HL-LHC Upgrades

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Outline

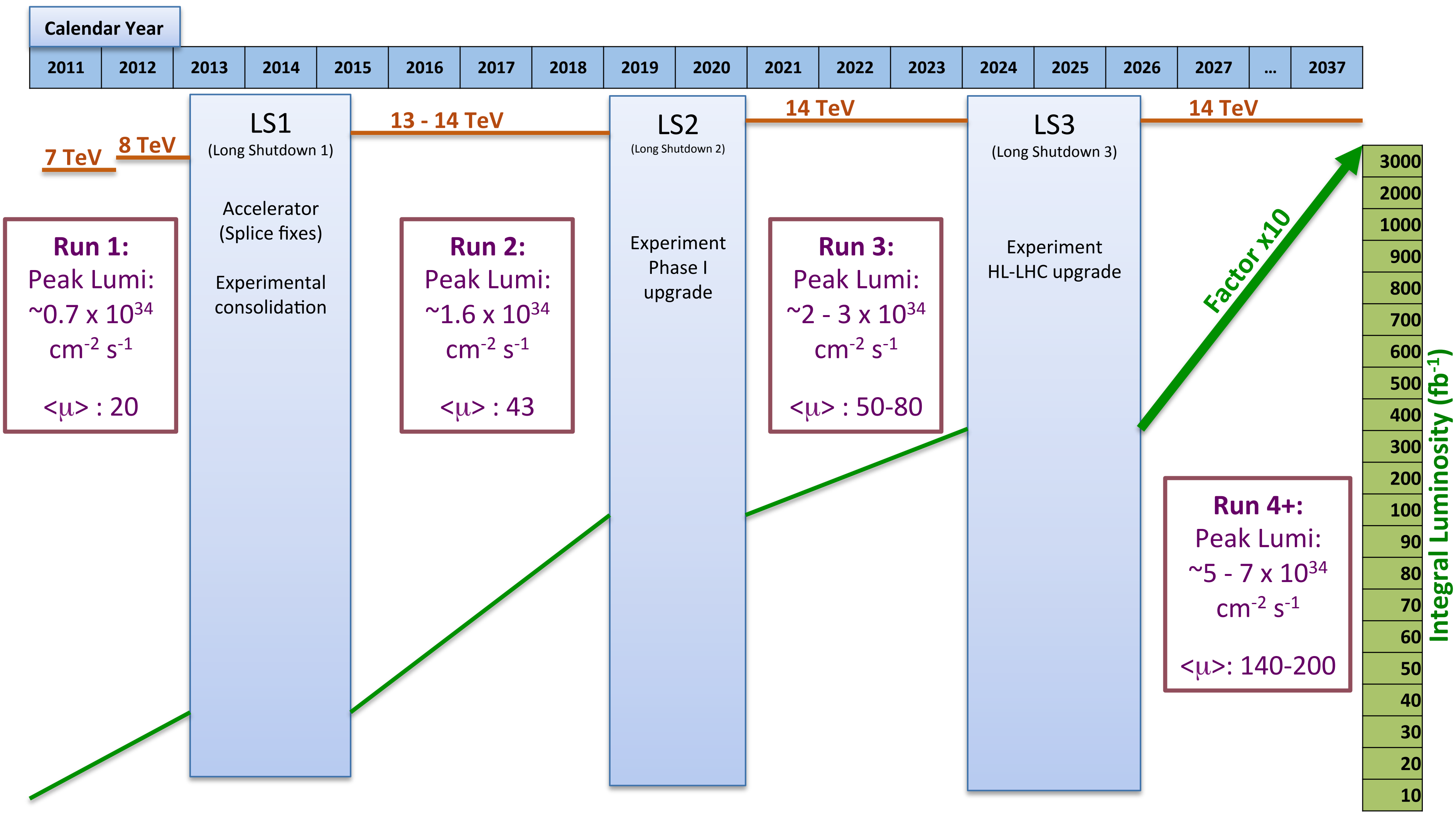
❖ There are three distinct parts to my presentation:

- The CERN HL-LHC approval process
- The International ATLAS Collaboration HL-LHC Activities
- HL-LHC preparations within the U.S. ATLAS Community

The Global Strategy

- The European Strategy in Particle Physics concluded in its 2013 report:
  - The discovery of the Higgs boson is the start of a major program of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this program. **Europe's top priority should be the exploitation of the full potential of the LHC**, including the high luminosity upgrade of the machine and the detectors with a view to collecting ten times more data than in the initial design, by around 2030.
- The U.S. P5 process concluded that:
  - [Recommendation 10]: Complete the LHC Phase I upgrades and continue the strong collaboration in the LHC with Phase II (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS & CMS). **The LHC upgrades constitute our highest-priority near-term project**.
  - Strongly endorsed by NSF MPS sub-committee (chair: YK Kim) for MREFC funding.
  - The HL-LHC upgrades will allow us to address three of the five science drivers of the field, as identified by P5:
    - ✓ Use the Higgs boson as a new tool for discovery
    - ✓ Identify the new physics of dark matter
    - ✓ Explore the unknown: new particles, interactions, and physics principles.

The HL-LHC Plan



The Experiment Upgrade Approval Process

❖ The CERN management, in coordination with the Resource Review Board (RRB), has identified a four-step HL-LHC approval and verification process:

1) **The overall scope and cost for the entire upgrade program for each experiment will be defined,** with the possibility to maintain different options which may depend on technical issues and/or on funding availability.

2) **The detailed technical design reports for the various subsystems will be reviewed.** These TDRs will naturally come at different times depending on the maturity of the projects, and will be reviewed individually, with the requirement that each fits in the overall approved plan for scope and cost (Project Baseline)

3) **The final design and construction readiness of the major detector components will be reviewed.** As in the second step, different sub-systems, and in some cases also different elements of the subsystems, will be ready at different times, and will be reviewed accordingly, with the requirement that they are compatible with the overall construction and installation plan (Start of Construction).

