Overview and Status of ATLAS Upgrade Program

K. Einsweiler, LBL
on behalf of the ATLAS Collaboration

- Brief overview of Phase-1 upgrades
- Key features of LoI Phase-2 Upgrade
- Current “Reference Scenario” for Phase-2 Upgrade
    - Options being explored => not a single monolithic design yet
    - Program to make major “baseline” decisions during 2016
    - TDRs defined, nominal schedules between Q4 2016 and Q4 2017

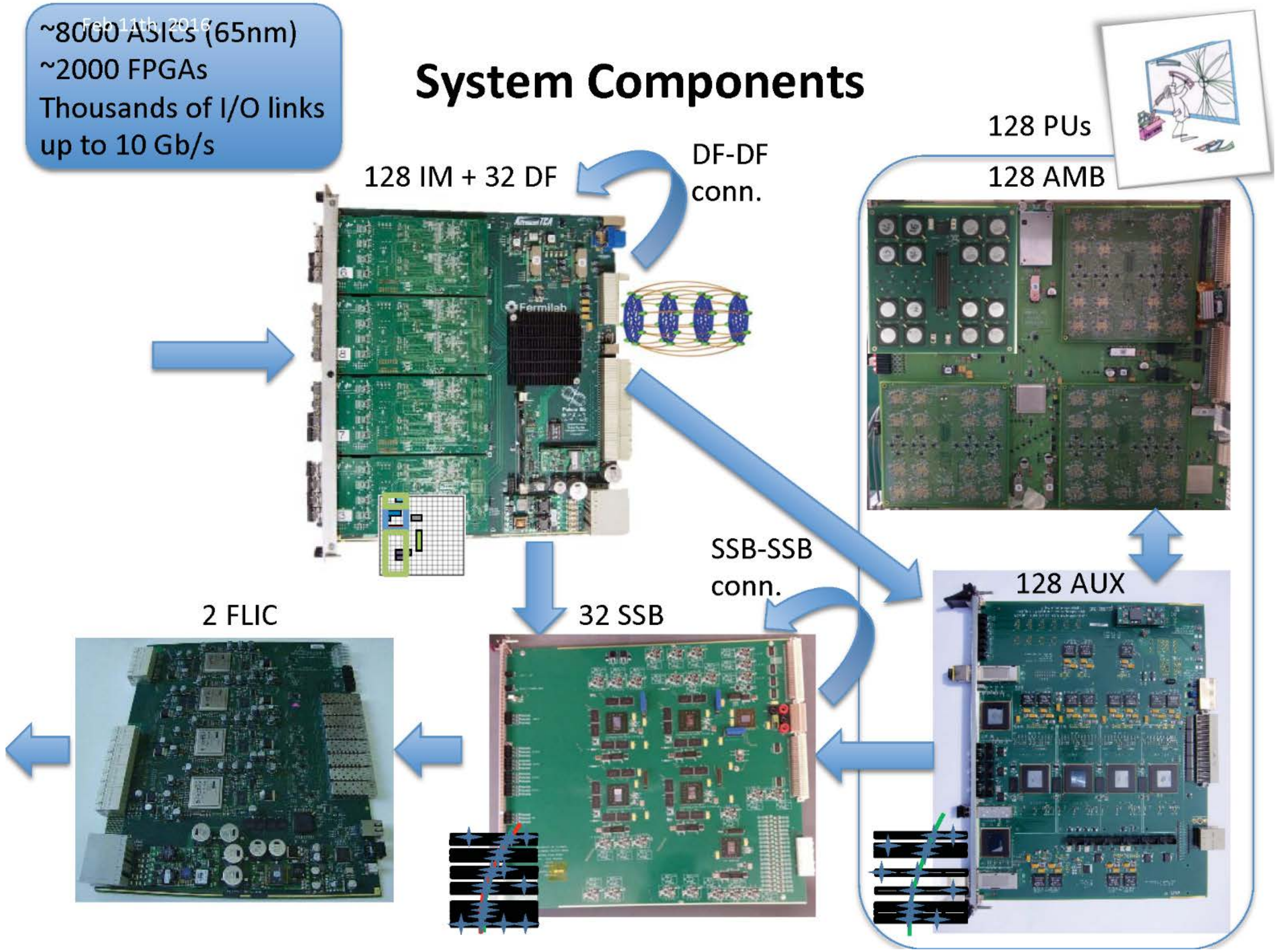
- Will hear more about all of these upgrades later in this workshop !

Brief Overview of Phase-1 Upgrades

- Four major TDRs submitted during 2013 and approved in Mar 2014. These upgrades provide improved capabilities for higher luminosities of Run 3, but also form the initial steps towards phase-2 detector (very much a “staged” upgrade program !).
- FTK (Fast Tracker Trigger, CERN-LHCC-2013-007):
  - Performs very fast pattern recognition and track fitting on ID data being transmitted to the HLT processor farm. Output is complete list of tracks above PT ~ 1 GeV.
  - Pattern recognition based on associative memories, 8K custom 65nm chips provide one billion patterns to match with IBL, Pixel, and SCT data (8 layers into pattern recognition, 12 layers total for fitting). Production chip submission in next few weeks.
  - Installation of FTK in ATLAS began in 2015, and will continue during 2016, leading to a full-coverage system which should be commissioned for physics when collisions begin in 2017.
  - FTK designs (to be based on still smaller feature size AM chips) will form critical ingredients of L1Track hardware trigger and FTK++ track reconstruction engine for phase-2 HLT.
- NSW (New Small Wheel, CERN-LHCC-2013-006):
  - These wheels are the innermost (closest to IP) stations of the “muon endcap”, located between the endcap calorimeter and the endcap toroid. The NSW will provide improved pointing to origin => reject more fake muons and control the rates at high L.
  - Replaces the current Small Wheel with an improved version based on newer chamber technologies (sTGC and Micromegas chambers) which are capable of operation throughout phase-2 (sTGC strips ~3mm pitch, MM strips ~0.5mm pitch). Use both sTGC and MM in L1 trig.
  - The readout and trigger electronics are all designed to be “phase-2 compliant”, so do not anticipate any changes in on-detector electronics during LS3. Pre-production in coming months.
  - “Module-0” pre-production for sTGC and MM sites is ongoing. Series production should begin in sTGC sites in the coming months, and in MM sites by the end of 2016. Very challenging !
  - Installation of NSW represents the first new phase-2 detector system !

Illustration of Components of FTK Trigger System

- I/O boards (DF/IM and FLIC) housed in ATCA, while core components (AMB/AUX/SSB) are housed in high-powered VME crates.

