Overview of ATLAS detector upgrade projects for HL-LHC in Sweden

"A summary of summaries"

Partikeldagarna 2018, Lund, Oct 16-17, 2018

Christian Ohm (KTH), also obo Lund, Stockholm and Uppsala ATLAS groups

ATLAS Sweden Day (Monday) featured an upgrade session

15:00 **High granularity timing detector** — 15m
Speaker: Bengt Lund-Jensen (KTH Royal Institute of Technology (SE))
HGTD_at_KTH.pdf

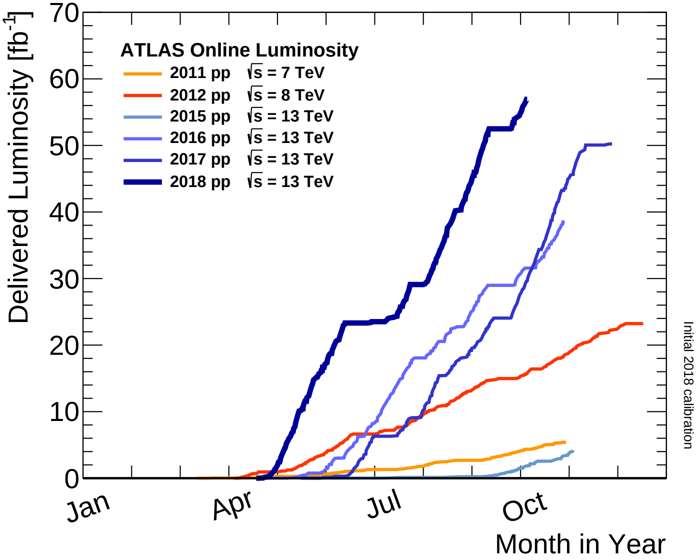
15:20 **ITk** — 15m
Speaker: Geoffrey Mullier (Lund University (SE))
ITkATLASDay_Final...

15:40 **LUCID** — 15m
Speaker: Vincent Hedberg (Lund University (SE))
LUCID.pdf

16:00 **Tile Calorimeter** — 15m
Speaker: Christian Bohm (Stockholm University (SE))
Tile.pdf

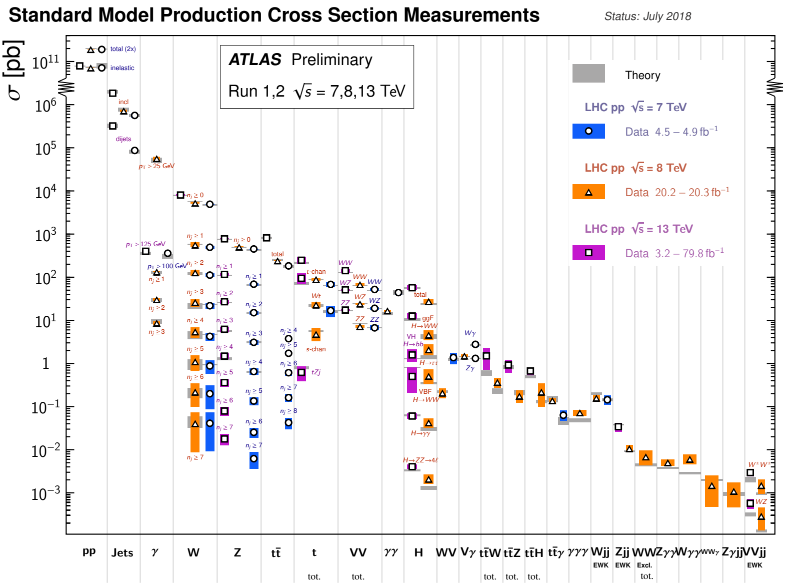
16:20 **Trigger upgrade** — 15m
Speaker: Mikael Martensson (Uppsala University (SE))
trigger_upgrade_mi...

Evolution of the LHC data set



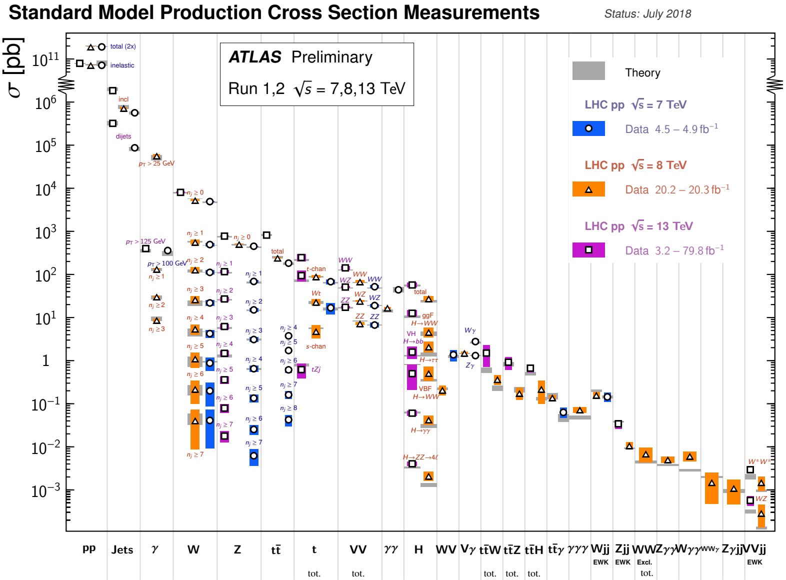
So far collected about 30 fb^{-1} at $\sqrt{s} = 7$–8 TeV and **nearly 150 fb^{-1} at 13 TeV!**

Standard Model holds up to experimental tests at LHC



Measurements of SM processes agree with predictions over many orders of magnitude!

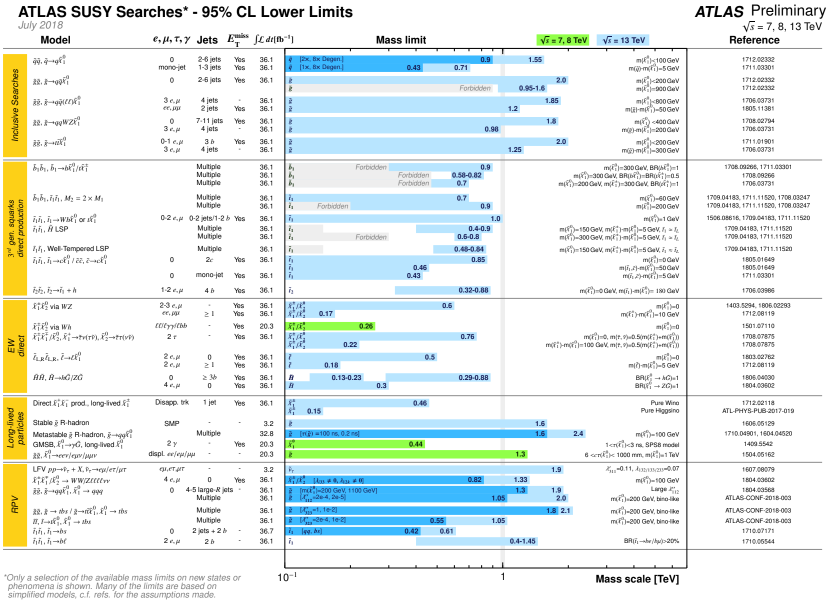
Standard Model holds up to experimental tests at LHC



Measurements of SM processes agree with predictions over many orders of magnitude!

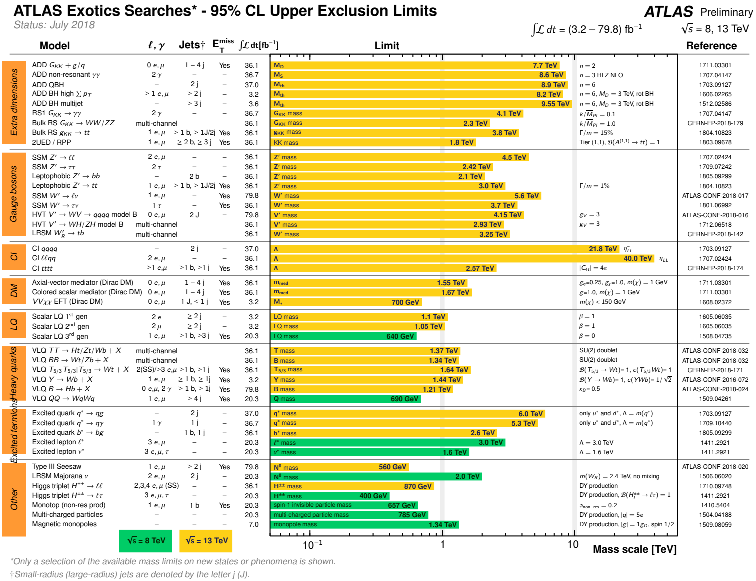
⇒ can model **backgrounds** to beyond-SM physics!

Results so far: exclusion limits for models of beyond-SM physics



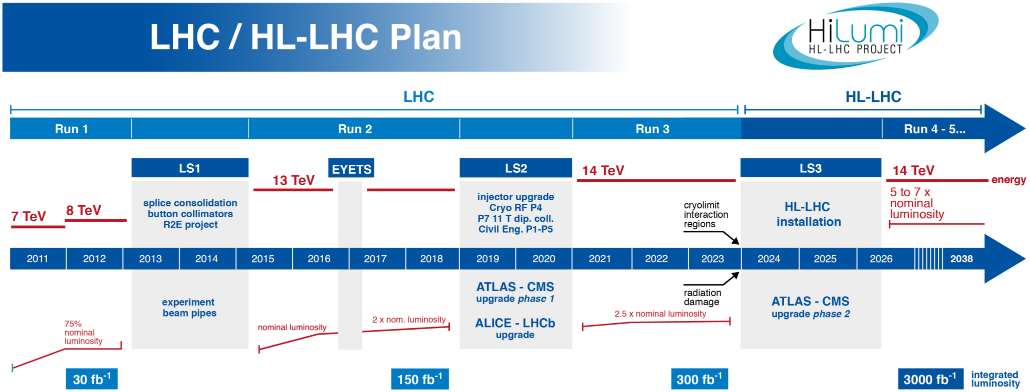
Extensive program of searches $\Rightarrow$ No evidence of SUSY particles!