4) As sub-systems are coming together in the experiment, **an operation readiness review should be held** to evaluate the capability of the completed detectors to provide the expected performance and mark the end of the Phase II upgrade construction project. (Project Completion).

Upgrade Approval Process (2)

- The process has been designed to enable the Experiments, together with the Funding Agencies and CERN, to each fulfill their responsibilities in the approval process in a timely way.
- In preparation for Step 1, the ATLAS and CMS experiment were asked to present their plans, including the impact on physics for three possible funding scenarios:
  - 200, 235 and 275 MCHF in units of "CORE COST".
  - The experiments were also asked to submit a preliminary money matrix specifying the potential available funding from various FAs.
- In response to this request, both ATLAS and CMS have put together a "scoping document" detailing the upgrade option for each scenario, the physics impact and the preliminary "money matrix".
  - This was reviewed by the LHC Experiments Committee (LHCC, chaired by F. Forti) and by the Upgrade Cost Group (UCG, chaired by S. Smith), and their conclusions reported to Resource Review Board (RRB) (10/15)
  - ATLAS Report: https://cds.cern.ch/record/2055248
  - CMS Report: https://cds.cern.ch/record/2055167

Summary of LHCC/UCG Findings:

(https://indico.cern.ch/event/407749/)

- Performance:
  - "For both experiments, the Reference Scenario [275 MCHF] provides performant detectors capable of addressing the physics at HL-LHC."
  - "In the Intermediate Scenario [235 MCHF], the nominal performance is only moderately deteriorated."
  - "The limitations of the Low Scenario [200 MCHF] are very apparent, offering significantly worse detector capabilities."
- Cost:
  - "Costing has been presented in great detail, assigning a quality flag to each estimate to define the level of uncertainty."
  - "The funding outlook represented in the money-matrix is guardedly optimistic, with substantive and encouraging interactions with FAs."
- General:
  - "Both experiments have attained a level of preparation and understanding that meet, and in some areas exceed, requirements for Step 1 approval."
  - **"The ATLAS and CMS Phase II upgrade projects are ready to proceed to Step 2 [TDR] that will establish a baseline cost and schedule for construction."**

The RRB Conclusions

Based on the LHCC and UCG findings and the subsequent endorsement by the CERN Management, the following statement was endorsed by the RRB :

"The RRB considers the Step 1 of the approval process for the Phase II Upgrades for the ATLAS and CMS experiments ***successfully completed****.*

A ***scale of funding*** *between the full funding and the intermediate scenario seems to meet the performance requirements.*

The CERN Management, supported by the recommendations of the LHCC and the UCG, deems as realistic the availability of prospective funds contained in the preliminary "Money Matrices" submitted by the experiments.

The experiments are therefore encouraged to proceed to the next step of the Phase II upgrades, as described in the document CERN-LHCC-2015-007. The LHCC and the UCG as well as the Management will regularly update the RRB on progress of the process."

