The upgrade of the ATLAS Trigger and Data Acquisition system for the High Luminosity LHC

Kazuki Todome (Science Tokyo)
on behalf of the ATLAS collaboration

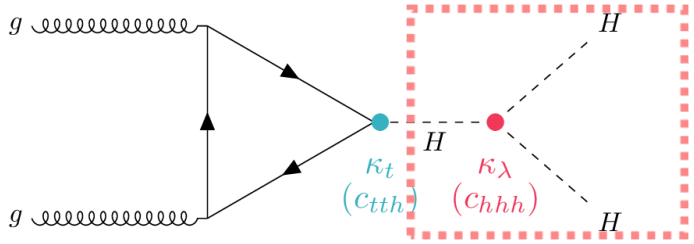
Institute of SCIENCE TOKYO

ATLAS EXPERIMENT

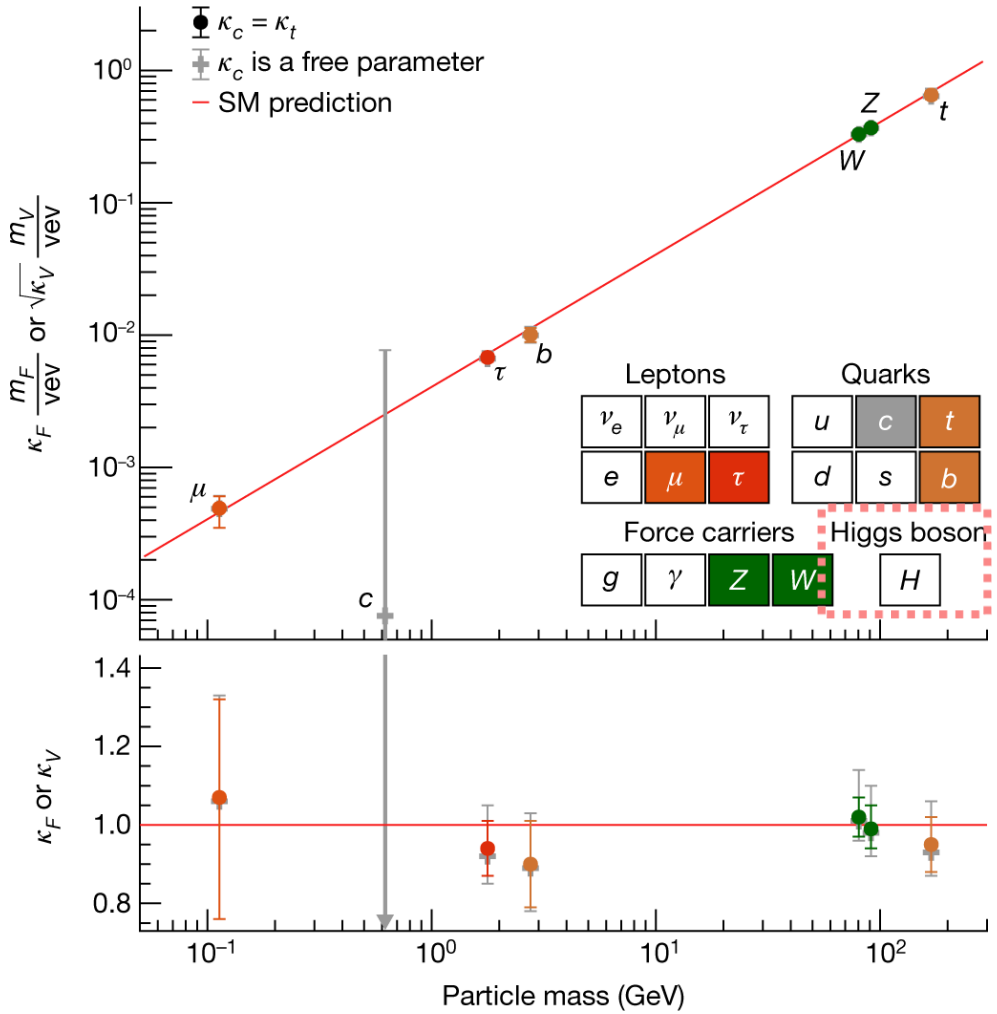
DIS2026 - 6 May 2026
Bologna

(One of) Physics Motivations

- Since Higgs boson discovery in 2012, a wide range of its characteristics have been measured until current Run3
- One of key characteristics we are missing today is Higgs boson self coupling



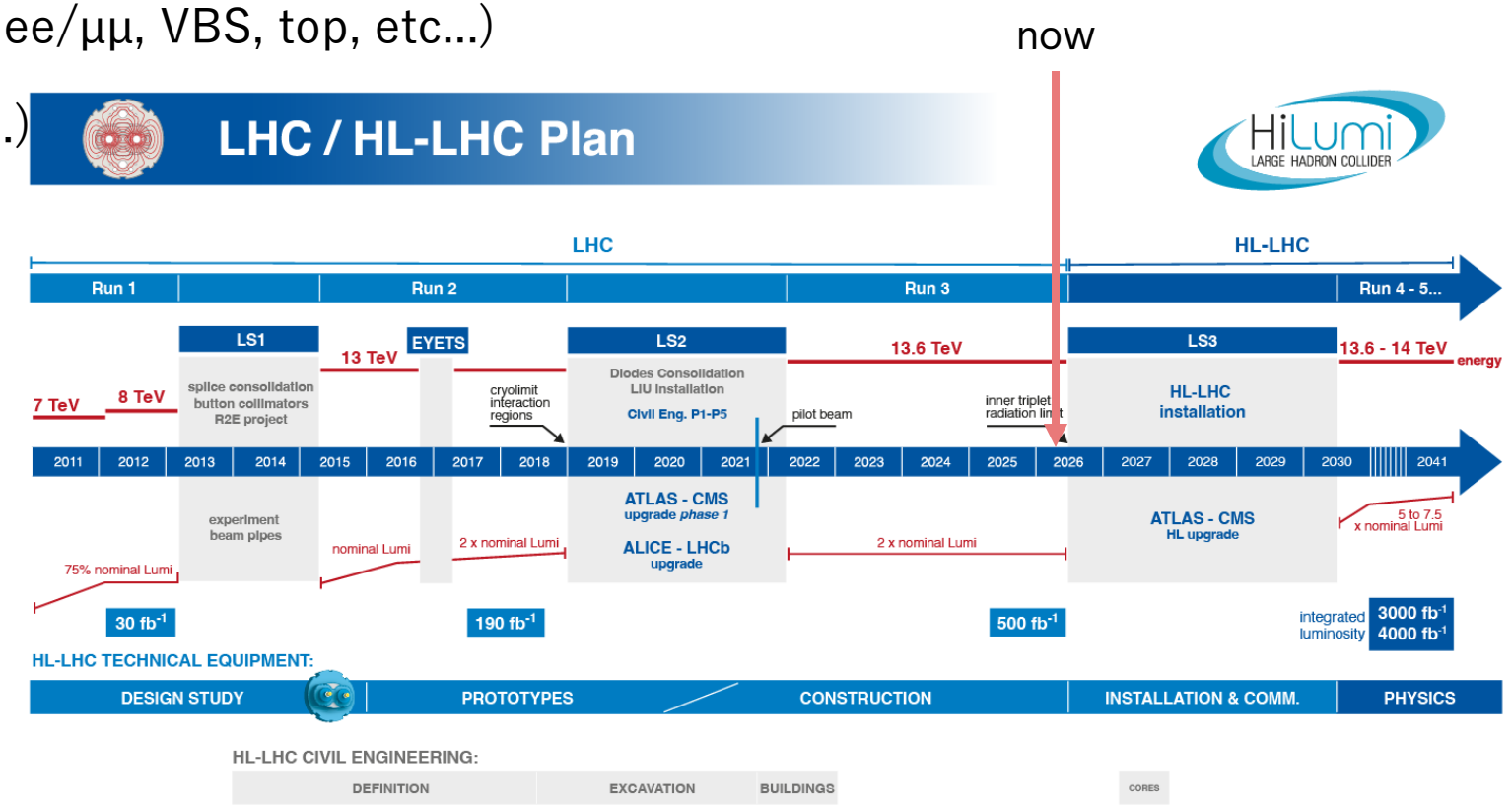
- What we need to measure is di-Higgs boson production
- However, di-Higgs boson production cross-section is O(10^{-3}) smaller than Higgs boson production cross-section
- Thus, we need to increase statistics (= integrated luminosity)



