U.S. ATLAS HL-LHC Status

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Columbia University
in the City of New York

on behalf of the

U.S. ATLAS HL-LHC Project Management Team

HEPAP

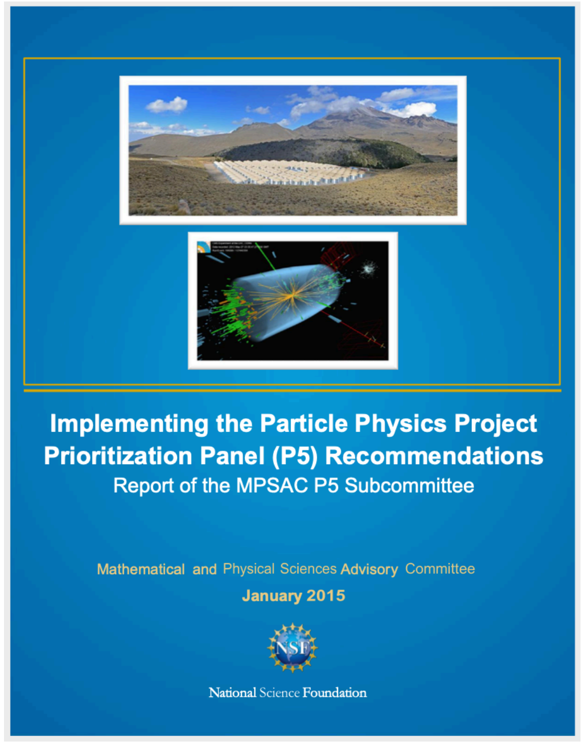
November 21-22, 2019

Outline

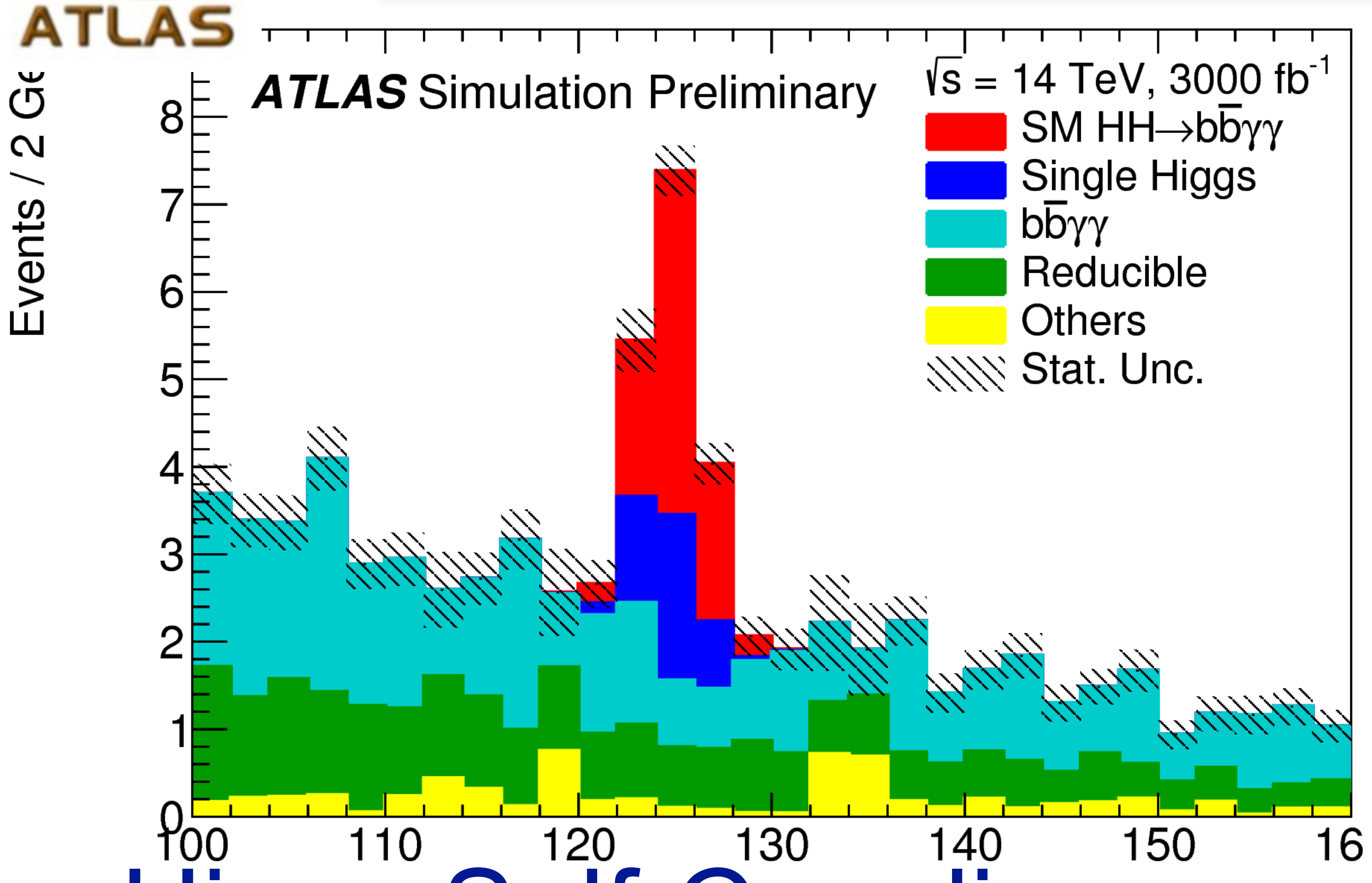
- U.S. participation in HL-LHC and ATLAS
- ATLAS HL-LHC upgrade and U.S. scope
- U.S. Project team
- Current stage in U.S. approval process
- Major risks
- DOE and NSF funding profiles
- Closing

U.S. Participation in the (HL-)LHC

- 2013 European Strategy Report:
  - Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.
- 2014 P5 prioritized roadmap for HEP for the coming decade:
  - Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.
- In 2015 endorsed by a subcommittee of the NSF MPS Advisory Committee:
  - The subcommittee strongly supports the NSF investment in the LHC phase-2 upgrades as a way to enable and participate in fundamental discoveries.

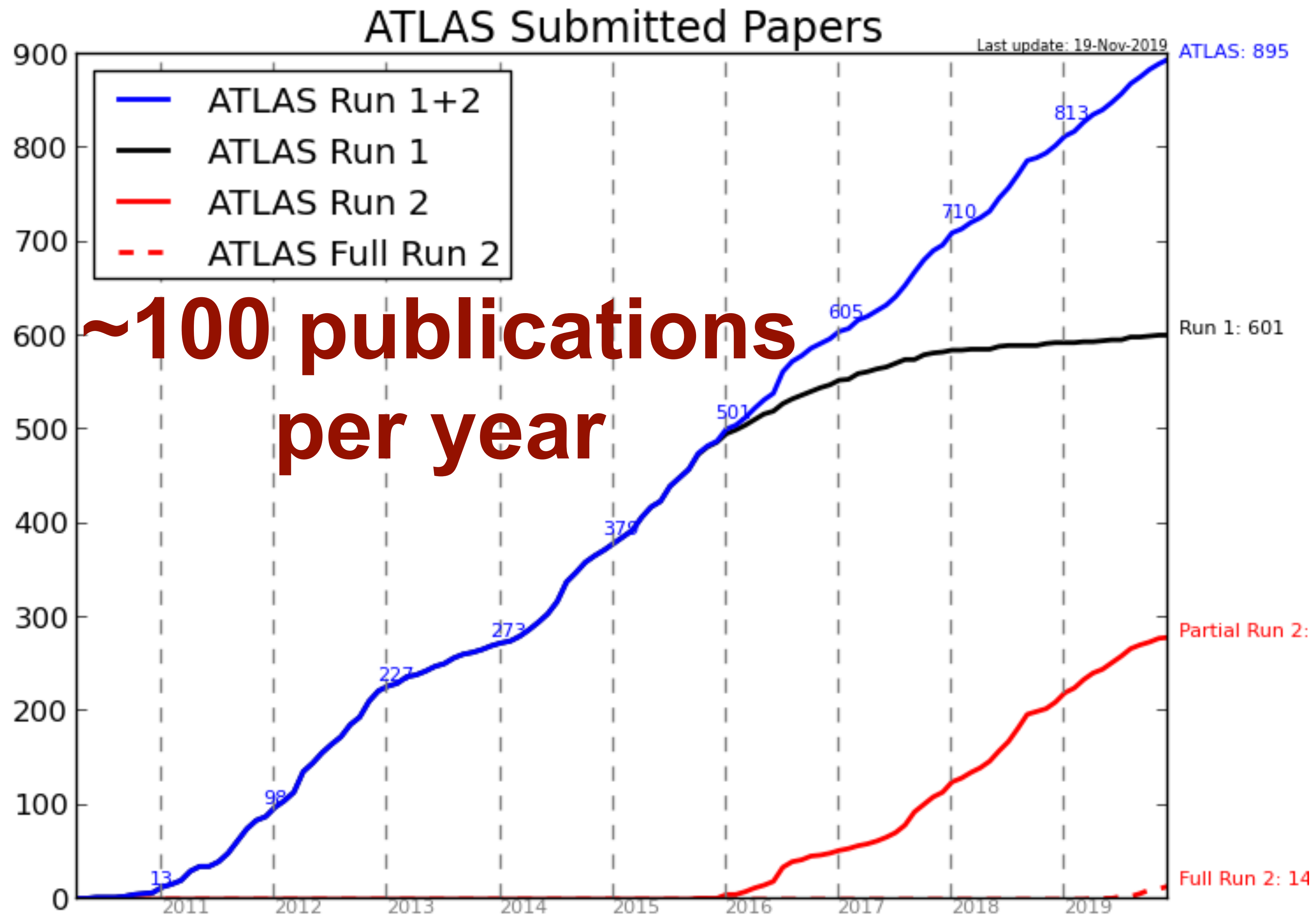


Science Factory!