Results so far: exclusion limits for models of beyond-SM physics

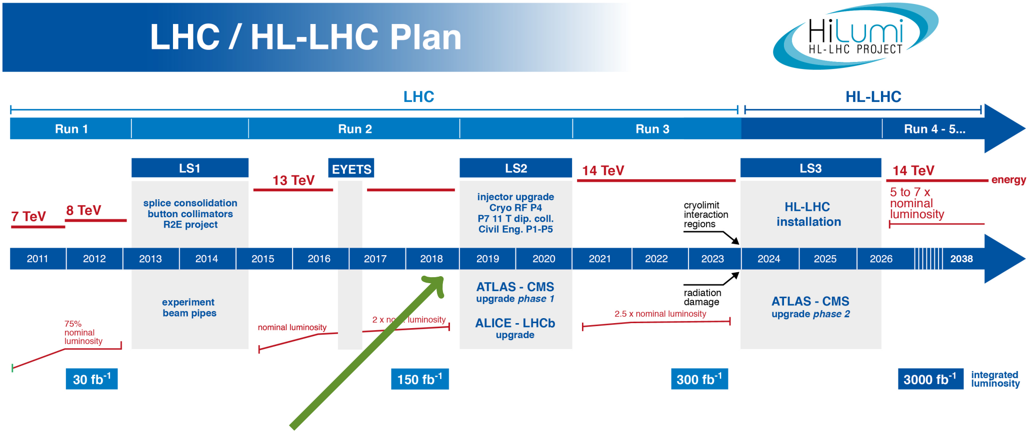


Same for other (non-SUSY) BSM physics $\Rightarrow$ no evidence of new physics.

Long-term schedule for the LHC

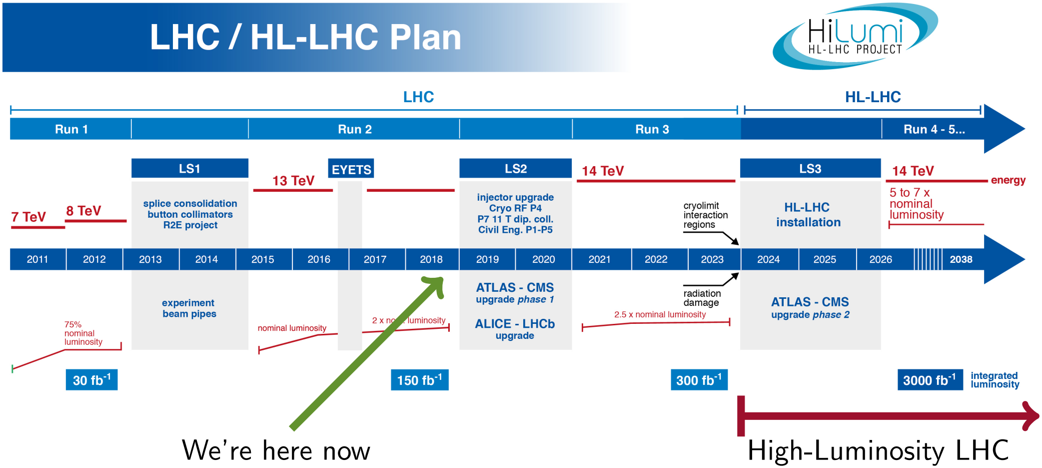


Long-term schedule for the LHC

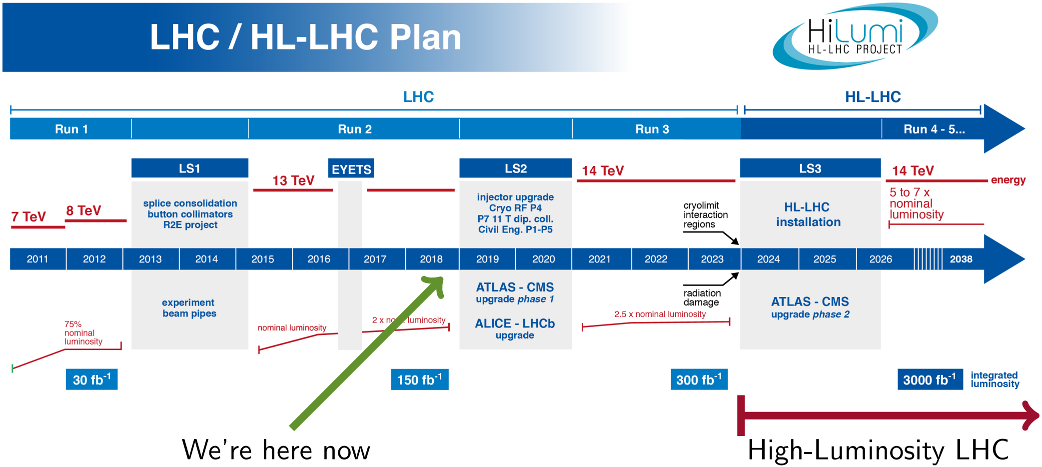


We're here now

Long-term schedule for the LHC

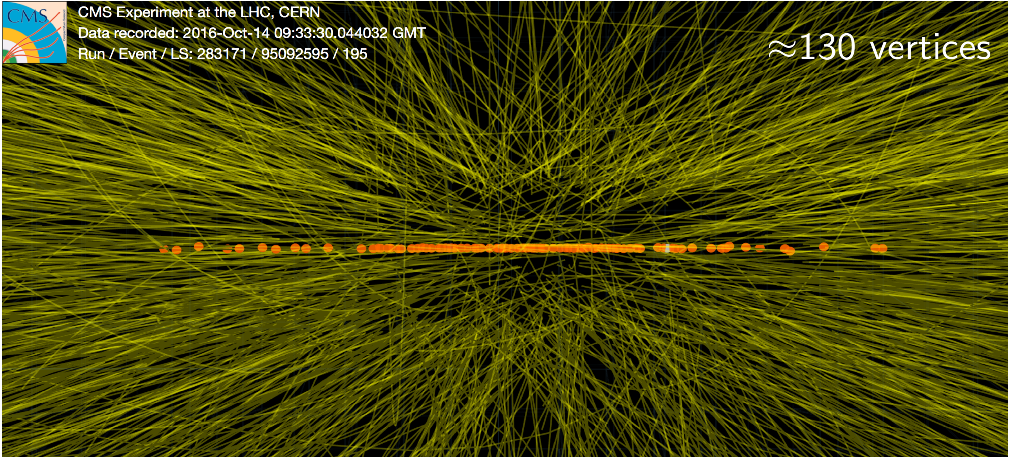


Long-term schedule for the LHC



Most published results at $\sqrt{s} = 13$ TeV so far use ~30 fb^{-1}
$\Rightarrow$ HL-LHC will deliver 100x as much!

Pileup at the HL-LHC

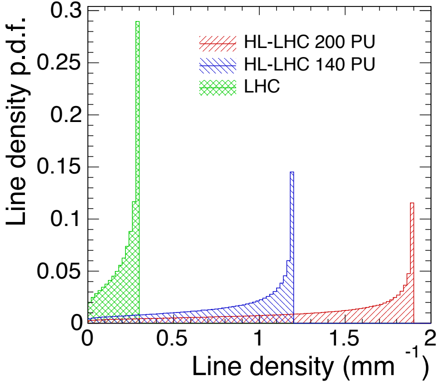


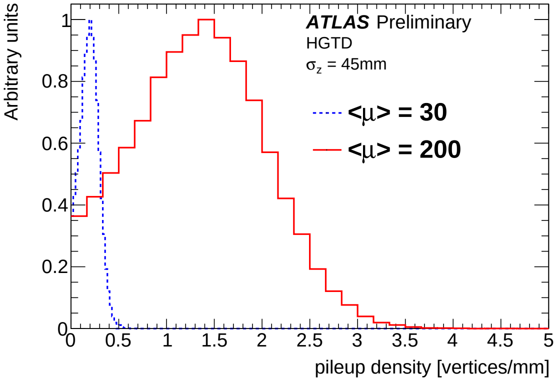
Real-life event (i.e. crossing of pp bunches) with ∼130 reconstructed vertices!

Pileup at the HL-LHC ($\mathcal{L} = 7.5 \times 10^{34}$ cm^{-2}s^{-1})

- Beam spot: RMS 45 mm
- Pileip of up to 200 pp interactions per bunch crossing ($\langle\mu\rangle = 200$)

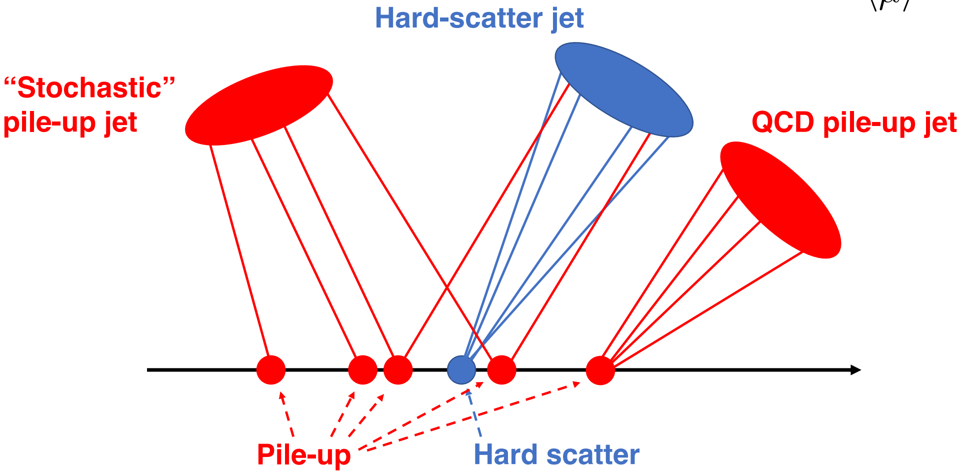
  $\Rightarrow$ 1.6 vertices/mm on average





Pileup: why is it bad?

