Performance of the ATLAS Transition Radiation Tracker Readout with Cosmic Rays and First High Energy Collisions at the LHC

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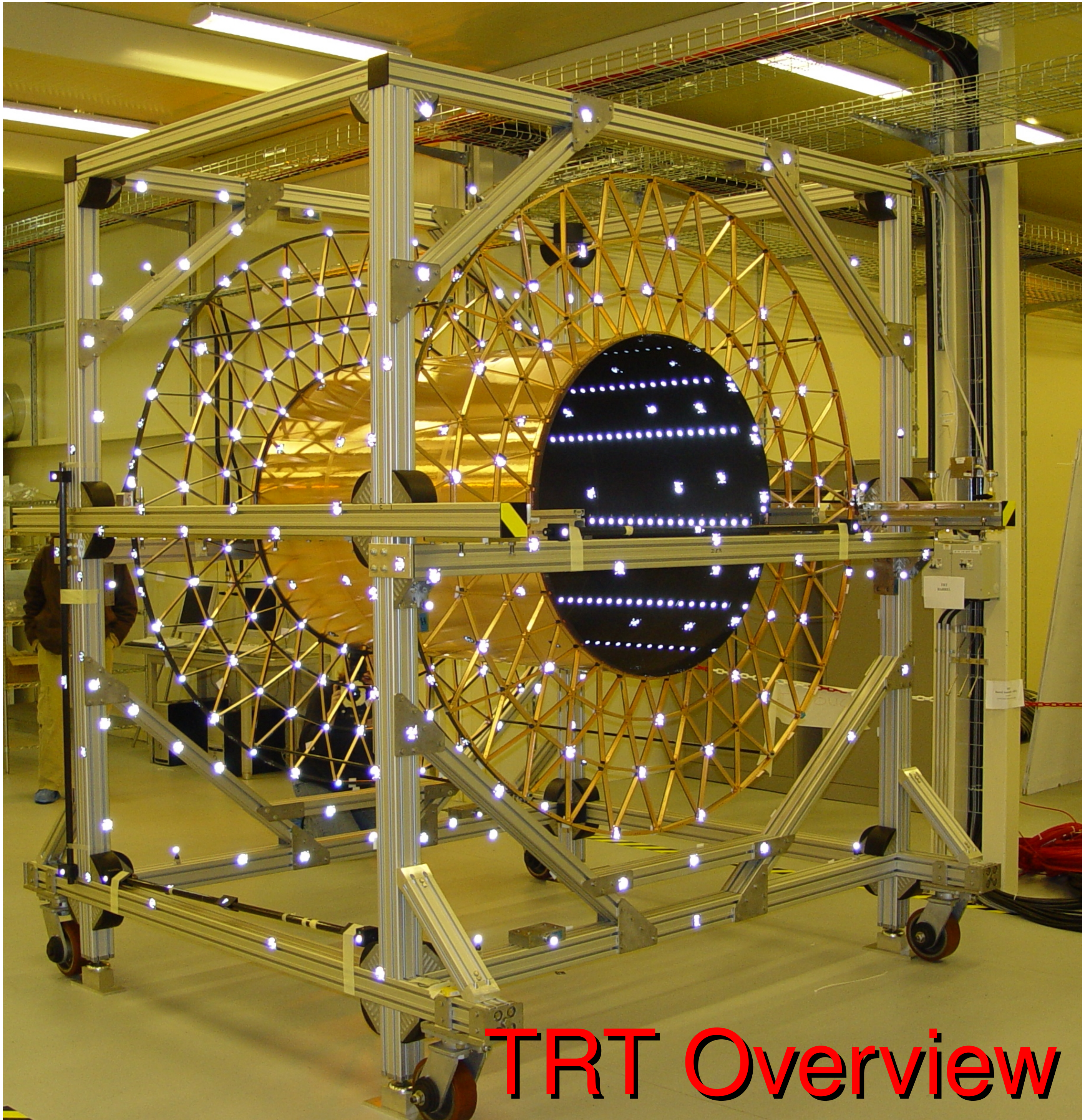
Outline

- TRT Overview
  - Goals and Design
  - Readout and Electronics
  - Calibration
- TRT Commissioning
  - Fast-OR Cosmics Trigger
  - Timing
  - Coverage and Occupancy
  - Readout Features
- TRT Performance
  - Operations
  - Position and Momentum Resolution
  - Hit Efficiency
  - Particle Identification
- Summary

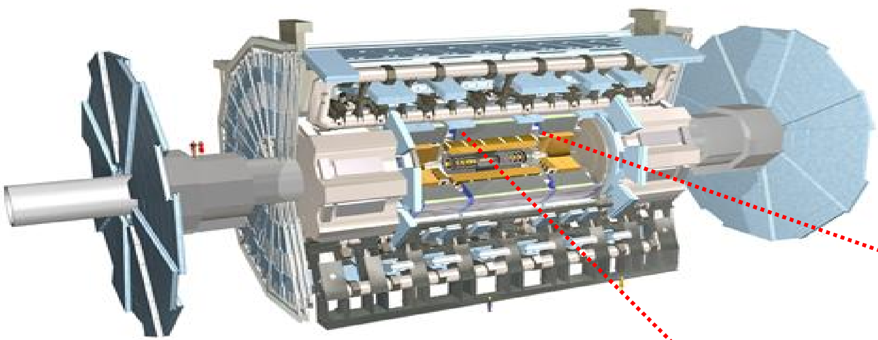


TRT Overview

TRT Goals and Highlights

- The TRT is both a tracker and a transition radiation detector
  - Tracking: provides ~36 hits on track, significant contribution to momentum resolution
  - Particle ID: Electron/pion separation (e.g. pion rejection factor ~20 for 90% electron efficiency)
- Major contributions to ATLAS commissioning:
  - **Fast-OR** cosmics trigger provided high rate of tracks for Inner Detector
  - Used good track time resolution (~ns) to become **timing reference**
- Design:
  - 4mm Ø "straw" tubes, straw cathode at -1.5kV, wire anode at 0V
    - $Xe/CO_2/O_2$ gas mixture provides active medium inside straws
  - Straw layers are interspersed with layers of radiator material to generate transition radiation (TR)

ATLAS Inner Detector

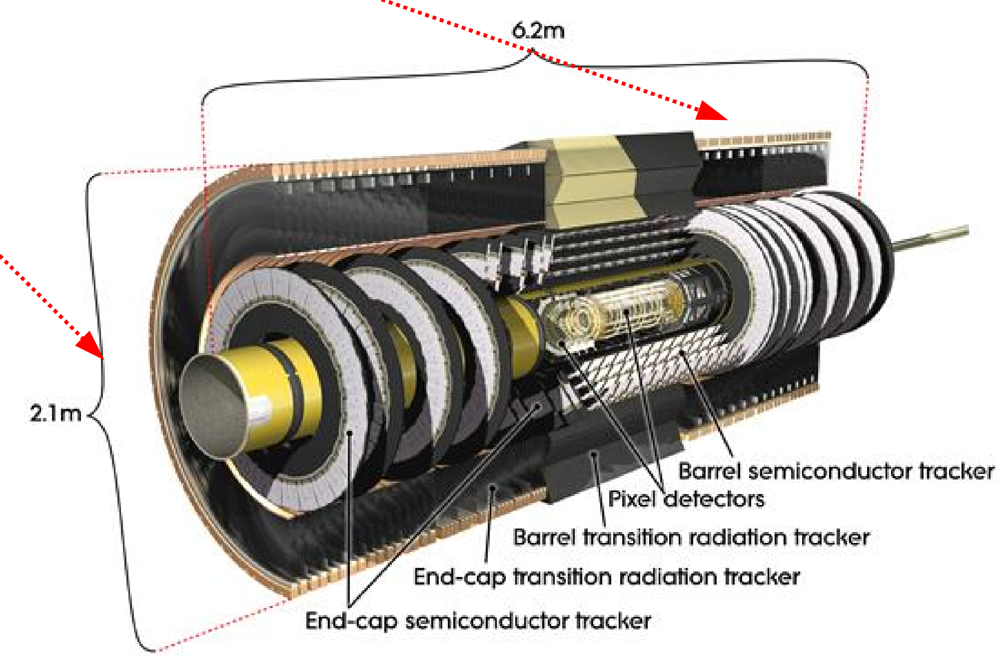


The Inner Detector consists of:

- Pixel detector
- Semiconductor Tracker (SCT)
- **Transition Radiation Tracker (TRT)**
  - All in a 2T solenoidal field

Performance goals:

