sup>ℓ,m,x,a</sup>, M. Asai<sup>g,ai</sup>, D. Axen<sup>i,t</sup>,  
 S. Banerjee<sup>bh,ℓ</sup>, G. Barrand<sup>an</sup>, F. Behner<sup>ℓ</sup>, L. Bellagamba<sup>c</sup>,  
 J. Boudreau<sup>bc</sup>, L. Broglio<sup>ar</sup>, A. Brunengo<sup>c</sup>, S. Chauvie<sup>bi,bk</sup>,  
 J. Chuma<sup>h</sup>, R. Chytrac<sup>a</sup>, G. Cooperman<sup>az</sup>, G. Cosmo<sup>a</sup>,  
 P. Degtyarenko<sup>d</sup>, A. Dell'Acqua<sup>aj</sup>, G. Depaola<sup>v</sup>, D. Dietrich<sup>af</sup>,  
 R. Enami<sup>ab</sup>, A. Feliciello<sup>bi</sup>, C. Ferguson<sup>bg</sup>, H. Fesefeldt<sup>ℓ,o</sup>,  
 G. Folger<sup>a</sup>, F. Foppiano<sup>ac</sup>, A. Forti<sup>as</sup>, S. Garelli<sup>ac</sup>, S. Giani<sup>a</sup>,  
 R. Giannitrapani<sup>bn</sup>, D. Gibin<sup>m,bb</sup>, J.J. Gómez Cadenas<sup>m,bo</sup>,  
 I. González<sup>q</sup>, G. Gracia Abril<sup>n</sup>, G. Greeniaus<sup>p,h,ag</sup>,  
 W. Greiner<sup>af</sup>, V. Grichine<sup>f</sup>, A. Grossheim<sup>m,z</sup>, P. Gumplinger<sup>h</sup>,  
 R. Hamatsu<sup>bj</sup>, K. Hashimoto<sup>ab</sup>, H. Hasui<sup>ab</sup>, A. Heikkinen<sup>ah</sup>,  
 A. Howard<sup>aj</sup>, A. Hutton<sup>d</sup>, V. Ivanchenko<sup>a,ba</sup>, A. Johnson<sup>g</sup>,  
 F.W. Jones<sup>h</sup>, J. Kallenbach<sup>aa</sup>, N. Kanaya<sup>i,h</sup>, M. Kawabata<sup>ab</sup>,  
 Y. Kawabata<sup>ab</sup>, M. Kawaguti<sup>ab</sup>, S. Kelner<sup>at</sup>, P. Kent<sup>r</sup>,  
 T. Kodama<sup>aw</sup>, R. Kokoulin<sup>at</sup>, M. Kossov<sup>d</sup>, H. Kurashige<sup>am</sup>,  
 E. Lamanna<sup>w</sup>, T. Lampen<sup>ah</sup>, V. Lara<sup>a,ℓ,bp</sup>, V. Lefebure<sup>ℓ</sup>,  
 F. Lei<sup>bg,bd</sup>, M. Liendl<sup>ℓ,a,bq</sup>, W. Lockman<sup>j,bm</sup>, F. Longo<sup>bl</sup>,  
 S. Magni<sup>k,au</sup>, M. Maire<sup>ao</sup>, B. Mecking<sup>d</sup>, E. Medernach<sup>a</sup>,  
 K. Minamimoto<sup>aw,ai</sup>, P. Mora de Freitas<sup>ap</sup>, Y. Morita<sup>e</sup>,  
 K. Murakami<sup>am</sup>, M. Nagamatsu<sup>aw</sup>, R. Nartallo<sup>b</sup>, P. Nieminen<sup>b</sup>,  
 T. Nishimura<sup>ab</sup>, K. Ohtsubo<sup>ab</sup>, M. Okamura<sup>ab</sup>, S. O'Neale<sup>s</sup>,  
 Y. Oohata<sup>bj</sup>, K. Paech<sup>af</sup>, J. Perl<sup>g</sup>, A. Pfeiffer<sup>a</sup>, M.G. Pia<sup>ad</sup>,  
 F. Ranjard<sup>n</sup>, A. Rybin<sup>ak</sup>, S. Sadilov<sup>a,ak</sup>, E. Di Salvo<sup>c</sup>,  
 G. Santin<sup>bl</sup>, T. Sasaki<sup>e</sup>, N. Savvas<sup>as</sup>, Y. Sawada<sup>ab</sup>,  
 S. Scherer<sup>af</sup>, S. Sei<sup>aw</sup>, V. Sirotenko<sup>ia,ℓ</sup>, D. Smith<sup>g</sup>, N. Starkov<sup>f</sup>,  
 H. Stoecker<sup>af</sup>, J. Sulkimo<sup>ah</sup>, M. Takahata<sup>ay</sup>, S. Tanaka<sup>bf</sup>,  
 E. Tcherniaev<sup>a</sup>, E. Safai Tehrani<sup>g</sup>, M. Tropeano<sup>ae</sup>,  
 P. Truscott<sup>bd</sup>, H. Uno<sup>aw</sup>, L. Urban<sup>v</sup>, P. Urban<sup>aq</sup>, M. Verderi<sup>ap</sup>,  
 A. Walkden<sup>as</sup>, W. Wander<sup>av</sup>, H. Weber<sup>af</sup>, J.P. Wellisch<sup>a,ℓ</sup>,

