What Enables Research in Experimental Particle Physics?

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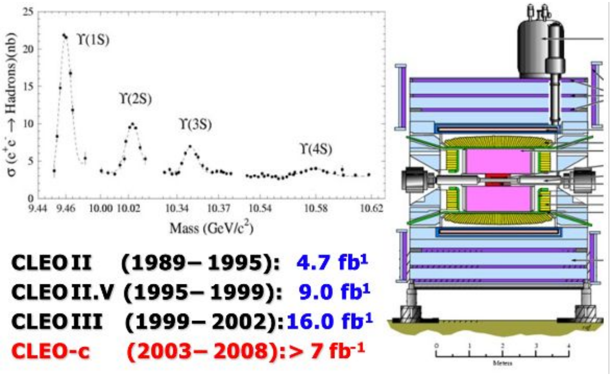
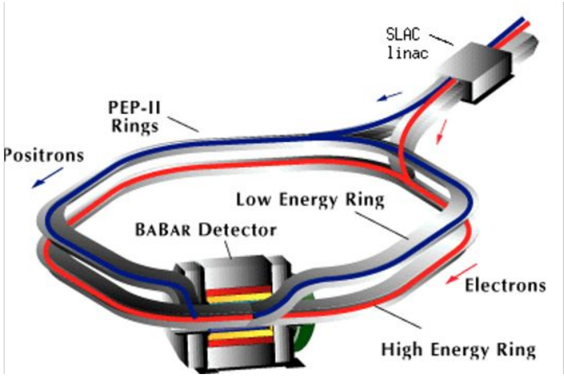
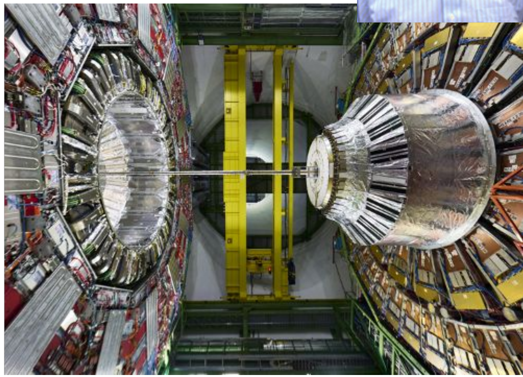
iris hep
Institute for Research & Innovation
in Software for High Energy Physics

Introductions…. Who am I?







CLEO-II(.5) @ Cornell

- Silicon detector calibration + operations
- Form-factor analysis in semileptonic decays
- Event generators

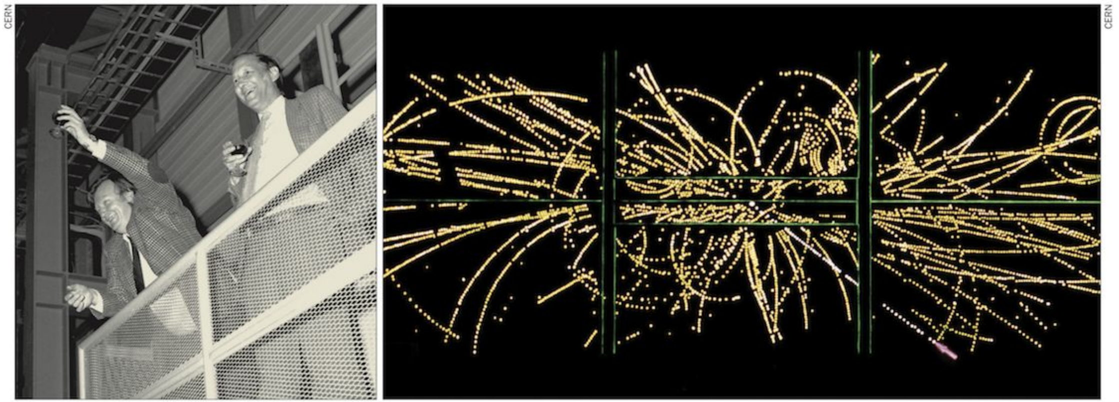
BaBar@SLAC

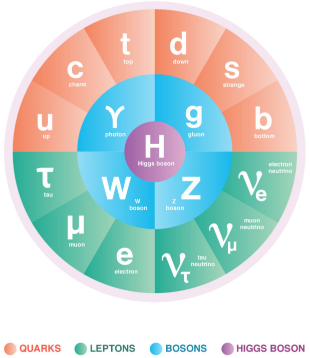
- CP violation analysis
- RPC detector operations + software
- Event generators ("EvtGen")
- Event reconstruction software

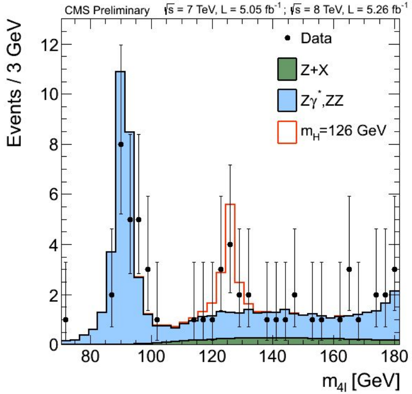
CMS@CERN

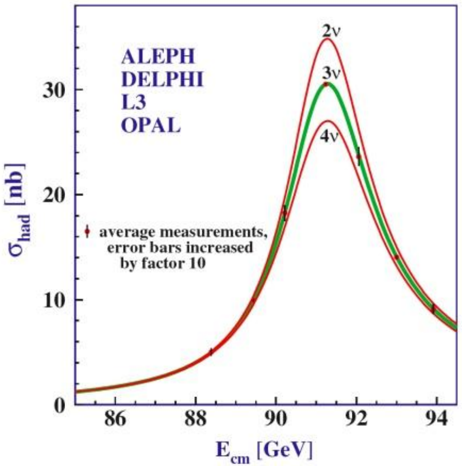
- Event reconstruction software
- Simulation techniques
- Computing resource projections
- IRIS-HEP

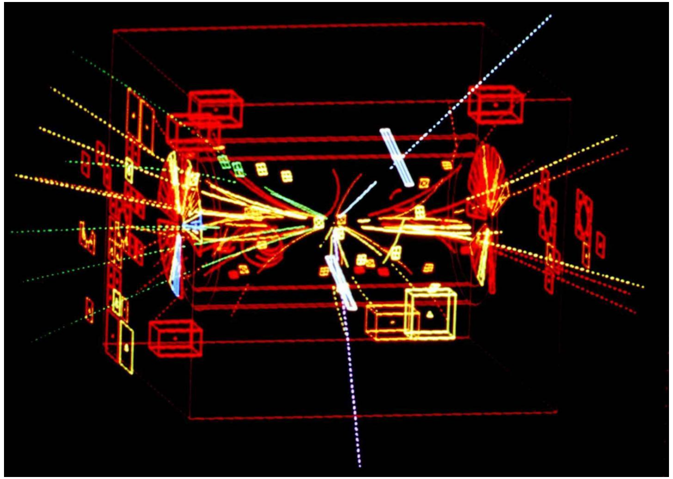
Experimental Development of the Standard Model

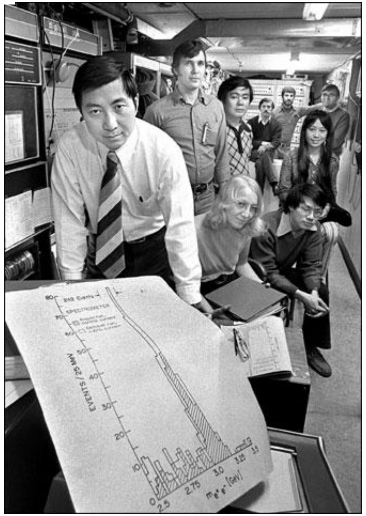










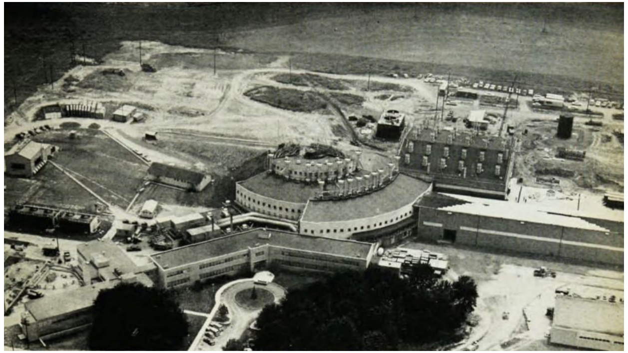


How did we get here?
(As experimentalists)

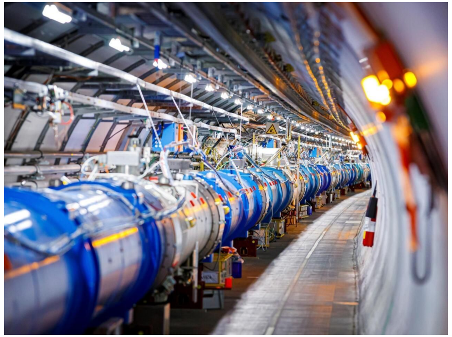
Big Science and Accelerators - larger and larger facilities

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

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

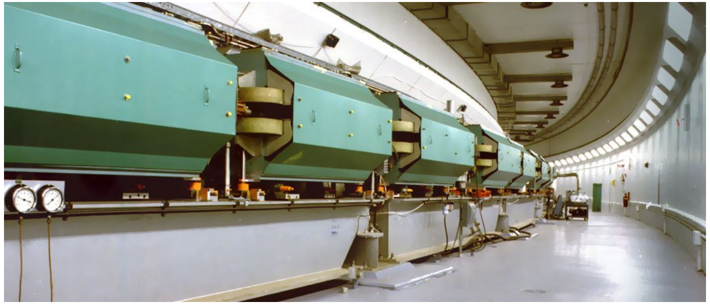


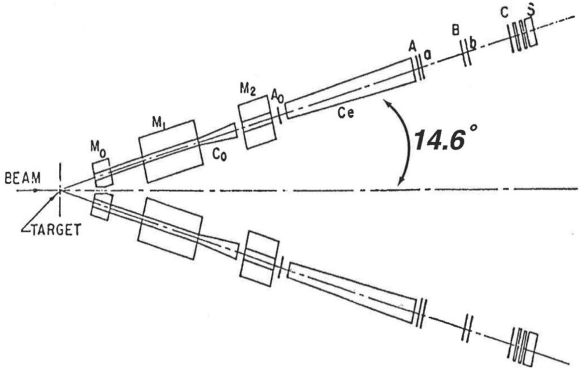
The Princeton-Pennsylvania Accelerator,
Milton White 1964 Physics Today 17(8): 27



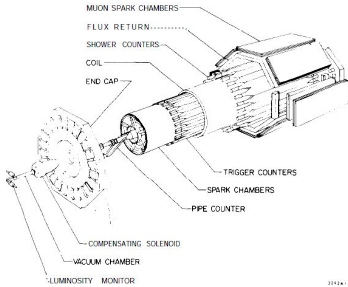
The Large Hadron Collider and
CERN first as a European laboratory
and then as a "world laboratory"