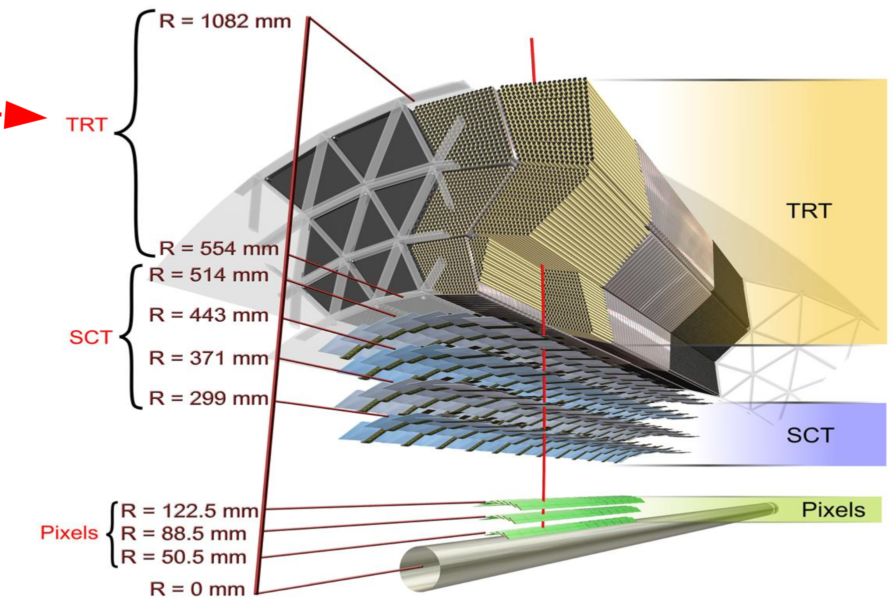
- Tracking for charged particles:
  - $p_T > 0.5$ and $|\eta| < 2.5$
  - $\sigma(p_T)/p_T = 0.05\% p_T \oplus 1\%$
- Electron ID (**TRT**):
  - $0.5 < p_T < 150$ GeV and $|\eta| < 2.0$

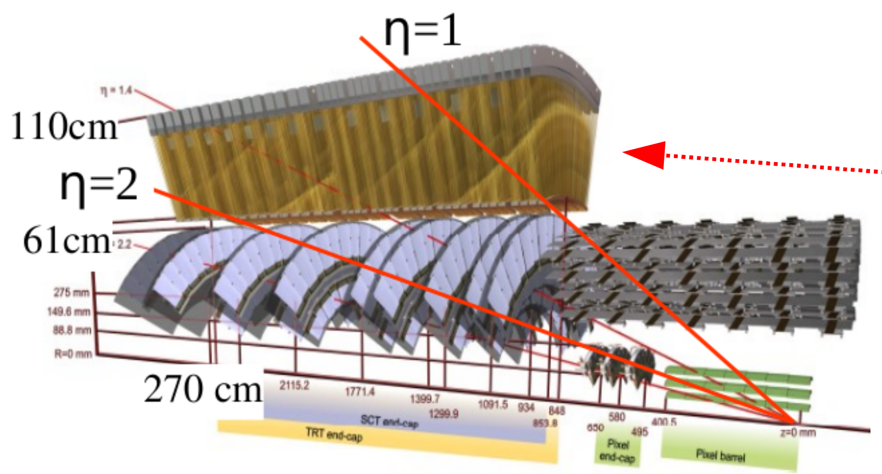


TRT Overview

TRT Barrel:

- 3 layers * 32 ϕ modules
- 1.44m long straws, parallel to beam axis
- Wires electrically split in middle
  - ~1.5cm dead region
  - Read out on both sides
- 105,088 readout channels

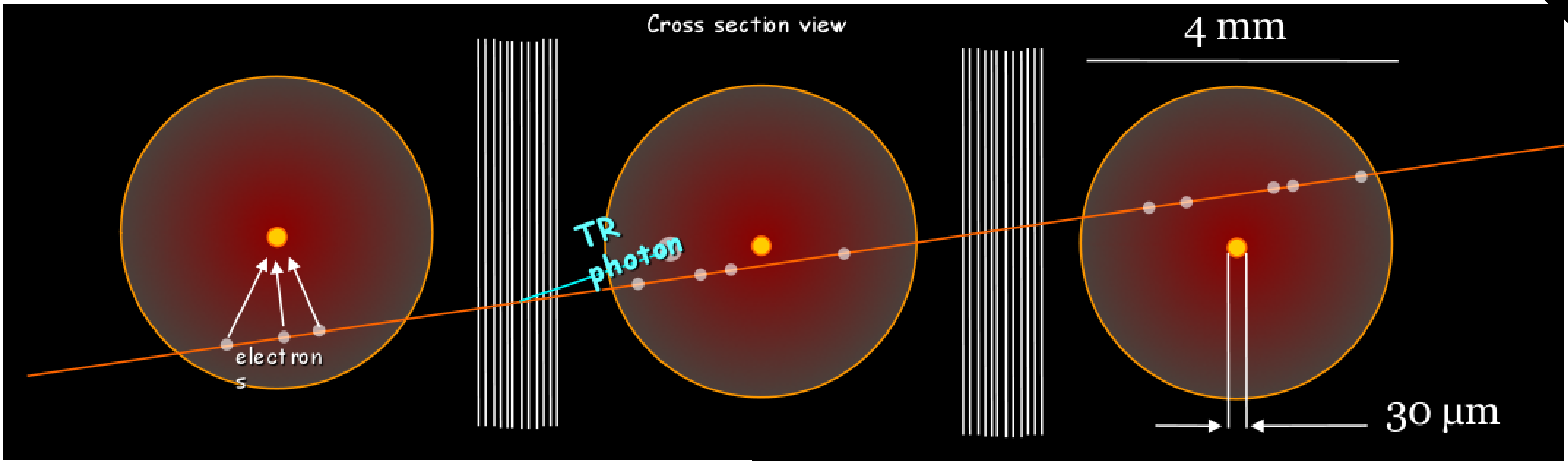


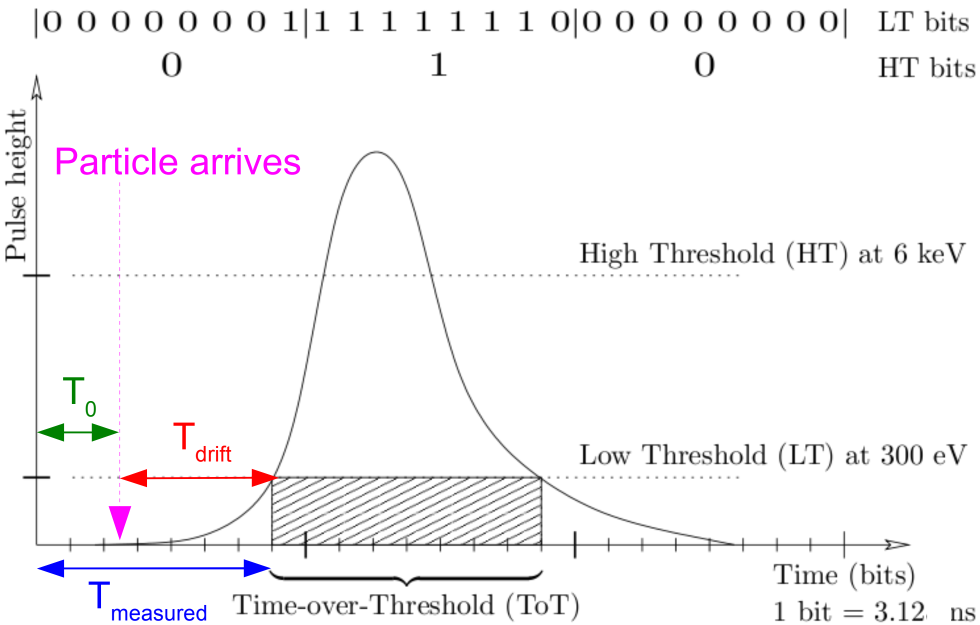


2 TRT Endcaps, each with:

- 20 wheels with 8 straw layers each
  - 12 A type wheels at lower Z
  - 8 B type wheels at higher Z
- 39cm long radial straws
- 120,880 readout channels

Principles of Detection

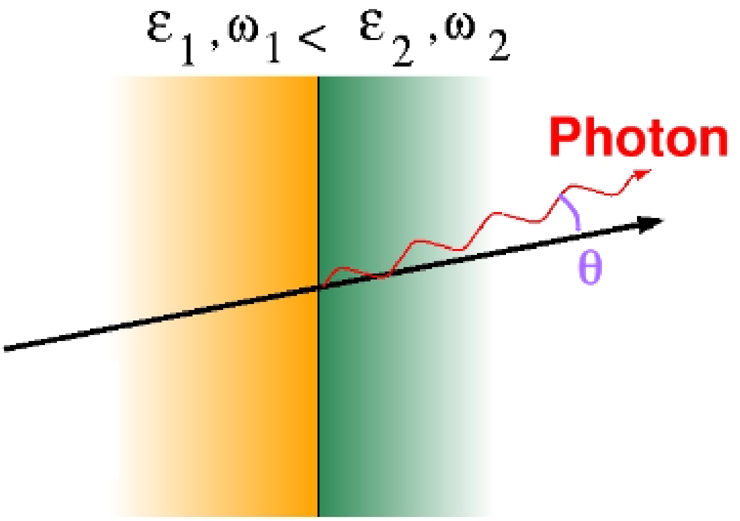




- Ionized electrons drift to straw wire to create signal (~several 100 eV)
  - Detect with **Low Threshold (LT)**
- TR photons generate signal ~10keV
  - Detect with **High Threshold (HT)**
  - Also with **Time over Threshold (ToT)**
- Readout granularity: **3.12ns**
  - 1/8 of 25ns LHC bunch crossing (BC)
  - Readout 3 BCs / trigger

