Potential U.S. scope as it relates to a Higgs Factory

HFCC Meeting
Stony Brook
November 8, 2024

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With many thanks to Jon Kotcher, Mike Tuts, Steve Nahn, Anders Rydt, all L2 and L3 coordinators and many more ….

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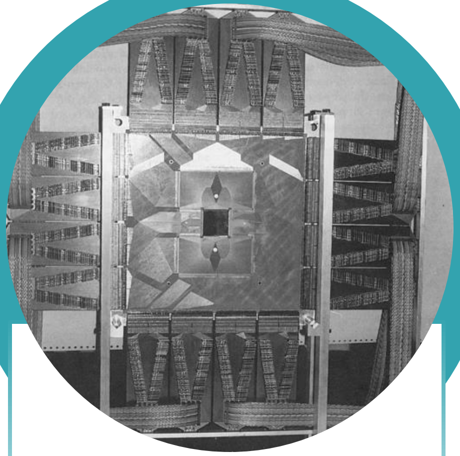
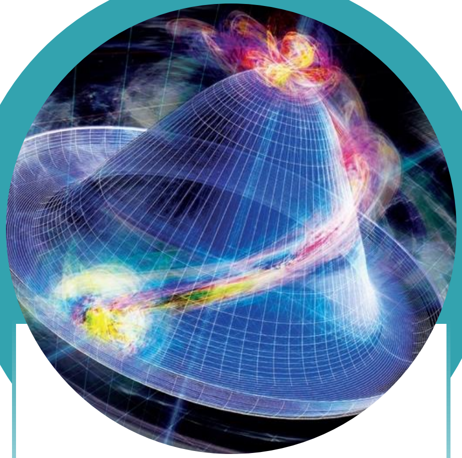
Outline: US Contributions



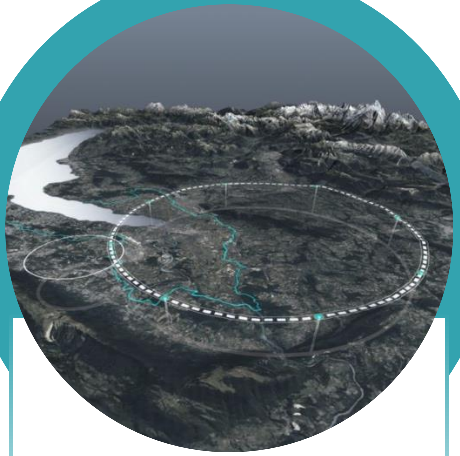
Historical Perspective

Innovation by the US HEP program



LHC +

US contributions to current collider experiments



Interests

Current strengths and interests of the community

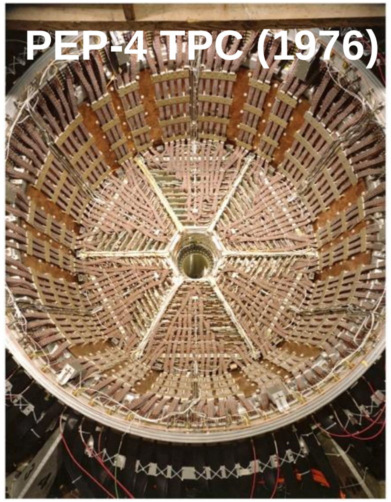
Perspective

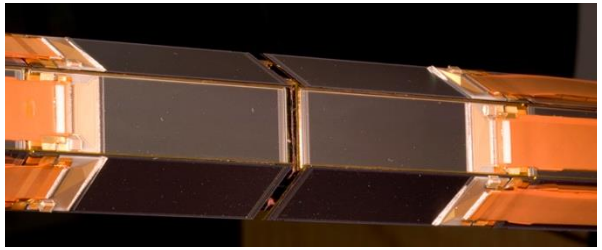
Keep perspective

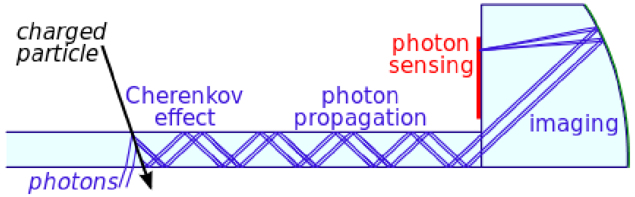
- *Apologies for incompleteness given limited time.*

A Bit of History

- The US has a remarkable legacy in the development and advancement of detector technologies for high energy physics.
  - Invention of the Time Projection Chamber
  - Advancing and scaling liquid argon calorimetry
  - Low-noise electronics
  - Silicon strip detectors
  - Detection Internal Reflected Cherenkov light
  - Low-mass silicon structures
  - Track trigger
  - Fiber Tracker
  - Deployment of Visible Light Photon Counters
  - LGAD detectors
  - Digital Calorimetry
  - …. …. ….

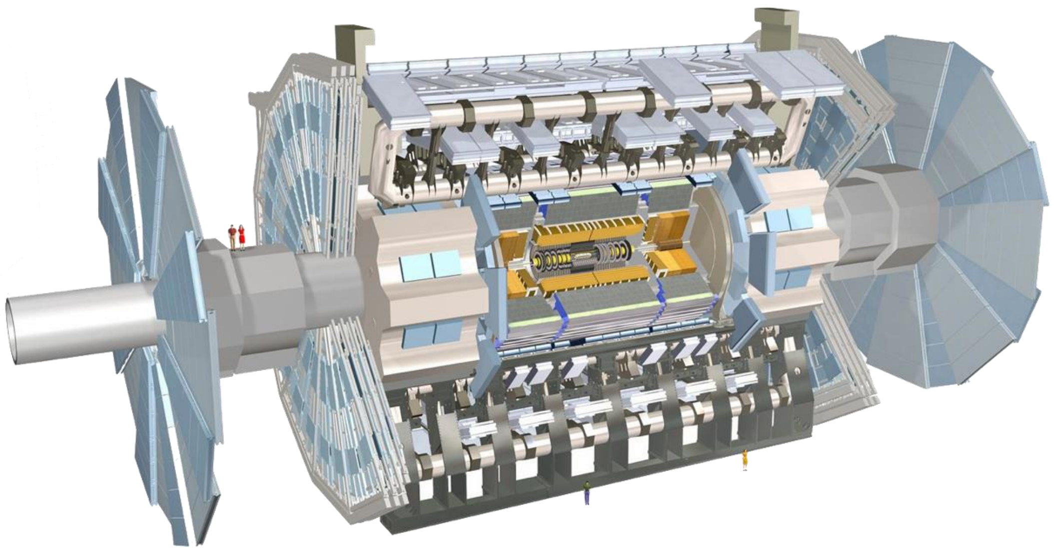


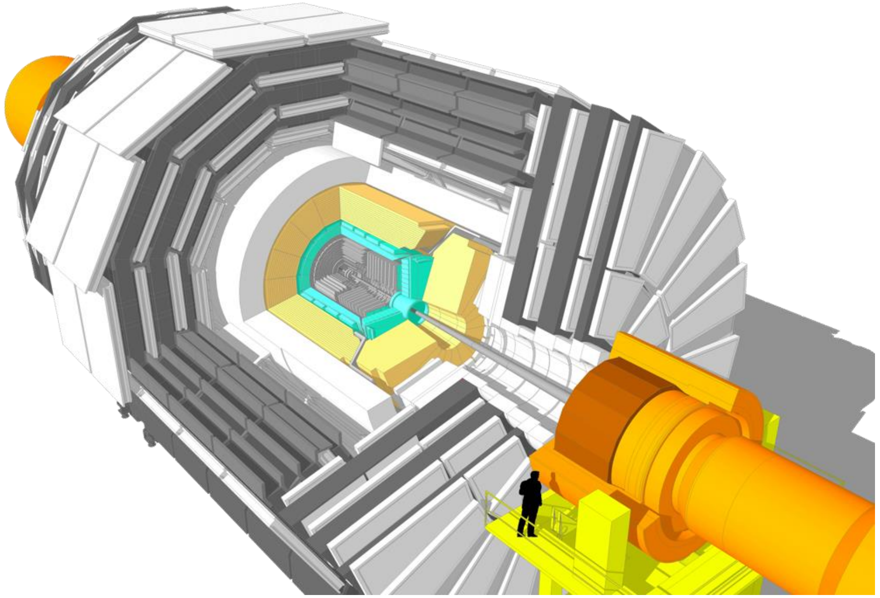




The LHC Experiments

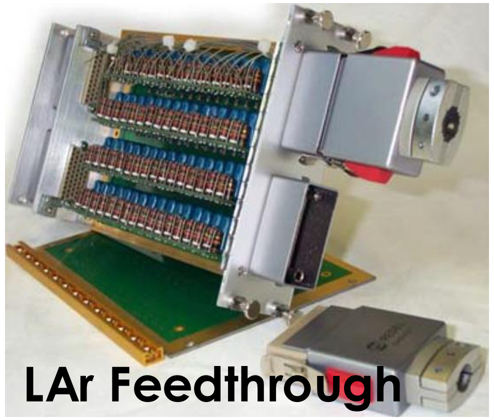
- The US had very significant scope for the construction of the two multi-purpose LHC experiments, ATLAS and CMS.

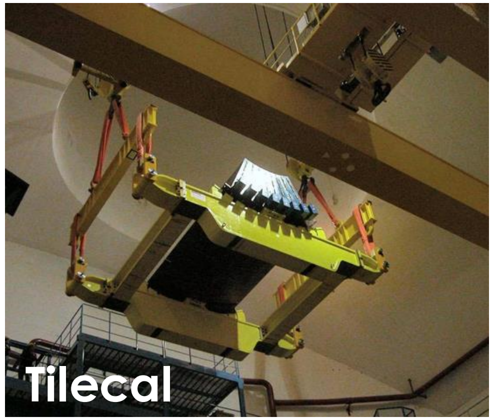


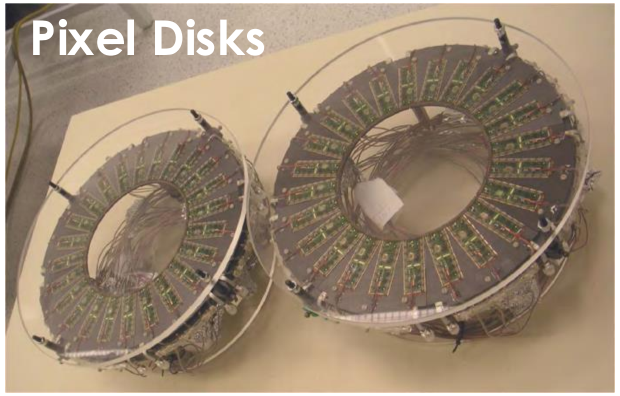


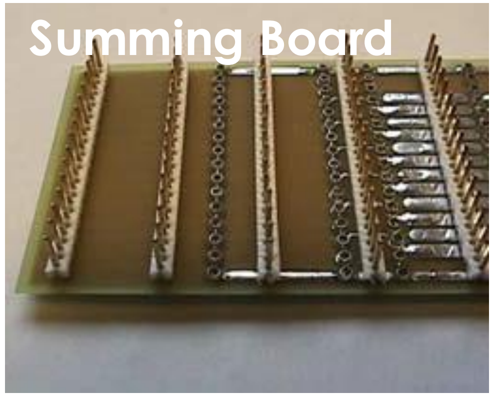
ATLAS Phase-0

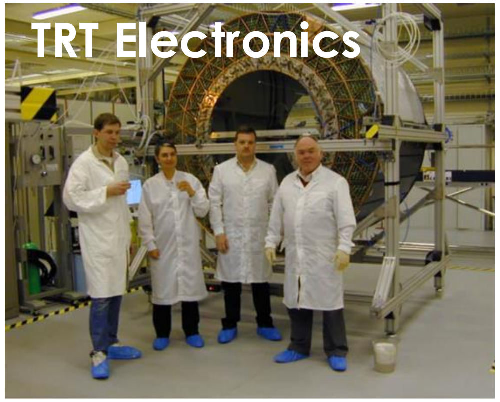
- Pixel tracker, Transition Radiation Tracker, LAr calorimeter, Tile calorimeter, Cathode Strip Chambers, ….

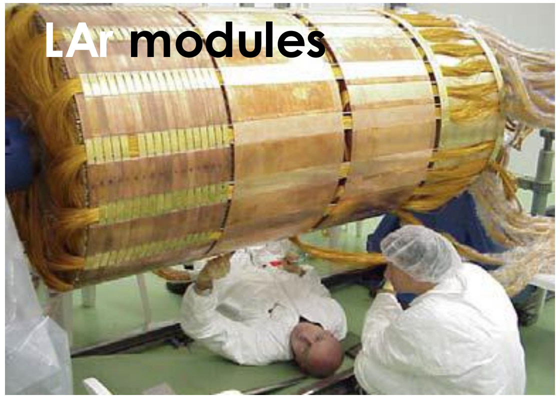












ATLAS Phase-0: Cost

DOE contributions and cost towards original ATLAS experiment

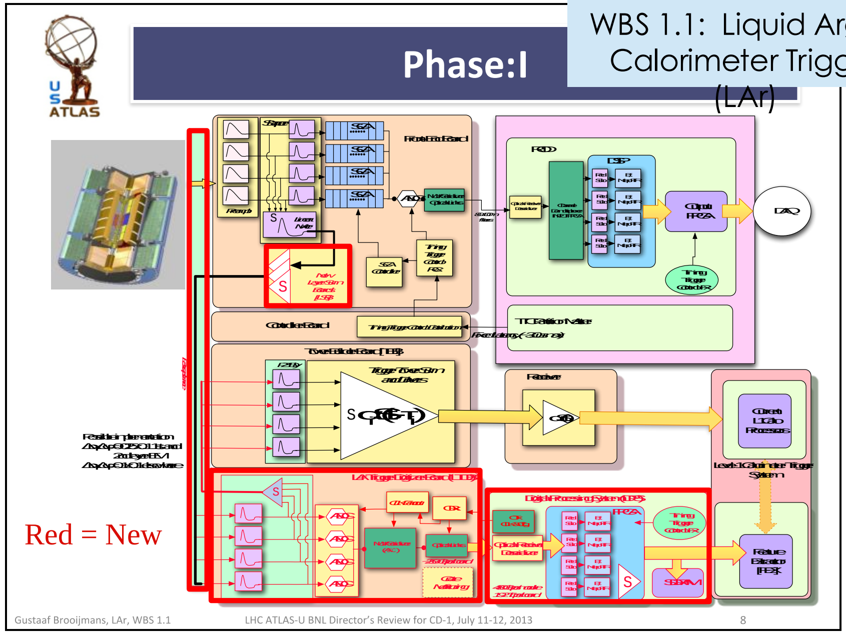
Project WBS Item	Budgeted Cost of Work Performed (through CD-4A)
1.1 Silicon Subsystem	$23,937.9k
1.2 TRT Subsystem	$11,878.3k
1.3 LAr Calorimeter Subsystem	$47,522.3k
1.4 Tile Calorimeter Subsystem	$11,552.3k
1.5 Muon Spectrometer Subsystem	$30,185.7k
1.6 Trigger/DAQ Subsystem	$5,170.6k
1.7 Common Projects	$15,313.5k
1.8 Education Outreach	$135.2k
1.9 Project Management	$8,380.2k
1.10 Technical Coordination	$3,095.3k
TOTAL U.S. ATLAS Project	$157,171.3k

Date: 30 Sept. 2005
CD-4a Closeout Report

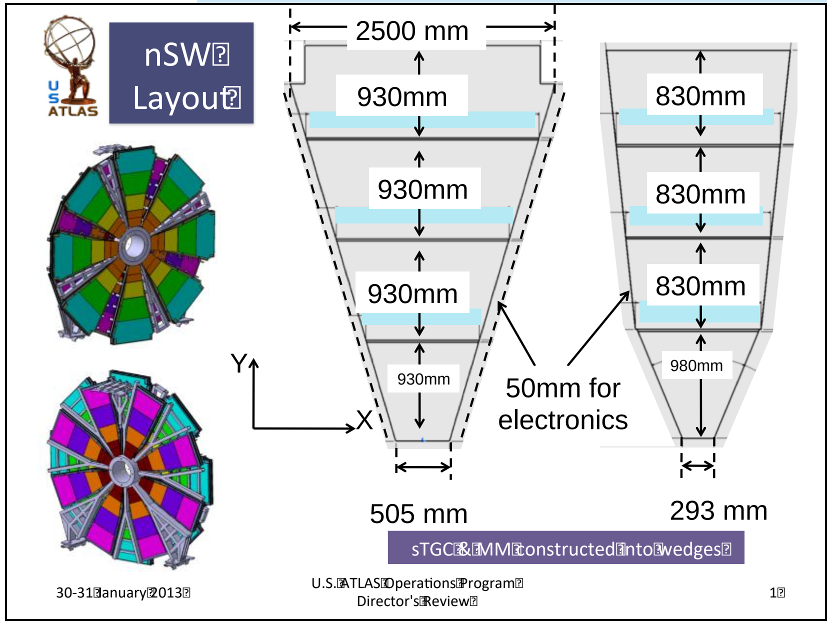
DOE Total contribution was $250M (ATLAS + CMS)
NSF additional contribution of $81M (ATLAS + CMS)