International ATLAS Planning for HL-LHC

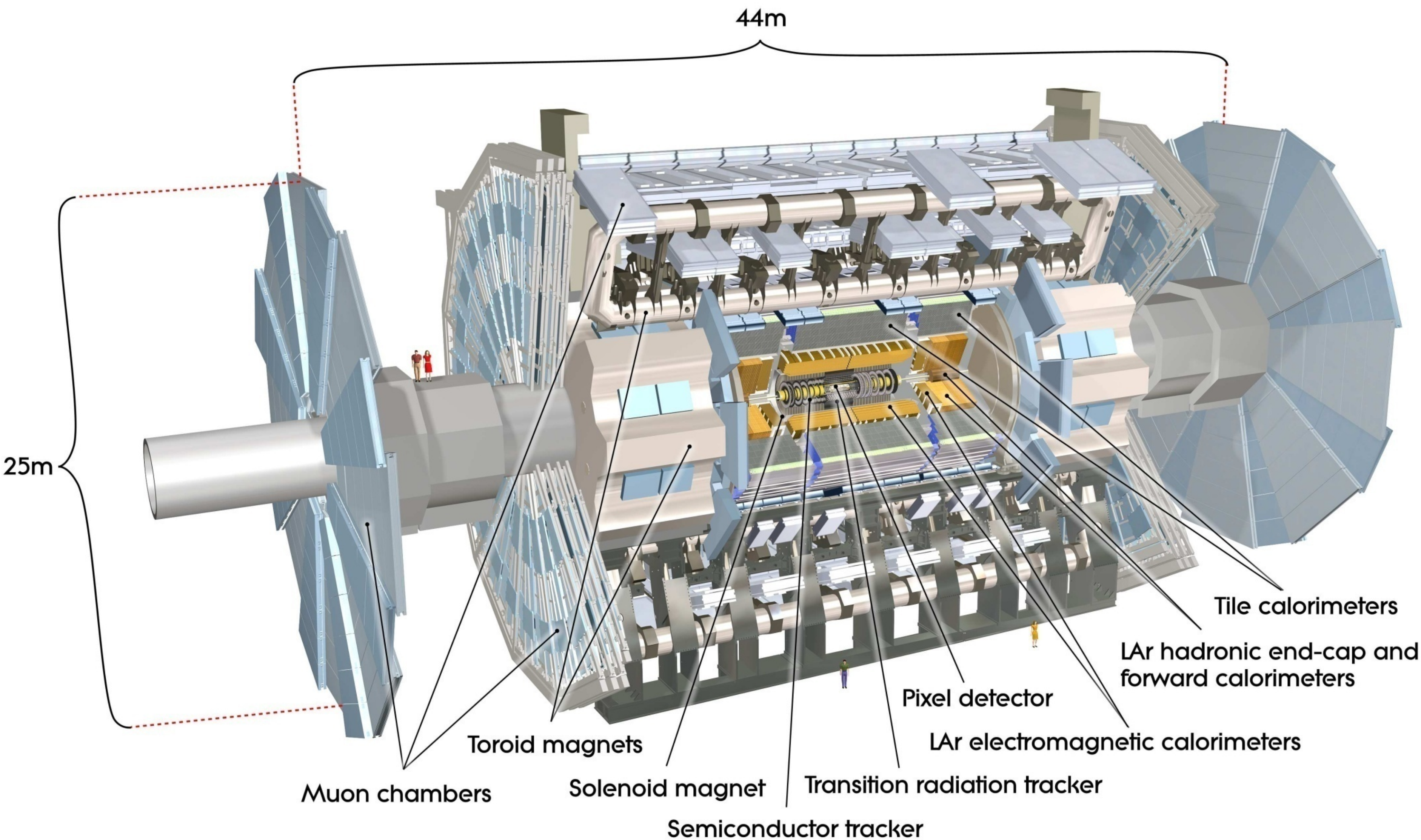
ATLAS HL-LHC Upgrades

- The current ATLAS detector was designed to operate at a luminosity of 10^{34} cm^{-2} s^{-1}, ~25 interactions/p-bunch-crossing and a 100 kHz Level-1 trigger rate for an integrated luminosity ~ 300 fb^{-1}.
  - The ongoing construction for Phase I upgrades is focused on providing additional triggering capabilities to allow operation at ~2 x 10^{34} cm^{-2} s^{-1}.
- The HL-LHC upgrades for the ATLAS detector are driven by:
  - The aging of the Inner Tracker, mostly due to radiation.
  - Increased occupancy and data volumes saturating readout links of the existing readout electronics.
  - The need to maintain low triggering thresholds with increasing trigger rates, to maintain physics acceptance.
  - Preparation for running over a decade at very high luminosity
    - > 5 x 10^{34} cm^{-1} s^{-1} with 140-200 interactions/crossing
    - Particle fluxes and energy deposition ~5 times higher than original design

The Upgrades

- Consequently, the primary elements of the detector upgrades in the reference scenario include:
  - Full Replacement of the Inner Tracker with an all-Si technology
    - Driven by the need to maintain tracking performance in a high radiation, high occupancy environment and to provide additional acceptance in the very forward region.
  - New Trigger/DAQ architecture
    - Driven by the need to retain low p_T thresholds at high luminosity to maintain physics acceptance and to handle increased DAQ rates.
  - New readout electronics for all systems
    - Driven by the need to handle increased readout data rates and providing additional handles for the trigger stage.
  - Other Options under consideration include:
    - Replacement of the Forward calorimeter and the innermost Muon chambers, installation of a forward timing detector & forward muon tagger.

The ATLAS Detector



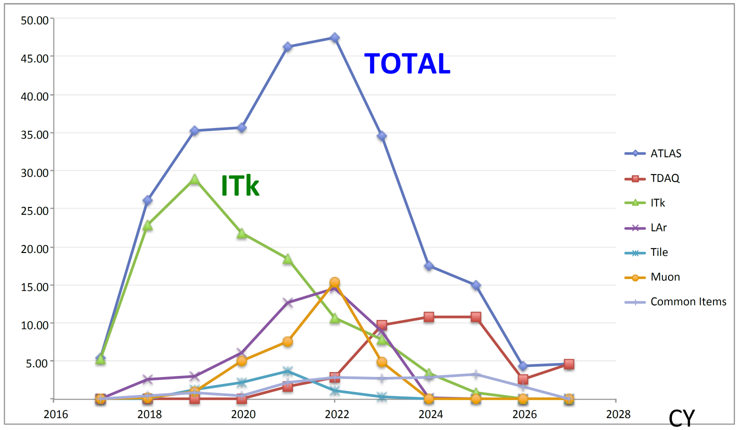
ATLAS HL-LHC Documents

- ATLAS HL-LHC Letter of Intent (LoI) completed and endorsed by collaboration at end of 2012
  - https://cds.cern.ch/record/1502664
  - Providing a description of the Phase II upgrades with physics justification and an initial cost estimate.
- Since then, a "scoping document" was released on 9/2015:
  - https://cds.cern.ch/record/2055248
  - The document described the proposed "Reference Detector" for the HL-LHC (corresponding to Core cost of 271 MCHF) with possible reductions corresponding to the Middle Scenario (228 MCHF) and Low Scenario (200 MCHF) and the corresponding physics impact:
    - Performance and physics reach is significantly enhanced with the Reference Scenario. In some physics searches, x2 (x4) integrated luminosity is required in the Middle (Low) Scenario to achieve the same significance as the Reference Scenario.

The Reference Detector

- **The Silicon Tracker (ITk):** 4 layers of pixel detector and 5 layers of Strip Detector and an extension of tracking to $|\eta| = 4.0$.
  - A task force is in place to further optimize this layout by mid-2016 (cost-neutral wrt reference scenario).
- **LAr Calorimeter:** Full readout electronics upgrade to allow 40 MHz streamed off detector for trigger consideration.
  - A forward Calorimeter and a timing detector is being considered.
- **Tile Calorimeter:** Full readout electronics upgrade to allow 40 MHz streamed off detector including allowing last layer information in Muon trigger.
- **Muon System:** Replacement of all on-chamber electronics, and replacement of MDTs with sMDT+RPC in the inner-barrel region.
- **Trigger/DAQ:** Two level hardware trigger (L0/L1) with a max rate of 1 MHz/400 kHz with 10 μs/6 μs latency and 10 kHz to disk.

ATLAS Core Cost Summary



Estimated spending profile for the reference scenario for each sub-system shown above.

