U.S. DEPARTMENT OF ENERGY | Office of Science

HEP Program Overview and Organization and Operations of the Large Hadron Collider Experiments

Fusion Energy Sciences Advisory Committee Meeting
August 31, 2021

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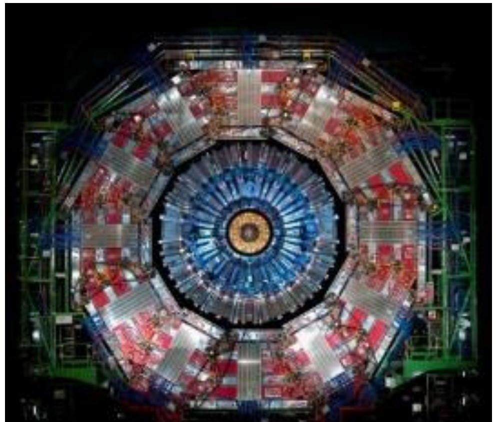
HEP: Basic Discovery Science and Technology Development to Support the Program

DOE High Energy Physics Mission is to understand how the universe works at its most fundamental levels by:

- **Discovering** the most elementary constituents of matter and energy
- **Probing** the interactions between them
- **Exploring** the basic nature of space and time

- **HEP develops and supports a specific portfolio of projects:**
  - Makes **significant, coherent contributions to facilities/experiments** selected for the program, including project management
  - Supports **R&D that will advance the state-of-the-art in particle accelerators and detectors** that will lead to new, more capable facilities
  - Supports **R&D to enable new and transformative capabilities** in AI/ML, QIS, and cross-cutting technology areas
  - Supports vibrant theory program to **provide the vision and extend our knowledge** of particles, forces, space-time, and the universe
- **DOE-HEP supports ~85% of U.S. particle physics (in $), including ~all national laboratories**


CMS at CERN LHC


Fermilab Muon g-2

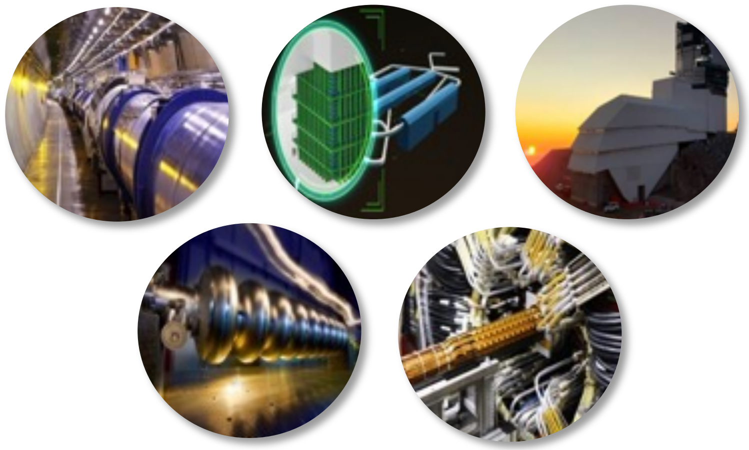

Vera Rubin Observatory

U.S. Particle Physics Strategic Plan

- **2014 U.S. Particle Physics Project Prioritization Panel's (P5) report guides DOE and NSF investments in particle physics**
  - Global vision of HEP is essential to success of DOE's priorities and mission
  - Addresses five Science Drivers that motivate particle physics to encompass a balanced program that deeply intertwines U.S. efforts with international partners
- **CERN is an important partner in achieving this vision**
  - The Large Hadron Collider (LHC) and the now progressing High-Luminosity LHC upgrade program are a core part of the U.S. program
  - CERN is a key partner in the U.S.-hosted international neutrino program: short- and long-baseline
  - R&D on advancing accelerator and detector technologies lays the foundation for enabling future particle collider facilities
- **DOE execution of P5 strategy requires navigating many factors**
  - Balanced program for projects, operations, and research
  - Coordination among U.S. and international partners

HEP Research Frontiers

Particle Physics Science Drivers	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●



High Energy Physics *is* Global

- **From Chapter 1 of the 2014 U.S. P5 Strategic Plan:**

- The scientific program required to address all of the most compelling questions of the field is **beyond the finances and the technical expertise of any one nation or region**.

Japan
International Linear Collider

U.S. Fermilab
Long-Baseline Neutrino Facility

CERN
Large Hadron Collider; Future Circular Collider

- The capability to address these questions in a comprehensive manner is within reach of a **cooperative global program**.
- The field is **at a juncture where the major players each plan to host one of the large projects** most needed by the worldwide scientific community.

DOE Particle Physics Agency Partnerships

NSF
- Proposal driven program
- Funds facilities and equipment, such as telescopes, through cooperative agreements with research consortia

DOE
- Mission driven program
- National Laboratory enterprise and National User Facilities provide important capabilities & expertise

NASA
- Mission driven program
- Expertise in human spaceflight, aeronautics, space science, and space applications
- Partnership enables unique science opportunities

HEPAP Coordination

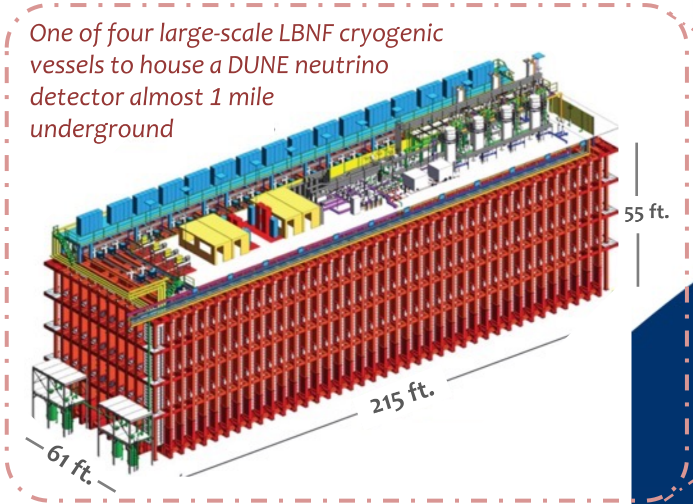
AAAC Coordination

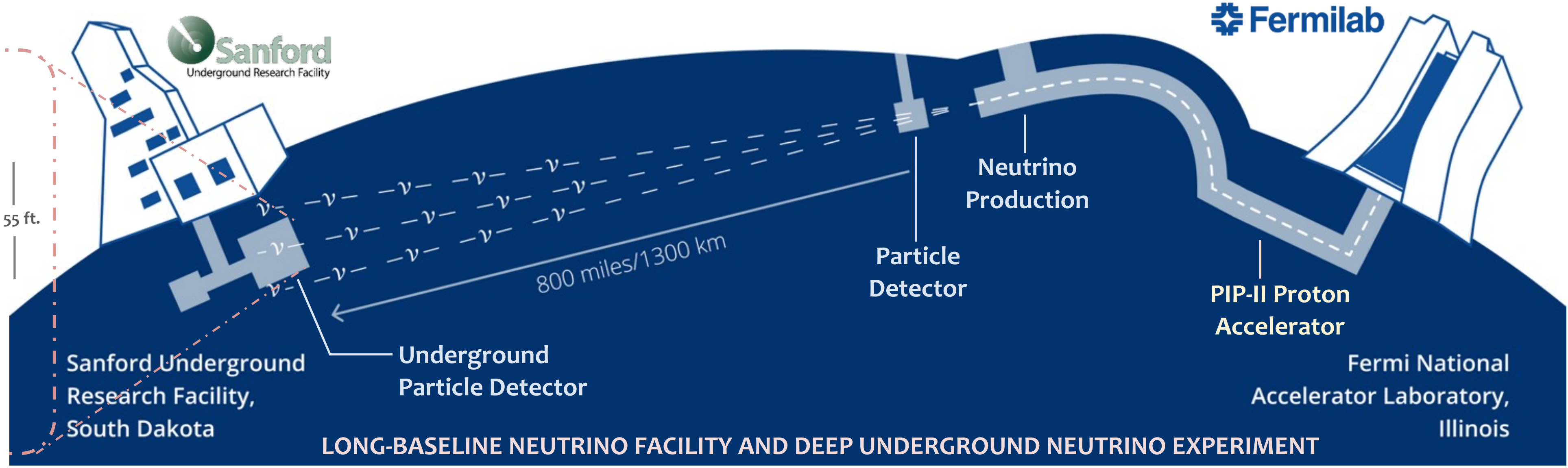
NSF	DOE	NASA
Strong Connections	Energy Frontier	
Modest Ties	Intensity Frontier	
Strong Connections	Cosmic Frontier	*Space-based experiments*
Strong Connections	Theoretical Physics	
Modest Ties	Technology R&D	

Department of Defense · NIST National Institute of Standards and Technology U.S. Department of Commerce · U.S. Department of Homeland Security · NIH National Institutes of Health

Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment

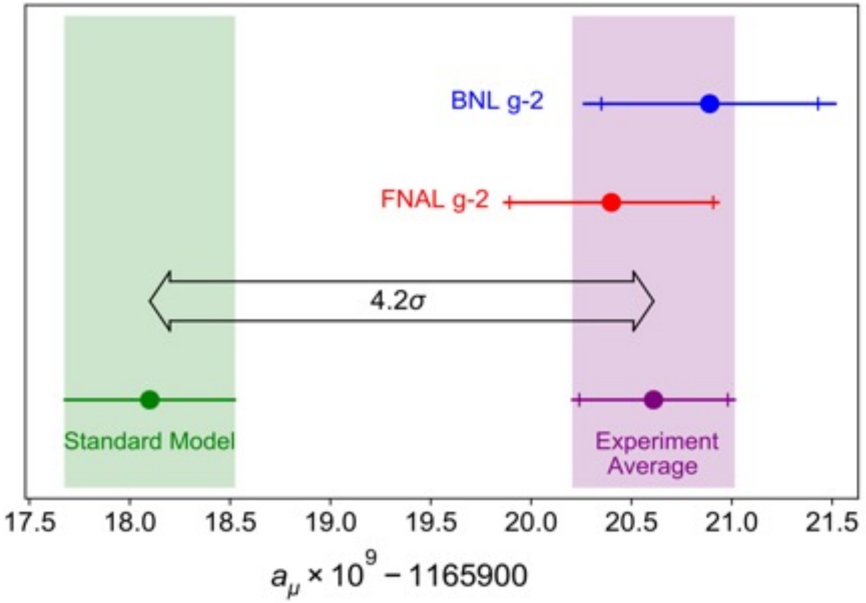
- **2014 U.S. P5 recommended Long-Baseline Neutrino Facility (LBNF) as the centerpiece of a U.S.-hosted world-leading neutrino program**
  - LBNF will produce the world's most intense neutrino beam, send it 800 miles through the earth to DUNE detectors
  - Proton Improvement Plan-II (PIP-II) accelerator will provide increased proton beam intensity (>1 MW) for the LBNF/DUNE endeavor
  - Strong support within the U.S. Government and by many global partners
- **International DUNE collaboration now includes over 1,300 collaborators from 201 institutions in 33 countries**





