THE ATLAS TRANSITION RADIATION TRACKER

TWEPP 2012

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On behalf of the ATLAS Collaboration

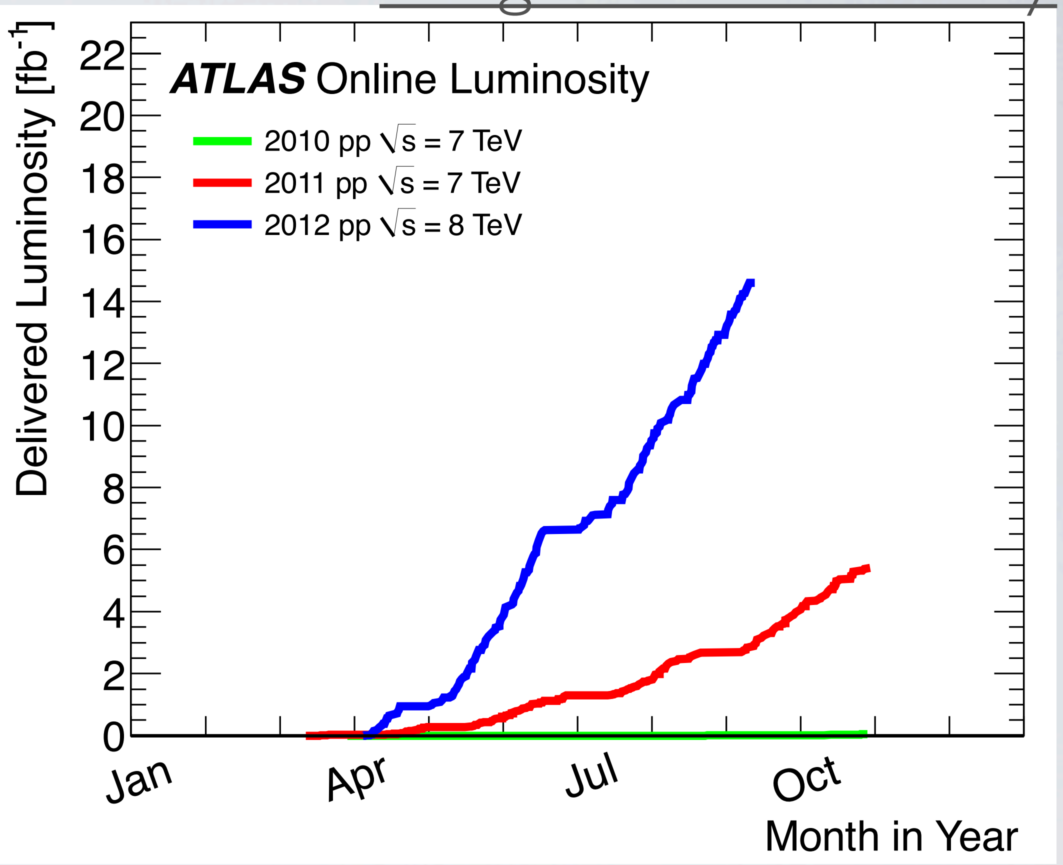
OUTLINE

1. The ATLAS Detector and the LHC Status
2. The Transition Radiation Tracker (TRT)
3. TRT Operation and Performance
4. Summary

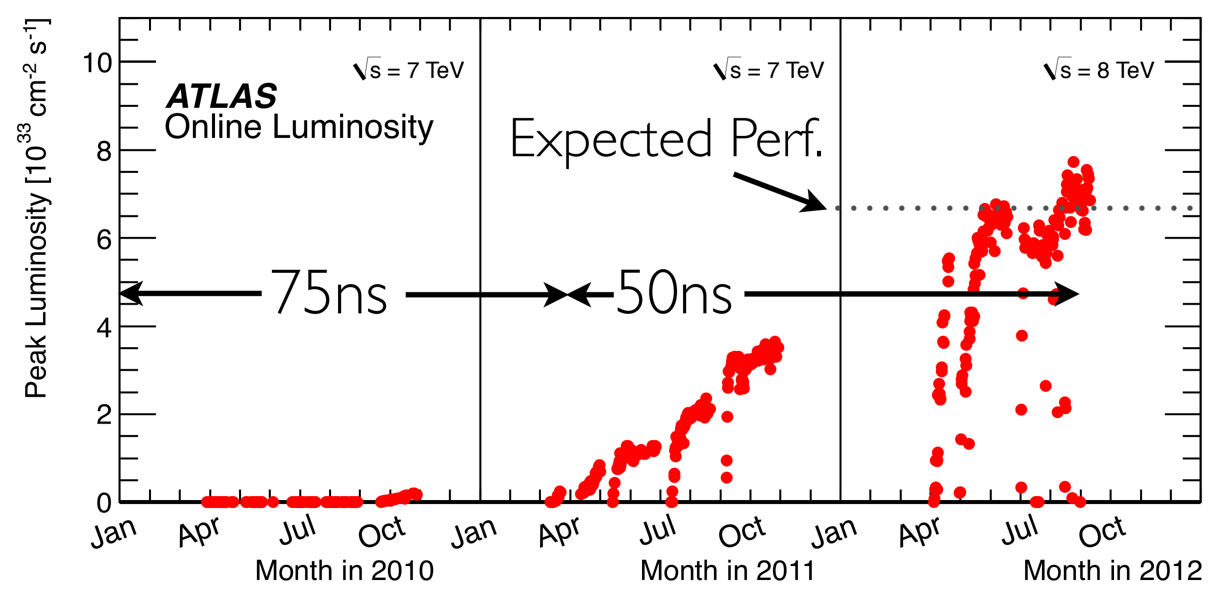
THE LHC STATUS

- The **LHC** is a hadron collider (pp, PbPb, pPb*)
- Synchronous collider operating at **40MHz** (25 ns bunch spacing, a.k.a. bunch crossing, design, 50 ns in practice)
- Design instantaneous luminosity of **10^{34} cm^{-2}s^{-1}** and **7 x 7 TeV**
- The LHC has been operating well since November 2009
- First collisions at **3.5 x 3.5 TeV**, March 30th 2010, currently operating with **4 x 4 TeV**
- **Instantaneous Luminosity** of **10^{33} cm^{-2}s^{-1}** and approaching **10^{34} cm^{-2}s^{-1}**
- Delivered **6 fb^{-1}** of 7 TeV data in 2011 and already has more than **14 fb^{-1}** of 8 TeV data for 2012 run
- **Heavy Ion (HI) Collisions** collected more than **150 ub^{-1}** of pb-pb data in 2011 with the TRT demonstrating that it can run in highly occupied events
- **More HI** data expected in 2013 **p-HI Run**

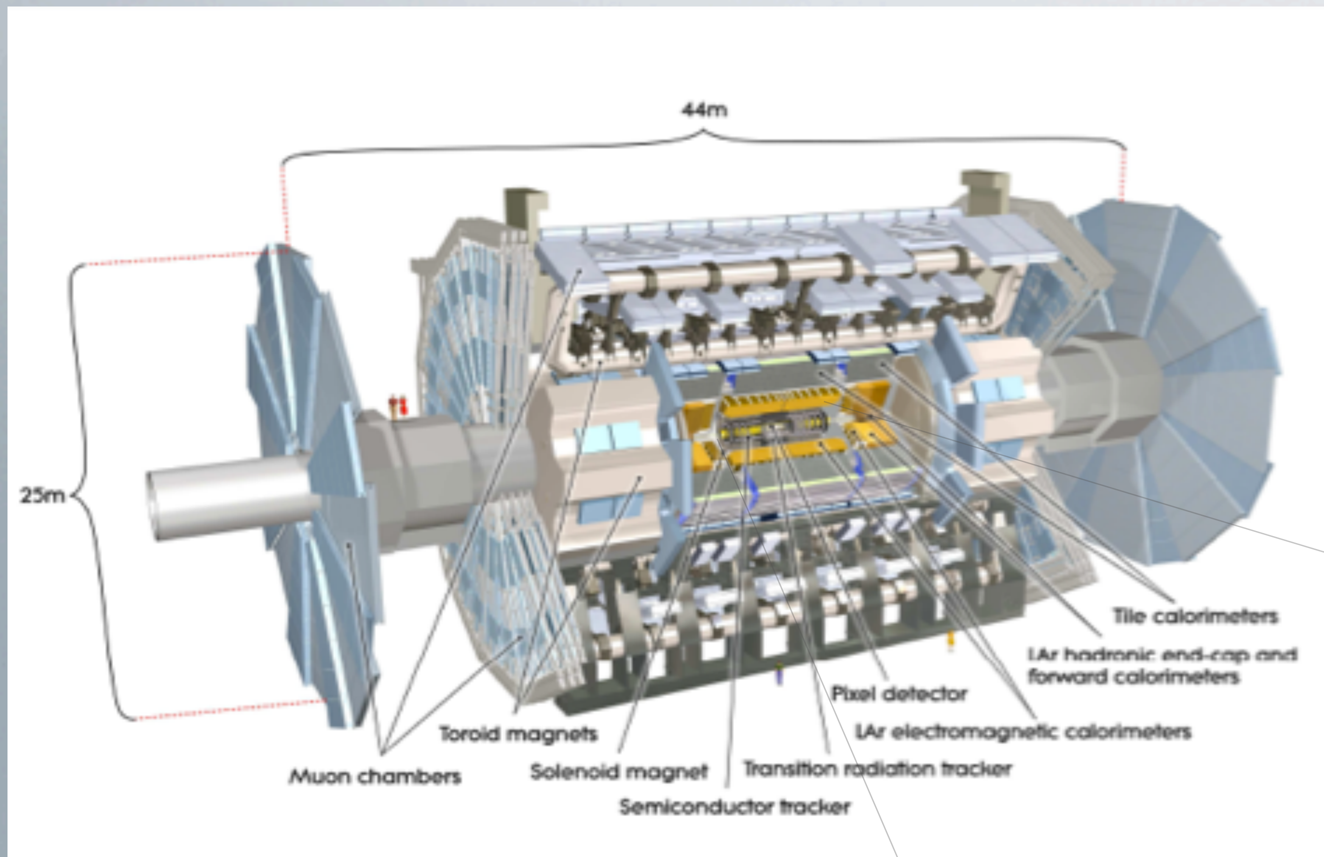
Integrated Luminosity



Peak Instantaneous Luminosity



Luminosities achieved with 50 ns bunch spacing

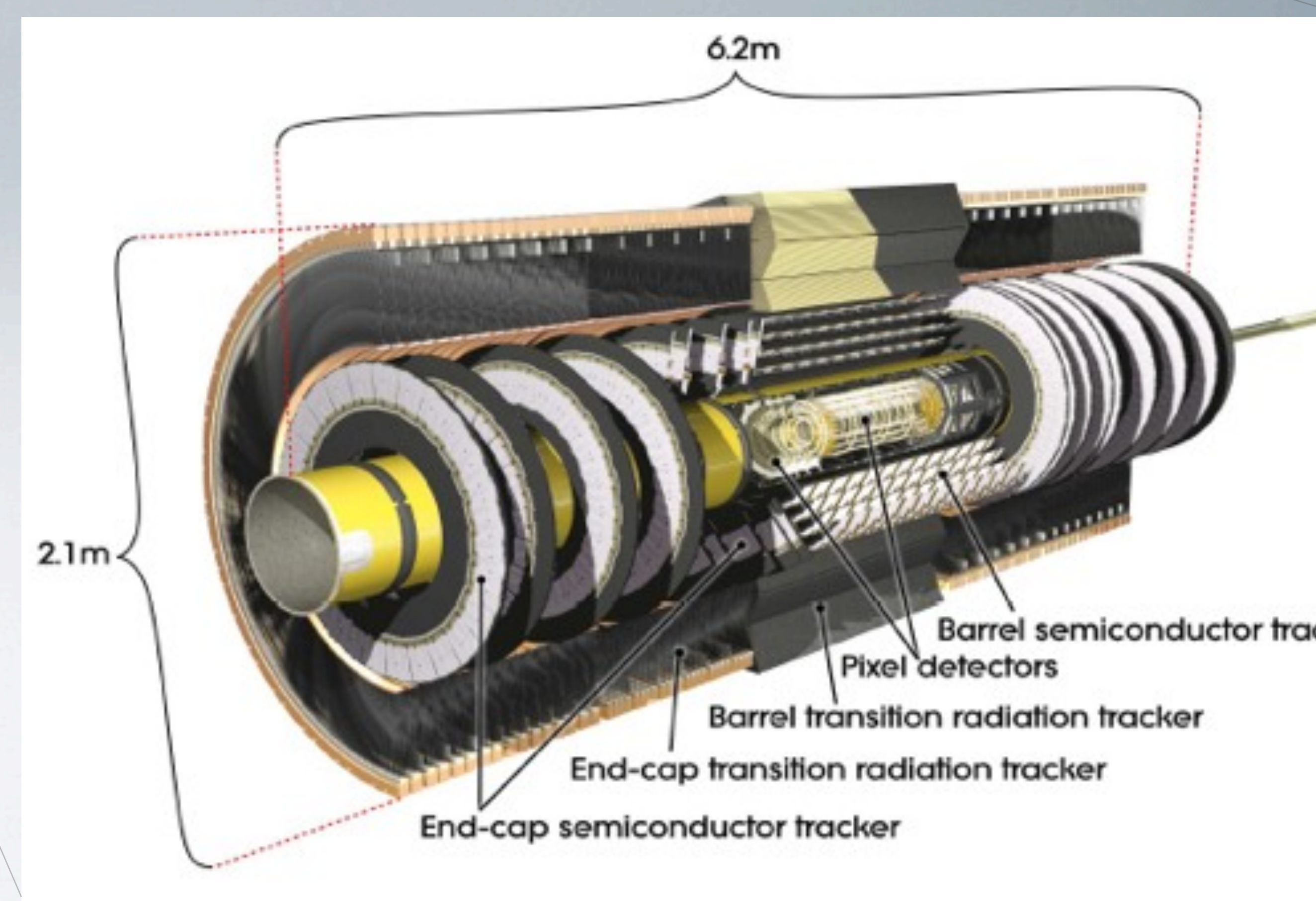


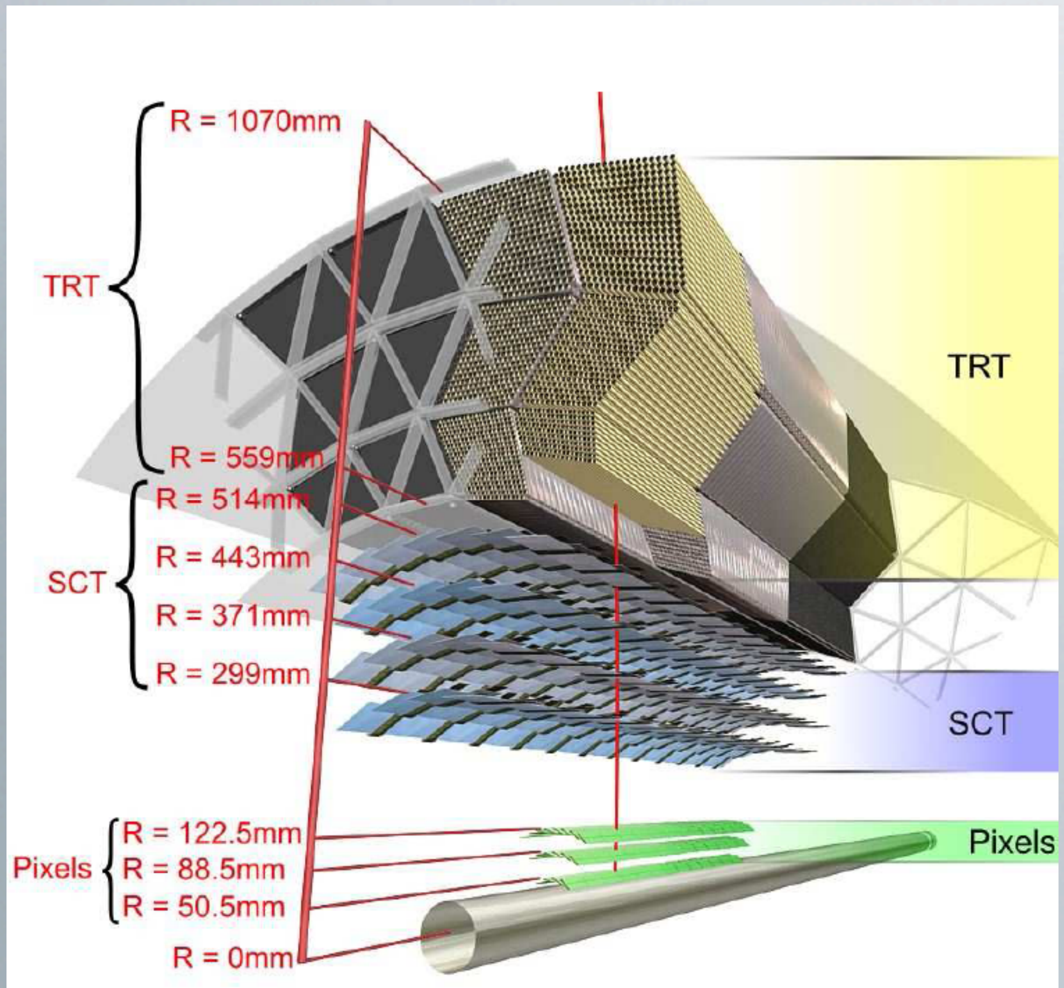
ATLAS DETECTOR

- The ATLAS Detector is a multipurpose collider detector
- Multi system muon detection
- 8 fold air core ~1.4T muon toroid
- Liquid Argon and Scintillator 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)



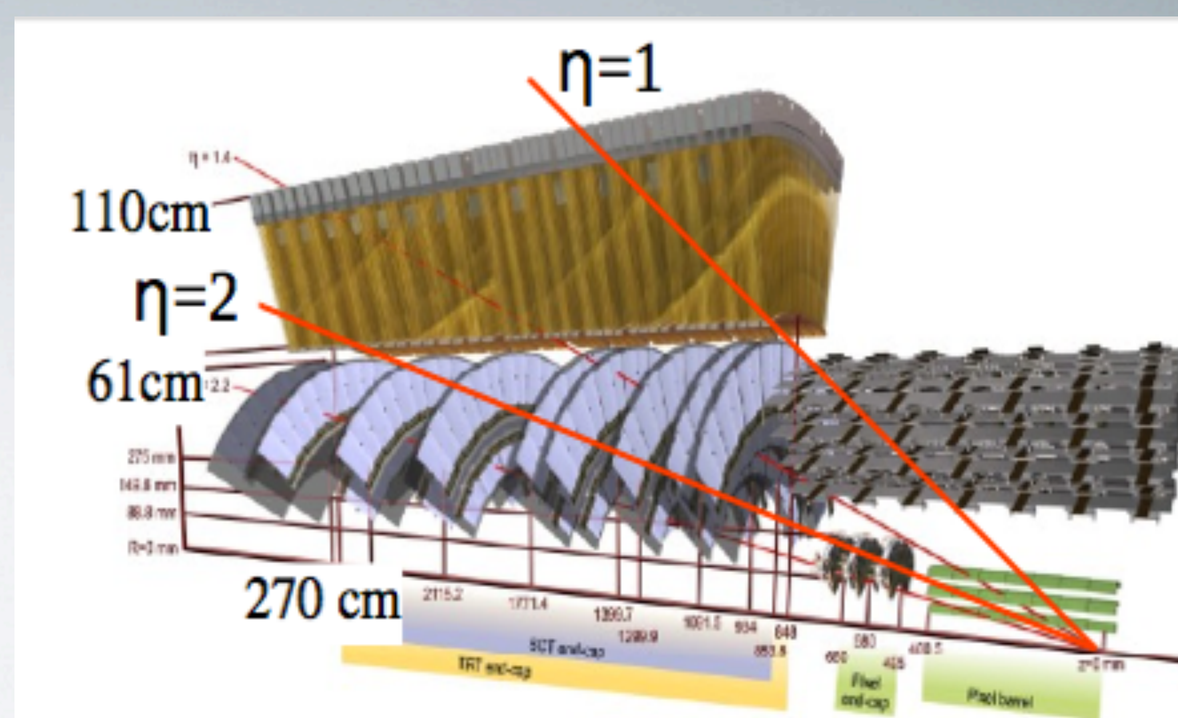


TRT Barrel

- 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
- 105,088 readout channels total
- 2 triangular front end electronics boards per module (4 boards for the outer modules)