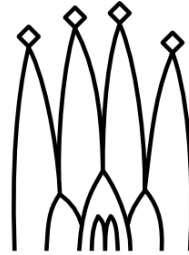


GSII



PRINCETON UNIVERSITY UC San Diego

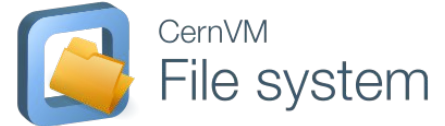
# 21st Century HEP: A Growing Ecosystem of Software Tools, Teams and Collaborations



**Gaudi**

## EvtGen A Monte Carlo Generator for *B*-Physics

Anders Ryd (ryd@hep.caltech.edu)  
David Lange (lange@charm.physics.ucsb.edu)  
Natalia Kuznetsova (natalia@charm.physics.ucsb.edu)  
Sophie Versille (versille@in2p3.fr)  
Marcello Rotondo (Marcello.Rotondo@roma1.infn.it)  
David Kirkby (davidk@slac.stanford.edu)  
Frank Wuerthwein (fkw@fnal.gov)  
Akimasa Ishikawa (akimasa@hepl.phys.nagoya-u.ac.jp)  
February 5, 2004



These are just some examples, there are many more...



# Collaborations



2000-



XRooT D

2003-



Istituto Nazionale di Fisica Nucleare



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



<http://iris-hep.org>

### 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](#)

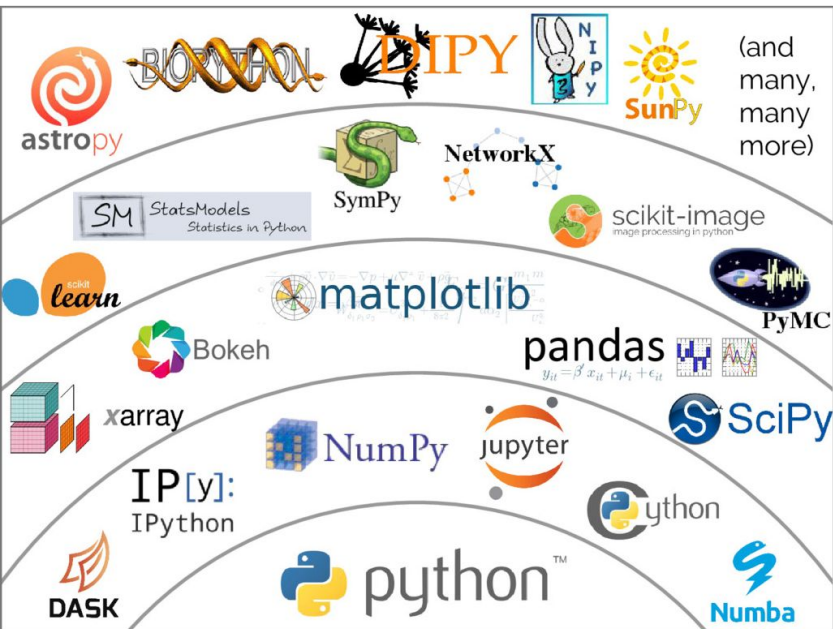
Conceived as a **“software upgrade”** project and guided initially by the “Community White Paper” roadmap developed in 2016-2017: it involves 21 universities, spanning ATLAS, CMS and LHCb.

