THE ATLAS TRANSITION RADIATION TRACKER

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James Degenhardt

University of Pennsylvania

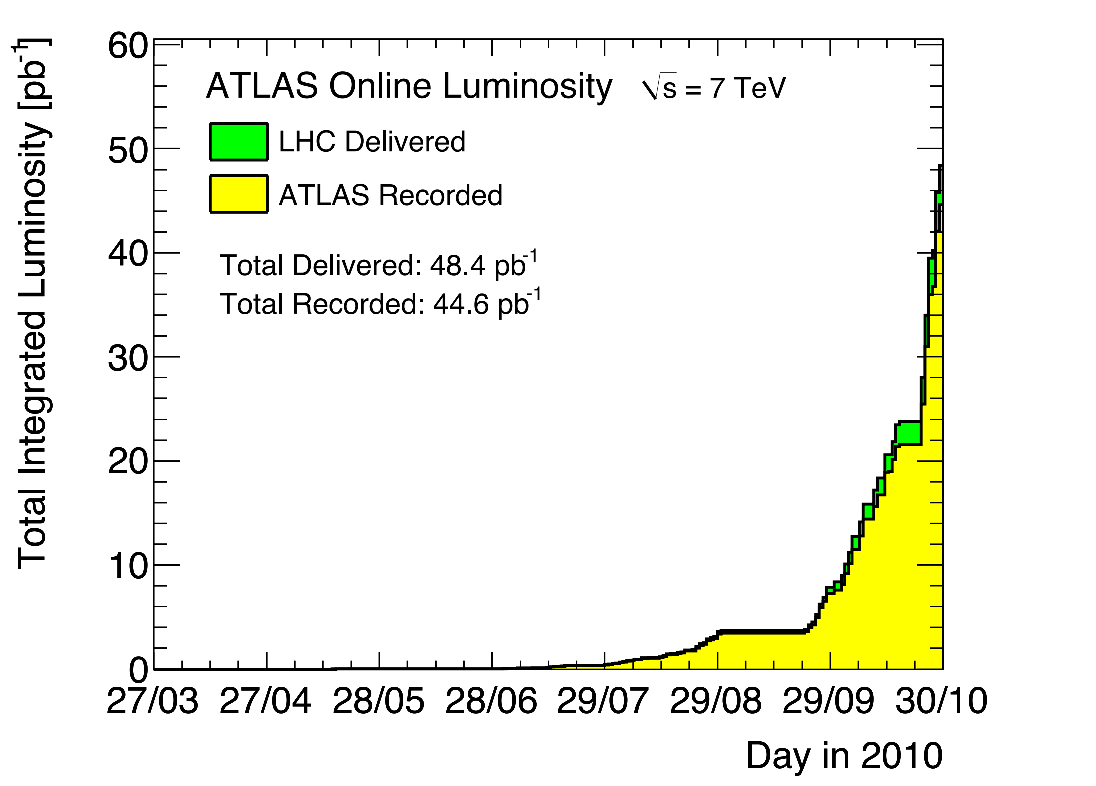
On behalf of the ATLAS TRT Collaboration

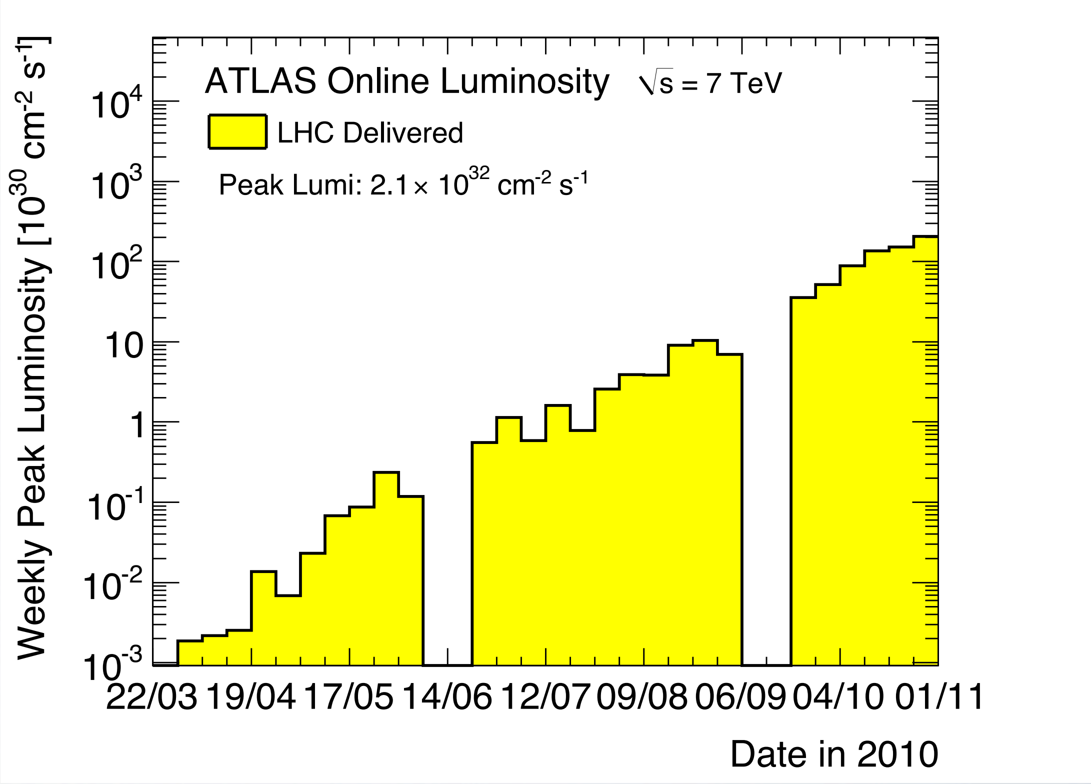
OUTLINE

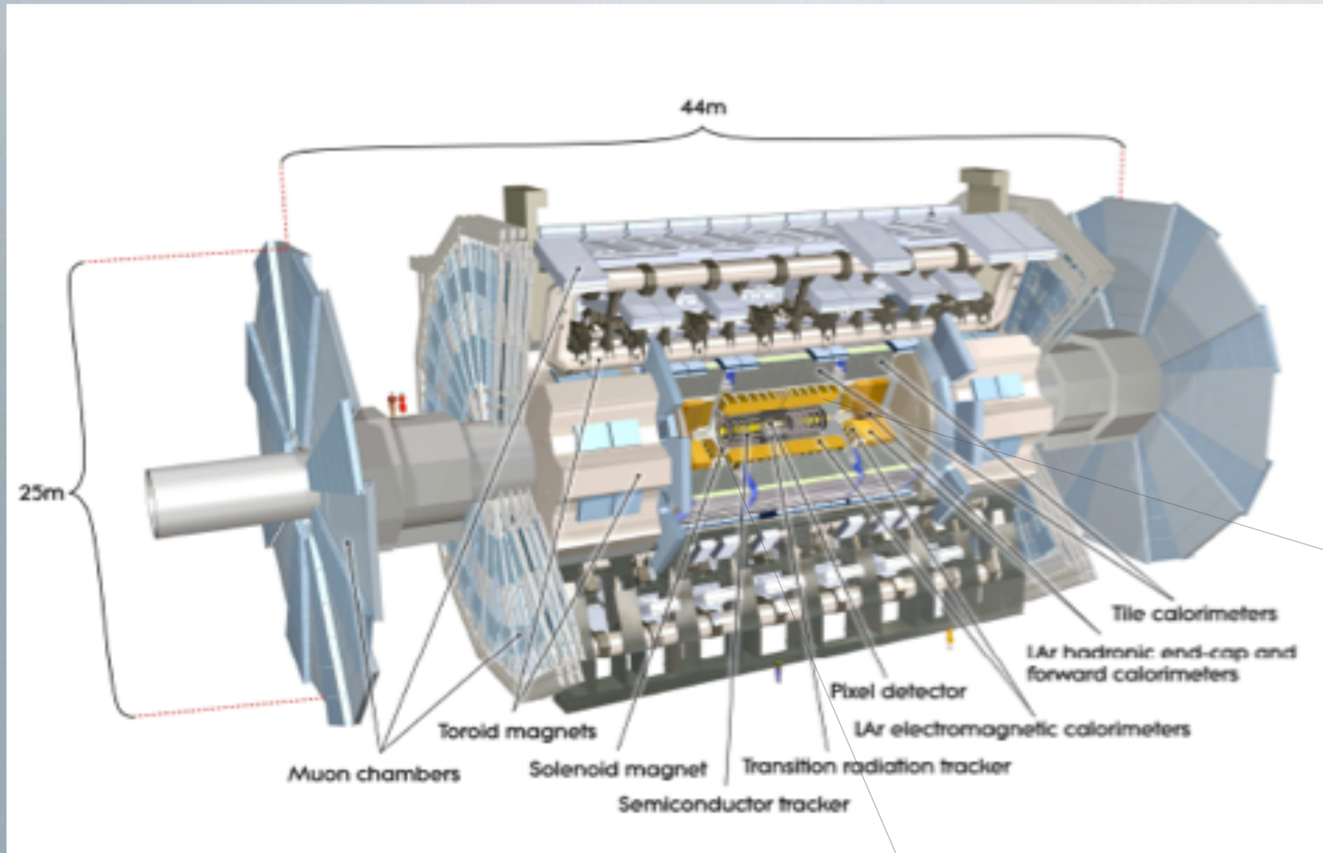
1. The ATLAS Detector and the LHC Status
2. The Transition Radiation Tracker (TRT)
3. TRT Operation and Performance (cosmic runs, 7 TeV data)
4. Summary

THE LHC STATUS

- The **LHC** is a hadron collider (pp and PbPb)
- Synchronous collider operating at **40MHz** (25 ns bunch spacing, a.k.a. bunch crossing, design)
- Design instantaneous luminosity of $\mathbf{10^{34}}$ $\mathbf{cm^{-2}s^{-1}}$ and **7 x 7 TeV**
- The LHC has been operating well since November 2009
- **First collisions** Nov. 22, 2009, 450 x 450 GeV
- First collisions at **3.5 x 3.5 TeV**, March 30th 2010
- First collisions with **Instantaneous Luminosity** of $\mathbf{10^{32}}$ $\mathbf{cm^{-2}s^{-1}}$ on October 14, 2010 (operation goal)
- Delivered over $\mathbf{40\ pb^{-1}}$ of 7 TeV data by October 31, 2010
- Start **Heavy Ion Collisions** November 11 2010 (TRT to play a key role)





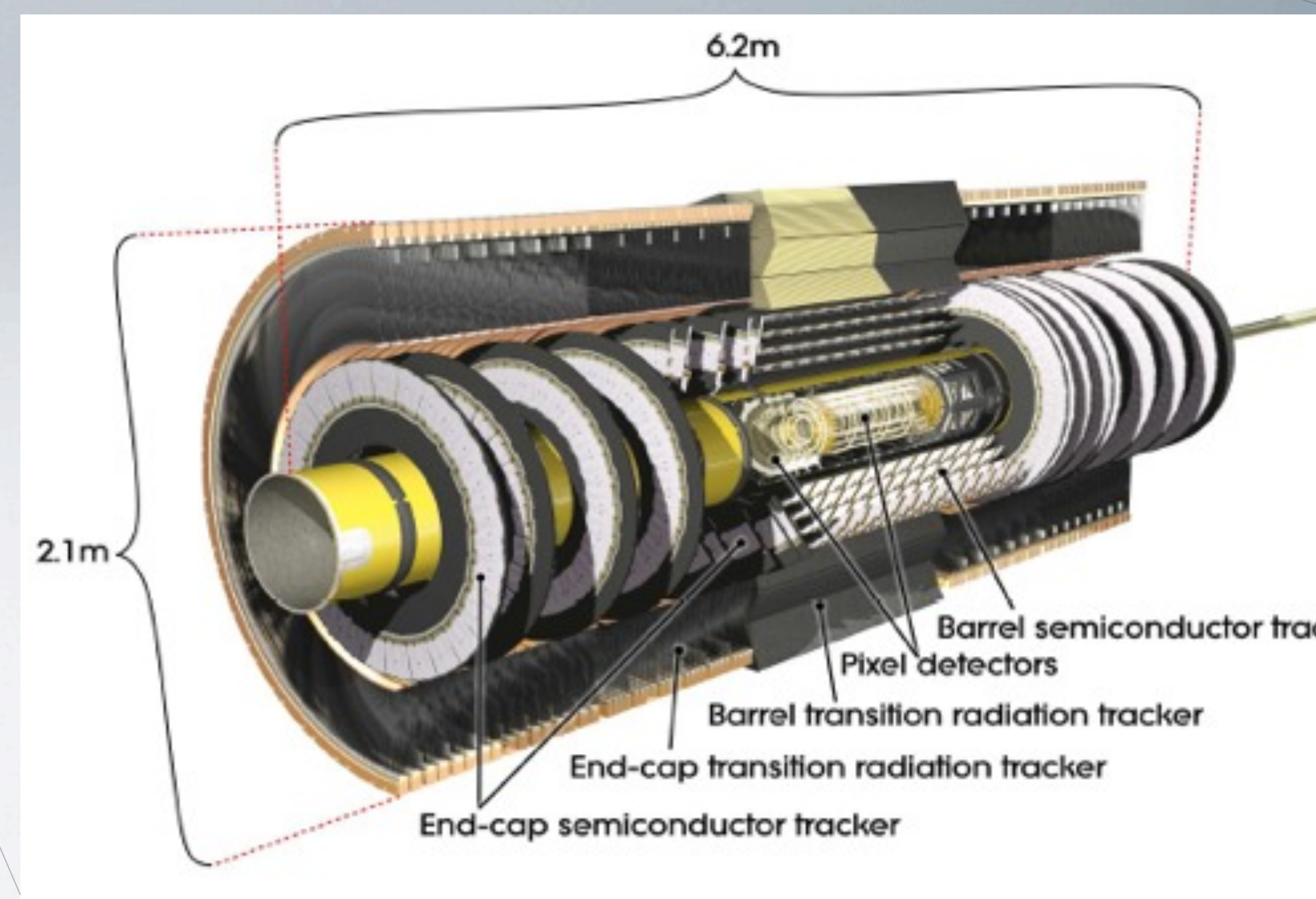


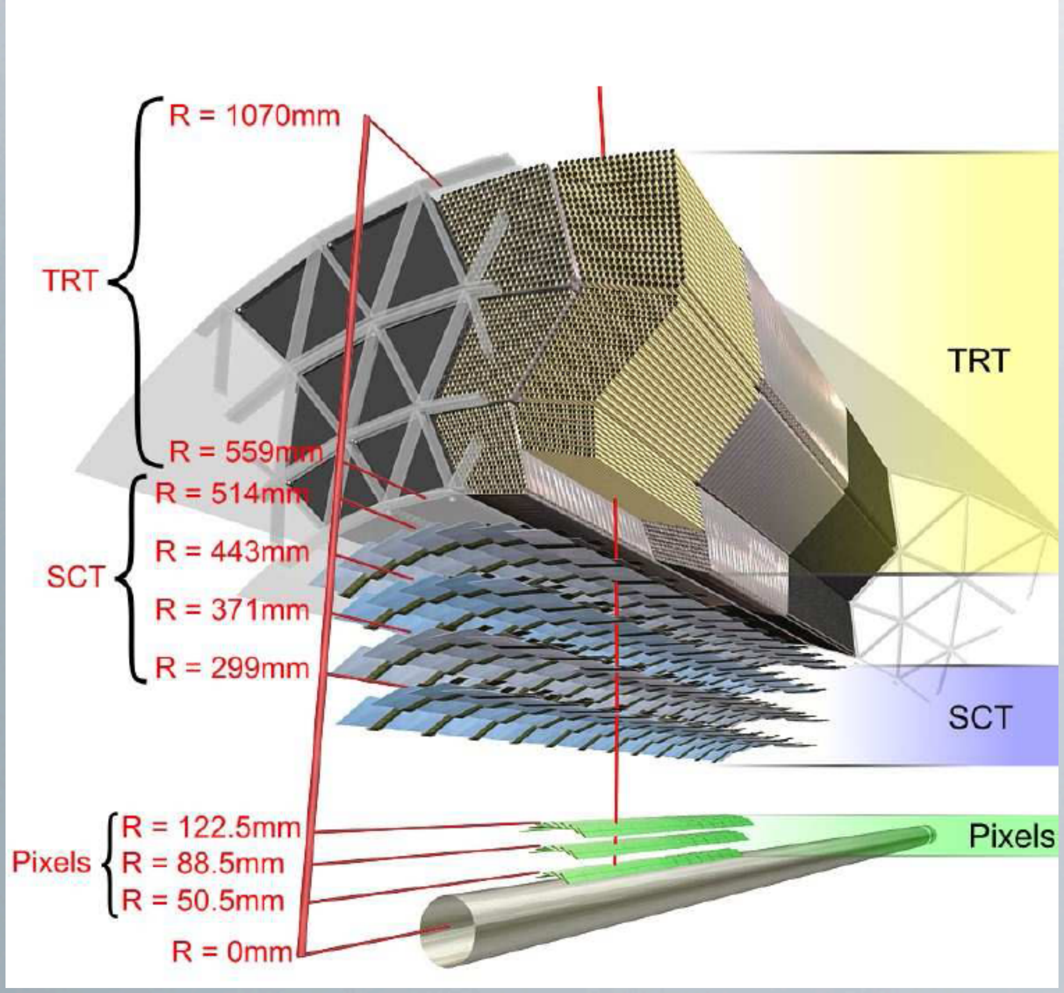
ATLAS DETECTOR

- The ATLAS Detector is a multipurpose detector
- Multi system muon detection
- 8 fold air core ~1.4T muon toroid
- Liquid Argon and Scintilator Tile Calorimetry
- Silicon inner tracker, straw outer tracker