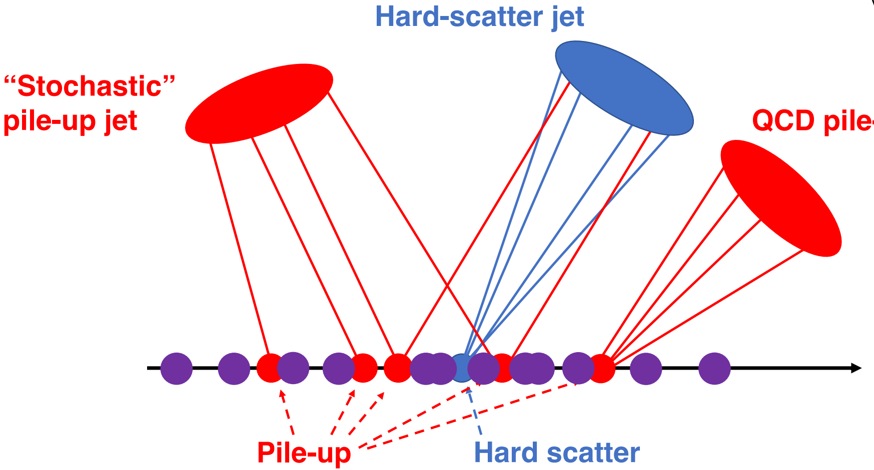
$\langle \mu \rangle = 30$



Need to associate: tracks to vertices, tracks to objects $\Rightarrow$ objects to vertices

Pileup: why is it bad?

$\langle\mu\rangle = 90$



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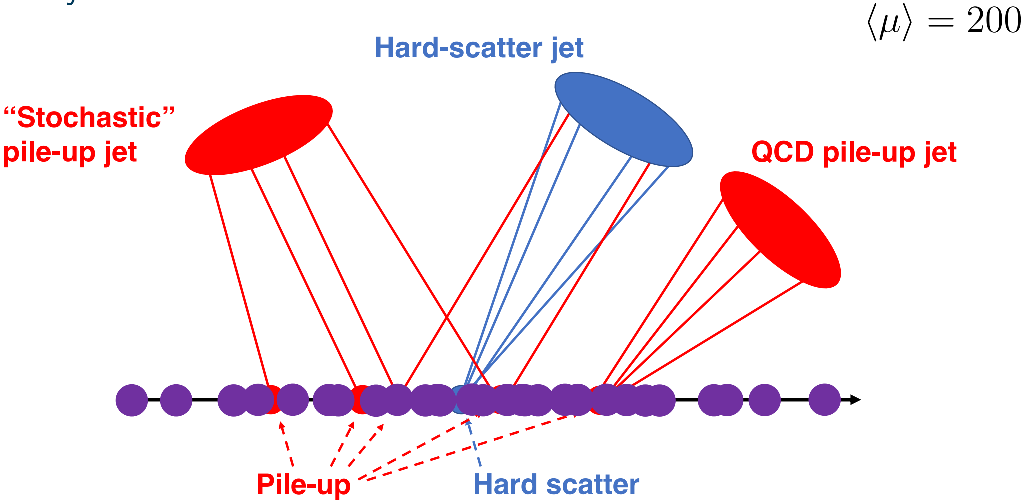

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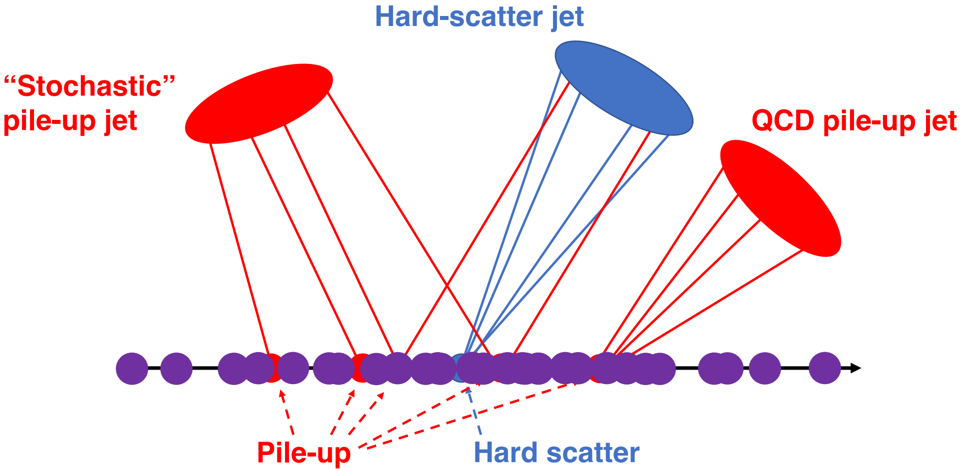
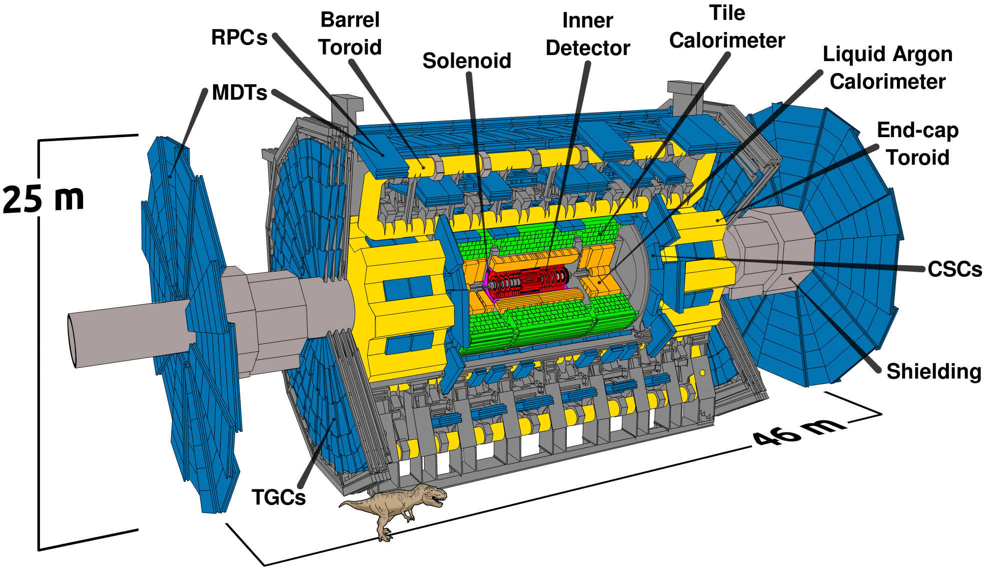


Need to associate: tracks to vertices, tracks to objects ⇒ objects to vertices

With so many more collisions, detectors will need to withstand much more radiation!

Upgrades of the ATLAS detector (full overview in scoping document)



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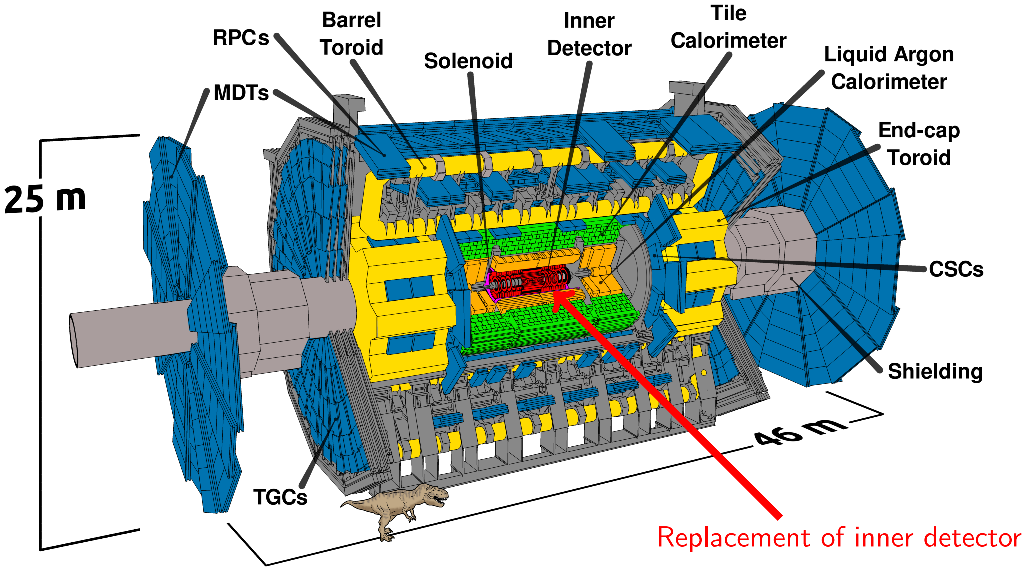
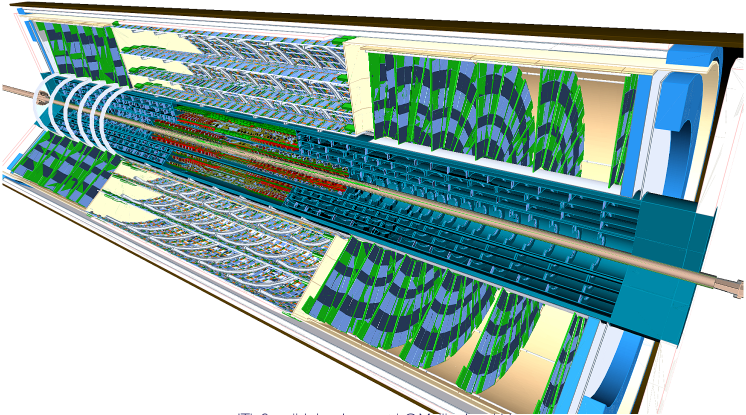


Replacement of inner detector

What is the ATLAS Inner TracKer (ITk)?

- HL-LHC (pileup $\langle\mu\rangle \approx 200$, radiation damage, triggering)
- New ATLAS Tracking detector
- Full silicon...