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.

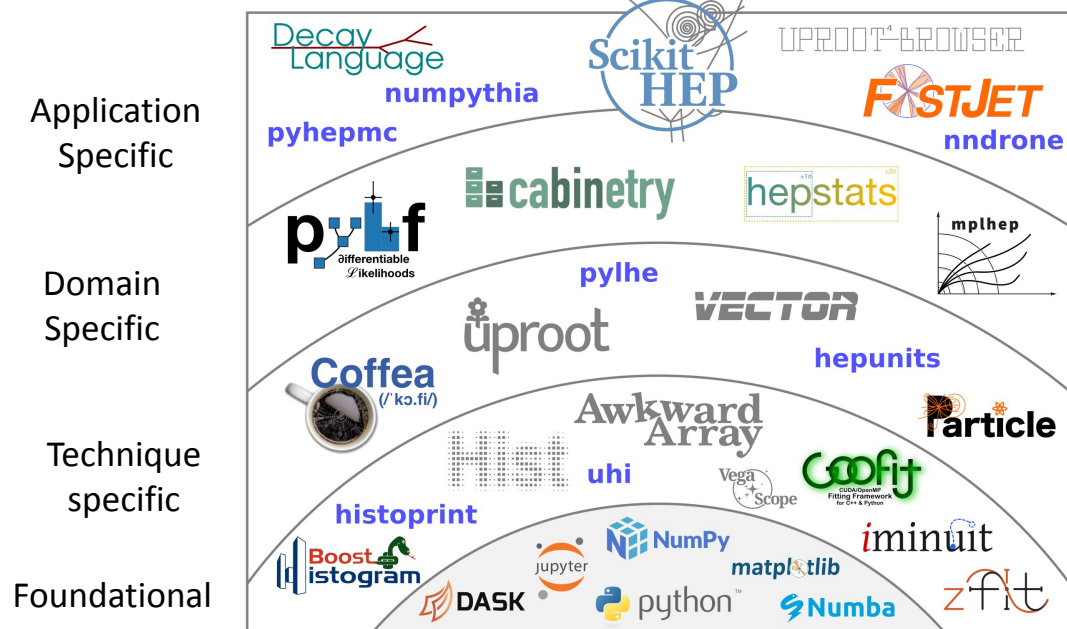
10-year project: Originally funded in 2018 as OAC-1836650 and renewed in 2023 through 2028 as PHY-2323298.