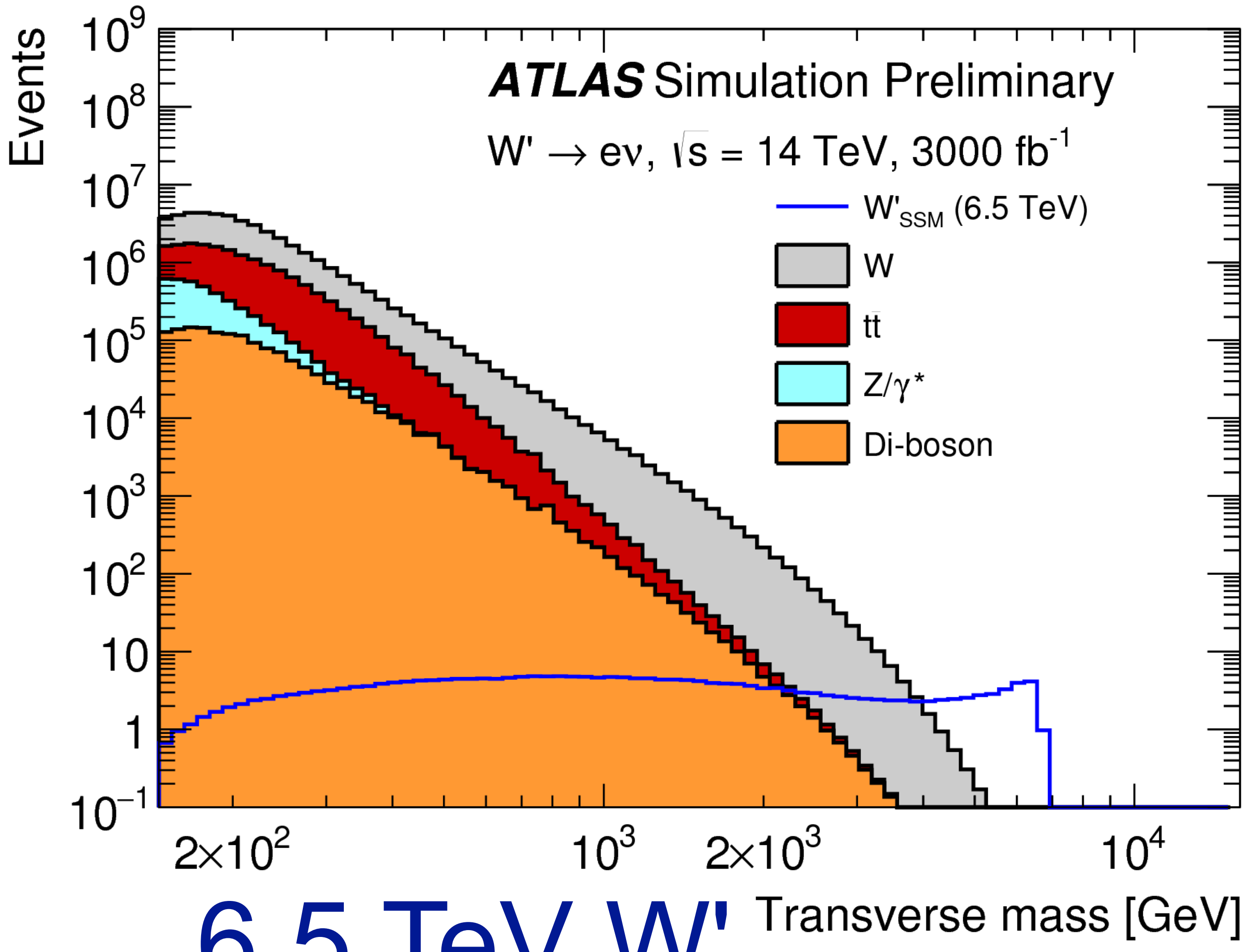


Higgs Self-Coupling

ATLAS-PHYS-PUB-2018-053



~100 publications per year

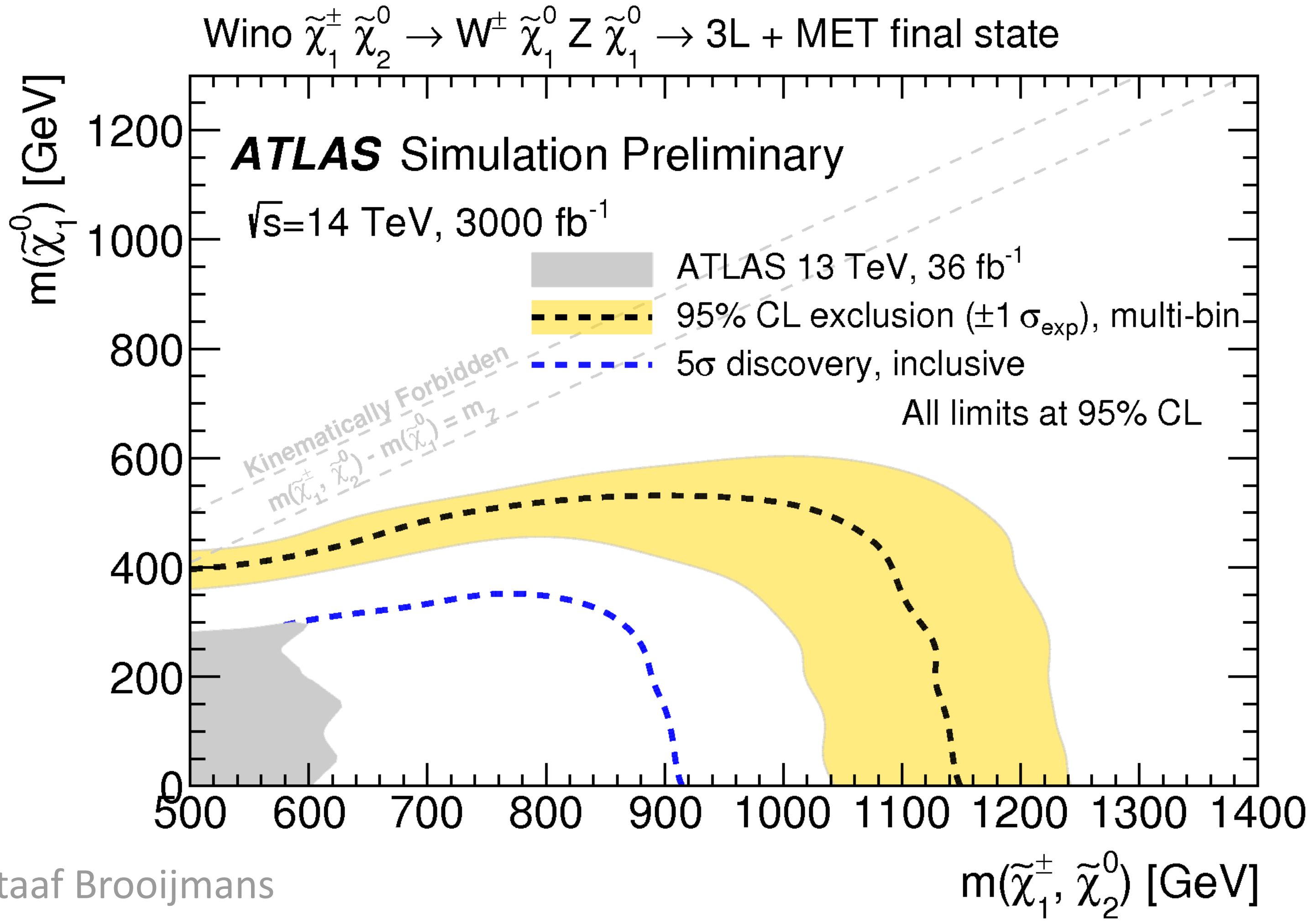


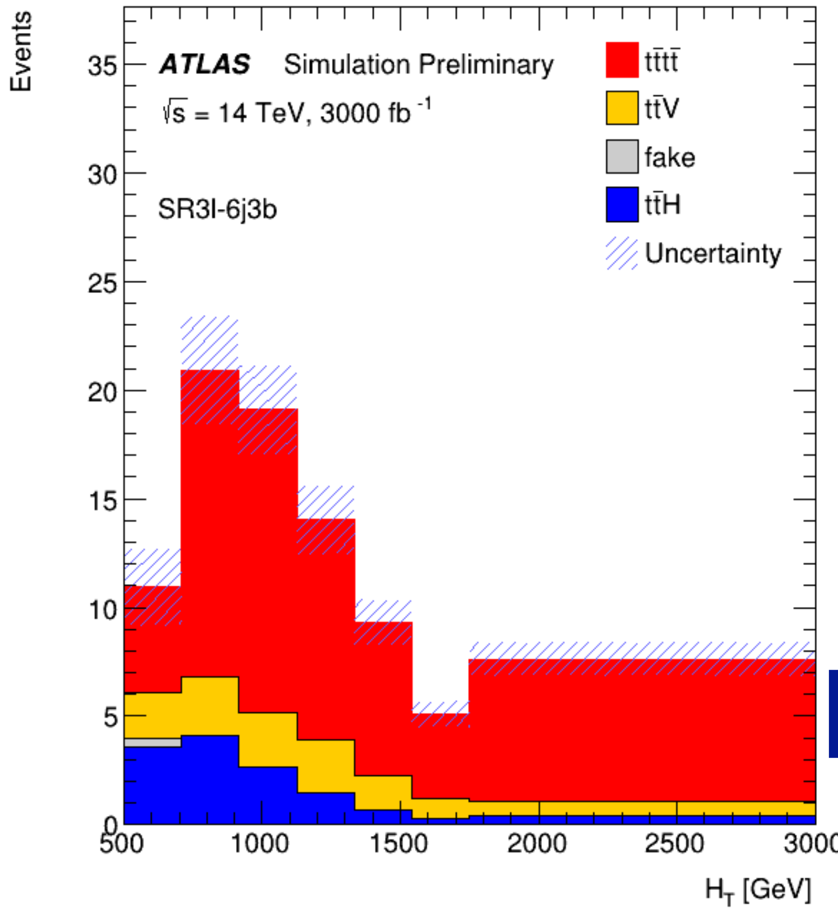
6.5 TeV W'

