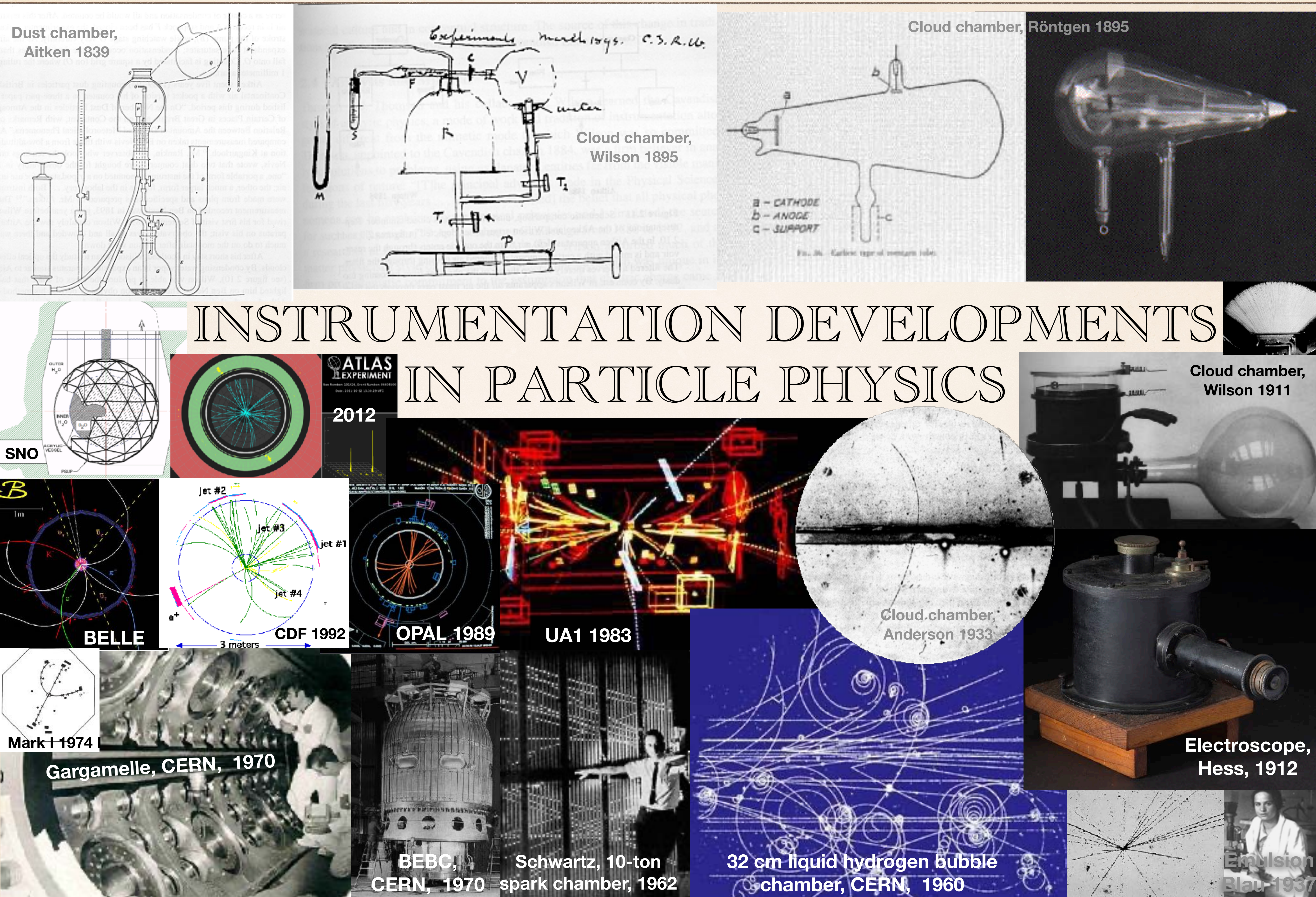
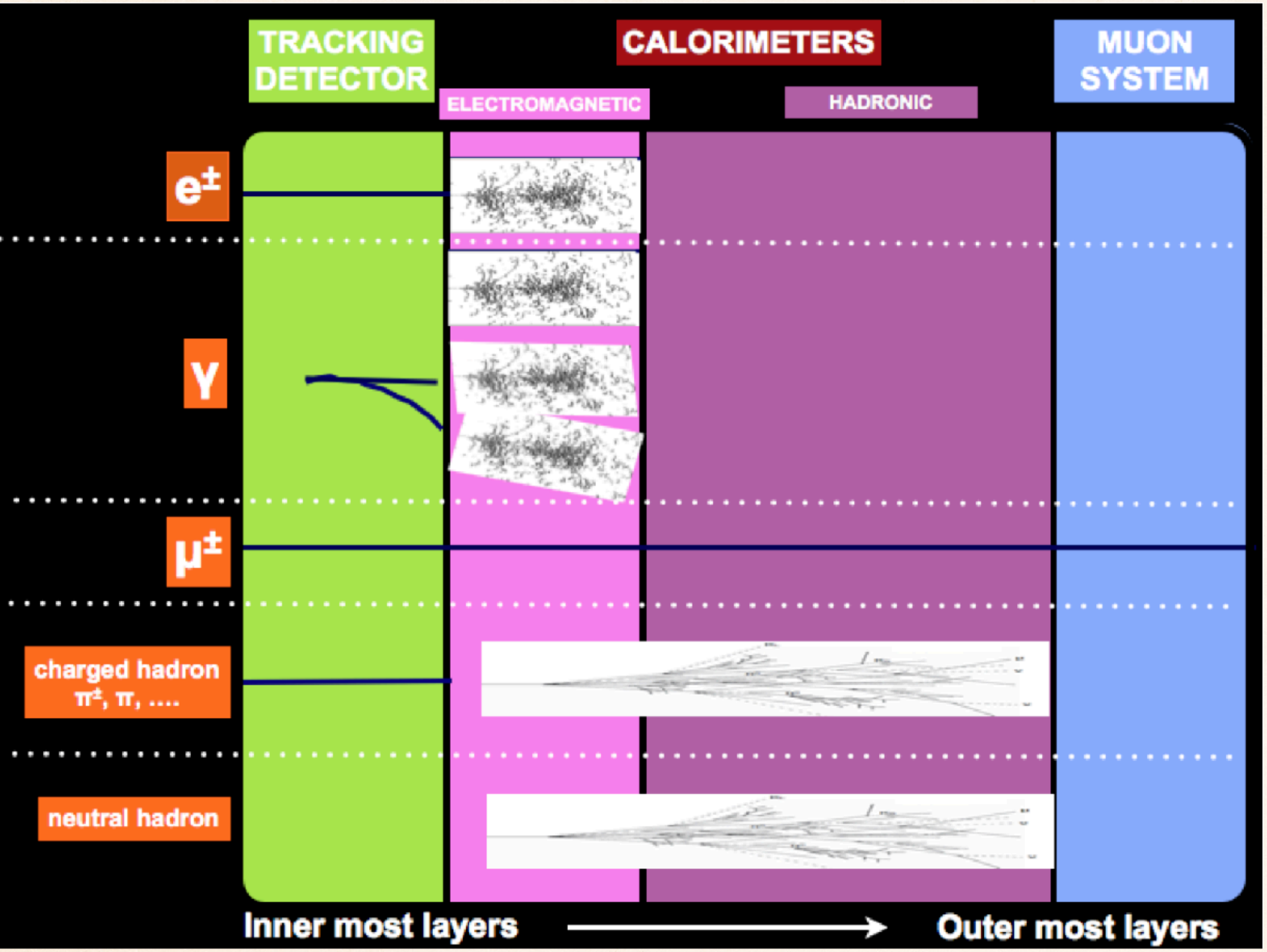
INSTRUMENTATION DEVELOPMENTS IN PARTICLE PHYSICS



FUNDAMENTALS



Brief History of Instrumentation

1906: Geiger Counter, H. Geiger, E. Rutherford
1910: Cloud Chamber, C.T.R. Wilson
1912: Tip Counter, H. Geiger
1928: Geiger-Müller Counter, W. Müller
1929: Coincidence Method, W. Bothe
1930: Emulsion, M. Blau
1940-1950: Scintillator, Photomultiplier
1952: Bubble Chamber, D. Glaser
1962: Spark Chamber
1968: Multi Wire Proportional Chamber, C. Charpak , …..

Physics Nobel Prizes for Instrumentation

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi Wire Proportional Chamber

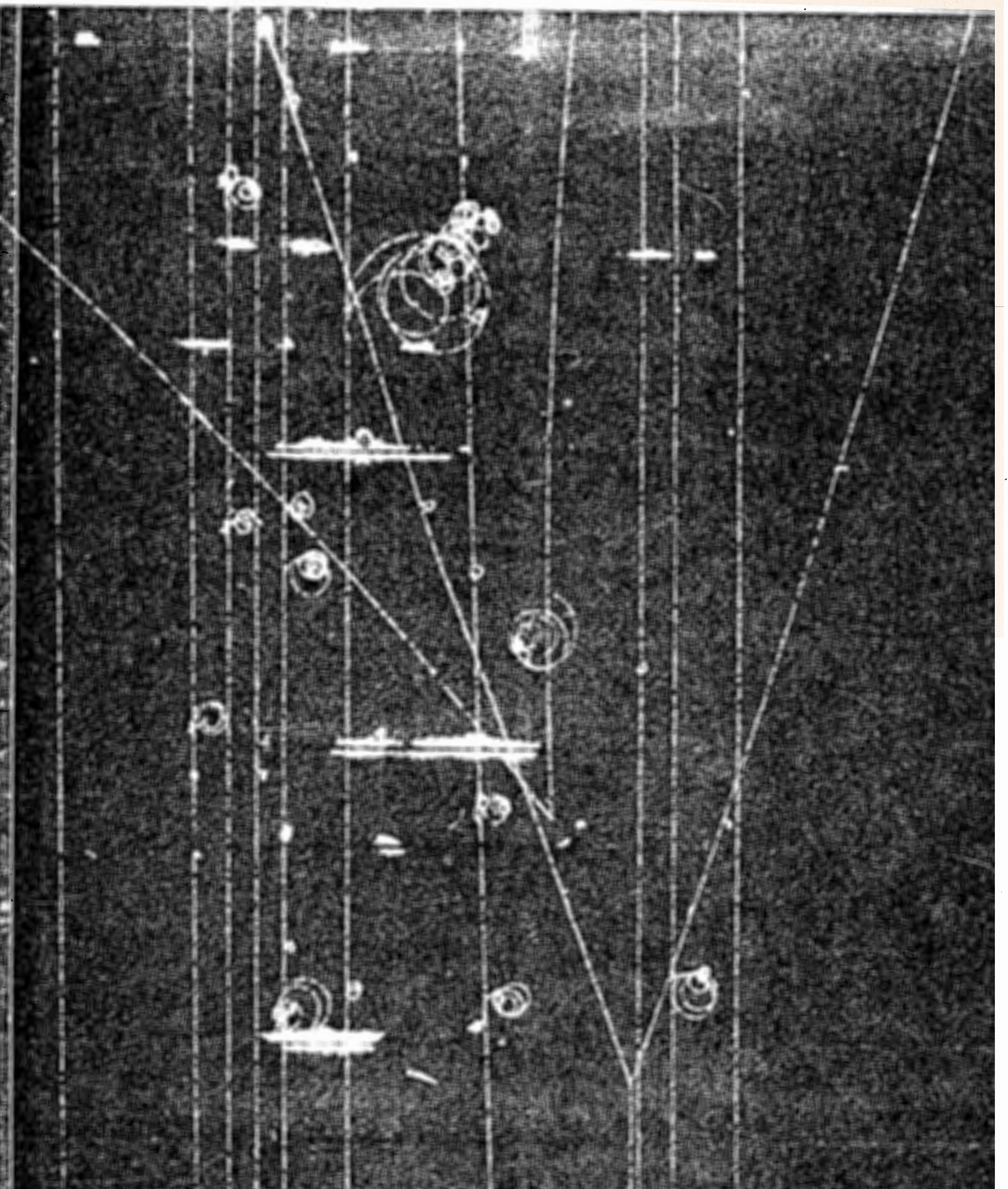
1970++ FOCUS OF TALK:

(1) TRACKING
(2) CALORIMETRY
(3) READOUT ELECTRONICS
(4) DATA ACQUISITION
(5) THE FUTURE

Many detectors covered in other talks

(1) TRACKING

A STRANGE PARTICLE TOPOLOGY

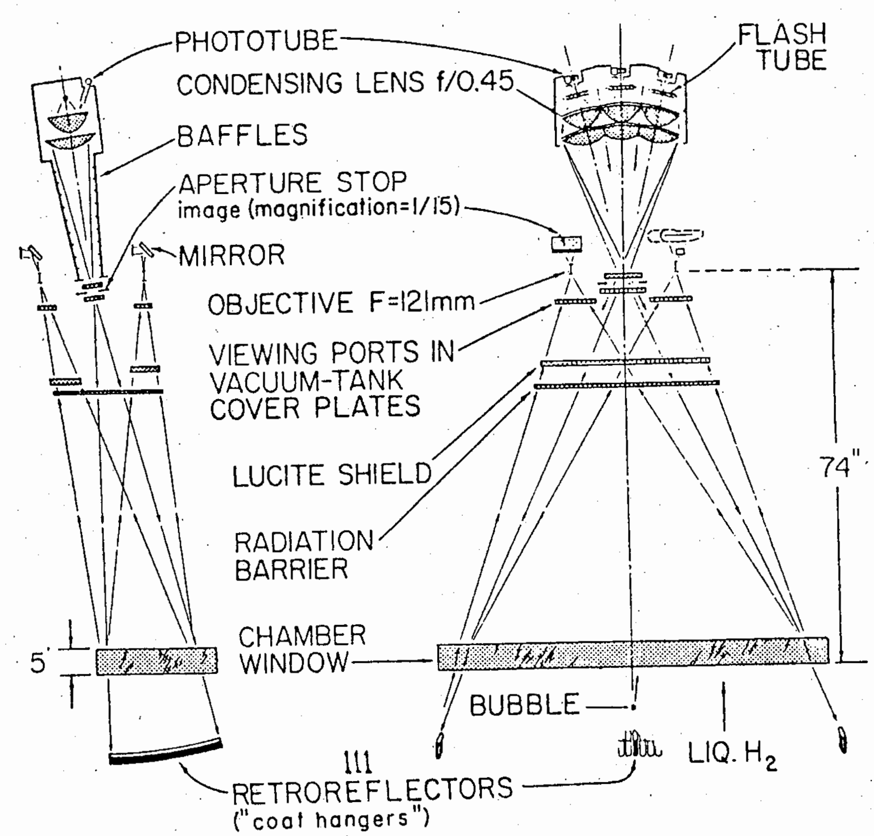


A. Goddard, MSc. Thesis, Toronto, 1975
"Strange Particles Produced by π⁺ p collisions at 10.3 GeV"
SLAC fixed target (Toronto/BNL)

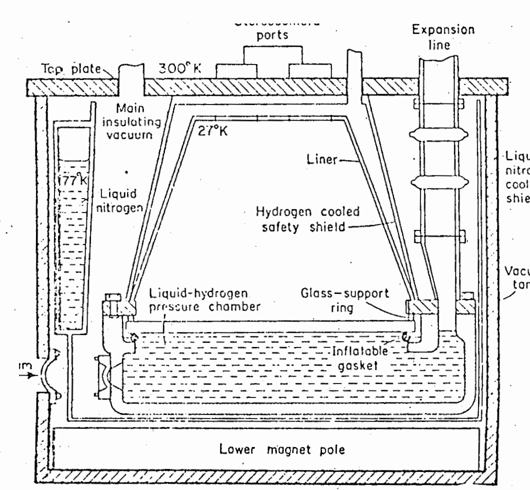
THE 82-INCH BUBBLE CHAMBER

Originally designed (in 1958) for use with the Berkeley 6 GeV Bevatron in investigating the properties of the newly discovered strange particles, it was enlarged and moved to SLAC in 1968.

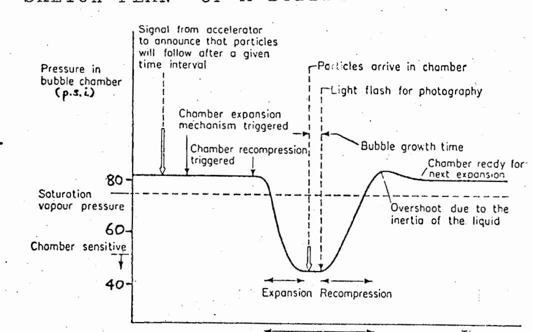
The top of the chamber is 5" thick optical glass, tilted approximately 6^0 from the horizontal. This permits stray bubbles and other impurities to roll out of the viewing area. Each interaction is photographed by three cameras situated at the vertices of a right-angled triangle. To avoid multiple track images a retrodirective illumination system is used. With this system only light scattered by the bubbles from behind is imaged in the camera and all other light is absorbed. The tracks therefore appear white on a black background. (see next page).



Optical system of the 82-inch chamber.



SKETCH PLAN OF A BUBBLE CHAMBER

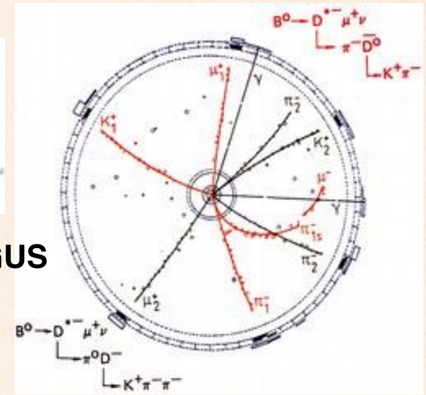


The sequence of operations in a bubble chamber.

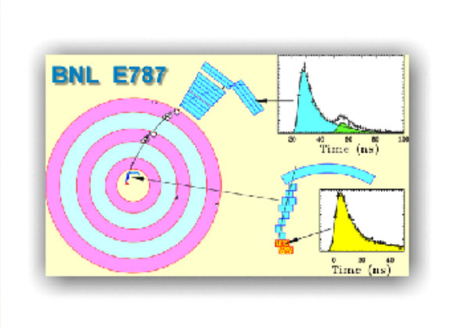
BRIEF HISTORY OF TRACKING IN CANADA

- ATLAS: BCM, DBM (Toronto), TRT-ROD (UBC, York)
- OPAL: vertex detector, z-chambers (Carleton, Montréal)
- BABAR: main central tracking chamber (UBC, TRIUMF, UVic, McGill)
- ARGUS: vertex detector (Toronto, York)
- ZEUS: forward straw tube tracker (York, Toronto)
- HERMES: large transition radiation tracker (6 modules) (TRIUMF, Simon Fraser)
- CDF SVX-II silicon tracker support mechanics, silicon detector project leader (Toronto)
- E531: large flat drift chambers (Toronto)
- E516: cylindrical MWPC tracking chambers as vertex detector (Toronto, Carleton)
- T2K near detector: large TPCs (Victoria, TRIUMF)
- BNL E787 central tracking chambers (TRIUMF)
- + A range of smaller tracking chambers of various types built for TRIUMF experiments
- Software (track finding and fitting and PID) includes the above plus:
    - E691 Si strip forward tracking (Toronto)
    - ZEUS vertex and central tracking (Toronto), …..

ARGUS

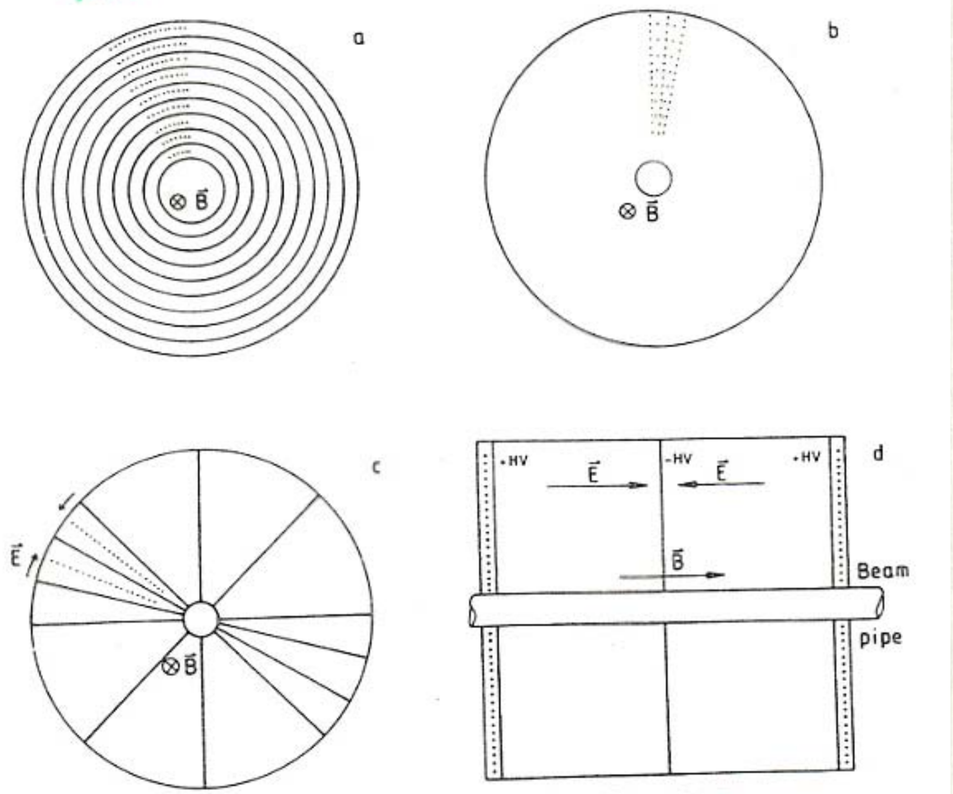


E531
E516
E691



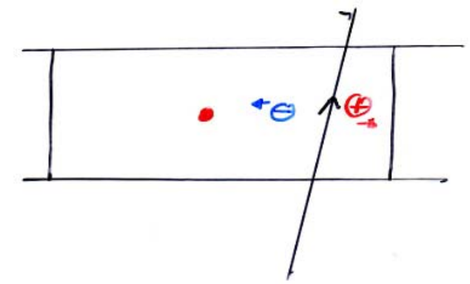
TRACKERS

PROPORTIONAL | DRIFT



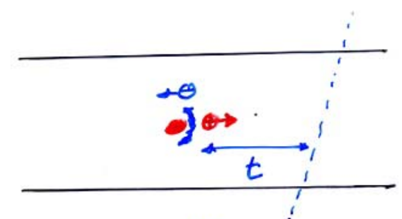
JET CHAMBER | TIME PROJECTION CHAMBER

SIGNAL IN DRIFT CHAMBER



① INITIAL IONIZATION GIVES NO SIGNAL
↓ NEED GAS AMPLIFICATION

②

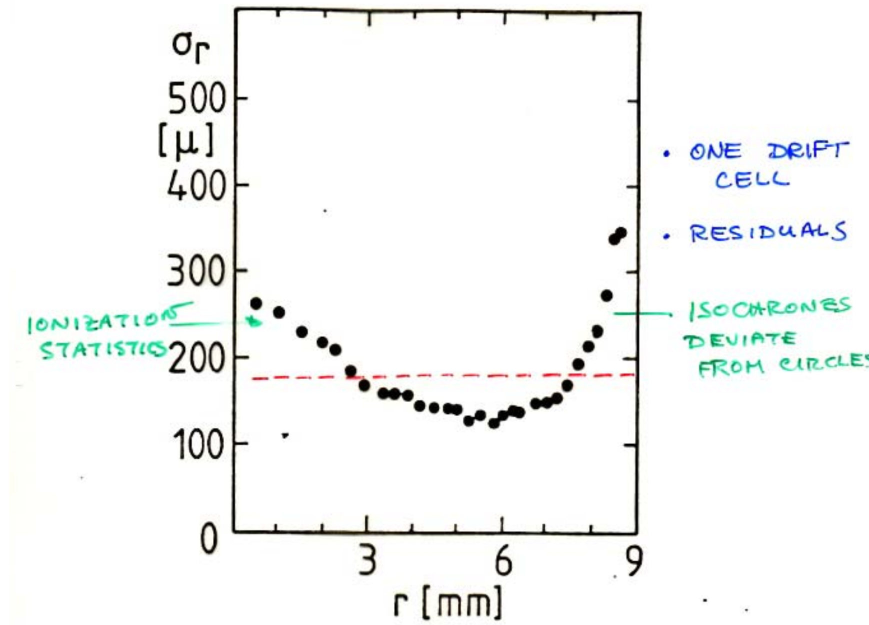


AFTER TIME 't' → ELECTRONS REACH REGIME OF GAS AMPLIFICATION

→ MORE e⁻ ⊖

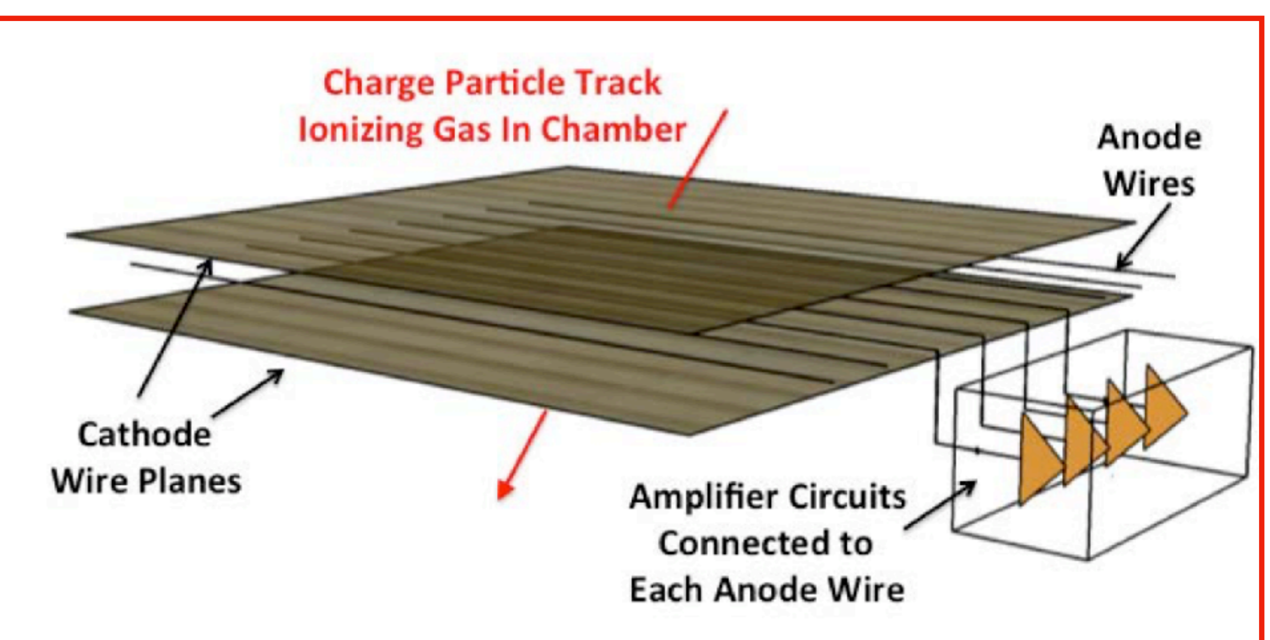
⊕→ THESE GIVE SIGNAL

DRIFT CHAMBER SPATIAL RESOLUTION

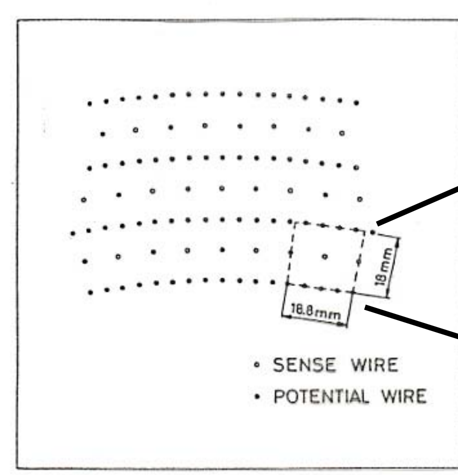


- $\langle \sigma_r \rangle = 180\,\mu$
- $\frac{\sigma_p}{p} = 1.2\% \cdot p$; $p > 1$ GeV/c
  $= 1.2\%$; $p < 1$ GeV/c

Wire chamber schematic:

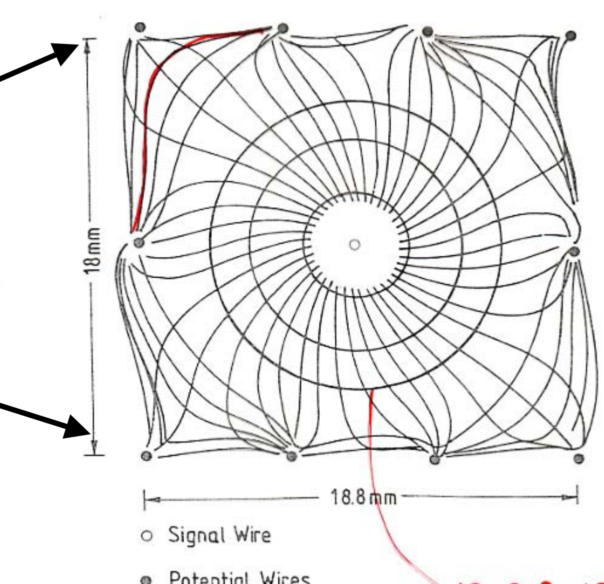


ARGUS DRIFT CHAMBER STRUCTURE



- PRECISION
- HIGH DENSITY OF INFORMATION
- PATTERN RECOGNITION VERY COMPLEX
  ↳ R-L AMBIGUITY RESOLVED BY TRYING ALL POSSIBLE COMBINATIONS

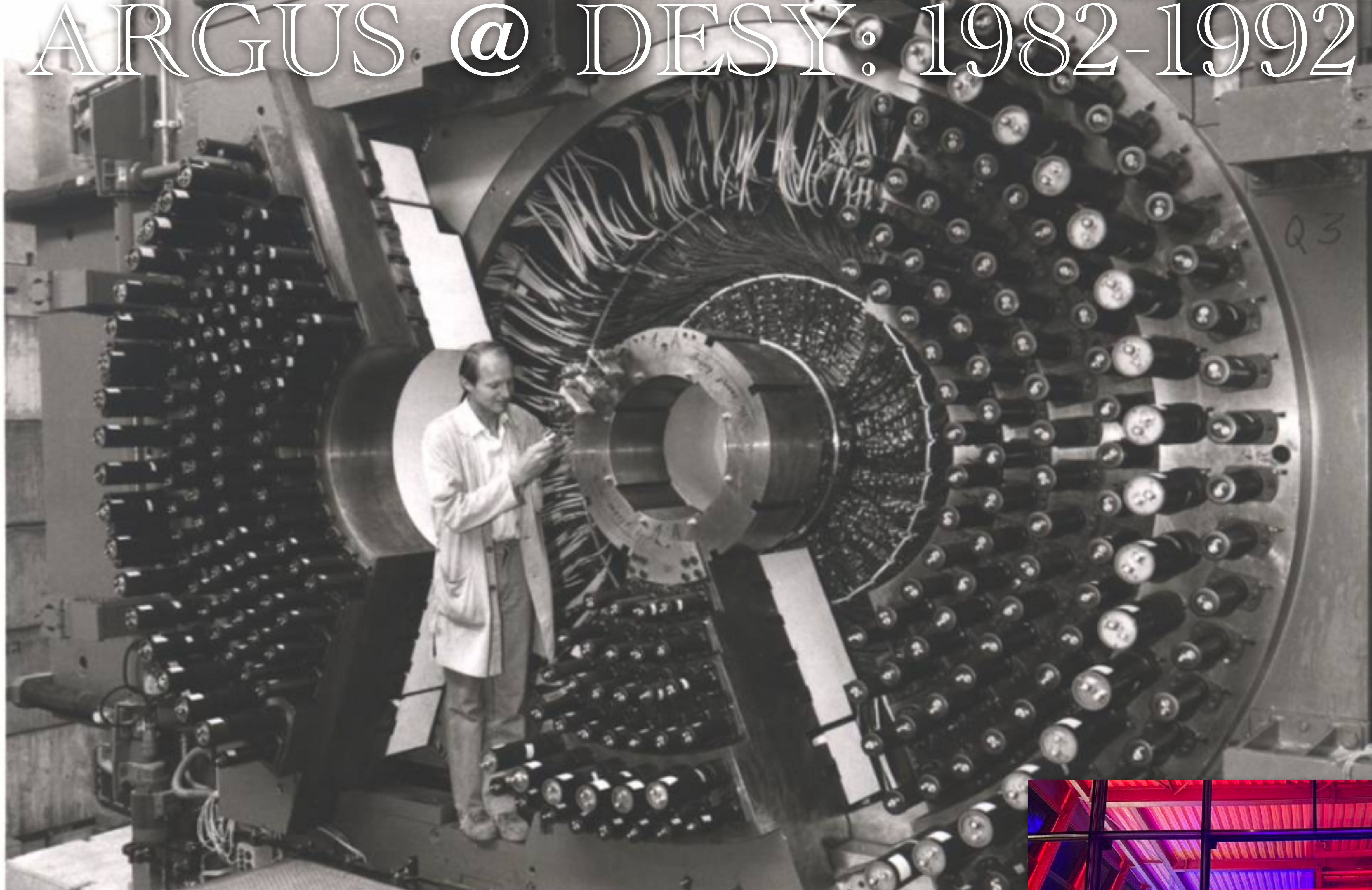
ARGUS DRIFT CHAMBER



COMPLICATED DRIFT TIME / SPACE RELATION IN CORNERS

. SIMPLE OVER MOST OF CELL

ARGUS @ DESY: 1982-1992



" Next a very strong team from the IPP Canada joined. It consisted of
P. Patel and T.S. Yoon, Montreal
J. Pentice and W. Frisken, Toronto
K. Edwards, Ottawa "

The Discovery of $B\overline{B}$ mixing
Walter Schmidt-Parzefall
Universität Hamburg

K.W. EDWARDS [6], W.R. FRISKEN [7], D.J. GILKINSON [8], D.M. GINGRICH [8], H. KAPITZA [6], P.C.H. KIM [8], R. KUTSCHKE [8], D.B. MACFARLANE [9], J.A. McKENNA [8], K.W. McLEAN [9], A.W. NILSSON [9], R.S. ORR [8], P. PADLEY [8], J.A. PARSONS [8], P.M. PATEL [9], J.D. PRENTICE [8], H.C.J. SEYWERD [8], J.D. SWAIN [8], G. TSIPOLITIS [9], T.-S. YOON [8], J.C. YUN [6]
Institute of Particle Physics [10], *Canada*

+ Argus micro-vertex drift chamber (IPP)

Argus, DESY, 1987

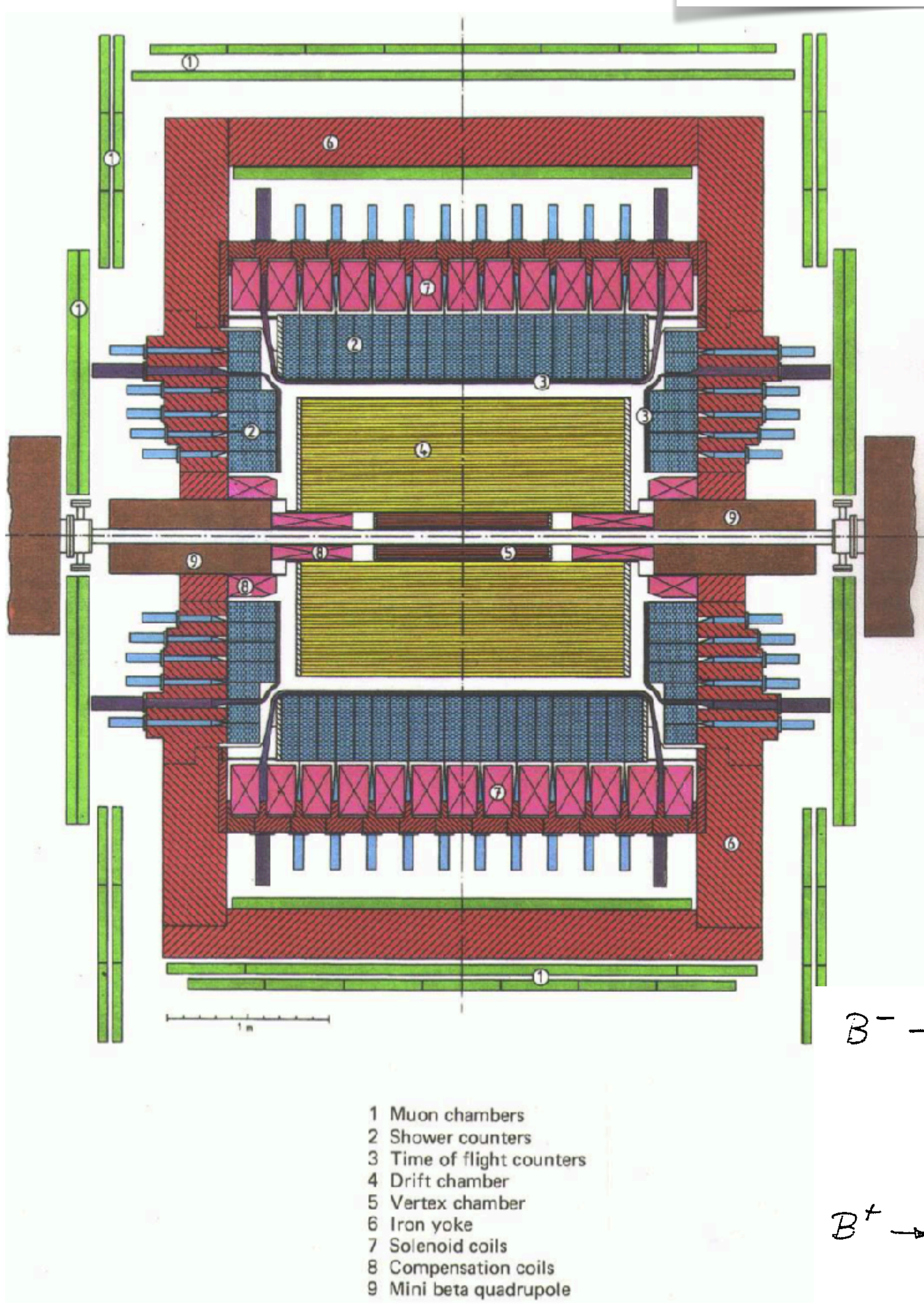
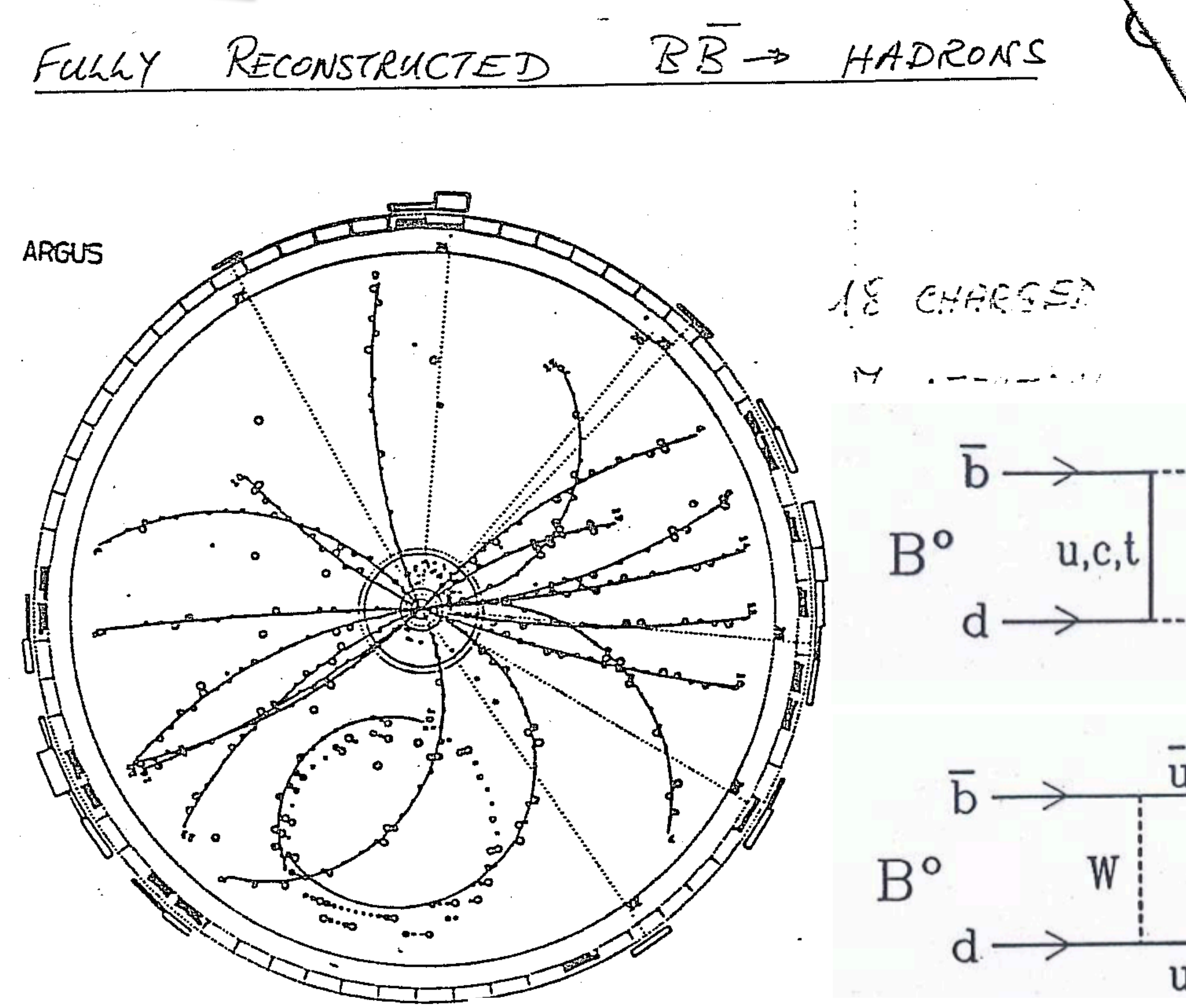
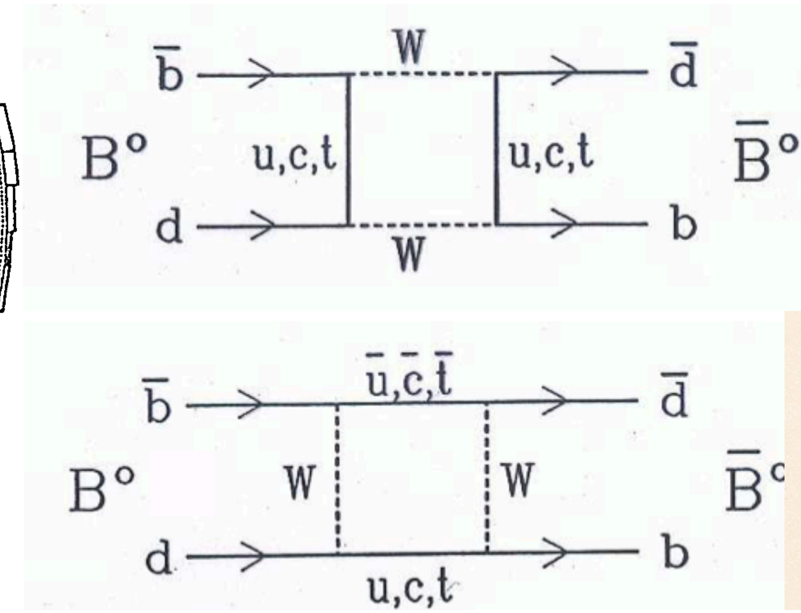
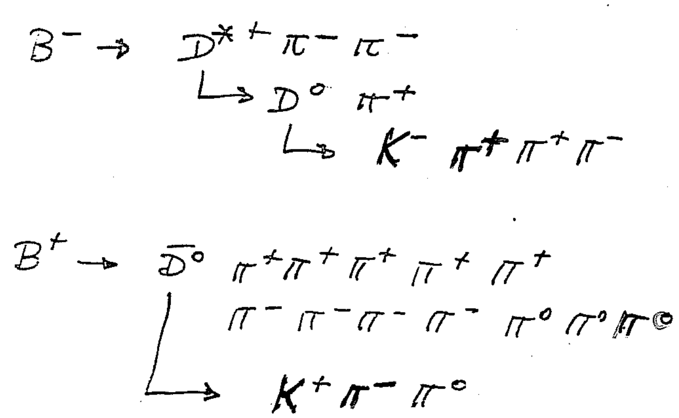


Figure 9: The final version of the ARGUS detector







The unknown CKM elements by 1987 were already constrained within

$$|V_{td}| = 0.002 \text{ to } 0.018, \qquad |V_{tb}| = 0.9986 \text{ to } 0.9993.$$

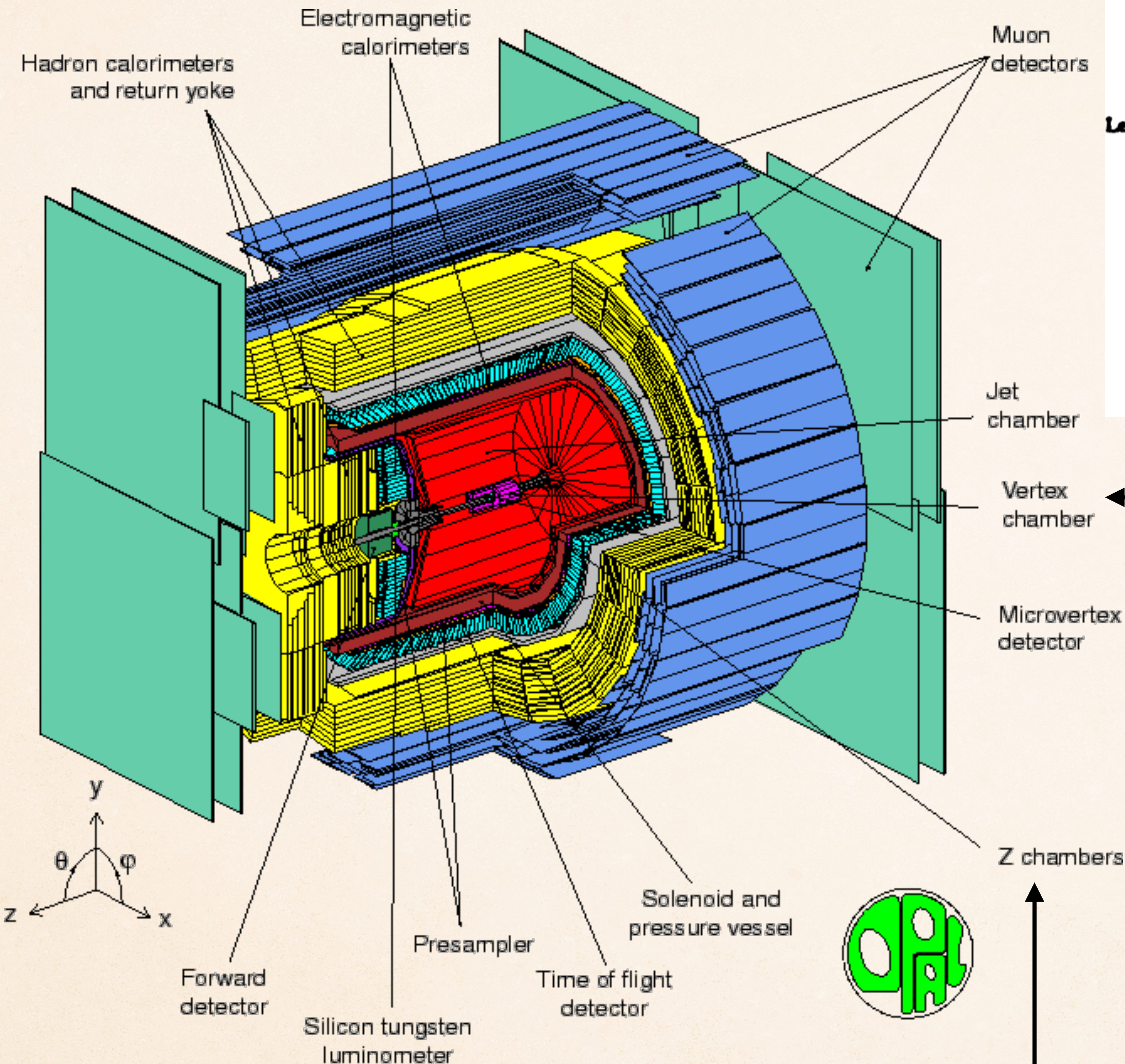
Taking the upper limit for $|V_{td}|$ one obtains a lower limit for m_t. Insertin these numbers into ΔM led to the surprise

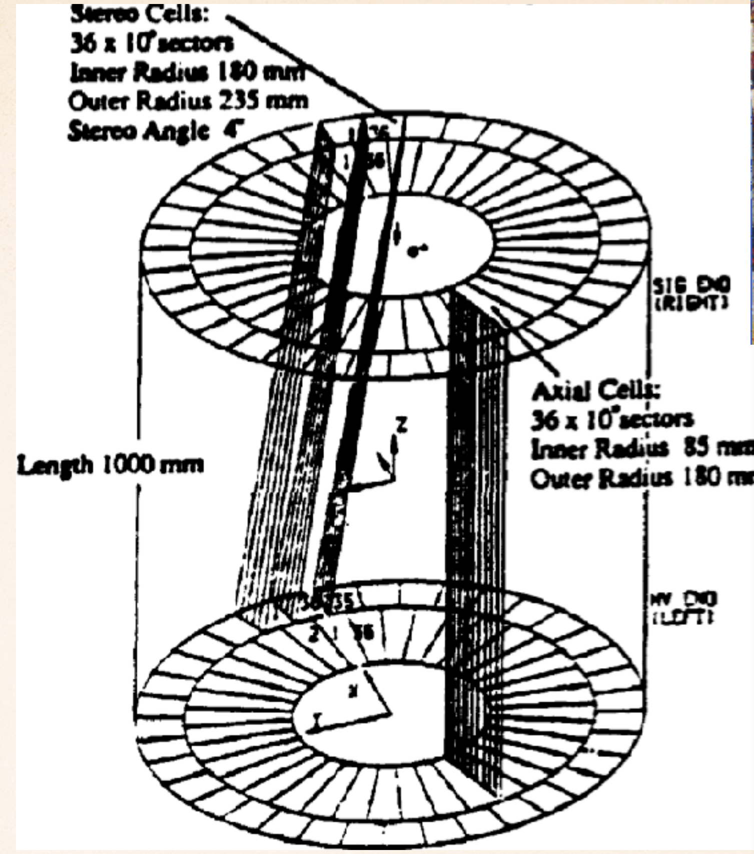
$$m_t > 50\,\text{GeV}.$$

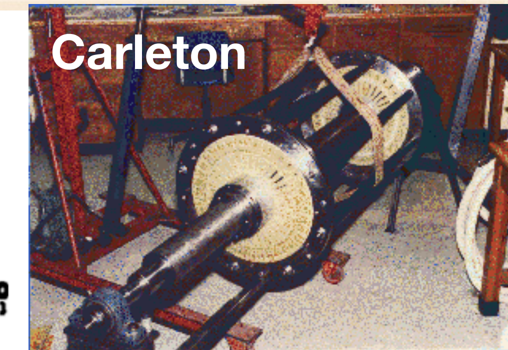
By 1987 it was the general belief, that the top quark mass was much smalle than 50 GeV, but we found, that it is much larger. Meanwhile the top quar was discovered. Indeed, its mass is 174.3±5.1 GeV.

OPAL @ LEP: 1989-2000

Designed as reliable detector ready at turn-on







The OPAL Vertex Detector

by

J. Michael Roney

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy

OPAL: Vertex Detector

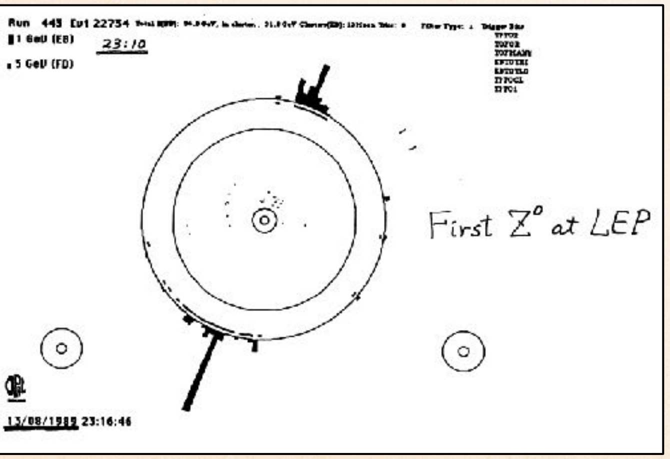
The vertex chamber is a 1 m long, 0.47 m diameter cylindrical drift chamber which is segmented radially into an inner layer of 36 cells with axial wires and an outer layer of 36 small angle (4 degree) stereo cells.

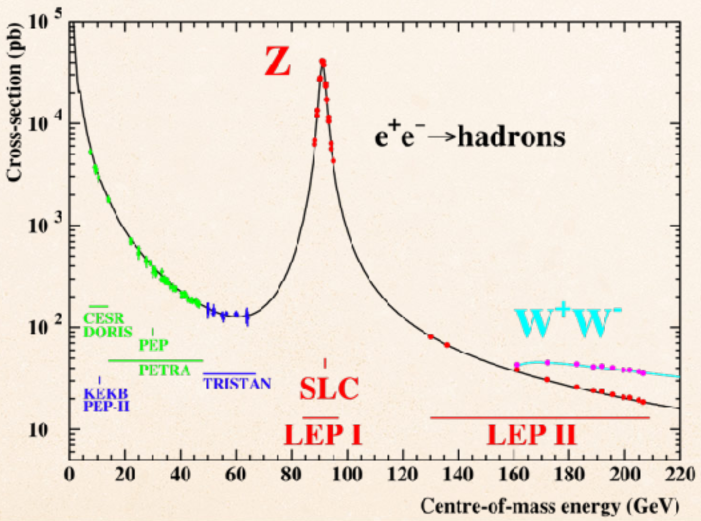
The axial cells provide a precise measurement of the position (50 microns) in the *r-phi* plane. A coarse measurement of the *z*-coordinate can be made by measuring the time difference between the signals from the two ends of the anode wire. The combination of axial and stereo cell information provides a precise *z* measurement for charged particles close to the interaction region.

