LHC Upgrade: Detectors

8[th] IDPASC SCHOOL
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Susanne Kühn, CERN

Recap: Lecture 1

- **HL-LHC** will provide exciting high-luminosity physics from 2027 onwards
  - Enormous detector challenges, especially for inner layers
  - New domain of particle rates and radiation levels

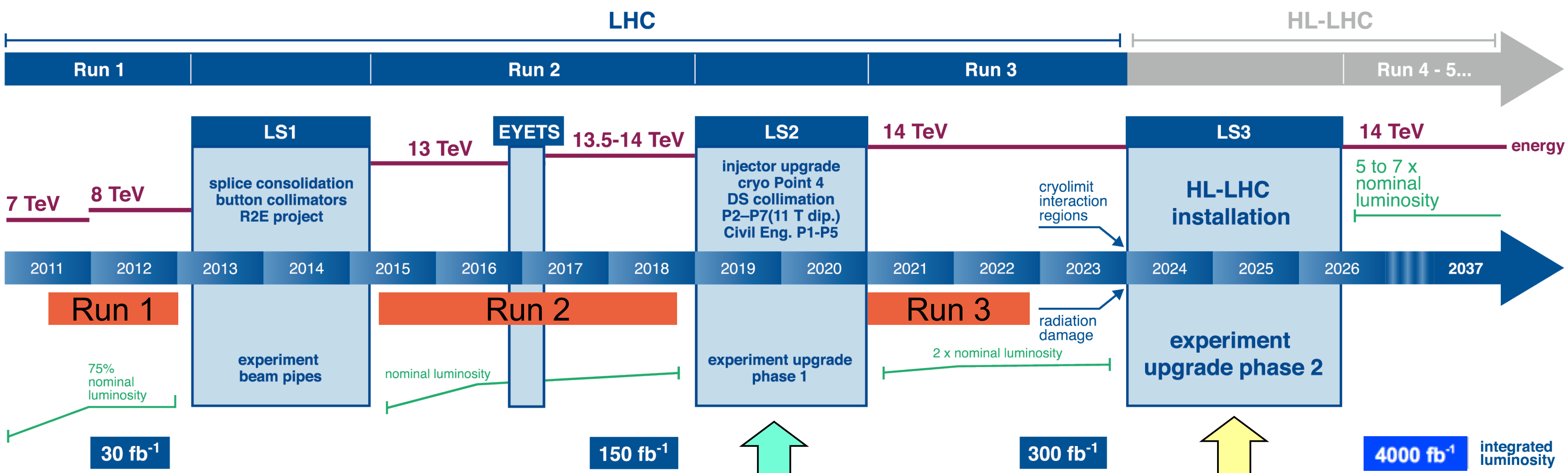
- ATLAS and CMS will replace **inner detectors** with all-silicon tracking detector

- CMS will get new endcap **calorimeter**: silicon + W/Cu and scintillators + steel
- Upgrade of calorimeter readout electronics for ATLAS and CMS

- Upgrade of **Muon** detectors to increase coverage and timing

Towards the High-Luminosity LHC: Detectors

LHC / HL-LHC Plan



Phase-1
Detector
Upgrade in
ATLAS and
CMS

Major Upgrade
in ALICE and
LHCb

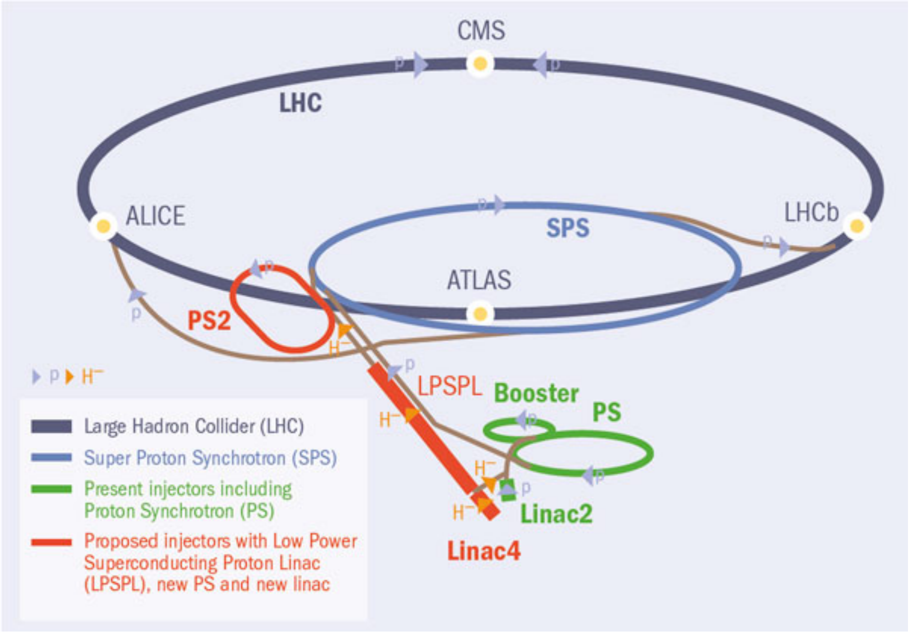
Phase-2
Major Upgrade
in ATLAS and
CMS

Lecture 2

Lecture 1

LHC Phase-1 Upgrade for Run 3

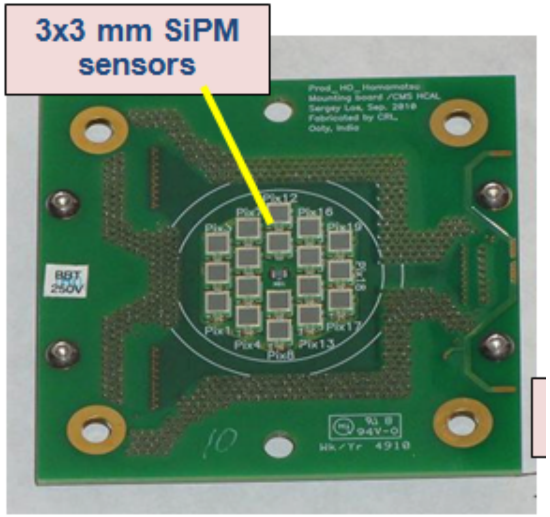
- Shutdown for 18 months
- L~2*10^{34} cm^{-2}s^{-1}, 25 ns bunch spacing, pile up <μ>~60
- LHC Injector Upgrade (LIU) Project
  - LINAC4 H^{-} injection
  - Increase of PS Booster injection energy from 50 MeV to 160 MeV by new power converters and new cavities
  - Increase of PS injection energy from 1.4 GeV to 2 GeV and new RF collimation and system
  - SPS: modification to main RF system, electron cloud reduction



Phase-1 Upgrades of ATLAS and CMS

Calorimeters: increase granularity for triggering
ATLAS: new Front-End for Liquid Argon (barrel and endcaps) calorimeter
CMS: new photo-detectors (Silicon Photo-multipliers instead Hybrid Photo Diodes) for hadron calorimeter

CMS

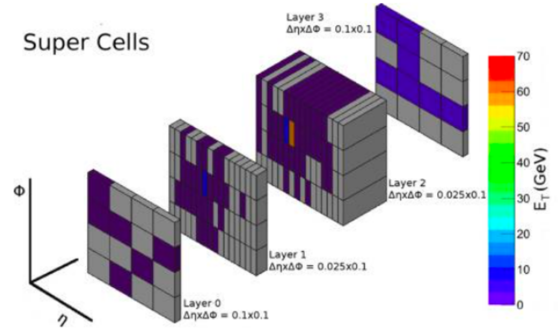


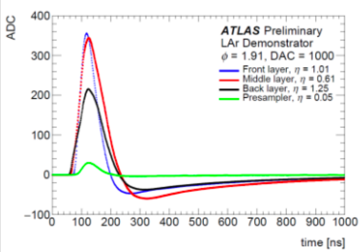
Muon systems: complete coverage → improve forward resolution for trigger
ATLAS: completing coverage, adding new forward disks
CMS: complete coverage of read-out chambers → increase read-out granularity (Cathode Strip Chambers)

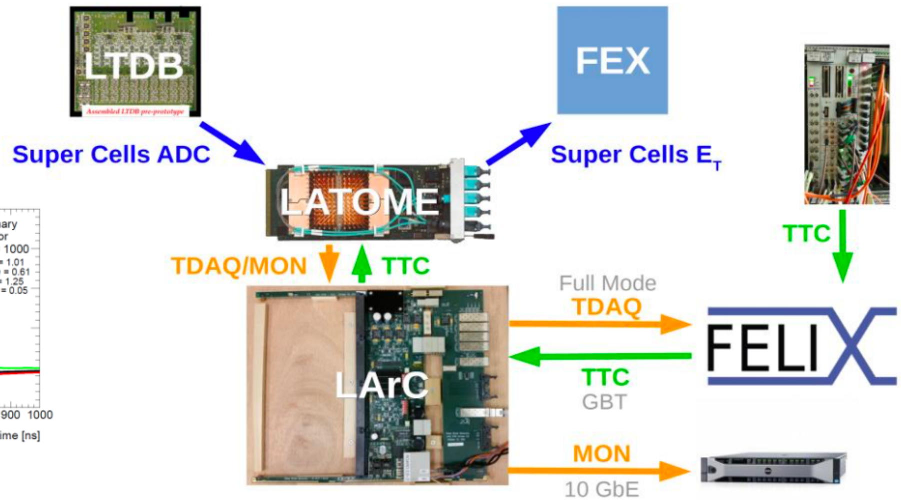
Trigger/DAQ: improve bandwidth and reduce processing
ATLAS: new back-end electronics
and Fast Track Trigger (FTK) input at High Level Trigger
CMS: new back-end electronics

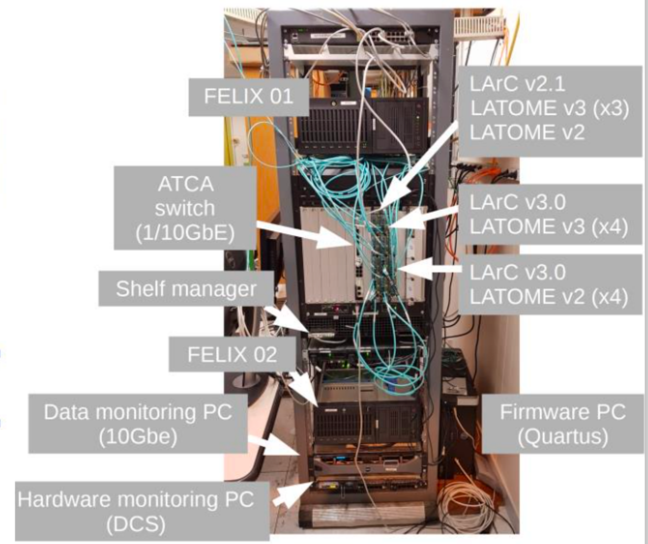
ATLAS Phase-1 Upgrade: LAr Supercells

- 124 LAr Trigger Digitizer Boards on front-end to read out new supercell trigger primitives
    - COTS analog components
    - ASICs: 130 nm CMOS 4-bit pipeline + 8-bit SAR ADC, 250 nm Si-on-Sapphire link-on-chip
- 31 LAr Digital Processing Blades for signal filtering, energy calculation, data buffering
    - ATCA carrier blades equipped with 4 FPGA advanced mezzanine cards







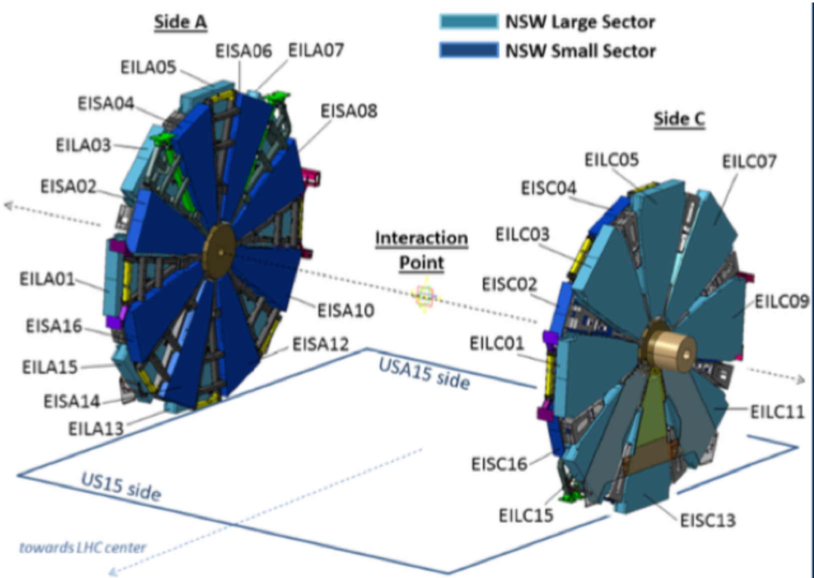


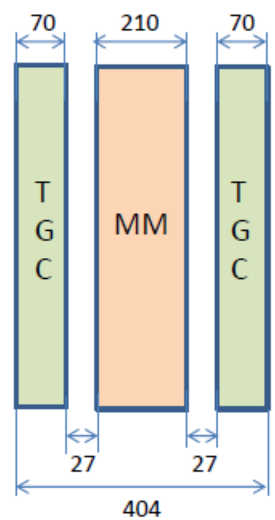
- Board production is being prepared - installation and commissioning in LS2
- Complex installation: removal of all front-end boards and installation of new baseplane
- System will remain during HL-LHC running

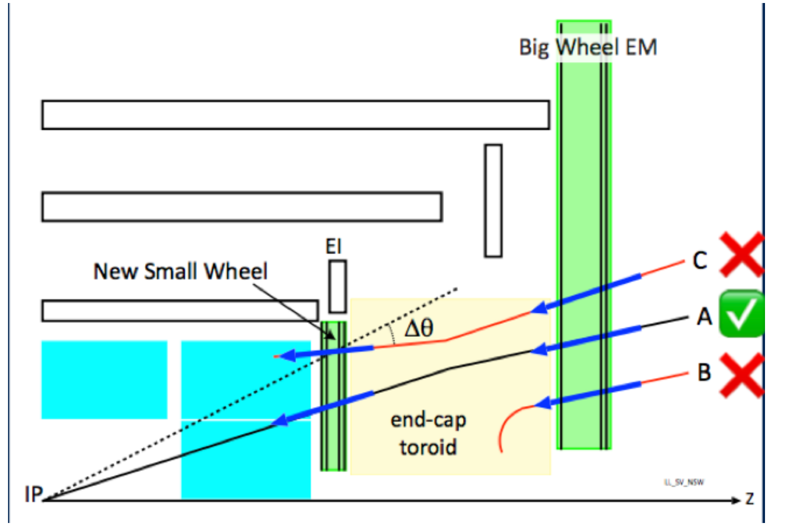
ATLAS Phase-1 Upgrade: Muon System

- Improved muon tracking for |η| > 1.3
- Reduce fake rates and keep precision at high rates for triggering

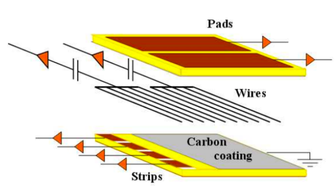
→ New Small Wheels







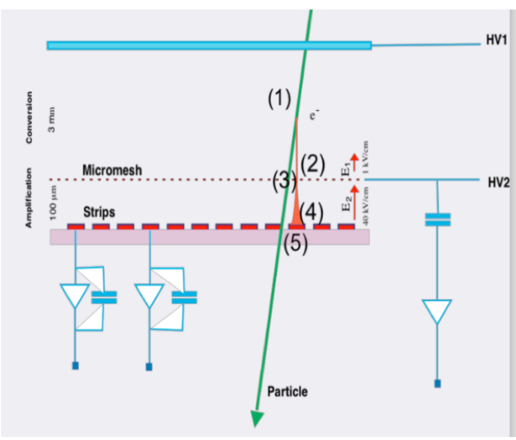
- Micromegas: ~1200 m² for precision tracking, high rate capable
- Small-strip thin gap chambers: ~1200 m² for triggering, bunch ID will give good timing, proven technology
- Space resolution < 100 μm



Recap: Micromegas

- Gas volume divided in two by metallic mesh
- Gain = 10², fast signal of 100 ns

TGC – Thin Gap Chambers



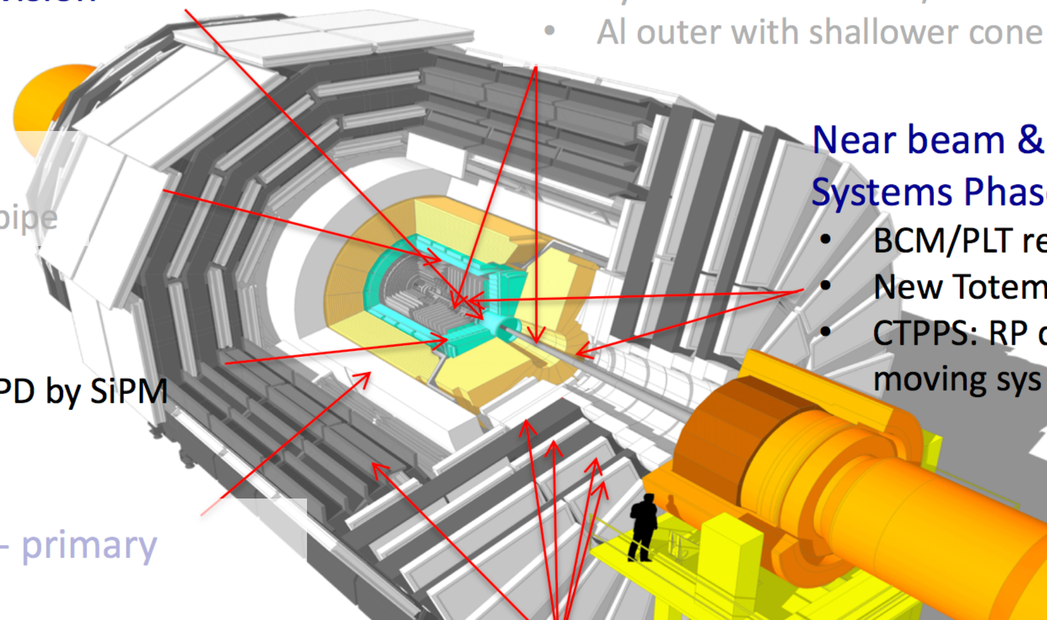
Overview CMS Phase-1

Pixel Tracker Phase-1 revision
- Replace L1, TBM, DC-DC

Barrel ECAL Phase-2
- New chilled water feed pipe

Barrel HCAL Phase-1
- Replace rad damaged HPD by SiPM

Magnet - yoke opening - primary infrastructure Phase-2
- Cooled freewheel thyristor+power/cooling
- New opening system (telescopic jacks)
- New YE1 cable gantry
- Primary power, cooling, cableways, USC