Nature 607 (2022) 52–59

HL-LHC Physics Goals

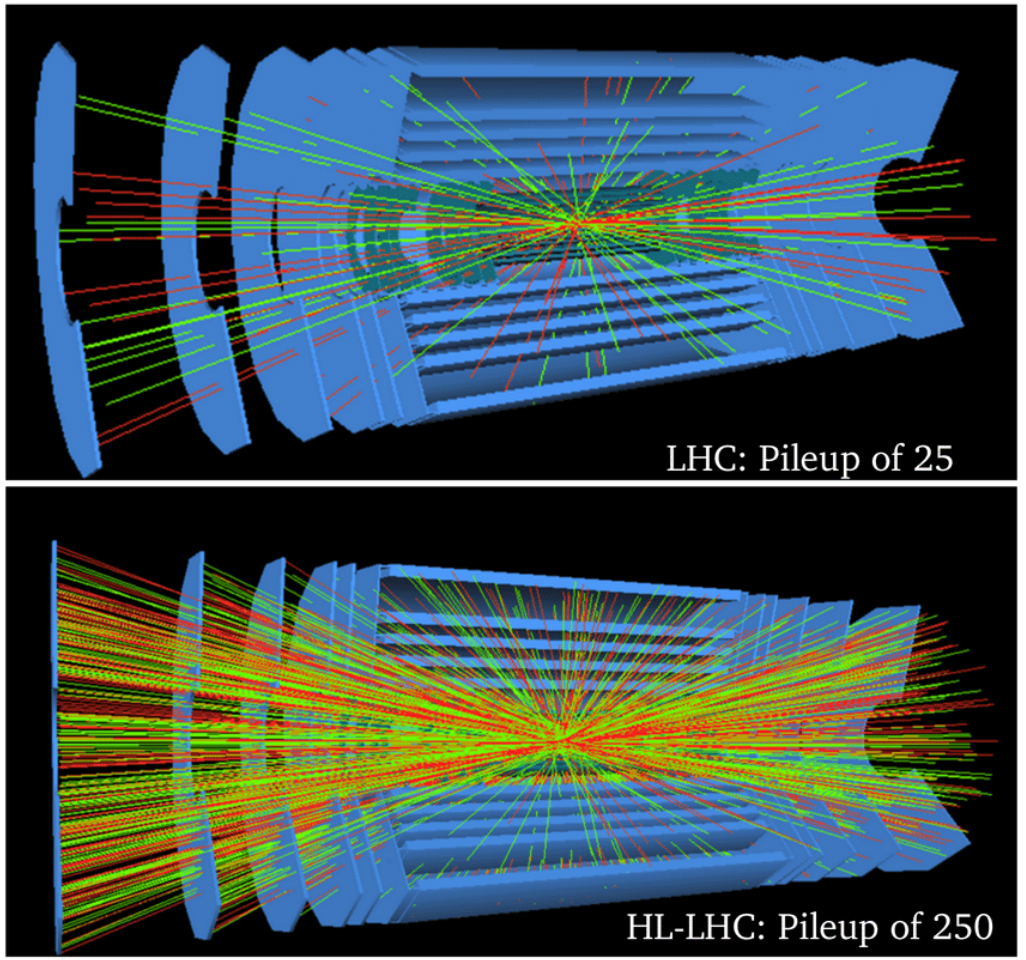
- HL-LHC project, planned from 2030, allows us to access phase space we couldn't reach due to statistics
  - Di-Higgs measurements (HH → 4b/bbγγ/bbττ)
  - Higgs precision measurements (H → bb/cc/μ μ/ττ/etc…)
  - SM precision measurements (Z → ee/μμ, VBS, top, etc…)
  - BSM search (SUSY, DM, LLP, etc…)



Challenge toward HL-LHC

- Access to this large-scale statistic is achieved by increasing the luminosity, which raises the pileup up to ~200 at a 40 MHz bunch-crossing rate, resulting in
  - The spatial density of the signal/background event becomes quite high
  - The frequency of signal events increases significantly
- Thus, adding to the beam upgrade, all ATLAS detector, its Trigger and DAQ system need to be upgraded

	Run3 (current)	HL-LHC
Instantaneous luminosity	2×10^{34} $cm^{-2}s^{-1}$	$5\text{-}7.5\times10^{34}$ $cm^{-2}s^{-1}$
Integrated luminosity	500 fb^{-1}	3000 fb^{-1}
pileup	~60	<200

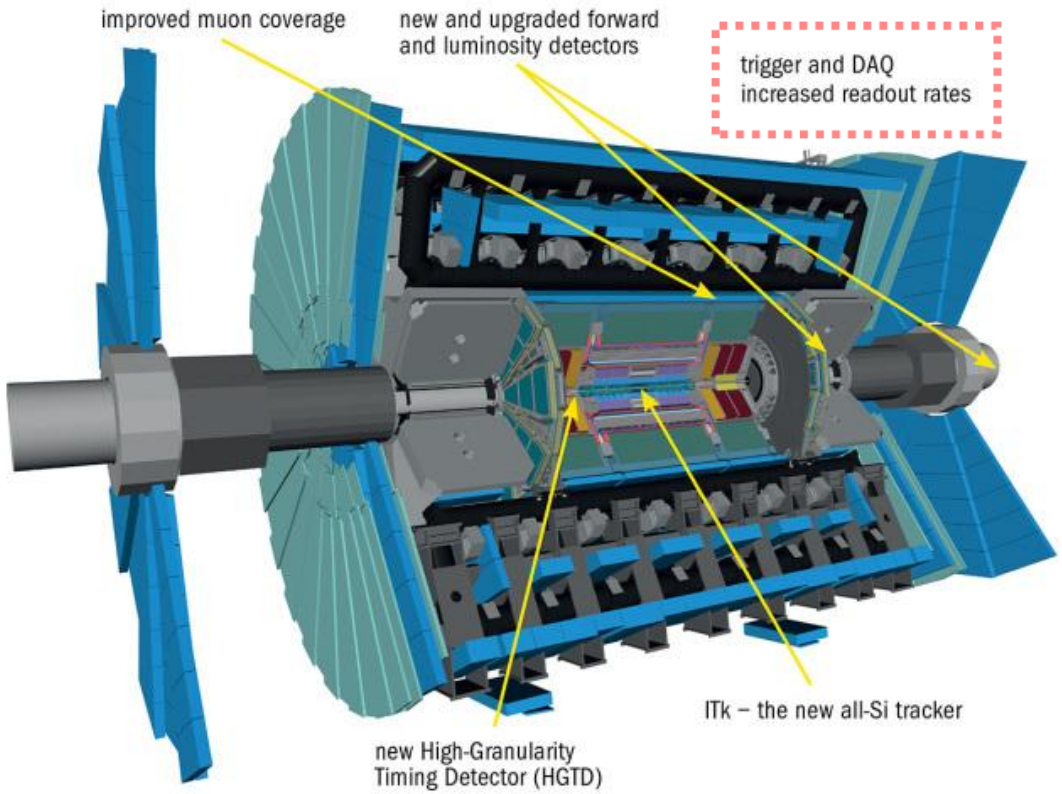


Upgrade menu for ATLAS detector

- Most of detector update topics are covered in various talks
  - Muon detector by Gabriella Gaudio
  - Luminosity detector by Vincent Hedberg
  - Inner Tracker (ITk) by Hao Pang

- Detector upgrades enable us to “observe” signal events buried among background events

- However, it is highly challenging to trigger and record them
  - With sufficient efficiency
  - Without exceeding data recording bandwidth



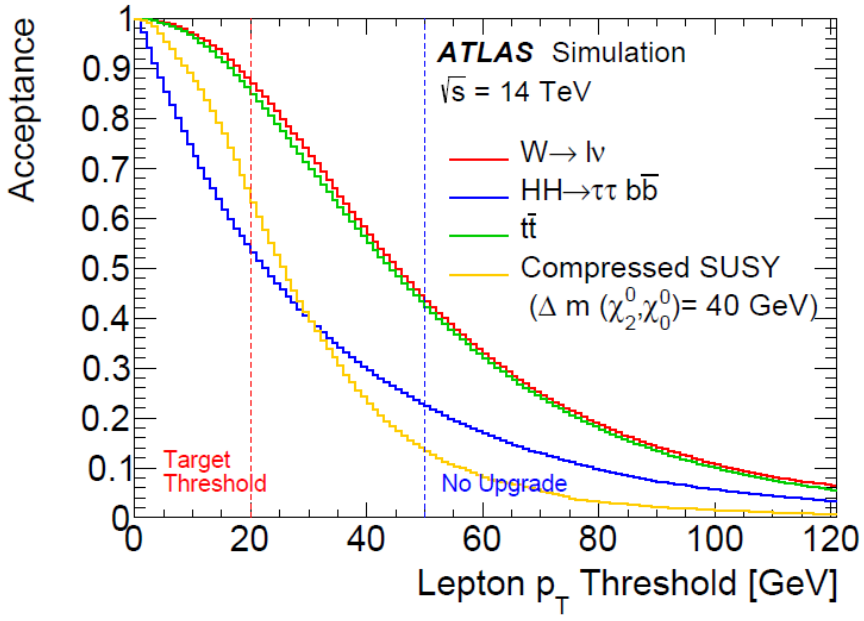
Critical effect without upgrade

Institute of SCIENCE TOKYO

- Simple extrapolation from the current system to HL-LHC
  - Level 1 trigger can only reach up to 100 kHz overall; thus, trigger threshold needs to be increased