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
- 122,880 readout channels per end-cap



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

CONDITIONS FOR TRT OPERATION AT 10^{34} $cm^{-2}s^{-1}$

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

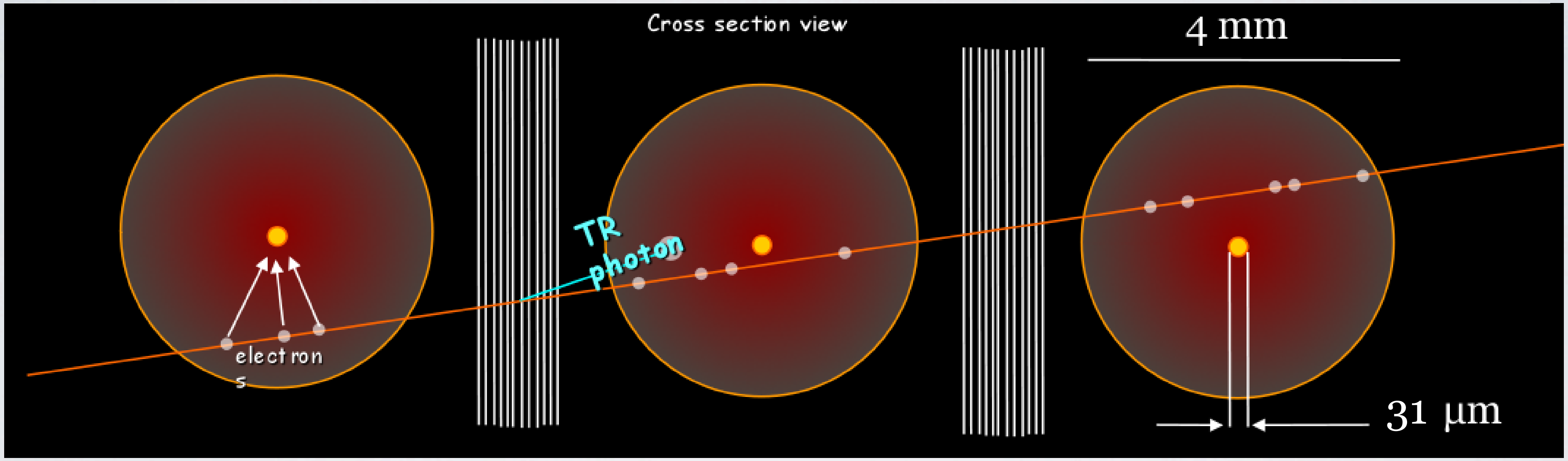
Particle Flux at 1m from IP

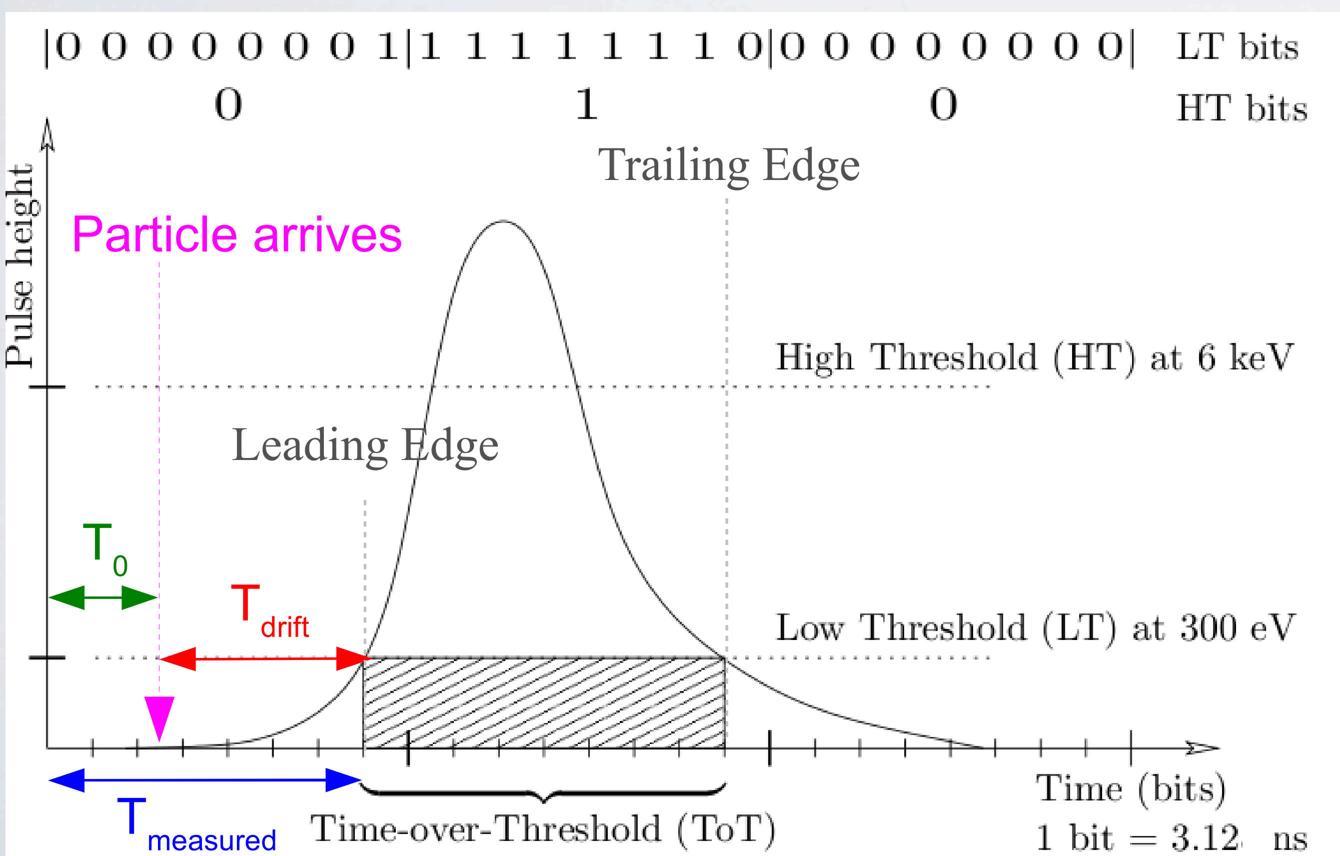
Charged	10^5 hadrons/cm^2 sec
Photons	10^6 photons/cm^2 sec
Neutrons	10^6 n/cm^2 sec

- 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: aging
- Chemically resistant straw materials: straw is basically an 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

THE DIGITIZED TRT SIGNAL

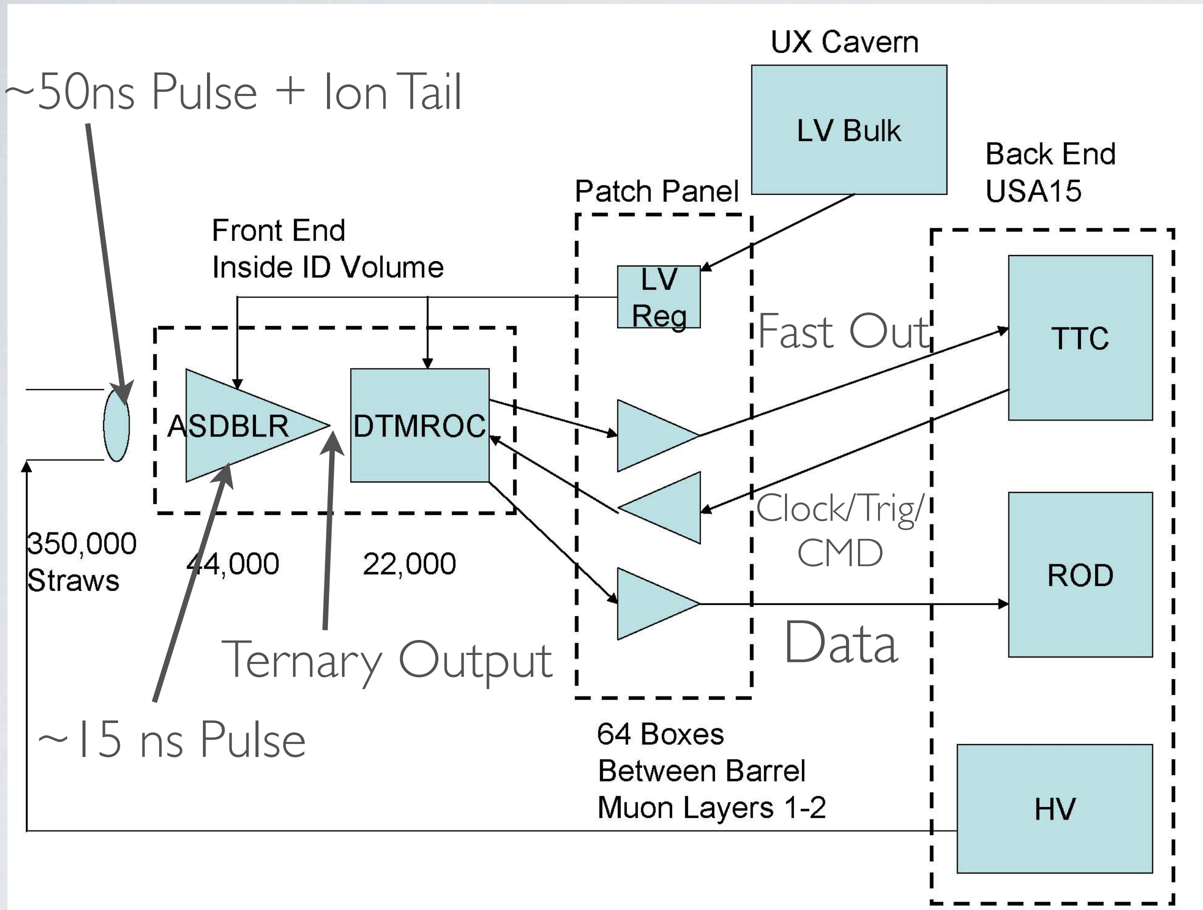




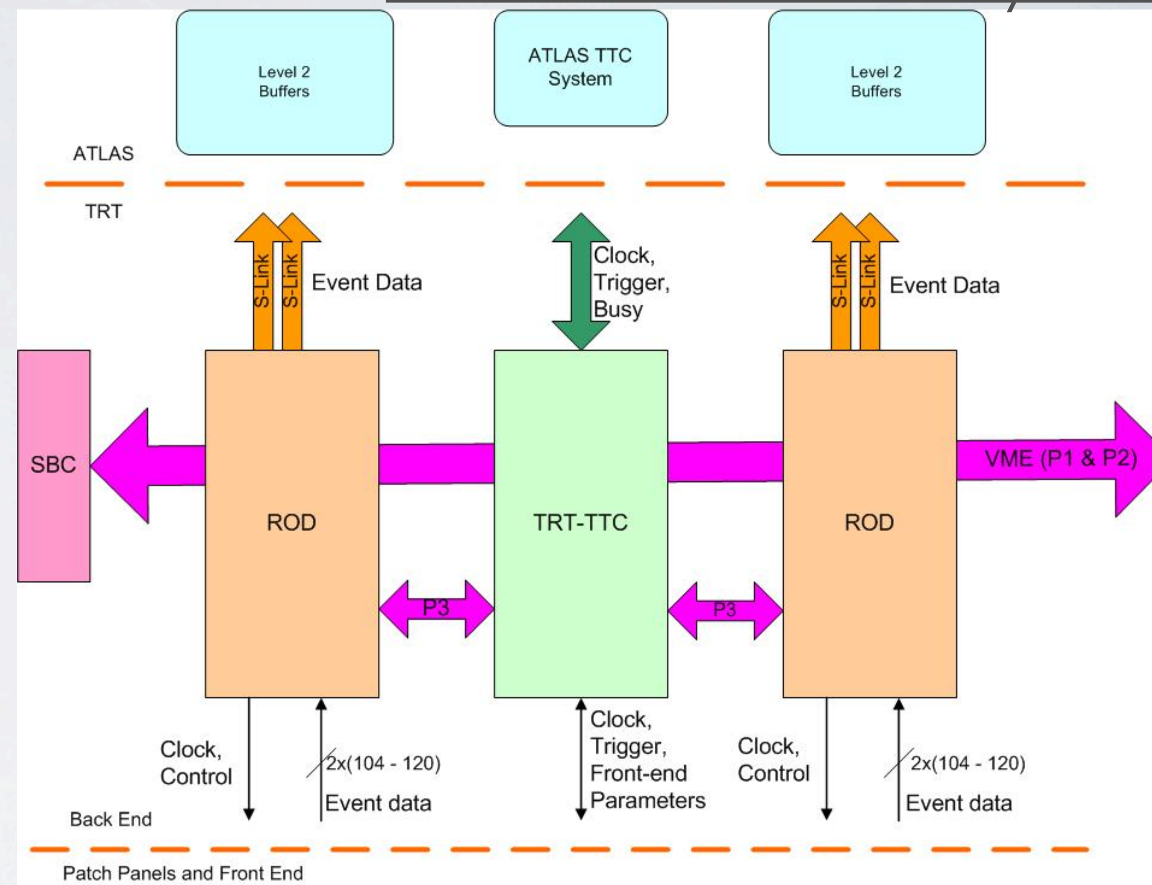
- Each straw signal is readout over 75 ns (3 bunch crossings)
- The discriminated signal is digitized into 24 bits (~ 3.12 ns)
- The 24 bits can also be thought of as time bins
- There is one High Threshold bit for every 25 ns
- **Trailing Edge (TE):** Independent of the particle position as it transits 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*

THE TRT READOUT CHAIN

Readout Chain Schematic



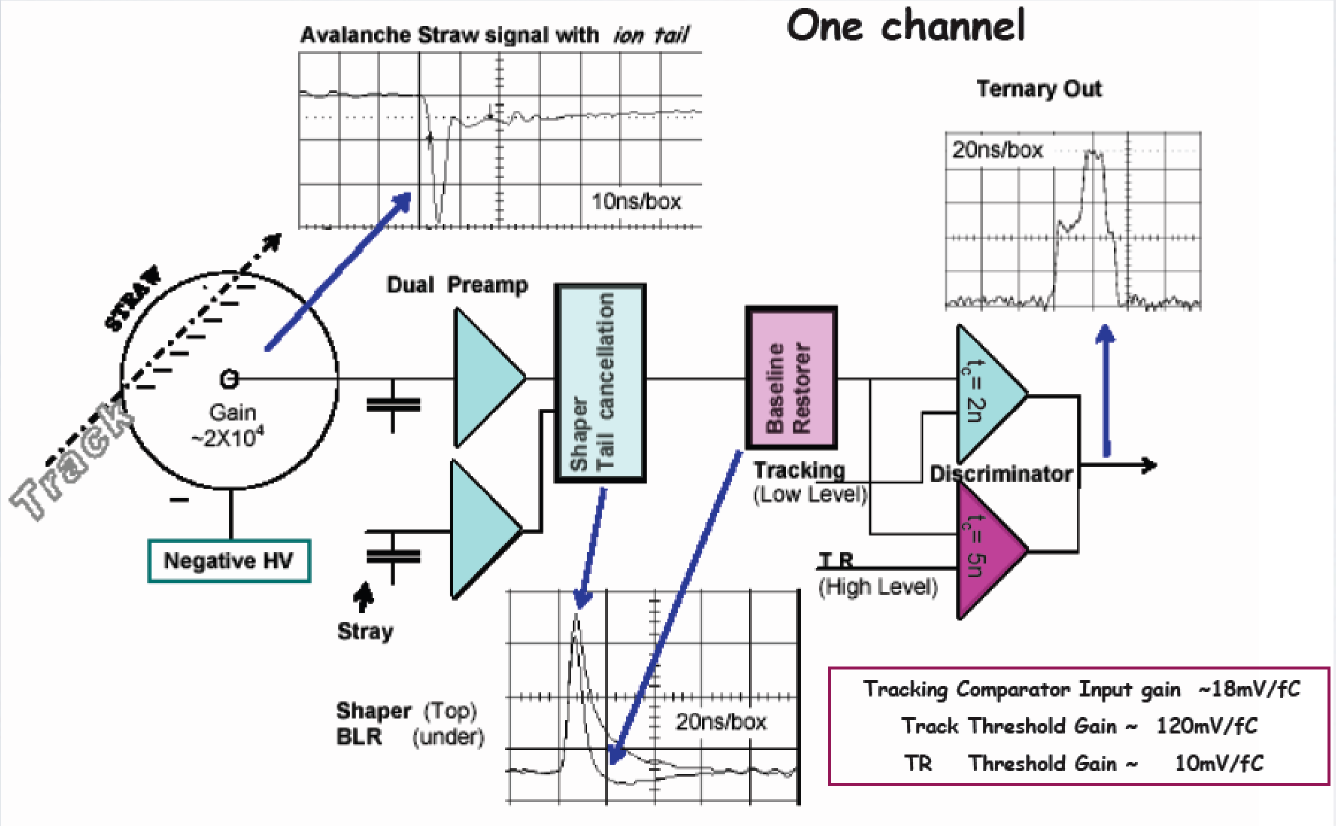
Backend VME Layout

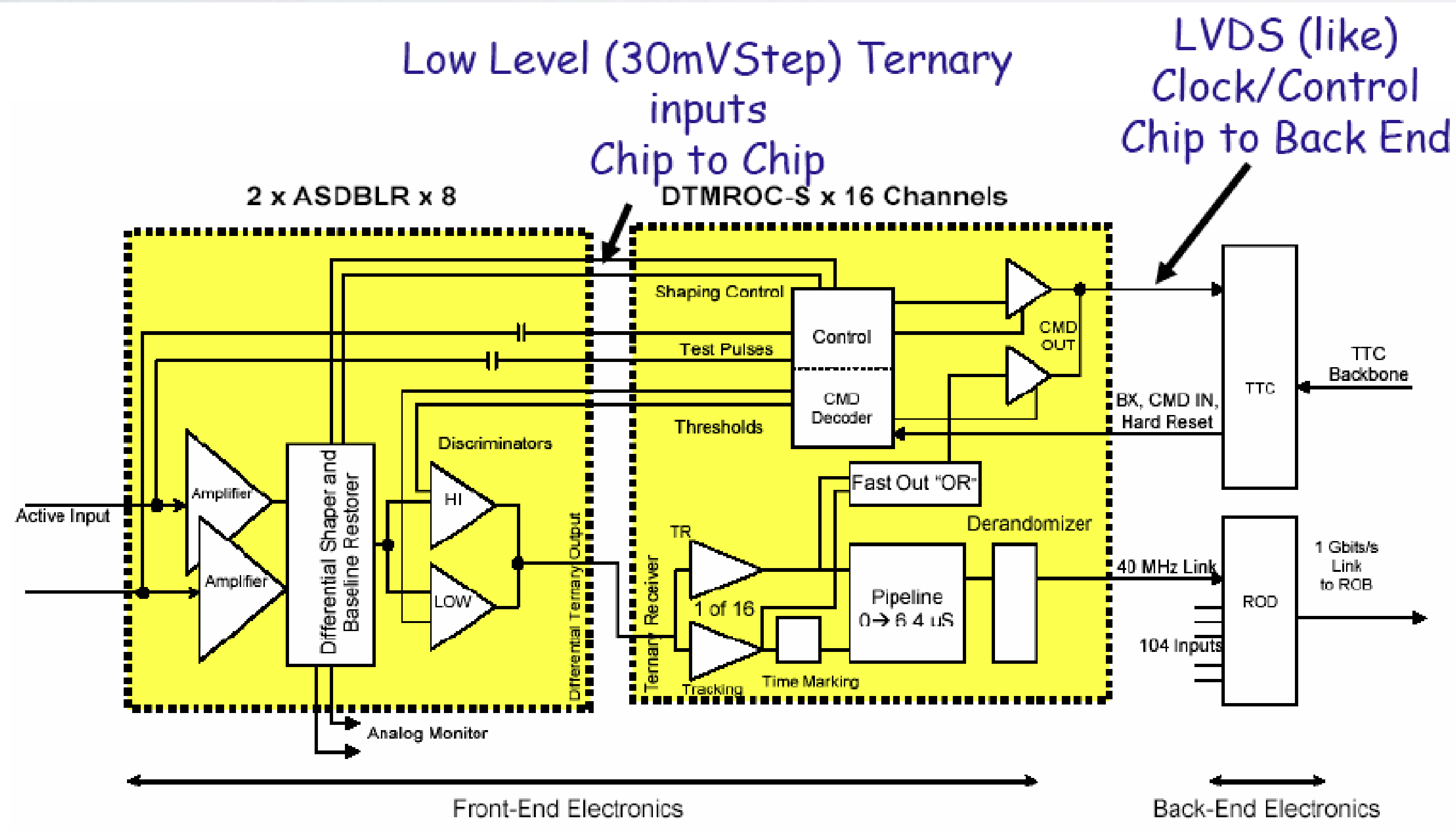


- The TRT Readout starts at the straw anode where the signal is shaped in the ASDBLR (50 ns signal plus large ion tail to 15 ns pulse)
- The analog signal is then digitized in time in the DTMROC
- The digitized signal is then sent to the backend via the Patch Panels (PPs) to the Read Out Drivers (RODs)