Beam-pipe Phase-2
- Cylindrical central Be/Al + Al bellows
- Al outer with shallower cone

Near beam & Forward Systems Phase-1
- BCM/PLT refit
- New Totem track det.
- CTPPS: RP det. & moving sys upgrade

Muon Systems Phase-2
- New Cathode Strip Chamber FE electronics for inner rings of endcap (disks 1, 2, 3 & 4)
- New GEM layer in inner ring of 1st endcap disk
- Major leak repair campaign in barrel RPC (green- house gas emission targets)
- Services for Phase-2 forward chambers

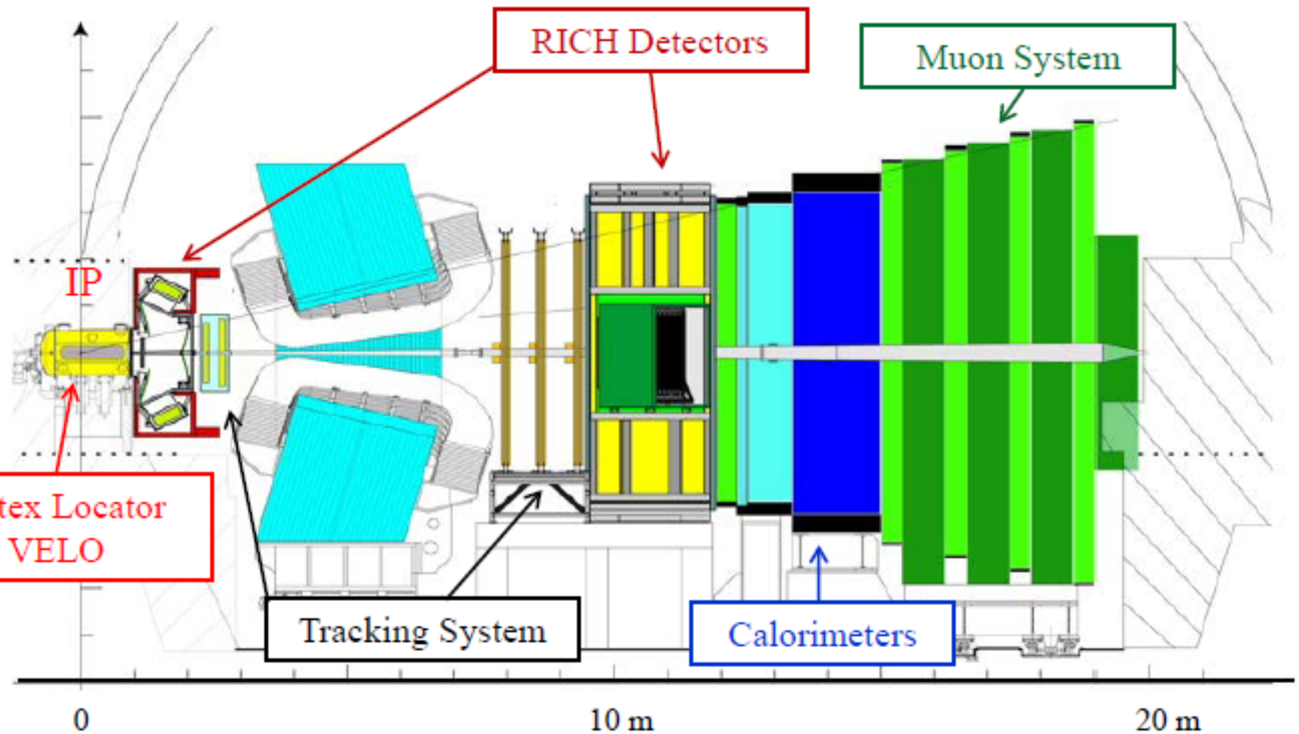
LHCb Detector Upgrades in Phase-1

Physics:

- Study CP violation and rare decays in b- and c-quark sector
- Search for deviations of SM due to virtual contributions of new heavy particles
- Complementary approach to search for New Physics → Requires high precision measurements and high statistics

General purpose single arm forward spectrometer ($2 < \eta < 5$)

Major upgrade in Phase-1



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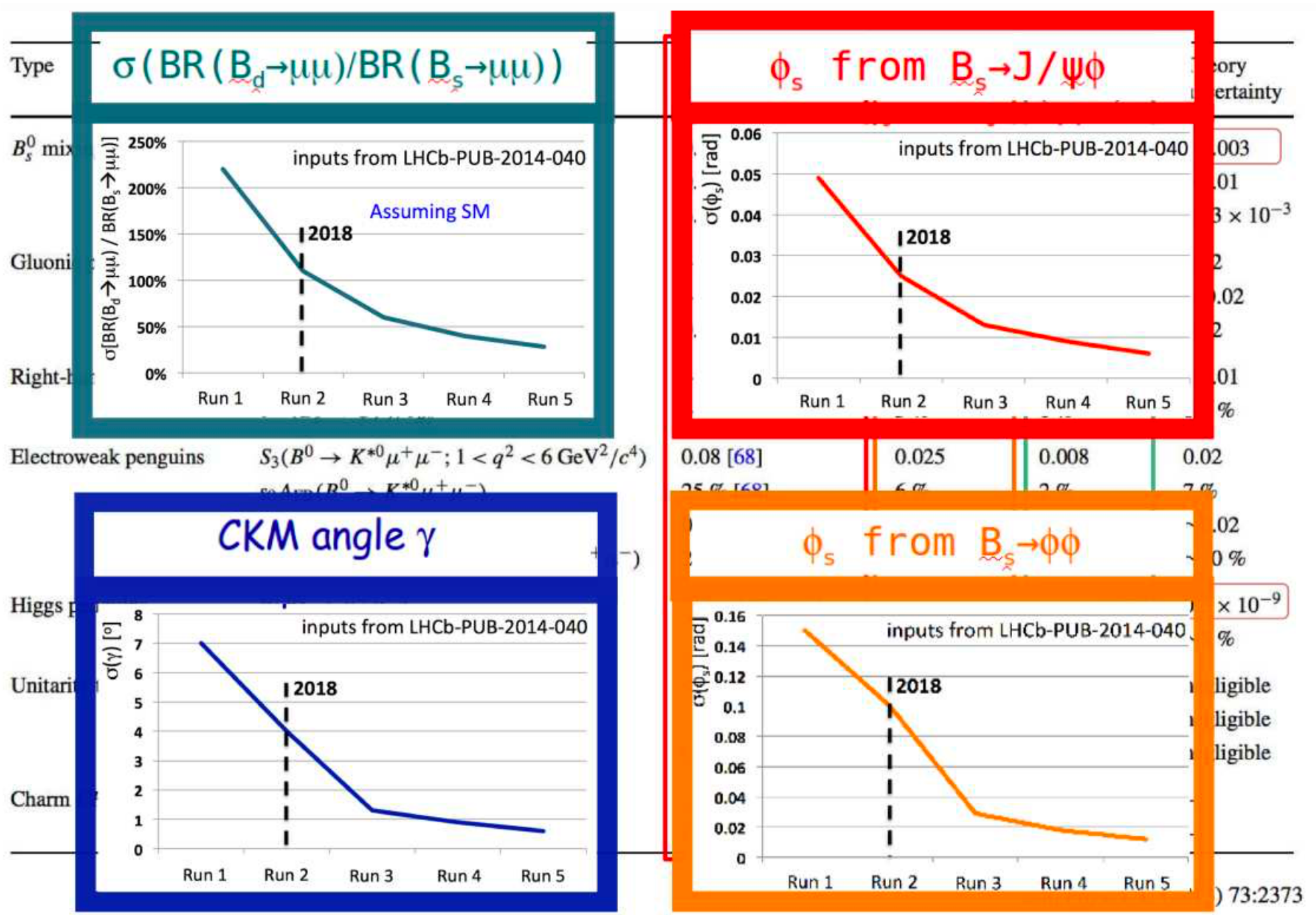
LHCb Upgrade Physics Expectations



Need to increase the precision to reach theoretical uncertainty ⇒ search for NP

[LHCB-TDR-12]

LHCb Detector Upgrade Strategy

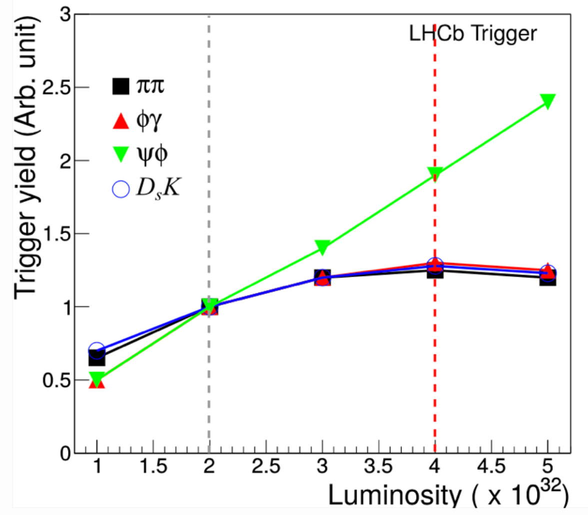
Challenges:

- Increasing luminosity → reduced trigger yield and high occupancy
- Increasing Pile-up
- Higher radiation

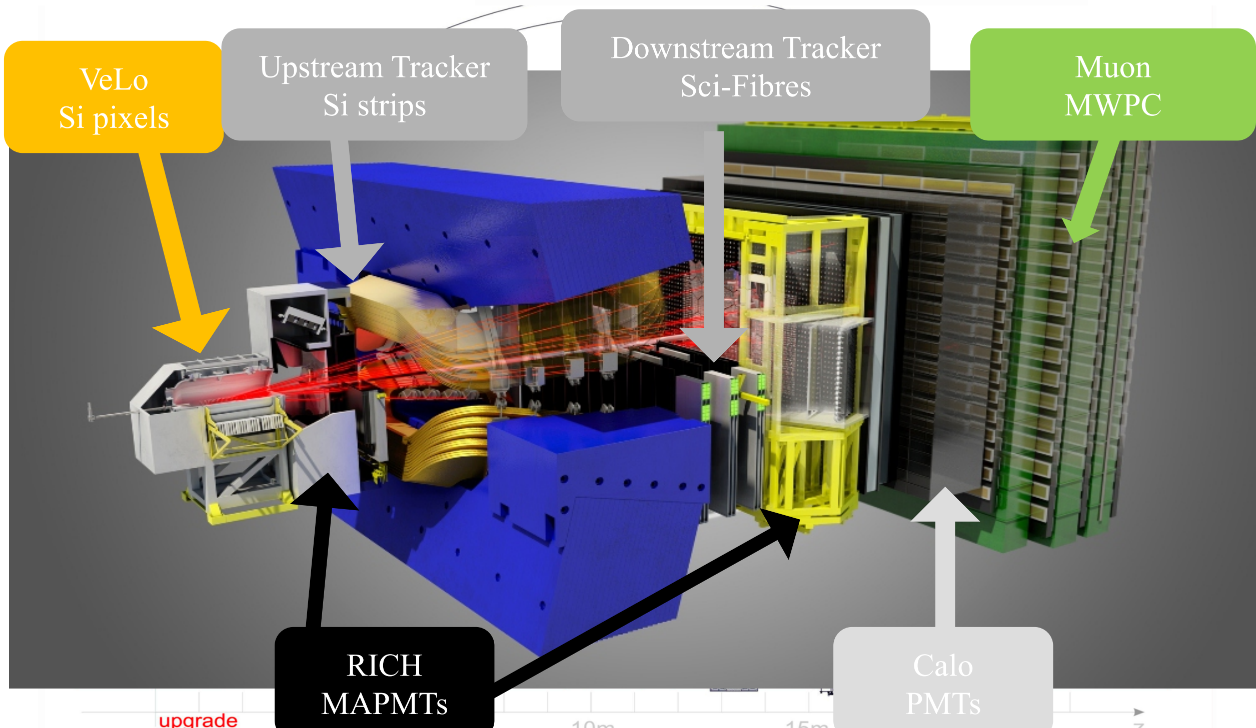
Improvement of sensitivity with

- Increase levelled luminosity up to $L \sim 2 * 10^{33} cm^{-2} s^{-1}$ to reach 8 fb^{-1}/year
- Trigger up to 40 MHz, record 20-100 kHz → full software trigger

→ Upgrade TDAQ
→ Replacement of all front-end electronics
→ Tracker upgrade

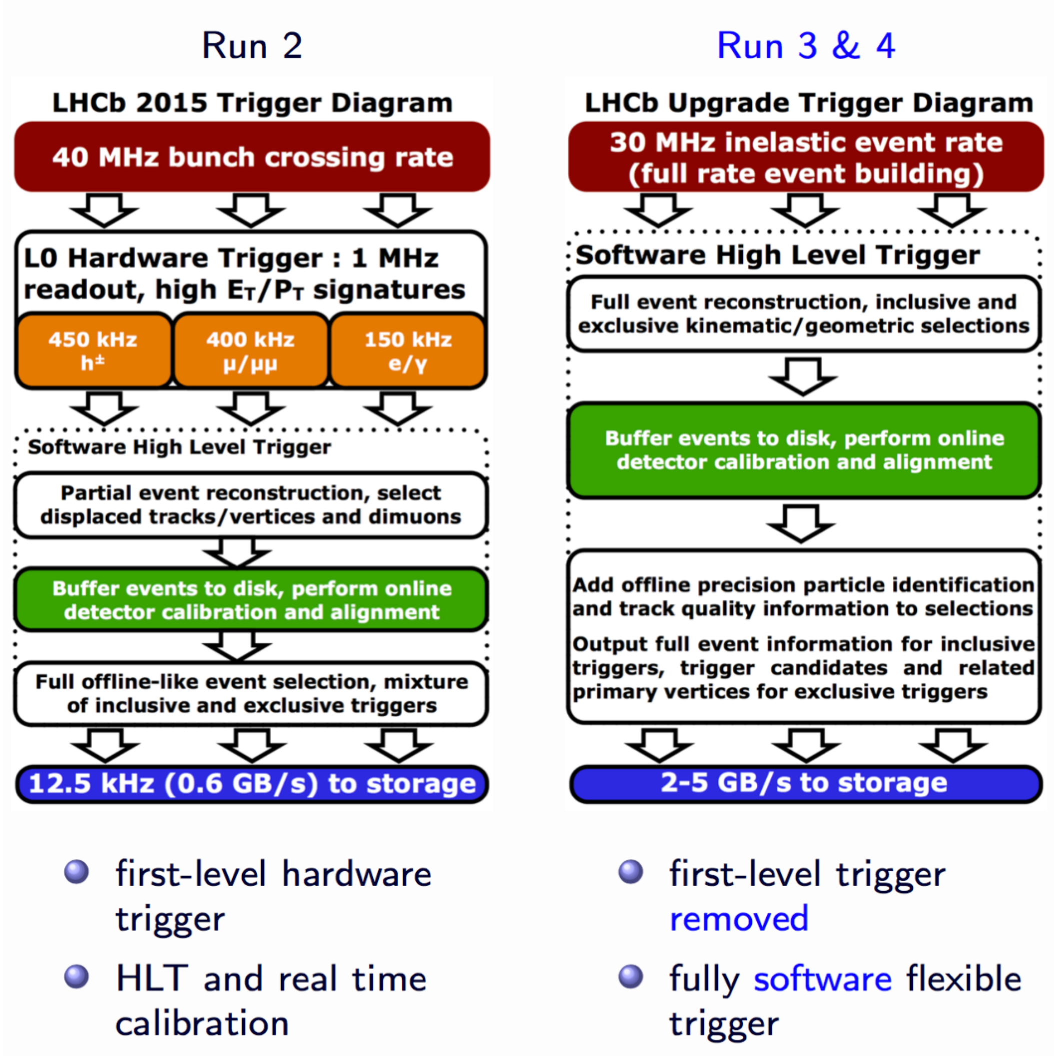


Trigger yield



LHCb Trigger Upgrade

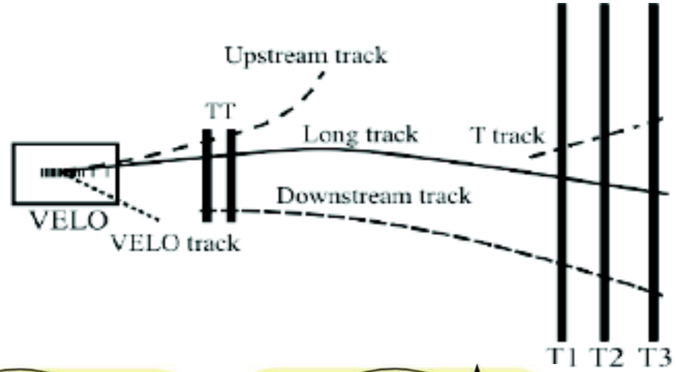
Use data from every bunch crossing and trigger in software → Upgrade electronics and DAQ