ATLAS Phase-1: Scope

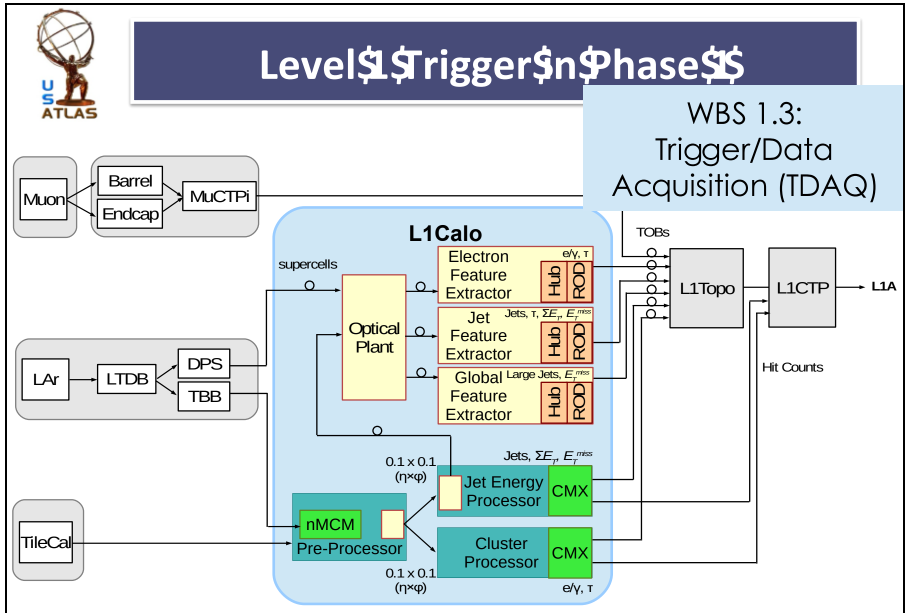
WBS 1.1: Liquid Argon Calorimeter Trigger (LAr)



WBS 1.2: Muon New Small Wheel (nSW)



WBS 1.3: Trigger/Data Acquisition (TDAQ)



- **US Focus:**
  - Increased granularity and functionality in the Liquid Argon Calorimeter Level 1 trigger.
  - Forward Muon (New Small Wheel) front-end readout, trigger, and alignment systems.
  - Use of fine-granularity LAr data in the Level 1 Calorimeter trigger, and overall readout system enhancement (TDAQ).

ATLAS Phase-1: Scope

- 1.1 Liquid Argon Calorimeter Trigger Readout (LAr)
  - 1.1.1 Baseplanes
  - 1.1.2 Layer Sum Boards
  - 1.1.3 Liquid Argon Trigger Digitizer Boards
  - 1.1.4 Back-End Electronics
- 1.2 Muon New Small Wheel (nSW)
  - 1.2.1 VMM Chip
  - 1.2.2 Front End Card
  - 1.2.3 ART Data Driver Card
  - 1.2.4 MM Trigger Processor
  - 1.2.6 nSW Alignment
  - 1.2.7 Trigger Data Serializer
- 1.3 Trigger/Data Acquisition (TDAQ)
  - 1.3.1 Algorithm Firmware
  - 1.3.2 FEX ATCA Hub
  - 1.3.3 FEX Fiber Plant
  - 1.3.4 gFEX System
  - 1.3.5 FELIX Firmware
- 1.4 Project Management

nSW is funded by DOE only.
Funding for LAr and TDAQ is split
between DOE & NSF.

Deliverables are at Level 3 or below,
and are uniquely assigned to NSF or DOE.
Control accounts, and reporting,
are at Level 3.

Green = DOE only, Red = NSF only, Purple = DOE & NSF

ATLAS Phase-1: Institutions

DOE

- Argonne National Laboratory
- University of Arizona
- Brandeis University
- Brookhaven National Laboratory
- Columbia University
- Harvard University
- Indiana University
- University of Michigan
- Michigan State University
- University of Oregon
- University of Pennsylvania
- University of Pittsburgh
- Southern Methodist University
- Stony Brook University

12 Universities, 2 National Laboratories

Key:
LAr , nSW, TDAQ, LAr + nSW, LAr + TDAQ, LAr + nSW + TDAQ

NSF

- Cornell
- Northeastern
- Rutgers
- Kansas
- Notre Dame
- Purdue
- Buffalo
- UIC
- Catholic U

Forward pixels and HCAL upgrades

ATLAS Phase-1: Cost

DOE

US ATLAS Phase I Upgrade, AYk$						
DOE	Total FY14	FY15	FY16	FY17	FY18	TOT
LAr	1,802	1,536	1,603	1,503	134	6,873
nSW	1,191	2,421	3,684	3,511	13	10,949
TDAQ	378	1,174	1,444	1,089	63	4,149
PM	799	699	619	592	521	3,732
Base Estimate Subtotal	4,170	5,830	7,349	6,695	731	25,703
Level 2 Project Contingency	-	2,229	1,941	1,540	129	5,839
Global Risk-Based Contingency	-	325	735	564	85	1,708
LHC ATLAS-U Total	4,170	8,383	10,025	8,799	945	33,250
Fractional Contingency	-	0.44	0.36	0.31	0.29	0.29
DOE Guidance	6,250	7,500	9,500	8,500	-	33,250
Guidance + Carryover	6,822	10,152	11,269	9,744	945	33,250
Balance/Carryover	2,652	1,769	1,244	945	-	-

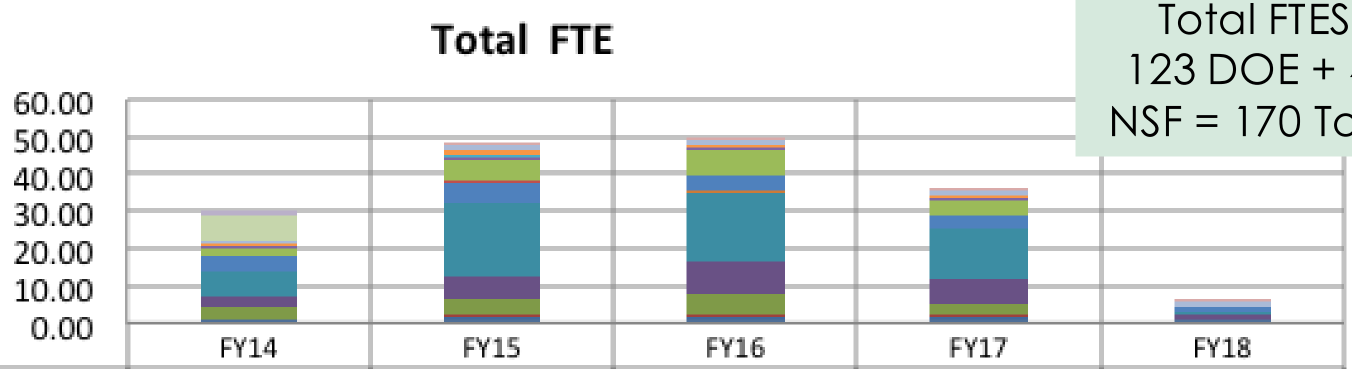
NSF

Total FY14	FY15	FY16	FY17	FY18	TOT
586	1,435	2,178	1,694	67	5,960
-	-	-	-	-	-
55	605	362	639	50	1,711
119	213	219	226	233	1,009
760	2,253	2,759	2,558	349	8,680
-	750	641	617	56	2,065
-	125	282	216	33	655
760	3,128	3,682	3,392	437	11,400
-	0.39	0.33	0.33	0.25	0.31
2,400	2,850	3,200	2,750	200	11,400
2,400	4,490	4,562	3,630	438	11,400
1,640	1,362	880	238	-	-

- Total DOE+NSF: $44.65M

ATLAS Phase-1: Labor

Total FTES:
123 DOE + 47
NSF = 170 Total

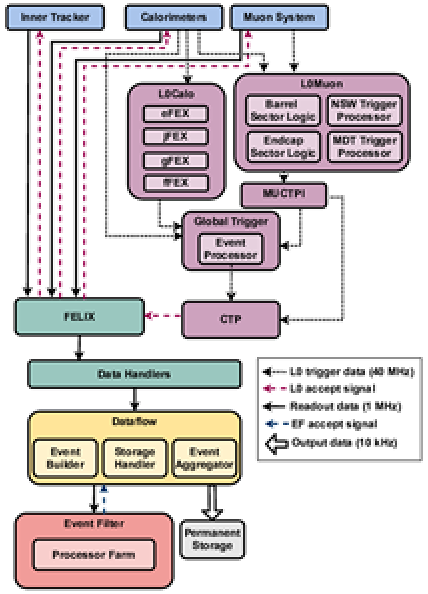


	FY14	FY15	FY16	FY17	FY18
MGMT (Act. through 4/2014)	1.07				
ENGR (Act. through 4/2014)	7.01				
U-Admin		0.50	0.50	0.50	0.25
Proj. Mgmt	0.75	1.40	1.40	1.40	1.18
U-Stu	0.56	1.40	0.61	0.40	0.04
U-Postdoc	0.35	0.58	0.36		
Inst-Phy	0.47	0.73	0.80	0.47	0.03
Postdoc	1.70	5.25	6.45	4.05	0.12
U-Eng	0.35	0.72	0.38	0.34	0.01
U-Phy	3.83	5.23	4.04	3.43	1.30
Physicist	0.14	0.25	0.23	0.21	
Engineer	6.82	19.23	18.59	13.09	1.01
Technician	2.52	6.26	9.05	6.74	0.73
Student	3.43	4.21	4.98	2.84	0.01
Designer	0.48	1.03	1.19	1.10	0.16
Admin	0.65	1.30	1.30	1.30	1.10

ATLAS Phase-II: Scope

Liquid Argon Calorimeter (LAr)
- electronics only - 40 MHz r'dout

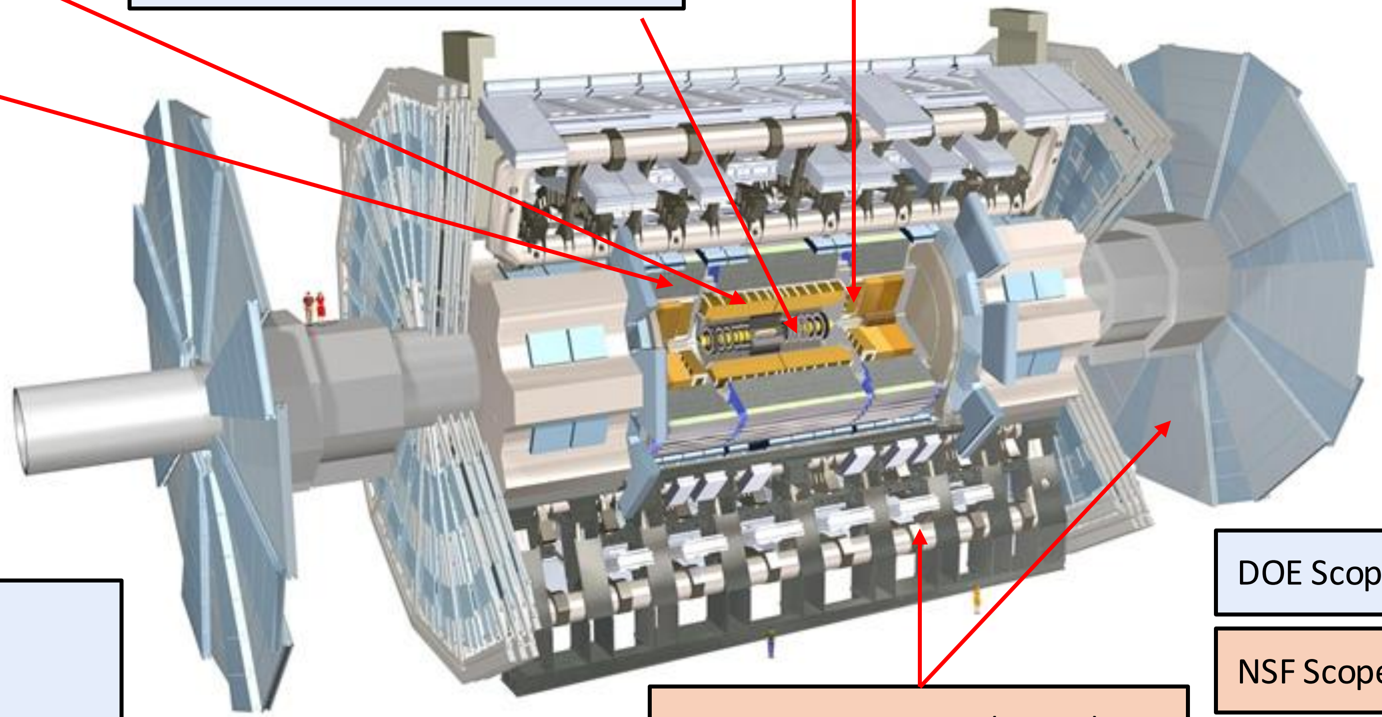
Tile Calorimeter (Tile)
- electronics only - 40 MHz r'dout



Trigger & DAQ (TDAQ)
- 1 MHz L0 Trigger
- tracking trigger
- new DAQ & dataflow

Inner Tracker (ITk)
- Pixel & Strips Detectors
- Mechanics & Electronics

HIgh Granularity Timing Detector (HGTD)
- improve pileup rejection at high eta



Muon Spectrometer (Muon)
- add chamber coverage
- replace electronics

DOE Scope

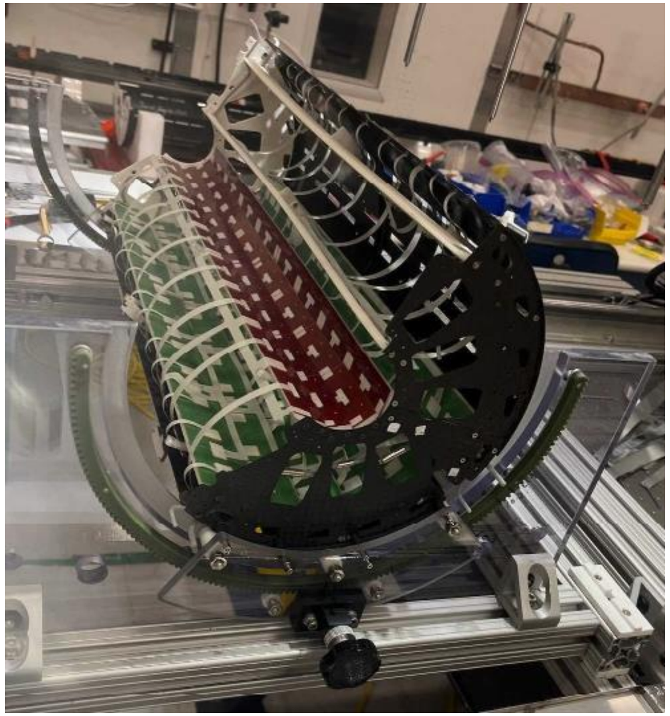
NSF Scope

ATLAS Phase-II: Institutions

Argonne National Laboratory
University of Arizona
Brandeis University
Boston University
Brookhaven National Laboratory
University of California, Irvine
University California, Santa Cruz
California State University
University of Chicago
Columbia University
Duke University
Harvard University
University of Illinois, Urbana-Champaign
Indiana University
University of Iowa
Iowa State University
Lawrence Berkeley National Laboratory
University of Massachusetts, Amherst
University of Michigan
Michigan State University
Northern Illinois University
New York University
Ohio State University
University of Oklahoma
Oklahoma State University
University of Oregon
University of Pennsylvania
University of Pittsburgh
SLAC National Accelerator Laboratory
Southern Methodist University
Stanford University
Stony Brook University
University of Texas, Arlington
University of Texas, Austin
University of Washington
University of Wisconsin
Yale University