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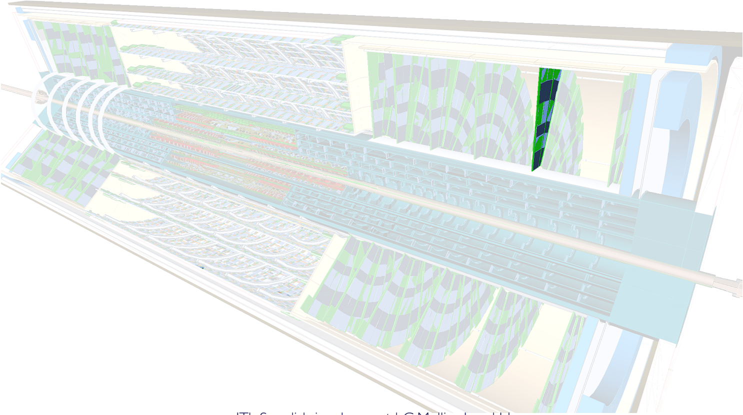

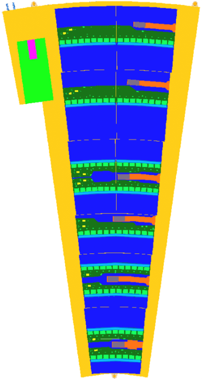

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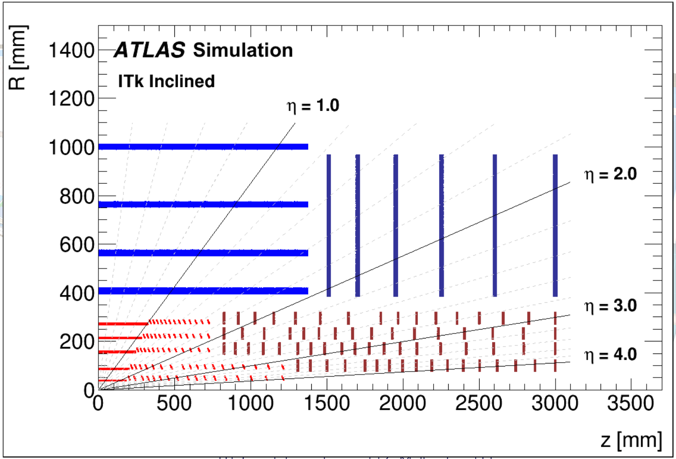
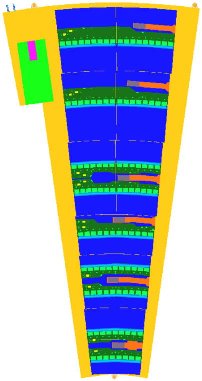




Scandinavian plan

- Four participating institutes in the Scandinavian ITk
  - Lund University
  - Uppsala University
  - Niels Bohr Institute
  - University of Oslo
- Pledged for $\approx$ 10% of the whole end-caps
  ↳ 432 modules of two types R1 and R3 50/50 split
- Production in industry (NOTE)
- Test and qualification of modules in institutes

Swedish Contributions

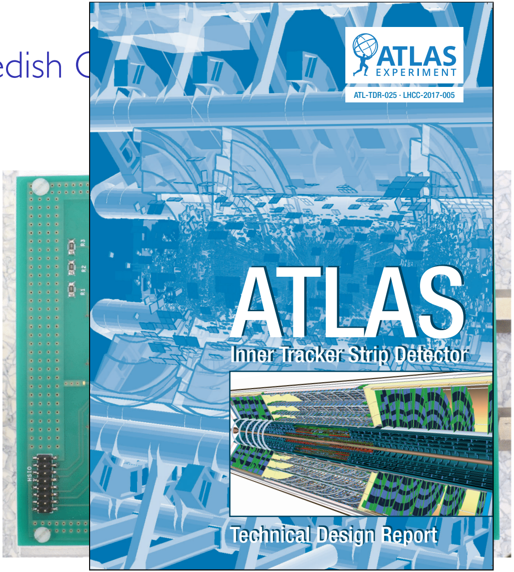
Uppsala / NOTE

- Module Assembly and manufacturing
  - Gluing expertise
  - Wire bonding expertise
  - Experience from SCT

Lund

- Module testing
  - Hyrbid testing before mounting on sensor
  - Full module test
  - DAQ expertise

Swedish C



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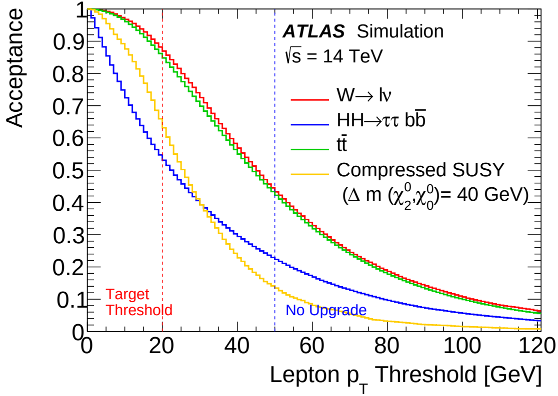
Hardware Tracking for the Trigger (HTT): Uppsala



- 5-7x design luminosity $\Rightarrow$ 5-7x more events with e.g. μ w/ $p_{\mathrm{T}} > 20$ GeV
- Bandwidth/resources limit how much more can be recorded $\Rightarrow$ raise thresholds, or improve trigger-level reco or raise thresholds!
- Also: tracking most CPU-intense part of reco already now, huge challenge to run full-scan tracking using software in time-critical trigger processing at $\langle\mu\rangle = 200$!

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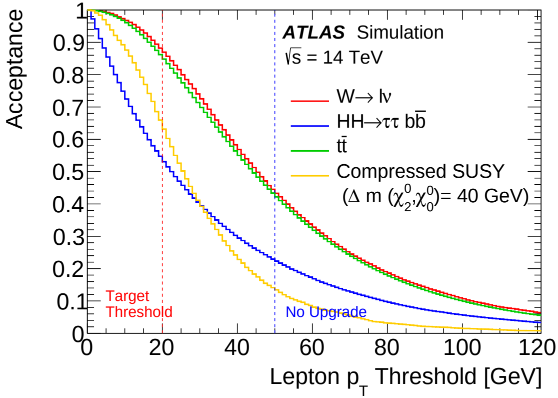

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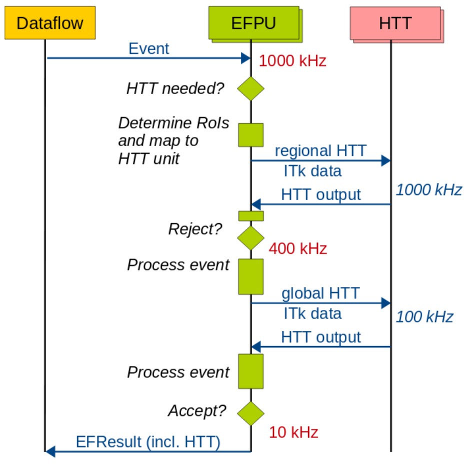
⇒ Hardware Tracking for the Trigger

Baseline trigger architecture

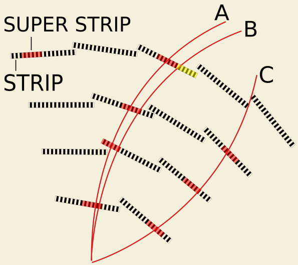
- Level-0 (L0) muon and calo triggers followed by Event Filter (EF).
- EF takes 1000 kHz of events from the L0 hardware trigger.
- L0 output is combined with the regional HTT (rHTT) output to reduce the rate to 400 kHz. Tracking in RoIs.
- EF can request the global HTT (gHTT) to help with full-event tracking at an expected rate of 100 kHz.
- The final rate is 10 kHz.



Pattern matching

- Using 8 ITk layers; up to 3 pixel layers.
- Pixels and strips are combined to coarser-resolution *super-strips*.
- Particle tracks will cross a pattern (set) of super-strips => program AM chips with these patterns.
- The AM will then tell you if a pattern of super-strips is consistent with particle track.
- Patterns trained using tracks from simulated muons.

- Each $\Delta\eta = 0.2$ by $\Delta\phi = 0.2$ RoI trained separately.
- We have 1 million patterns per RoI.
- Outputs *roads* to the track fitting step.



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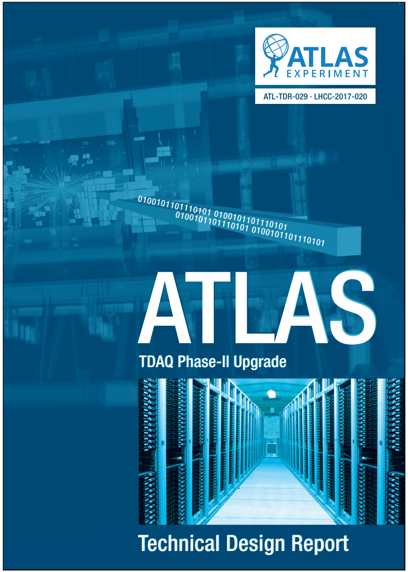
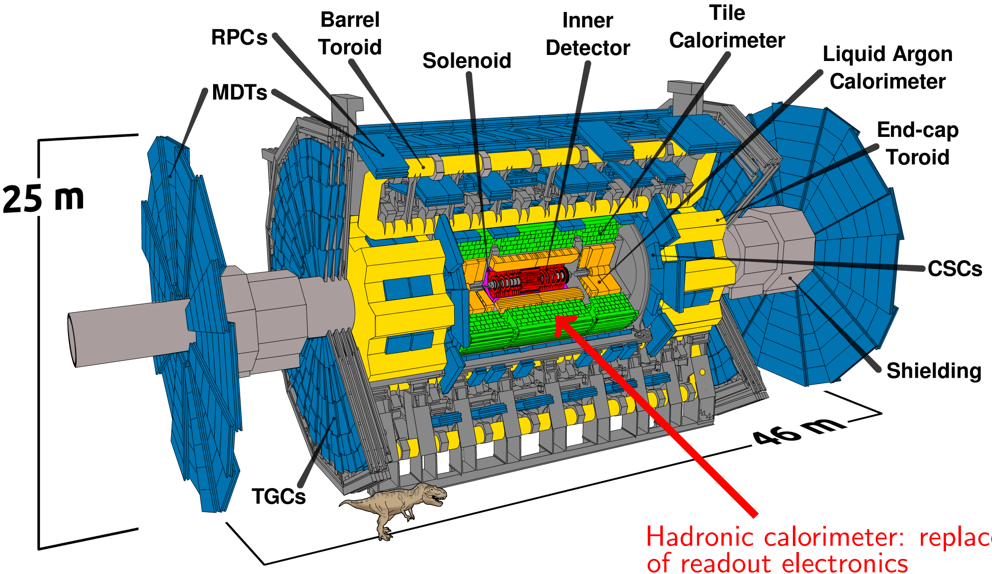