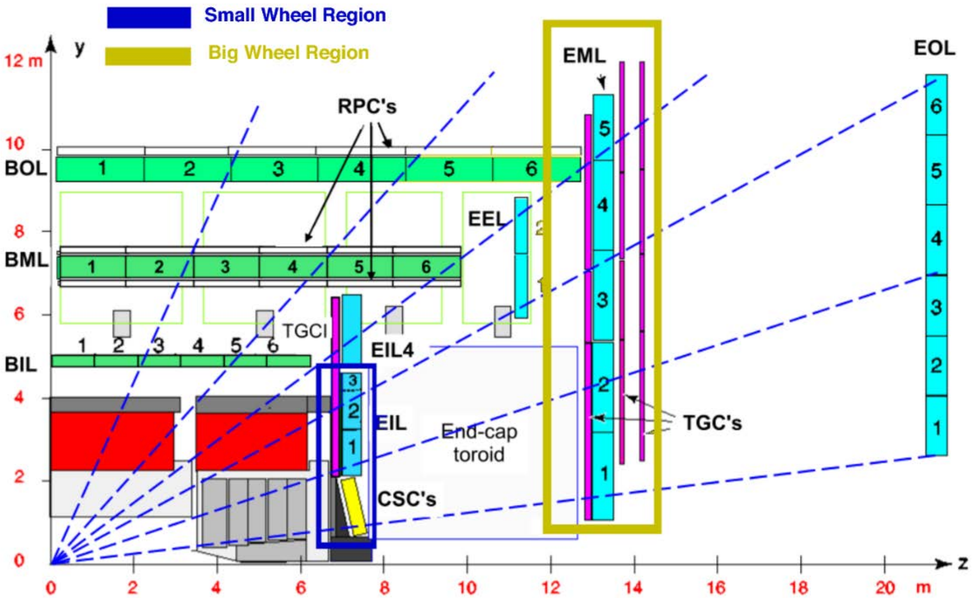


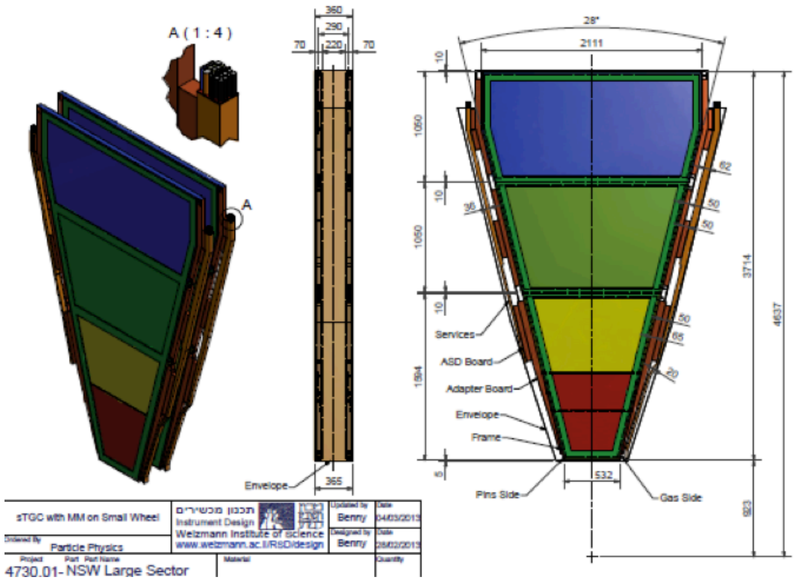
Status of FTK Trigger System

- AM06 (400M transistor 65nm ASIC) arrived in Jan, and all preliminary testing indicates that it works well (slow corner only for now, ~80% yield).
- Integration in ATLAS started in mid-2015. Now includes all connections from ID to FTK, roughly 25% of input boards (32/128) and output boards (FLIC) with minimal electronics to inject input data after clustering into ATLAS DAQ. Support software (DAQ, DCS, monitoring) largely ready.
- Trigger menu development (vertexing, flavor-tagging, tau reconstruction, jet/MET pileup corrections) proceeding well. Continue HLT tracking in parallel with FTK tracking during commissioning phase.
- There are three top-level milestones for the project to reach its goal of production operation for physics when collisions start in 2017 (May):
  - Operation of a complete chain in P1 using a fully loaded AMB (64 AM06 on 4 LAMB). Milestone = April 2016.
  - Operation of the complete barrel system for μ=40 (16 AMB, initially with only 32 AM06 per board = Jul 2016, then with fully loaded AMB = Sep 2016). Commission this system fully before the end of pp collisions.
  - Operation of complete coverage system for μ=40 (32 AMB, fully populated) and commissioned by Apr 2017 (preferably earlier). Could be 64 AMB ?
- Schedule is complex because of AM06 and board availability.

Illustration of Components of NSW System

- Present SW will be replaced by NSW. Radius ~5m, composed of 16 sectors (8 “small” and 8 “large” to provide overlaps between sectors).
- Each sector contains two sets of two “quadruplets” (4-layer chambers) of Micromegas detectors mounted on either side of a support structure.
- Two additional sets of three “quadruplets” of sTGC chambers are mounted on top, forming structure with 8 MM and 8 sTGC measurements.
- FE electronics and data transmission mounted on sides of each sector.





Brief Overview of Phase-1 Upgrades

- LAr Phase-1 Upgrade (CERN-LHCC-2013-017):
  - Maintain low thresholds and high efficiency for L1 triggers on electrons, photons, and jets at higher luminosities of Run 3 by introducing more segmentation into trigger data.
  - Improved segmentation: trigger tower ($\Delta\phi x \Delta\eta$ = 0.1 x 0.1) →10 supercells (4 depth segments, first and last $\Delta\phi x \Delta\eta$ = 0.1 x 0.1, two middle $\Delta\phi x \Delta\eta$ = 0.1 x 0.025)
  - New supercell information is digitized on-detector by new digitizer boards (LTDB), and sent over high-speed optical fibers to the upgraded phase-1 L1 calorimeter trigger.
  - This upgrade to Run 3 L1Calo will allow it to operate as Run 4 L0Calo (see later slide for explanation of two-stage hardware trigger architecture for phase-2).
- TDAQ Phase-1 Upgrade (CERN-LHCC-2013-018):
  - Major ingredients are upgrades of L1Calo (also phase-2) + L1Muon (partially phase-2).
  - The L1Calo upgrade will use improved segmentation supercell data, and implement three "Feature Extractors" (FEX's) which will process the supercell data. The eFEX will identify electrons and photons, the jFEX will identify standard jets, do calculations of MET, HT, and the gFEX will identify large-R jets, do calculations of MET, HT.
  - Some elements of this upgrade package have already been at least partially installed in LS1 (L1Topo, new CTP, Tile-muon trigger).
  - New phase-1 detectors (L1Calo, NSW) use phase-2 compliant DAQ based on FELIX interface, implementing a heterogenous switching fabric (DAQ, Ctrl/Cfg, TTC, DCS).
- AFP (Forward Proton Detector, CERN-LHCC-2015-009) TDR approved Jun 2015.

Illustration of Components of Phase-1 LAr Upgrade

- Replace analog sums for current Trigger Towers with digitization of Supercell (10/Trigger Tower) information, transmitted optically off-detector.