INNER DETECTOR

- Provides charged particle tracking above 0.1 GeV and $|\eta| < 2.5$. $\eta = -\ln\tan(\theta / 2)$.
- Electron identification for particles with $|\eta| < 2.0$ and $0.5 < p_T < 150$ GeV
- Immersed in 2 T solenoidal field
- Consists of Pixel detectors, Semiconductor Tracker (SCT) and Transition Radiation Detector (TRT)



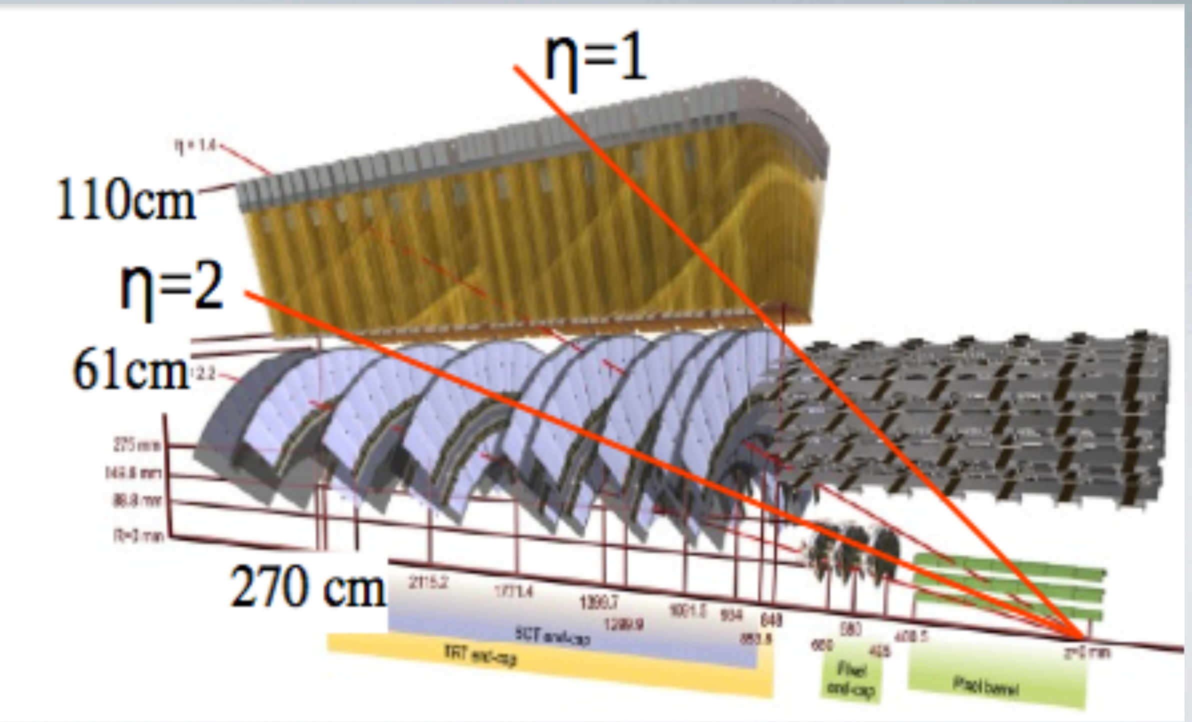


TRT Barrel

- 3x32 modules
- 1.44 m* straws parallel to the beam axis
- wires electrically split in the middle to reduce occupancy (~1.5cm dead region)
- each end read out separately
- 105088 readout channels total
- 2 triangular front end electronics boards per module

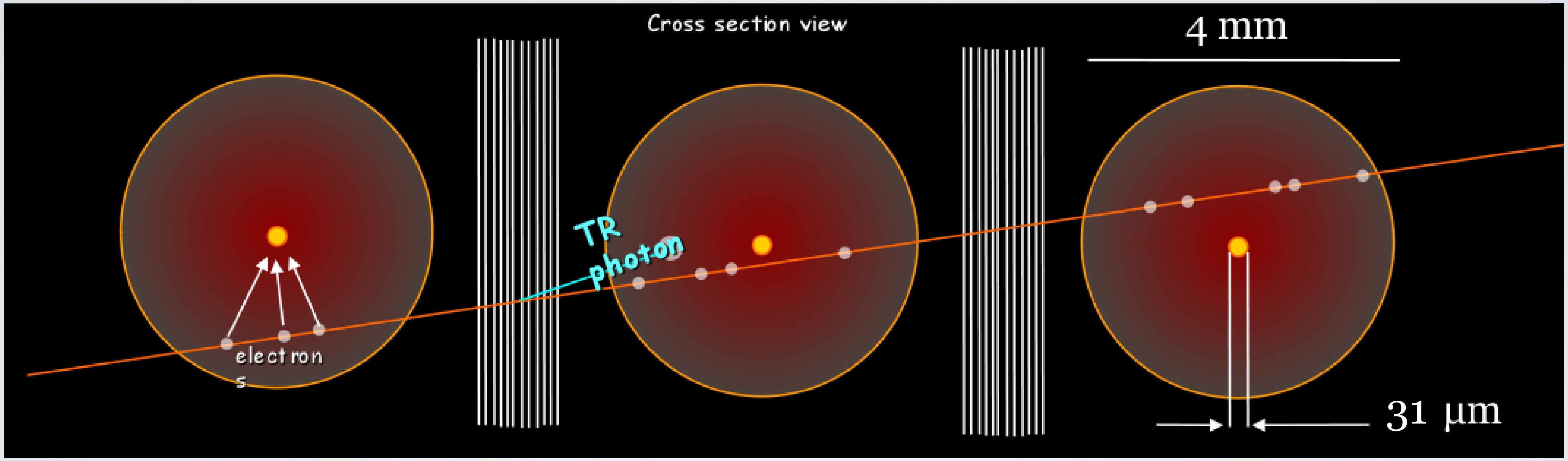
TRT End-cap

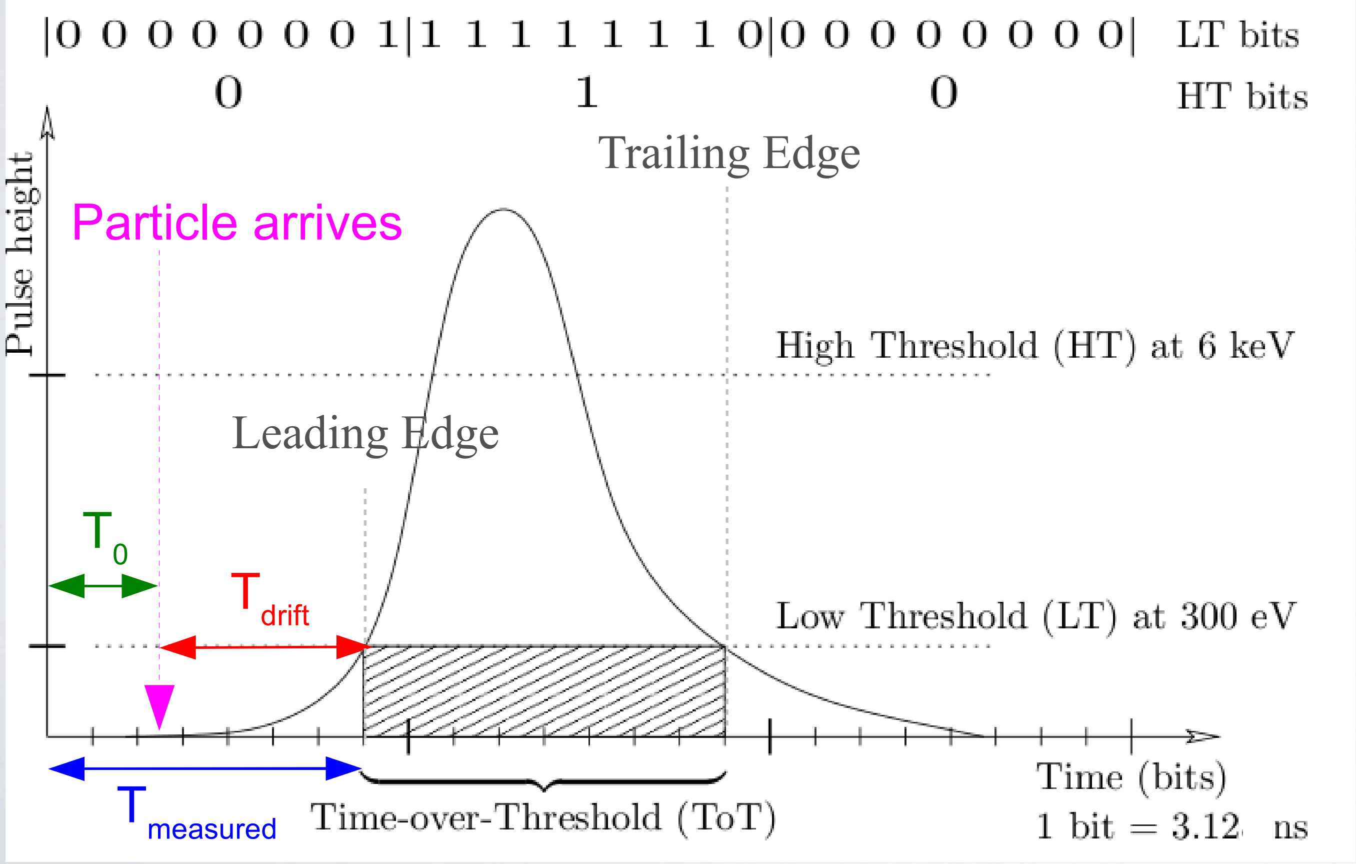
- 12 A type wheels with 8 layers of straws each
- 8 B type wheels with 8 layers of straws where the layers are spaced further apart
- 39 cm long radial straws
- 122880 readout channels per end-cap



* first 8 layers of straws in barrel are only active for 312 mm from electronics.