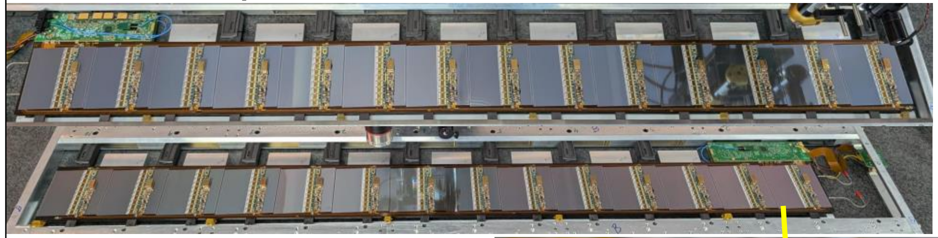
ATLAS Phase-II: DOE Cost

WBS	Total
Deliverables	
6.01 Pixel	34,921
6.02 Strips	48,055
6.03 Global Mechanics	17,459
6.04 LAr	6,804
6.07 Data Handling/DAQ	14,188
6.09 Common Costs	3,370
6.10 PMO	15,883
Total Deliverable Base Cost	140,680
Total Deliverable CTG	***74,838***
Contingency on Deliverables	
MC Contingency (89% CL)	31,677
Top-Down (PM) Contingency	31,677
Fractional Contingency	0.423
Total Deliverable Cost	***172,357***
Install. & Integ. (I&I)	
6.11 Inst. & Integ. (I&I)	17,418
Contingency on I&I (30%)	5,225
Total I&I Cost	**22,643**
Total Project Cost (Deliv. + I&I)	***195,000***
Funding/Carryover	**Total**
DOE Funding (Deliv. + I&I)	200,00
Guidance + Carryover	-
Balance/Carryover	-

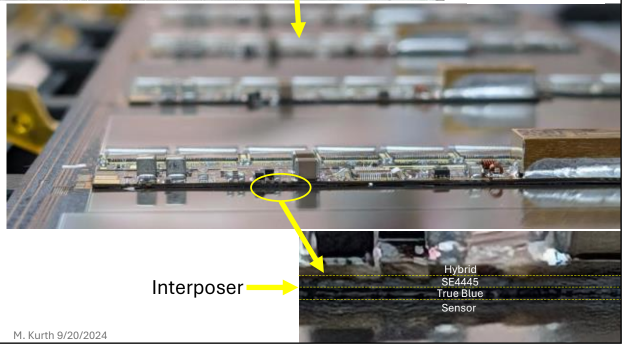


TPC (DOE): $200M

1st US interposer stave loaded



- 28 interposed modules
- Bonding and testing next week
- TC down to -45C before sending to RAL for climate chamber TC



ATLAS Phase-II: NSF Cost and Institutions

Task (WBS)	Institution
LAr front end electronics, ADC ASIC, optical chips	Columbia, SMU, UT Austin
LAr front end-board	Columbia, Pittsburgh
LAr Back-End Electronics	Columbia, NYU, SMU, Stony Brook, Arizona
TileCal Main Board	Chicago
TileCal ELMB2 Motherboard	MSU
TileCal LVPS	NIU, UT Arlington
Muon Monitored Drift Tubes, sMDT	MSU, Michigan
Muon TDC ASIC	Michigan
Muon Chamber Service Module	Michigan
Muon L0MDT trigger	BU, UC Irvine, UMass Amherst
Trigger Level 0 Calorimeter Trigger System Optical Plant	MSU
Trigger Global Event processor Firmware and Algorithms	Indiana, MSU, Chicago, Oregon, Pittsburgh, SMU, Stanford
Trigger Event Filter Tracking	NIU, Arizona, UC Irvine, Chicago, UIUC, Penn

Effort: On-project (technical) 210 FTE-Years; Uncosted scientific labor (off project) 77 FTE-Years
Cost (AYk$) TPC: $82,850 (includes contingency)

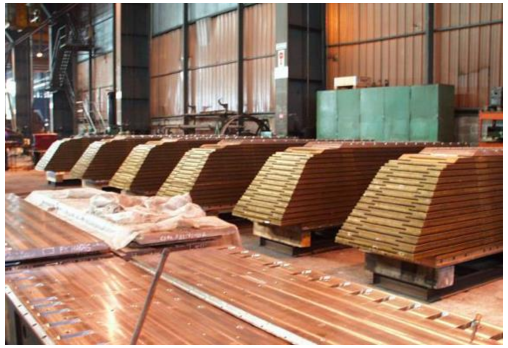
ATLAS To Date

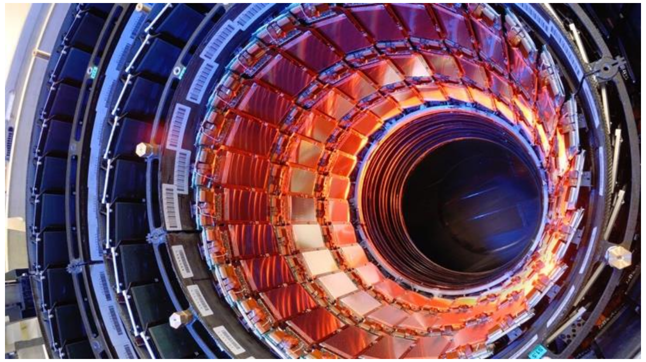
- The U.S. has made, and continues to make, substantial and unique contributions to the ATLAS detector.
- Approximately ~ 20% of the Ph.D. physicists are from the U.S – 14% on the DOE HEP side.
- The U.S. holds ~ 30% of the Level 1, 2 & 3 leadership positions on the International ATLAS HL-LHC upgrade.
- Total contributions: $151.2M + $33.3M + $200M (DOE)
  $(share of $81M) + $11.4M + $82.9M (NSF)

  This does not include operating costs, which is approximately $25-$27M/yr per experiment from DOE and $10-$11M/yr from NSF!

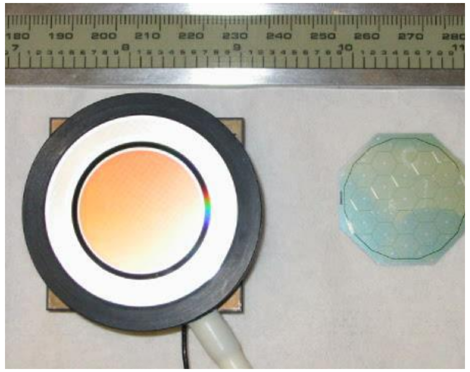
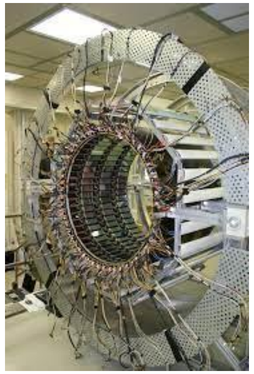
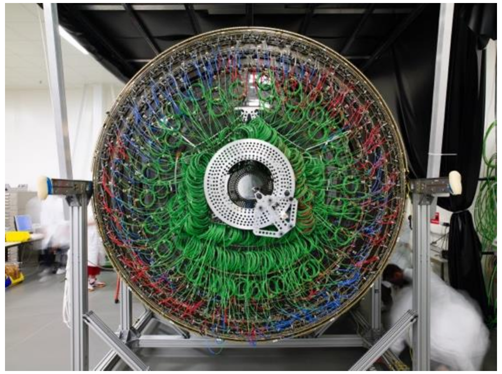
CMS Phase-0

- Pixel and strip tracker, calorimeter (HB, HO, HE and HF), muons, trigger, electronics, readout, ….





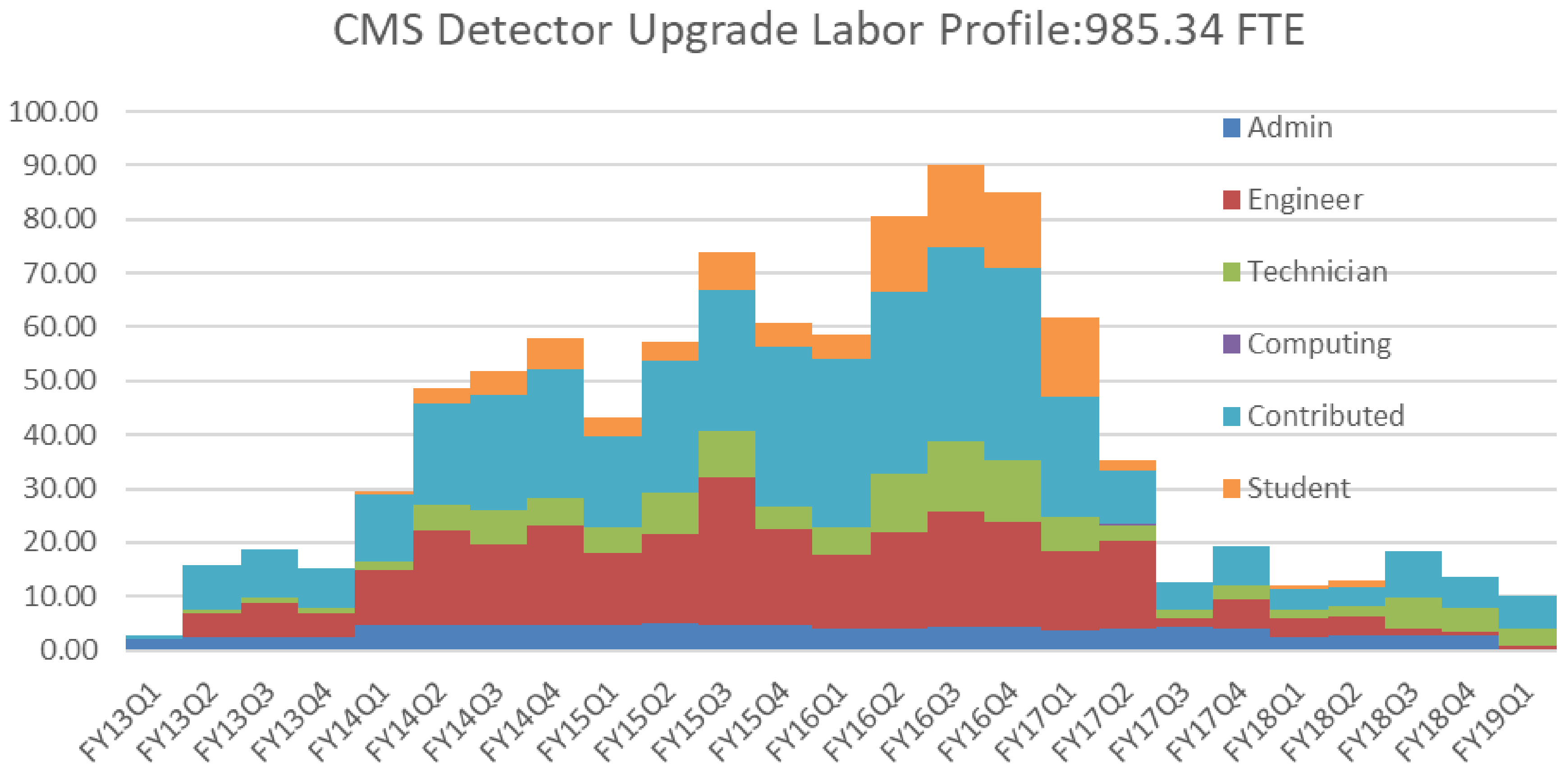
First time full silicon tracker

DOE contribution to the construction of the original detector construction the same as for ATLAS

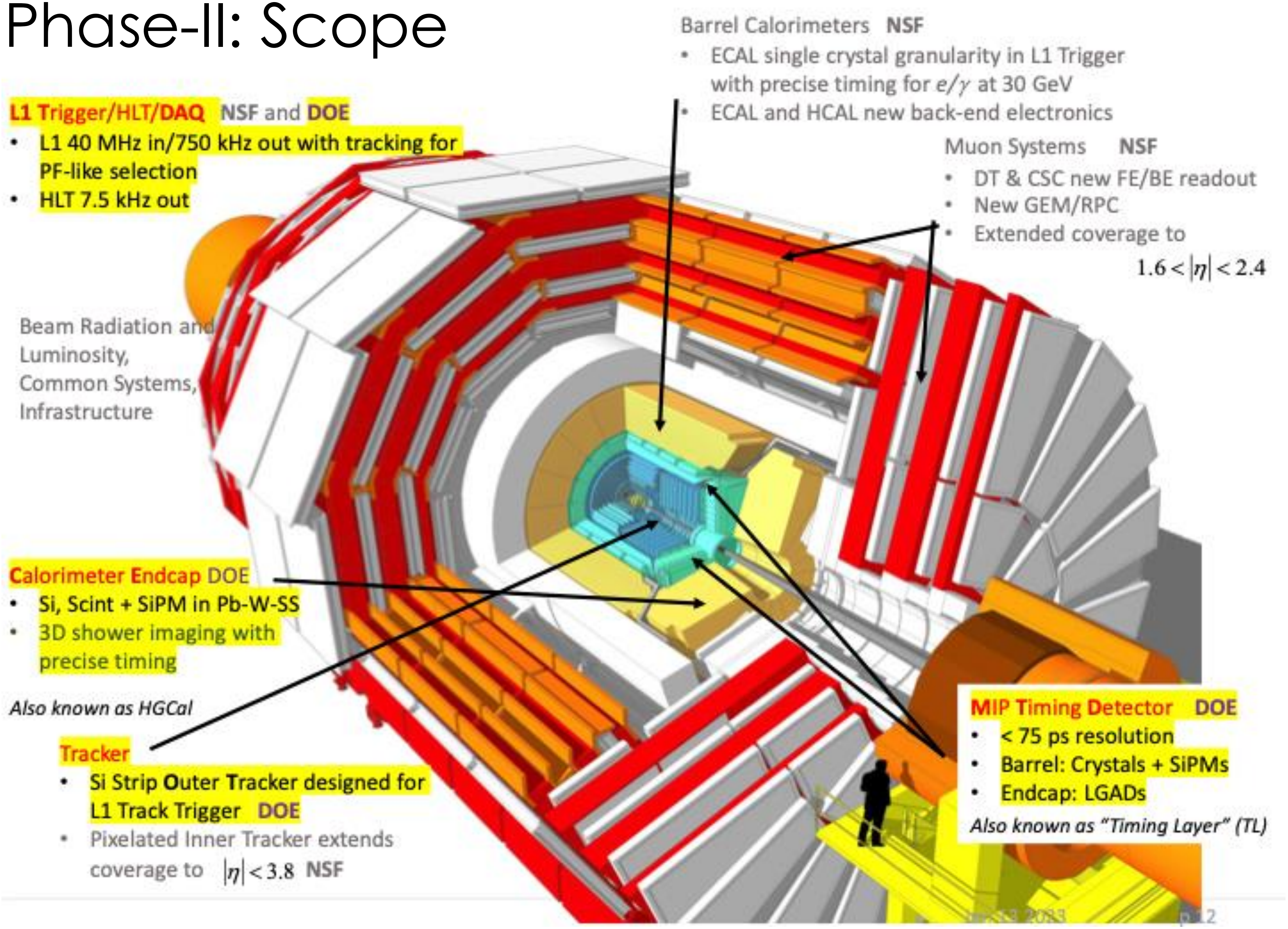
CMS Phase-I: Labor (DOE)

Phase 1: Actual Cost 40.8M (includes NSF and DOE) for about 21 Institutes,



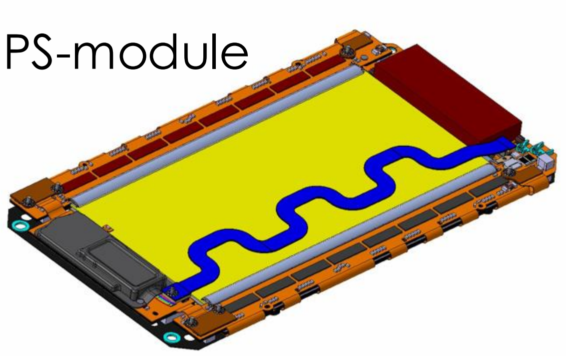
985 FTE over 6 years. 408 of them Contributed labor, 97 Student, 91 Admin, Rest Technical