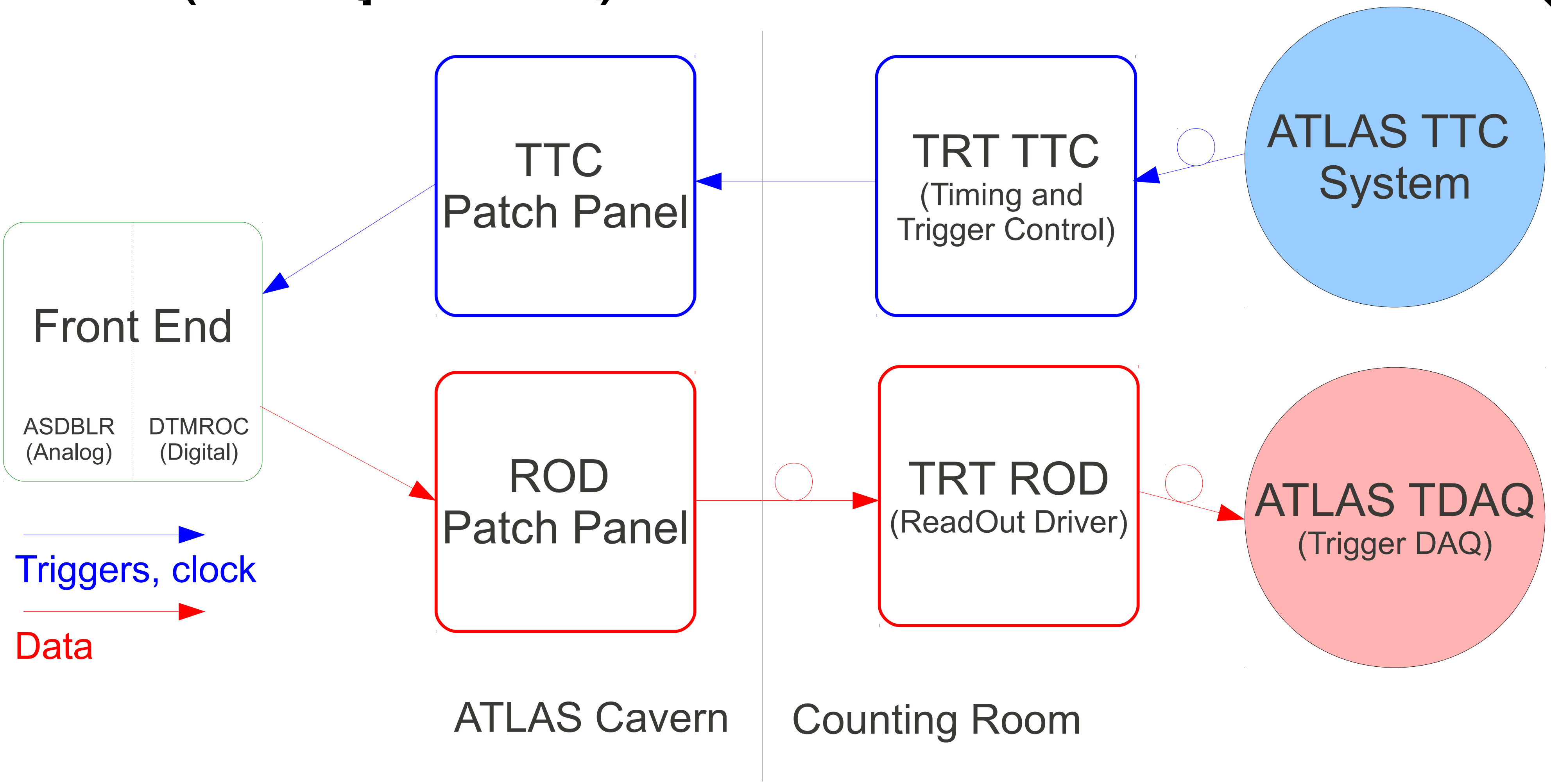
Particle Identification

- **Transition radiation**: photon emitted by a charged particle when traversing the boundary between materials with different dielectric constants (ε_1,ε_2)
  - **Intensity** $I \propto \gamma = E/m$, $\theta \propto 1/\gamma$
  - Low photon **emission probability** per transition
    - Many transitions needed
      - Intensity eventually limited by saturation effects
  - Emitted **energy** $\propto (\varepsilon_1 - \varepsilon_2)$
    - Gas and plastic give photon energies 5 – 30 keV
  - Gas with high photon absorption (high Z) required
    - Xenon-based mixture



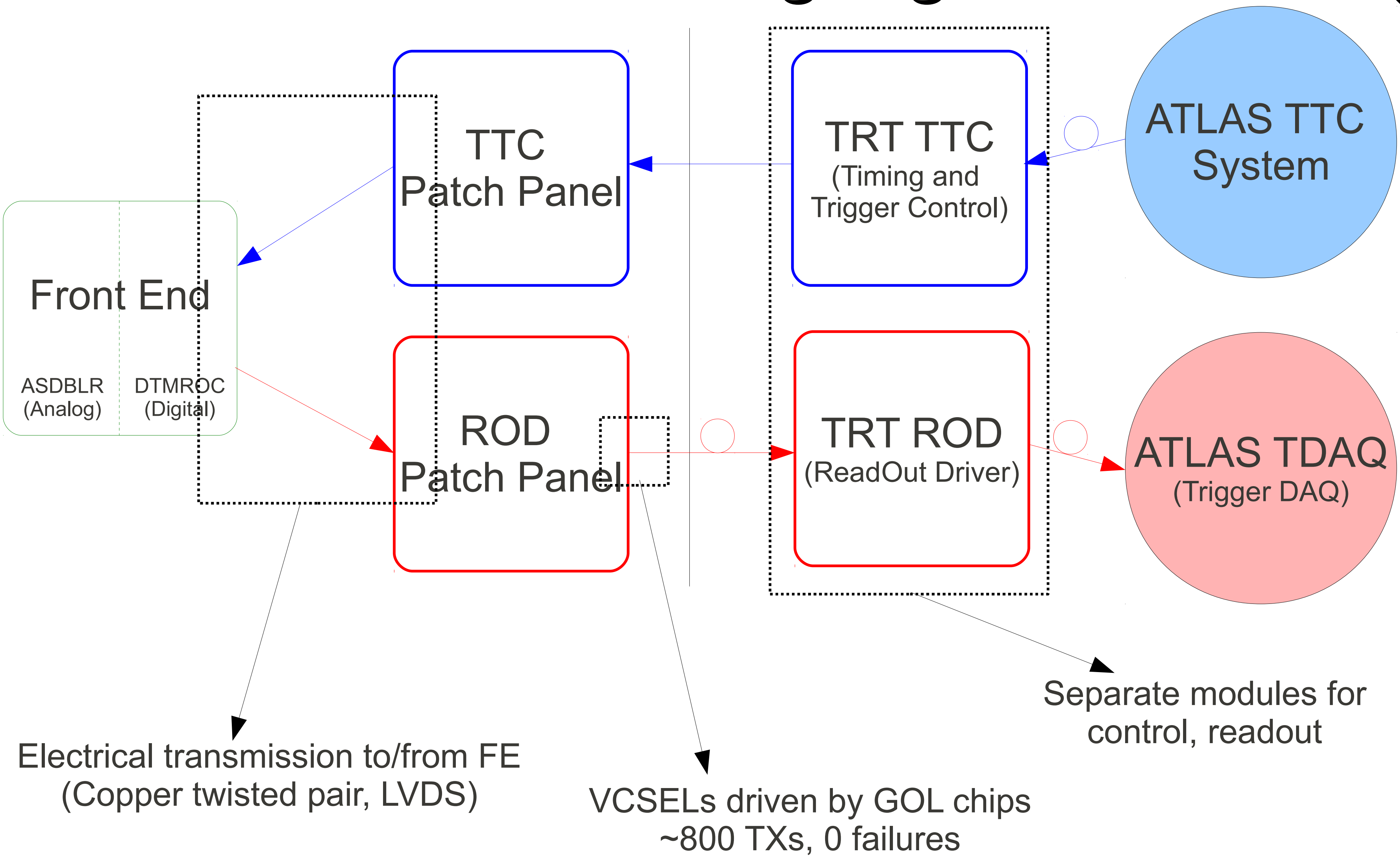
- Discriminate electrons from hadrons based on number of HT hits on a track
  - Use statistical power of many transitions, many straws crossed