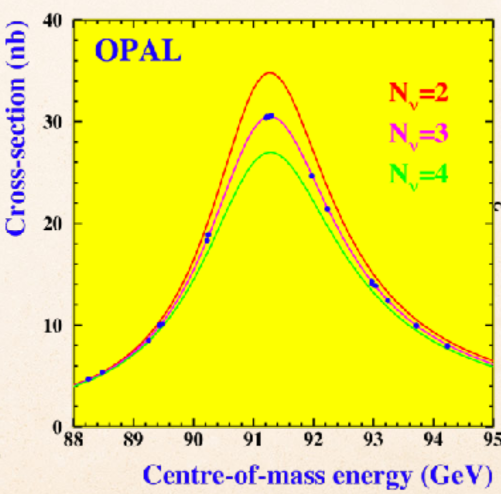
Nucl.Instrum.Meth.A 279 (1989)

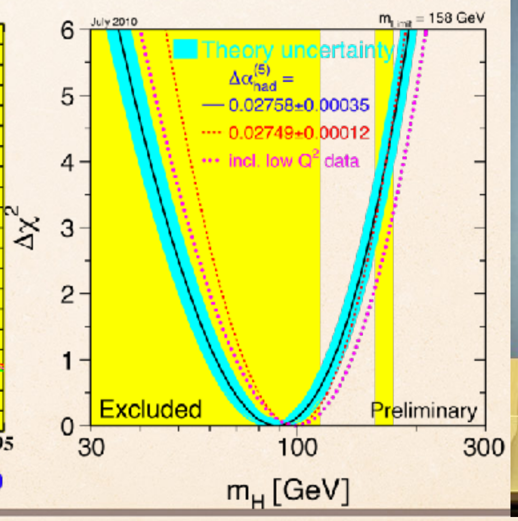
The Central Z subdetector surrounds the Central Jet (CJ) chamber and makes precise measurements of the z position of a particle's track as it exits CJ. CZ is made up of 24 chambers each of which is 4 m long, 500 mm wide and 59 mm thick. Each chamber is divided into 8 cells along the *z*-direction, each cell contains 6 sense wires lying perpendicular to the z-direction. Its resolution is 300 μm in z and 1.5 cm in r-ϕ.   Nucl.Instrum.Meth.A 265 (1988)

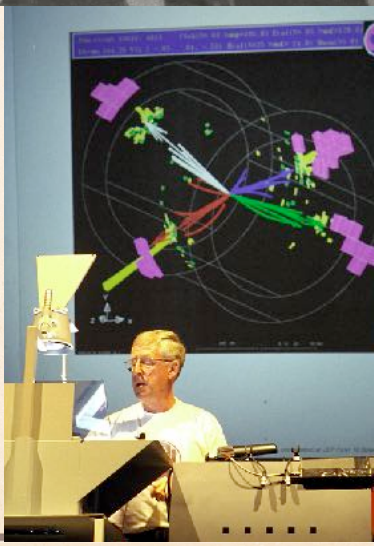
Early OPAL Collaboration











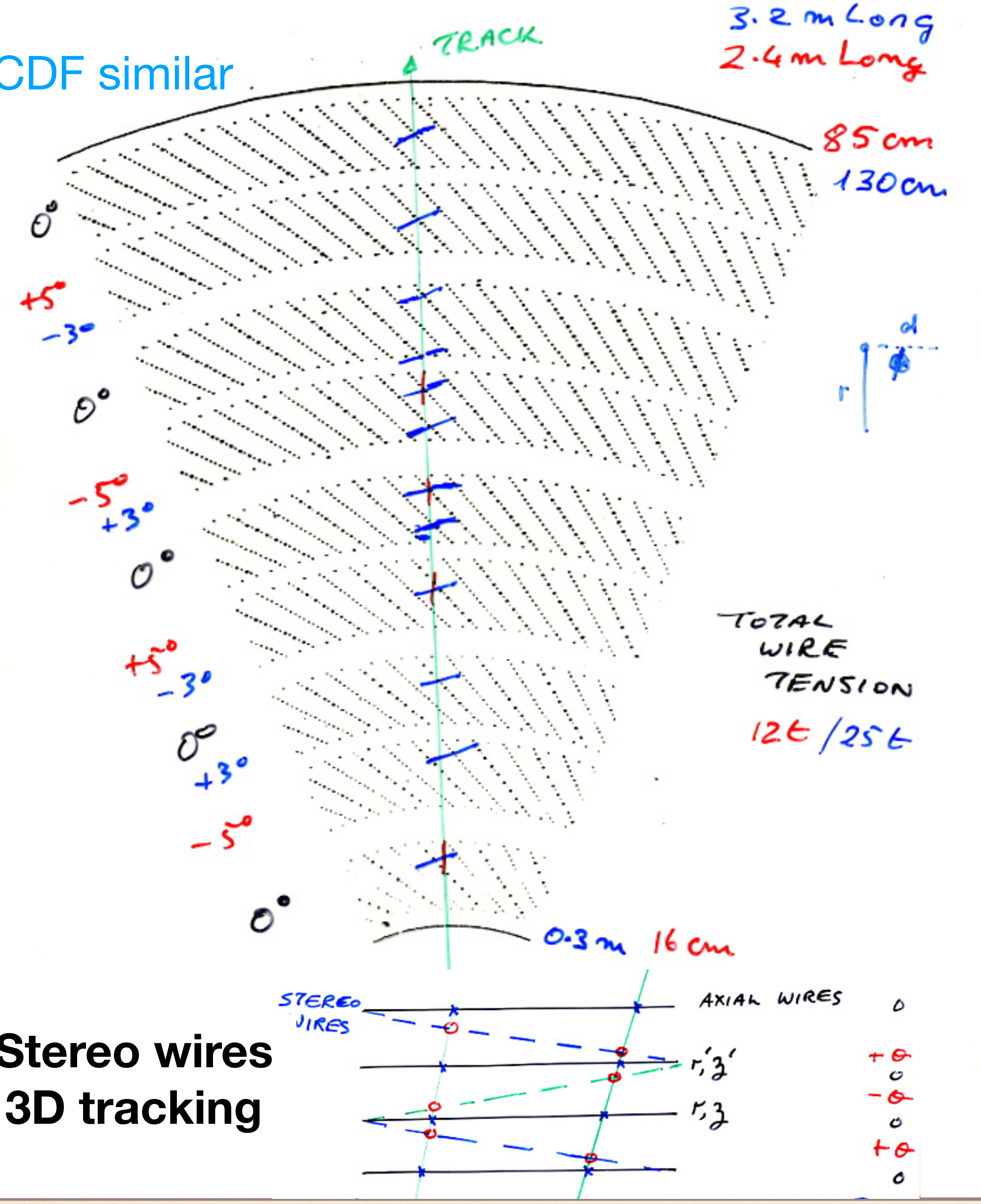
ZEUS @ HERA: 1992–2007

Central Tracking Detector (CTD)

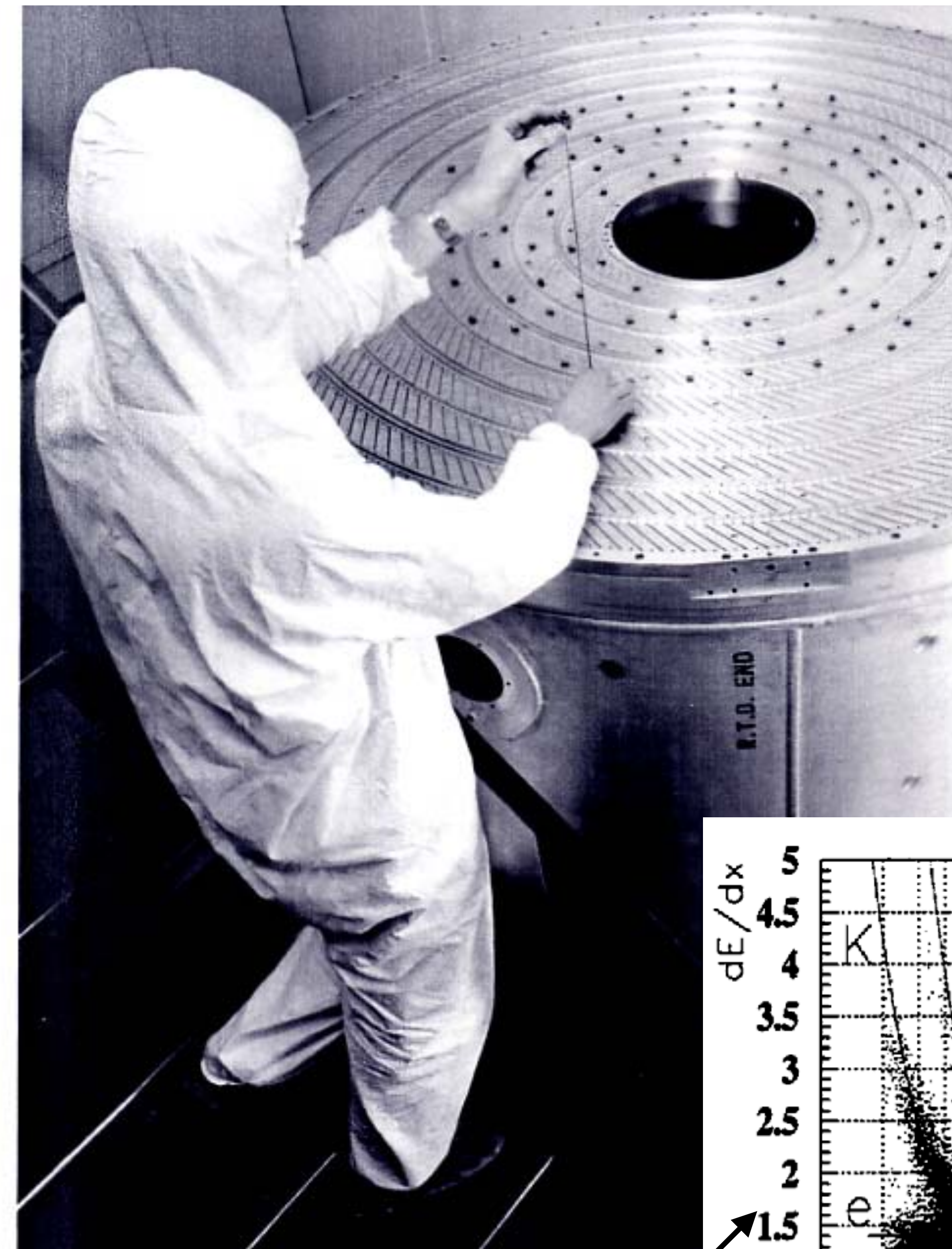
In 1994, the CTD working gas was a mixture of Ar (85%), CO_2 (8%) and ethane (7%), bubbled through ethanol. The single hit-efficiency was around 95%, while the single hit resolution was 260μ. For isolated tracks, the tracking efficiency was better than 98%, while for multi-track events it was at least 95%. The momentum resolution for full-length tracks was:

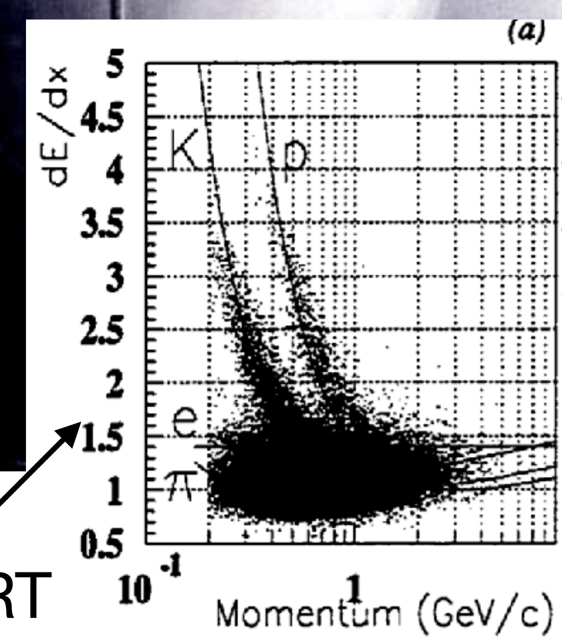
$$\frac{\sigma(p_T)}{p_T} \cong 0.005 p_T(GeV) \oplus 0.016 \qquad (2\text{-}5)$$

CDF similar



Stereo wires
3D tracking





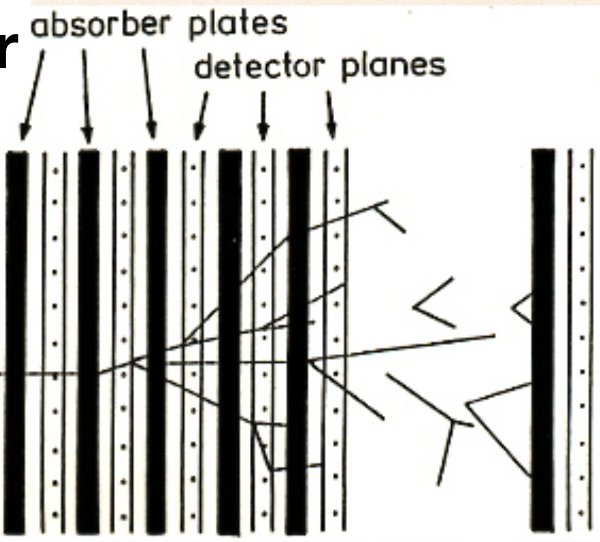
First ZEUS CTD dE/dx
(Canadian team)

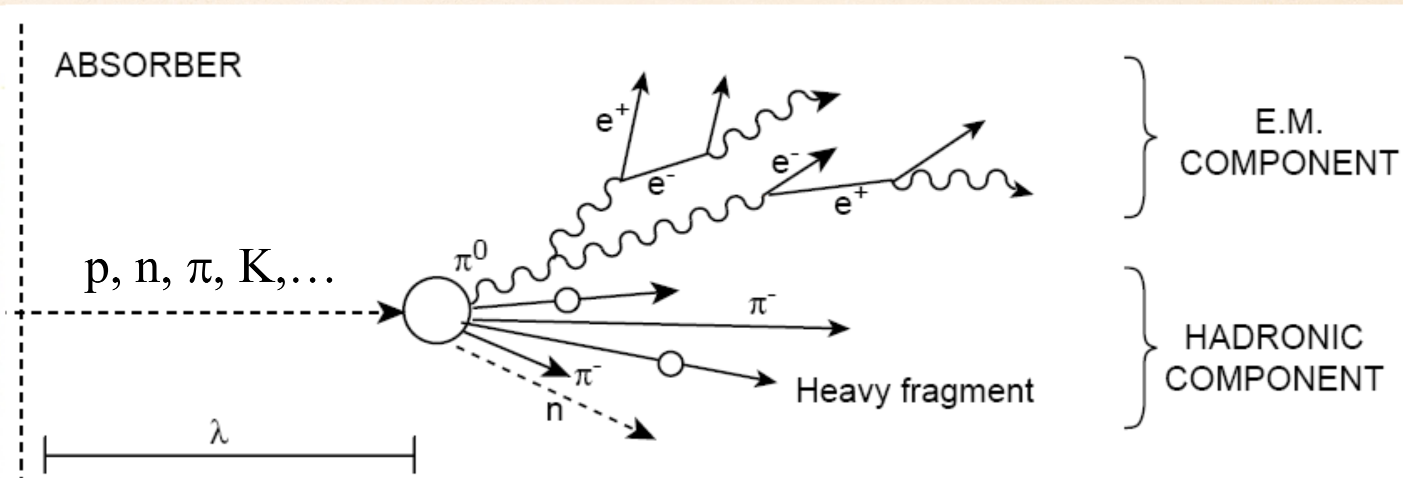
RT

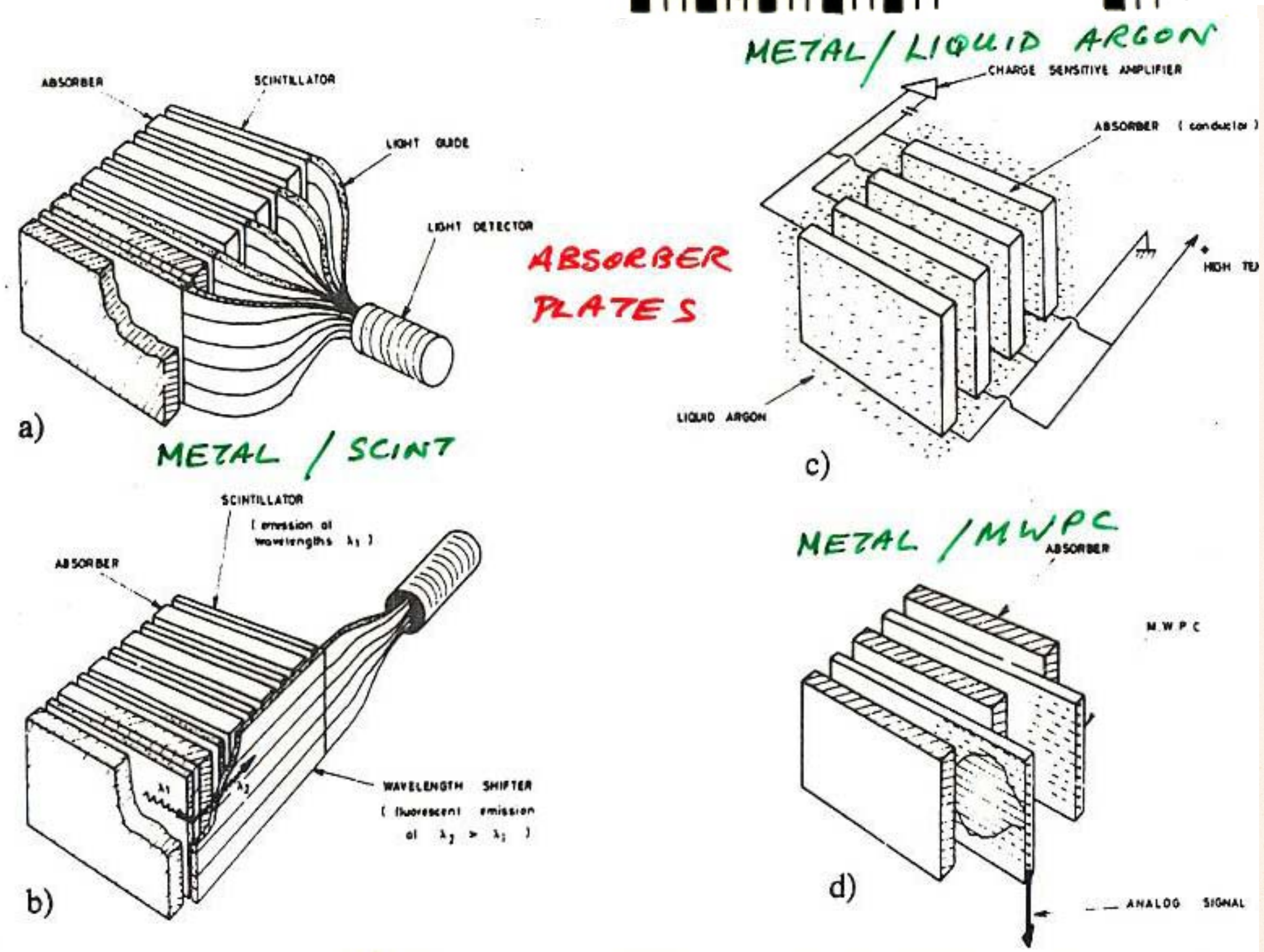
2) CALORIMETRY

(1) Sampling calorimeter

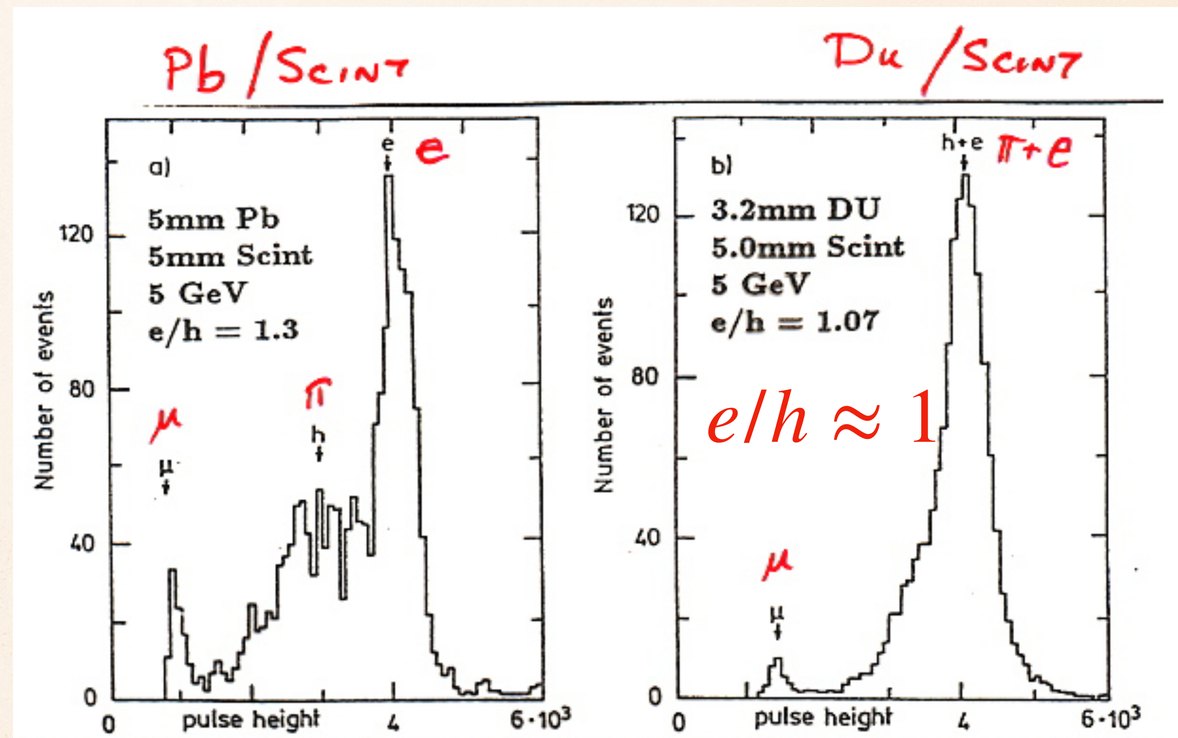
- HI DENSITY ABSORBER — ABSORB SHOWER
- LOW DENSITY DETECTOR — COUNT PARTICLE XINGS







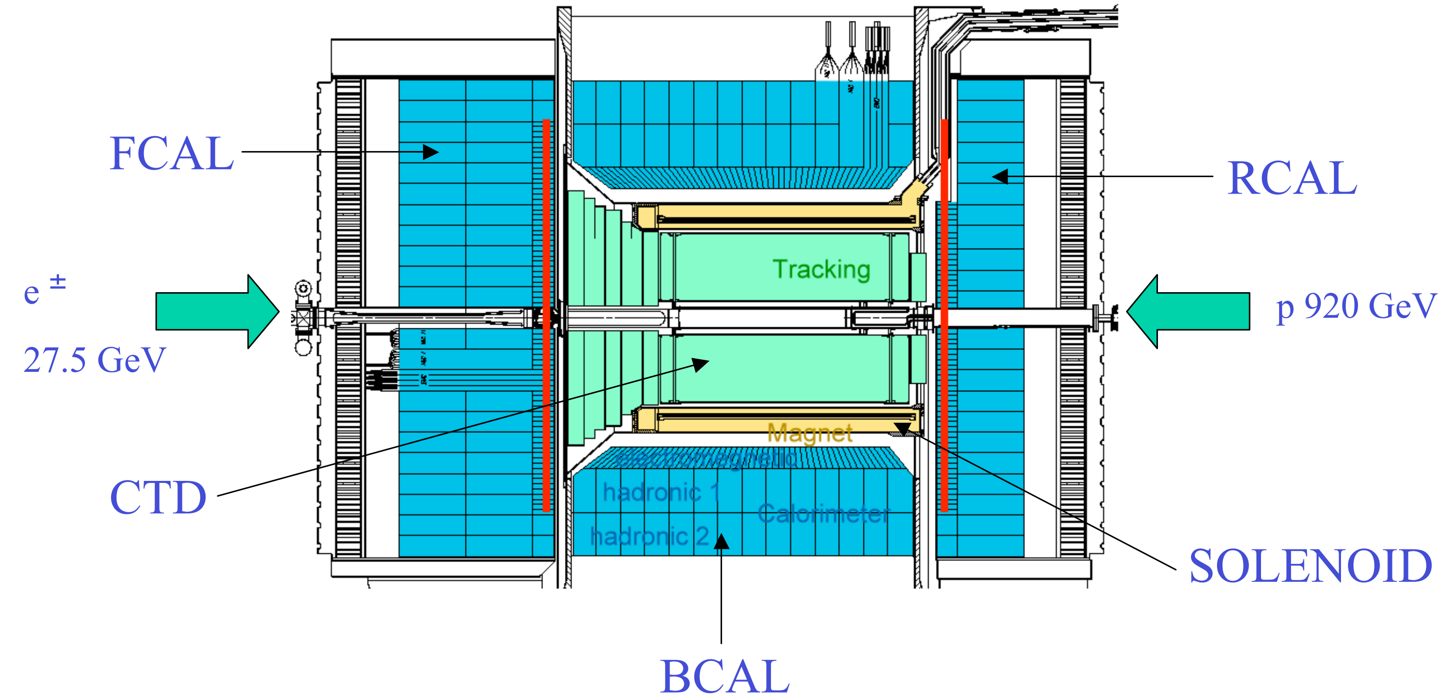
- Different response between electromagnetic interactions (e) (ionisation) and hadronic (h) (inelastic interactions energy lost to nuclear binding in e.g. Fe).
- Optimum resolution e/h ~1. -> **ZEUS Depleted Uranium**

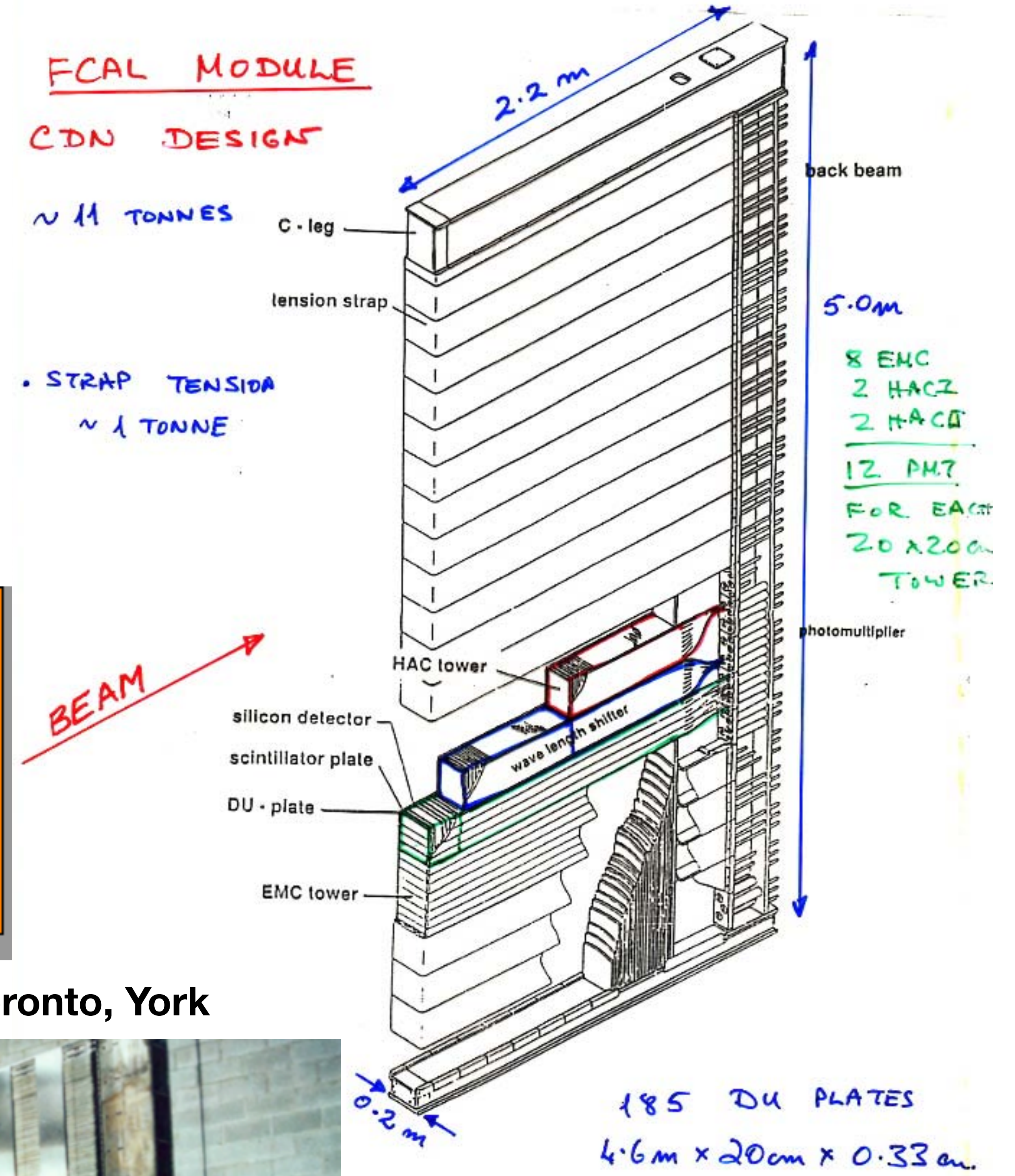


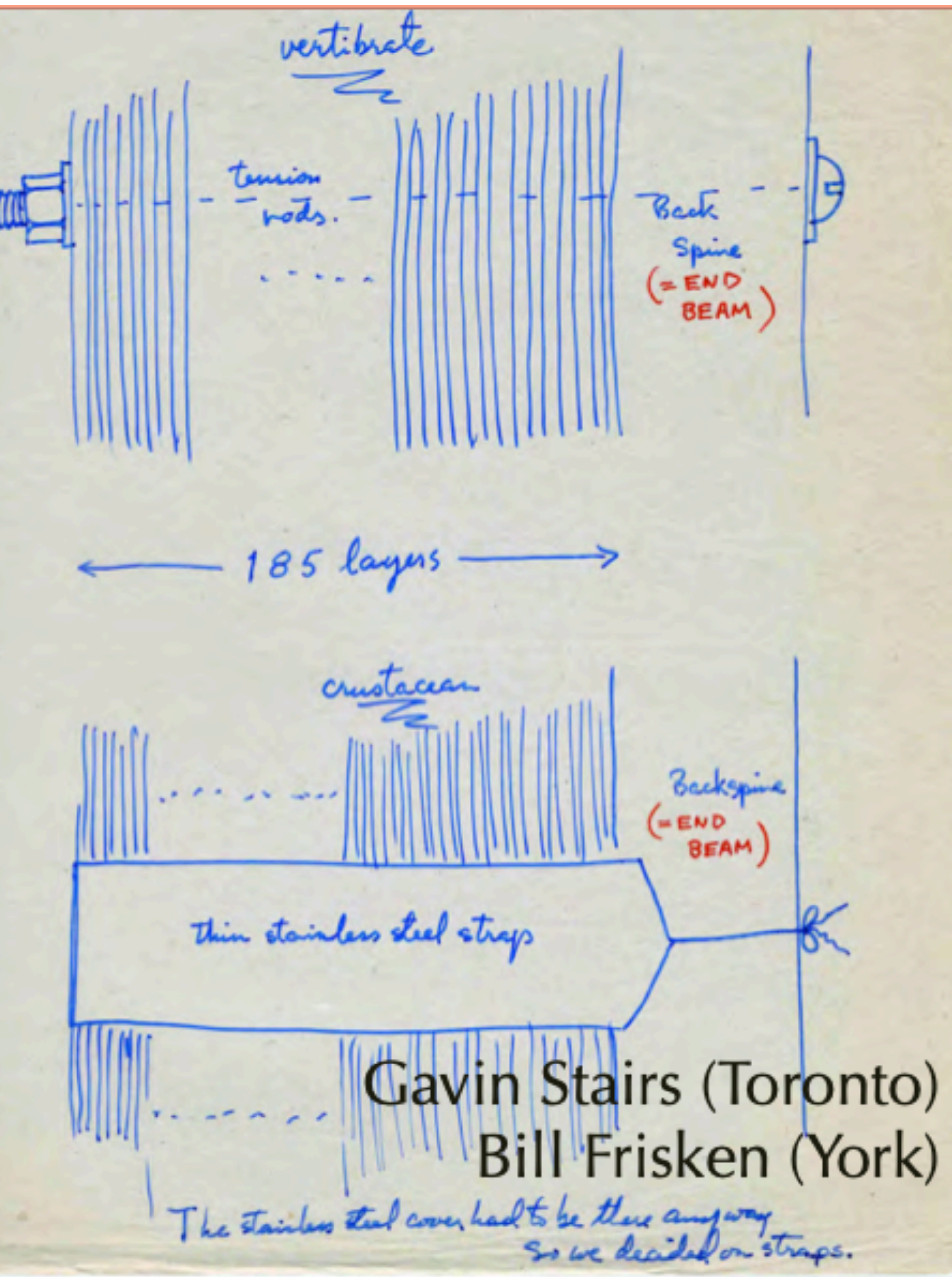
3.14 Pulse height distributions of 5 GeV electrons, hadrons and muons measured with a lead scintillator (5mm Pb, 5mm Scint) calorimeter (a), and a depleted-uranium scintillator (3.2mm DU, 5mm Scint) calorimeter (b) (ZEUS).

(2) Also Homogeneous calorimeters

(Not shown, see OPAL Pb-Glass, CMS ECAL PbWO4..)







Gavin Stairs (Toronto)
Bill Frisken (York)

ZEUS

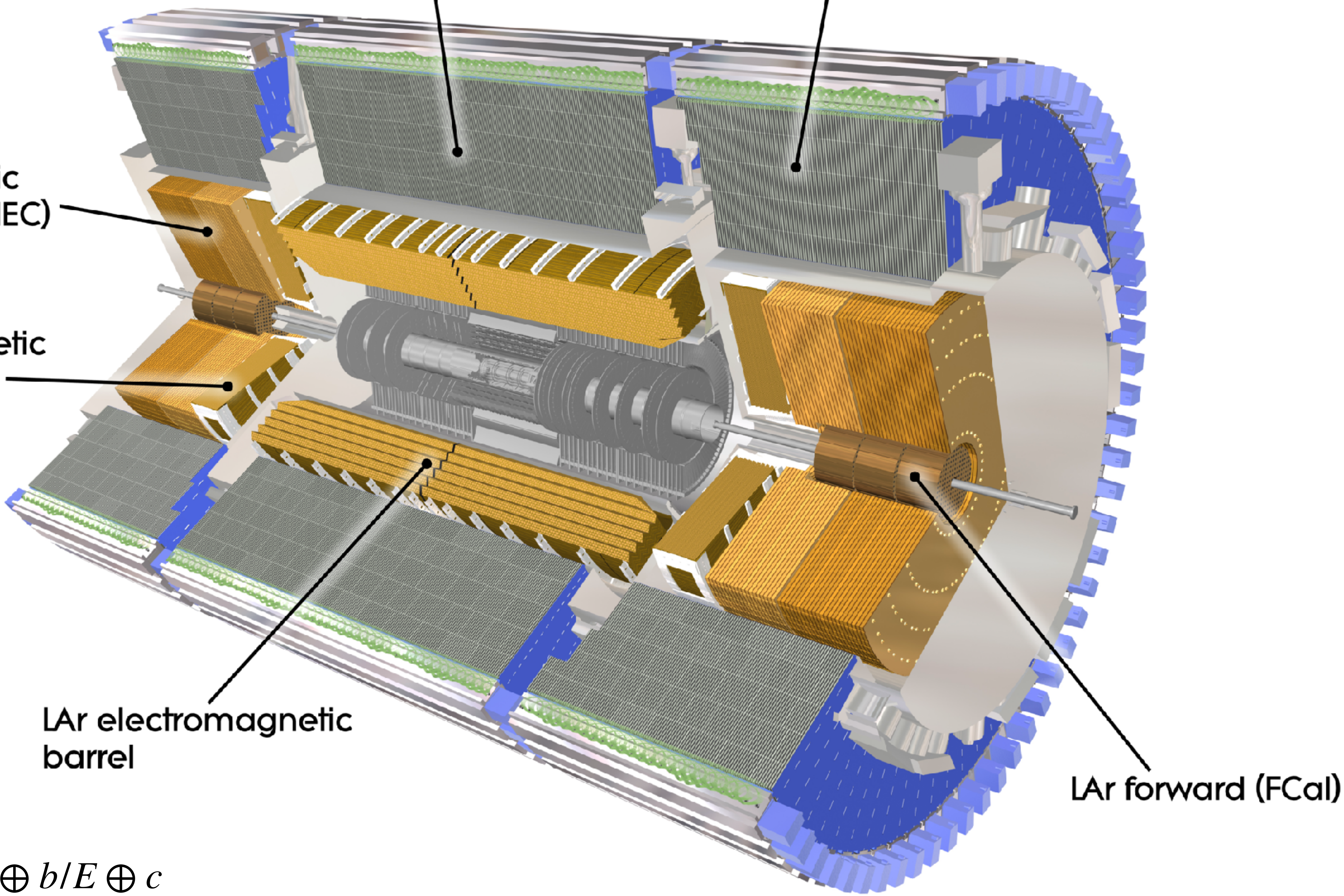
Canada: McGill, Toronto, York

FCAL assembly in Toronto

The ZEUS Collaboration around LoI.

1993 IPP
Past & Future

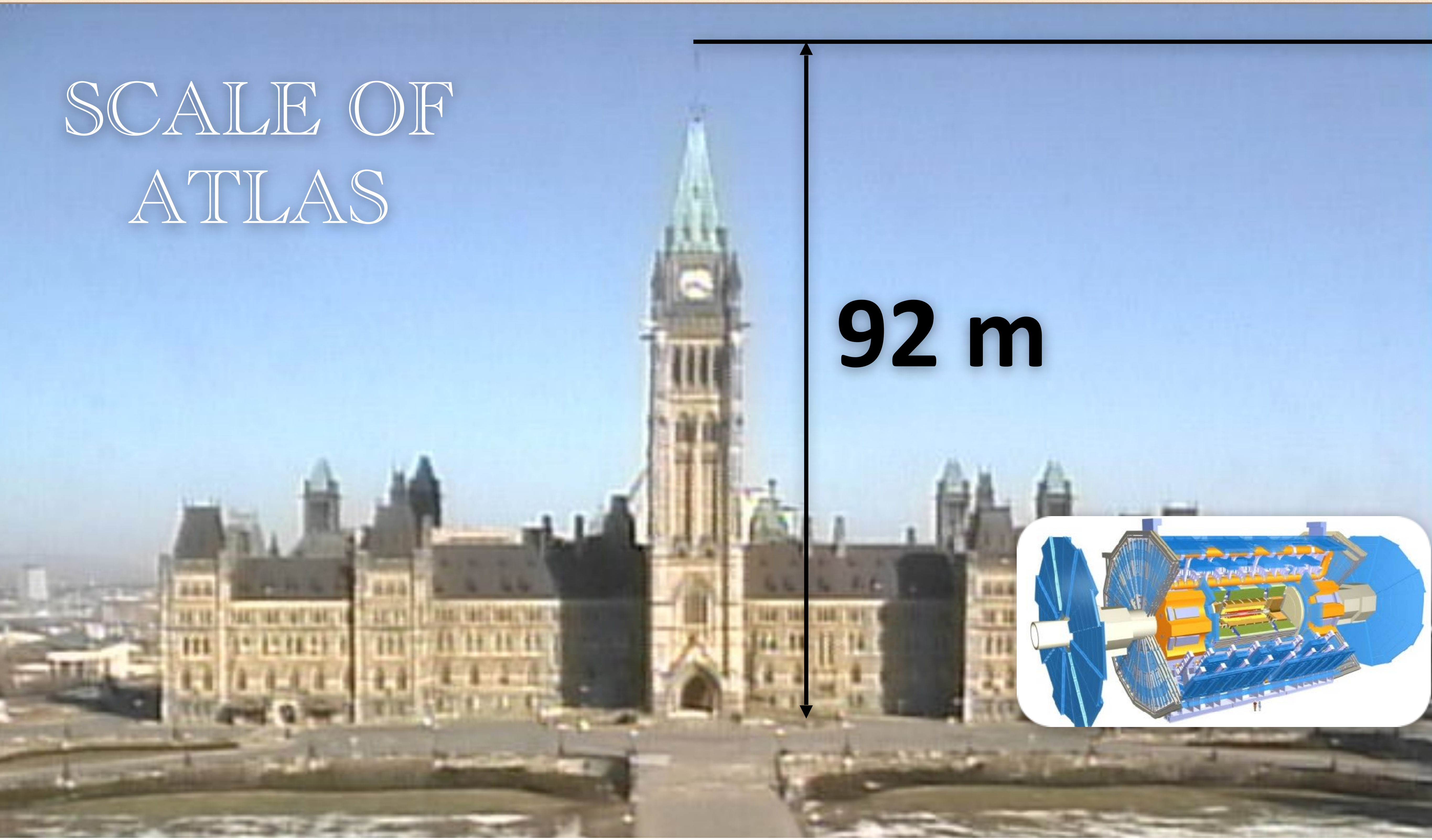
2000'S: ATLAS @ LHC CALORIMETRY



$$\sigma/E = a/\sqrt(E) \oplus b/E \oplus c$$

E resolution: a = stochastic term, sample fluctuations, b: electronics noise, c constant (dead material etc.)

SCALE OF ATLAS



ATLAS installed 92 m underground at CERN

Simon Fraser University
University of Alberta
McGill
TRIUMF
University of Toronto
Université de Montréal
University of Victoria
UBC
Université York University
Carleton University
Institute of Particle Physics
ATLAS

ATLAS LIQUID ARGON (LAR) CALORIMETER

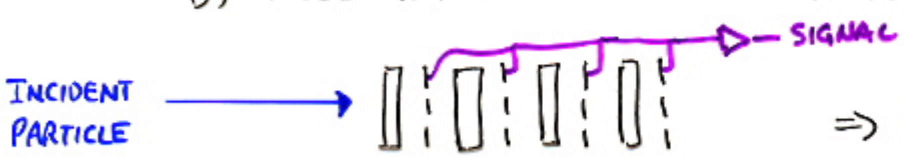
LIQUID ARGON CALORIMETRY

→ SOLVES PROBLEMS WITH RADIATION DAMAGE OF SAMPLER MATERIALS (SCINTILLATOR, SILICON etc.) BY RECYCLING ~~ABSORBER~~ ACTIVE MATERIAL

→ TYPICAL PROBLEM IS SIGNAL FORMATION TIME:

a) CHARGE COLLECTION TIMES IN LAr GAPS IS LONG (MANY μs EVEN FOR THIN GAPS)

b) NEED LONG SERIES OF SIGNAL CONNECTIONS



⇒ LARGE CAPACITANCE
" RC TIME CONSTANT.

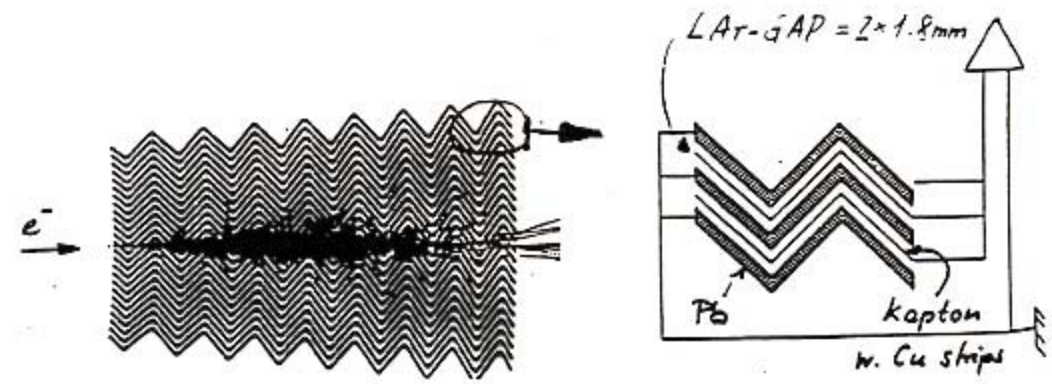
GAP WIDTH + NUMBER OF GAPS ⇒ LARGE CAPACITANCE. THIS ACTS AS A RESERVOIR OF CHARGE. FLUCTUATIONS ON THIS CHARGE ($\sqrt{N_e}$) CONTRIBUTES TO NOISE OF READOUT

⇒ IMPORTANT CONTRIBUTION TO LOW ENERGY ELECTRON / PHOTON SHOWERS

(e.g. ATLAS $H \to \gamma\gamma$ ↳ ~50GeV PHOTONS).

(11)

ACCORDIAN CALORIMETER



- NO DEAD REGIONS
- GOOD UNIFORMITY
- HIGH GRANULARITY
- READ ELECTRONICS MOUNTED ON CALORIMETER FACE

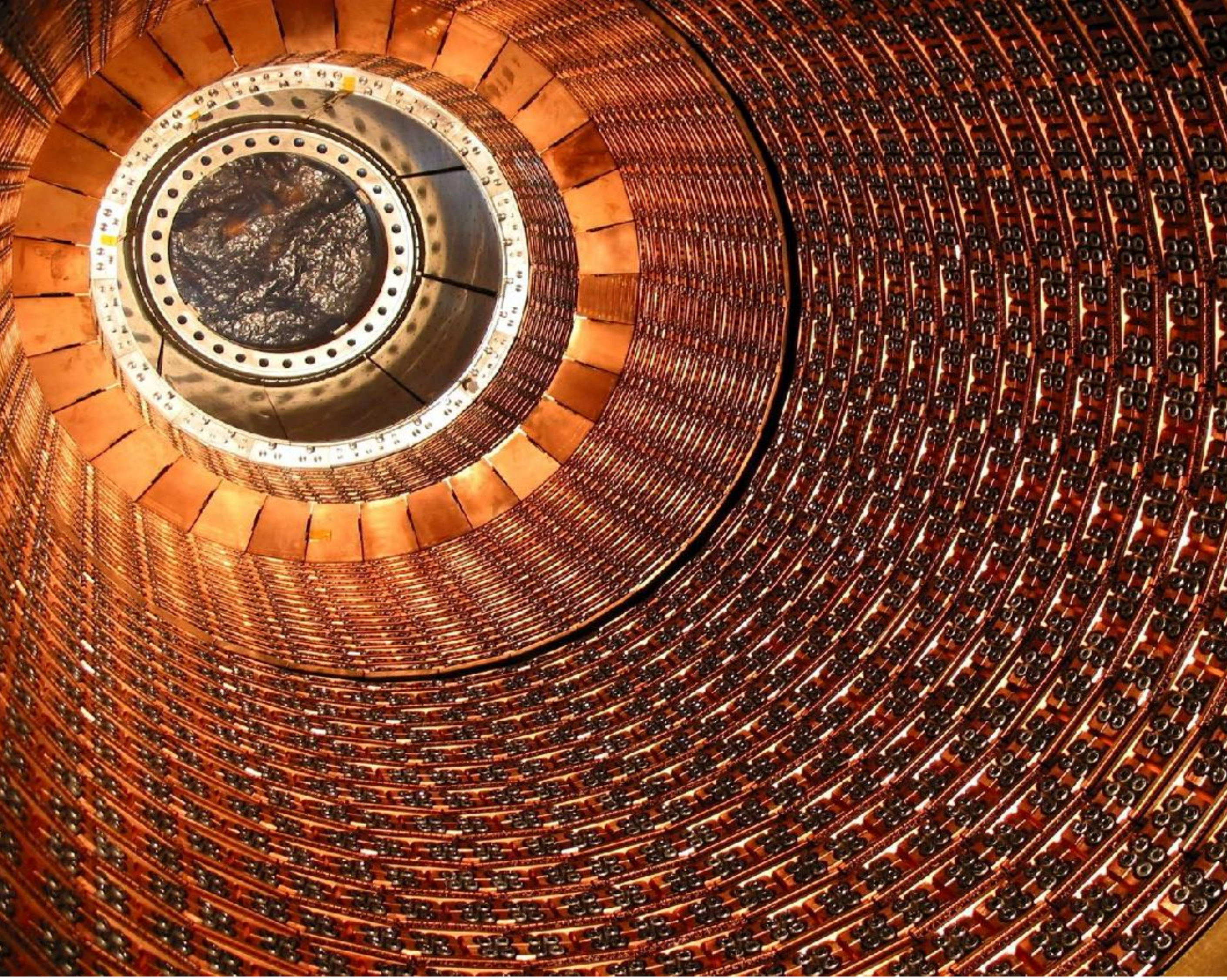
ONLY NEED ACCORDIAN FOR EM SECTION.

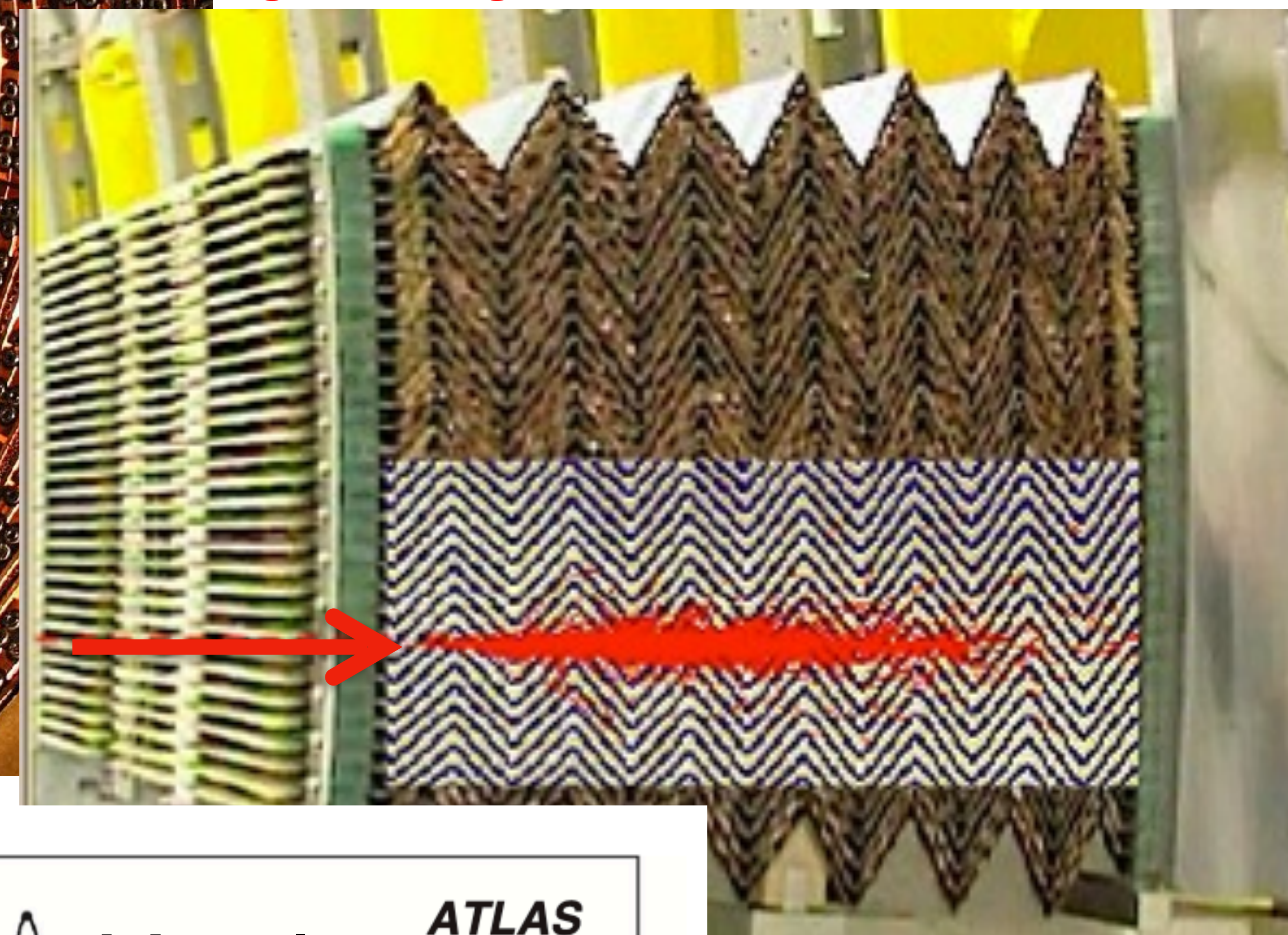
IN OTHER PARTS OF ATLAS USE OTHER "INGENEOUS" SAMPLER GEOMETRIES

e.g. FORWARD CALORIMETER WITH LAr SHISH-KABOB GEOMETRY, 400 μm GAPS IN W ⇒ GOOD CONTAINMENT.

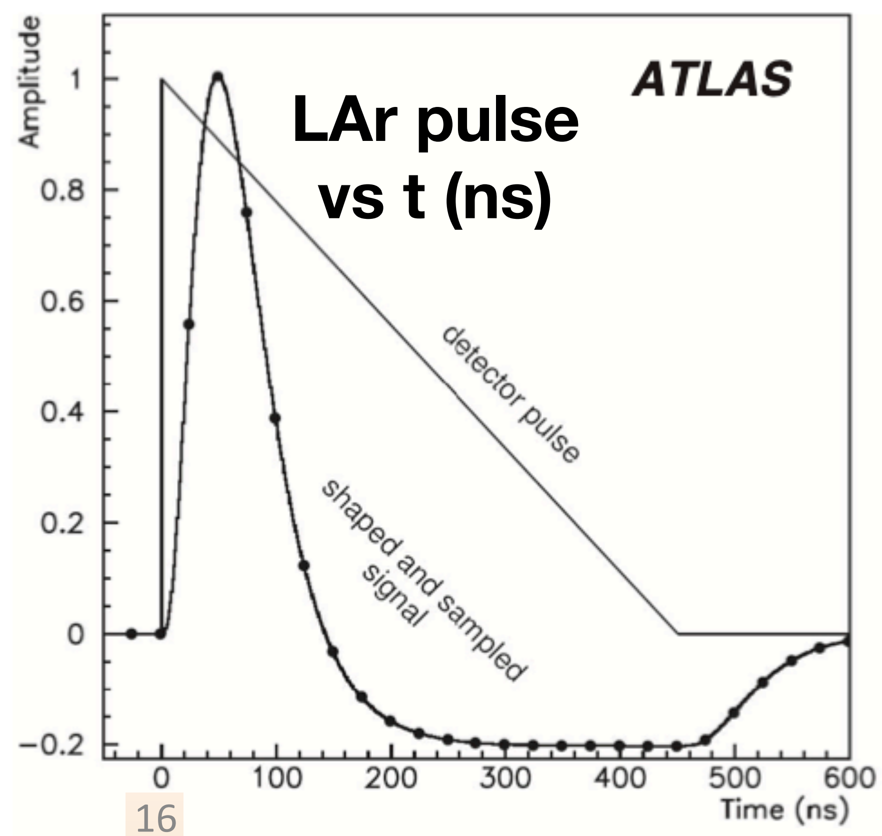
(12)

Liquid Argon (LAr) Calorimeter





- Electron / photon identification
- Lead absorber initiates shower
- Particles ionize liquid Argon (90K)
- High Voltage between plates cause ions and electrons to drift
- Collected charge is proportional to energy of particle



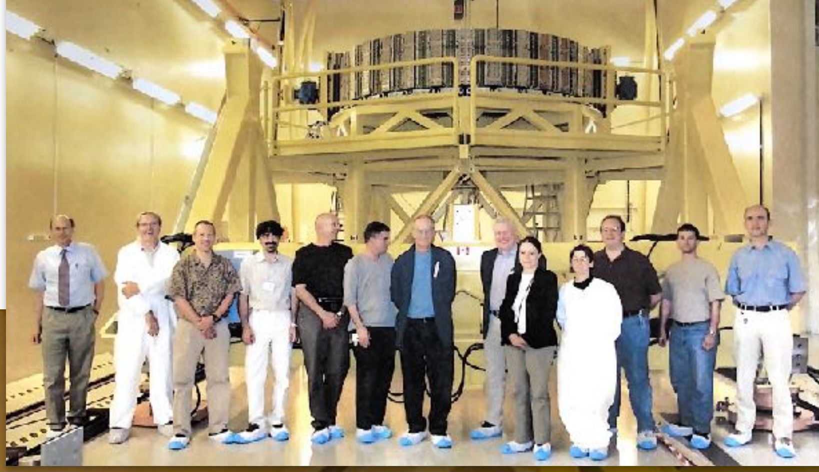
Optimal filter: E, t

$$E = \sum_{i=1}^{n} a_i (s_i - P);$$

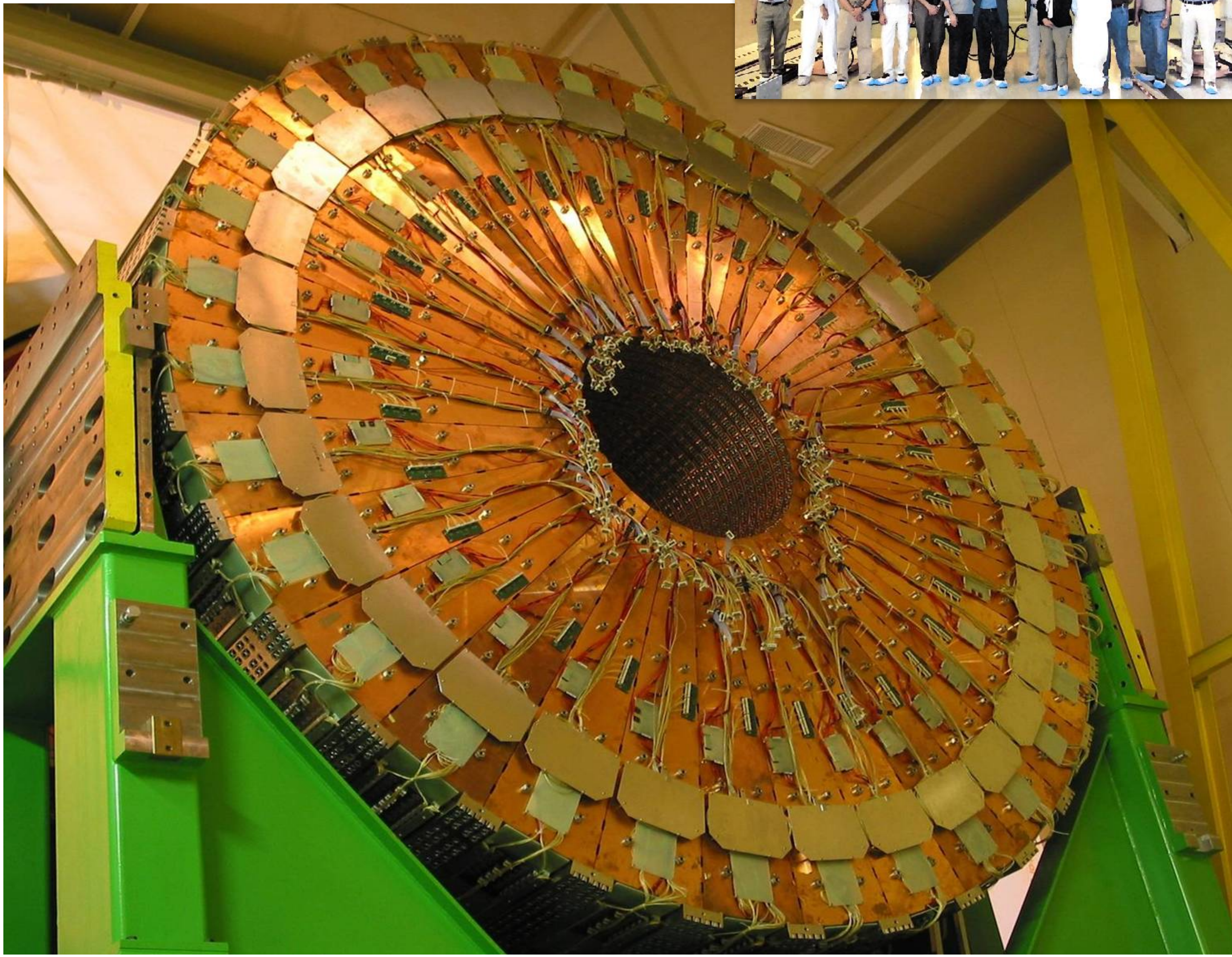
$$E \times \tau = \sum_{i=1}^{n} b_i (s_i - P);$$

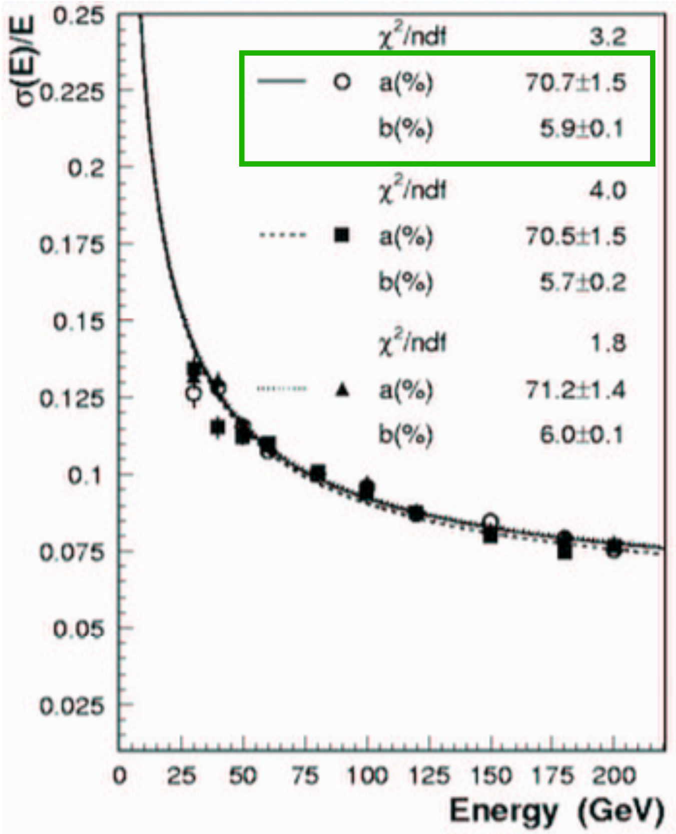
Canada: Hadronic End Cap calorimeter

On the insertion stand, Aug. 2004



Hadronic Endcap (HEC) consists of two wheels. The front wheel has copper plates of thickness 25mm, while this is relaxed to 50mm in the rear wheel due to the lower energy resolution requirement; the distance between the copper plates is 8.5mm. Each wheel consists of 32 modules. The HEC is 10λ deep, and has a lateral modularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ out to pseudorapidity of 2.5, and $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ beyond 2.5.