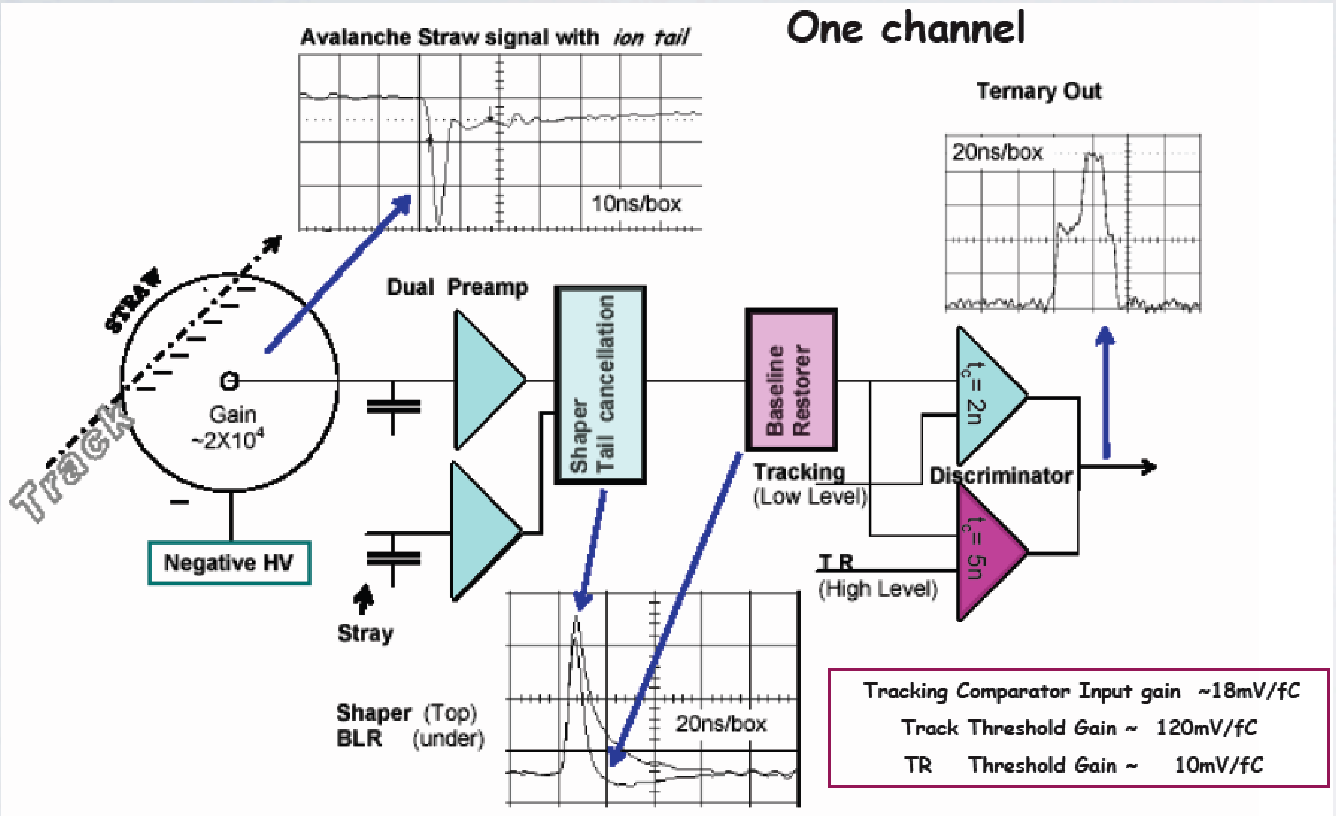
THE DIGITIZED TRT SIGNAL

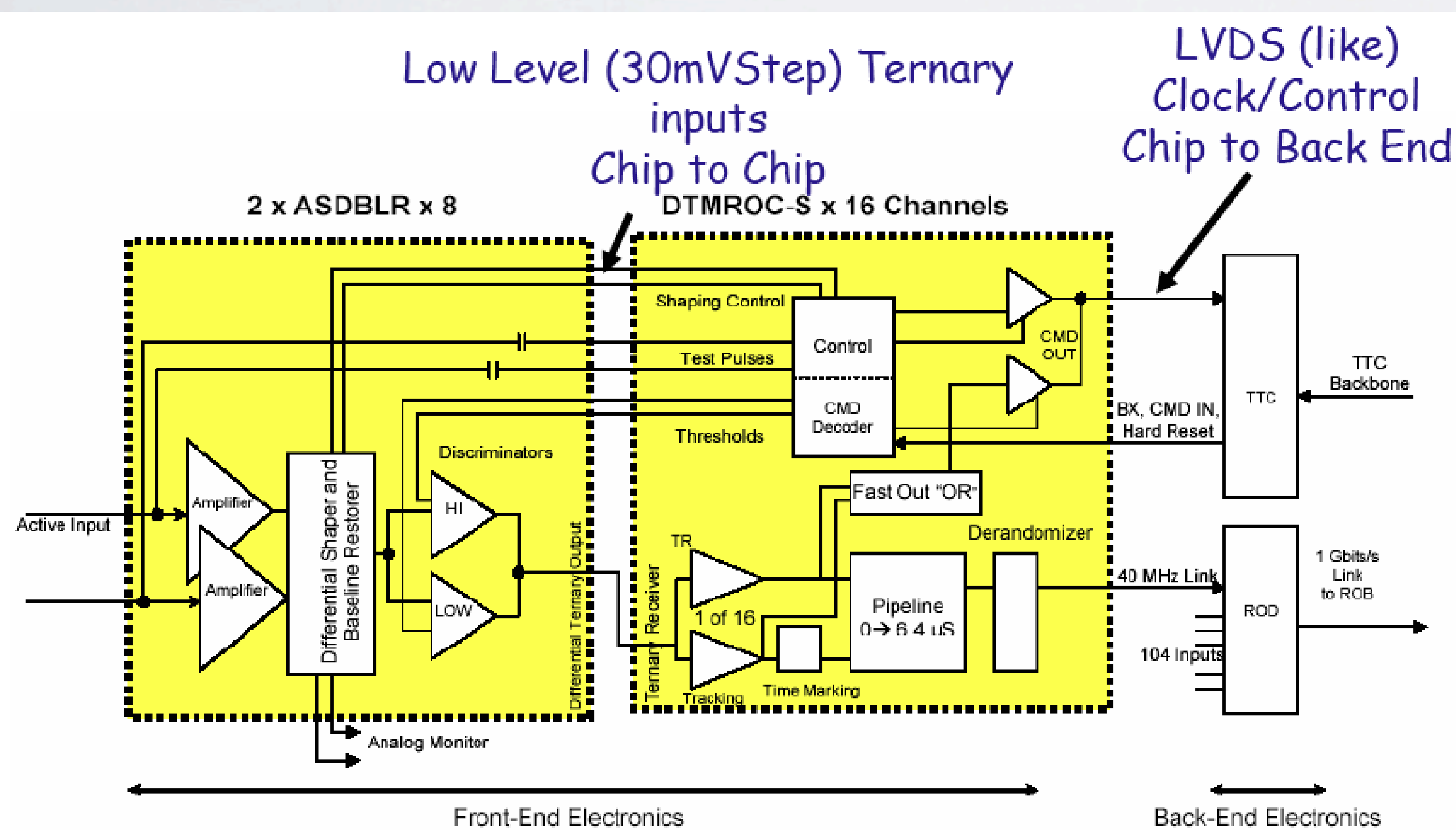




- Each straw signal is readout over 75 ns (3 bunch crossings)
- The discriminated signal is digitized into 24 bits (~ 3.12 ns). The 24 bits can also be thought of as time bins
- There is one High Threshold bit for every each bunch crossing
- **Trailing Edge (TE):** Independent of the particle position as it transits the straw: electrons furthest from the wire, nearest the straw wall
- **Leading Edge (LE):** Dependent on where the particle transits the straw. Indicates minimum distance of approach.
- **Time Over Threshold (ToT)**: Dependent on the particles path length and accumulated ionization or *dE/dx*

TRT READOUT CHAIN



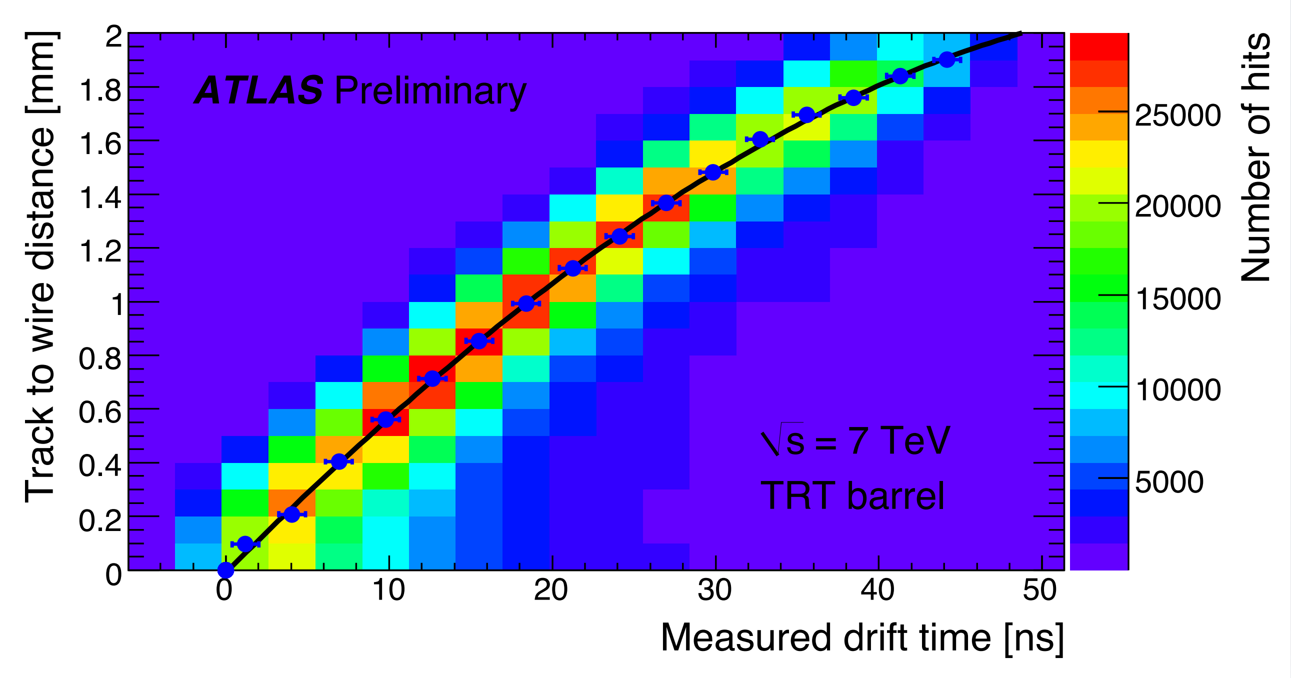


- Rate/straw upto **20MHz** (50ns), **48ns** maximum drift time
- **ASDBLR**: Amplifier/shaper with ion tail cancellation and baseline restoration
- **Two discriminators** for each channel
  - 200 - 300 eV (15% MIP) tracking threshold
  - ~6 keV TR threshold
- Digital pipeline, **6 µs deep**
  - Tracking bit stored every **3.12 ns**
  - TR bit stored every 25 ns

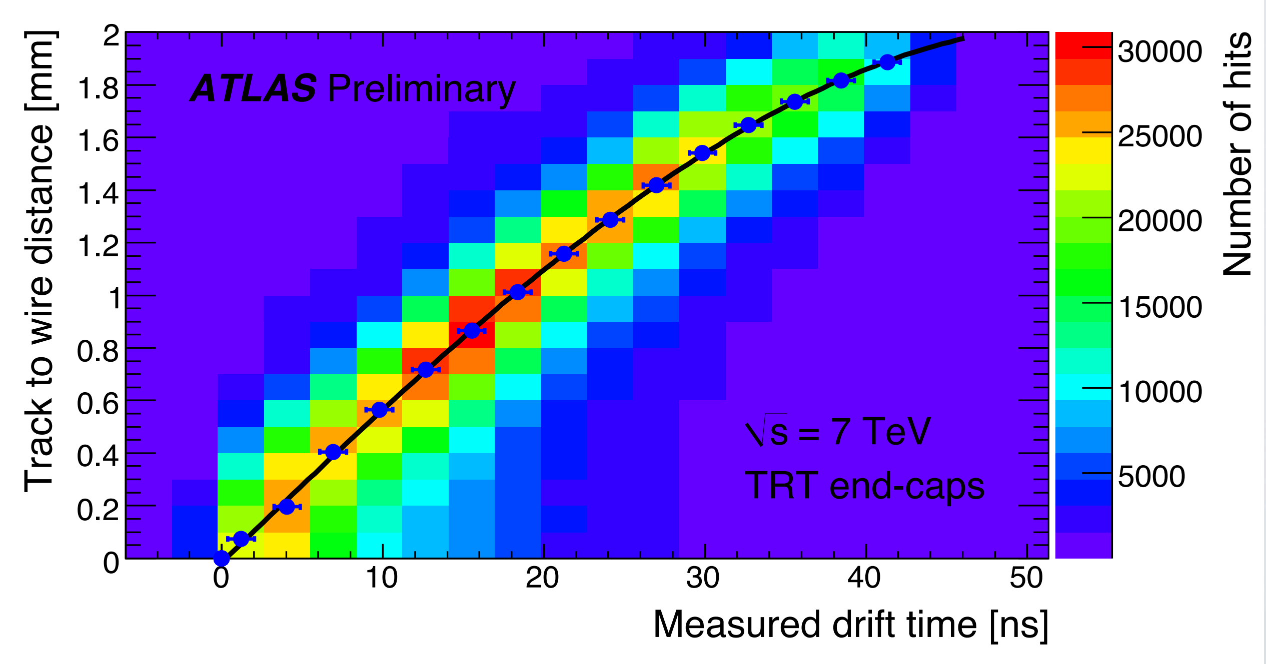
SETTINGS AND CALIBRATION

- **Hardware Settings**:
  - **Timing Delays**
    - Delay tuning as fine as 0.5ns used to align all readout channels in time with LHC collisions
  - **Thresholds**
    - Low threshold, calibrated to produce uniform 2% noise occupancy across detector.
    - High threshold, set to produce uniform response to pions across the detector.
- **Offline Calibrations** (every 24hrs):
  - **R-T Relation**
    - Parameterization that relates measured drift time to track-to-wire distance
  - **T_0 Constants**
    - Further align readout channels in time (within +/- 0.5ns)
    - Plus overall constant for full detector
      - Sensitive to global changes ~**100ps**