Uppsala group responsible for design and testing of Pattern Recognition Mezzanine cards featuring:

- Associative Memories that hold track patterns
- FPGAs that perform first track fitting

Upgrades of the ATLAS detector

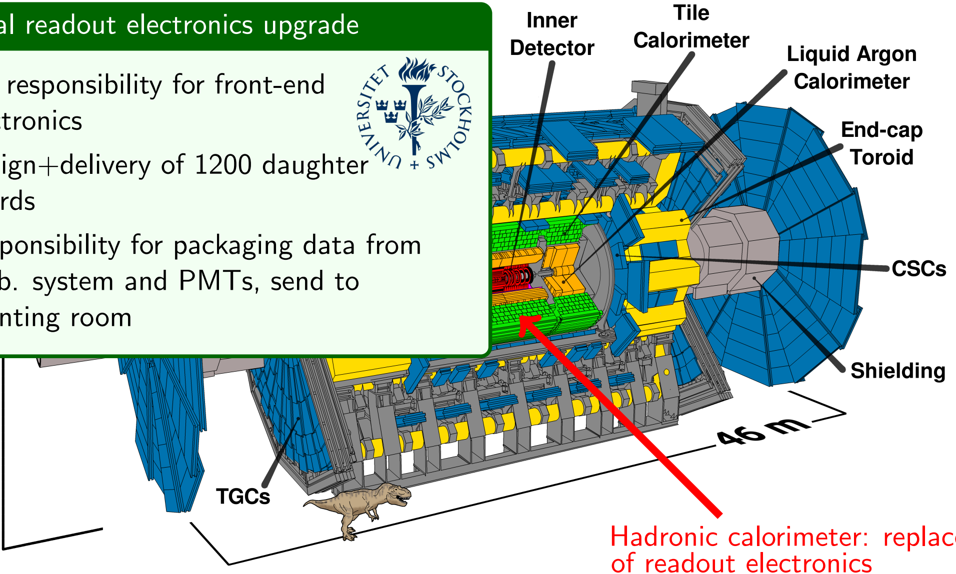


Hadronic calorimeter: replacement of readout electronics

Upgrades of the ATLAS detector

TileCal readout electronics upgrade

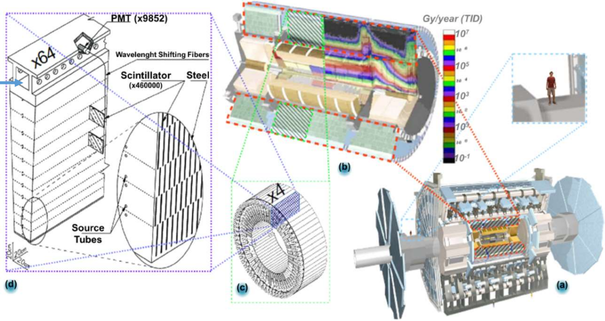
- Big responsibility for front-end electronics
- Design+delivery of 1200 daughter boards
- Responsibility for packaging data from calib. system and PMTs, send to counting room

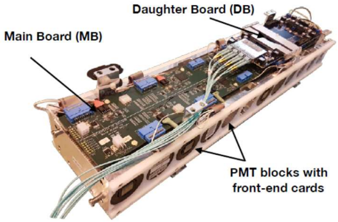


Hadronic calorimeter: replacement of readout electronics

Stockholm is responsible for producing 850 (1200) DaughterBoards including spares

Now 1 SuperDrawer per section
→ 4 MiniDrawers per section





- **The DaughterBoard is responsible for:**
- Communication with off-detector electronics via a 9.6 Gbps uplink and a 4.8 Gbps downlink
- It is highly redundant and designed to minimize risk for failure and in case of failure minimize its consequences
- It allows local and remote reprogramming of on-detector FPGAs and their PROMs
- Physics and calibration data is acquired from PMTs and FE-boards via the MainBoard
- Monitors temperature, current, voltage
- Controls the Cs-calibration system
- and the on-detector HV-system (the back-up HV-system)

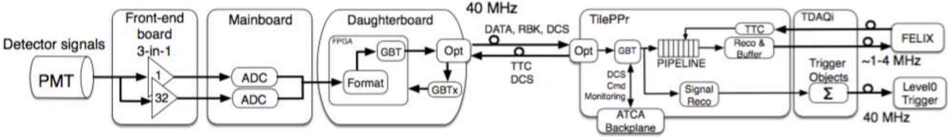
DBv5

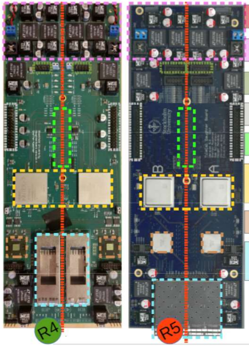
Several DB prototypes have been developed version 4 has proven to be fully functional but changing to last version of the FPGA used (Xilinx Kintex) improved radiation tolerance (~30 times) and communication reliability.

In the transition we also changed from single mode fibers to multimode gaining robustness and better selection of components

Migration from 2 QSFP to 4 SFP+ 6 links - saving fibers and connectors.

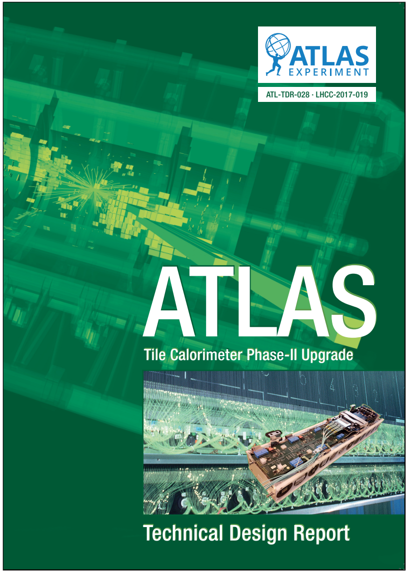
The firmware has also been restructured and simplified





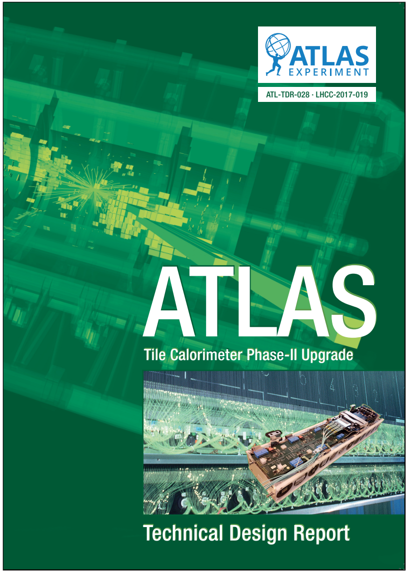
- 2x independent sides
- Power circuitry.
- 2x Cs interface
- 2x HVOpto interface
- 400 pin FMC
- 2x FPGAs
  (2x Kintex7 || 2x Kintex Ultrascale+)
- 2x GBTx
- Optic Transceivers
  (2x QSFPs || 4x SFPs)

Tile calorimeter front-end electronics: Stockholm



Lots of tests: test beam, irradiation and B-field!

Tile calorimeter front-end el



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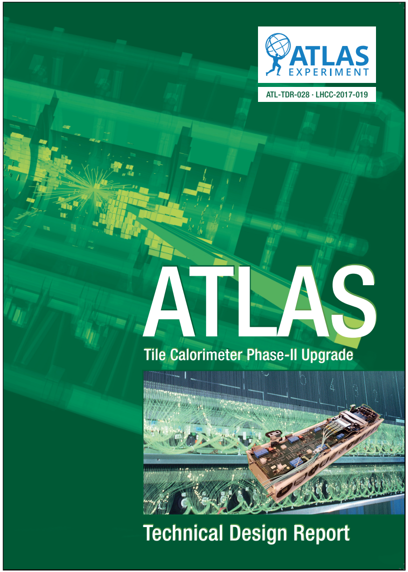

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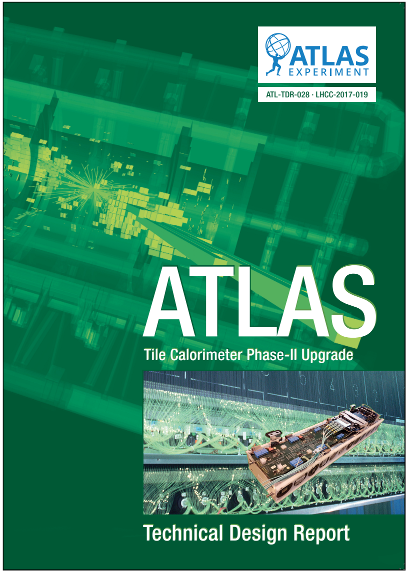
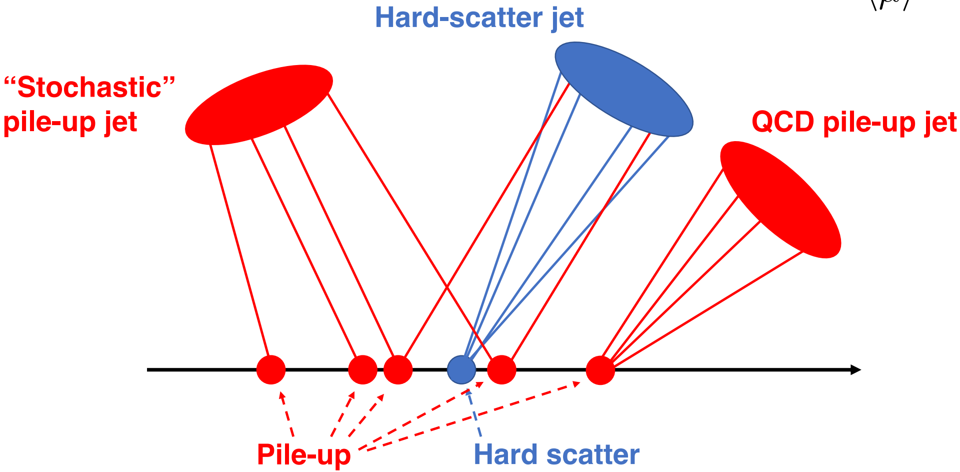


Christophe Clement (SU) also overall TileCal Upgrade Project Leader!