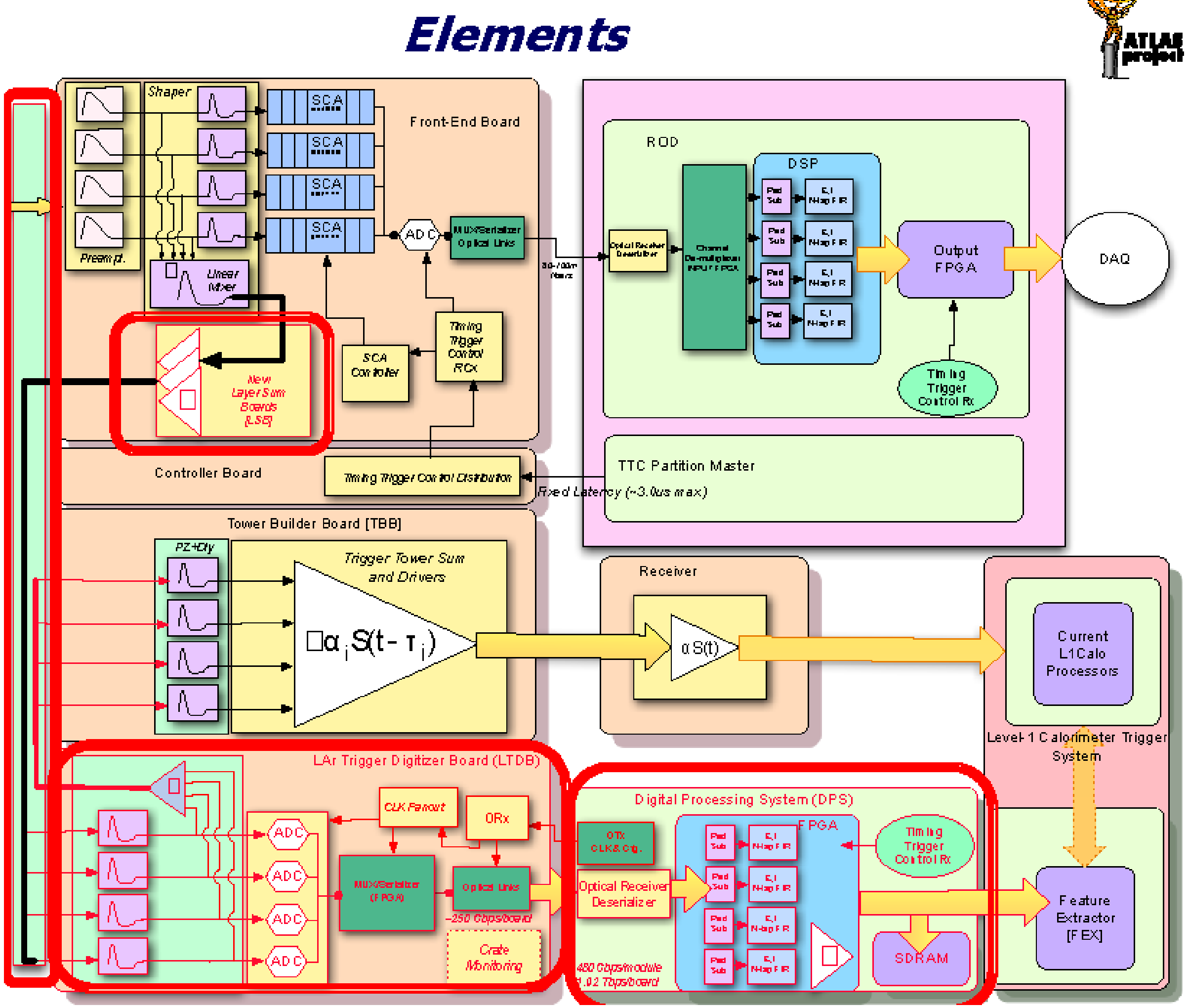
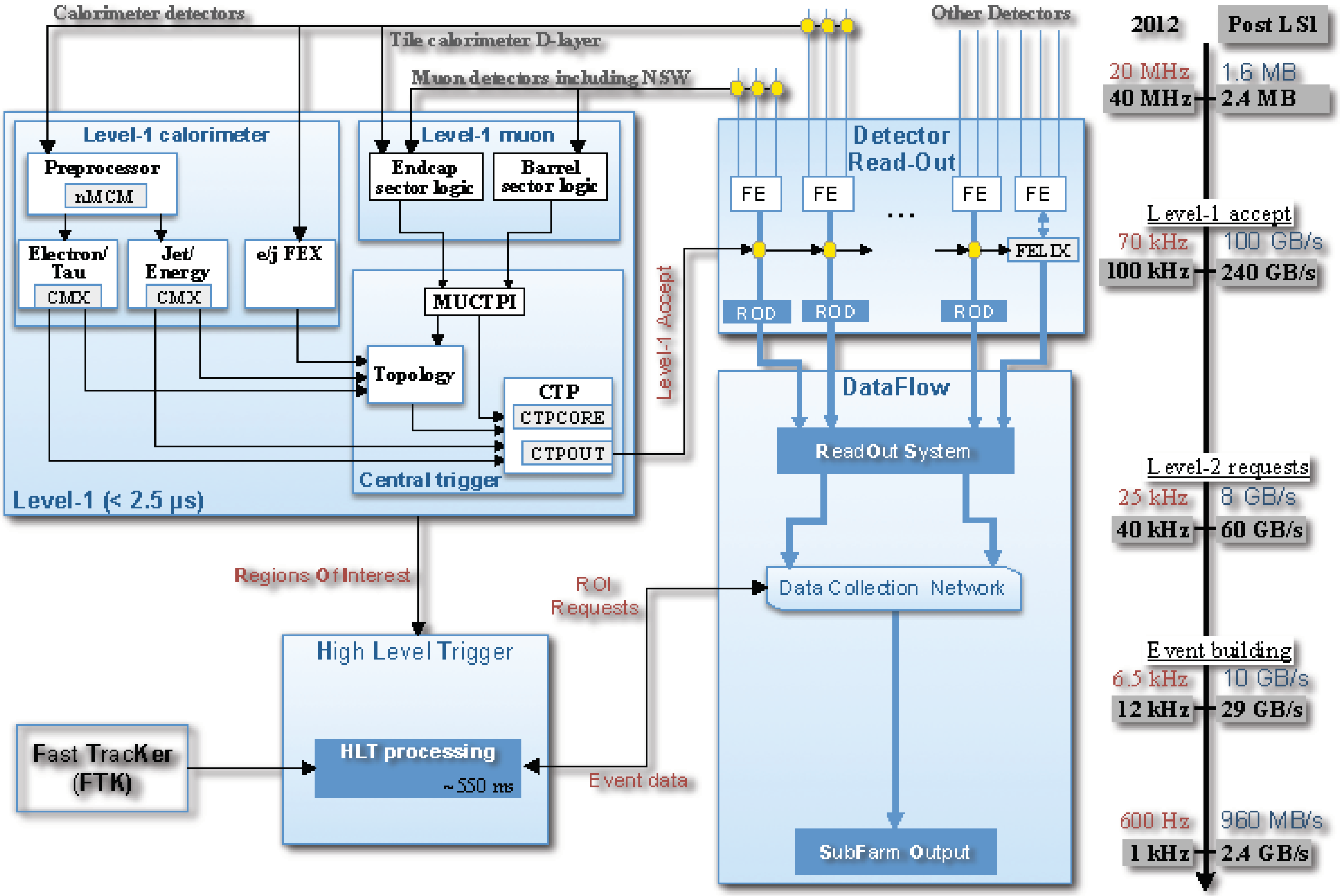


Illustration of Components of Phase-1 TDAQ Upgrade

- Major components include L1Calo upgrade (all digital), Muon upgrade (sector logic and MUCTPI) + FELIX DAQ upgrade for phase-1 systems.