Muon g-2 Experiment

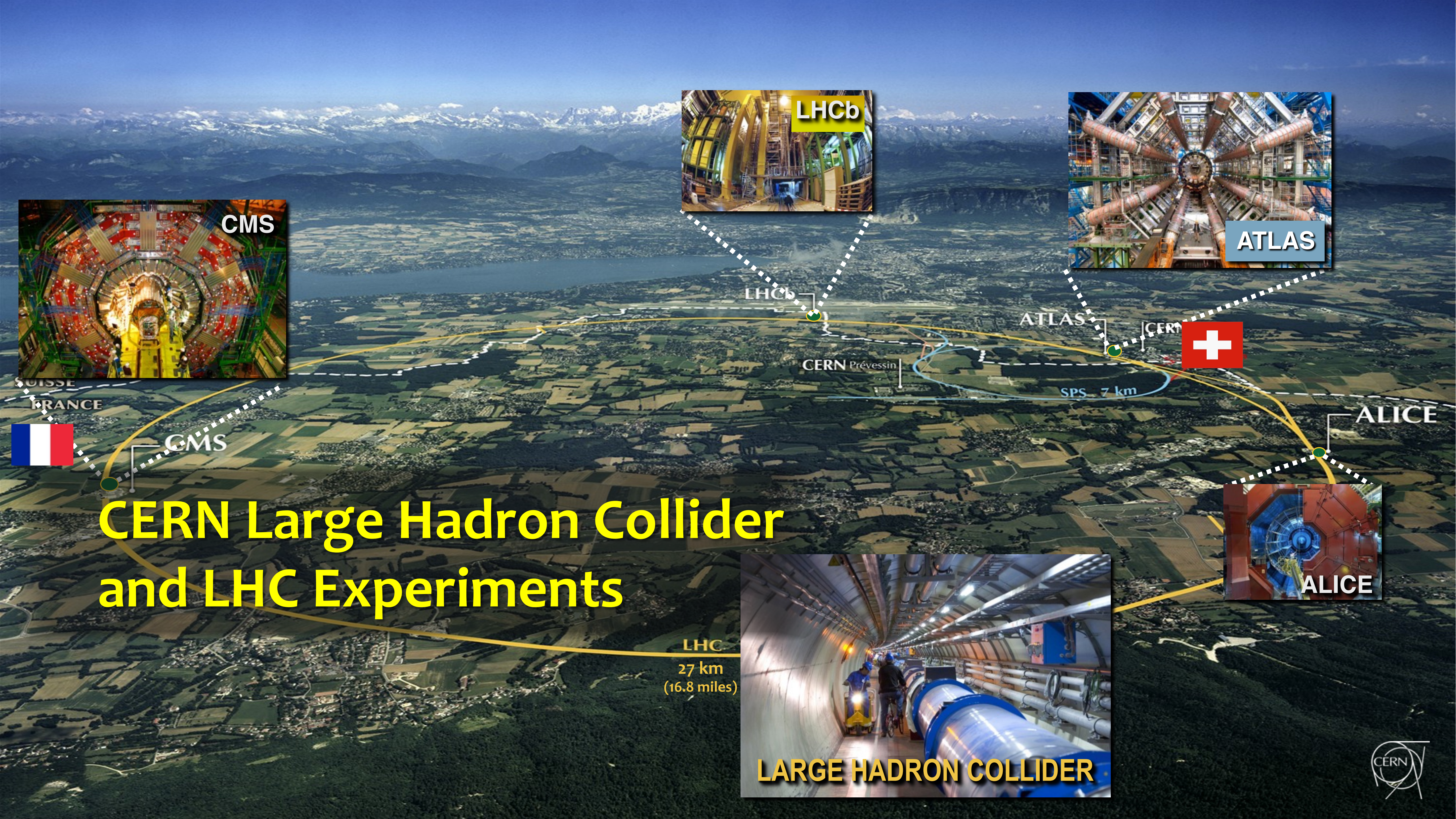
- **Precisely measure muon anomalous magnetic moment**
  - $a_\mu \equiv (g_\mu\text{-}2)/2$
  - g_μ = g-factor of the muon; strength determines the rate at which a muon precesses (gyrates) in an external magnetic field
  - For muons, g-factor is slightly different from 2 primarily due to radiative corrections
  - Any measured deviation from Standard Model calculations can hint at new physics
- **First result in April 2021 after initial running at Fermilab**
  - Strongly agrees with the earlier BNL result from 1997-2001 running and diverges from theory by 4.2σ
  - Based on ~6% of total expected statistics
  - PRL: https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.126.141801
- **For additional precision, g-2 collaboration at Fermilab now sifting through more data from the 2nd and 3rd runs**
- **The 4th run is ongoing; and a 5th run is being planned**



HEP Cosmic Physics Program

- **Dark energy program through suite of complementary surveys, in partnership with NSF**
  - **Fast sky scanning survey catch dynamic events, like supernovae:** *Vera C. Rubin Observatory* now being commissioned
  - **Deep, high accuracy surveys study dim, more distant objects:** *Dark Energy Spectroscopic Instrument (DESI)* taking data
- **Dark matter searches through direct detection experiments with multiple technologies, in partnership with NSF**
  - **First-generation experiments produced world’s most sensitive searches**
  - **Progressing towards next-generation experiments:** *ADMX-G2* operating; *LZ* in commissioning; *SuperCDMS-SNOLAB* in fabrication, *DarkSide-20k* in R&D
- **Study high-energy particles produced from cosmos, in partnership with NSF and/or NASA**
  - **Cosmic- and gamma-ray detectors on Earth and in space:** *Fermi/GLAST; HAWC; and the Alpha Magnetic Spectrometer on the International Space Station*
- **Study cosmic acceleration imprint on cosmic microwave background, in partnership with NSF and/or NASA**
  - **New generation now operating:** *SPT-3G*
  - **Next state-of-art project now in R&D, moving to baseline:** *CMB-Stage 4*





LHCb
CMS
ATLAS
ALICE
LHCb
ATLAS
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
CERN Large Hadron Collider
and LHC Experiments
LHC
27 km
(16.8 miles)
LARGE HADRON COLLIDER
CERN

CERN Model for Hosting LHC Program

- **The "CERN Model" such as the one used by CERN for hosting the LHC accelerator facility and the LHC experiments has worked well for executing large infrastructure science projects with contributions from multiple international partners**
  - DOE Office of High Energy Physics has tailored and adapted the model for our own Fermilab-hosted Long-Baseline Neutrino Experiment (LBNF) and Deep Underground Neutrino Experiment (DUNE)
  - Implementing the model for LBNF/DUNE maintains compliance with applicable DOE policies and procedures
    - for example, CERN serves as the laboratory and a governing body while, in the U.S., DOE is the governing entity and Fermilab is the laboratory ⇒ requires tailoring model to the Laboratory-DOE relationship
- **CERN Model is based on separation of the governance of the Infrastructure (Host Lab or Facility) and of the Experiments**

Governance of CERN (I)

- **At CERN, two complementary governance constructs are deployed:**
  - Formal Treaty Organization for the Host Lab: to run the infrastructure (i.e., facility or LHC accelerator)
  - Flexible Organization, based on best effort – through MOUs stipulated among the international Funding Agencies and CERN, as the Host Lab: to construct and operate the experiments
- **From a CERN perspective, Experiments are composed of international collaborators and are not a legal entity and are not owned by the Host Lab**
  - Collaborators, including those from the Host Lab, work cooperatively together to design, build, and operate the Experiment to pursue science
  - The Host Lab nevertheless provides certain services and resources such as electricity and office space to collaborators to facilitate experimental operations
  - Collaborators from institutes are under the administrative and technical supervision and control of the Host Lab, including:
    - Compliance with its applicable rules regarding admission to and use of premises
    - Safety, operating, and health-physics procedures, environmental protection, access to information, cyber-security, and code of conduct

Governance of CERN (II)

- **The infrastructure of CERN, including decisions for its facilities — such as the LHC — is run by the 23 Member States, each of which as 2 official delegates to CERN Council**
  - One representing the government's administration
  - The other representing national scientific interests

- **Each Member State has a single vote and most decisions require a simple majority, although in practice the Council aims for a consensus as close to possible to unanimity**

- **The Council is highest governing authority of CERN Organization**
  - Defines strategic programs, setting annual goals, reviews expenditures, and adopts CERN's annual budget through a principle of a 5-year rolling budget in the context of a 10-year vision for the organization ⇒ budget known as the "Medium-Term Plan" (MTP)
    - Under CERN Model, the Host Lab (CERN) is responsible for ~75% of costs for construction of, or any upgrade to, the LHC Facility ⇒ costs are balanced in MTP through CERN Member State annual dues
    - Remaining ~25% of LHC facility construction or upgrade costs facilitated through non-Member States via international cooperative agreements, including the fraction contributed by DOE
  - **Whereas, ~75% of experiments' costs secured through international partnerships and ~25% by Host Lab**

Governance of CERN (III)

- **CERN Council is assisted by the Scientific Policy Committee (SPC) and Finance Committee (FC)**
  - SPC advises Council of scientific matters related to the CERN Organization
  - FC addresses budgetary, procedural, personnel and commercial matters

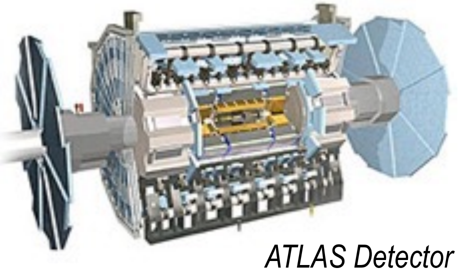
- **CERN Director-General, appointed by the Council, manages CERN Laboratory**
  - Assisted by a directorate and runs the Laboratory through a structure of departments

- **While the experiments are quasi-independently managed with respect to the Host Lab, the Host Lab maintains oversight through the LHC Resources Review Board (RRB) for the LHC experiments**
  - Chaired by CERN Director for Research and Computing (*i.e.*, Host Lab's management)
  - Composed of 1 delegate per [international] Funding Agency + management of Host Lab
  - Each Funding Agency has the same voting power, independent of their contribution
  - *More discussion on LHC RRB later in this talk…*

