The ATLAS TRT: from dream to reality

CERN/DRDC/90-38
DRDC/P8
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DETECTOR R&D PROPOSAL

INTEGRATED HIGH-RATE TRANSITION RADIATION DETECTOR AND TRACKING CHAMBER FOR THE LHC

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SUMMARY

The development of an integrated transition radiation detector (TRD) and charged-particle tracker for use in an LHC detector is proposed. The purpose of such a detector is to identify electrons efficiently, while rejecting the potentially very large background, originating mainly from overlaps between an energetic π^0 and a charged hadron and from electron pairs. A low-mass structure of radiator materials and proportional straws will generate and detect transition radiation X-rays and will track charged particles. Readout for the straw signals, and trigger processors correlating the TRD signal with external detectors, will be developed. A small prototype, sufficient to contain a high-energy jet and followed by a fine-grained calorimeter, will be tested. An engineering prototype will be constructed to verify the design for a large detector.

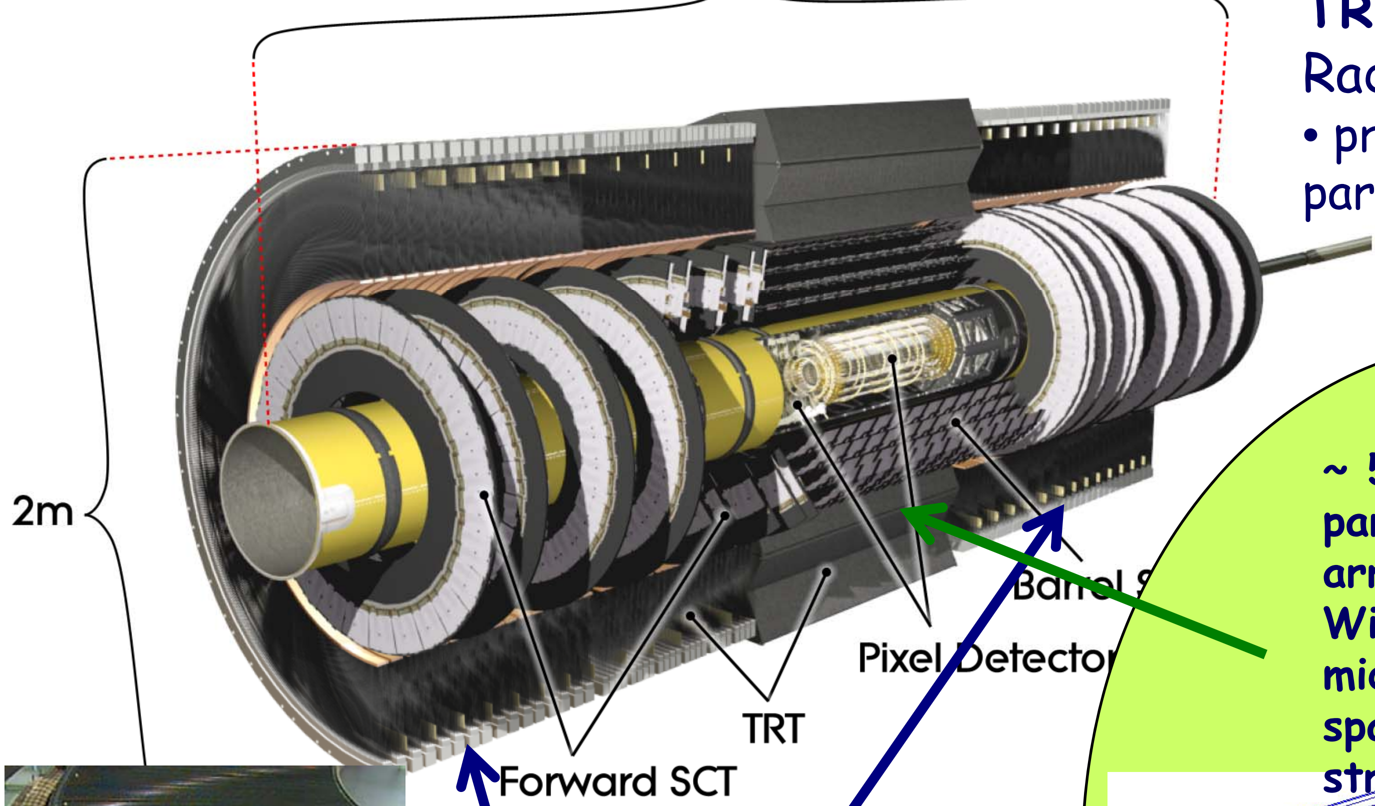
* Contact person
** Spokesperson

Turkey joined in 1998:
E. Arik, S. Cetin

Timeline to remember

1989: R&D begins (RD6 project)
1994: LHC machine approved. First full-size TRT prototype completed (10,000 channels in one end-cap wheel)
1996-1998: major TDRs for ATLAS construction approved
2000: assembly of barrel modules and end-cap wheels starts in earnest. Front-end electronics specified and vendor chosen.
2002: wire-joint crisis
2003-2004: web crisis
2000-2007: many other crises, extensive test-beam and validation work
2006: installation of barrel ID in ATLAS
2007: installation of ID end-caps in ATLAS
2008: first global cosmics with magnetic field and Xenon gas and first signals from beam

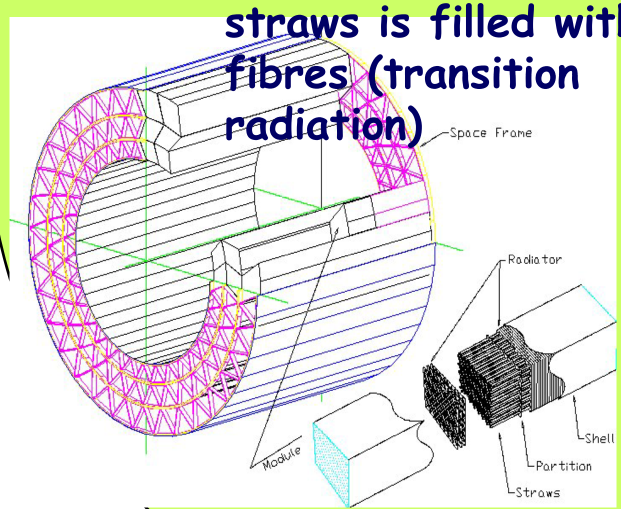
ATLAS Inner Detector



TRT = Transition Radiation Tracker

- provides tracking AND particle identification

TRT Barrel:
~ 53000 straws parallel to beam axis arranged in modules;
Wires are split in middle of the straw;
space between straws is filled with fibres (transition radiation)



TRT End-Caps:
Each ~125000 radial straws arranged in wheels;
160 straw planes along z separated by radiator foils (transition radiation)

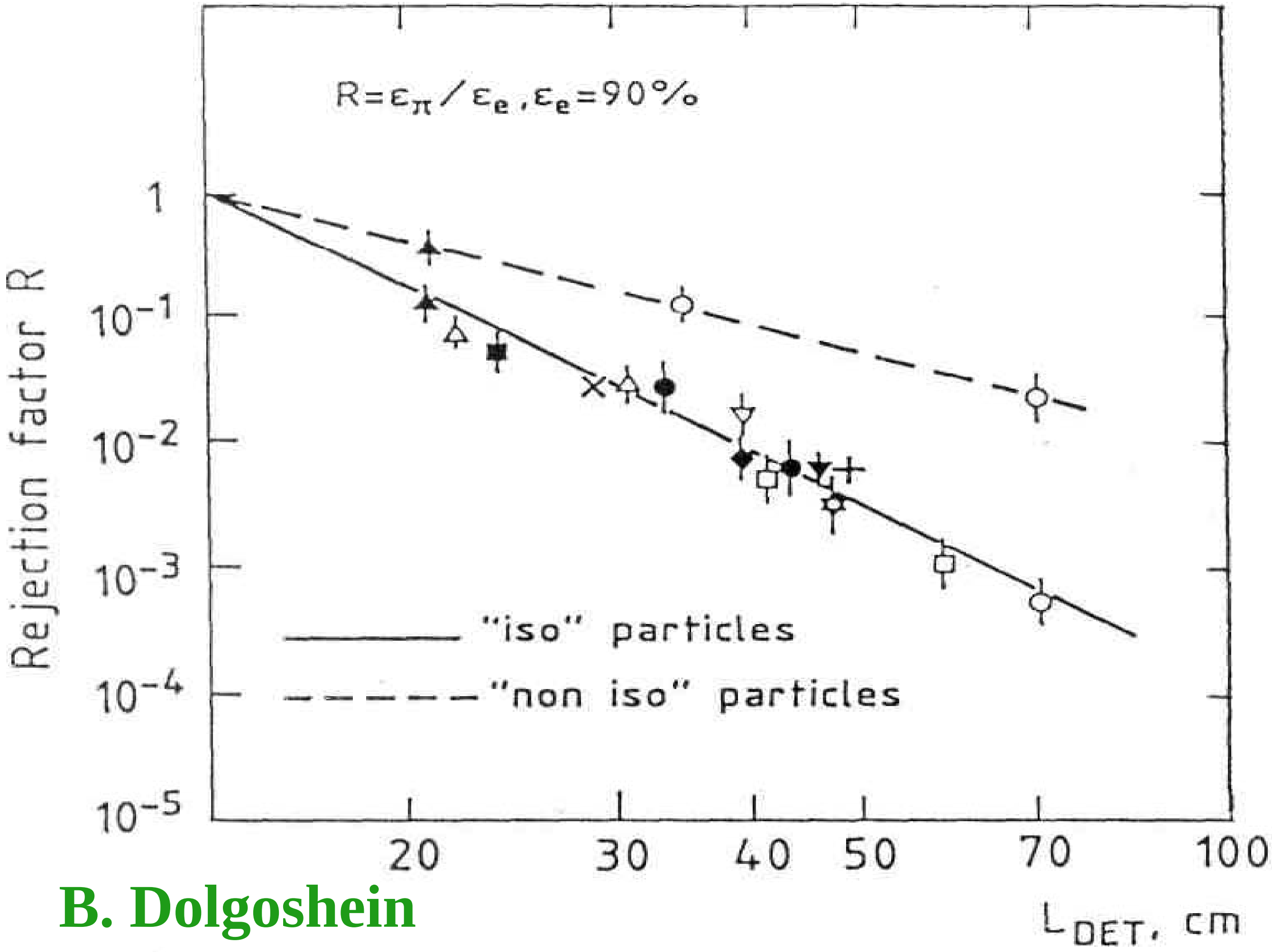
Transition Radiation: a historical perspective