Trigger	Level-1 p_T Threshold [GeV] at $\mathcal{L} = 3 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	Level-1 Rate [kHz]	Level-1 p_T Threshold [GeV] at $\mathcal{L} = 7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
isolated single e	32	14	50
di-e	19	5	35
single μ	25	15	40 (with low efficiency)

- This threshold results significant reduction of signal acceptance
  - HH → bbττ: only ~20%
  - Compressed SUSY: only ~15%
  - W → l ν , ttbar: only ~45%

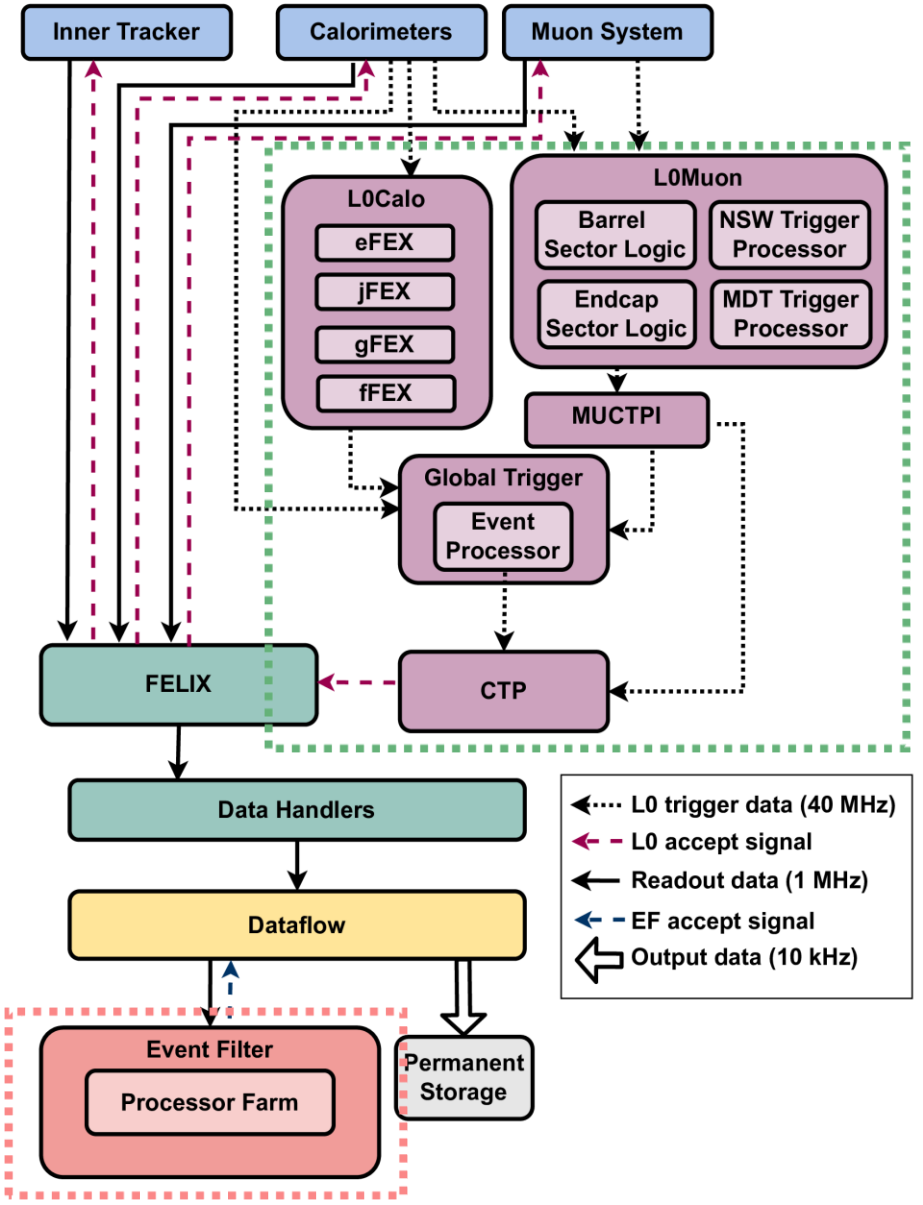


CERN-LHCC-2017-020

- It's crucial to upgrade Trigger and Data Acquisition (TDAQ) system

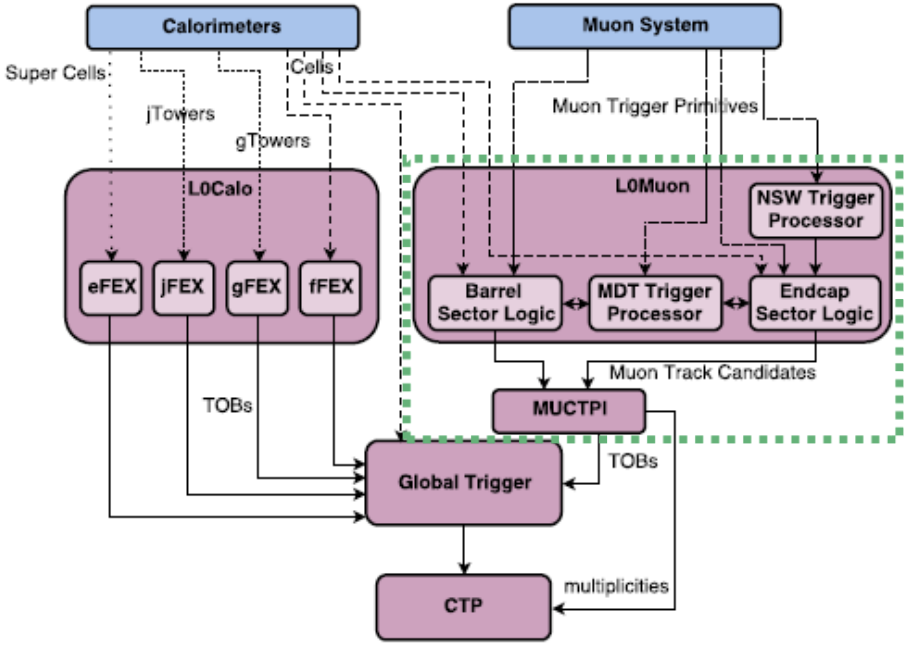
New TDAQ architecture at HL-LHC

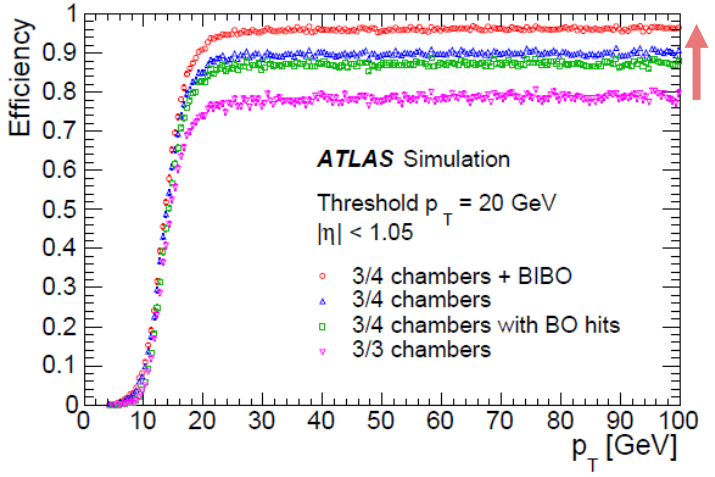
- ATLAS TDAQ system is composed of two systems
  - Level 0 Trigger system
    - Based on calorimeters and muon system signals, send trigger to all sub-detectors
    - 40 MHz input
    - 1 MHz output (Run3: 100 kHz)
  - Event Filter
    - Based on all sub-detector signals, filter event to be recorded into permanent storage
    - 1 MHz input (Run3: 100 kHz)
    - 10 kHz output (Run3: 2.5 kHz)