Sub System (Core Cost in MCHF)	Reference Detector	Middle Scenario	Low Scenario
Silicon Tracker (ITk)	120.4	-7.2	-23.6
LAr Calorimeter	46.0	-13.6	-13.6
Tile Calorimeter	8.6	-	-
Muon System	34.1	-8.8	-12.8
Trigger/DAQ	43.3	-11.4	-18.2
Forward Detector	1.3	-	-
Integration & Installation	17.4	-1.6	-3.0
TOTAL	**271.1**	**-42.6**	**-71.2**

Estimate for Ref. scenario & reductions for Mid/Low

- The costing for each sub-system, incl. profile, has been worked out in detail.
  - The ITk has the longest construction time and requires funding early on. Production phase for ITk is expected to begin in FY19.
- ATLAS management has gathered input from all countries on their potential contributions to the HL-LHC upgrades, which has been discussed with LHCC/UCG.
  - Initial consultation suggests a realistic possibility for securing the needed funds.
  - U.S. contribution is planned to be ~20% of the "core cost", comparable to its "fair-share".

The International ATLAS Process

- Within each subsystem there are discussions and reviews of components
- Once R&D is sufficiently mature, the subsystem leaders schedule an Initial Design Review (IDR) based on a comprehensive design document
  - Overall performance, technical requirements, initial cost estimate, preliminary schedule and milestones
- The sub-system project is formalized and launched after the IDR is completed. Initial institutional interests to the upgrades are collected.

Table 26. IDR and TDR schedule of the ATLAS Phase-II UPRs

Upgrade PRoject (UPR)	IDR	TDR
ITk-Strip ITk-Pixel	Q4 2014	Q4 2016 Q4 2017
LAr	Q3 2016	Q3 2017
TileCal	Q3 2016	Q3 2017
Muon	Q2 2016	Q2 2017
TDAQ	Q1-2016	Q4 2017

- The project moves to the TDR stage. Final commitments are made following the completion of the TDR. These MoUs specify the formal engagements with each country.