- V.I.Ginzburg and I.M.Frank 1946
- G.M.Garibian : X-rays 1958

1908-1978

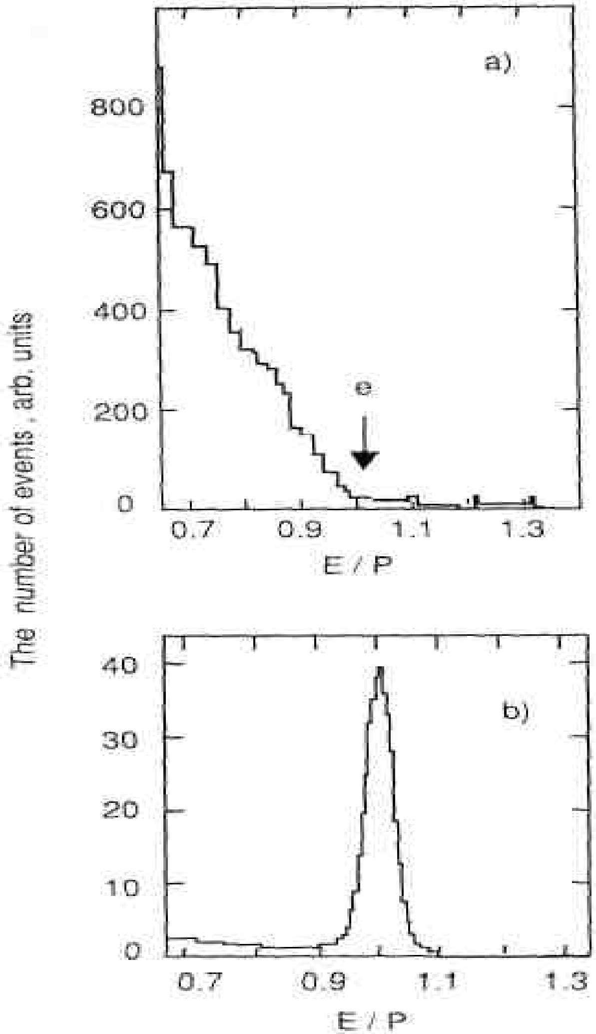
- A.I.Alikhanian and his collaborators from Armenia : first observations and investigations of transition radiation: 1961-70
  → Particle Identification

Transition Radiation: a historical perspective



B. Dolgoshein

Transition Radiation: a historical perspective



Electron efficiency 100%

Pion efficiency 100%

No TRD cuts

Electron efficiency 99.5%

Pion efficiency 0.06%

With TRD cuts

E-715 : Sigma hyperon beta decay experiment (PNPI)

Distinctive features of TRT history

- TRT collaboration has always been reasonably small in size with ~ 13 institutes and ~ 90 people working in one capacity or another together with assembly teams during period of mass construction
- TRT has had to fight hard from day 1:
  - Real estate (all-silicon/MSGC tracker was a serious option in the early days
  - Funding (13 institutes in TRT vs ~ 30 or so in SCT)
  - Engineering and infrastructure: very few member states and only CERN as a big lab
- In the following, I will attempt to give a flavour of the difficulties encountered on the long and winding road from initial naïve R&D ideas to the actual construction of a large gaseous detector with 350'000 wires

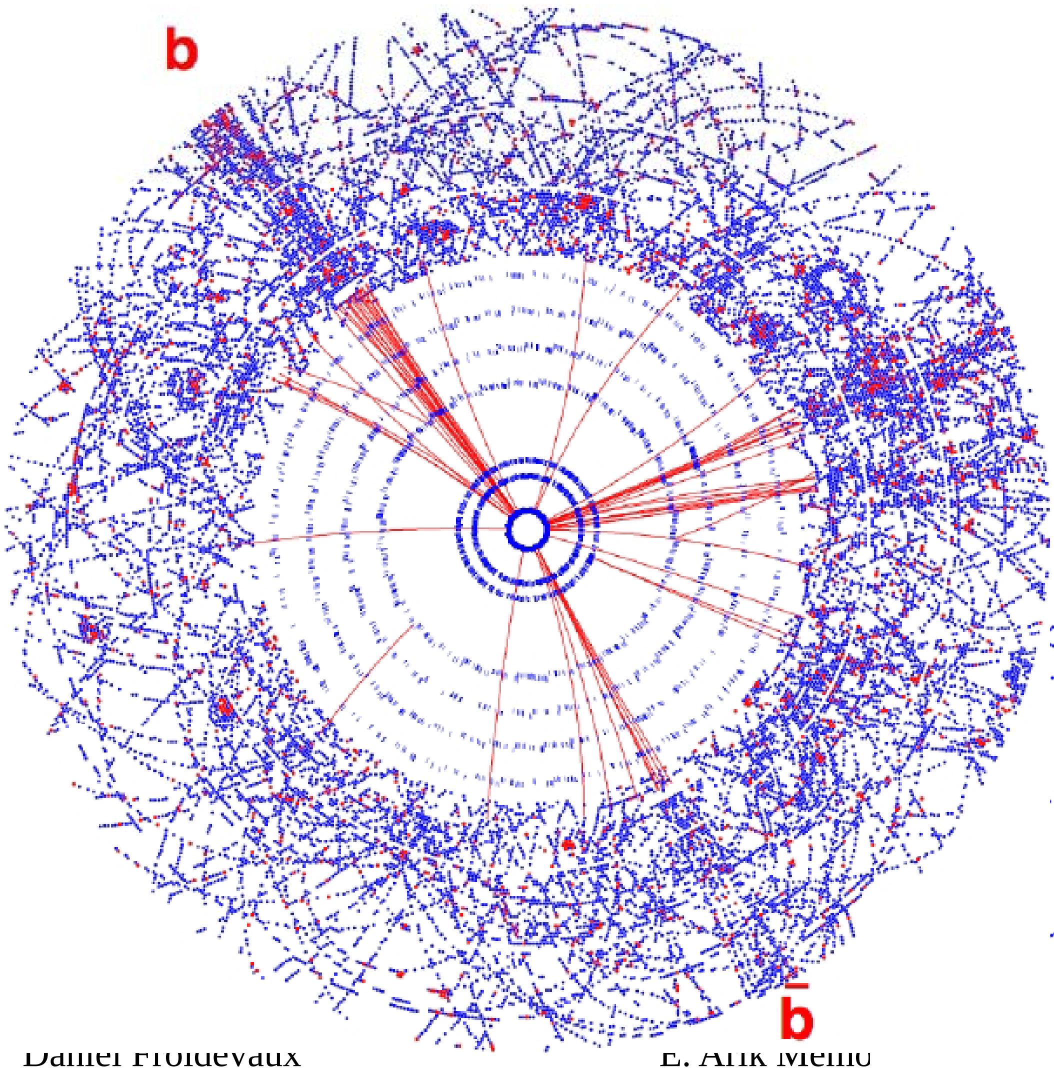
Serious conceptual design started in RD6 in early 90s

- Electrical modelling of straw response (including measurement of straw response without amplifier, leading to much better understanding of long ion tails, of behaviour different from expected $1/(t+t_0)$, etc)
- Careful study of straw behaviour at high repetition rate (up to 20 MHz for the innermost long barrel straws with significant contributions from photons/neutrons)
- Occupancy calculations, time and time again!
  - Occ = $1 - e^{-<n>}$ with <n> defined as rate at which straw crossed by particles
  - Need to define over which time interval: 75 ns, 25 ns, 12 ns or 10 ns (going from crude calculation for readout to refined calculation for drift-time measurements)
  - Average occ of e.g. 20% leads to $0.2^{35} \sim 10^{-25}$, less than overall silicon prob.

Serious conceptual design started in RD6 in early 90s

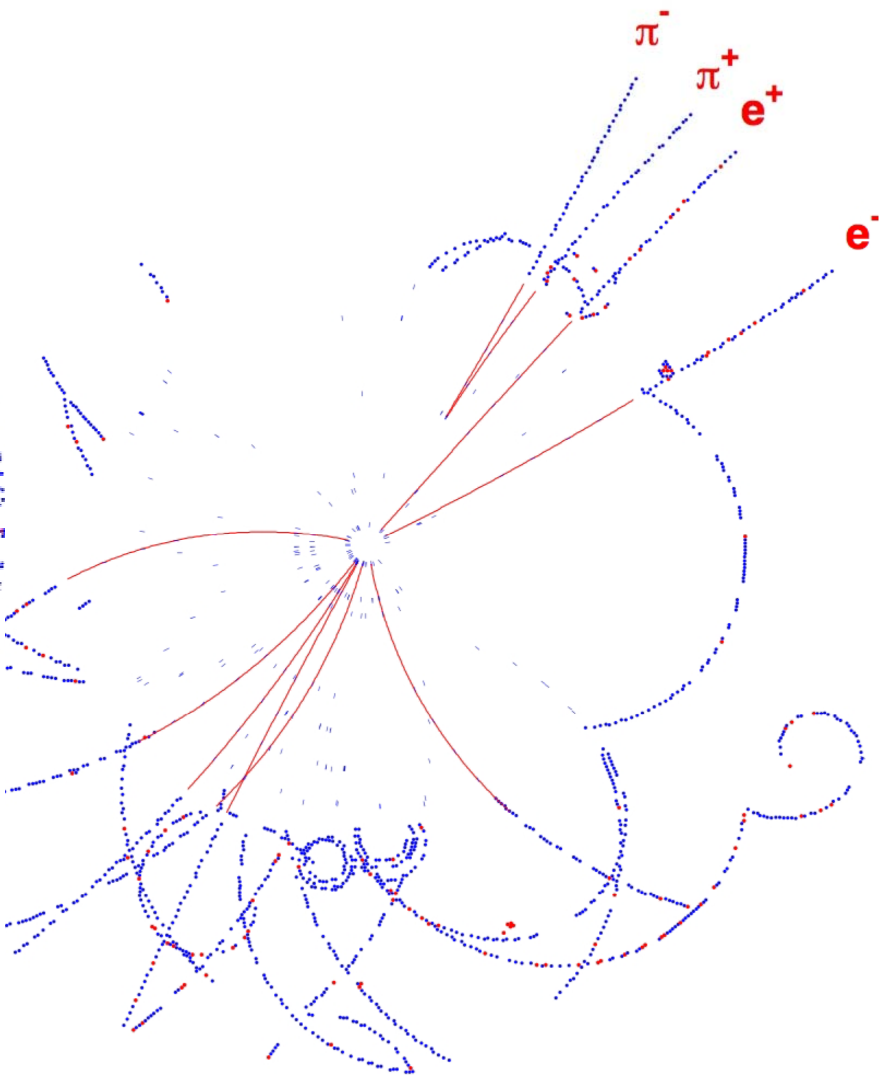
ATLAS Barrel Inner Detector

$H \rightarrow b\bar{b}$



ATLAS Barrel Inner Detector

$B_d^o \rightarrow J/\psi\, K_s^o$



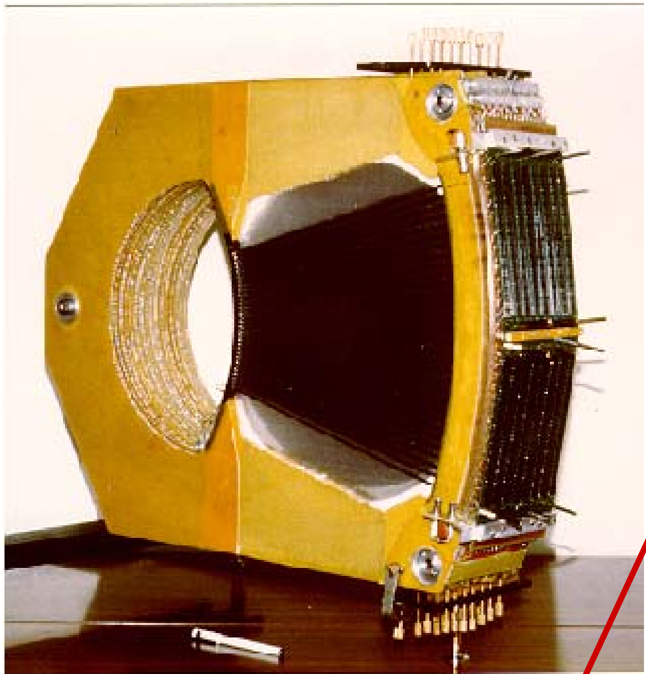
Serious conceptual design started in RD6 in early 90s