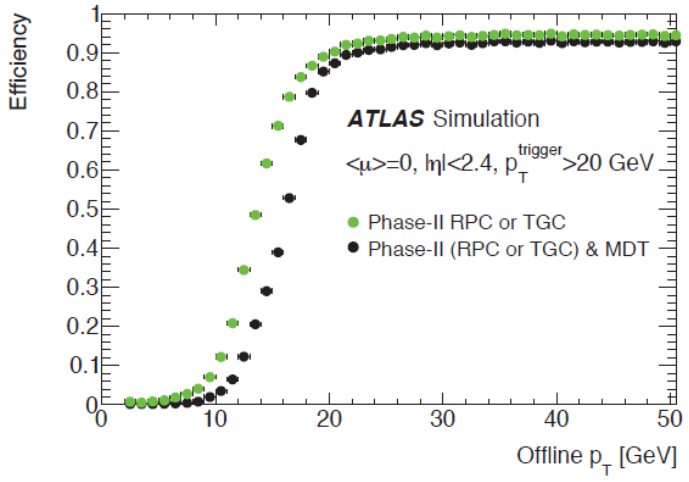
L0 Muon

- Upgrade menu:
  - New detectors (RPC, TGC, NSW) to cover blind spots
    - Improve efficiency from ~80% to ~96%
  - MDT (Monitored Drift Tube) signal is available for L0
    - pT accuracy is improved due to high position resolution
    - Turn-on curve is getting more accurate
- Benefit example: No Upgrade case accepts only 1% of SUSY signal with di-muon trigger, but this can be improved to 27%

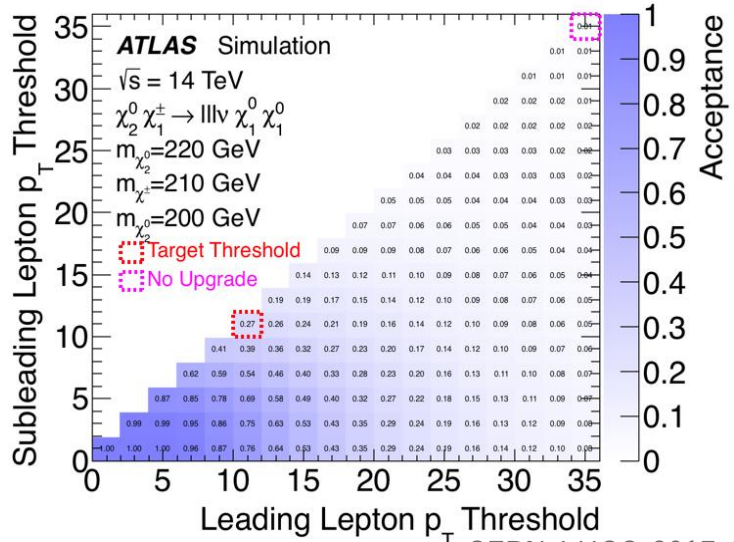




(a) *RPC triggers for the Barrel Region ($|\eta| < 1.05$)*

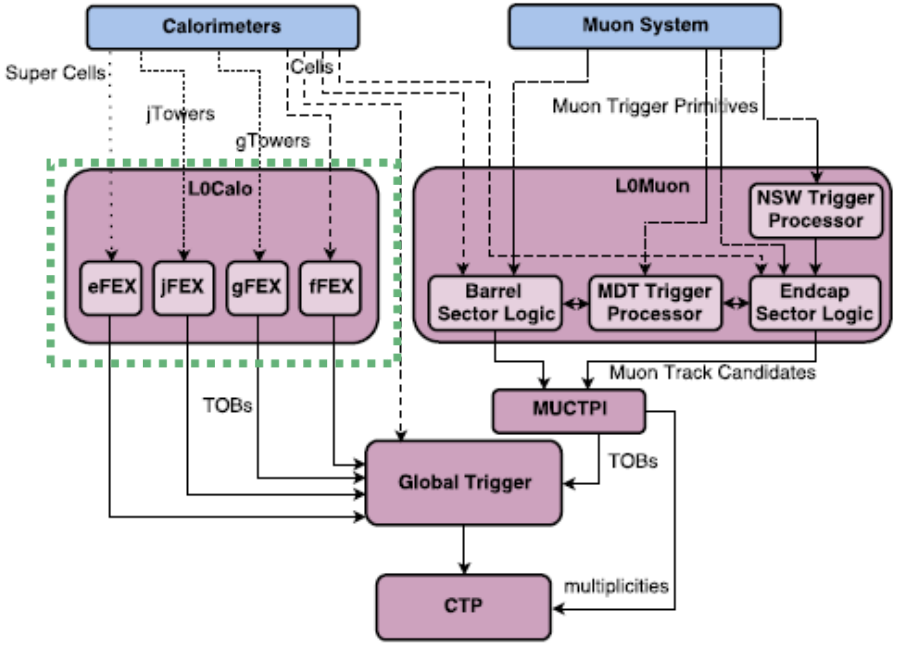


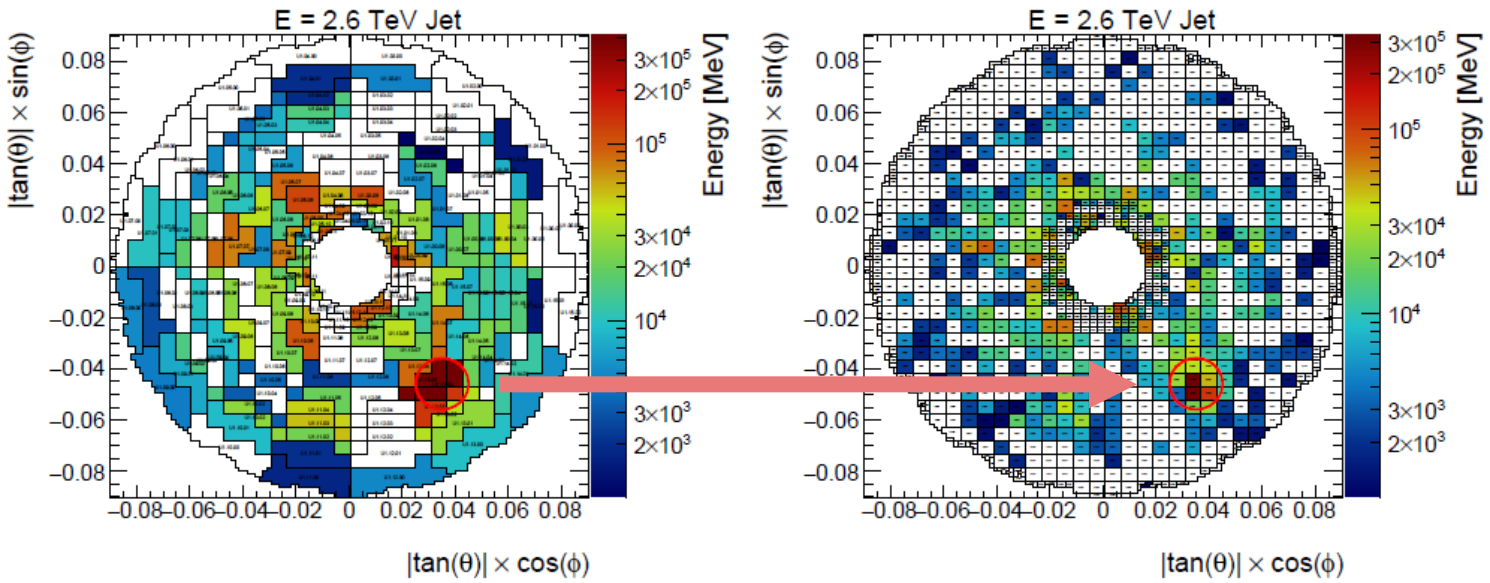
(b) *Muon trigger ($|\eta| < 2.4$) with or without MDT.*



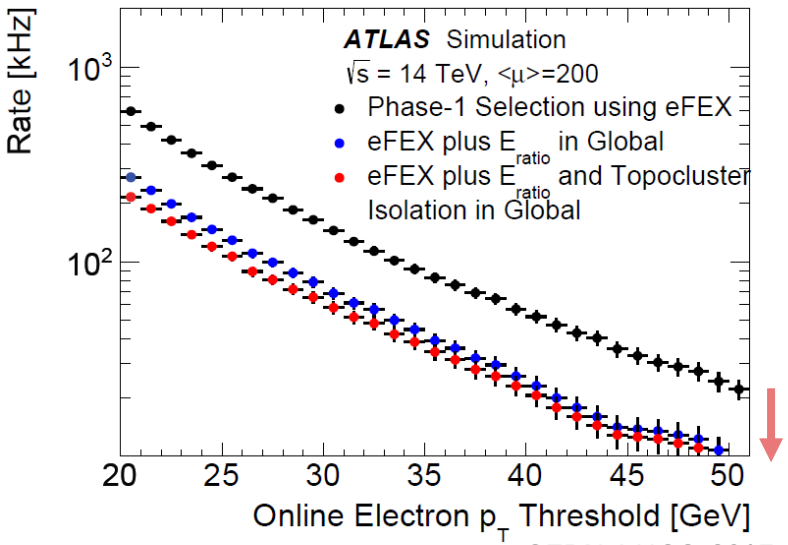
L0 Calo

- Upgrade menu:
  - Replace all front-end system to enable full-granularity readout at 40 MHz
  - High granularity cell level signal is to be available in L0
    - Resulting higher granularity jet reconstruction
- Benefit example: single electron trigger rate can be highly reduced by suppressing jet → e fake (using Global trigger, next page)