(Simplified) Readout Overview

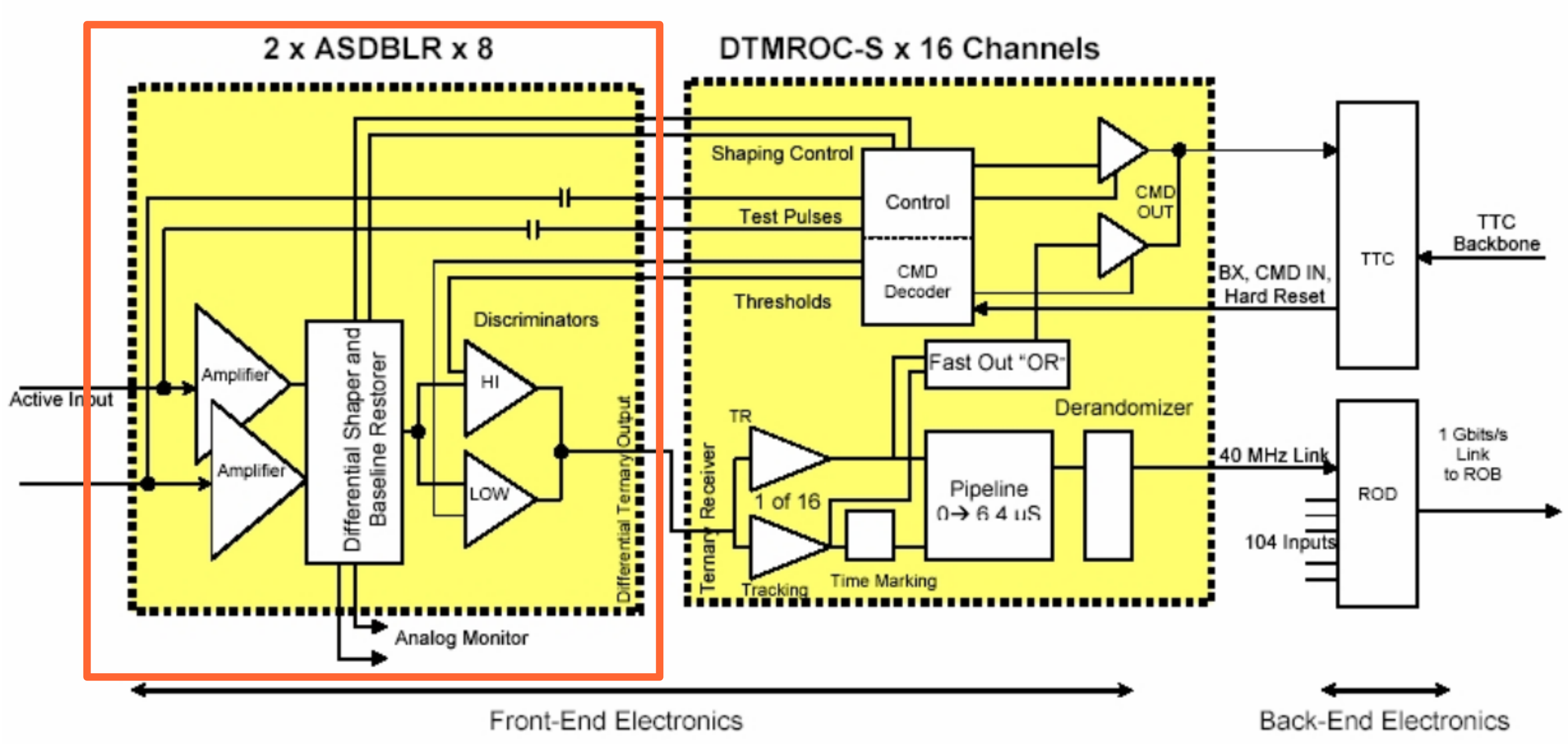


- ROD granularity chosen for L2 trigger:
  - 1/32 in ϕ for barrel, ½ of 1/32 in ϕ for endcaps

Readout Highlights



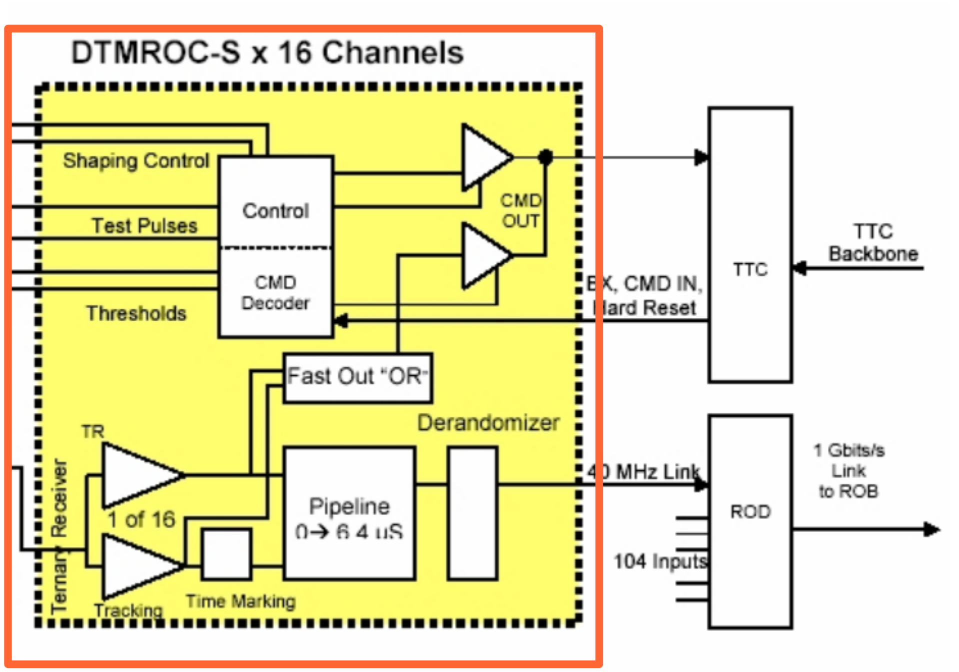
Front End Electronics



- Amplifier, shaper, discriminator, baseline restorer (**ASDBLR**)
  - Analog chip, receives input from **8 channels**
- 2 discriminators, for **low** and **high** thresholds
  - **Ternary output** to DTMROC

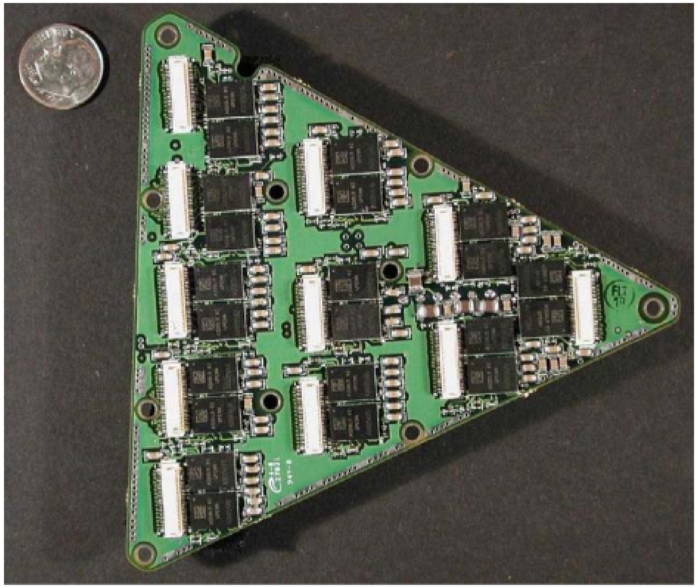
Front End Electronics

- Digital Time Measurement Readout Chip (**DTMROC**)
  - Digital chip, receives input from 2 ASDBLRs (**16 channels**)
- **88kHz** max readout rate
- Key registers **triplicated** to minimize single event upset (SEU) impact
- Fast-OR output used to generate **trigger** (more later)
- **Temperature** and **voltage** (analog and digital) **readback**
  - Useful for tuning operating voltages, monitoring during runs
- **Test pulse** injection at ASDBLR input



Front End Electronics

- **Barrel**: analog and digital chips are mounted on opposite sides of the same PCB
  - Analog and digital grounds coupled by distributed low value resistors
- **Endcaps**: analog and digital chips mounted on separate PCBs
- Analog (±3V) and digital (2.4V) powered separately