- Event fragments are buffered on DTMROCs until Level 1 accept
- From the RODs the events are sent to the ATLAS Level 2 trigger
- Level 2 readout is base on Regions of Interest (ROI)
- Full events are passed to the Event Filter and permanent storage after a High Level Trigger accept

TRT FRONT END READOUT

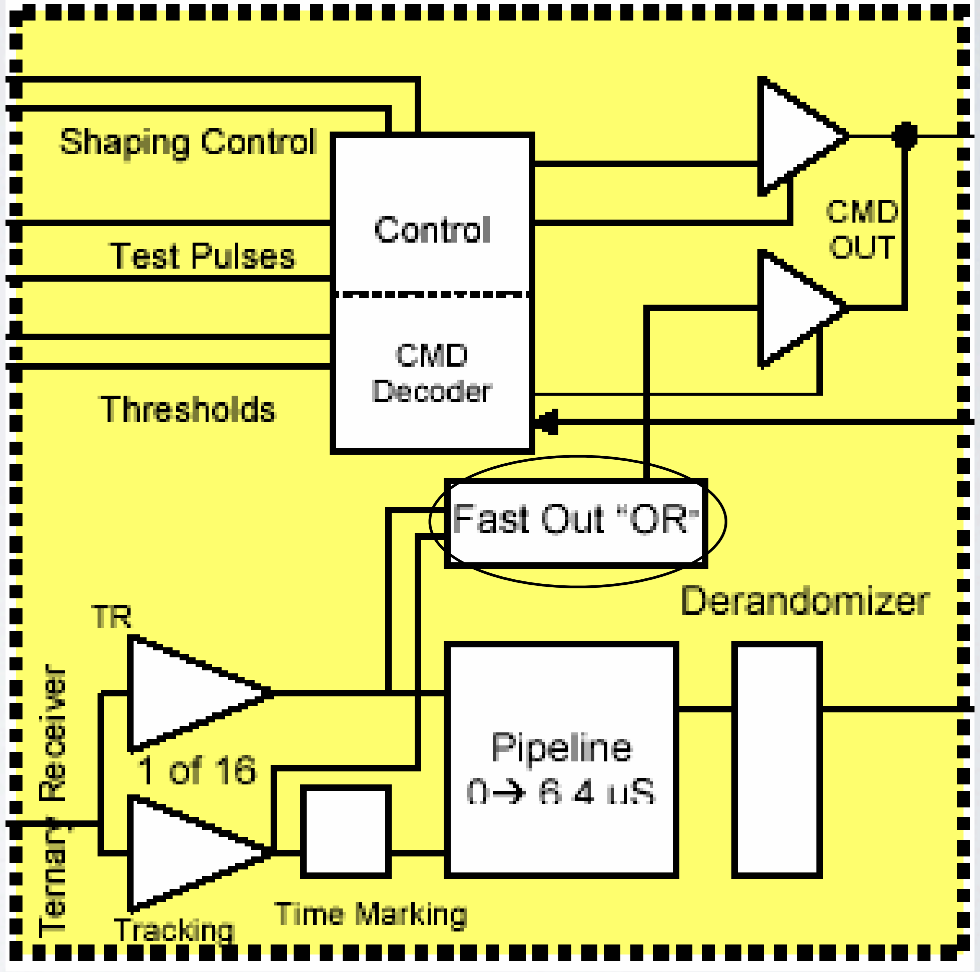




- Rate/straw up to **20MHz** (50ns), **48ns** maximum drift time
- **ASDBLR**: Amplifier/shaper with ion tail cancellation and baseline restoration
- **Two discriminators** for each channel
  - 200 - 300 eV (15% MIP) tracking threshold ~**2fC** (LT)
  - ~6 keV TR threshold ~**120fC** (HT)
- Digital pipeline, **6 µs deep**
  - Tracking bit stored every **3.12 ns**
  - **TR** bit stored every **25 ns**

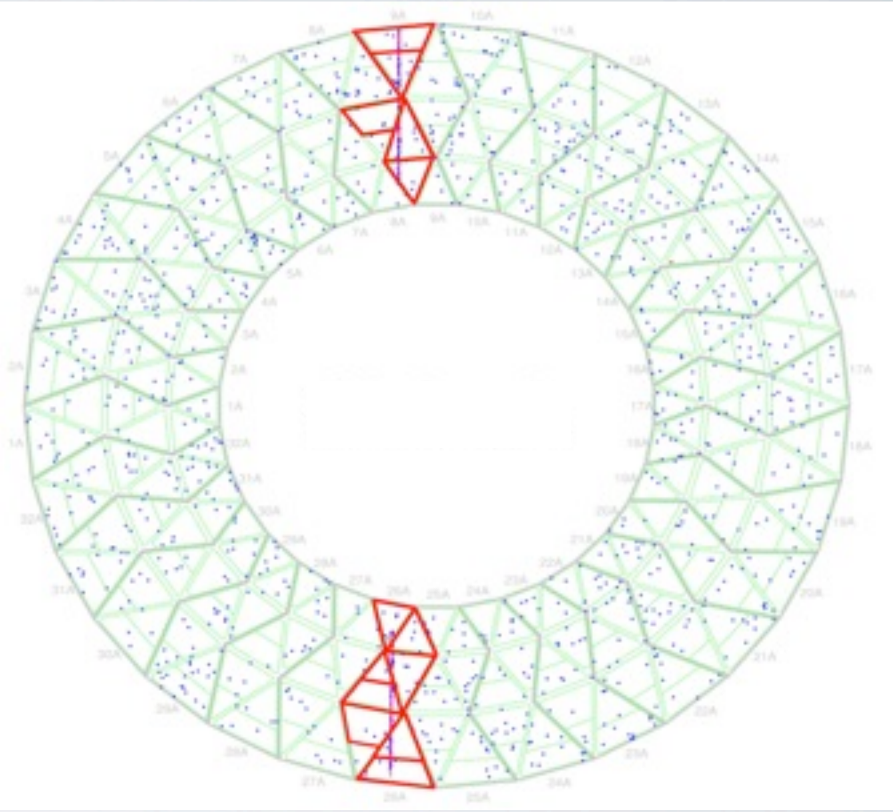
SOME READOUT FEATURES OF DTMROC

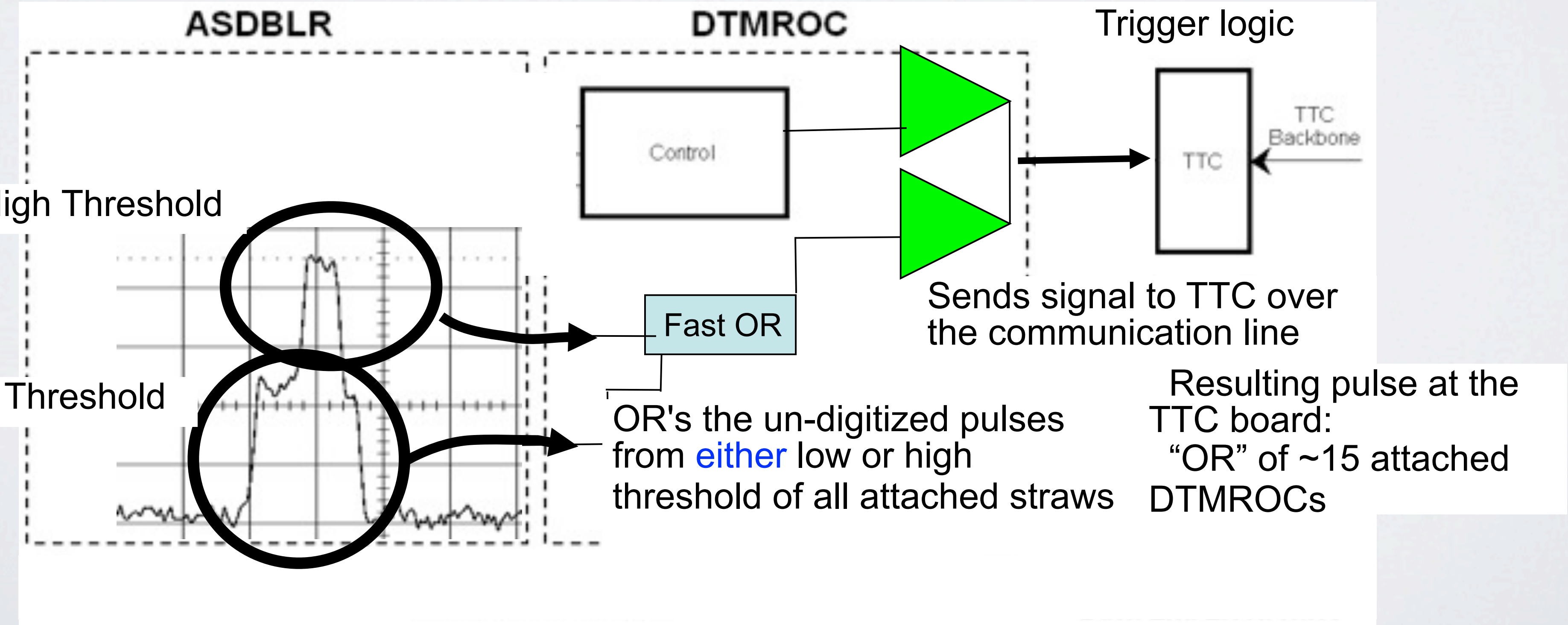
- **The Fast-Out allows quick sampling of data outside of ATLAS readout chain**
  - Can use fast-out signal to **trigger** events for simple debugging
- Fast-Out feature also allows for the option of providing a **Level One Trigger** to the ATLAS Trigger system
- **Fast-Out** and **FE Polling** (for SEU detection and correction) **share the same TTC line** (CMD OUT)
- **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 (estimated with test beams before installation)
  - Triplicate DTMROC registers make most SEUs harmless
  - Measured rate of SEU at **1e33cm^{-2}s^{-1}** is **2e-4 Hz**
  - Extrapolated rate (from measured rate) at **1e34 cm^{-2}s^{-1}** is **2e-3 Hz**



FAST-OR COSMICS TRIGGER

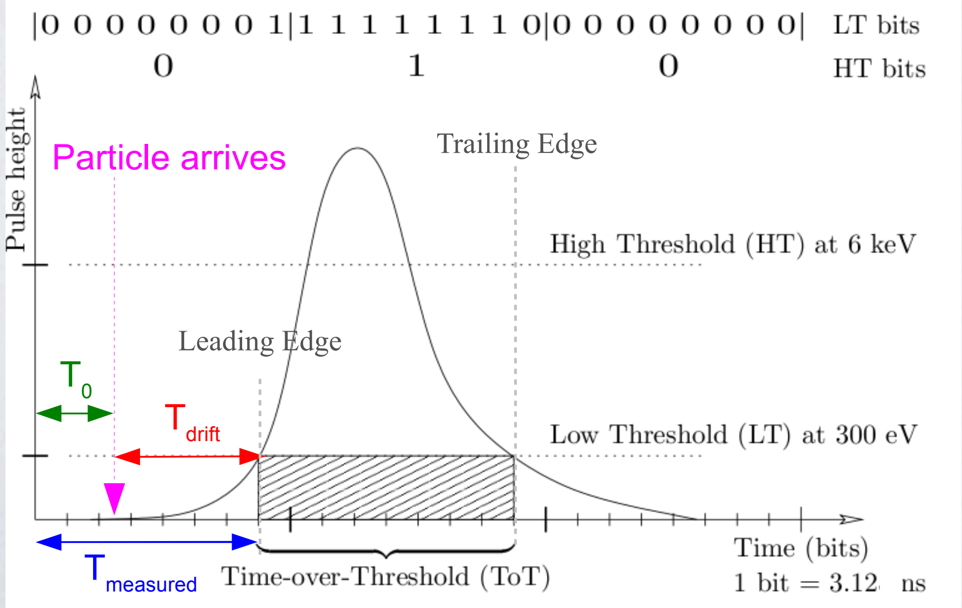
- Early detector **commissioning relied heavily on cosmics** for timing, alignment and calibration.
- TRT Fast-OR was the **primary cosmic trigger** for ATLAS timing and alignment.
- **Use Fast-OR output** of DTMROC chips
- Single FE DTMROC signals are then OR-ed, resulting in a FE board trigger granularity
- 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
- FAST-OR used in **dedicated cosmic runs only**
- **Investigations are ongoing for using the trigger in collision running** for dedicated highly ionizing particle searches.



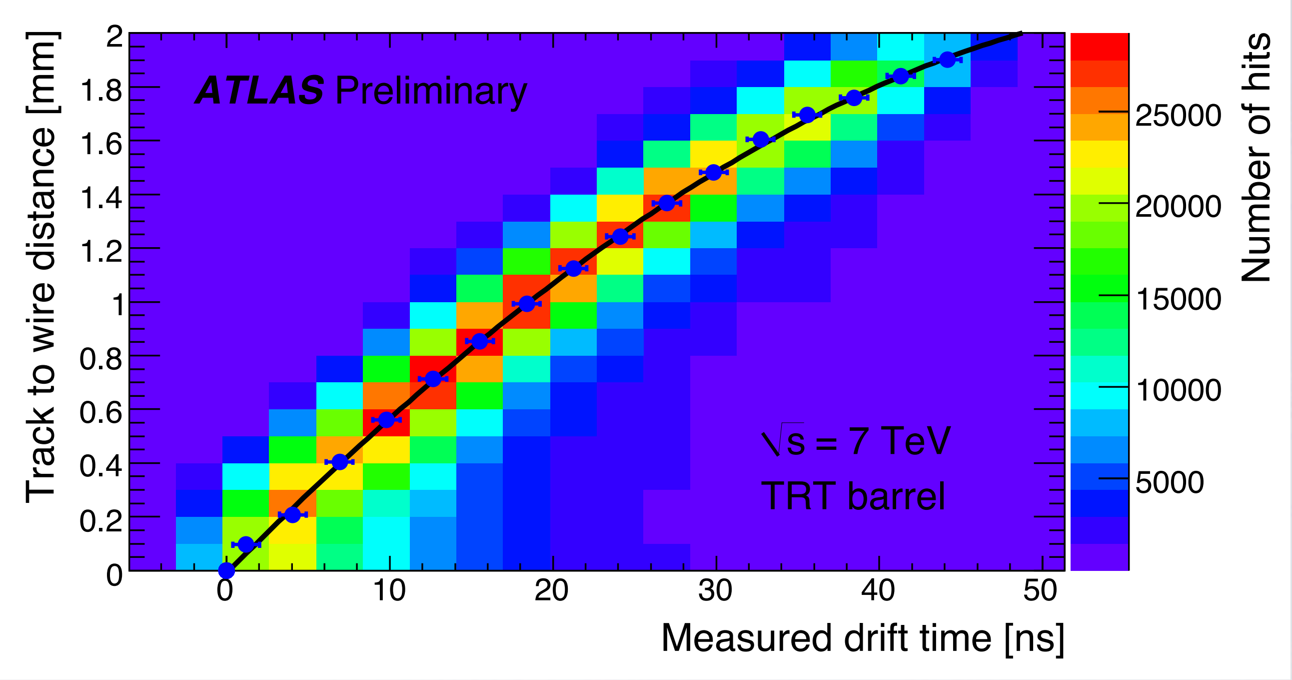


SETTINGS AND CALIBRATION

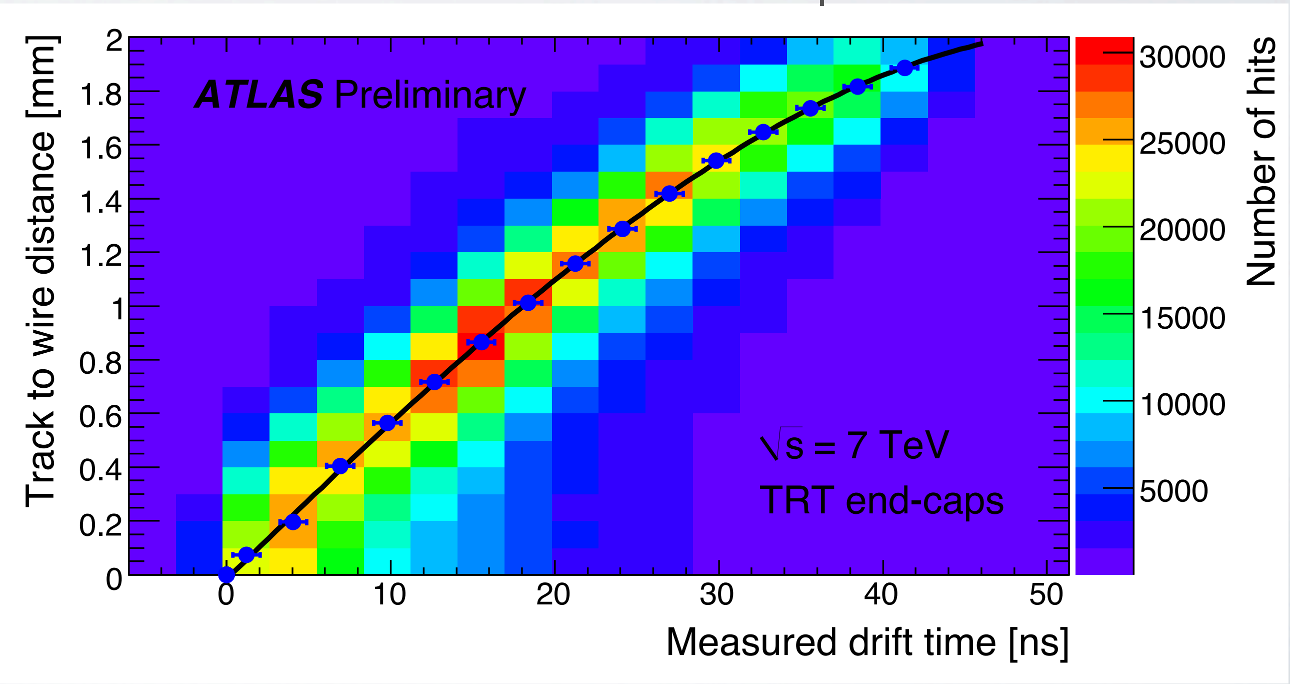
- **Hardware Settings**:
  - **Timing Delays**
    - Delay tuning as fine as 0.5ns used to align all readout channels in time with LHC collisions
  - **Thresholds**
    - Low threshold, calibrated to produce uniform 2% noise occupancy across detector
    - High threshold, set to produce uniform response 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** after applying T_0 corrections and comparing runs