Scoping Document : Schedule

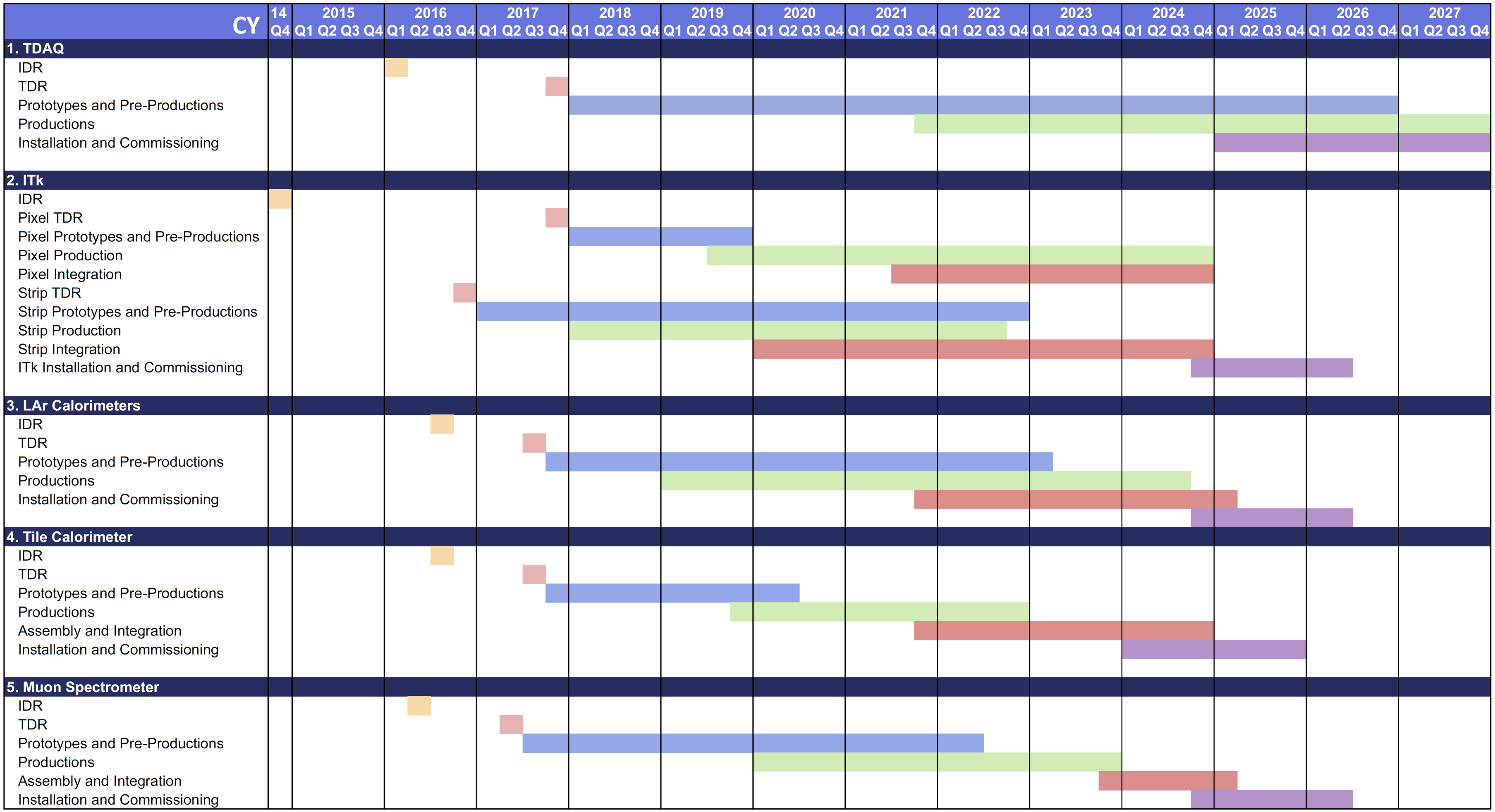


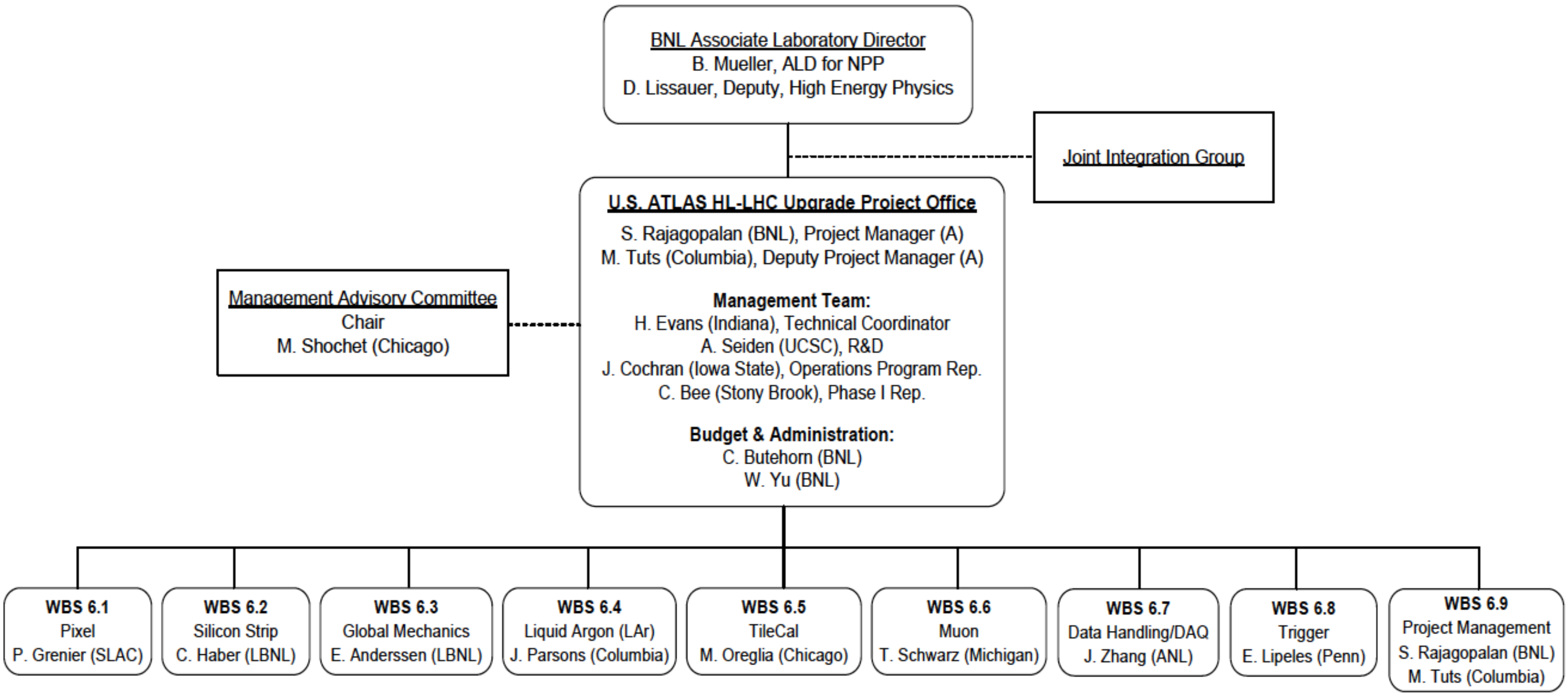
Figure 70. Top-level summary of the milestones and time-line of the ATLAS Phase-II upgrade projects.

U.S. ATLAS Planning for HL-LHC

U.S. ATLAS

- The process of finalizing US contributions to ATLAS HL-LHC upgrades is complex : involving coordination between US groups, international ATLAS and US funding agencies.
  - Phase-II organization is in place with acting project managers.
  - Aspirations based on experience and expertise of US groups collected.
  - Bottom-Up cost estimate of US proposed deliverables, incl. Labor.
    - WBS, BoE, Risks, Contingency are evolving.
  - Top-Down prioritization based on uniqueness of US contributions and budget profiles and baseline to meet funding guidance.
  - DOE and NSF scope meeting requirements of each agency identified.
  - Discussions with various sub-systems in international ATLAS active.
    - Similar process in international community ongoing, with the expectation that responsibilities will be captured in MOUs shortly after the TDR's are completed.
    - U.S. contribution expected to be consistent with "fair-share".

U.S. ATLAS HL-LHC Organization



U.S. Scope

- U.S. ATLAS has defined the scope of its potential contributions to the HL-LHC upgrades.
  - Driven by the interests and experience of the U.S. groups.
  - Discussion within collaboration and building consensus was vital.
  - Active discussions with international ATLAS at all levels to ensure that U.S. planning is integrated at the overall collaboration level.
- **DOE Scope:**
  - Focuses on the production of the Barrel ITk (Pixel and Strip detector) and associated common support infrastructure; DAQ hardware focusing on data flow elements, and FE chip development for LAr.
  - Significant involvement of four national Labs: ANL, BNL, LBNL, SLAC and leveraged with University contributions.
- **NSF Scope:**
  - Development of readout electronics for LAr, Tile, Muons and Trigger in support of providing robust trigger strategies at high luminosities.
  - Significant involvement of NSF supported Universities.

DOE: Guidance & Process

- Current R&D will be supported by the U.S. ATLAS Operations Program until HL-LHC project funds materialize.
  - OPC funds are planned to support prototyping effort prior to start of production.