TRT Barrel R-T Relation

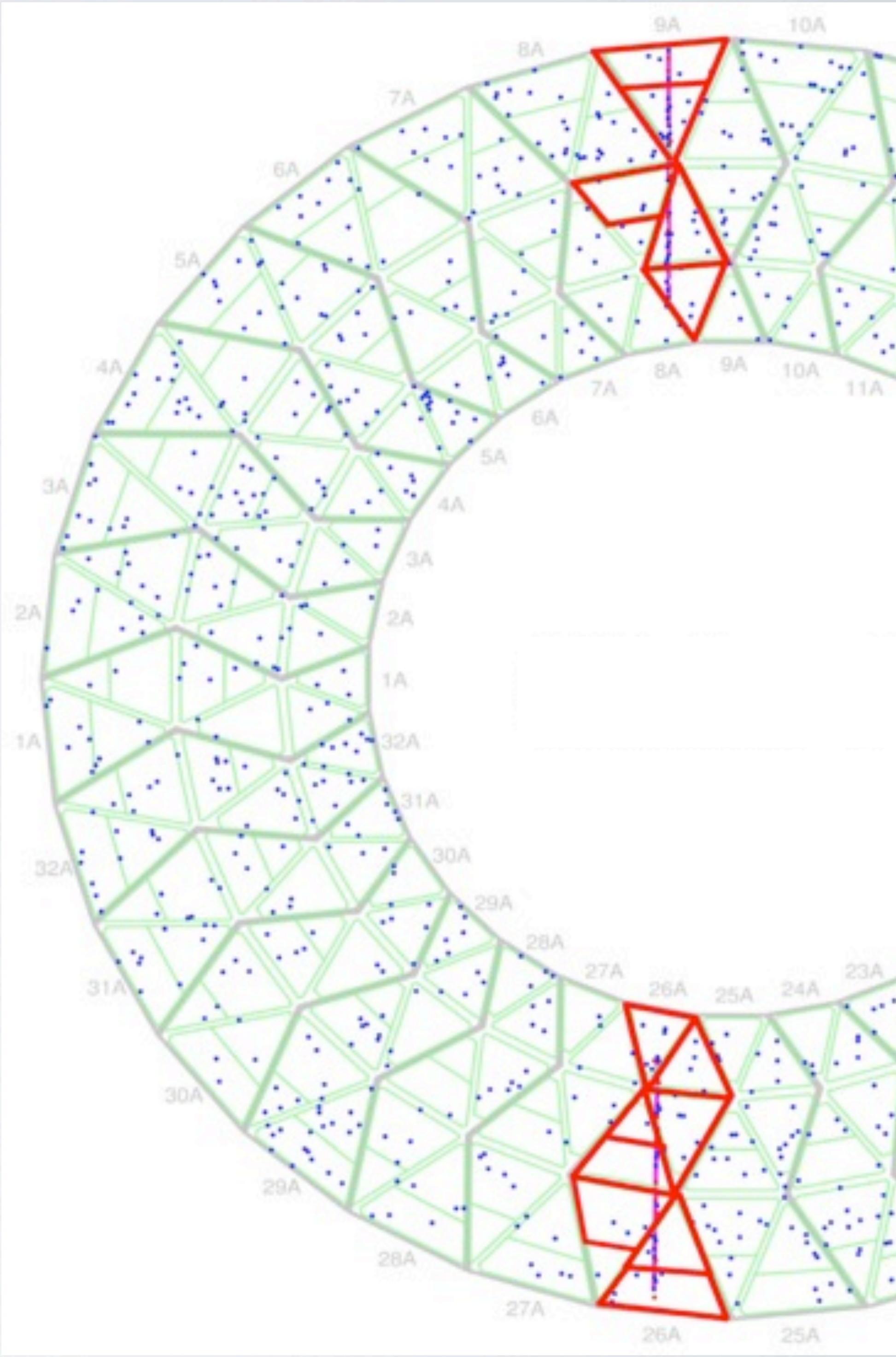


TRT End-cap R-T Relation



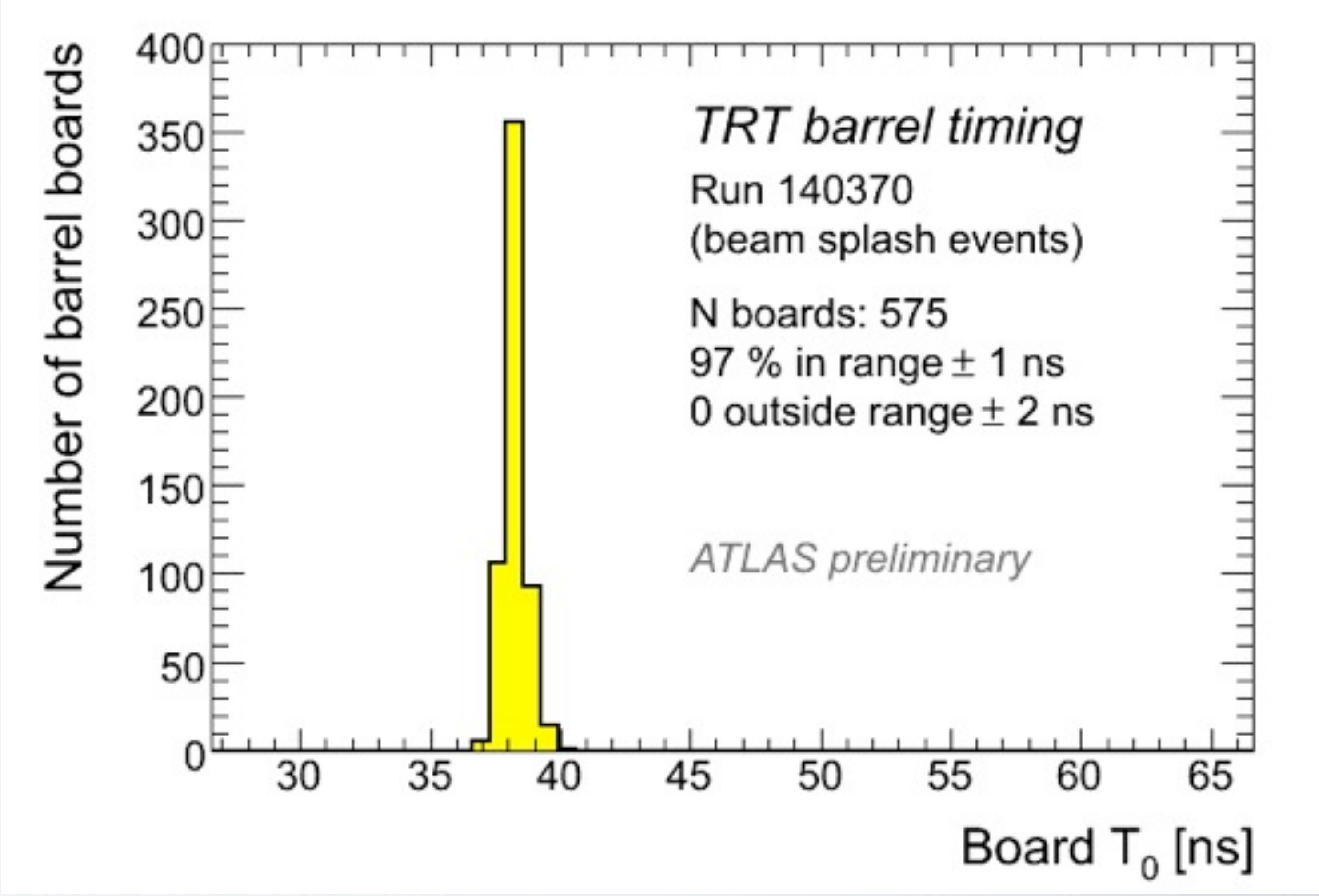
FAST-OR COSMICS TRIGGER

- Early detector **commissioning relied heavily on cosmics** for timing, alignment and calibration.
- TRT Fast-OR was the **primary cosmic trigger** for ATLAS timing and alignment.
- **Use Fast-OR output** of DTMROC chips
- DTMROCs then OR-ed, resulting in FE board trigger granularity
- In practice: **set HT to ~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



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**
  - Already timed-in using cosmic, verified with beam splash
  - spread ~**1ns**
- **Endcaps**
  - Timed-in with beam splashes
  - Spread ~**3ns**



OPERATIONS AND DATA QUALITY

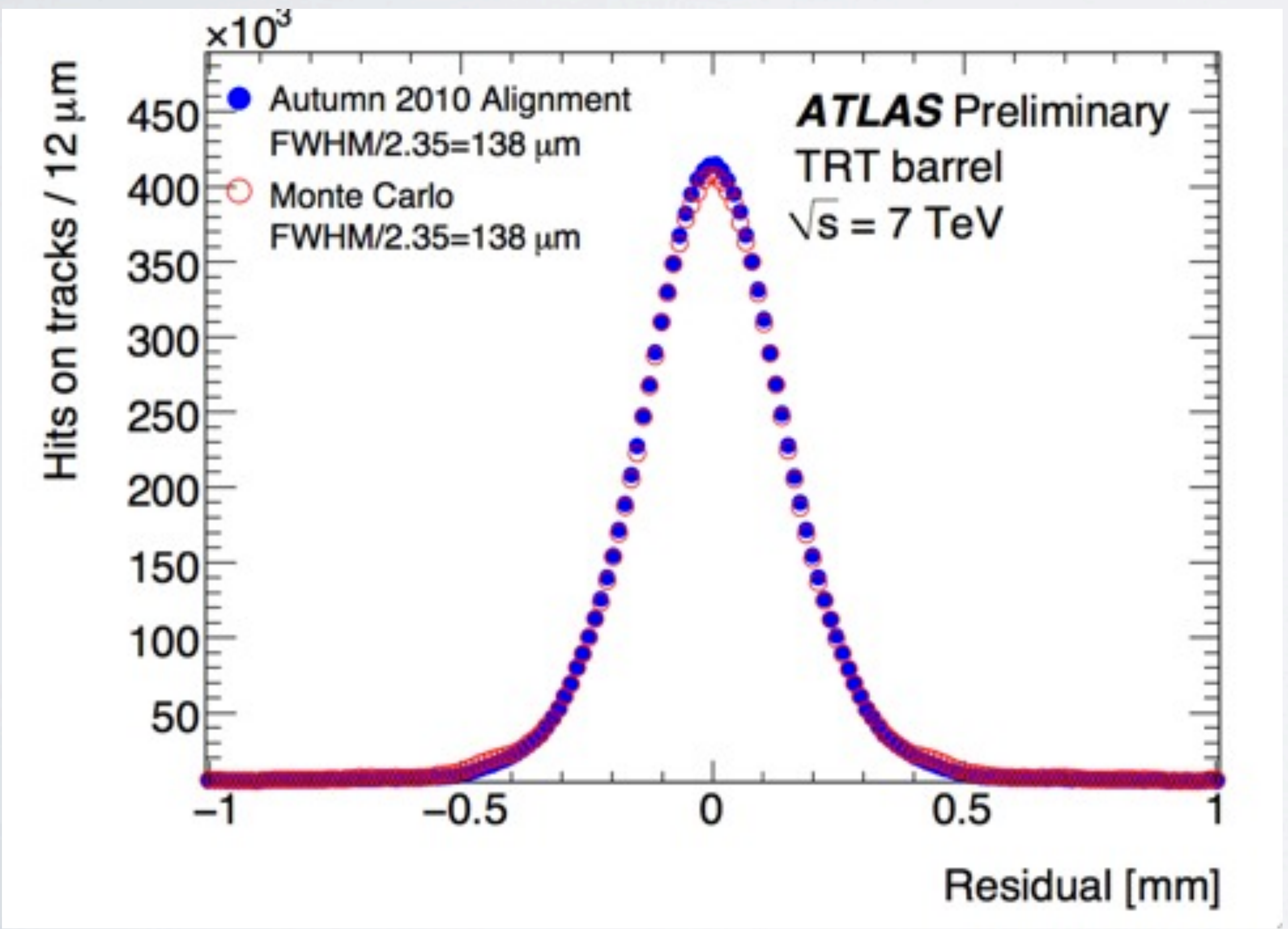
- Active and providing good quality data for **100%** of **LHC stable beam periods** during 2009 and 2010
  - Highest among ATLAS sub-detectors!
  - Thanks to:
    - Lots of **hard work** over the years by many people (the hard work is still continuing!)
    - **Automated** and **streamlined procedures**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

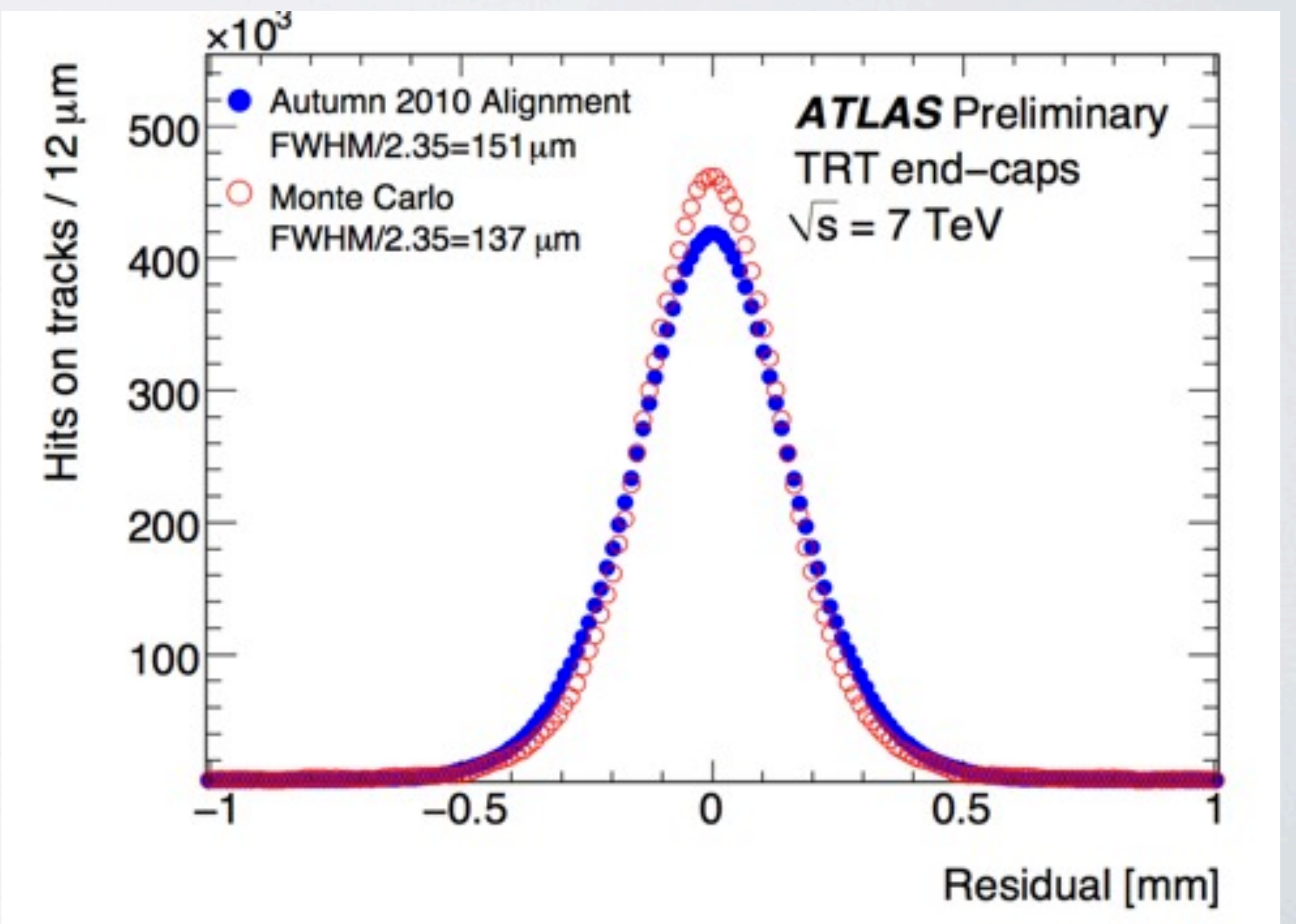
Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	TGC	CSC
96.7	97.5	100	93.8	98.8	99.0	99.7	98.6	98.5	98.6	98.5

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

POSITION RESOLUTION

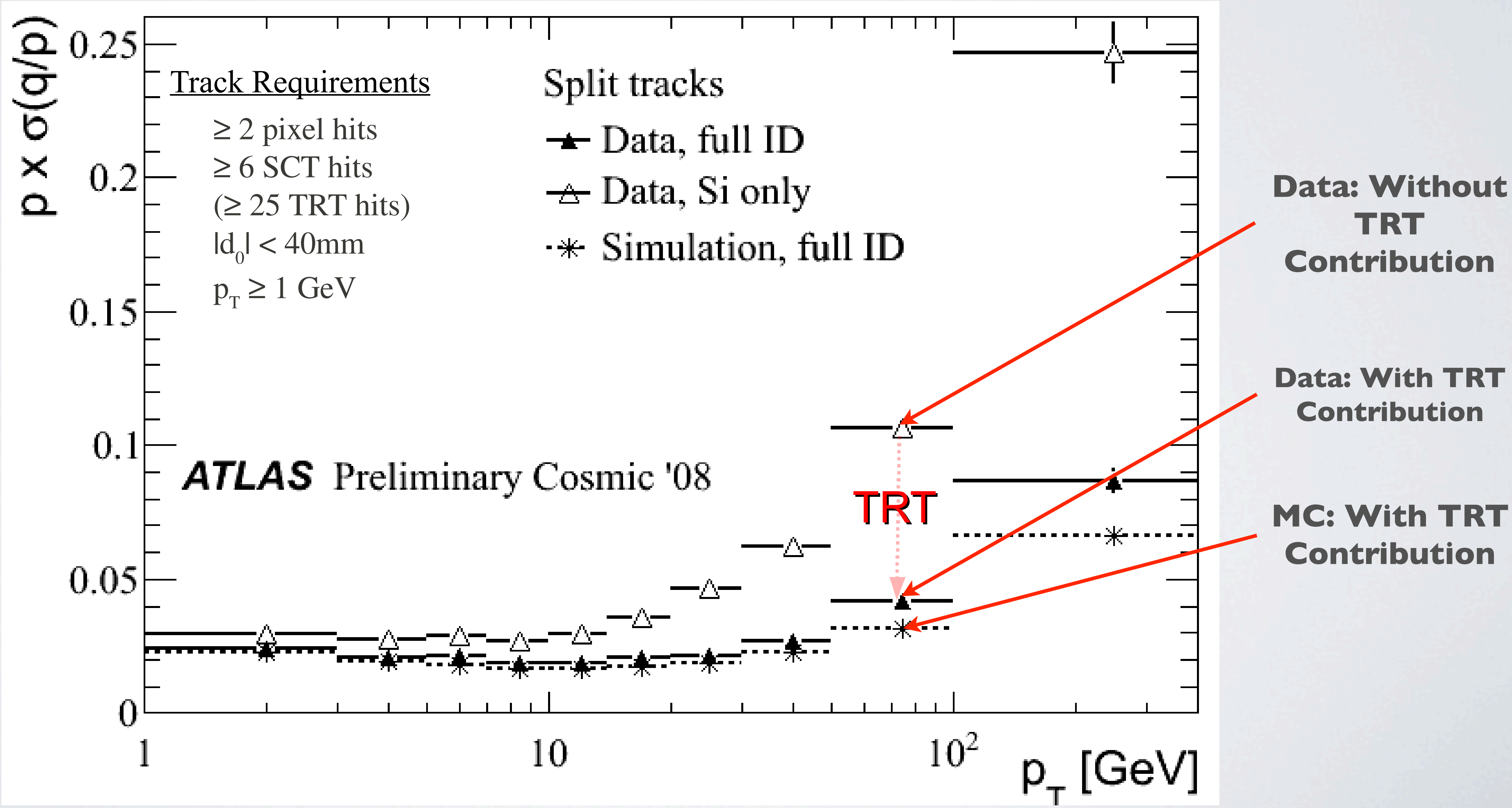
- Barrel exceeding design, approaching intrinsic limit of ~130um!
- Endcaps not as easily studied with cosmics, but catching up fast
- **Lots of work done** to get this far, including:
  - Alignment, calibration, tracking software