ATLAS and CMS Experiments at the LHC – Today

ATLAS Collaboration at the LHC

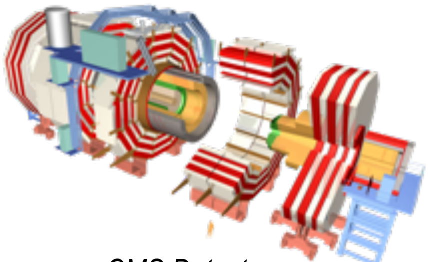
- 2,900 scientific authors with 1,200 PhD students
- 180 institutes from 40 countries
- 33 U.S. institutes supported by DOE; 10 supported by NSF
- DOE 15.5%; NSF 3.6% of international ATLAS



ATLAS Detector

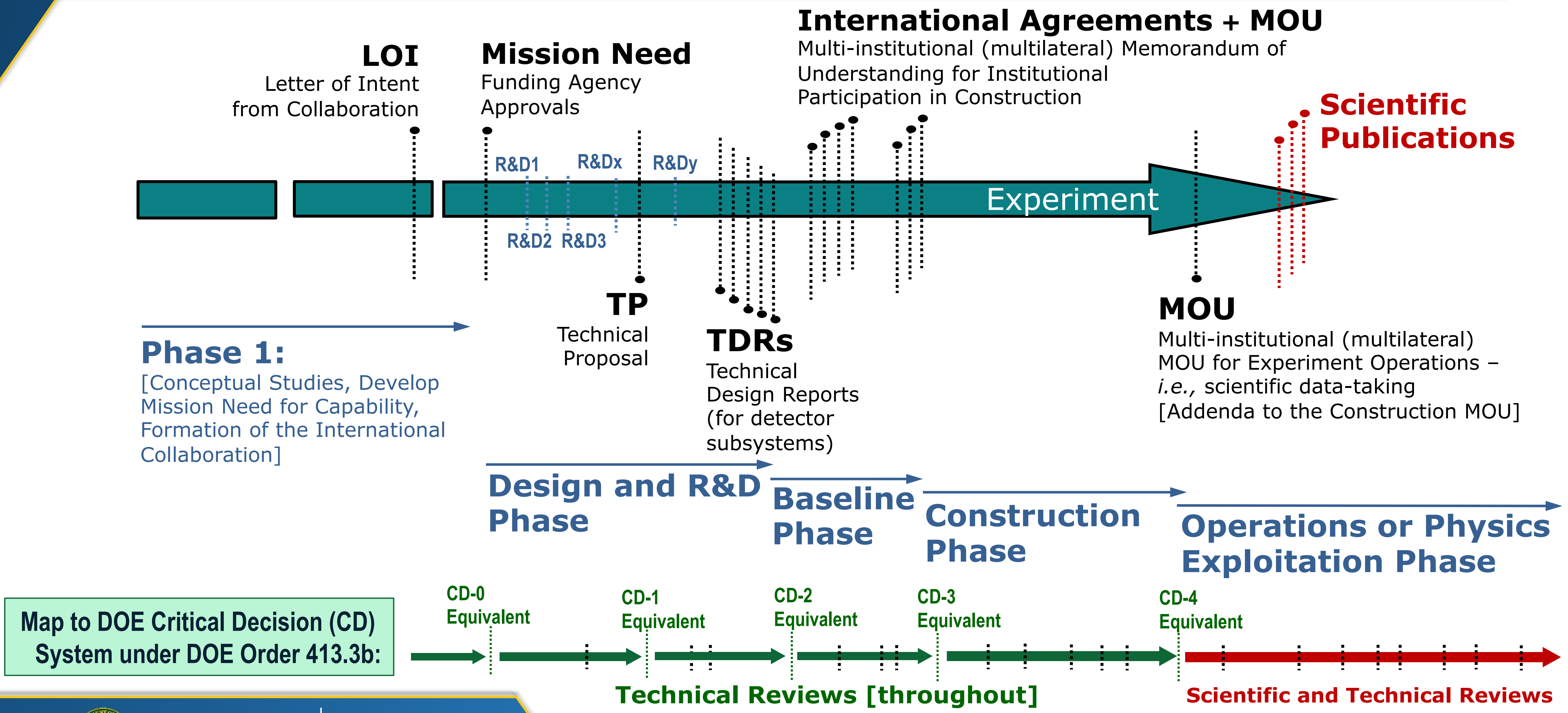
CMS Collaboration at the LHC

- 3,100 scientific authors with 1,170 PhD students
- 241 institutes from 54 countries
- 35 U.S. institutes supported by DOE; 17 supported by NSF
- DOE 22.3%; NSF 5.7% of international CMS



CMS Detector

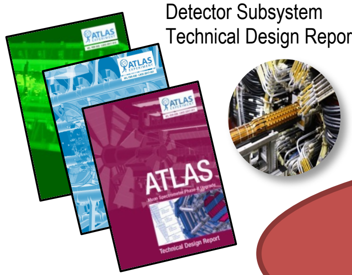
Five Phases of the Experiment

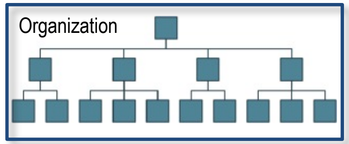


Organizational Features of the Experiments

- **To allow for optimizing flexibility, efficiency, and independence of experiments of international scope and size, while retaining the necessary scientific, scheduling and budgetary oversight and control, four components are necessary for success:**

Detector Subsystem
Technical Design Reports





A strong management team *plus* oversight ability by the Host Facility

Both R&D and Construction Programs well structured and financed

Strong contributions leveraging expertise of individuals in the *global* scientific community

European Strategy

U.S. P5 Strategy

A “road map” for a program well planned at all levels (science community, funding agencies and their advisory bodies)

Experiment’s Detectors and Physics

Experiment Governance as Defined by MOU

- **An Executive Committee directs the execution of the [international] Experiment, including its detector construction project and subsequent operations phase**
  - Composition includes the Experiment's Spokesperson, Resource and Technical Coordinators, and the Chair of the Institutional Board (IB)
  - Spokesperson and IB Chair are elected; Resource and Technical Coordinators are appointed but Host Lab (CERN) staff members to ensure compliance of Host Lab policies/procedures (*e.g.*, finances, safety, …)
- **IB is a policy and decision-making body of the Collaboration**
  - Composed of a representative from each collaborating institution
  - Body to approve and new incoming collaborating institutions or collaborators
- **Host Lab conducts oversight through the LHC Resources Review Board (RRB)**
  - The Funding Agency body responsible for pluri-annual monitoring of Experiments' resources
  - Chaired by CERN Director for Research and Computing
  - Monitors general financial and resource support, including the use of Common Funds for Common Projects
    - Based on review & recommendation of dedicated Construction, Operations, or Computing Scrutiny Groups
  - Funding Agency delegates discuss annual detector maintenance and operation (M&O) progress and plans
  - Endorse the construction and annual M&O budgets of the experiment's detector
  - Funding Agency delegates endorse multi-institutional construction or operations MOUs for the experiment

Host Lab Coordination

- **Additional committees/groups assist CERN and LHC experiments in program planning**

- **LHC experiments Committee (LHCC)**
  - Monitors the LHC experiments' scientific and technical programs
  - Reviews proposals for new experiments and/or experiments' upgrades
  - Monitors construction of detectors and their schedule and milestones
  - Committee composed of scientific experts not directly involved in LHC experiments or at least in the experiments that are reviewed

- **Maintenance and Operations (M&O) Resources Scrutiny Group**
  - Scrutinize the experiment collaboration's M&O reports and estimate, including Common Fund contributions, for preceding year plans for the following year and subsequent two years
  - Advise the LHC RRB on any course of action to be taken

- **Computing Resources Scrutiny Group**
  - Scrutinize experiments' use of computing resources for the preceding year and overall resource requests for following year and subsequent two years
  - Examine institutional pledges for resource allocations to Tier-1 and Tier-2 computing facilities
  - Advise the LHC RRB on any course of action to be taken