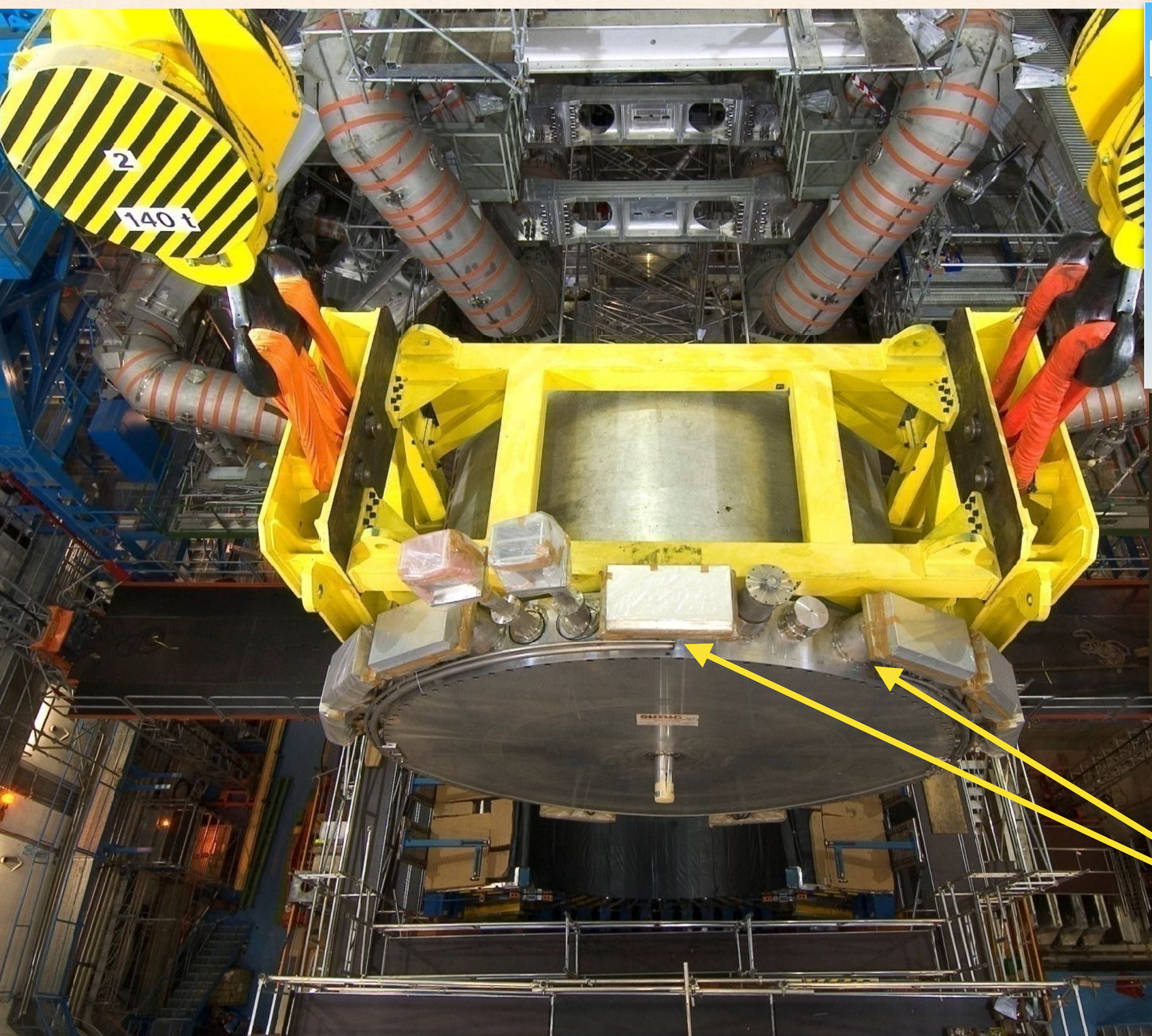
Achieved design resolution

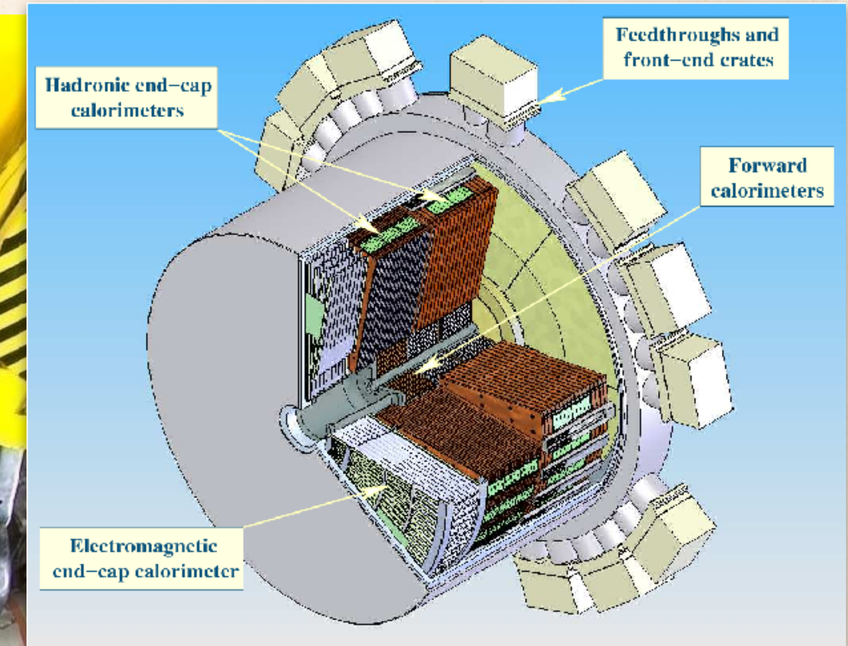
$$\frac{50\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus 3\% \leq \frac{\sigma}{E}(\mathrm{jets}) \leq \frac{100\%}{\sqrt{E\,(\mathrm{GeV})}} \oplus 10\%.$$

TRANSPORT OF 1 ENDCAP CALORIMETER TO ATLAS UNDERGROUND PIT, CERN, SEPTEMBER 2005

Photo by RT

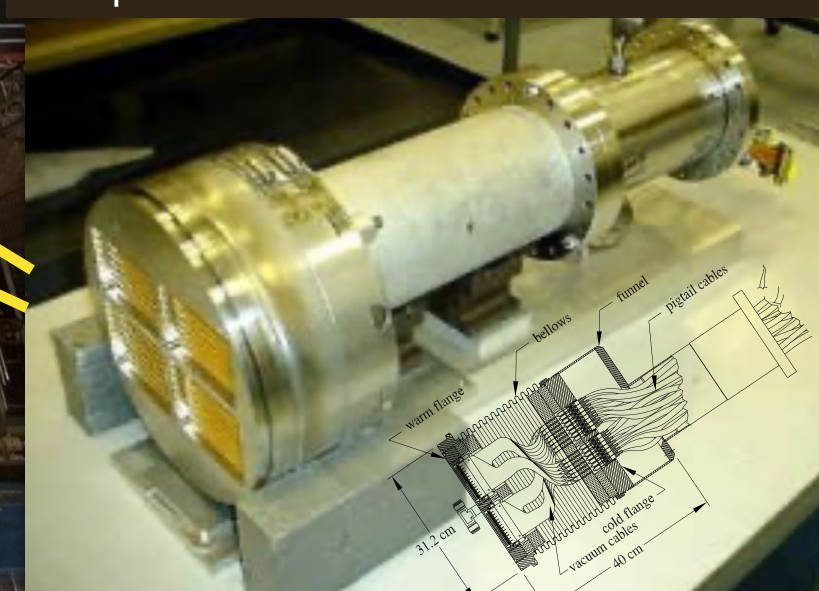
ENDCAP INSTALLATION IN ATLAS

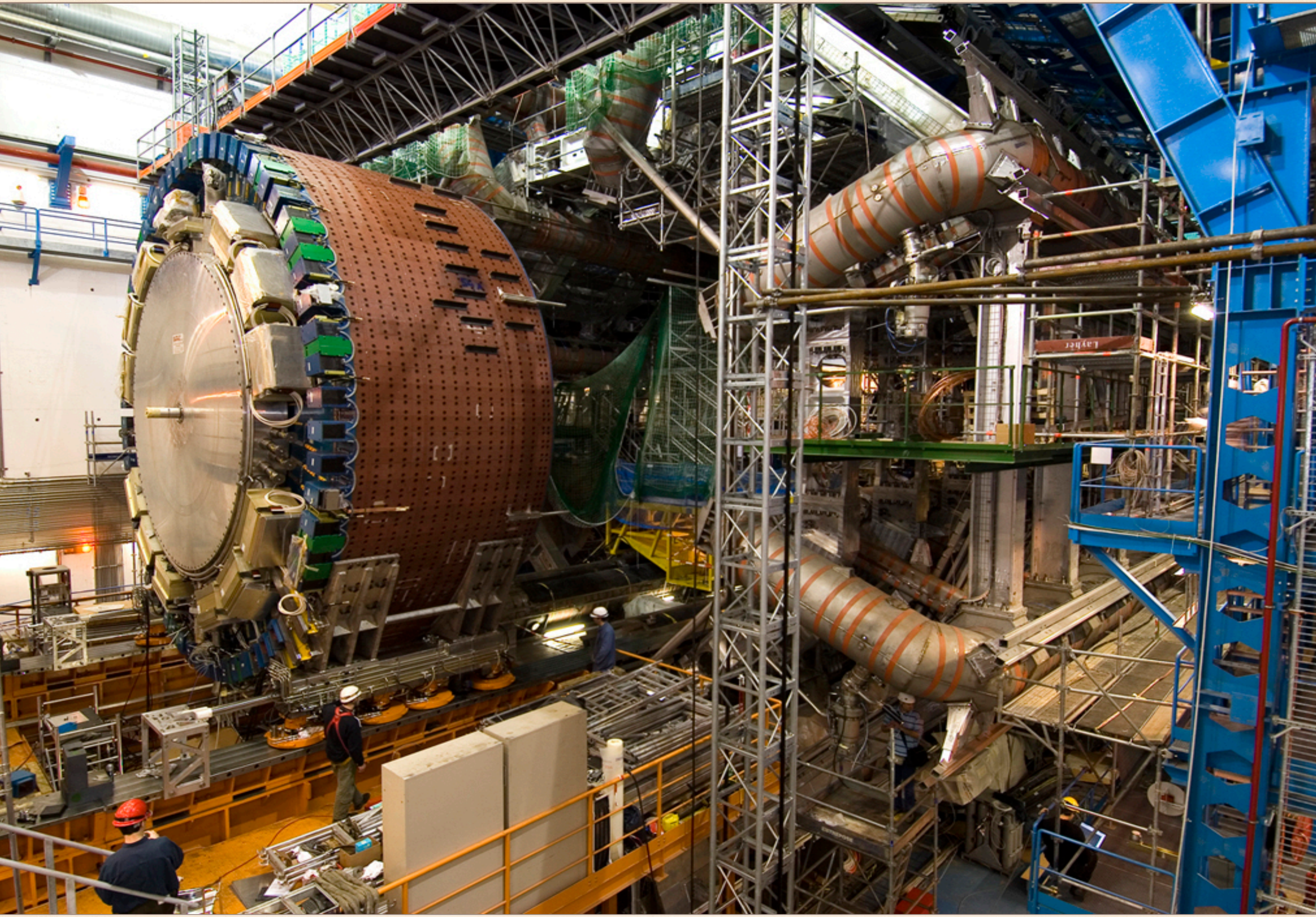




Cryostat Feedthroughs
(U.Victoria, UBC, TRIUMF)

The design is based on gold plated conductive pins insulated and sealed by ceramic or glass inserts in a stainless stee carrier. The carriers are then welded into the cold and ambient (temperature) flanges. A total of 1920 signal and calibration lines per feedthrough assembly is required.





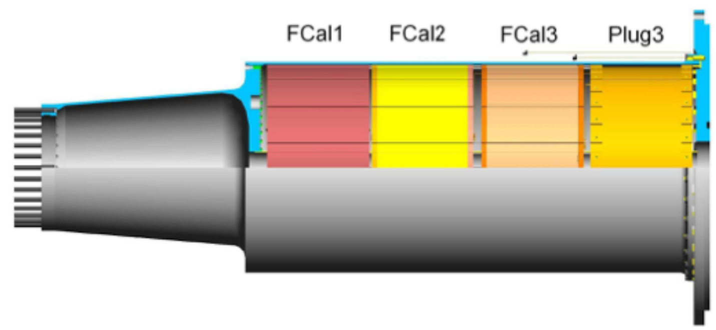
ATLAS Forward Calorimeter (FCal)

FCal1

Support Tube

Signal Cables run to rear

Carleton University,
University of Toronto



Assembly at CERN

CERN Testbeam

FCAL Covers the high pseudorapidity regime $3 \le |\eta| \le 5$.

Most challenging issues are radiation damage resistance, reliability, and the resistance to space charge limitations.

Annual radiation fluence is 10^{16} neutrons cm^{-2} and 2×10^{6} Gy; the thermal load is 100 watts.

Physics role: ensure hermeticity & tag very forward jets.

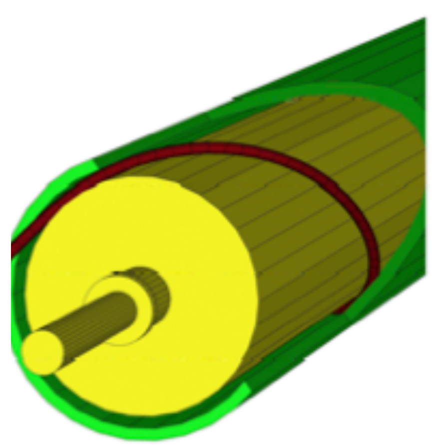
Resolution in transverse energy is most important. Due to the high energy of the particles in this region, the stochastic term in the energy resolution is not the most important, and the lateral modularity has to be chosen such that the angular resolution does not dominate the transverse energy resolution.

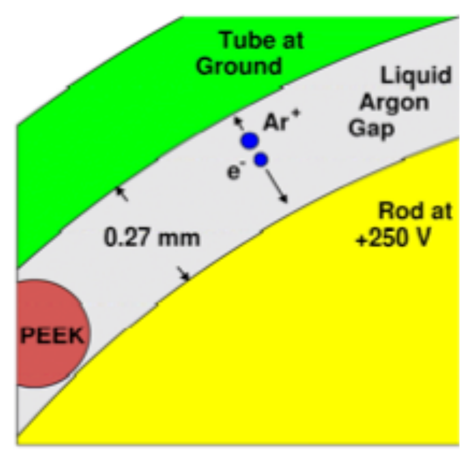
In order to achieve an E_T resolution of 10%, the requirement on the energy resolution is:

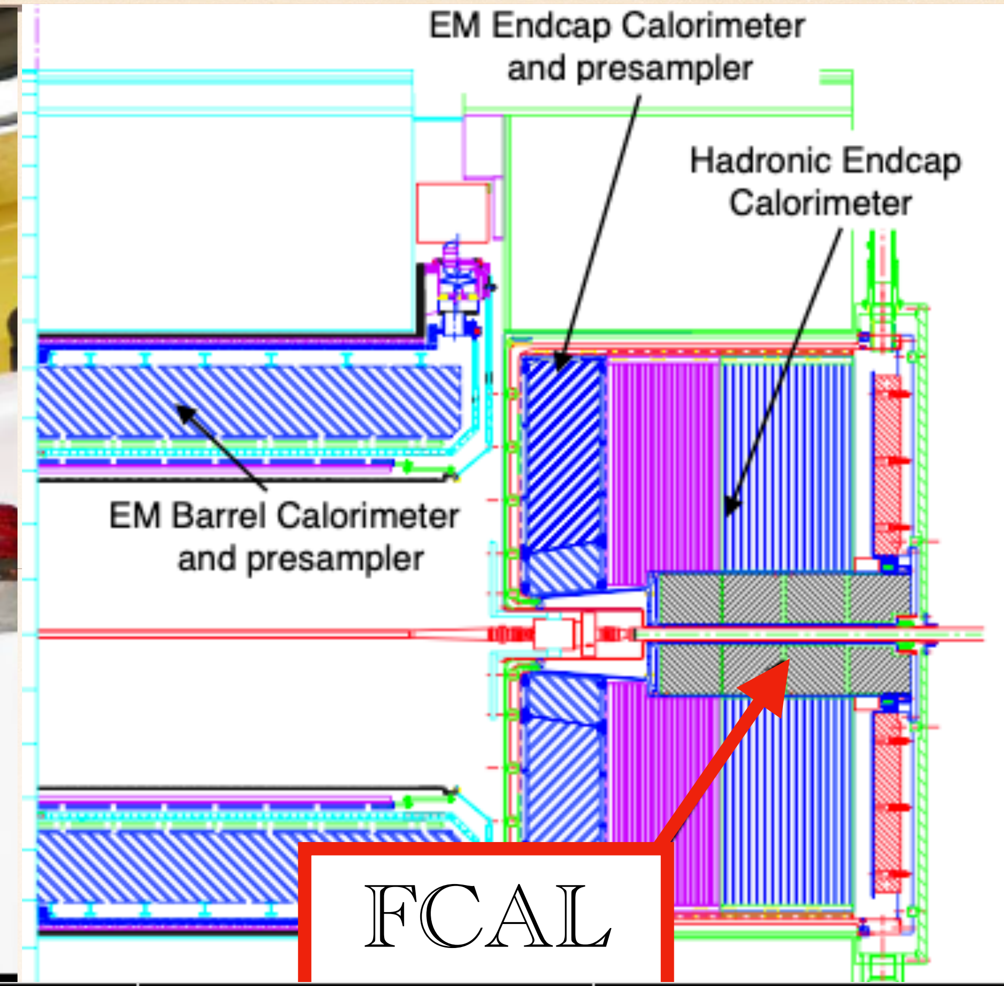
$$\frac{\sigma}{E}\,(\text{jets}) \le \frac{70\%}{\sqrt{E\,(\text{GeV})}} \oplus 7\%,$$

and the lateral modularity is $\Delta\eta \times \Delta\phi \approx 0.2 \times 0.2$.

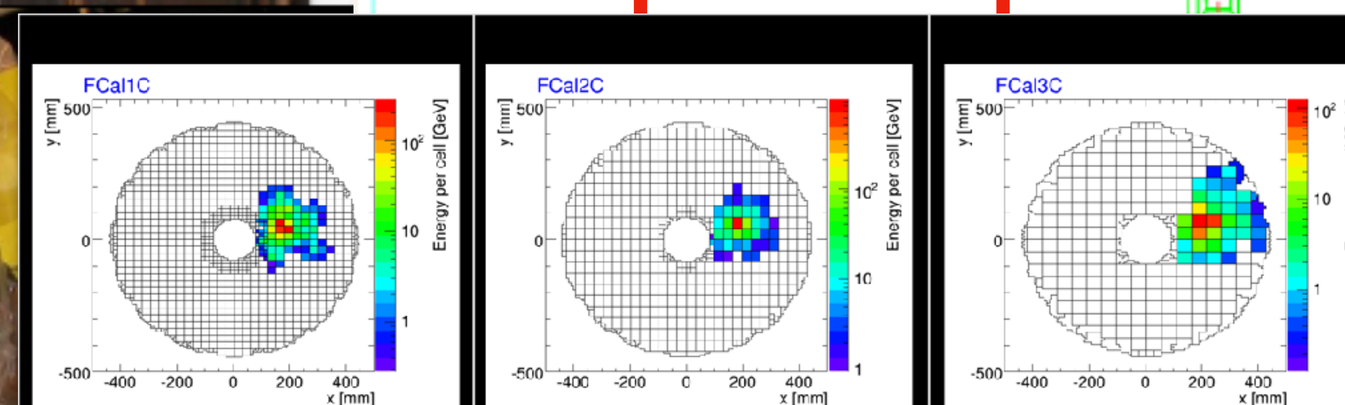
The particle flux in the very forward region of ATLAS requires extremely narrow LAr gaps, to avoid problems due to positive ion buildup. narrow gap size is achieved using a novel electrode structure; copper tubes, which form the cathode of the LAr cell are set into an absorber matrix, copper in the case of the EM module and tungsten in the case of the two hadronic modules. Into each of these tubes is inserted an anode rod, made of the same material as the absorber matrix. Each rod, which has a diameter slightly less than the inner diameter of the tube, is positioned concentrically using a helically-wound radiation-hard plastic fibre (PEEK), which maintains a very narrow, annular LAr gap. This gap size is 250μm for the electromagnetic modules, and 375μm (500μm) for the first (second) hadronic modules.



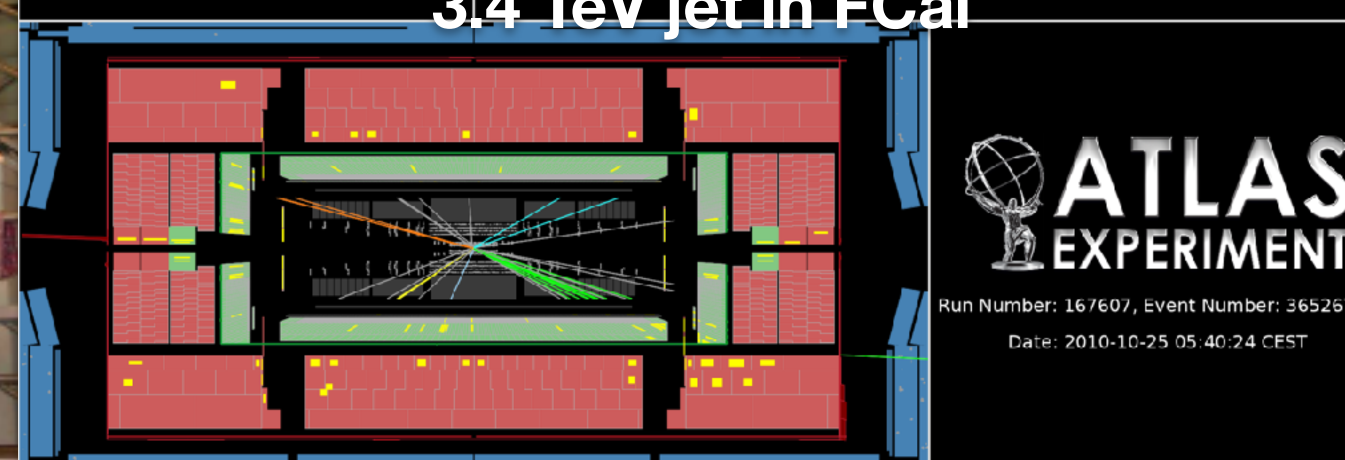




Insertion into
Endcap
calorimeter
At CERN

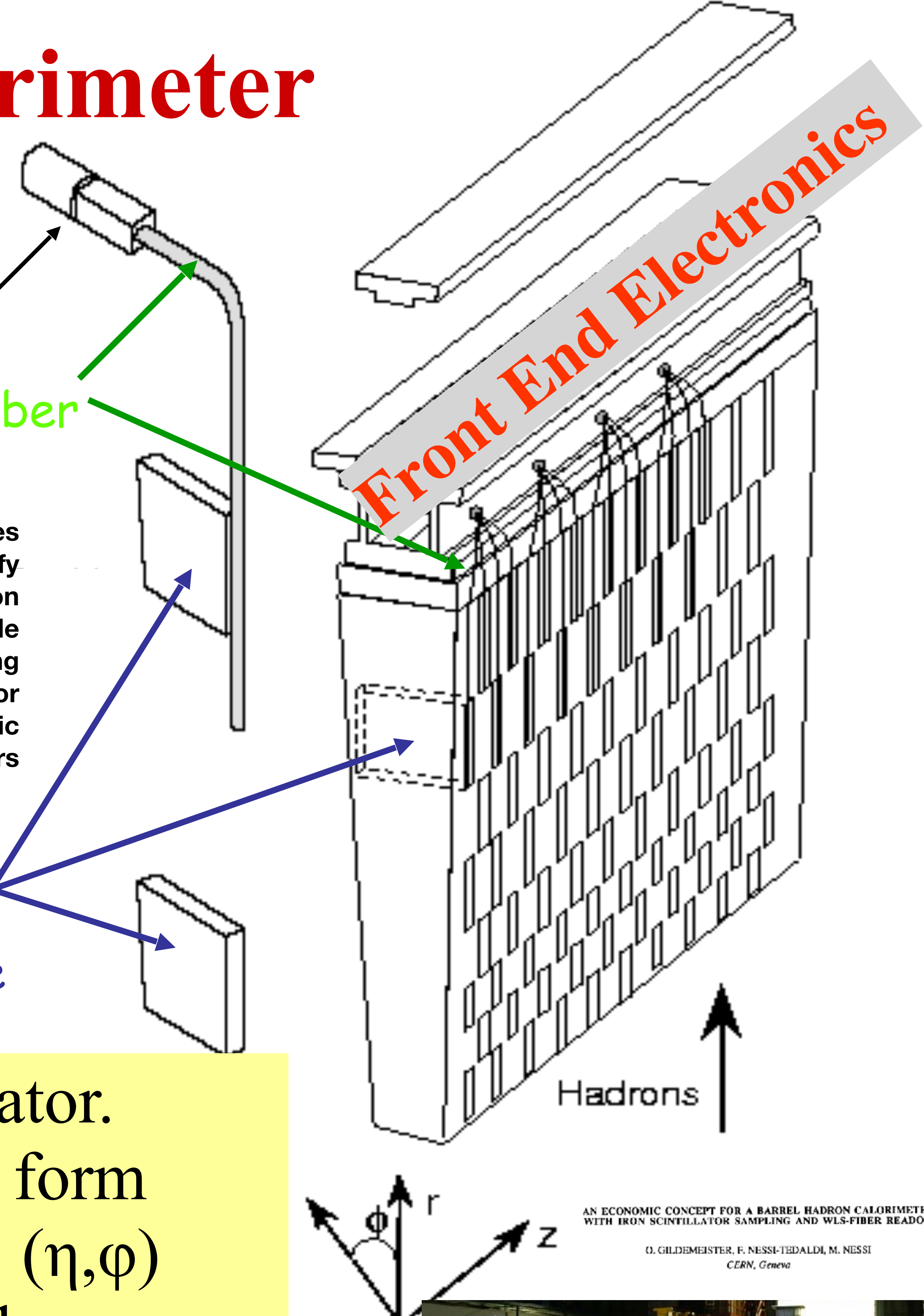


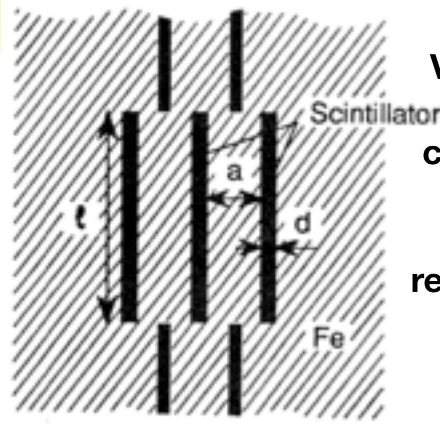
3.4 TeV jet in FCal



ATLAS hadronic tile calorimeter (TileCal):

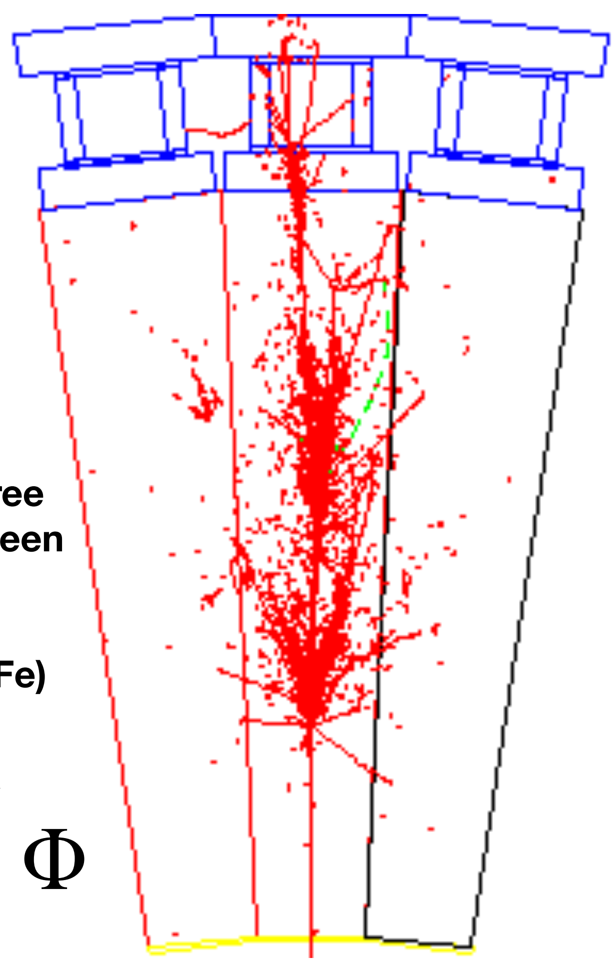
Measure light produced by charged particles in plastic scintillator.





Vertical tiles simplify construction while maintaining resolution for hadronic showers

Plastic scintillator inside steel absorber structure



7λ

λ Mean free path between inelastic collisions (17 cm in Fe)

Φ

Particles

- 2 fibres / scintillator.
- Bundle fibres to form cells of 0.1 x 0.1 (η,φ)
- 2 PMT's per cell

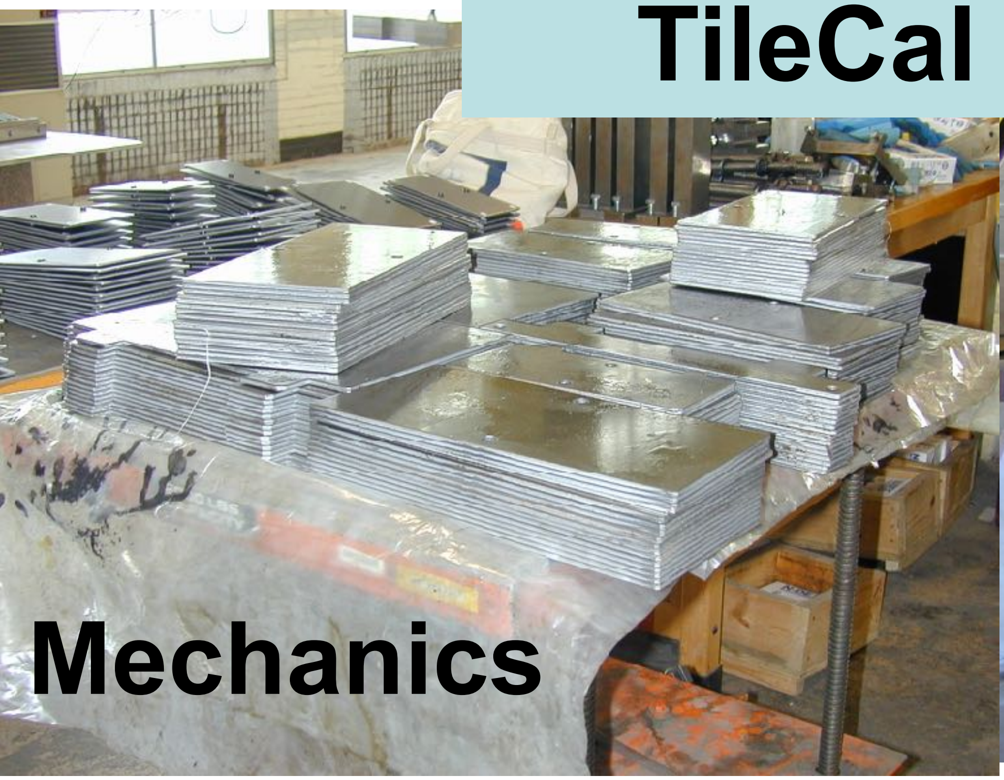
AN ECONOMIC CONCEPT FOR A BARREL HADRON CALORIMETER WITH IRON SCINTILLATOR SAMPLING AND WLS-FIBER READOUT

O. GILDEMEISTER, F. NESSI-TEDALDI, M. NESSI
CERN, Geneva


Gildemeister, UA2 calorimeter

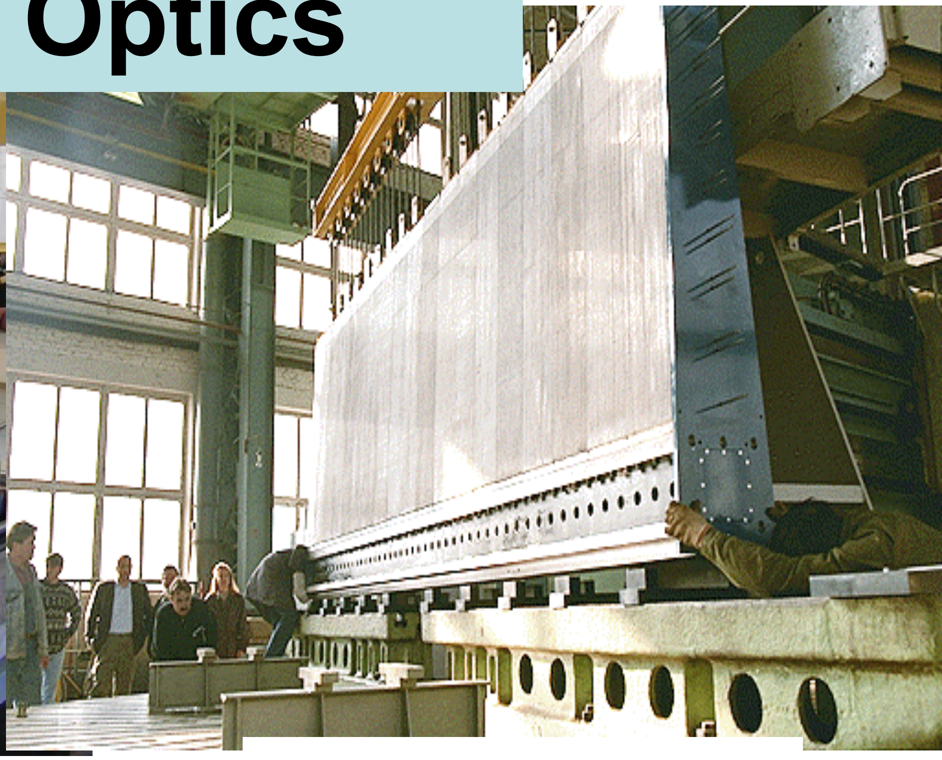
Performance: With em calorimeter, precise measurement of hadrons, jets, taus & missing transverse energy (ETmiss) w. jet resolution σ/E ~ 50%/√E [GeV] ⊕ 3%, response linearity within ~ 1% up to few TeV energies and good ETmiss.

TileCal Mechanics and Optics

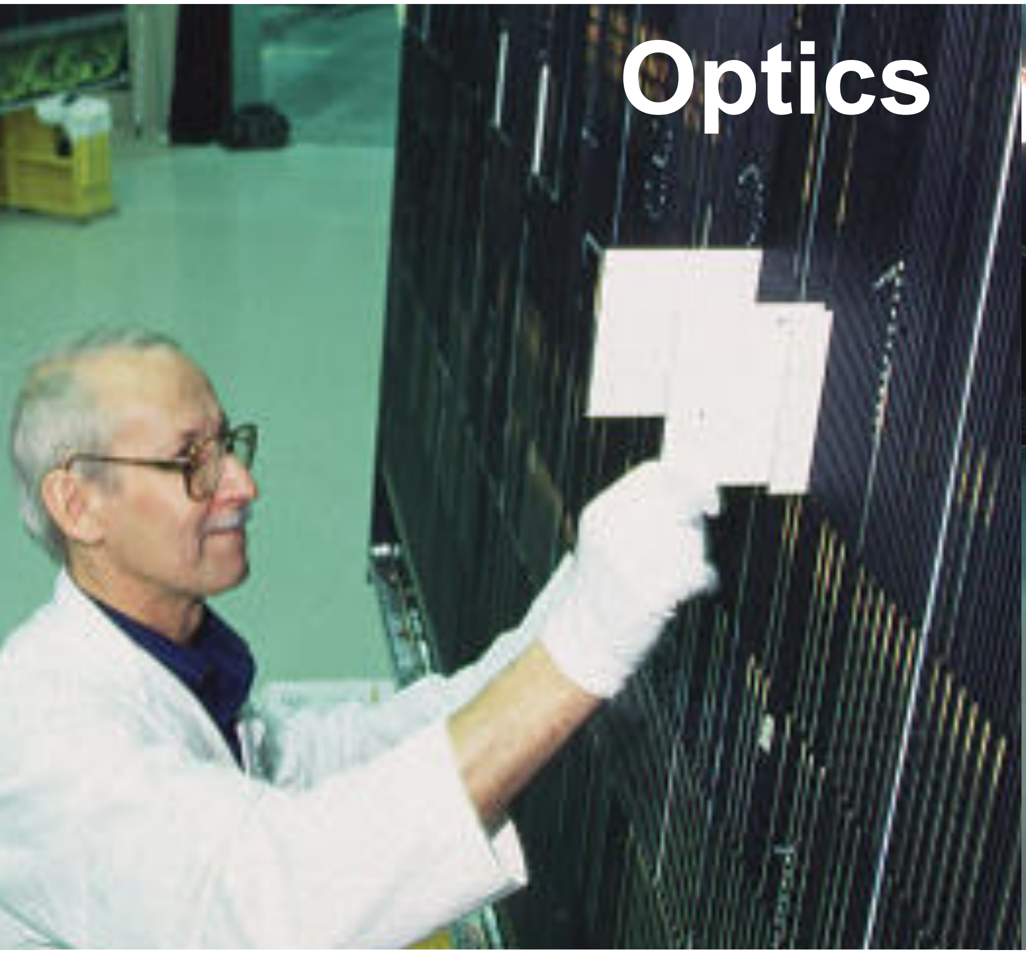


Laminated steel

Epoxy glue + press submodule



Assembled Module

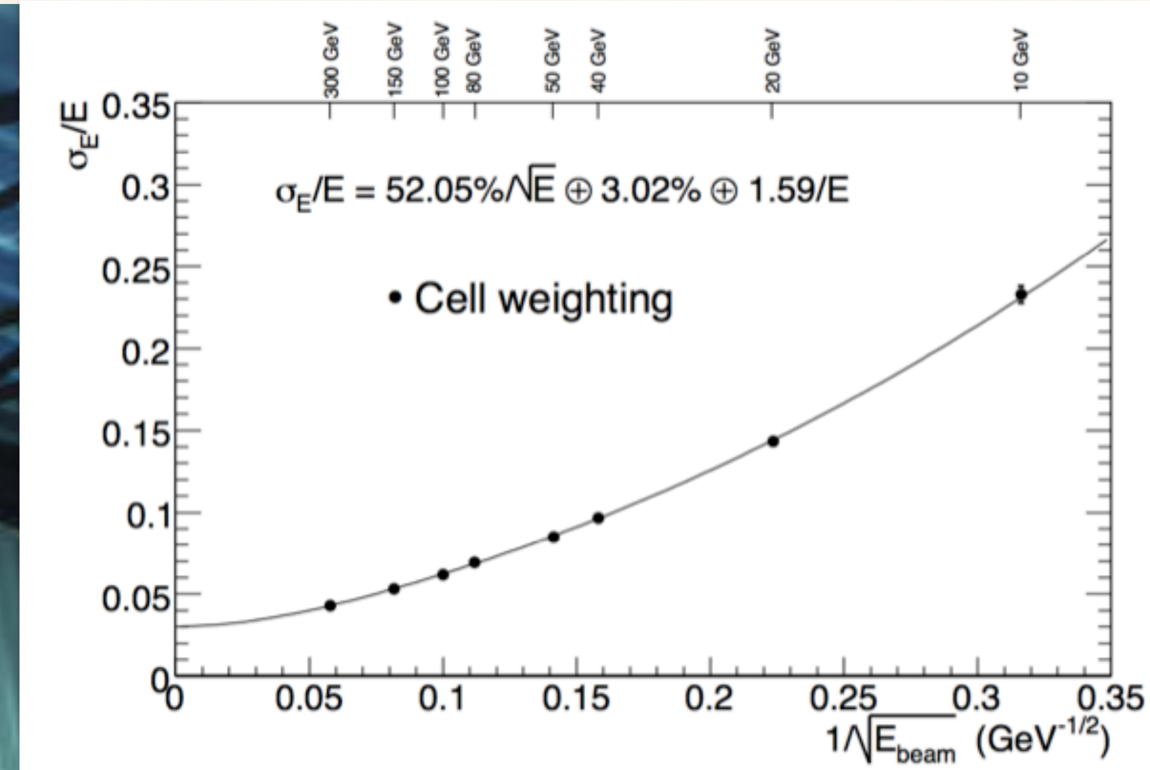


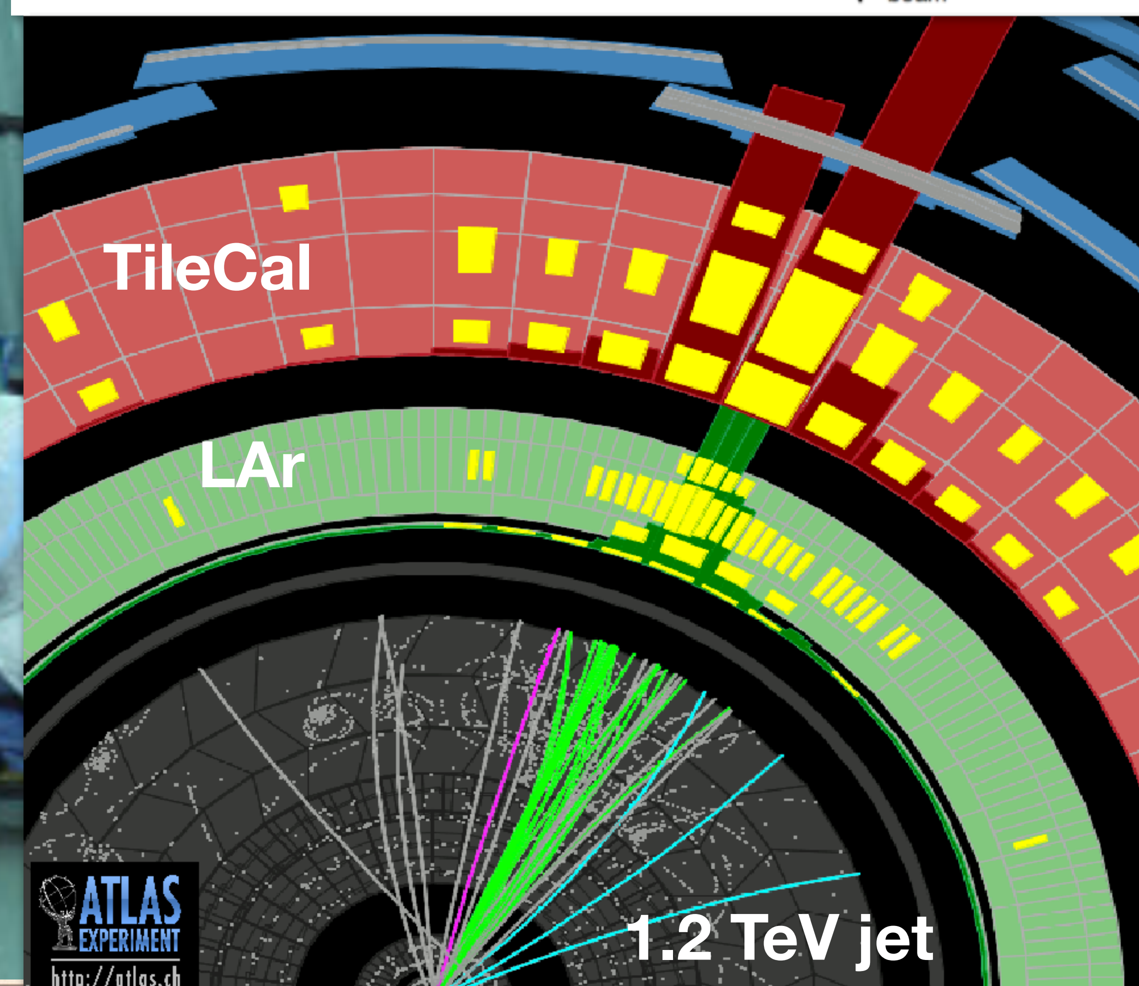
Insert tiles in module

Insert profiles with fibres

Fibre routing

ONE TILECAL BARREL MODULE





Calorimetry R&D in CALICE at McGill

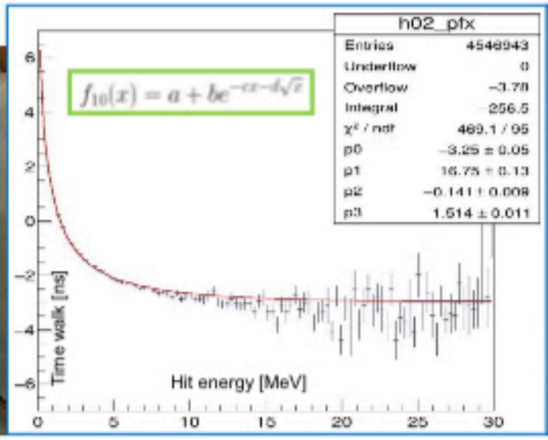
Group led by François Corriveau (IPP/McGill)

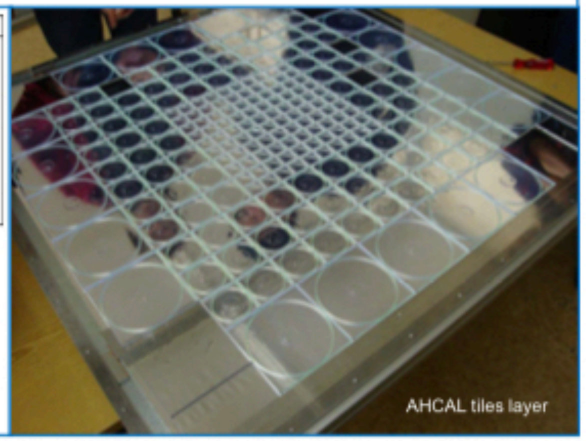
Main activities on very high granularity detectors (few cm^2):

Started in 2006 working on the Analog Hadronic Calorimeter (AHCAL) with simulation, alignment and performance analyses, *in situ* track segment calibration, new algorithm techniques..

With NSERC funding, McGill joined Argonne (ANL) to design, build and test the novel Digital Hadronic Calorimeter (DHCAL) prototype until completion. Several publications followed.

Now on the improved AHCAL with added accurate timing information for each hit to discriminate background and further particle ID. The new CMS forward detector is based on this technology.





INSTITUTE OF PARTICLE PHYSICS

HQP on detector R&D:

6 graduate students
17 undergraduate students

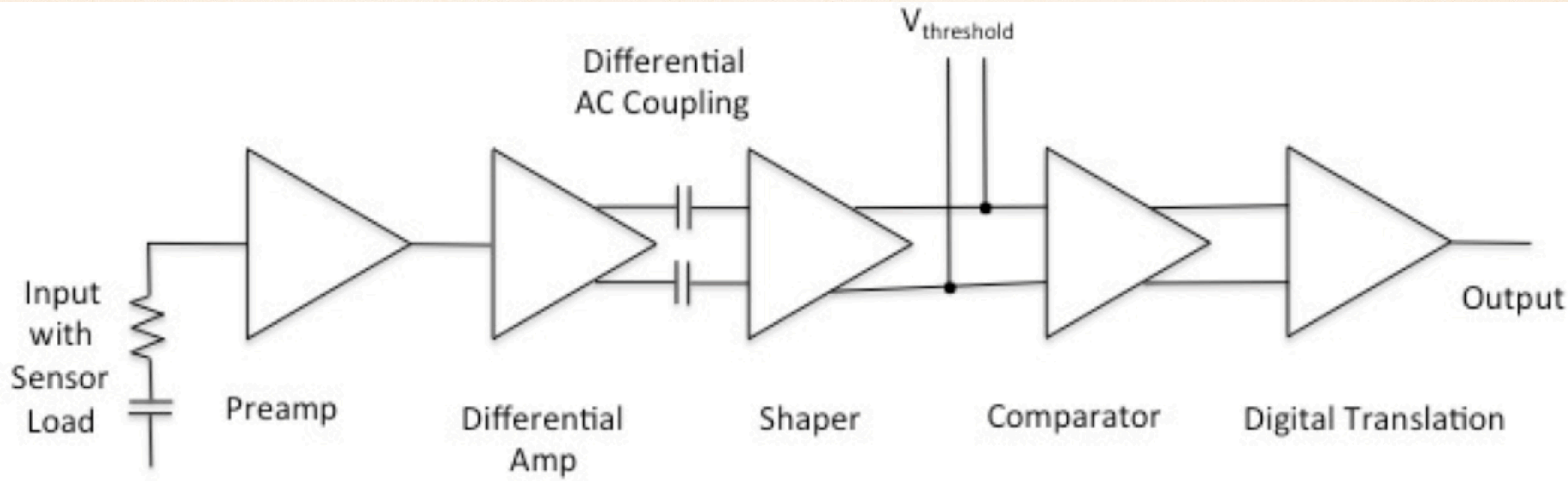
Funding since 2010:

NSERC individual Discovery Grant renewed (-2024)
2× contracts with ANL for visiting M.Sc. students
5× DAAD German summer student awards
6× NSERC USRA summer student awards
1x Mitacs Graduate Student Award for Germany
2× DAAD 3-month fellowships at MPP Munich (FC)

CALICE Collaboration on calorimetry R&D:

18 countries, 60 institutes, 350 physicists/engineers
Originally for ILC experiments, now also generic R&D

3) READOUT ELECTRONICS



- Example of hit/no-hit readout for tracker

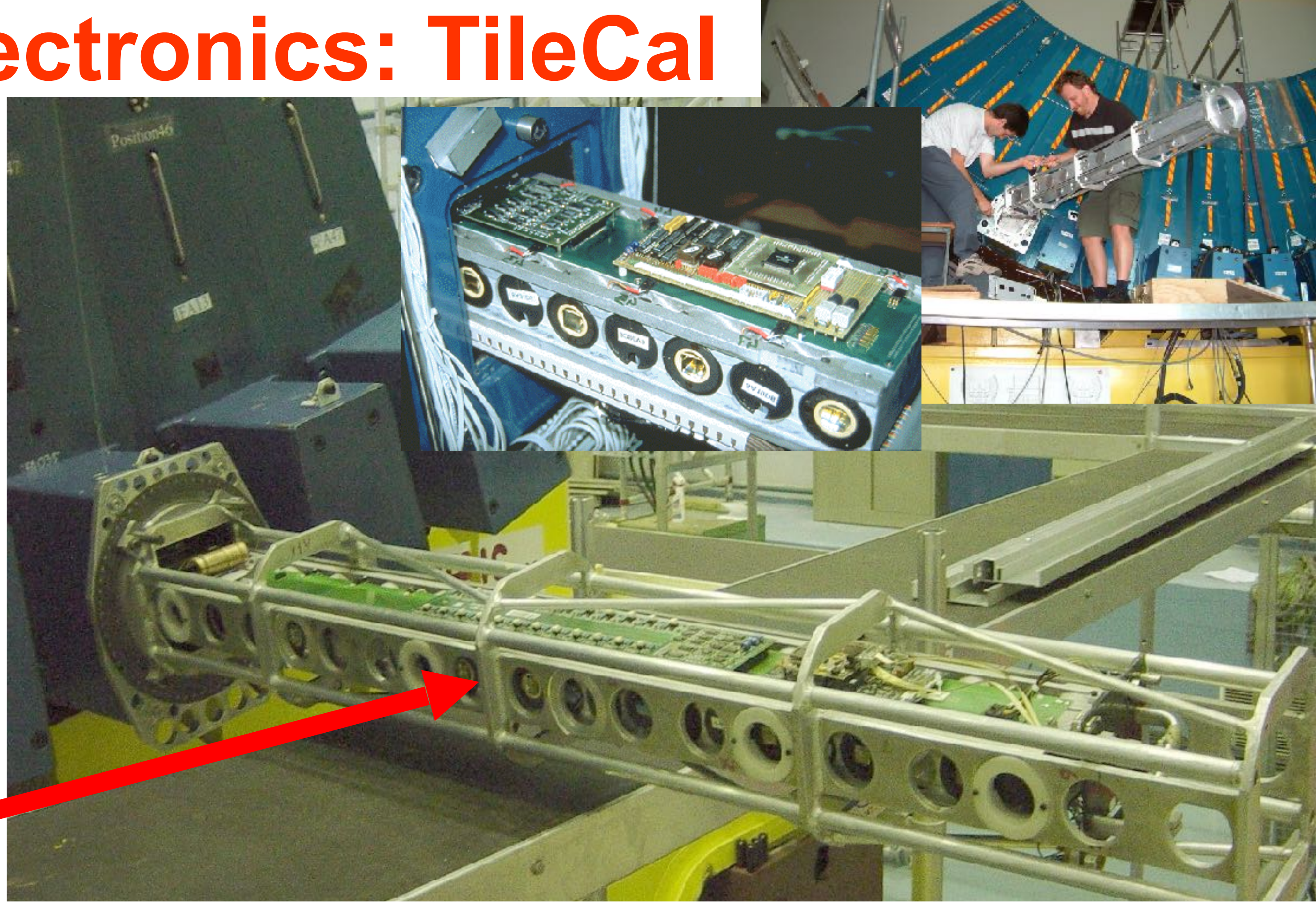
$$Noise\ Occupancy \propto \exp - \left(\frac{V^2_{threshold}}{2\sigma^2}\right)$$

- $V_{threshold}$: setting of comparator
- Example: if expected occupancy ~ 1% (e.g. ATLAS silicon tracker occupancy) —> $V_{threshold}/\sigma > 4:1$ (Signal/Noise)
- Typically require S/N > 20:1

Example of Front-End Electronics: TileCal

(More examples in ATLAS upgrade)

- Process 10000 PMT signals
- Effective 16 bit dynamic range
  - Up to 2 TeV in a single cell
  - Down to 30 MeV per cell
    - Must see muons @ 350 MeV/cell for calibration, monitoring, e- ID
- Readout should not degrade calorimeter energy resolution
  - Electronics noise low when merging cells into jets
- Radiation-tolerant >10 years
- Provide Level-1 Trigger tower sums
- Electronics located in 256 “drawers”
  - Each 3 m long, 50 kg



PMT drift over LHC Run 2 monitored at % level

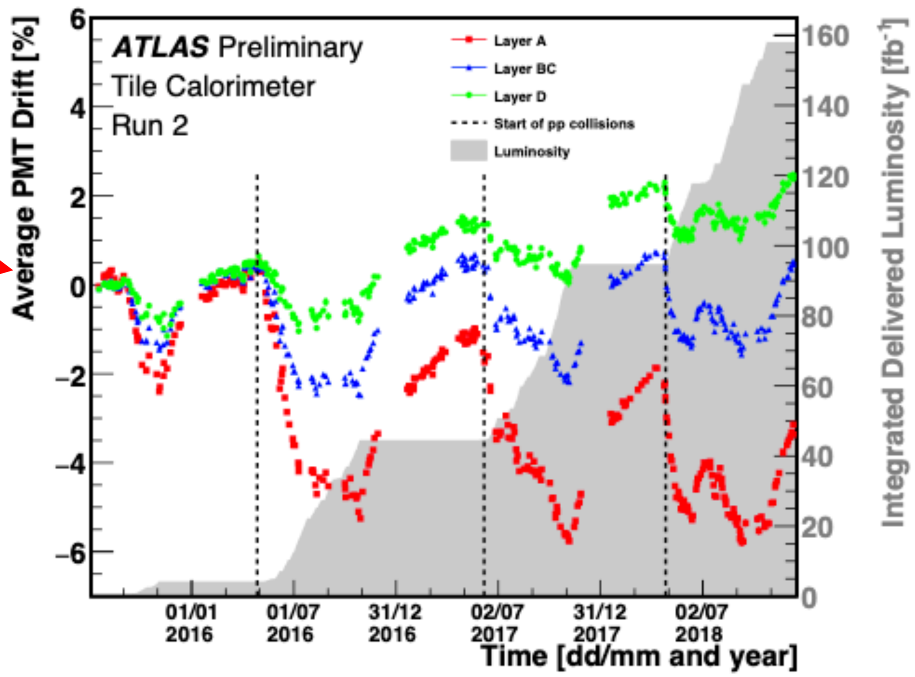
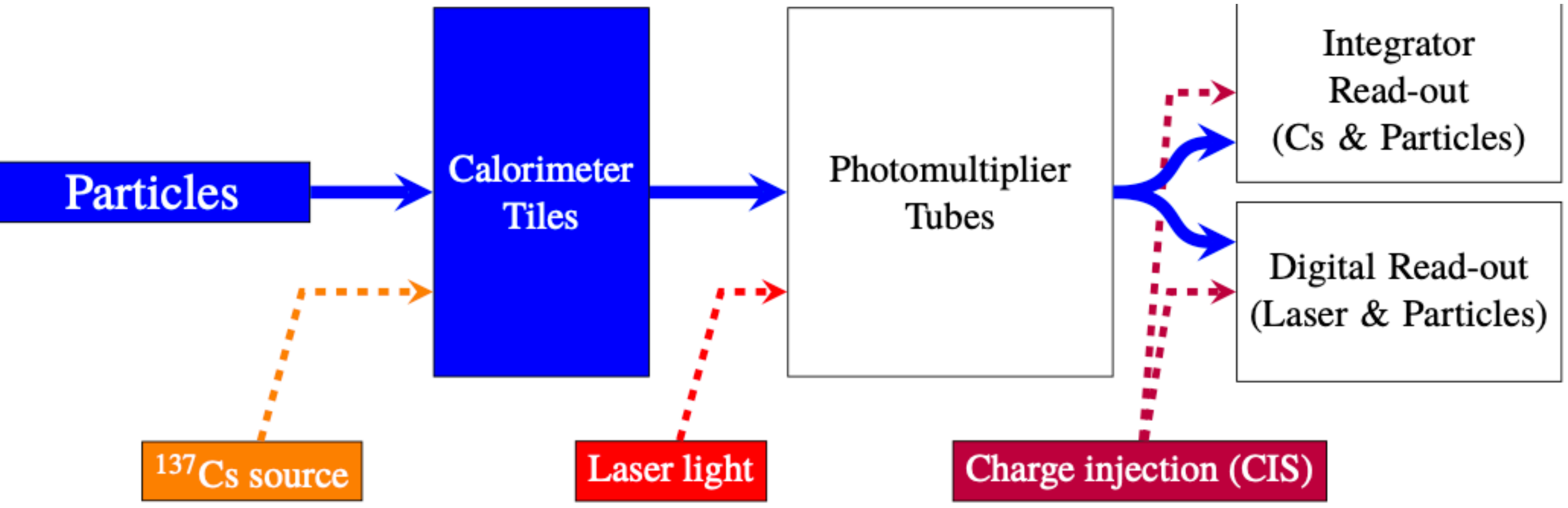
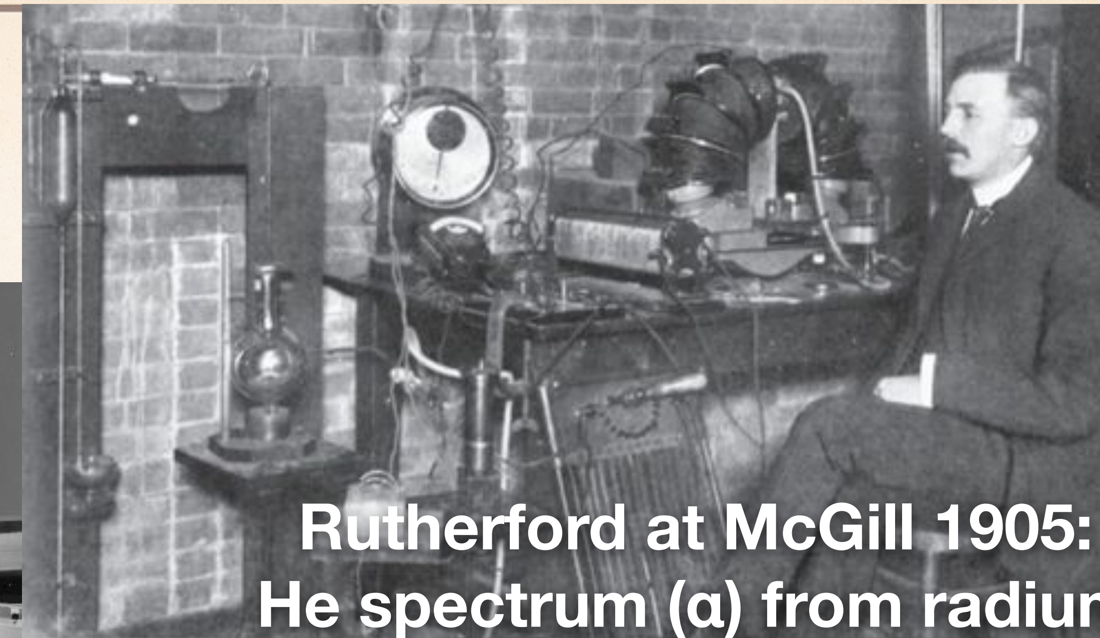


Figure 2. Drift of the PMTs reading out the three longitudinal layers in TileCal as a function of time during the LHC Run 2. The grey area represents the integrated delivered luminosity during Run 2 [3].