# Leveraging data science for HEP analysis

Scientific Python / PyData vision/ecosystem



Developing HEP data analysis ecosystem



# PyHEP development

## 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](mailto:hsf-pyhep-organisation@googlegroups.com).

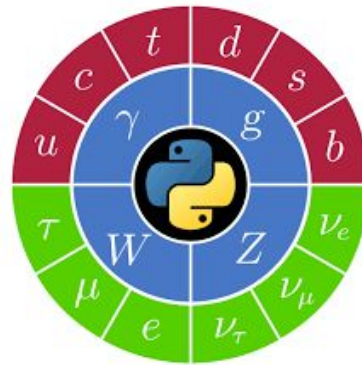
### Getting Involved

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

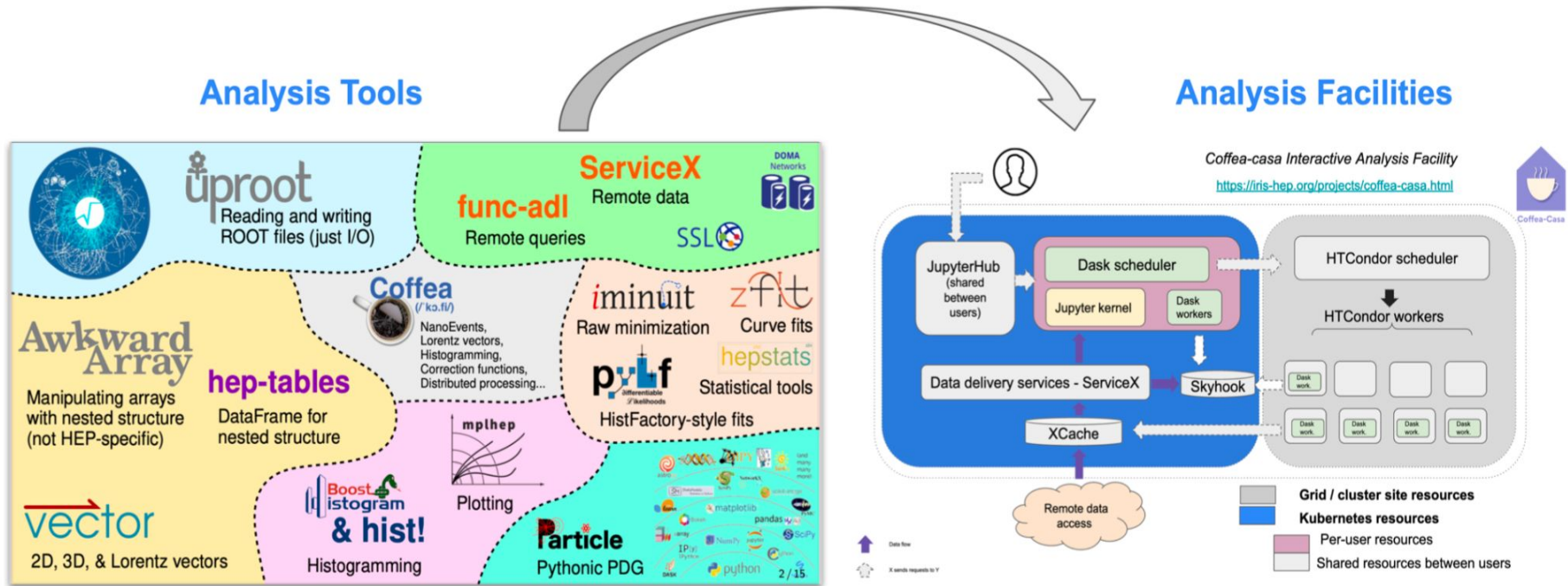
- [Gitter channel PyHEP](#) for any informal exchanges.
- [GitHub repository of resources](#), e.g., Python libraries of interest to Particle Physics.
- PyHEP Workshop Twitter handle: [@PyHEPConf](#)

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

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



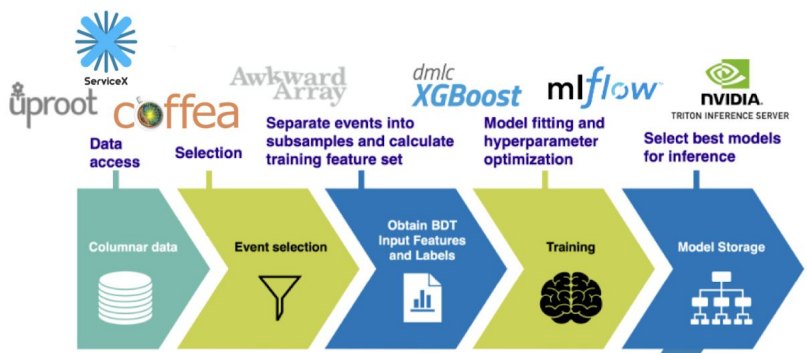
# Building “systems” rather than just tools: Analysis tool chains and facilities