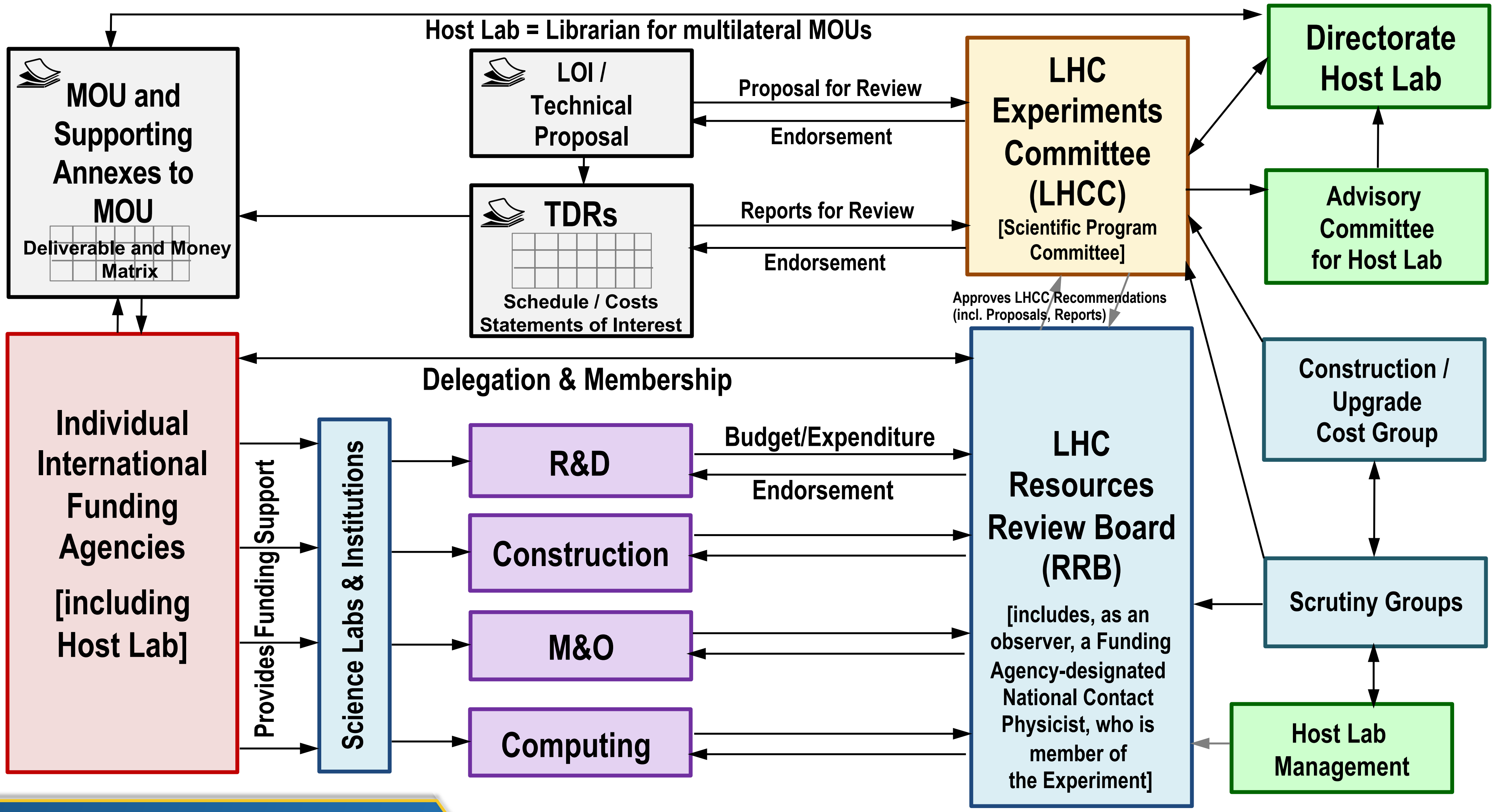
MOU Process for Construction Phase

- **Groups of interest begin forming for project systems, subsystems, and working groups, …**
  - Each subsystem has its own internal organization, which reflects in a smaller scale the Experiment’s organization
  - Each interested group begin carving out areas of contributions to the overall project
  - Each system has project leader to manage activities and resources
- **A multilateral MOU memorializes a common understanding by all participants to the project**
  - Preparation of initial draft of the MOU is bottom-up process
  - Relies on ”matrix” (tabular) structure for all deliverables = components, assembly, or other items from a partner
  - Every institute is responsible of the work which has been assigned to institute’s collaborators
  - Ensures experiments coordinate to successfully interface all deliverables from each international partner
  - Once matrix and project milestones are established, activate reporting mechanisms within the collaboration

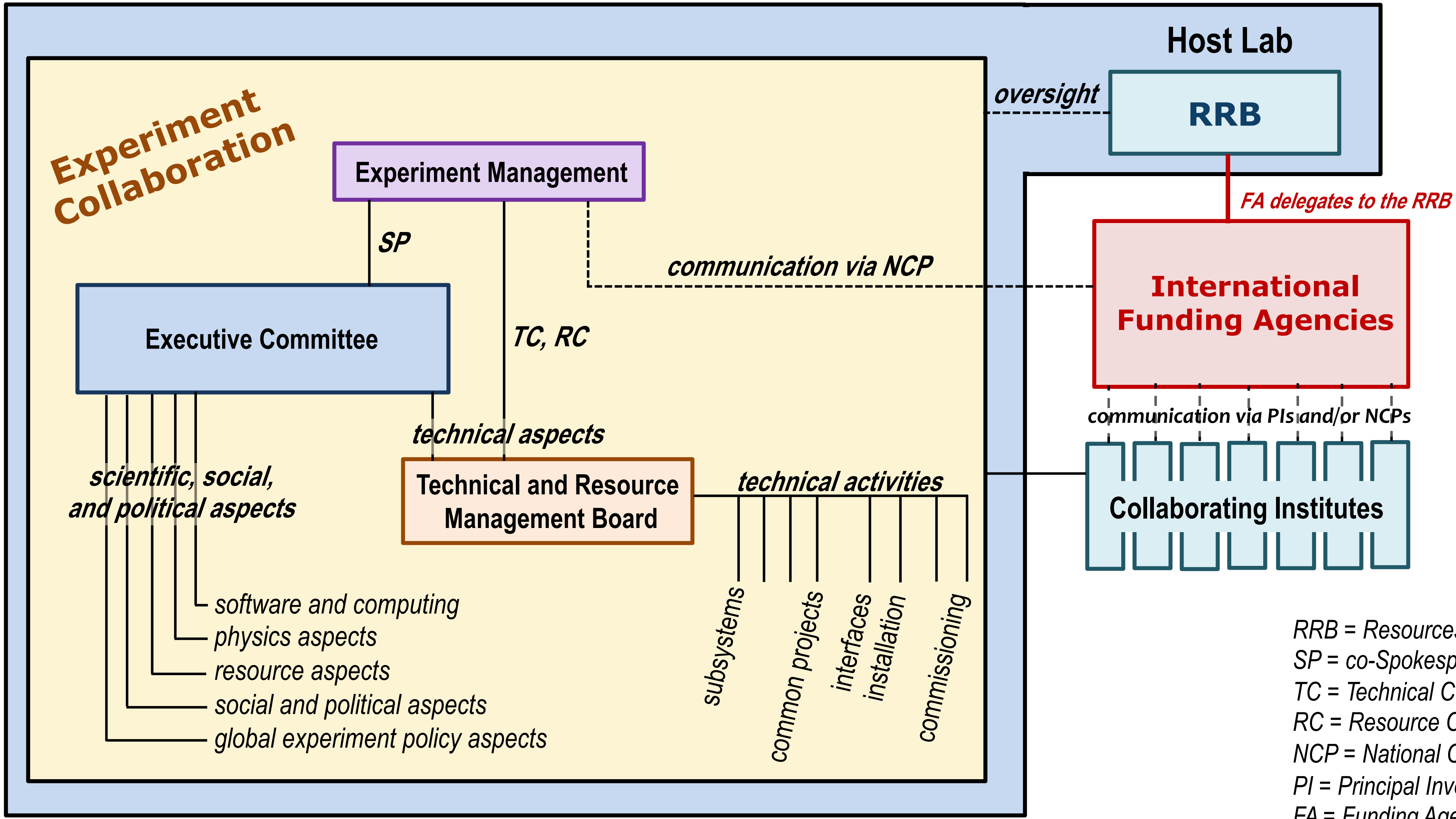
Funding Agency (Country)	Code	Subsystem 1	Subsystem 2	Subsystem 3	…	Subsystem *n*	Common Project (Infrastructure)	Total ($M)
Funding Agency *1* (Country *1*)	FA*1*	$10M		$20M		$14M	$3M	47
Funding Agency 2 (Country 2)	FA2		$15M			$1M	$1.5M	17.5
…								
Funding Agency *n* (Country *n*)	FA*n*	$6M	$9M	$18M		$3M	$3.3M	39.3
TOTAL ($M)	**—**	**16**	**24**	**38**		**18**	**7.8**	**103.8**

- **Host Lab is signatory to MOU with each partner ⇒ maintain oversight of activities at Host Lab**
  - Experiment’s Project Coordinator, jointly with Technical Coordinator, monitor technical execution of system activities

Experiment Approval and Monitoring Process



International Funding Agency Coordination with Experiments



RRB = Resources Review Board
SP = co-Spokespersons
TC = Technical Coordinator
RC = Resource Coordinator
NCP = National Contact Physicist
PI = Principal Investigator
FA = Funding Agency

Project MOU for the LHC Experiments (I)

- **To ensure coordination of all Participants and their Funding Agencies on a large-scale complex project with many subsystems ⇒ multilateral (multi-institutional) MOU**
  - One MOU for all Participants, signed with each Participating Institution or Funding Agency by Host Lab

- **Construction MOUs for the large-scale ATLAS and CMS detectors contain two sections:**
  - **"Core document"** comprises provisions on purpose of MOU, organization and management of experiment collaboration, role of RRB, general responsibilities of collaborators and host lab, rights and benefits of collaborating institutes, administrative and financial modalities, common funds, and provisions on dispute and amendment processes
  - **"Annexes to the MOU"** lists definitions, collaborating institutions, funding agencies sponsoring the project, organizational structure and contacts, matrix for the contributions, schedule and milestones

- **Technical details in the MOU for each detector subsystem are captured from the individual Technical Design Reports that are prepared by the Collaboration prior to the MOU**

- **MOUs are non-binding arrangements**
  - Based on "best-effort" principle ⇒ Participants *"recognize that the success of the project depends on participants adhering to its provisions."*
  - For many international partners, MOUs enable coordinating with their corresponding government ministries to secure their own funding for the project

Project MOU for the LHC Experiments (II)

- **Deliverable Matrices of collaborating institute's Funding Agency discussed in MOU's Annexes:**

Subsystems for Detector Construction

Annex 4 : Sub-detector Structure of the ATLAS detector

The ATLAS detector is structured into the following sub-detector units, which will be used throughout this document:

- **Inner Detector**	Pixel Detector (PD) Semiconductor Tracker (SCT) Transition Radiation Tracker (TRT)
- **Solenoid Magnet**	
- **Liquid Argon Calorimeter**	Electromagnetic Barrel Calorimeter (EMB) including a pre-sampler (PS) End Cap Calorimeters (EC) Electromagnetic End Cap Calorimeter (EMEC) Hadron Calorimeter (HCAL) Forward Calorimeter (FCAL)
- **Tile Calorimeter**	Barrel Tile Extended Barrel
- **Toroid Magnets**	Barrel Toroid End-Cap Toroids
- **Muon Detection System**	Monitored Drift Tube Ch. (MDT) Cathode Strip Chambers (CSC) Resistive Plate Chambers (RPC) Thin Gap Chambers (TGC)
- **Trigger, Data Acquisition and Detector Control System**	Level 1 Trigger Level 2 Trigger DAQ and Event Filter Detector Control System (DCS)
- **Detector Infrastructure**	
- **Off-line Data Handling**	

Matrix of [Funding Agencies, Subsystems]