3 Calibration systems



4) DATA ACQUISITION



Rutherford at McGill 1905:
He spectrum (α) from radium

PDP 10 CERN 1974
BEBC 70 mm film

ERASME: a bubble chamber film
measuring system CERN 1974

- Bubble/cloud chambers: DAQ was photograph. Spark chambers (1964, Cronin & Fitch CPV) 1 trigger level camera
- e+e-: LEP: 5-10 Hz accept almost all collisions, CLEO III few 100's Hz
- Hadron colliders: Tevatron Run 2 2-20MHz beam collisions 2Hz trigger rate output Run 1, ZEUS eps: 10**7 Hz -> 5 Hz, ATLAS 400 Hz output rate.

DAQ: ZEUS
Third Level Trigger (TLT)

The Zeus Third Level Trigger Hardware Architecture and the Control System

D.Bailey, D.Bandyopadhyay, F.Benard, S.Bhadra, F.Chlebana, M.Crombie, R.S.Orr, C.Sampson, R.Teuscher

The Zeus TLT Group, Department of Physics, University of Toronto, Toronto, Ontario, M5S 1A7, Canada

CHEP 1992

The ZEUS third level trigger system consists of parallel branches of Silicon Graphics 35S RISC servers. Each server has a 36MHz processor, 32MBytes of memory, and a 200MByte disk. The Third Level Trigger interface with the ZEUS Event Builder comprises six VME crates, each containing a triple ported memory from which the trigger nodes read complete events via the Fermilab Branch Bus. The Branch Bus is connected to each node through the single VME slot in the 35S. The system is divided into six branches corresponding to the six Event Builder crates. The processing nodes output accepted events concurrently through the Fermilab crossbar switch to a VAX cluster and an IBM mainframe. The event I/O in each branch is controlled by separate input and output mangement processes. The allocation of hardware resources and supervision of the overall job is done by a job manager process.

The Use of the ZEUS Offline Event Reconstruction Code in the ZEUS Third Level Trigger System

D. Bailey, D. Bardyopadhyay, F. Bénard, S. Bhadra, F. Chlebana, M. Crombie, G. Harner, R. S. Orr, C. Sampson, R. Teuscher

A High Speed DMA Extender for the ZEUS Third Level Trigger Silicon Graphics 4D/35S Processors.

D. Bailey, D. Bandyopadhyay, F. Bénard, S. Bhadra, F. Chlebana, M. Crombie, M. Nagy[1], R.S. Orr, C. Sampson, G. Stairs, R. Teuscher

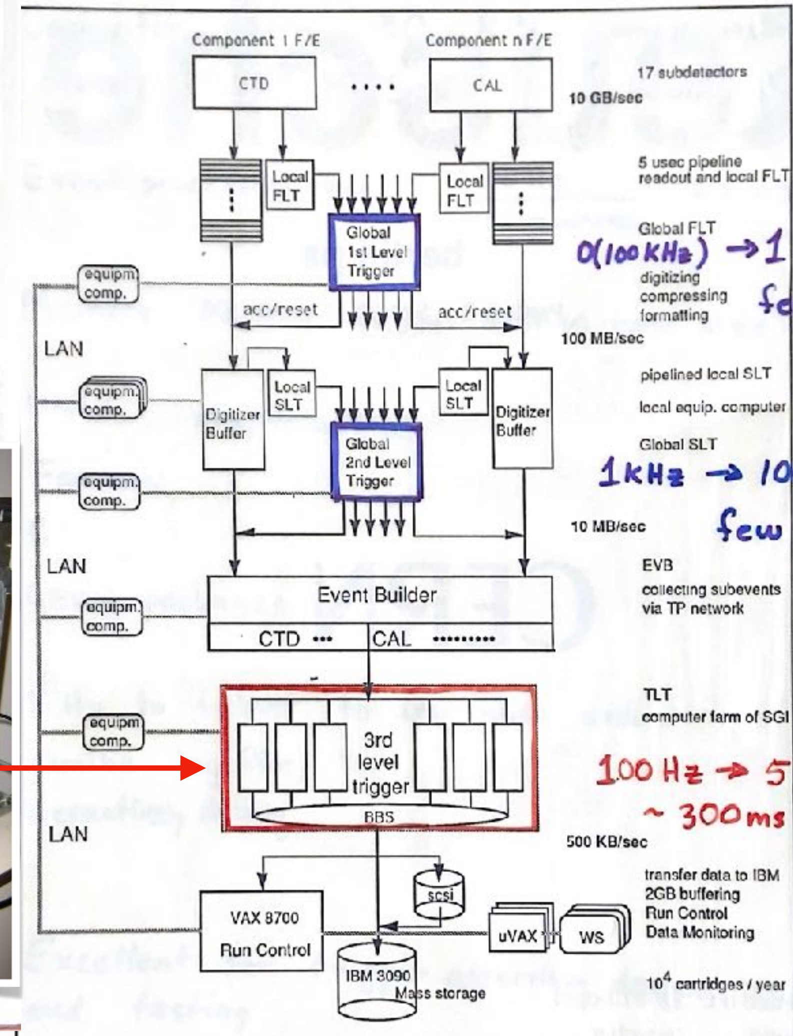
TLT Environment

- Computer farm 30 RISC commercial proc. > 10^3 MIPS
- Event processing time $\frac{100\text{ Hz}}{30\text{ machines}}$ → ~300ms average
- Memory 32 MB (upper limit on code size)
- UNIX, nfs, telnet
  FORTRAN
  C
  CERN packages

Online Background Reduction in the Zeus Third Level Trigger

R. Teuscher

Zeus Third Level Trigger Group

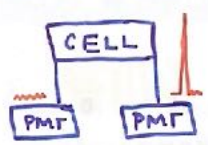


Outline of the ZEUS data acqusition system

TLT was needed on day-1!

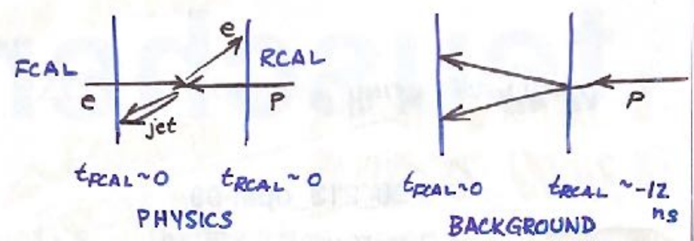
First TLT Cut : Spark Cut

- Events triggered on large calorimeter energy
  1 PMT : large signal
  paired PMT : negligible

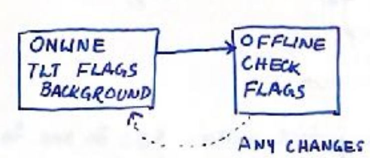


- Cut of this nature not forseen in original trigger design
  - FLT : hardware changes
  - SLT : could in principle cut but processors designed to see calorimeter cells, not PMT's
  - TLT : full raw data available calorimeter reconstruction code easily modified to flag, then later cut
- Independent analysis code run offline to verify TLT algorithm and determine safety
- After extensive offline checks, TLT started cutting 30% raw event reduction

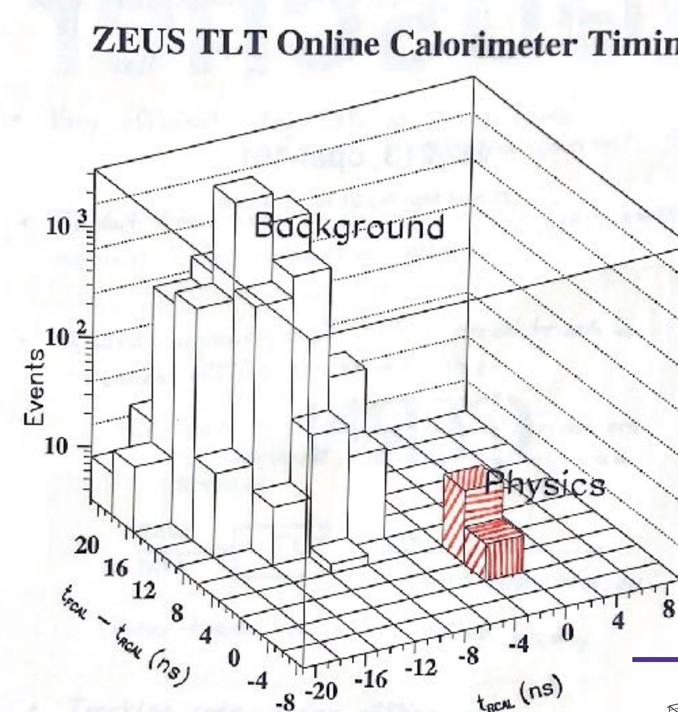
Second TLT Cut : Timing



- ZEUS calorimeter provides particle arrival times (few GeV energy) with resolution ~ 1 ns
  Beam gas : $|t_{FCAL} - t_{RCAL} - 12| \le 8$ and $|t_{RCAL} + 12| \le 8$
  Physics : $|t_{FCAL} - t_{RCAL}| \le 8$ and $|t_{RCAL}| \le 8$
  else unknown timing
- Algorithm quickly implemented in TLT ~ 1 day
  most time spent in physics testing ~ 1 mo
- FORTRAN → any physicist may examine

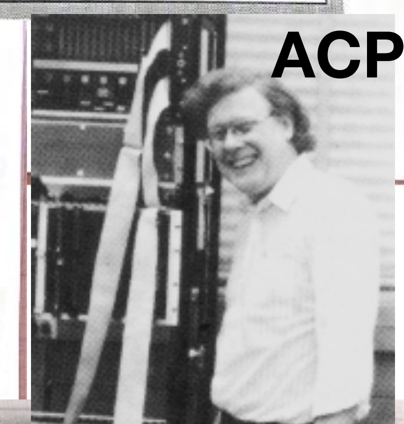


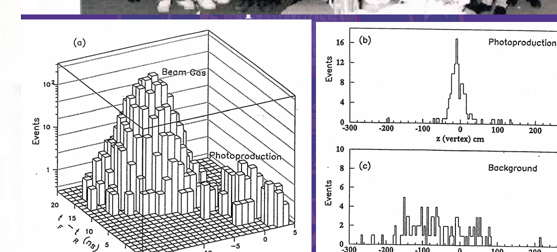
- CUT approved ; TLT prescales 1/6 as further check
  now cut transferred to SLT



Example of one of 50+ online histograms

ACP

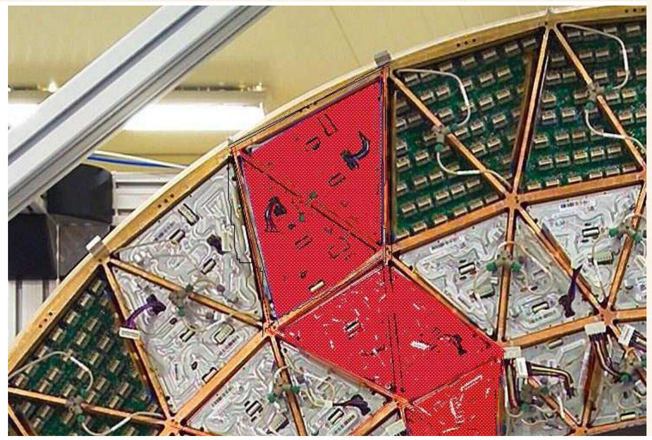


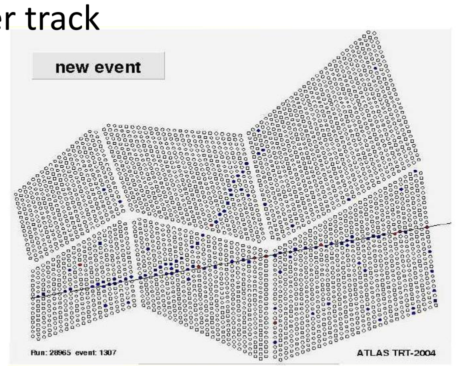


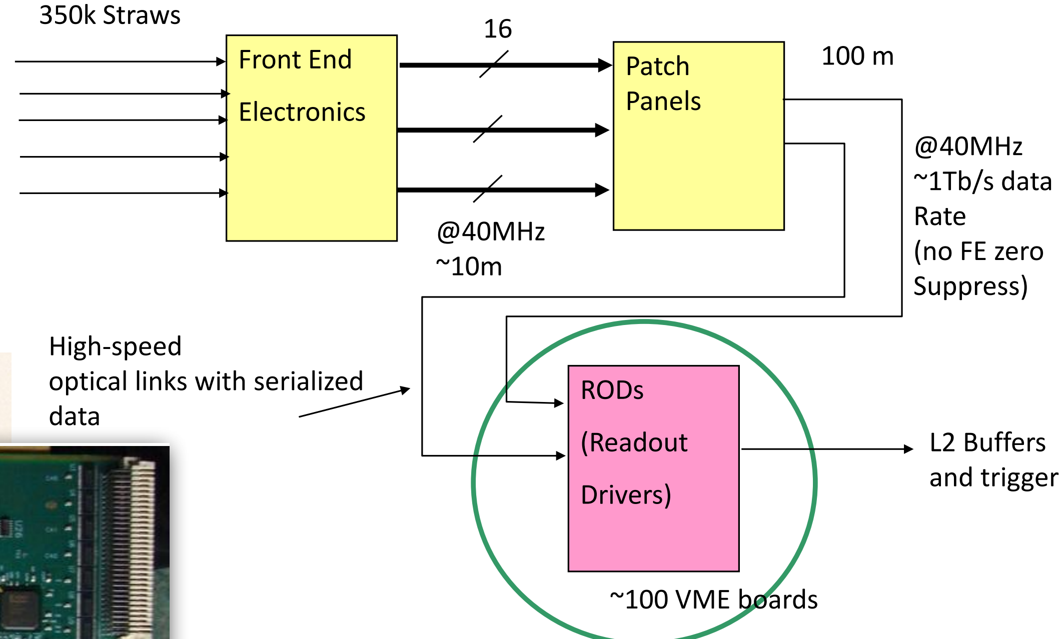
SOME OTHER EXAMPLES OF DATA ACQUISITION

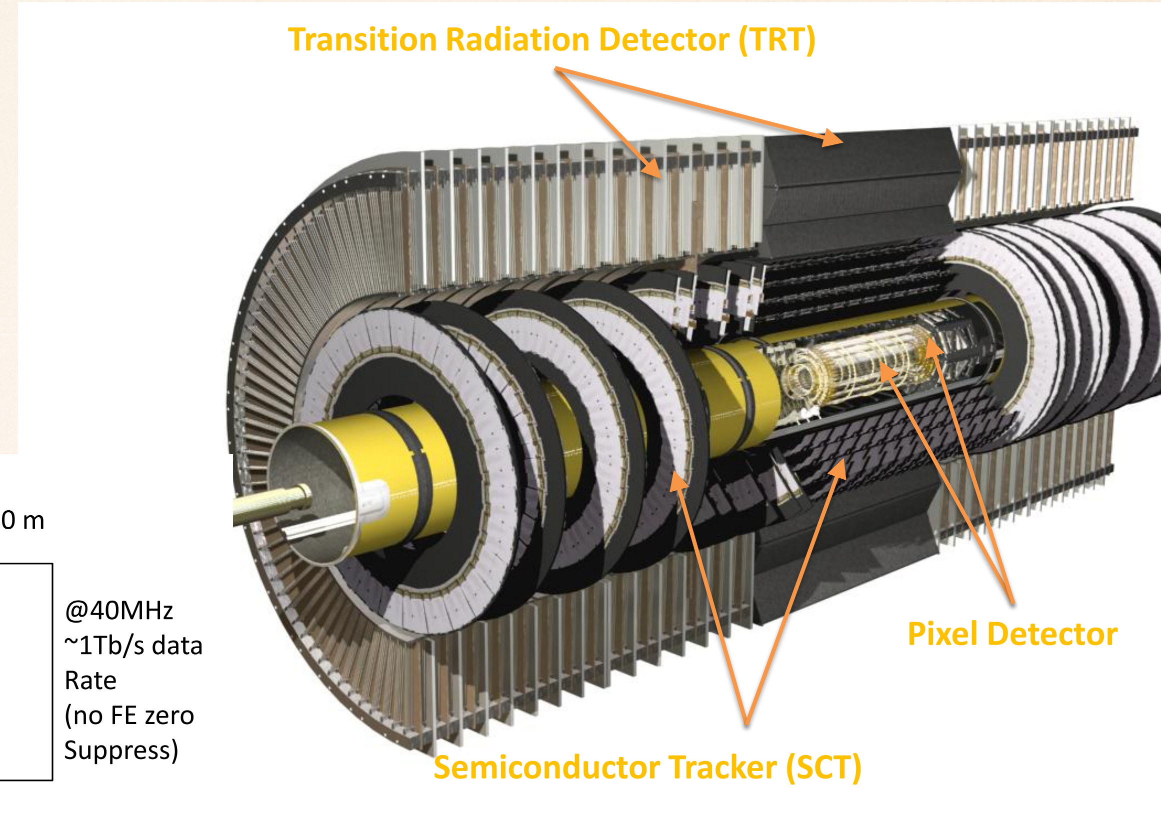
- ATLAS Transition Radiation Tracker (TRT) Readout Drivers (G. Gay et al UBC)

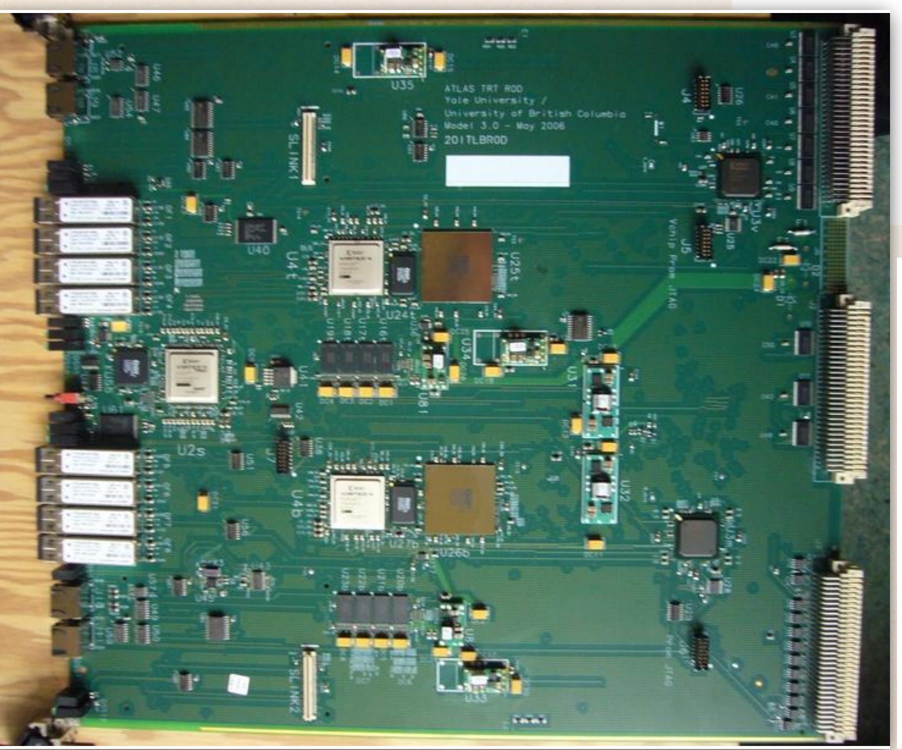
- 52,544 straws
- 3 layers of modules
- 32 modules (phi sectors) per layer
- Shaped funny so no radial dead spots
- 73 layers of straws per sector
- Axial only, no stereo for z extraction
- 7mm straw spacing (4mm diameter, so ~55% coverage)
- ~36 hits per track





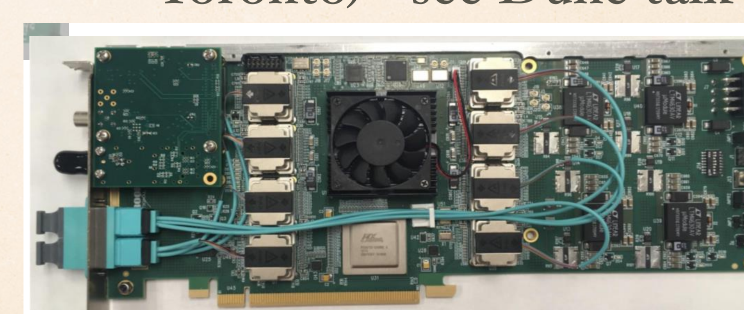






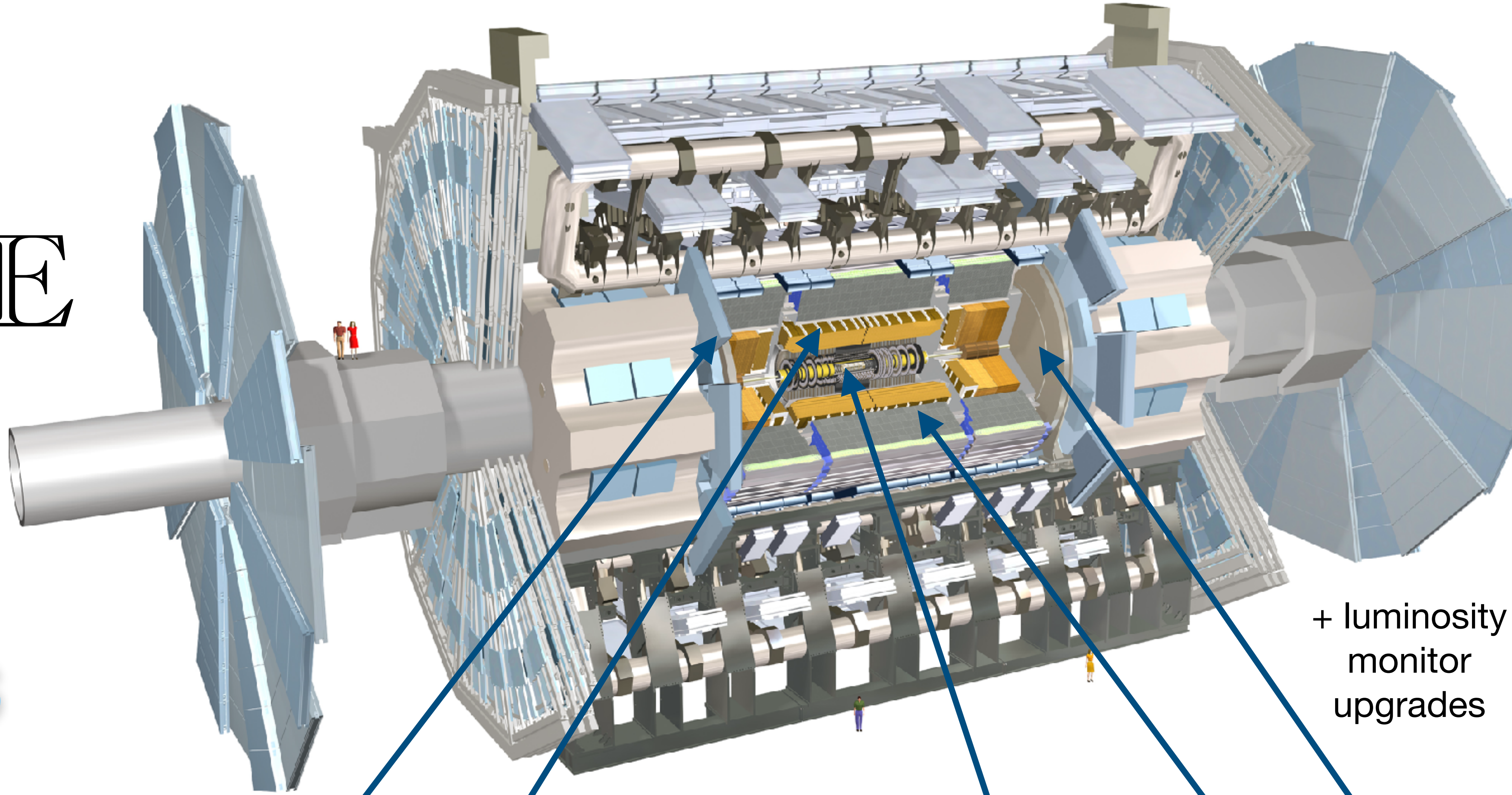
- ~100 VME boards, each with 8x1.6 GHz optical inputs receive digitized data from each straw (27 bits/straw/trigger)
- Check for errors (single-event upset, data format errors, etc), Buffer data
- Compress, based on the entropy of the data using specialized chip developed for internet routers.

- ATLAS FELIX Front-End Link Exchange (N.Ilic et al / IPP/ Toronto) - see Dune talk



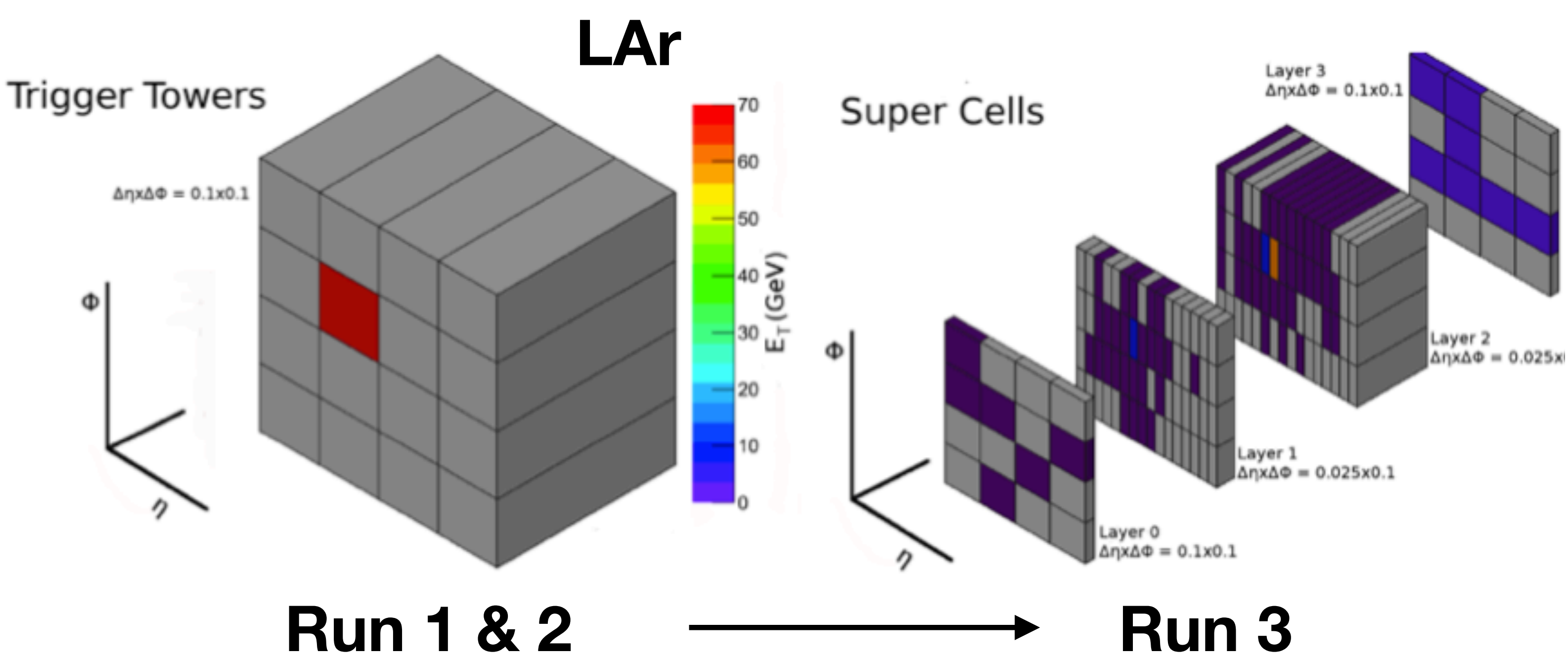
5) THE FUTURE

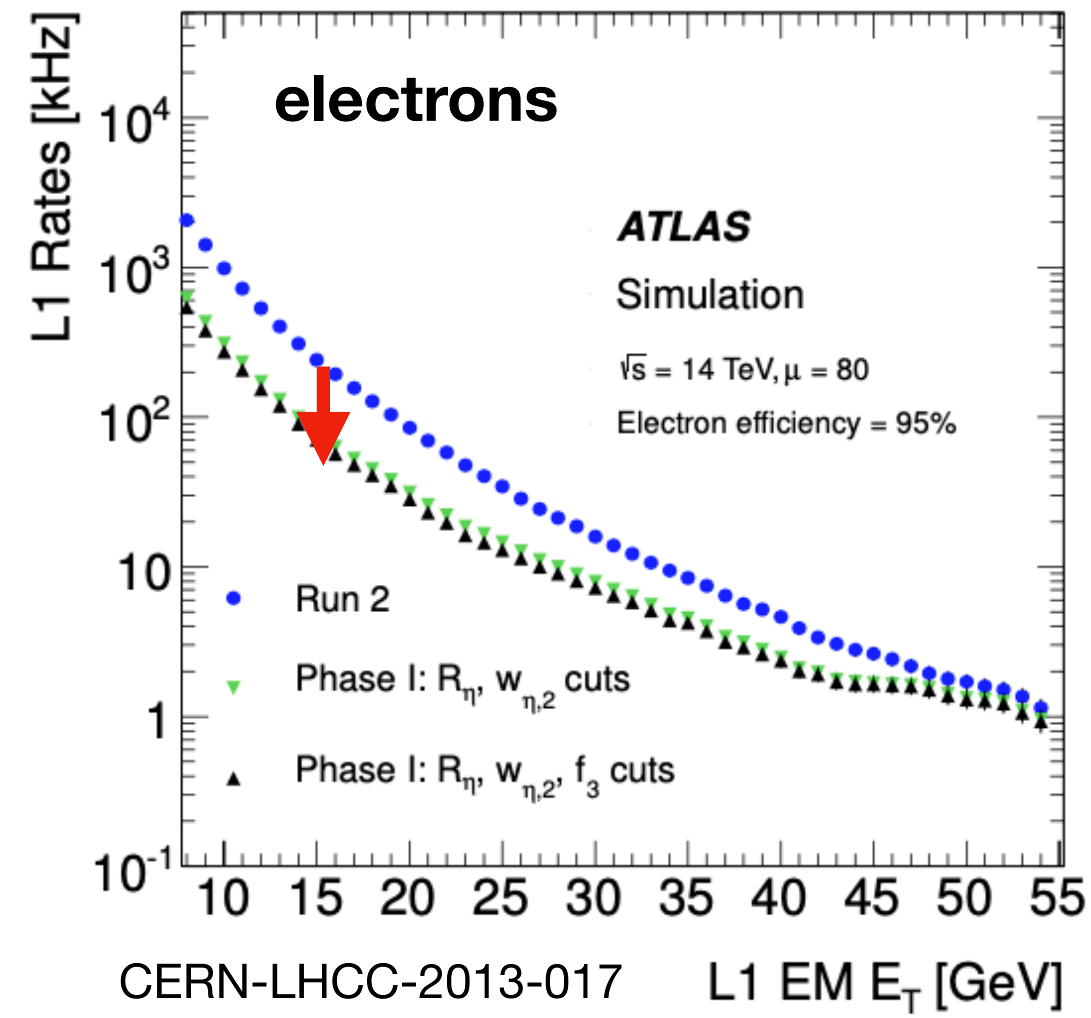
ATLAS Upgrades

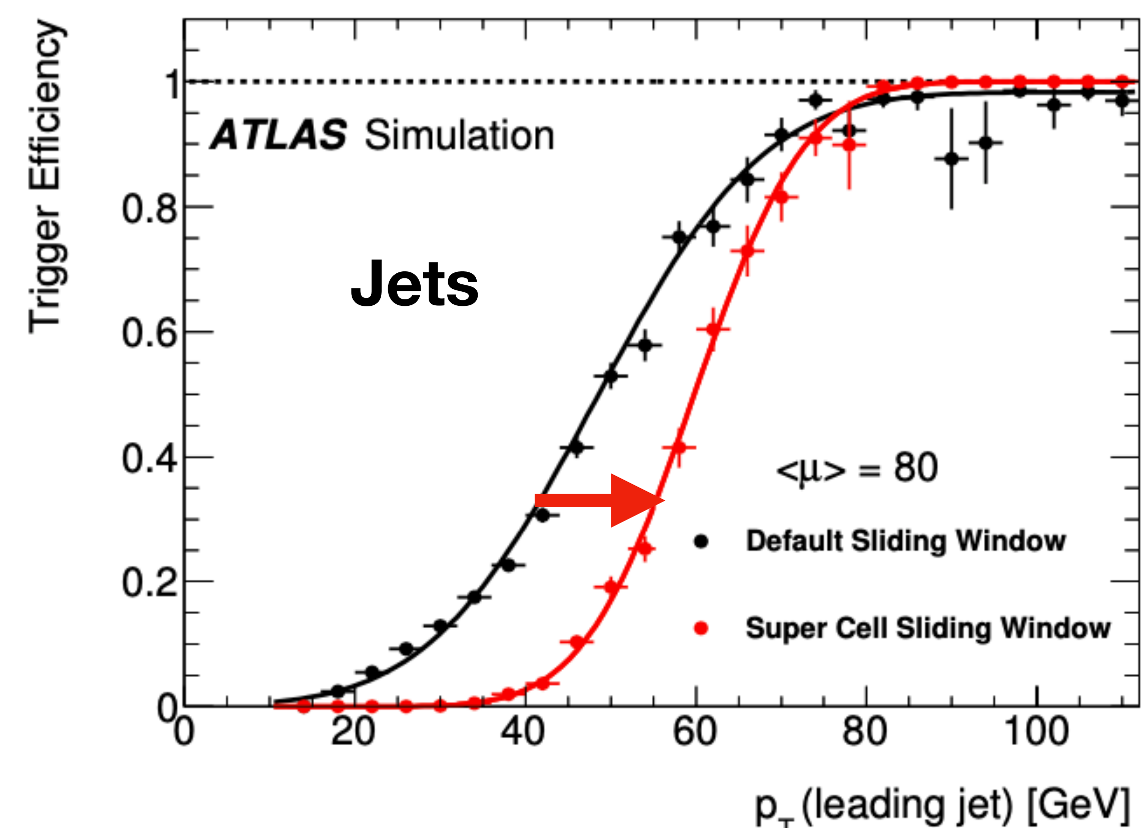


System	Now: Phase-I	Future: Phase-II
Muon	New Small Wheels (NSW)	Muon chambers for inner barrel Continuous readout.
Tracking		All-silicon Inner Tracker (ITk) w. $\|\eta\| < 4$
Calorimeters	Level-1 (L1) trigger electronics Liquid Argon (LAr):	LAr: Continuous readout Tile Calorimeter (TileCal): Continuous readout
Timing		High-Granularity Timing Detector (HGTD)
Trigger / DAQ	Trigger hardware - Higher purity e/γ triggers - Lower forward muon fake rate	L1 rate increased: 1 MHz High Level Trigger increased: 10 kHz

Upgrades to Calorimeters

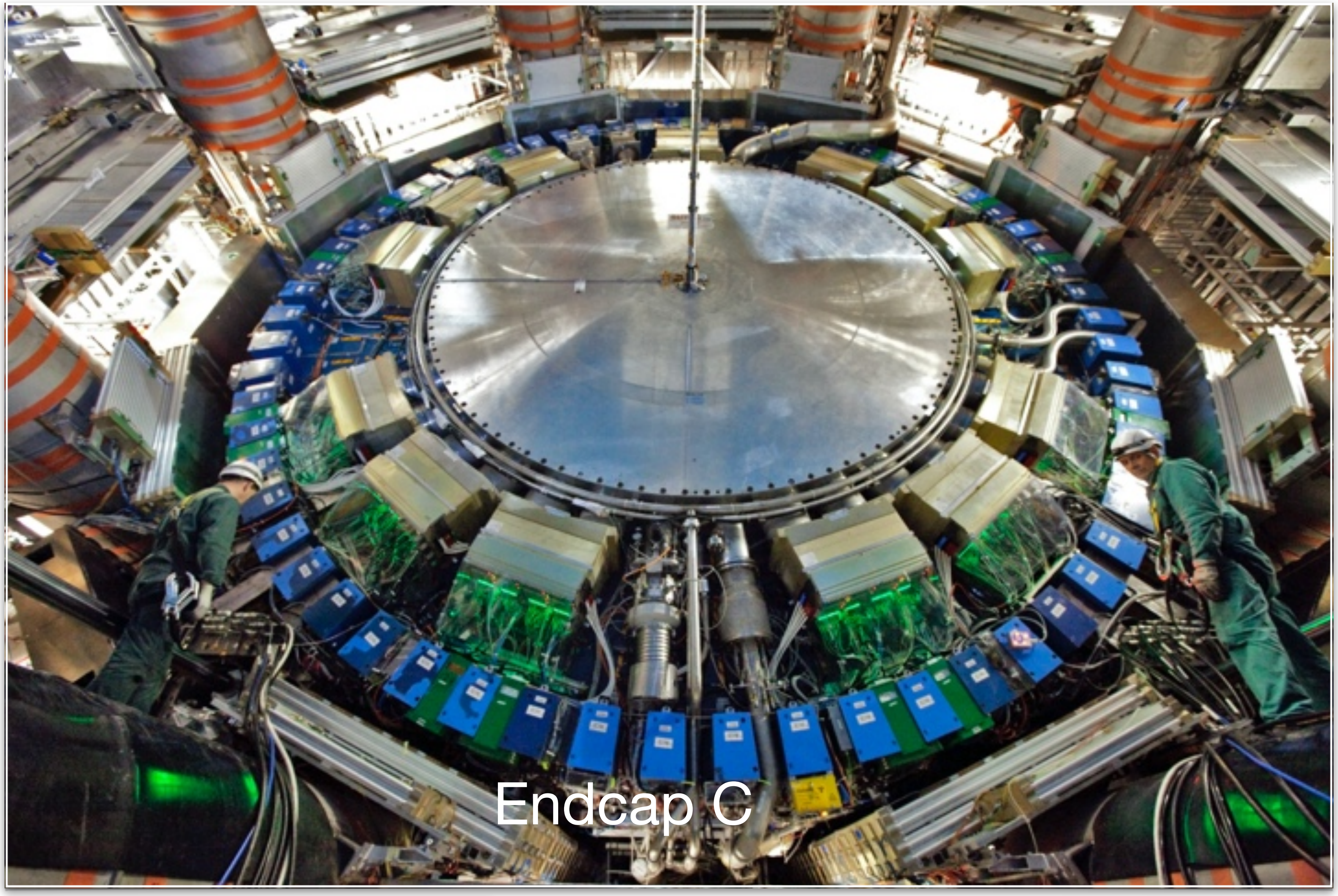




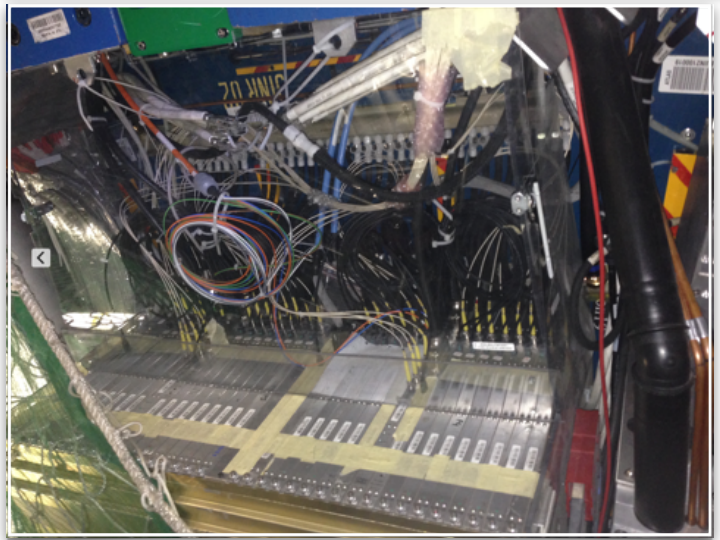


- **Phase-1**: LAr trigger electronics with higher granularity “Super Cells”, longitudinal shower information
  - Electrons: high efficiency & reduced trigger rate
  - Jets: Improved resolution
- **Phase 2**: LAr and TileCal data streaming at 40 MHz, radiation-tolerant electronics

Upgrades to LAr Calorimeter

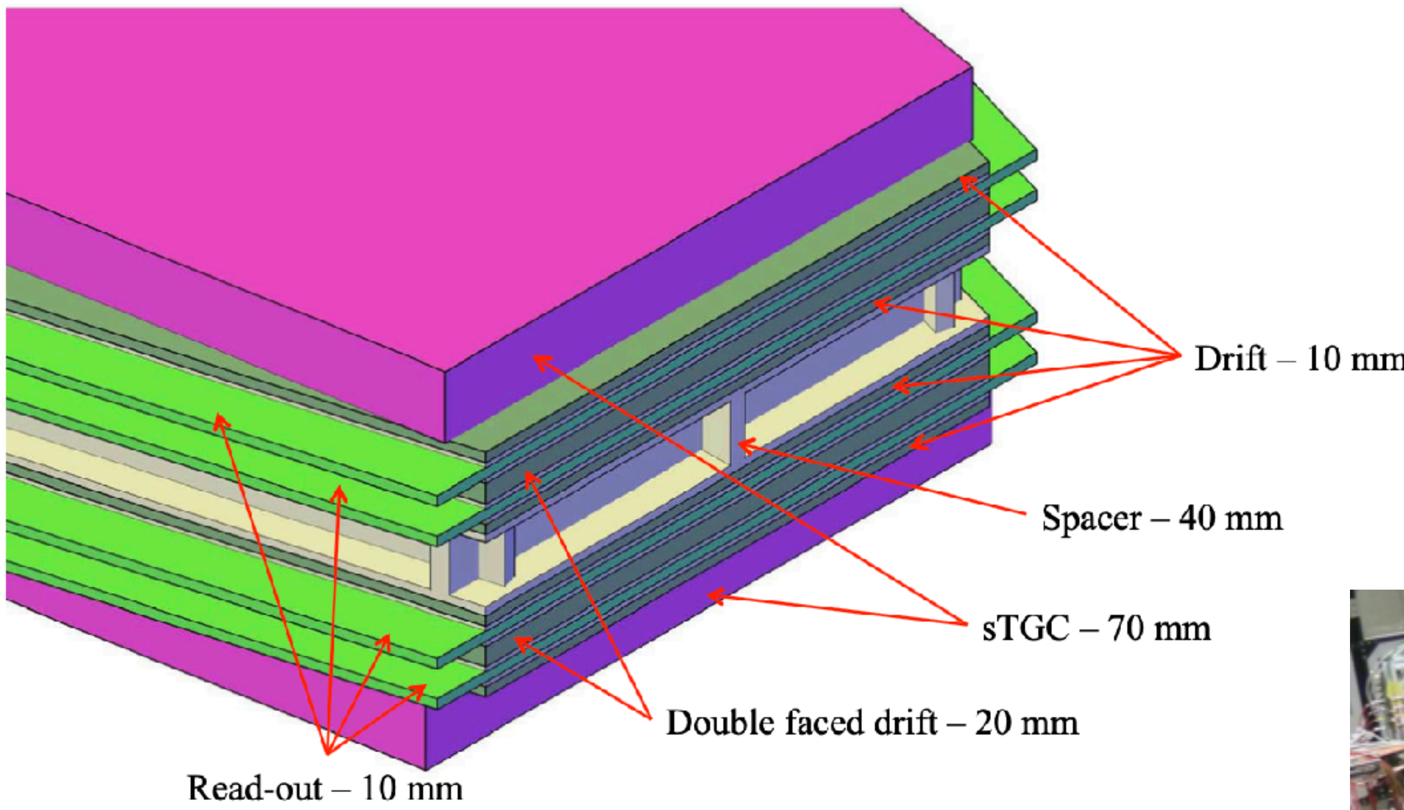


Back-end crates



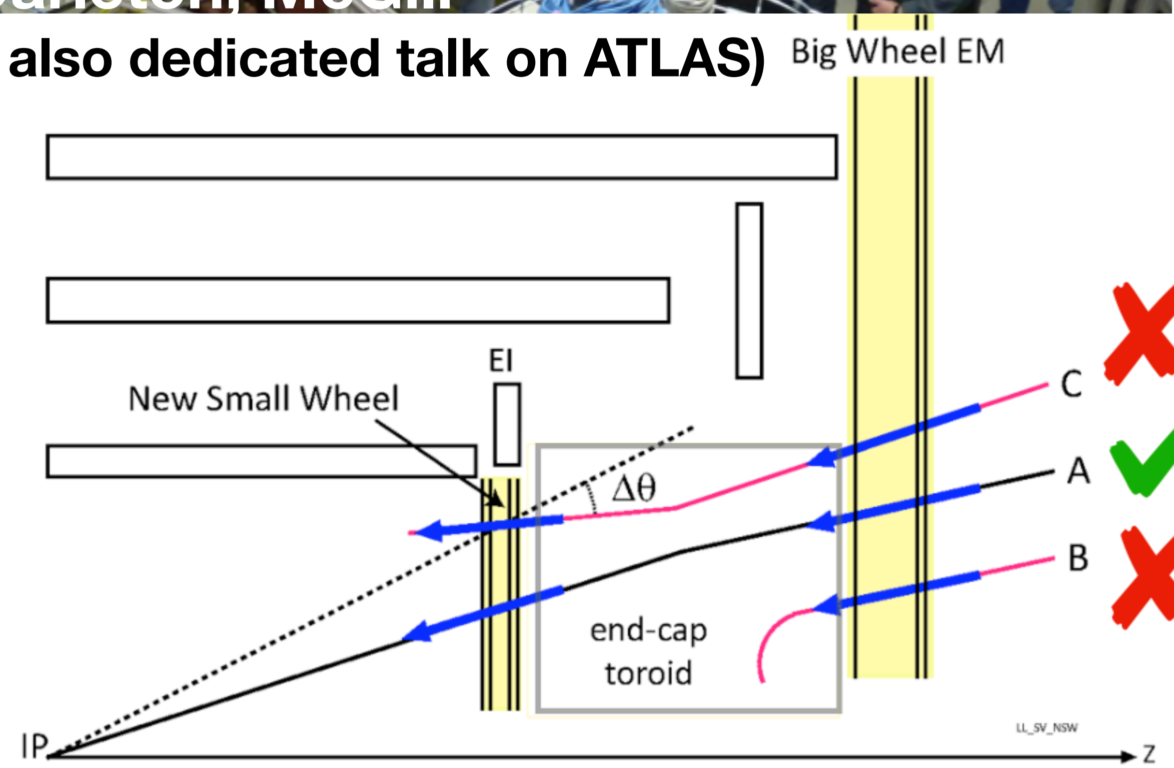
Front-end crates

Phase-1: Muon Upgrade

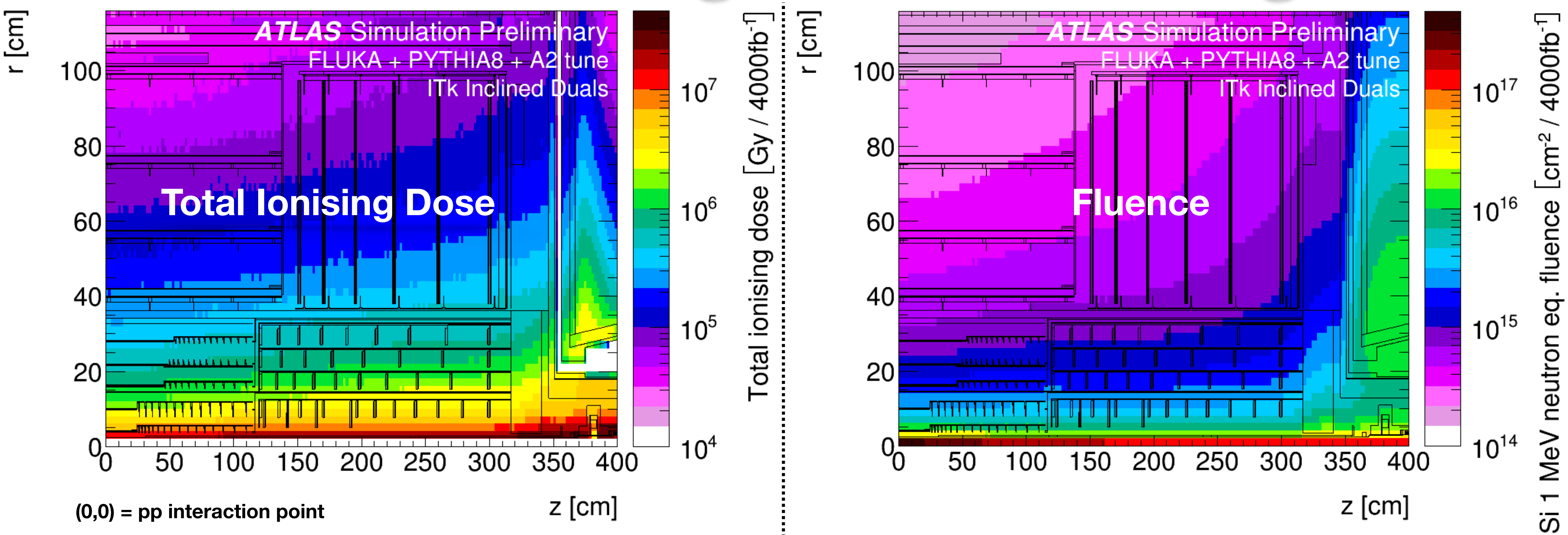


- New Small Wheels (NSW) will replace current inner muon endcap wheels
- Thin-Gap Chambers, primary trigger, < 1 mrad resolution
- MicroMegas, primary tracking, resolution < 100 microns
- Now data taking at CERN

(see also dedicated talk on ATLAS)



Future Challenge: Radiation Damage



The inner **tracker** (ITk) must continue to perform at the High-Luminosity LHC (HL-LHC) up to 4000 fb^{-1} (except Pixel Inner System replaced @ 2000 fb^{-1}.):

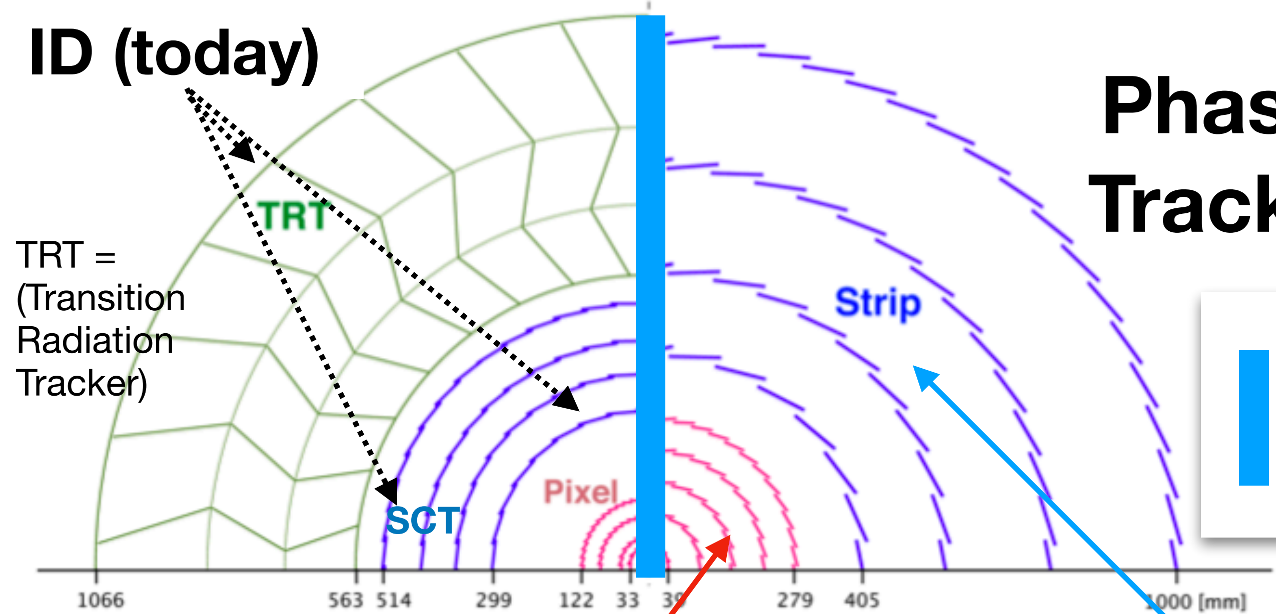
➢ **Detector Sensor technologies** (Si planar, 3D, diamond) qualified for: (3-19x10^{15} n_{eq}/cm^2, 2-10 MGy)
- NIEL (Non-Ionizing Energy Loss)
  —> bulk damage (trapping centres), depletion voltage and leakage current increase

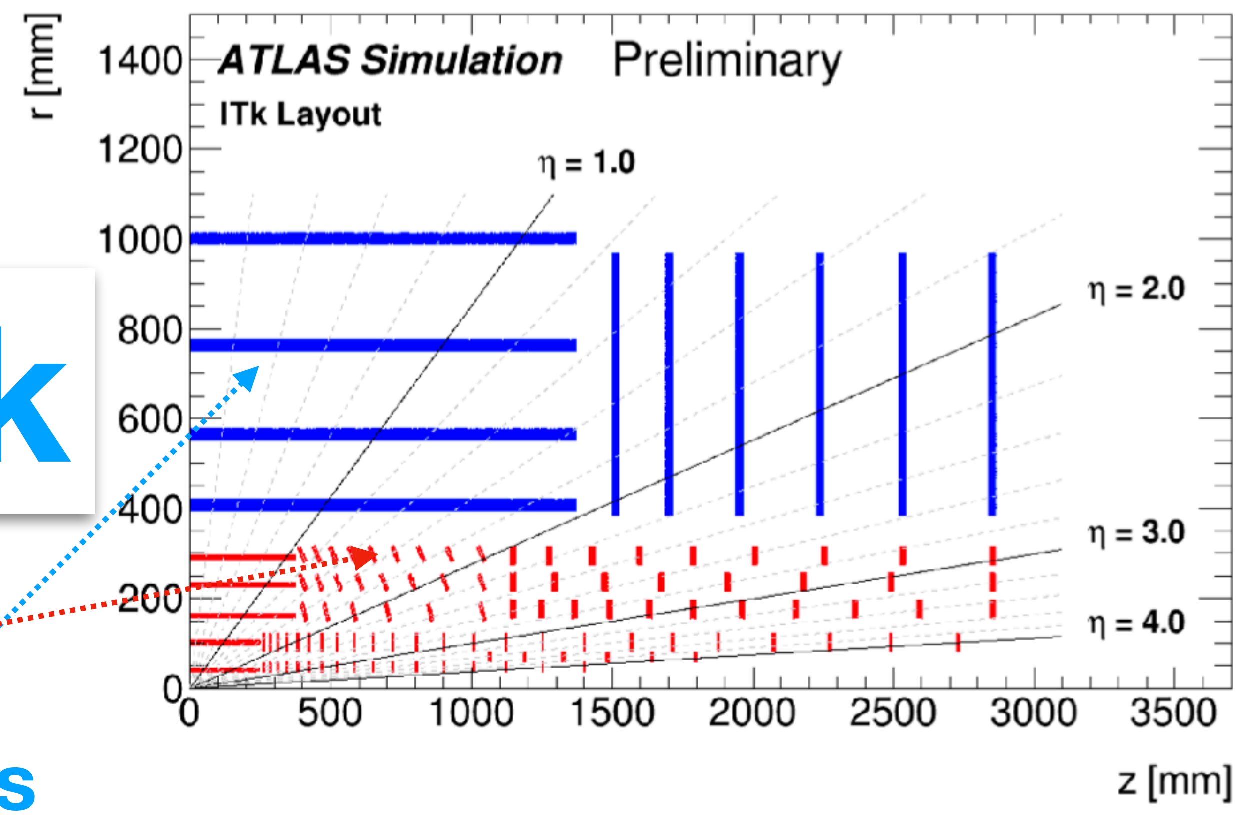
➢ **Front-End Readout ASICs** (Application Specific Integrated Circuits) qualified for:
- TID (Total Ionising Dose) —> surface effects, transistor damage and ageing effects
- SEE (Single Event Effects) induced by heavy ions and hadrons —> either soft errors (no permanent damage: Single Event Upsets,…) or hard errors (permanent damage: Single Event Latchup)