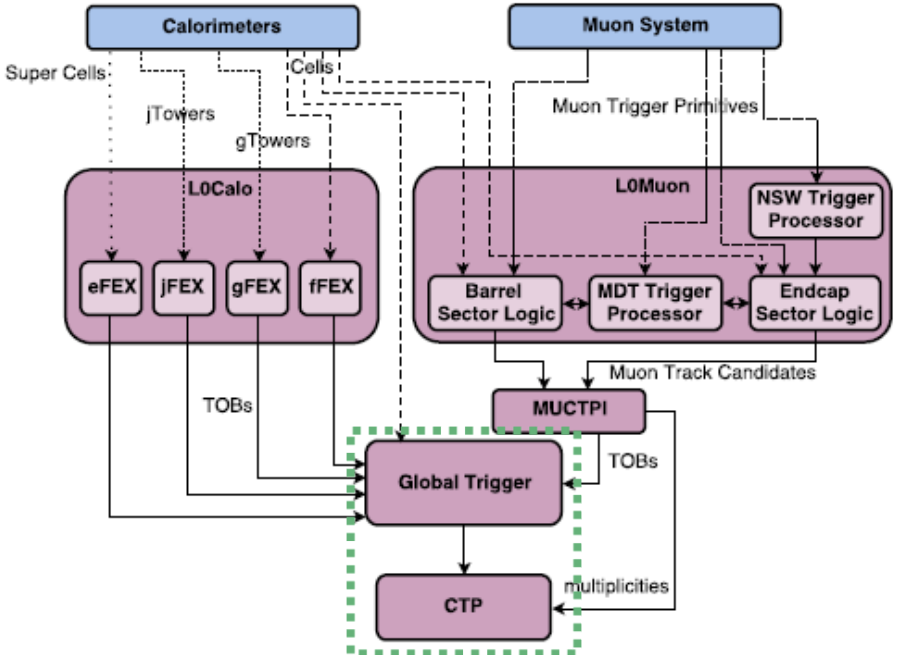
CERN-LHCC-2017-020

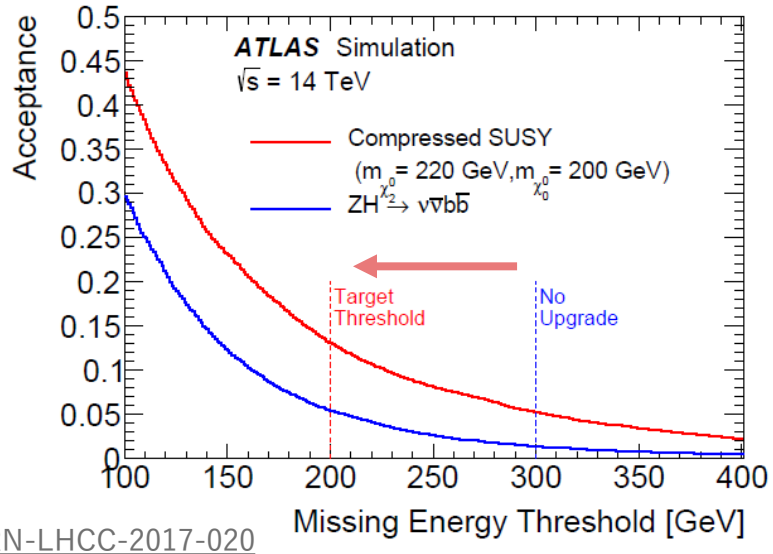


CERN-LHCC-2017-020

L0 Global Trigger and CTP

- L0 Global Trigger: Combining calorimeters and muon system outputs, perform offline like reconstruction, such as
  - topo-clustering
  - anti-kT jet reconstruction
  - high resolution E_T^{miss} estimation
- New approach made possible by new generation FPGA and recent Multi-Gigabit Transceiver
- CTP (Central Trigger Processor): combining 1024 trigger item (512 for Run3) to generate L0 Trigger
- Benefit example: E_T^{miss} Trigger threshold can be decreased down to 200 GeV, resulting in a SUSY acceptance improved from ~5% to ~15%