8.1 Update of the ATLAS Detector Funding by Funding Agency
(CORE MoU, in 1995 ATLAS MCHF)
revision October 24, 2001

Funding Agency	Inner Det.	LAr Cal.	Tile Cal.	Muon cham.	Trigger/ DAQ/con	Common Projects	Total
Armenia			0.1			0.1	0.2
Australia	1.4					1.1	2.5
Austria					0.3	0.3	0.6
Azerbaijan						0.1	0.1
Belarus						0.2	0.2
Brazil			0.1			0.1	0.2
Canada	0.1	8.4				6.6	15.1
China NSFC+MSTC		0.3		0.3		0.4	1.0
Czech Republic	0.5		0.5			0.6	1.6
Denmark	0.9				1.0	1.4	3.3
Finland						0.1	0.1
France IN2P3	2.1	17.8	2.1			17.0	39.0
France CEA*		5.7		2.2		5.8	13.7
Georgia						0.1	0.1
Germany BMBF	7.9	3.2		2.5	4.7	14.2	32.5
Germany MPI	1.7	1.6		0.9		3.3	7.5
Greece				1.0		0.7	1.7
Israel				2.5	0.4	2.1	5.0
Italy	5.0	3.7	1.3	9.3	5.9	19.8	45.0
Japan	6.8			6.8	4.5	14.0	32.1
Morocco		0.2				0.1	0.3
Netherlands	1.8			3.0	0.9	6.7	12.4
Norway	2.4					1.8	4.2
Poland	0.4				0.2	0.4	1.0
Portugal			1.0		0.3	0.9	2.2
Romania			0.3			0.3	0.6
Russia	3.4	4.7	1.1	3.5		8.0	20.7
JINR	0.5	0.7	0.8	1.0	0.1	2.3	5.4
Slovak Republic		0.3				0.2	0.5
Slovenia	0.8					0.7	1.5
Spain	1.2	2.3	2.0			4.3	9.8
Sweden	3.1	1.5	0.9		0.6	4.7	10.8
Switzerland	4.9	1.1			4.0	8.5	18.5
Taipei	1.0	0.7				1.3	3.0
Turkey					0.2	0.2	0.4
United Kingdom	13.1				5.9	15.0	34.0
US DOE + NSF	12.0	16.9	3.6	8.8	4.0	35.5	80.8
CERN	9.0	8.6	3.0	1.5	11.5	27.4	61.0
Total	80.0	77.7	16.8	43.3	44.5	206.3	468.6
Rev. CORE detector cost	78.5	80.0	15.2	42.5	45.9	208.7	470.8
Total - cost	1.5	-2.3	1.6	0.8	-1.4	-2.4	-2.2

Matrix of [Funding Agencies, Subsystem 1]

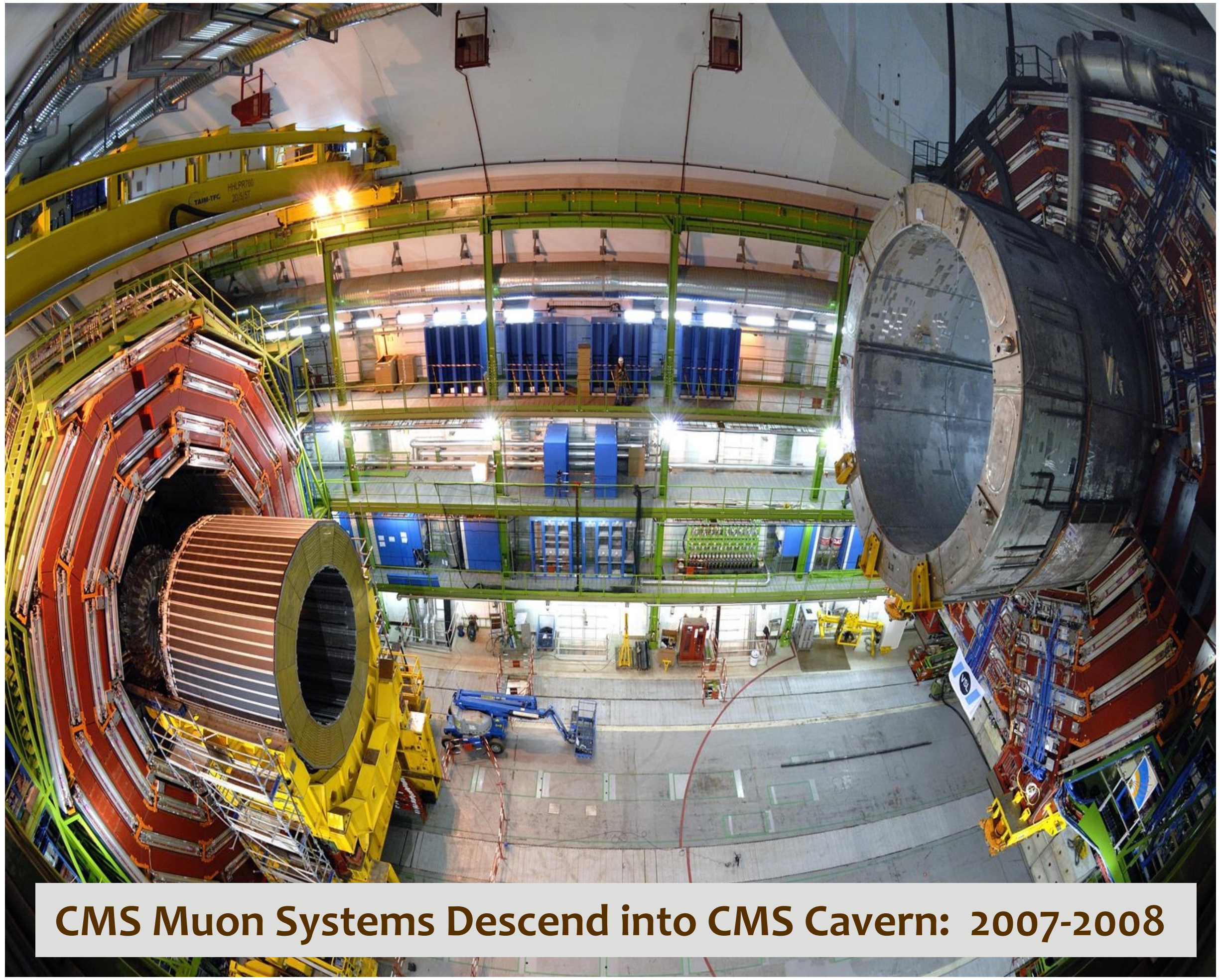
8.2 ATLAS Inner Detector funding and deliverables by funding agency
(CORE MoU, in 1995 ATLAS MCHF)
revision October 24, 2001

Funding Agency	CORE value (MCHF)	Type of Deliverable: Mechanics,sensors,gas,cooling	Optics	Read-out electronics,boxes	Photodetectors	Front-End Electronics	Calibration	Voltage Suppliers
Armenia								
Australia	1.4	•						•
Austria								
Azerbaijan								
Belarus								
Brazil								
Canada	0.1						•	
China NSFC+MSTC								
Czech Republic	0.5	•						•
Denmark	0.9			•				
France IN2P3	2.1	•				•		
France CEA								
Georgia								
Germany BMBF	7.9	•						•
Germany MPI	1.7	•						•
Greece								
Israel								
Italy	5.0	•				•		•
Japan	6.8	•		•				
Morocco								
Netherlands	1.8	•		•		•	•	
Norway	2.4	•		•		•		
Poland	0.4	•		•				•
Portugal								
Romania								
Russia	3.4	•						
JINR	0.5	•						
Slovak Republic								
Slovenia	0.8	•		•				
Spain	1.2	•		•		•		
Sweden	3.1	•		•		•		
Switzerland	4.9	•				•		•
Taipei	1.0		•	•				
Turkey								
United Kingdom	13.1	•		•		•	•	•
US DOE + NSF	12.0	•		•		•		
CERN	9.0	•		•		•	•	•
total	80.0							

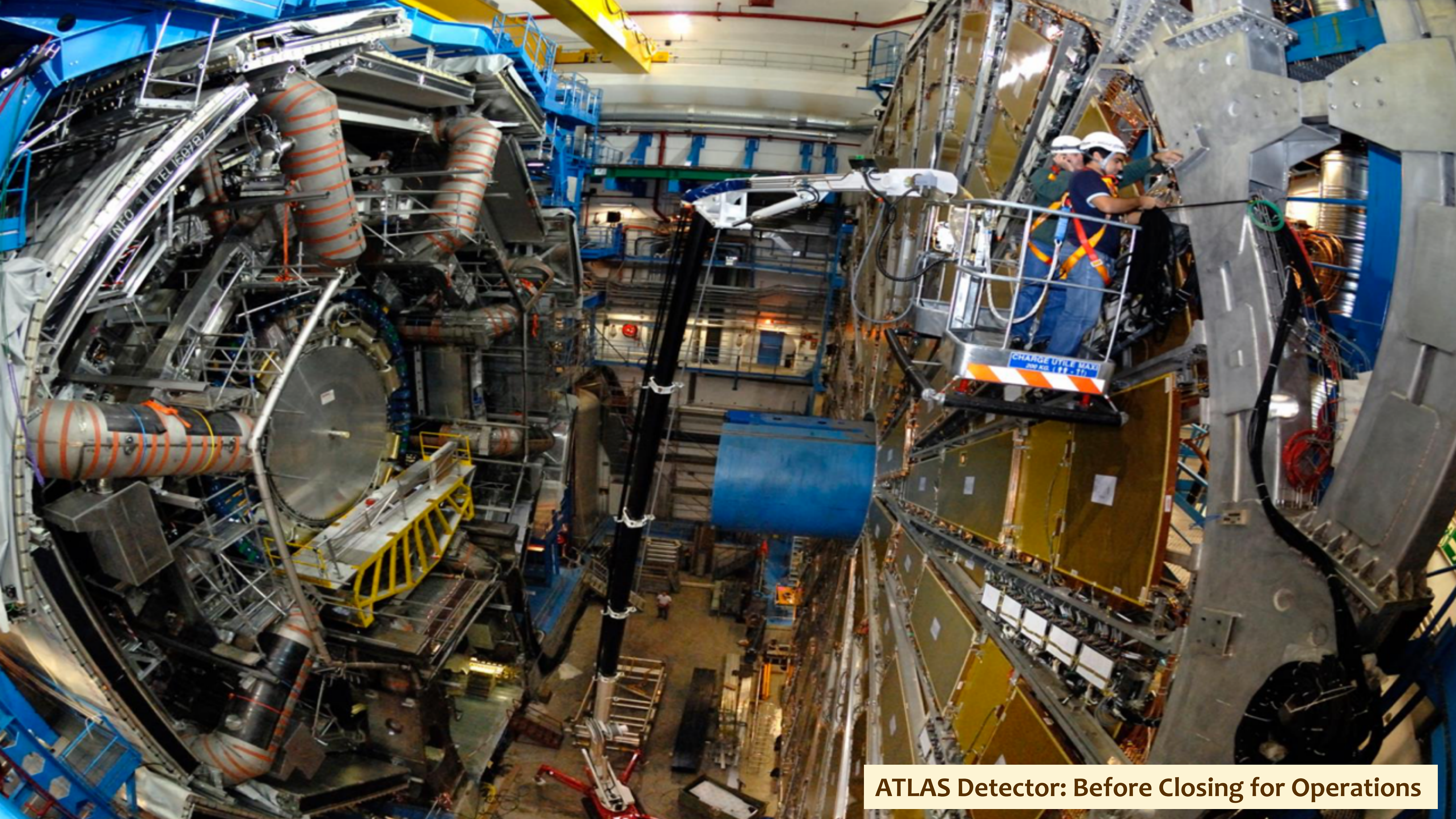
Example for ATLAS Detector:
Total Detector Cost (all International Partners): 468.6 MCHF