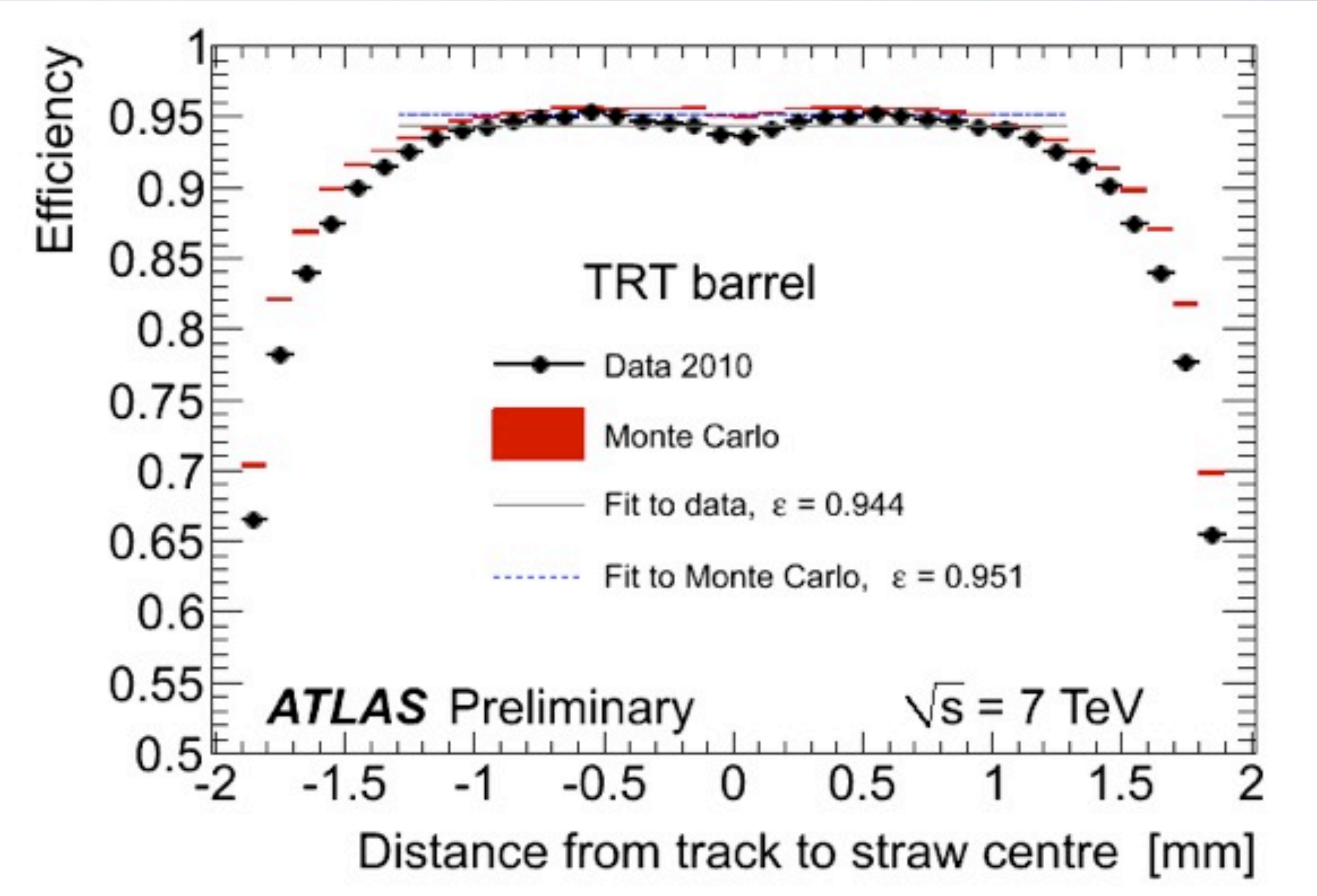
MOMENTUM RESOLUTION

- With its long lever arm, TRT contributes significantly
  - Radius of last barrel SCT layer: 514mm
  - End of TRT Barrel: 1068mm
- TRT greatly improves the momentum resolution at higher p_T



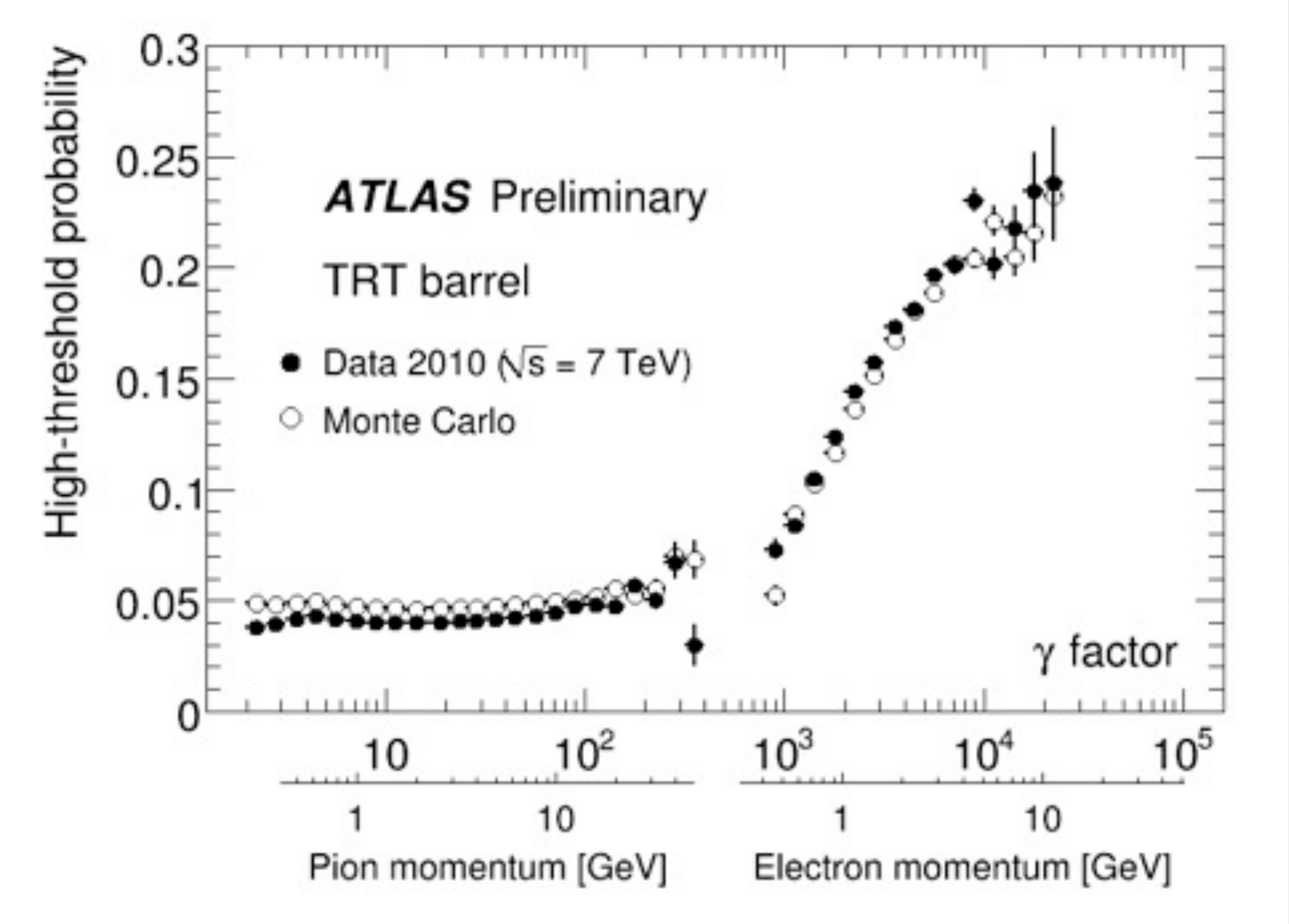
STRAW HIT EFFICIENCY

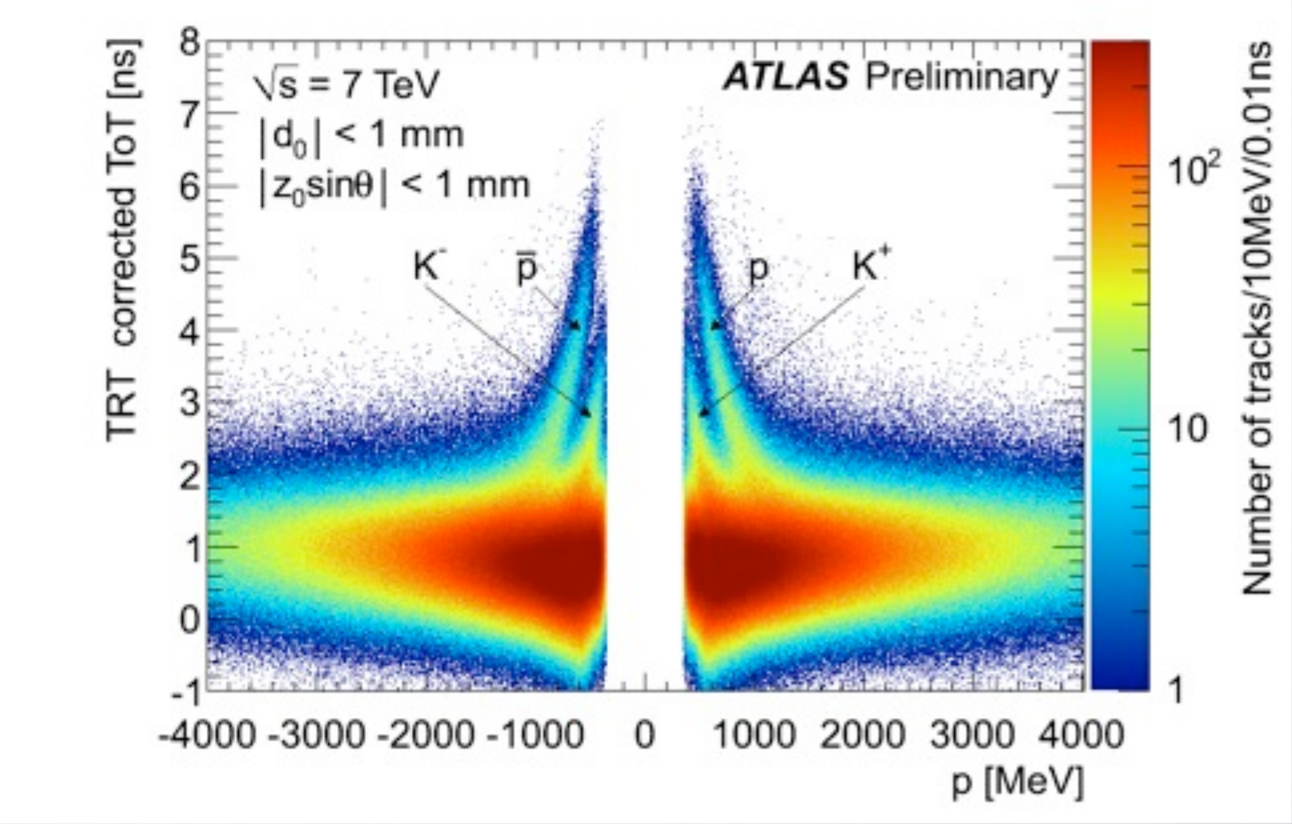
- Hit Efficiency ~**94%** in plateau
  - drop outside plateau is due to geometry and reconstruction effects
  - Dead channels excluded (~2%)
- Monte Carlo was tuned to 900 GeV data
- Plot requirements on tracks
  - **≥ 1 pixel hits, ≥ 6 SCT hits, ≥ 15 TRT hits**
  - **p_T > 1 GeV, $|d_0|$ < 10mm, $|z_0|$ < 300mm**
  - d_0 is the transverse impact parameter
  - z_0 is the longitudinal impact parameter



PARTICLE IDENTIFICATION

- Transition Radiation probability depends on gamma factor of a particle
  - Turn on curve also depends on **geometry, properties of the radiator**
  - **Different radiators** in barrel and end-caps
- Select electrons, pions, in data to tune and validate:
  - Pions: hadron enriched sample from all tracks
  - Electrons: tag and probe using photon conversions
- ToT tuned using path length corrections
  - Can discriminate Kaons, protons



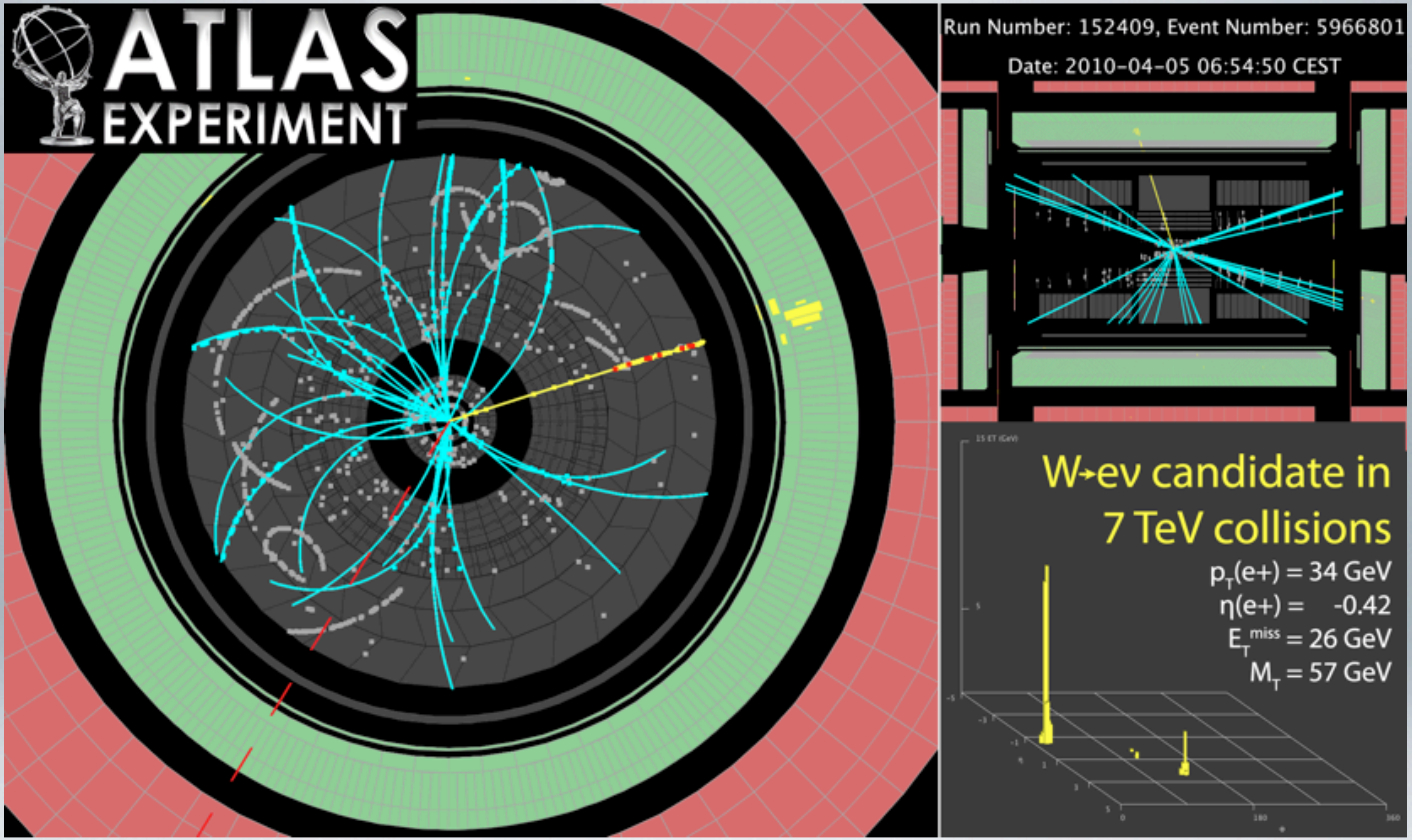


SUMMARY

- TRT is operating smoothly: 100% uptime in physics runs
- Excellent TRT performance with further optimization still possible
- TRT already providing key contributions to early physics results
- LHC Heavy Ion run will provide good test at high occupancy
  - 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!)