- **Occupancy calculations, time and time again!**
  - **But large correlations from straw to straw (low-energy loopers from photon conversions, etc), so need to study realistically fake rates vers R_{min} and R_{max} of TRT**
  - **Thanks in particular to I. Gavrilenko and P. Nevski, TRT survived real estate battle reasonably well and got $\Delta R \sim$ 40-50 cm, which is what is required for a performant detector at the LHC**
  - **One often hears: previous TRD detectors have not worked, especially at hadron colliders. This is simply not true: they have worked for what they were meant for but they were not useful for physics because MC studies were not done to predict the real backgrounds to be faced.**
  - **ATLAS TRT is a greatly improved TRD + tracking concept and has no such excuses with 20 years of detailed simulation behind it**
  - **TRT will provide L2 robustness and also pattern recognition and momentum measurements. In addition, it will help us identify electrons in an environment worse by ~ factor 100 than Tevatron**

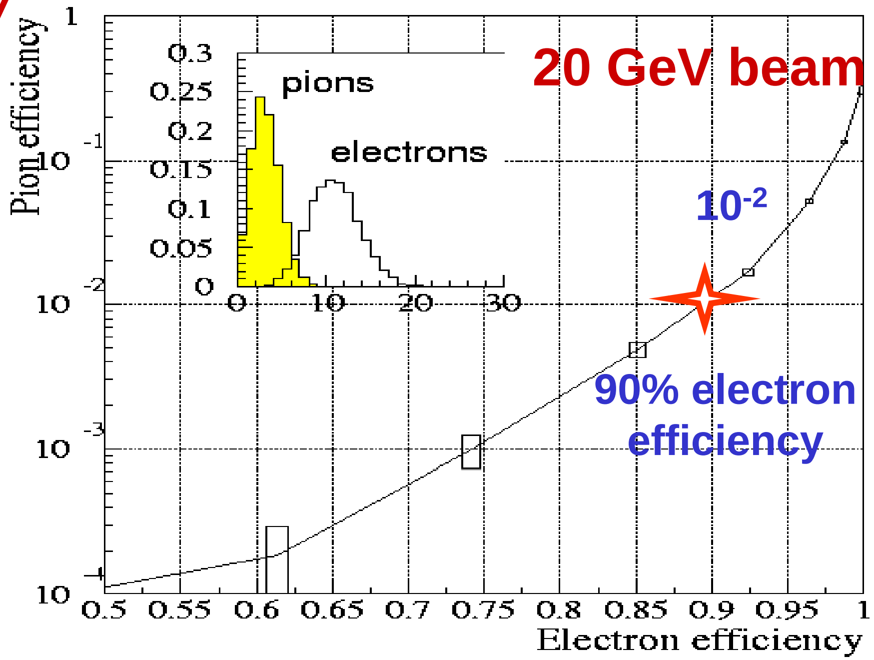
The ATLAS Transition Radiation Tracker: the challenge

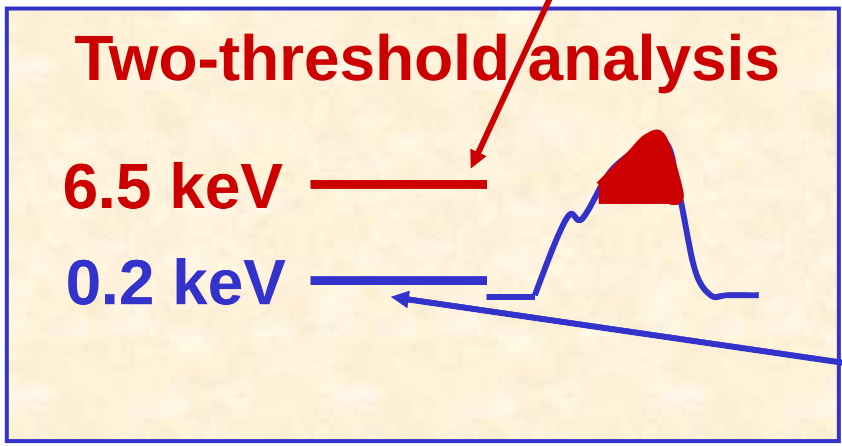
- **Very high occupancy:** up to 40%
- **Very high counting rate:** up to 20 MHz/straw
- **Short bunch crossing interval:** 25 ns
- **High TR efficiency:** Rejection e/h ~100
  →Xe gas circulation, TR radiator choice
- **High spatial resolution, good pattern recognition**
- **Radiation environment:** ~ 10 MRad
  ~ 10^{14} n/cm^2 year
- **Fast and chemically passive straw gas:** Ageing!
- **Chemically resistant straw materials:**
  operating straw works as an electro-chemical reactor
- **Minimal amount of material (in radiation lengths)**
- **Extremely precise and robust mechanical structure:**
  ~ 100 μm/few m ~10^{-5}
- **Temperature stability:** straw cooling

The ATLAS TRT: test-beam prototypes

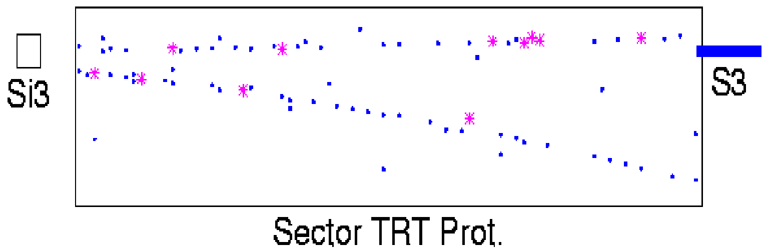


Particle identification





γ-conversion outside TRT



Tracking

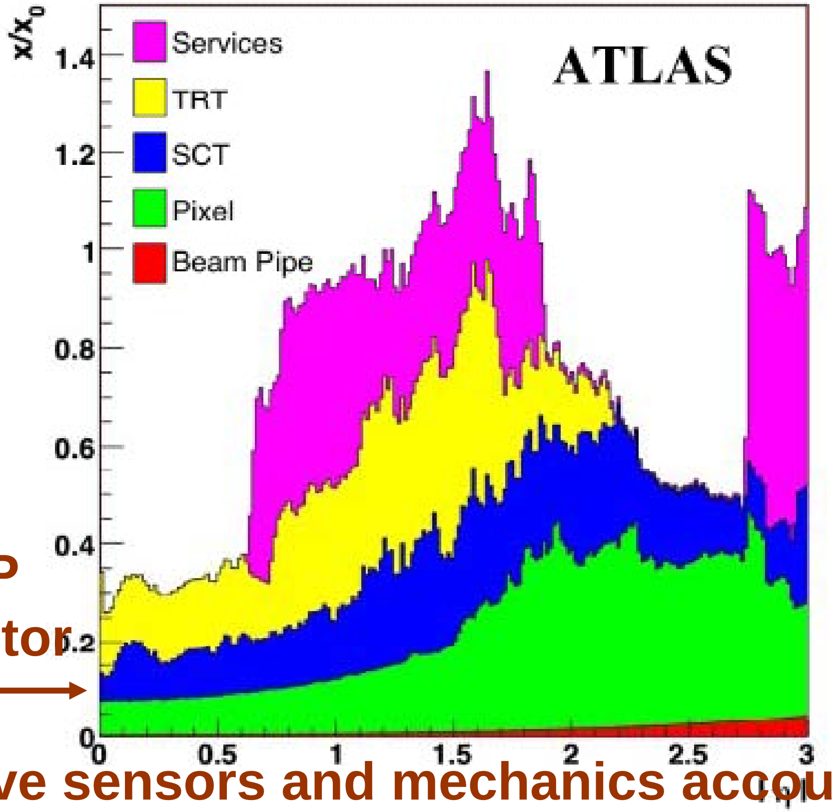
Lessons from construction

- **Usual lessons (?)**
  - Move from R&D to production is difficult for physicists and even for engineers (it took perhaps seven years to specify radial envelope for TRT end-cap electronics!)
  - Money, money, … US is special, Russia is so special, ATLAS CORE units were about as understandable as Russian "uslovnye edinitsy". Had to deal with "Buchhalter" in Russia (fearsome people), Soros and ISTC (Moscow centralism), ATLAS agreement ping-pong games (Schmid-Nordberg vs Khovansky-Zaitsev), and "amateur management" (Daniel, Philippe and a few others declared over a few coffees in 1994 that TRT cost would be about 13 MCHF based on 10 line items)
  - People management
  - Test-beam validation (culmination in 2004 with CTB, still not published!)
- **Huge size and complexity of ATLAS**
  - Material budget
  - Radiation issues and ageing (first of wires and straws, then of people) …

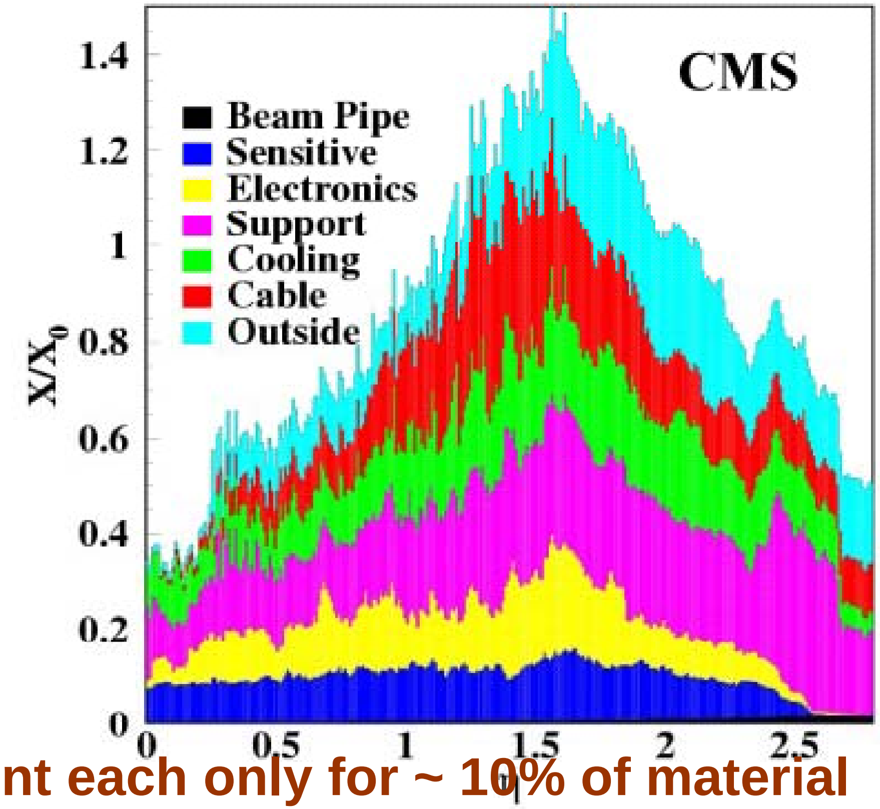
ATLAS/CMS: from design to reality

Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons



Weight: 3.7 tons



LEP detectors →

- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

ATLAS/CMS: from design to reality

TABLE 5 Evolution of the amount of material expected in the ATLAS and CMS trackers from 1994 to 2006

Date	ATLAS $\eta \approx 0$	$\eta \approx 1.7$	CMS $\eta \approx 0$	$\eta \approx 1.7$
1994 (Technical Proposals)	0.20	0.70	0.15	0.60
1997 (Technical Design Reports)	0.25	1.50	0.25	0.85
2006 (End of construction)	0.35	1.35	0.35	1.50

The numbers are given in fractions of radiation lengths (X/X_0). Note that for ATLAS, the reduction in material from 1997 to 2006 at $\eta \approx 1.7$ is due to the rerouting of pixel services from an integrated barrel tracker layout with pixel services along the barrel LAr cryostat, to an independent pixel layout with pixel services routed at much lower radius and entering a patch panel outside the acceptance of the tracker (this material appears now at $\eta \approx 3$). Note also that the numbers for CMS represent almost all the material seen by particles before entering the active part of the crystal calorimeter, whereas they do not for ATLAS, in which particles see in addition the barrel LAr cryostat and the solenoid coil (amounting to approximately $2X_0$ at $\eta = 0$), or the end-cap LAr cryostat at the larger rapidities.

constr.)