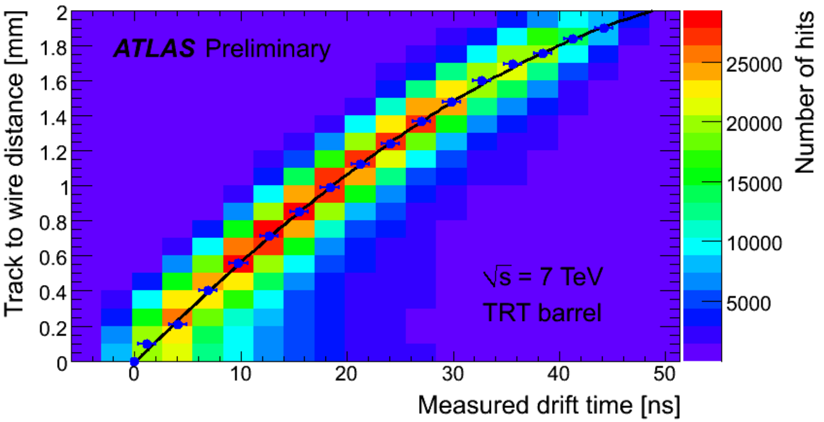


Barrel ASDBLRs

Endcap DTMROCs

Settings and Calibration

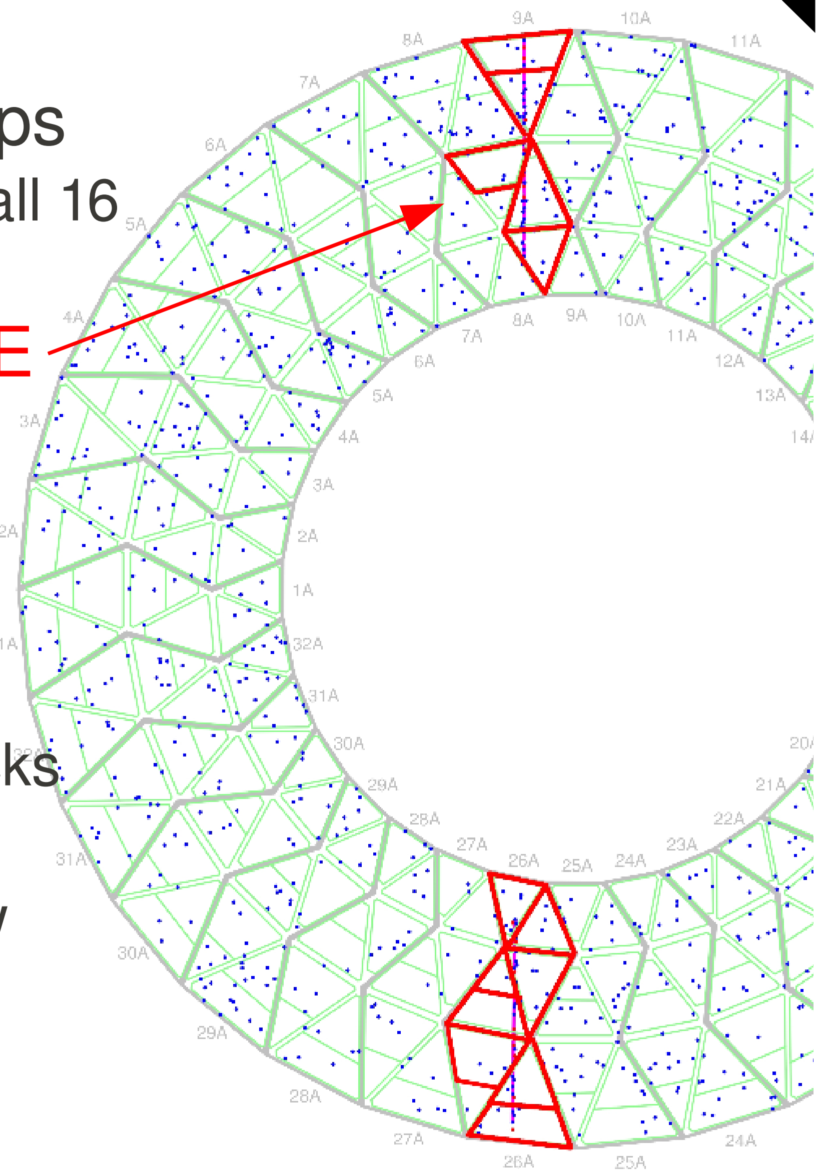
- **Hardware settings**:
  - **Timing delays**
    - Coarse (25ns) and fine (0.5ns) delay settings to align all readout channels in time with LHC collisions
  - **Thresholds**
    - Low threshold, used for drift time measurement, set to MIP levels (~300eV or ~2fC)
    - High threshold, used for Particle ID, set to TR levels (~6keV or ~45fC)
- **Offline calibrations** (every 24 hrs):
  - **R-T relation**
    - Relates measured drift time to track-to-wire distance
  - **T_0 settings**
    - Further align readout channels in time
    - Plus overall constant for full detector
      - Sensitive to global changes ~100ps



TRT Commissioning

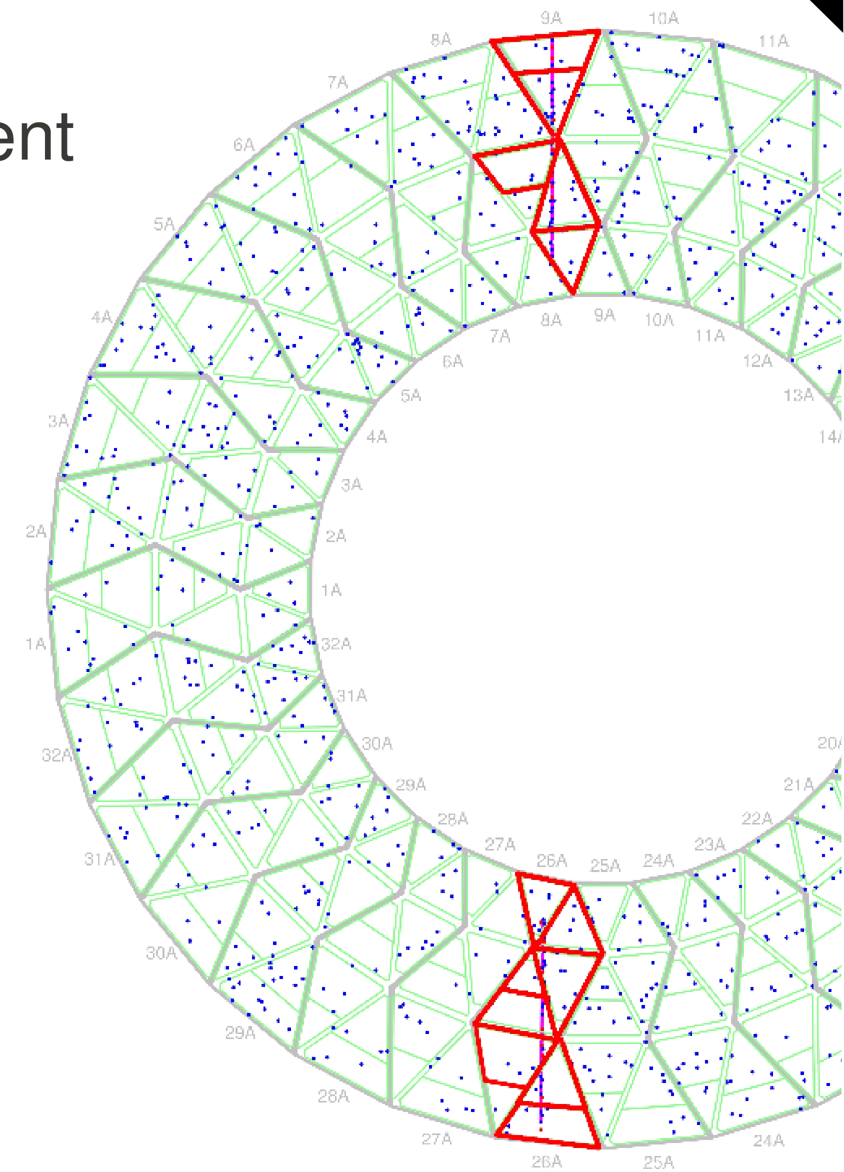
Fast-OR Cosmics Trigger

- Uses Fast-OR output of DTMROC chips
  - ORs together discriminator outputs from all 16 channels (either LT or HT)
- DTMROCs then OR-ed, resulting in FE board trigger granularity
  - Fine for cosmics, too coarse for collisions
- In practice: set HT to near MIP levels
- Pure, high rate, and low jitter:
  - **98%** of events triggered in barrel had tracks
  - Total rate for barrel + endcaps: ~**20Hz**
  - **> 90%** of triggers fall in 25ns time window