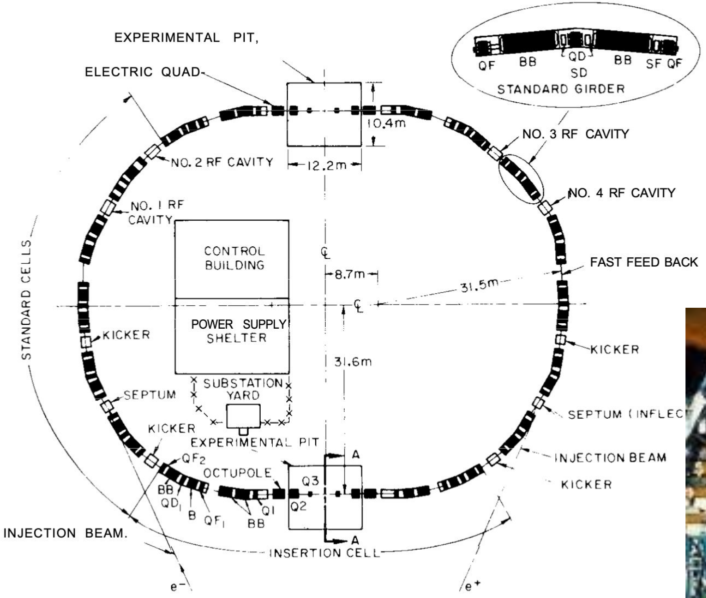
AGS at BNL delivering protons on a fixed target





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

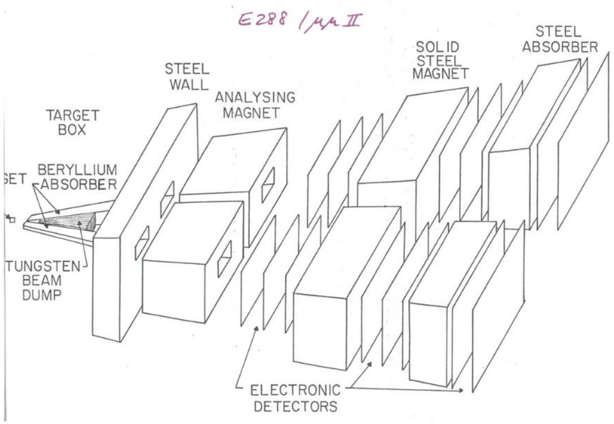




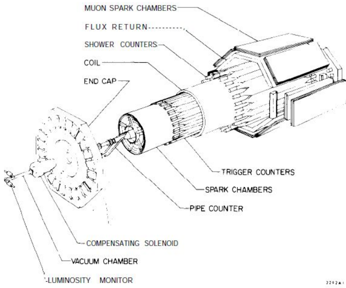
1. Schematic of the SPEAR storage ring.

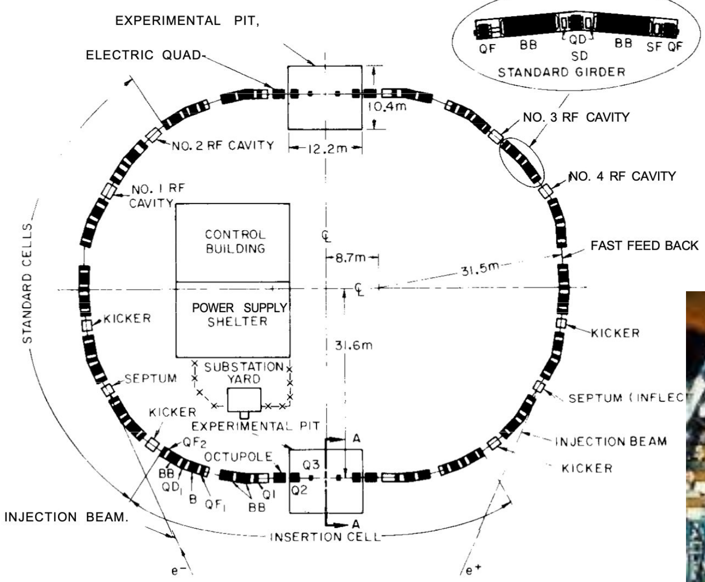
J and Psi discoveries in 1974

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

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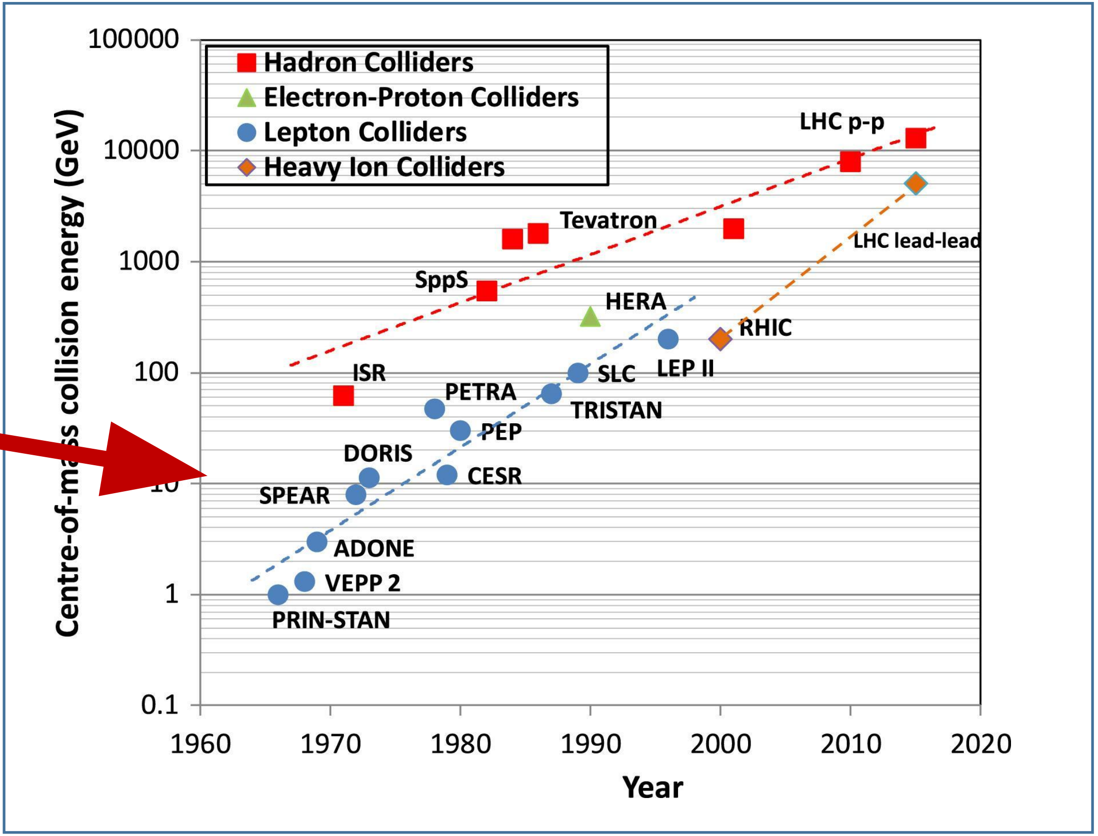
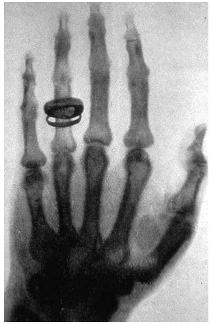
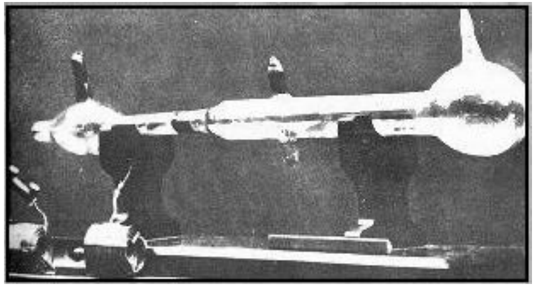


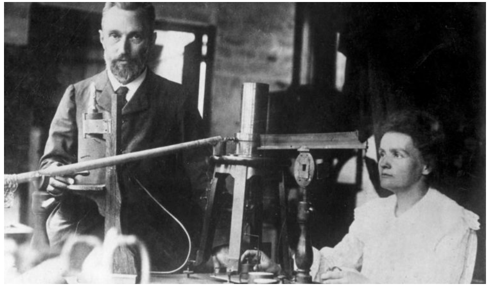
Tools ⟵⟶ Discoveries

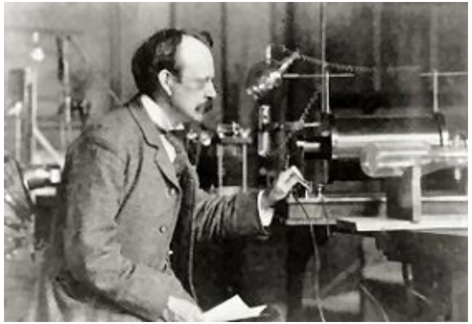




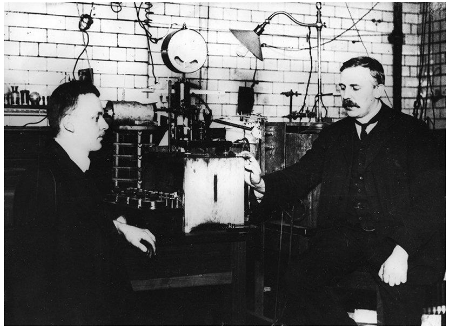
1895 - Roentgen discovers x-rays using cathode ray tubes

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)



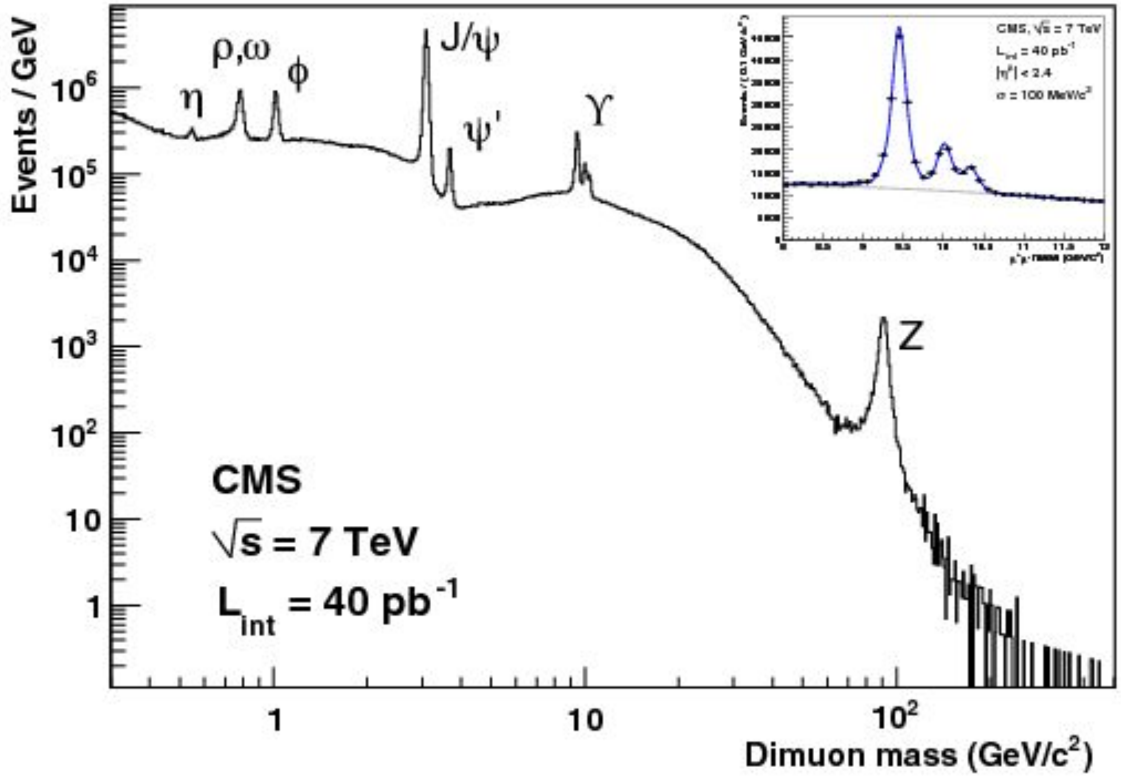
1911 - Rutherford, Geiger, Marsden use radioactivity to explore atomic structure and discover the nucleus

Evolution in particle physics

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

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

On yet later experiments the particle may become a background.