TRT Barrel R-T Relation



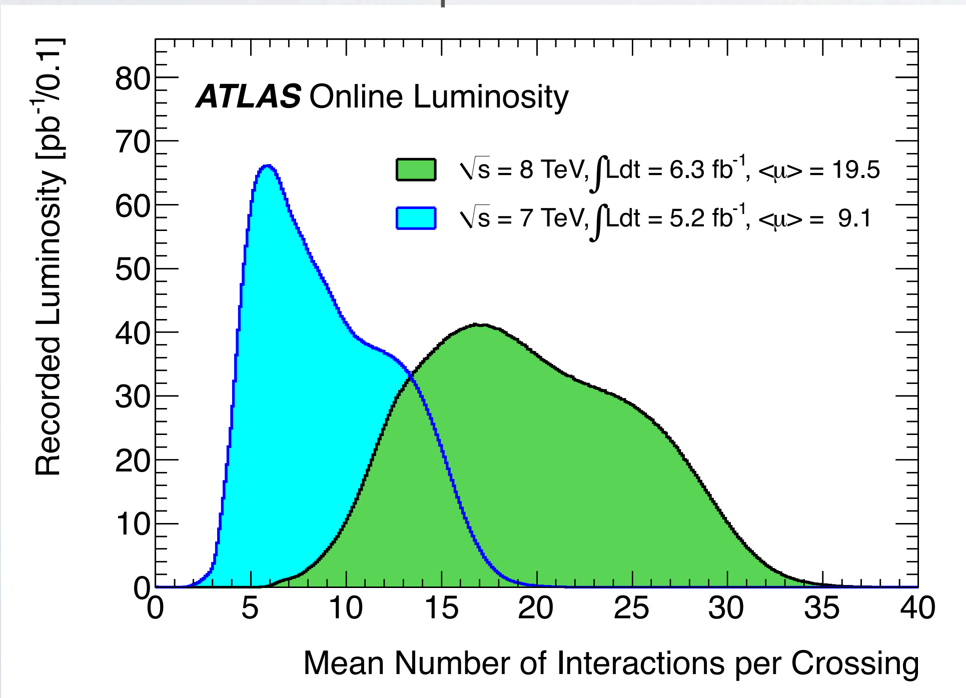
TRT End-cap R-T Relation



TRT IS NOT WITHOUT CHALLENGES

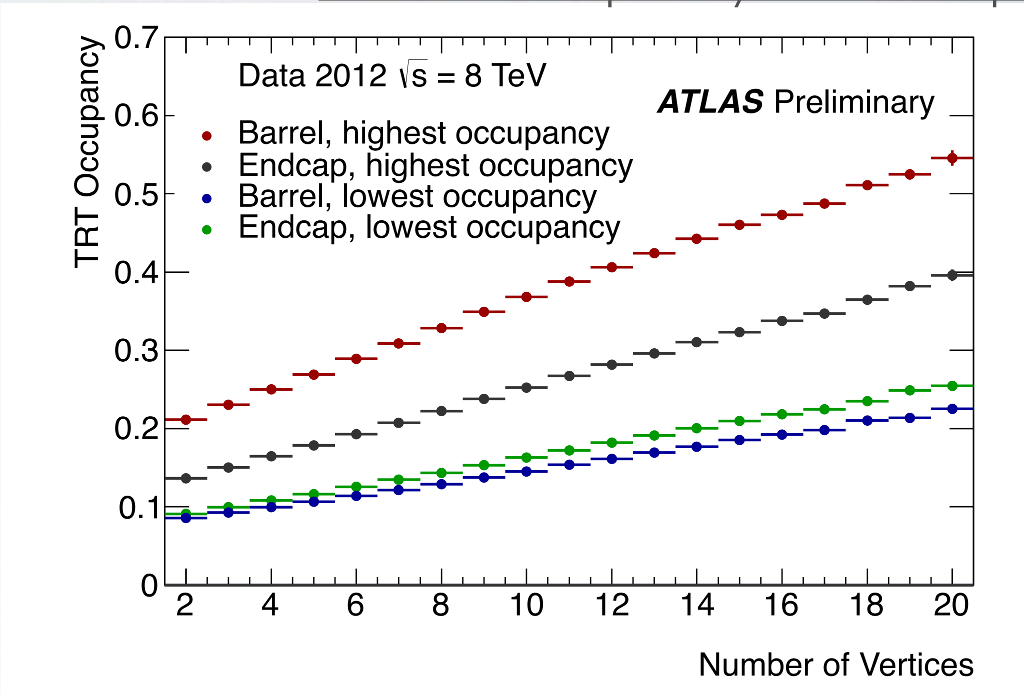
- The TRT readout chain has a **long chain** (~6) of **QPLL** (Quartz Phase Lock Loop) chips to keep the system synchronized
  - The chain of QPLLs is **very sensitive** to abrupt **clock changes** and drift
  - **Automatized resynchronization procedures** have been developed to minimize impact of QPLLs loosing lock
  - **Rarely occurs during data taking**, and mostly occurs during clock changes (which take place outside of collisions)
- The TRT is experiencing unprecedented gas leaks though **leak rate (and Xe loss) is still at the level of TDR design tolerances**
  - The detector is **taking action to minimize the impact** of the leaks
  - In the extreme case the gas mixture will need to be changed, and the TRT is prepared for this contingency
  - TRT electronics are **explicitly designed** to **handle either Xe or Ar** as the active gas. (with Ar the TR functionality is lost, but pulse separation is improved at high rates)
  - Data Quality is not compromised

Pileup in ATLAS Data

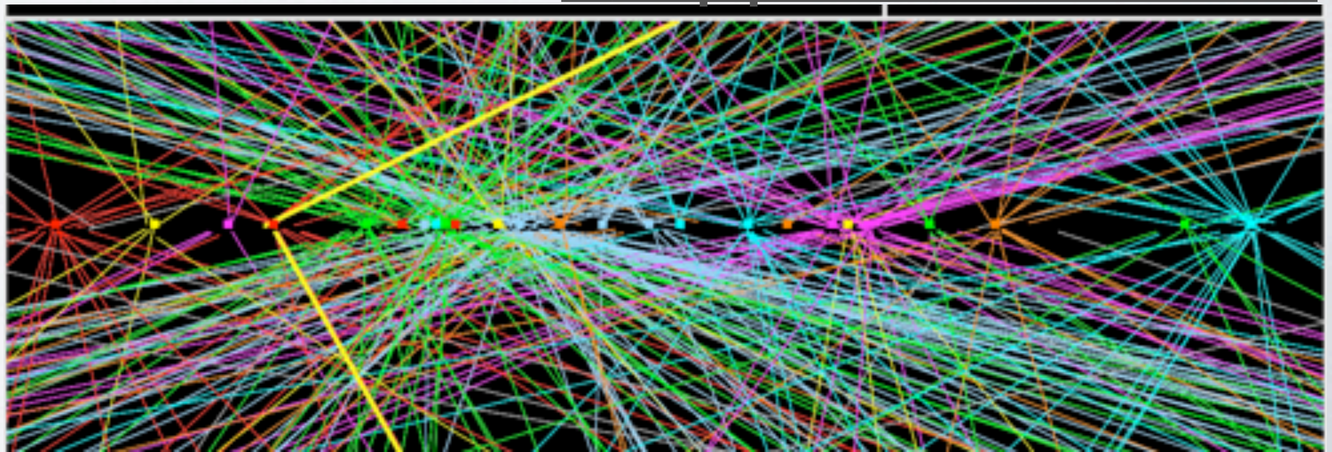


- Collision **Pileup** is a real challenge that all LHC detectors must confront
  - Performance degradation at highest luminosities is small and matches predictions from simulation
- **Data compression** demonstrated some problems in 2011 HI Run
  - When using Houghman compression, bit flips observed in specific RODs and large event fragment sizes seen.
  - Compression escapes and ROD firmware suspected to be part of problems
  - Using zero suppression scheme, behavior was no longer observed
  - Compression studies demonstrated that escapes are sensitive to pileup conditions
  - Multiple tables now available to handle different conditions

TRT Occupancy vs. Pileup



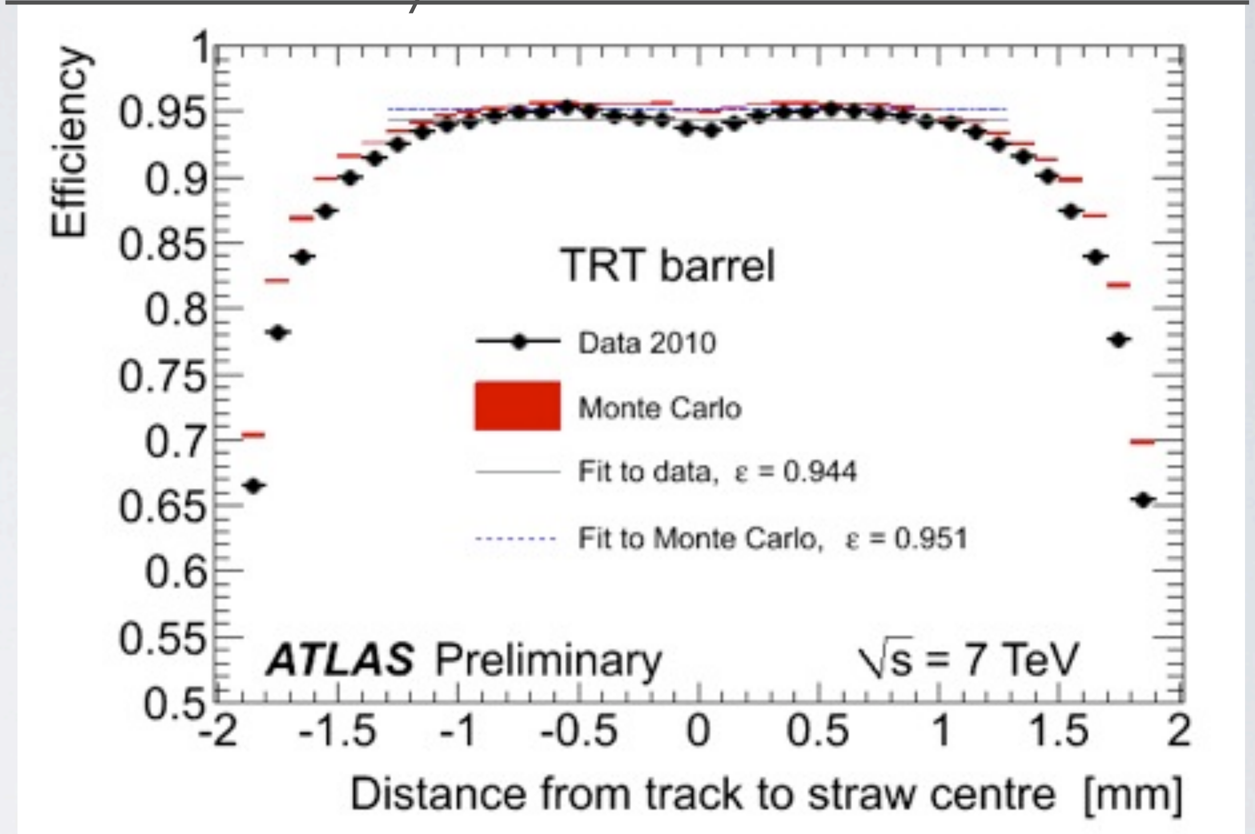
Z→μμ with 25 vertices



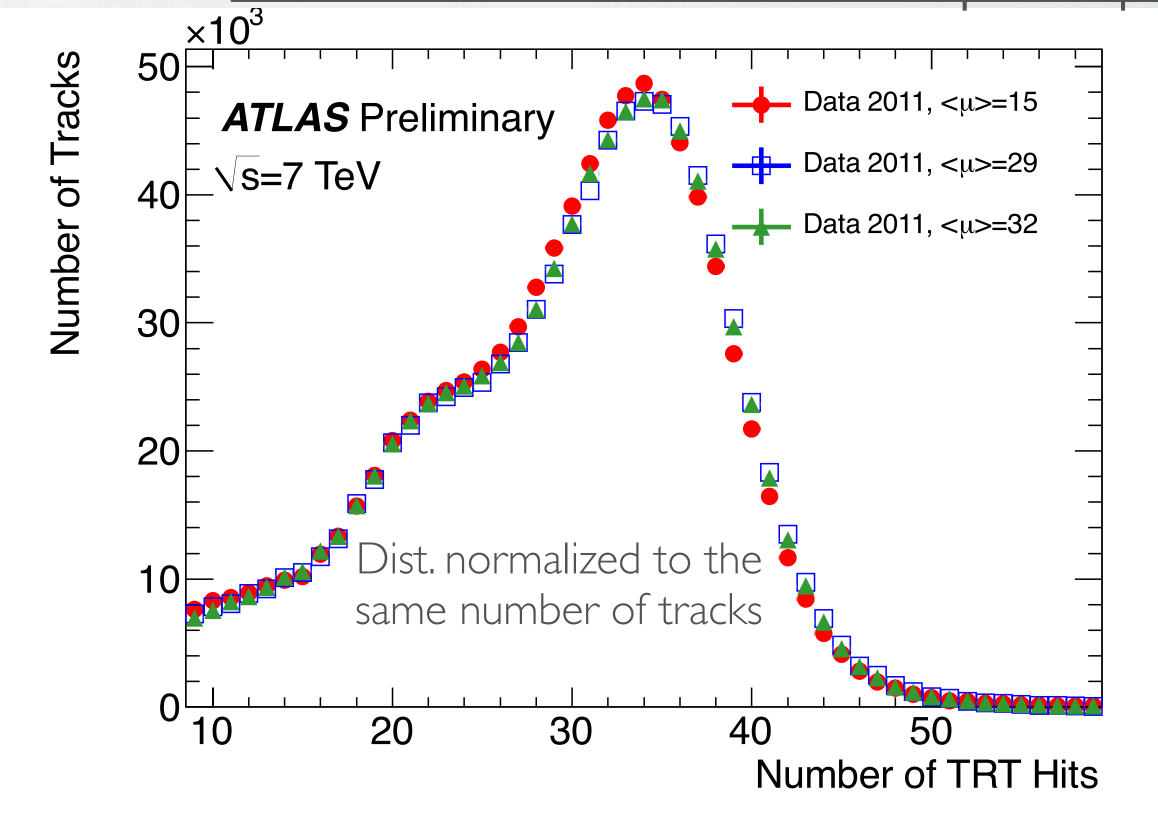
STRAW HIT EFFICIENCY

- Hit Efficiency ~**94%** in plateau
  - drop outside plateau is due to geometry and reconstruction effects
  - Dead channels excluded (~2.5%)
- Monte Carlo was tuned to 900 GeV data
- Plot requirements on tracks for hit efficiency study
  - ≥ 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
- **More stringent cuts** are added to tracks requirements in the presence of pile-up
- Effect of low efficiency near the straw edges is minimized from **continuous tracking** hits
- In the presence of **large pileup**, the straw **hit efficiency is close to constant**