ATLAS and CMS Detectors' Installation

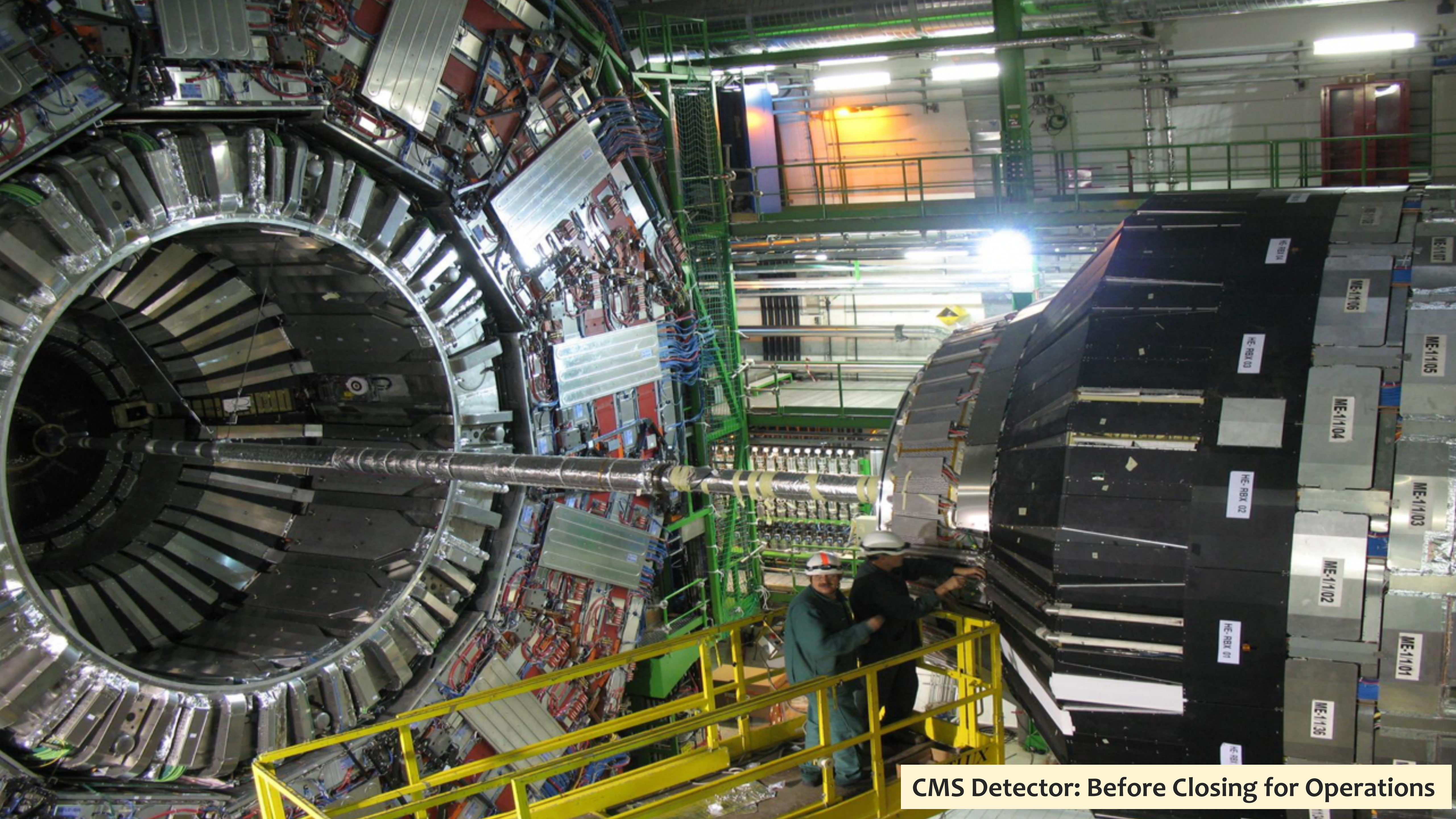
ATLAS Muon System Descend into ATLAS Cavern: 2008



CMS Muon Systems Descend into CMS Cavern: 2007-2008



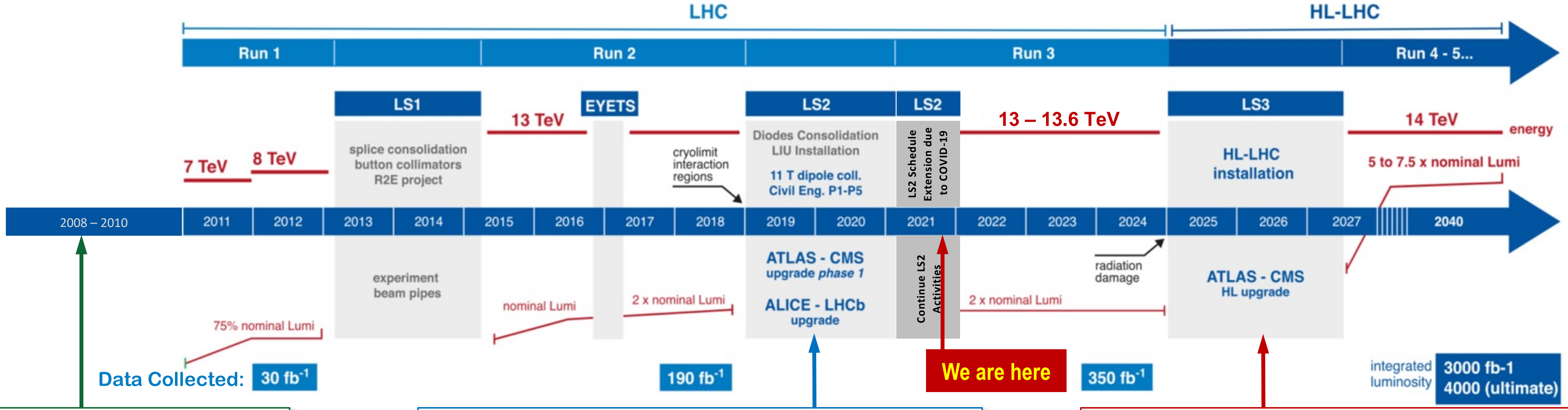
ATLAS Detector: Before Closing for Operations



CMS Detector: Before Closing for Operations

LHC and LHC Experiments: Timeline

- **The international partners on the LHC experiments, including DOE and NSF, coordinated and built the detector subsystems or components, which have been installed and commissioned**
  - Installation & commissioning phase transitions over to regular maintenance and operations (M&O) phase
  - M&O phase focuses on exploitation: operating detectors and collecting, storing, and analyzing data
- **LHC timeline driven by periods for physics runs interleaved with technical shutdowns for accelerator or detector consolidation and/or upgrade installation & commissioning activities**



LHC Accelerator and Detector Commissioning and Ramp-up to Start LHC Operations (2008-2010)

2nd LHC shutdown (2019-2021; extended due to COVID-19)
- LHC Injectors Upgrade (to deliver brighter bunches)
- LHC consolidation activities
- Install initial [Phase-1] LHC experiments upgrades

3rd LHC shutdown (2025 to mid-2027)
- HL-LHC installation, including accelerator upgrade's Nb_3Sn focusing magnets near interaction regions;
- Install CMS and ATLAS HL-LHC detector upgrades

DOE's Role in LHC Research and Operations

- **DOE supports LHC scientists — including investigators, postdoctoral researchers, and students — as well research scientists, and engineering, technical, and other professional staff**
  - Scientific staff are typically supported by the DOE/HEP Research Program
  - Engineering and technical staff, particularly those undertaking operations or project activities, are supported by the DOE/HEP Operations or Projects funds, respectively
- **Support by DOE is provided through a merit-review process**
  - University research grants typically re-compete for support every ~3-4 years
  - Research programs of the DOE national laboratories are reviewed every ~4-5 years
  - DOE Early Career Research awards are funded for 5-years and then typically phase into DOE base funding
- **DOE/HEP holds a Principal Investigator Meeting annually to guide community on HEP program and priorities, budget process, and any issued/upcoming funding opportunity announcements**
- **DOE LHC program manager's guidance at PI meetings include**
  - Groups develop coherent program: balanced roles in physics research, operations, and upgrade projects
    - Such service type of work in operations or hardware tasks are requested by international ATLAS and CMS
  - Any operations or project roles be aligned with U.S. ATLAS and U.S. CMS [national] plans and priorities
  - Physics research plans be aligned with the international collaboration's plans and priorities
  - Groups utilize any available resources and facilities at their institution — *e.g.*, clean room; HPCs at labs; …
  - DOE and research groups foster safe, diverse, equitable, and inclusive working environments
- **After merit review, DOE program manager discusses with U.S. ATLAS/CMS program managements DOE's plans for support to university groups to ensure LHC activities at CERN continue & succeed**

LHC Experiments: Maintenance & Operations

- **Detector operations for efficient running during data-taking period is nationally coordinated**
  - One National Contact Physicist (NCP) per Funding Agency manages the program for each nation
  - NCP is the funding agency point of contact for agency's interactions with the international experiment
  - NCP, as an observer, accompanies the Funding Agency delegate at the LHC RRB meeting

- **U.S. ATLAS and CMS Operations Program**
  - Joint program coordination by DOE and NSF; program scope is funded separately by each agency

- **U.S. funds support**
  - Operations Program Management
    - Includes maintaining ~8-10% annual reserves to address issues arising during the course of operations
  - Detector Maintenance & Operations (M&O)
    - M&O of U.S.-built detectors or detector components
    - Meet U.S. obligations to international CMS and ATLAS via contributions to Common Funds (*next slide…*)
  - Software & Computing
    - Support U.S. Tier-1 (DOE) and Tier-2 (NSF) computing facilities
    - Enable physics analyses by supporting computing hardware, core software, tools and provisions
    - ESnet transatlantic network for transfer of data from Tier-0 (Host Lab: CERN) to U.S. Tier-1s