"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†

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
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and

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(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.

DESIGN REPORT

FOR THE

FERMILAB COLLIDER DETECTOR FACILITY

(CDF)

AUGUST, 1981

August, 1981

DESIGN REPORT

For the Fermilab Collider Detector Facility (CDF)

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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

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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:

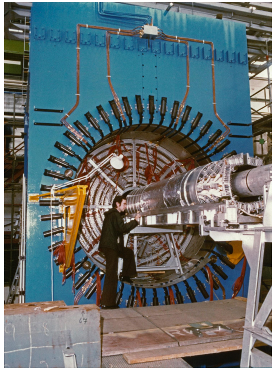
1. VAX: The high level CPU will be a VAX.

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.

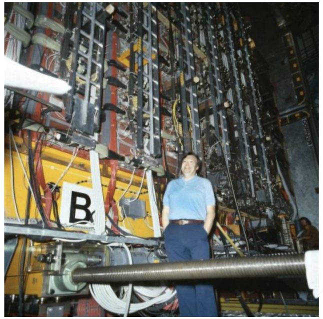
CDF CDR

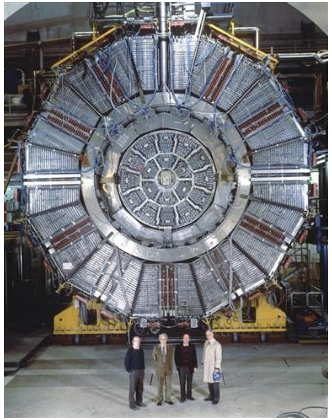
And there was a similar evolution towards collider detectors, larger (international) collaborations at PETRA with 4 fixed experiments, UA1 and UA2 at the SppS, at LEP with 4 fixed experiments. And also non-collider collaborations such as EMC were building long running (evolving) facilities.



29 JUNE 1978

UA1 experiment approved





Towards larger international experiments

BABAR

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ia, South Carolina, USA

Stanford, California, USA
loom, C. Boeheim, A. Boyar
Cottrell, D.H. Coward, D.P. C
ie, T. Fieguth, D. Freytag, I
d, J. Hoeflich, W. Innes, C.I
rebs, P. Kunz, W. Langeveld
ttison, R. Melen, K. Moffeit,
a, B.N. Ratcliff, S.F. Schaffn
E.J. Soderstrom, J. Vav'ra, S
Yu

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D. Breton, R. Cizeron, S. Du, A.-M. Lutz, J.M. Noppe, S. Plaszczynski, M.-H. Schune,
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Ecole Polytechnique Palaiseau, LPNHE, *Palaiseau, France*
L. Behr, G. Bonneaud, P. Matricon, G. Vasileiadis, M. Verderi

LPNHE des Universités Paris 6 et Paris 7, *Paris, France*
M. Benayoun, H. Briand, J. Chauveau, P. David, C. De La Vaissiere, L. Del Buono, J.F. Genat,
O. Hamon, P. Leruste, J. Lory, J.-L. Narjoux, B. Zhang

INFN, Sezione di Milano and Università di Pavia, *Pavia, Italy*
P.F. Manfredi, V. Re, V. Speziali, F. Svelto

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F. Forti, D. Gambino, M. Giorgi[†], A. Lusiani[‡], P.S. Marrocchesi, M. Morganti[†],
G. Rizzo, G. Triggiani[†], J. Walsh

Prairie View A&M University, *Prairie View, Texas, USA*
M. Gui, D.J. Judd, K. Paick, D.E. Wagoner

Princeton University, *Princeton, New Jersey, USA*
C. Bula, C. Lu, K.T. McDonald

Academia Sinica, *Taipei, Taiwan*
H.-Y. Chau, M.-L. Chu, S.-C. Lee

University of Texas at Dallas, *Richardson, Texas, USA*
J.M. Izen, X. Lou

INFN, Sezione di Torino and Università di Torino, *Torino, Italy*
F. Bianchi, D. Gamba, G. Giraudo, A. Romero

INFN, Sezione di Trieste and Università di Trieste, *Trieste, Italy*
L. Bosisio, R. Della Marina, G. Della Ricca, B. Gobbo, L. Lanceri, P. Poropat

TRIUMF, *Vancouver, British Columbia, Canada*
R. Henderson, A. Trudel

Tsinghua University, *Beijing, China*
Y.P. Kuang, R.C. Shang, B.B. Shao, J.J. Wang

Vanderbilt University, *Nashville, Tennessee, USA*

er

Canada

://indico.cern.ch/event/1182767/contribu

BABAR

Technical Design Report

The *BaBar* Collaboration

March, 1995

11

Computing

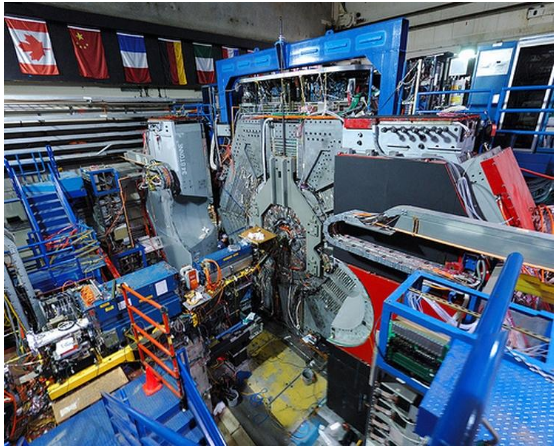
There are a number of computing challenges for the proposed *BaBar* detector. The data rates are high for an e^+e^- collider, and there is a large quantity of useful data which must be stored and analyzed. Convenient interactive access must be available for the efficient extraction of physics results. 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.

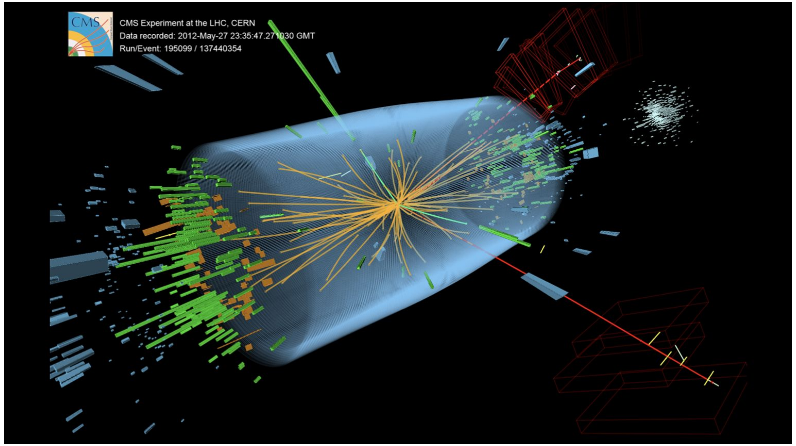


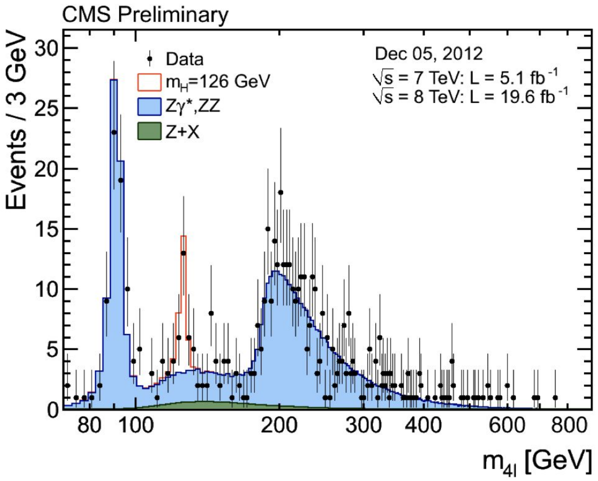
March, 1995

50 pages on Computing


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





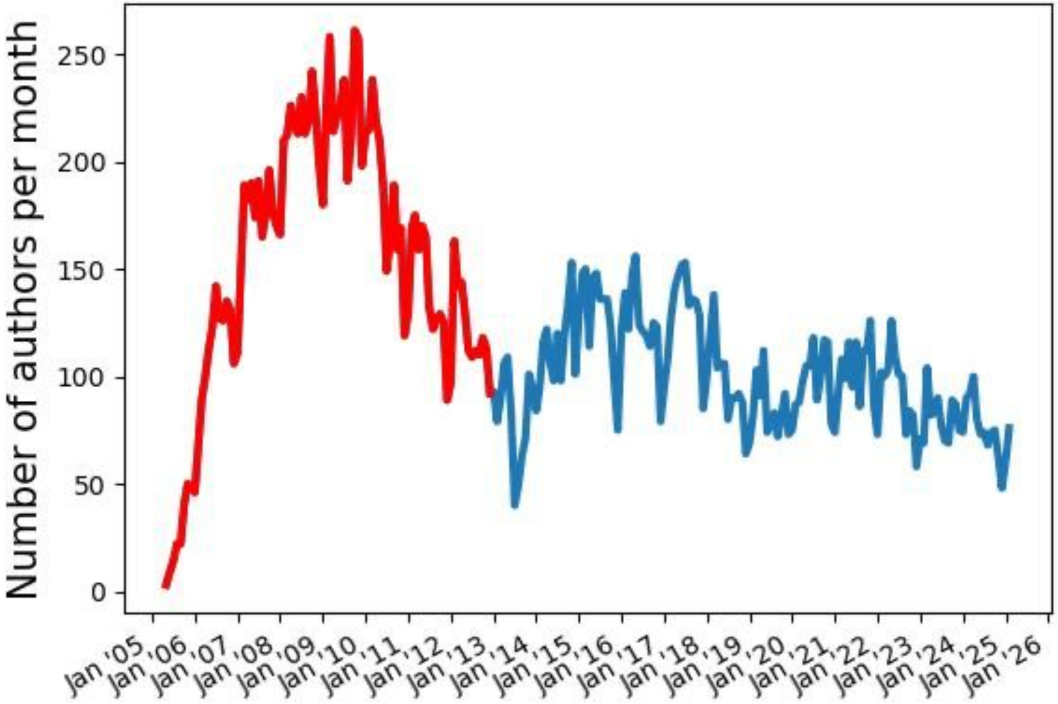
Large scale software
and computing
infrastructures