ATLAS-PHYS-PUB-2018-044

SUSY

ATLAS-PHYS-PUB-2018-048



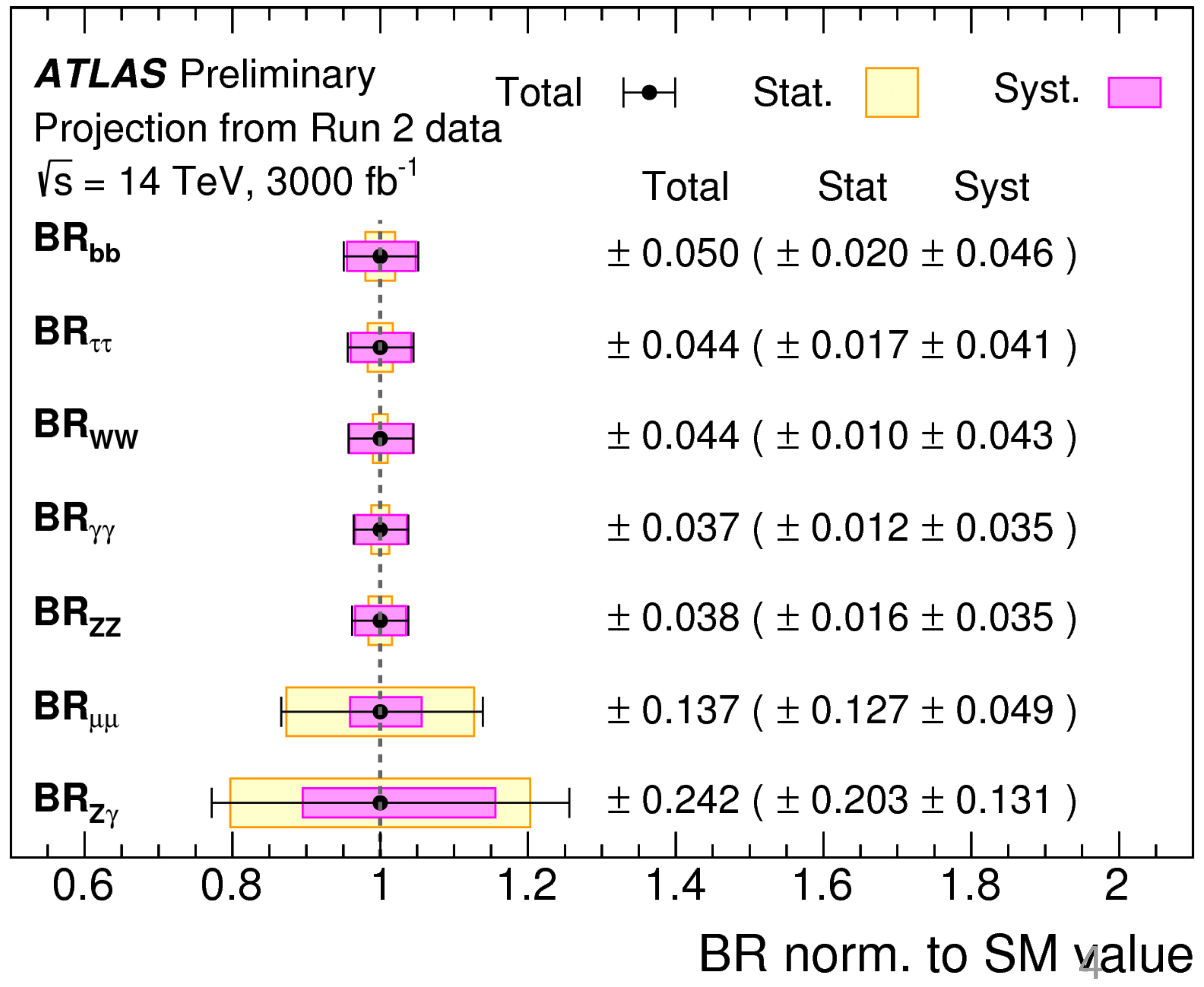


Higgs Production and Decays

ATLAS-PHYS-PUB-2018-054

Measure $t\bar{t}t\bar{t}$ production to ~10%

ATLAS-PHYS-PUB-2018-047



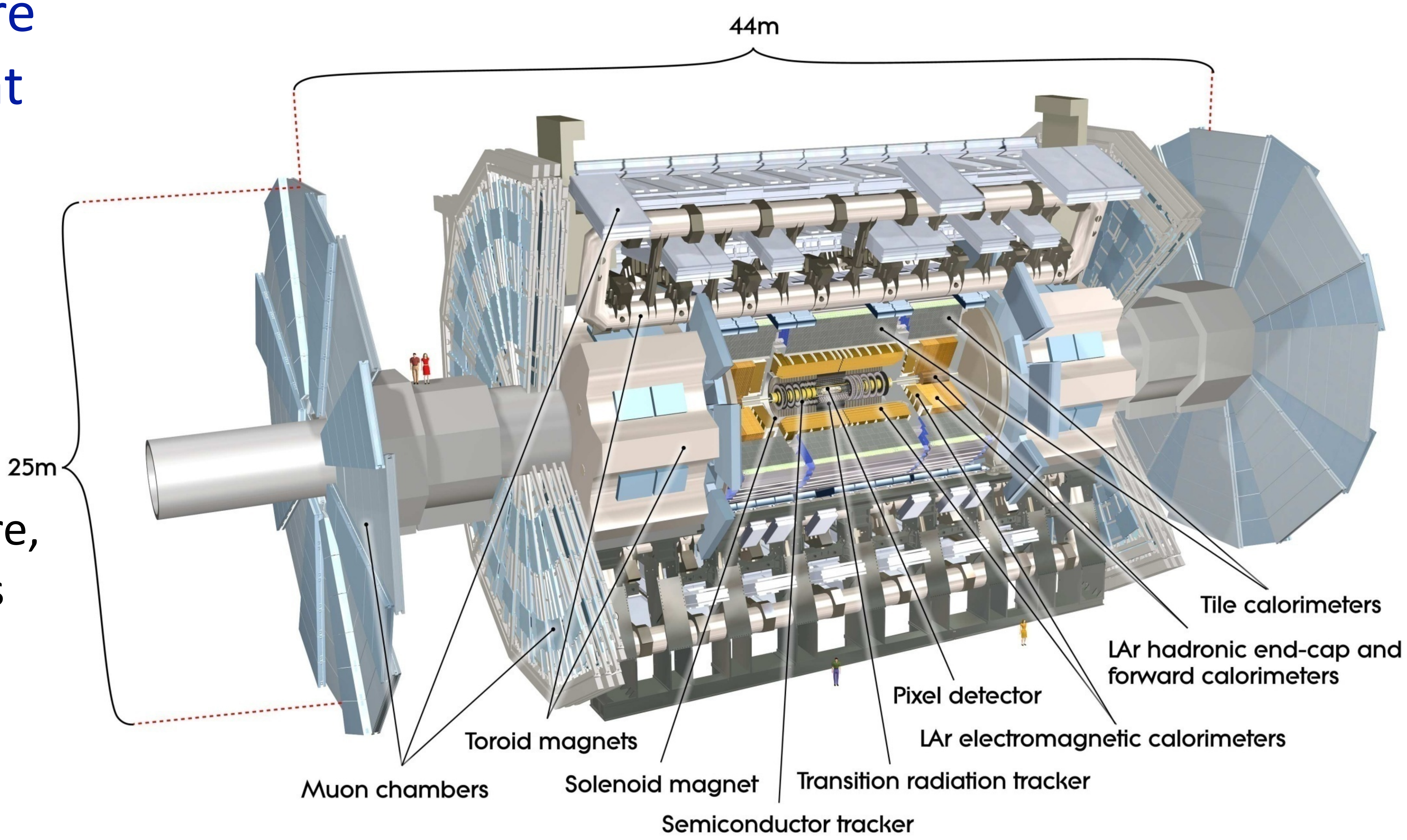
HL-LHC Timeline

<table>
<tr><th colspan="4">2010</th><th colspan="4">2011</th><th colspan="4">2012</th><th colspan="4">2013</th><th colspan="4">2014</th><th colspan="4">2015</th><th colspan="4">2016</th><th colspan="4">2017</th><th colspan="4">2018</th><th colspan="4">2019</th></tr>
<tr><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td></tr>
<tr><td></td><td colspan="11">Run 1: 7-8 TeV, 0.7×10^{34} ($\mu\approx23$), 25 fb^{-1}</td><td colspan="8">LS1</td><td colspan="2"></td><td colspan="14">Run 2: 13 TeV, 2×10^{34} ($\mu\approx55$), 150 fb^{-1}</td><td colspan="4">LS2</td></tr>
<tr><th colspan="4">2020</th><th colspan="4">2021</th><th colspan="4">2022</th><th colspan="4">2023</th><th colspan="4">2024</th><th colspan="4">2025</th><th colspan="4">2026</th><th colspan="4">2027</th><th colspan="4">2028</th><th colspan="4">2029</th></tr>
<tr><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td><td>Q1</td><td>Q2</td><td>Q3</td><td>Q4</td></tr>
<tr><td colspan="4">LS2</td><td></td><td colspan="11">Run 3: 14 TeV, $2\text{-}3\times10^{34}$ ($\mu\approx55\text{-}80$), 300 fb^{-1}</td><td colspan="10">LS3</td><td></td><td colspan="13">Run 4: 14 TeV, $5\text{-}7.5\times10^{34}$ ($\mu\approx140\text{-}200$), 3-4000 fb^{-1}</td></tr>
</table>

- HL-LHC upgrades to be installed during “Long Shutdown 3”, currently planned for 2024-2026
  - LS3 is the milestone that drives the construction completion schedule

The ATLAS HL-LHC Upgrade

- HL-LHC will deliver 3-4 times more luminosity than original design, at 5-7 times instantaneous rate
- To realize full physics potential, ATLAS will
  - Replace the inner detector with a full silicon tracker
  - Replace the trigger system to use more, better information in trigger decisions
  - Increase readout bandwidth
- U.S. participates in all principal elements, bringing often unique expertise in their realization



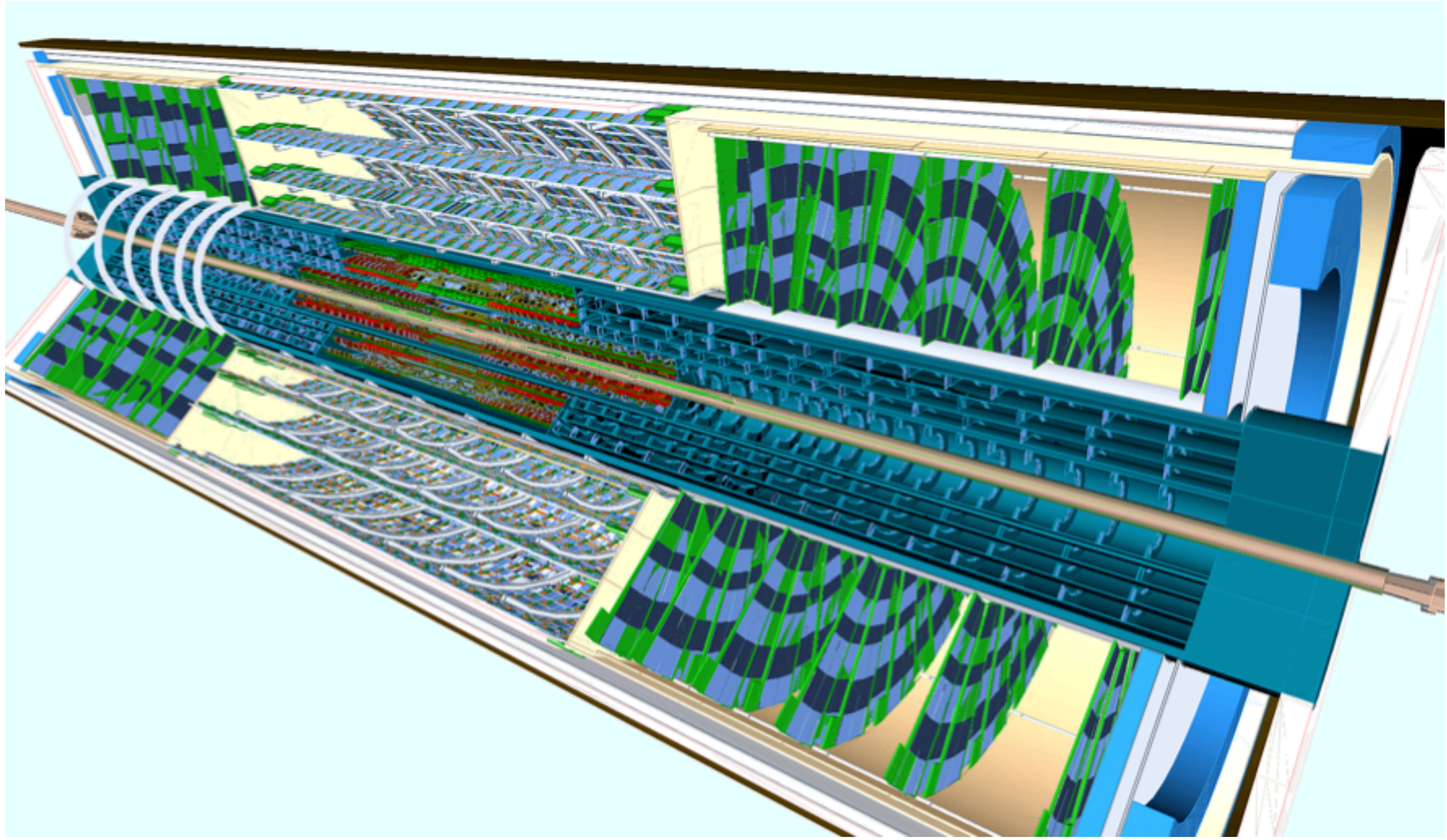
U.S. Involvement in ATLAS

- ATLAS is a large international collaboration
  - ~3000 authors, experiment will have a 40+ year lifetime
  - U.S. is about 20% of collaboration (18.2% “fair share” as of 9/9/2019, compared to 17.1%/18.6% in 2018/2017)
    - Significant influence on processes & decisions, but non-negligible fraction of construction responsibilities of interest to multiple countries
    - Negotiations converged with writing of MoUs (now being signed)
  - U.S. holds ~25% of the Level 1, 2 and 3 leadership positions on the international HL-LHC ATLAS upgrade
    - Reflects the broad and well-recognized expertise in the U.S., and its strong historical engagement in the experiment
  - U.S. contributions to HL-LHC have been carefully crafted to adhere to the funding guidance while maximizing impact
    - Factors considered include physics goals, ATLAS needs, U.S. expertise and historical role, past institutional performance, junior colleague development, etc.