RELATED TALKS AND PAPERS

- TRT Presentations
  - CERN Detector Seminar on TRT by Christoph Rembser
    - http://indico.cern.ch/conferenceDisplay.py?confId=91040
  - TWEPP 2010: Performance of the ATLAS Transition Radiation Tracker read-out with cosmic rays and first high energy collisions at the LHC
    - http://indico.cern.ch/materialDisplay.py?contribId=110&sessionId=35&materialId=slides&confId=83060
- ATLAS Inner Detector and TRT Papers
  - The ATLAS Inner Detector commissioning and calibration (Submitted to EPJC)
    - http://arxiv.org/abs/1004.5293
  - The ATLAS Transition Radiation Detector (TRT) Fast-OR Trigger
    - http://cdsweb.cern.ch/record/1229213/files/ATL-INDET-PUB-2009-002.pdf
  - The ATLAS TRT electronics (JINST 3:P06007, 2008)
    - http://www-library.desy.de/cgi-bin/spiface/find/hep/www?irn=7829213
  - The ATLAS TRT barrel detector (JINST 3:P02014,2008)
    - http://iopscience.iop.org/1748-0221/3/02/P02014/
  - The ATLAS TRT end-cap detector (JINST 3:P10003,2008)
    - http://iopscience.iop.org/1748-0221/3/10/P10003/
  - The ATLAS Transition Radiation Tracker (TRT) proportional drift-tube : Design and Performance (JINST 3:P02013,2008)
    - http://iopscience.iop.org/1748-0221/3/02/P02013/
- The ATLAS Technical Design Report
  - http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html


ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
pT(e+) = 34 GeV
η(e+) = -0.42
ETmiss = 26 GeV
MT = 57 GeV

BACKUPS

CONDITIONS FOR TRT OPERATION

Counting Rate per wire	20 MHz
Ionization Current Density	0.15 µA/cm
Ionization Current per wire	10 µA
Power dissipated by ionization current per straw	15 mW
Total ionization current in detector volume	3 A
Total dissipated energy in the detector volume from ionizing particles	5 kW
Charge collected over 10 years of LHC operation	10 C/cm

Total Radiation Dose after 10 years

Neutrons	10^{14} n/cm^2
Charged Particles	10 MRad

Particle Flux at 1m from IP

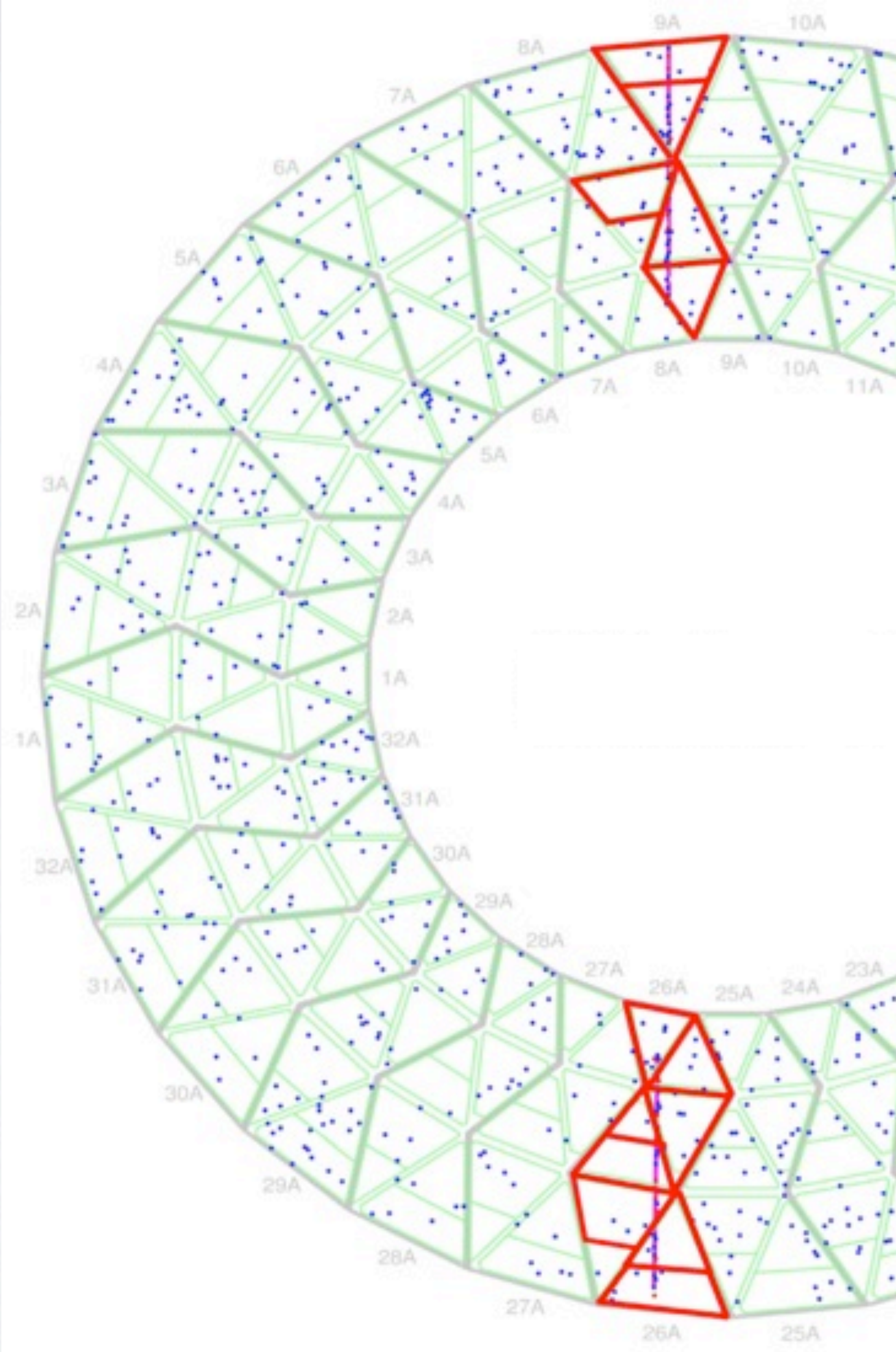
Charged	10^5 hadrons/cm^2 sec
Photons	10^6 photons/cm^2 sec
Neutrons	10^6 n/cm^2 sec

- Occupancy up to 30% *
- Short bunch crossing interval: 25 ns
- High spatial resolution, good pattern recognition: many space points
- Fast and chemically passive active gas: ageing
- Chemically resistant straw materials: straw is basically and electrochemical reactor
- minimal amount of material in front of calorimeter
- Precise and robust mechanical structure: ~100µm/m ~10^{-5}
- Stable temperature: active cooling

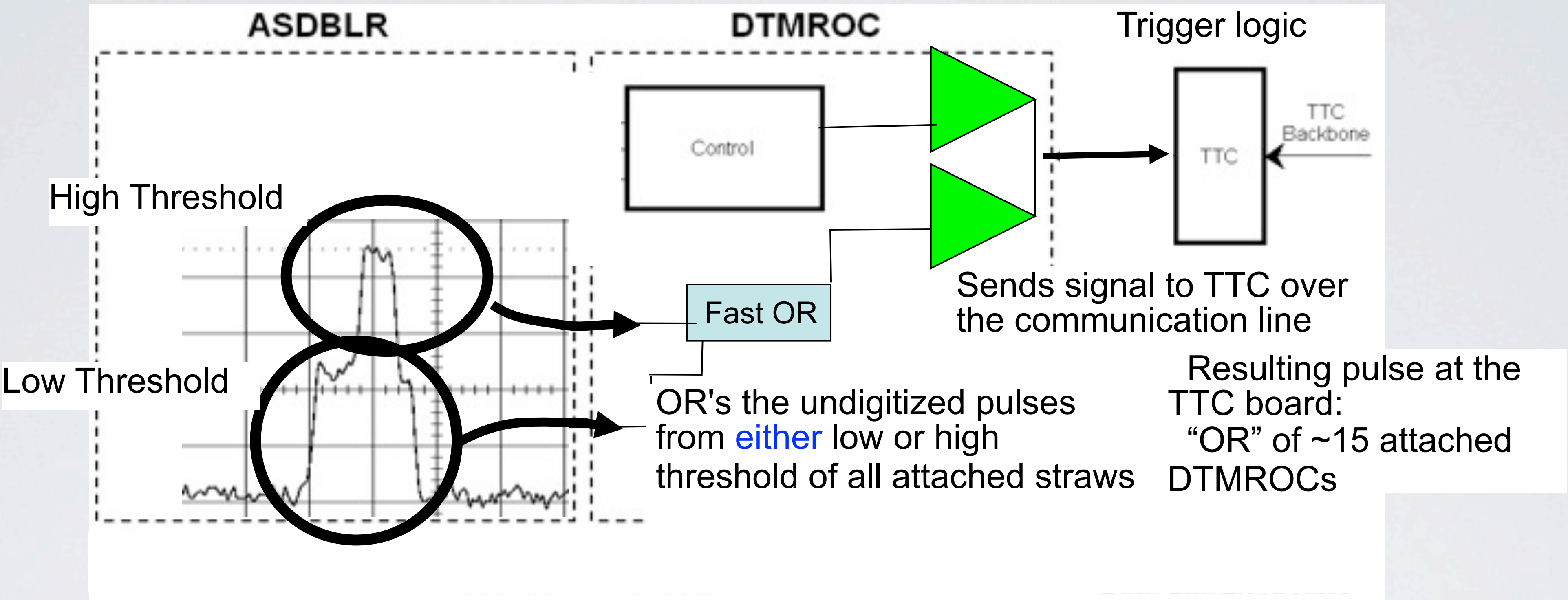
* possibly higher occupancy with Heavy Ion physics

FAST-OR TRIGGER COSMICS TRIGGER

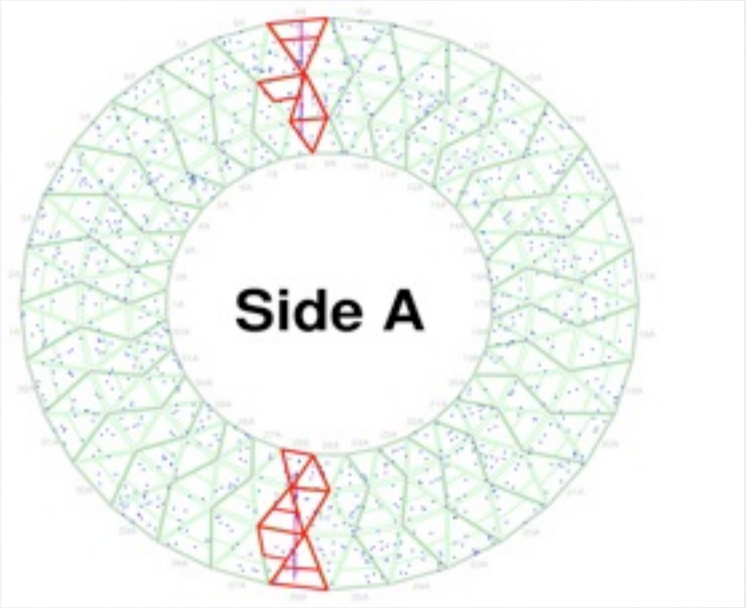
- Implemented quickly after LHC incident in Fall 2008:
  - First tracks in October 2008
  - Fully timed in May 2009
- Major Contributor to ATLAS commissioning:
  - High rate of tracks for Inner Detector
    - Alignment, timing
  - Timing reference for other triggers
    - Especially barrel muon trigger



TRT FAST-OR TRIGGER



- Level 1 Trigger for cosmics
- Extremely useful for ATLAS
- Development started in Sept. 2008, first cosmic data recorded in October 2008

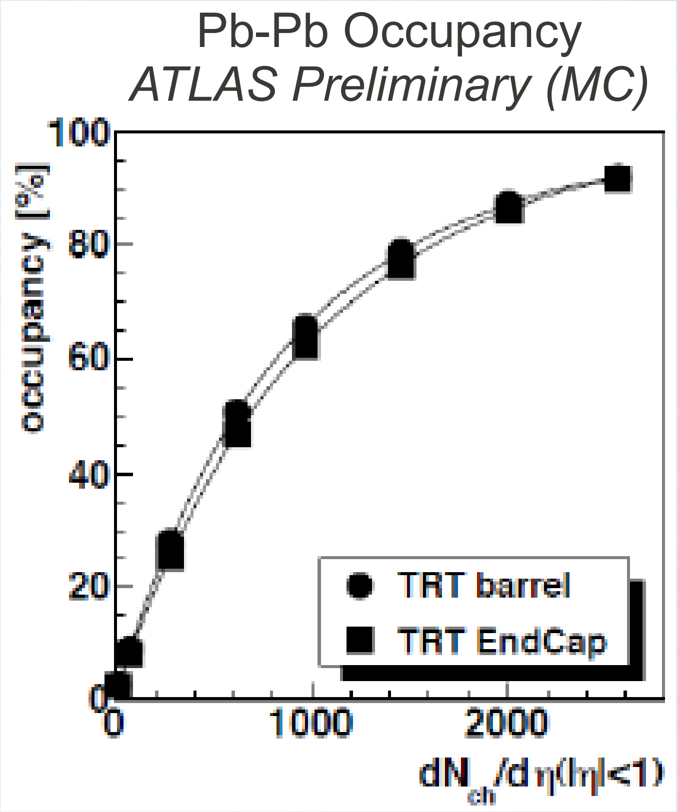


ADVANCED READOUT FEATURES

- 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 LHC ramps
      - i.e. large changes in frequency or fast changes in phase
      - TRT is most sensitive because of the QPLL chain in the TRT readout