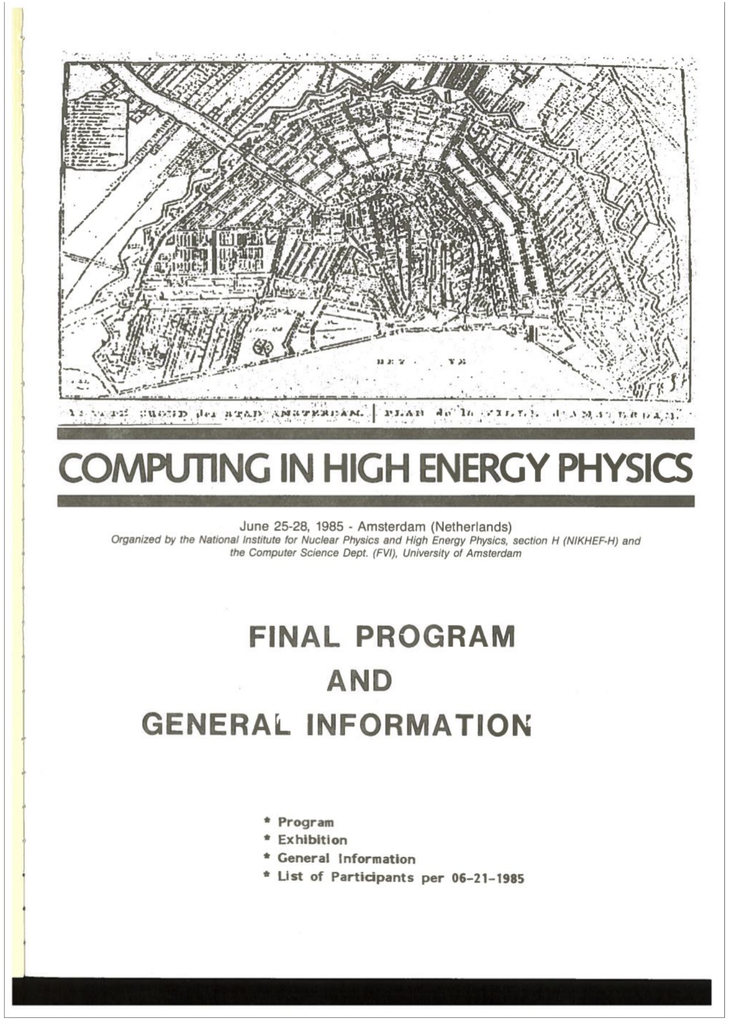
Today: Large scale collaborative software development in HEP - CMSSW Example

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.





Computing in High Energy Physics Conference Series

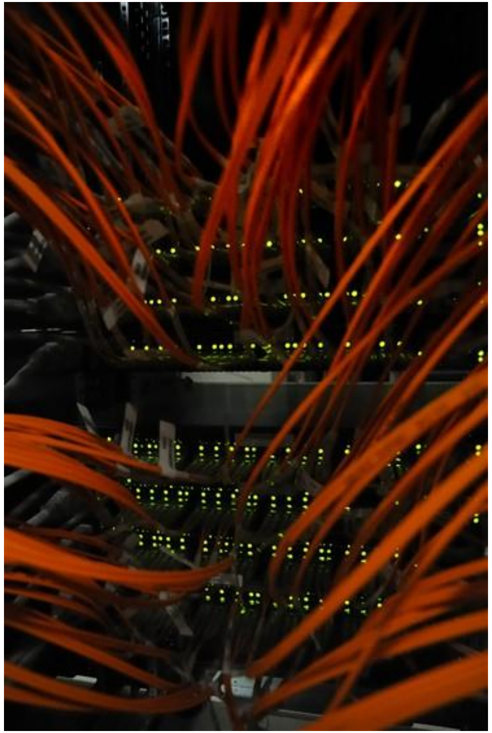
Every 18 months since 1985.

Initial conference was heavily focused on topics highly connected to computing hardware, data acquisition and networking.

Software became an ever present topic as things involved.

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

Cyberinfrastructure?

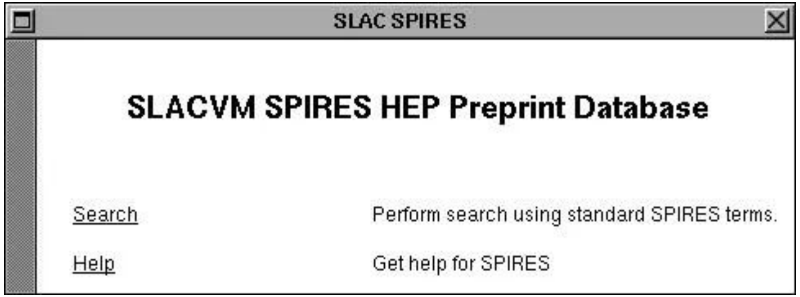


Conceptual motivations behind the HEP Software Foundation

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.

Communications and Information Management



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

2004-

Software in High Energy Physics

MC Simulation of the “passage of particles through matter”


CERN-DD 78-2 c1

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

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

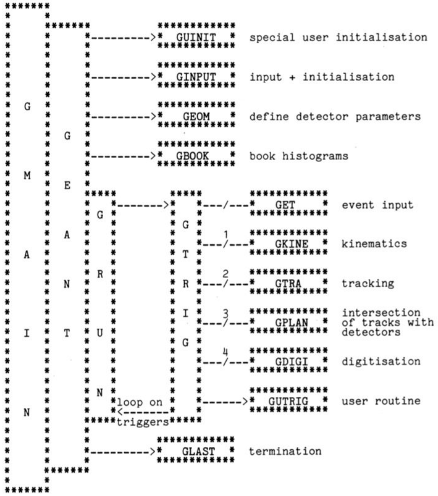
[redacted]

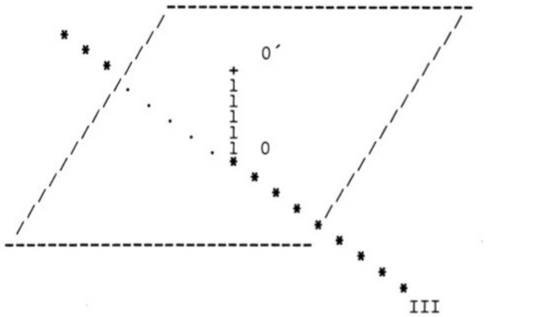
CM-P00059731

SIMULATION PROGRAM
FOR
PARTICLE PHYSICS EXPERIMENTS

GEANT

USER GUIDE
AND
REFERENCE MANUAL



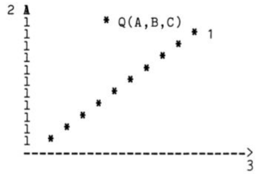


2.3 REFERENCE SYSTEM

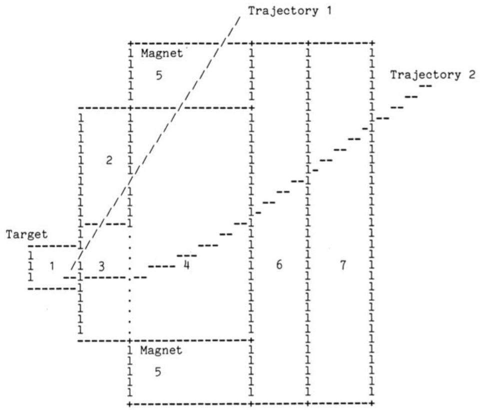
The master reference system is determined according to the way the user represents the kinematical quantities. Consequently this system will also be referred to as the user system.

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.



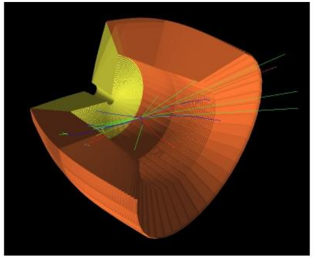
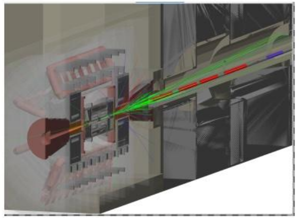
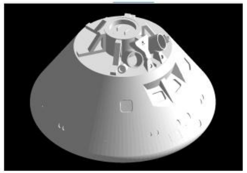
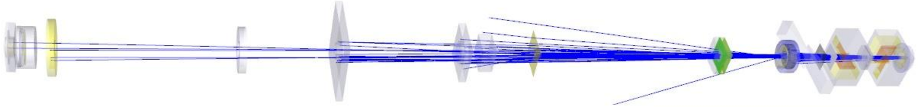
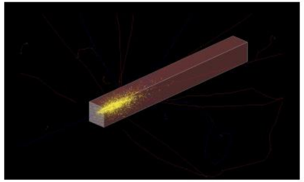
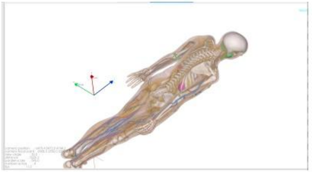
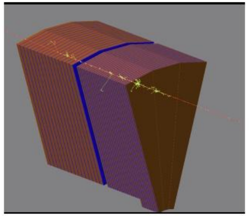
GEometry ANd Tracking (GEANT) Software

FORTRAN

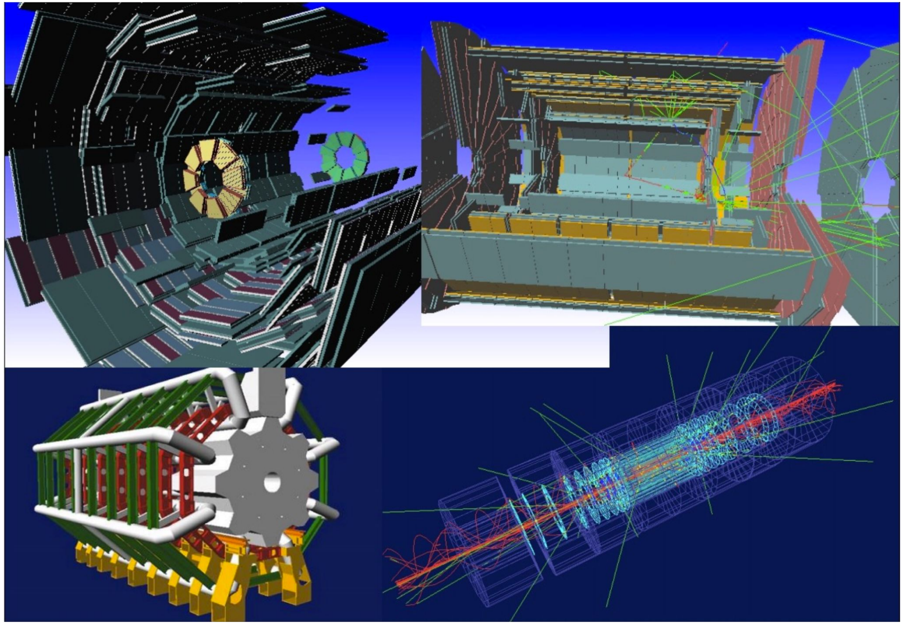
MC Simulation

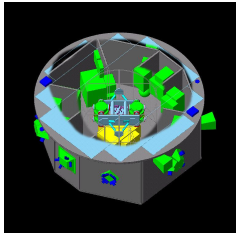
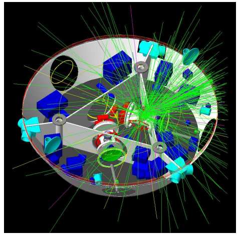
C++ 1995-