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/>



func\_adl formulate

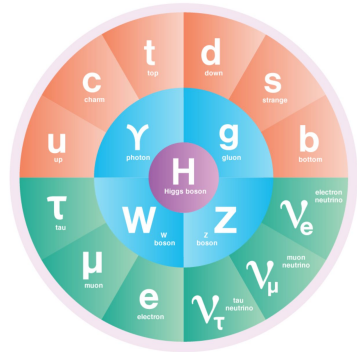


Modularity & interfaces

Declarative configuration

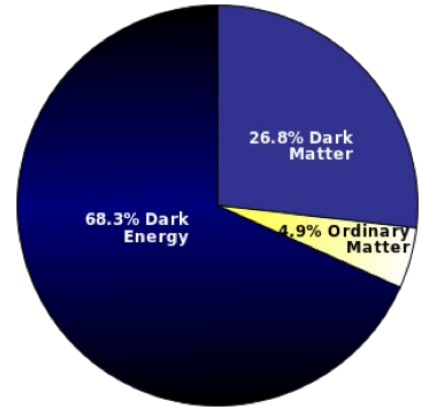


# Science Drivers - Beyond the Standard Model of Particle Physics

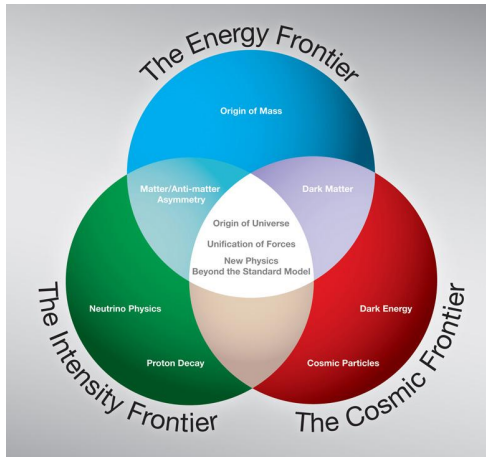


● QUARKS ● LEPTONS ● BOSONS ● HIGGS BOSON

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

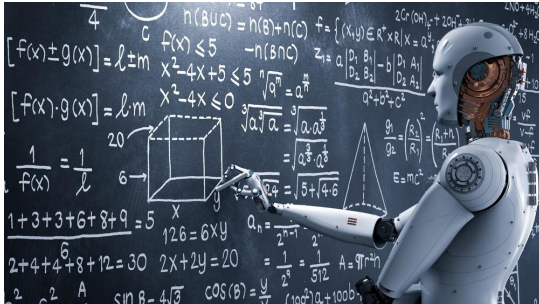
# And the Future for HEP?



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]**

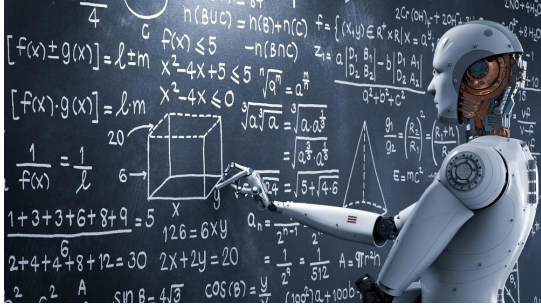


The **HEP Software Foundation** facilitates cooperation and **common efforts** **[2010's and 2020's era]** in High Energy Physics software and computing internationally.



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

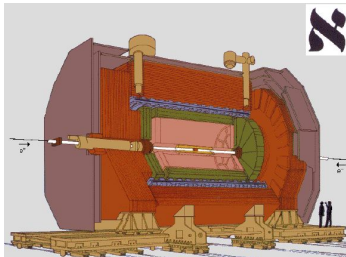
# And the Future for HEP?



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

For clarity, I also don't consider myself an “AI evangelist” as such, but instead (perhaps like many of you?) recognize that the technology can have a potentially transformative impact on our science and thus we need to embrace it and see just how far we can take it. **How we do science in the 2030s is likely to be very, very different from from the past 3 decades and everything that preceded it.**

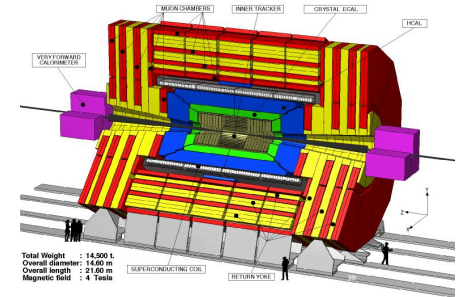
**Alph@CERN**



**BaBar@SLAC**



**CMS@CERN**



# An AI-Native Research Ecosystem and a corresponding collaboration?

arXiv > hep-ex > arXiv:2602.17582

Search...