- **Joint U.S. funding agency (DOE + NSF) review of the above scope held every ~2 years**

ATLAS and CMS M&O Obligations: Common Funds

- **Annual costs to Common Funds for maintaining and operating the ATLAS and CMS experiments is divided into 3 categories:**
- M&O–A:
  - Expenses that are shared by the entire collaboration in proportion to the number of scientific staff holding PhD (or equivalent) and are entitled to be authors of scientific publications of the collaboration
  - Example cost drivers include secretariat services, GSM phones and network communication services, …
  - Total international M&O–A budget (2020): ATLAS = 14.68 MCHF; CMS = 15.65 MCHF
  - DOE contribution (2020): ATLAS = 2.29 MCHF; CMS = 3.47 MCHF
- M&O–B:
  - Expenses borne by part of the collaboration to common costs related to the M&O of sub-detectors/systems that are the responsibility of institutes or groups
  - Typically those groups that originally built and delivered the sub-detectors/systems
  - Total international M&O-B budget (2020): ATLAS = 5.56 MCHF; CMS = 5.7 MCHF
  - DOE contribution (2020): ATLAS = 1.04 MCHF; CMS = 2.07 MCHF
- M&O–C:
  - General M&O expenses that are provided to the collaboration by CERN, acting in its role as the Host Lab for the LHC experiments

LHC Software & Computing: WLCG

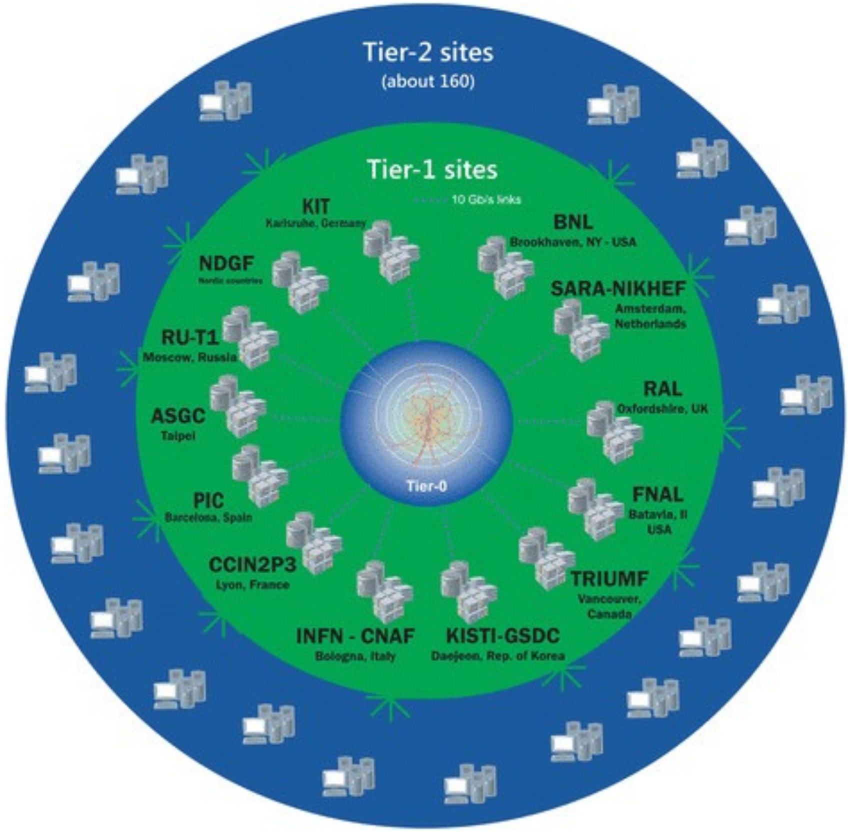
WLCG
Worldwide LHC Computing Grid

High Energy Physics computing embraced a large-scale distributed model since early 2000s based on grid technologies, federating national and international grid initiatives

Tier-0
Central Hub at CERN:
data recording,
reconstruction and
distribution

Tier-1
permanent storage,
re-processing and analysis
U.S.: BNL (ATLAS), Fermilab (CMS)

Tier-2
Simulation,
end-user analysis



Round-the-Clock Support

167 sites,
42 countries

~1M CPU cores

~1 EB of storage

> 2 million jobs/day

10-100 Gb link
Transfer ~100 PB/year

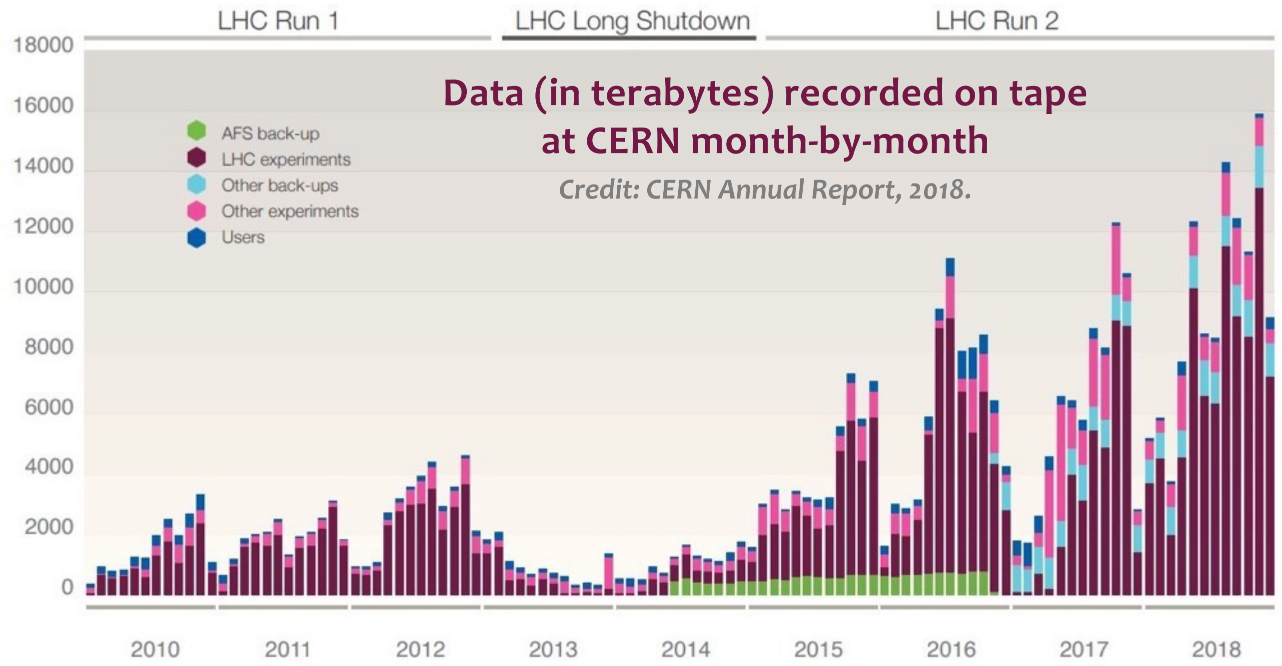
1 TB ~ 10-100 CHF

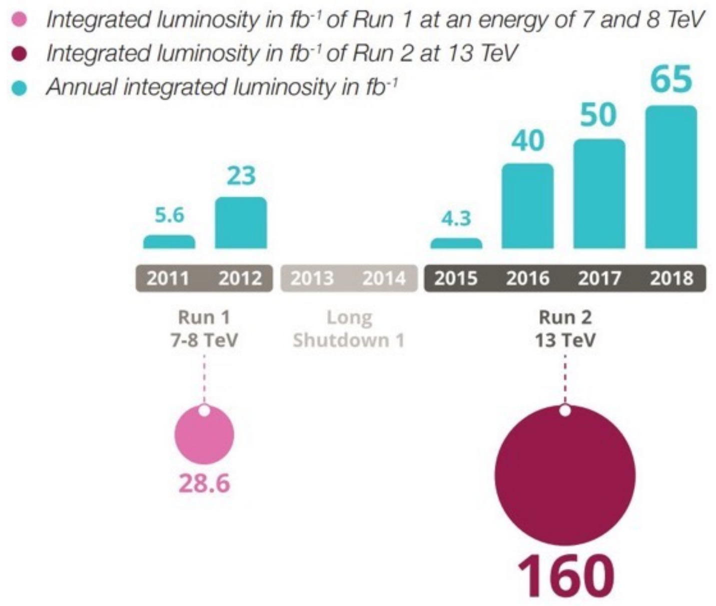
1 core ~ 100 CHF

Hardware lifetime: 3-5 years

WLCG: Worldwide LHC Computing Grid – an international collaboration to distribute and analyze LHC data
Integrates computer centers worldwide that provide computing and storage resources into a single infrastructure accessible by all LHC physicists.

LHC Software & Computing: U.S. Program

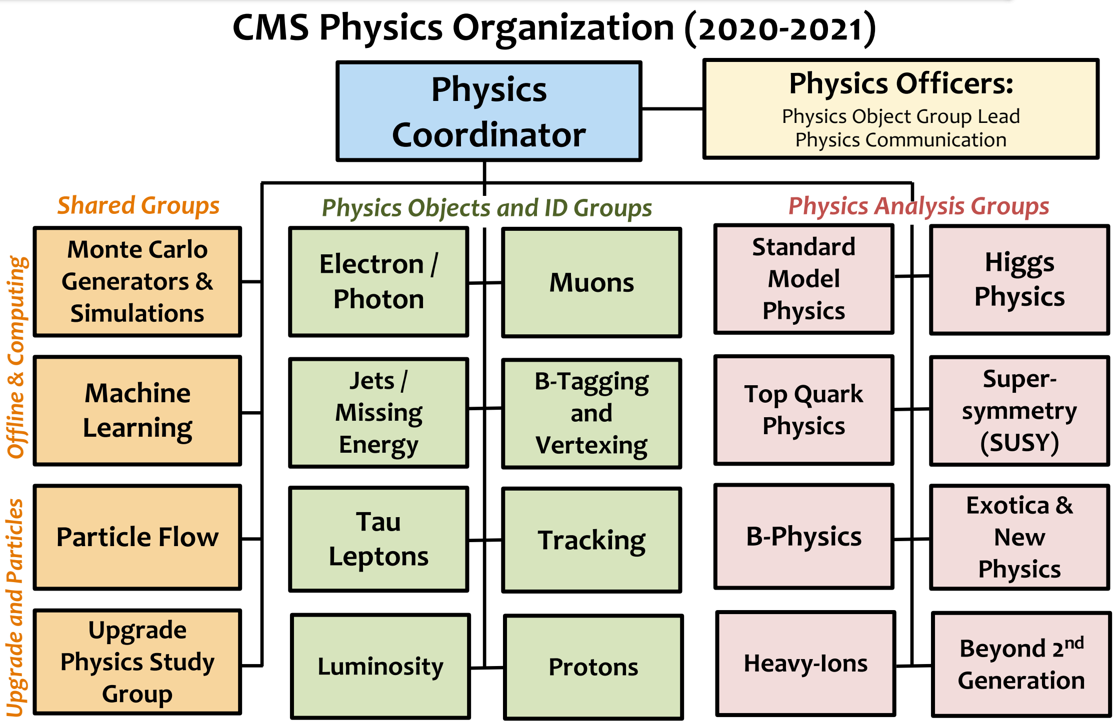




- **Nationally-coordinated U.S. operations activities for LHC software & computing have broad scope**
  - Particle-ID and subsystem reconstruction: natural involvement deriving from U.S. detector responsibilities
  - Core software: framework with interfaces to services, data, algorithms
  - Develop geometry, calibration, alignment, and general analysis algorithms
  - Leverage use of opportunistic computing resources – *e.g.*, HPCs at DOE national laboratories
- **Tier-1 (DOE) and Tier-2 (NSF) computing facilities coordinated with each international collaboration and WLCG to provide certain level of resources for the respective experiment**