GEANT4
A SIMULATION TOOLKIT

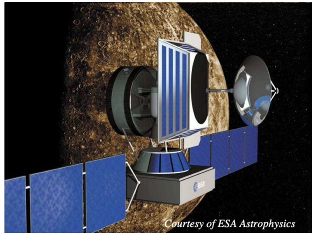








Many applications beyond particle physics



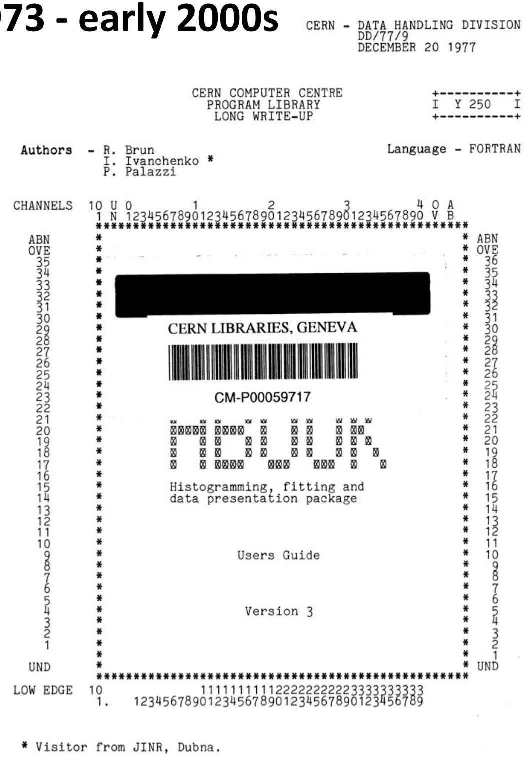
LISA Pathfinder



Bepi Colombo

Visualization and Data Analysis

1973 - early 2000s


CERN - DATA HANDLING DIVISION
DD/77/9
DECEMBER 20 1977

CERN COMPUTER CENTRE
PROGRAM LIBRARY
LONG WRITE-UP

I Y 250 I

Authors - R. Brun
I. Ivanchenko *
P. Palazzi

Language - FORTRAN

[redacted]

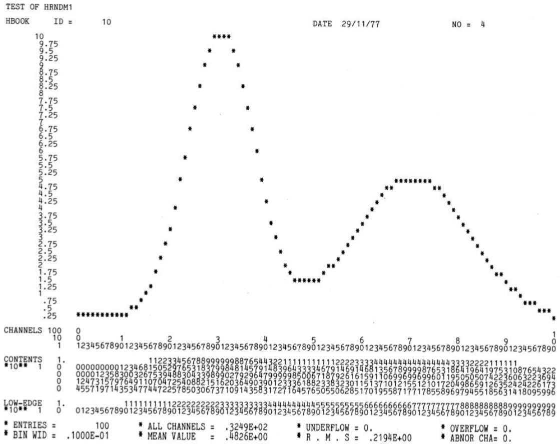
HBOOK

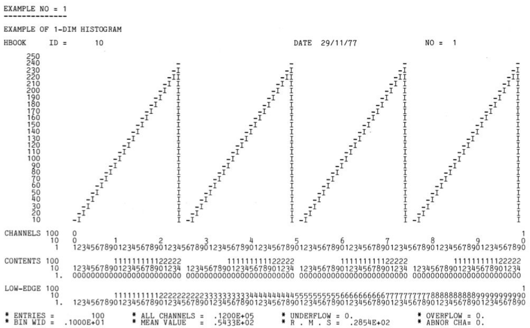
Histogramming, fitting and
data presentation package

Users Guide

Version 3

* Visitor from JINR, Dubna.



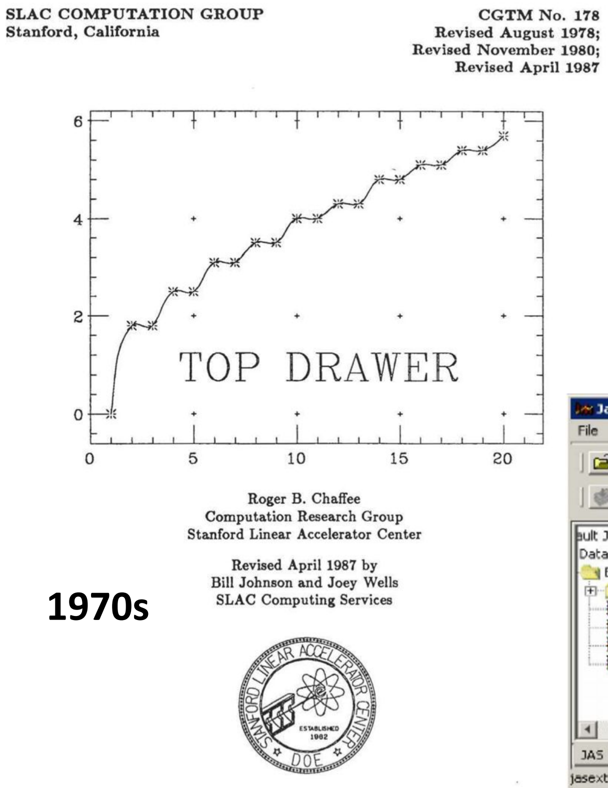



```
      SUBROUTINE HEXAM1
C
C     ****************************************************************
C     *                                                              *
C     *    HBOOK BASIC EXAMPLE USING 1-DIM HISTOGRAM,                *
C     *    SCATTER-PLOT AND TABLE.                                   *
C     *                                                              *
C     ****************************************************************
C
C          SETS GLOBAL TITLE
C
      CALL HTITLE(15HEXAMPLE NO = 1$)
C
C          MAXIMUM SIZE OF BLANK COMMON FIXED TO 1000
C
      CALL HLIMIT(1000)
C
C          BOOKING OF 1-DIM SCATTER-PLOT AND TABLE
C
      CALL HBOOK1(10,27HEXAMPLE OF 1-DIM HISTOGRAM$,100,1,101,0)
      CALL HBOOK2(20,24HEXAMPLE OF SCATTER-PLOT$,100,0,1,40,1,41,30)
      CALL HTABLE(30,17HEXAMPLE OF TABLE$,15,1,16,40,1,41,1000)
C
C          FILLS 1-DIM HISTOGRAM
C
      DO 10 I=1,100
      W=10*MOD(I,25)
   10 CALL HFILL(10,I,0,W)
C
C          FILLS SCATTER-PLOT
C
      X=-0.005
      DO 20 I=1,100
      X=X+0.01
      DO 20 J=1,40
      Y=J
      IW=MOD(I,25)*MOD(J,10)
      IWMAX=J-MOD(I,25)+10
      IF(IW.GT.IWMAX)IW=0
   20 CALL HFILL(20,X,Y,IW)
C
C          FILLS TABLE
C
      DO 30 I=1,20
      DO 30 J=1,40
   30 CALL HFILL(30,I,J,I+J)
C
C          PRINTS ALL HISTOGRAMS WITH AN INDEX
C
      CALL HISTDO
C
      RETURN
      END
```

HBOOK - Statistical Analysis and Histogramming

Visualization and Data Analysis

1990s


SLAC COMPUTATION GROUP
Stanford, California

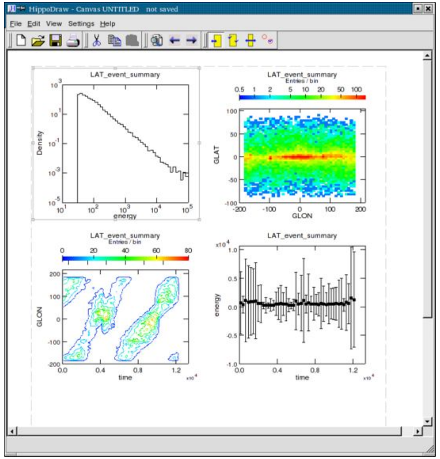
CGTM No. 178
Revised August 1978;
Revised November 1980;
Revised April 1987

Roger B. Chaffee
Computation Research Group
Stanford Linear Accelerator Center

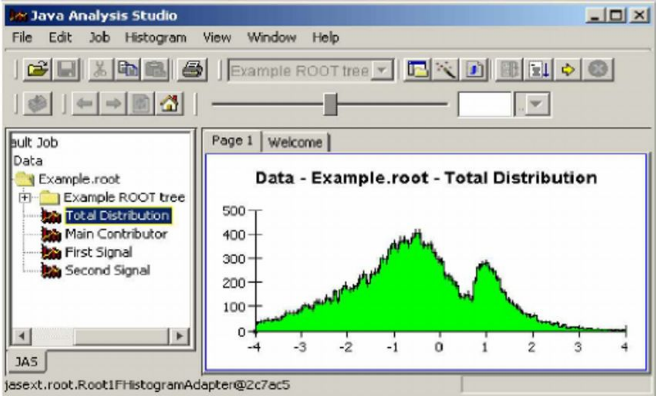
Revised April 1987 by
Bill Johnson and Joey Wells
SLAC Computing Services

1970s

Top Drawer



Hippodraw



Java Analysis Studio (JAS)

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.

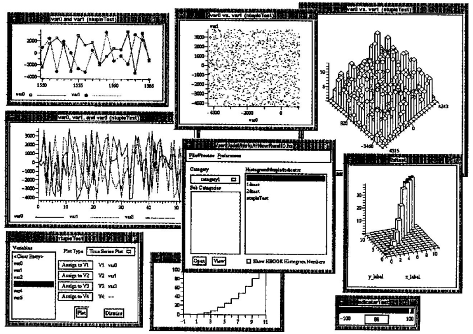


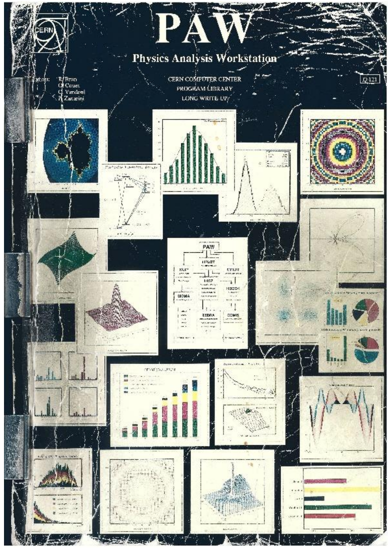
Figure 1. Viewing Data with Histo-Scope

1992(?)- [unclear]

Visualization and Data Analysis

ROOT
Data Analysis Framework

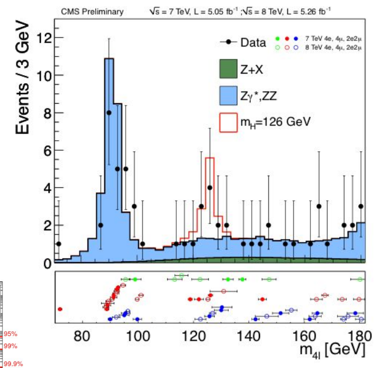
C++ 1995-

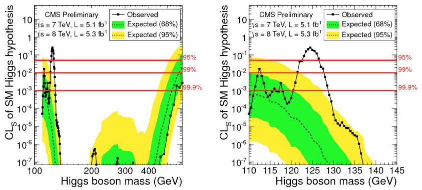


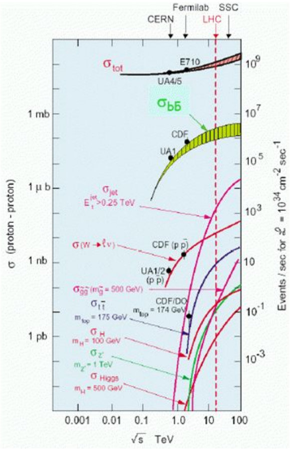
1984 -
early
2000s
FORTRAN

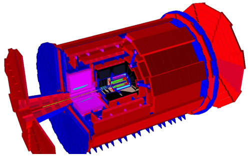
ROOT Manual - Functional parts

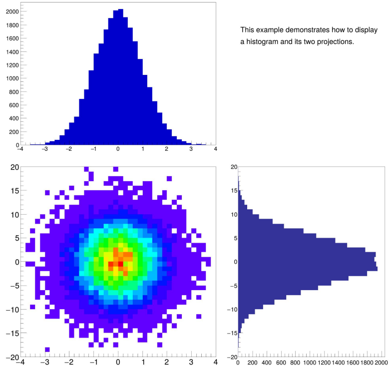
- Histograms
- Graphs
- Graphics
- Fitting
- Dataframes
- Trees
- RooFit
- Machine learning with ROOT
- Python interface
- Mathematical libraries
- Physics vectors
- Geometry
- I/O Concepts
- I/O of custom classes
- Signal/Slot communication
- JSROOT
- How to embed ROOT in a GUI
- The C++ interpreter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











Building different types of collaborations

ROOT
Data Analysis Framework

Collaborate With Us

We warmly welcome your contribution to ROOT!