Back to pileup

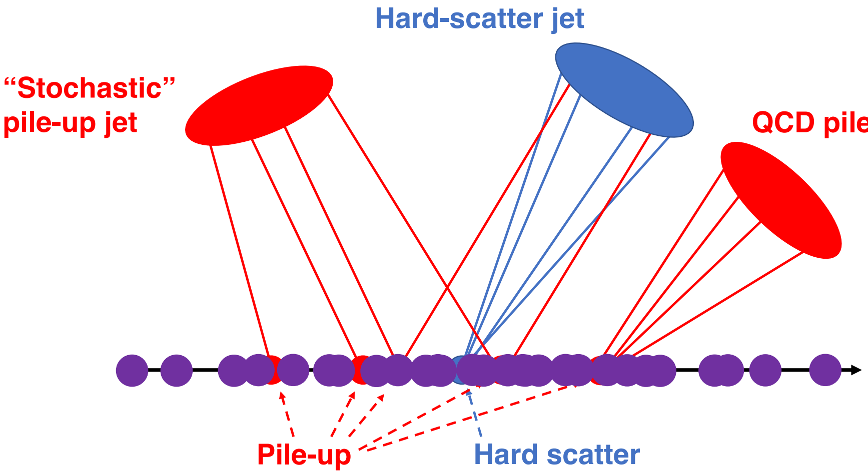
$\langle \mu \rangle = 30$



Need to associate: tracks to vertices, tracks to objects $\Rightarrow$ objects to vertices

Back to pileup

$\langle \mu \rangle = 200$



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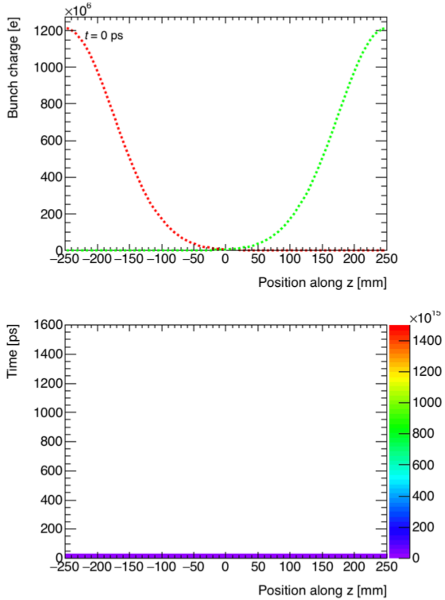
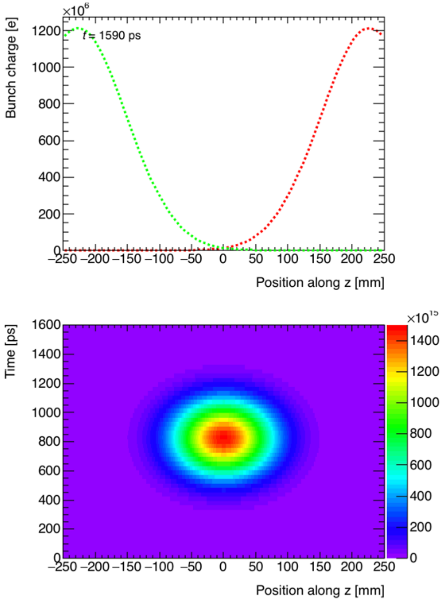
A new idea: Exploit the *time dimension* of the beam spot

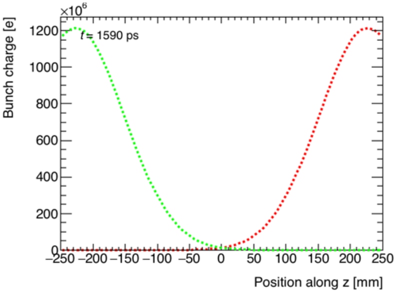


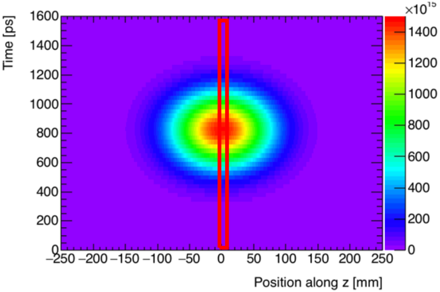
The solution: Exploit the *time dimension* of the beam spot



The solution: Exploit the *time dimension* of the beam spot

- Tracks coming from z region look like they're from one vertex
- Expect up to $\sim$10 vertices in region $\sim z_0$ resolution





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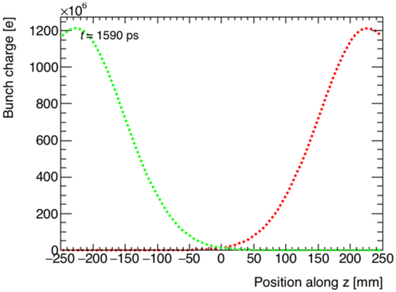
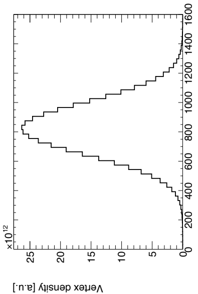
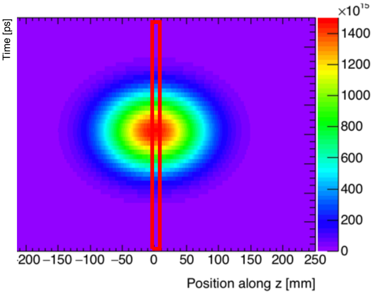




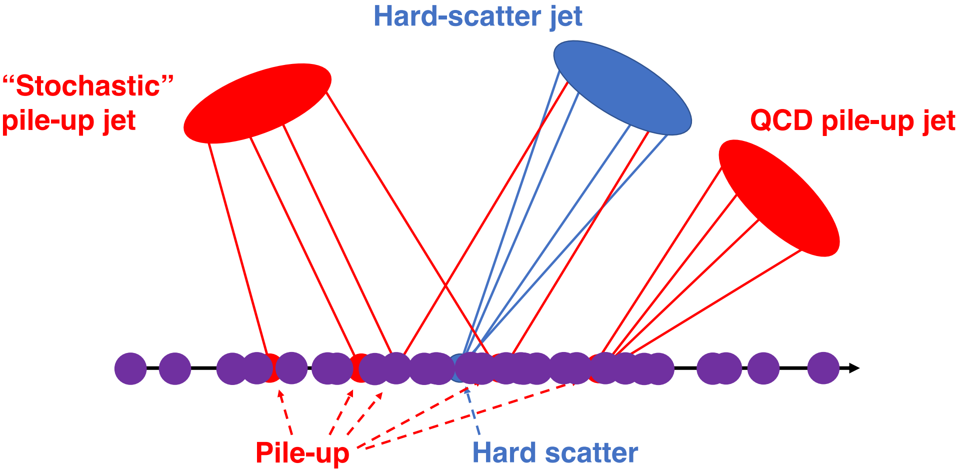


- With time info, the vertices can be resolved!
- Time projection (left) has bin size of 30 ps

(No crossing angle here, AU for z-scale, animation for illustration only!)

Forward region most challenging

$\langle \mu \rangle = 200$



Measure time of tracks and thereby vertices $\Rightarrow$ improve track-to-vertex association!

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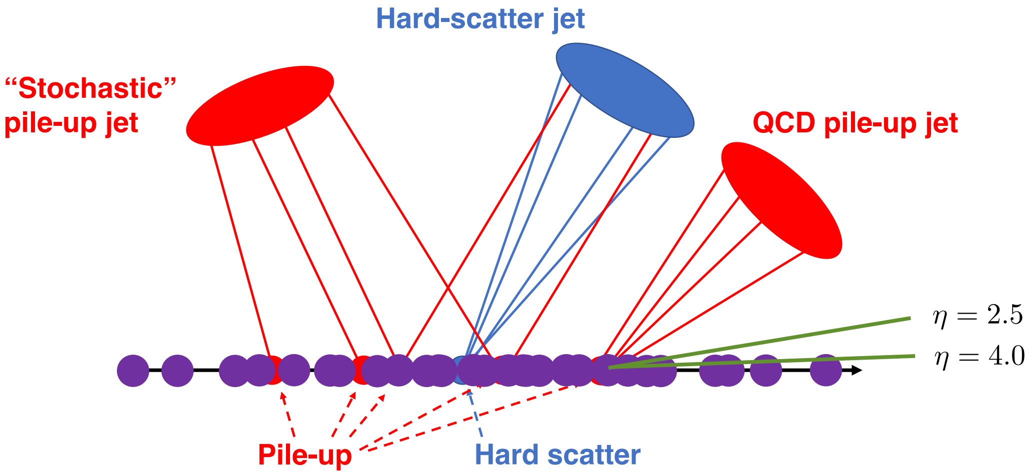