LHC Experiments: Physics Research Groups

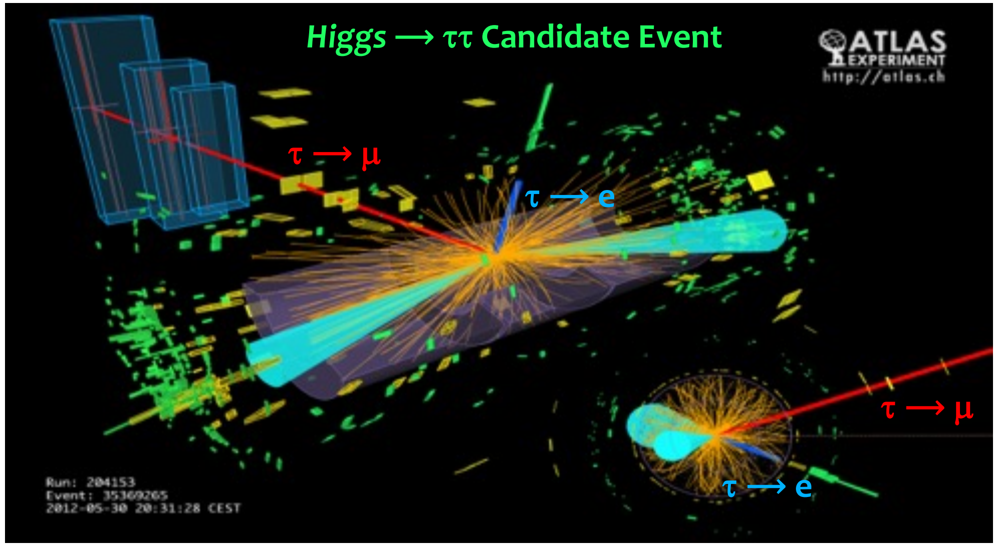
- **While project and operations commitments tend to be nationally coordinated, physics research is coordinated directly with the international collaboration**
  - To drive physics results in collaboration, a Physics Coordinator leads suite of topical physics groups and related subgroups (*e.g.,* particle object & performance groups)
- **Collaborators (investigators and their group) encouraged to work within a physics group based on their interests and expertise**
  - Collaborators may pursue wide-range of research topics
  - A global collaborative approach encouraged ⇒ no one country controls any one physics topic or study



- **Individual groups encouraged to be involved in all stages of an analysis, from bottom-up**
  - Calibration and particle reconstruction algorithms ⇒ particle object-ID ⇒ develop analysis code ⇒ study measurement's uncertainties ⇒ draft publication paper ⇒ address comments from internal review of paper ⇒ submit for publication
  - Recently, innovative approaches to analyses – *e.g.,* most LHC analyses applying machine learning algorithms
- **Leadership is encouraged where investigators can lead physics group or related subgroups**
  - Group convenor positions based on significant past accomplishments to advance studies for the collaboration

U.S. Physics Research Guidance and Reviews

- **DOE guidance to investigators and groups are aligned with collaboration's guidance**
  - U.S. research groups are advised to be integrated into any of the physics groups in the collaboration
  - Be involved in all stages of an analysis that eventually lead up to a physics publication
- **Merit (peer) reviews evaluate scientific output, impact, and accomplishments of each PI and the overall group**
  - Also consider group's plans during next 3-4 year grant period with established expertise and forward-looking evolution



- **DOE research reviews – for both university grants + laboratory groups – emphasize that groups engage in physics research complemented with operations/computing or upgrade activities**
  - **Balanced program** where physics research is aligned with the international collaboration's plans and the operations/upgrade activities align with U.S. responsibilities and commitments to the experiment
  - Multi-investigator groups work with collaboration to determine proper balance in each for their overall group
- **U.S. CMS and U.S. ATLAS each have dedicated facilities at DOE laboratories to advance a cohesive effort by the U.S. universities and labs in physics research**
  - U.S. CMS LHC Physics Center (Fermilab), and U.S. ATLAS Centers (Brookhaven, Argonne, SLAC, and Lawrence Berkeley National Labs) also promote U.S. university and lab partnerships

Fermilab CMS LHC Physics Center (LPC)

- **Although the hub for LHC experiments' activities are at CERN, regional centers established at DOE national laboratories to serve the large U.S. user base and advance U.S. activities**
  - CMS LHC Physics Center (LPC) at Fermilab is a nexus for physics analyses, software and computing support, and mentorship & training on a range of activities for the CMS collaboration
  - DOE merit reviewers: "Center of Excellence" for U.S. CMS that is championed by the full collaboration
  - Similar centers for U.S. ATLAS at Brookhaven, Argonne, SLAC, and Lawrence Berkeley National Labs
- **Offers variety of programs such as topical workshops, seminars, CMS data analysis schools, …**



- **LPC serves as a critical link for physicists to participate in CMS in the U.S.**
  - Annually (pre-COVID) over 350 users with 100 resident at Fermilab; includes all 52 U.S. institutions on CMS taking full advantage of lab resources; also assists those unable to travel to CERN
  - International: visiting CMS colleagues from Europe, Asia/Pacific, and Latin America
- **Model very successful and adopted by Fermilab Neutrino Center and HEP Theory community**

Some Closing Observations and Remarks

- **CERN's model for running experiments has demonstrated success over the years; some metrics include**
  - Since beginning of LHC operations, the ATLAS and CMS experiments together have published over 2,100 physics papers in peer-reviewed scientific journals
  - Reliable computing operations: DOE Tier-1 computing facilities at Fermilab and Brookhaven National Lab consistently maintaining over 96% uptime during LHC operations
  - U.S. researchers well-integrated into the collaborations' programs and hold leadership roles, including serving as past Spokespersons and Deputy Spokespersons for the experiment
- **An outside observer may remark that LHC experiments are structured too "corporate-like"**
  - The structure works!
  - Organized structure needed particularly for an experiment with over 3,000 global collaborators from over 40 countries and funding agencies
  - Model is based on each collaborator having a collective ownership of the experiment and operating with an inherent and shared vision for delivering success
  - Each ATLAS and CMS experiment, while collaborative are also competitive with each other ⇒ drives results
- **DOE, NSF, and CERN management regularly meet during the full life-cycle of program**
  - Prior to LHC RRB meeting, U.S. has opportunity to discuss with Host Lab any issues, if they arise
  - Past discussion topics have included U.S. program planning, fiscal budget processes, as well as logistical topics such as CERN's assistance in accommodating U.S. researchers/students at the CERN hostel

HEP RESEARCH SPANS

MORE THAN **160** ACADEMIC, NONPROFIT, AND INDUSTRIAL INSTITUTIONS

12 DOE NATIONAL LABORATORIES

42 STATES AND WASHINGTON, D.C.

13 CORE RESEARCH THRUSTS

OVER **400** ANNUAL HEP PUBLICATIONS IN PEER-REVIEWED SCIENTIFIC JOURNALS

SUPPORTED RESEARCHERS

1,115 PhD SCIENTISTS
(325 *POSTDOCTORAL RESEARCHERS*)

595 GRADUATE STUDENTS

HEP | BY THE NUMBERS (FY 2020)

HEP's mission is to understand how the universe works at its most fundamental level by discovering the elementary constituents of matter and energy, probing the interactions between them, and exploring the basic nature of space and time.

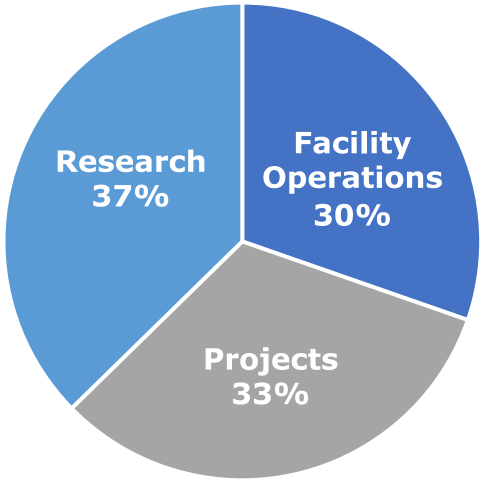
20 NOBEL PRIZES IN PHYSICS

$390 MILLION RESEARCH BUDGET
$25M SBIR/STTR, $118M UNIVERSITIES, $247M DOE LABS

2,215 USERS AT **3** HEP FACILITIES
FERMILAB ACCELERATOR COMPLEX, SLAC FACET-II, BROOKHAVEN ATF

PRESIDENTIAL EARLY CAREER AWARDS FOR SCIENTISTS AND ENGINEERS (PECASE)
15

OVER **300** ACTIVE AWARDS



$317 MILLION
SCIENTIFIC USER FACILITIES AND EXPERIMENTAL OPERATIONS BUDGET
LHC, SURF, RUBIN/LSST, DESI, LZ, AMS, TEST FACILITIES, ETC.

$338 MILLION
LINE-ITEM CONSTRUCTION PROJECT AND MAJOR-ITEM OF EQUIPMENT BUDGET
LBNF/DUNE, PIP-II, HL-LHC-ACCELERATOR, HL-LHC-ATLAS, HL-LHC-CMS, CMB-S4, ACORN

U.S. DEPARTMENT OF ENERGY

Office of Science