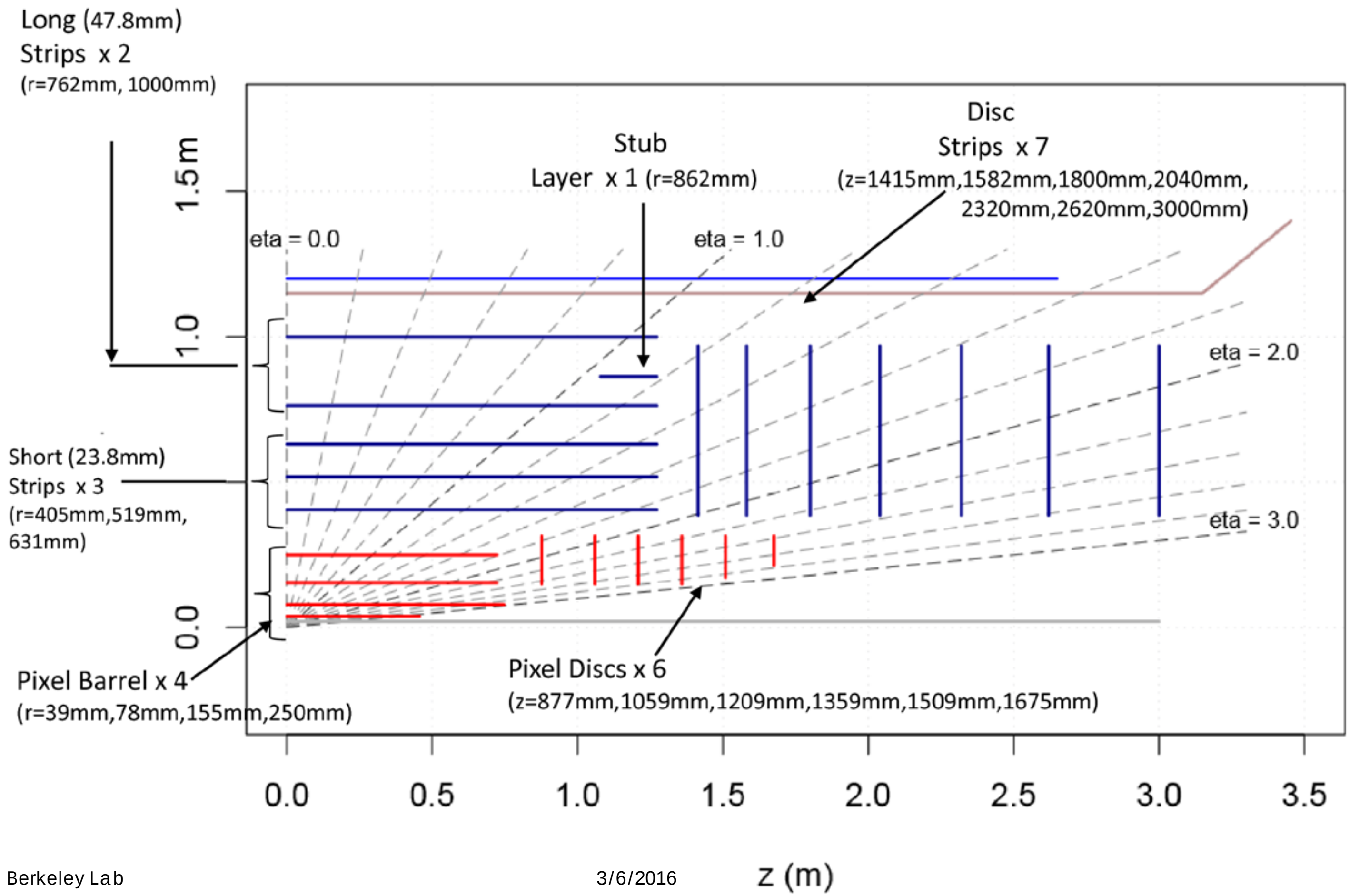


Brief Summary of LoI Phase-2 Detector

- Defined in official (CERN-LHCC-2012-022) document from Dec 2012. Design was optimized for luminosity-leveled 5×10^{34} or μ=140 (some results at μ=200).
- Nominal cost was 230 MCHF, with an improved version (including a fifth pixel layer and a new FCal, plus other modest improvements) costed at 275 MCHF.
- Dominant cost item was new tracker, ITk, with nominal cost of 131.5 MCHF. Major upgrades to TDAQ (23.3 MCHF), major upgrades of LAr electronics based on streaming of all data off-detector with 40/80 MHz digitization rate (32.1 MCHF), major upgrades of TileCal electronics (7.5 MCHF), and major upgrades of muon electronics (19.6 MCHF). A common fund of 16.3 MCHF also included.
- Trigger architecture implements two hardware trigger levels (L0, L1), where the L0Calo is essentially the phase-1 L1Calo, and the L0Muon is an improved version of phase-1 L1Muon. L0 rate was > 500 kHz, and L1 rate into HLT was 200 kHz. At L1, one critical element is an FTK-like trigger L1Track, which in combination with the L0 triggers feeds into L1Global (L1Muon and L1Calo).
- Replace all LAr FE and BE electronics, replace all TileCal on-detector and off-detector electronics, replace "most" on-chamber muon electronics and provide support for MDT in L0Muon trigger, move muon trigger electronics off-detector.

Phase-2 LoI ITk Layout

- Pixel system in LOI ITk layout has 4 barrel layers and 6 disks (~8 m^2). Strip system has 5 barrel layers (and 1 stub layer) plus 7 disks (~190 m^2). Provides at least 14 hits over full eta range, counting strip layer as 2 hits, pixel layer as 1 hit.



Evolution Towards Reference Detector in Scoping Doc

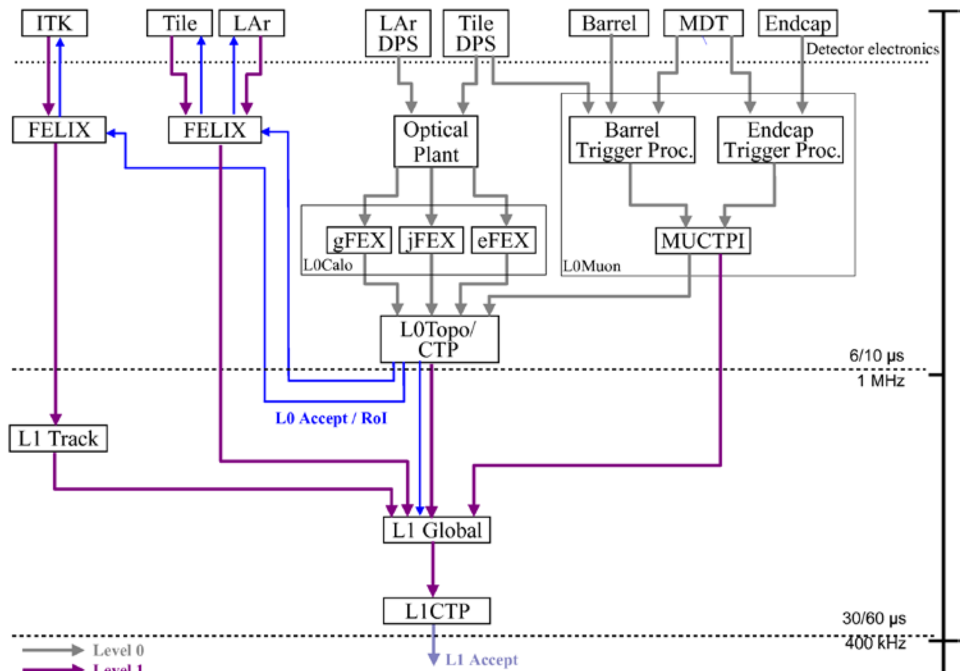
- Start from LoI ITk layout for Reference design, constrained by need to be able to carry out performance simulations without long development. New Layout TF now working.
- Add large-η extensions to ITk, Pixels only, extending to η=3.2 or η=4.0 (maximum).
- Add sFCal with improved high-lumi performance and finer segmentation (improve both ϕ and η segmentation by factor 2 by reduced ganging of readout electrodes).
- Consider adding finely segmented W/Si thin calorimeter with precision timing to cover region $2.4 < \eta < 4.0$ for improved vertexing and e/γ performance (MBTS region).
- Add BI RPC+sMDT upgrade plus updated MDT electronics for hardware triggering (replace existing on-chamber electronics where possible – ideally everywhere).
- Add segment-tagging muon station in front of NSW ($2.6 < \eta < 4.0$) to match extended ITk η coverage – extension of NSW at smaller radius in same shielding structure.
- Add more powerful L1Track (uses ITk data in L0 ROI) and FTK++ (event filter track processor) AM track processors to handle more patterns per second (higher μ, lower track P_T, more input layers, larger η coverage, higher rates to match new L0/L1 rates).
- Consider adding Forward detector upgrades if compelling concepts emerge (current forward detectors are ALFA/AFP, LUCID, ZDC – consider accelerator issues too).
- Some of these options are well-defined with clear advantages, some of them are at a more conceptual stage with less developed performance/physics cases. Converge as rapidly as possible during 2016 to baseline detector => submit all TDRs by end-2017.