CMS Phase-II: Scope

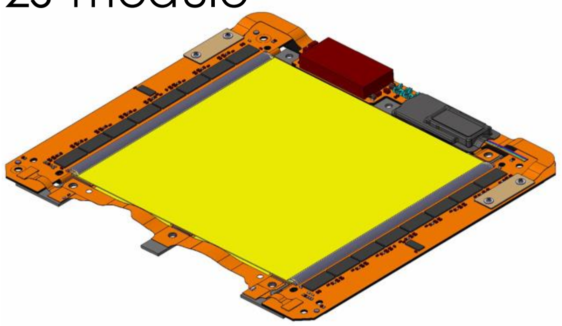


CMS Phase-II: Scope

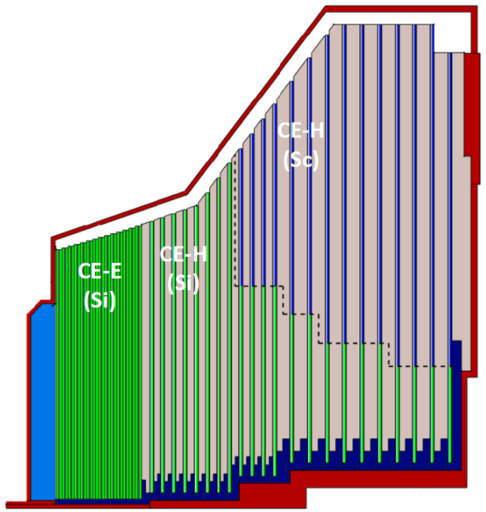
PS-module

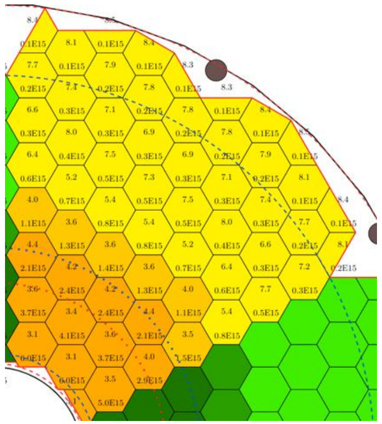


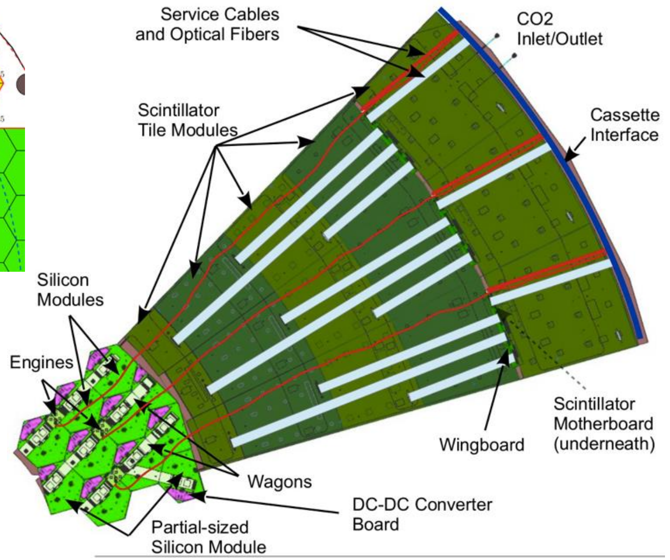
2S-module



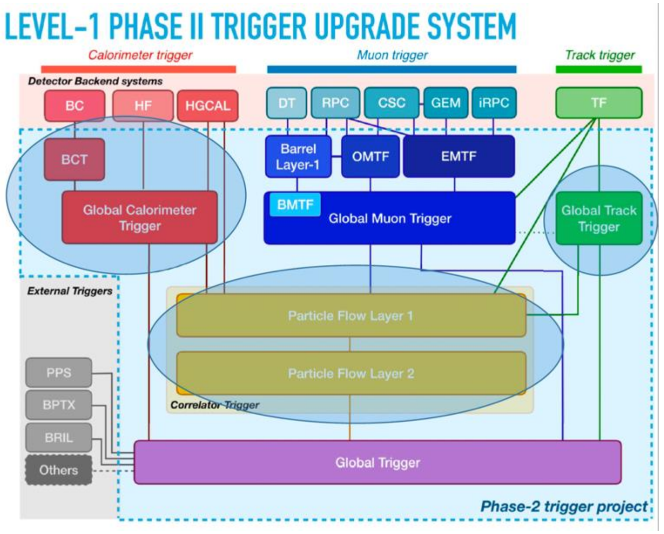
Silicon Outer Tracker



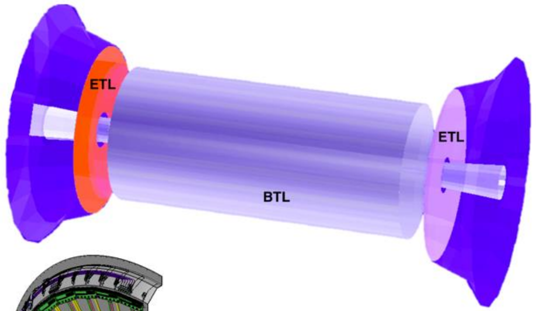


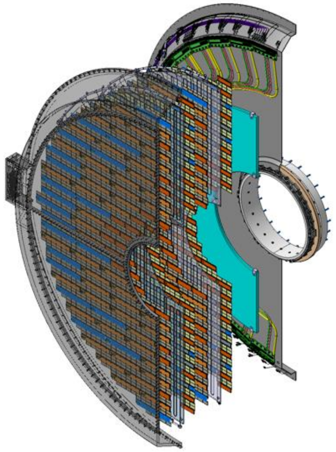


Endcap
HGCAL
(silicon/
scintillator)



Trigger

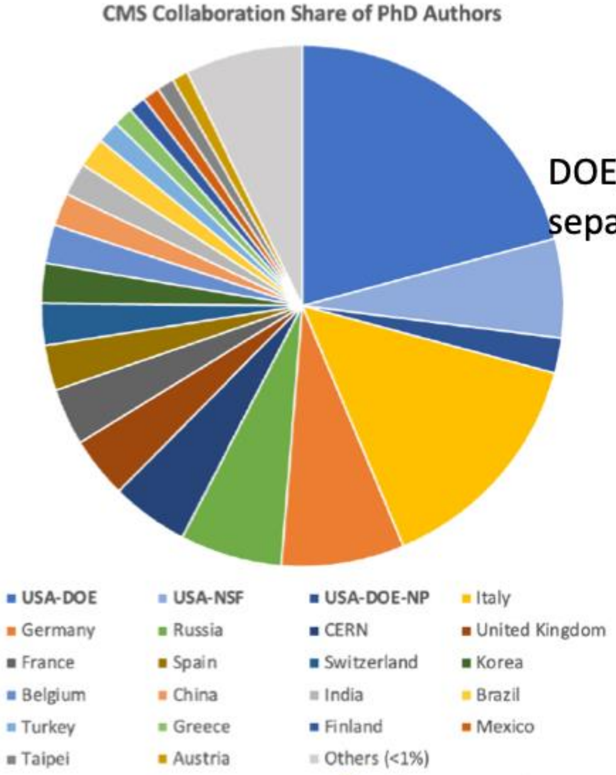




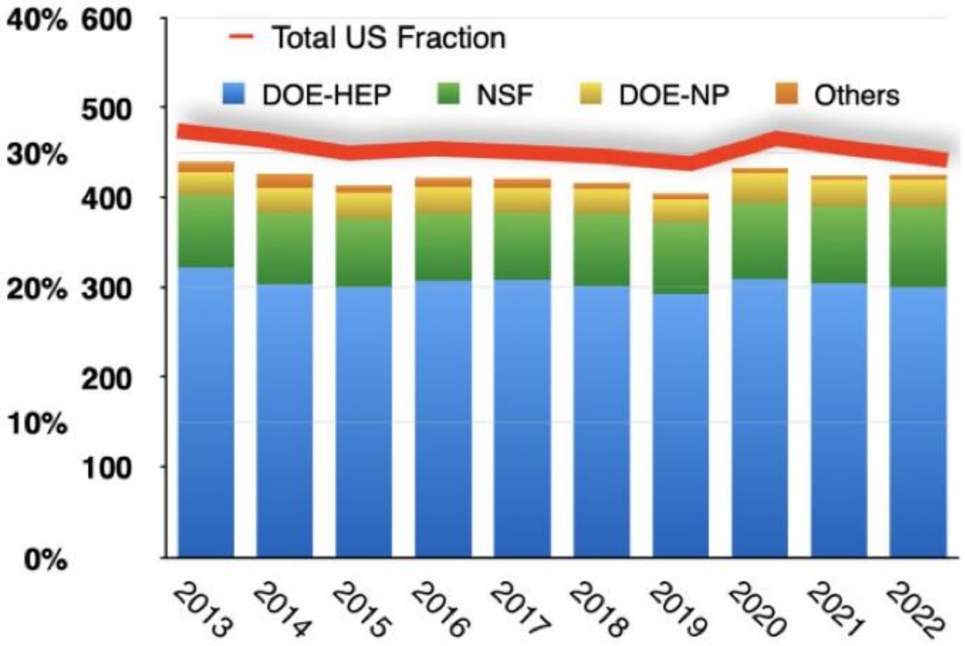
Timing Layer
LYSO and
LGAD

CMS Phase-II: Institutions

- US CMS is **30% of CMS**
  - 51 member institutions, plus 2 associate and 2 cooperating members
  - Essentially constant over many years



DOE, NSF and DOE–NP are separated in this chart.



CMS Phase-II: Cost

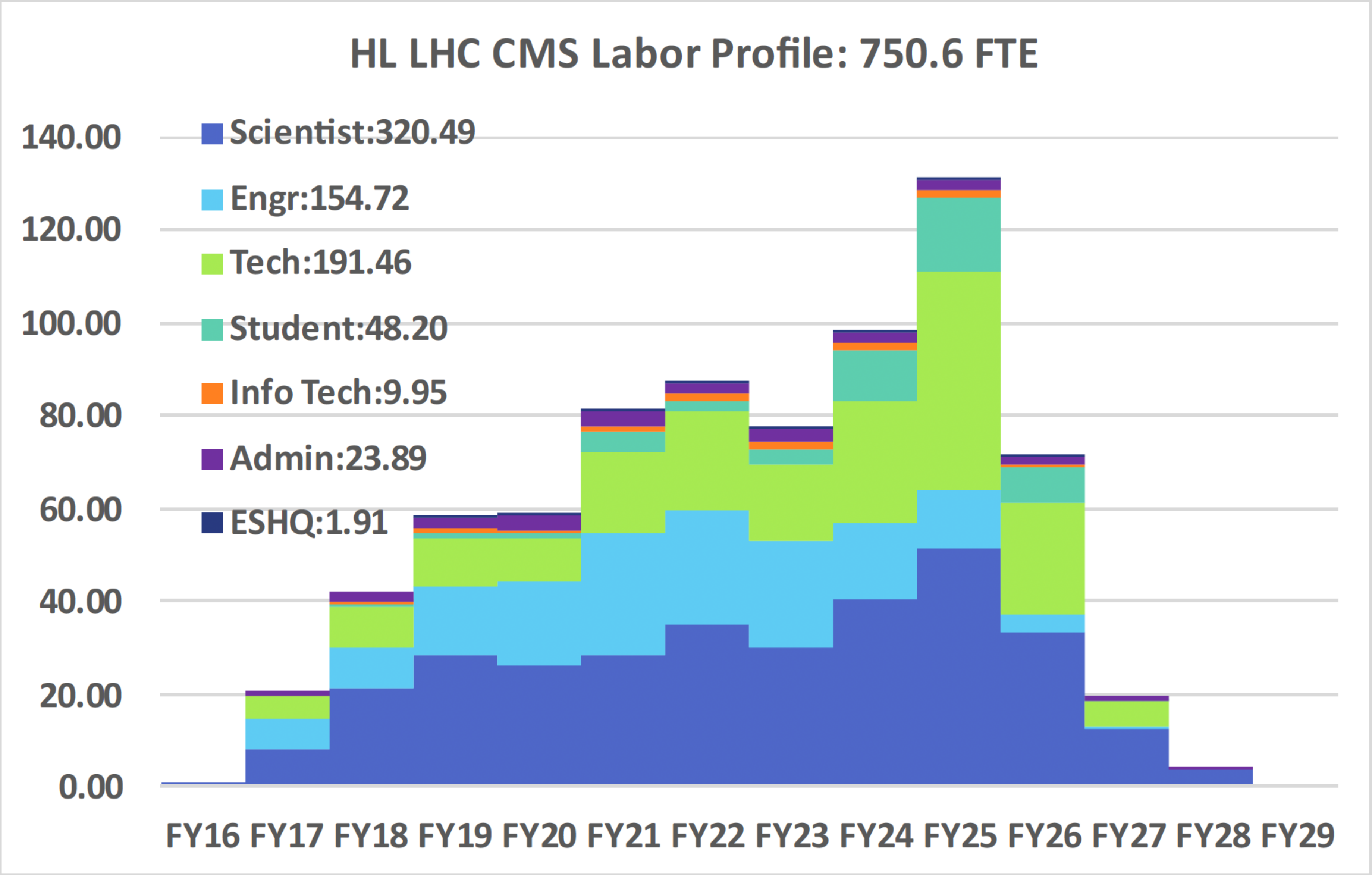
Total cost ($M)

	Labor BAC	Labor EU	Material BAC	Material EU	Total BAC	Total EU	Total = AC + ETC + EU + RC
402.1 Project Management	13,218	556	8,573	1,206	21,791	1,762	200.00
402.2 Outer Tracker	23,680	2,821	26,827	2,945	50,507	5,766	
402.4 Calorimeter Endcap	28,996	4,782	27,805	5,705	56,801	10,487	
402.6 Trigger and DAQ	6,310	912	5,225	756	11,535	1,669	
402.8 Timing Layer	10,850	2,230	10,111	1,510	20,961	3,739	
TOTAL	**83,054**	**11,301**	**78,540**	**12,123**	**161,594**	**23,424**	**200.00**

	Total
Non-I&I	186.00
I&I (Integration and Installation)	14.00
Total	**200.00**

Total funding available (Jan. 2023): $200M

CMS Phase-II: Effort (DOE)



CMS Phase-II: NSF Cost and Institutions

Task (WBS)	Institution (32)
Barrel Calorimeter - ECAL	Notre Dame, Northeastern, Minnesota, Virginia, and Wisconsin
Barrel Calorimeter – HCAL	Maryland and Notre Dame
Forward Muons - CSC	Northeastern, Rice, Texas A&M, The Ohio State U., and UCSB
Forward Muons – GEM	Boston, Florida Inst. of Tech., Rice, Texas A&M, UCLA, Wisconsin, and Wayne State
Forward Pixels - ROC & Sensors	Cornell, Kansas State, Purdue Northwest, U. of Colorado, UIC, UTK, Siena College, UC Riverside
Forward Pixels – Modules	Catholic U. of A. Nebraska, Boston, Florida Inst. of Tech., Purdue U., Purdue Northwest, The Ohio State U., UIC
Forward Pixels – Electronics	Boston, Cornell, Kansas State, Rice, Ohio State U., UIC, U. of Kansas, Vanderbilt
Forward Pixels - Mechanics and Integration	Cornell, Purdue U., UC Davis, Johns Hopkins, SUNY Buffalo,, U. of Puerto Rico
Trigger - Muon Trigger	Rice, Texas A&M, UCLA, U. of Florida
Trigger - Track Trigger	Boston, Cornell, Northeastern, Northwestern, Notre Dame, The Ohio State U., Rutgers, U. of Colorado, UTK

Effort: On-project (technical) ~200 FTE-Years; Uncosted scientific labor (off project) 170 FTE-Years
Cost (AYk$) TPC: $88.00M (includes contingency)

Observations

- The U.S. holds ~ 30% of the Level 1, 2 & 3 leadership positions on the International LHC HL-LHC upgrade projects, commensurate with the US participation in the experiment.
- This reflects the broad and well-recognized expertise in the U.S., and its strong historical engagement in the experiment.
- The U.S. has in general many leadership positions in the LHC experiments, including spokespersons for CMS and upcoming ATLAS spokesperson.