Inner Tracker (ITk)

DOE Scope

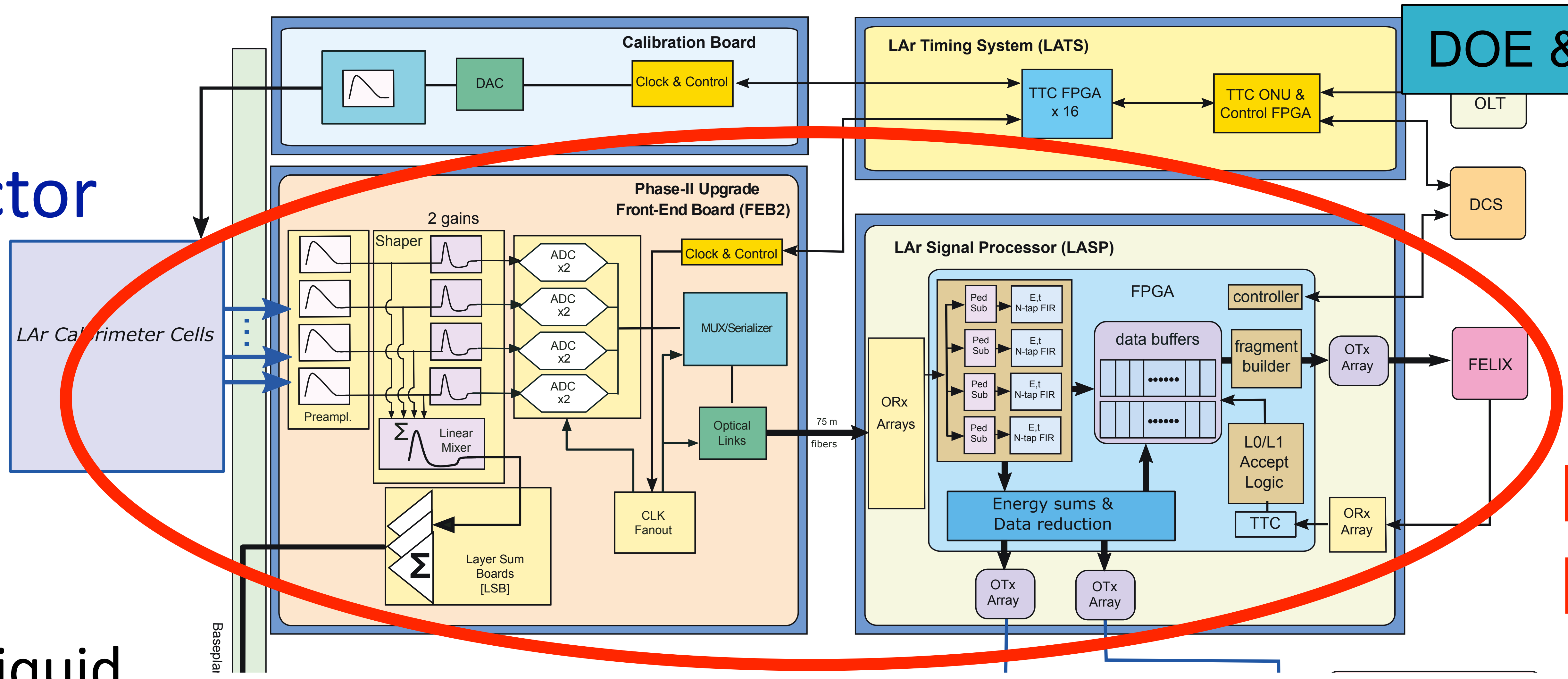
- New all-silicon tracker
  - ~165 m^2 of strips (vs 68 m^2 now)
  - ~13 m^2 of pixels (vs 2 m^2 now)
- U.S. will deliver
  - Half of the barrel strip detector
  - The inner pixel system, i.e. everything within ~15 cm of the beam
  - Most carbon fiber mechanical structures
- Relies on unique U.S. expertise, in particular
  - Complex ASIC design
  - Design and construction of large carbon fiber structures
  - Efficient production lines



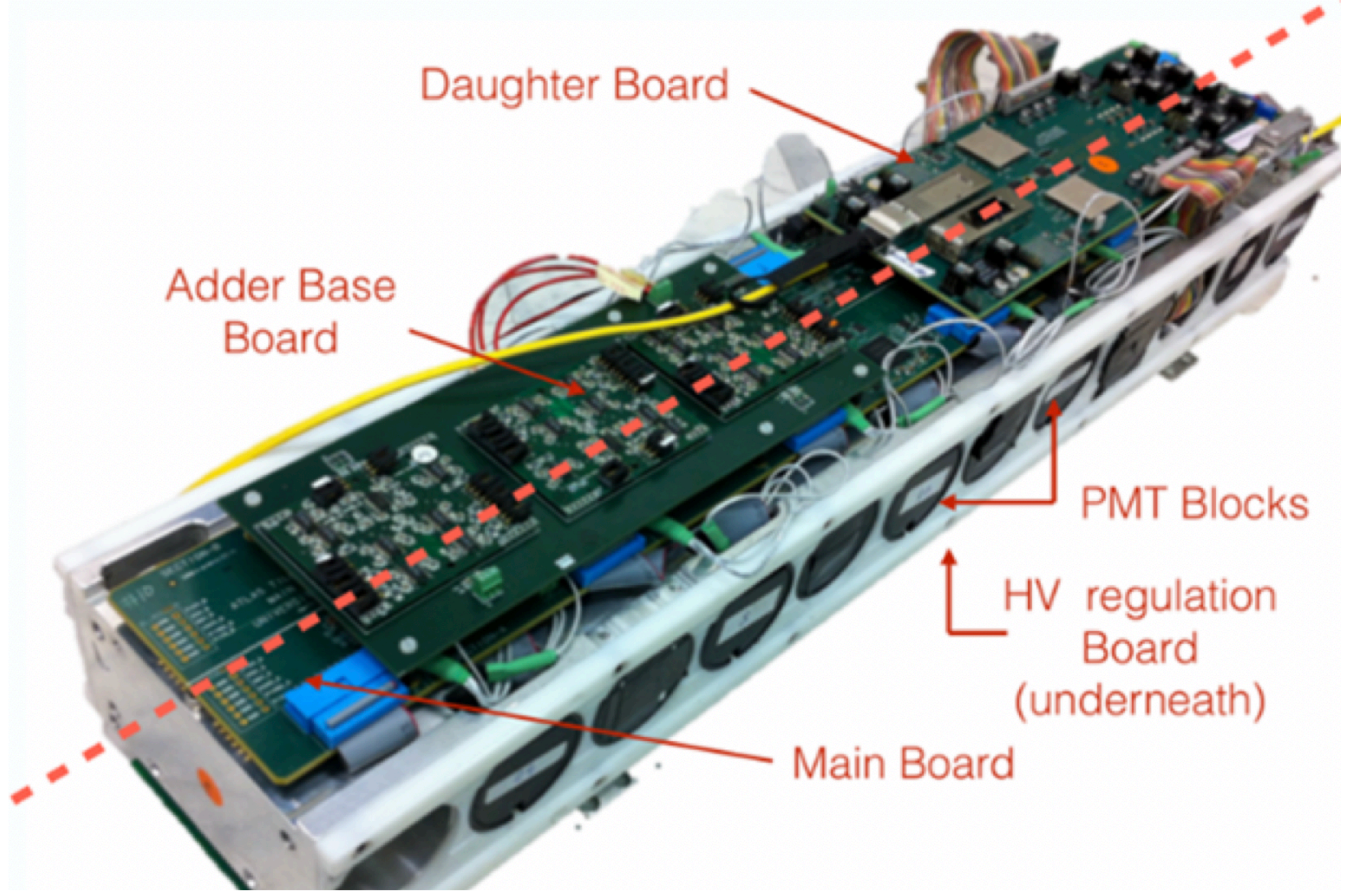
Calorimeters

- Full replacement of calorimeter electronics, both on- and off-detector
  - All data shipped off-detector at bunch crossing rate (40 MHz)
  - Calorimeters themselves are kept
- U.S. will deliver
  - Front-end readout electronics for both liquid Argon and scintillating Tile calorimeters
  - LAr off-detector electronics at the interface to the DAQ system
  - Half of on-detector low voltage power supplies for Tile calorimeter
- Also here unique U.S. expertise
  - Complex ASICs
  - High precision analog electronics