Hit Efficiency vs. Hit Position in Straw



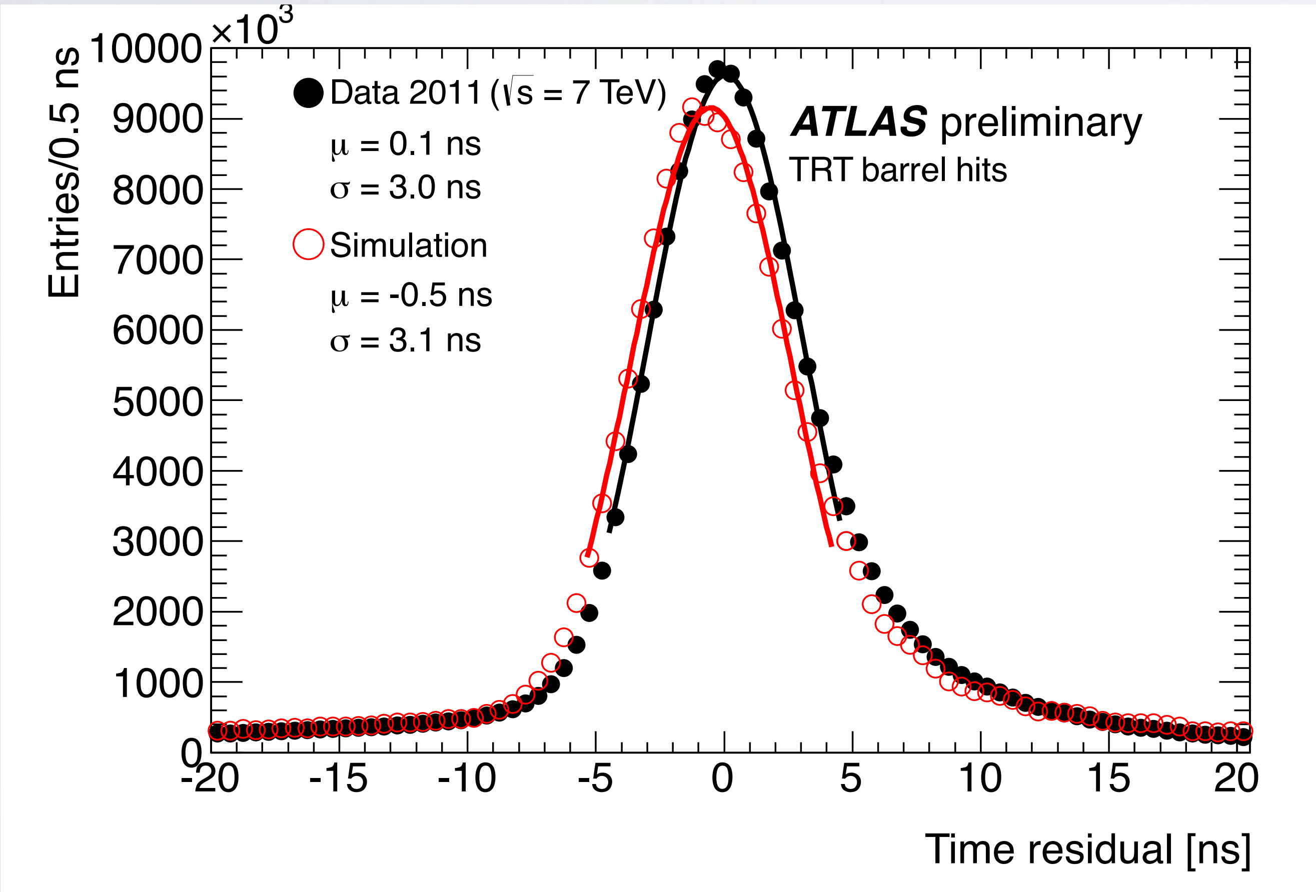
TRT Hits on Track vs. pileup

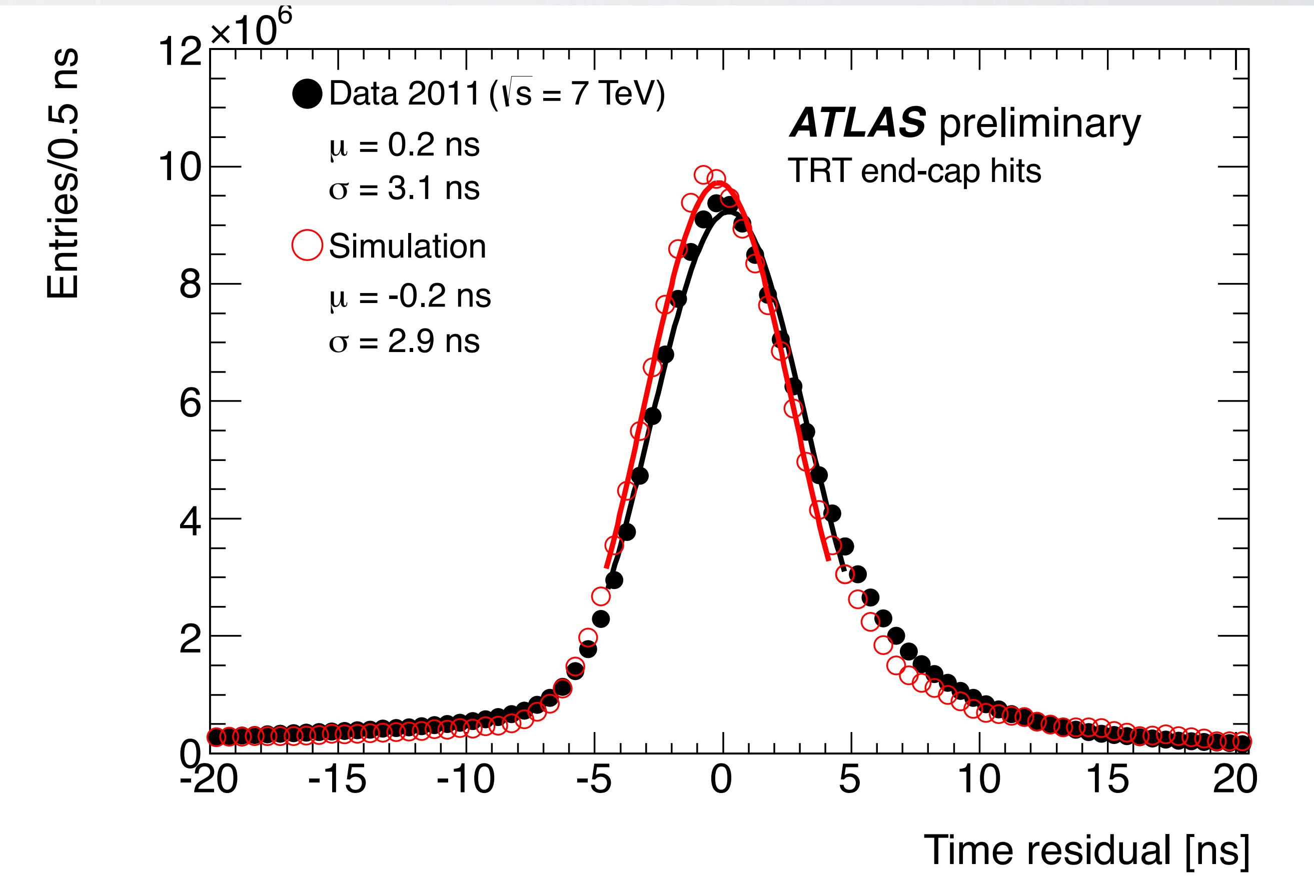


TIMING

- 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**
  - Time residual spread ~**3ns**
- **Endcaps**
  - Time residual Spread ~**3ns**
- TRT Time residual is at the level of simulation

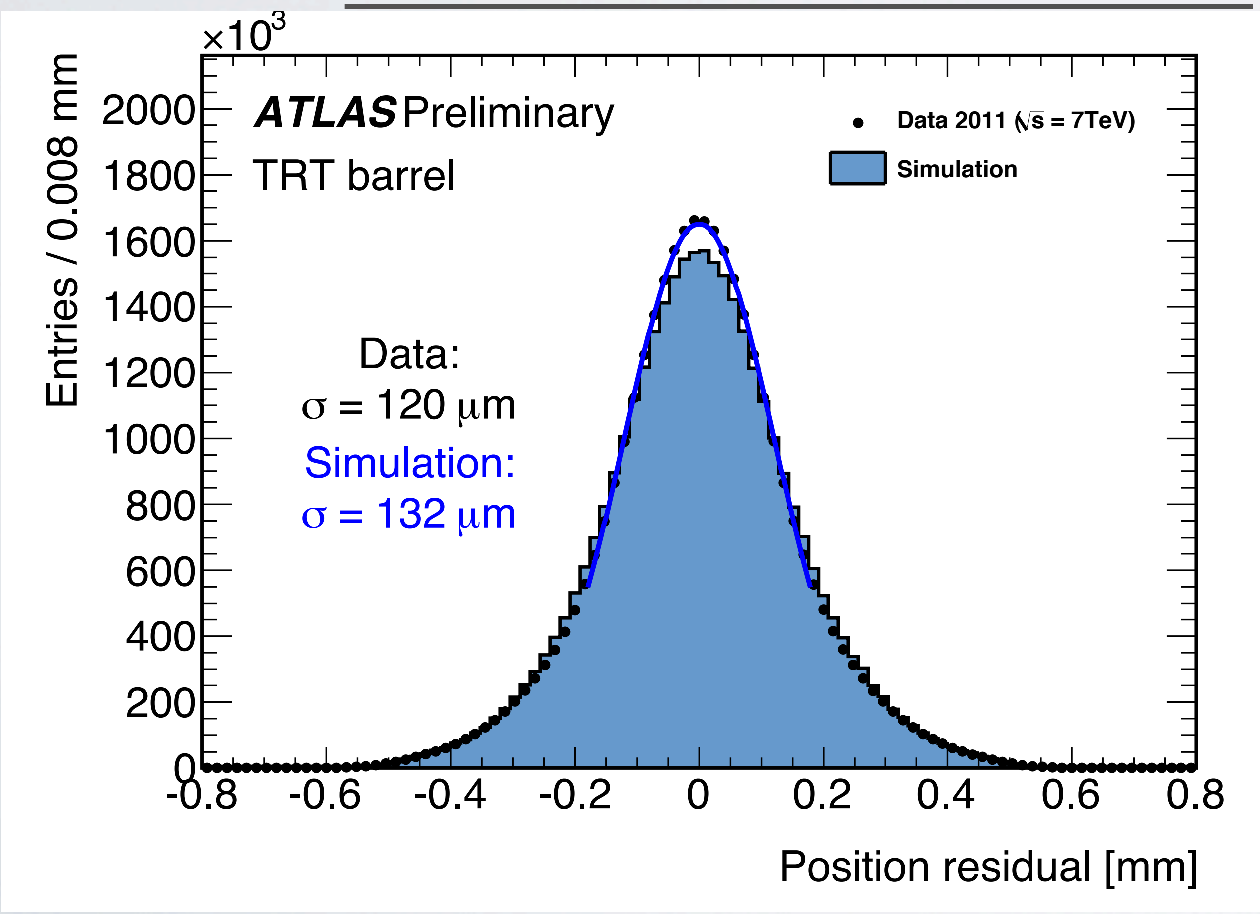




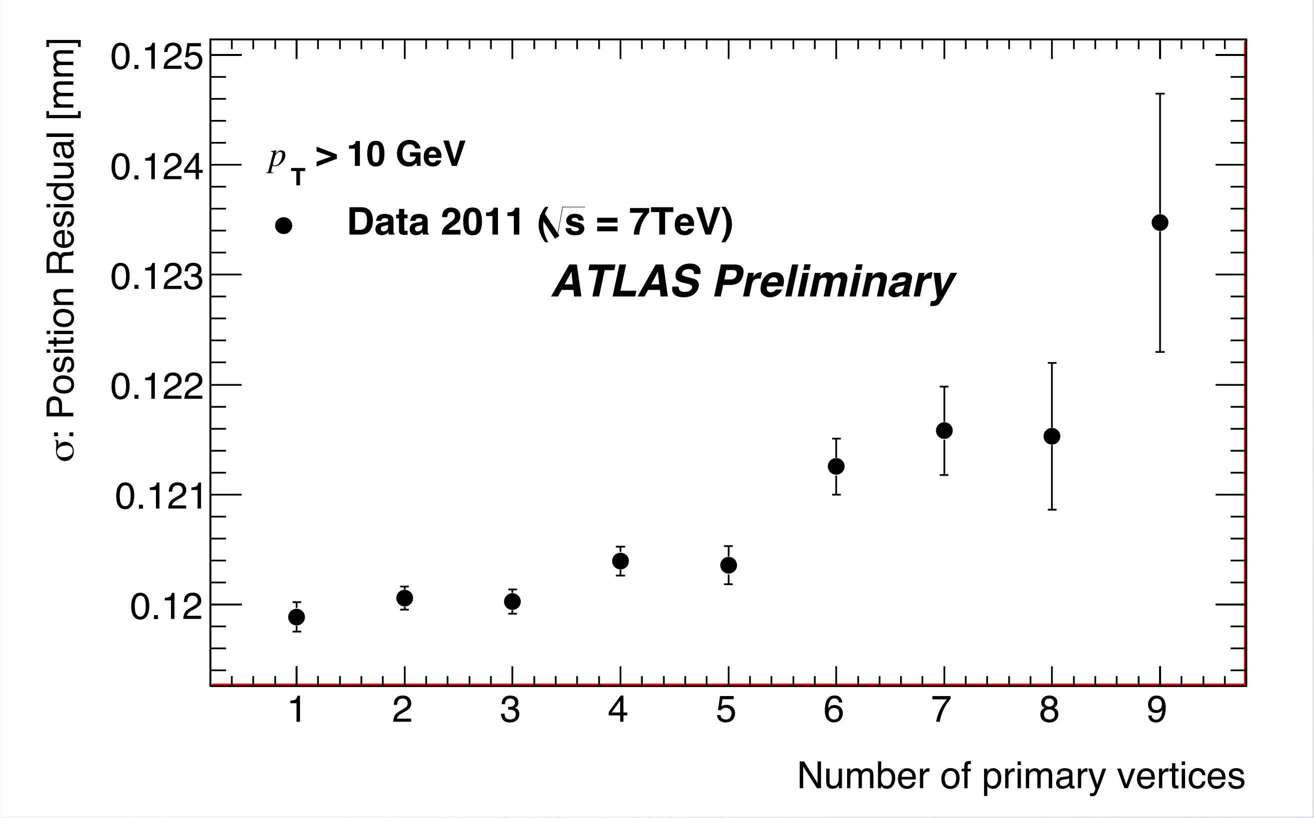
POSITION RESOLUTION

- Barrel performance exceeding simulation performance 120**μm** (data) vs.132**μm** (simulation)!
  - Short straws demonstrate position resolution smaller than 100**μm**
- **Lots of work done** to get this far, including: alignment, calibration, tracking software
- Position resolution of the TRT is at expected level or better

TRT Position Resolution



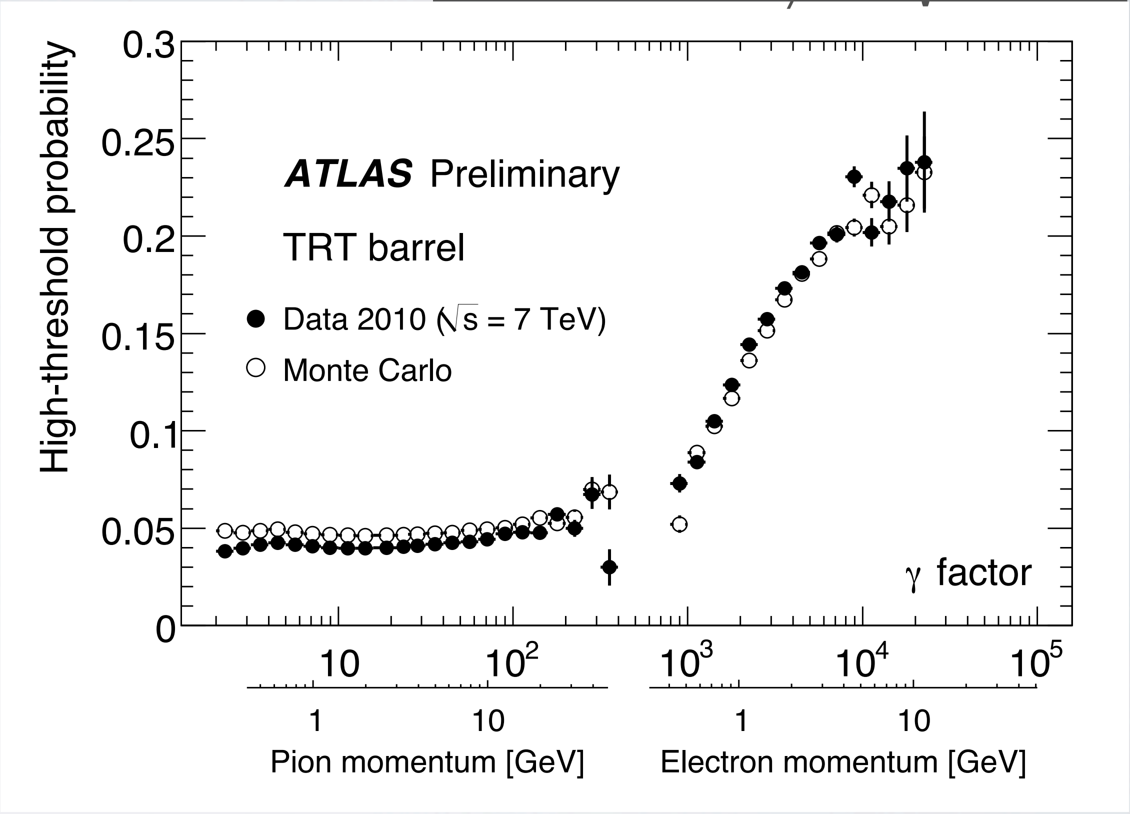
TRT Position Resolution vs Pileup



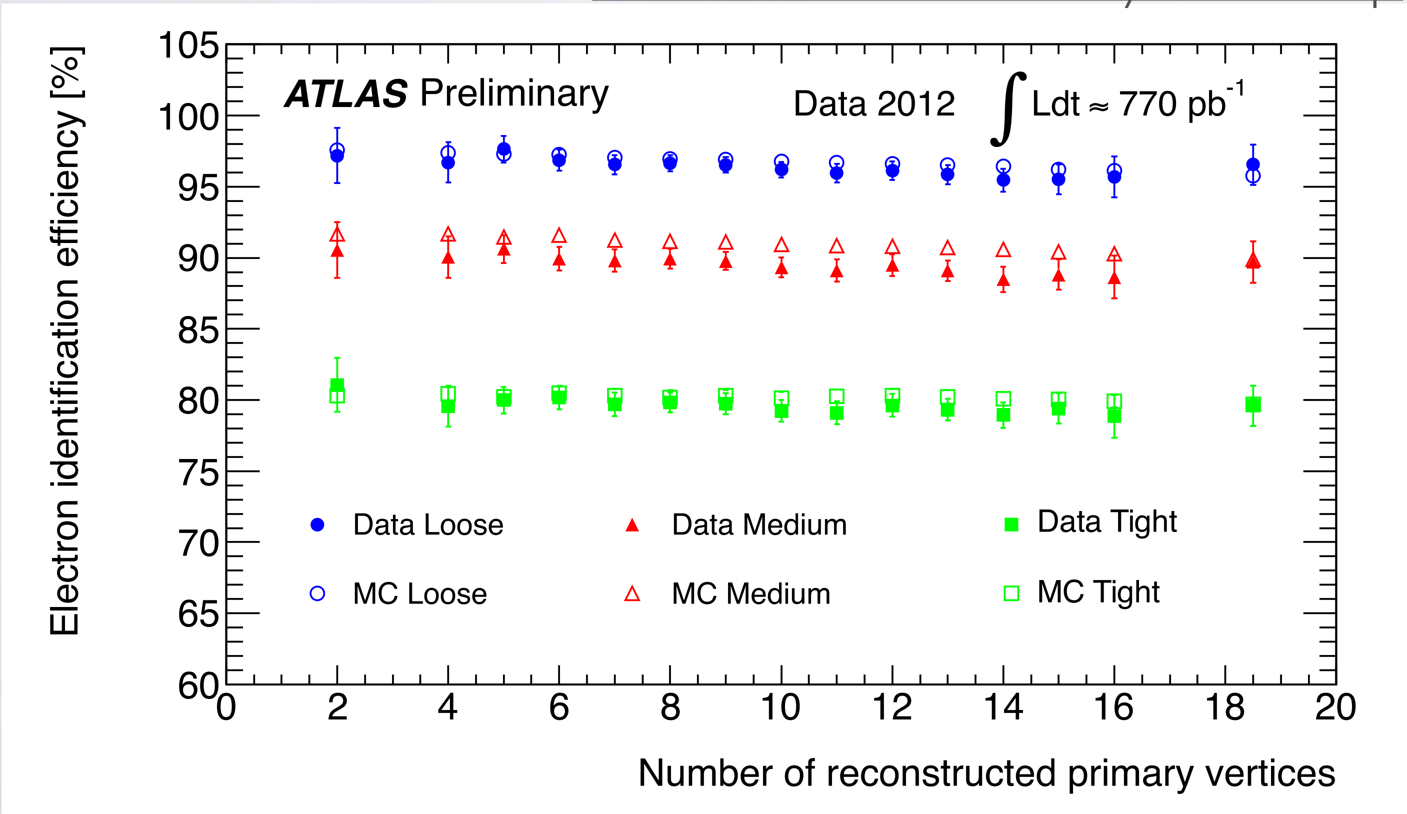
ELECTRON IDENTIFICATION

- Electrons are Identified by the presence of High Threshold hits (from the presence of Transition Radiation) along the track
- By selecting tracks with a relatively large number of HT hit fraction on the track, the TRT is able to discriminate electrons from charge pions
- HT fraction is a key input to ATLAS electron Identification