L2/L3 Structure

HFSC

- **Tracker** – Carl Haber, Christoph Paus
  - Silicon
  - LGADS
  - Gaseous
  - Straw
  - Mechanics
- **Calorimeter** – Michael Begel, Bob Hirosky
  - Dual Readout
  - Nobel
  - Si-W
  - Tile-Sci
- **Muon** – Marcus Hohlmann, Bing Zhou
  - Drift Tubes
  - RPC
  - u-Rwell
- **Readout** – Zeynep Demiragli, Sasha Paramonov
  - Trigger
  - DAQ
- **AIM** – Julia Gonski, Jim Hirschauer
  - AI-Hardware
  - Common Electronics
  - Detector Concepts
- **PSC** – Lothar Bauerdick, Mike Hance
  - Physics Studies
  - Geometry
  - Software
  - Computing
  - User Support

AIM: AI, Integration and Microelectronics
PSC: Physics, Software & Computing

Technology Interests and Institutions: Tracker

Carl Haber
Christoph Paus

- Solid state tracking with **MAPS**
  - FNAL, SLAC, Caltech, Brown, BNL, Oregon, MIT
- Fast timing for **TOF/PID**
  - FNAL, BNL, SLAC, UCSC, LBNL
- Solid state tracking/time **testing and simulation**
  - MIT, Brown, Brandeis, SLAC, FNAL, Caltech, Stony Brook
- **Straw tube** trackers
  - Michigan, Duke, Tufts, MSU, UMass, Harvard, UCI
- **Drift chambers**
  - BNL
- **TPC**
  - Hawaii
- **PID** with dE/dx and dN/dx
  - Michigan, BNL, UT Austin
- **Gas tracking optimization**
  - UT Austin, SLAC
- Low mass **support structures** and components
  - Purdue, LBNL, U Washington, FNAL, Cornell, Florida, Hawaii
- Detectors optimized for **low systematic errors**
  - LBNL

Recent Perspective

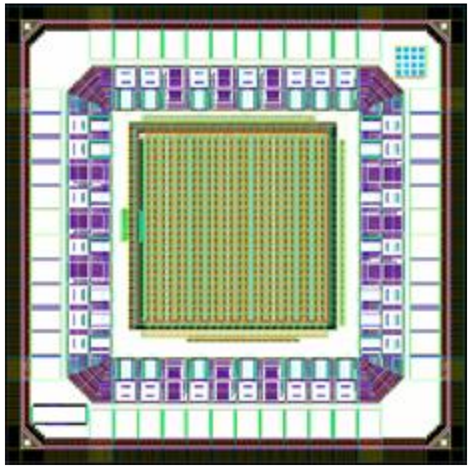
- US brings experience in both lepton and hadron collider physics
- CDF/D0/Babar/ATLAS/CMS silicon tracking and vertexing
- Extensive IC design experience
- Low mass support structures - composites engineering
- Straw tube, muon drift tube, and New Small Wheel gas tracking projects for ATLAS
- Large scale production of modules and components for trackers
- Leader in R&D for LGADs - silicon, and now SiC
- Design and construction of CMS and ATLAS new fast timing layers
- HF has many technical synergies with EIC program - strong US efforts here with already collaboration between HF and EIC communities

Vision for Possible Work Packages

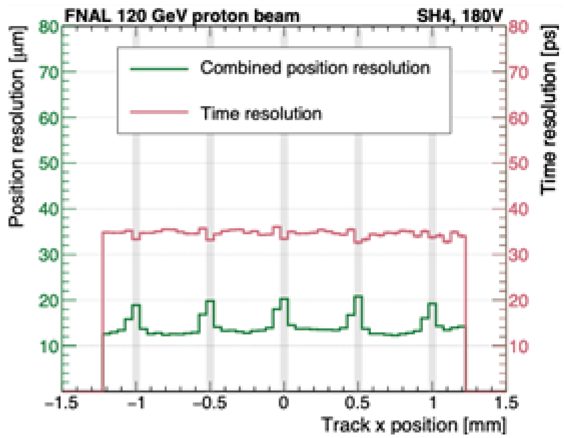
- Solid State Tracking
  - Participate in the development of the MAPS devices
  - Integration of components into tracking systems, fabrication, testing
- Fast Timing
  - Overall design of a TOF wrapper layer
  - Development of appropriate LGAD (or other) device, plus readout
  - Fabrication and testing
- Gas Tracking
  - Further development of gas tracking system - studies of multiple approaches
  - Develop and fabricate dN/dx electronics system
  - Construct gas tracker in chosen technology
- Low Mass Support
  - US is capable both developing technology/solutions and fabricating and delivery support structures on any scale from micro-vertex to global supports

SS and Timing: ongoing efforts and interests

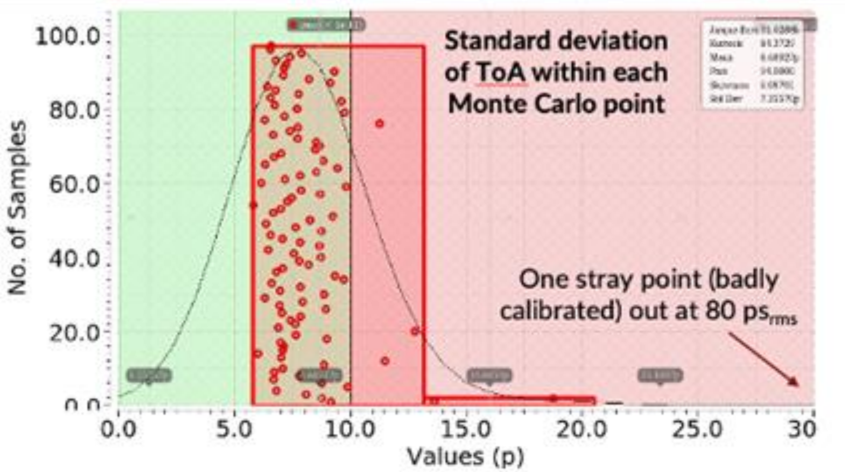
- Development of **Monolithic Active Pixel Sensors**
  - Partnership with Skywater Technologies 90nm, optimize process for HEP sensors
    - **Goal**: US manufactured sensor capability for HEP experiments
  - Prototypes with TJ 65nm as part of a CERN WP1.2 collaboration (ALICE)
    - **Goal**: use state of the art CMOS process to achieve low power consumption and aim for O(nsec) timing
- Developments of 3D-integrated sensors
  - Partnership with TJ 65nm and TSMC 28nm to utilize state-of-the-art technologies for HEP
    - **Goal**: development of 3D-integrated, low-mass and low-power trackers
- Fast timing R&D leveraging HL-LHC expertise
- Interest in ramping up our simulation efforts to evaluate tracking and timing detector requirements needs.



Picture of Napa-p2 from WP1.2 shared submission

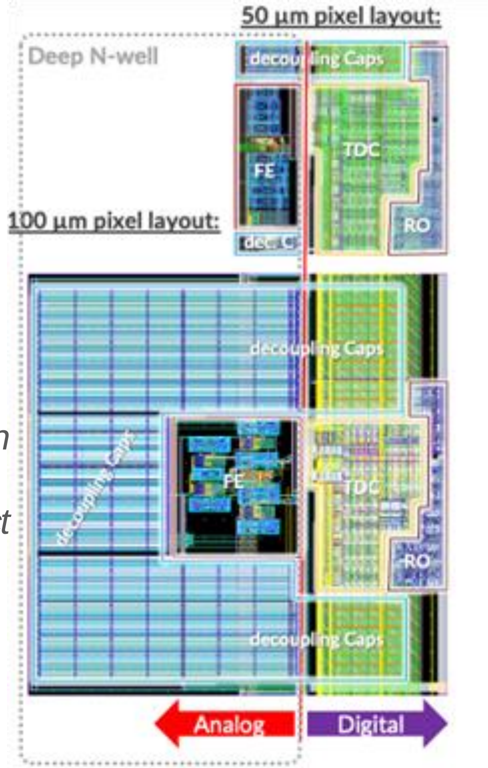


Sensors with uniform 10-15 μm and 30-35 ps resolution across surface



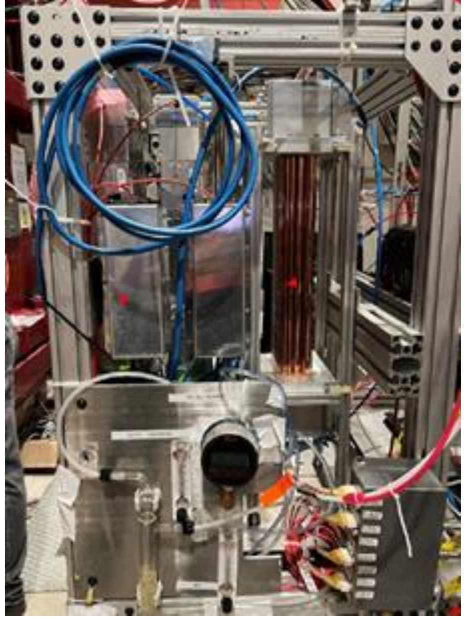
Expected performance of the 3D-integrated devices

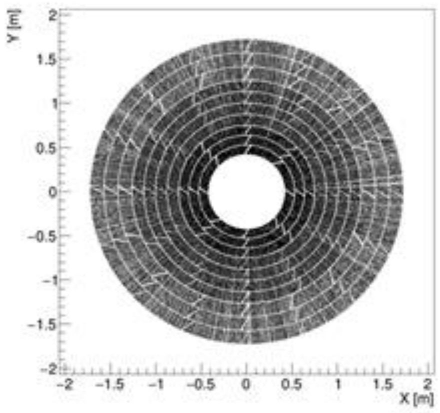
Layout of the MPW submission for the 3D-integrated project

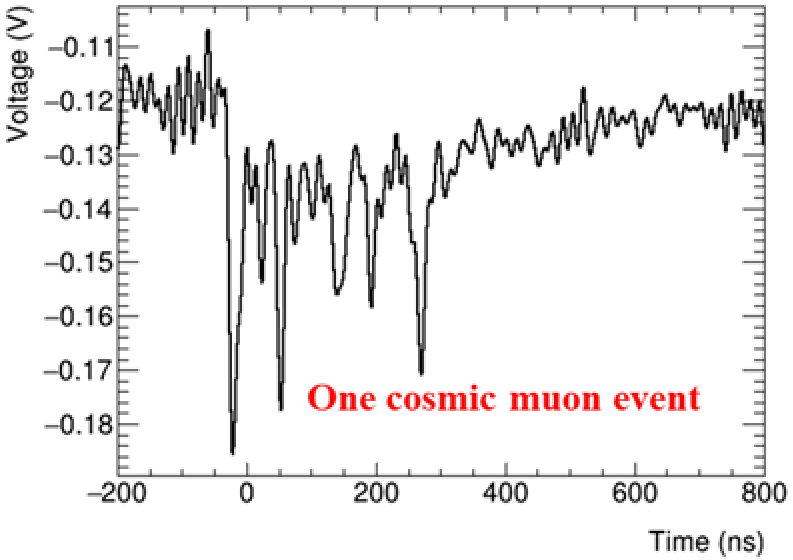


Gaseous tracker: ongoing efforts and interests

- **Simulation studies:**
  - Implemented a strawman model of a straw tracker inside GEANT and estimated the material budget
  - Performing Garfield++ simulation to understand the gas mixture
  - Implement track fitting algorithm, perform detector optimization studies
- **Test beam studies:**
  - Test beam studies together with a group producing thin-wall straws
  - Plan to perform dE/dX and dN/dX studies with various types of particles at different energies at Fermilab and CERN
- **dE/dX and dN/dX:**
  - Need to detect single electron peaks and then perform clustering
  - Currently using NIM modules and an oscilloscope to record waveforms for cosmic ray studies in the lab
  - Design a frontend board and record waveforms using CAEN waveform digitizer
- **Prototype chamber**:
  - Plan to build a prototype chamber with ~25 straws given to us from the NA62 experiment
  - Develop straw assembly procedure and design/fabricate endplates
  - Perform cosmic ray and test beam studies to understand the position resolution and dE/dX (dN/dX) capabilities
- **Wire studies:**
  - Study wires produced by different vendors
  - Investigate carbon fiber wires







US Comparative Efforts (Carl, Christoph)

- **Solid State Tracking**
  - Historic center of gravity for MAPS is in Europe, but they seek more collaboration
  - US groups will have to focus to become major participants in this area but we have strong IC design groups in place
  - Growing effort in US for EIC which can also help HF work
  - Strong capabilities in simulation and design/optimization, MDI
- **Fast Timing**
  - US is a major center for the development, testing, and fabrication of LGAD technology and electronics, both basic R&D and for the ATLAS and CMS upgrades.
  - Highly competitive internationally
- **Gas Tracking**
  - Highly competitive based upon multiple ATLAS projects - straws, MDT, NSW
  - TPC’s from heavy ion program and BELLE II upgrade
  - Strong DCH effort already in Italy (IDEA collaboration)
- **Low Mass Support**
  - US is capable of both developing technology/solutions and fabricating and delivering support structures on any scale from micro-vertex to global supports. We are world leaders in this area.

Technology Interests - Calorimetry

Michael Begel
Bob Hirosky

- US HEP has demonstrated deep expertise and leadership across multiple calorimeter technologies
- Technology interests:
  - Dual Readout Calorimetry
    - Calvision, DREAM/RD52
  - Noble Liquid
    - ATLAS ECAL, D0
  - Silicon-Tungsten
    - CMS HGCAL, CALICE
  - Tile-Scintillator
    - ATLAS Tile CAL, CMS HCAL/HGCAL

Dual Readout Calorimetry

- Significant US contributions to construction, operation, calibration of CMS precision crystal ECAL
- **DREAM/RD52**: In the last decade, demonstration of DR technique in spaghetti-style (fiber) calorimeter + initial study of S/C separation in DR homogeneous crystal ECAL (DOE supported)

- **CalVision Consortium**:
  - First (and so far only) to demonstrate collection of sufficient Cherenkov signal for DR application
  - Advanced DD4HEP GEANT model
  - Innovative studies in longitudinal segmentation via timing in fiber HCAL
  - Extensive R&D program to study practical detector design and blue sky materials
  - Building strong US collaboration: ~25 university and lab groups so far. High levels of participation.
  - Funding via DOE HEP R&D program (7/22--3/25). Renewal submitted.
    - Primary goals: first demonstrations of
      - **(1) state-of-the-art EM resolution in crystal+SiPM, 2-layer ECAL and**
      - **(2) DR application in xtal(EM)+fiber(HAD) hybrid calorimeter**

  - US groups are already making leading contributions to detector R&D in this area
    - Complementary approaches, both targeted and blue sky, compared to international R&D

Nobel Liquid Calorimetry

- LAr technology
  - Excellent energy resolution and good timing properties with proven linearity, stability, and uniformity yielding small systematic uncertainties → crucial for precision measurements program
  - Take advantage of recent developments for large LAr TPC including cold electronics (eg ASICs)
  - Complementary to silicon- and gaseous-detector tracking systems [particle flow]
  - Intrinsic radiation tolerance → important for FCC-hh

  - Interests expressed by: BNL, UAZ, USB, Austin, Columbia, Irvine
    - Novel LAr calorimeter and TPC technology (BNL in collaboration with CERN)
    - Detector simulation for physics optimization and possible joint work on module development and testing (Stony Brook Univ)
    - Inclusion of AI/ML algorithms on the readout ASICS (UT Austin)
    - Novel design of endcap EM calorimeter (Arizona)

Silicon-Tungsten and Tile-Scintillator Calorimetry

- Strong use efforts of the years including contributions to CALICE collaboration and CMS HGCAL design and construction
  - Supports highly granular readout for 3D shower imaging
  - Well suited to particle flow algorithms
  - Can have fast timing capabilities
  - Interests expressed by: Oregon, Kansas, SLAC
- MAPS for Future Collider Calorimetry (Oregon, SLAC)
  - SLAC leading a collaborative effort to develop MAPS for EM calorimeter;
  - Oregon is assuming responsibility for simulation performance of the MAPS
- Si-W based e+e- collider precision luminosity measurements (Kansas):
- Long history of US expertise in tile-scintillator calorimetry
  - Scintillator production facility and R&D at FNAL
  - CMS HCAL construction, readout, operations
  - CMS HGCAL hadronic section
  - Interests expressed by: NIU, UTArlington, UMD, Iowa, FNAL

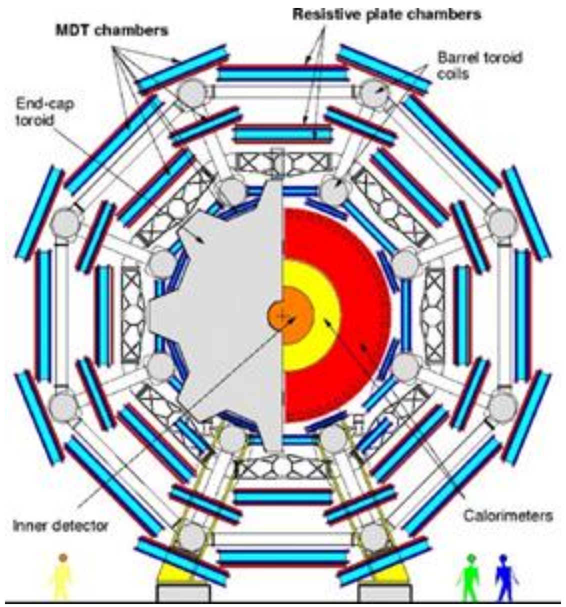
Technology Interests and Institutions - muons

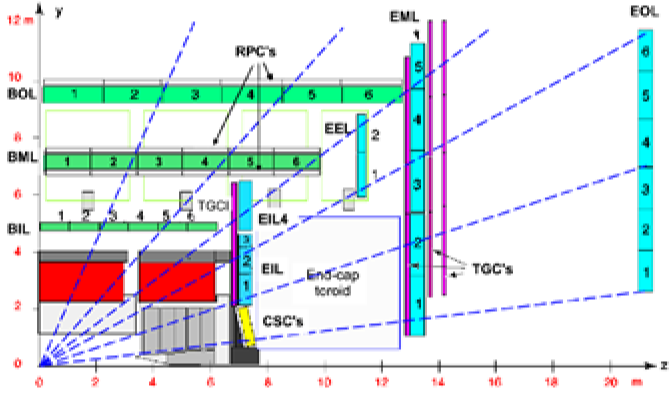
Marcus Hohlmann
Bing Zhou

- **Eco-friendly drift gas mixture**, optimization for safety, efficiency, and resolution
  - UM, FIT, Tufts
- **Drift-tube** (round and rectangular) based large, robust, and inexpensive muon detector
  - Harvard, Tufts, MSU, UCI, UM, UMASS
- **MPGD (μ-RWELL)** muon detector (fast timing)
  - FIT, JLAB
- **Front-end electronics** (low-noise ADT, fast timing, FPGA-based TDAQ) for muon detector
  - Umass, Harvard, UM
- **Scintillator bars** (read out using wave-length shifting fiber and SiPM)
  - SLAC
- **Perspective:** the U.S. has a large role in the development and production of large-area muon detector for the LHC. There is strong synergy with the EIC.