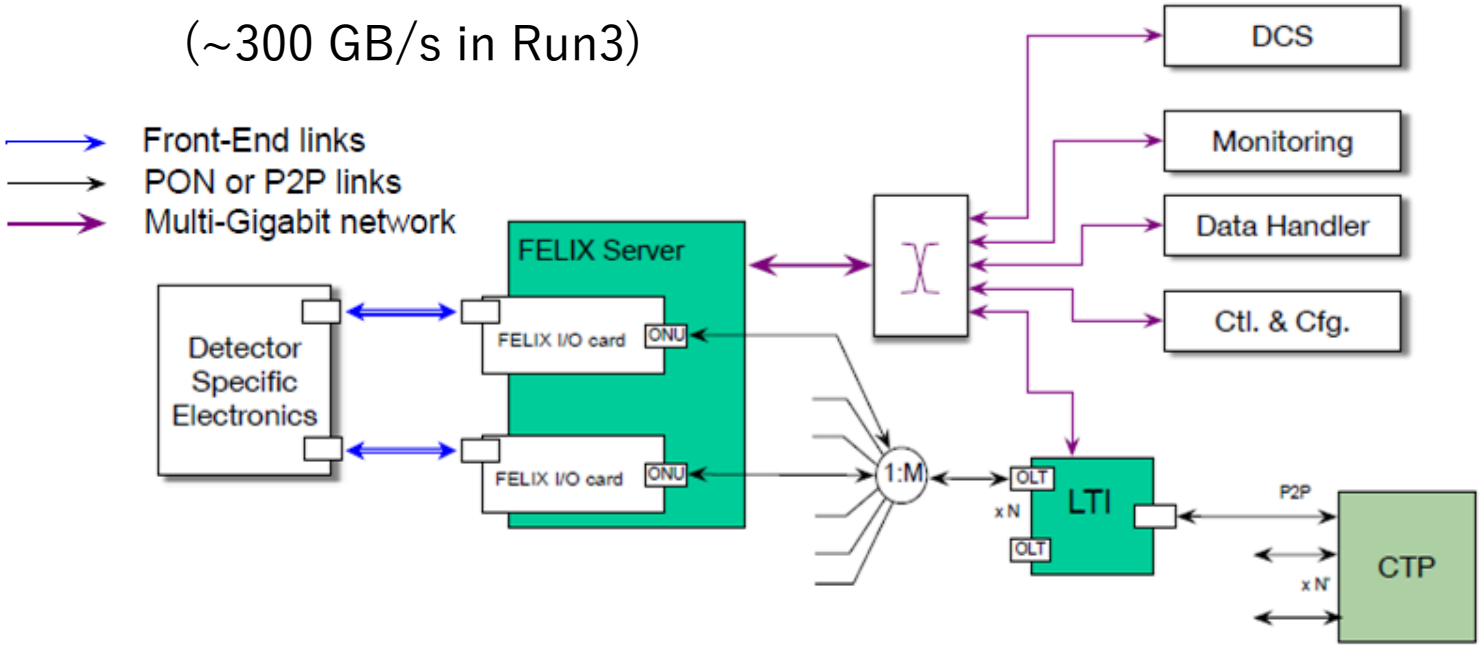


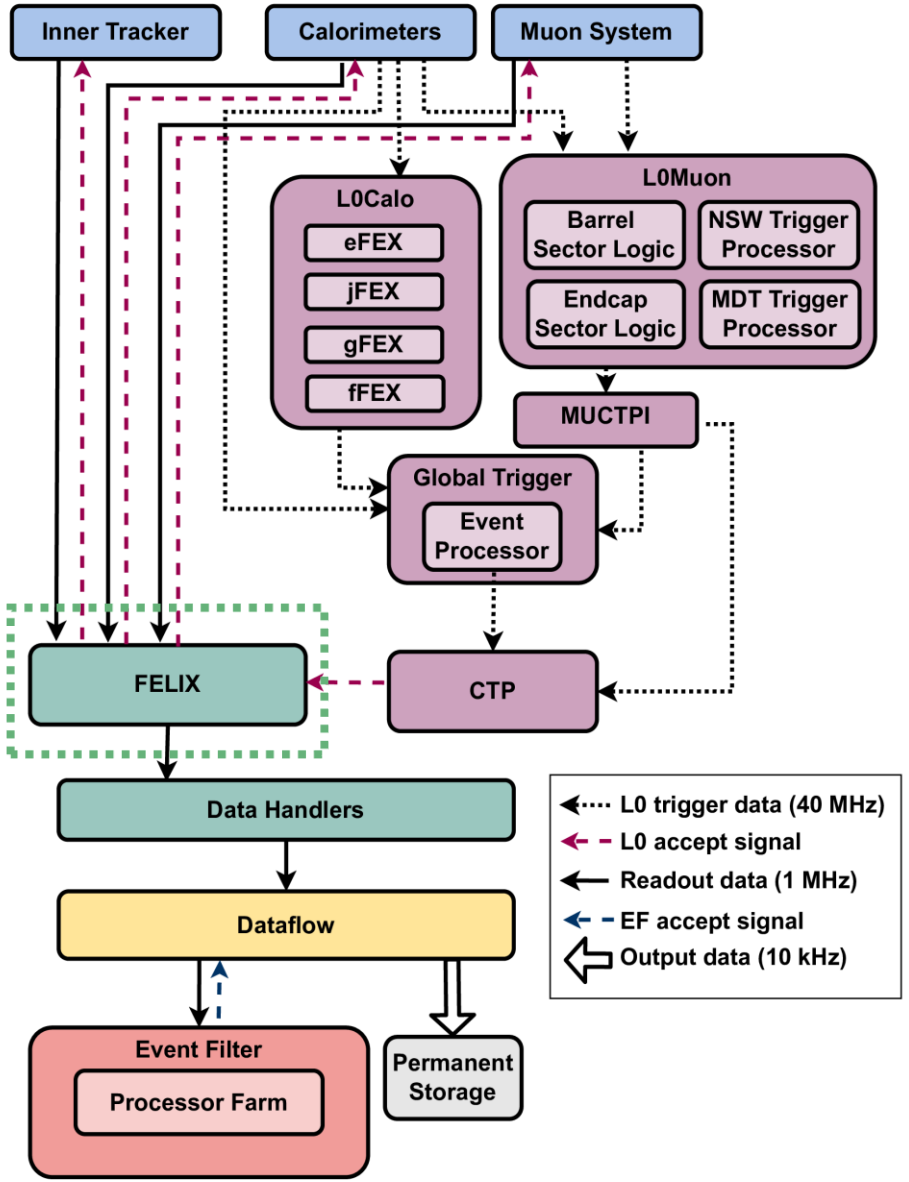


CERN-LHCC-2017-020

FELIX

- Replacing sub-detector specific custom hardware, FELIX to be used as a uniform DAQ system
  - This system is built with commodity networking equipment and servers, making it easy to scale and upgrade in the future
  - This system collects all detector signals, then distributes 4.6 TB/s data to commodity network (~300 GB/s in Run3)



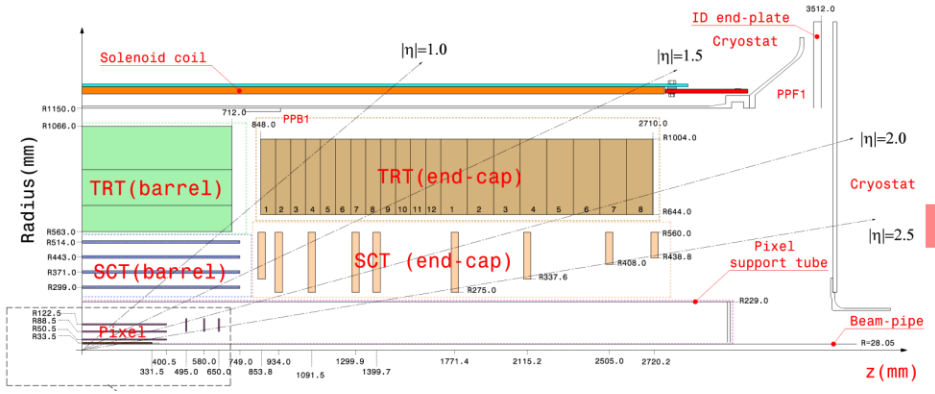


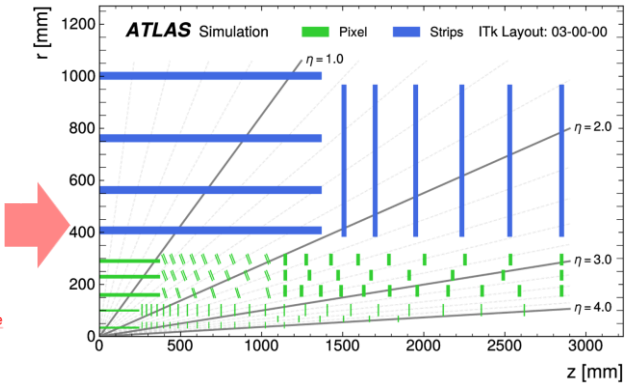
Event Filter

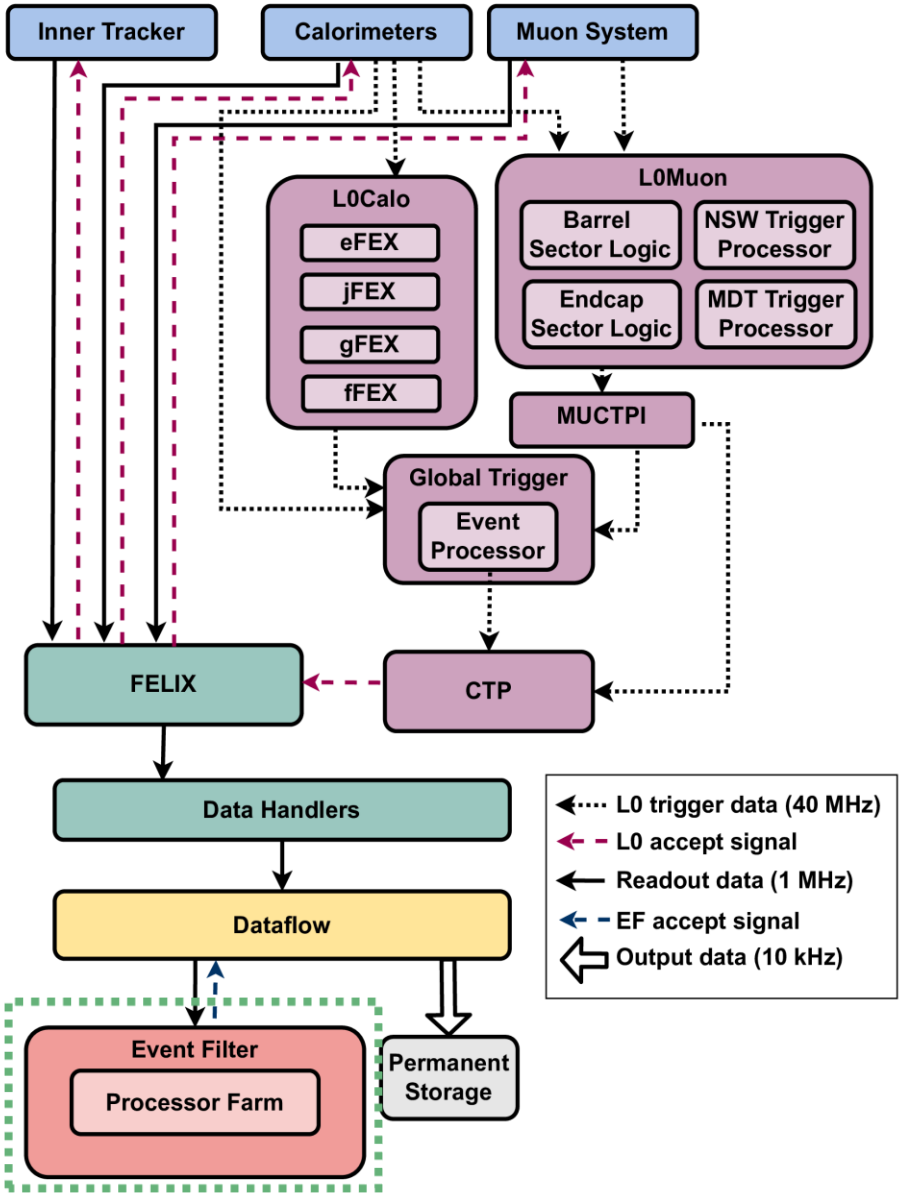
- Filter events useful for physics analysis, to record into permanent storage

- At this stage
  - Run3: request-driven access to data
  - Event Filter: full event building

- Challenging point: Tracking, because of ITk
  - Wider range of coverage $|\eta|<2.5$ to $|\eta|<4.0$
  - All high granularity silicon: from 100 Mch to more than 5 Gch