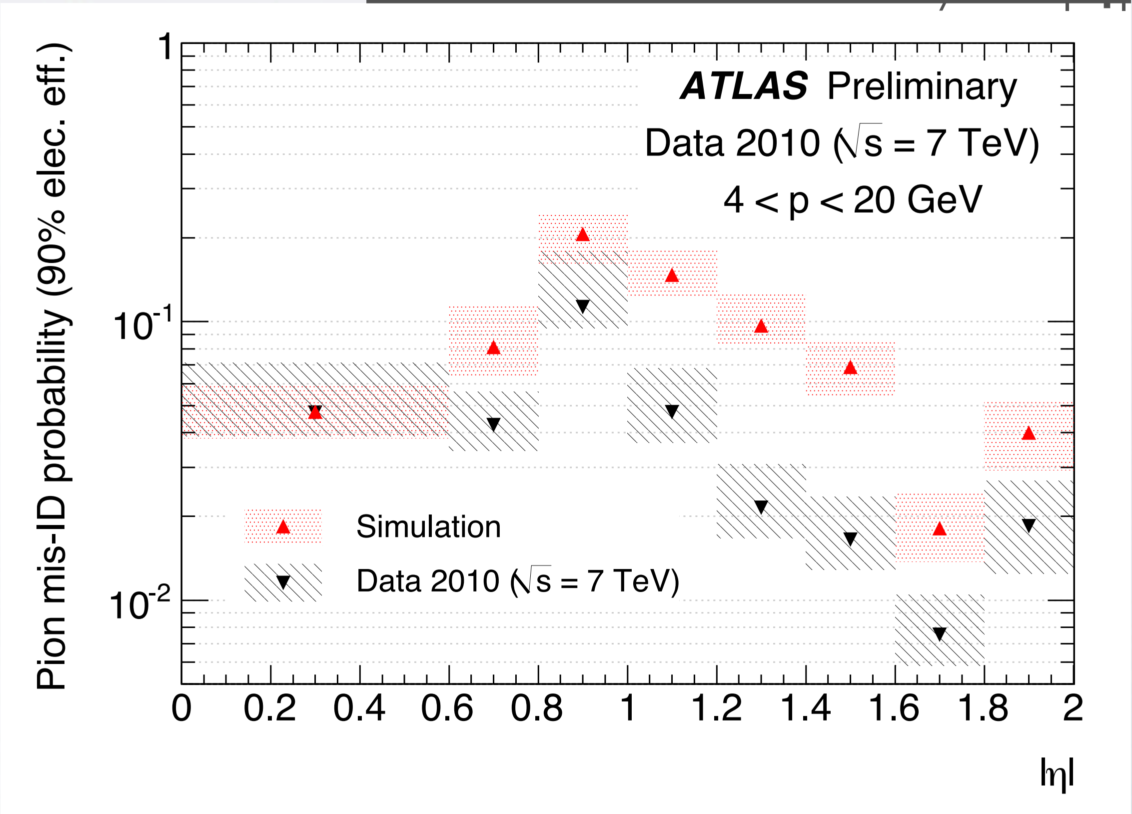
HT Probability vs. γ Factor



Electron ID Efficiency vs. Pileup

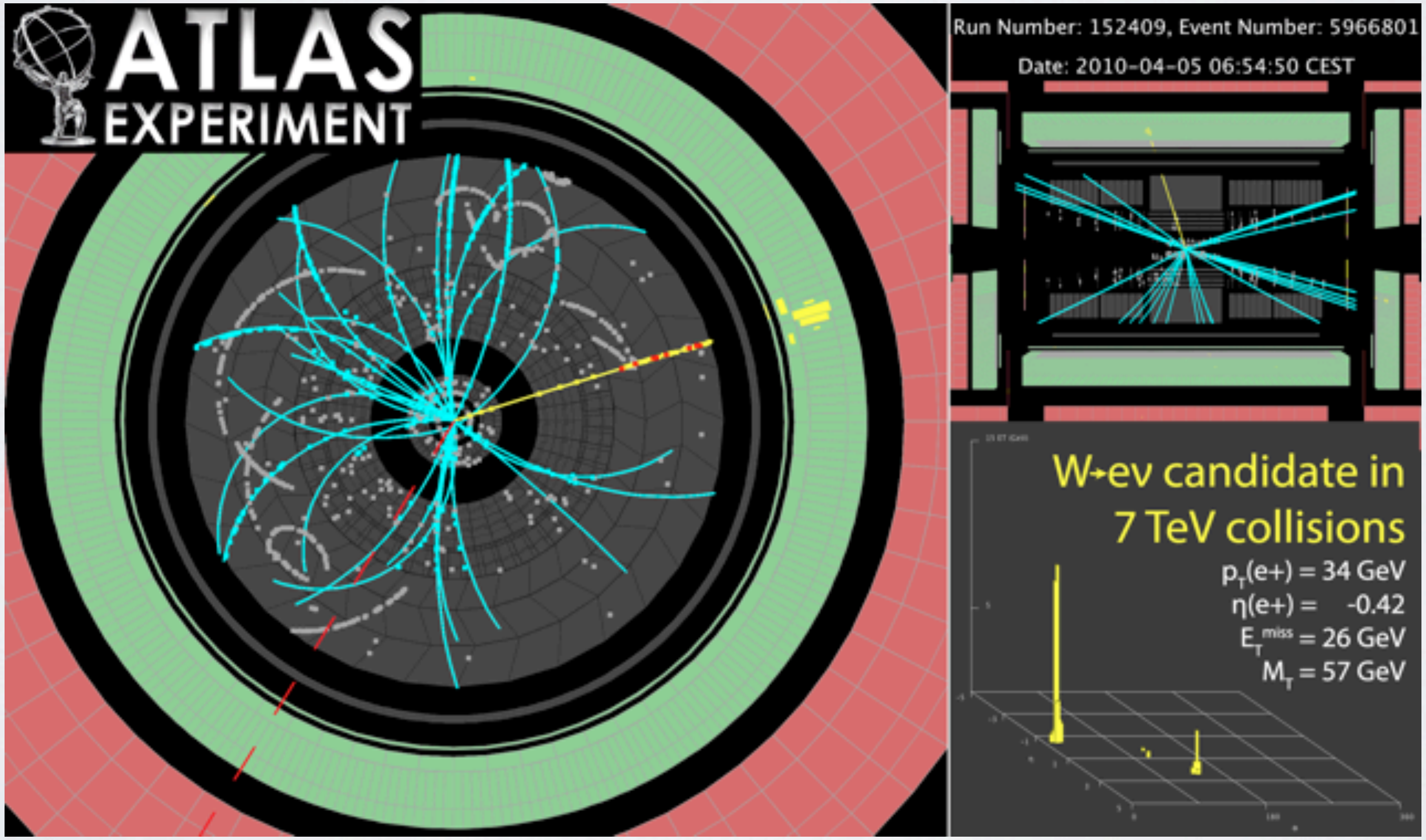


Pion mis-ID Probability vs. |η|



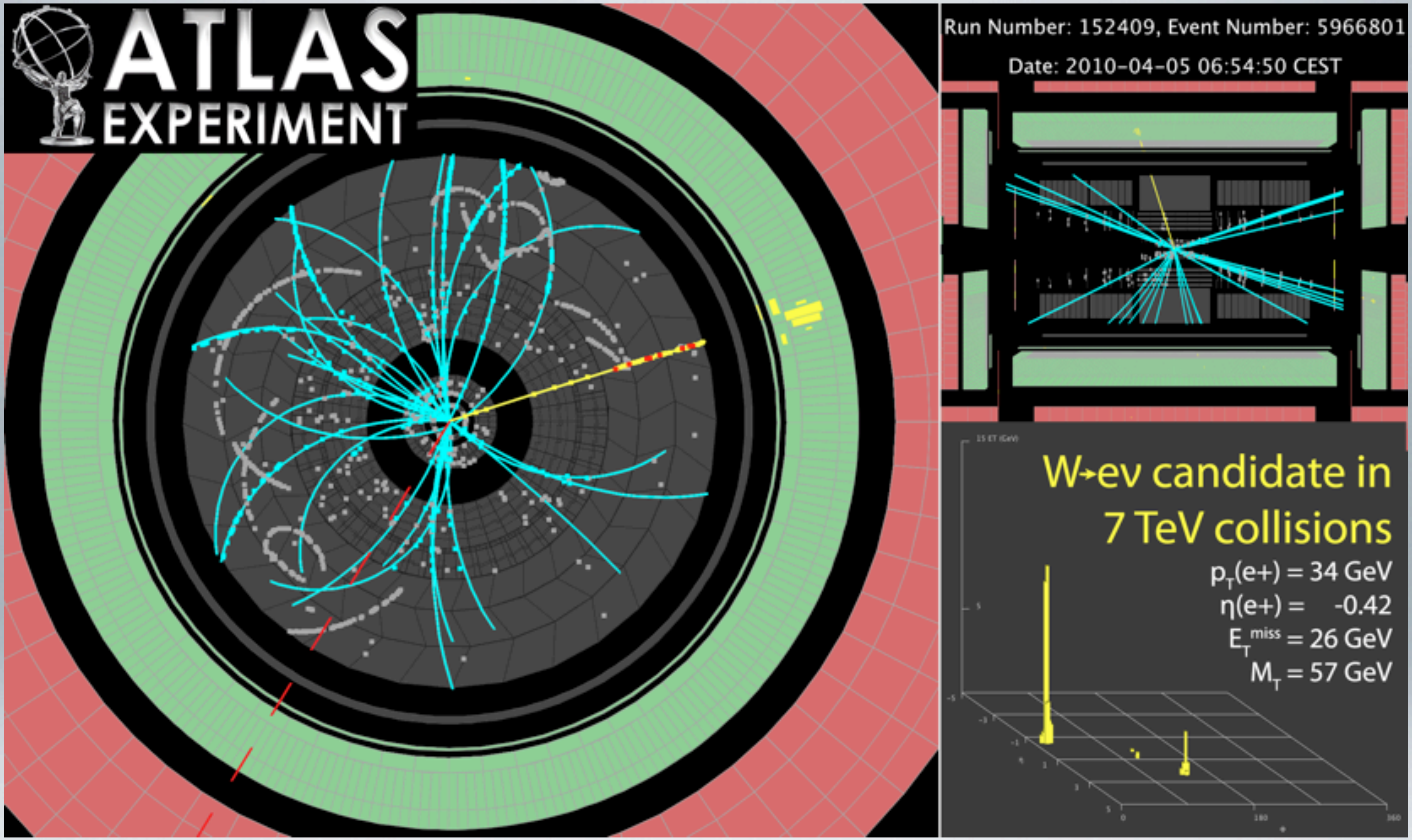
SUMMARY

- TRT is operating smoothly: >99% uptime in physics runs
- Excellent TRT performance with further optimization still possible
- 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
  - Performance of the ATLAS Inner Detector Track and Vertex Reconstruction in the High Pile-Up LHC Environment
    - https://cdsweb.cern.ch/record/1435196/files/ATLAS-CONF-2012-042.pdf
  - The ATLAS Inner Detector commissioning and calibration (EPJC 70:787-821, 2010)
    - 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
p_T(e+) = 34 GeV
η(e+) = -0.42
E_T^miss = 26 GeV
M_T = 57 GeV

BACKUPS

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

ATLAS p-p run: April-June 2012

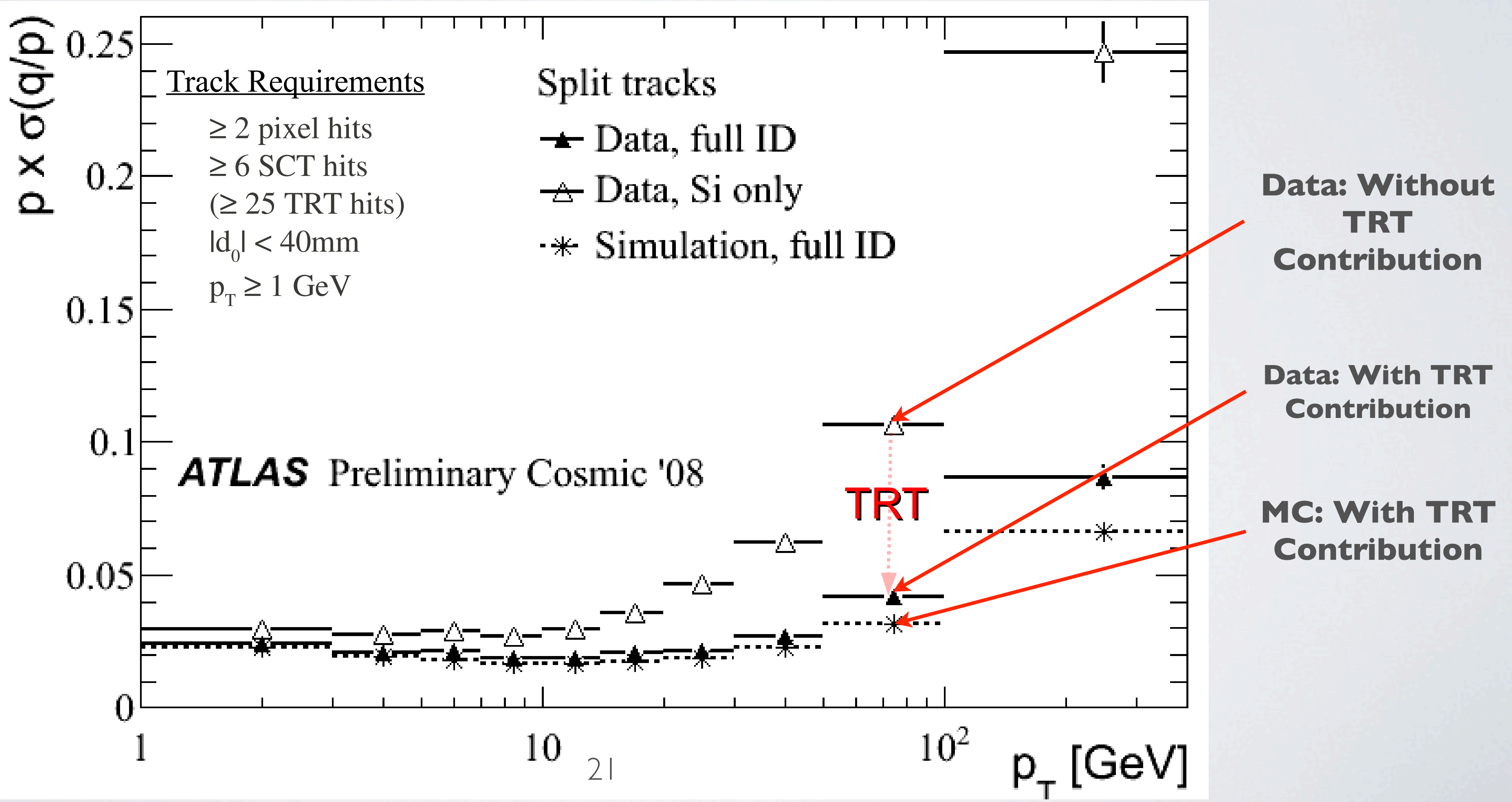
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
100	99.6	100	96.2	99.1	100	99.6	100	100	99.4	100

All good for physics: 93.6%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and June 18th (in %) – corresponding to 6.3 fb^{-1} of recorded data. The inefficiencies in the LAr calorimeter will partially be recovered in the future.

MOMENTUM RESOLUTION

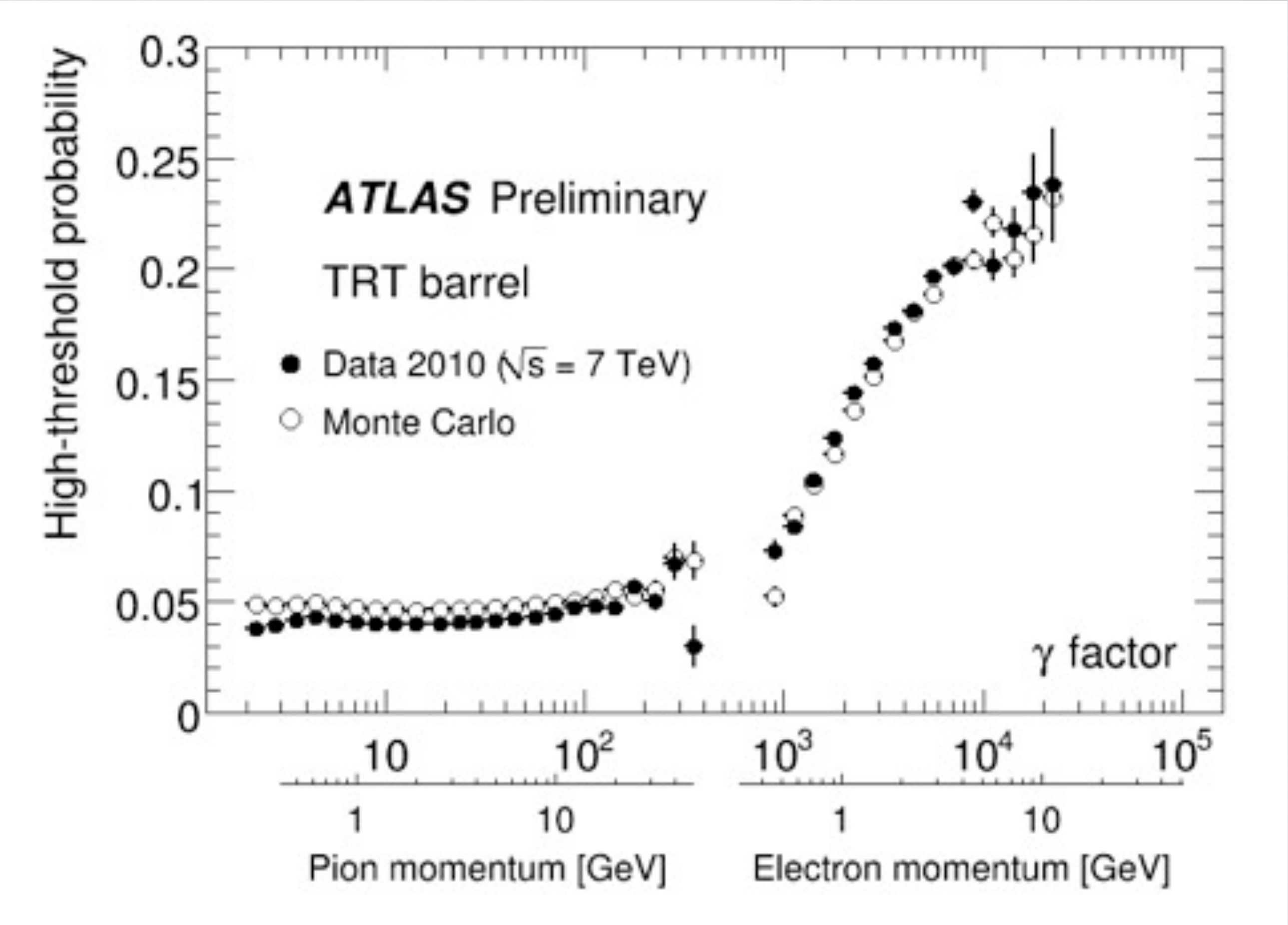
- With its long lever arm, TRT contributes significantly
  - Radius of last barrel SCT layer: 514mm
  - End of TRT Barrel: 1068mm
- TRT greatly improves the momentum resolution at higher p_T