Fast-OR Cosmics Trigger

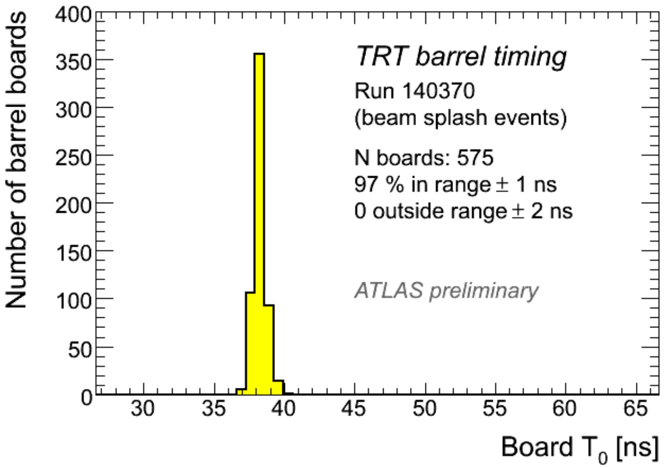
- Implemented quickly after LHC incident in Fall 2008:
  - First tracks in October 2008
  - Fully timed in May 2009
- Major contributor to ATLAS commissioning:
  - High rate of tracks for Inner Detector
    - Alignment, timing
  - Timing reference for other triggers
    - Especially barrel muon trigger



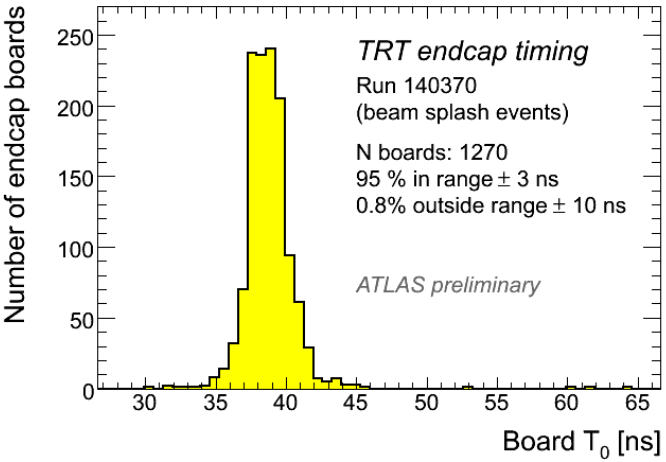
Timing

- Readout window is 75ns, while maximum drift time is ~50ns
  - Requires timing precision ~ns to see leading and trailing edges
- Hardware delays adjusted at level of FE boards

- **Barrel**
  - Timed in using cosmics, verified with beam splash
  - Spread ~1ns



- **Endcaps**
  - Timed in with beam splashes
  - Spread ~3ns



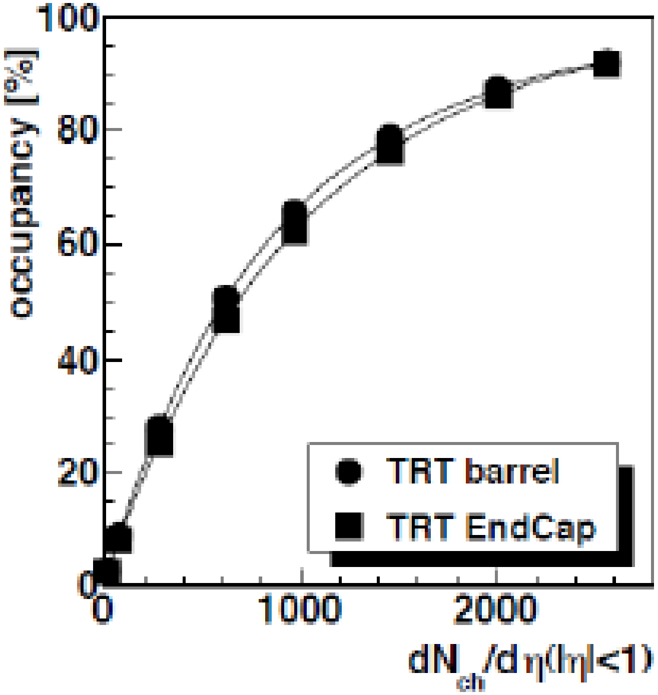
Coverage & Occupancy

- 2% of channels dead (1% mechanical and 1% electronics)
  - Additional ~1% of channels with reduced efficiency

- Tune LT settings to achieve uniform noise occupancy of 2%
  - May eventually tune for uniform efficiency, but good first pass
- See drift time occupancy ~3% at luminosity of 10^{31} $cm^{-2}s^{-1}$
  - Expect occupancy ~30-40% at 10^{34} $cm^{-2}s^{-1}$
  - Also expect average occupancy ~30-40% in upcoming LHC heavy ion run
    - Occupancies > 80% for central collisions

Pb-Pb Occupancy

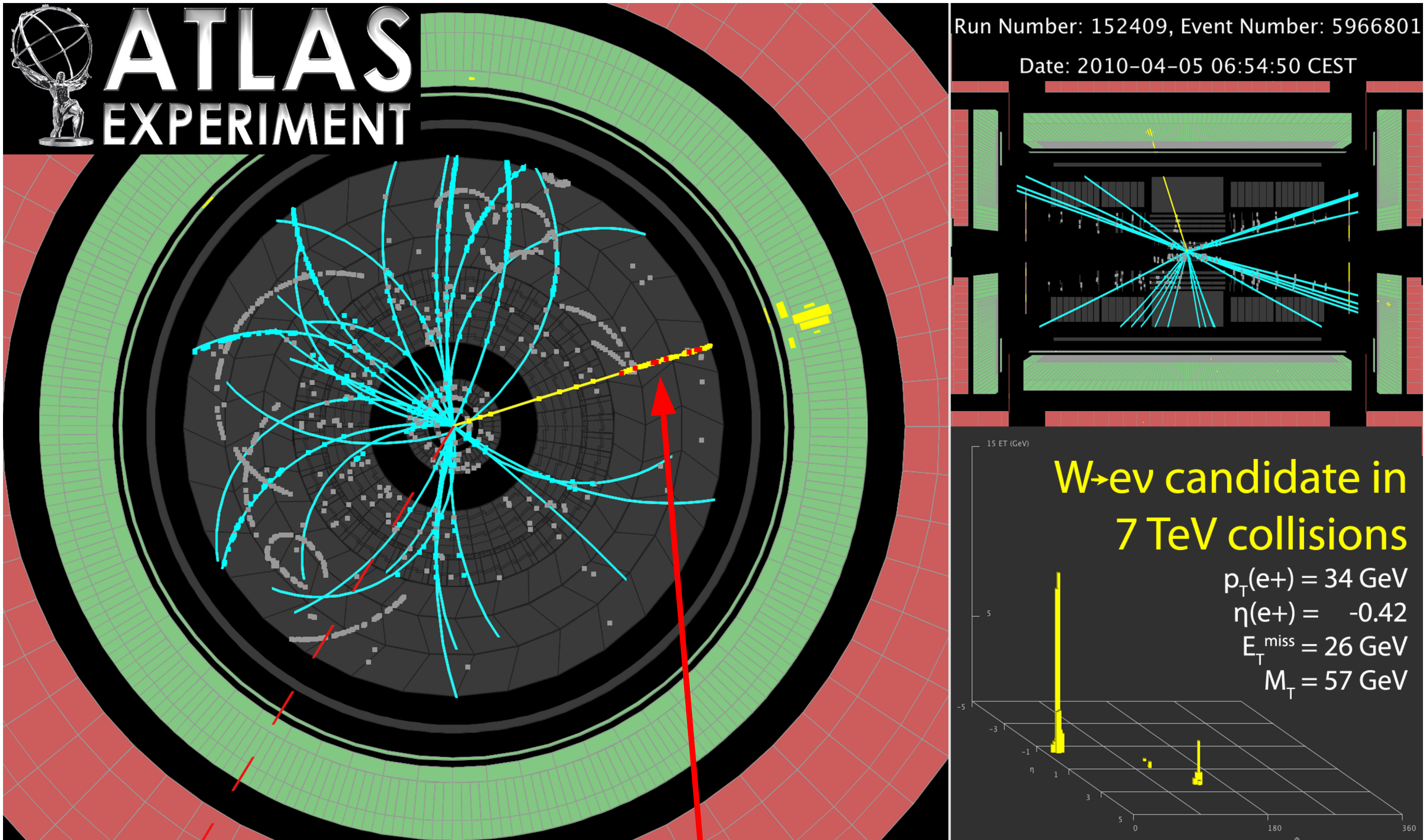
ATLAS Preliminary (MC)



Advanced Readout Features

- Huffman encoding algorithm provides lossless compression in the RODs, to cope with high occupancy
- Automatic readout recovery procedures:
  - SEUs can disrupt DTMROC configuration
    - → Monitor registers at ~65Hz and rewrite any changed values
    - Expect SEU rate < O(Hz) for full system at nominal LHC conditions
      - Triplicate DTMROC registers make most SEUs harmless anyway
  - Clocks (QPLLs) are sensitive to changes in LHC clock
    - Typically see problems switching to/from LHC clock, during ramps
      - i.e. large changes in frequency or fast changes in phase
      - TRT is more sensitive because we have a chain of QPLLs
    - → Automatically detect problems and resynchronize QPLLs/readout
  - For other readout problems
    - → Can remove, reconfigure, and reinsert RODs in ongoing run
    - Removal is automatic, recovery is a shifter action