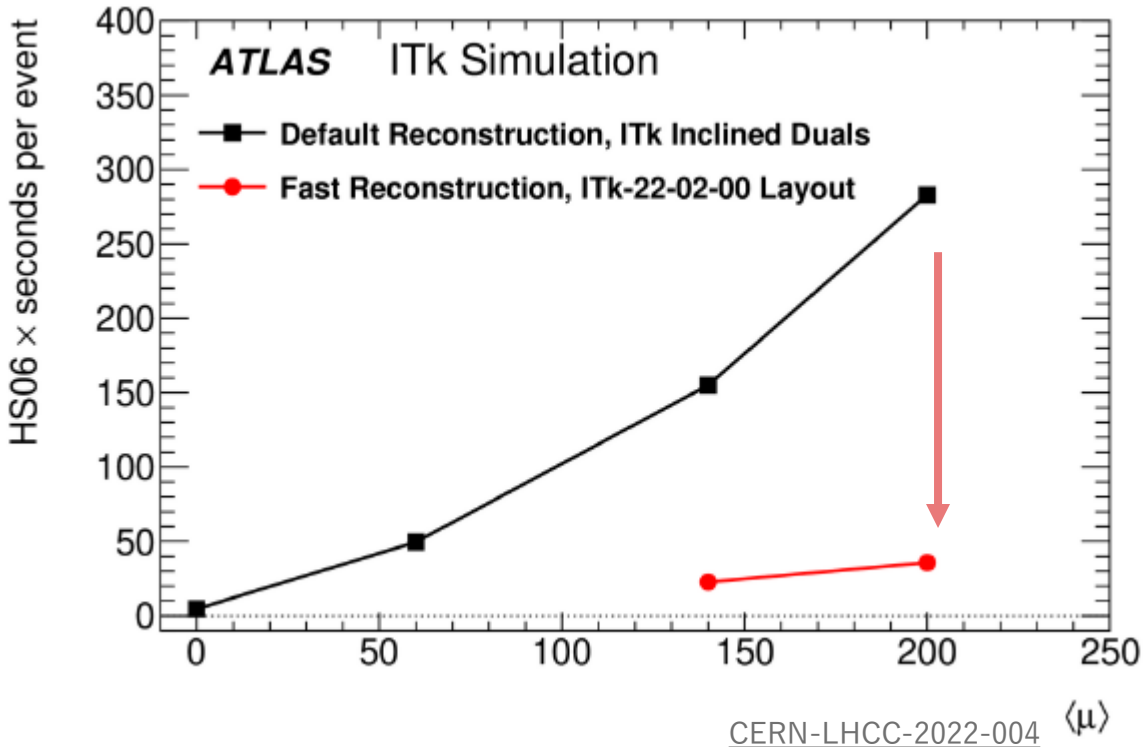




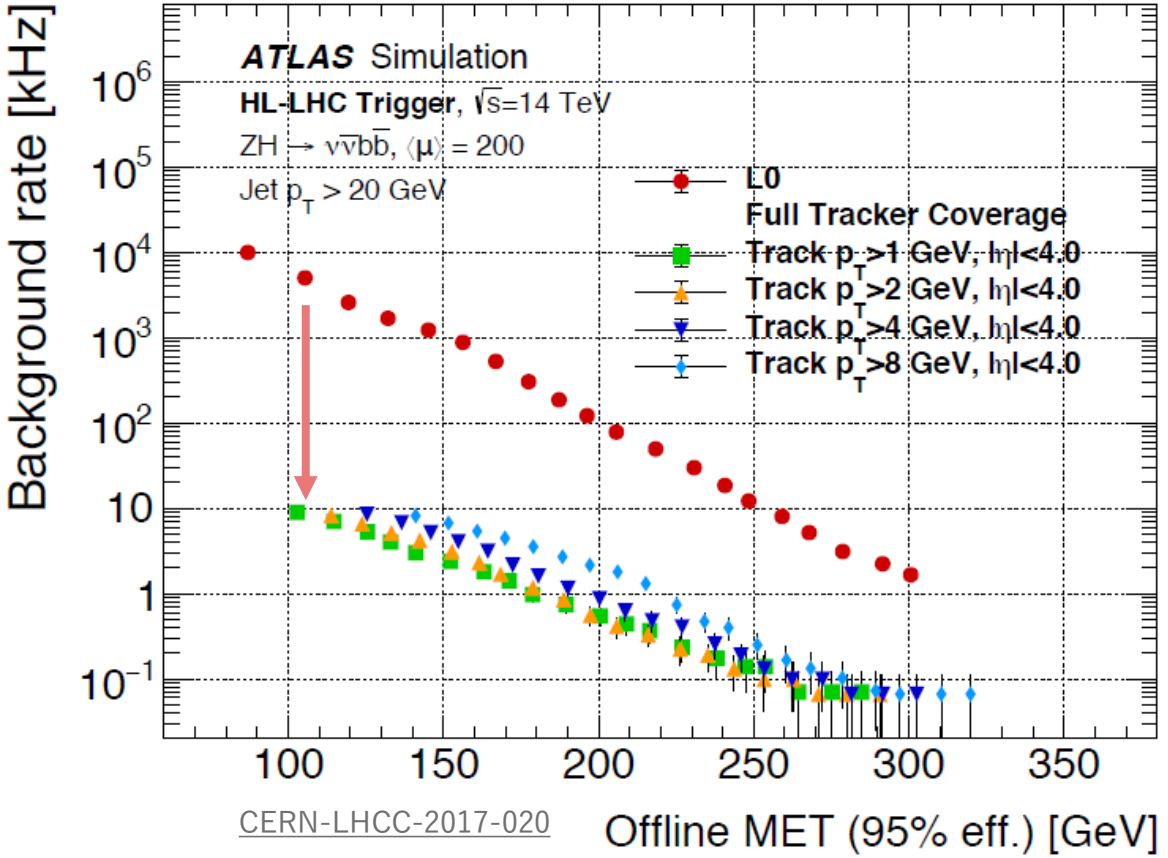


Event Filter Tracking

- From 5 Gch ITk signal, there are 10k tracks /event must be reconstructed.
- Track reconstruction part (Event Filter Tracking) is the most resource-consuming part of the Event Filter
- Through software optimization, the CPU-based tracking reached 8 times speedup
- Benefit example: Fake background rate firing E_T^{miss} trigger can be suppressed ~$O(10^{-2})$ at most thanks to track-based pileup suppression