➢ **Material (cable, glue, composite…) must be qualified**
- TID can compromise chemical/mechanical integrity

Phase 2 Tracking

ITk





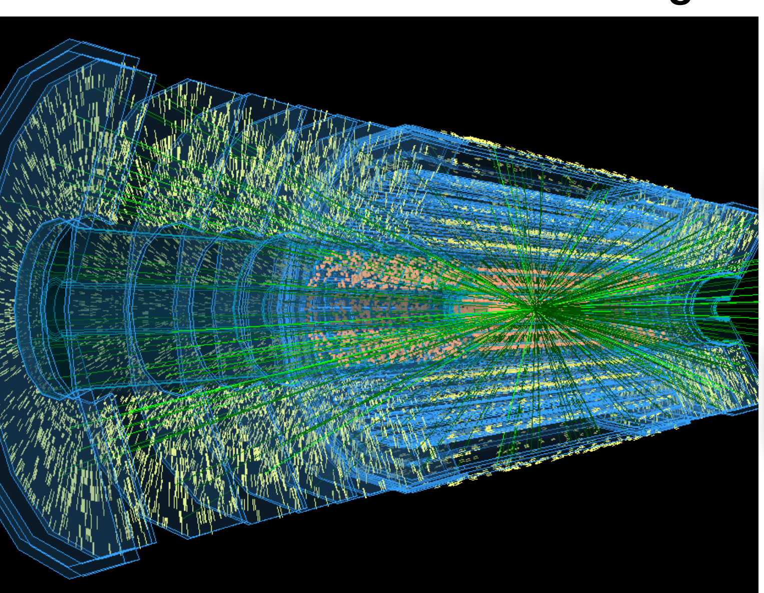
ITk Pixels

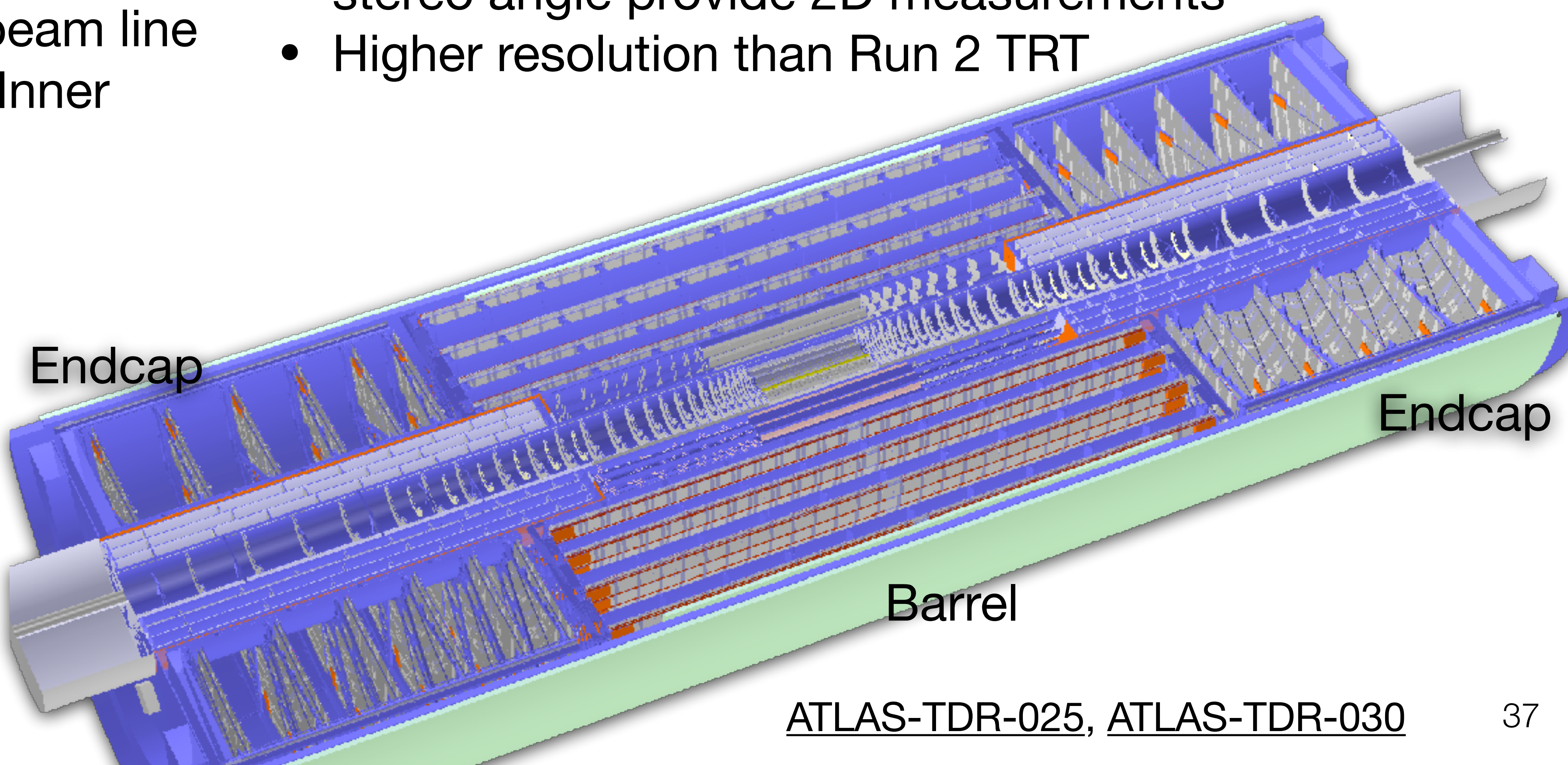
- **5** barrel layers + **5** EC (EndCap)
- Inclined sensors
- Covers $|\eta| < 4$ (was 2.5)
- 1st layer 35 mm from beam line
- Higher resolution than Inner Detector (ID) pixels

ITk Strips

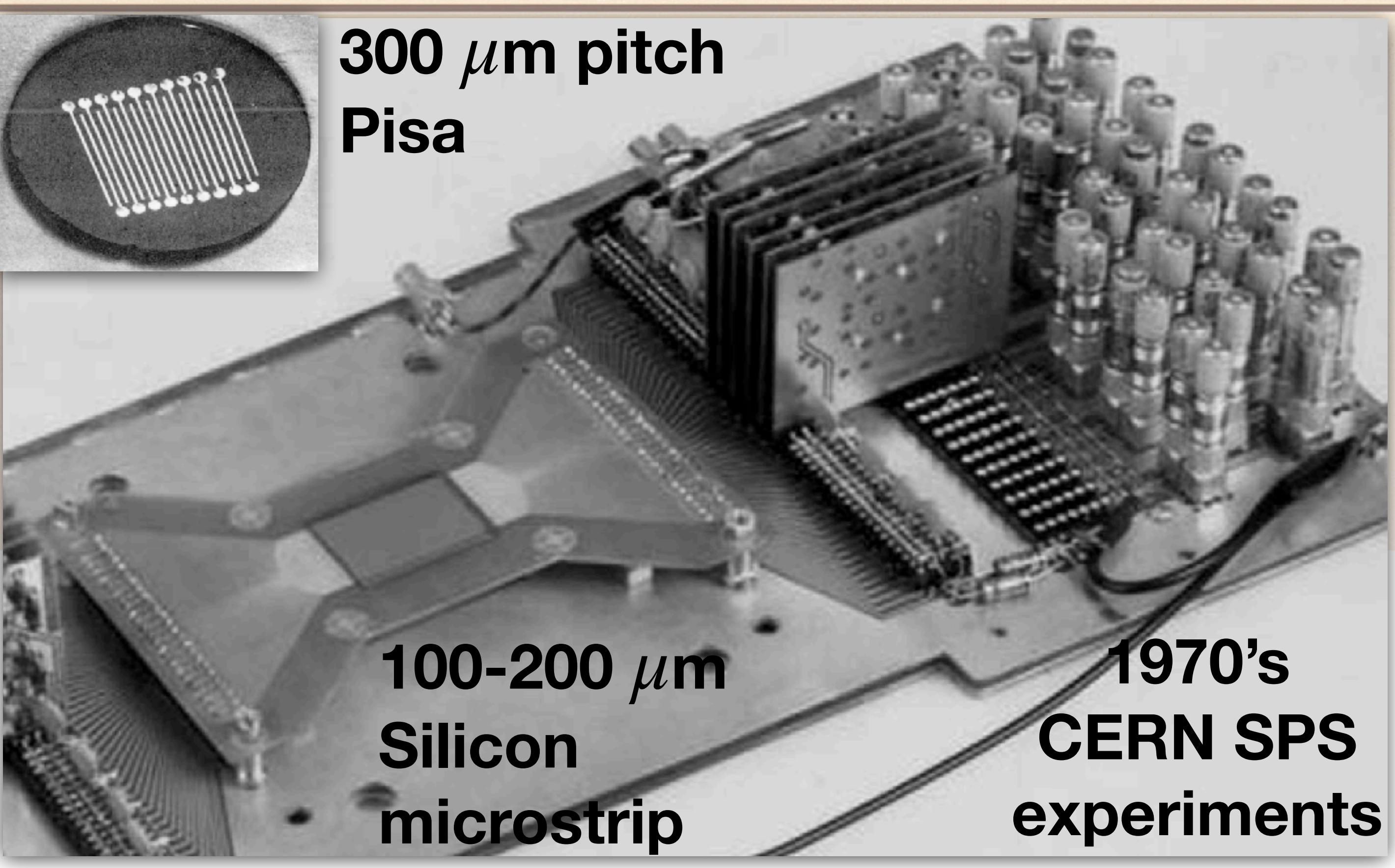
- **4** barrel layers + **6** EC (Endcap) rings
- Silicon microstrip modules with small stereo angle provide 2D measurements
- Higher resolution than Run 2 TRT

High-Luiminosity LHC (HL-LHC)
200 interactions/bunch crossing



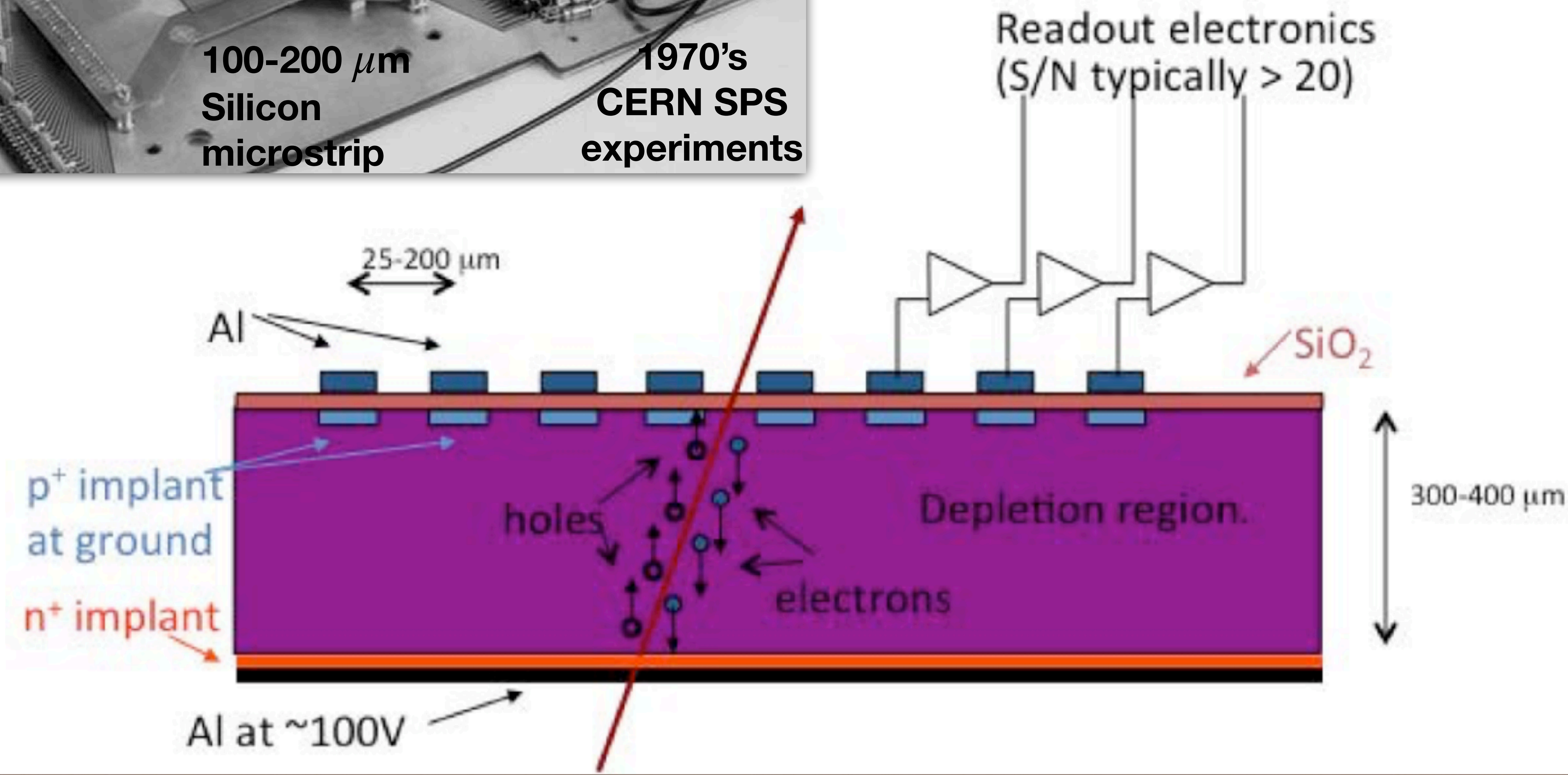


ATLAS-TDR-025, ATLAS-TDR-030

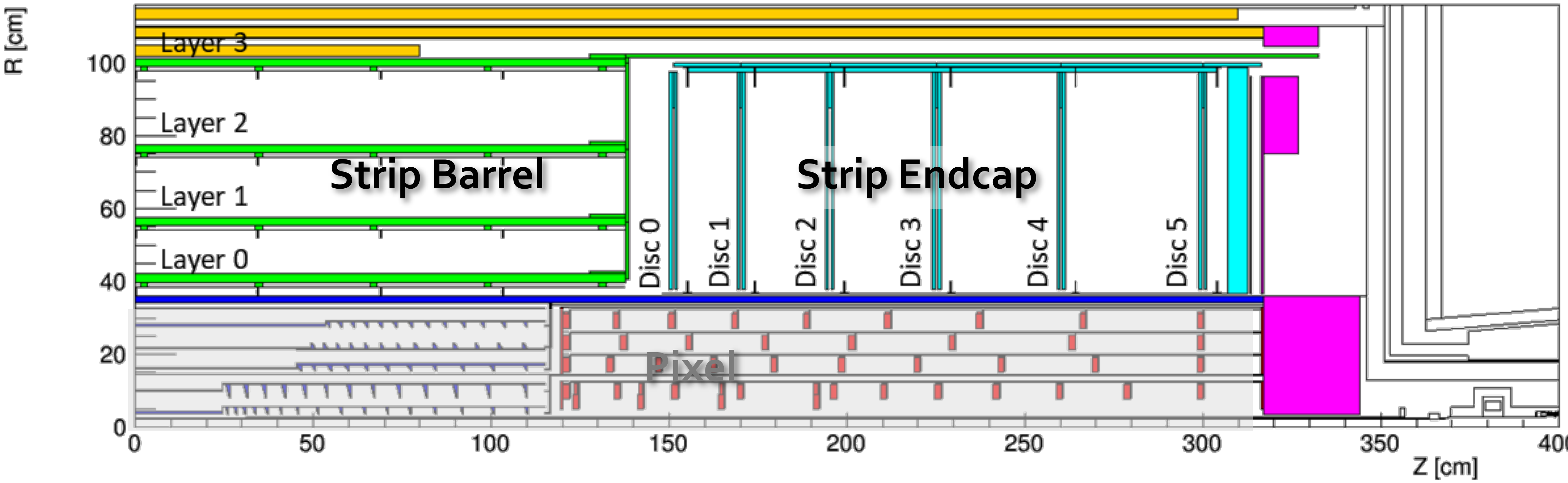


SILICON MICROSTRIP SENSORS

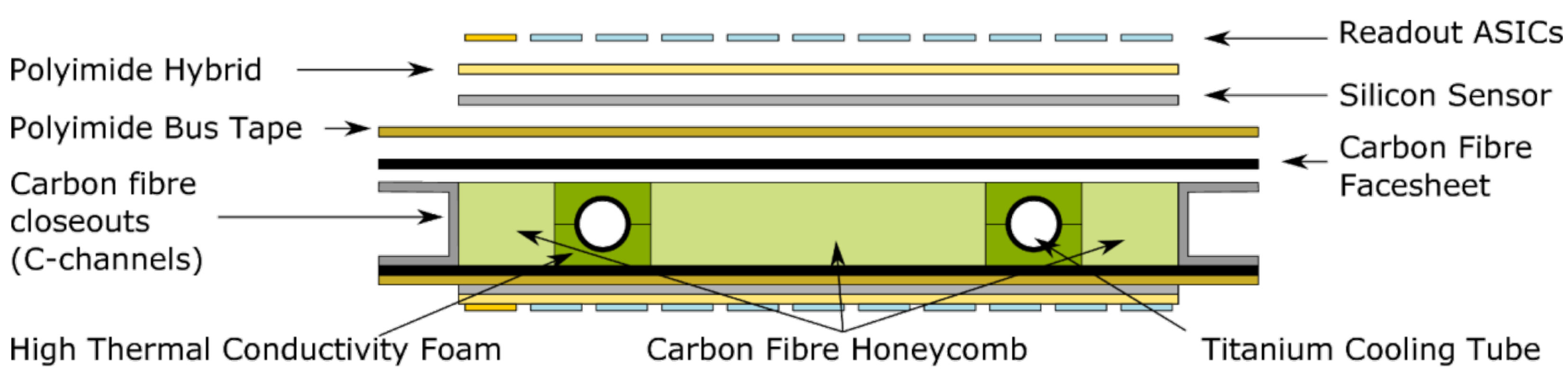
- Advantage: pitch of O(100) μm vs drift chamber spacing ~mm, scintillator ~ cm.



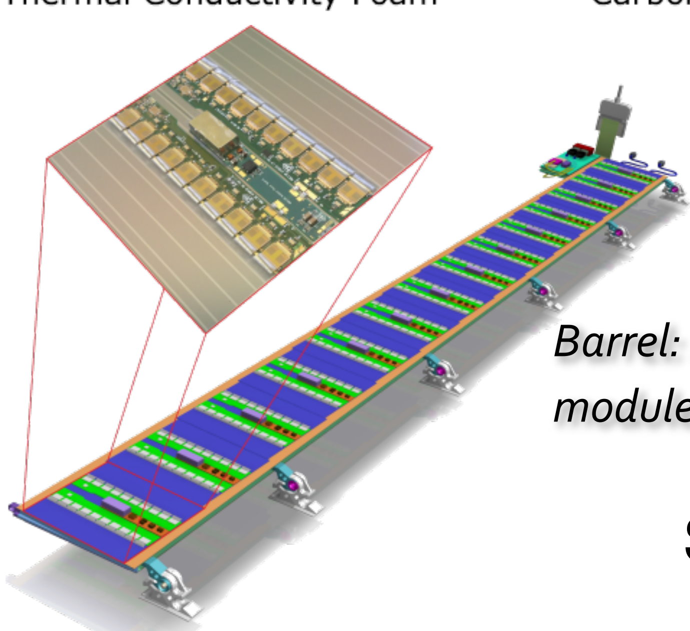
ATLAS ITk Strip Overview



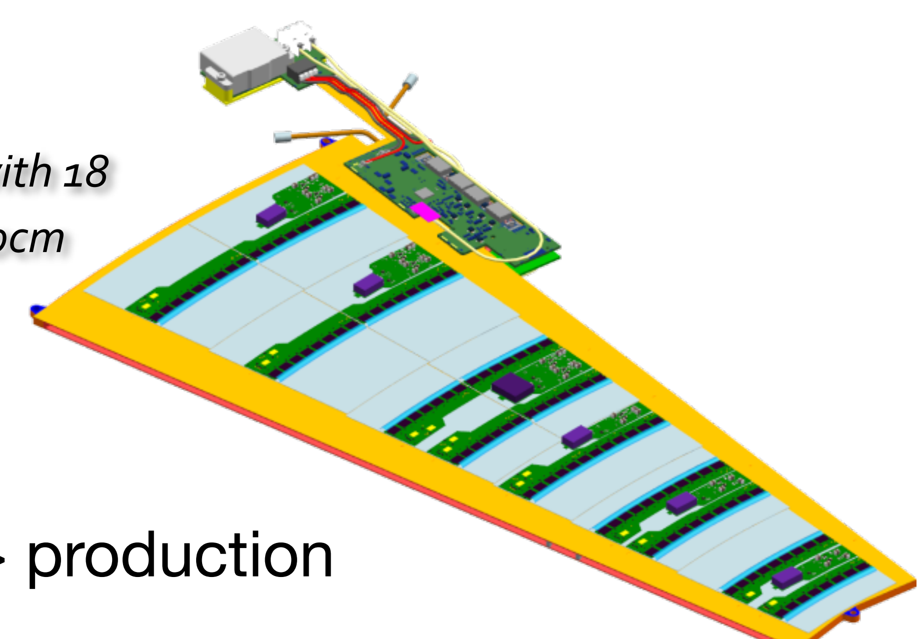
Barrel: 4 barrel layers instrumented with modules on the two sides of the stave local support
Endcap: 6 disks instrumented with modules on the two sides of the petal local support



	Barrel	Endcap
# of modules	10976	6912
# of Local Support	392	384
Surface [m²]	104.8	60.4



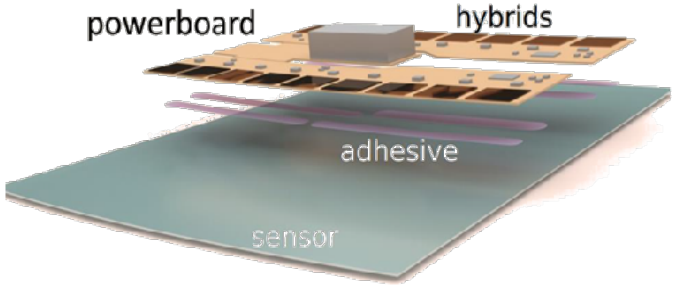
Barrel: Stave is loaded with 28 modules → Length ~ 140 cm



Endcap: Petal is loaded with 18 modules → Length ~ 60cm

Strips: transition pre-production -> production

Strip Sensors



- n-in-p float-zone sensors with p-stop isolation, ~320 µm thickness
- 8 different sensor types (2 barrel, 6 EC)

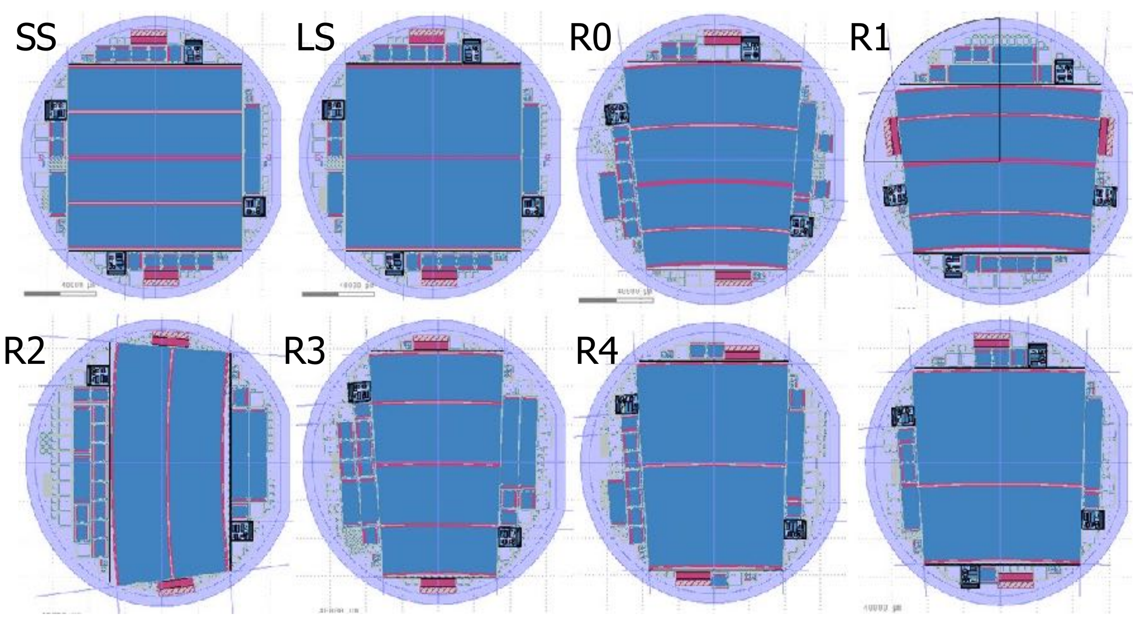
✓ Sensor produced by Hamamatsu.
  - Mini sensors and other test structures on each wafer.

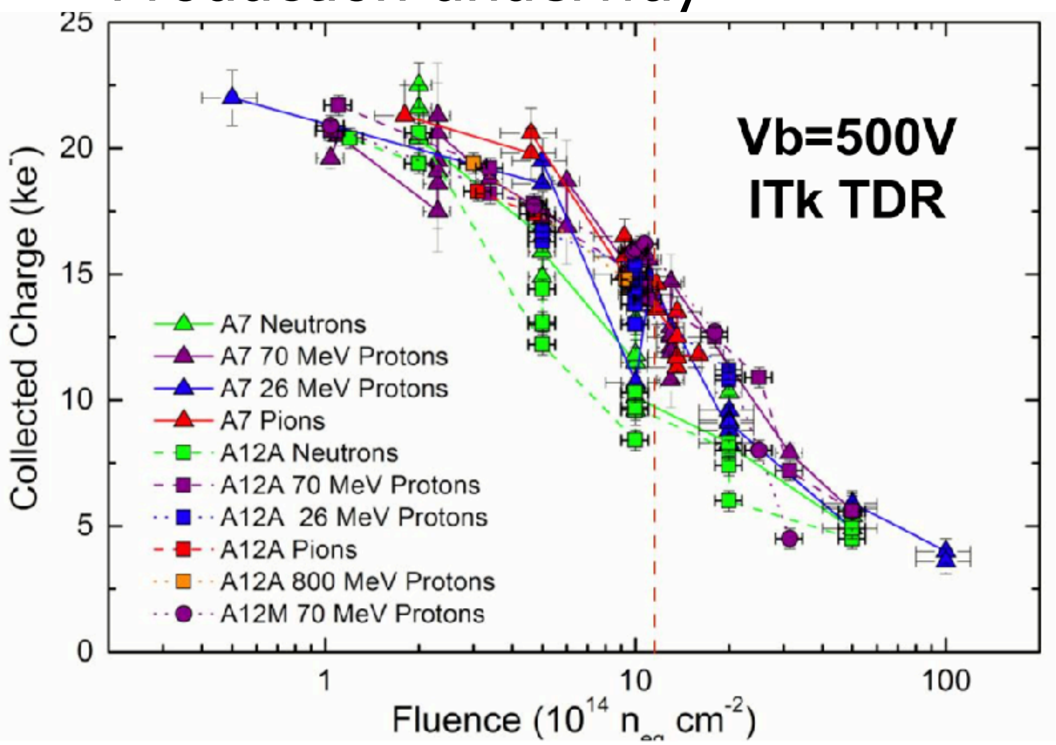
✓ Sensors during production probed in Canada (Carleton, SFU), mini-sensors tested in Toronto after irradiation

✓ Pre-production completed.

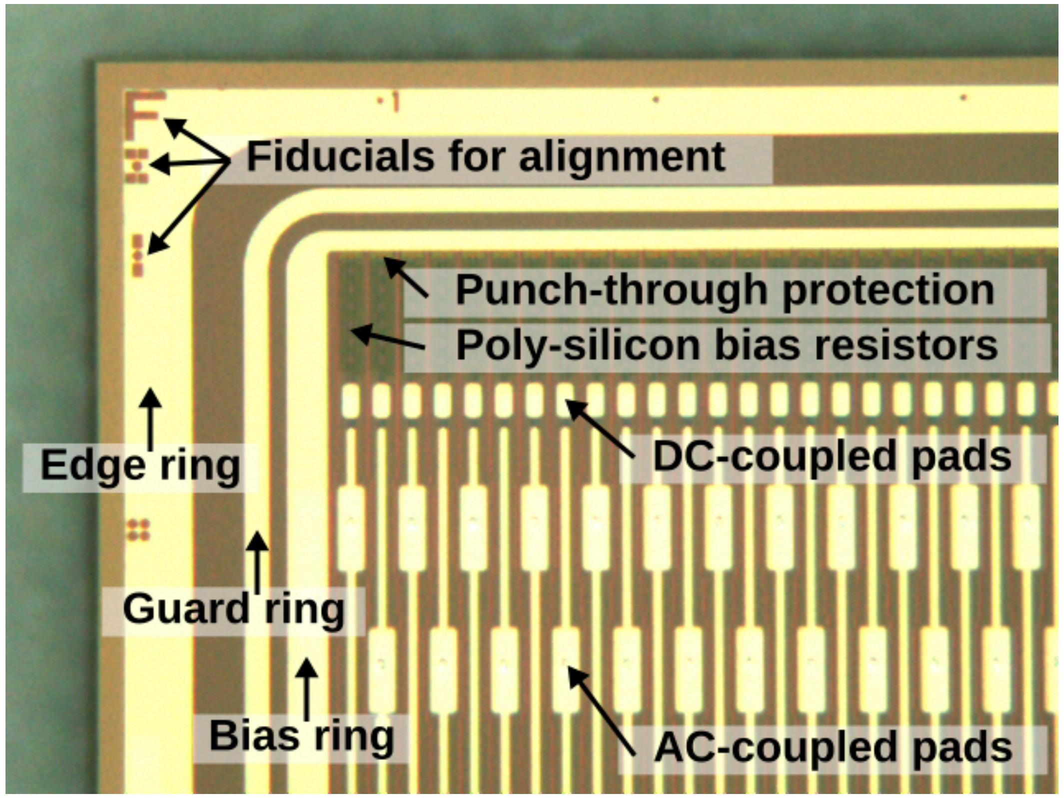
✓ Production underway

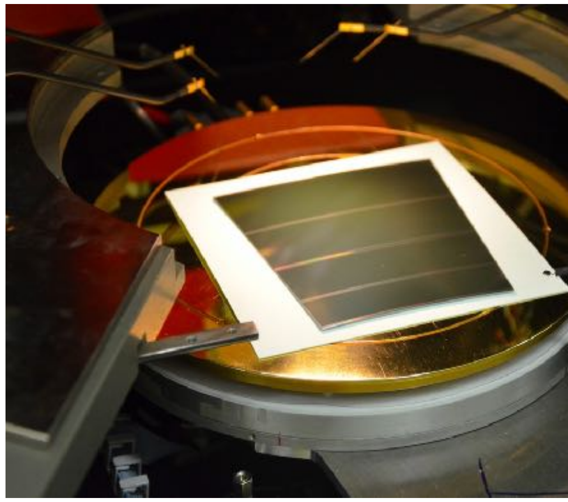
8 pre-production masks





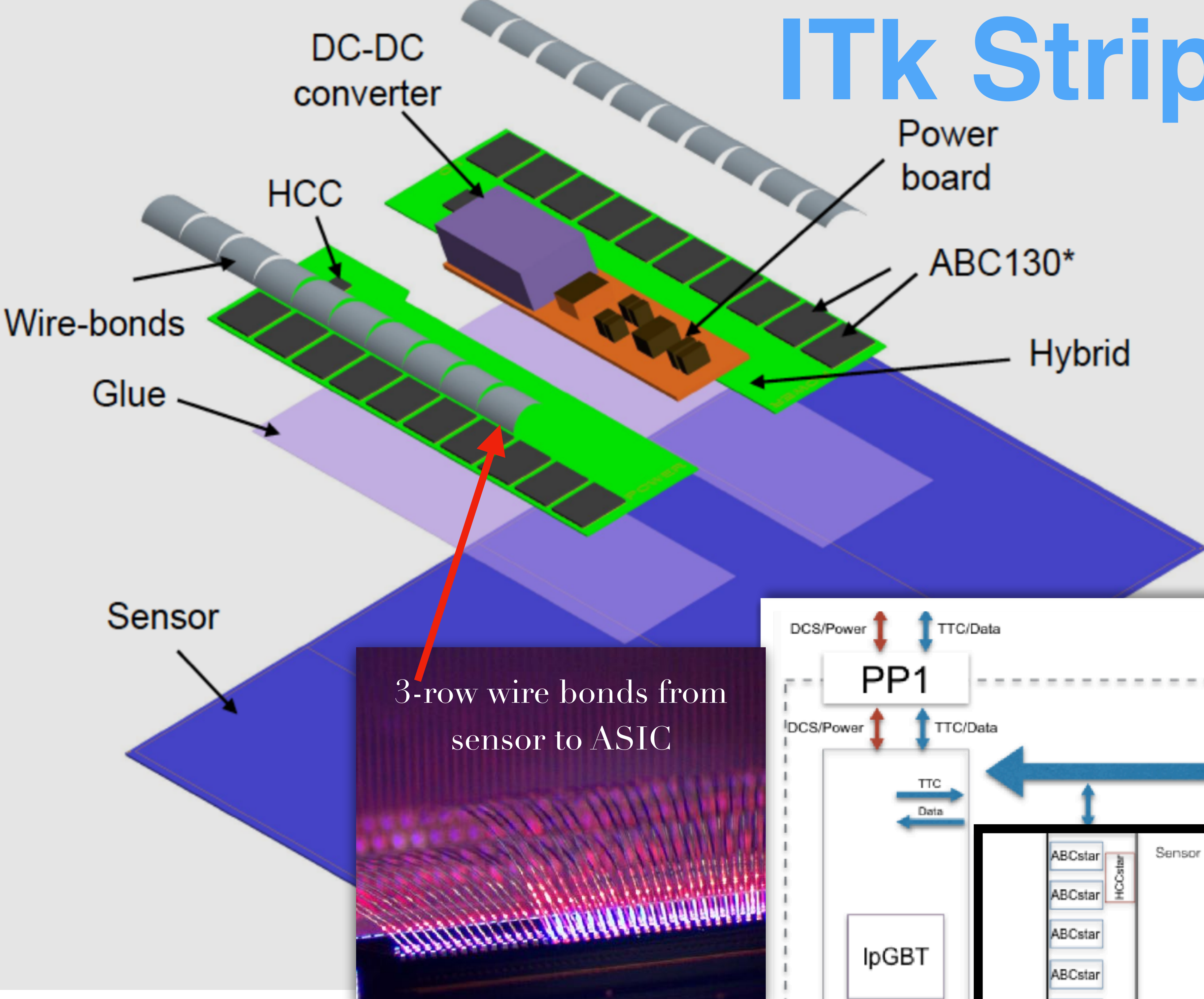
Charge collection efficiency vs fluence





Since the radiation induced impurity in silicon contributes dominantly acceptor like states, n–in–p devices are non-inverting.

ITk Strips Module



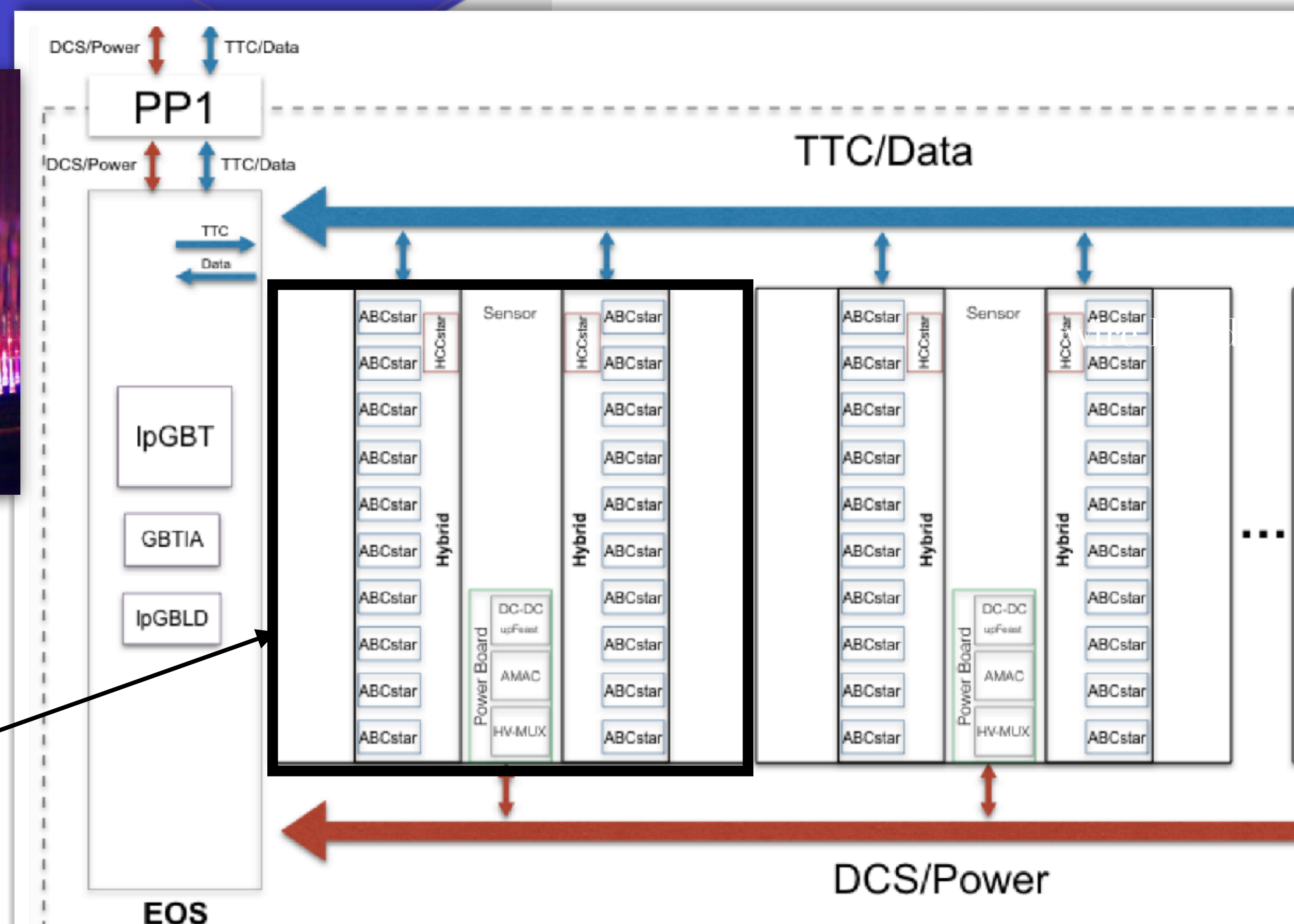
Front-End (FE) **ASICs:** ABC + HCC

Hybrid: PCB containing ASICs reading out silicon microstrip sensor

Sensors: Silicon microstrip sensors, 10x10cm, ~300 μm thick, 75 μm pitch

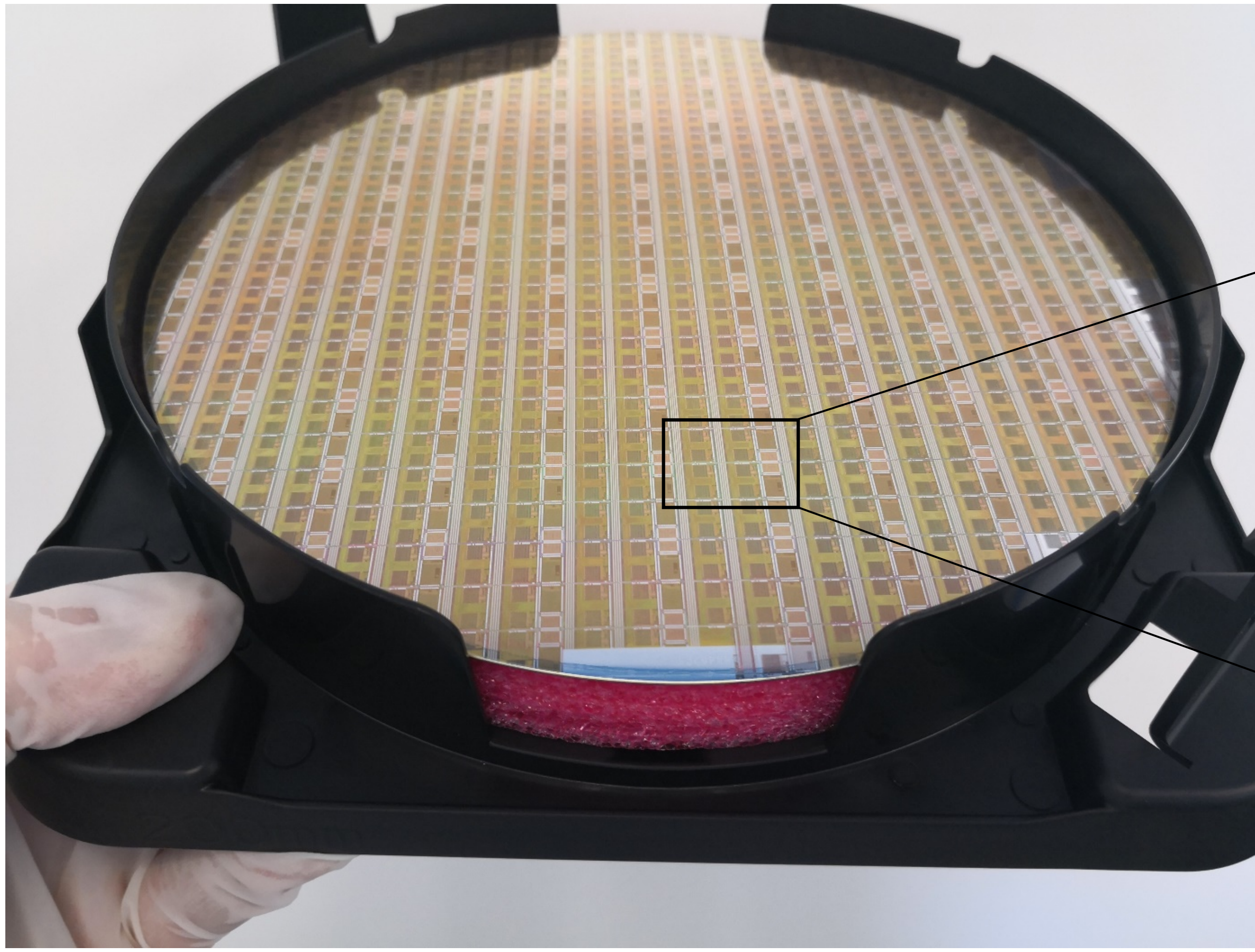
Module = hybrid + sensor

groups of modules -> barrel stave or EC “petal”

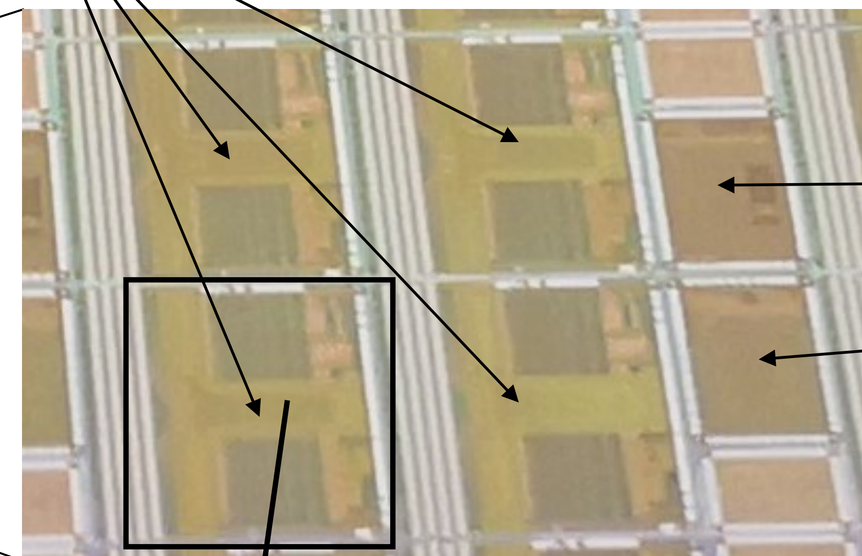


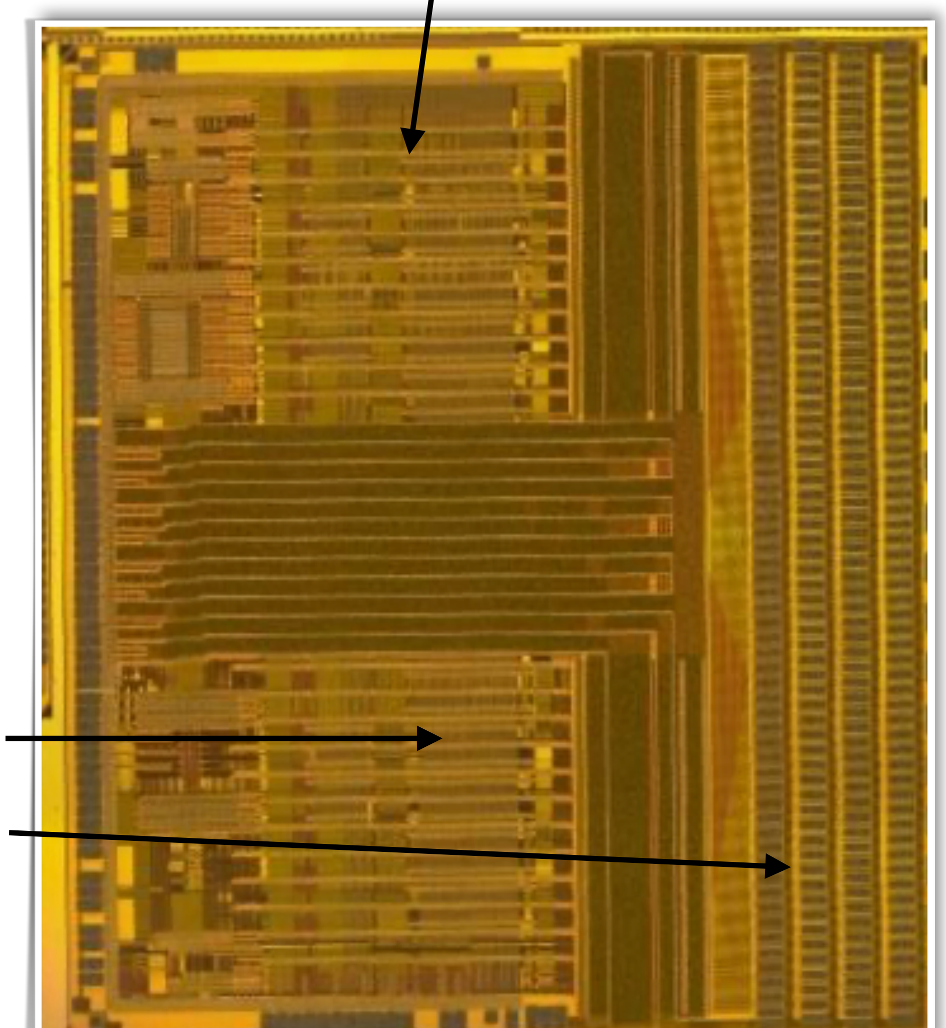
ITk Strips Front-End ASICs

Technology: GF (ex IBM) 130nm CMOS8RF technology



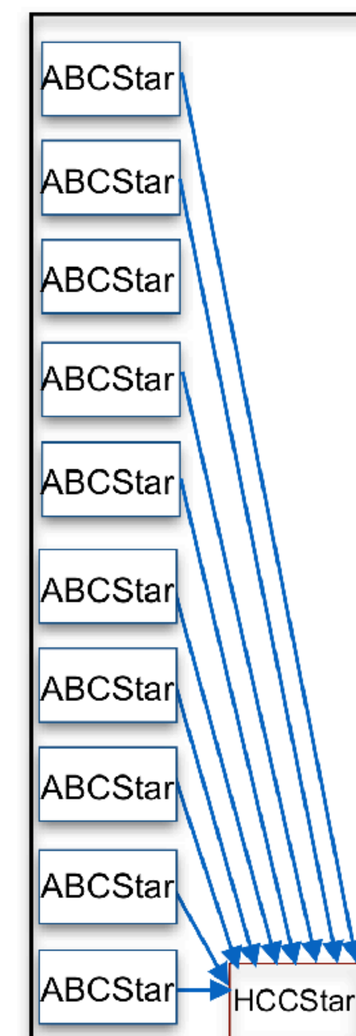
Wafer with pre-production ASICs



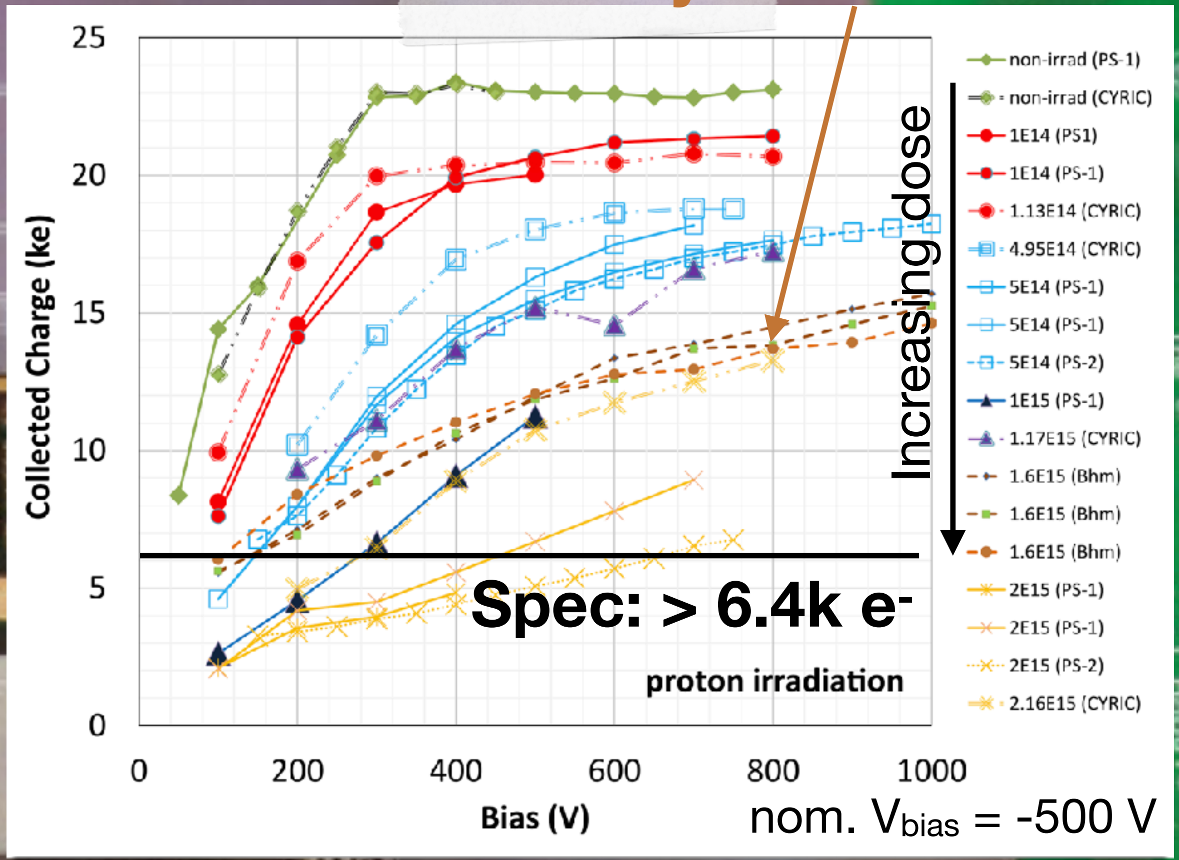


ABCStar (ATLAS Binary Chip) die showing I/O and 4 rows of front-end pads

Star architecture



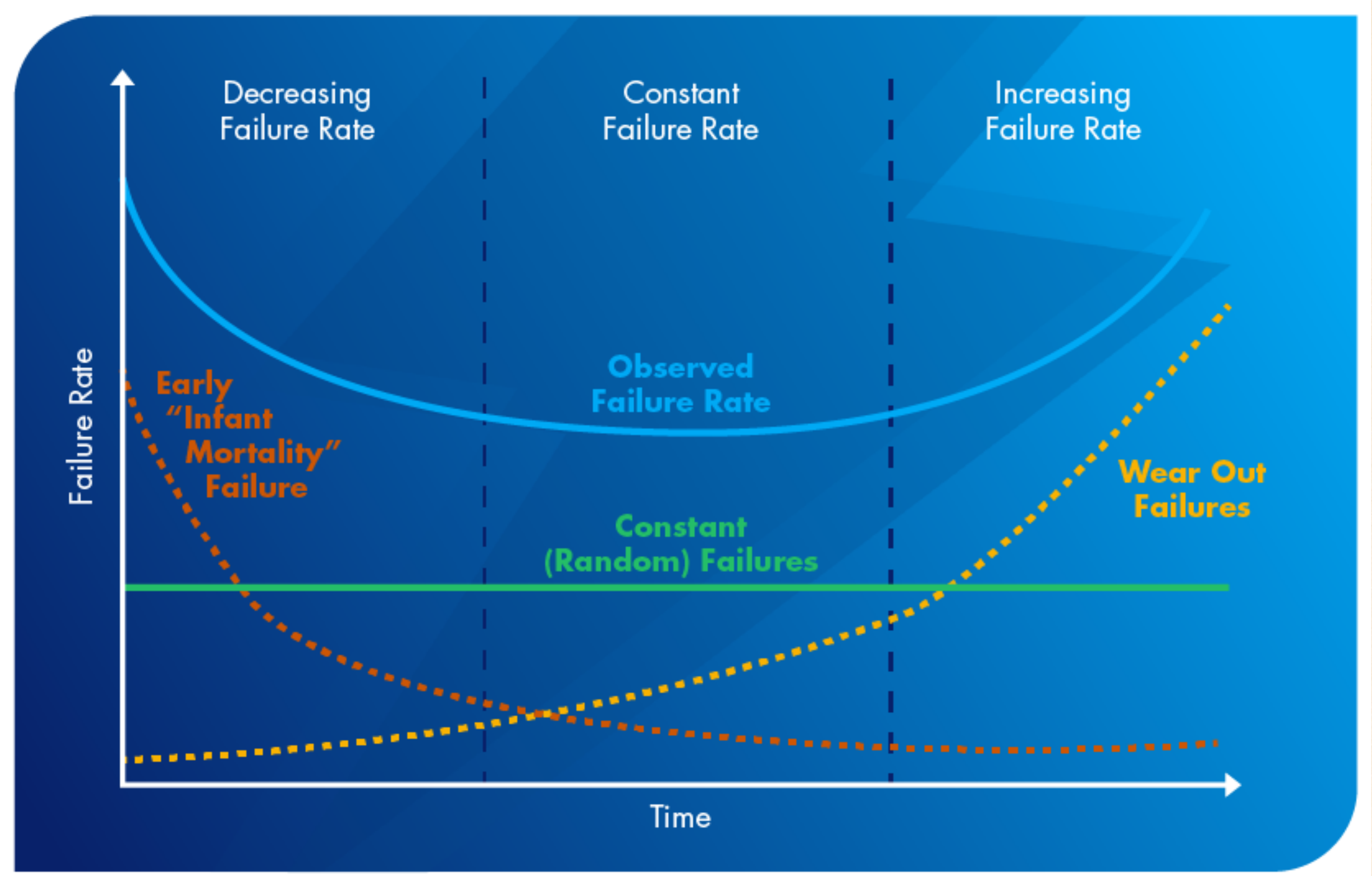
Phase 2: ITk
Silicon Microstrips



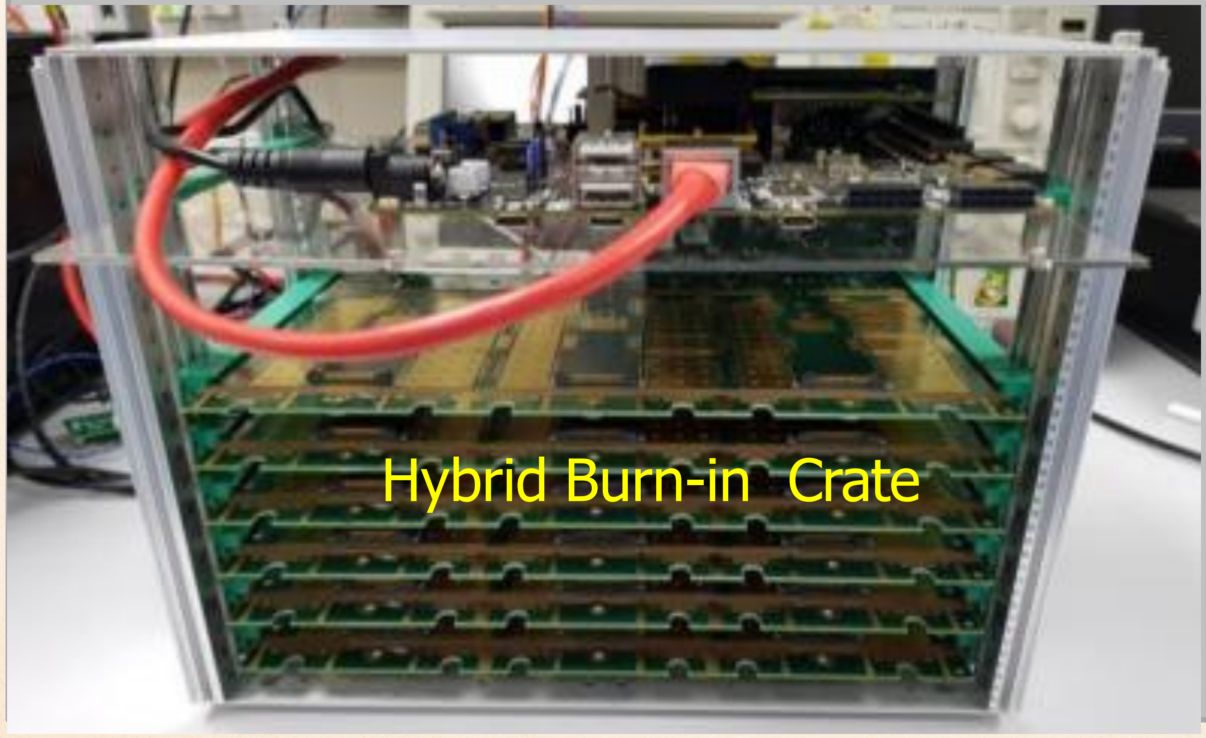
Sensor charge collection efficiency
NIM A 983 (2020) 164422