DOE & NSF Scope



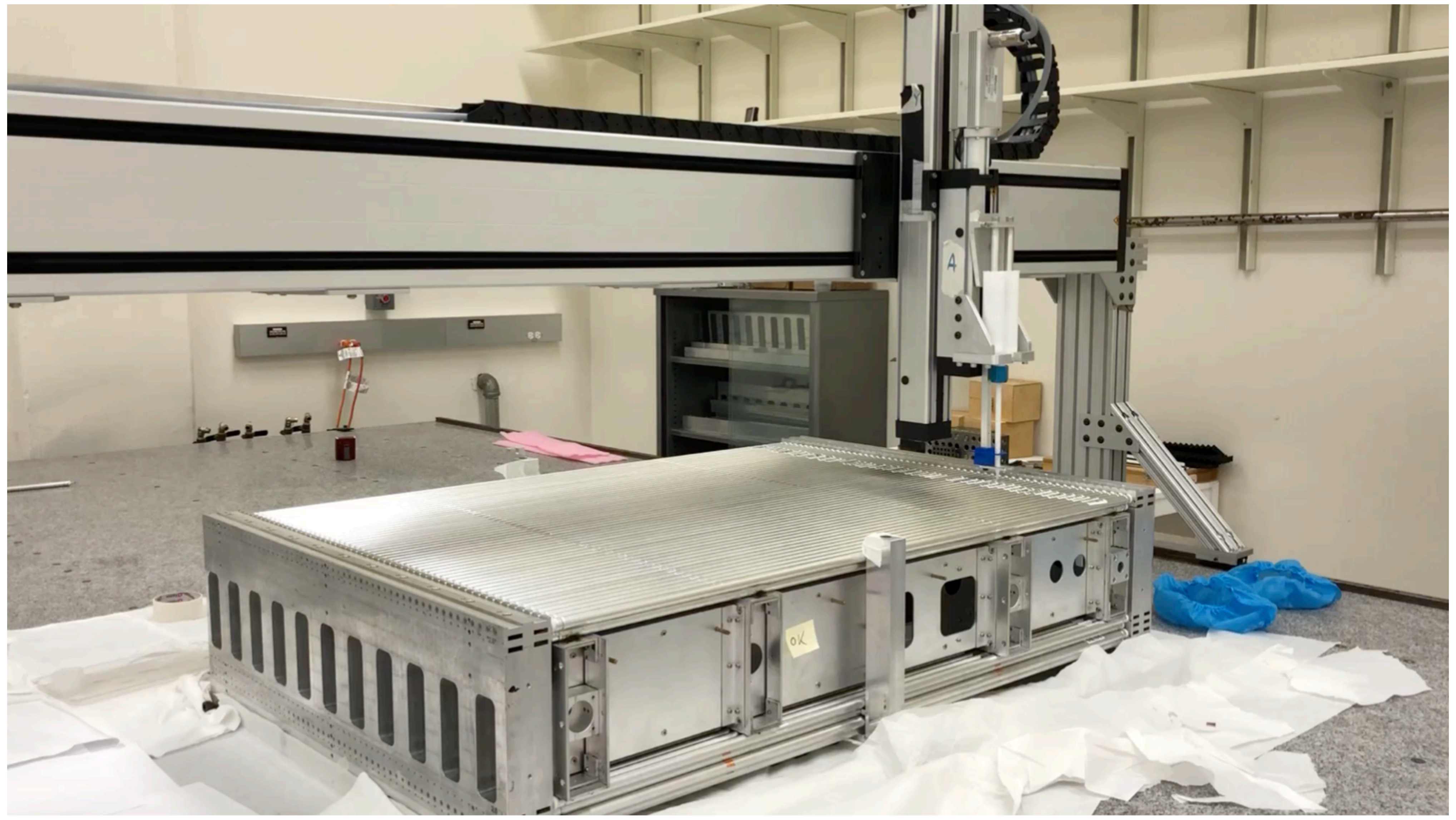
New LAr Electronics



Tile “Drawer” Prototype

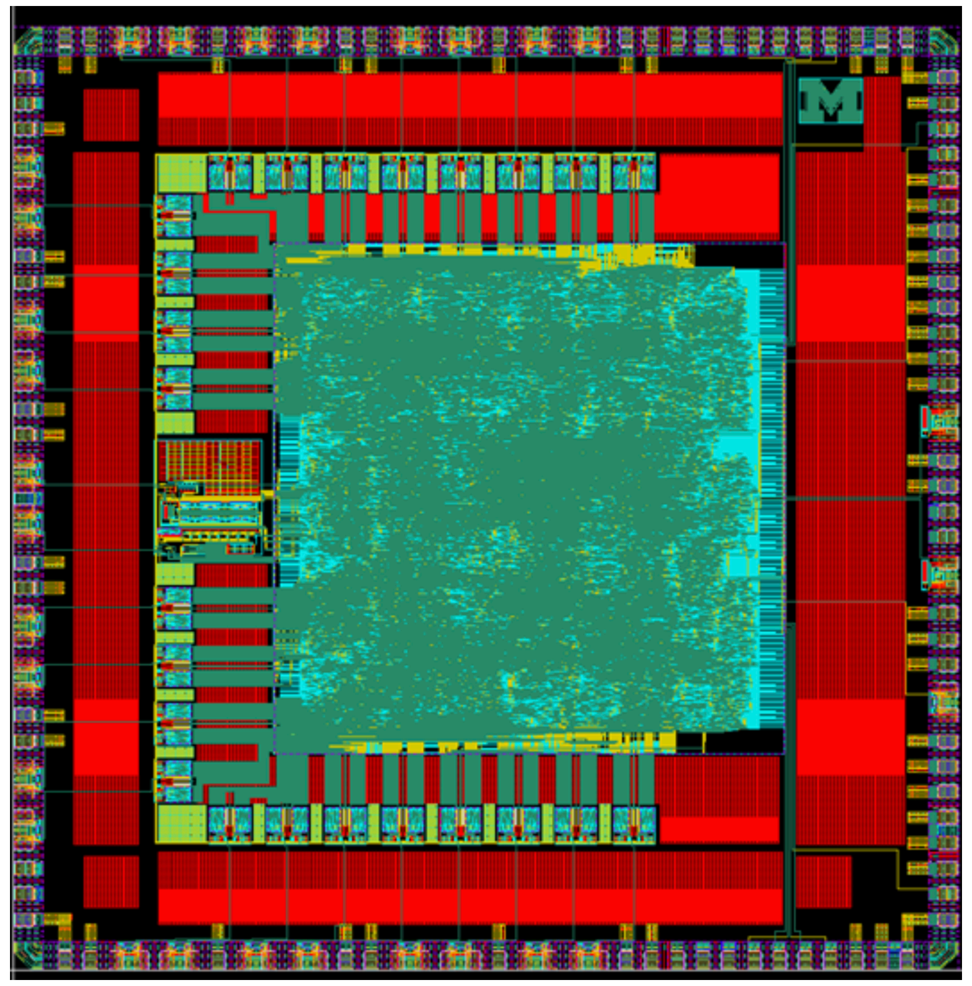
Muon System

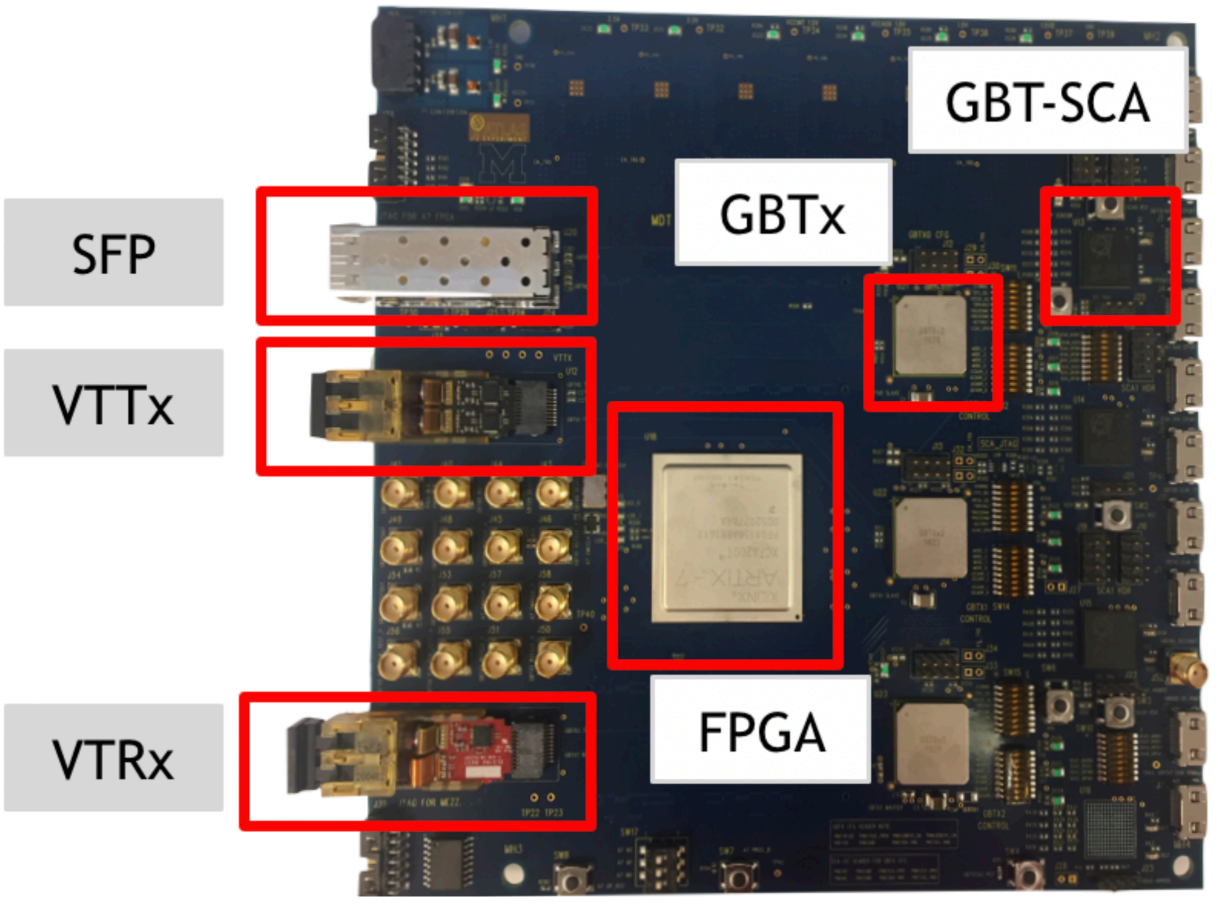
- Full electronics replacement, both on- and off-detector
- Additional chambers to close gaps in coverage
- U.S. will deliver
  - Half of new chambers
  - On- and off-detector electronics
- Relies on U.S. expertise in
  - Chamber construction
  - ASIC design