Phase-2 Trigger and DAQ Architecture

- Based on split L0/L1 architecture. L0 latency similar (10μs) to that of current L1 latency => similar approaches. L0 trigger based on phase-1 L1Calo with FEX architecture, and new L0Muon trigger.
- L1 latency significantly longer (60μs) => introduce L1Track AM-based track finder (P_T~2-4 GeV), driven by L0 ROIs (no L0 tracking trigger). L1Global based on L1Track, full calorimeter data, and L0Muon. Allows track/calo matches for e/μ/τ/jets, keep thresholds low, includes modest pileup suppression.
- Revisiting hardware trigger architecture, with option for transmission of all data off-detector at L0 rate of 1 MHz. Re-examining implementation of L1 in that case.

Note: HLT processing farm specified for output rate of 10 kHz.

Event size estimated to be ~5 MB.



Note: L1Global needs to provide capability for processing roughly 40 events in parallel.

Note: current phase-2 readout architecture has all systems except NSW and ITk streaming data off-detector before L0. Those high-occupancy detectors challenged to transmit at L0 rate.

Development of Simplified Phase-2 Trigger Menus

- Now have relatively detailed models for basic ingredients of phase-2 triggers at L0 and L1. Put this together into simplified trigger menus (collection of specific triggers, with thresholds and requirements), and predict rates. Provides a powerful metric of the performance of the TDAQ system.

Item	Offline p_{T} Threshold [GeV]	Offline $\|\|$	L0 Rate [kHz]	L1 Rate [kHz]	EF Rate [kHz]
isolated Single e	22	< 2.5	200	40	2.20
forward e	35	2.4 – 4.0	40	8	0.23
single γ	120	< 2.4	66	33	0.27
single μ	20	< 2.4	40	40	2.20
di-γ	25	< 2.4	8	4	0.18
di-e	15	< 2.5	90	10	0.08
di-μ	11	< 2.4	20	20	0.25
$e - \mu$	15	< 2.4	65	10	0.08
single τ	150	< 2.5	20	10	0.13
di-τ	40,30	< 2.5	200	30	0.08
single jet	180	< 3.2	60	30	0.60*
fat jet	375	< 3.2	35	20	0.35*
four-jet	75	< 3.2	50	25	0.50*
H_{T}	500	< 3.2	60	30	0.60*
$E_{\mathrm{T}}^{\mathrm{miss}}$	200	< 4.9	50	25	0.50*
jet + $E_{\mathrm{T}}^{\mathrm{miss}}$	140,125	< 4.9	60	30	0.30*
forward jet**	180	3.2 - 4.9	30	15	0.30*
Total			~1000	~400	~10

Results of simplified illustrative trigger menu for 7x10^{34}, where the totals include overlap removal.

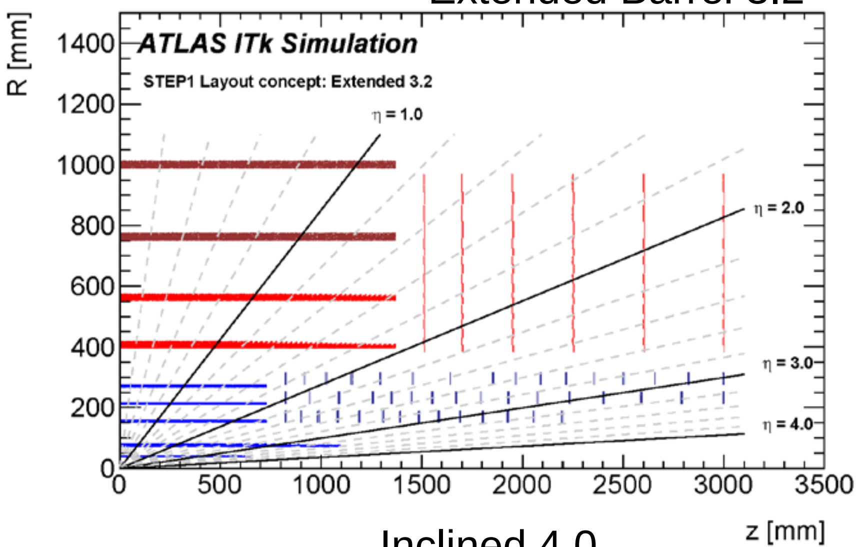
Rates are based on combination of extrapolation from Run 1 and 2, plus simulation.

ITk Layout Strategy and Issues

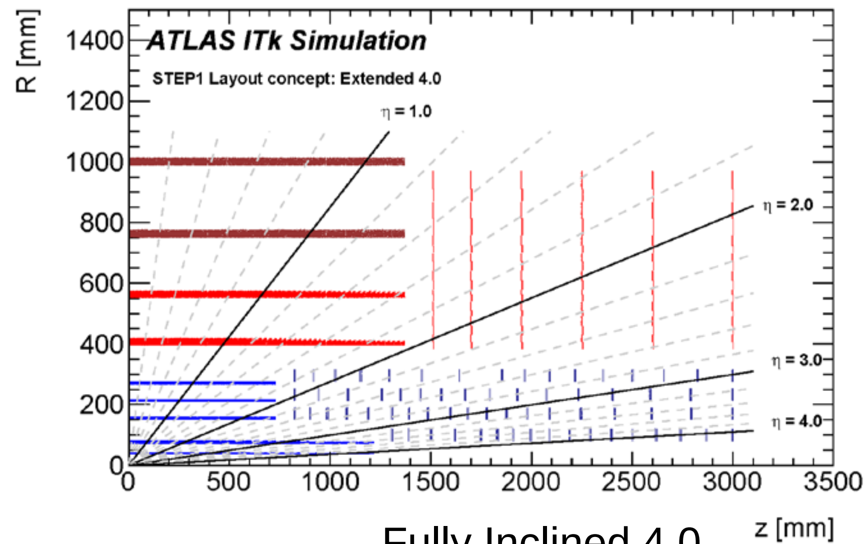
- Layout TF set up to revisit requirements for tracker, survey possible layouts, develop performance studies, and converge towards a final layout during 2016.
- New fast-simulation packages and streamlined geometry creation allow more rapid evaluations and comparative studies => fairly rapid progress in exploring non-traditional layout approaches.
- Particular challenge is finding effective ways to extend pixel tracker out to η=4.0 (maximum possible in ATLAS tracker volume). Very strong message from Scoping Document studies ! Control of material and services are critical to avoid increases in neutron fluences and degradation of calorimeter performance.
- Basic concept involves a reduced scope Strip system with 4 barrel layers and 6 disk layers, driven by Scoping Document studies. The Pixel layout is presently taken to be 5 barrel layers, and different options are being considered for the forward region to optimize the forward tracking (roughly beyond η=2).
- Use innovative local support structure designs: rings in forward region, truss-like structures in barrel region, especially for “inclined” layouts where intermediate sensor orientations are used in barrel/endcap “transition” regions. Many ideas !
- Rely on serial powering and electrical data transmission out of Pixel volume to minimize services material. Area of intensive study !
- Strip layout converging rapidly for Strip TDR later in 2016, while final Pixel layout may converge only towards end-2016…