Help | Adva

High Energy Physics – Experiment

[Submitted on 19 Feb 2026]

## Building an AI-native Research Ecosystem for Experimental Particle Physics: A Community Vision

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Experimental particle physics seeks to understand the universe by probing its fundamental particles and forces and exploring how they govern the large-scale processes that shape cosmic evolution. This whitepaper presents a vision for how Artificial Intelligence (AI) can accelerate discovery in this field. We outline grand challenges that must be addressed to enable transformative breakthroughs and describe how current and planned experimental facilities can implement this vision to advance our understanding of the vast and complex physical world from the smallest to the largest scales. We show how facilities currently under construction, such as the HL-LHC, DUNE and soon EIC, can both benefit from and serve as proving grounds for this vision, while also enabling a longer-term goal for how future experiments -- like FCC-ee at CERN, IceCube-Gen2, a Muon Collider in the U.S., and smaller to mid-scale projects -- can be fully AI-native. We describe how a truly national-scale collaboration, jointly managed across large funding partners, and involving both DOE laboratories and universities, can make this happen.

## AI-NATIVE RESEARCH ECOSYSTEM - PARTICLE PHYSICS

### GC 1: ACCELERATED EXPERIMENT DESIGN

Differentiable Simulations, Active Learning, Co-optimize Detectors, Triggers, Beams and Costs

### GC 2: INTELLIGENT SENSING AND INSTRUMENTATION

On-detector Inference, Physics-Aware Compression, Capture Rare Signals

AI-NATIVE EXPERIMENTAL LIFECYCLE

Agent-Orchestrated Systems, Fast AI Simulation, Foundation Models, Uncertainty-Aware Inference

AI-Driven Monitoring, Diagnosis, Operational Decision Support, Reduce Downtime & Calibration

### GC 4: FROM DATA TO DISCOVERY

### GC 3: AUTONOMOUS EXPERIMENTS

<https://arxiv.org/abs/2602.17582>

Also in the whitepaper, and US specific: A pitch for a national scale collaboration.

However our experiments are global, and much like we built the WLCG, we need to understand how the international collaboration will work to build an AI-native ecosystem in the global “information laboratory”