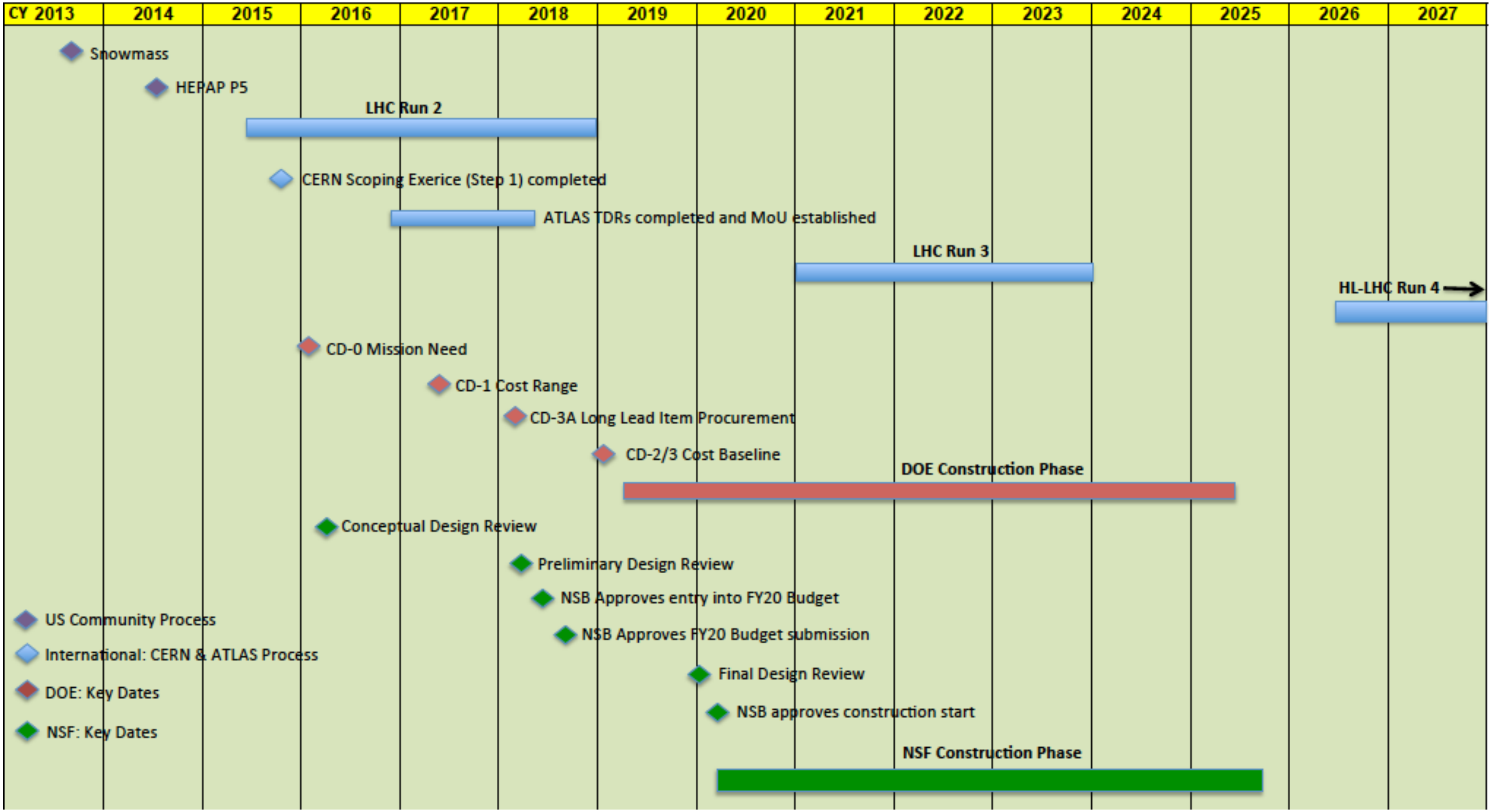
(M$)	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24	*Total*
OPC	1.25	14.0							*15.25*
TEC			31.5	42.3	26.1	20.1	10.0	4.75	*134.75*
TPC	1.25	14.0	31.5	42.3	26.1	20.1	10.0	4.75	*150.00*

- CD-0 for HL-LHC is expected early 2016. This will allow OPC funds to begin flowing in FY17.
- Given our experience with Phase I, we expect CD-1 will take place 1 – 1.5 years after CD-0, followed by a CD-2/3 (by ~ end of 2018).

NSF: Guidance & Process

- U.S. ATLAS and U.S. CMS will submit a joint MREFC proposal, with an expected funding of $75M per experiment.
  - In practice, two proposals under a unified MREFC umbrella.
  - Science Case document completed in May 2015 and Director has given permission to move forward to a Conceptual Design Review (CDR).
  - We are currently preparing for the CDR, including putting together a Project Execution Plan (PEP). We are targeting a CDR for March 2016.
    - This will be followed with a Preliminary Design Review (PDR). Following a successful PDR, NSF will submit a single MREFC appropriation request for construction as part of FY20 budget request to Congress. Two separate awards will be made to fund US ATLAS and US CMS proposals.
    - A Final Design Review will occur early FY20 prior to the flow of MREFC funds.
- Two sources of funds to support R&D and prototyping through FY20:
  - U.S. ATLAS Operations Program, that will contribute ~$1M per year.
  - Additional "planning funds" (~$6M) will be sought directly from NSF for the period FY17-FY20. Encouraging discussions with NSF ongoing.

Key DOE/NSF dates



Conclusion

- CERN Management has defined a target cost range and given its endorsement to move toward the next stage in the process (TDR).
- International ATLAS is rapidly moving toward TDR:
  - Initial Design Review (IDR) completed for ITk and defined as a "project". Other sub-system IDRs on schedule to be completed by 2016.
  - TDRs scheduled between 2016-2017 for all sub-systems
  - U.S. ATLAS community actively engaged at all levels in ATLAS
- U.S. ATLAS planning for HL-LHC progressing rapidly
  - Increasing effort to complete the R&D effort and commission the design with prototypes.
  - DOE CD-0 in preparation at agency and expected within 1-2 months.
  - CDR for NSF planned for March 2016.
  - Additional funds from both NSF and DOE are expected in FY17.
- A well defined process is in place to formalize this upgrade project at both NSF and DOE.