TRT Performance



TRT High Level hits in RED

Operations and Data Quality

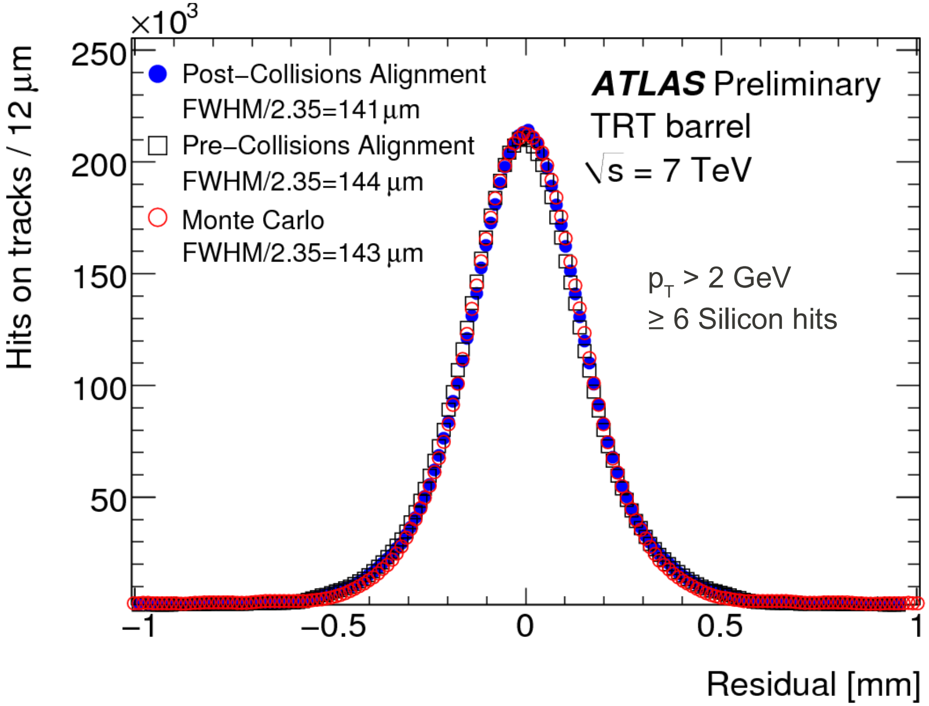
- *Active* and providing *good quality data* for **100%** of LHC stable beam periods during 2009 and 2010
  - Highest among ATLAS subdetectors!
- Thanks to:
  - Lots of **hard work** over the years by many people, still continuing!
  - **Automated** and **streamlined procedures** for DAQ, DCS
    - Including automatic recovery from common readout problems
  - Continuing improvements in data quality monitoring
  - Can run with nominal HV regardless of beam conditions

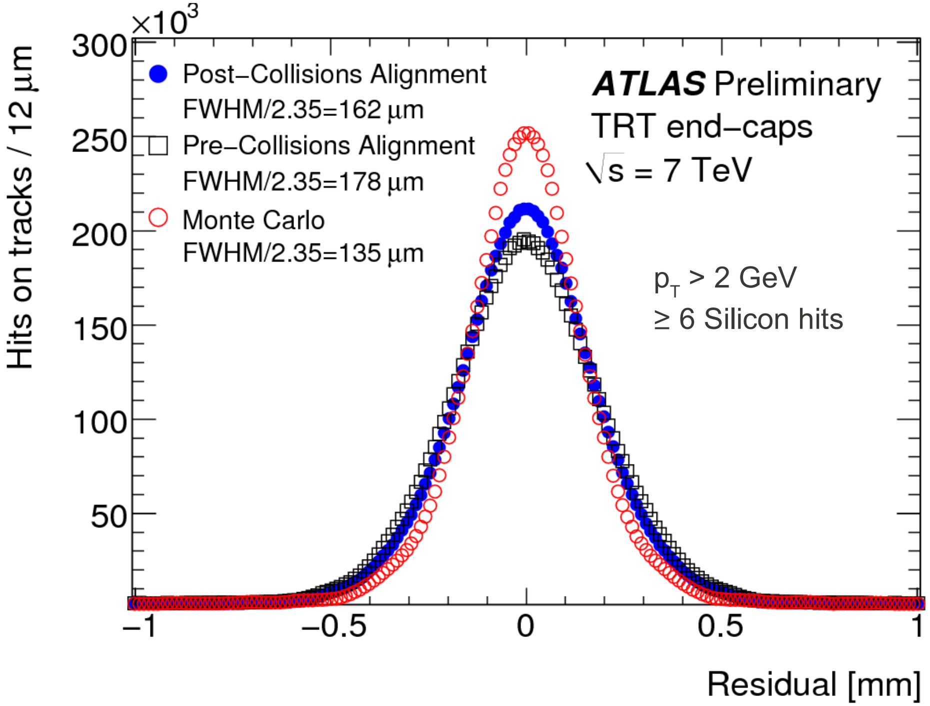
Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	TGC	CSC
97.7	96.4	100	94.4	98.7	99.3	99.2	98.5	98.3	98.6	98.3

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams at √s=7 TeV between March 30th and August 14th (in %)

Position Resolution

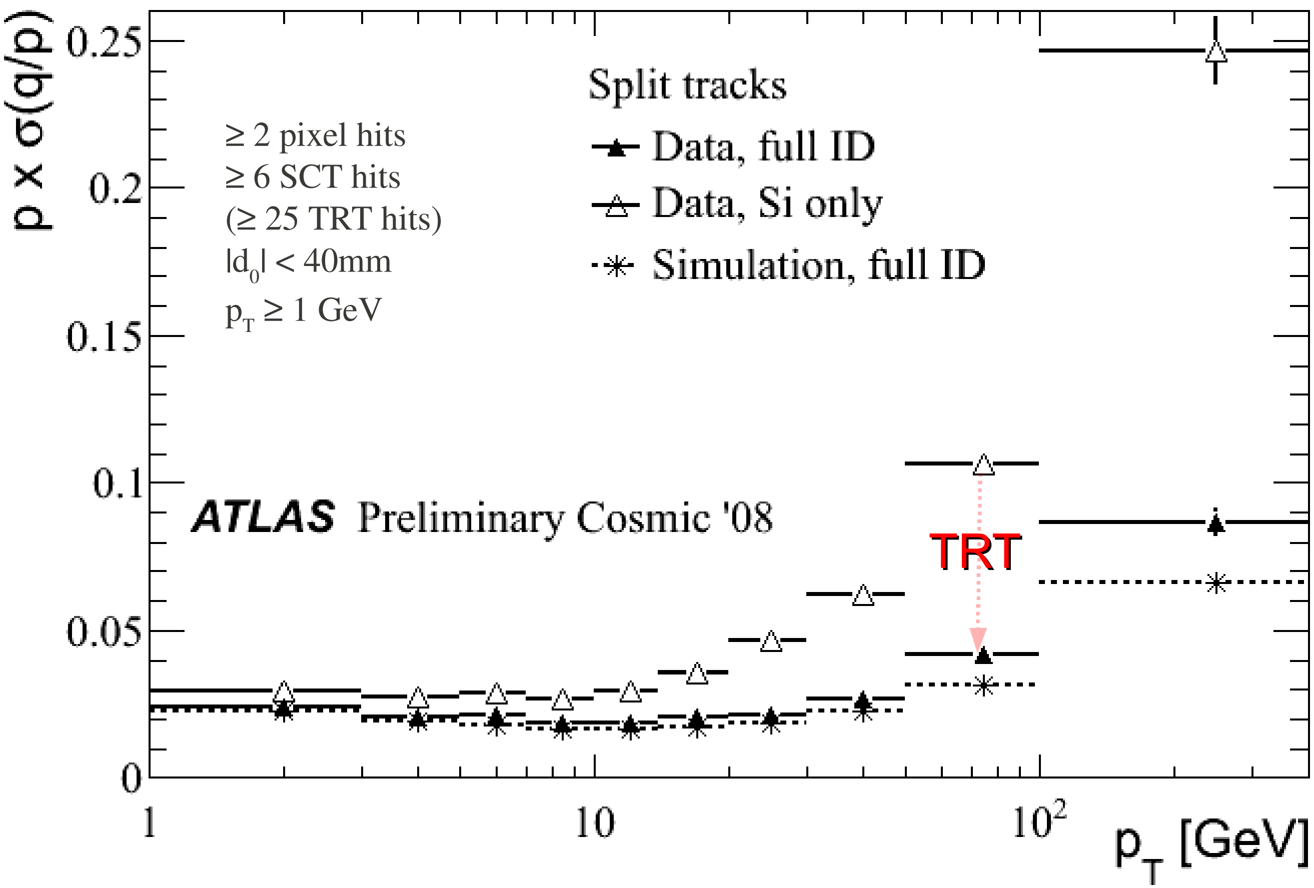
- **Barrel** exceeding TDR, approaching intrinsic limit of ~130μm!
- **Endcaps** not as well studied with cosmics, but catching up
  - Latest improvements in alignment, etc. not reflected here
- Lots of work to get here, including:
  - Alignment, calibration, tracking software