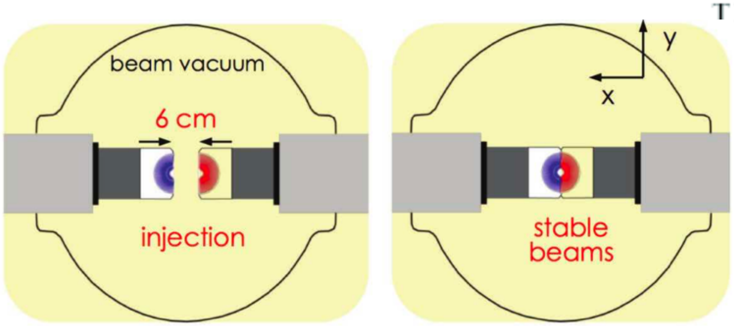


LHCb Tracker Upgrade: VErtex LOcator

Current detector

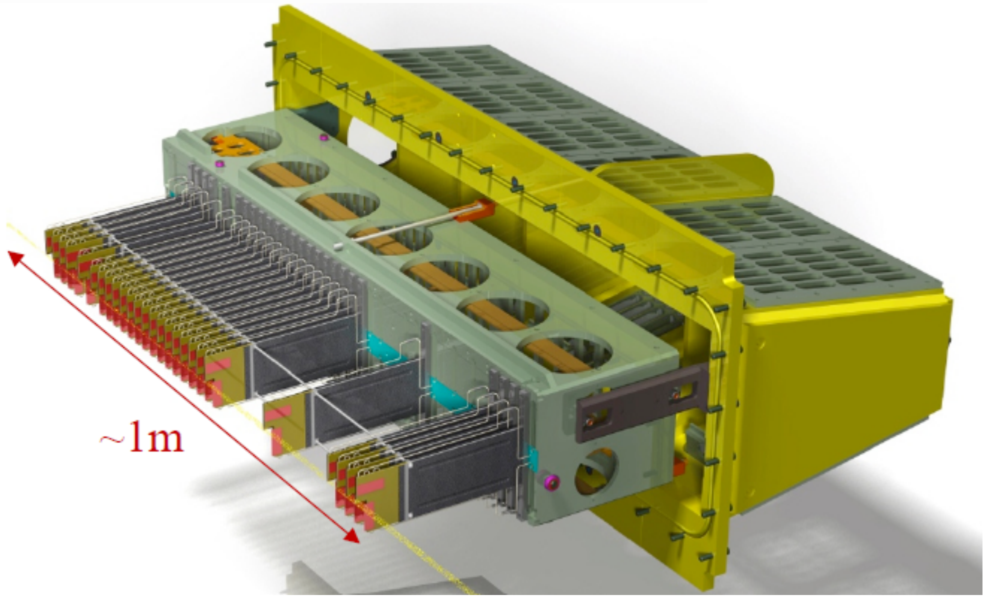
- semi-circular modules, silicon strip sensors
- two retractable halves separated from the LHC vacuum by RF foil
- closest active strip at 8.2 mm from beam line
- one interaction per bunch crossing
- $\sigma_{IP} \sim 20\mu m$ for high p_T tracks





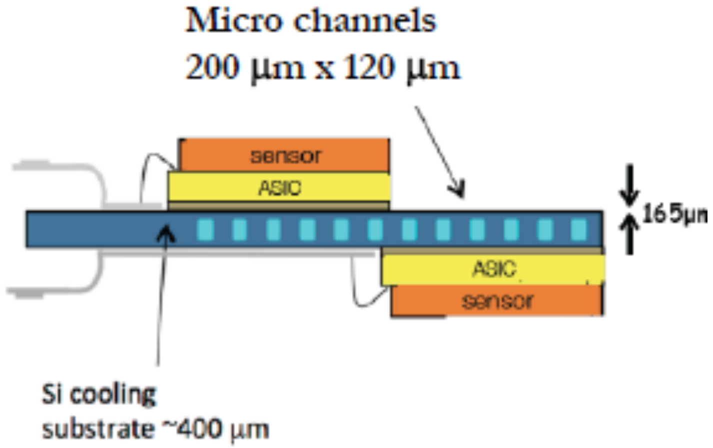
Requirements and challenges:

- $\sim$ 5 interactions per bunch crossing
- measure impact parameter (IP) to high precision
- high tracking efficiency
- tolerance to high dose ($8 \times 10^{15} n_{eq} cm^{-2}$): 10 times the current VELO and highly non-uniform

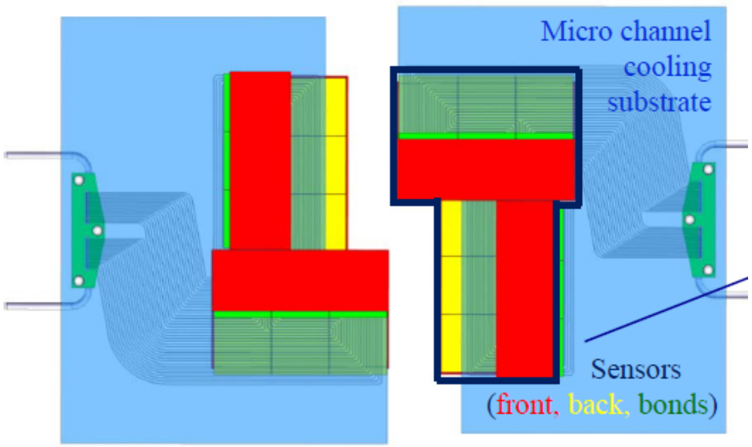


VELO Design

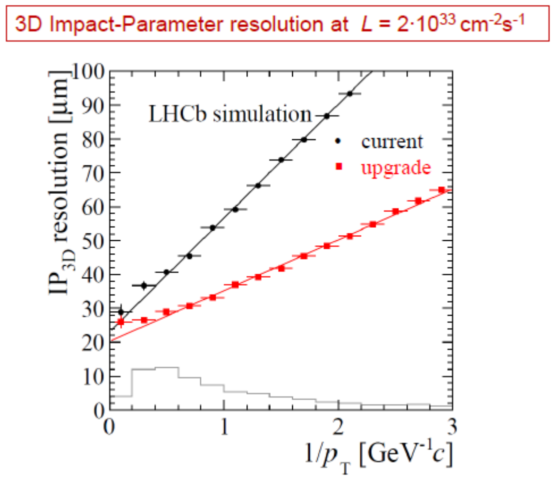
- From strips → L-shaped modules of hybrid silicon pixel detectors
- Micro-channel CO_2 cooling
- Thinner RF-foil between sensor and LHC vacuum
- Closer to beam (5.1 mm)



PIXELS: 50x50 µm²
max. dose Φ~8*10^{15} N_{eq} cm^{-2} for 50 fb^{-1}
ASIC: VELOPIX 130 nm sustain ~400 MRad



Sketch of two modules



note: full GEANT Monte Carlo with standard LHCb simulation framework

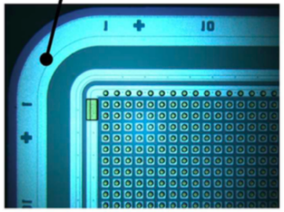
Challenges:
- Readout chip with high data rate 4x5.12 Gbit/s

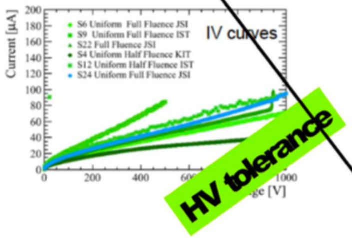
First use of micro-channel cooling in experiment

VELO: Prototyping

Pixel sensors

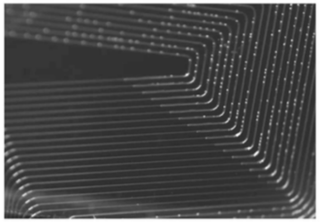
prototyped to withstand 1000V



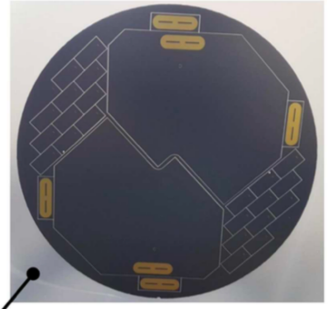


rounded corners

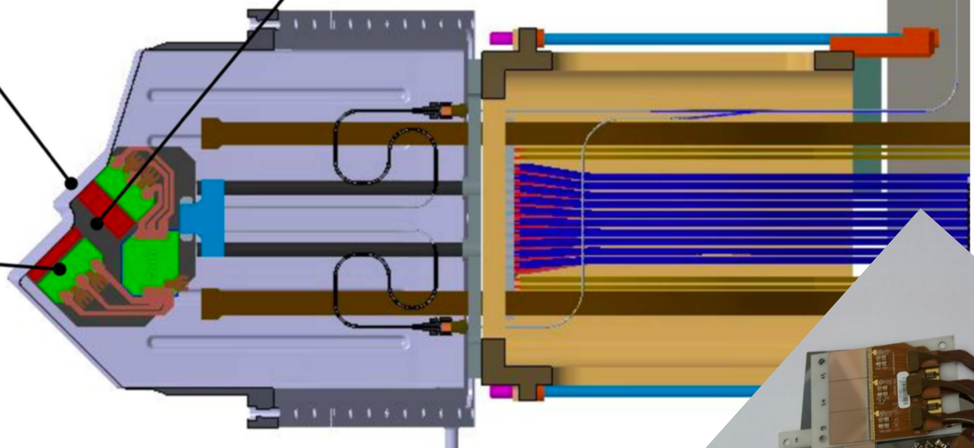
Module Cooling



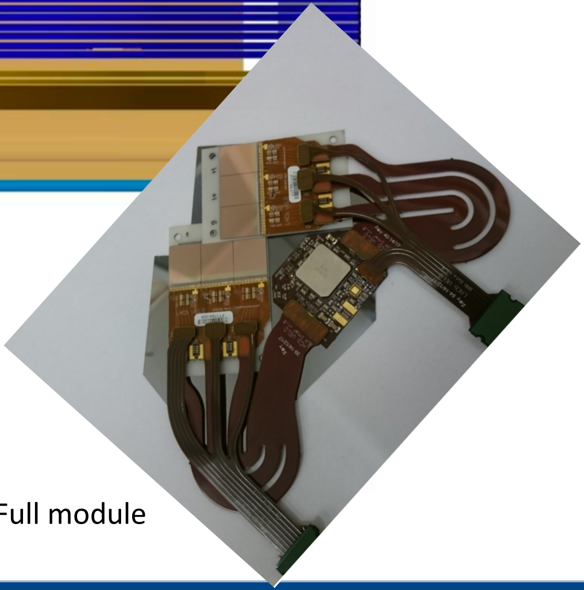
CO_2 circulating in microchannels



Plasma diced microchannel wafers



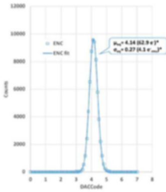
zoom onto module region

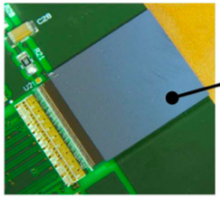


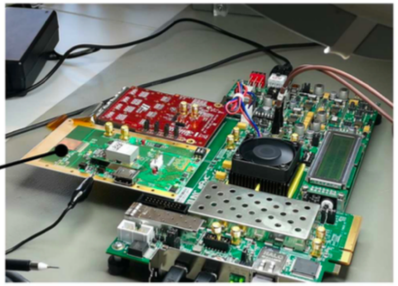
Full module

VeloPix ASIC

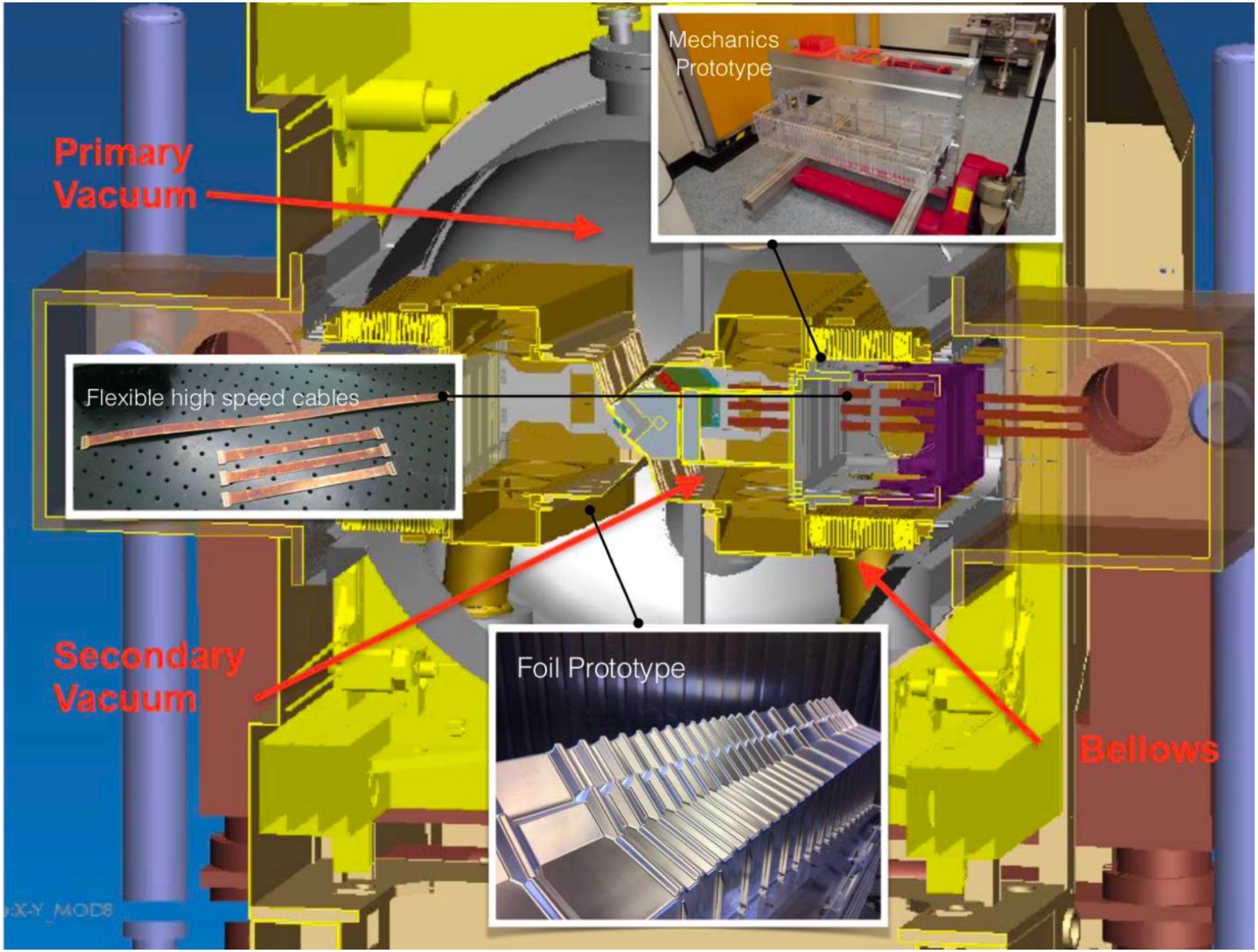
excellent performance;