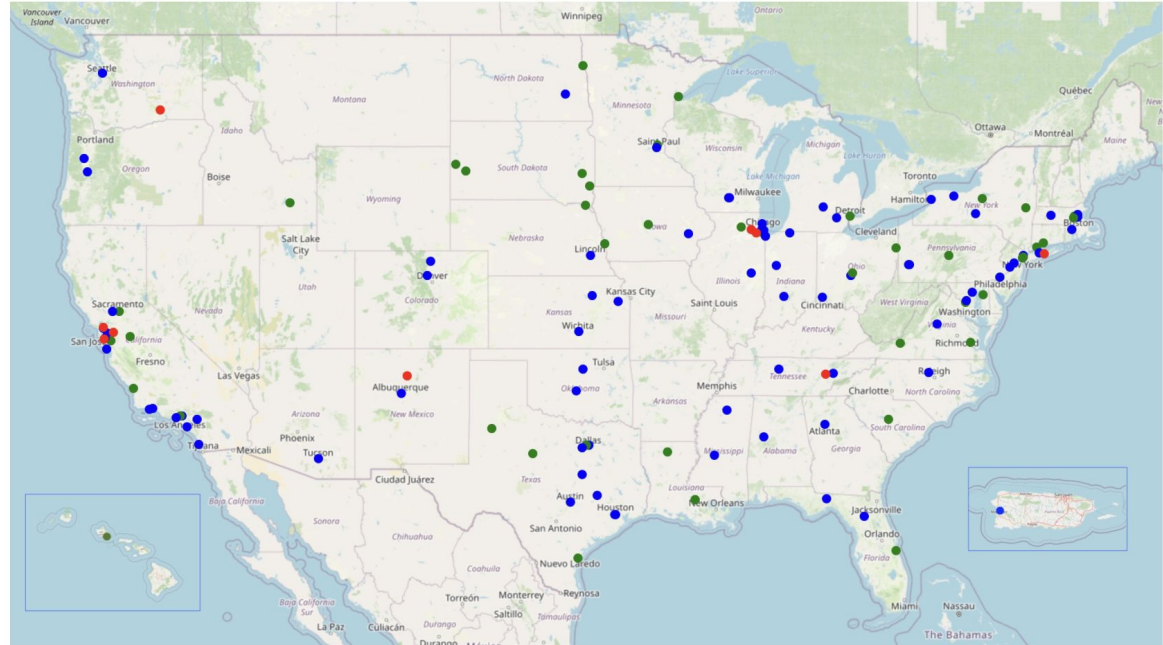
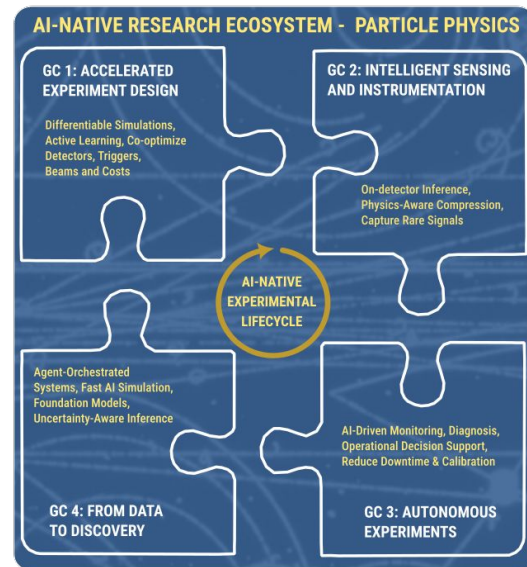
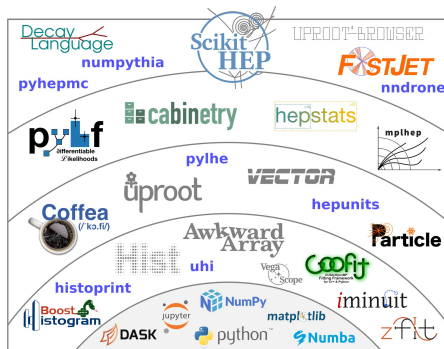
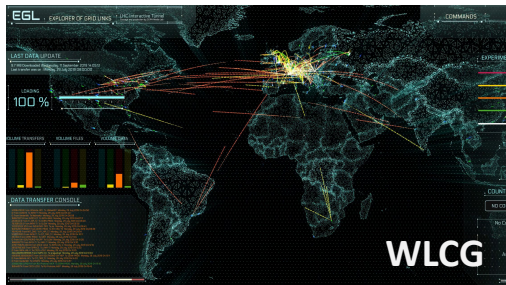
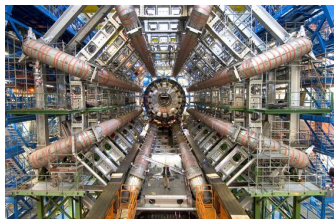
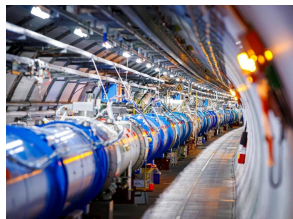


Figure 7: U.S. Institutions (blue and green dots = universities, red dots = DOE labs) that are currently part of large national-scale funded projects: U.S. ATLAS Operations (DOE/NSF, 33 institutions), U.S. CMS Operations (DOE/NSF, 44 institutions), DUNE Operations (DOE, 16 institutions), HEP-CCE (DOE, 4 labs), IRIS-HEP (NSF, 16 universities), A3D3 (NSF, 12 universities). Additional universities that are part of the U.S. ALICE, U.S. ATLAS, U.S. CMS and (U.S.) DUNE scientific collaborations are shown in green. Taken together, these overlapping experiments and projects tightly connect 9 DOE labs and 124 different universities and colleges.

# 21st century “Facilities” and The “Information Laboratory”



Accelerators/Detectors → Data → Ubiquitous Computing → Software Tools → AI Native Ecosystem

← Global Scientific Collaborations →