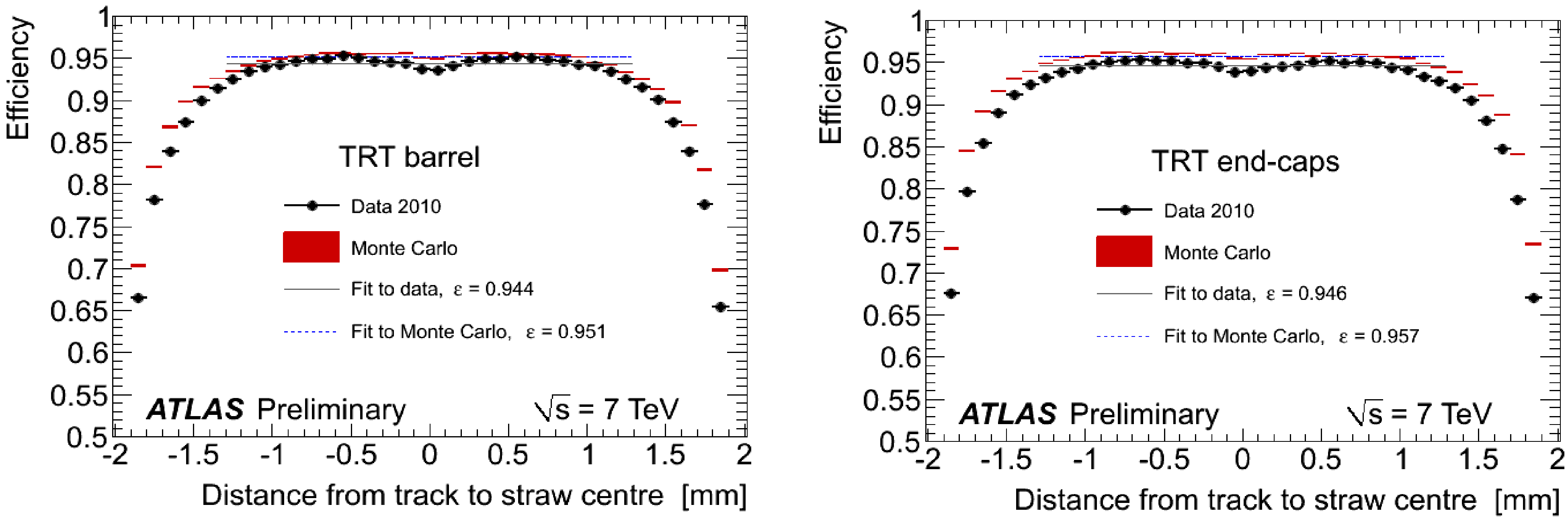
Momentum Resolution

- With its long lever arm, **TRT contributes significantly**
  - Radius of last barrel SCT layer: 514mm
  - End of TRT barrel: 1068mm



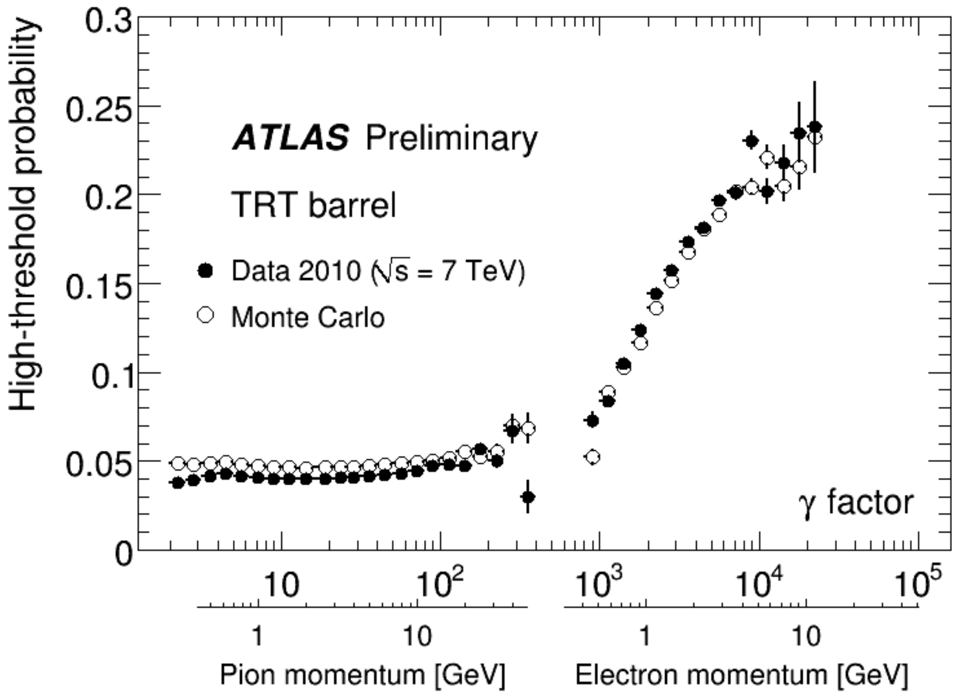
Straw Hit Efficiency

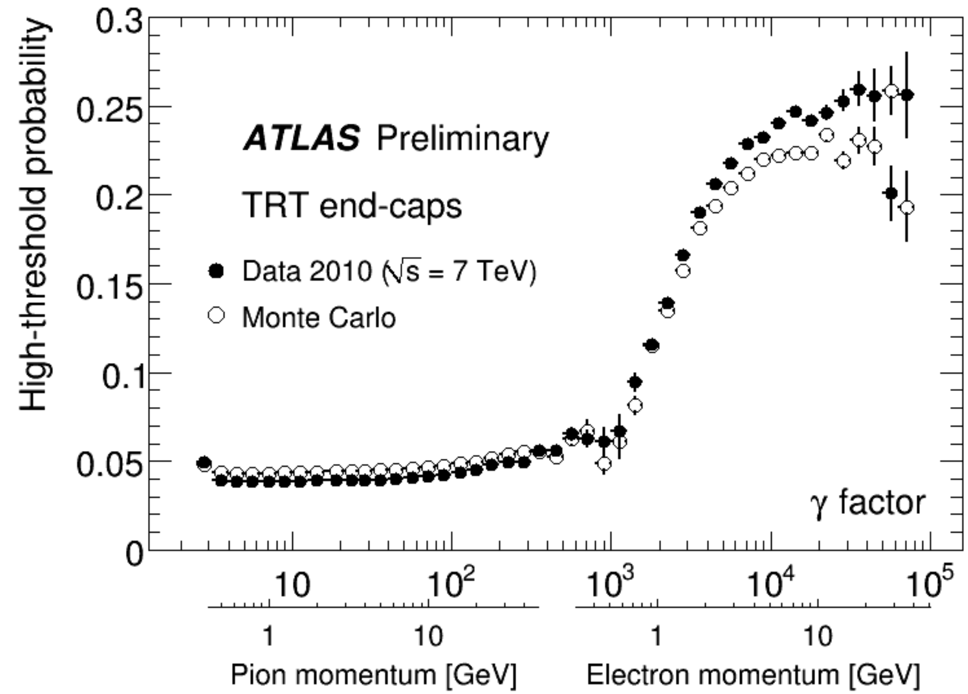
- Hit Efficiency ~**94%**
  - Restricted to ± 1.3mm to remove geometry and reconstruction effects
  - Dead channels excluded (2%)
- Monte Carlo was tuned to 900 GeV data
- Plot requirements:
  - ≥ 1 pixel hits, ≥ 6 SCT hits, ≥ 15 TRT hits
  - $p_T > 1$ GeV, $|d_0| < 10$mm, $|z_0| < 300$mm



Particle Identification

- Transition radiation probability depends on the γ factor of a particle
  - Turn on curve also depends on geometry, properties of the radiator
    - Different radiators in barrel and endcap
    - Endcap radiator spacing varies with the Z position of the wheel
- Select electron, pions in data to tune and validate:
  - Pions: hadron enriched sample from all tracks
  - Electrons: tag and probe using photon conversions





Summary & Outlook

- TRT operates smoothly: 100% uptime in physics runs
- Performance already **excellent** and studies are continuing
- TRT being used in first round of physics analyses, especially for electron ID
- LHC Heavy Ion run will provide a good test at high instantaneous luminosity
  - TRT plans to run at or near nominal settings
- TRT is in great shape to provide high quality data for its expected lifetime (and probably beyond!)

Thanks

- to everyone in the TRT and ATLAS communities for all the hard work to get to this point!
- Special thanks to Sasa Fratina, Liz Hines, Ken McFarlane, Fred Leuhring, Andrey Loginov, Mitch Newcomer, Christoph Rembser, Anatoli Romaniouk, Rick VanBerg, and Peter Wagner
- And thanks to you for listening!