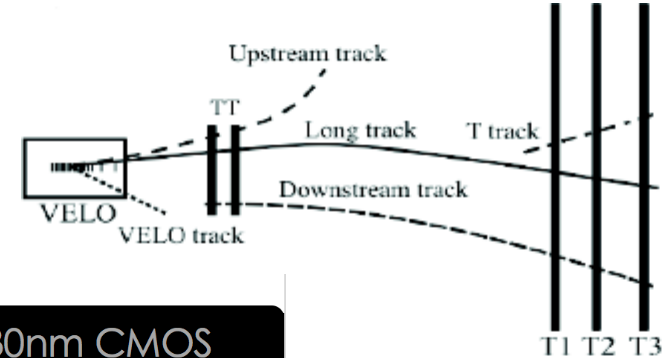


VELO: Prototyping

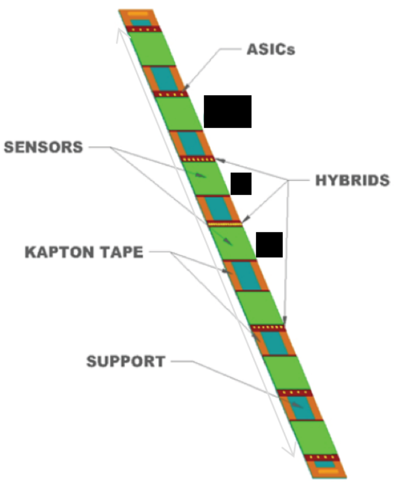


Upgrade of upstream tracker

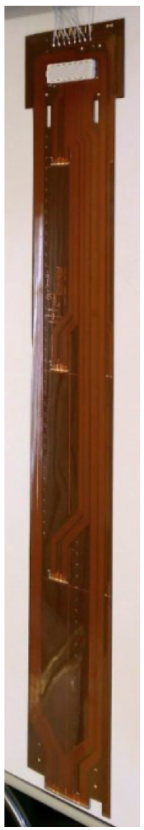
Silicon strips tracker
- N-i-p sensors

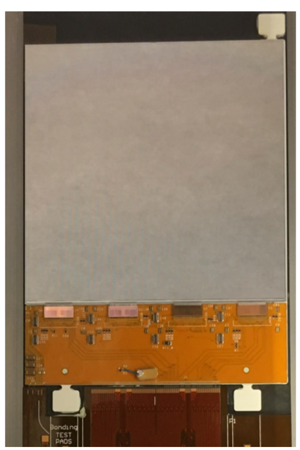


4 planes of 16 staves

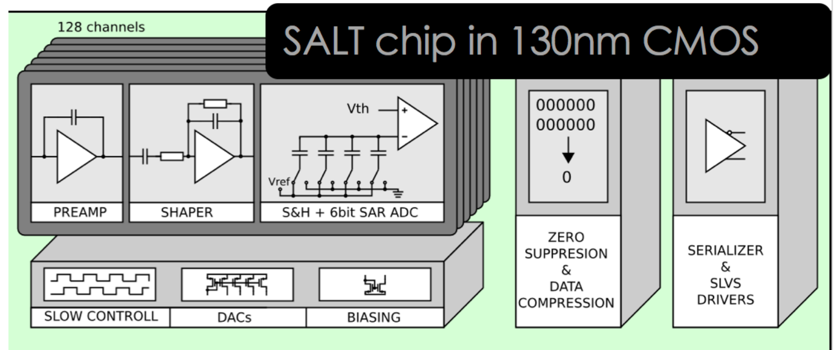


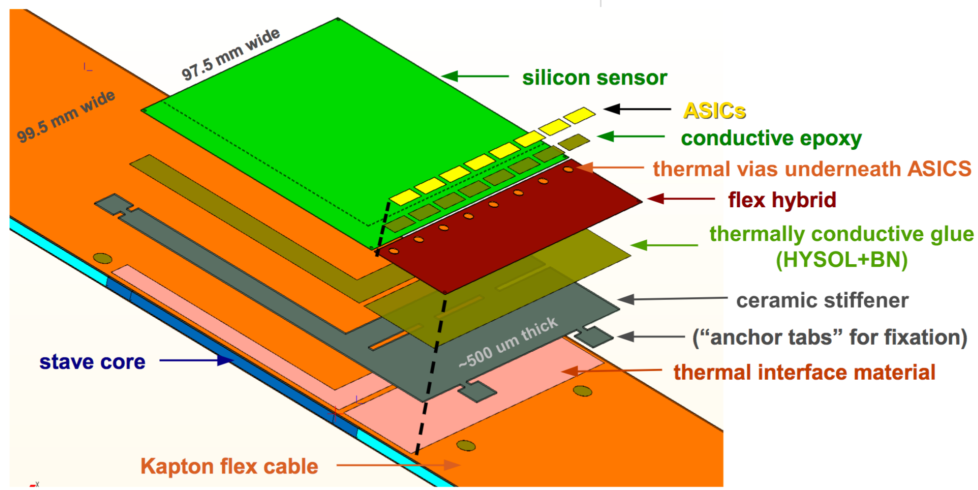
Proto tapes & modules





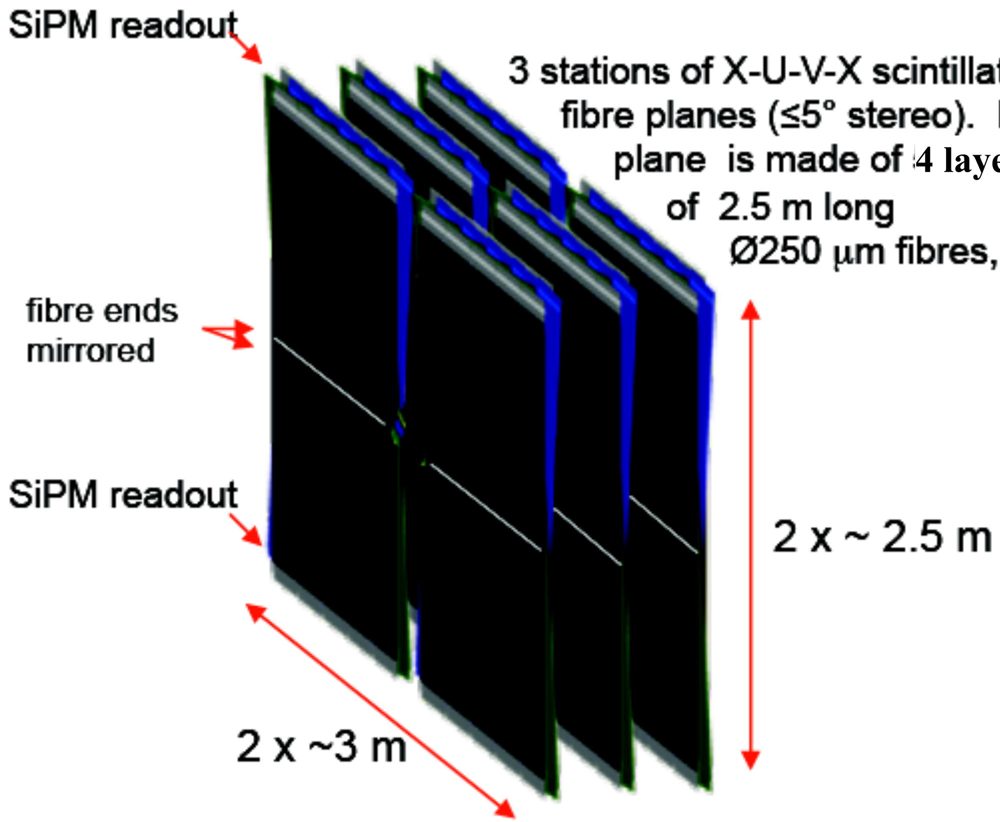
SALT chip in 130nm CMOS



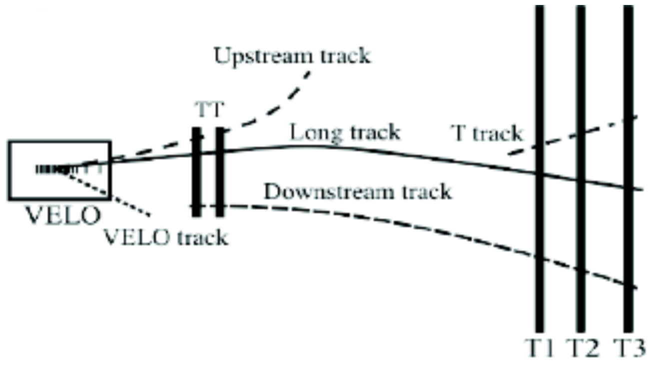


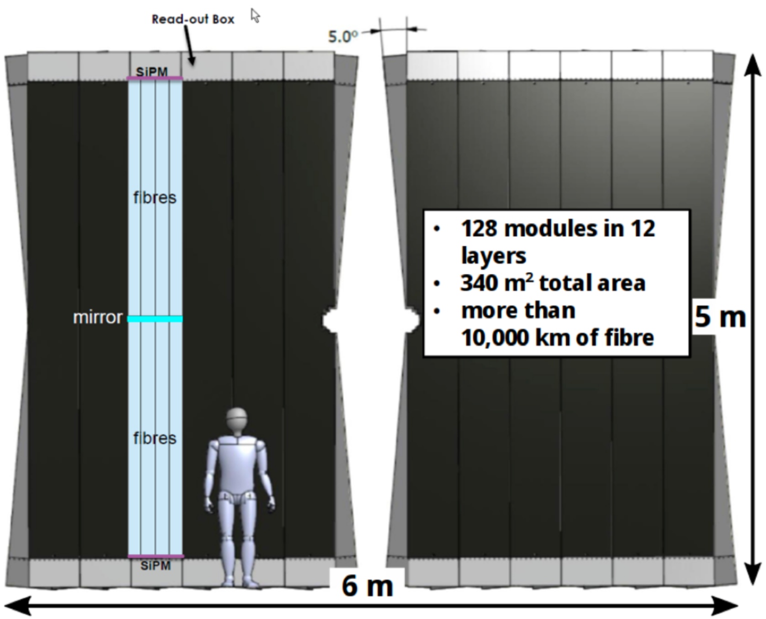
Upgrade of downstream tracker

Replacement of downstream tracker (T stations): straw drift tubes → scintillation fibre tracker



3 stations of X-U-V-X scintillating fibre planes (≤5° stereo). Every plane is made of 4 layers of 2.5 m long Ø250 μm fibres,.

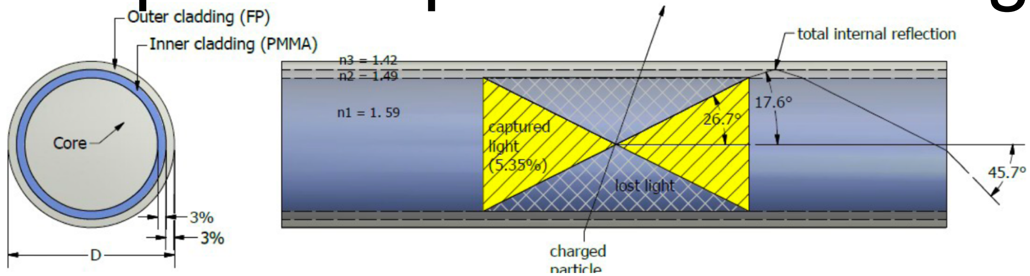




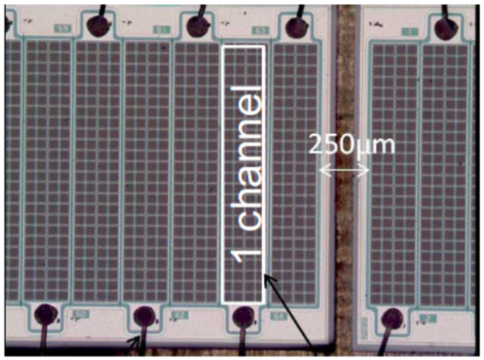
- 128 modules in 12 layers
- 340 m² total area
- more than 10,000 km of fibre

- 40 MHz readout
- Hit efficiency ~ 99 %
- Hit resolution < 100 μm

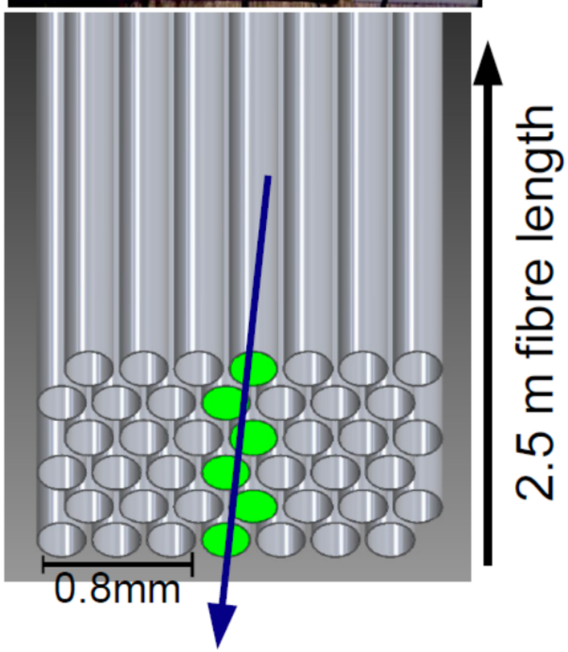
Recap: Principle of scintillating fibre detector

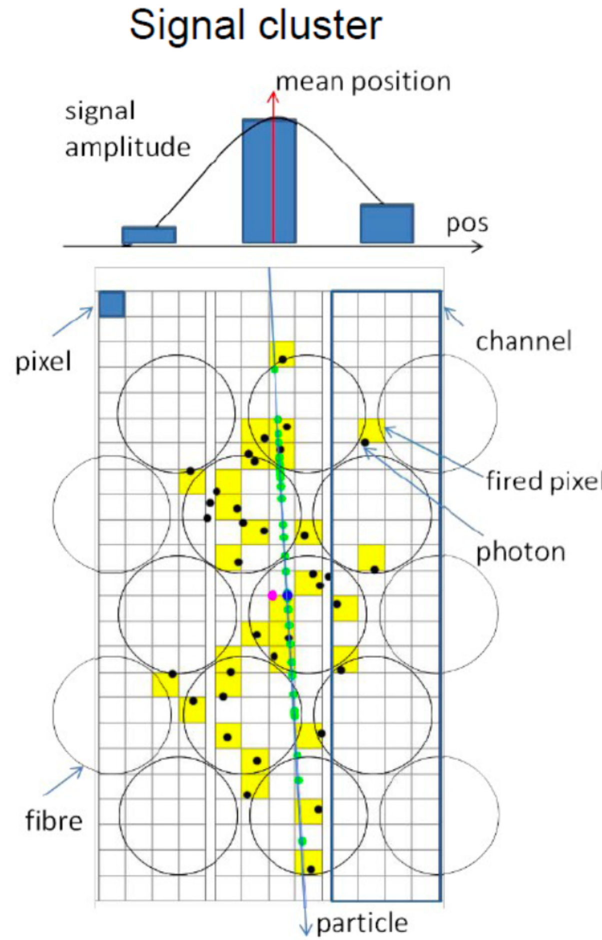


SiPM array



Scintillating Fibres (0.250mm diameter)

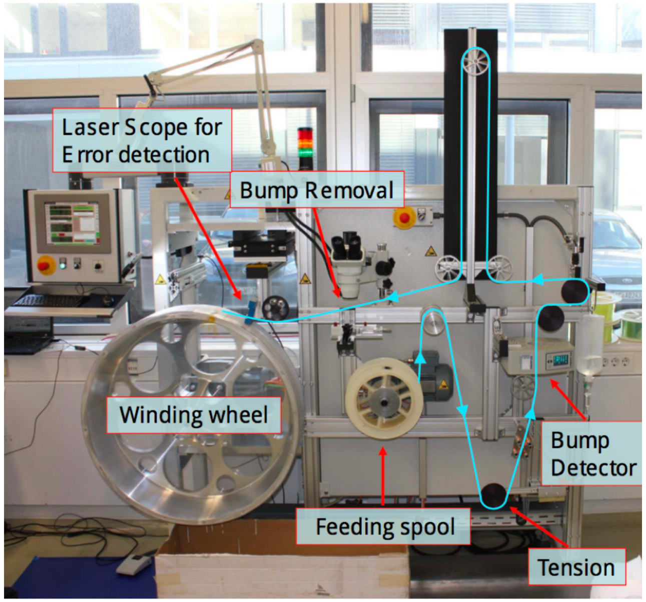


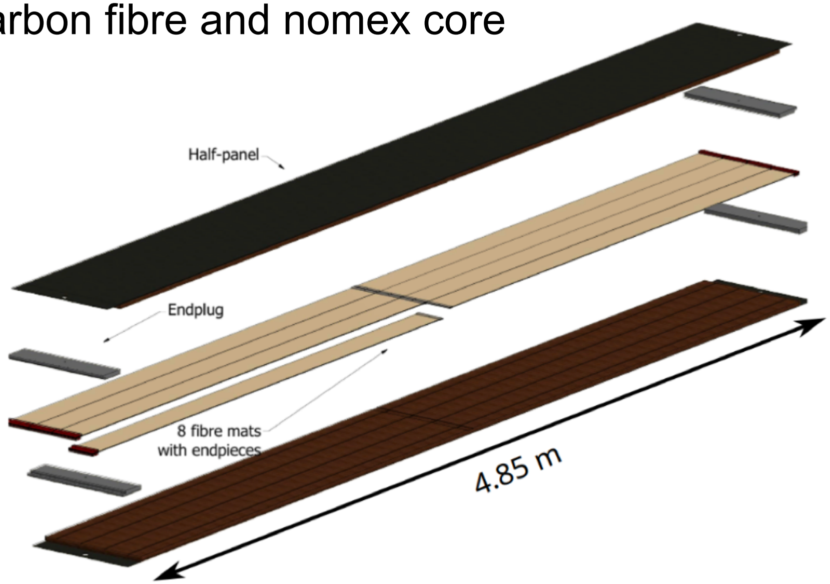


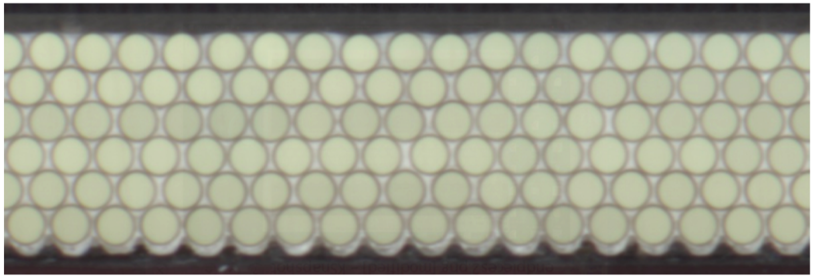
Light yield of a 6-layer mat: 15–20 photo electrons
(for particles near mat mirror)

Design of downstream tracker

- Fibres of polystrene base + activator + wavelength shifting dye
- Attenuation length ~3.5 m, Light emission peak ~460 nm
- Winding machine to lay 6 layers of fiber and glue onto a wheel
- Mats are glued into modules. Structures from carbon fibre and nomex core