Backup slides

ITk and Calorimeter

- ITk: Four layers of pixel detector and 5 layers of Strip Detector and an extension of tracking to $|\eta| = 4.0$ in the reference scenario.
- Calorimeter: Full readout electronics upgrade to allow 40 MHz streamed off detector for trigger consideration.

Table 3. Upgrade plans of the ATLAS ITk and calorimeter systems for the three scenarios considered [2].

Detector System	Scoping Scenarios Reference (275 MCHF)	Middle (235 MCHF)	Low (200 MCHF)
Inner Tracker			
Pixel Detector	$\|\eta\| \leq 4.0$	$\|\eta\| \leq 3.2$	$\|\eta\| \leq 2.7$
Barrel Strip Detector	✓	✓ [No stub layer]	✓ [No stereo in layers #2,#4] [Remove layer #3] [No stub layer]
Endcap Strip Detector	✓	✓ [Remove 1 disk/side]	✓ [Remove 1 disk/side]
Calorimeters			
LAr Calorimeter Electronics	✓	✓	✓
Tile Calorimeter Electronics	✓	✓	✓
Forward Calorimeter	✓	✗	✗
High Granularity Precision Timing Detector	✓	✗	✗

Muon Spectrometer

- Improve the muon trigger
- New sTGC in forward region
- Finer granularity based on MDT's
- New RPC & sMDT in barrel increase coverage and redundancy at L0, reduced in lower scenarios
- Partial replacement of current MDT electronics in lower scenarios

Table 4. Upgrade plans of the ATLAS Muon system for the three scenarios considered [2].

Muon Spectrometer	Scoping Scenarios Reference (275 MCHF)	Middle (235 MCHF)	Low (200 MCHF)
Barrel Detectors and Electronics			
RPC Trigger Electronics	✓	✓	✓
MDT Front-End and readout electronics (BI+BM+BO)	✓	✓ [BM+BO only]	✓ [BM+BO only]
RPC Inner layer in the whole layer	✓	✓ [in half layer only]	✗
Barrel Inner sMDT Detectors in the whole layer	✓	✓ [in half layer only]	✗
MDT L0 Trigger Electronics (BI +BM+BO)	✓	✓ [BI +BM only]	✓ [BI +BM only]
End-cap and Forward Muon Detectors and Electronics			
TGC Trigger Electronics	✓	✓	✓
MDT L0 Trigger and Front-End read-out electronics (EE+EM+EO)	✓	✓ [EE +EM only]	✓ [EE +EM only]
sTGC Detectors in Big Wheel Inner Ring	✓	✓	✓
Very-forward Muon tagger	✓	✗	✗