Chamber Construction Facility

TDC Chip



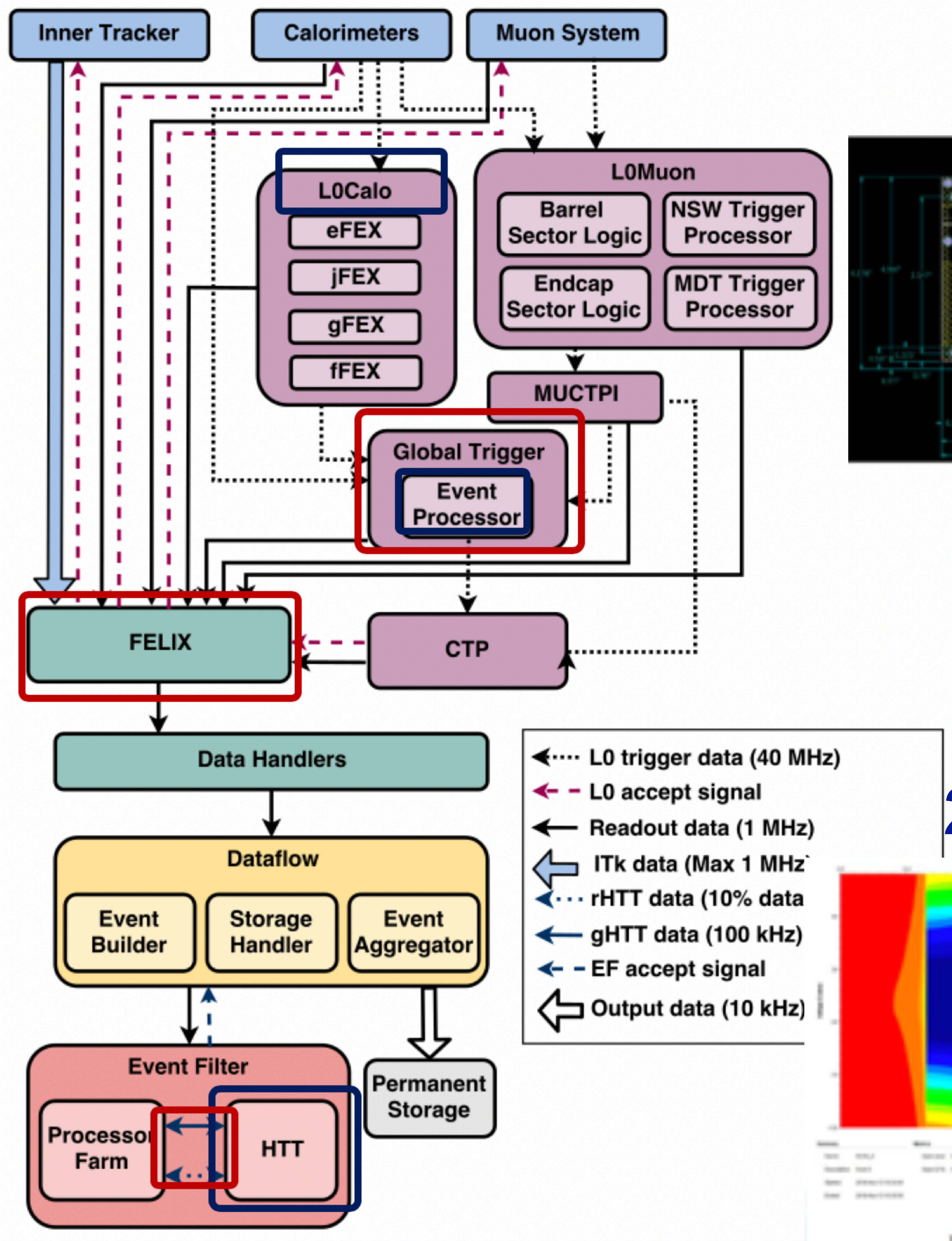


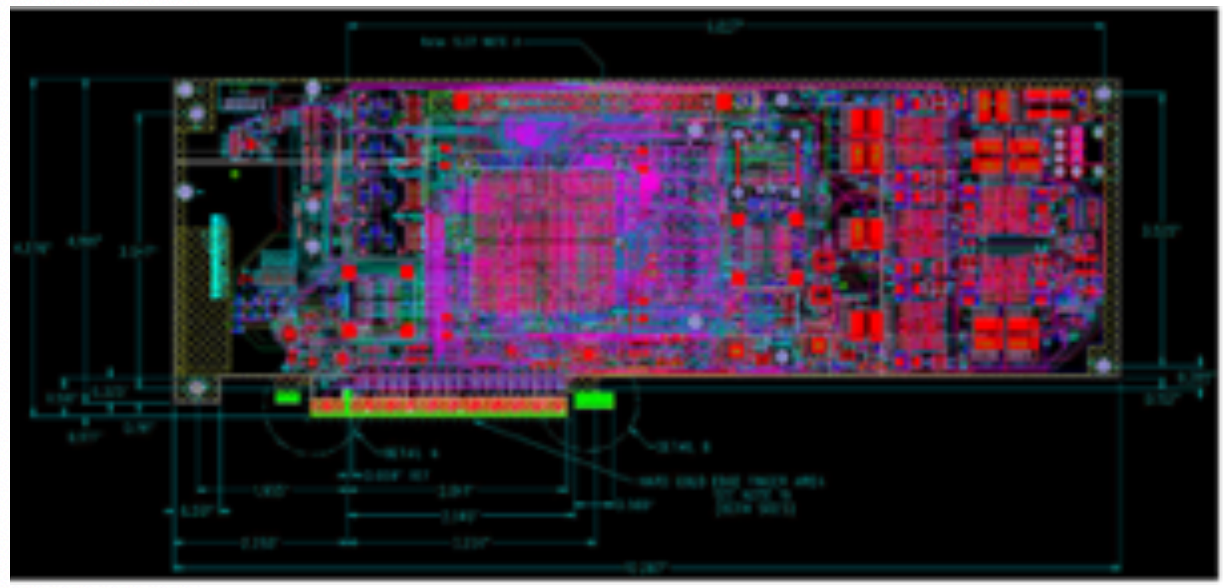
Chamber Service Module

Trigger and Data Acquisition

DOE & NSF Scope

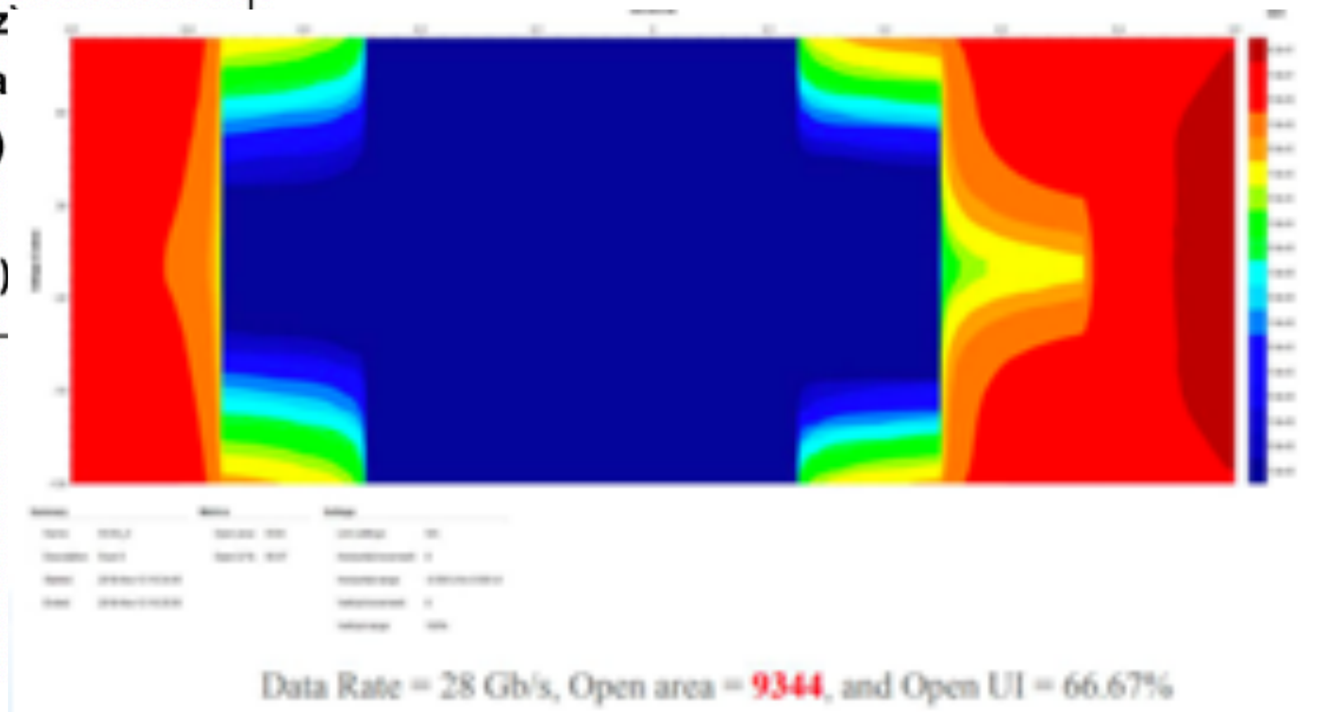
- Big increase in rates and bandwidth:
  - 100 kHz ⇒ 1-4 MHz hardware trigger accept rate
  - 1 kHz ⇒ 10 kHz output to tape
  - Highly interconnected system with many latest generation FPGAs
- U.S. to deliver (hardware and firmware):
  - Hardware Global Trigger Event Processor
  - ~Half of Hardware Track Trigger
  - Detector-to-DAQ interface (FELIX)
- Relies heavily on U.S. expertise with implementation of high end FPGAs
  - And US industrial know-how





Global Module Demonstrator

28 Gbps eye diagram



U.S. ATLAS Organization

- Central project office hosted at Brookhaven National Lab
  - Columbia University is the principal institution for the MREFC, with NSF-focused project office that complements that at BNL
- Project office structure based on experience with original ATLAS construction, Phase-I upgrade, …
  - Experienced team in project management, development and execution
- U.S. ATLAS HL-LHC project team functions in a fully integrated fashion, managing both DOE- and NSF-funded scope

U.S. ATLAS HL-LHC Upgrade Project Office

J. Kotcher (BNL), Project Manager
G. Brooijmans (Columbia), Deputy PM, Project Development
H. Evans (Indiana), Deputy PM, Technical Coordination
M. Tuts (Columbia), NSF Principal Investigator
P. Novakova (BNL), Assistant PM, Project Controls
G. Redlinger (BNL), Risk Manager
J. Hobbs (SBU), Operations Cooperative Agreement PI
L. Stiegler (BNL), ES&H Liaison
C. Gortakowski (BNL), QA/QC Liaison

Budget & Administration:
R. Freedman (BNL), Administrative Assistant
A. Garwood (Columbia), Administrative Assistant
C. Butehorn (BNL), Budget Oversight

Organization to Level 3

- **WBS 6.01** Pixels — P.Grenier (SLAC), J.Metcalfe (ANL) D
  - **6.1.1** Mechanics — J.Love (ANL)
  - **6.1.2** Local Supports — R.Coelho Lopes de Sa (UMASS)
  - **6.1.3** Comm/Power — M.Hance (UCSC)
  - **6.1.4** FE Chip — M.Garcia-Sciveres (LBNL)
  - **6.1.5** Modules — J.Metcalfe (ANL)
  - **6.1.6** Integration — C.Vernieri (SLAC)
- **WBS 6.02** Strips — C.Haber (LBNL), G.Sciolla (Brandeis) D
  - **6.2.1** Stave Cores — J. Ashenfelter (Yale)
  - **6.2.2** Readout Electronics — E. Thomson (Penn)
  - **6.2.3** Hybrid Assembly — *(retired)*
  - **6.2.4** Modules — G. Sciolla (Brandeis)
  - **6.2.5** Stave Assembly — A. Tricoli (BNL)
- **WBS 6.03** Global Mechanics — E.Anderssen (LBNL), M.Oriunno (SLAC) D
  - **6.3.1** Integ. Syst. Test — E.Anderssen (LBNL)
  - **6.3.2** Outer Cyl/Bulkhead — D.Boettcher (LBNL)
  - **6.3.3** Pixel Support Tube — T.Claybaugh (LBNL)
  - **6.3.4** Structural Bulkhead — M.Oriunno (SLAC)
  - **6.3.5** Strip Shells — T.Claybaugh (LBNL)
  - **6.3.6** Infrastructure — E.Anderssen (LBNL)
- **WBS 6.04** Liquid Argon (LAr) — J.Parsons (Columbia), H. Ma (BNL) D
  - **6.4.1** FE Electronics — T.Andeen (UT Austin)
  - **6.4.2** Front End Board 2 — J.Parsons (Columbia)
  - **6.4.3** BE Electronics — A.Haas (NYU)
  - **6.4.4** System Integration — H.Xu (BNL)
  - **6.4.5** PA Shaper — H.Ma (BNL)
- **WBS 6.05** Tile — M.Oreglia (Chicago), D.Miller (Chicago) D
  - **6.5.1** Main Board — M.Oreglia (Chicago)
  - **6.5.3** ELMB MB — J.Huston (MSU)
  - **6.5.4** LVPS — H.Hadavand (UT Arlington)
- **WBS 6.06** Muon — T.Schwarz (Michigan), A.Taffard (UCI) D
  - **6.6.1** sMDT — R.Schwienhorst (MSU)
  - **6.6.3** TDC — J.Zhu (Michigan)
  - **6.6.4** CSM — T.Schwarz (Michigan)
  - **6.6.5** L0MDT — A.Taffard (UCI)
- **WBS 6.07 & 6.08** TDAQ — S. Majewski (Oregon), J. Zhang (ANL) D
  - **6.7.1** Global Common Module — M.Begel (BNL)
  - **6.7.3** FELIX — G.Redlinger (BNL)
  - **6.7.4** Readout Interface Firmware — A.Paramonov (ANL)
  - **6.8.1** L0Calo Fiber Optic Plant — D. Hayden (MSU)
  - **6.8.2** Hardware Track Trigger — E. Lipeles (Penn), J. Adelman (NIU) D
  - **6.8.3** Global Event Processor — W. Fisher (MSU)
- **WBS 6.09** Common Projects — C.Butehorn (BNL)
- **WBS 6.10** Project Mgmt — J.Kotcher (BNL), M.Tuts (Columbia)
- **WBS 6.11** Install & Commiss — H.Evans (Indiana)