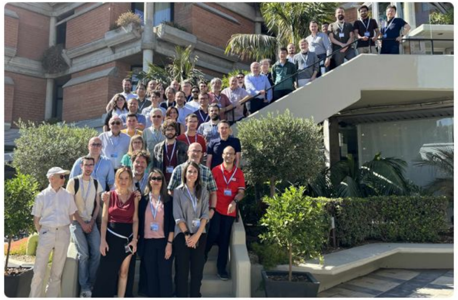
There are two ways in which you can contribute:

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

CERN

UNIVERSITY OF OSLO PRINCETON UNIVERSITY UC San Diego

GEANT4
A SIMULATION TOOLKIT



Collaboration

Geant4 team and documents

(As of 2003)

GEANT4 Collaboration

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

acts

DELPHES fast simulation

Gaudi

EvtGen
A Monte Carlo Generator for B-Physics

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February 5, 2004

SHERPA

Scikit HEP

DD4hep

CernVM File system

HEPData

hls 4 ml

These are just some examples, there are many more…

iNSPIRE HEP

CERN

DESY.

Fermilab

cnrs IN2P3

SLAC

Why we started EvtGen

b-decay chains are full of interesting sequential decays

$$B \to D^* \ell \nu \quad \hookrightarrow D\pi$$

$$B \to D^* \ell \nu \quad \hookrightarrow D\gamma$$

$$B \to D^* \; D^* \quad \hookrightarrow D\pi \; \hookrightarrow D\pi$$

$$B \to D^* \; D^* \quad \hookrightarrow D\pi \; \hookrightarrow D\gamma$$

We wanted to correctly simulate all correlations while only implementing the nodes in each decay tree

$$B \to D^* \ell \nu \qquad B \to D^* D^*$$

$$D^* \to D\pi \qquad D^* \to D\gamma$$

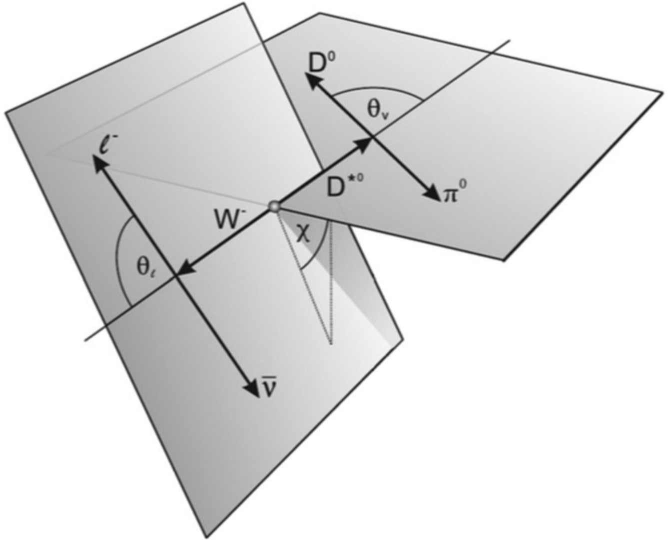
CLEO's event generator at the time ("QQ") was not structured to allow this. Correlations had to be handled by implementing the entire decay chain together as one model

Modeling correlations in decay chains

Modeling these correlations is unnecesary to correctly model particle multiplity and momentum spectra

But as CLEO moved to higher (3M BB events!) statistics analysis, modeling correlations became more and more important

Given the ability to perform time-dependent measurements, modeling these correlations became essential for BABAR/Belle (etc)



Our implemenation via individual decay amplitudes proved to be the right approach

It provided a natural separation of the physics (and implementation) into individual pieces made it easier for

- Analysts to contribute **reusable** code
- Us to convert pheno results of interest into EvtGen components.

We managed the computational complexity found ways to apply Monte Carlo algorithms efficiently (eg, accept-reject sampling could be done step by step by tracking spin-density matrices as computations were done)

$$A = \sum_{\lambda_{D^*}\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau} \times A^{D^*\to D\pi}_{\lambda_{D^*}} \times A^{\tau\to\pi\nu}_{\lambda_\tau}$$

$$P_B = \sum_{\lambda_{D^*}\lambda_\tau} |A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}|^2.$$

$$\rho^{D^*}_{\lambda^*_D\lambda'_{D^*}} = \sum_{\lambda_\tau} A^{B\to D^*\tau\nu}_{\lambda_{D^*}\lambda_\tau}[A^{B\to D^*\tau\nu}_{\lambda'_{D^*}\lambda_\tau}]^*$$

$$P_{D^*} = \frac{1}{\mathrm{Tr}\,\rho^{D^*}} \sum_{\lambda_{D^*}\lambda'_{D^*}} \rho^{D^*}_{\lambda_{D^*}\lambda'_{D^*}} A^{D^*\to D\pi}_{\lambda_{D^*}}[A^{D^*\to D\pi}_{\lambda'_{D^*}}]^*$$

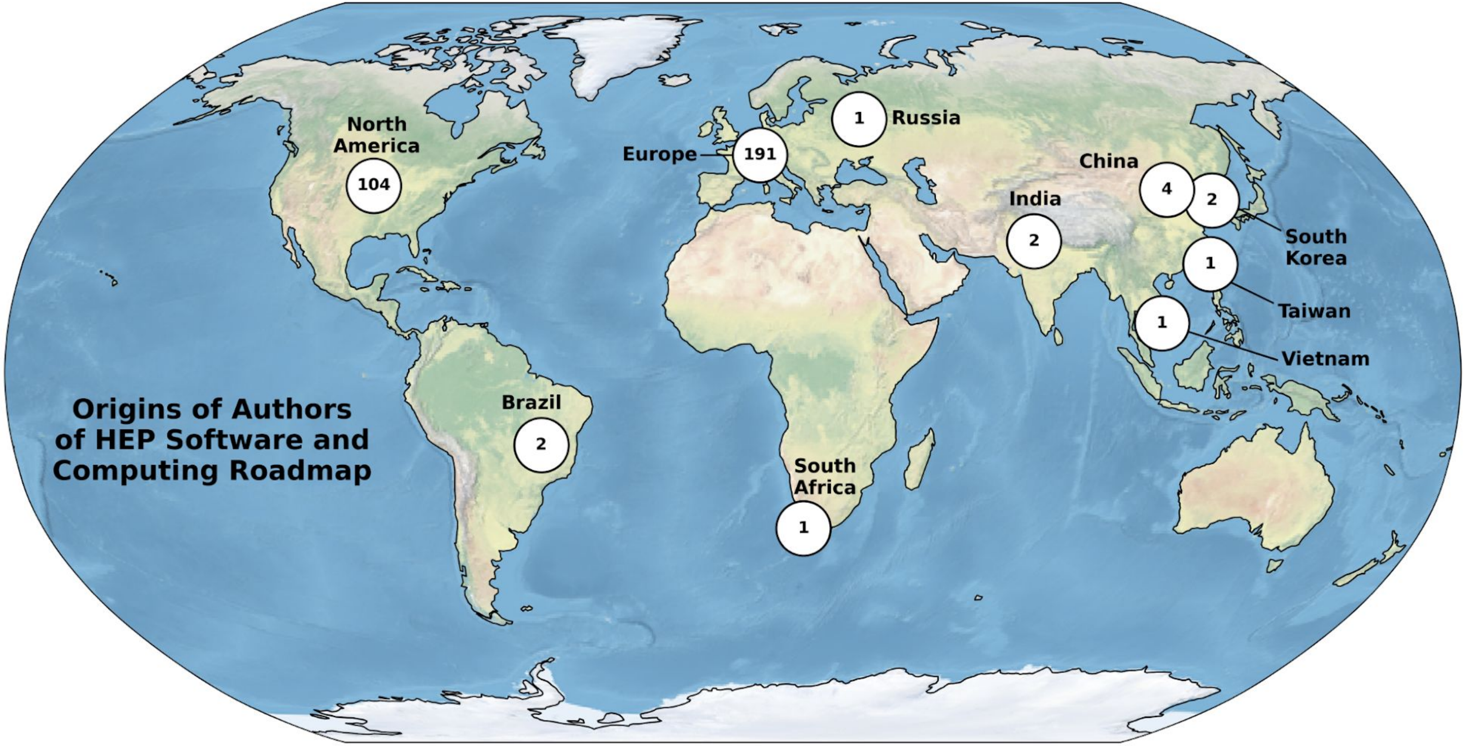
Community Structures Reflect Our Community Evolution/Needs

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

Despite the fact that software contributions in the experiments come from across the globe, nearly all authors of the "HSF Community Roadmap" in 2017-2018 for software/computing R&D towards HL-LHC and other future experiments 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

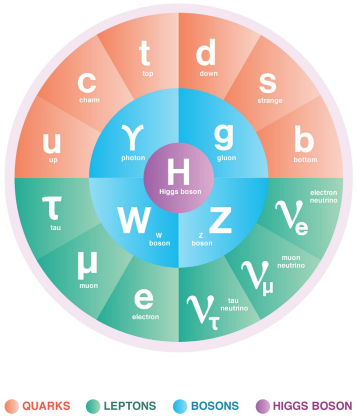
We have run software workshops hosted by HEP groups across India

- 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

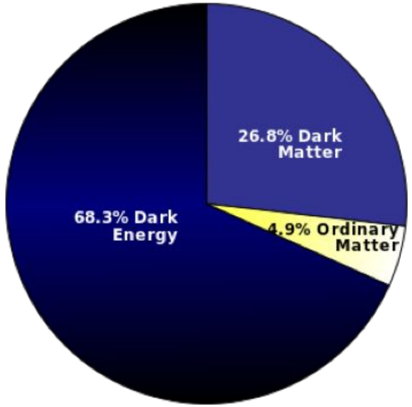
Scientific Python

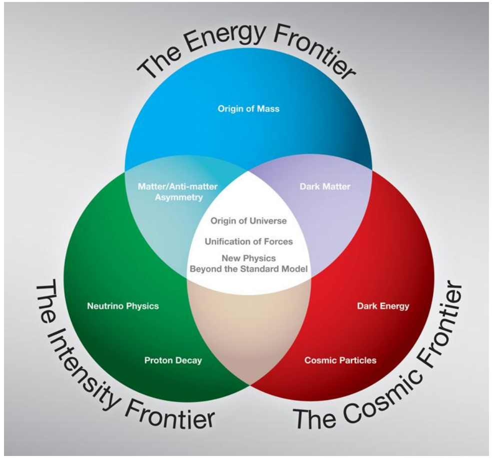
Marshmallow Challenge

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.