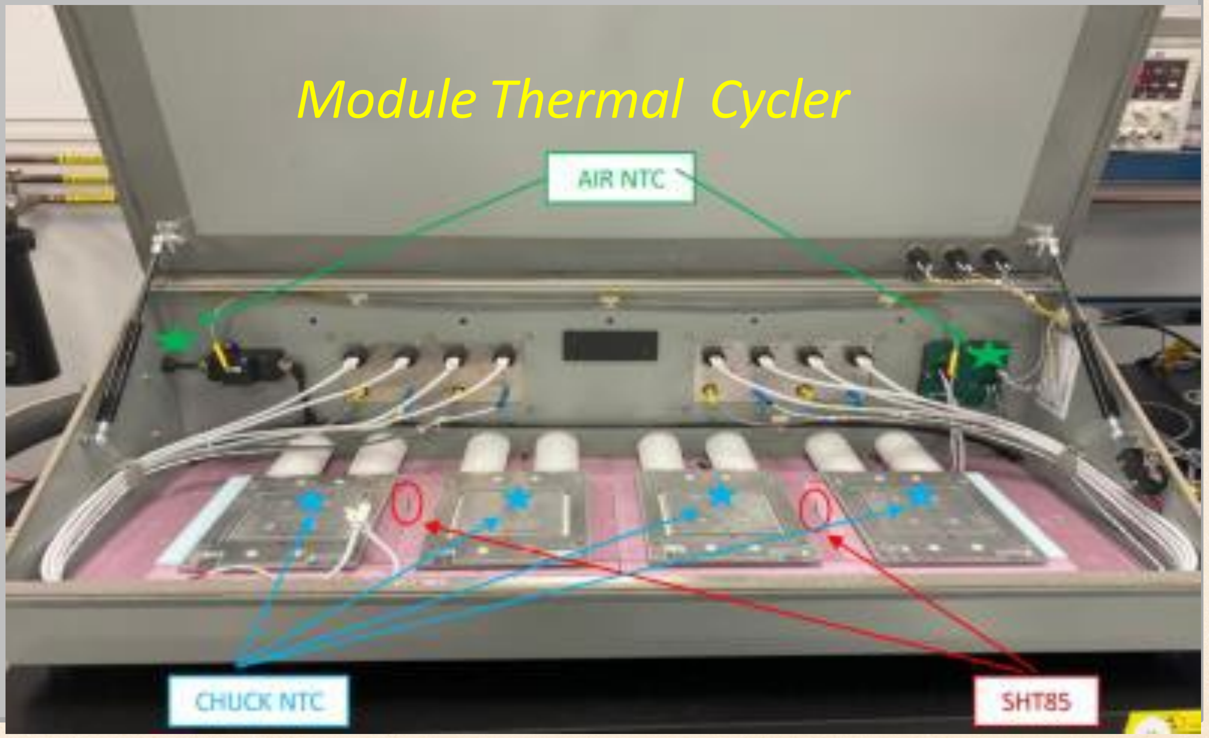
ELECTRONICS LIFETIME

“Bathtub curve”

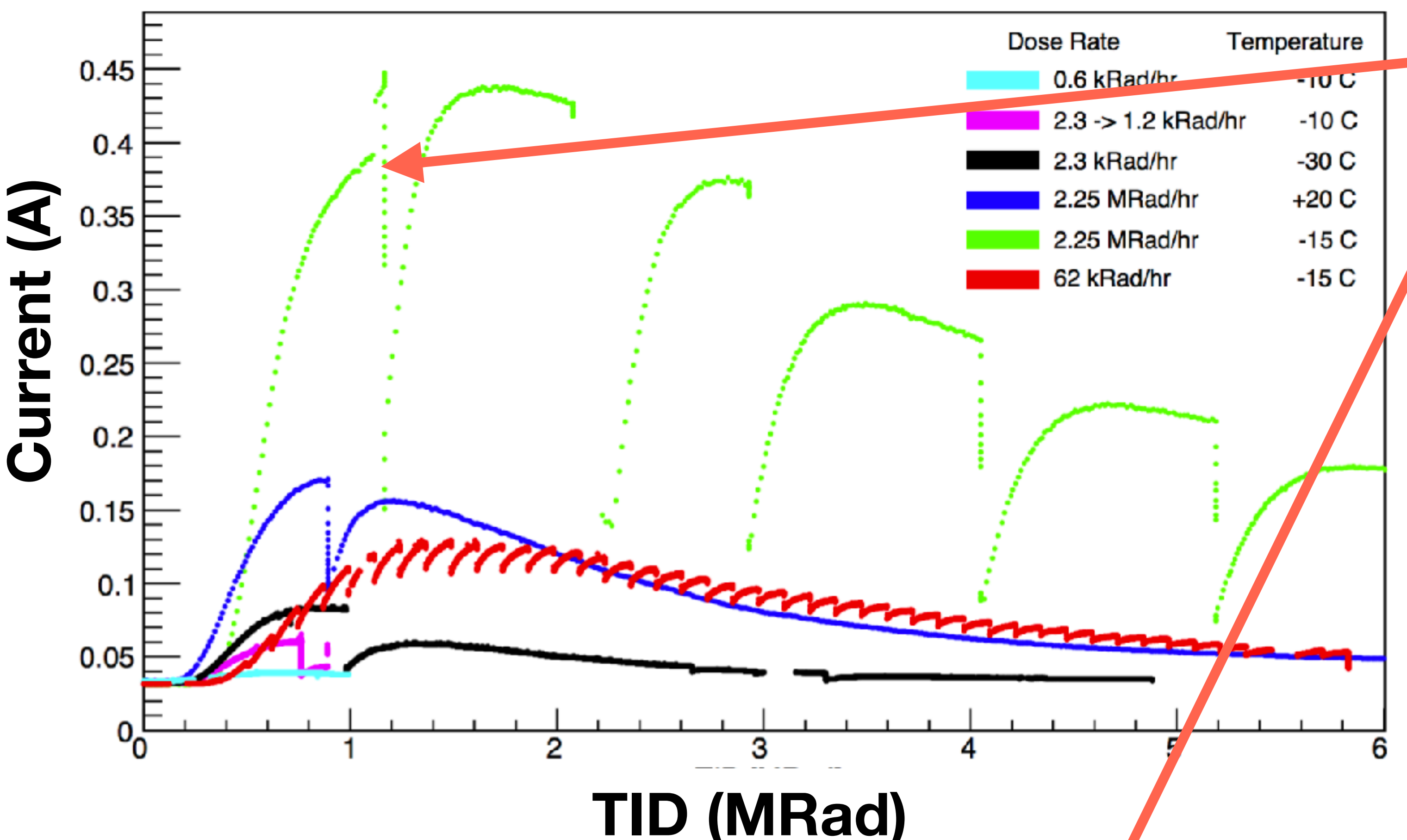


Electronics burn-in systems (ATLAS ITk - U. Montreal / Toronto)



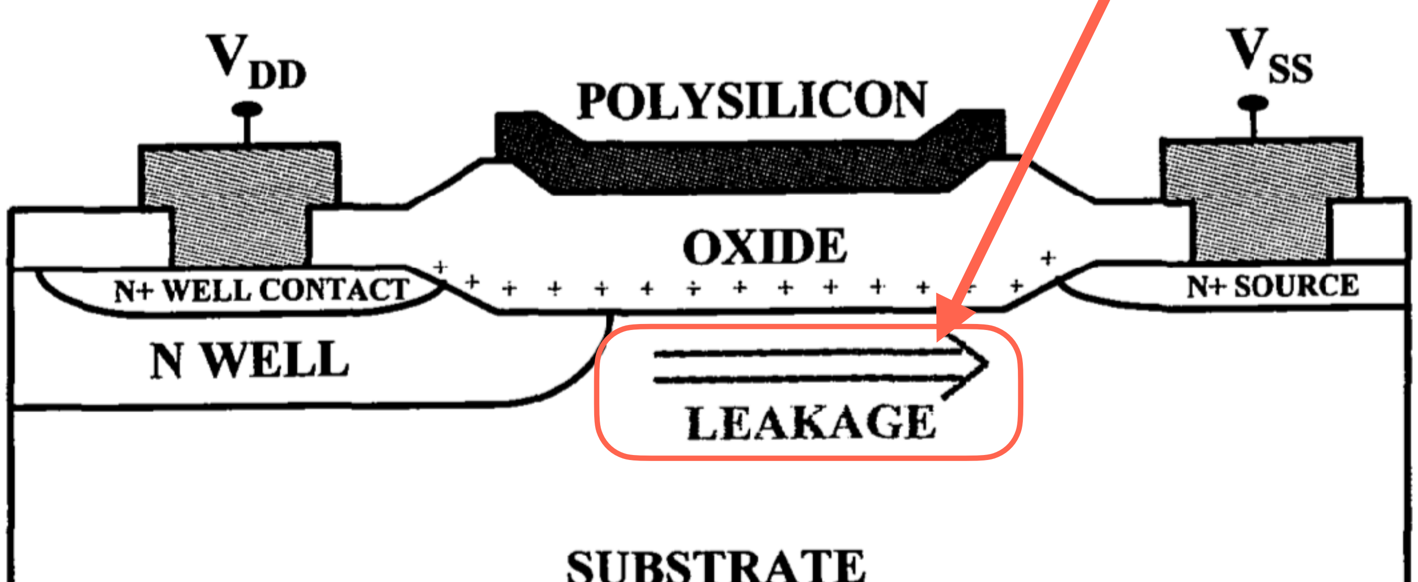


ELECTRONICS AND RADIATION



R. Hunter, MSc thesis, Carleton, 2017
+ Canadian IPP CERN summer student + Canadian grad student + RT

- "**TID bump**" ASIC digital current increase vs Total Ionising Dose (here with prototype 130nm ATLAS ITk CMOS vs ASICs)
- Formation of parasitic pathways in transistor logic - well known phenomenon "rediscovered"
- Fixed with enclosed transistors in final ASIC



Faccio, Int.J. High-Speed Electronics (2004)

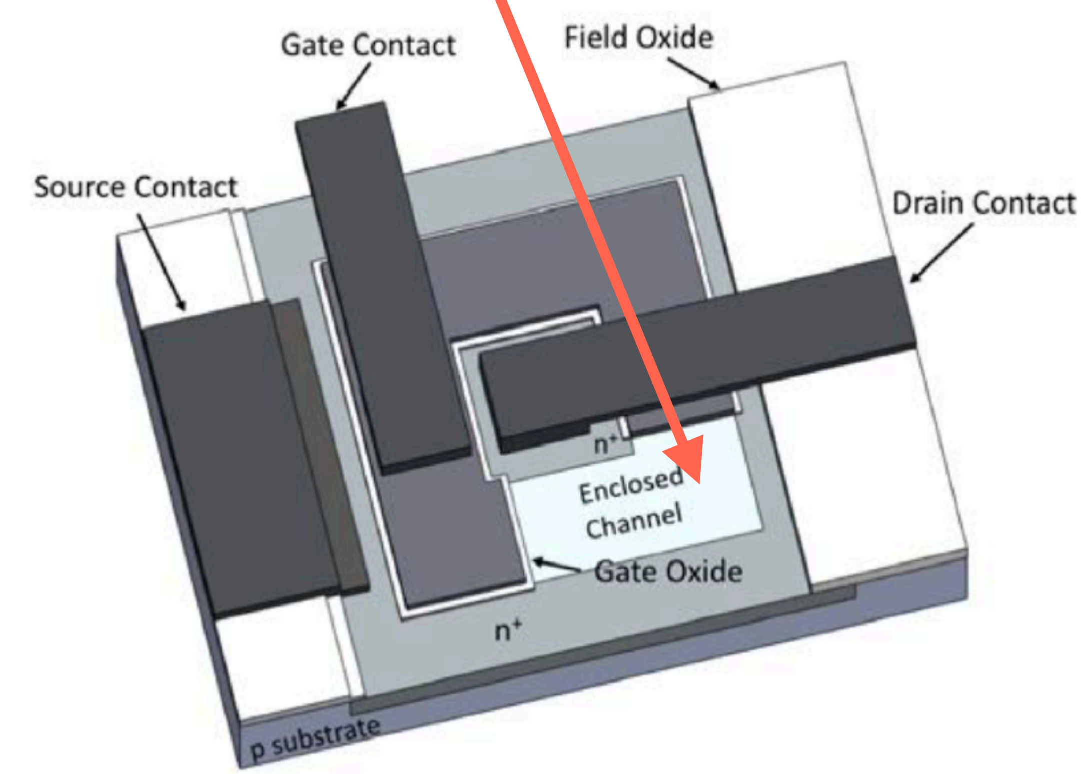


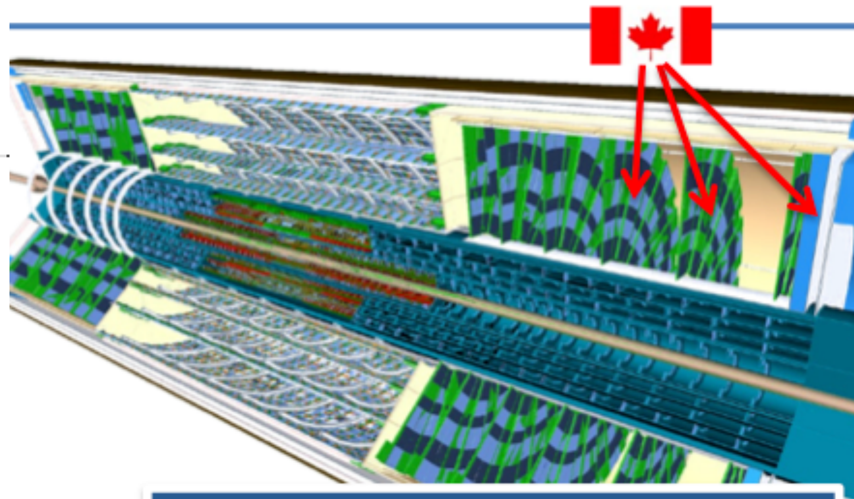
Figure 12: NMOS Transistor with Enclosed Geometry
The field oxide has been cut away except under the source & drain contacts and the gate & gate oxide cut away in the front segment to allow a view of the enclosed structure with the drain enclosed by the gate which is in turn enclosed by the source.

Grillo

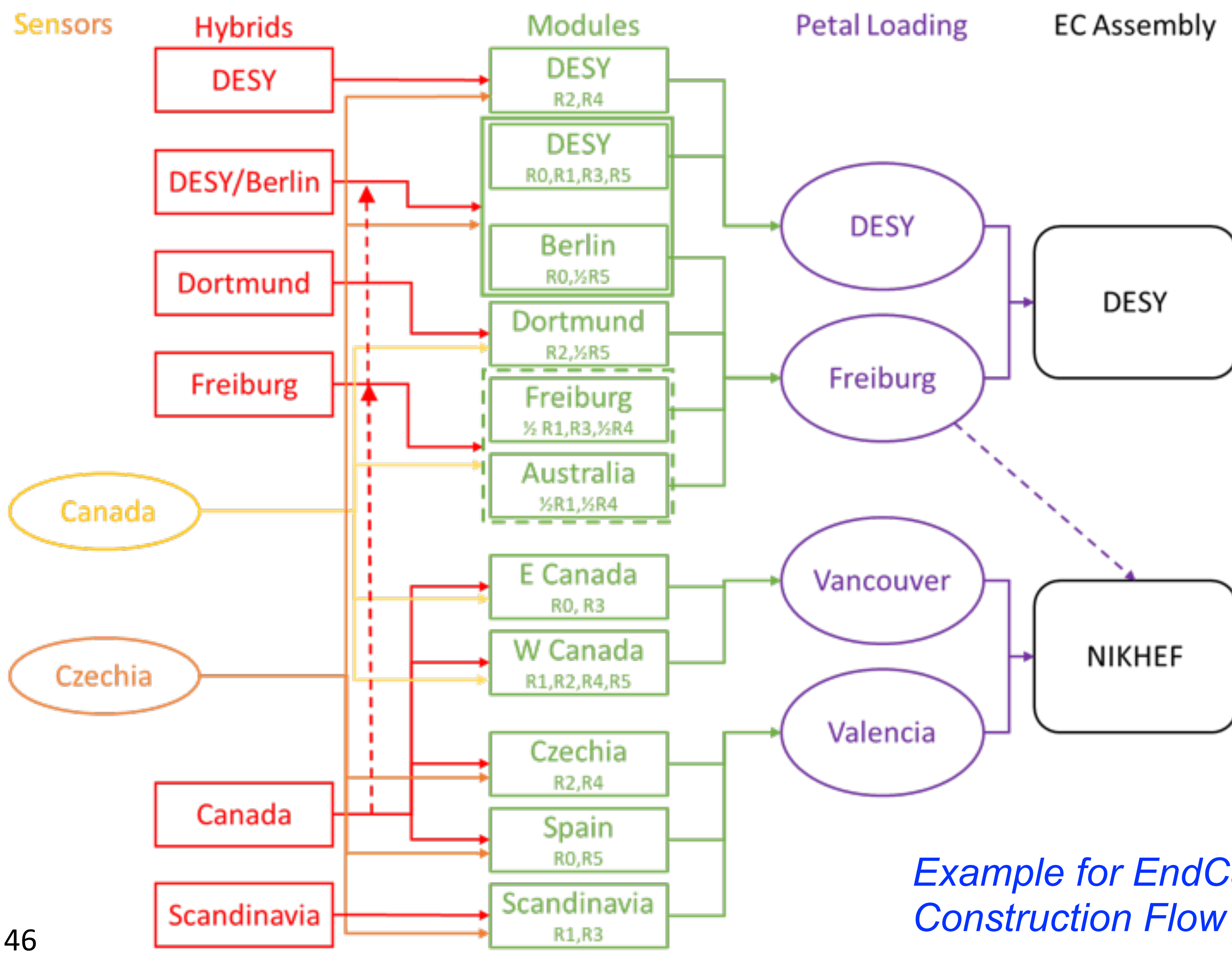
Moving to construction: ITk Strips

✓ Modular concept of components: designed for mass production from the beginning (industry standard design rules, simplified construction,…)

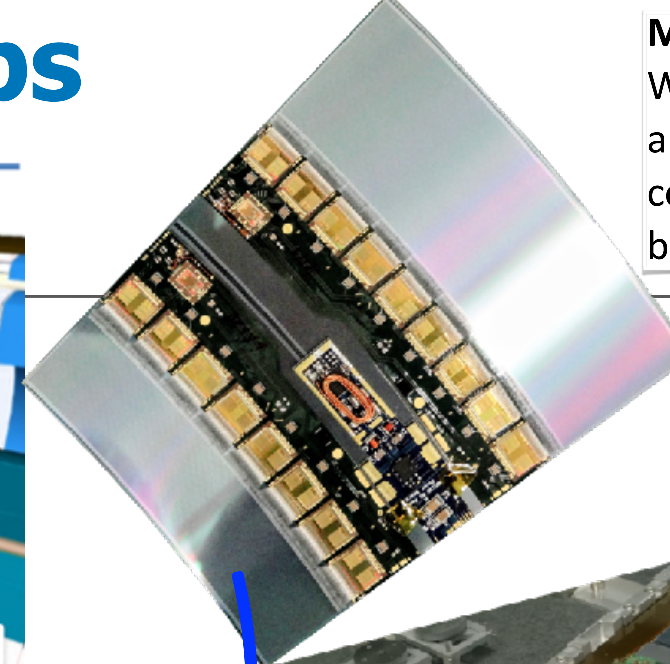
- Assembly & testing @ multiple sites
- Simplifies final assembly
- Earlier test of full system



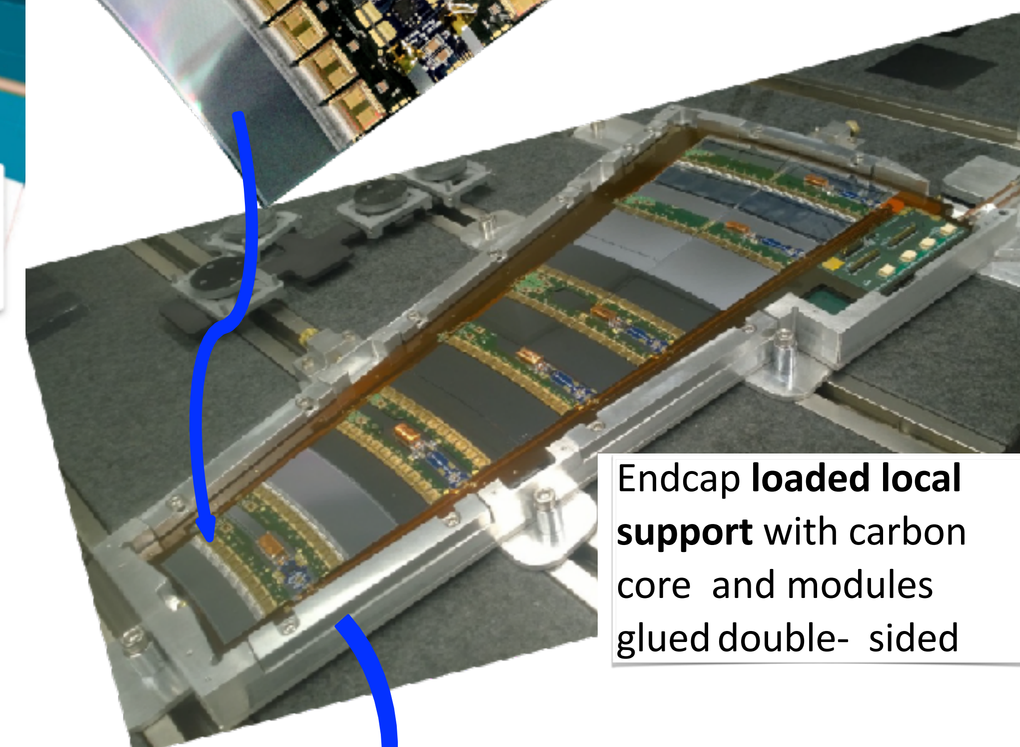
Canada is building about 2½ / 6 endcap disks (1500 ITk modules)



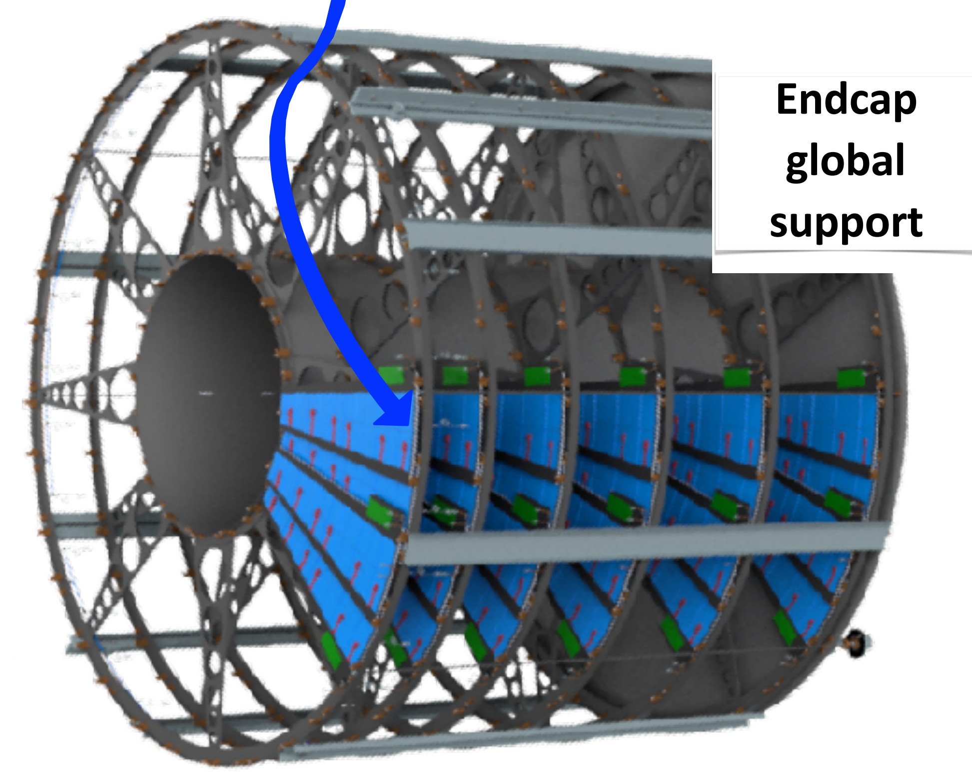
Example for EndCap Construction Flow



Module (endcap R0) With FE chips, sensor and hybrid (DC-DC converter, power board, HCC chip)



Endcap **loaded local support** with carbon core and modules glued double- sided

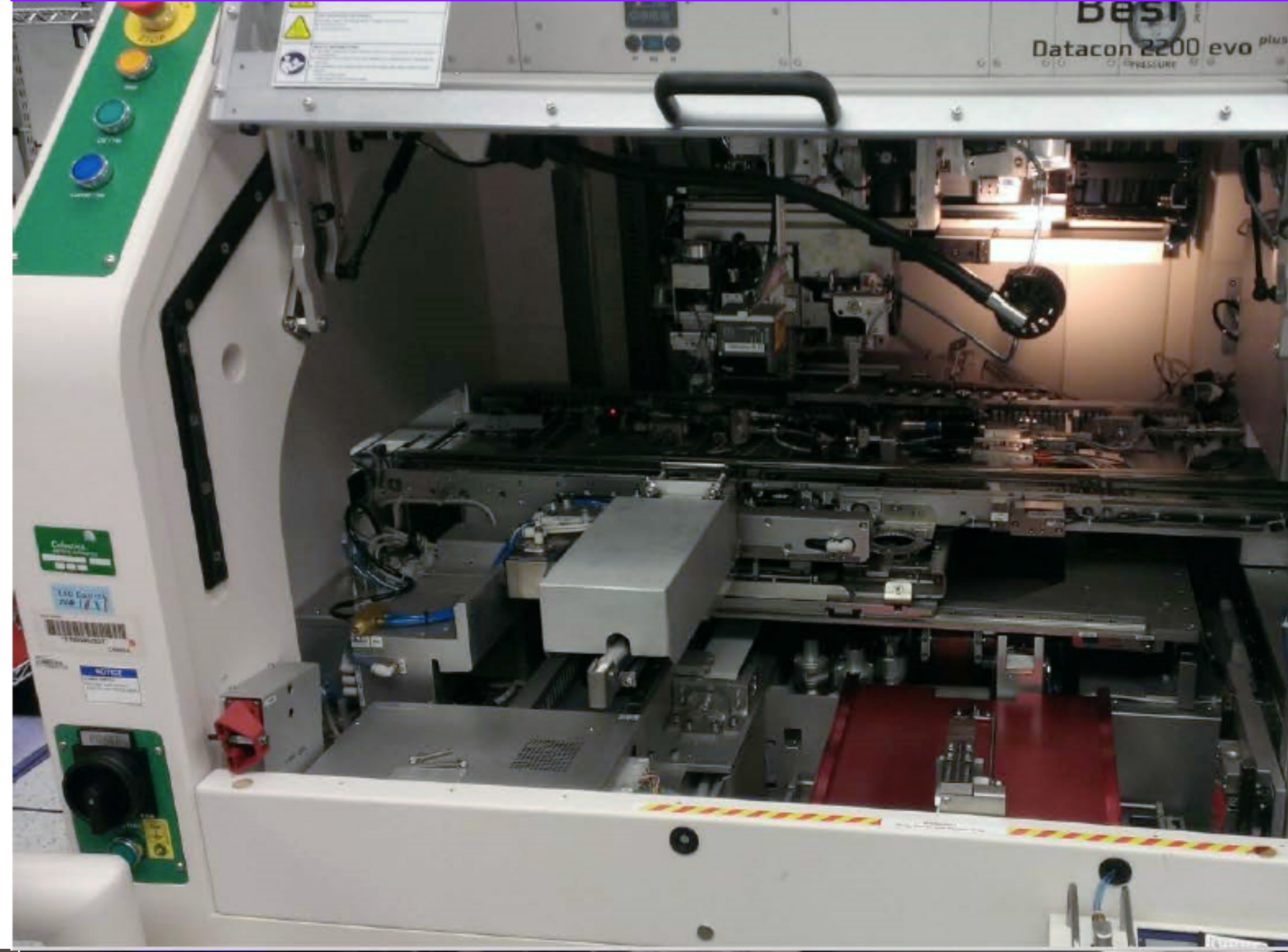


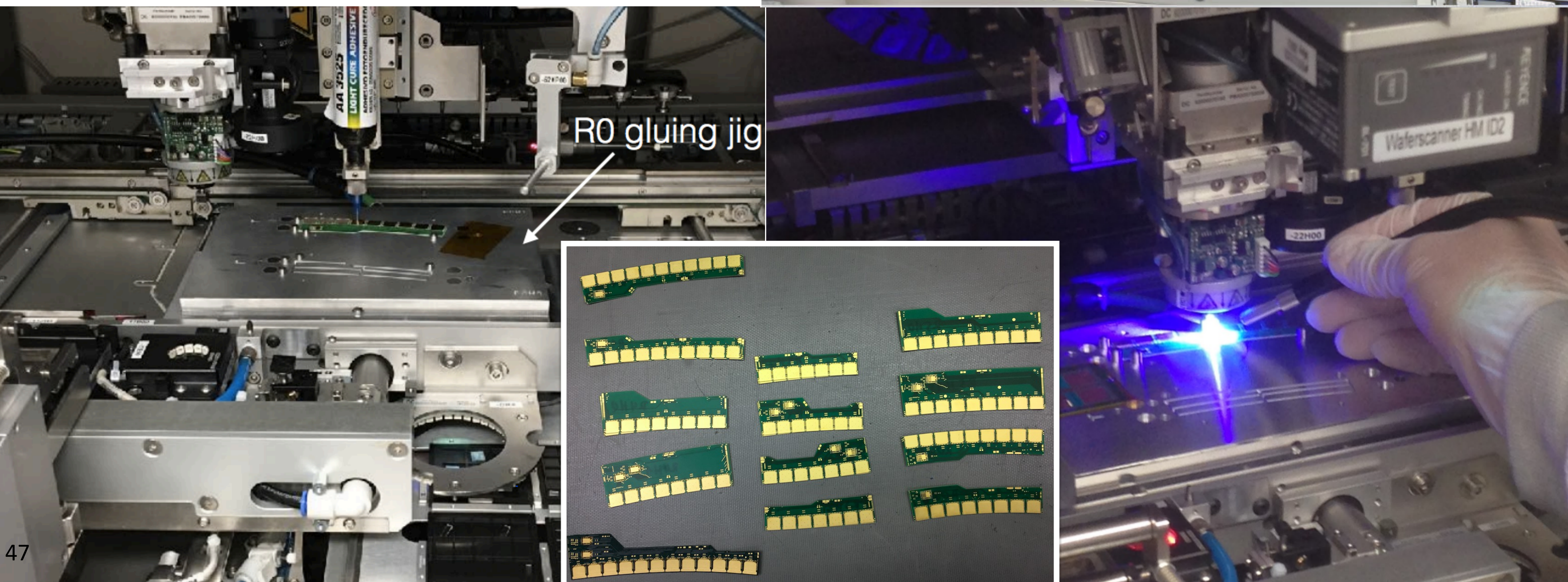
Endcap global support

Collaboration with Canadian Industry

ITk has also been working with a Canadian industrial partner to automate the process of hybrid production. In industry, mass production involving IC/PCB mounting universally done by robotic machines know as “die bonders” or “pick ’n’ place” machines.

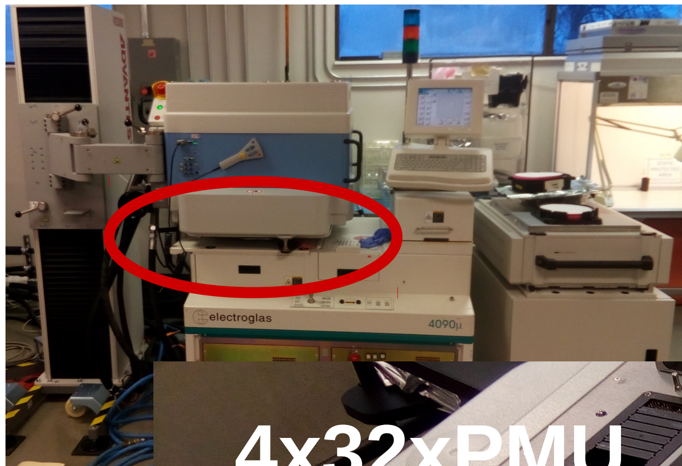
Here you see the example of ASIC attachment to the PCB hybrid using UV-cured adhesive.

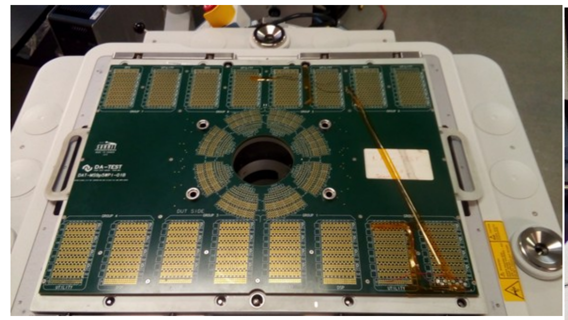


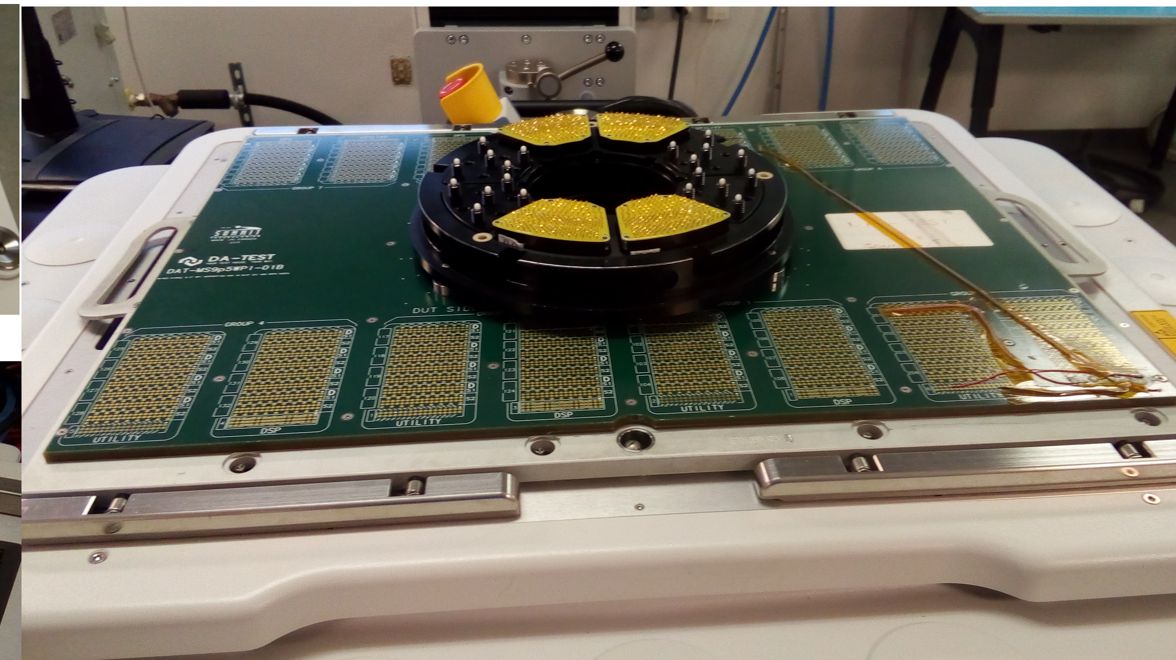


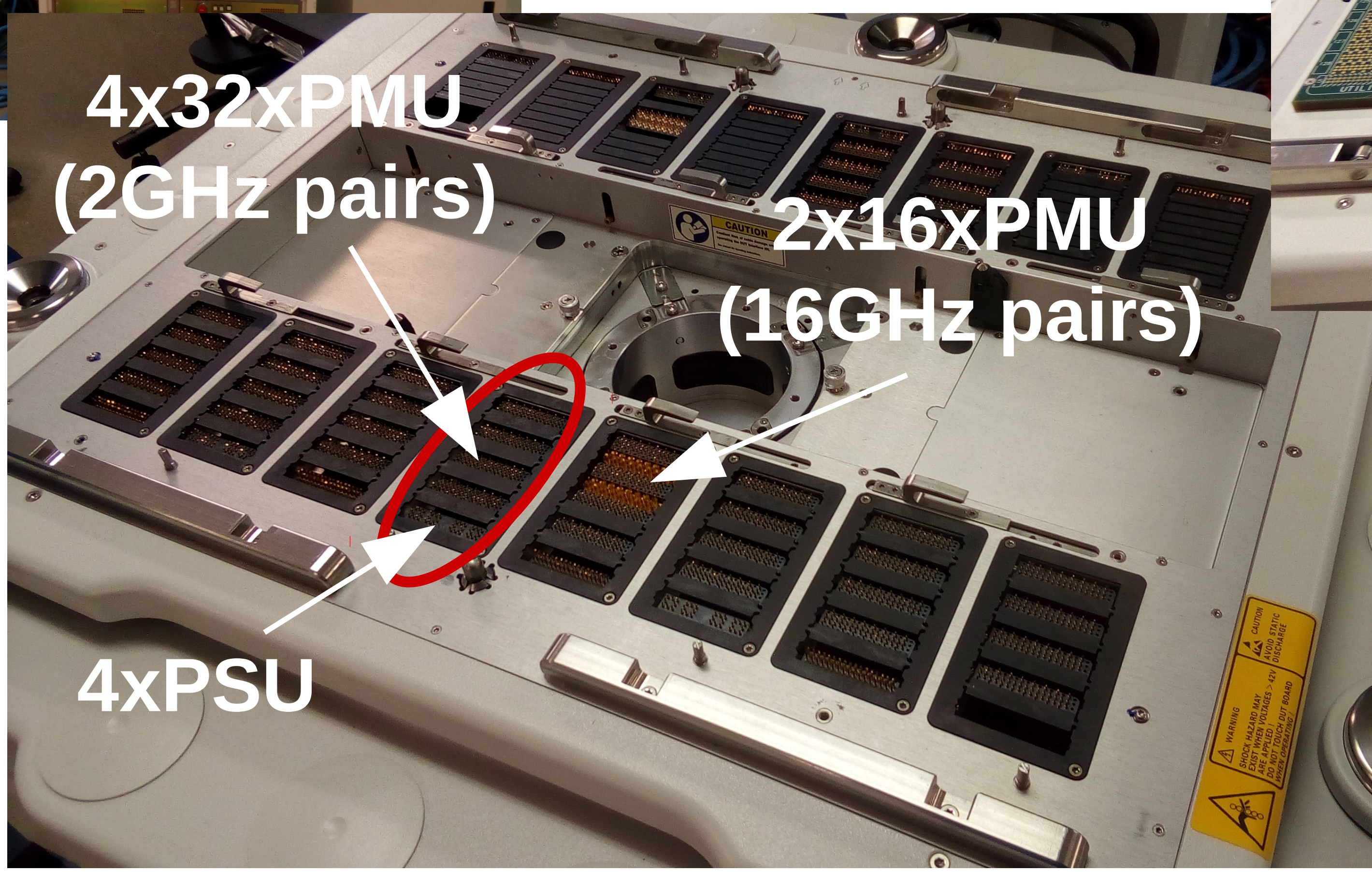
Celestica™

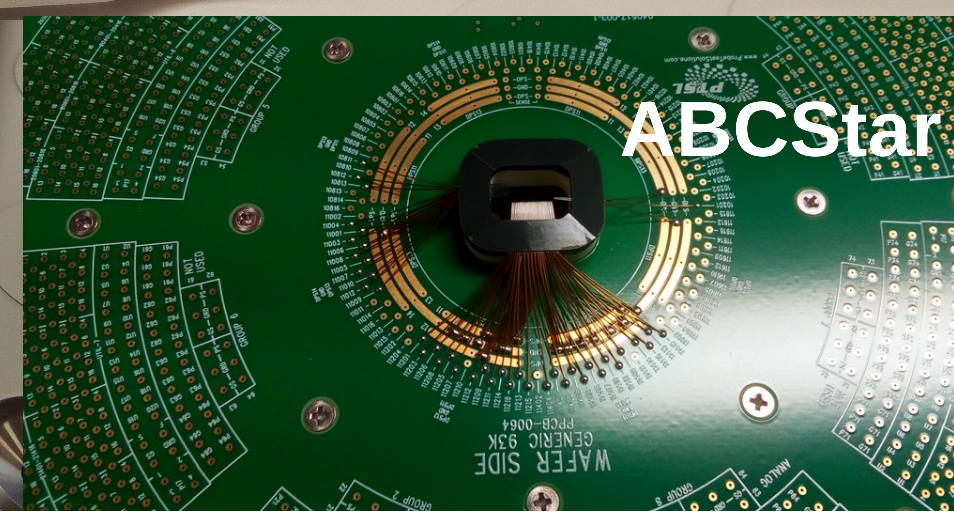
ASIC Wafer Probing and Dicing in Canadian Industry







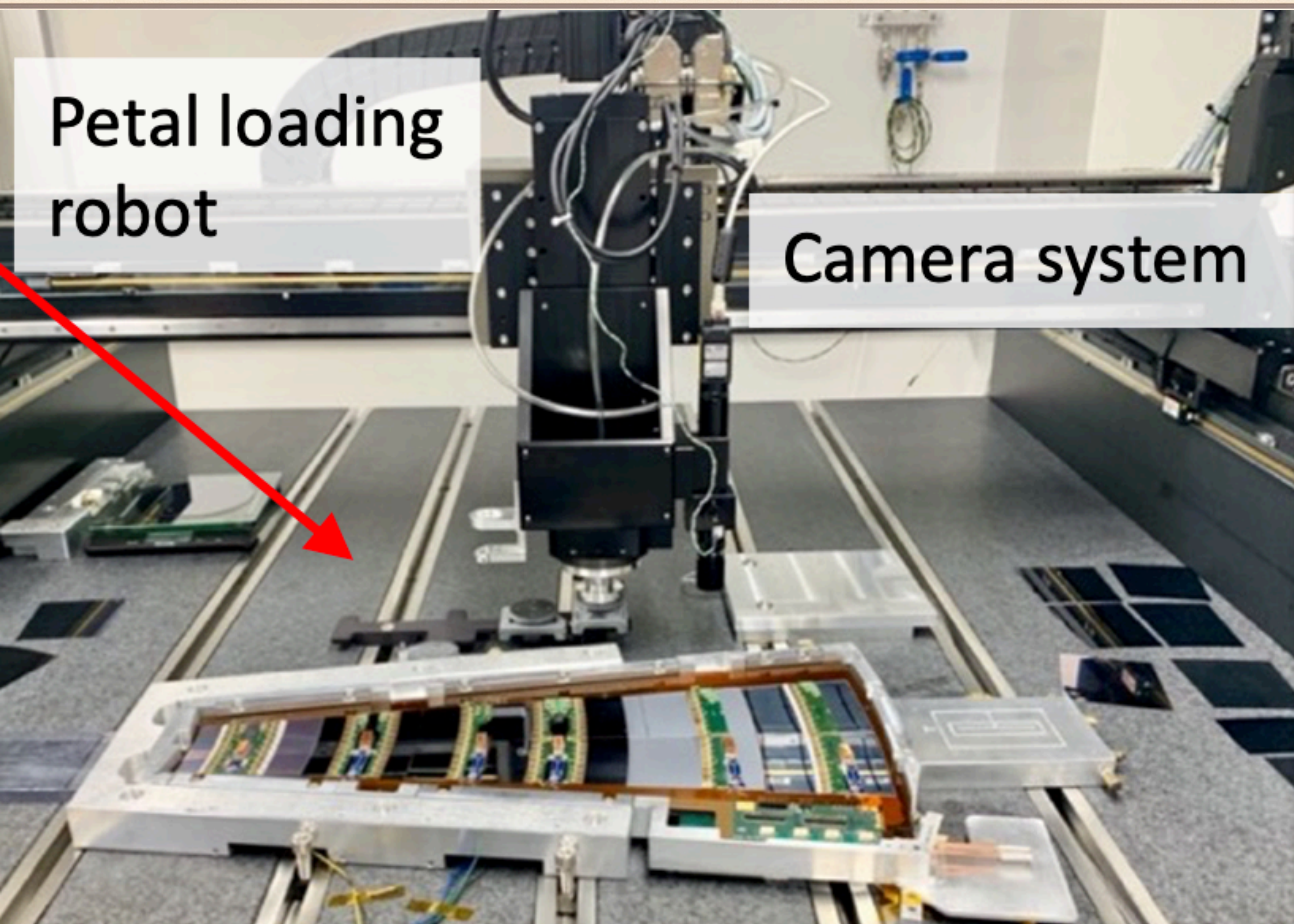


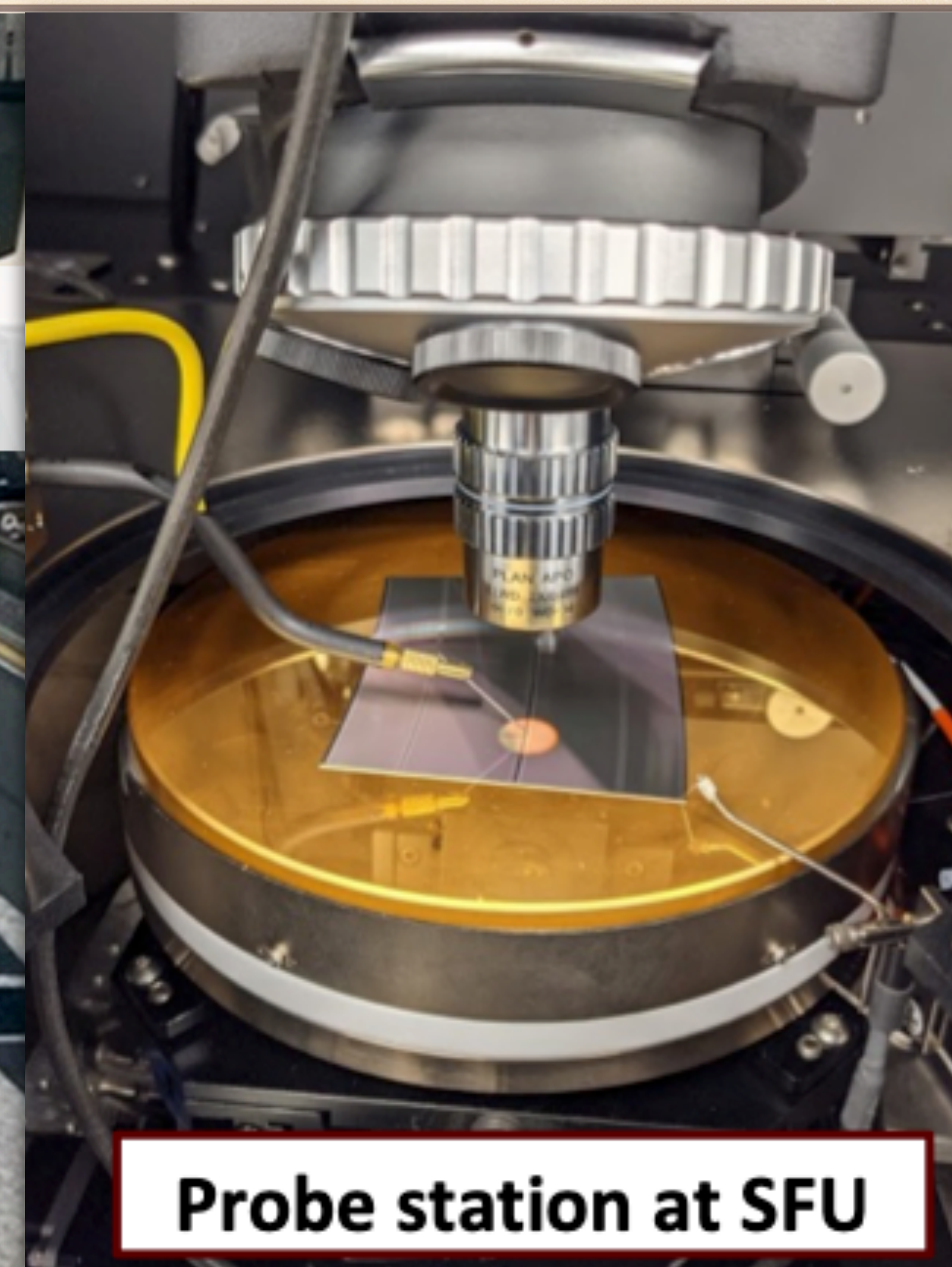


Custom ITk probe card

PMU = Parametric Measurement Units

Close to Carleton - group members embedded in industry - accessible - rare in industry used to customarily large volumes 1000's wafers


Petal loading robot
Camera system


Probe station at SFU


UBC clean room

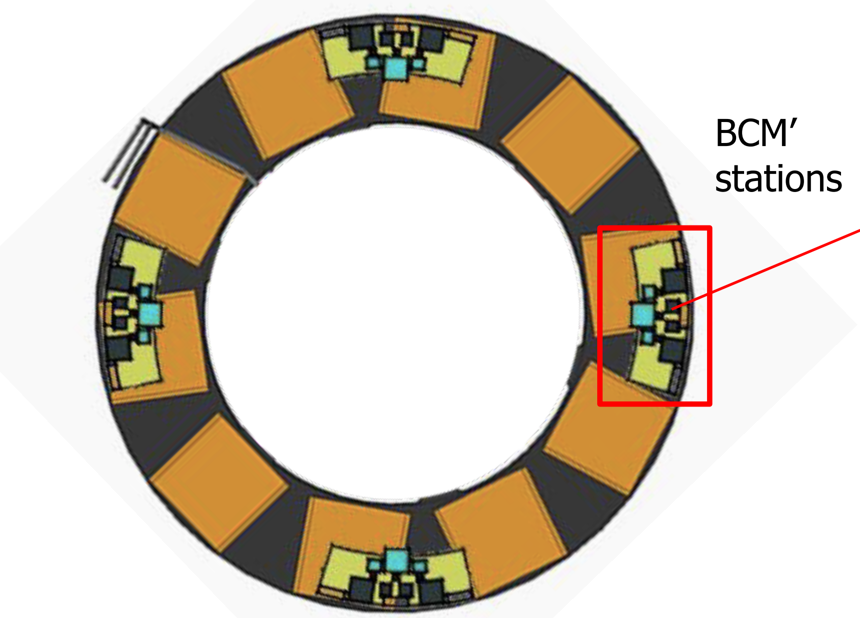

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION
FONDATION CANADIENNE POUR L'INNOVATION
ATLAS
Cleanroom at TRIUMF

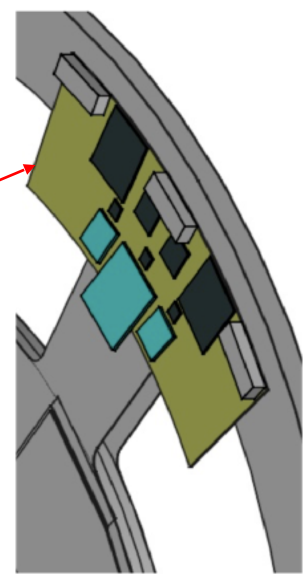
Luminosity and Beam Protection

✓ **1. Beam Conditions Monitor Upgrade (BCM')**

✓ Provides Fast (bunch-by-bunch) safety system for ATLAS, Luminosity measurement and Background monitoring

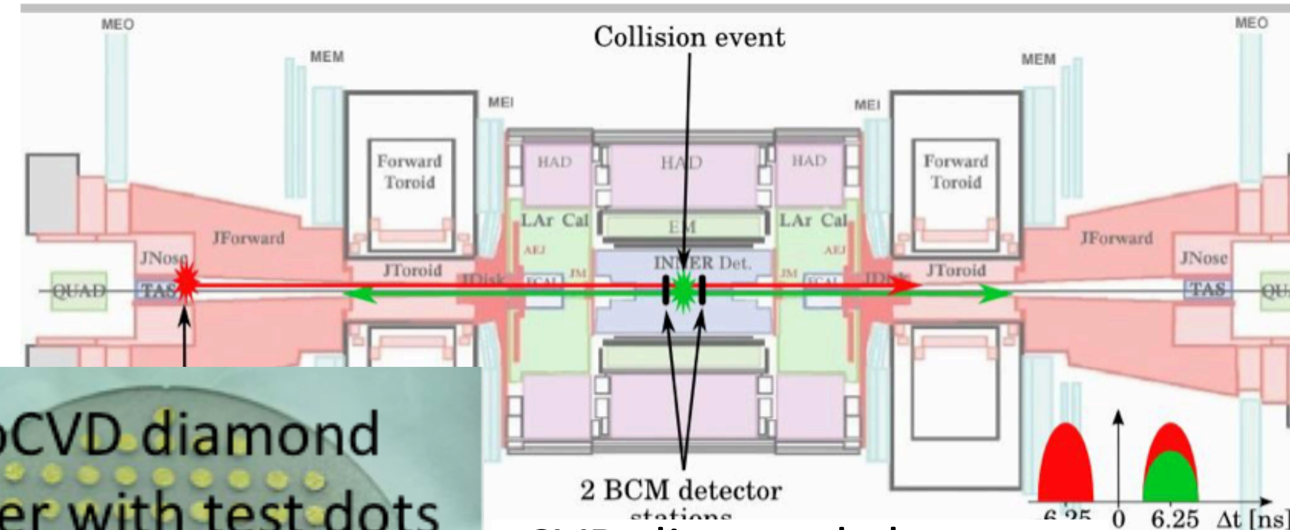
✓ Inner Pixel system: Separate ring; 4 stations per side with abort, lumi BCM' and BLM.