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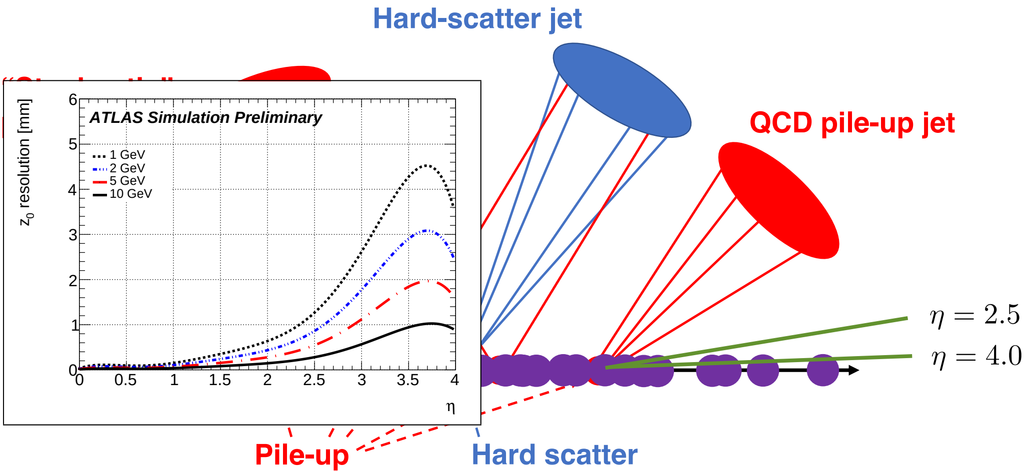
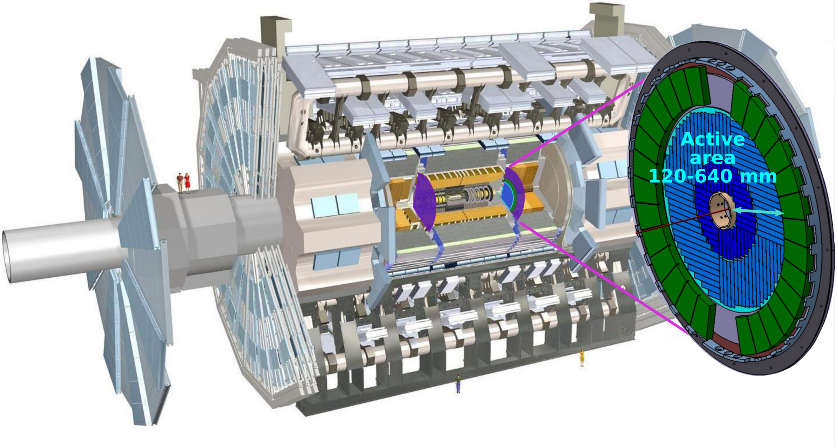


Measure time of tracks and thereby vertices ⇒ improve track-to-vertex association!

High-Granularity Timing Detector (HGTD)



HGTD will provide timing measurements for charged particles in $2.4 < \eta < 4.0$.

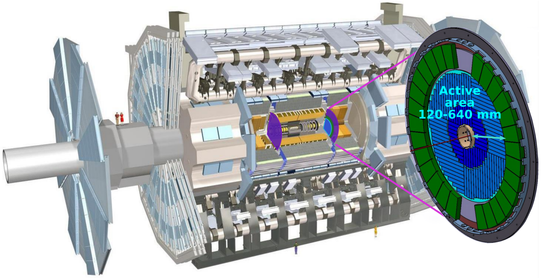
High-Granularity Timing Detector (HGTD): KTH

Mitigate pileup by exploiting that beam spot has *time dimension*, spread ~ 200 ps

- Two endcap disks at $z = \pm 3.5$ m, Si-based Low Gain Avalanche Diode technology, 1.3×1.3 mm^2 pixels
- $\sigma_t = 30$ ps/track in acceptance: $120 \text{ mm} < R < 640 \text{ mm} \Rightarrow 2.4 < |\eta| < 4.0$
- KTH responsibility: functionality to use as luminometer ⇒ off-detector FPGA-based electronics boards

Coordination responsibilities:

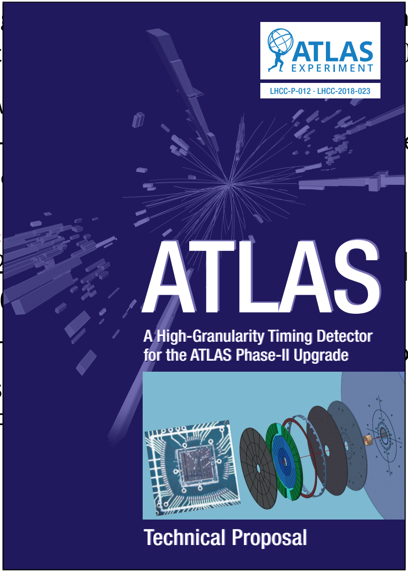
- Bengt L-J: Electronics Coordinator
- Jonas S: Luminosity & Trigger/DAQ Coordinator
- CO: editor of Expression of Interest and Technical Proposal ⇒ approved!



High-Granularity Timing Detector (HGTD): KTH

Miti ... m
spot ... 00 ps

- T ... Si ... e te ...
- σ_t ... 12 ... $|\eta| <$ 4.(...
- K ... use as ... FF ...



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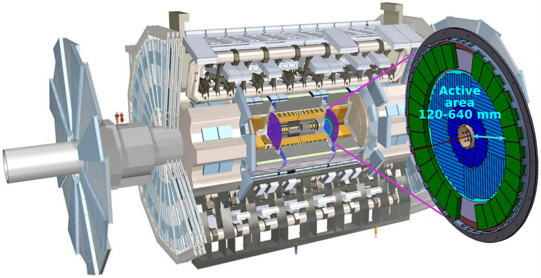
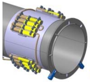
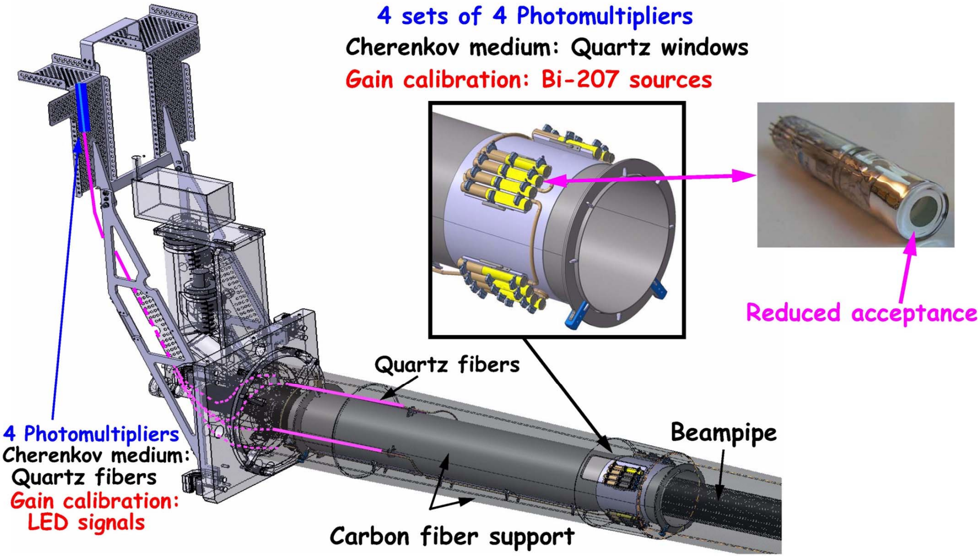


LUminosity Cherenkov Integrating Detector (LUCID): Lund

- Entire ATLAS physics program depends on being able to measure luminosity
- Challenges for detectors:
  - Provide reliable measurements at very low (10^{-3}) and high (200 at HL-LHC) number of interactions per bunch crossing
  - Stable detector performance: measurement always needed, typically special LHC fill per year for calibrations
  - Needs to be insensitive to activated material ("afterglow")
  - Needs to survive high levels of radiation
- LUCID is and has been main luminosity detector in ATLAS so far in Run 2
- Current detector will not work at HL-LHC, looking at options for similar uncomplicated but intelligent and versatile luminosity detectors with redundancy
- Vincent Hedberg (Lund) with technicians/engineers designed and constructed LUCID at CERN, he has been LUCID Project Leader and convener for Luminosity Group for many years, now thinking about upgrades for higher luminosities

The present detector



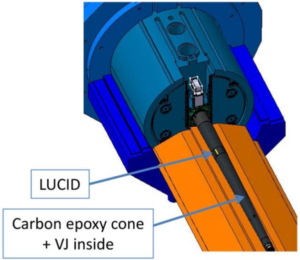


Problems at the high luminosity LHC

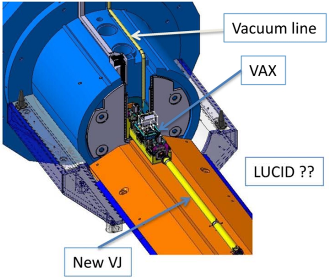
With μ-values going up to 140-200 the present type of quartz photomultiplier detector will saturate (hits in every bunch crossing).

Vacuum equipment will also be installed at the present LUCID location.

Current Layout: without VAX



Future Layout : VAX integrated

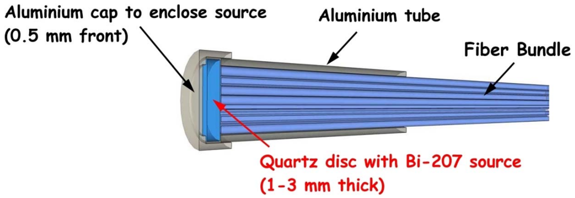


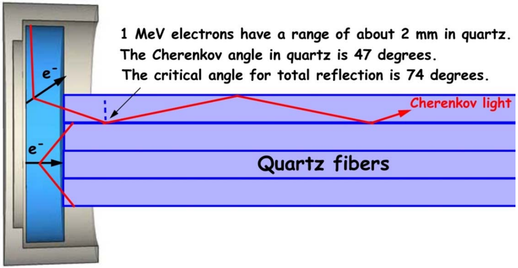
Possible solutions:

- Place a new quartz photomultiplier detector in another location.
- Build quartz fiber detectors monitored by Bi-207.