US Muon Expertise - ATLAS Muon Spectrometer

Precision muon detectors: **Monitored Drift Tube (MDT) chambers +CSC**

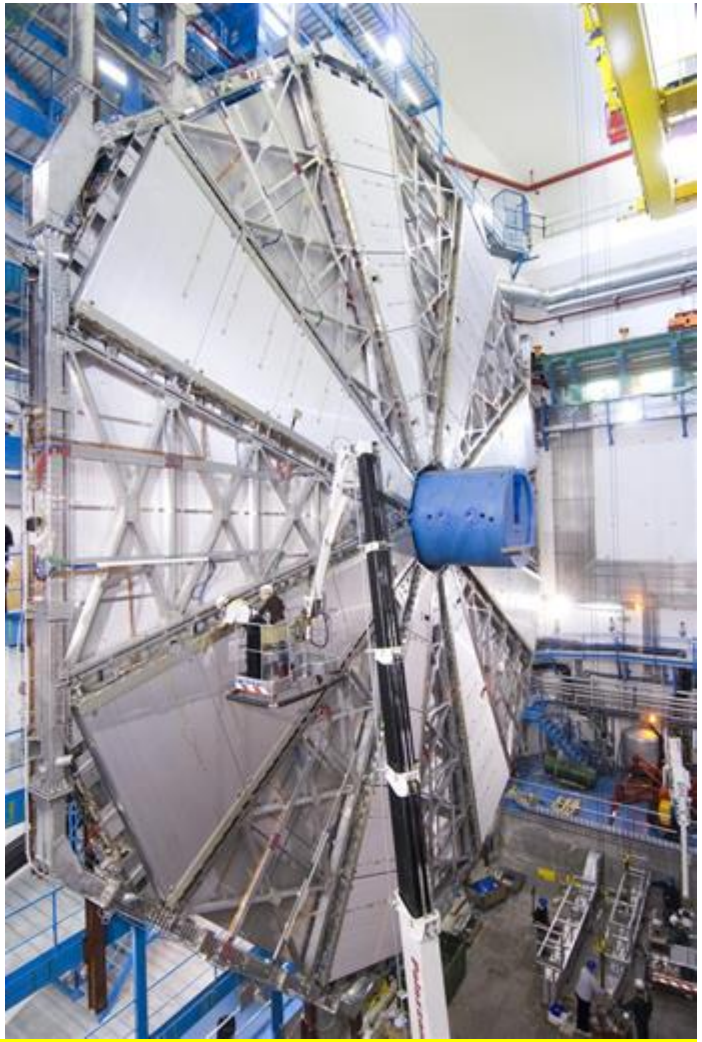




Magnet: Solenoid (inner) + Toroid (outer)

Muon MDT chamber, tube d=3 cm, 80µm/wire

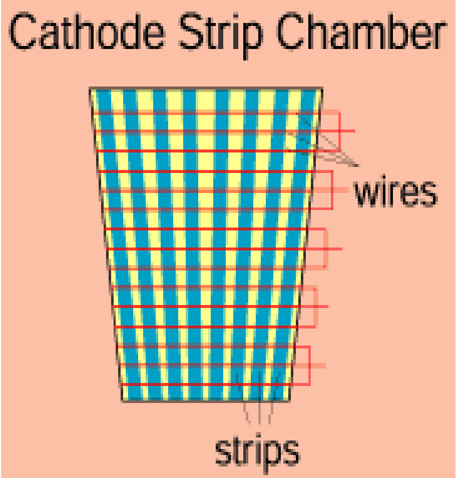
Large chamber construction at UM

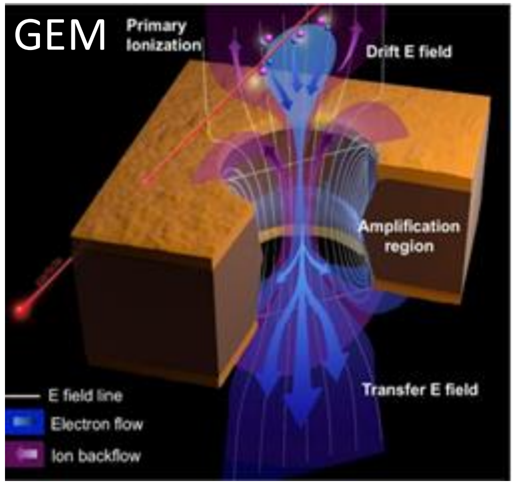


Big Wheel (endcap) built in the US, installation in ATLAS

US Muon Expertise – CMS Muon Spectrometer

CMS precision endcap muon detectors: **Cathode Strip** & **Triple-GEM** Chambers

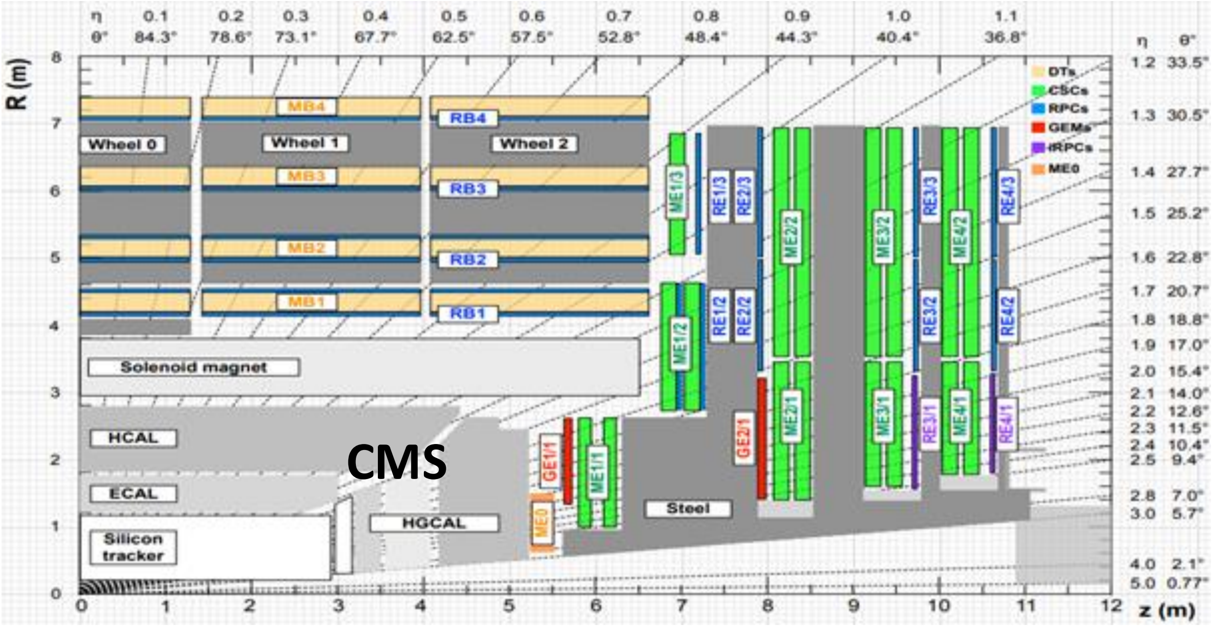




GE2/1 GEM Installation

Endcap CSC disk built by US

Muon subsystem	Cathode strip chamber (CSC)	Gas electron multiplier (GEM)
$\|\eta\|$ range	0.9–2.4	1.55–2.18
Number of chambers	540	72
Number of layers/chamber	6	2
Surface area of all layers	$7000\ m^2$	$60\ m^2$
Number of channels	266 112 (strips) 210 816 (wire groups)	442 368
Spatial resolution	50–140 μm	100 μm
Time resolution	3 ns	<10 ns



The FCC-ee Muon System R&D

The muon system is the largest sub-detector in colliding beam experiments. For FCC-ee detector concept design studies, the technology choices remain largely open, particularly for the ALLEGRO experiment.
US institutes possess strong technical expertise in muon system design and construction, drawing from experience with past and current high-energy physics experiments (see examples of the ATLAS CMS muon detectors).
Key priority is to develop robust, large-area muon/gaseous detectors with fast timing and high spatial resolution.

Muon identification and detection

- Tracking (trigger) System, the outmost part of a detector (large volume)
- Front-end electronics (fast timing, and precision tracking)

} Muon detector technology R&D (high priority)

Combined with

- Central tracker with interaction vertex determination
- EM/Hadron calorimeter & muon filter
- Magnetic field(s)

} R&D for experiment design

There are three muon detector R&D areas (L3's) in the US

- Drift tube-based detector
- μ-RWELL (MPGD) based detector
- Electronics for muon detection

The Drift Tube Muon Detector R&D for HF

- **Simple, Robust,** and **inexpensive** suitable for large scale construction
- Capable of achieving **< 200 μm single wire resolution** for all muon incident angles
- Capable of determining T_0 with triggerless readout mode with ~ns time resolution, determine BCID

The proposed R&D with high priority; modest funding request in FY2025

- **Study of chamber drift gas**
  - Need new environmentally friendly gas mixtures with low GWP
  - Using the existing infrastructure to study different gas mixture with cosmic rays and test beams.
- **Construct and study the squared drift tube performance**
- **Build a prototype chamber** by using the existing UM squared-drift tubes to with redesigned end-plugs to locate wire with high precision, in a configuration of 2 multi-layers, each has 4 drift tube layers. To develop and study
  - An efficient wiring process with high precision, including an on chamber gas system
  - Measure the spatial resolution and efficiency using the ATLAS MDT electronics and MiniDAQ system with cosmic rays and test beams
  - Compare the test results with Garfield simulations

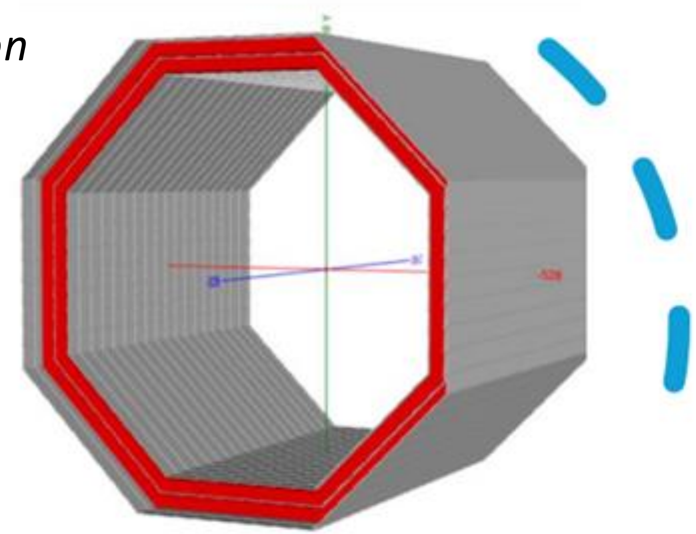
The µRWELL Muon Detector R&D for HF

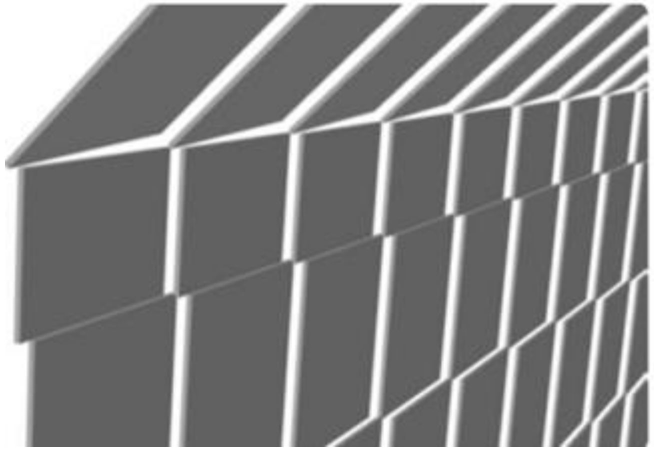
- A modern micro-pattern gas detector (MPGD) with single amplification stage
- Currently proposed by IDEA experiment for muon system

The Proposed R&D:

- **Develop MPGD production capabilities in the US**
  - Currently only CERN can provide MPGD components
  - Lead times for procurements are long (6-12 mos.) and increasing
  - Efforts in the past decade to develop commercial vendors (TechEtch, Mecaro, Tectra) have failed; presumably market too small
  - JLAB is interested in developing a fabrication site
  - Transfer MPGD production technology from CERN; long lead time.
- **Study eco-friendly gas mixtures for µRWELL**

IDEA Muon system

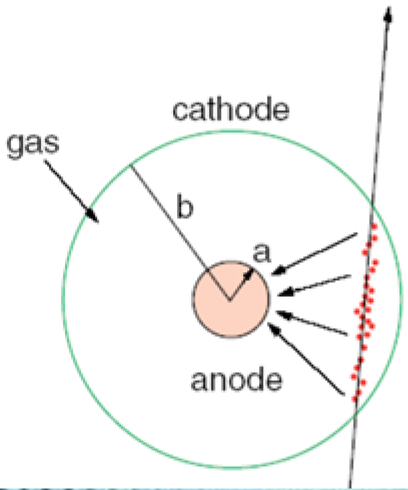


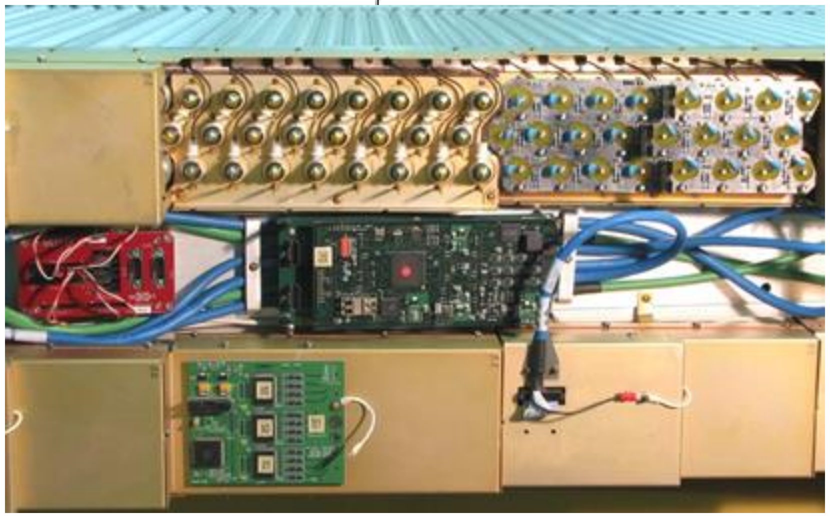


50cm x 50cm µRWELL modules

The Muon Detector Electronics R&D

- Capable of **3D** tracking achieving **< 200 μm single wire resolution** and **<1cm in 2nd coord (along tube)**
- Capable of **trigger:** determining t_0 with triggerless readout mode with <ns time resolution, determine BCID





The Proposed R&D with high priority;

- **Study extensions of current drift tubes to satisfy 3D tracking & trigger requirements – would make it possible to use drift tubes as single technology for muons**
  - Explore drift tubes for 3D tracking, including the non-precision 2nd coordinate (along the tube direction.
  - **Study signals in simulation, build design and prototype new electronics hedgehog card**
  - Read out MDT signals using triggerless streaming mode with **BCID determination using current electronics**
- **Investigate new low-power electronics with precise timing resolution**
  - Simulations toward future low-power digital TDC designs with sub-200ps measurement resolution.