- Electrons lose between 25% and 70% of their energy before reaching EM calo
- Between 20% and 65% of photons convert into e^+e^- pair before EM calo
- Need to know material to ~ 1% X_0 for precision measurement of m_W (< 10 MeV)!

Impact of CF_4: operation under irradiation

TRT survival target: reach 10 C/cm of wire

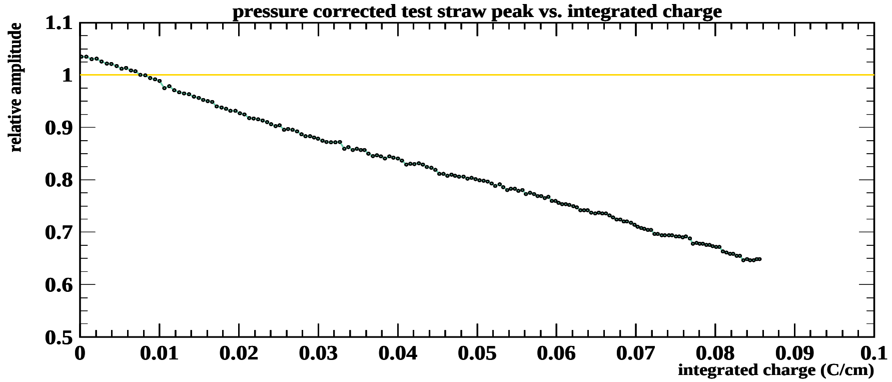
But beware and don't forget:
at high radiation, CF_4 comes with:
F-based active species (HF,F,F_2)

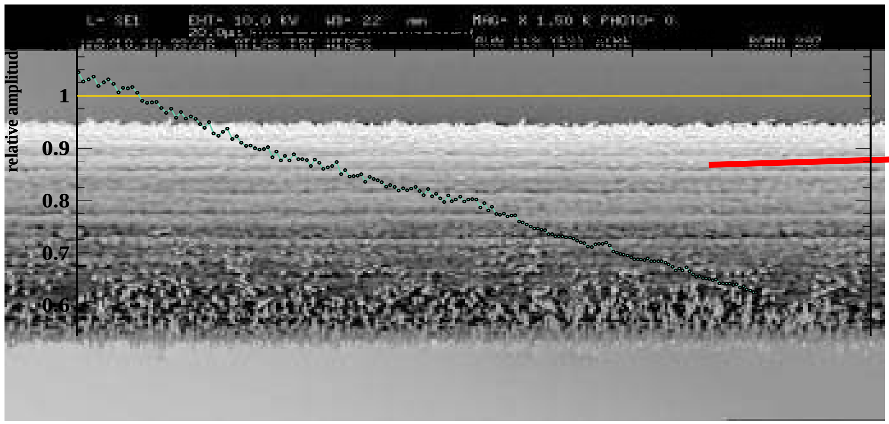
- *Attack of Si-based materials*
- *Si-transfer in the system*
- *Glass wire-joint problem*

Silicon problem under irradiation and HV: nightmare for gas detector comes true!

First observation of Si -polymerisation in the straws

Run 118 - Test Peak Position vs. Integrated Charge

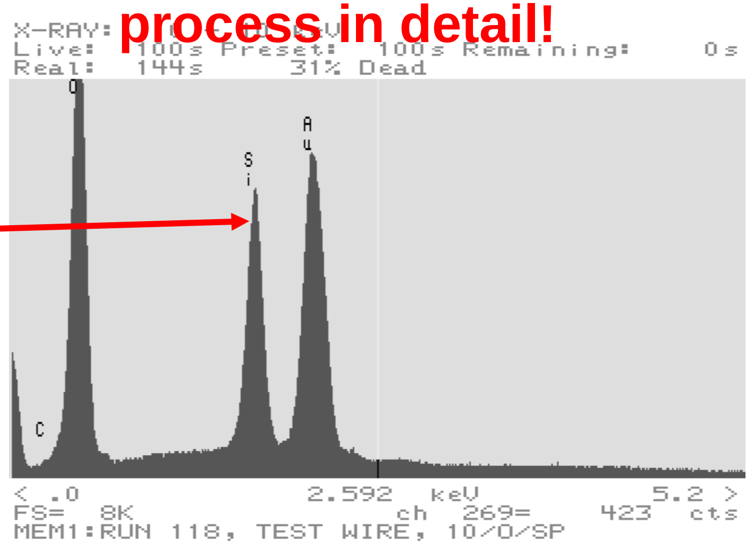




Details

- **Current 0.1 μA/cm**
- **Straw contained traces of Si-based lubricant used by straw producer (not intentionally!)**
- **Amplitude drop is very fast ~10% in one day!**

Control manufacturing process in detail!

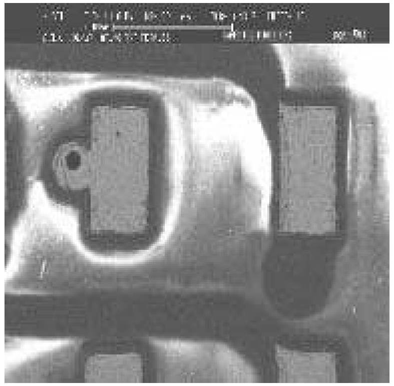


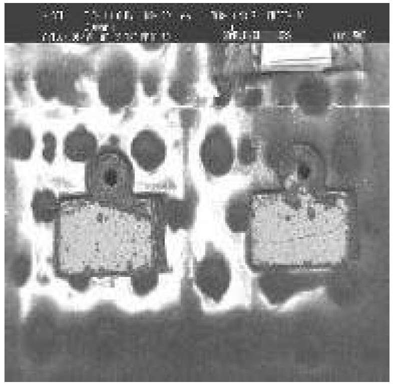
Silicon problem under irradiation and HV: nightmares can be even worse! Silicon migrates!

After 5 years of LHC operation

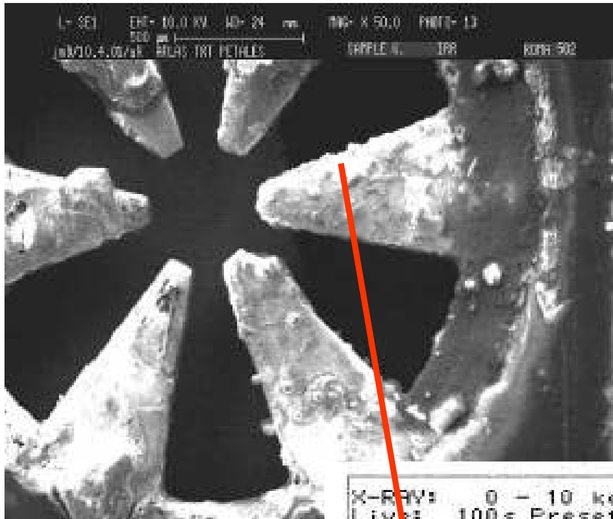
Etching of coverlay on PCB

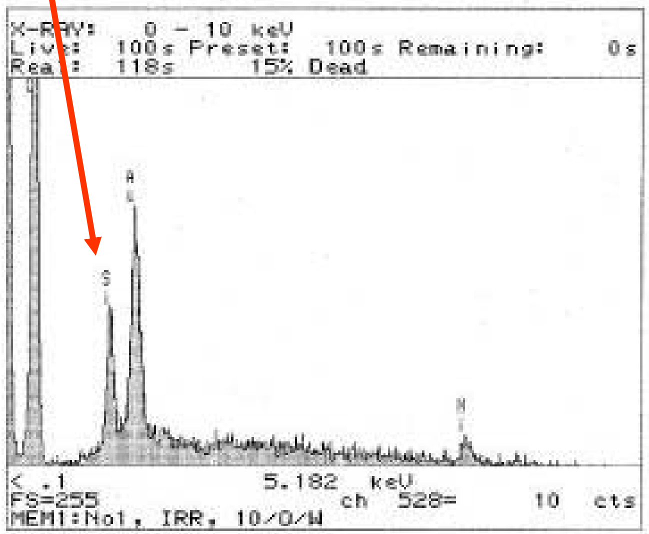
Before exposure | **After exposure**





Destruction of petals in Webs



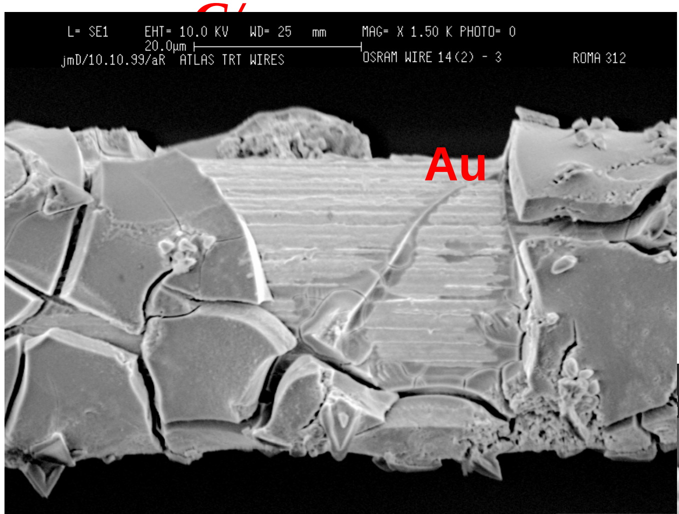


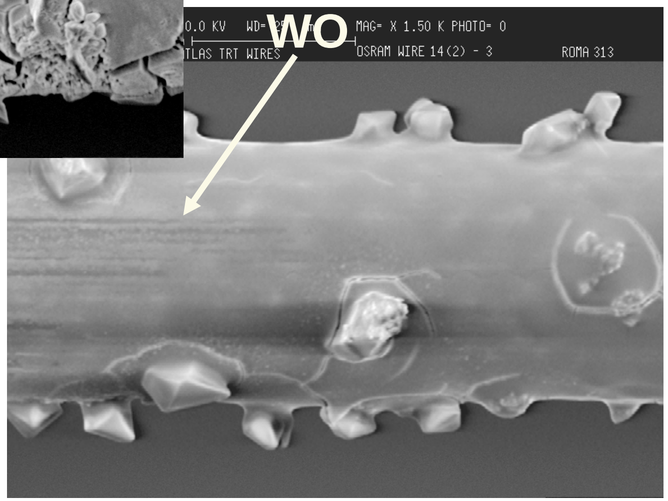
Impact of CF_4: gold damage under high humidity

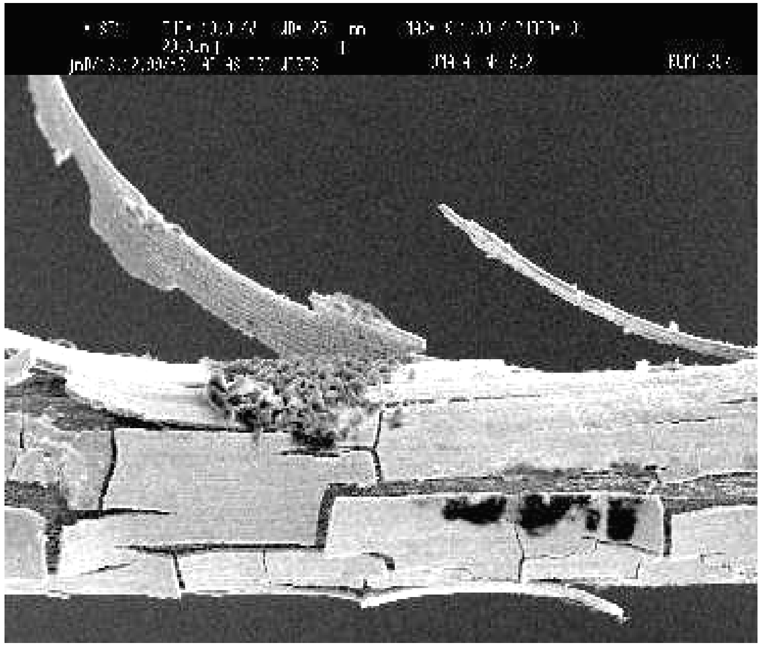
Any wire can be destroyed completely: some faster than others