CERN-LHCC-2022-004

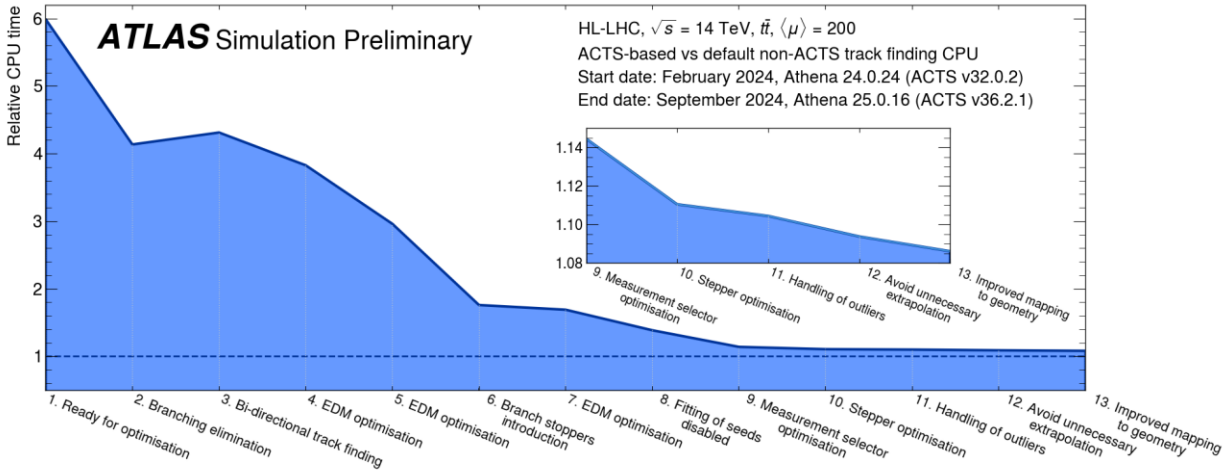


CERN-LHCC-2017-020

EFT Technologies

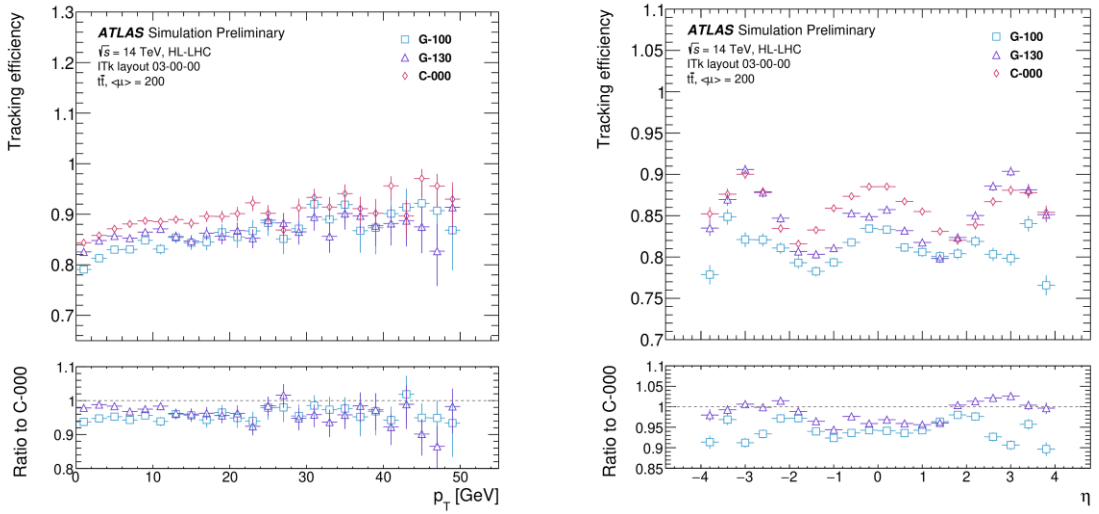
- Current plan to move:
  CPU-only fast-tracking / mixed CPU+GPU tracking

- CPU option:
  mature technologies integrated within
  ACTS (A Common Tracking Software)
  - Achieved throughput comparable to the highly optimized baseline,
    using a modern, multi-thread framework



ATL-PHYS-PUB-2024-017

- CPU+GPU option:
  Taking advantage of highly parallel GPU architecture
  - Boosts throughput of parallelizable tasks
  - Opportunity to run GBTS (Graph-Based Track Seeding) or more complex algorithms



ATL-DAQ-PUB-2025-003

Target trigger menu

- With all the updates introduced, it will be possible to maintain or even lower pT threshold in HL-LHC

- Furthermore, those upgrade enables the introduction of entirely new triggers targeting forward region, which is useful for
  - VBF inclusive
  - Precision measurements for proton PDF etc...

Table 6.4: *Representative trigger menu for 1 MHz Level-0 rate. The offline p_T thresholds indicate the momentum above which a typical analysis would use the data.*

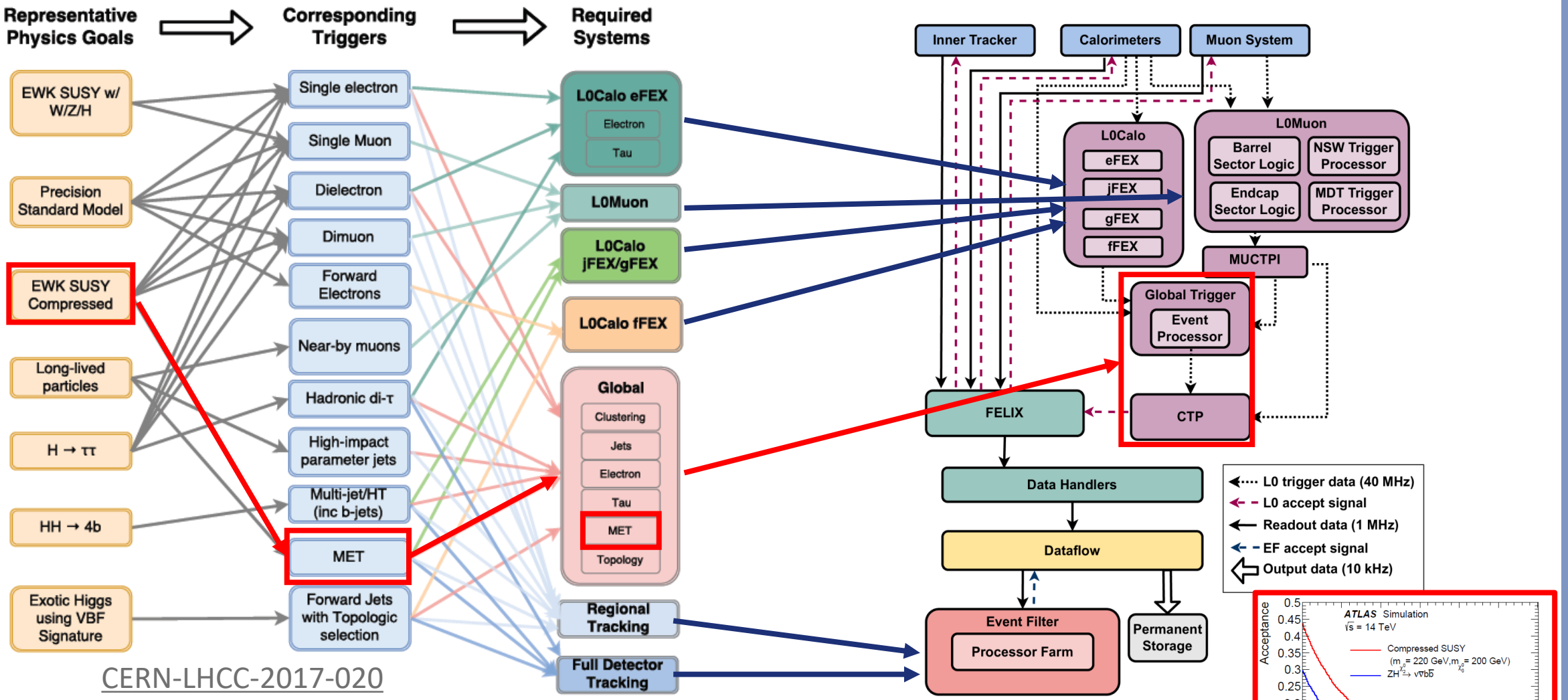
Trigger Selection	Run 1 Offline p_T Threshold [GeV]	Run 2 (2017) Offline p_T Threshold [GeV]	Planned HL-LHC Offline p_T Threshold [GeV]	L0 Rate [kHz]	After regional tracking cuts [kHz]	Event Filter Rate [kHz]
isolated single e	25	27	22	200	40	1.5
isolated single μ	25	27	20	45	45	1.5
single γ	120	145	120	5	5	0.3
forward e			35	40	8	0.2
di-γ	25	25	25,25		20	0.2
di-e	15	18	10,10	60	10	0.2
di-μ	15	15	10,10	10	2	0.2
$e-\mu$	17,6	8,25 / 18,15	10,10	45	10	0.2
single τ	100	170	150	3	3	0.35
di-τ	40,30	40,30	40,30	200	40	0.5^{+++}
single b-jet	200	235	180	25	25	0.35^{+++}
single jet	370	460	400			0.25
large-R jet	470	500	300	40	40	0.5
four-jet (w/ b-tags)		45†(1-tag)	65(2-tags)	100	20	0.1
four-jet	85	125	100			0.2
H_T	700	700	375	50	10	0.2^{+++}
E_T^{miss}	150	200	210	60	5	0.4
VBF inclusive			2x75 w/ ($\Delta\eta > 2.5$ & $\Delta\phi < 2.5$)	33	5	0.5^{+++}
B-physics^{++}				50	10	0.5
Supporting Trigs				100	40	2
Total				1066	338	10.4

† In Run 2, the 4-jet b-tag trigger operates below the efficiency plateau of the Level-1 trigger.
$^{++}$ This is a place-holder for selections to be defined.
$^{+++}$ Assumes additional analysis specific requires at the Event Filter level

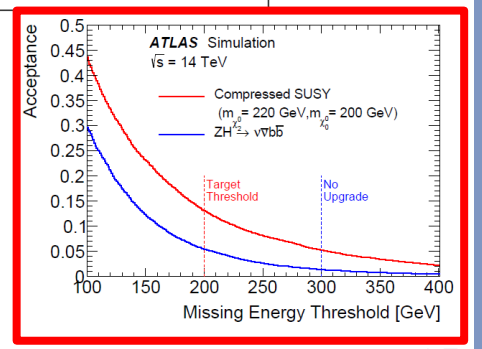
CERN-LHCC-2017-020

Overall review

Institute of SCIENCE TOKYO



CERN-LHCC-2017-020



- All benefits introduced in this talk are just a part of our physics goals
- These upgrades will open the door to a wide range of unknown physics

CERN-LHCC-2017-020

Summary

- ATLAS is fundamentally restructuring its TDAQ system toward HL-LHC
  - L0 Muon
  - L0 Calo
  - L0 Global
  - Event Filter
  - Trigger menu

- By overcoming the challenge of 200 pile-up, these upgrades ensure that broad signal of new physics, such as di-Higgs and dark matter, are successfully captured rather than lost in the background

- End of Run3 is reaching, and we are transitioning toward full speed HL-LHC construction