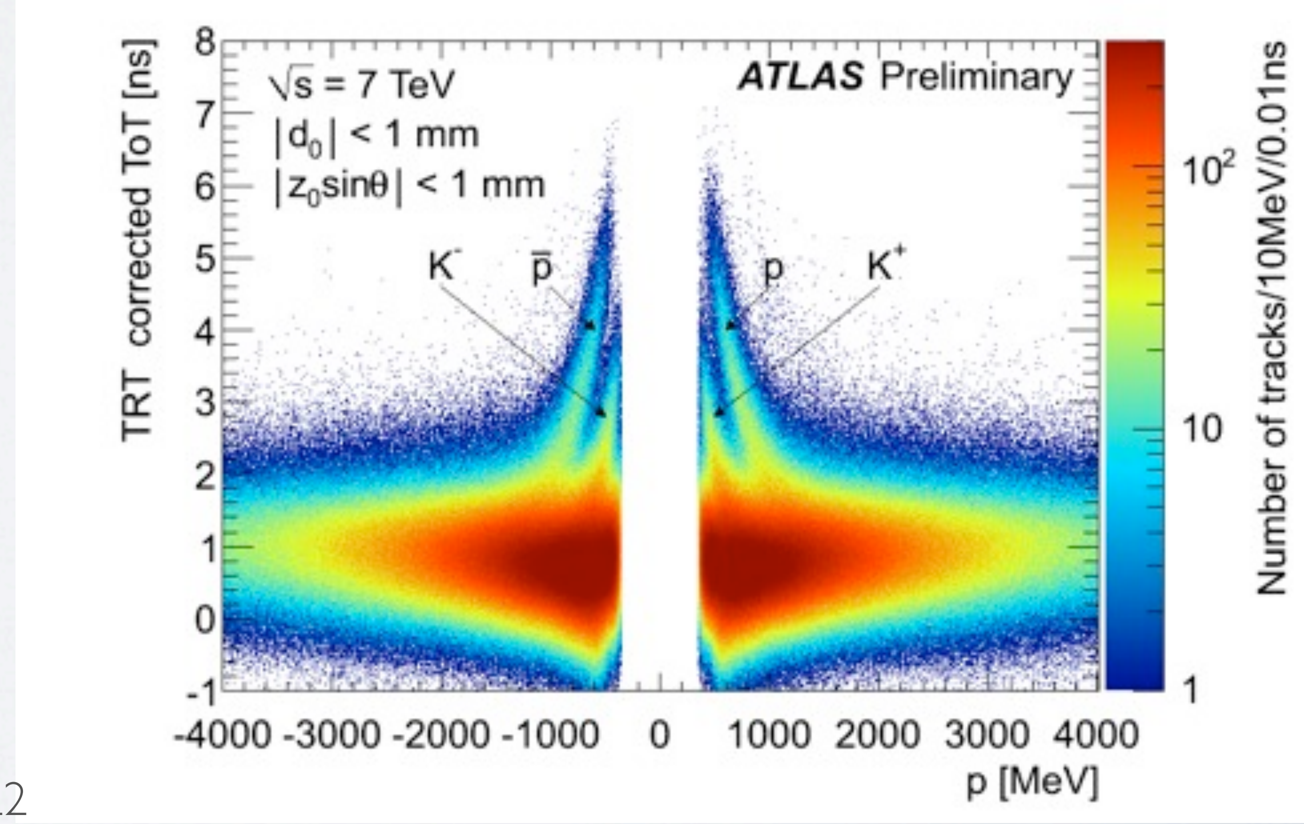


PARTICLE IDENTIFICATION

UPDATE

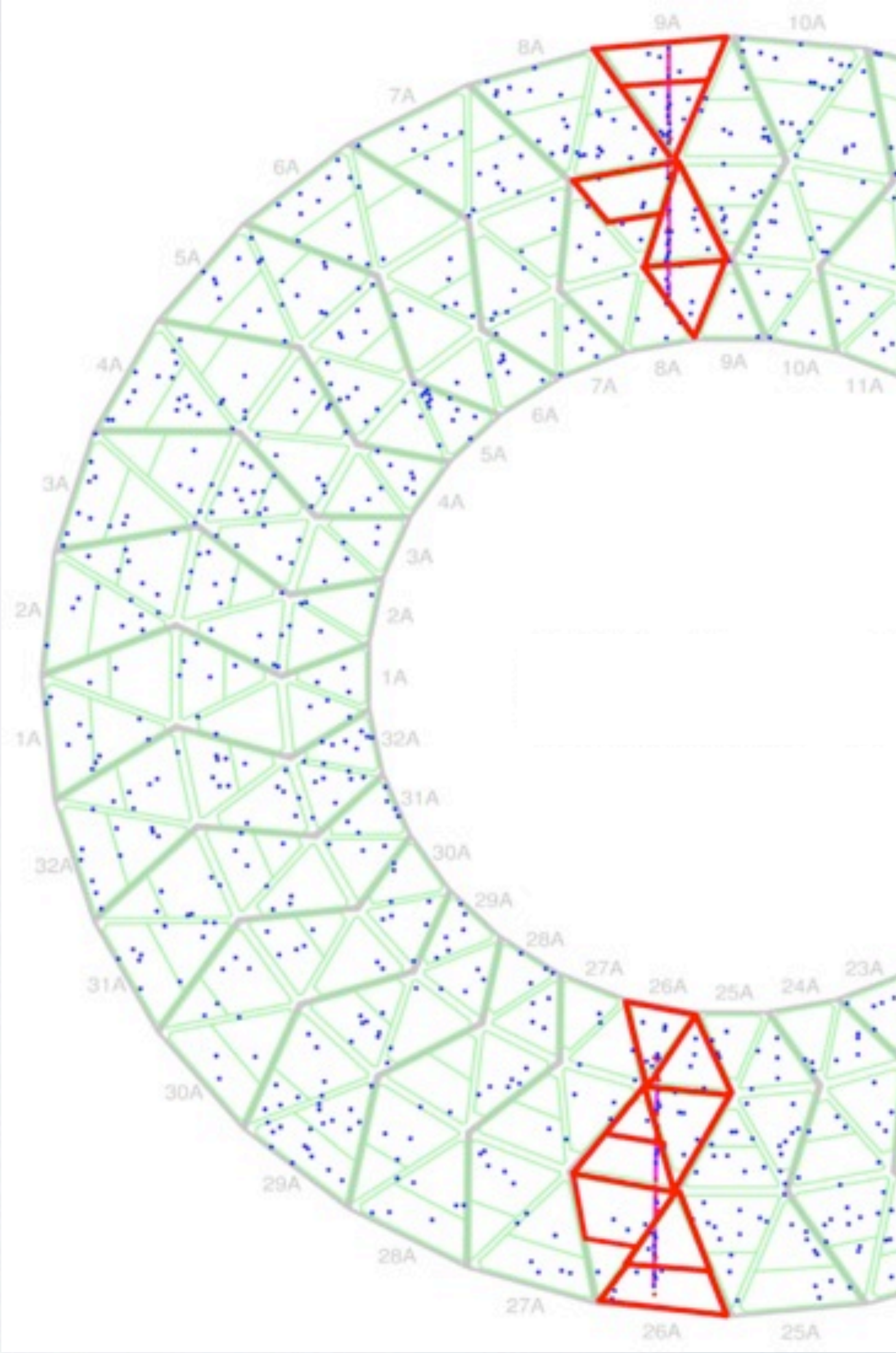
- Transition Radiation probability depends on gamma factor of a particle
  - Turn on curve also depends on **geometry, properties of the radiator**
  - **Different radiators** in barrel and end-caps
- Select electrons, pions, in data to tune and validate:
  - Pions: hadron enriched sample from all tracks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





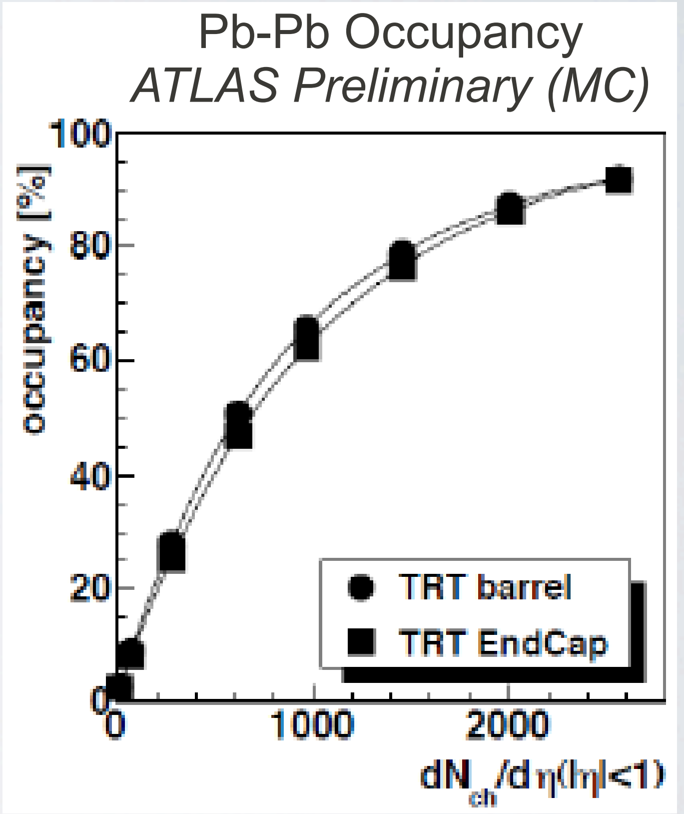
FAST-OR TRIGGER COSMICS TRIGGER

- 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



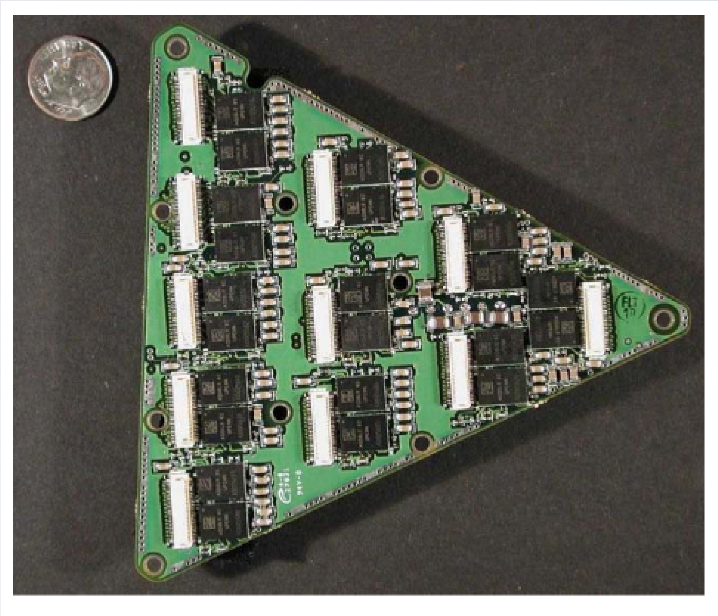
COVERAGE & OCCUPANCY

- **2.5%** of channels **dead** (**1%** mechanical and **1.5%** 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