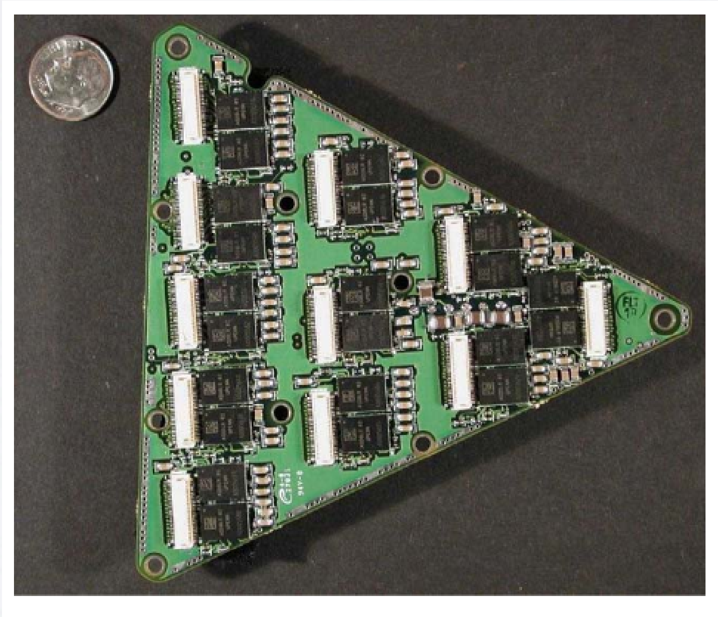
COVERAGE & OCCUPANCY

- **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



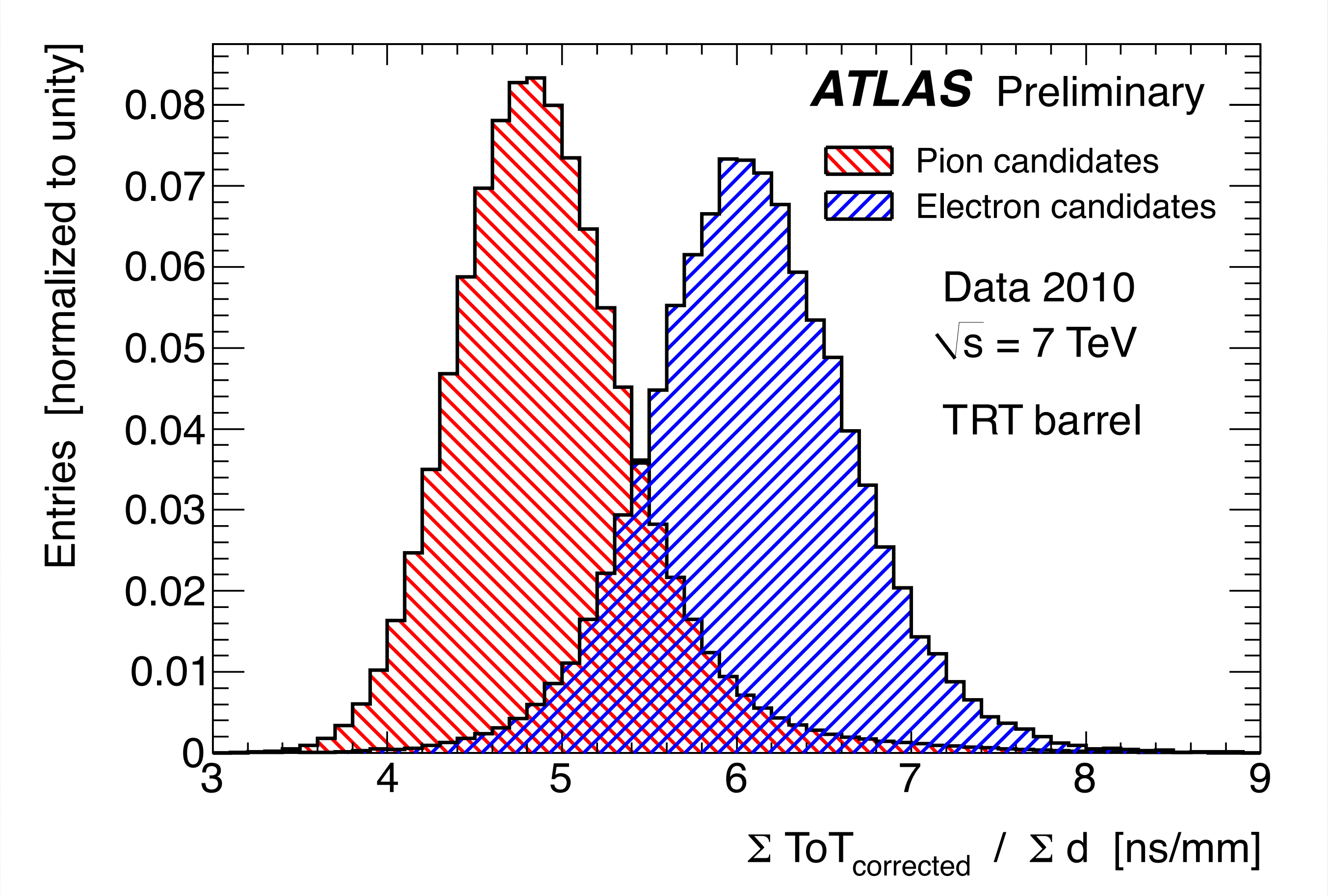
FRONT END ELECTRONICS

- **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

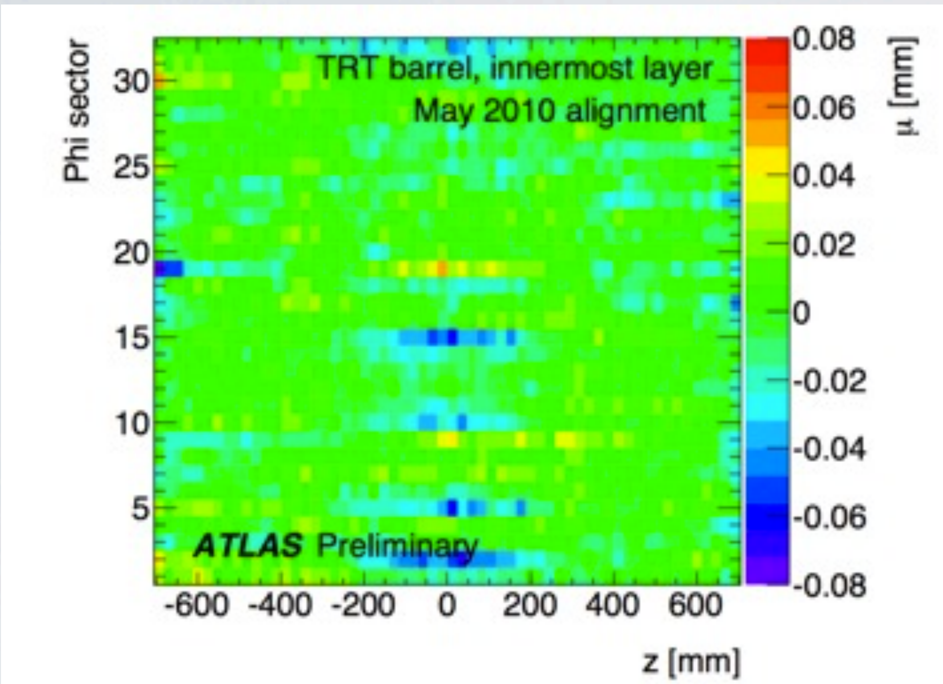


TIME OVER THRESHOLD AS A DISCRIMINATOR

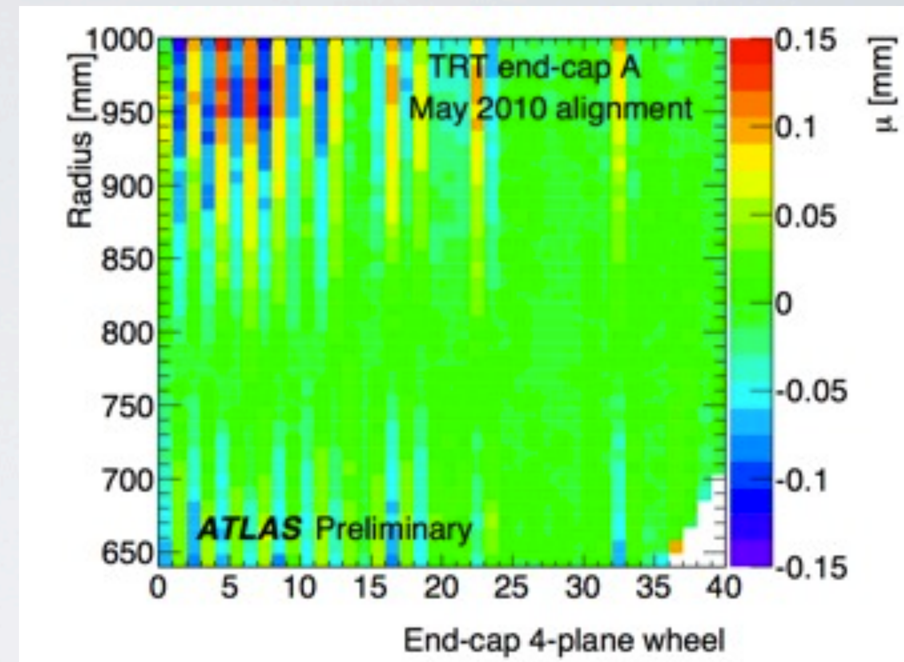
- ToT distributions for pion and electron candidates
- Clearly demonstrates discrimination power
- ToT is corrected for distance from wire and global **z** coordinate