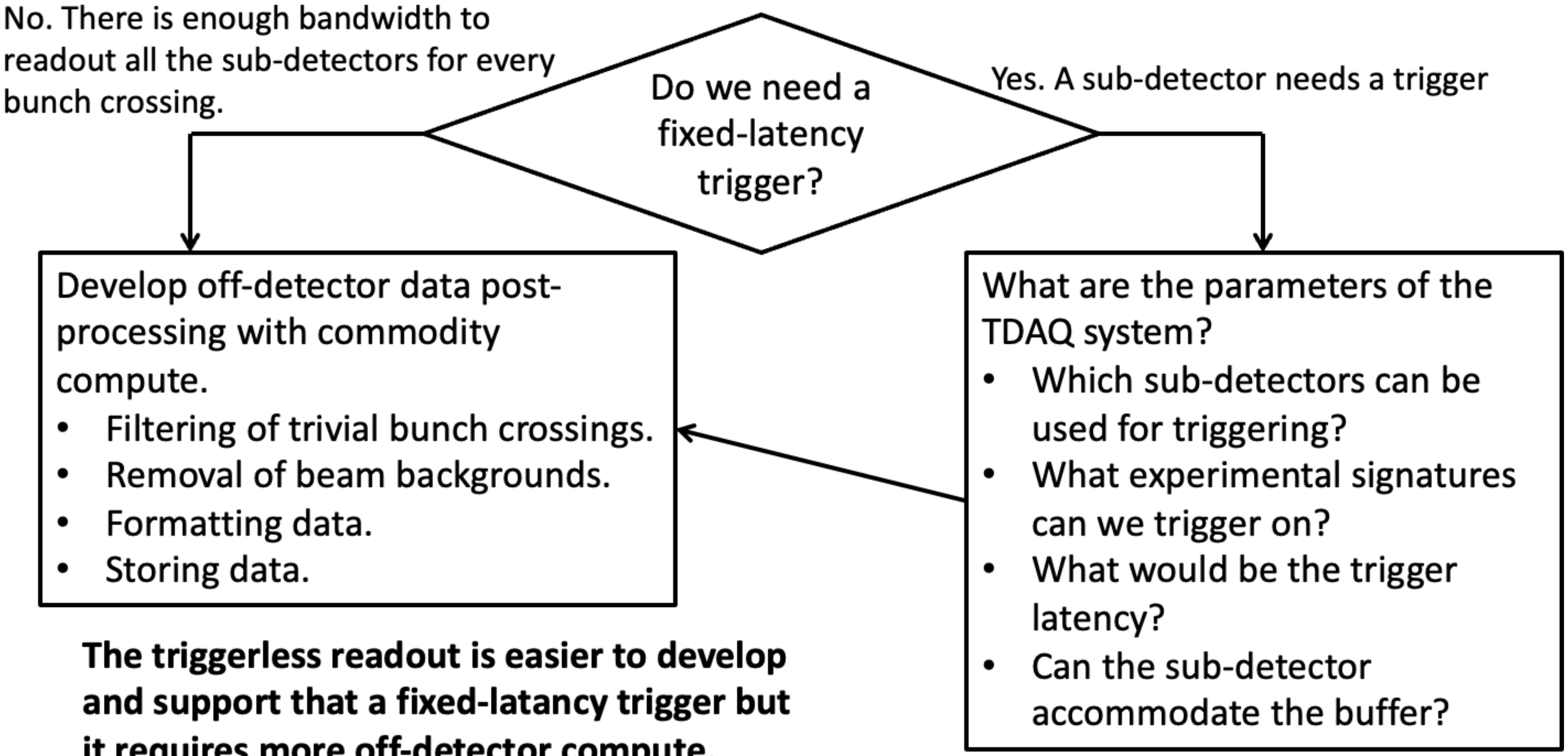
Technology Interests and Institutions– TDAQ

Zeynep Demiragli
Sasha Paramonov

- **Perspective:** the U.S. has and continues to play a major role in Trigger and Data Acquisition at Level 1 and at the High Level Trigger, especially at the LHC experiments. The first implementation of a track trigger was at CDF.

- **Embedded FPGAs offer reconfigurable digital logic in an ASIC**
  - SLAC, LBNL, Baylor, Fermilab, UHawaii, Umichigan
- **Heterogeneous processing for future HEP experiments**
  - BU, The Ohio State, FNAL, ANL, BNL
- **Trigger concepts**
  - UMass Amherst (t.b.c.)
- **Real-time machine learning**
  - SLAC
- **Autonomous systems**
  - SLAC, UChicago

TDAQ Architecture decision tree



The triggerless readout is easier to develop and support that a fixed-latancy trigger but it requires more off-detector compute.

Disruptive Innovation

- The ability to read-out the sub-detectors for every bunch crossing can be enabled by several key technologies
  - Intelligence on detector: advance data reduction (ML/AI, etc)
  - High-rate sampling and timing (4D readout, etc)
  - Levering emerging technologies (high-speed optical link/Si-Pho, etc)

Requires coordination with the AIM and detector groups.

- The off-detector post-processing can also benefit from modern computing architectures
  - AI/ML accelerators like Google TPU
  - GPUs or IPUs (e.g. Graphcore Intelligence Processing Units)

Requires coordination with the software and computing group.

Data rates and up-link bandwidth

- Data volume in some sub-detectors is driven by the beam backgrounds.
- Accurate simulations of the backgrounds and detector response are key to the TDAQ architecture decision process.
- It is desirable to have realistic GEANT4-based detector simulation of all the detector concepts.

Requires coordination with the software and simulations group.

Technology Interests and Perspective – AIM

Julia Gonski
Jim Hirschauer

- **Perspective:** the US has played a major role in influencing detector design and construction through:
  - ASIC design for HEP experiments
  - Microelectronics R&D
  - R&D for AI in hardware (FPGAs, ASICs)
  - HEP experiment design and construction
  - Physics studies for optimization of HEP detector concepts
- **Institutions:** "HFCC AIM" group has evolved from "Readout/ASICs" in P5 Higgs factory costing exercise
  a. Community surveys led to 4 main labs and 6-10 universities interested
  b. ~20 scientists, ~50 engineers, ~20 postdocs, ~10 students

Scope and Objectives – AIM

- **Near-term WP priorities:**
    a. Detector design/optimization "competition": consolidation of benchmarks, samples, and code frameworks to facilitate new ideas and optimization strategies (prep FY25, launch FY26)
    b. AI in ASIC design, emerging microelectronics technology
- **Longer term WP ideas:**
    a. AI:
        i. SG1: Codesign: advanced algorithms ←→ hardware platforms
    b. Integration:
        i. SG1: AI-based optimization of detector designs
    c. Microelectronics
        i. SG1: Common IP blocks in 28nm
        ii. SG2: Digital & optical backend
        iii. SG3: Emerging technologies (eg. silicon photonics)
        iv. SG4: Precision clock distribution
        v. SG5: Power management
        vi. SG6: Open source design/fabrication

Technology Interests and Perspective – PSC

Lothar Bauerdick
Mike Hance

- **Perspective:**
- The US has been a driver for innovations in HEP computing, certainly for the LHC and now the HL-LHC, but also in Astro-Particles (e.g. Vera-Rubin) and other areas.
- Many US institutions are leaders and have significant expertise in leading-edge physics software and computing, in ML/AI application to physics software, in core software and computing infrastructure innovation, in algorithms like particle tracking, calorimeter clustering, simulation, as well as software architecture and libraries.
- Together with Computational HEP projects like HEP-CCE and the IRIS-HEP Software Institute, the Open Science Grid, ESnet, projects like HTCondor, Globus and others, university and national lab's Tier-1 and Tier-2 computing centers and HPC providers, the US has a rich computing ecosystem and is very well connected with the international community, including the WLCG and CERN.

Vision and Goals – PSC

Lothar Bauerdick
Mike Hance

- Grow the Higgs Factory engagement in several key areas:
- **Core SW**
  - Improve performance and full-sim detector models
- **Analysis SW**
  - Ease entry into analysis
- **Detector Modeling**
  - Work with L2 detector areas to support implementation of full-sim detector models
- **Computing**
  - Identify analysis computing resources for users where they can easily start and scale up analyses
  - Identify and bring grid US computing resources to facilities for MC production

Some Observations

- The U.S. particle physics community has a history of developing novel detector concepts and has broad expertise.
- The U.S. experimental HEP workforce is formidable, and has been a trusted partner with CERN on the LHC. The investment to-date in the construction + upgrades of the two multi-purpose detectors exceeds one billion dollars, excluding accelerator investment and operational costs.
- The community will continue to collaborate with the next proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise.
- The aim for a high precision and discovery machine will require **leadership, novel technologies and new ideas**.

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2021- 25: Feasibility Study → **2027/2028:** project approval by CERN Council → **2032:** construction starts → **2041:** HL-LHC ends → **2045:** Operation of FCC-ee → **2070:** Operation of FCC-hh

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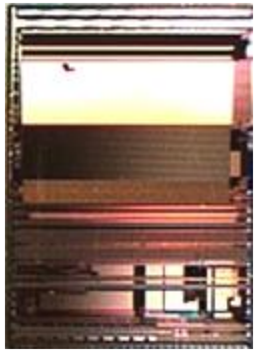
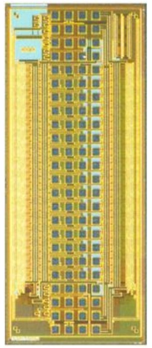
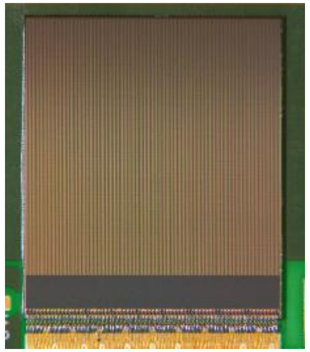
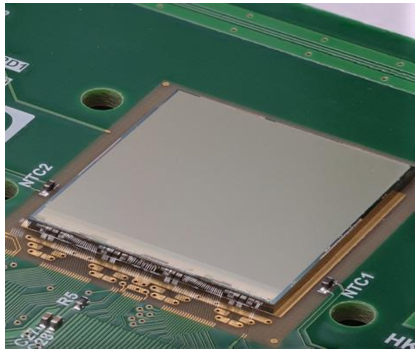
- There is plenty of time to explore new ideas; think out of the box and **rethink current paradigms**.

Keep an Open Mind

- Let's continue to "bounce ideas" for **new detector technologies** to strengthen the case for **a** Higgs Factory; we will all benefit.

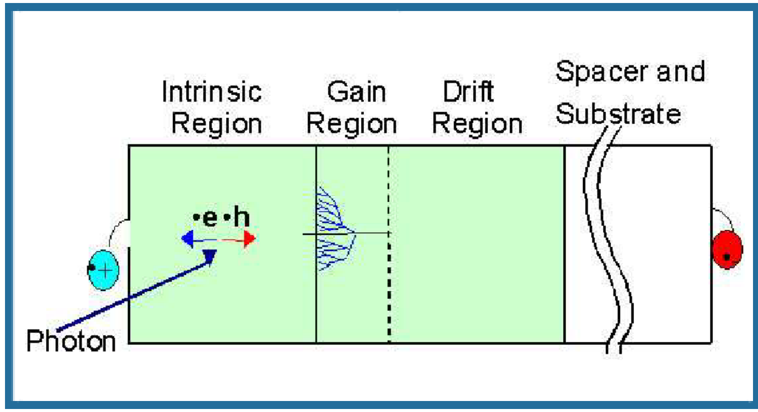
The Underpinning Of Scientific Progress

SVX (CDF 1990)	SVX3 (Fermi 1998)	SVX4 (Fermi 2002)	DCDB (Belle 2015)	Velopix (LHCb 2022)	RD53 (HL-LHC 2022)
					
UTMC 1.2 µm rad-hard CMOS	Honeywell 0.8 µm Mixed-signal CMOS	TSMC 0.25 µm mixed-signal CMOS	TSMC 180nm CMOS	TSMC 130nm CMOS, 20.5 Gbps	TSMC 65nm CMOS, noise <100 e;
Doi: 10.1109/23.12699	*Doi.org/10.1016/S0168-9002(97)01301-6*	*Doi:10.1109/TNS.2004.836027*	*Doi:10.1109/NSSMIC.2011.6154365*	*Doi: 10.1088/1748-0221/10/01/C01057*	*Doi: /10.22323/1.343.0157*

- Continued through progress with MAPS technology and parallel progress in opto-transceivers by industry

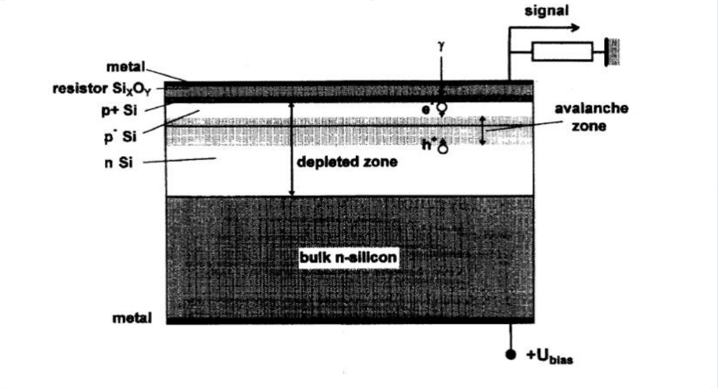
The Underpinning Of Scientific Progress

VLPC
(Rockwell, 1987)



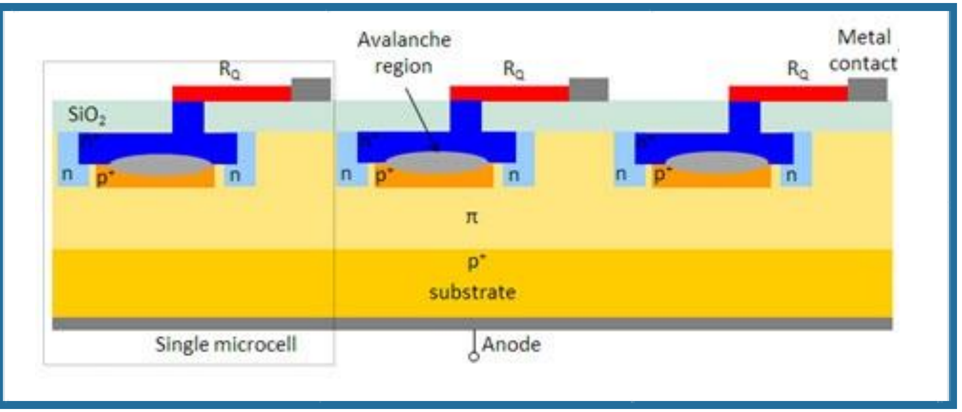
Bross et al., NIM A477, 172 (2002)

MRS APD
(Russia, ~1995)



Antich et al., NIM A 389 (1997) 491

MPPC
(Russia, ~2003)



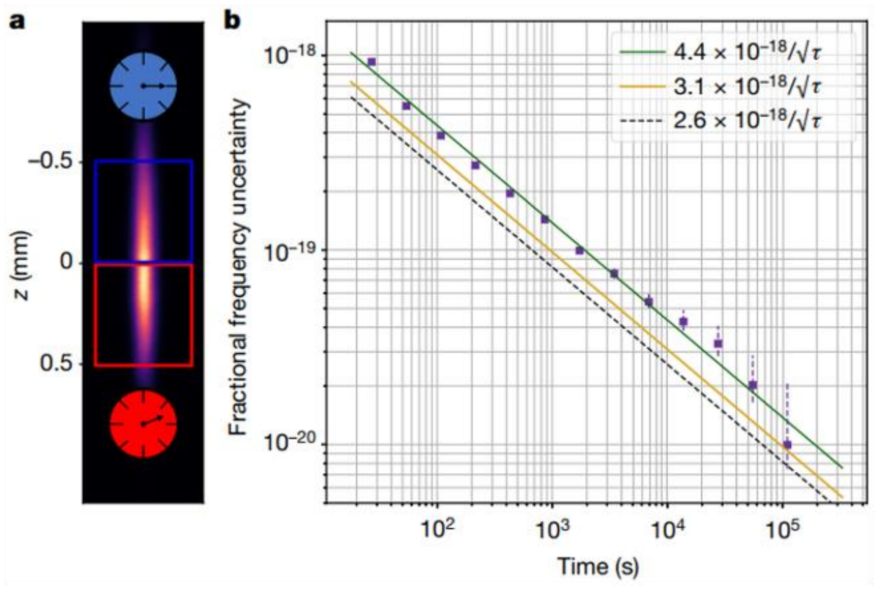
Dolgoshein et al., NIM A 504 (2003) 48
Sadygov patent (1998)

- From difficult beginnings (VLPC operated at 7K for Dzero scintillating fiber tracker) to being a workhorse for the field in a mere twenty years.