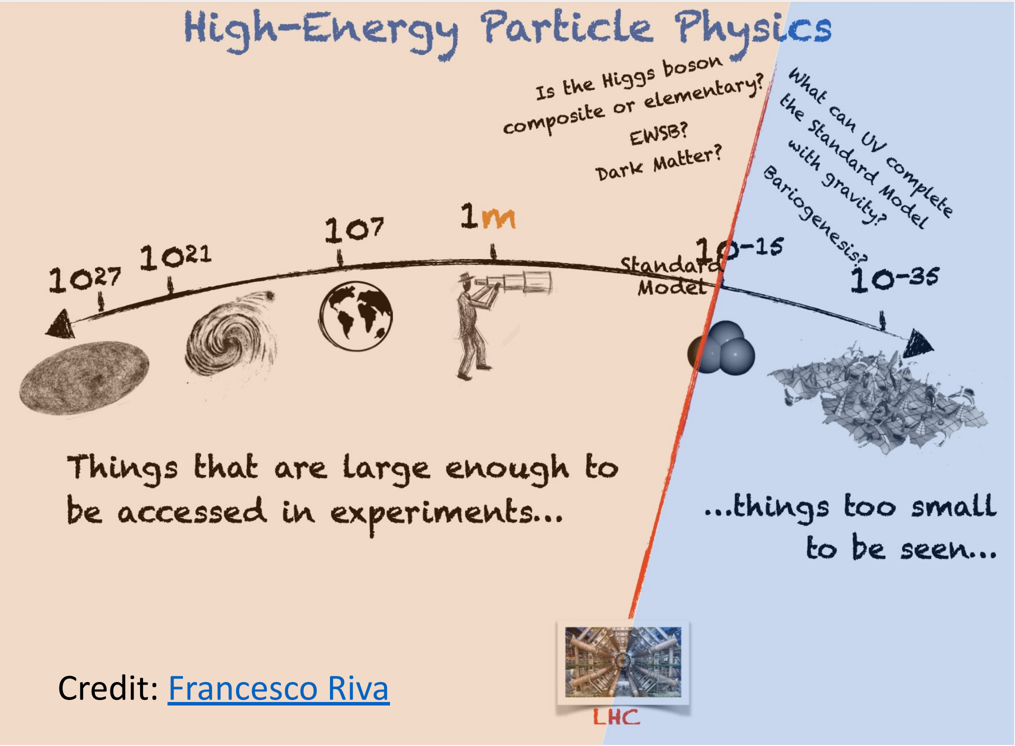




From "Building for Discovery - Strategic Plan for U.S. Particle Physics in the Global Context" - Report of the Particle Physics Project Prioritization Panel (P5):

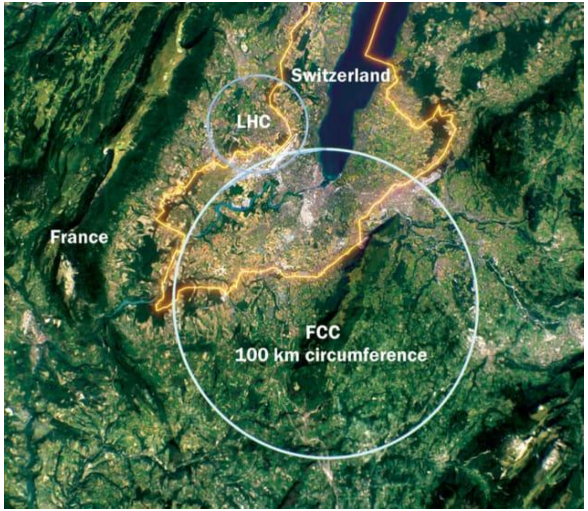
1) Use the Higgs boson as a new tool for discovery
2) Pursue the physics associated with neutrino mass
3) Identify the new physics of dark matter
4) Understand cosmic acceleration: dark energy and inflation
5) Explore the unknown: new particles, interactions, and physical principles

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

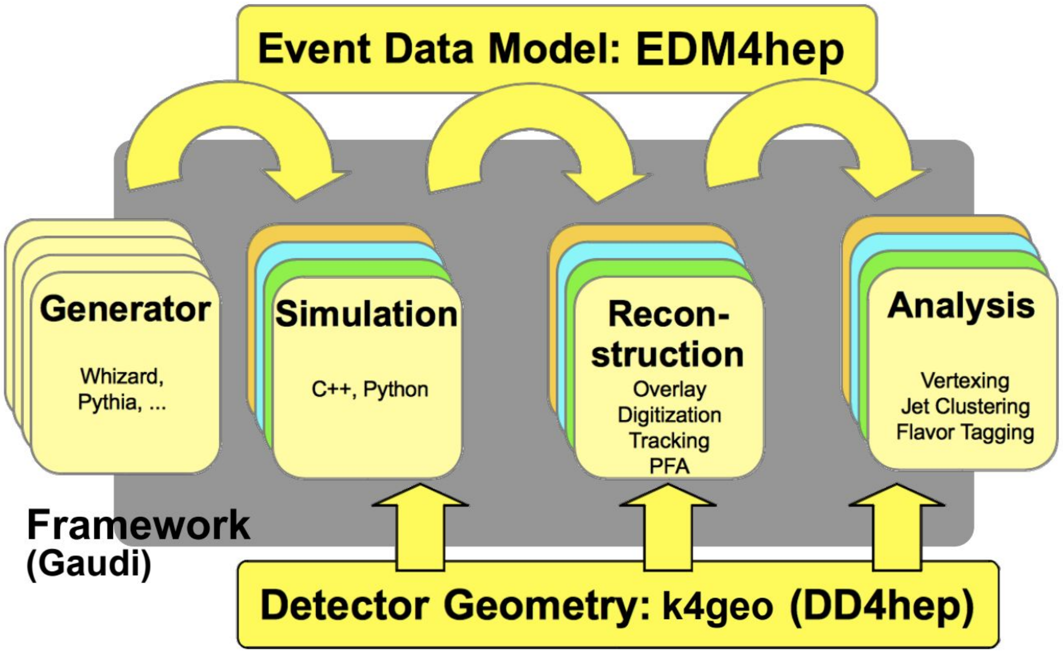


CERN aims to approve FCC-ee as next generation e+e- collider in 2028

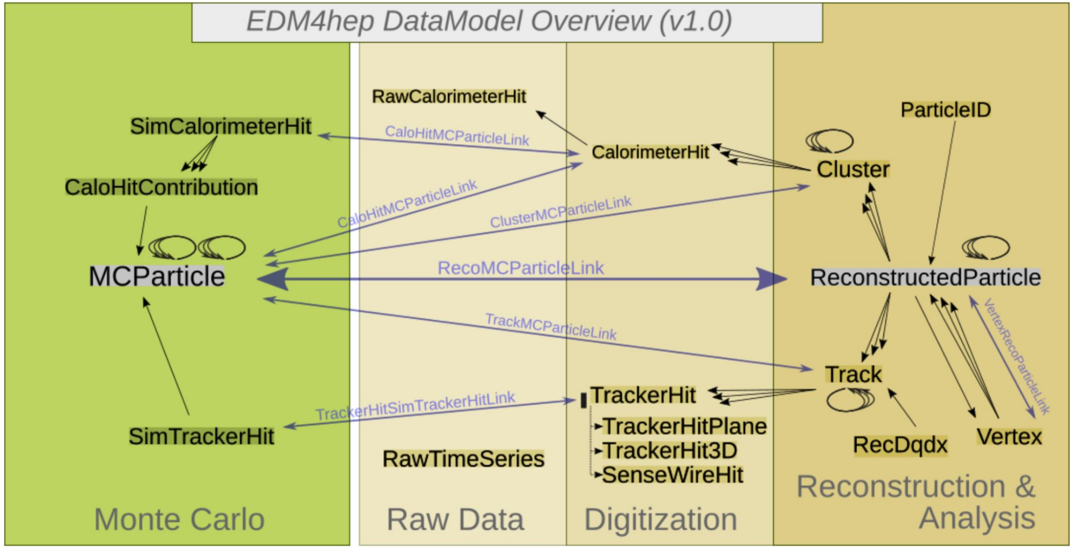
Future Colliders: Can we effectively share software development costs across experiments or facility concepts?

Key4Hep builds on LHC components (eg, Gaudi) to provide a full data processing framework and common data model

Community driven with participation from future experiments: FCC, ILC, CLIC, CEPC, EIC, Muon Collider, etc



Can we adopt a common data model?



A common data model fosters algorithm reuse in Key4hep, and allows analysis codes to be re-used and shared across detector concepts

How far can a model of common software be taken?

It remains to be seen if and how much of a software ecosystem can be maintained in common between experiments at different facilities and at different stages of their lifecycle

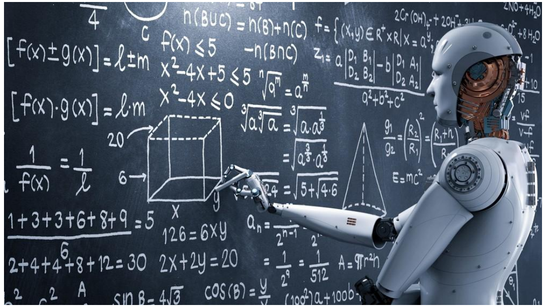
Practical considerations

- Competition naturally moves groups to closed development models
- Forking off is easier than coming back together
- It is more difficult to establish a common timeline for releases as projects move out of a R&D/simulation phase towards data taking
    - For example: data model and core components are likely easier to share than higher level components

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?

An AI-Native Research Ecosystem and a corresponding collaboration?

arXiv > hep-ex > arXiv:2602.17582

Search...

Help | Adva

High Energy Physics – Experiment

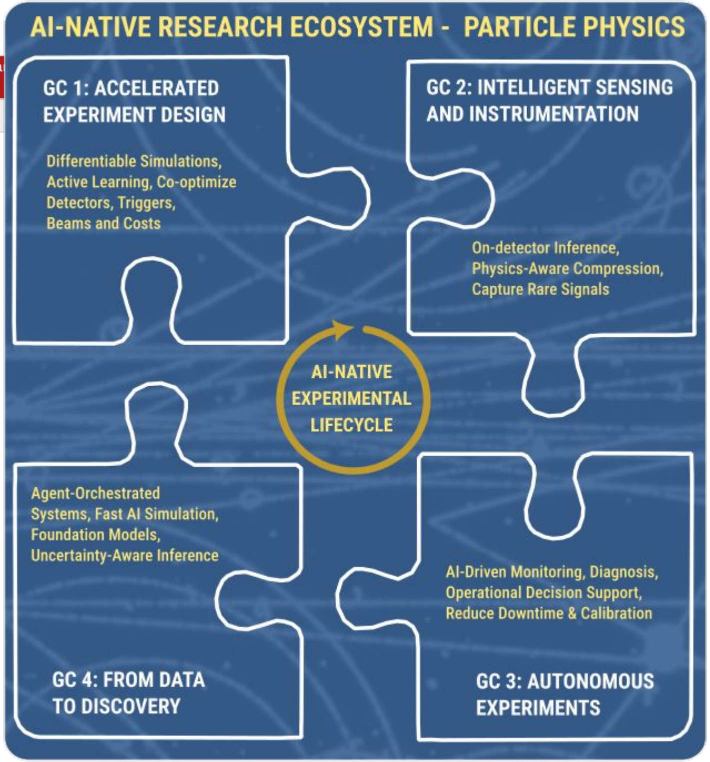
[Submitted on 19 Feb 2026]