- **OSRAM wire, 3 % Au**
- **Standard mixture +1.2% H_20 and 1.5% O_2 Total dose: *0.5 C/***

- **Luma wire, 5 % Au,**
- **Ni-substrate**
- **Standard mixture +1.2% H_20 and 1.5% O_2 *Total dose: ~3 C/cm***

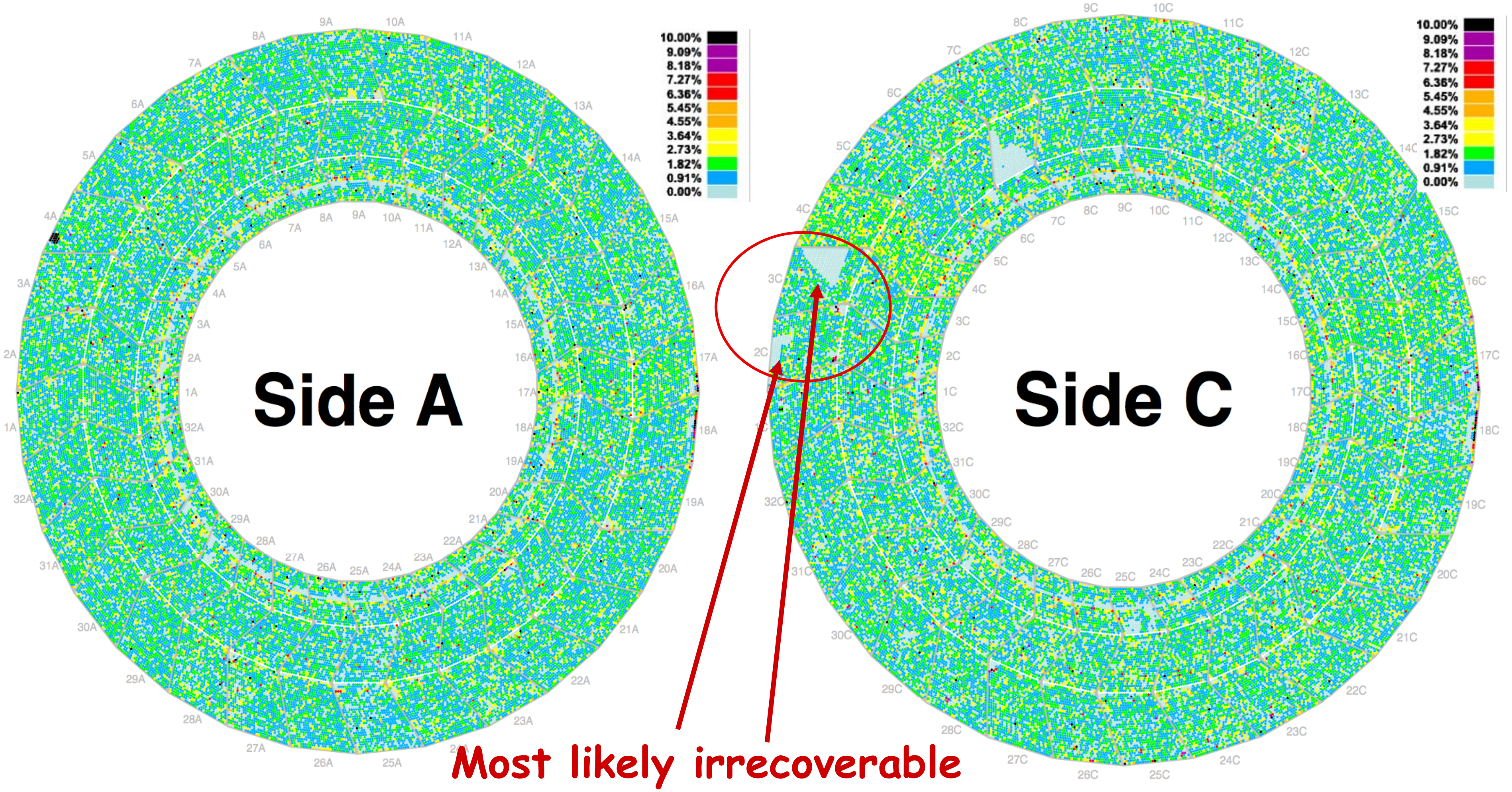






Presence of molecular oxygen makes processes more complicated!

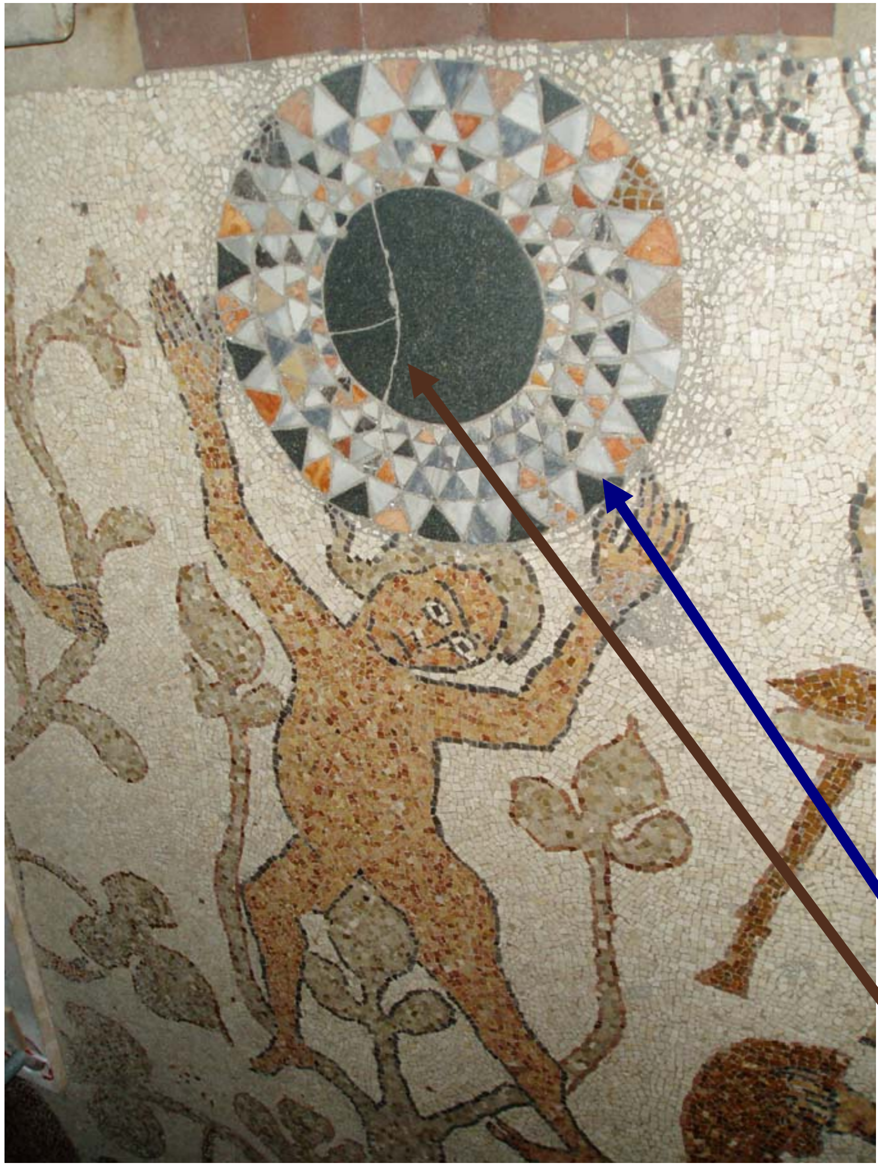
Results from most recent operation of TRT (global cosmics with all magnets on)



Barrel and end-cap TRT now fully operational with Xenon gas (2% of channels dead and irrecoverable)

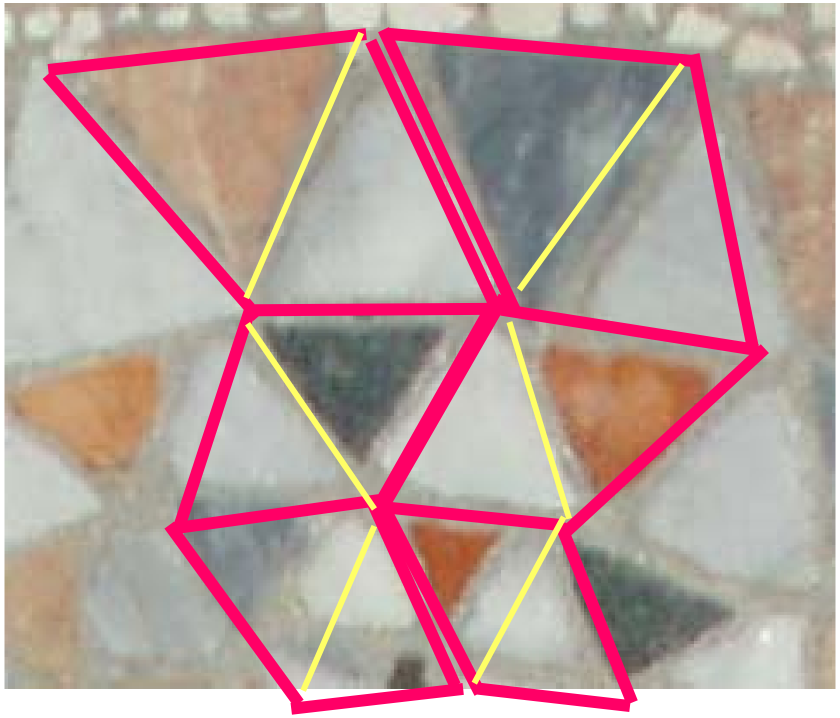
TRT Design & Simulation of Cosmics: work started Centuries ago*…