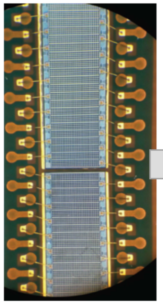


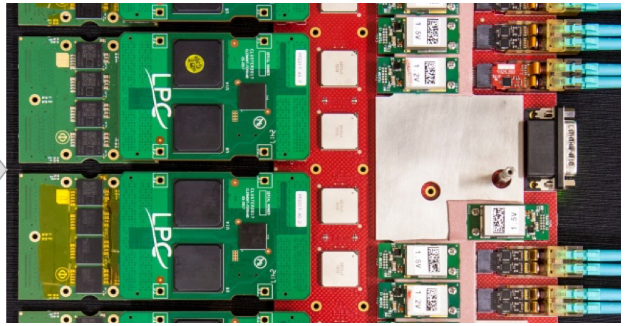




- SiPM arrays coupled to fibers with photon detection efficiency of 45%

- Dedicated readout chip for signal processing

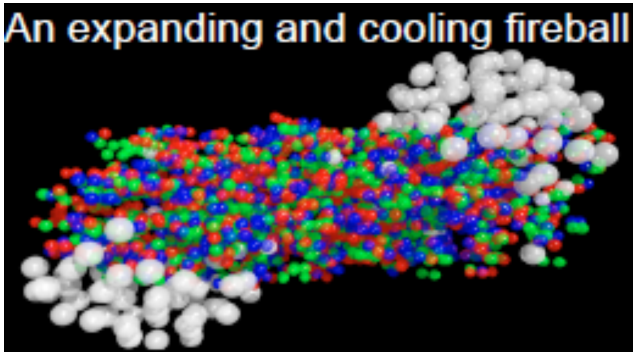


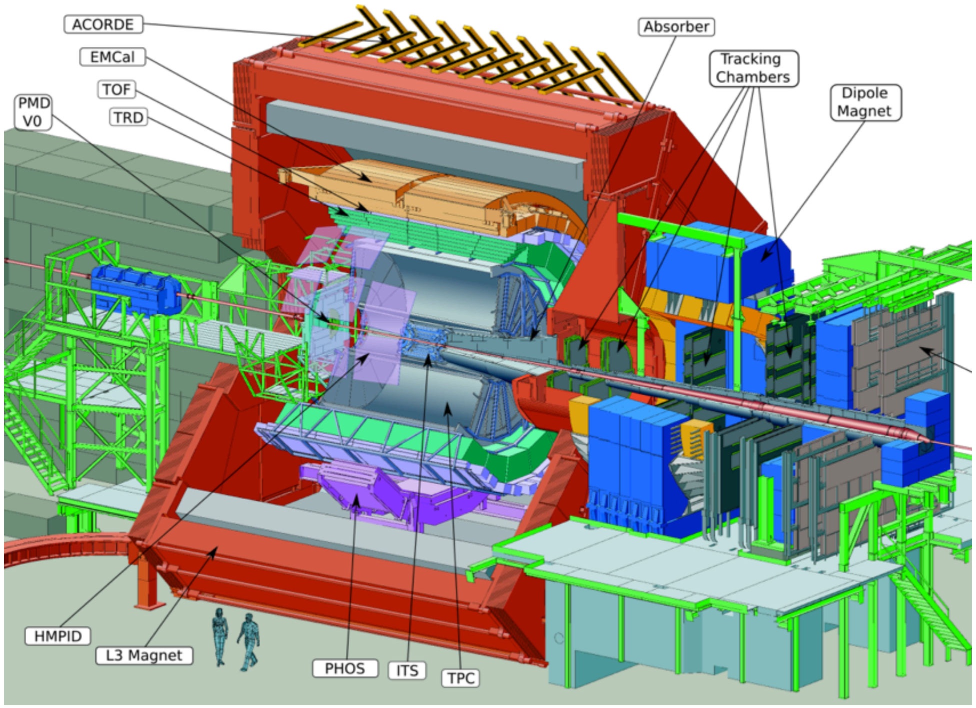


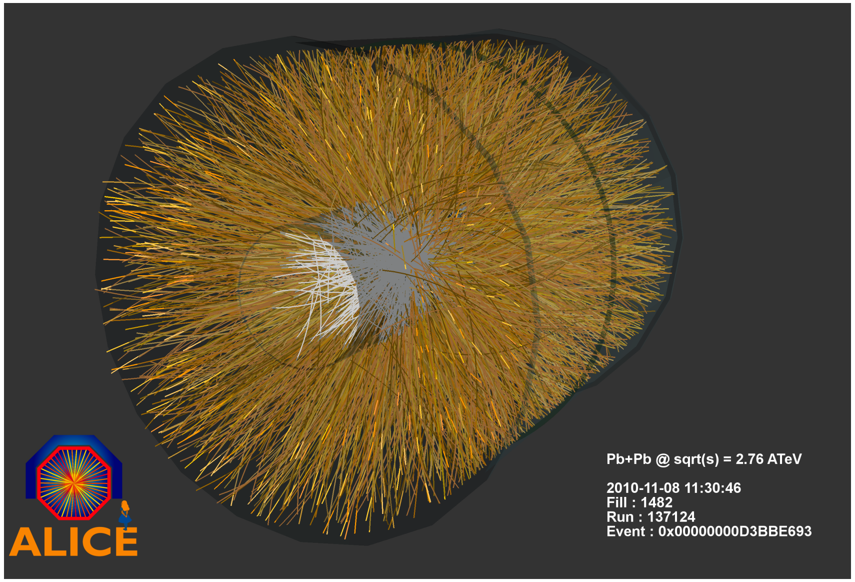
ALICE Experiment

Physics:

- Relativistic Heavy ion collisions produce a complex system of strongly interacting matter → Quark Gluon Plasma
- Study its properties (thermodynamics, flow, evolution, parton interaction with the medium) using light hadrons, heavy-flavour, jets, photons, dileptons, …







LHC heavy ion programme extended to Run 3 and 4

ALICE Upgrade in Phase-1

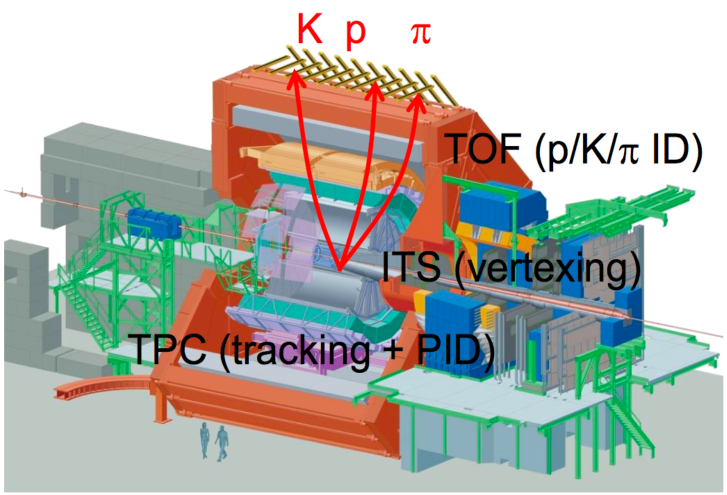
Main detector requirements

- High tracking efficiency and resolution at low p_T
  - Increase granularity, reduce material thickness
- High-statistics, un-triggered data sample
  - Increase readout rate, reduce data size (online data reduction)
- Preserve excellent particle ID capabilities
  - Consolidate and "speed-up" PID detectors

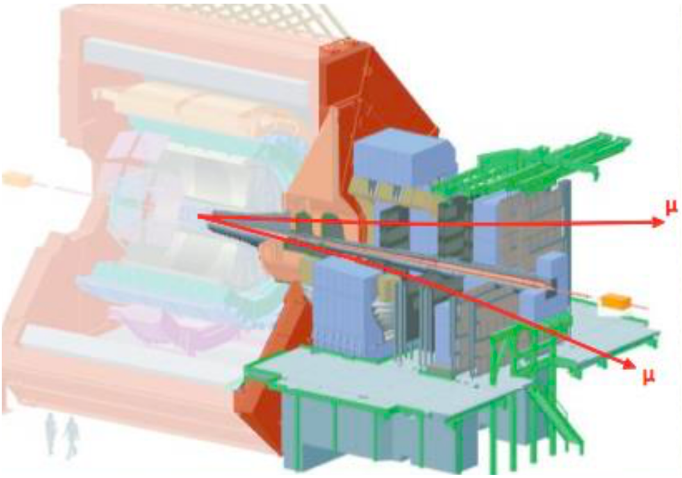
Decay modes targeted by upgrade programme include:

- D mesons into hadrons ($D_s \rightarrow K^- K^+ \pi^+$)
- HF baryon into hadrons ($\Lambda_c^+ \rightarrow p K^- \pi^+$, $\Lambda_c^+ \rightarrow p K_S^0$, $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$)
- Beauty into charmonium/hadrons ($B \rightarrow J/\psi + X$, $B^+ \rightarrow D^0 \pi^+$)
- Charmonium into leptons ($\psi(2S) \rightarrow \mu^+ \mu^-$)
- Beauty and charm into single leptons + X

Observables with low S/B and very difficult to trigger on



$\Lambda_c^+ \rightarrow pK^-\pi^+$



$\psi(2S) \rightarrow \mu+ \mu-$

Large rapidity and p_T range, down to low p_T

3

→ Operate ALICE at a high rate: from 3 kHz → 50 kHz to register all Pb-Pb events continuous

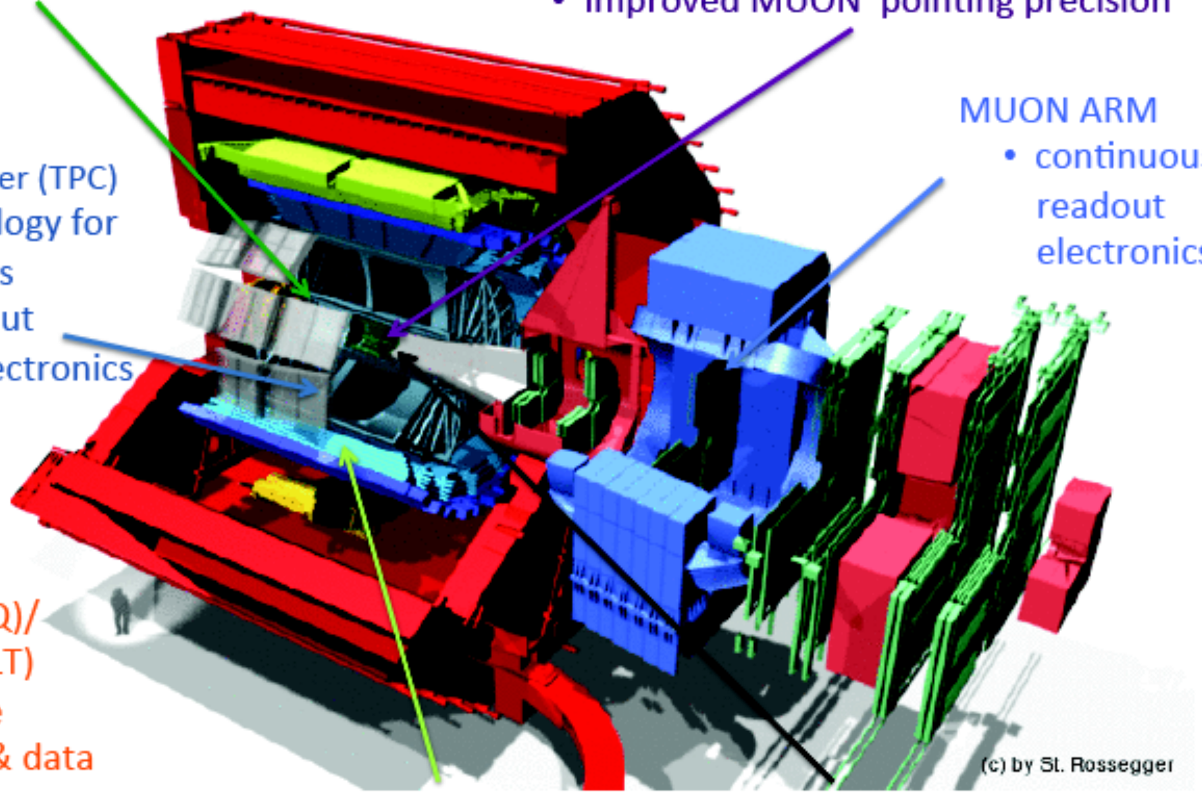
ALICE Upgrade in Phase-1

New Inner Tracking System (ITS)
- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)
- new Si tracker
- Improved MUON pointing precision

MUON ARM
- continuous readout electronics

Time Projection Chamber (TPC)
- new GEM technology for readout chambers
- continuous readout
- faster readout electronics



New Central Trigger Processor

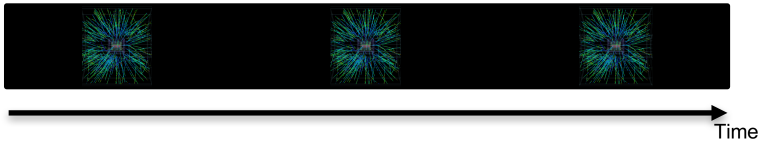
Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

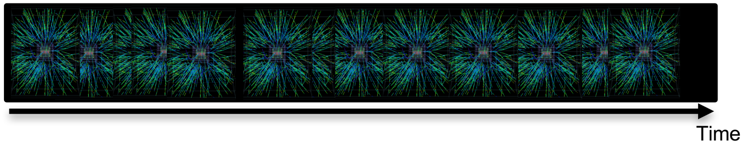
New Trigger Detectors (FIT)

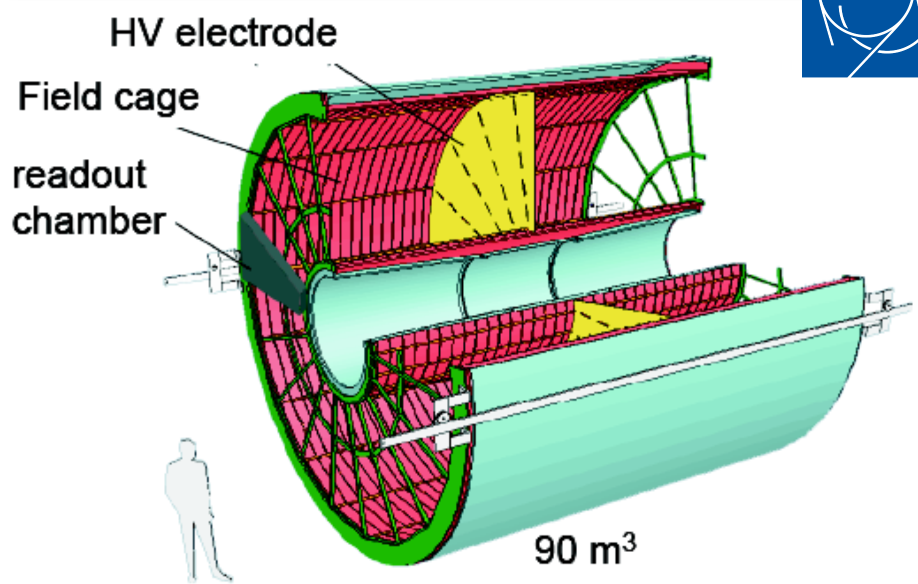
Upgrade of the ALICE TPC

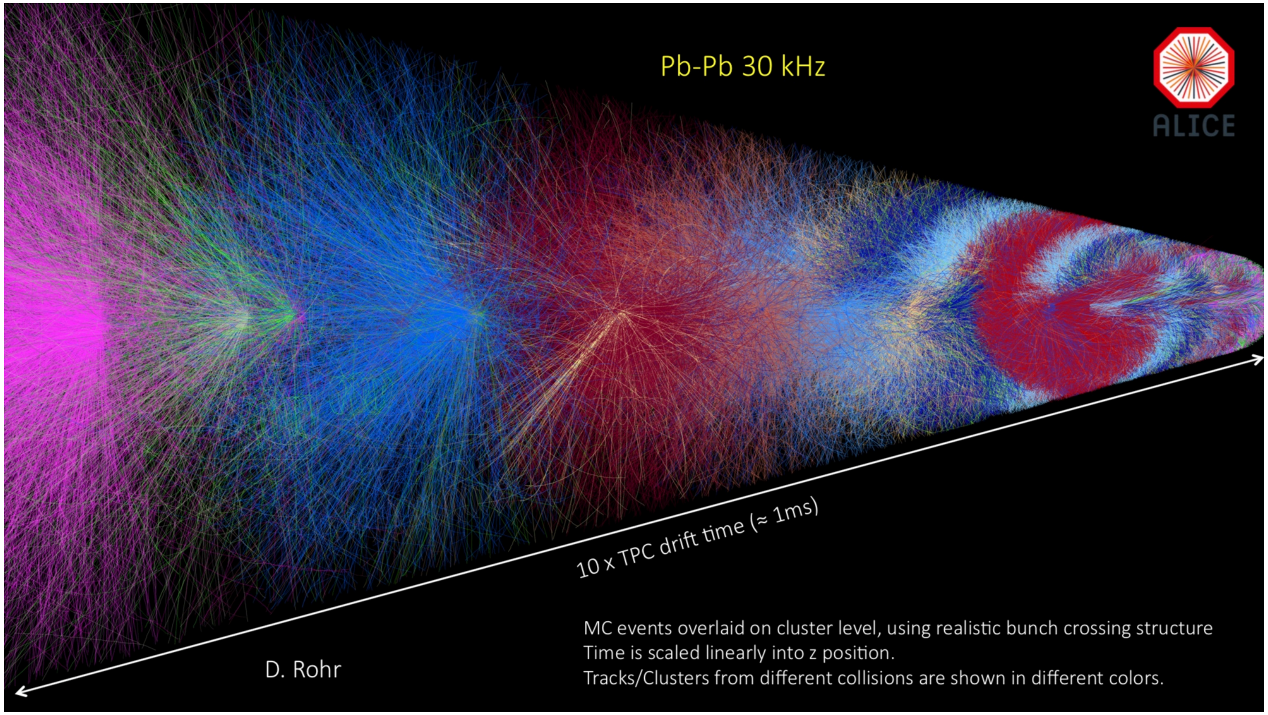
Current readout (MWPC) limit rate to 3.5 kHz (ungated readout leads to ion accumulation and distortion of electron drift)