A LUCID fiber detector for run 3 and 4

The present idea for a LUCID-3 detector is a fiber detector with a Bi-207 source at the end of the fiber bundles that can provide Cherenkov light for calibrations.





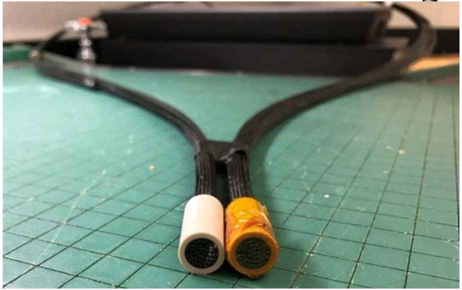
Summary of ATLAS upgrade activities in Sweden

- **All-silicon Inner Tracker (ITk): Lund and Uppsala**
  - Increased pileup $\Rightarrow$ need improved performance, more radiation tolerant detector needed
  - Readout: current ID can't handle HL-LHC occupancies, ITk readout enables new hardware-based tracking in the trigger system
- **Hardware Track Trigger (HTT): Uppsala**
  - Hardware tracking can cope with high pileup $\Rightarrow$ improve trigger $\Rightarrow$ unchanged thresholds
  - Uppsala responsible for design and testing of Pattern Recognition Mezzanine cards
- **Tile calorimeter: Stockholm**
  - Design and production of 1200 daughter boards
  - Critical part of readout electronics, all data goes through this path
- **High-Granularity Timing Detector (HGTD): KTH**
  - Silicon precision-timing detector exploits time spread of beam spot
  - KTH responsible for luminometer functionality
- **LUminosity Cherenkov Integrating Detector (LUCID): Lund**
  - Luminosity critical for entire ATLAS physics program, LUCID main detector so far
  - HL-LHC pileup requires upgraded detector: several prototypes being investigated

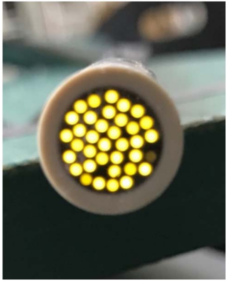
All projects moving forward!

Back-up

First results with a prototype



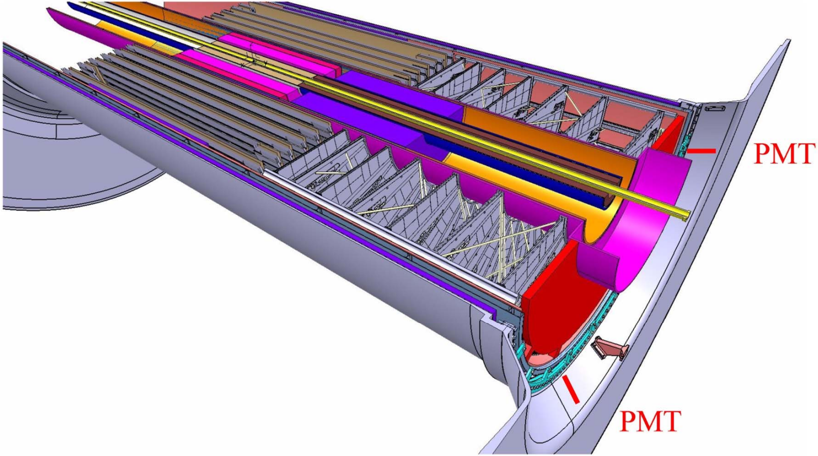
- A group at the university of Alberta has done the first prototype tests.
- A 2.45 m long PUV800 quartz fiber bundle with 35 fibers was used.
- Each end was epoxied in ferrules and polished.



- One fiber end was connected to a Hamamatsu R760 photomultiplier.
- 50 ml of a Bi-207 solution was applied directly to the fibers on the other end and was let to dry.

Another possibility being explored for run 4

The possibility of installing photomultipliers with Bi-207 in the inner detector region for run 4 is under investigation.

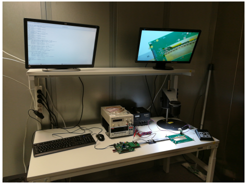


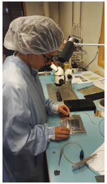
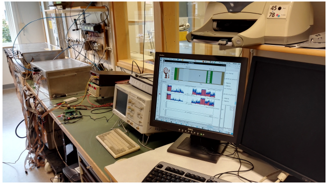
These photomultipliers have to be insensitive to the magnetic field and radiation hard: Micro Channel Plate PMTs and Silicon PMTs are possibilities.

Equipment in institutes (Excluding NOTE)

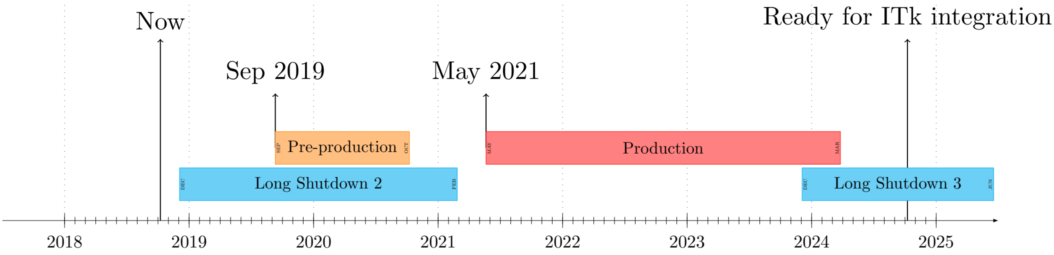
✔ Ready to be used
✓ Needs to be brought up to specs
✗ Plans to procure / designing

	Clean room	Metrology	Probe station	Wire bonder	Thermal Cycling	DAQ Setup	Storage
Lund	✓	✗	✗	✗	✗	✔	✗
Uppsala	✔	✔	✔	✔	✓	✓	✓




Timescale



- All sites required to pass inspection test to make sure to be up to collaboration standard
- Done shortly before Pre-prod, 5% of total pledged amount
- Installation of ITk during LS3

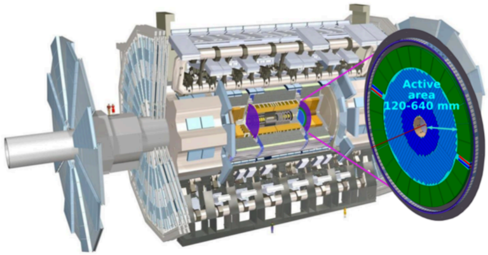
The HGTD

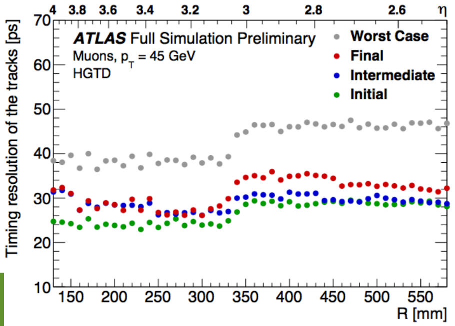
The HGTD will provide time measurements for objects in the forward regions of the ATLAS detector.

- Coverage: $2.4 < |\eta| < 4.0$
- Target $\sigma_t^{track} \sim 30$ ps

Design based on 1.3×1.3 mm^2 silicon pixels (2×4 cm^2 sensors) → optimised for < 10% occupancy and small capacitance

Number of hits per track:
- 2 in $2.4<|\eta|<3.1$
- 3 in $3.1<|\eta|<4.0$





Sensors

Low Gain Avalanche Detectors

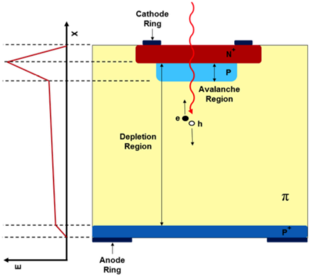
Pioneered by CNM Barcelona and developed within 5-year CERN- RD50 effort

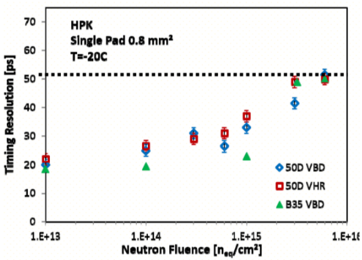
Necessary time resolution achieved in test-beam studies at CERN and Fermilab

Good charge collection, gain ~20, time resolution before/after irradiation

Time resolution better than 50 ps per hit up to 5×10^{15} neq/cm2 with bias voltage 10% below breakdown

Successful prototypes from several vendors





Readout

ALTIROC ASIC bump-bonded to sensors

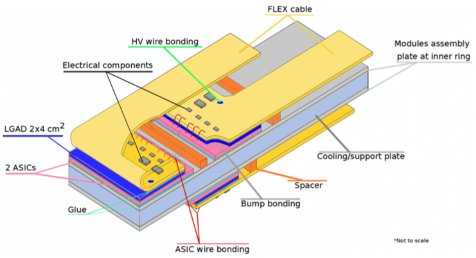
Single pixel read-out (225 channels/ASIC)

Meets radiation hardness / timing requirements

Reads out:

at 1 MHz, after trigger: **full hit information**

at 40 MHz: **number of hits** at outer radii for each ASIC (real-time, per-crossing luminosity measurement with time-sideband subtraction)



HGTD as luminometer

G. Salam at LHCP 2016:
Luminosity is potentially *keystone measurement* for LHC precision programme

- Count hits within 320 mm < R < 640 mm
- Time-averaged hit multiplicity per BCID
- Estimate of better than 10^{-3} stat uncertainty using 1 s integration time
- Out-of-time sideband subtraction
- Online lumi measurement 40 MHz readout intended for real-time feedback to LHC lumi-leveling
- Could provide low-latency per-BCID estimate for trigger