*discovered by A.Romaniouk



ATLAS
12th centaury mosaic.
Otranto cathedral, Italy

Overlay of classical/modern design

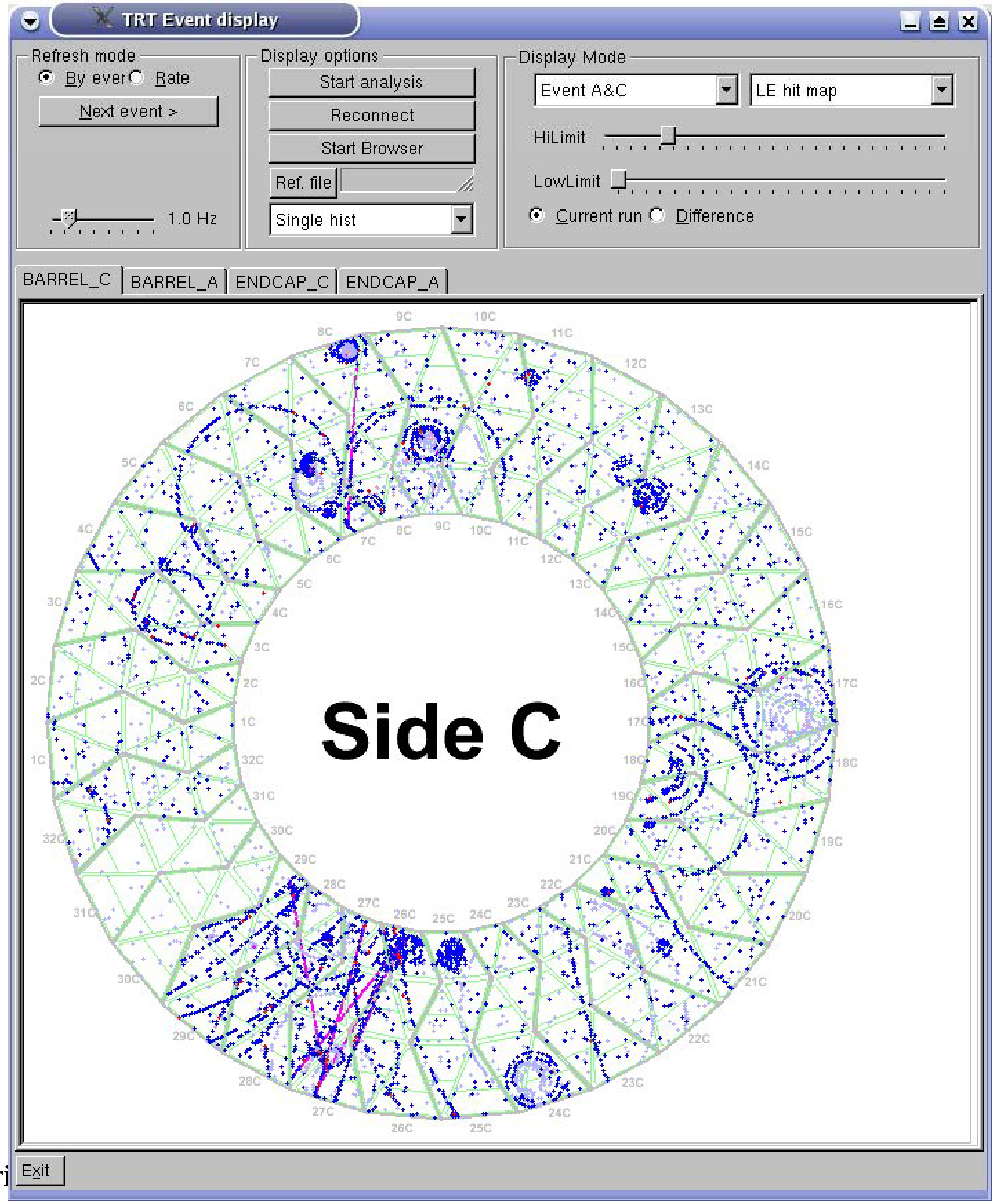


"Original" classical design: 4 layers

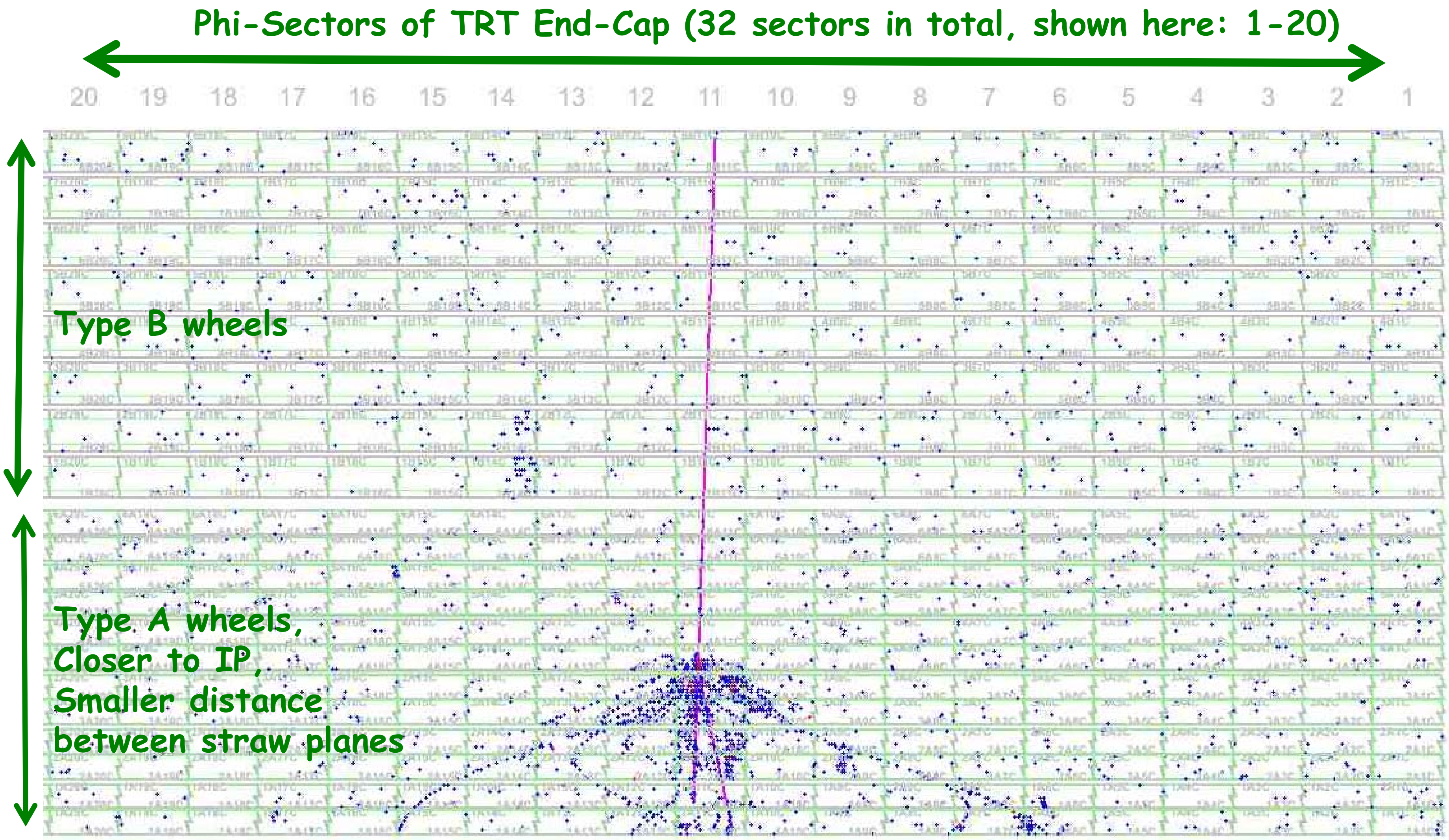
Simulation of a cosmic particle?

A TRT Event (23.8.08)

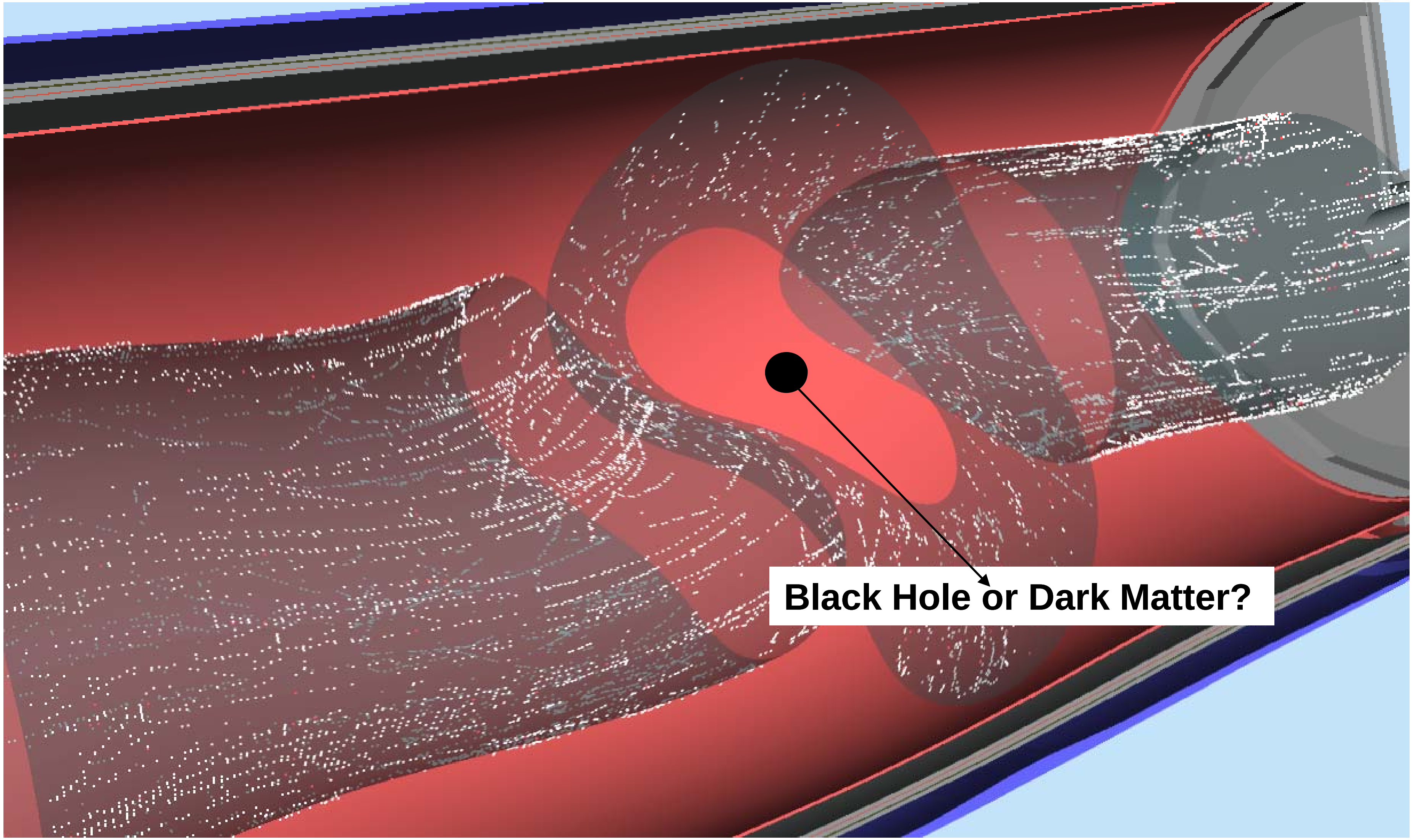
- With ATLAS Solenoid on: TRT is working as expected
  - Example: cosmic particles seen with the TRT Barrel
  - Events remind of bubble-chamber photos…