Goal: readout with 50 kHz continuously





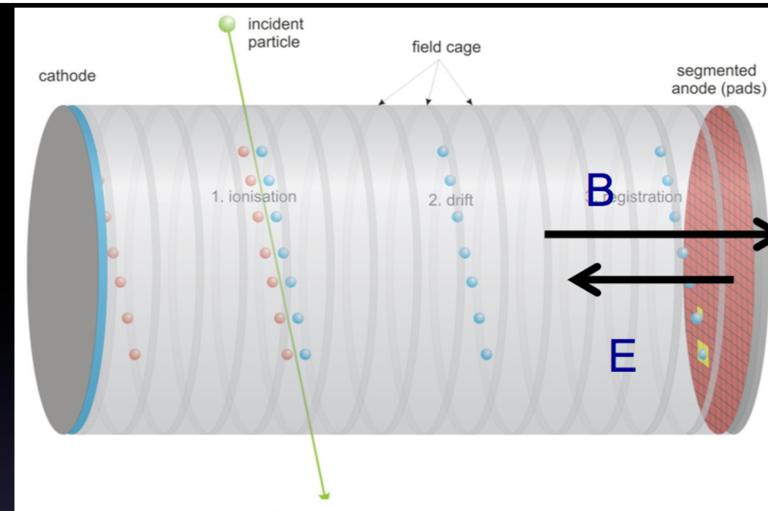


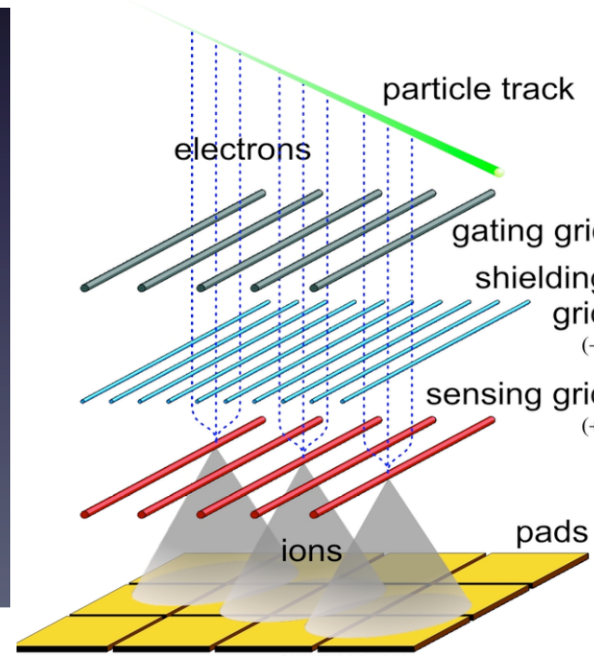
→ Preserve at high rate current tracking, momentum resolution and Particle ID performance

→Replace readout with **GEMs Gas Electron Multipliers** and new electronics, same field cage

Recap: The Time Projection Chamber (TPC)

- D.R. Nygren in 1976
- Full 3-D reconstruction
  - XY: MWPC and pads of MWPC at the endcap
  - Z: from drift time measurement (several meters)
    - Field cage for very homogenous electric field
- Typical resolution
  - z and y ≈mm, x=150-300 μm
  - dE/dx ≈5-10%
- Advantages:
  - Complete track information → good momentum resolution
  - Good particle ID by dE/dx
- Challenges
  - Long drift time limited rate
  - Large volume (precision)
  - Large voltages (discharges)
  - Large data volume
  - Difficult operation at high rate

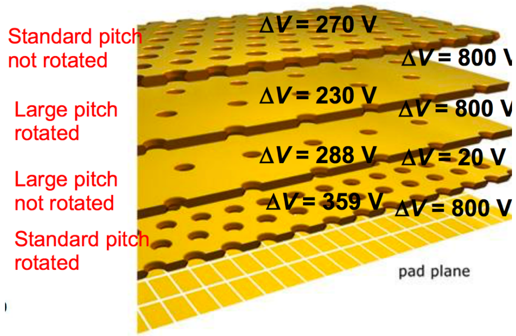


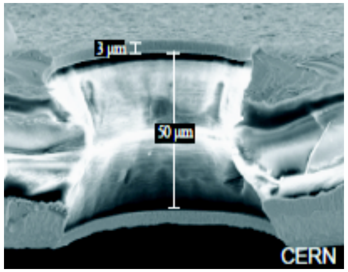


TPC of ALICE: drift time of 125 μs, Ions drift back → gating grid closed for 280 μs → max 3.5 kHz trigger rate

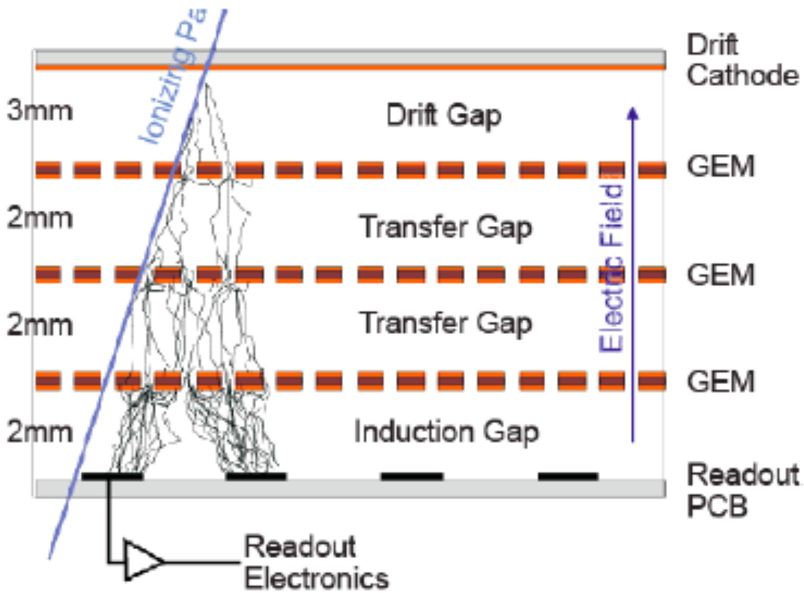
Upgrade of the ALICE TPC

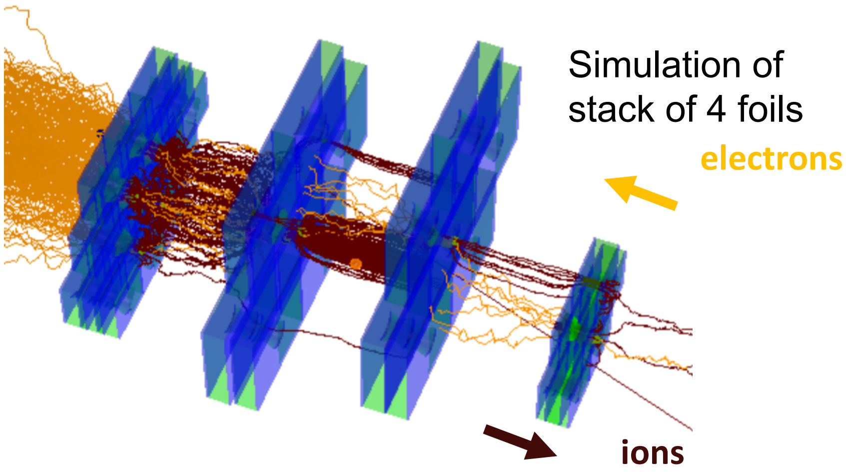
- Replacement of readout wire chambers with quadruple-GEM chambers
- GEMs designed to minimize ion back flow to allow continuous, ungated, untriggered readout
- Replacing the front-end electronics with new ASIC (SAMPA)
- Development of software to compress raw data of 3.2 TB/s from TPC





GEM foil

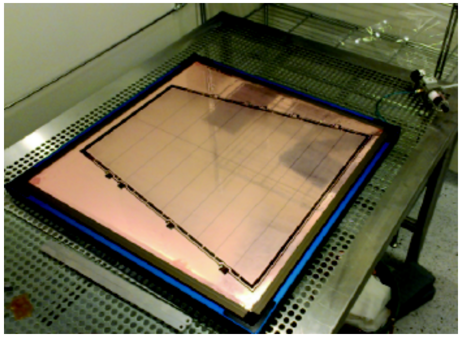


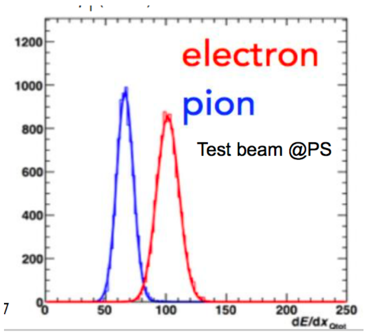


Simulation of stack of 4 foils

First time large area foils

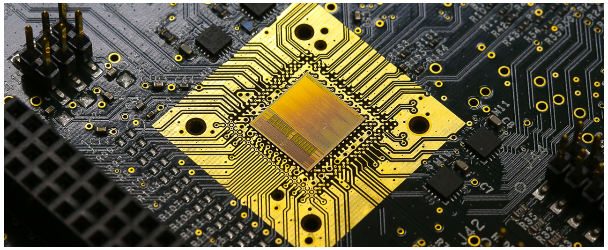
Foil prototype



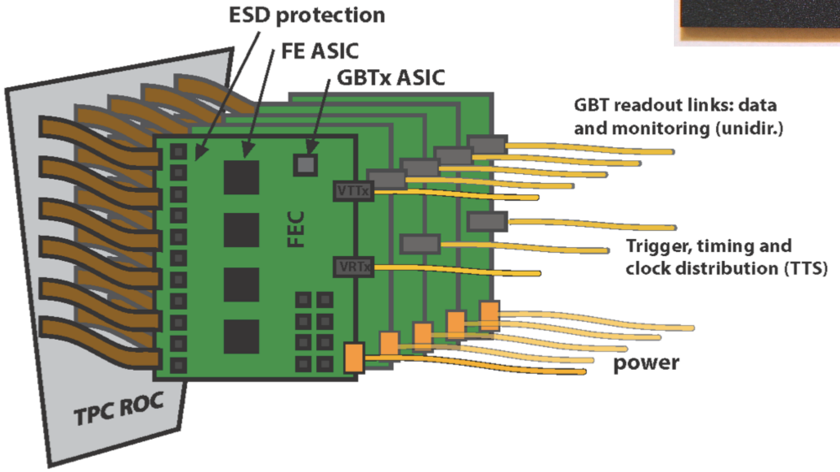


New readout ASIC in ALICE

- SAMPA chip with 32 channels for new TPC readout and readout of Muon Chambers
- ADC: 10 bit resolution



In TPC
→ 524000 channels @ 50 kHz readout rate
→ 16380 front-end ASICs



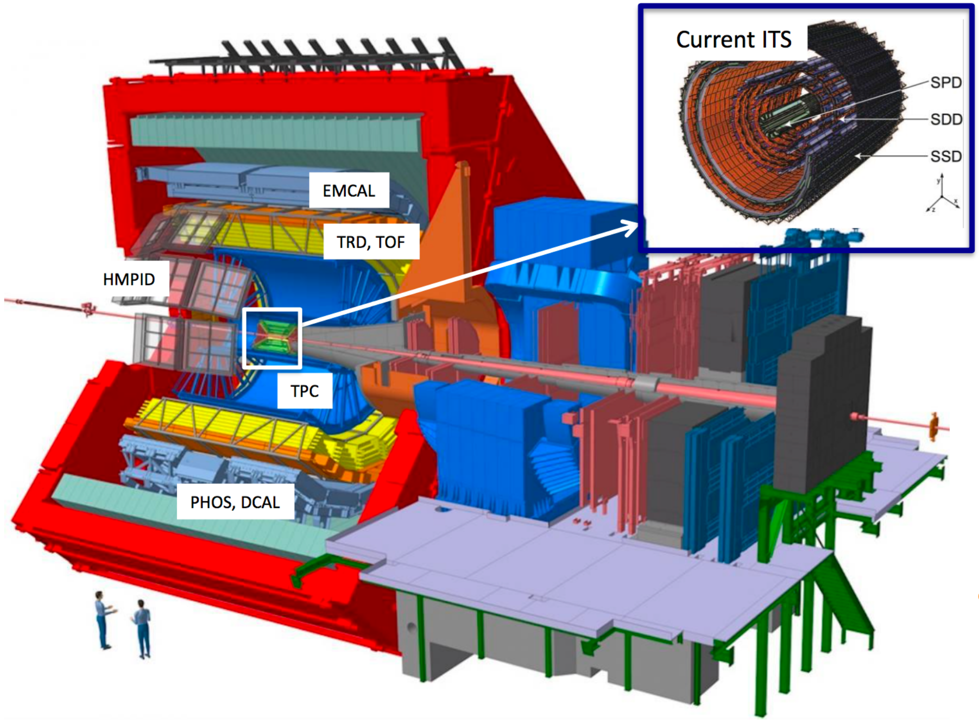
In Muon Chambers
→ 19000 Front-end cards with 2 SAMPAs

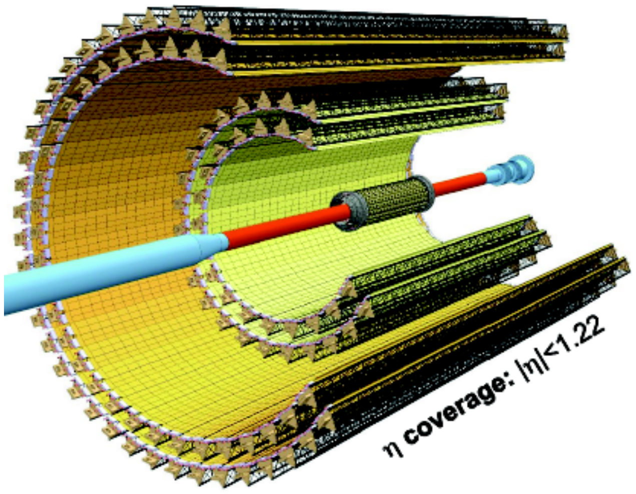
Successful beam test with low noise
Production started

Together with LHCb: Development of Common Readout Units

The new, v2 PCIe40 CRU card

ALICE Inner Tracking System (ITS) Upgrade





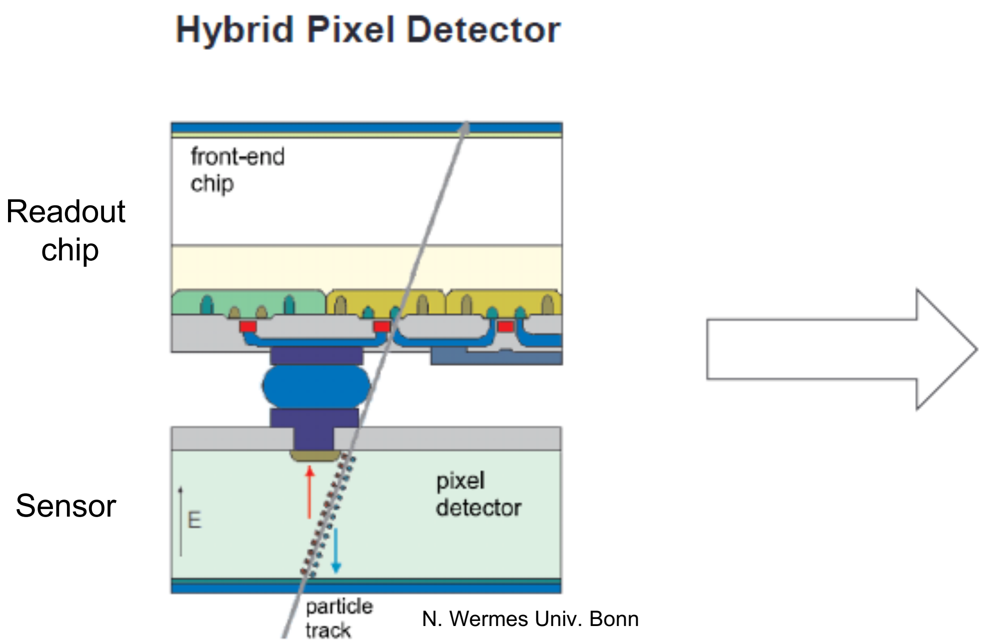
- Improve impact parameter resolution by a factor of 3, in particular for very low p_T through reduction of
  - Distance to IP
  - Material budget
  - Pixel Size

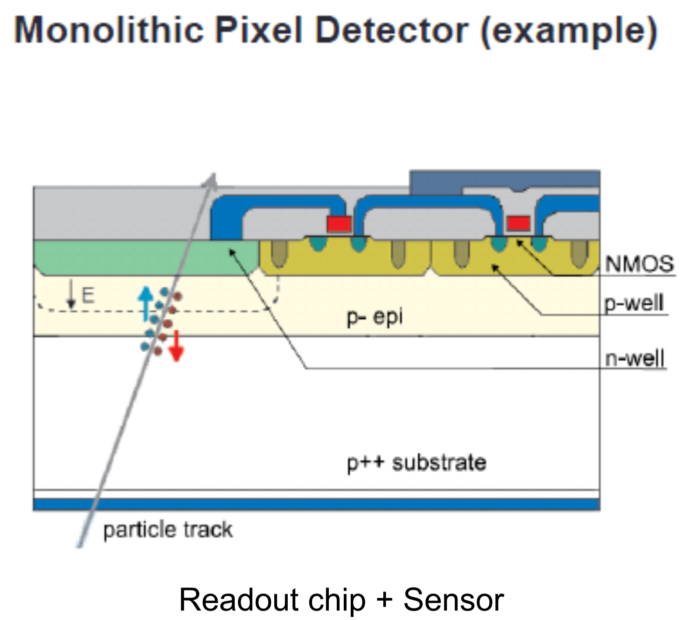
- 3 inner (0.3%X_0), 4 outer layers (0.8%X_0)
- Use 50 μm thick monolithic pixel sensors
- Faster readout (x50) (rate currently limited by TPC and ITS to 1 kHZ for Pb-Pb)
- 10.3 m^2 and 25 G-pixel

comparison: 300 μm Silicon ~ 0.3% X_0
no cooling, no mechanical support ...