TRT ALIGNMENT MAPS

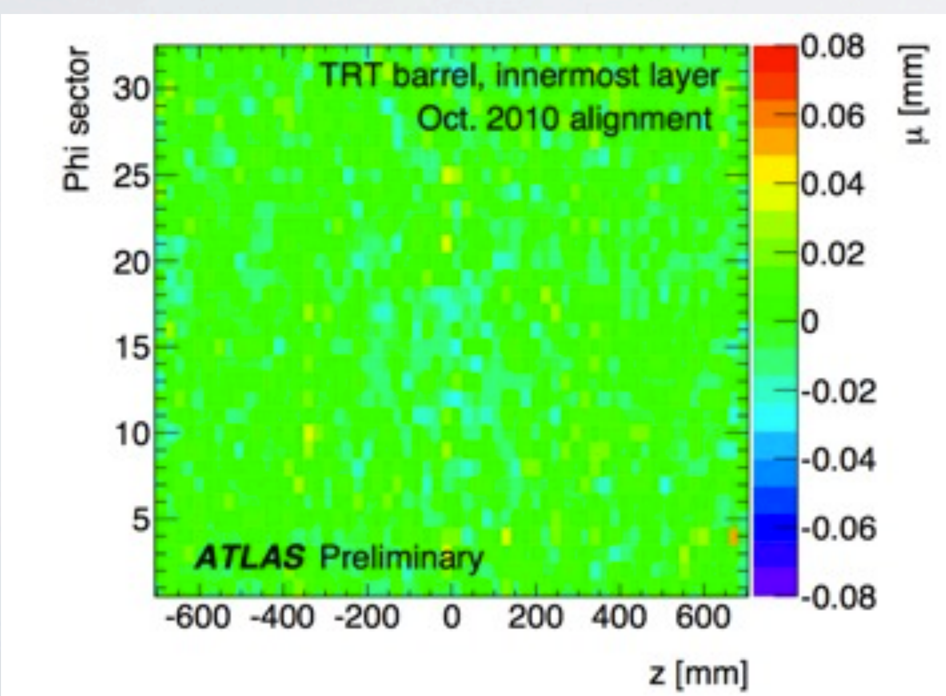


May Alignment

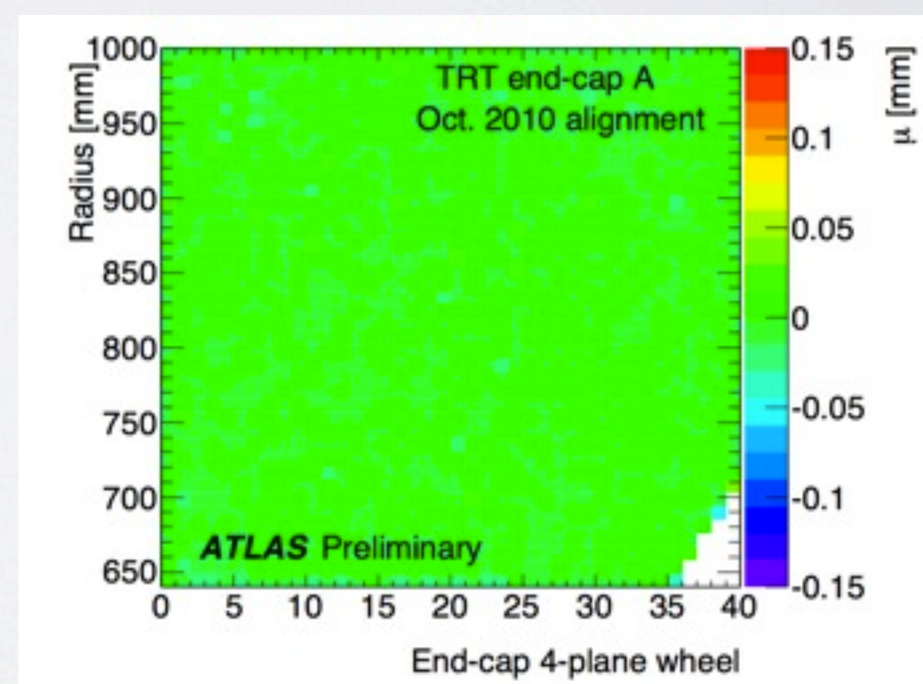


Barrel

End-cap

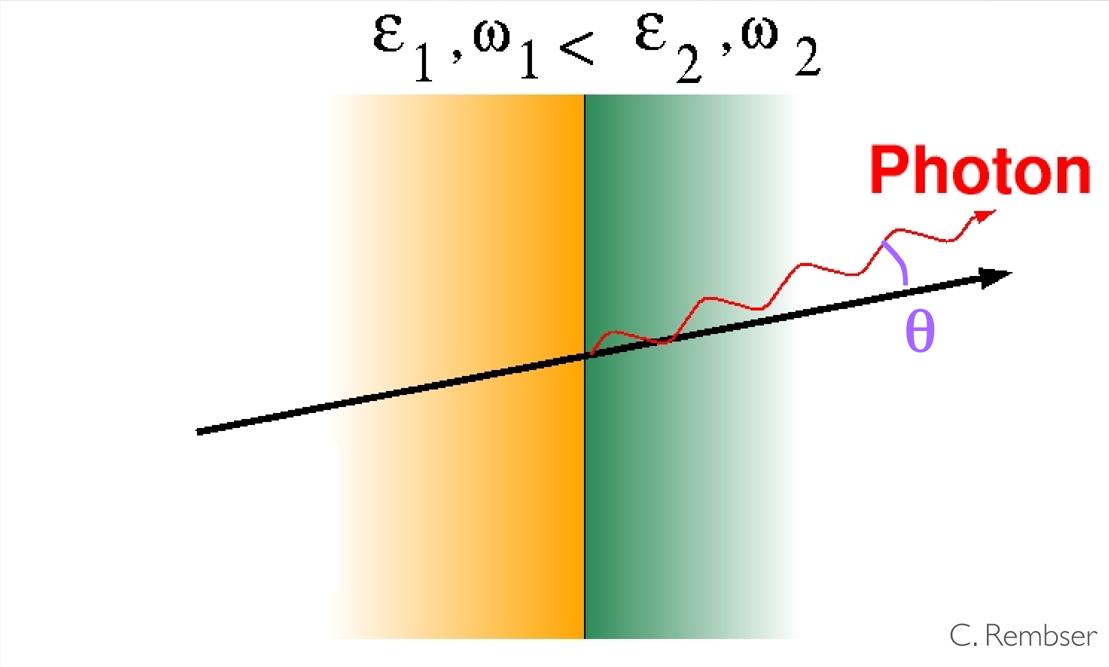


Oct. Alignment



PARTICLE IDENTIFICATION

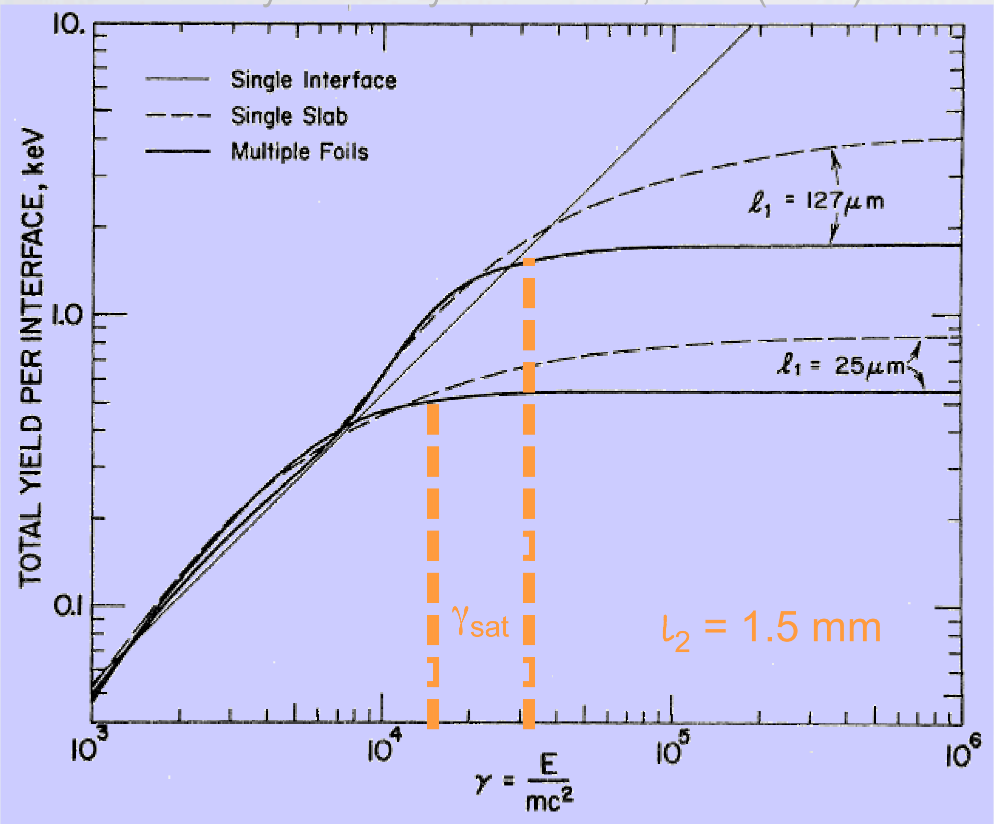
- **Transition Radiation**: photon emitted by a charged particle when traversing the boundary between materials with different dielectric constants(ε_1,ε_2).
    - **Intensity**: $I \propto \gamma = E/m$, $\vartheta \propto 1/\gamma$
- Low photon **emission probability** per transition
    - Many transitions needed
        - Intensity eventually limited by saturation effects
- Emitted **energy** $\propto$ (ε_1-ε_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



- **Time Over Threshold (ToT)** is used as a measure of a particle's *dE/dx* through the straw.
- Corrections to ToT for path length are performed for proper *dE/dx* measurement.
- Measuring the corrected ToT then provides an additional discriminator for particle ID in the TRT.

TR PHYSICS

M. Cherry et al. Phys. Rev. D10, 3594 (1974)



Saturation

The formation zone effect limits the increase of the TR yield with particle energy at

$\gamma_{sat} \approx 0.6\ (\ell_1\ \ell_2)^{½}\ \omega_{p1}/c$

To identify electrons with momenta

p_T > 1 GeV/c:

choose ℓ_1 ℓ_2 to get $_{sat} \approx 2 \cdot 10^3$

good e/pion separation in momentum range

1 GeV/c < p < 200 GeV/c

(illustration on the left is for higher momenta →γ > 1000)

Detectable photon yield

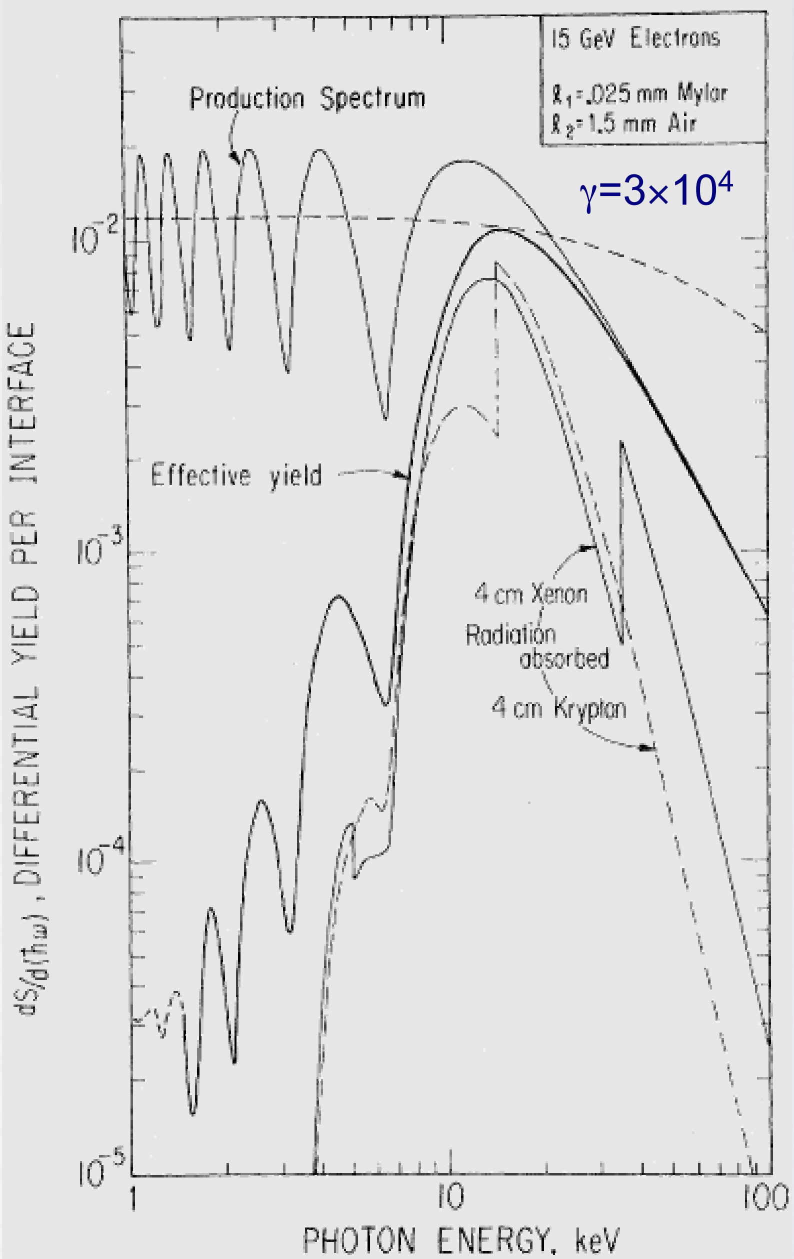
In practice, the useful radiator length is limited – to a few cm at $\gamma_{sat} = 2{\cdot}10^3$ – as a balance is reached between TR generation and absorption

The number of TR X-rays detected per electron by typical TRD modules is $N_X < 10$

Typical detectors usually consist of several TRD modules behind one another

TR PHYSICS

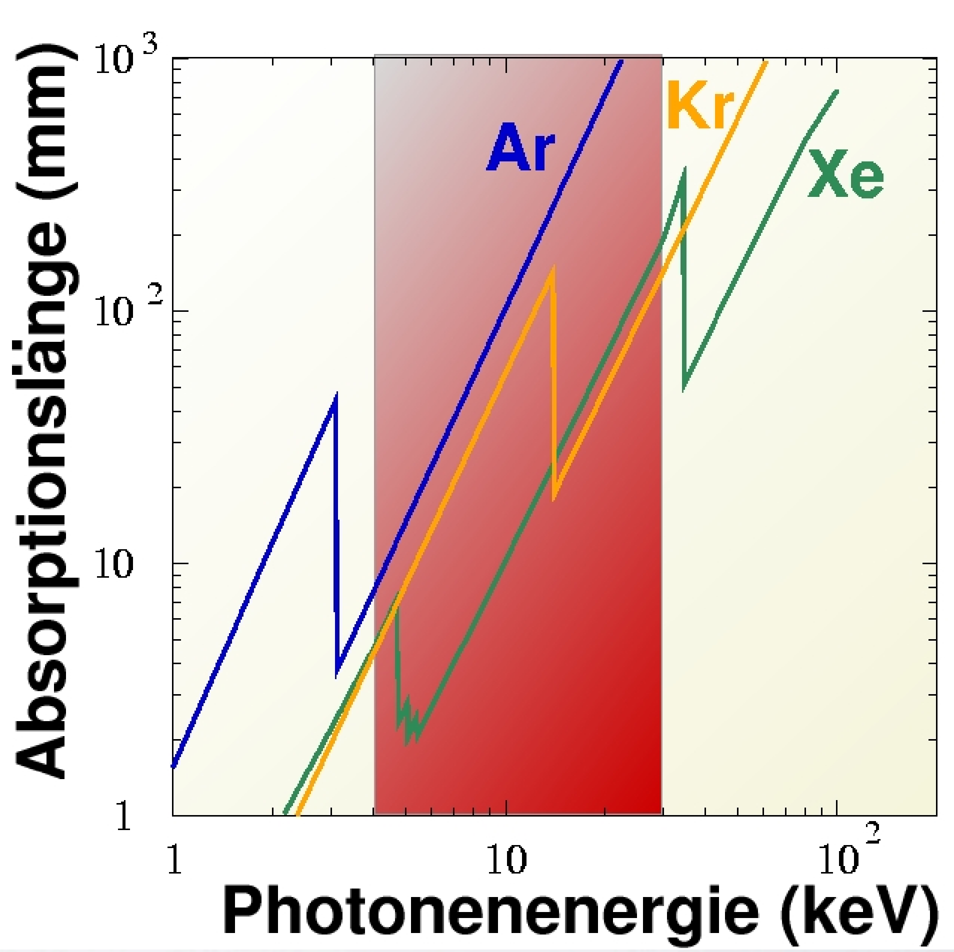
- Single interface
  - total rad. Energy ($W \propto \gamma$)
  - narrow forward cone $\propto 1/\gamma$
  - $dW/d\omega$ = const. O(a) for $\omega < \gamma\omega_{p2}$
    - ω_{p2} = plasma frequency (ω_{air} ~ 0.7 eV)
  - frequency cut-off $\omega < \gamma\omega_{p1}$
    - ω_{p1} ~ 20 – 30 eV
- Periodic radiator
  - interference pattern in $d^2W/d(\Omega)d\omega$
  - Formation zone effect limits energy spectrum to
    $\omega < \gamma\omega_{p1} l_1/z_1$ if $l_1 < z_1$
    - formation length $z_1 = 2\gamma c/\omega_{p1} > 10\ \mu m \cdot \gamma/10^3$
      $\omega_{max} \approx l_1 \omega_{p1}^2/(2\pi c)$ independent of particle energy!
  - TR X-rays below a few keV are absorbed in the radiator
  - Thin, Xe-based X-ray detectors rapidly become inefficient (transparent) above ω ~ 15 keV



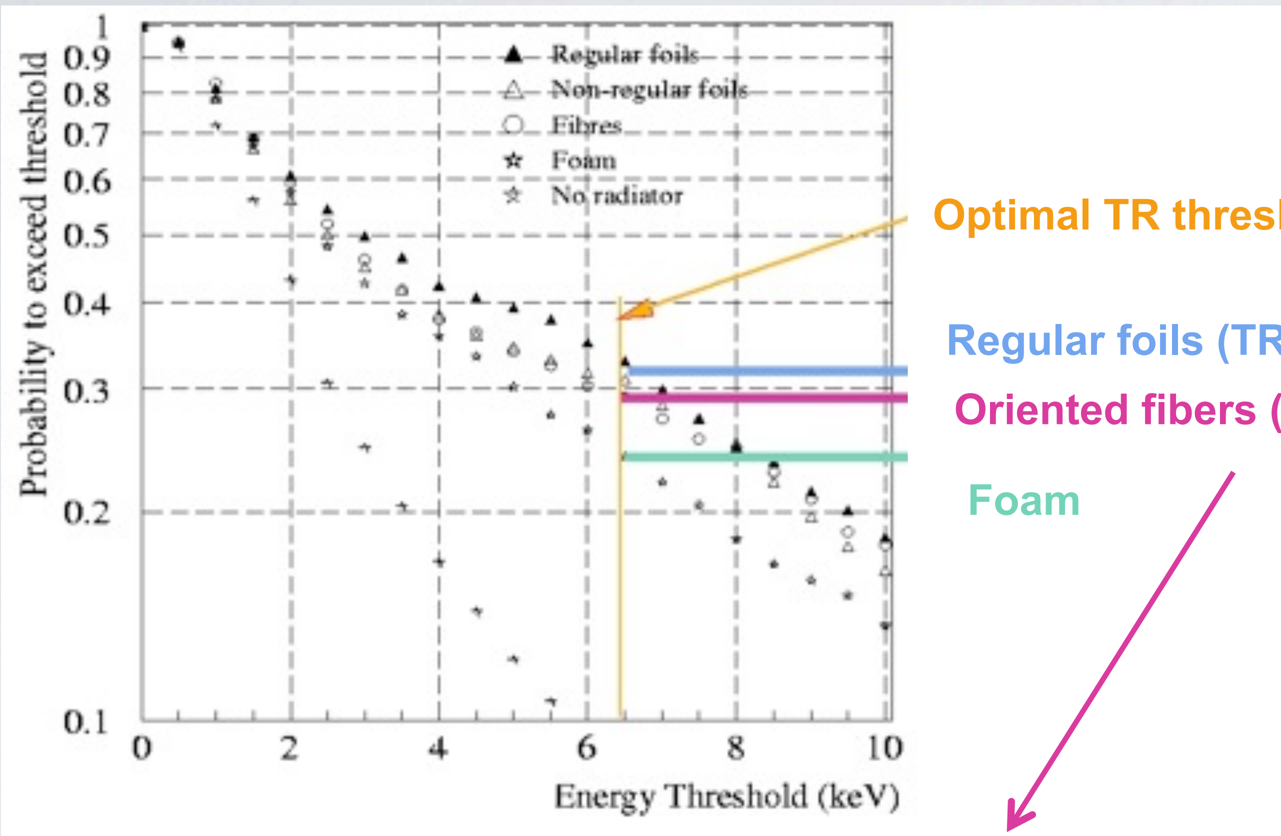
M. Cherry et al. Phys. Rev. D10, 3594 (1974)

CHARACTERISTIC DESIGN OF A TRANSITION RADIATION DETECTOR

- A Typical TRD consists of:
  - Radiator: production of TR photons
    - Regular radiators (foils), e.g. Li, Polyethylene, Mylar, ect.
    - Irregular radiators (foam, fibers), e.g. carbon fibers, carbon foam, Polystyrene, Poly...
    - Embedded in a gas volume: CO_2
  - Detector: to track charged particle, to observe TR photon
    - Gas chambers using high Z gas with efficient absorption of photons
  - Example: ZEUS TRD



EXAMPLES OF RADIATORS



Optimal TR threshold (~6.5 keV)

Regular foils (TRT end-caps)

Oriented fibers (TRT barrel)

Foam