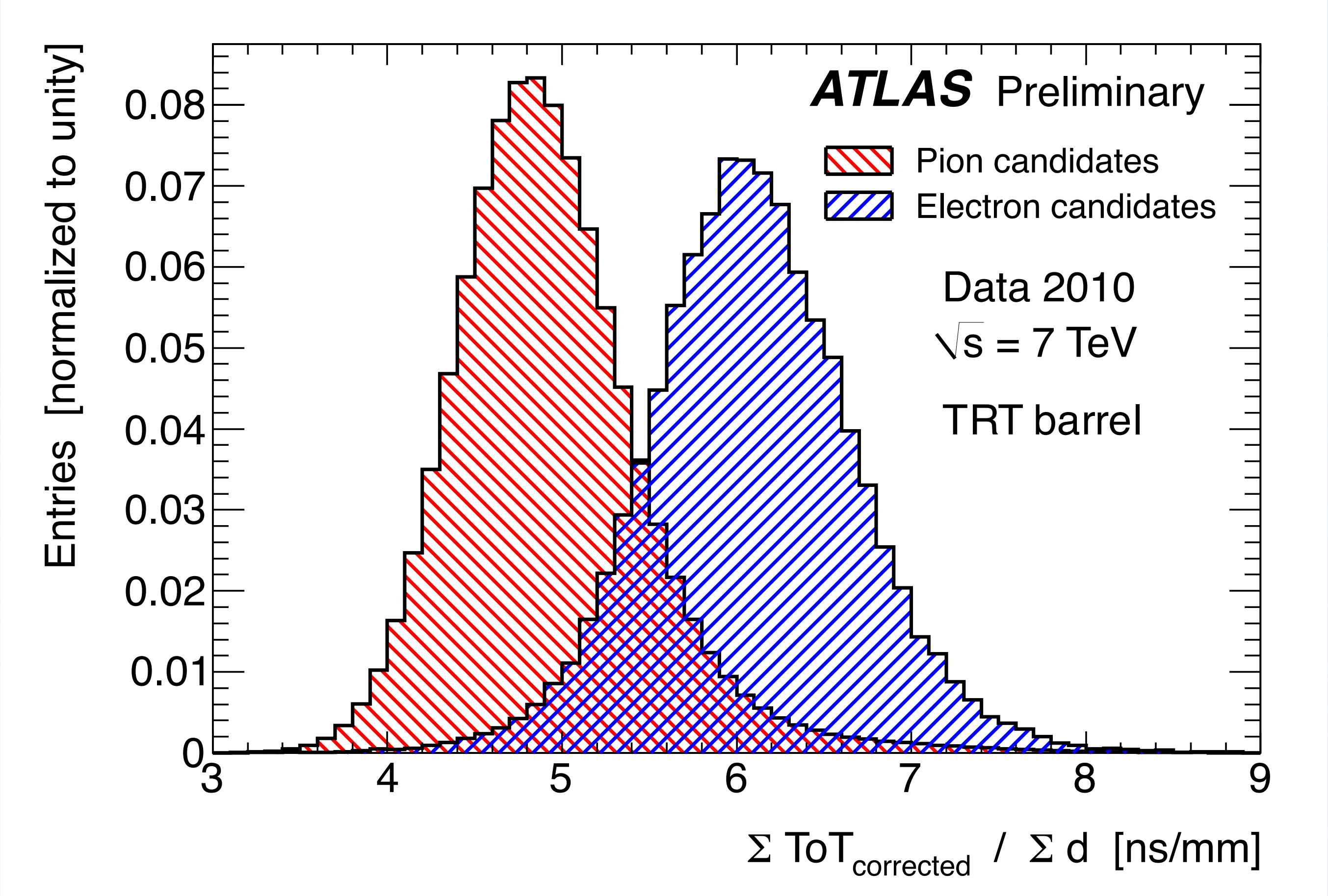
FRONT END ELECTRONICS

- **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



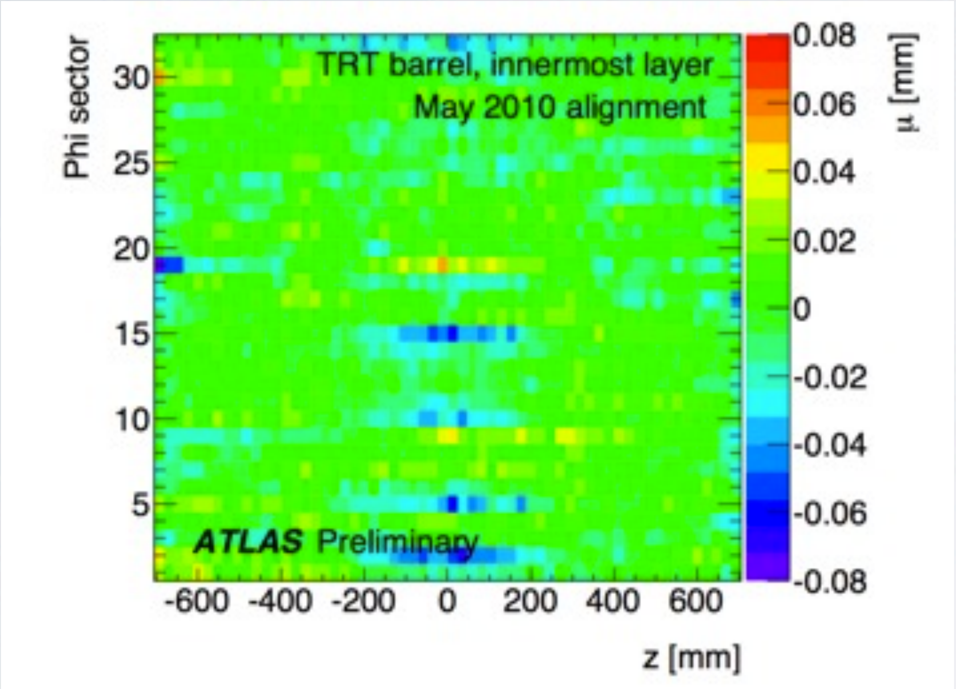
TIME OVER THRESHOLD AS A DISCRIMINATOR

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

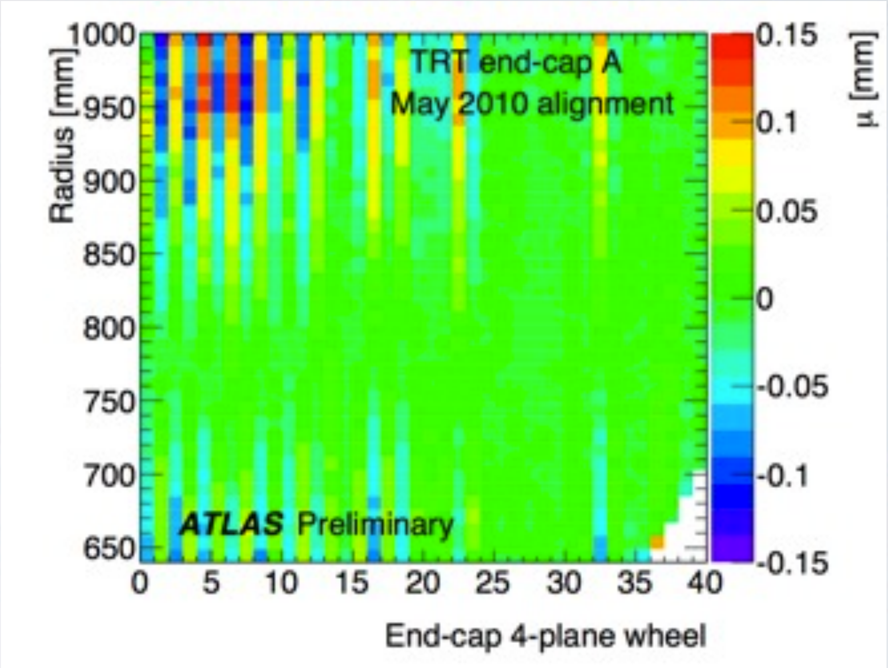


TRT ALIGNMENT MAPS

UPDATE

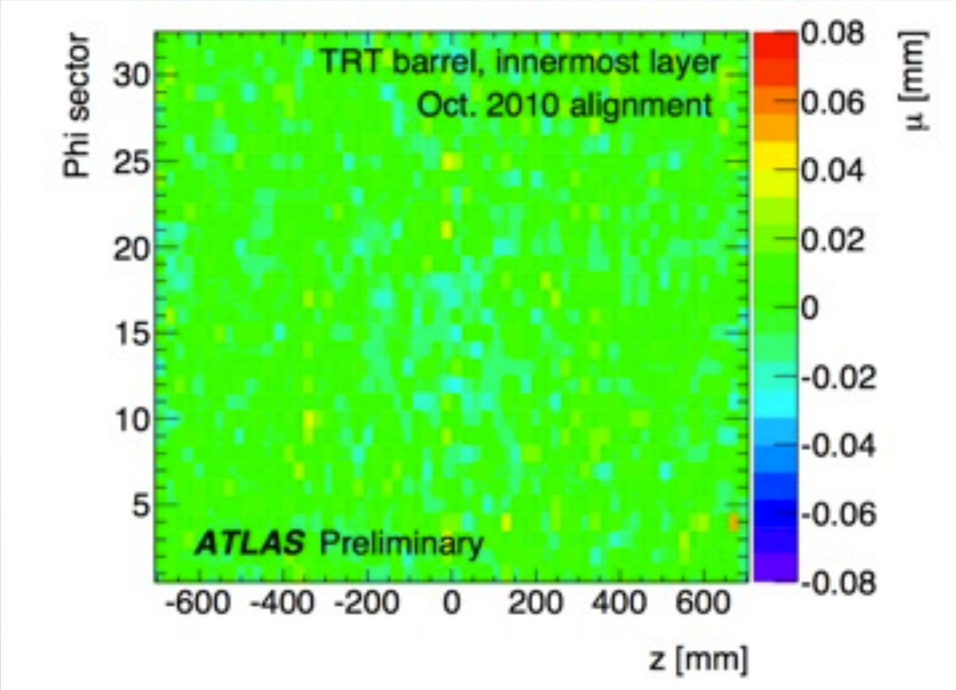


May Alignment

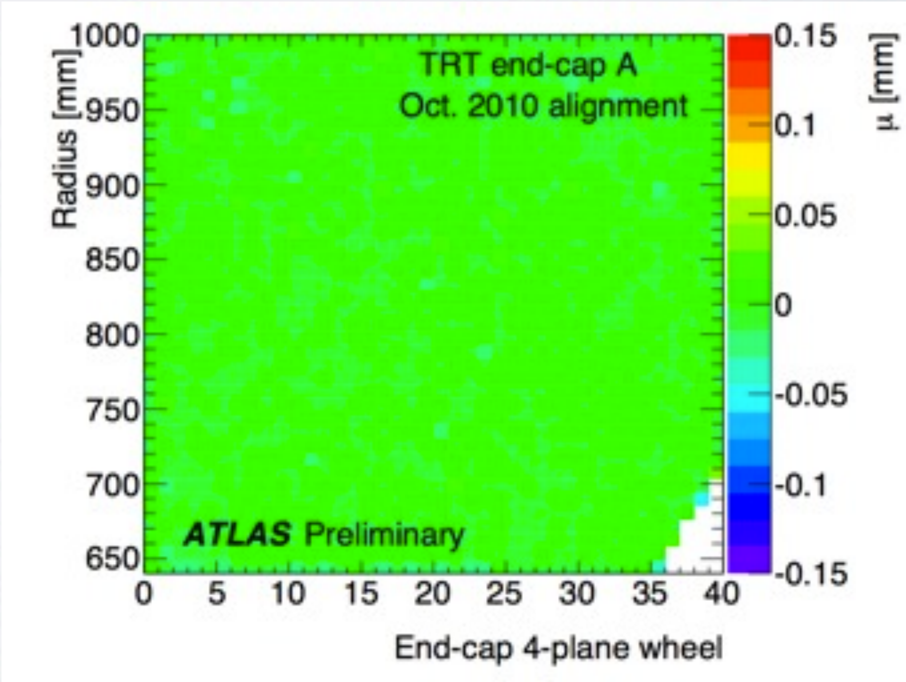


Barrel

End-cap

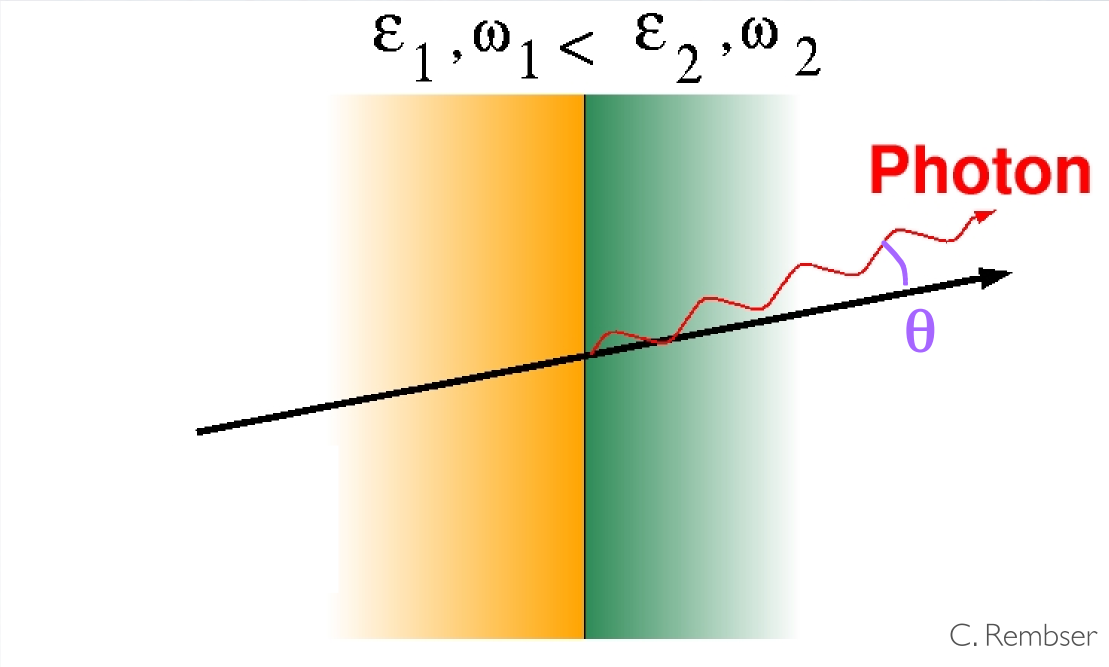


Oct. Alignment



PARTICLE IDENTIFICATION

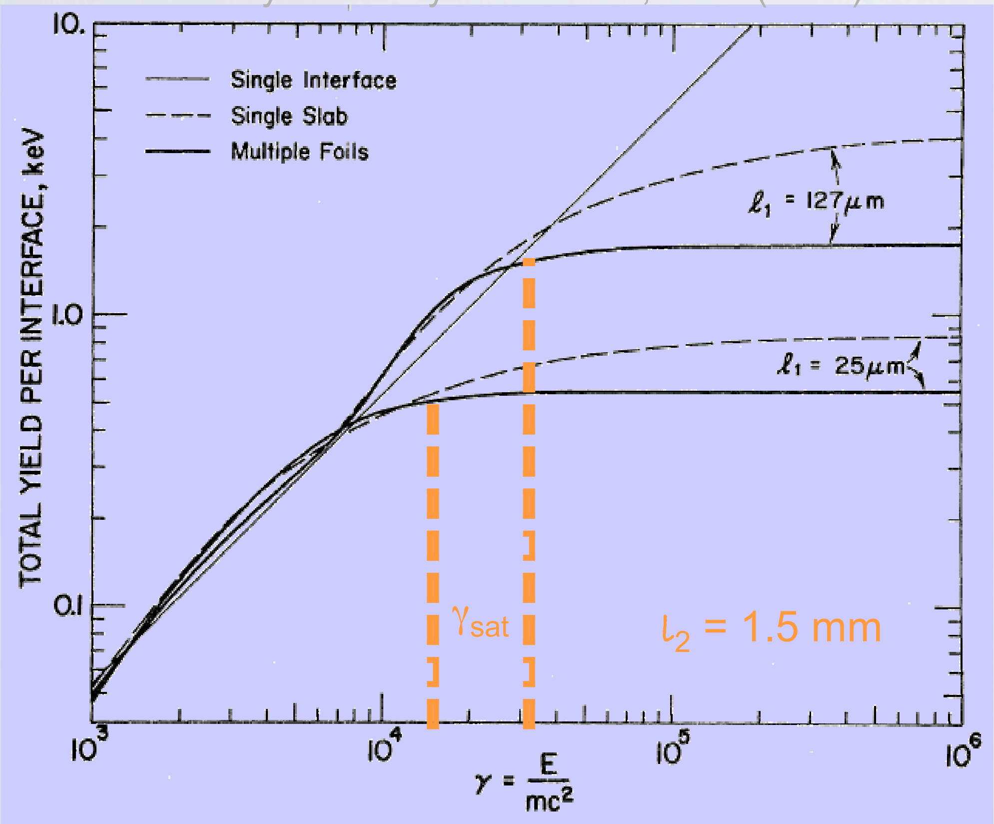
- **Transition Radiation**: photon emitted by a charged particle when traversing the boundary between materials with different dielectric constants(ε_1,ε_2).
    - **Intensity**: $I \propto \gamma = E/m$, $\vartheta \propto 1/\gamma$
- Low photon **emission probability** per transition
    - Many transitions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

$\gamma_{sat} \approx 0.6\ (\iota_1\ \iota_2)^{½}\ \omega_{p1}/c$

To identify electrons with momenta

p_T > 1 GeV/c:

choose $\iota_1\ \iota_2$ 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

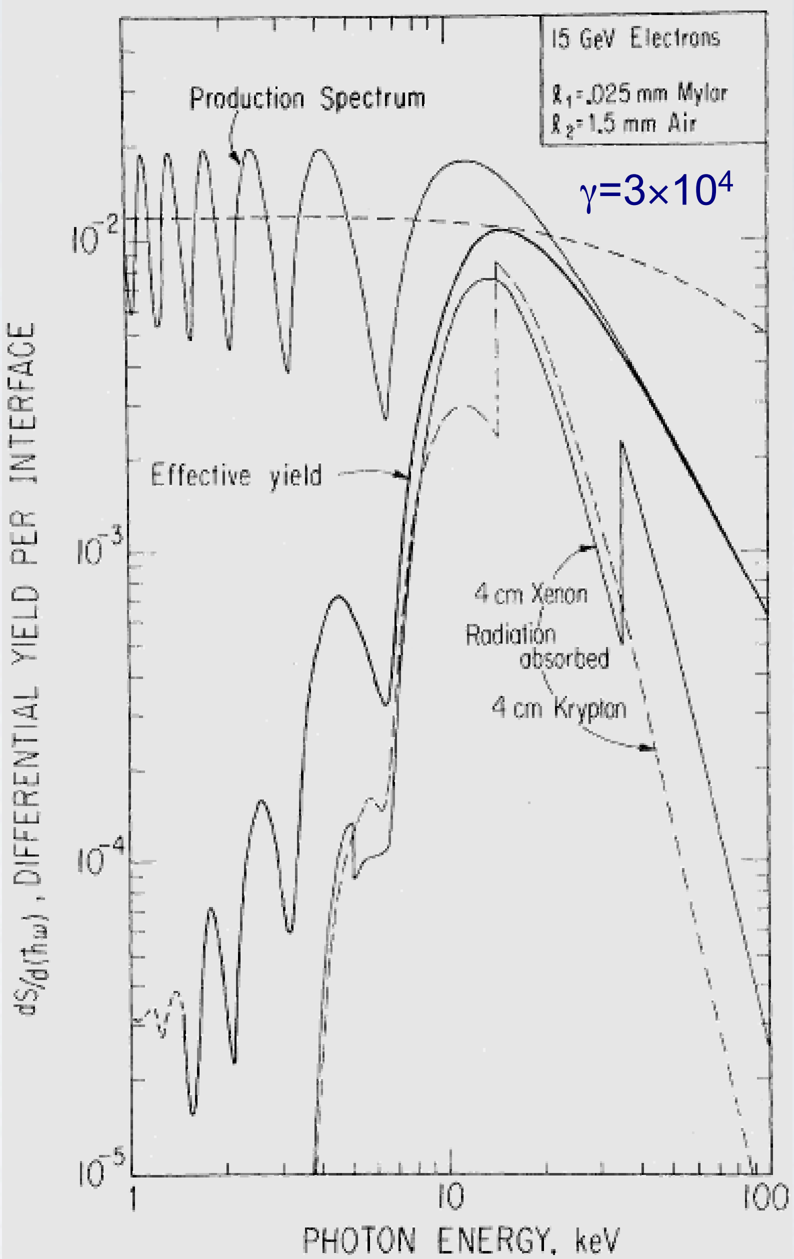
In practice, the useful radiator length is limited – to a few cm at $\gamma_{sat} = 2{\cdot}10^3$ – as a balance is reached between TR generation and absorption

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

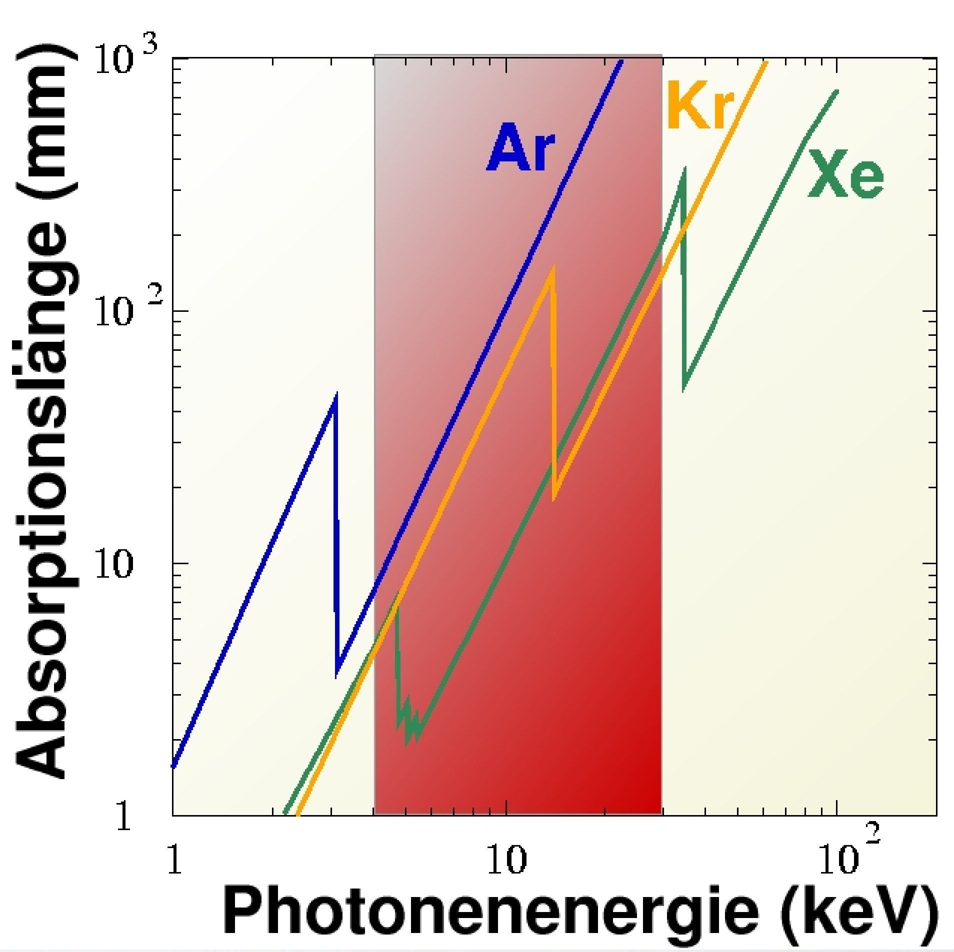
- Single interface
  - total rad. Energy ($W \propto \gamma$)
  - narrow forward cone $\propto 1/\gamma$
  - $dW/d\omega$ = const. O(a) for $\omega < \gamma\omega_{p2}$
    - ω_{p2} = plasma frequency (ω_{air} ~ 0.7 eV)
  - frequency cut-off $\omega < \gamma\omega_{p1}$
    - ω_{p1} ~ 20 – 30 eV
- Periodic 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 $z_1 = 2\gamma c/\omega_{p1} > 10\ \mu m \cdot \gamma/10^3$
      $\omega_{max} \approx l_1\omega_{p1}^2/(2\pi c)$ <u>independent of particle energy</u>!
  - 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



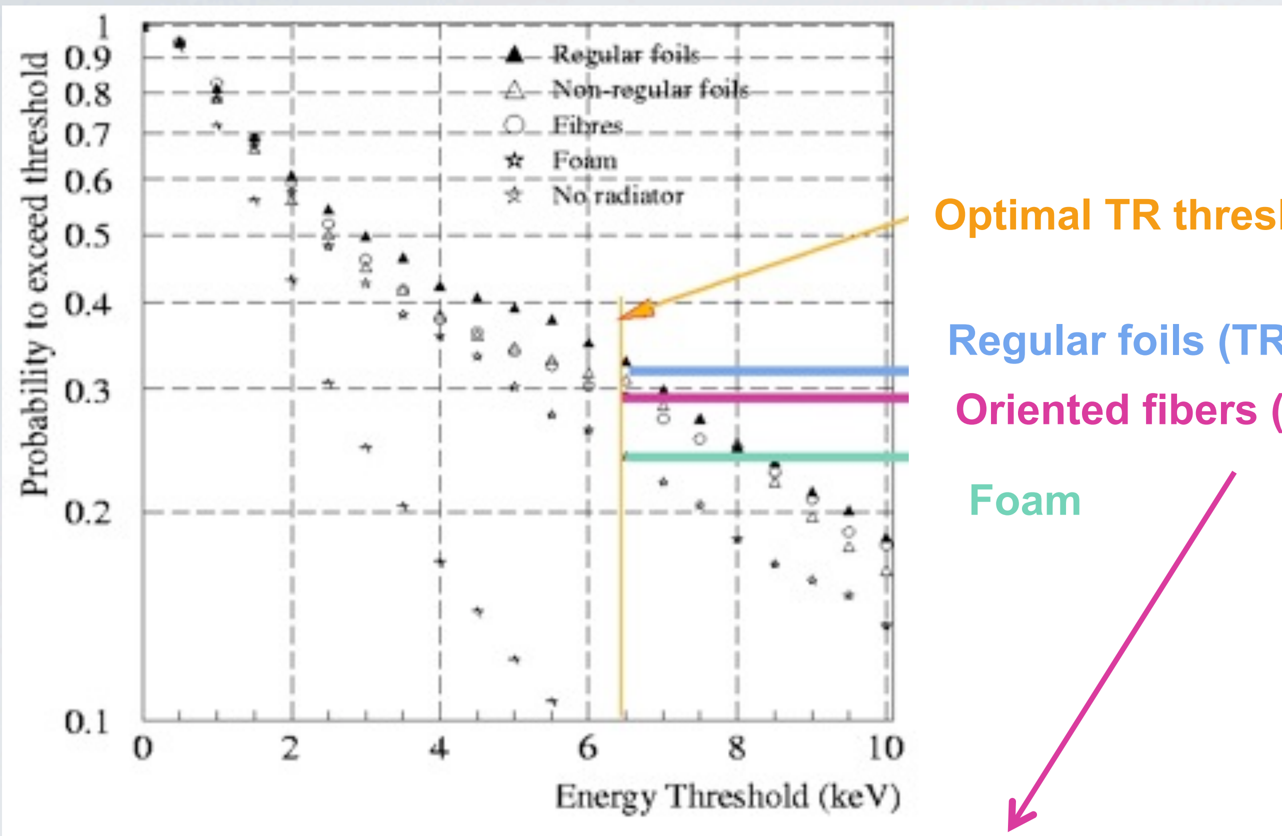
M. Cherry et al. Phys. Rev. D10, 3594 (1974)

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