Combining silicon sensor and readout electronics

Alternative for light detector: CMOS technology



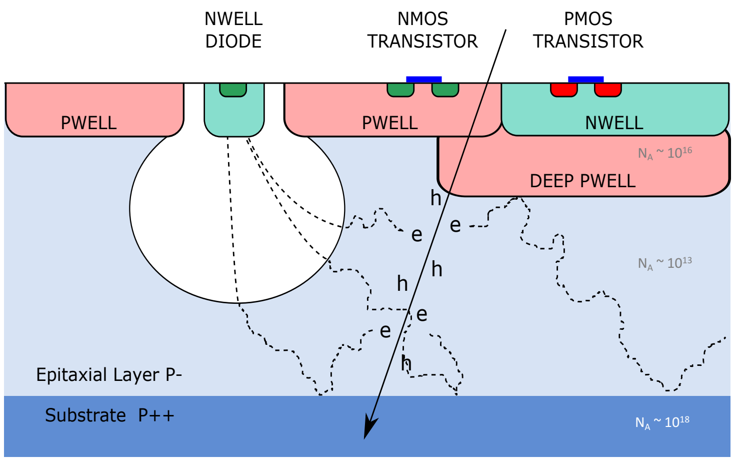


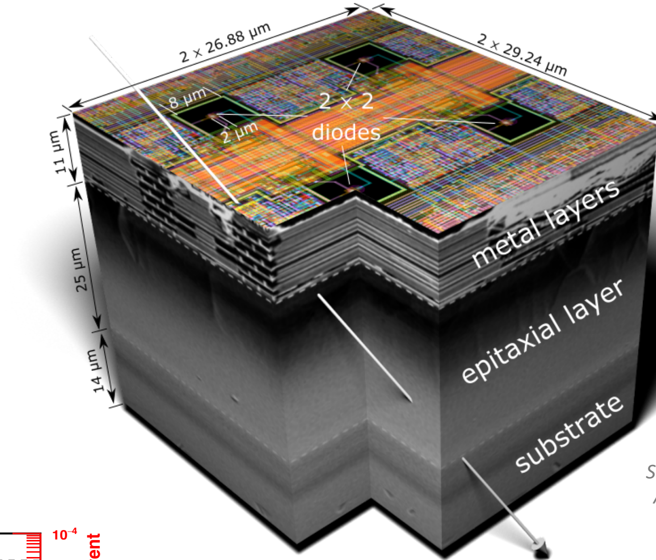
- Sensor element is n-type material (deep n-well) in low resistivity p-type substrate, size > 15 x 15 µm², thickness O(100 µm)
- Pre-amplifier integrated in sensor
- Depletion with low bias voltage, signal around 1000-2000 electrons
- Commercial process → cost reduction
- Tests after irradiation show good performance

Monolithic Active Pixel Sensors

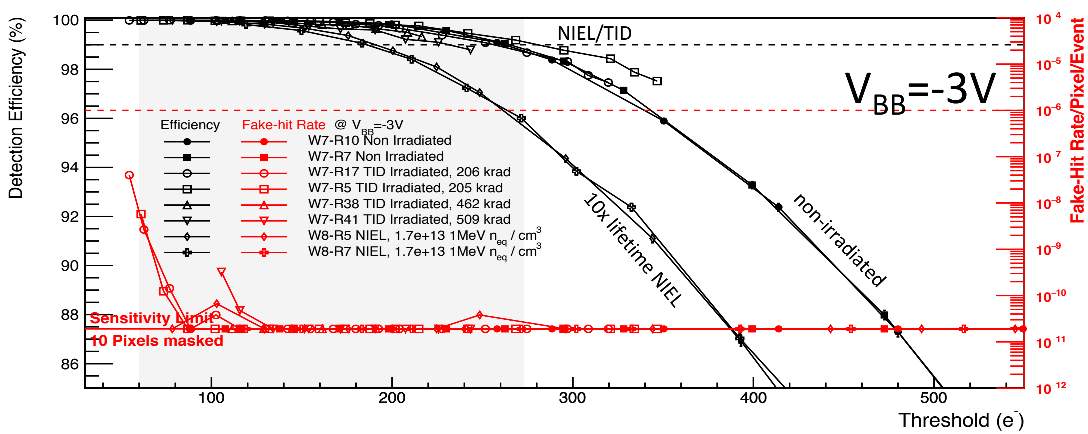
CMOS Pixel Sensor using TowerJazz 0.18 μm CMOS Imaging Process

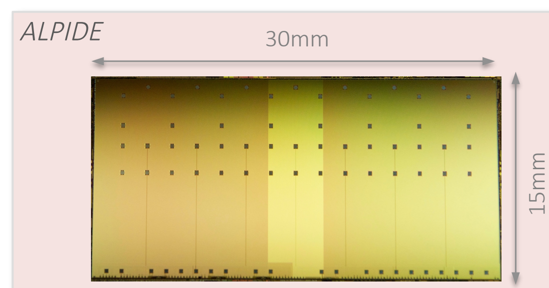
- Small n-well diodes → low capacitance and reverse bias voltage ~6 V
- Deep p-well shields on n-well of PMOS transistor
- Pixel size 28 μm x 28 μm





SEM picture of ALPIDE cross section

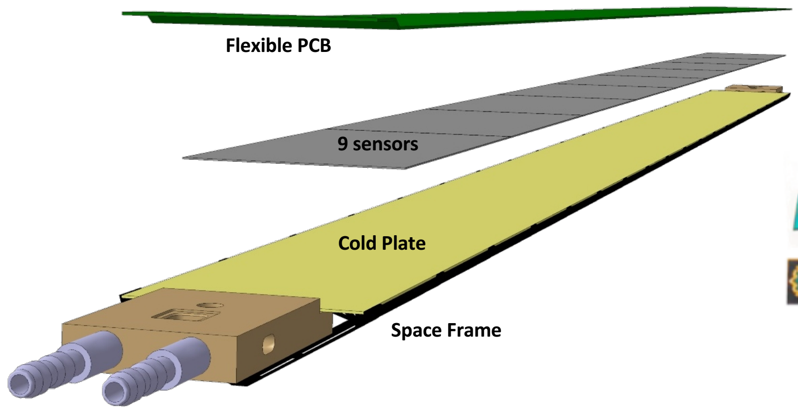




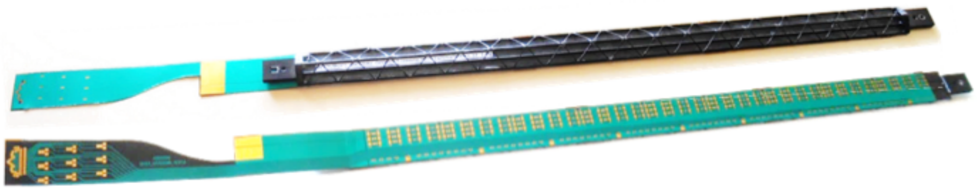
Resolution of ~6 μm at a threshold of 300 electrons

Large CMOS detector

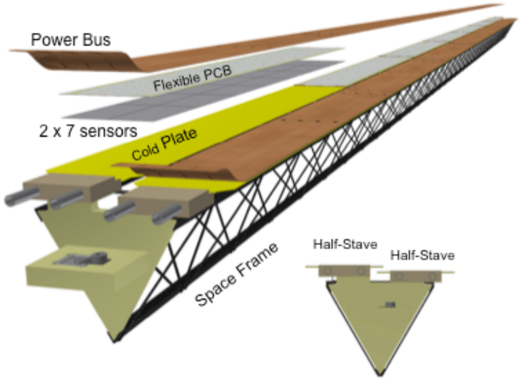
ITS Prototypes

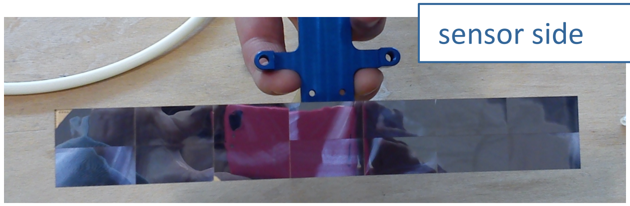


Inner Barrel

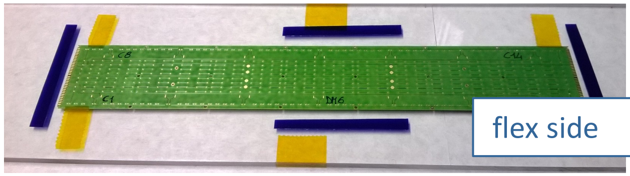


Outer Barrel

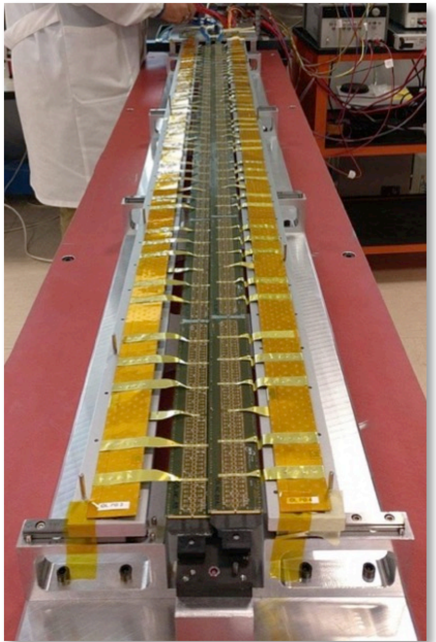




sensor side



flex side

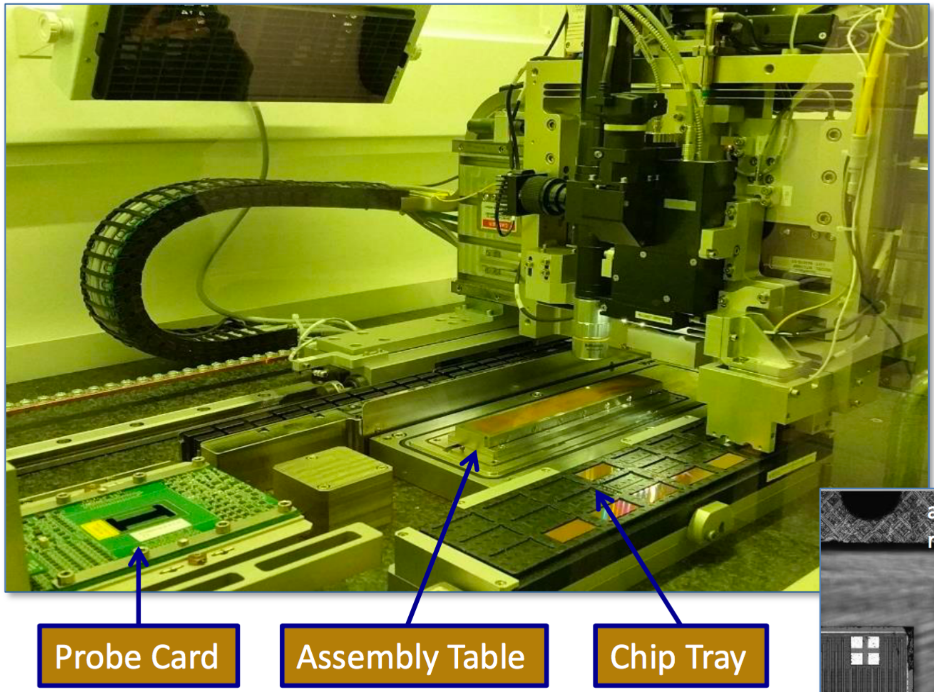


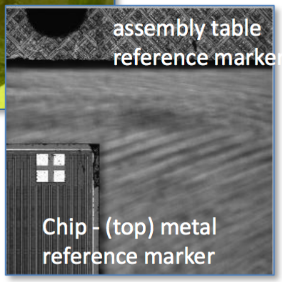
102 million pixels, average noise ~5e

ITS Assembly

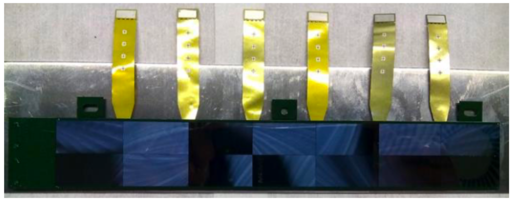
Automated module assembly (custom-made machine)

- Placement accuracy < 5um

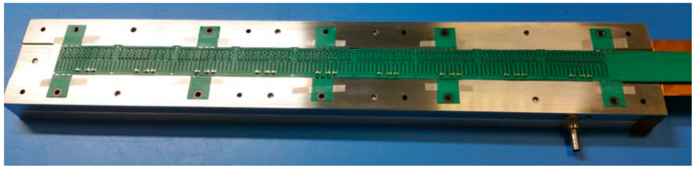




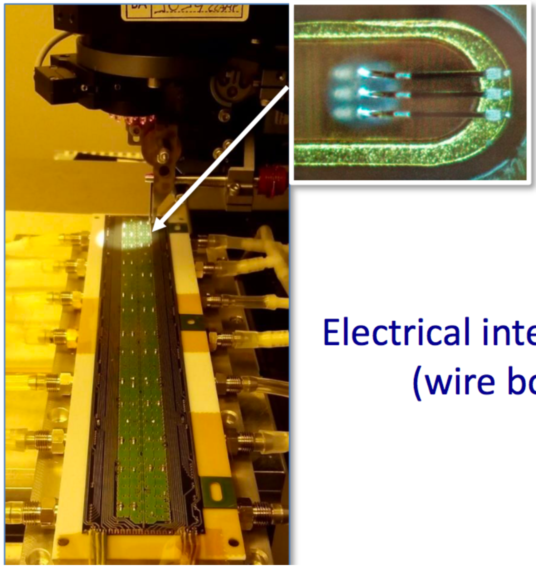
6 machines distributed to different construction sites



Sensor side (OB)



FPC side (IB)

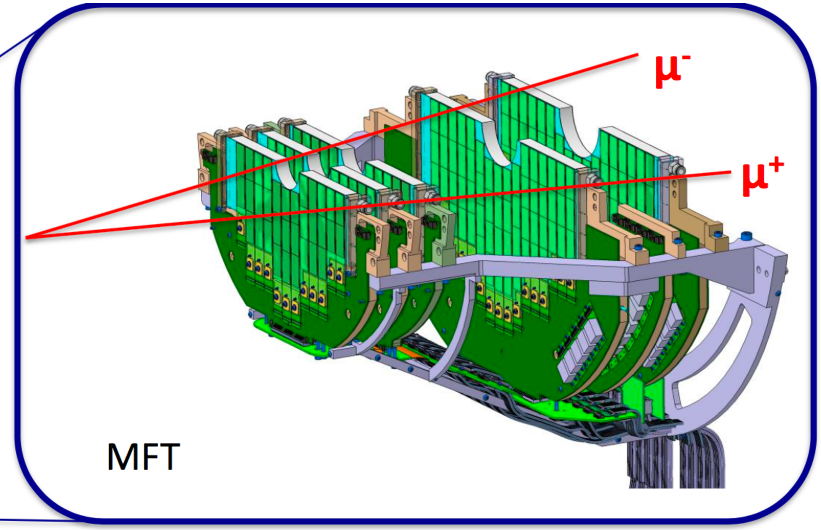


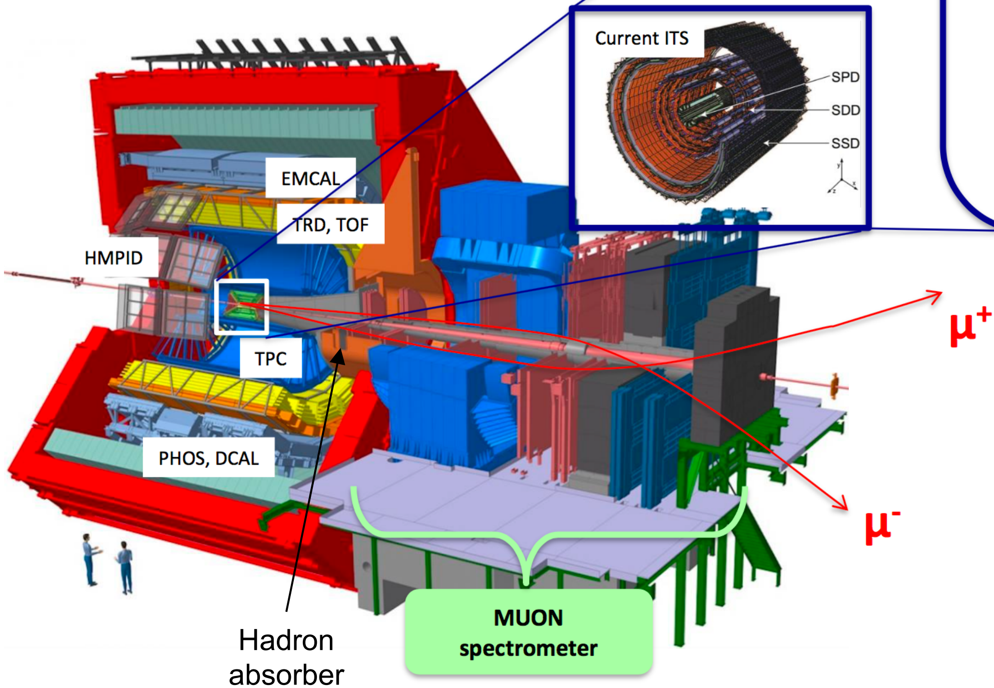
Electrical interconnection (wire bonding)

Courtesy of Marielle Chartier

New ALICE Muon Forward Tracker (MFT)

New vertexer for the Muon Spectrometer at forward rapidity:
High resolution
Low-material budget
Silicon Pixel Tracker

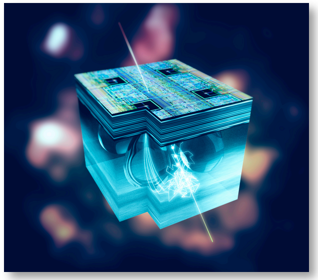




Muon tracks extrapolated and matched to the MFT tracks before absorber.