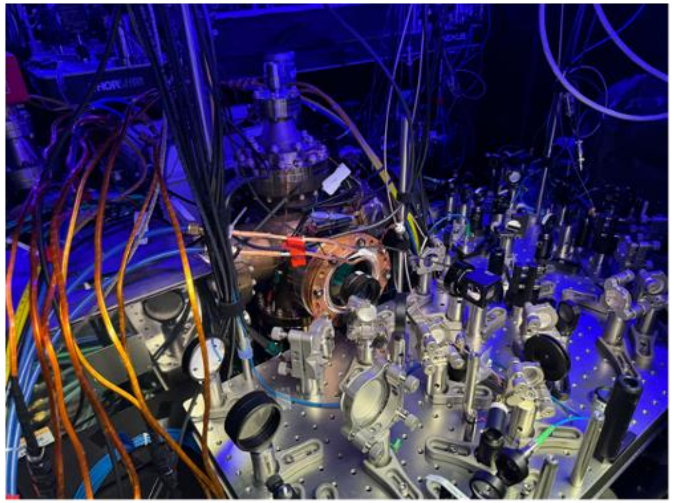
VLPC: Visible Light Photon Counter
MRS: Metal- Resistor-Semiconductor
MPPC: Multi-Pixel Photon Counter (SiPM)

Sensing has moved clock precision to 21st digit

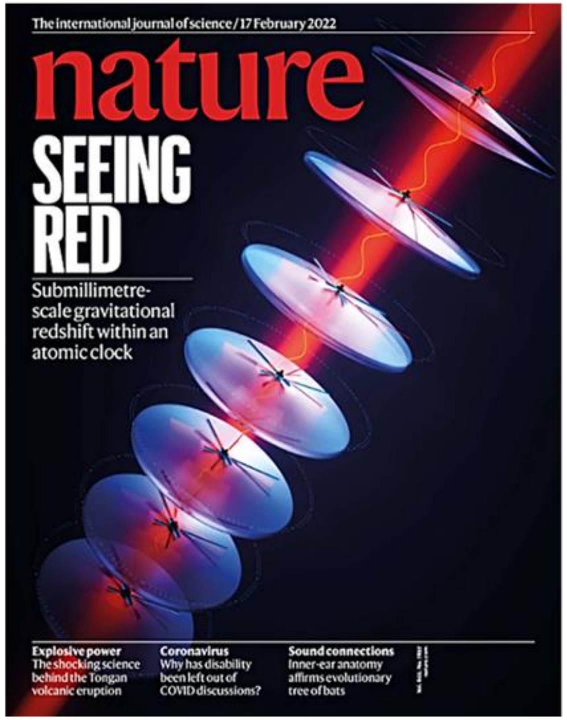
QSA's advances in metrology deliver unprecedented accuracy in sensing, opened the doors to measuring the gravitational redshift using only a millimeter atomic sample instead of kilometer scale experiments



Measurement results



Experimental setup in Boulder



Measuring the gravitational redshift predicted by general relativity once required measurements separated by thousands of kilometers, now it can done over millimeter length scales

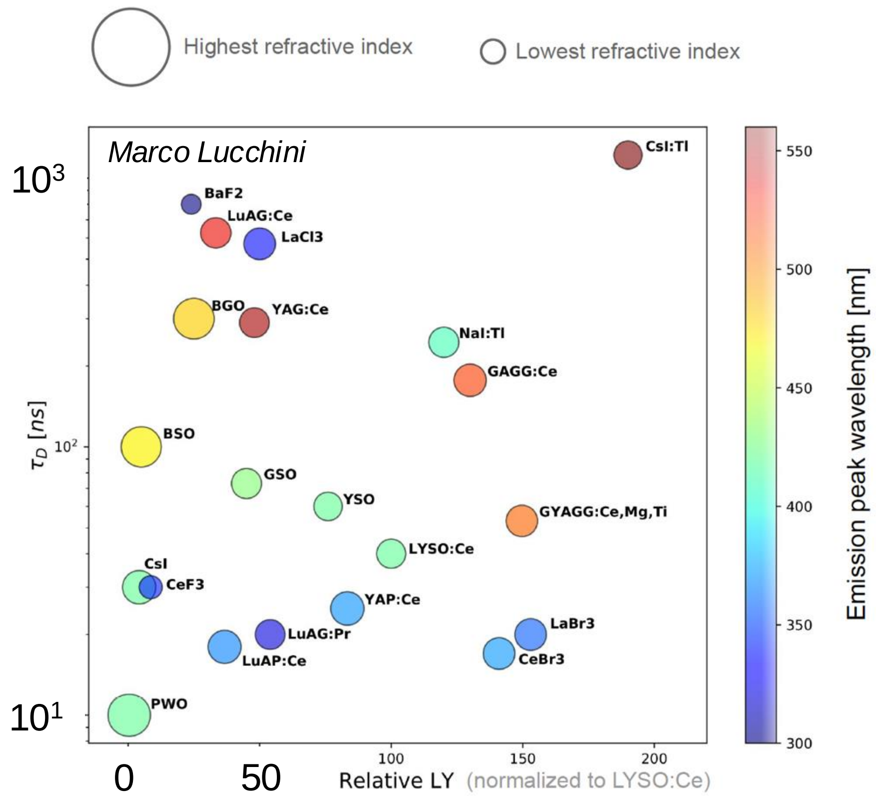
University of Colorado Boulder

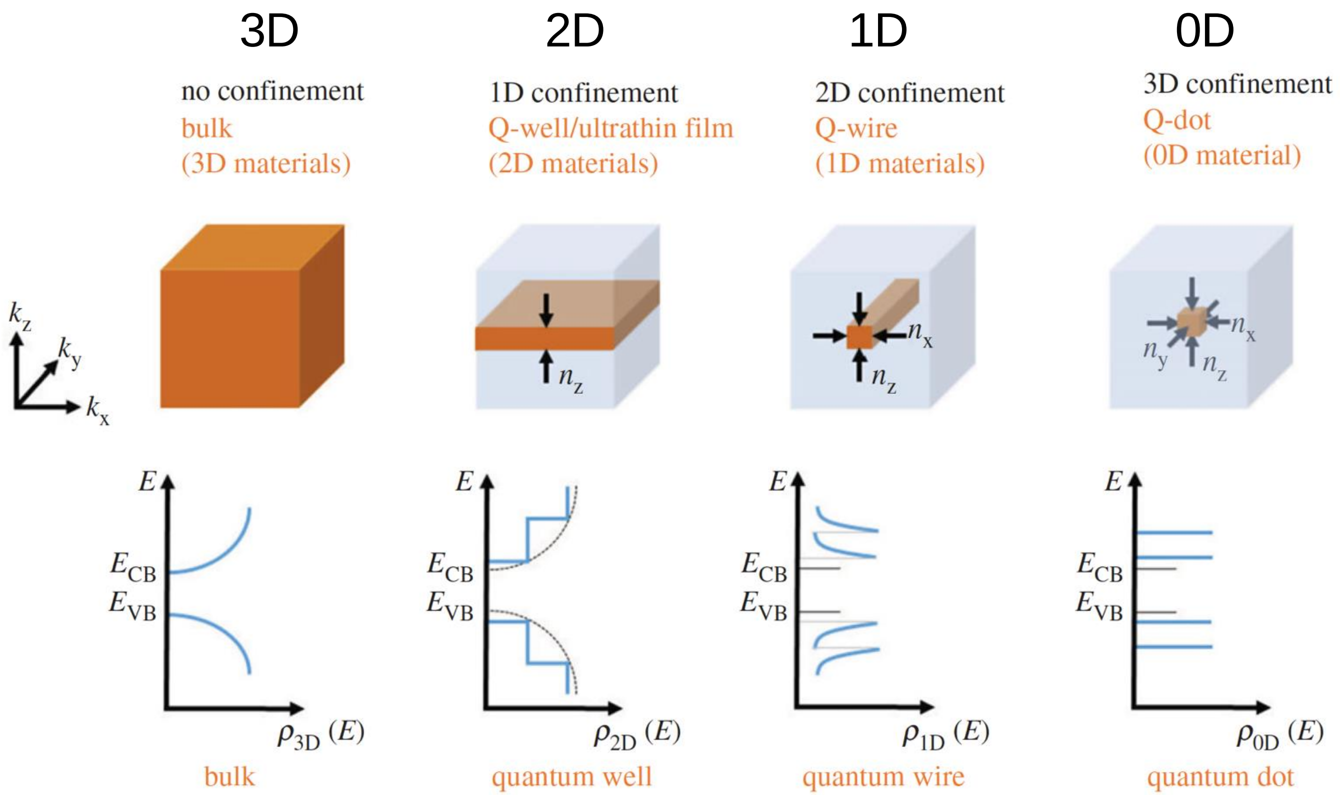
Nature **602,** 420 (2022)

DRD5

Crystal Calorimetry

- Traditionally, crystal – fully absorbing – calorimetry has obtained the best energy resolution





rsos.royalsocietypublishing.org R. Soc. open sci. 5: 180387

- Huge range of possibilities through **quantum engineering** of materials

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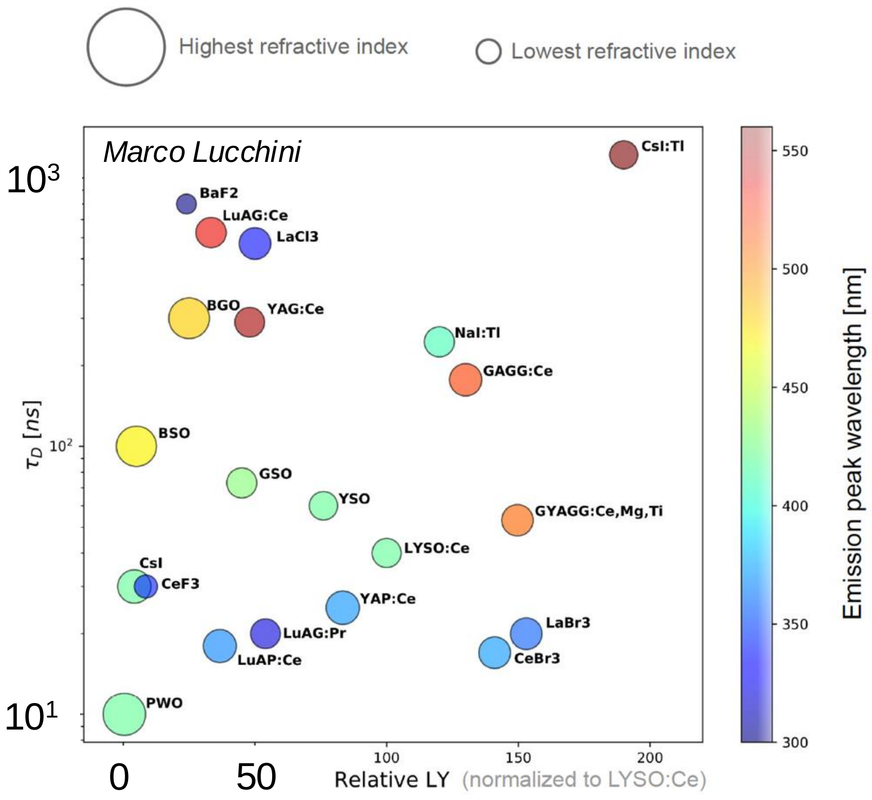
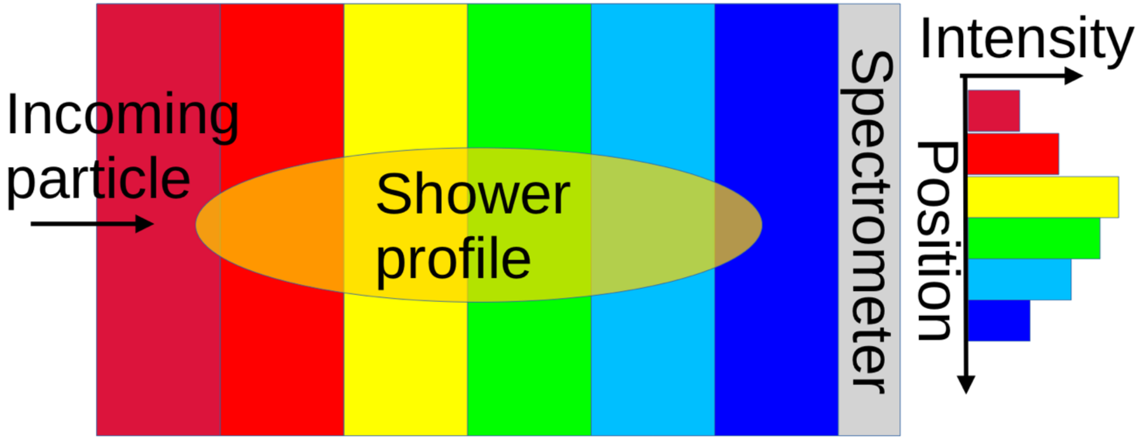


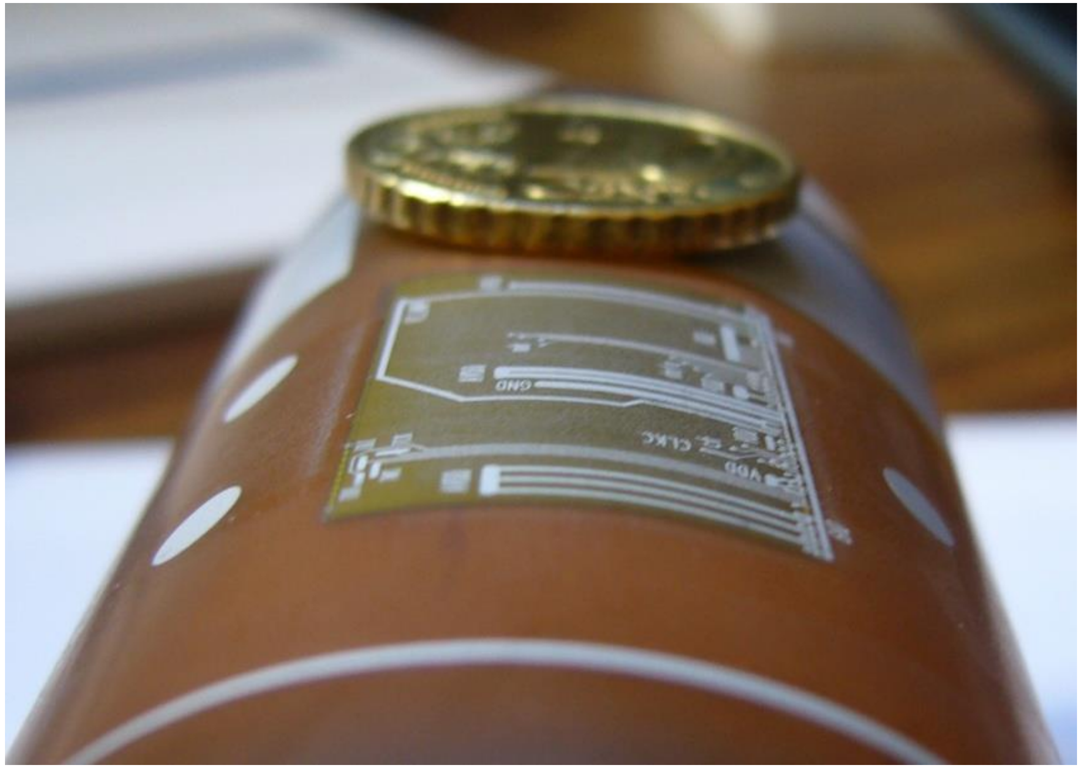


(shower profile via ***spectrometry***)

M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)
Y.T. Lin & G. Finlayson, Sensors 23, 4155 (2023)

- Huge range of possibilities through **quantum engineering** of materials

Flex embedded sensors



Already more than a decade ago, PLUME, SERVIETTE and PLUMETTE collaboration investigated and succeeded at **embedding thin MAPS sensors in Kapton flex**

New fabrication and packaging technologies for CMOS pixel sensors are **closing the gap between hybrid and monolithic**

https://indico.cern.ch/event/276611/contributions/622863/attachments/502969/694527/dulinski_FEE-2014.pdf

Conclusion

- The U.S. has the breadth and depth for strong participation in the development of the experimental program of a future Higgs factory, resources permitting.
- The priority is completing the HL-LHC detector upgrades and resources are currently dedicated to its completion.
- The community will continue to collaborate with the next proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise.

With many thanks to Jon Kotcher, Mike Tuts, Steve Nahn, Anders Rydt, all L2 and L3 coordinators and many more ….