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

Thea Klaeboe Aarrestad, Alaa Abdelhamid, Haider Abidi, Jahred Adelman, Jennifer Adelman-McCarthy, Shuchin Aeron, Garvita Agarwal, Usman Ali, Cristiano Alpigiani, Omar Alterkait, Mohamed Aly, Oz Amram, Saeed Ansari Fard, Aram Apyan, John Arrington, Marvin Ascencio-Sosa, Mohammad Atif, Aneesha Avasthi, Muhammad Bilal Azam, Bhim Bam, Joshua Barrow, Rainer Bartoldus, Amit Bashyal, Aashwin Basnet, Ayse Bat, Lothar A. T. Bauerdick, John Beacom, Chris Bee, Michael Begel, Matthew Bellis, Rene Bellwied, Rakitha Beminiwattha, Gabriele Benelli, Douglas Benjamin, Catrin Bernius, Binod Bhandari, Avinay Bhat, Meghna Bhattacharya, Saptaparna Bhattacharya, Prajita Bhattarai, Sudip Bhattarai, Wahid Bhimji, Jianming Bian, Burak Bilki, Mary Bishai, Kevin Black, Kenneth Bloom, Brian Bockelman, Johan Sebastian Bonilla Castro, Tulika Bose, Nilay Bostan, Othmane Bouhali, Dimitri Bourilkov, Dominic Brailsford, Gustaaf Brooijmans, Elizabeth Brost, Maria Brigida Brunetti, Quentin Buat, Brendon Bullard, Jackson Burzynski, Paolo Calafiura, Rodolfo Capdevilla, Fabian Andres Castaño Usuga, Raquel Castillo Fernandez, Fabio Catalano, Viviana Cavaliere, Flavio Cavanna, Giuseppe Cerati, Aidan Chambers, Maria Chamizo-Llatas, Philip Chang, Andrew Chappell, Arghya Chattopadhyay, Sergei Chekanov, Jian-ping Chen, Yi Chen, Zhengyang Chen, J. Taylor Childers, Hector Chinchay, Yuan-Tang Chou, Tasnuva Chowdhury, Neil Christensen, Wonyong Chung, Rafael Coelho Lopes de Sa, Simon Corrodi, Kyle Cranmer, Matteo Cremonesi, Roy Cruz, Mate Csanad, Mariarosaria D'Alfonso, Carlo Dallapiccola, Daine Danielson, Sridhara Dasu, Gavin Davies, Kaushik De, Patrick de Perio, Klaus Dehmelt, Marco Del Tutto, Carlos Ruben Dell'Aquila, Sarah Demers et al. (359 additional authors not shown)

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.

https://arxiv.org/abs/2602.17582



Conclusions

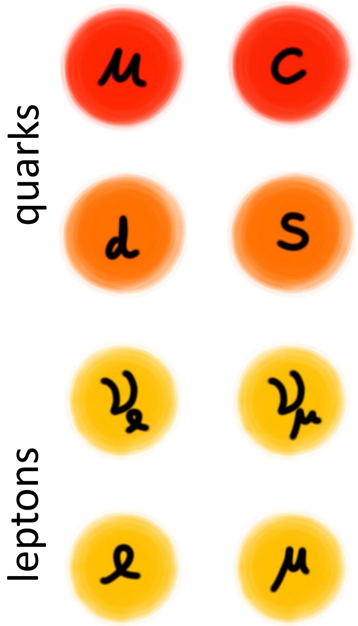
- Experimental science is enabled by tools innovation, which become facilities enabling further science. Our science has been driven by accelerator and detector innovation.

- 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.

Thank You!

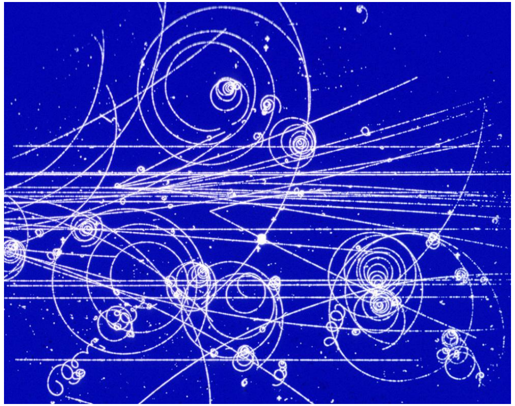
November “Charm” Revolution: Two families of fermions?



+ anti-particles

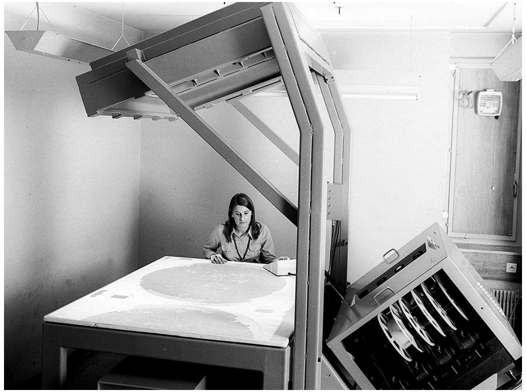
(i.e. copies of opposite charge)

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

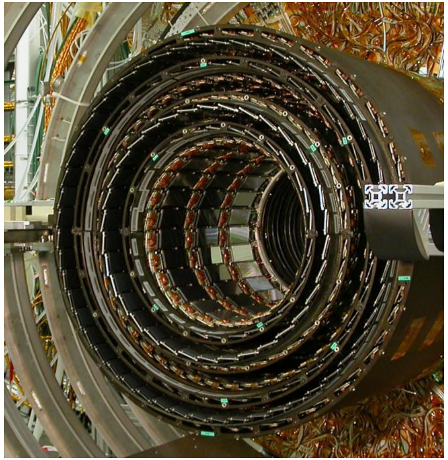


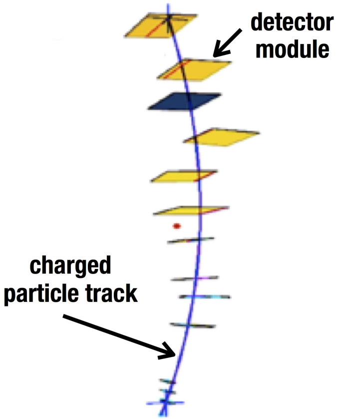
Bubble chamber photography

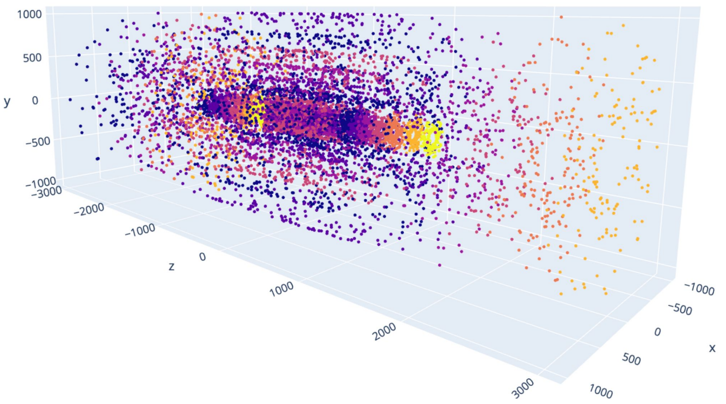
By-hand "scanning" of the photos



Modern detectors with (digital) electronic readout







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

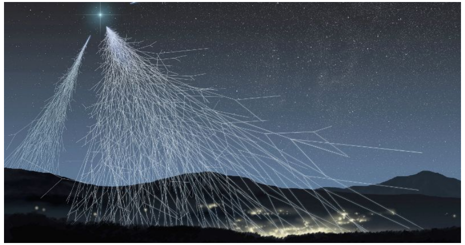
1949: Neutral pion discovery at the Berkeley 184 inch Cyclotron (Bjorklund et al)

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

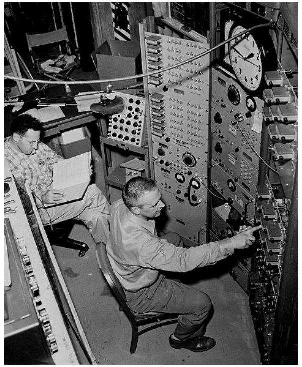
1956: Discovery of the neutrino (Cowan, Reines, et al), using nuclear reactor

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)



Collaborations

dCache

DESY.

2000-

Fermilab

XRootD

2003-

SLAC

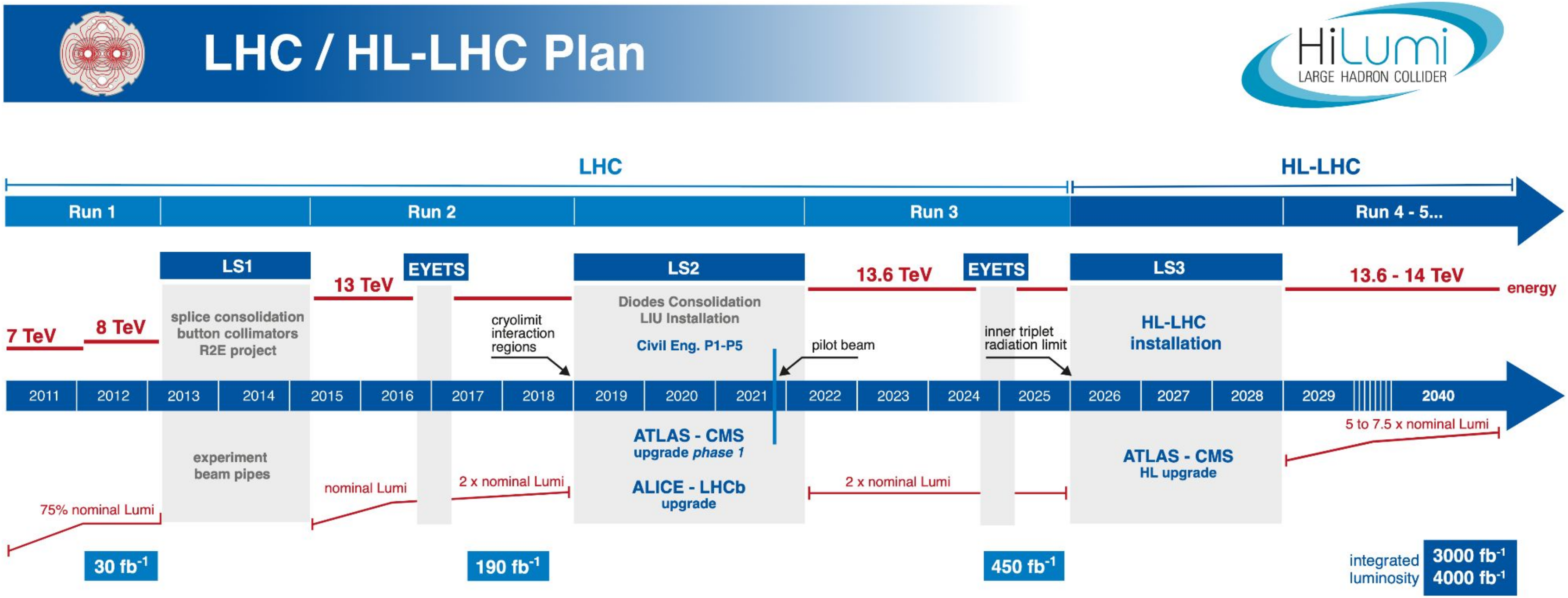
CERN

INFN

Istituto Nazionale di Fisica Nucleare

UCSD

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 with continued data analysis beyond that date.