39 Institutions (incl. 4 national labs)

Blue = DOE
Orange = NSF

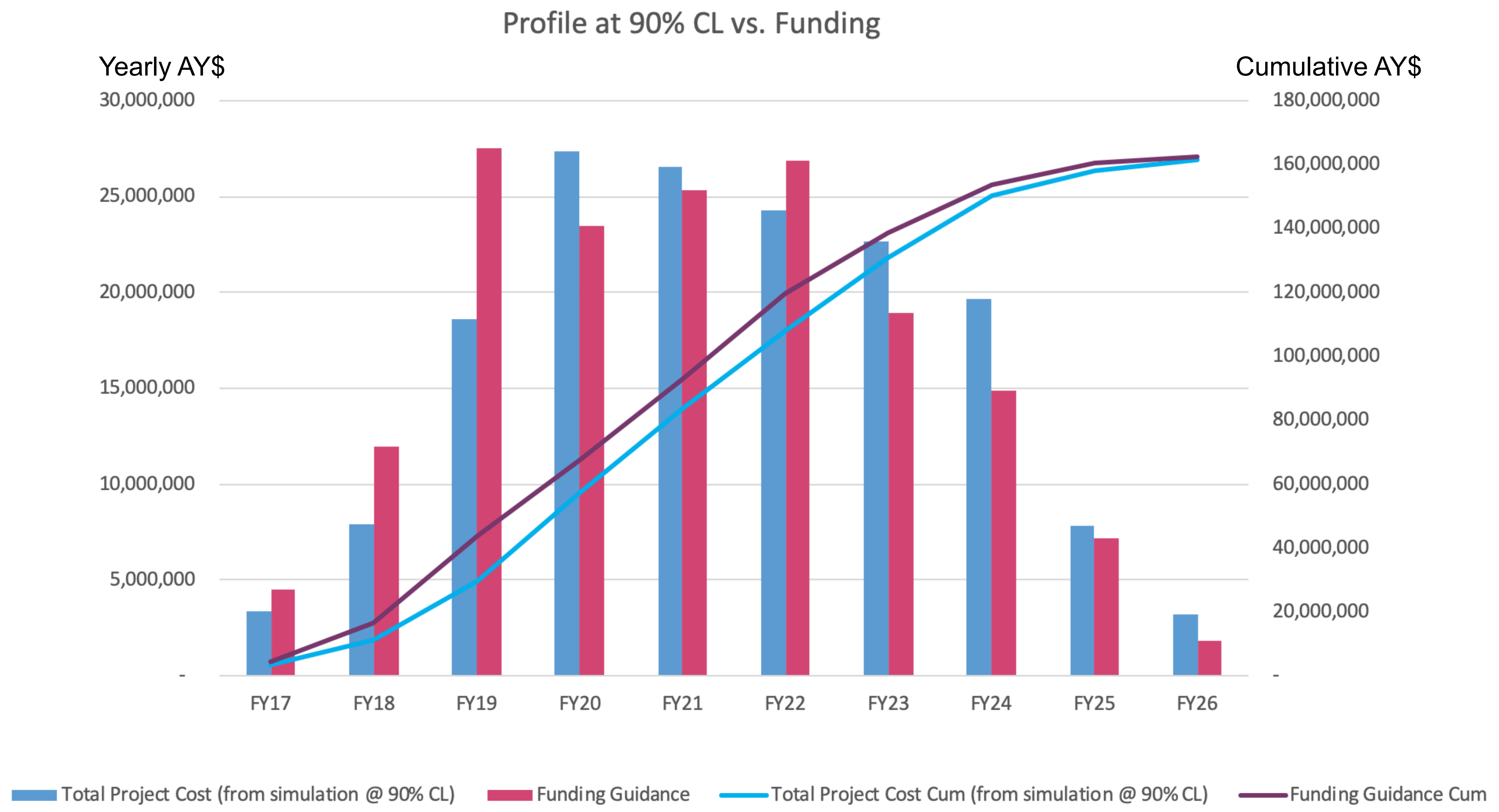
U.S. Context

- DOE scope (ITk and Trigger and Data Acquisition) funding guidance is $163M (incl. $10M for I&C)
  - Critical Decision 0 was approved April 13, 2016
  - Critical Decision 1 received ESAAB approval September 23, 2018
  - IPR and CD-3a review July 9-11, 2019, CD-3a received ESAAB approval October 11, 2019
  - Planning for CD-2/3 in December 2020
- NSF scope (trigger improvements, including sending all calorimeter data off-detector), funded through MREFC to start April 2020 at $75M (plus $11M in R&D funds 2016-2020)
  - (MREFC request is $150M shared between ATLAS and CMS)
  - Preliminary Design Review January 16-18, 2018
  - NSB approval to enter Final Design Phase given July 18, 2018
  - Final Design Review held September 11-13, 2019
  - To be presented to NSB for project start at February 4-5 NSB meeting
- Overall a ~$250M project, all cutting-edge technology

Risk and Contingency

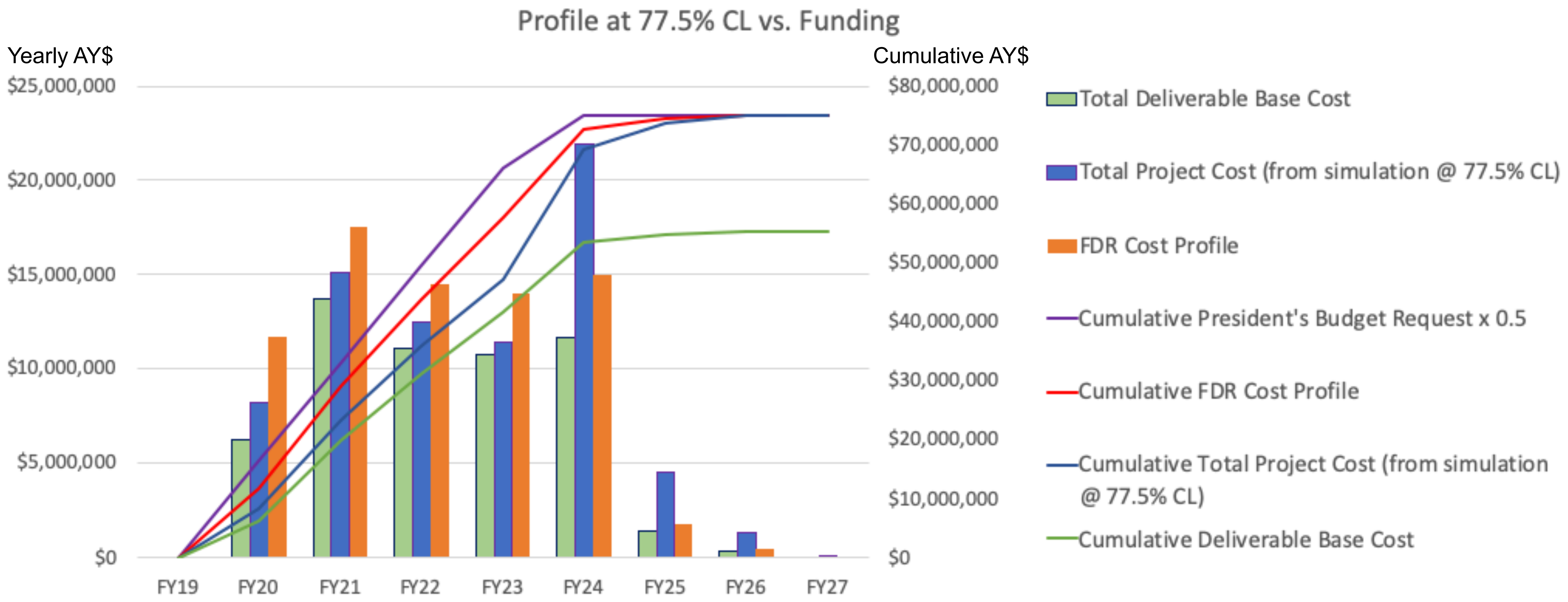
- Project is generally in the “late prototype” phase
  - *Technological* risk has been largely eliminated, i.e. we know our technology choices will allow us to meet our requirements/specifications
  - But the devil is in the details: still lots of room for things to need additional time and money (e.g. additional ASIC prototyping round, production QC taking more effort than expected, …)
- And there are some large “global” risks
  - Escalation rate
  - Loss of scientific (“uncosted”) effort due to research program funding tightness
    - Crucial to our mission: students and postdocs learn to develop and build detectors, work with cutting-edge technology
    - Represent ~35%/20% of “technical” labor in DOE/NSF scope
  - Commodity volatility
  - CERN delay
- At this time, we have ~37% contingency on the cost-to-go
  - Prudent number, but not overly so, given experience from original construction and Phase-I upgrade

Project Funding, DOE Scope



- Funding guidance (red) matches project cost (blue) profile well
  - Cost profile obtained from base cost + simulations to determine contingency profile
  - ~$10M "buffer" in FY20-22 corresponds to ~6 months of execution

Project Funding, NSF Scope



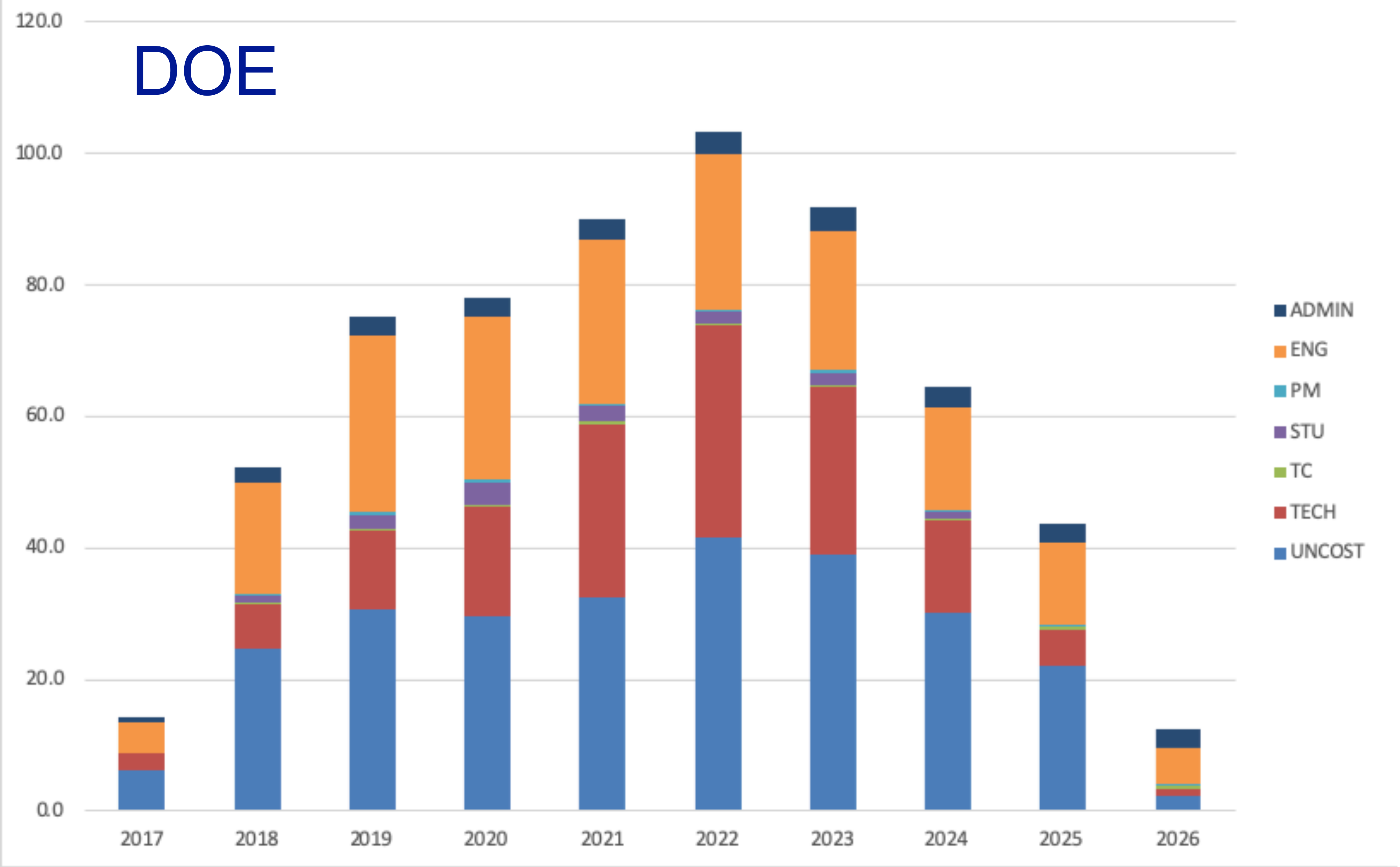
- "FDR Cost Profile" is our proposed funding profile, initially slightly below 50% of the President's Budget Request
  - MREFC is shared with CMS, which needs a little more than half early on
  - Also here some buffer between the funding and simulated profiles