An Event (23.8.08) in TRT End-Cap C

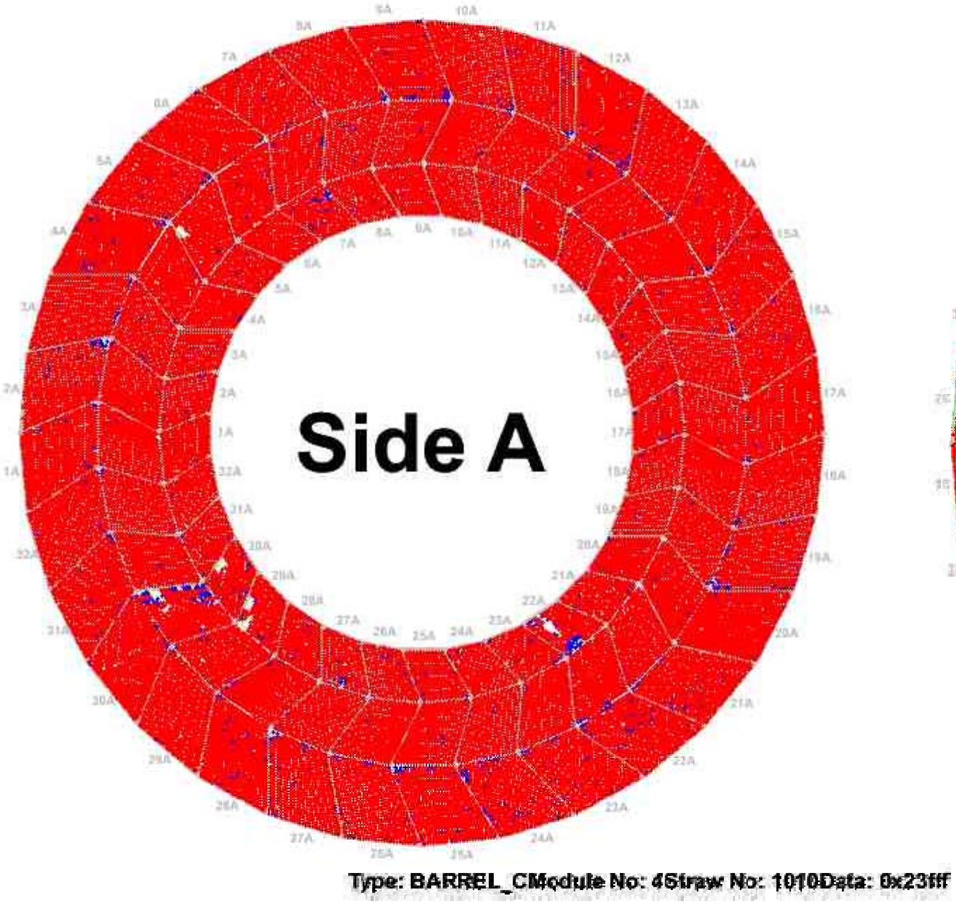


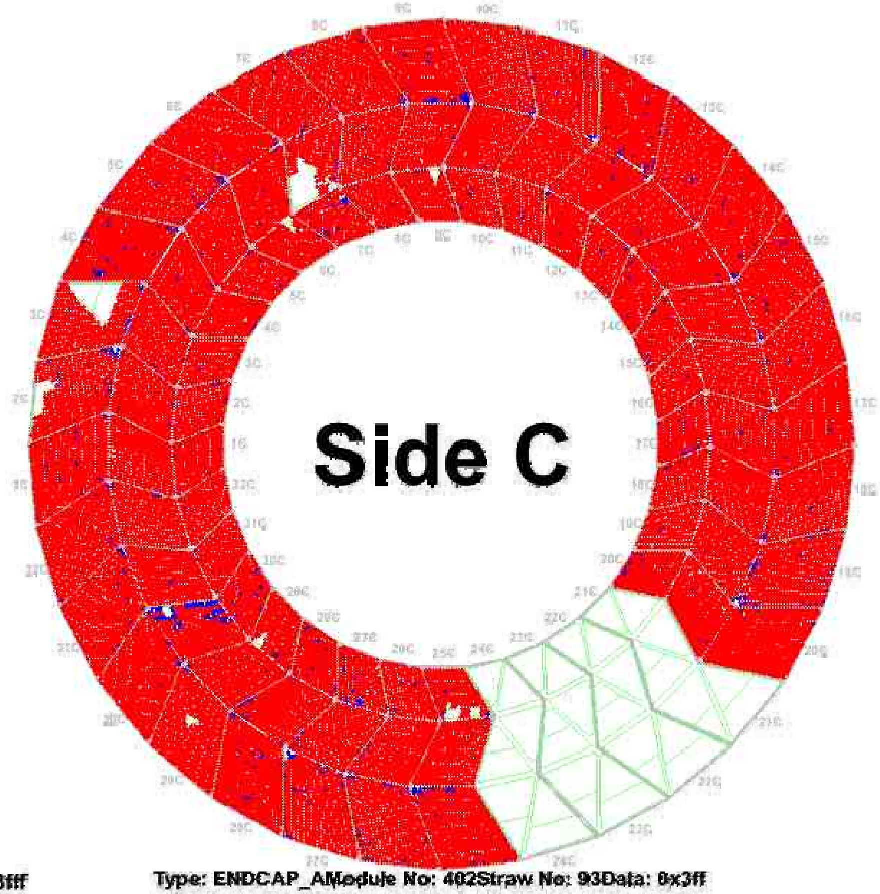
TRT Beam Halo Event



TRT Beam Splash Event #4

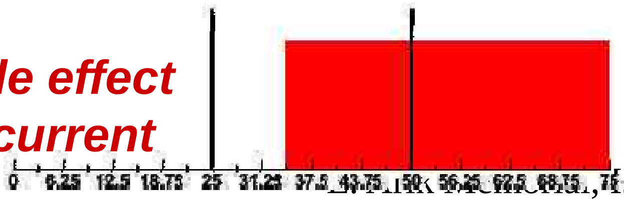
Barrel side A | **Barrel side C**

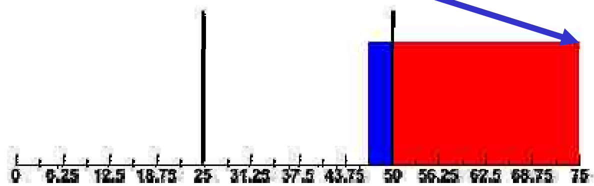




Signals from the straw
Red colour means HL Threshold fired.