ITk Layouts Under Evaluation by Layout TF

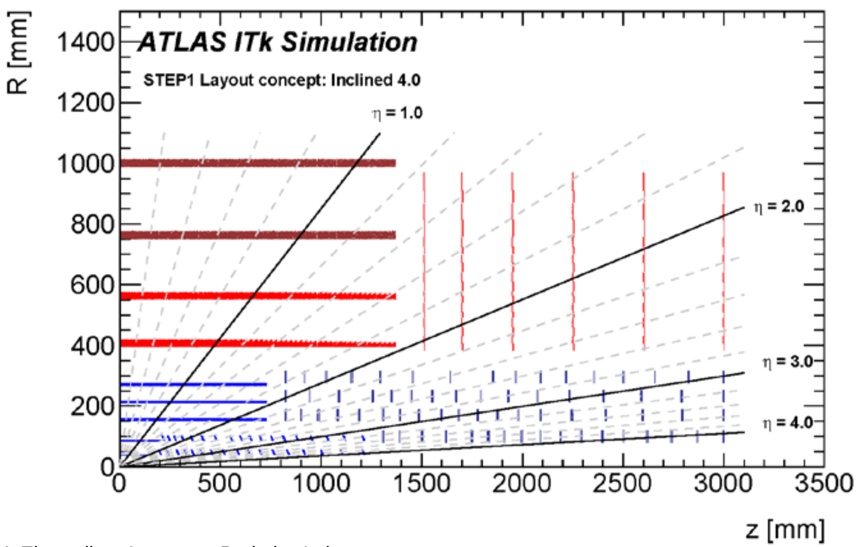
Extended Barrel 3.2



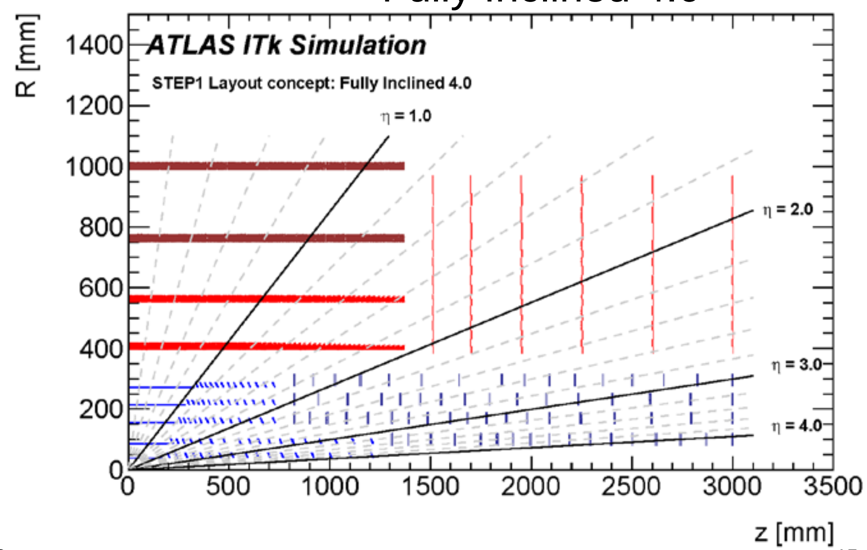
Extended Barrel 4.0



Inclined 4.0

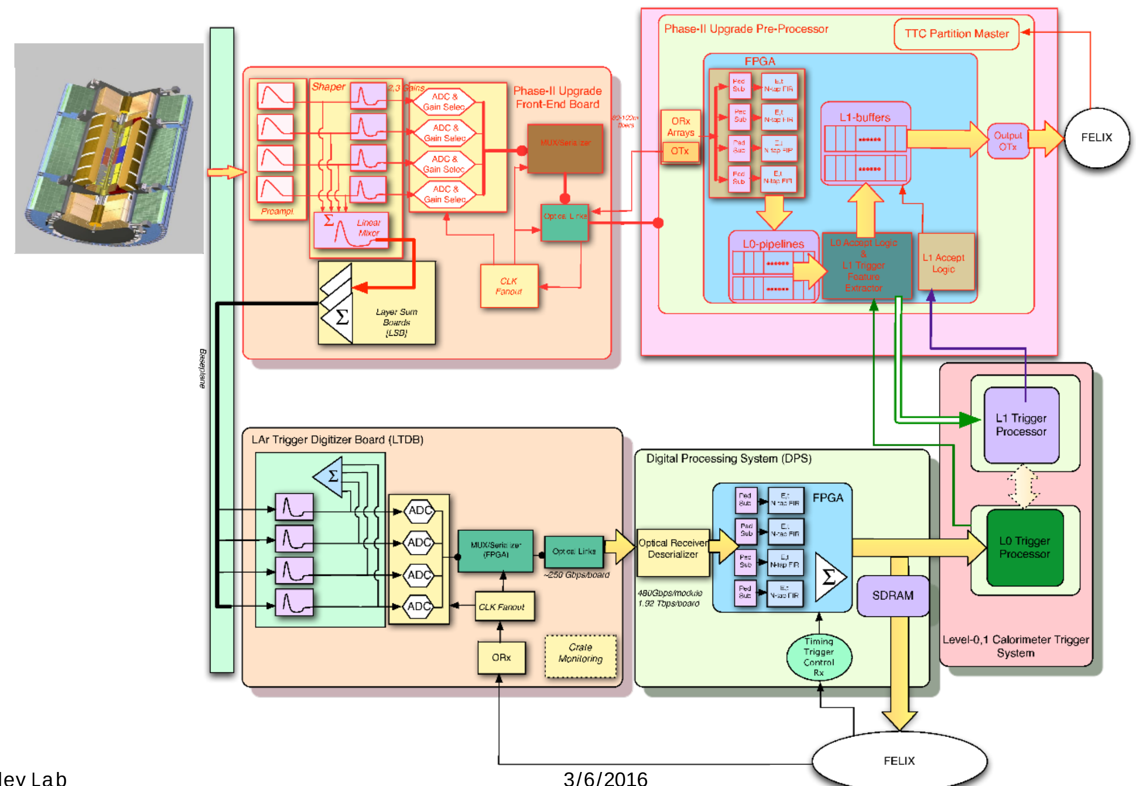


Fully Inclined 4.0



LAr Phase-2 Upgrades

- Need to replace:
  - LAr front-end electronics (on-detector) and related on-detector powering
  - LAr back-end electronics (off-detector)
- LAr front-end electronics:
  - Move to a digital 40/80 MHz streaming output which also provides ROI-based finely segmented data to L1Calo in phase-2 (supercell trigger data from phase-1 will be used for L0Calo in phase-2). Allows higher performance transforms to be used off-detector to extract maximum information for each event. Use lpGBT link system.