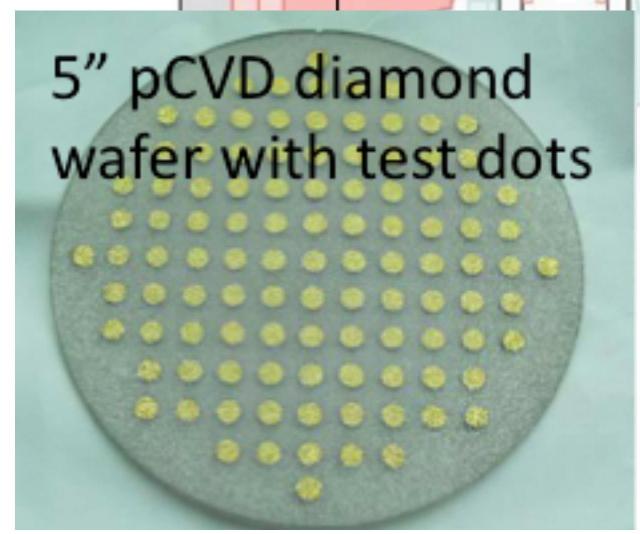




BCM TOF concept

- Collisions: in-time
- Background: out-of-time

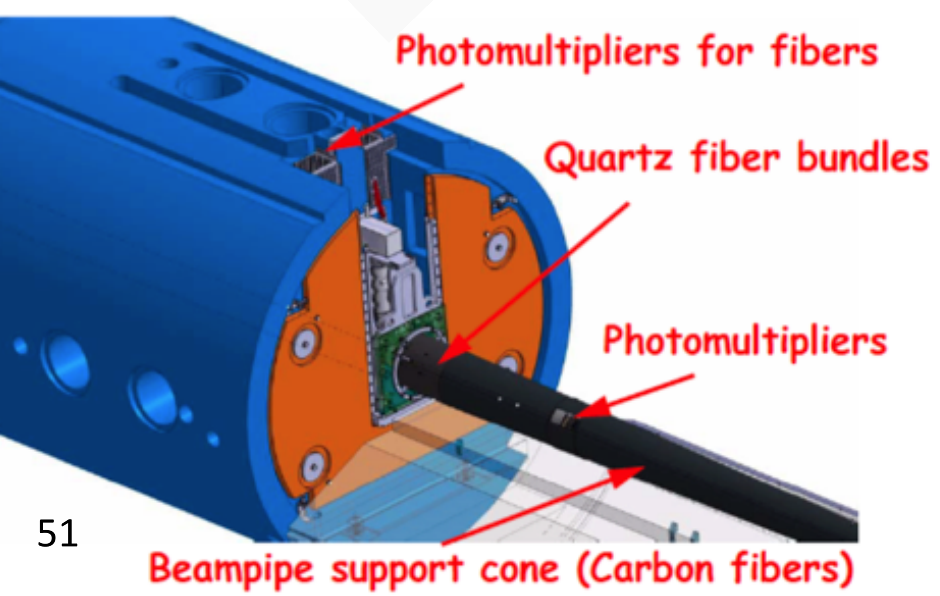




pCVD diamond chosen as sensor material

- robustness (no cooling), low C, negligible I, fast signal, radiation hard

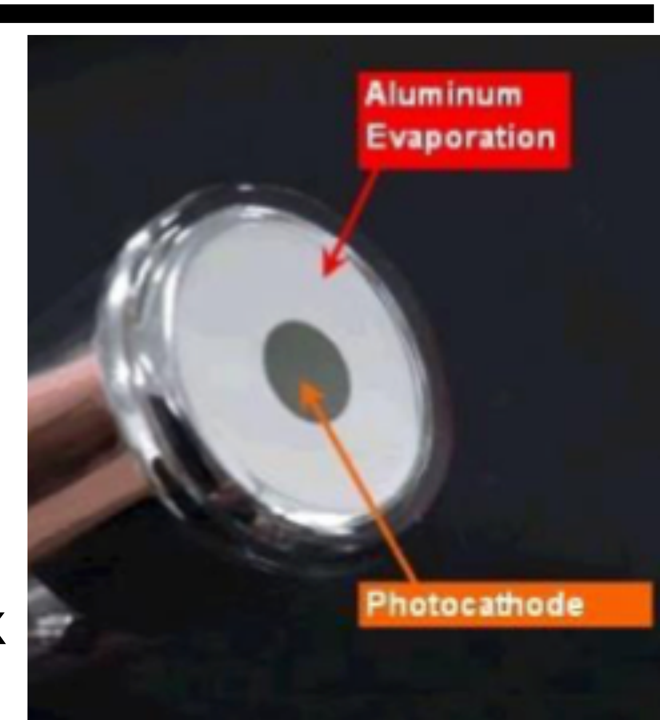
2. LUCID (LUminosity Cherenkov Integrating Detector) Upgrade



Pinfold et al

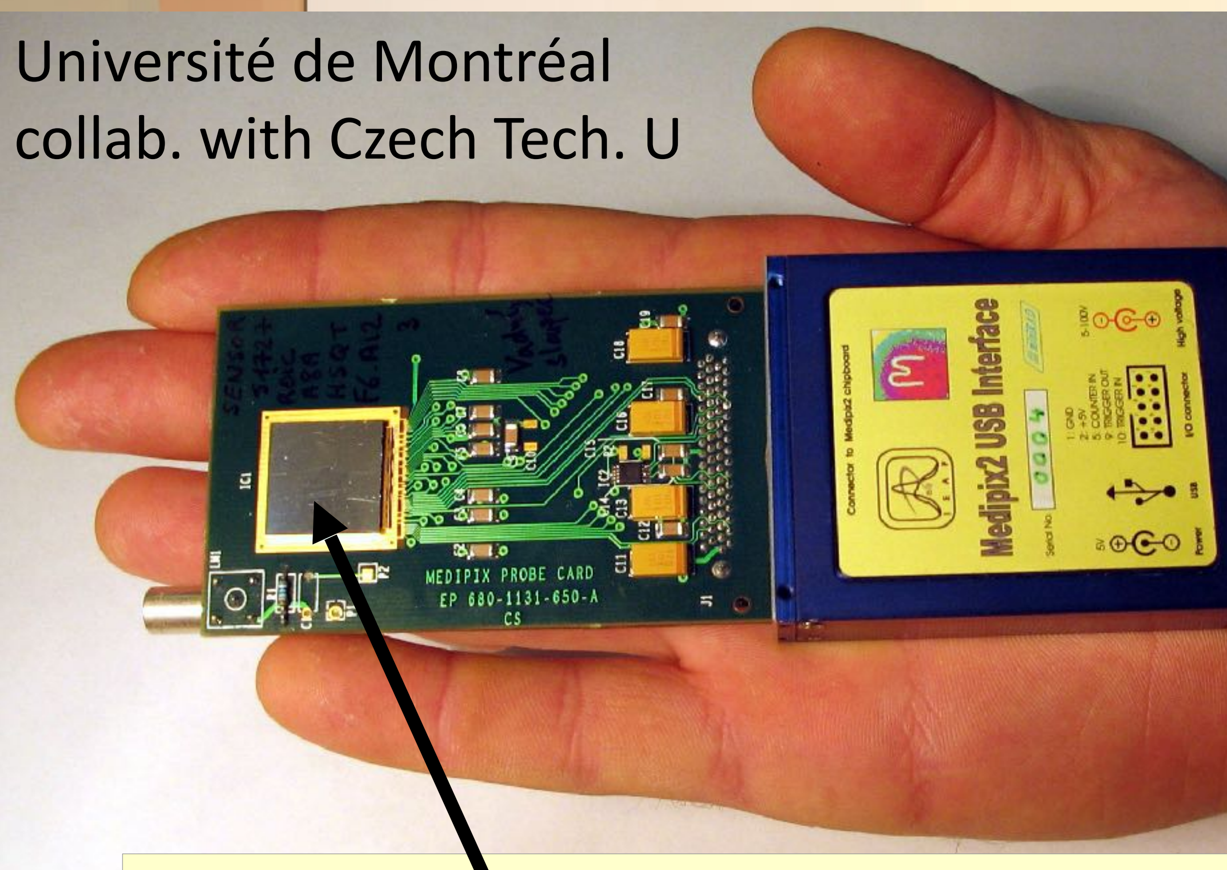
- Replace all PMTs with MOD-PMTs (modified: Aluminum ring deposited on inside of windows)
- Reduce PMT acceptance

  -> avoid saturation @ high μ
- Move detectors to region w. lower flux



Canada & Medical Applications

Université de Montréal
collab. with Czech Tech. U

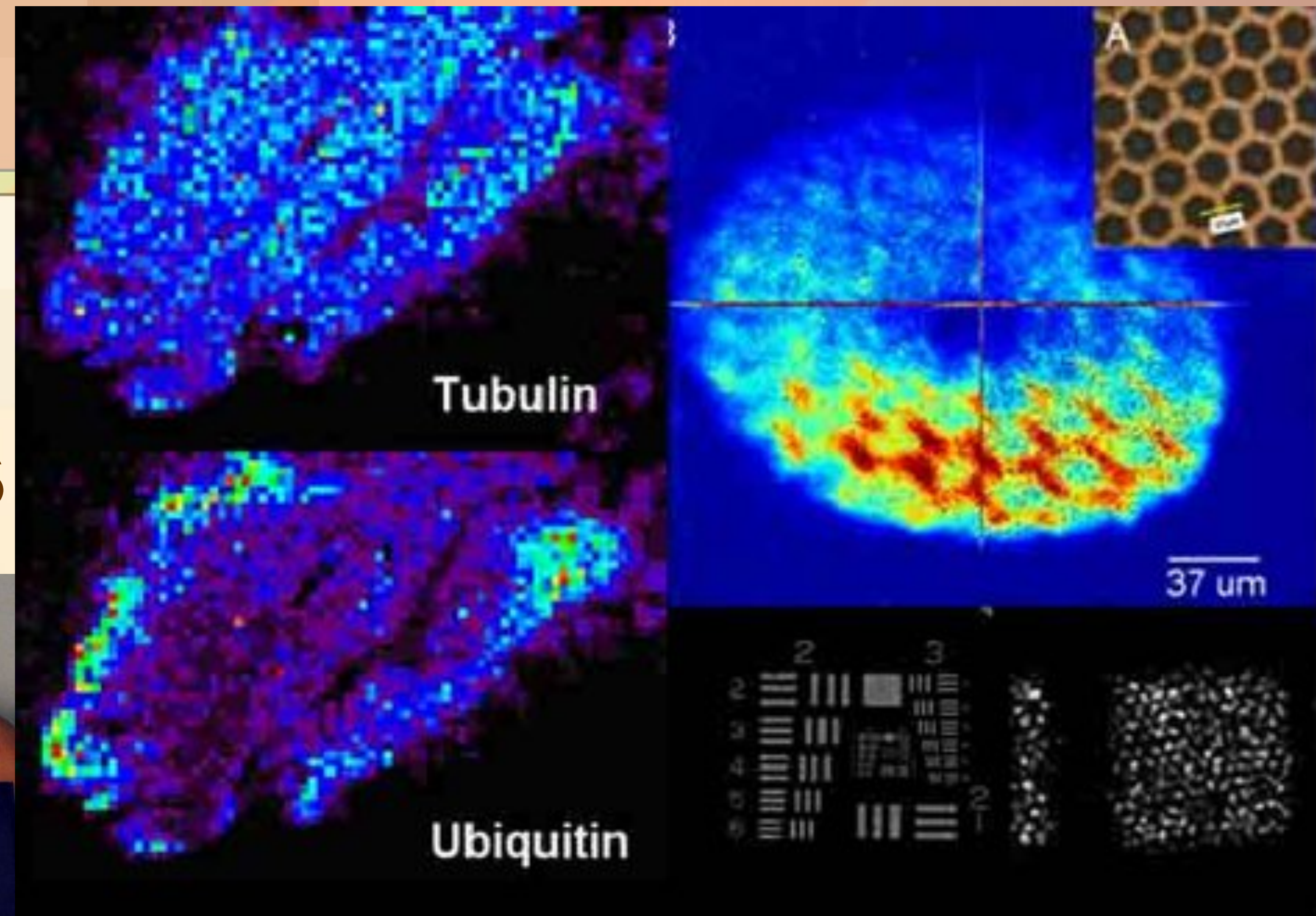


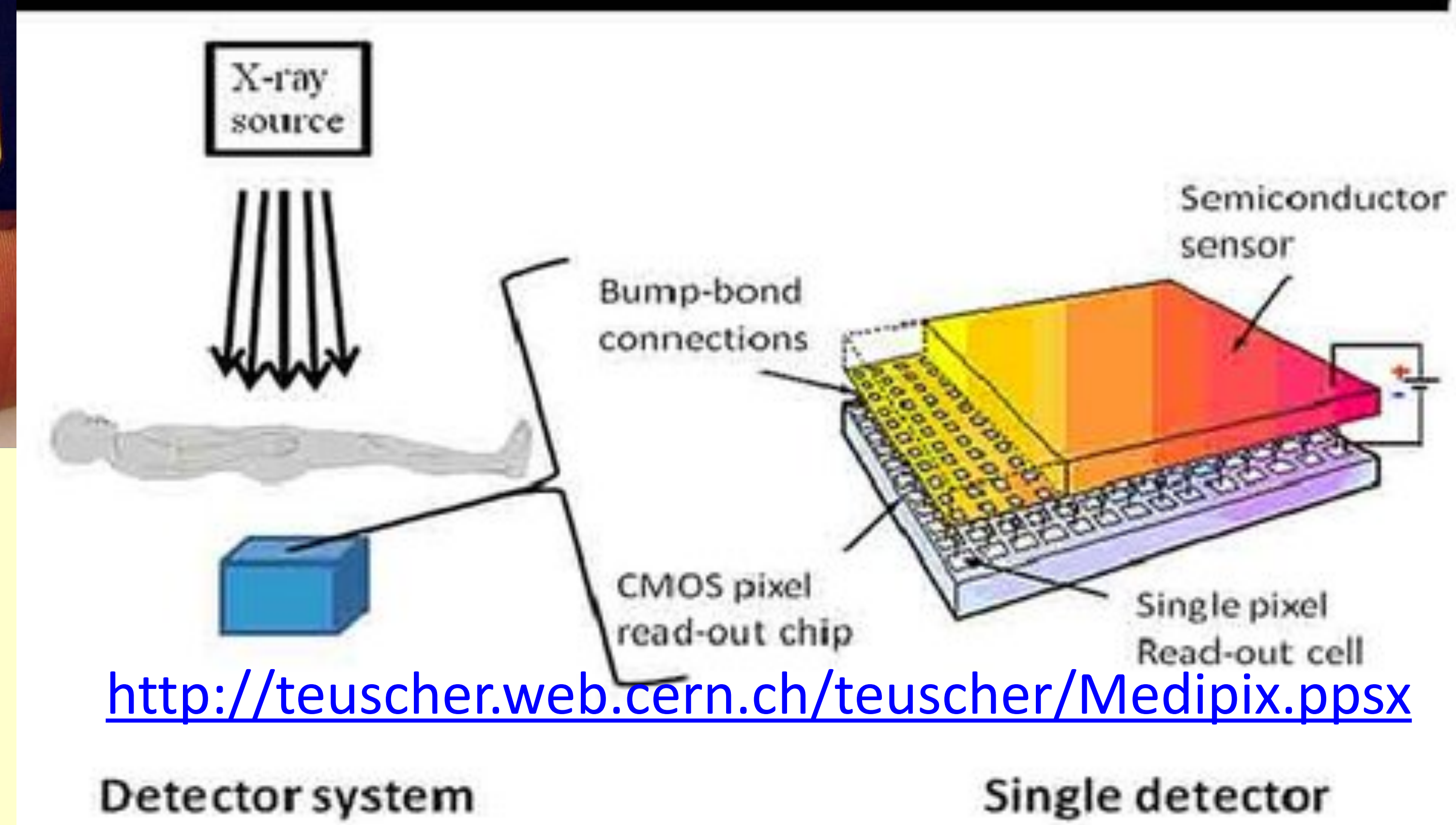
Medipix / Timepix

Pixels: 256 x 256

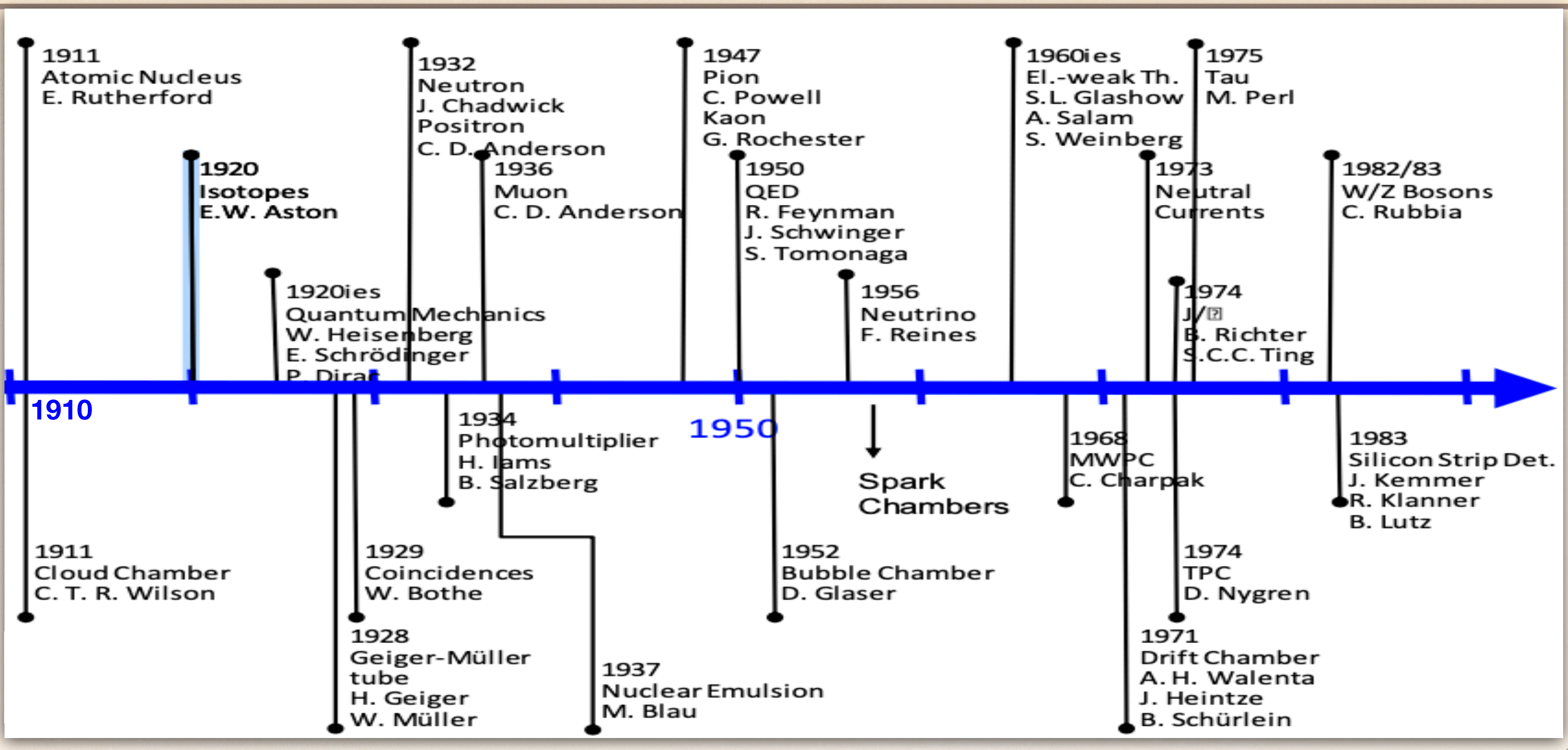
Pixel size: 55 x 55 μm^2

Area: 1.5 x 1.5 cm^2





http://teuscher.web.cern.ch/teuscher/Medipix.ppsx



First **visual** detectors (cloud chamber, chamber, streamer, photographs). Then **interactions** of particles with material to create electronic signal: (gas detectors, spark chambers, multi-wire proportional chambers, drift chambers, time projection chambers, straw tube). Now **semiconductors.**

- Could only cover a small sample, many others (SNO, T2K, SuperCDMS, Belle, BaBar, DUNE, fixed target, … see dedicated talks for more).
- Surprises happen (e.g. failures in optical links - VCSELS (vertical-cavity surface emitting lasers) on-detector, likely due to humidity. Unexpected wire bond corrosion (humidity)…
- Accelerators often exceed design luminosity (ATLAS SCT still running past design lifetime).
- Plan B is necessary and very likely will be used! (e.g ZEUS TLT used much earlier than expected).
- Design for radiation hardness crucial for LHC detectors (ASIC triplication, SEE/SEU tests).
- Collaboration between universities, laboratories & industry part of Canadian success story.

REFERENCES

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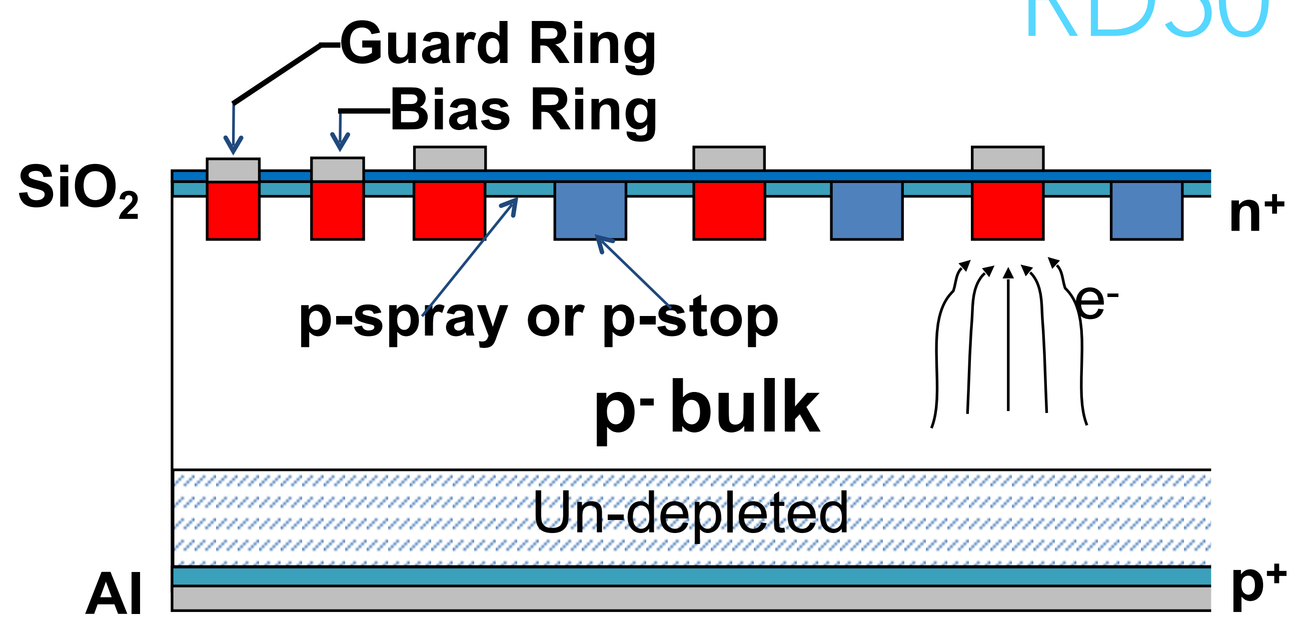
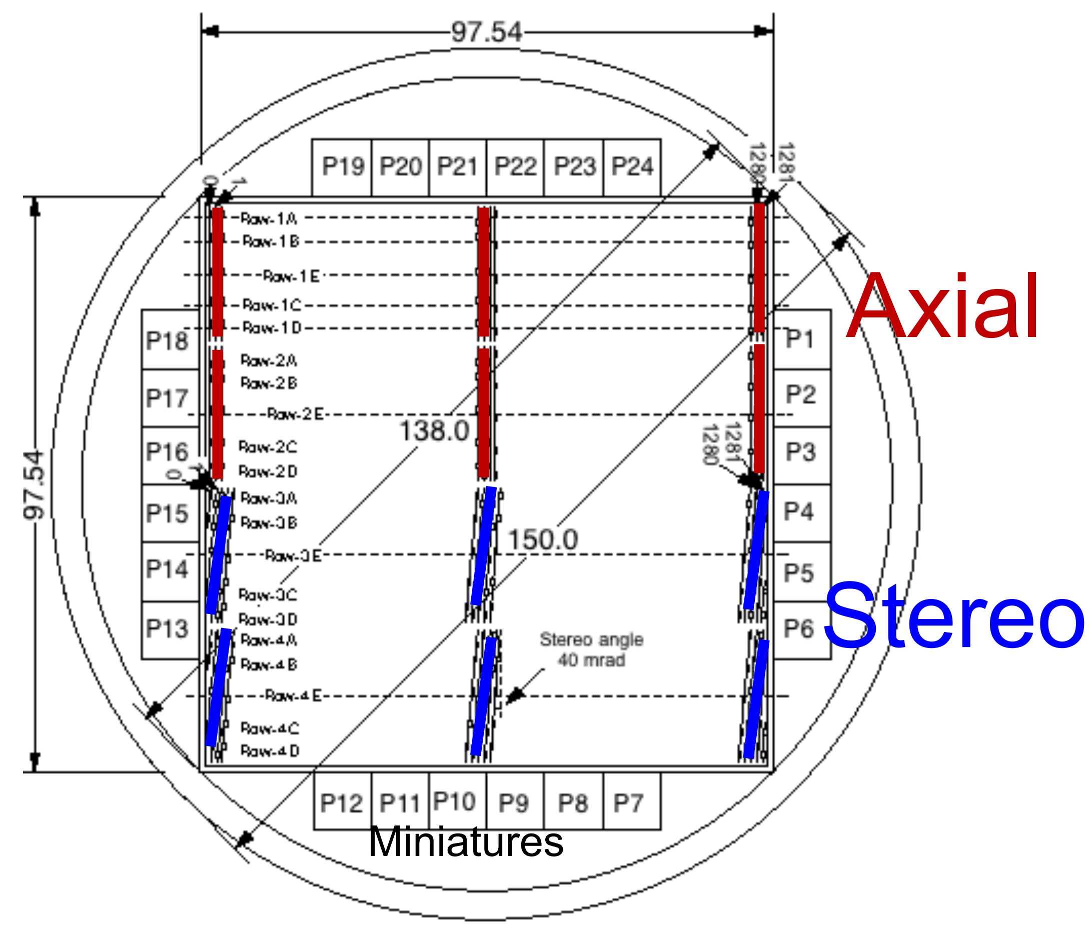
BACKUP

Si Strips: Radiation Hard n-in-p Silicon Sensors

RD50

- n^+-strip in p-type substrate (n-in-p)
  - Collects electrons
    - like current n-in-n pixels
    - Faster signal, reduced charge trapping
  - Depletes from the segmented side
    - Good signal even under-depleted
  - Single-sided process
    - 30-40% cheaper than n-in-n
    - More foundries and available capacity world-wide
  - Easier handling/testing
    - due to lack of patterned back-side implant
- Collaboration of ATLAS with Hamamatsu Photonics (HPK)
  - ATLAS07
  - 9.75x9.75 cm^2 sensors (6 inch wafers)
  - 4 segments (2 axial, 2 stereo), 1280 strip each, 74.5 mm pitch
  - FZ <100>, 320 µm thick material
  - Miniature sensors (1x1 cm^2) for irradiation studies





ATLAS07 sensor to study axial and stereo layouts

Y. Unno, et. al., Nucl. Inst. Meth. A, Vol. 636 (2011) S24-S30

(ATLAS12 qualification done summer '14)

ITk Strips in Numbers

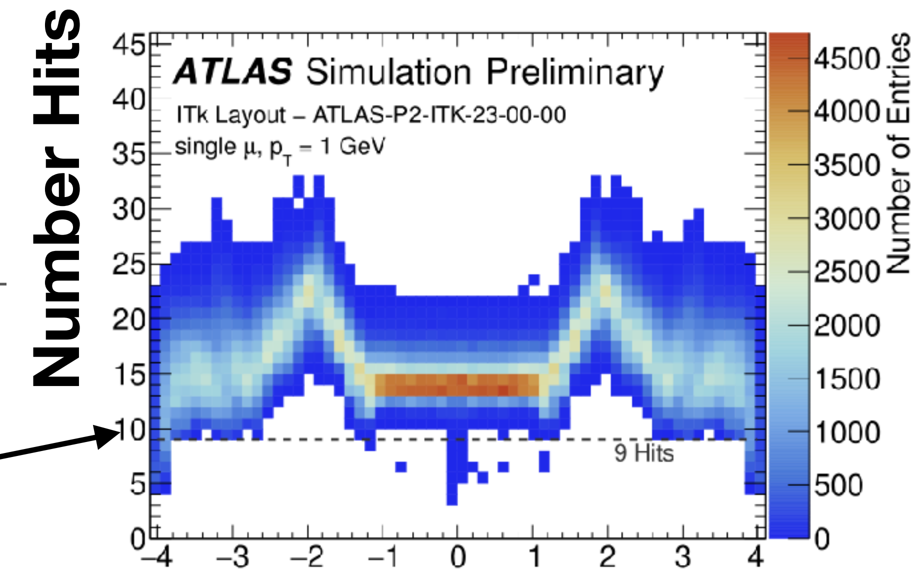
Table 5.1: Number of components for the ITk Strip Detector in barrel (top half) and end-cap (bottom half). The numbers for the barrel are for the full barrel with 2.8 m length. The numbers for the end-caps (EC) are given both for one and both end-caps.

Barrel Layer:	**Radius [mm]**	**# of staves**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
L0	405	28	784	1568	15680	4.01M	7.49
L1	562	40	1120	2240	22400	5.73M	10.7
L2	762	56	1568	1568	15680	4.01M	14.98
L3	1000	72	2016	2016	20160	5.16M	19.26
Total half barrel		196	5488	7392	73920	18.92M	52.43
Total barrel		392	10976	14784	147840	37.85M	104.86
End-cap Disk:	**z-pos. [mm]**	**# of petals**	**# of modules**	**# of hybrids**	**# of of ABCStar**	**# of channels**	**Area [m^2]**
D0	1512	32	576	832	6336	1.62M	5.03
D1	1702	32	576	832	6336	1.62M	5.03
D2	1952	32	576	832	6336	1.62M	5.03
D3	2252	32	576	832	6336	1.62M	5.03
D4	2602	32	576	832	6336	1.62M	5.03
D5	3000	32	576	832	6336	1.62M	5.03
Total one EC		192	3456	4992	43008	11.01M	30.2
Total ECs		384	6912	9984	86016	22.02M	60.4
Total		**776**	**17888**	**24768**	**233856**	**59.87M**	**165.25**

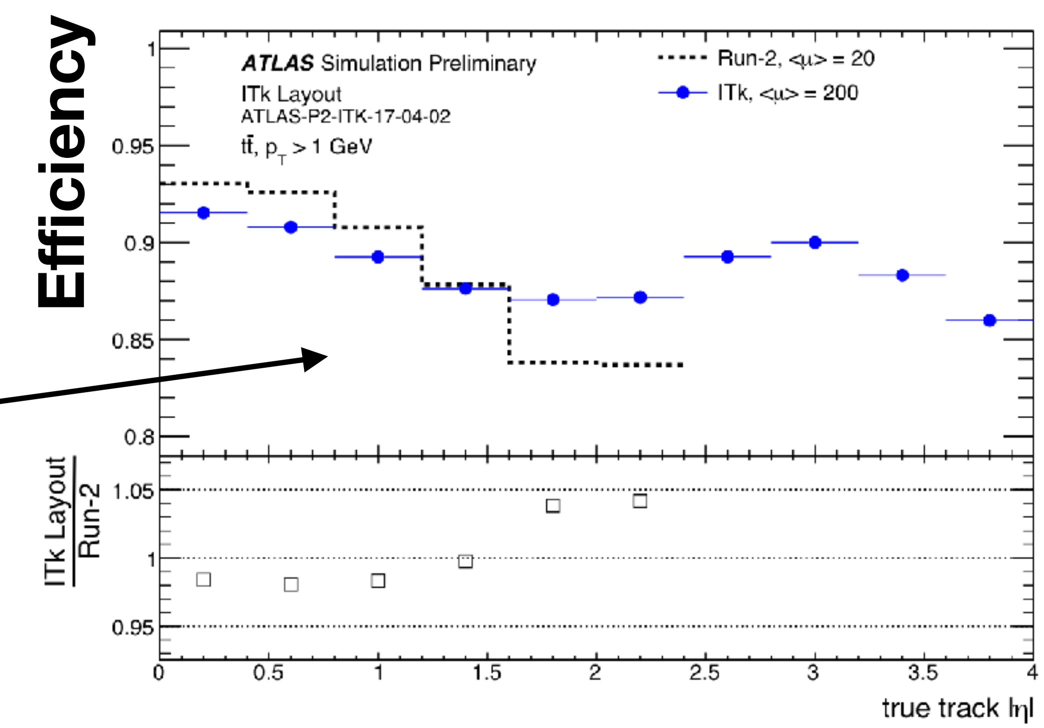
ITk Tracking Performance

✓ ITk layout designed to guarantee **hermetic** coverage within |η| <4

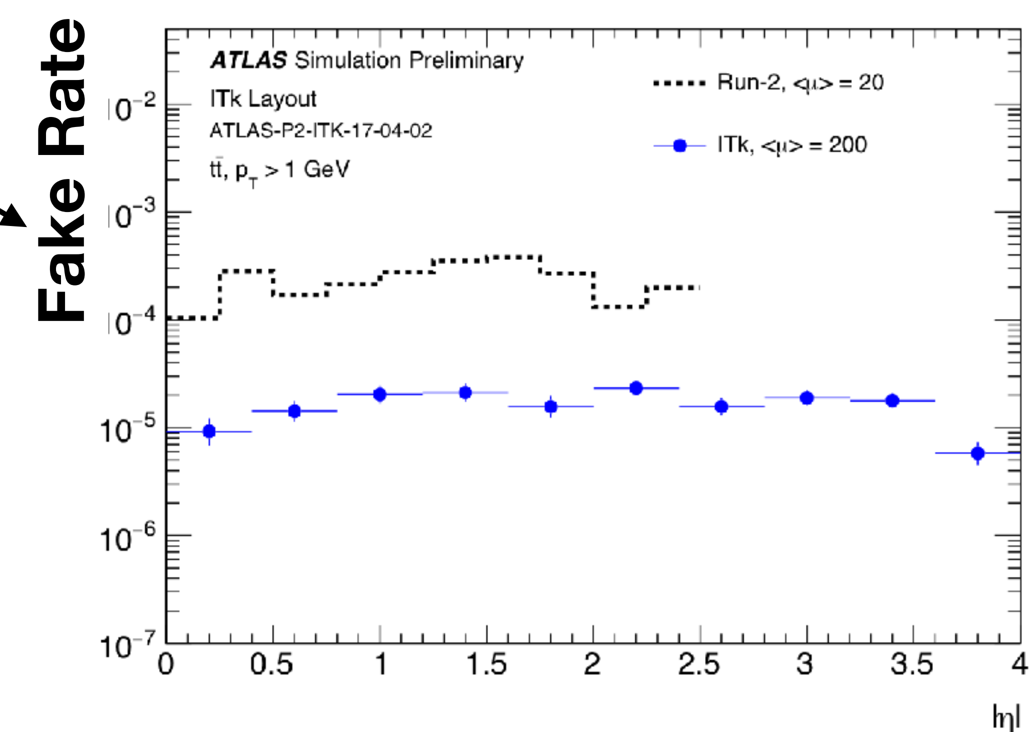
- Provides at least **9 hits** for all particles with p_T> 1 GeV within $|z_{vertex}|$ < 150 mm
  - Allows for **tighter track selection** without compromising reconstruction efficiency



- Maintain **efficiency over 85%** up to |η| <4, comparable to Run2 ID at <μ> =20



- Improves the **fake rate over Run2 ID,** <u>even with a 10x increase in pile-up</u>.



Overall significant improvement thanks to

- Reduced material budget → minimize material interactions
- Increase in overall hit counts → tighter track selection
- Improved hermeticity → more hits, fewer holes

RADIATION HARDNESS

Table 1: Examples of Required Radiation Hardness of Two Typical Collider Detectors (From [9,10,11]) For definitions of the units in this table, see the Appendix.

	Total Ionizing Dose	Non-ionizing Fluence (1 MeV neutron equivalent)
BaBar		
Inner Silicon Strip Detector	20 kGy	Negligible
Outer Calorimeter	100 Gy	Negligible
ATLAS		
Inner Pixel Detector	500 kGy	10^{15} n_{eq}/cm^2
Outer Muon Spectrometer	20 Gy	10^{12} n_{eq}/cm^2

A. Grillo

Table 2.9: The maximal 1 MeV neutron equivalent fluences and total ionising dose for different parts of the Pixel Detector, for the baseline replacement scenario for the inner section. All values have been multiplied by a safety factor of 1.5.

Luminosity	Layer	Location	R (cm)	z (cm)	Fluence (10^{14} n_{eq}/cm^2)	Dose (MGy)
2000 fb^{-1}	0	flat barrel	3.9 *	0.0	131	-
			4.0	24.3	-	7.2
		inclined barrel	3.7	25.9	123	-
			3.7	110.0	-	9.9
		end-cap	5.1	123.8	68	6.3
2000 fb^{-1}	1	flat barrel	9.9	24.3	27	1.5
		inclined barrel	8.1	110.0	35	2.9
		end-cap	7.9	299.2	38	3.2
4000 fb^{-1}	2-4	flat barrel	16.0	44.6	28	1.6
		inclined barrel	15.6	110.0	30	2.0
		end-cap	15.3	299.2	38	3.5

*** Updated in 2020: 3.9 -> 3.4 cm, Fluence -> 188 E+14 neq/cm**2**

Pixel 3D sensors

3D sensor technology has matured in the last 20 years and is now becoming a standard choice where extreme radiation hardness is critical. In ATLAS, part of the Insertable B-Layer (IBL) relies on 3D pixel sensors.

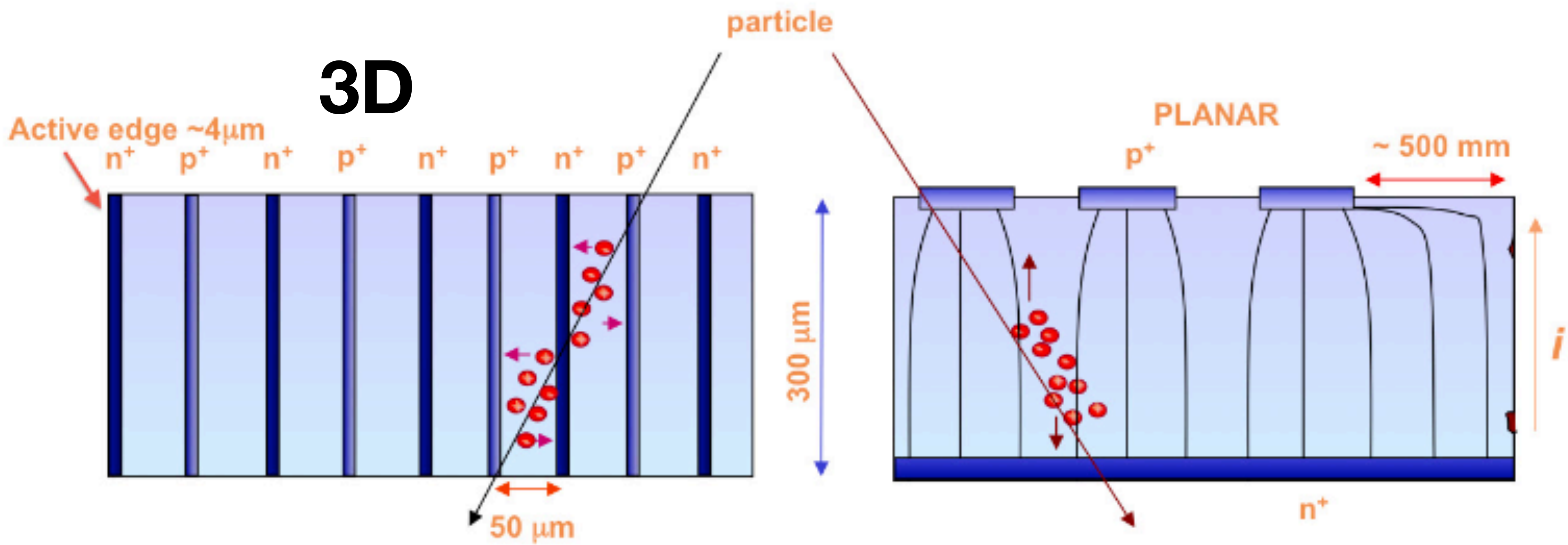
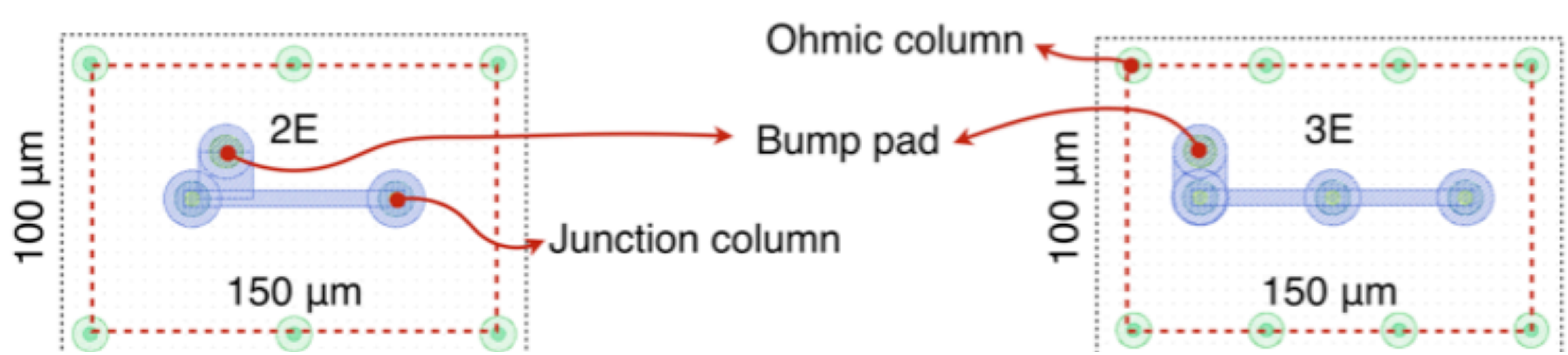


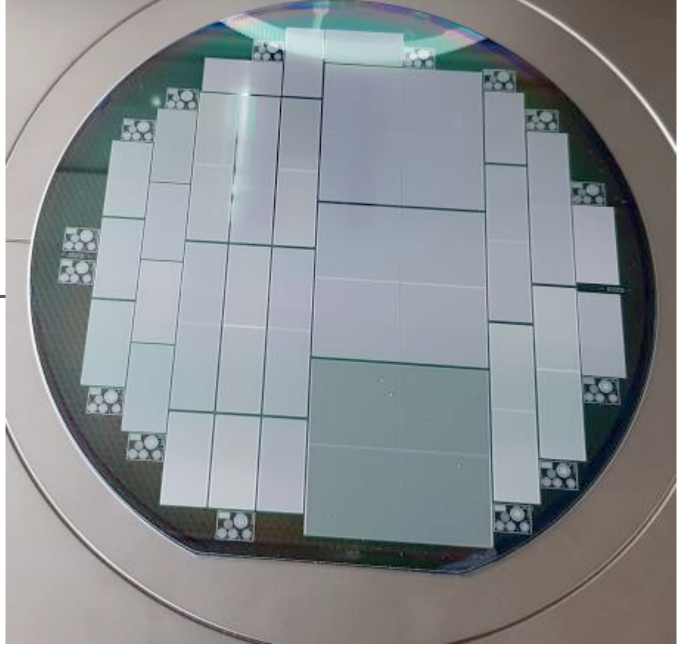
Figure 4.7: Schematic view of electrode arrangement and charge collection in planar and 3D pixel sensors.

1E: 1 electrode / pixel
2E: 2 electrodes / pixel
3E: 3 electrodes / pixel



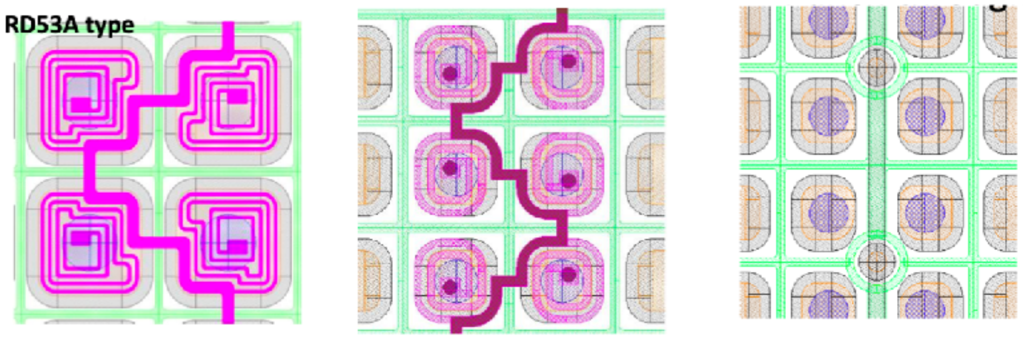
Pixel Planar Si sensors

- Thin n-in-p planar sensors: **IBL (Insertible B-Layer)** in ID today uses 200 μm n-in-n planar sensors with 50x250 μm^2 pixel cells.
- **ITk** will use n-in-p technology (single side process) with 50x50 μm^2 pixel cells: 150 μm for the outer layers; 100 μm for the inner Layer-1



✓ Required performance

- First results show clear operating hit efficiency >97%
- Bias voltage at end of lifetime up to:
  - 600 V for 150 μm active thickness
  - 400 V for 100 μm active thickness

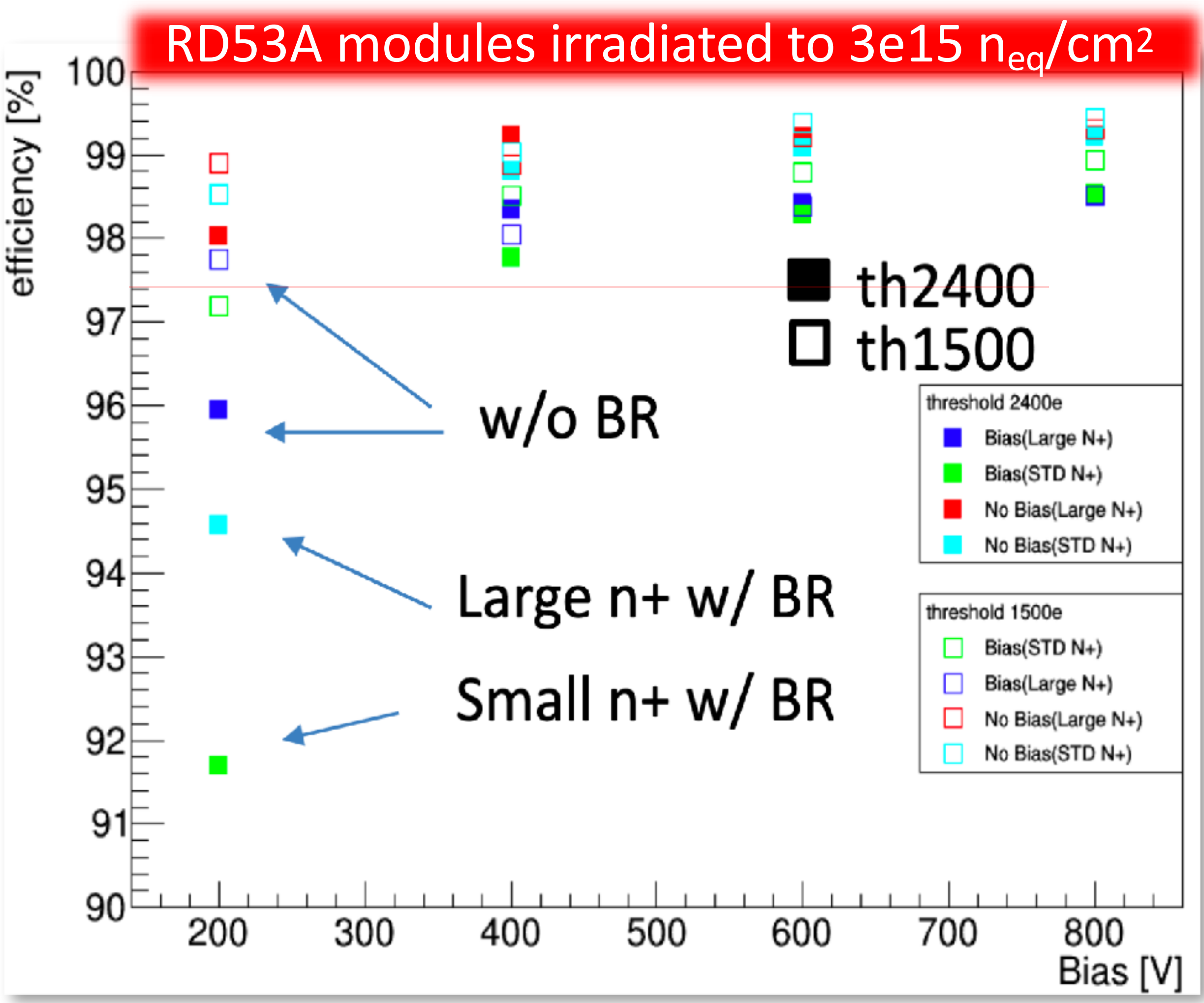


✓ Market Survey almost finalized

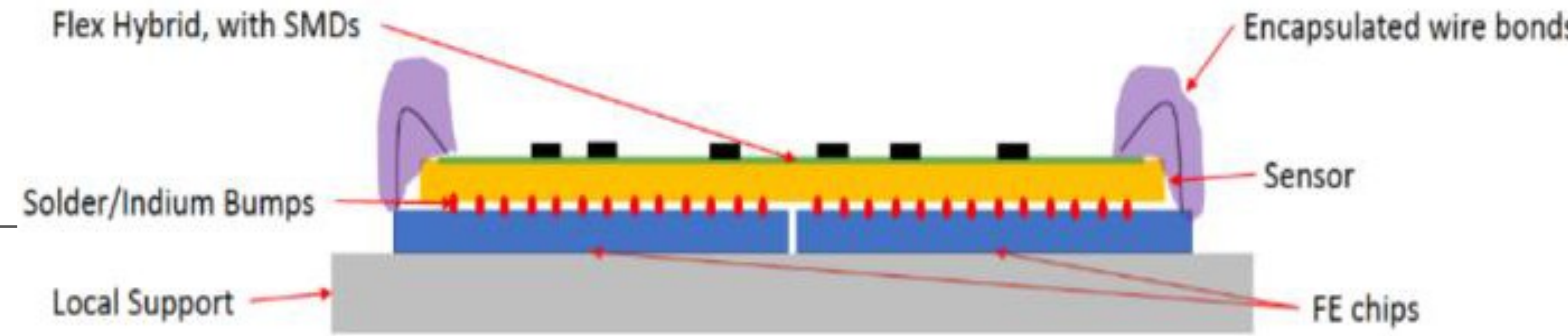
- Tender issued by the end of the year

✓ Vendors are optimizing the final design

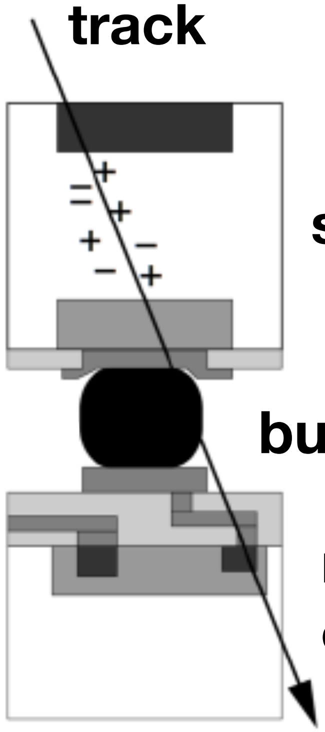
- Different biasing solutions allowed
  - Punch through (PT)
  - Bias Rail (BR) and bias resistor
  - Temporary Metal (TM)
- Dimension of the n+ implant



Pixel Modules



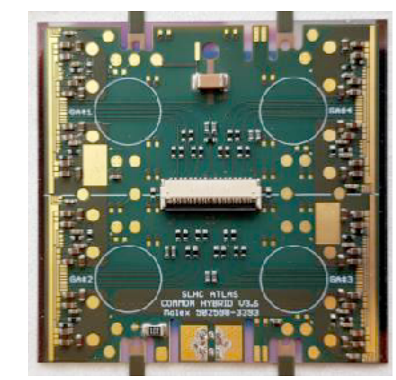
65 nm CMOS



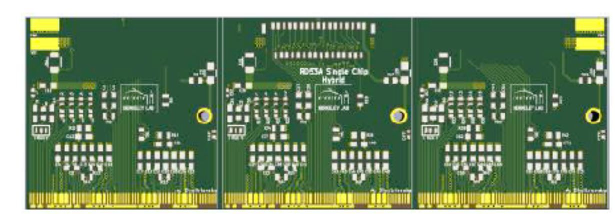
✓ Several module prototype stages have helped to reach maturity in several aspects:

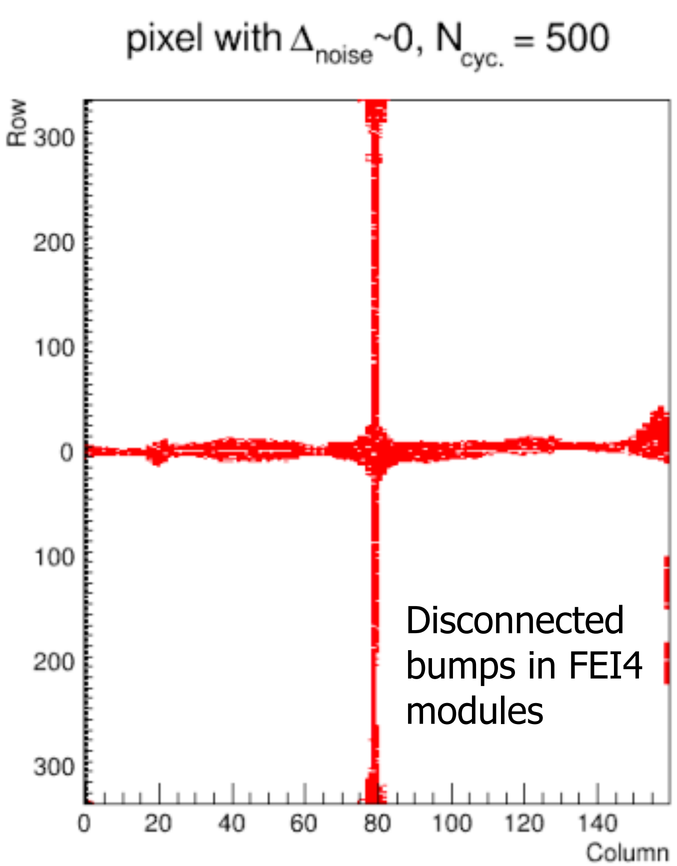
- General module design explored with FEI4 prototypes
- Extensive studies with ~ 250 RD53A module prototypes: thermal cycling, serial powering, new demonstrator to explore system aspects, …
- ITkPixV1 modules coming.

RD53A Quad Dummy



RD53A Triplet Flex for Layer 0





✓ Hybridization

- Demonstration of fine-pitch bump-bonding on RD53A successful.
- Market survey of vendors running for different process steps: bump deposition, UBM, flip-chip.
- Concern: Thermal cycling causes bump stress, in case of large CTE mismatch between flex (Cu) and Si. Observed in inter-chip regions of FEI4 quads.
  - Improves with parylene coating of the assembled modules and mitigations in interfaces and flex design.

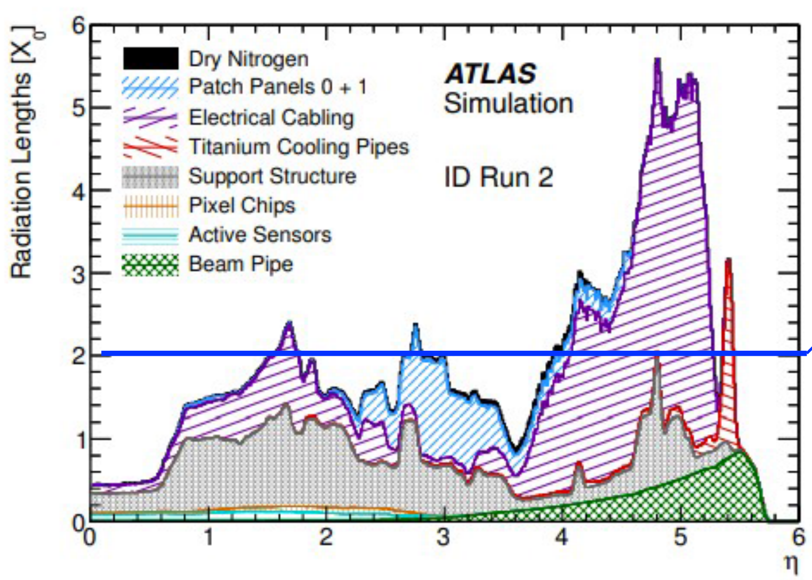
✓ Flex-Hybrid

- Designs for common flex hybrids finished (RD53A)/ongoing (ITkPixV1).
- Reduced Cu content to mitigate CTE mismatch with Si

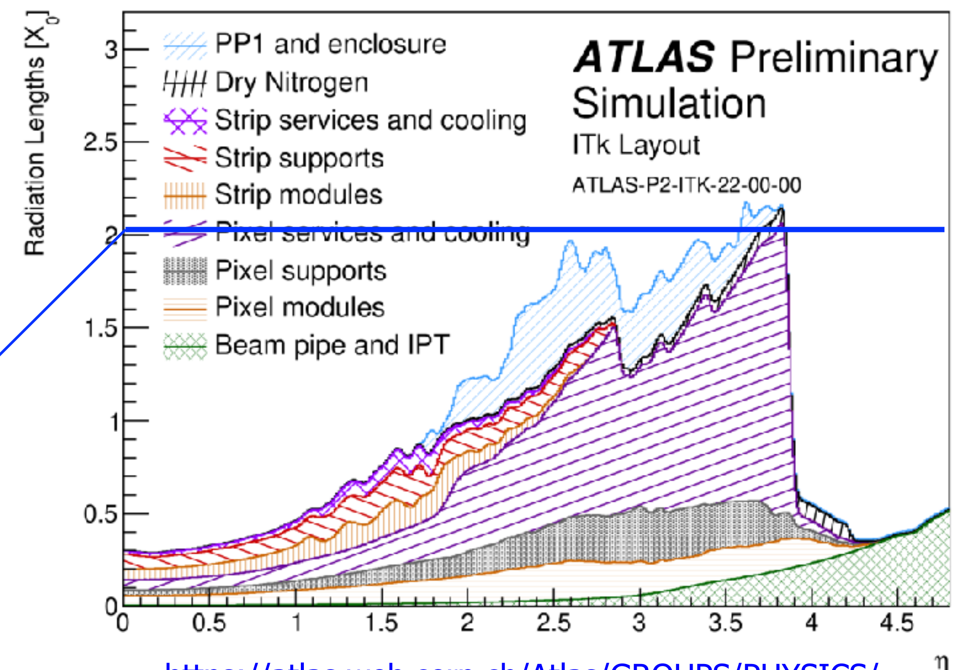
ITk Material Budget

✓ With the increased surface and granularity wrt ID, X_0 mitigation thanks to:

- Strip: DC-DC powering and data transmission with optical links and lpGBT
- Pixel: Thinned sensors and FE, Serial powering, inclined region in the Outer Barrel, increased readout speed
- Common (ITK and Strip): Light structures, cooling designs optimized as well as material choice wrt the requirements (precision, stability, contain the thermal run away, …)
- NB: Material budget is regularly updated as the engineering design evolves



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2017-021/

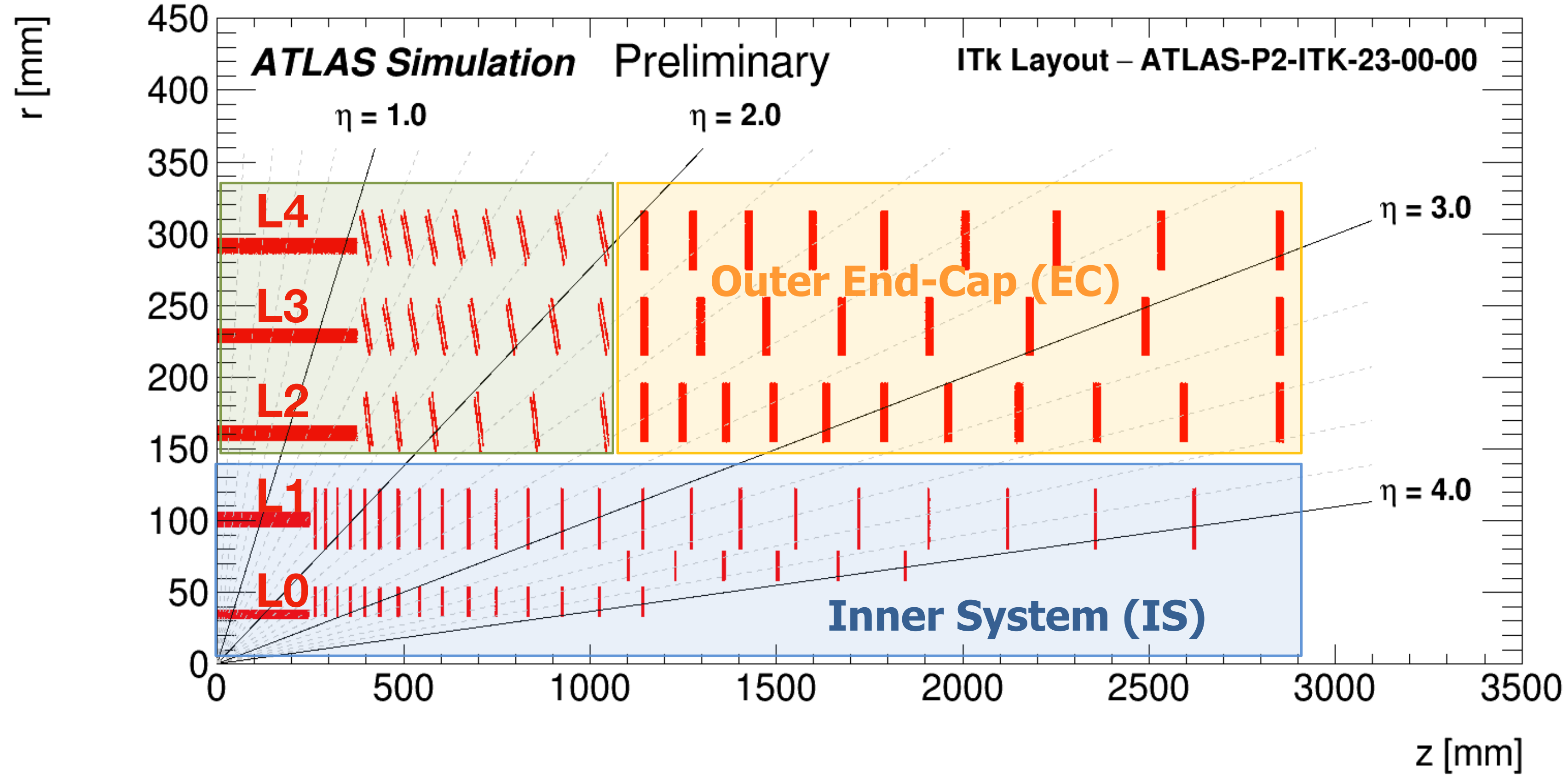


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2019-001/

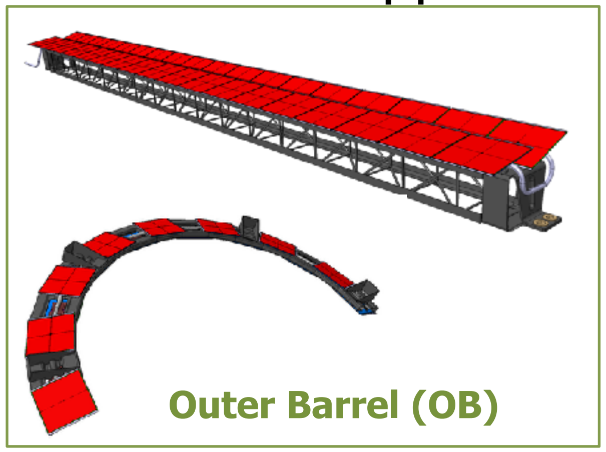
Reduced material budget versus current ID in Run 2.