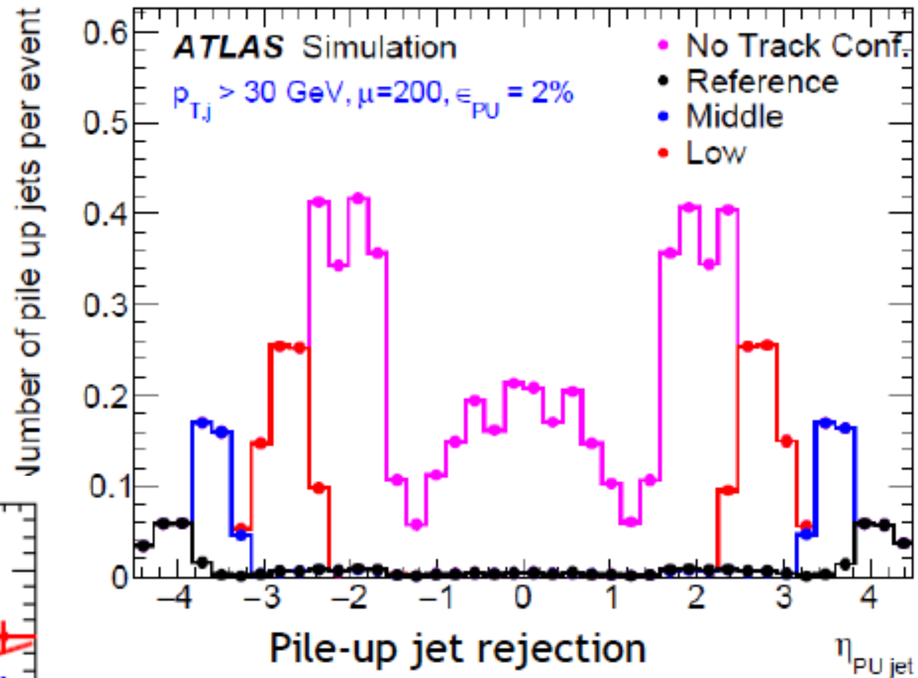
Trigger/DAQ

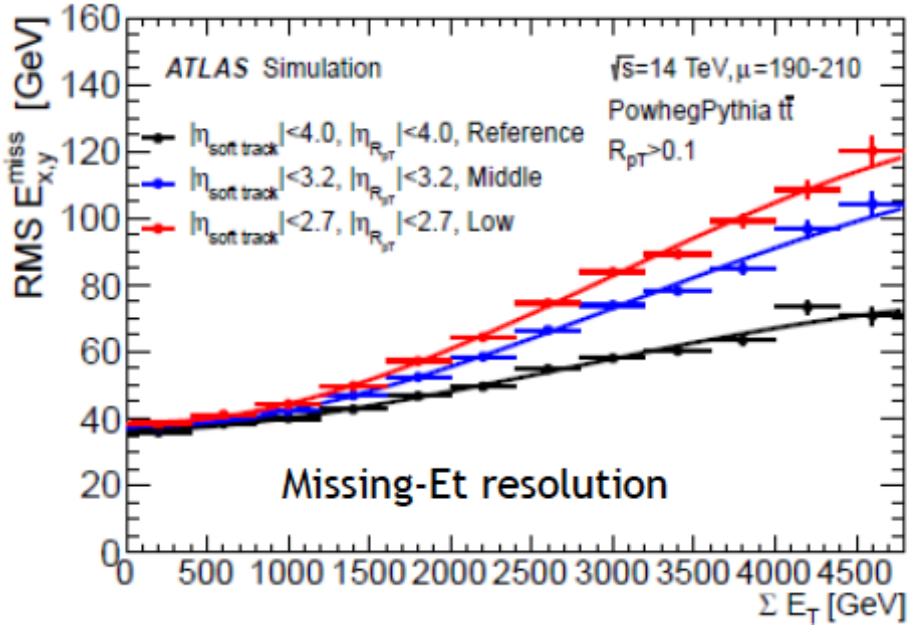
- Two Level FPGA based "custom harware" trigger: 1MHz @ Level-0
- Performance degrades for lower scenarios
- L0 trigger & L1 tracker trigger follow η coverage
- L1 track trigger pT threshold increases
- High Level trigger rate decreases and FTK++ thresholds increase
- DAQ readout rate decreases

Table 2. ATLAS TDAQ upgrade plans for the three scenarios considered [2].

Trigger and Data Acquisition	Scoping Scenarios Reference (275 MCHF)	Middle (235 MCHF)	Low (200 MCHF)
Level-0 Trigger System			
Central Trigger	✓	✓	✓
Calorimeter Trigger (e/γ)	$\|\eta\| < 4.0$	$\|\eta\| < 3.2$	$\|\eta\| < 2.5$
Muon Barrel Trigger	MDT everywhere RPC-BI Tile-μ	MDT (BM & BO only) Partial η coverage RPC-BI Tile-μ	MDT (BM & BO only) No RPC-BI Tile-μ
Muon End-cap Trigger	MDT everywhere	MDT (EE&EM only)	MDT (EE&EM only)
Level-1 Trigger System			
Output Rate [kHz]	400	200	200
Central Trigger	✓	✓	✓
Global Trigger	✓	✓	✓
Level-1 Track Trigger (*RoI based tracking*)	$p_T > 4$ GeV $\|\eta\| \leq 4.0$	$p_T > 4$ GeV $\|\eta\| \leq 3.2$	$p_T > 8$ GeV $\|\eta\| \leq 2.7$
High-Level Trigger			
FTK++ (*Full tracking*)	$p_T > 1$ GeV 100 kHz	$p_T > 1$ GeV 50 kHz	$p_T > 2$ GeV 50 kHz
Event Filter	10 kHz output	5 kHz	5 kHz
DAQ			
Detector Readout	✓ [400 kHz L1 rate]	✓ [200 kHz L1 rate]	✓ [200 kHz L1 rate]
DataFlow	✓ [400 kHz L1 rate]	✓ [200 kHz L1 rate]	✓ [200 kHz L1 rate]

Detector Performance Impact



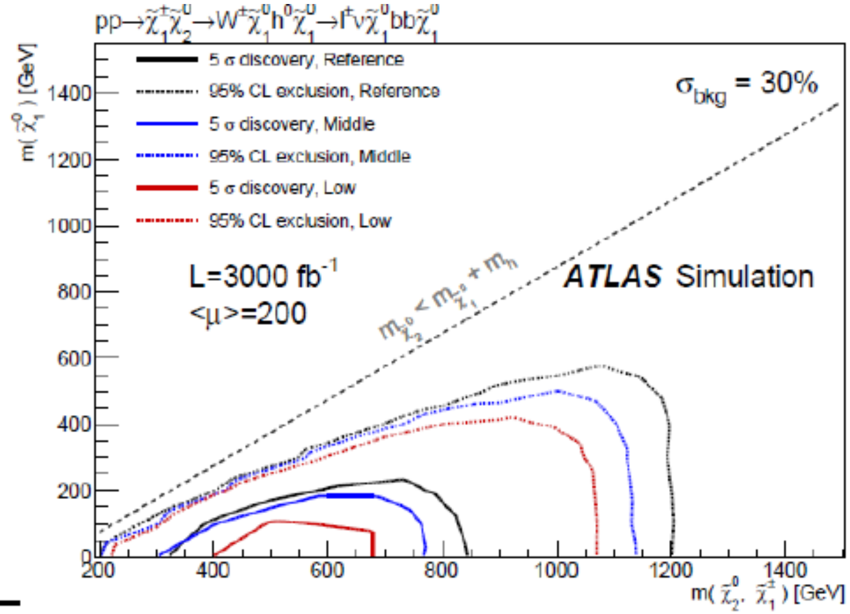


Physics Impact

Two clear conclusions:

- Performance of the Reference detector is significantly enhanced over the Middle scenario
- Performance of the Low detector is too poor, especially - but not only - for tracking and the robustness of it

Reference detector sets the standard



Fractional uncertainties on cross-sections of various vector-boson scattering processes

Scenario	VBF $H \to WW^{(*)}$	VBF $H \to ZZ^{(*)}$	VBS ss$W^{\pm}W^{\pm}$
Reference	0.14	0.134	0.059
Middle	0.20	0.137	0.11
Low	0.30	0.142	0.13

Performances of three detector layouts for two searches, and equivalent luminosity reductions

Scenario	SUSY $\chi_1^{\pm}\chi_2^0 \to \ell b\bar{b} + X$		BSM $HH \to b\bar{b}b\bar{b}(M_{G^*_{KK}}$=2.0 TeV)	
	Mass (GeV)	$\mathcal{L}^{int}_{equiv.}$ [fb^{-1}]	Significance	$\mathcal{L}^{int}_{equiv.}$ [fb^{-1}]
Reference	850	3000	4.4	3000
Middle	770	6000	4.5	
Low	675	12000	3.1	7200