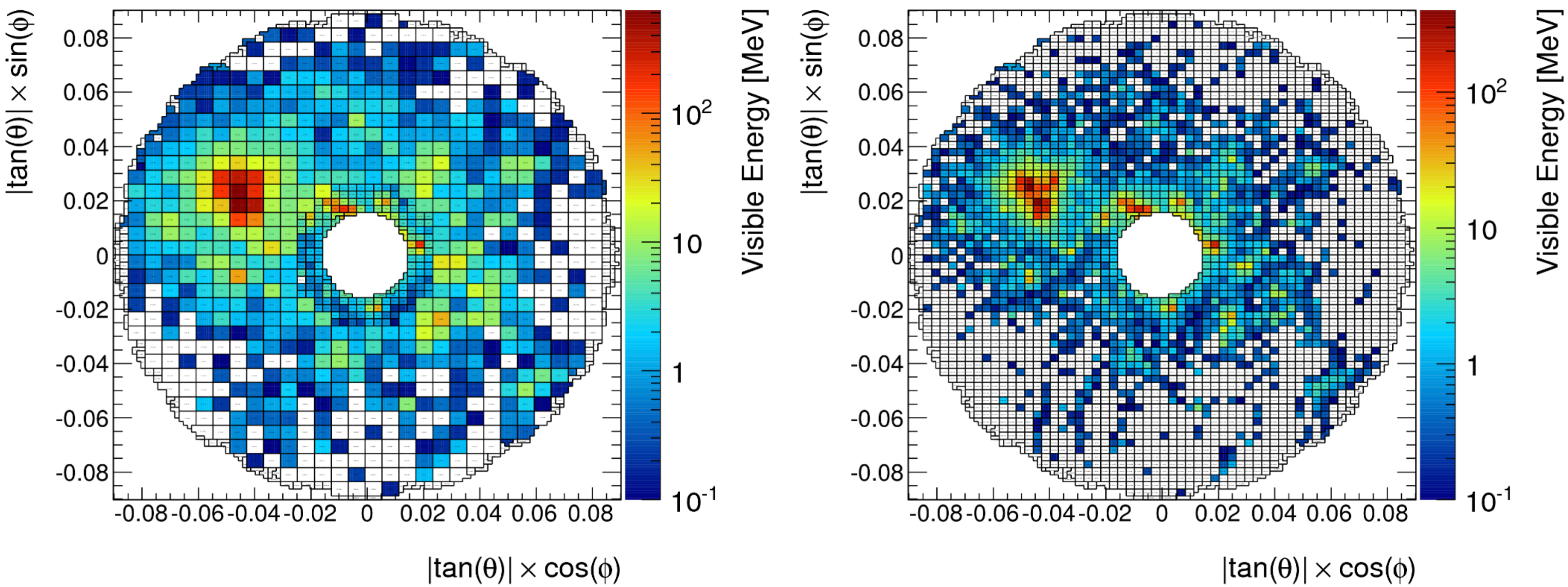


Phase-2
Data Path

Phase-1
Trigger Path

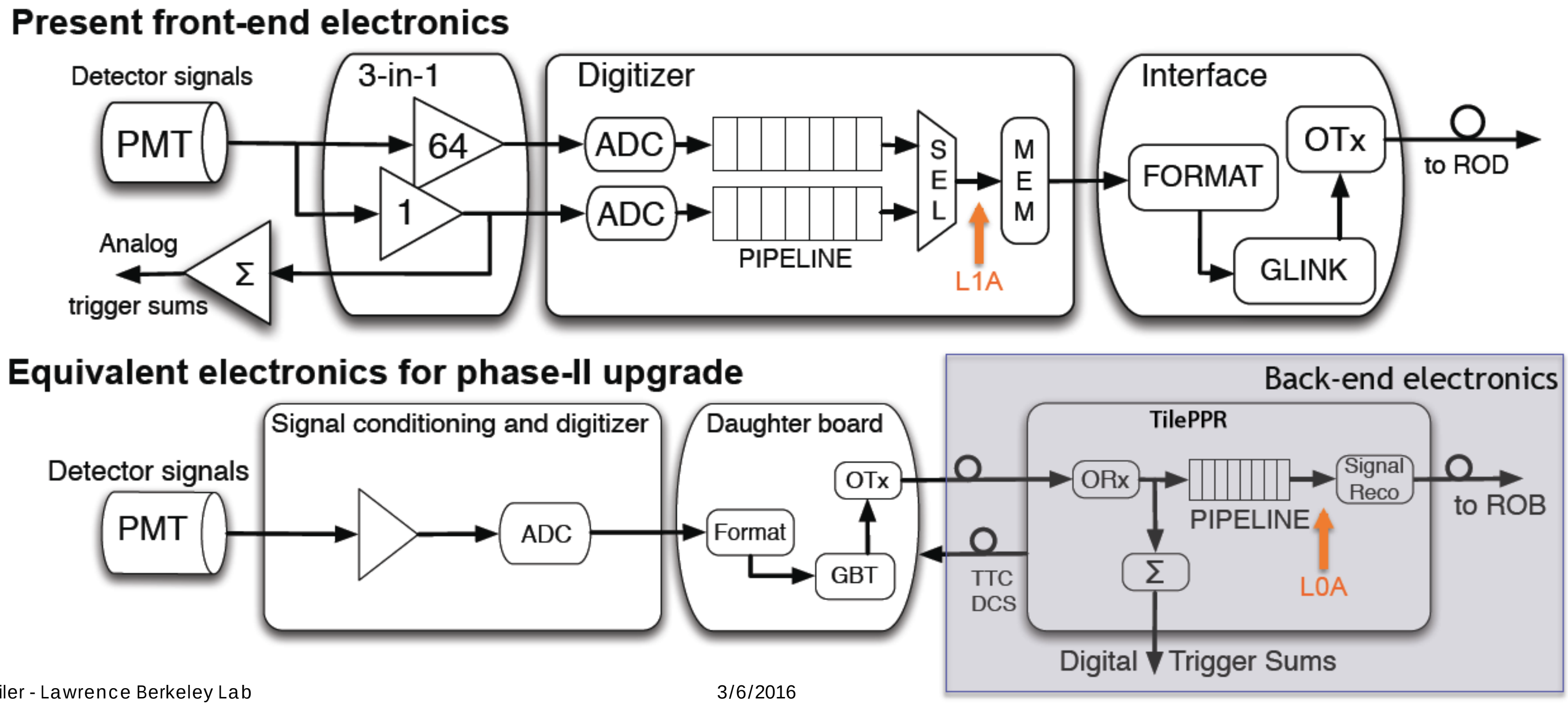
Proposed FCal → sFCal Upgrade ($3.2 < \eta < 4.9$)

- Propose reduced LAr gap of ~100μ, improved HV distribution, local cooling loops to eliminate concerns with instantaneous luminosity (studies still underway to assess impact if these improvements not done – LAr boiling is principal risk…)
- Presently 2x2 summing done inside each FCal module and additional 2x2 summing done on back of HEC. Explore impact of removing one level of summing => segmentation better by 2 in both directions. More segmentation => lower pileup noise.
- Full simulation geometry model results: example of jet in FCal (left) and sFCal (right):