Each straw signal has a trailing edge at 75ns

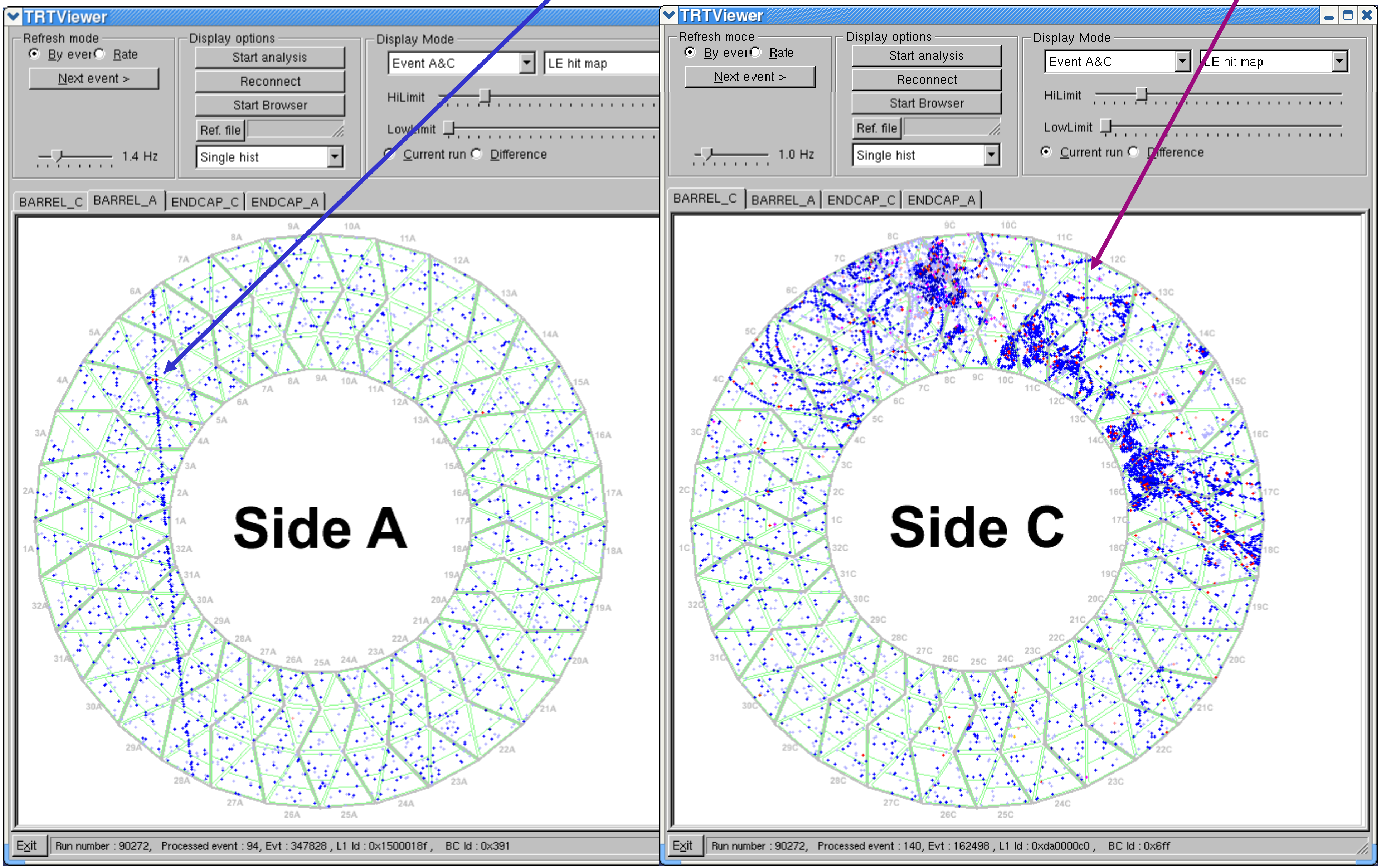




No noticeable effect on the HV current

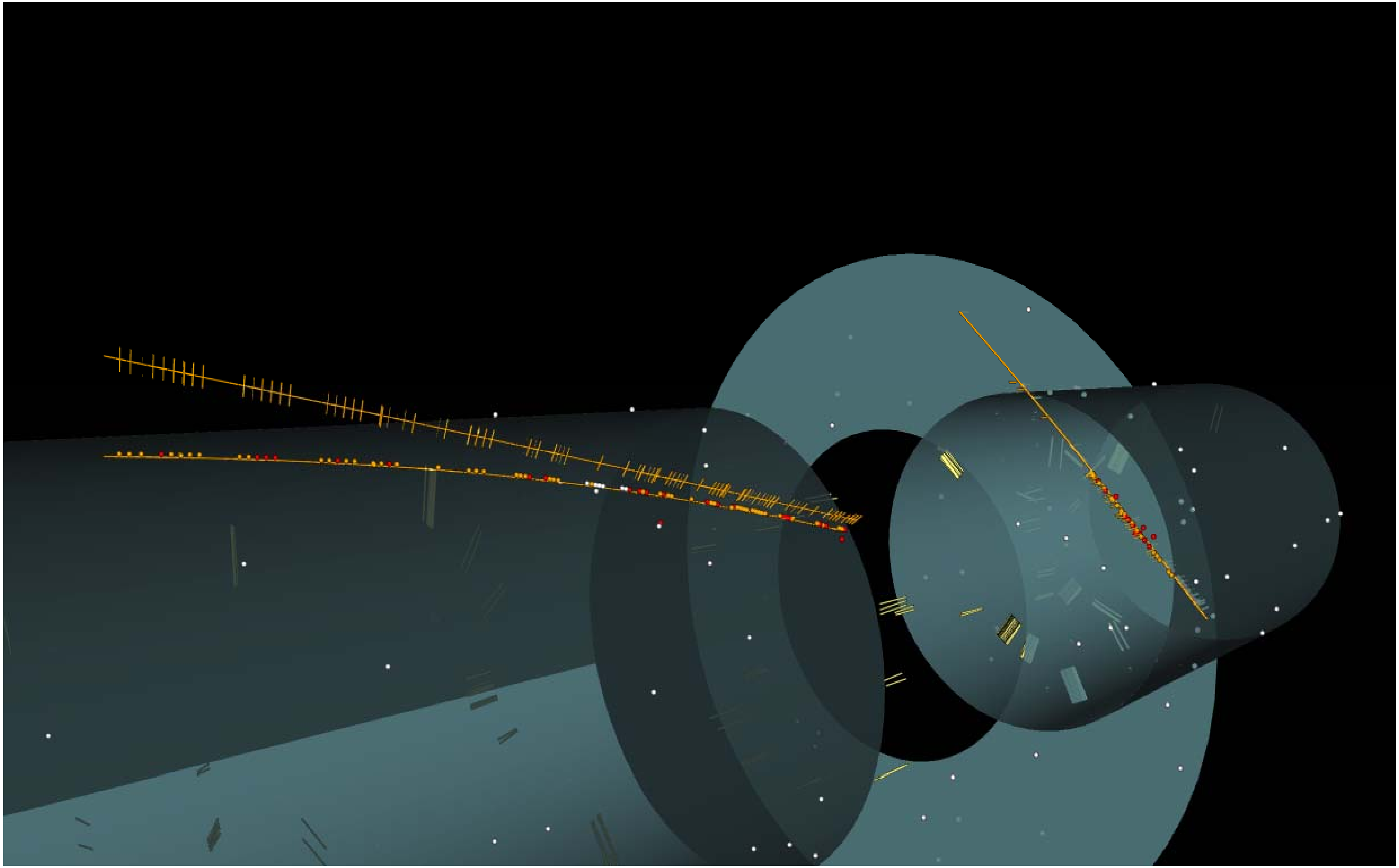
TRT Cosmics with B-field and Xenon gas

Many TRT hits: pT = 10.1 GeV, 139 TRT hits… but even cosmics can be messy!



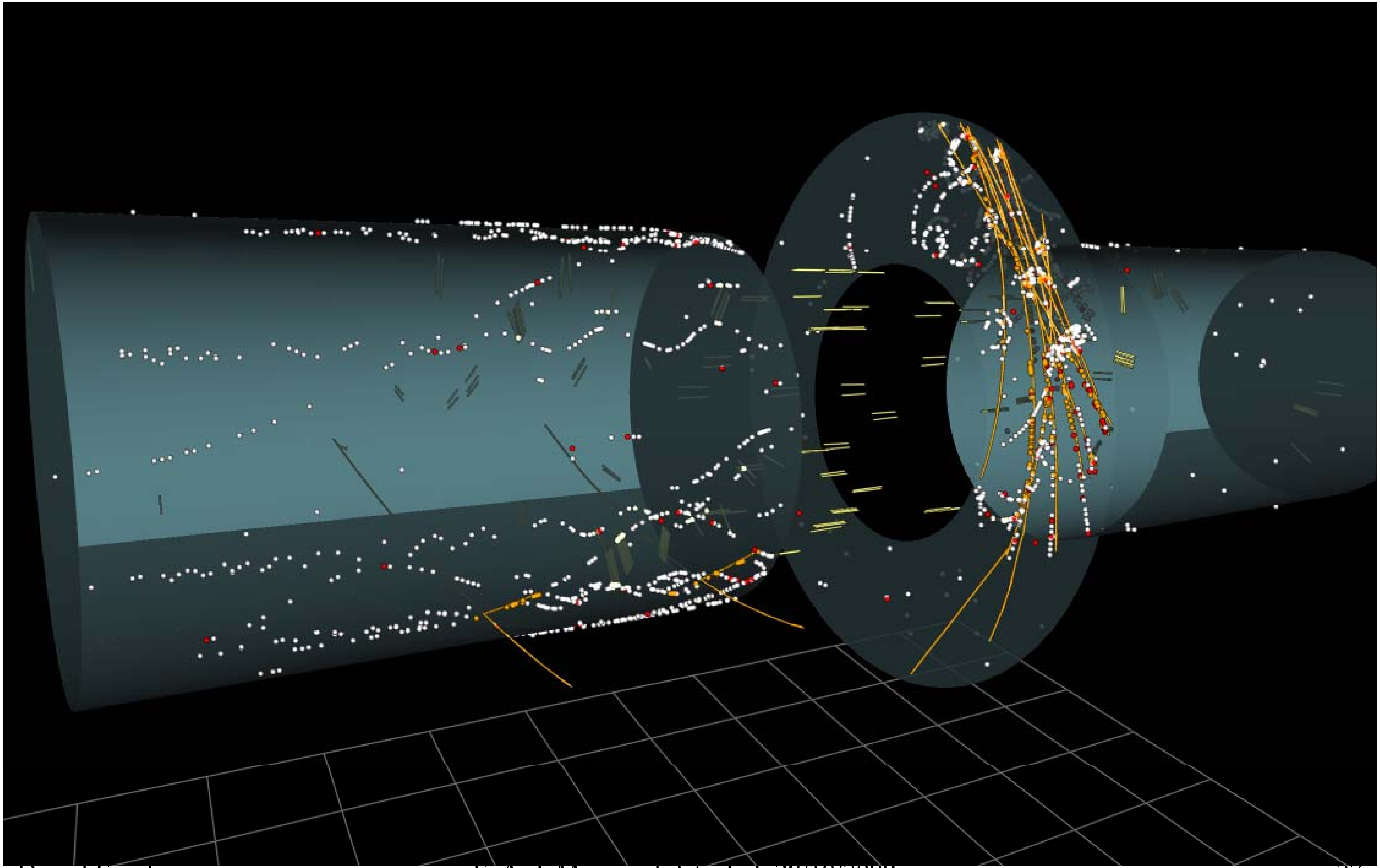
TRT Cosmics with B-field and Xenon gas

Cosmic track traversing both TRT end-caps



TRT Cosmics with B-field and Xenon gas

Cosmic shower in barrel TRT, loopers in one end-cap TRT

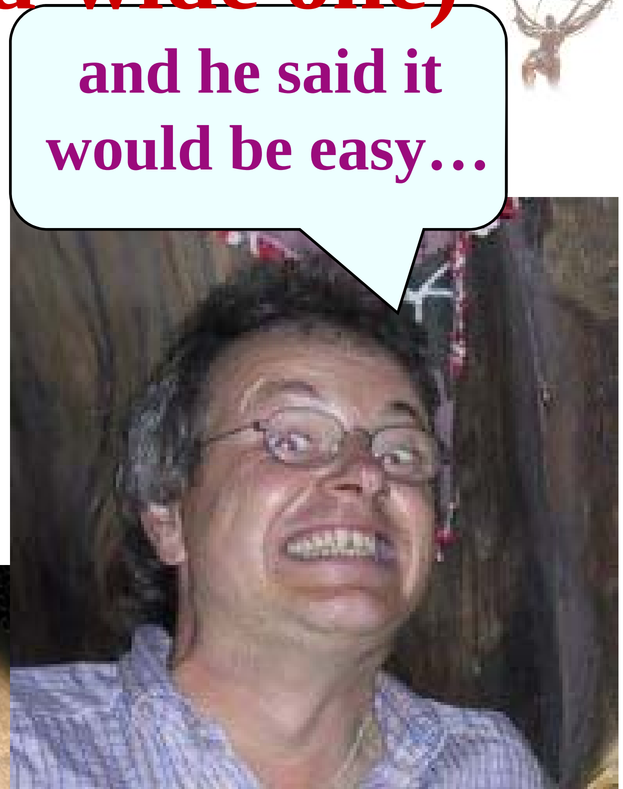


Decadence usually comes from top-down

Istanbul, May 2001

And eventually reaches all levels

T d-wide one)



Let us n
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1. Less
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2. High
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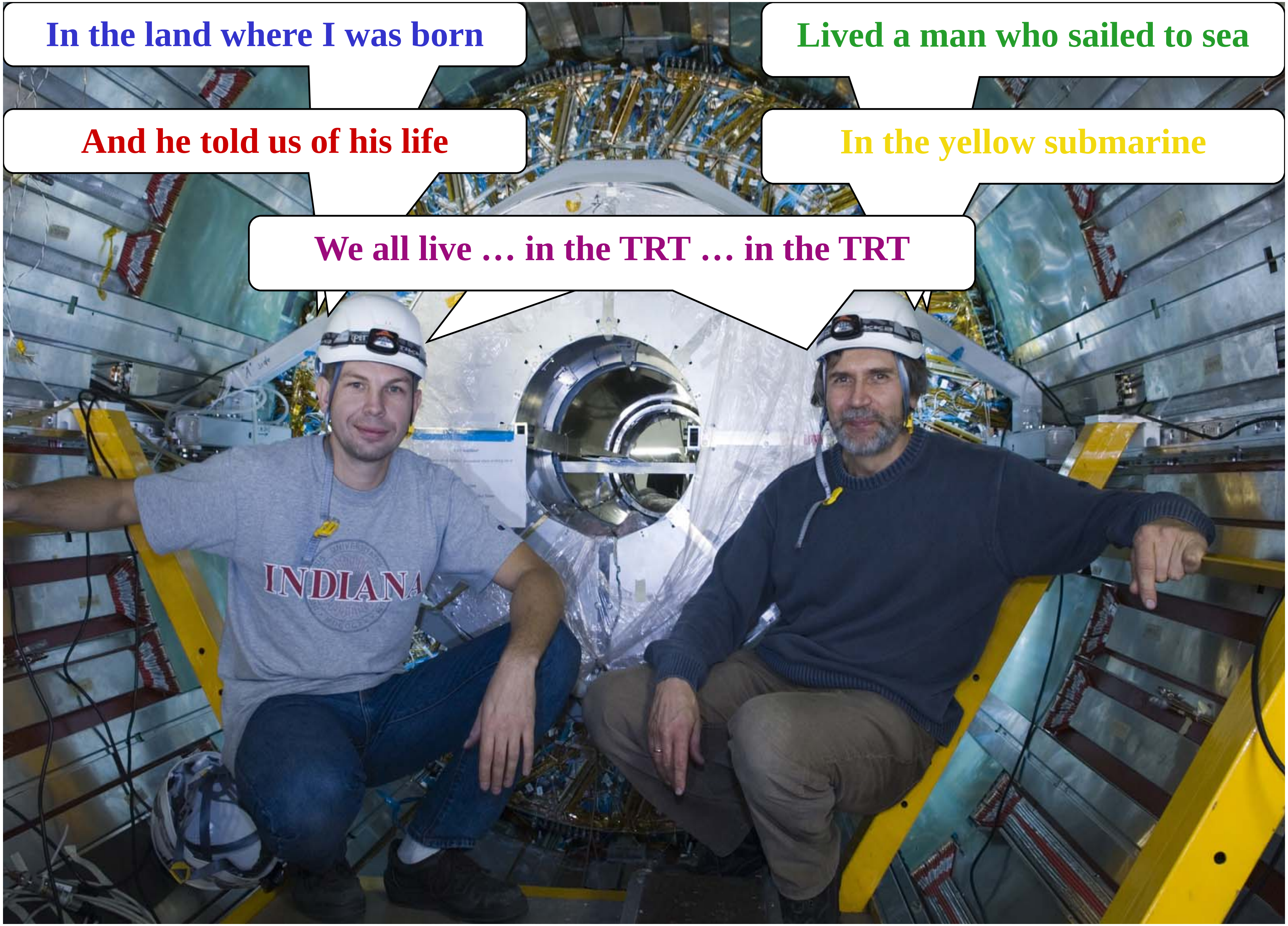
follo


In the land where I was born
Lived a man who sailed to sea
And he told us of his life
In the yellow submarine
We all live … in the TRT … in the TRT
INDIANA