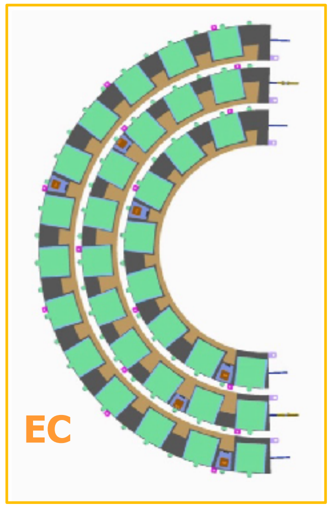
→ Minimize effects of multiple-scattering and energy losses before outer detectors.

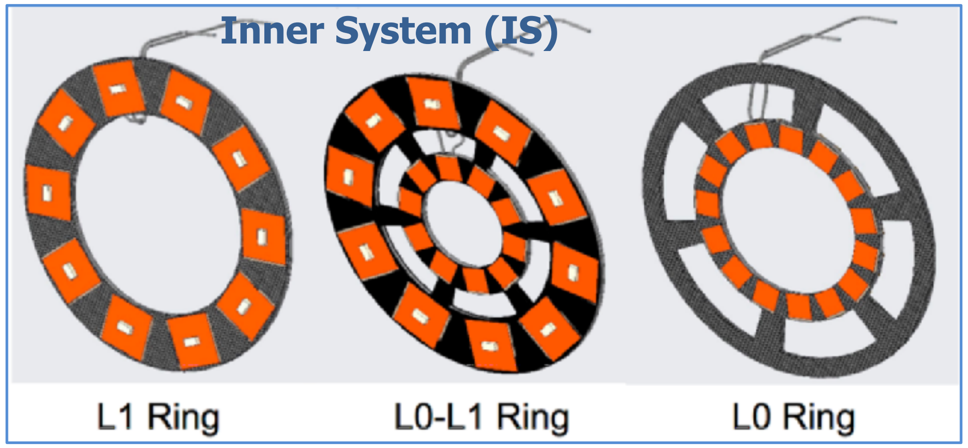
ITk Pixel Overview



Local supports:

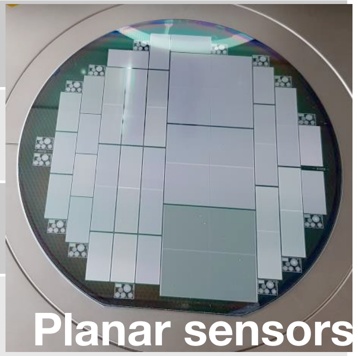


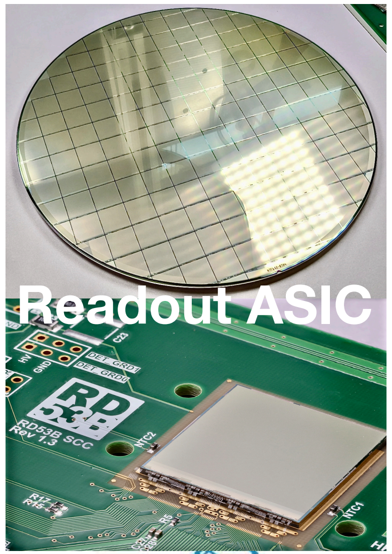




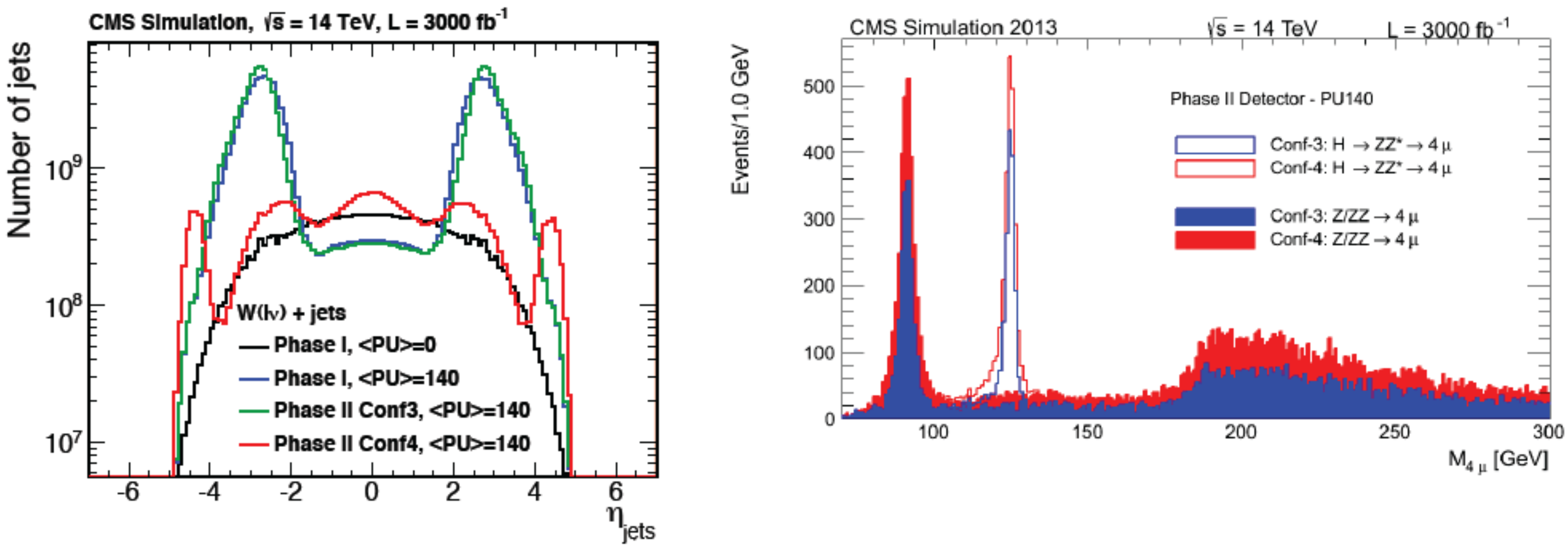
Pixels: transition from R&D to pre-production

Layer	Sensor Type	Thickn. [μm]	Sensor Size [μm²]	Module Type	Modules installed	Replacement (2000 fb⁻¹)	Fluence w/ SF [1e15 n_{eq}/cm²]
L0 barrel	3D n-in-p	150	25x100 1E	Triplet	288	Yes	18
L0 rings	3D n-in-p	150	50x50 1E	Triplet	900	Yes	18
L1	Planar n-in-p	100	50x50	Quad	1160	Yes	4
L2-4	Planar n-in-p	150	50x50	Quad	6816	No	4-1



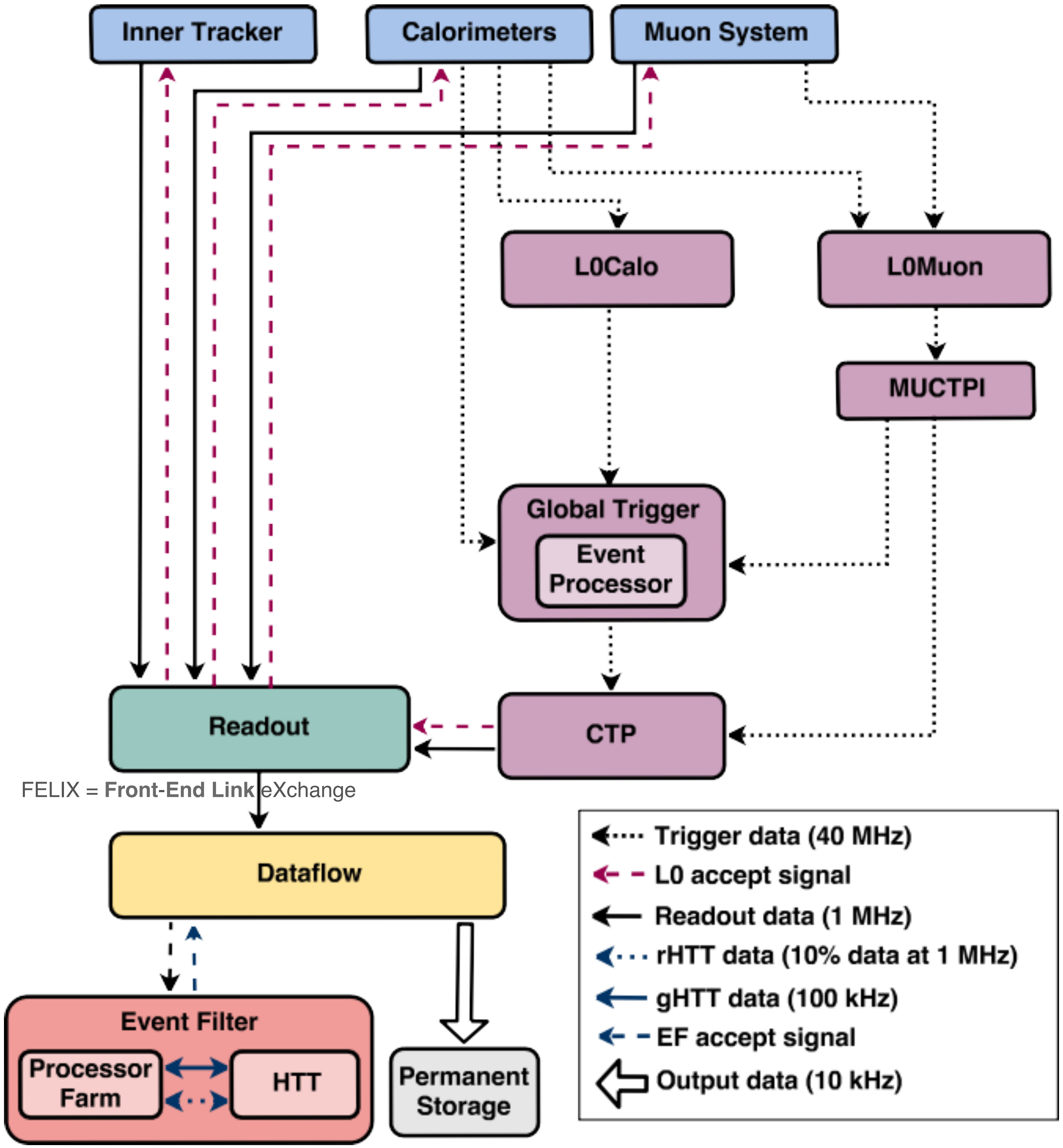


Benefits of Very Forward Tracking: CMS Examples

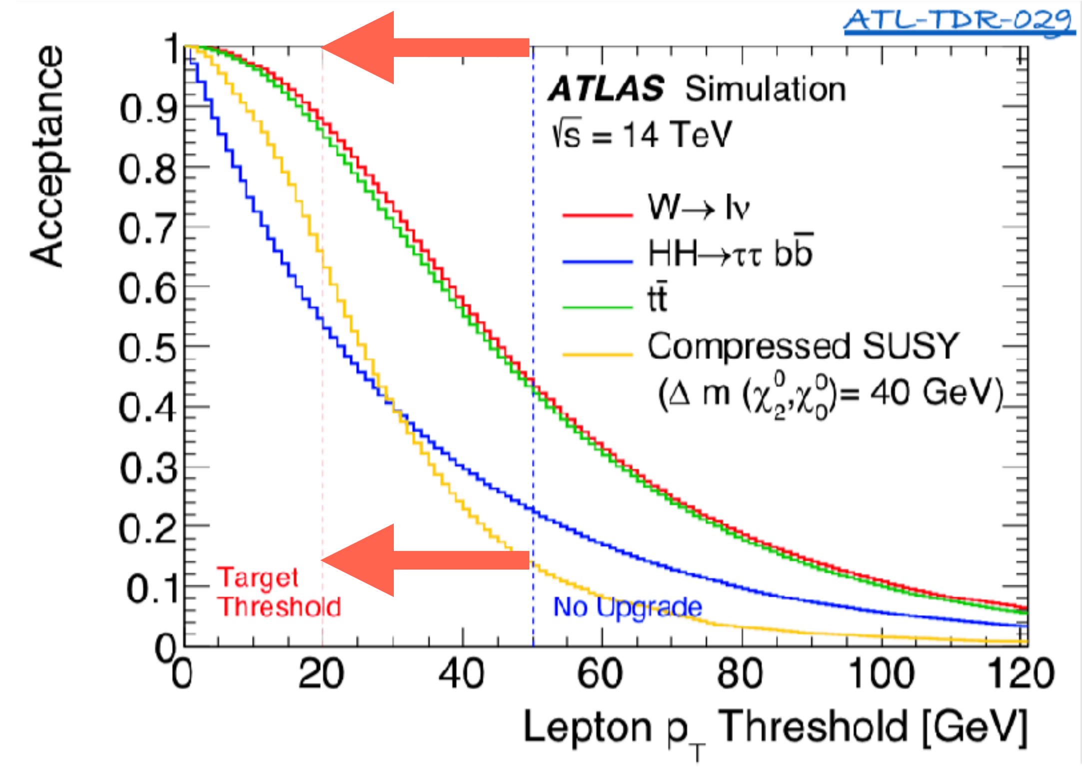


- Forward jet tagging is very important for VBF analyses
  - Dramatic increase in the number of pile-up jets in the region without tracker coverage
  - Tracking in the very forward region helps to suppress the background by as much as x3-10
- Extended tracking and muon reconstruction up to η~4 increase acceptance for H→ZZ*→4μμ by ~40%
  - Golden mode to study many of the Higgs properties

Phase-2 Trigger Upgrade



The Phase-II TDAQ upgrade enables lowering the single lepton Level-0 threshold to 20 GeV from 50 GeV, (projected threshold w/o upgrade).



Trigger in 3 systems:

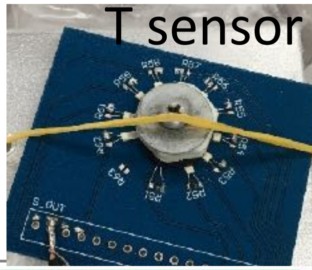
1) **Level-0 Trigger**
2) **Readout & Dataflow**
3) **Event Filter**

1) L0Trigger Data from the detectors @ 40 MHz
Latency: within **10 μs** (2.5 μs today)

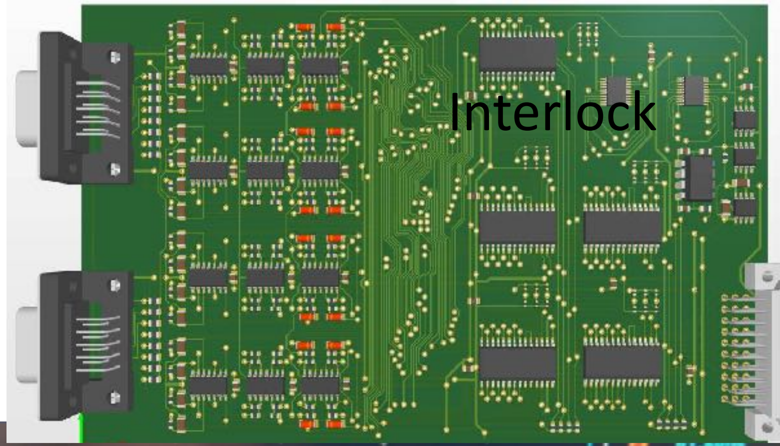
2) Complete event-data then transmitted through Readout & Dataflow into Event-Filter @ **1 MHz** (100 kHz today)

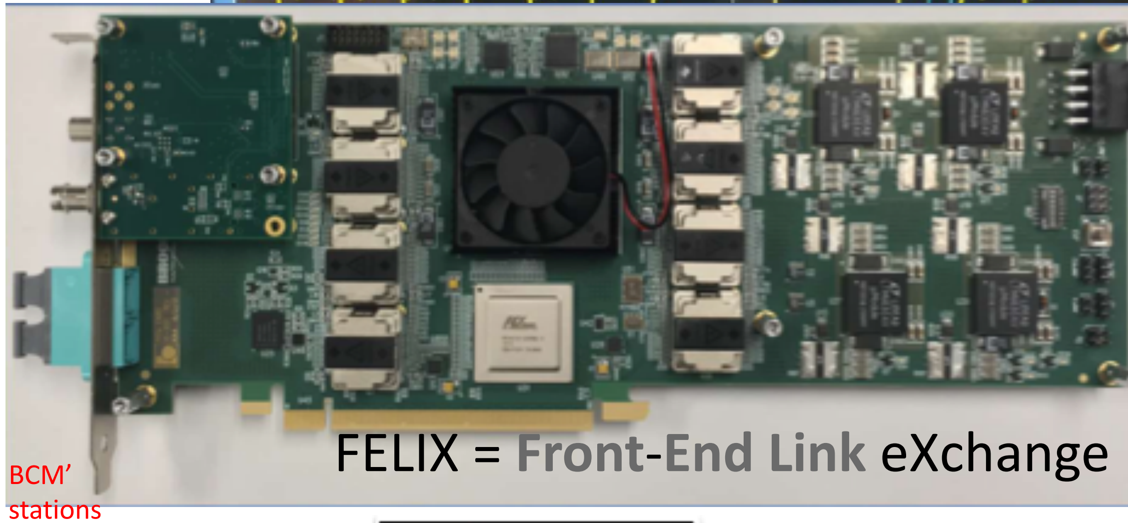
3) Event Filter performs event reconstruction & selection + info from HW-based tracking (HTT).
Final selected events (5 vs 2 MB today) then transferred to permanent storage @ **10 kHz**
(1 kHz today)

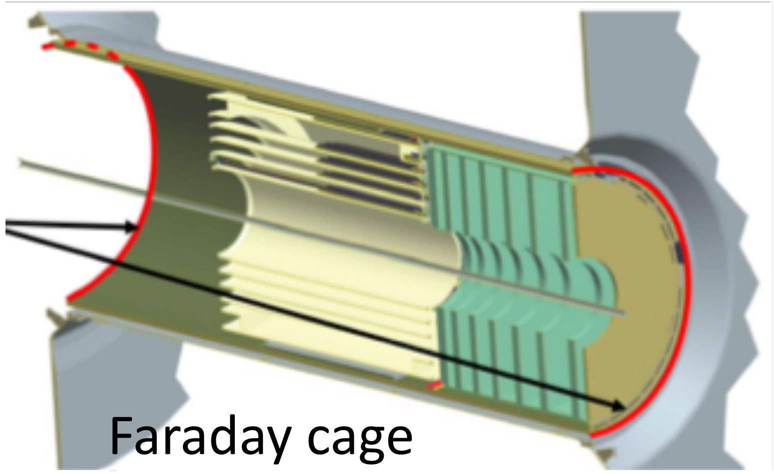
ITk Common Electronics

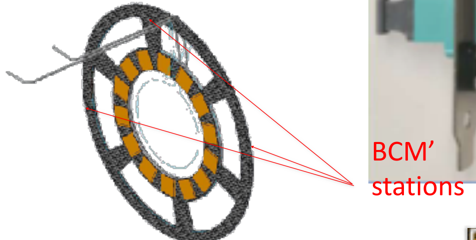


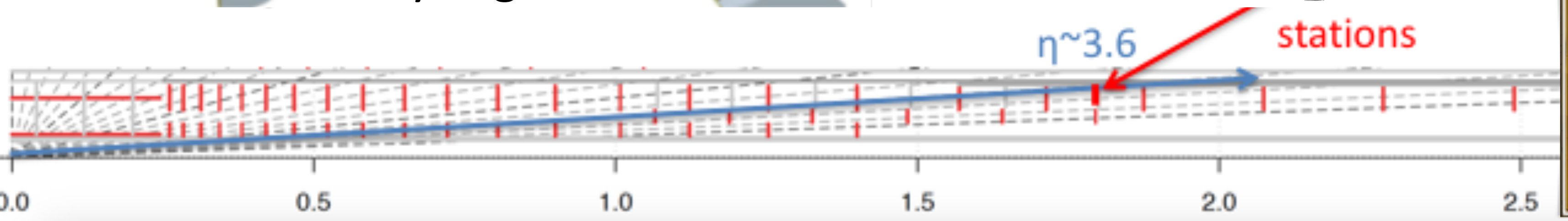
1. Environmental Monitoring
2. Interlock System
3. Grounding & Shielding
4. Luminosity and Beam Protection
5. Phase I FELIX Readout for ITk
6. Online Software

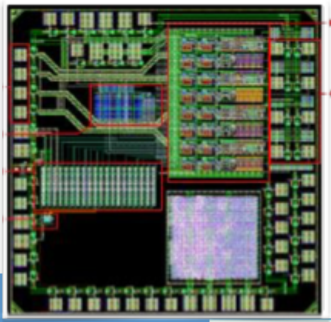












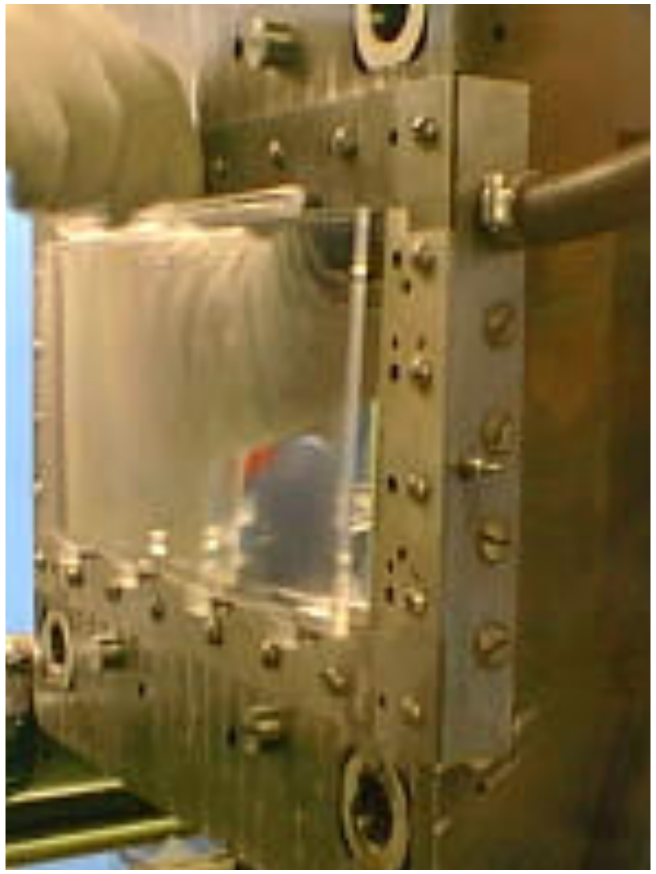
Scintillating tiles production

Granulated polysterene

Mixing components

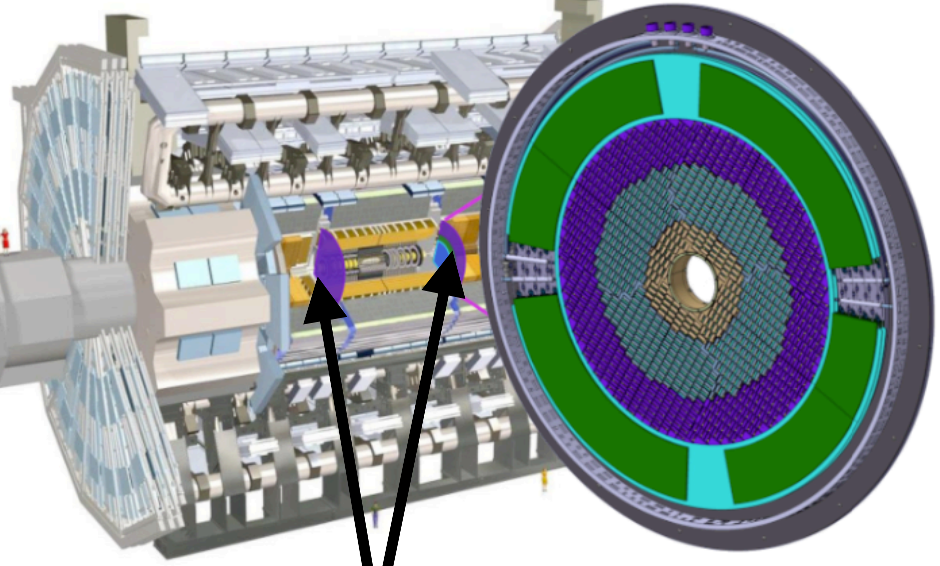
Pressing of tiles

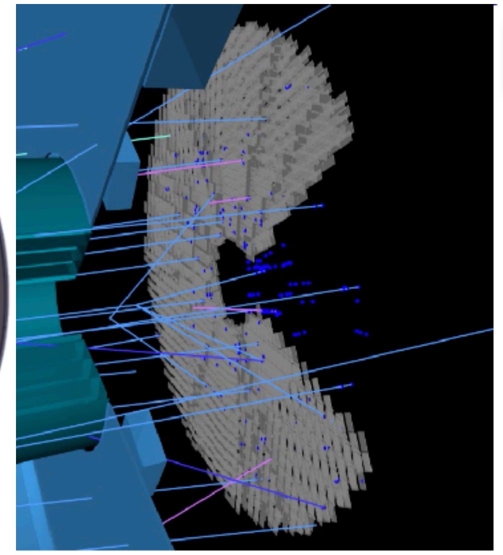
- 465 000 tiles ; 80 tons
- Done by injection molding (2min/tile)
- 3 mm thick tiles in 11 sizes
- Polystyrene + PTP (1.5 %) + POPOP (0.4 %).
- Peak of light emission at 420 nm.
- 40 cm attenuation length.
- 64 photoelectrons/GeV

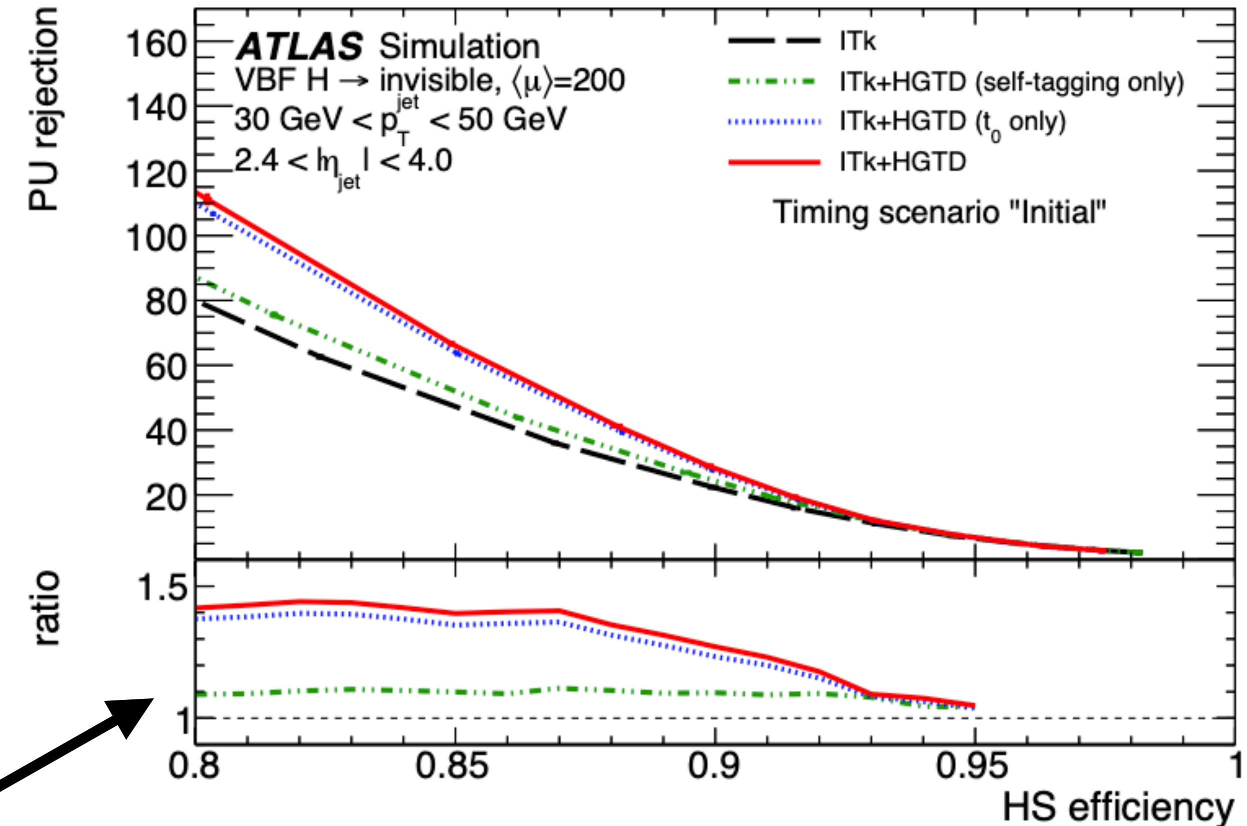


Tiles finished

Phase-2: High Granularity Timing Detector (HGTD)

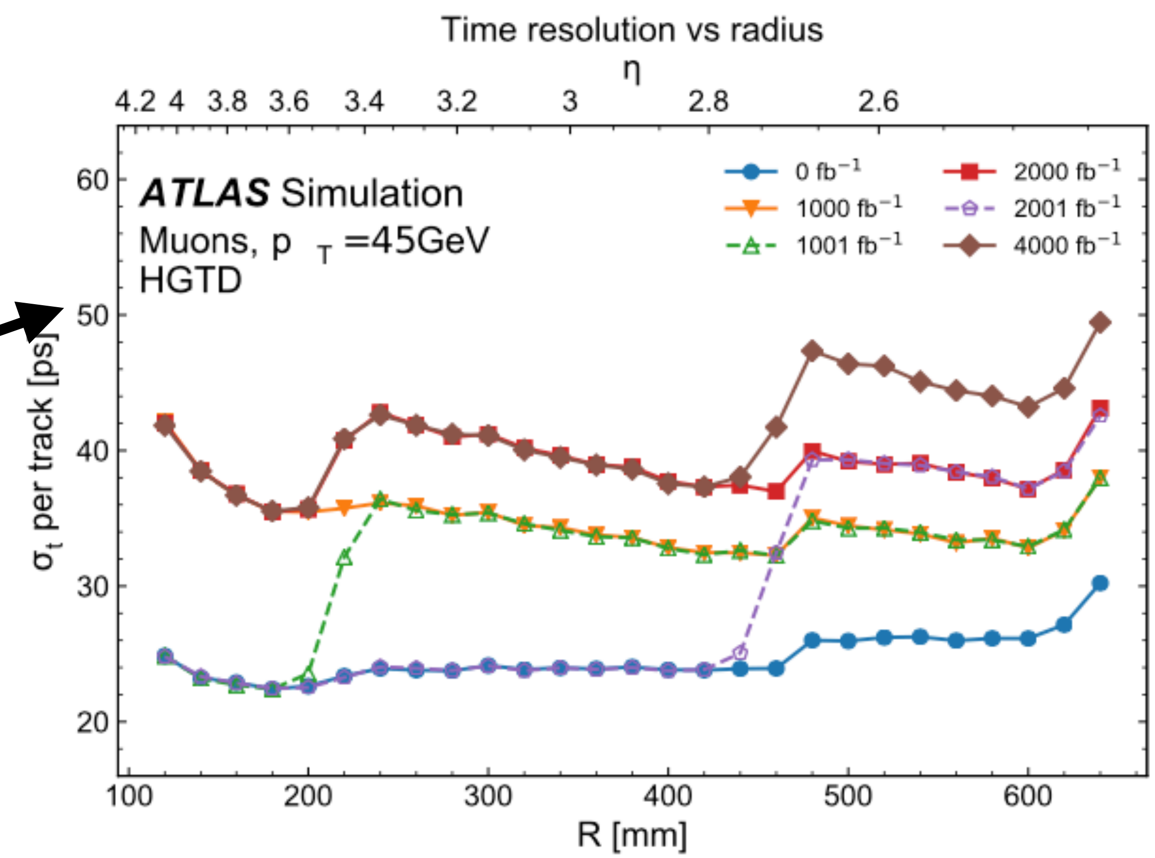






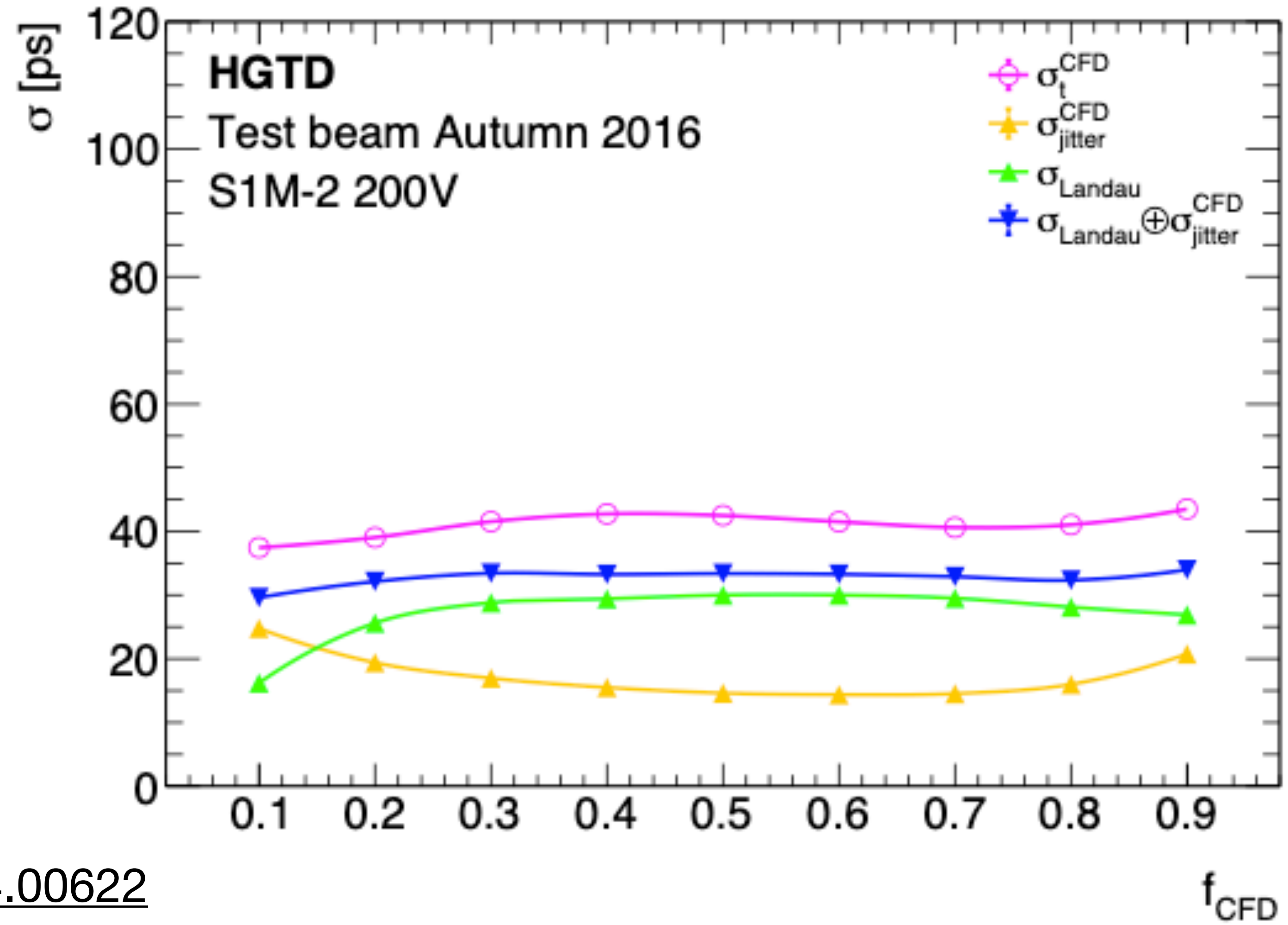
- LGADS (Low-Gain Avalanche Detectors) located on cryostat wall between barrel and endcap calorimeters 2.4 < |η| < 4.0
- Timing information enhances pileup jet rejection combined with ITk
- Req. resolution: 30-50 ps/track
- Constraints: thickness < 12.5 cm, Fluence 2.5+15n/cm2, TID 2 MGy

ATLAS-TDR-031



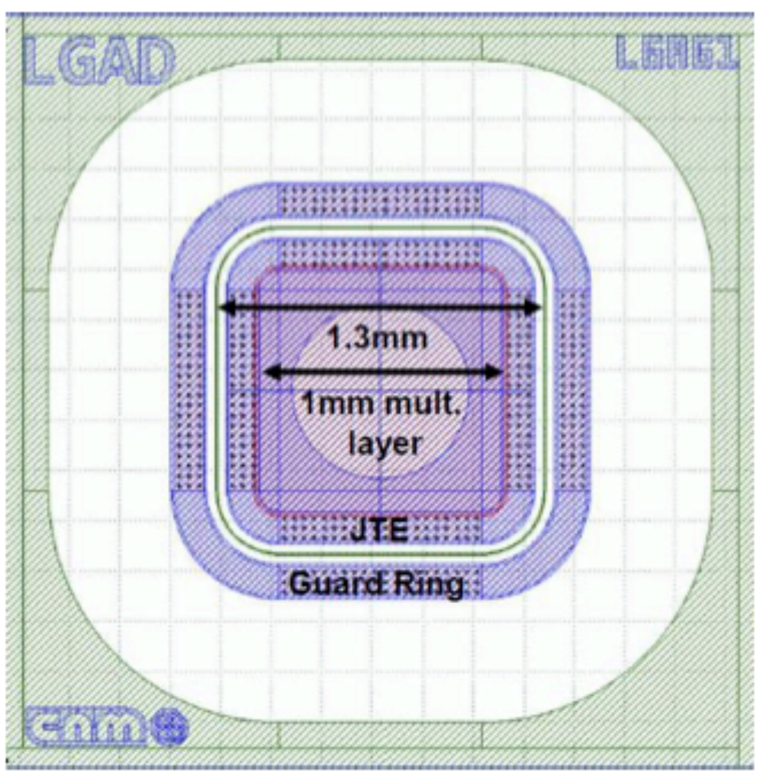
See talk by C. Ohm

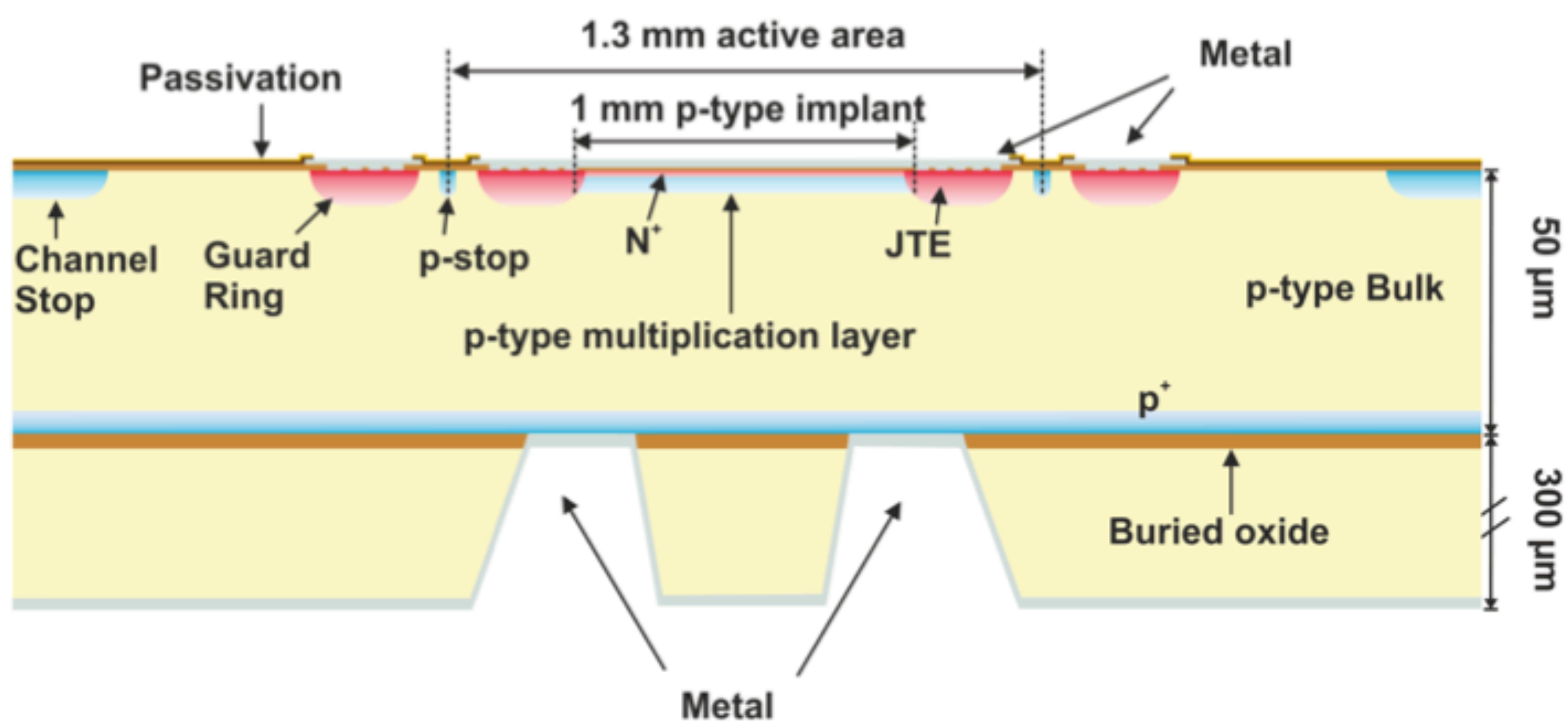
HGTD Time resolution



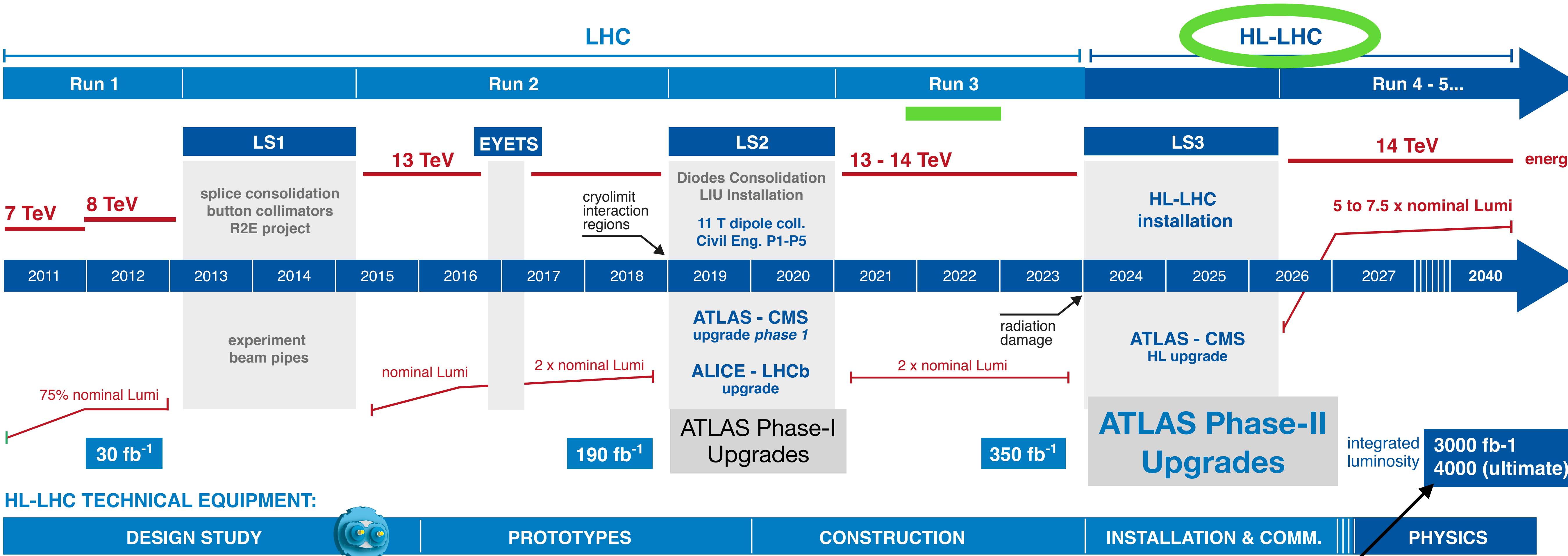
- Test beam results: https://arxiv.org/abs/1804.00622

Single Pad LGA



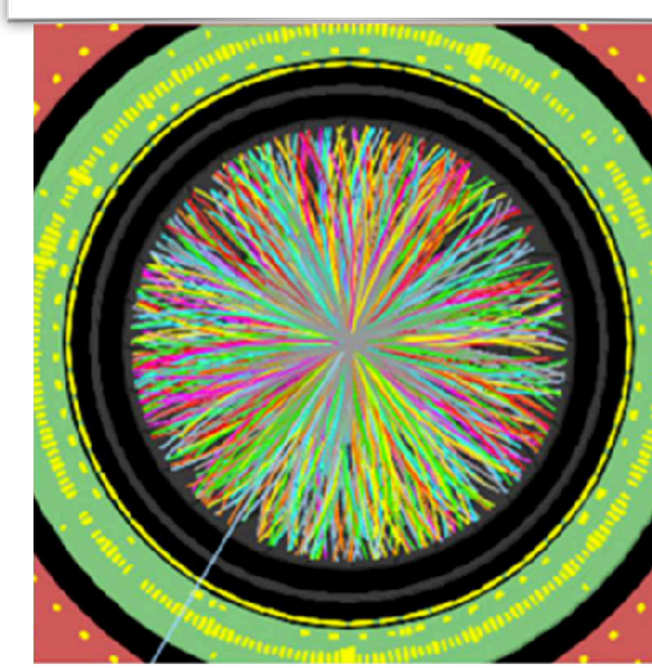


LHC / HL-LHC Plan



LHC/ HL-LHC Plan (last update January 2021)

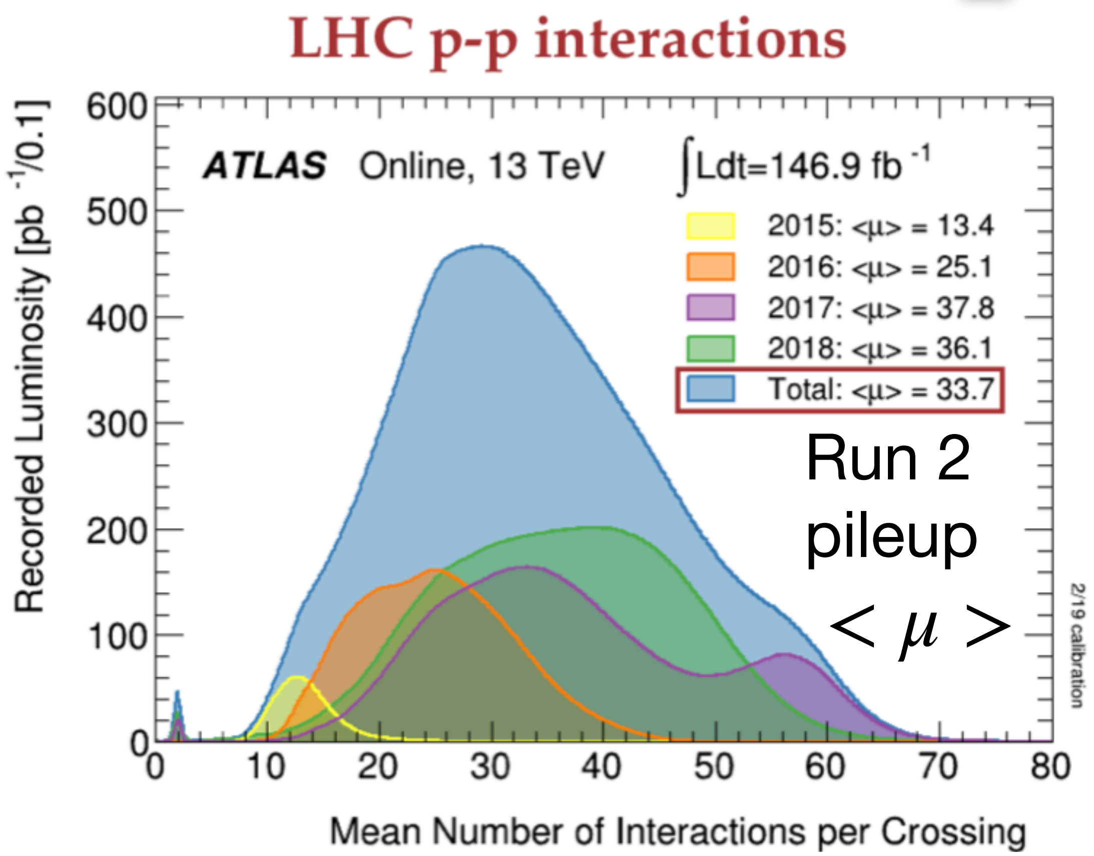
4000 fb-1 ultimate

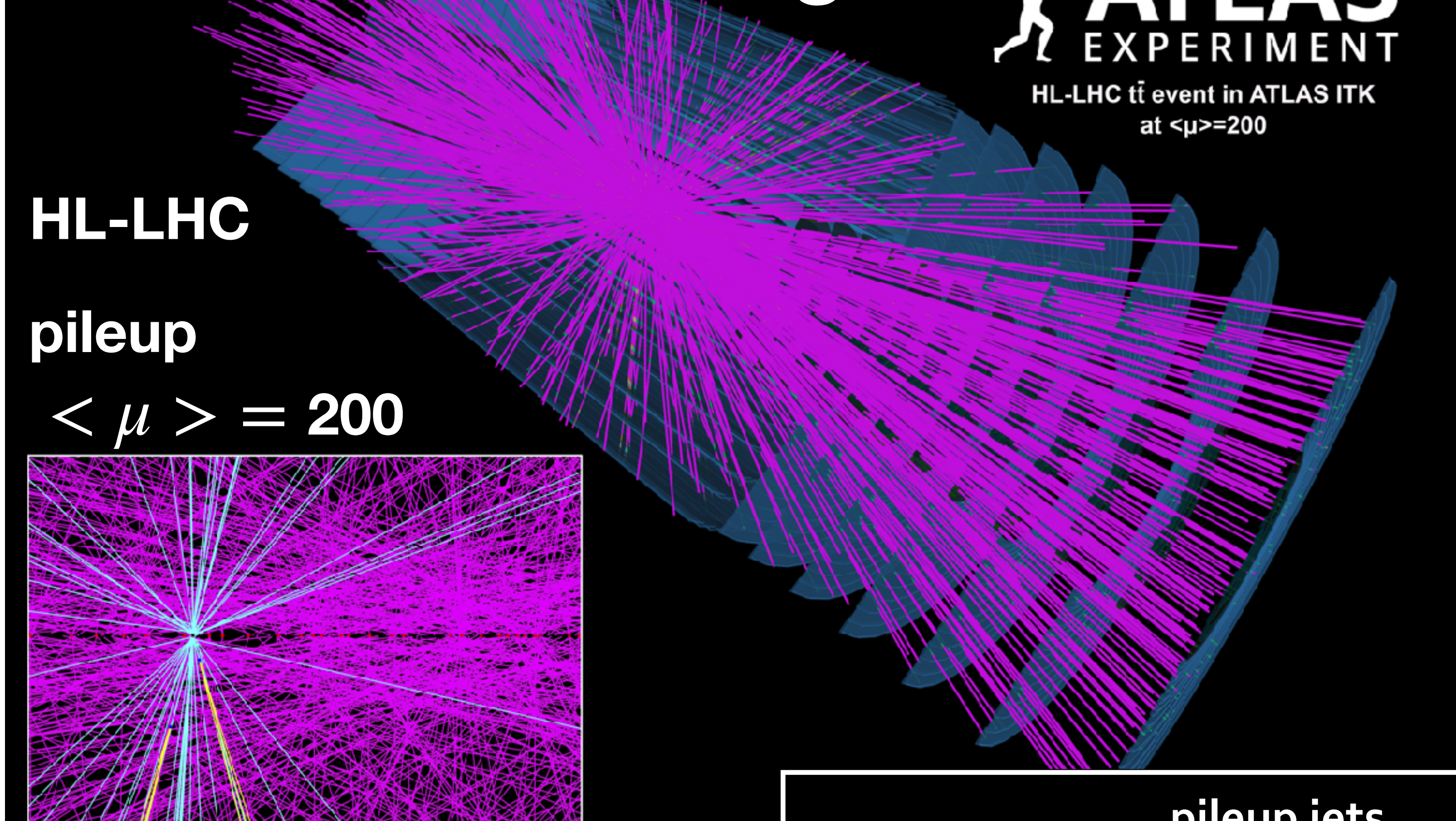


- High-Luminosity LHC formally approved by CERN Council in June 2016
- High priority of worldwide subatomic physics community
- -> Significant **detector challenges** in this environment with up to 200 separate proton-proton collisions per 25 ns bunch-crossing (pileup) … see slides ahead…
- **First**: physics prospects —>

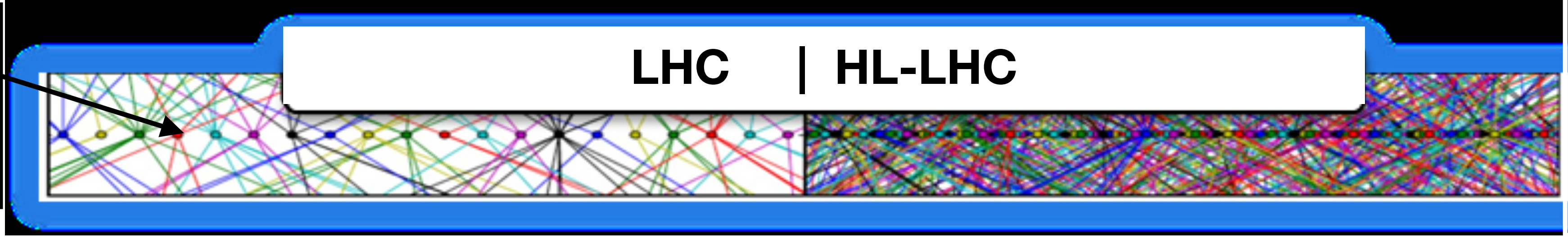
—> Pileup

Detector Challenges





collision vertices 1 event



	<μ>	pileup jets pT>30GeV
Run-1	20	0.04 @ 7 TeV
HL-LHC	200	**7.4** @ 14 TeV

➔ 10x the luminosity reach of first 10 years of LHC operation

	Energy	Instantaneous $\mathcal{L}$	Integrated $\mathcal{L}$	Pileup
Run 2 LHC	13 TeV	2×10^{34} cm^{-2}s^{-1}	300 fb^{-1}	37
HL-LHC (Nominal)	14 TeV	5×10^{34} cm^{-2}s^{-1}	3000 fb^{-1}	140
HL-LHC (Ultimate)	14 TeV	7.5×10^{34} cm^{-2}s^{-1}	4000 fb^{-1}	200

Integrated $\mathscr{L}$ per year: 250 fb^{-1} (baseline), > 300 fb^{-1} (ultimate)