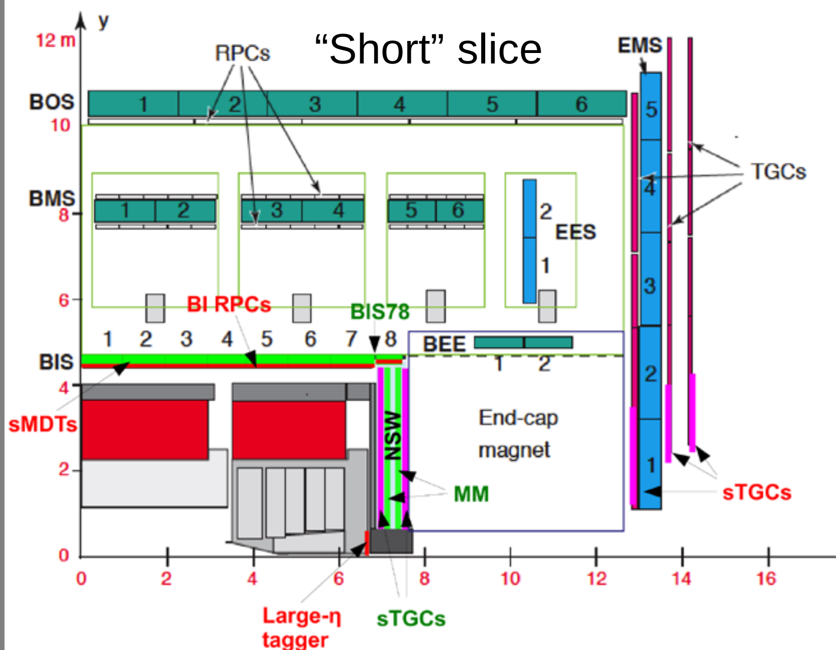
TileCal Phase-2 Upgrades

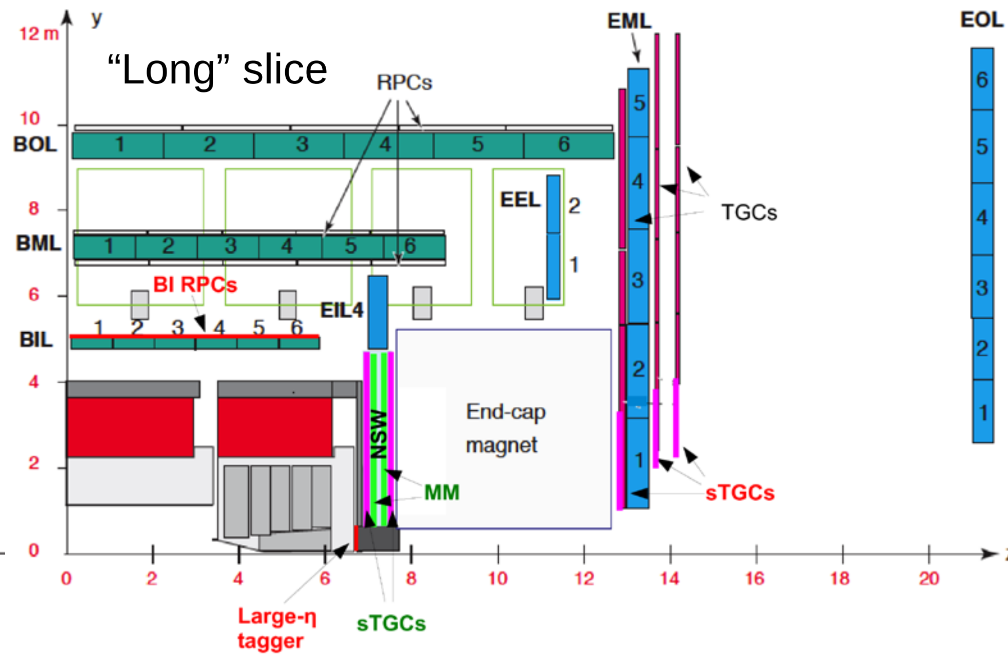
- Need to replace current front-end electronics with new signal conditioning and digitization capable of continuous operation at 40 MHz to provide low-latency inputs to L0Calo trigger and DAQ system. Stream data at 40 MHz off-detector, as for new LAr front-end electronics.
- Transmit all of this information off-detector using GBT links, and new back-end electronics contains pipelines, derandomizers, and initial summing for trigger. The digital trigger information is provided directly to the phase-1 FEXs.



Muon Phase-2 Upgrades

- Assume that it is possible to change all of the MDT electronics on the innermost barrel layer of the muon system. This eliminates any artificial limits on the L1 trigger rate and L1 latency arising from the legacy electronics.
- Replacing MDT electronics on all BI chambers allows making more significant changes. In particular, it provides the possibility to add RPCs on the innermost layer (current system has 3 doublets of RPCs, two on BM and one on BO). It also allows the use of an RPC-seeded MDT trigger in L0 => sharper P_T thresholds.
- These upgrades will require very substantial work inside ATLAS !





Muon Phase-2 Upgrades

- Proposal is to replace the BIS (smaller, inner) chambers with new chambers built using sMDT (15mm diam tubes), which leaves space to add a triplet of RPCs on the outside of these new chambers. The present MDT chambers do not allow installation of the new RPC layers (no space !)
- In addition, a triplet of RPCs would be added on the outside of the present BIL chambers (larger, outer). Here, original chambers are retained (enough space).
- Presently require all 3 doublets to fire => sensitive to single chamber efficiency and OR of all acceptance holes (of which there are many) !
- Adding a fourth layer => can implement 3/4 coincidence using all three barrel layers and reach Acceptance*Efficiency in the range of 90-95% for barrel muons (+ reduced sensitivity to lower efficiency of original RPCs).
- Finally, consider addition of a muon tagger (for segment-tagged muons, meaning an ITk track linked to a track segment behind the calorimetry in ATLAS) in the region $2.6 < \eta < 4.0$. This would effectively extend the current NSW acceptance to cover the new phase space covered by the very-forward ITk.
- Have implemented a region in the NJD shielding/support for NSW to allow installing such a layer. Note the ECT field is essentially gone by η=2.7, so unlike NSW/BW, this tagger would not bring any momentum information.

Consider Highly Segmented Timing Detector

- Extension of tracking coverage to beyond η=2.5 exposes scoping decisions made for initial detector, where calorimeter segmentation in EMEC, HEC, and FCal was reduced to save cost in regions where no precision reconstruction of most physics objects was considered useful…
- Forward region suffers from very high pileup in phase-2, and is the region where timing information could be most easily used to associate (somewhat probabilistically) energy depositions with vertex positions.
- In ATLAS, there is a thin region on front of the ECC which has been occupied by a layer of scintillators (so-called MBTS = MinBias Trigger Scintillators), recently refurbished during LS1 for use in Soft QCD and related HI measurements. Easily accessible during YETS => flexible installation scenarios even after LS3.
- Consider option of a “thin” (O(5cm)) layer in the region $2.4 < \eta < 4.0$ to provide additional information in this complex region. Also consider W/Si (or Cu/Si to reduce neutrons) to provide “pre-shower” information. Recover some missing segmentation for electron/photon/jet reconstruction, add high-precision timing (O(50ps) or better) to also provide vertex-tagging capability.

Convergence to Baseline Phase-2 Detector

- TDAQ system is considering options for hardware trigger architecture, which also affect the “front-end” of the HLT architecture. Aim for an overall decision by end 2016. TDR targeted for Dec 2017.
- ITk Layout TF is working through options for layout, particularly in the Pixel region, which are very different than what was presented in the Scoping Document. Expect to converge on Strip layout by mid-2016 in time for ITk Strip TDR to be submitted in Dec 2016. Pixel layout will take longer, but will converge in time to submit ITk Pixel TDR in Dec 2017.
- LAr calorimeter upgrade has an option to replace the present FCal with an sFCal. This decision, based largely on balancing risk versus performance, is expected to be made by mid-2016. TDR in Fall 2017.
- The Muon upgrade is focusing on an aggressive upgrade in which all of the legacy on-detector electronics is replaced (this was thought to be completely impractical at the time of the LoI in 2012). The scope of this activity will be finalized by mid-2016. TDR in Summer 2017.
- Expect to reach an overall baseline for Phase-2 upgrades this year, and will then proceed to submit all TDRs on a timescale of end-2017.