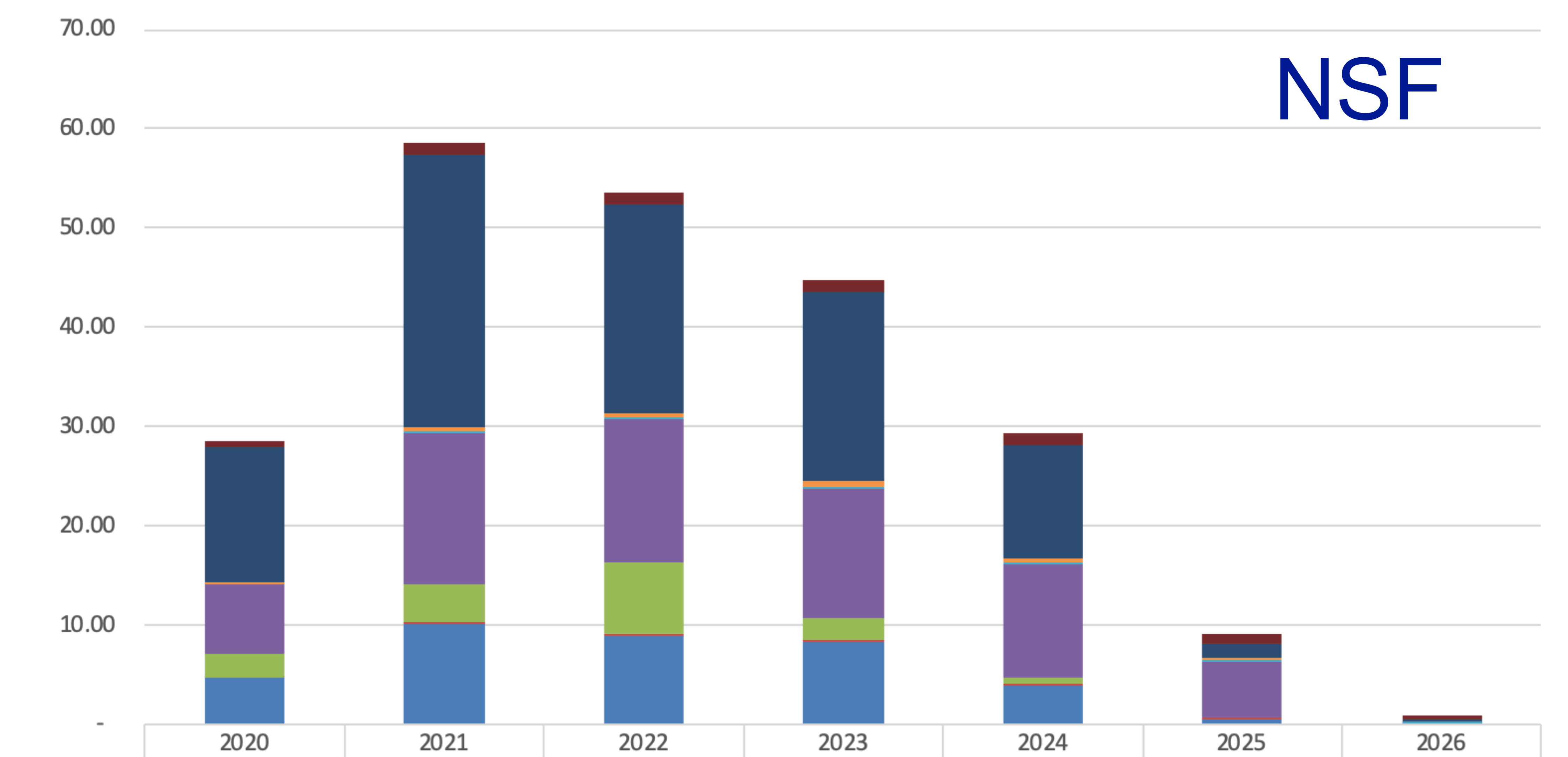
Closing

- U.S. ATLAS HL-LHC project exploits U.S. expertise to make key contributions to ATLAS detector upgrade
  - $250M project, all high tech
  - Fantastic opportunity for young people to work on cutting-edge technology
  - Huge science output
- Project is on strong footing, finishing prototyping phase
  - NSF Final Design Review passed, NSB approval for construction expected in February 2020
  - DOE CD-2/3 planned for late CY 2020
    - CD-3a in hand for long-lead items
- Project schedule driven by LHC Long Shutdown 3
  - Construction will run 2020-2025, followed by installation and commissioning

Supplemental Material

Labor Profiles





	2020	2021	2022	2023	2024	2025	2026
ADMIN	0.61	1.20	1.20	1.20	1.20	1.10	0.49
ENG	13.62	27.41	20.97	19.16	11.42	1.38	0.15
PI	0.25	0.50	0.50	0.50	0.50	0.25	
PM	0.08	0.17	0.17	0.17	0.17	0.17	0.08
SCI	6.91	15.18	14.34	13.16	11.47	5.63	0.05
STU	2.40	3.91	7.26	2.08	0.51		
TC	0.08	0.17	0.17	0.17	0.17	0.17	0.08
TECH	4.69	10.11	8.98	8.38	3.99	0.47	0.07

DOE Cost Table

WBS	FY16+17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	Grand Total
Deliverables Only											
6.01 - Pixel	658	1,145	4,091	5,907	7,062	4,815	2,338	1,482	230	-	27,730
6.02 - Strips	1,587	3,789	5,481	6,789	6,252	5,824	4,983	2,925	789	-	38,419
6.03 - Global Mechanics	541	890	2,140	4,501	1,637	860	198	-	-	-	10,768
6.04 - LAr	219	376	957	643	1,147	889	1,157	508	248	-	6,145
6.07 - Data Handling/DAQ	64	277	1,055	1,507	1,866	2,371	2,587	2,138	-	-	11,866
6.09 - Common Costs		85	85	85	951	951	951	951	-	-	4,060
6.10 - Project Office	313	1,317	1,615	1,777	1,812	1,879	1,946	1,993	1,955	2,013	16,619
Total Deliverable Base Cost	**3,382**	**7,879**	**15,424**	**21,210**	**20,727**	**17,590**	**14,161**	**9,998**	**3,222**	**2,013**	**115,607**
Total Deliverable Base CTG	**-**	**-**	**8,814**	**21,210**	**20,727**	**17,590**	**14,161**	**9,998**	**3,222**	**2,013**	**97,735**
Risk-Based Cont. (MC)	*-*	*-*	*606*	*3,647*	*3,547*	*2,898*	*3,206*	*3,724*	*1,392*	*28*	*19,048*
Maturity-Based Cont. (MC)	*-*	*-*	*2,013*	*2,564*	*2,134*	*3,380*	*3,595*	*3,698*	*149*	*-*	*17,532*
Total MC Cont.	*-*	*-*	*2,619*	*6,211*	*5,681*	*6,277*	*6,800*	*7,422*	*1,541*	*28*	***36,580***
PM Cont.	**-**	**-**	**5,000**	**9,500**	**9,200**	**8,500**	**3,000**	**1,300**	**400**	**8**	**36,908**
Fractional Cont. on CTG	-	-	0.567	0.448	0.444	0.483	0.212	0.130	0.124	0.004	0.378
Total Deliverable Cost	**3,382**	**7,879**	**20,424**	**30,710**	**29,927**	**26,090**	**17,161**	**11,298**	**3,622**	**2,021**	**152,515**
DOE Guidance (no I&C)	4,515	12,000	27,500	23,460	25,040	25,910	17,200	12,400	3,890	600	152,515
Guidance + Carryover	4,515	13,133	32,754	35,790	30,120	26,102	17,213	12,452	5,044	2,021	
Balance/Carryover	**1,133**	**5,254**	**12,330**	**5,080**	**192**	**13**	**52**	**1,154**	**1,421**	**0**	
TPC: Deliverables + I&C											
I&C Base Cost	-	-	-	-	307	979	1,590	2,324	3,107	1,139	9,447
I&C Cont.	-	-	-	-	3	11	110	176	193	61	553
Total I&C Cost					**310**	**990**	**1,700**	**2,500**	**3,300**	**1,200**	**10,000**
Total Deliverable Cost	**3,382**	**7,879**	**20,424**	**30,710**	**29,927**	**26,090**	**17,161**	**11,298**	**3,622**	**2,021**	**152,515**
Total Project Cost	**3,382**	**7,879**	**20,424**	**30,710**	**30,234**	**27,069**	**18,751**	**13,622**	**6,729**	**3,160**	**162,515**

NSF Cost Table

All Costs in k$	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	Total
6.4 LAr	$1,080	$4,985	$3,785	$5,102	$3,540	$325	$44	$0	$18,861
6.5 Tile	$818	$2,255	$1,051	$368	$0	$0	$0	$0	$4,493
6.6 Muon	$2,455	$3,483	$3,256	$2,130	$369	$0	$0	$0	$11,693
6.8 Trigger	$841	$1,584	$1,839	$1,940	$6,545	$1	$0	$0	$12,750
Total Deliverable Base Cost	**$5,194**	**$12,306**	**$9,931**	**$9,541**	**$10,454**	**$327**	**$44**		**$47,797**
6.9 Common Costs	$310	$103	$103	$103	$103	$207	$0	$0	$930
6.10 PMO	$751	$1,277	$1,075	$1,105	$1,084	$856	$337	$0	$6,484
Total Base Cost	**$6,255**	**$13,686**	**$11,109**	**$10,749**	**$11,641**	**$1,389**	**$381**		**$55,211**
Total Project Cost (from simulation @ ~77.5% CL)	$8,204	$15,124	$12,453	$11,441	$21,937	$4,506	$1,322	$12	**$75,000**
Yearly Contingency (from simulation @ ~77.5% CL)	$1,949	$1,438	$1,344	$692	$10,296	$3,117	$941	$12	**$19,789**
FDR Cost Profile	$11,700	$17,500	$14,500	$14,000	$15,000	$1,800	$500	$0	**$75,000**
Available Yearly Contingency - FDR Cost Profile	$5,445	$3,814	$3,391	$3,251	$3,359	$411	$119	$0	**$19,789**
Yearly fractional contingency	87%	28%	31%	30%	29%	30%	31%		