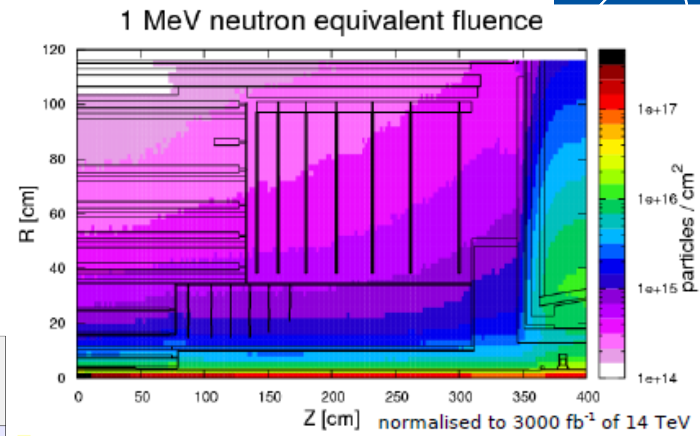
High pointing accuracy gained by the muon tracks after matching with the MFT tracks.

- 5 silicon pixel disks with same MAPS as in ITS



Summary: Silicon Detectors

- Several new silicon detectors foreseen in upgrade have to withstand doses of up to
  $\Phi \sim 2 * 10^{16}\, N_{eq}/cm^2$, ~1.5 GRad (ATLAS, CMS),
  $\Phi \sim 8 * 10^{15}\, N_{eq}/cm^2$ (LHCb)



Experiment	Type	Speciality
CMS Phase 1	Tracker pixels	Planar: n+-in-n
ALICE Phase 1	ITS + Muon forward tracker	NEW: Monolothic Active Pixel Sensors/CMOS
LHCb Phase 1	Pixel tracker + upstream tracker	NEW: Micro channel cooling, Pixel sensors; Strip sensors
ATLAS Phase 2	Tracker strips and pixels	Strip: n-in-p, 300 µm, 160 m² Pixel: n-in-p planar and 3D, 100/150/200 µm, 13 m², high η extension
CMS Phase 2	Tracker strips and pixels	Strip: n-in-p, 200 µm thick, 210 m² Pixel: n-in-p, 200 µm, 5 m², high η extension
CMS Phase 2	Silicon for calorimeter	Si sensors hexagonal p-in-n, 200 µm, 700 m²

New technologies:
- CMOS
  Micro channel cooling
  Serial powering
  Si in calorimetry

Challenge:
Low material
Fine granularity
Integration on large areas

Common R&D in RD50 Collaboration

Summary: Gaseous Detectors

Main use as muon detectors, work very well in all phases of LHC

1) **Upgrade without changing detectors**
   - Modify electronics (DT CMS, ALICE RPC)
   - Continue (largest part in ATLAS, CMS, LHCb)
2) **Upgrade by scaling standard geometries**
   - Increased acceptance (ATLAS MDTs, TGCs in new small wheel)
   - Increased granularity (CSC CMS)
3) **Upgrade by introducing novel gas detectors**
   - Micromegas (ATLAS new small wheel, 1200 m²)
   - GEMs (TPC ALICE, forward muon system CMS, LHCb 50 kHz readout)

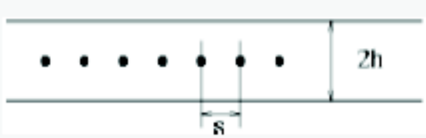
Common R&D in RD51 Collaboration

Geiger- Müller (1908), 1928
Drift Tube (1968)

1)

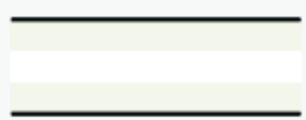
G. Charpak, 1968
Multi Wire Proportional Chamber

2)



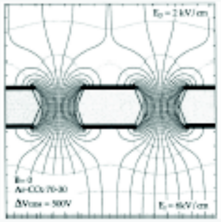
R. Santonico, 1980
Resistive Plate Chamber

3)



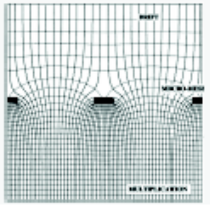
F. Sauli (1997)
Gas Electron Multiplier

4)



I. Giomataris et al. (1996)
Micro-mesh gaseous chamber (Micromegas)

5)



Summary: Electronics

- **Large part of upgrades covers replacement**
  - Read-out electronics
  - Power supplies
  - Front-end electronics
  - Trigger electronics

- **Common issue**
  - Fast, radiation hard (up to 1MGy), low power readout electronics for tracking detectors
    → R&D effort in RD53 Collaboration
  - Deploying COTS (Commercial of the shelf) components

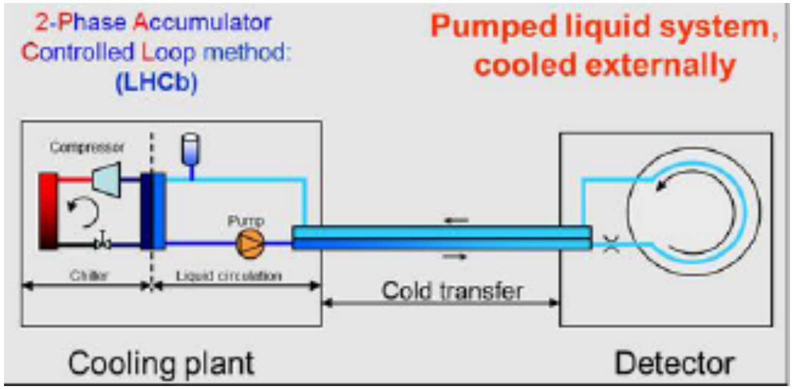
- **Common development**
  - Fast data transmission required: common R&D on Gbps optical link
  - Radiation hard and magnetic hard: DC-DC converters
  - Frame contracts for IC technologies
    (65 nm and 130nm TSMC and in use IBM 130 nm, Techno de On-Semi 350 nm)

Summary: Calorimetry, Activation and Cooling

- Calorimetry
  - Upgrade of readout and electronics in several calorimeter parts required
  - Part of CMS calorimeter (to be upgraded due to radiation dose in Phase-2): new silicon/copper and scintillator/steel endcap calorimeter

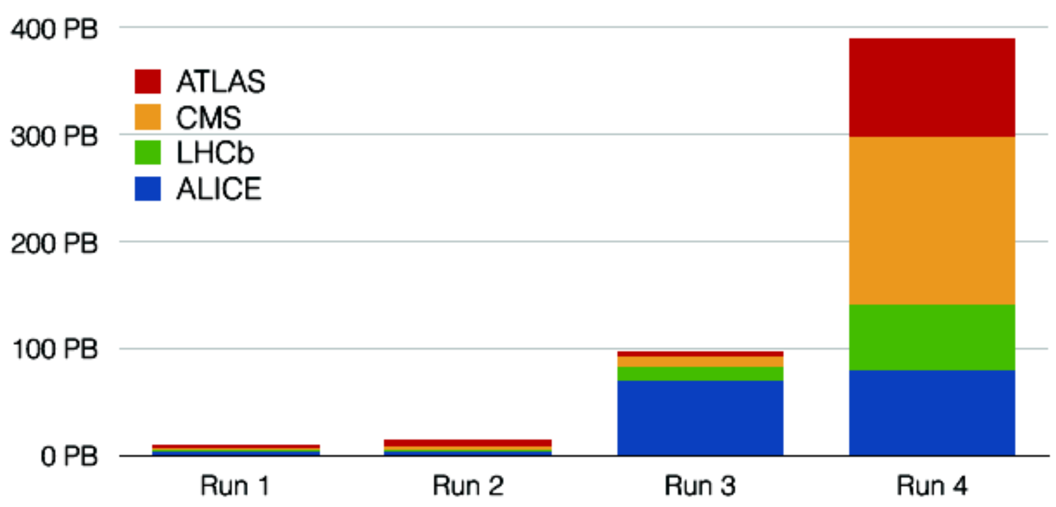
- Radiation doses in Phase-2 and activation of material to be considered
  → effect shielding and handling

- Detector cooling with evaporative CO_2 cooling:
  - 15...130 bar
  - 200...300 J/g instead of ~2 J/g in mono-phase cooling system
  - Allows thinner and longer pipes
  - New cooling plants LHCb 2*7 kW, ATLAS 6*30 kW, CMS 9*45 kW



Summary: Triggering

- Triggering
  - ALICE and LHCb plan to read out all data with upgraded electronics
  - ATLAS and CMS include tracking → control Level 1 rate
    With different approaches similar HLT rate of 5-10 kHz in Phase-2
  - Upgrades by hardware and software modifications (new electronics on various systems, TDAQ infrastructure, Track Trigger)
  - Collecting a lot of data → Imposes challenge for further offline processing



New physics results

UPGRADE OF THE LHC

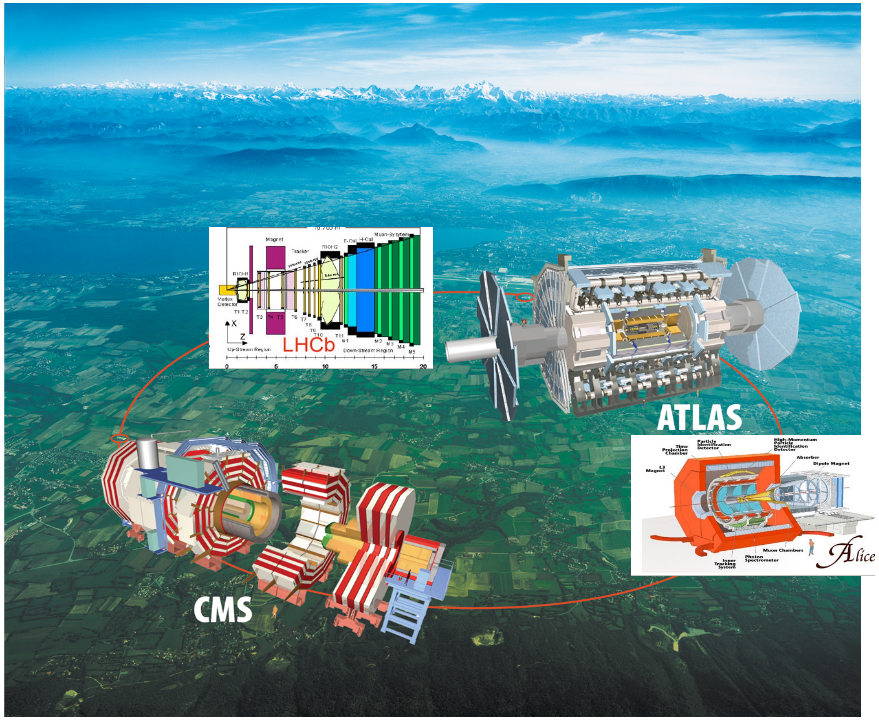
- Exciting physics program with 4000 fb^{-1} possible
- Search for new particles and measurements of Higgs properties

- Technical challenges ahead
  - High radiation environment
  - High rate of pile up and occupancy
  - High trigger rates

- LHC and all 4 experiments have coherent plans to perform upgrade of systems
  - Main issues: Silicon tracking detectors, electronics and trigger strategies

- Collaboration between experiments for upgrades in the context of RD50, RD51 and RD53 R&D Collaborations

Thank you!



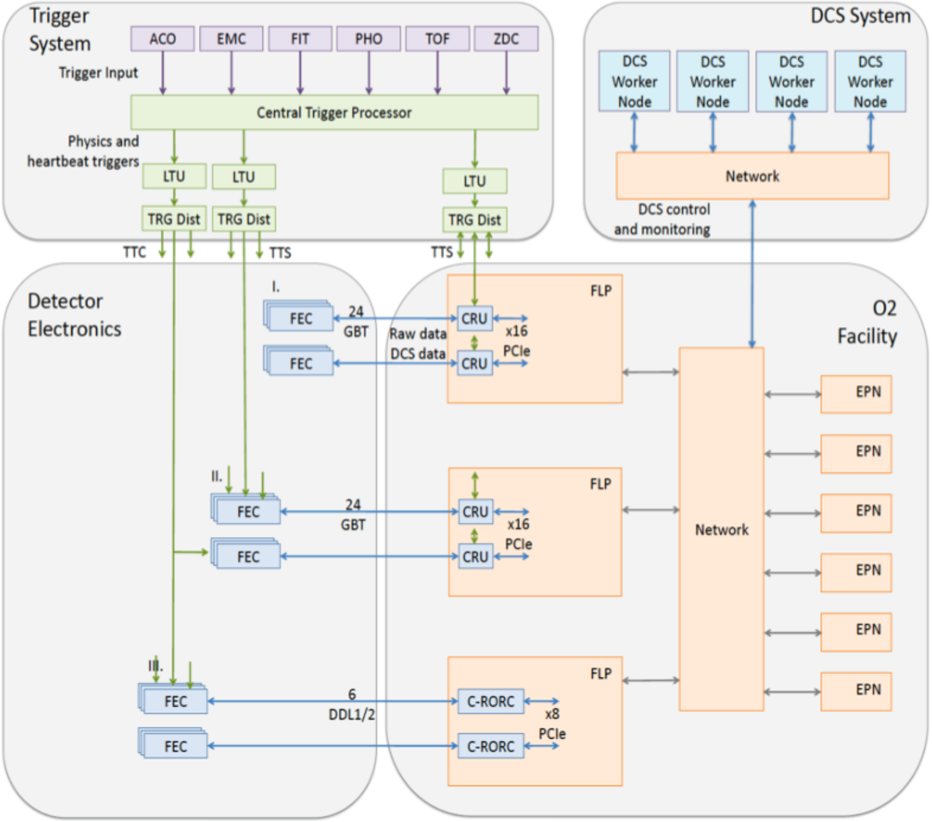
SPARE

Acknowledgment

Stefano de Capua, Hamer, Alexander Kluge, Ken Wyllie, Marielle Chartier, Plamen Hopchev, Daniela Bortolletto, Jike Wang, Arabella Martelli, Arnulf Strassner, Riccardo Vari, Ingrid Maria Gregor, Karl Jakobs, Ulrich Parzefall, Didier Contardo, Silvia Gambetta, Zhongbao Yin

ALICE Readout & Online-Offline System (O2)

- To keep up with the 50 kHz interaction rate, the upgraded detectors (ITS and TPC) will be read out continuously.



- Data (1.1 TB/s) transferred in continuous mode or by using minimum bias trigger to First-Level Processors (FLPs)
- The heart beat triggers to 'chop' data in Sub-Time Frames (STFs) to be inspected for initial data volume reduction in FLPs.
- STFs assembled to Time Frames (TFs) in the Event Process Nodes (EPNs).
- On-the-fly data volume reduction by EPNs synchronously.
  - Global reconstruction, calibration and data compression
- Further reconstruction performed asynchronously to improve the data quality.
- 85 GB/s to storage for Pb-Pb at 50 kHz interaction rate

20/5/2017 O^2 TDR, CERN-LHCC-2015-006 24

Overview ATLAS Phase -1

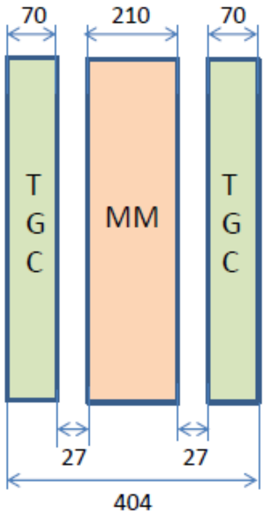
Concept, Three major projects are Phase-1 LAr upgrade, Phase-1 TDAQ upgrade, and NSW. All of these upgrade projects must be "phase-2 compliant", and will continue to be used during HL-LHC operations.

- **Phase-1 LAr:** Upgrade of trigger path for LAr calorimeter. Analog trigger tower sub-divided into 10 supercells digitized into 12-bits@40 MHz, and transmitted optically to FPGA-based back-ends for calibration and signal processing.
- **Phase-1 TDAQ:** Includes L1Calo upgrade to digital "feature extractors" (eFEX for e/τ, jFEX for small-R jets and MET, gFEX for large-R jets), TREX (tile feature extractor), updated Sector Logic and MUCTPI (Muon trigger upgrade), and FELIX (network-based switching fabric for phase-1 and phase-2)
- **NSW:** replacement for present small wheels ($1.3 < \eta < 2.7$) based on sTGC and MicroMegas chamber technologies with 8+8 measurement planes and sophisticated digital trigger processor to provide track segments pointing back to the vertex and matching endcap muon systems.

ATLAS Phase-1 Upgrade: Muon System

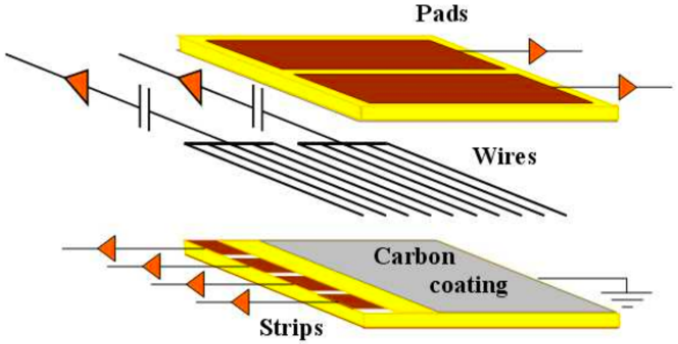
- Improved muon tracking for |η| > 1.3
- Reduce fake rates and keep precision at high rates for triggering

→ New Small Wheels



TGC – Thin Gap Chambers

The TGC is a multiwire chamber with 50μm diameter gold-plated tungsten wires, comprising the anode plane, located between FR4 walls coated with resistive carbon that serves as the cathode. The spacing between the wires is 1.8 mm and the anode-cathode spacing is 1.4 mm. The operational gas is a mixture of 55% CO_2 and 45% n-pentane. The carbon coating is transparent so that signals can be read out from strips or pads outside the gas volume.



Micromegas

- Gas volume divided in two by metallic mesh
- Gain = 10^2, fast signal of 100 ns