Introduction to the LHCb detector

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CERN

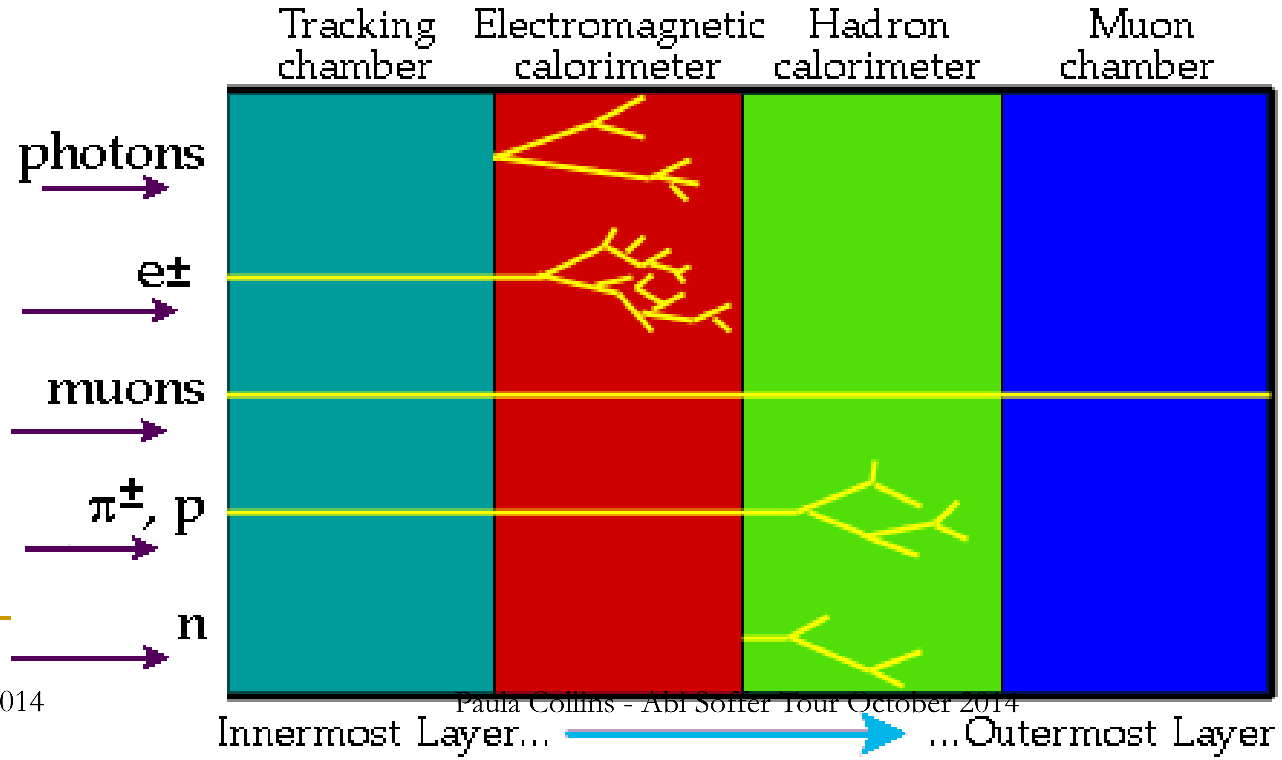
- Brief tour of the LHCb experiment
- Focus on
  - RICH system
  - Silicon Vertex Detector
- LHCb upgrade in preparation

- Talk partly stolen from Vladimir Gligorov, Monica Pepe-Altarelli, Guy Wilkinson,

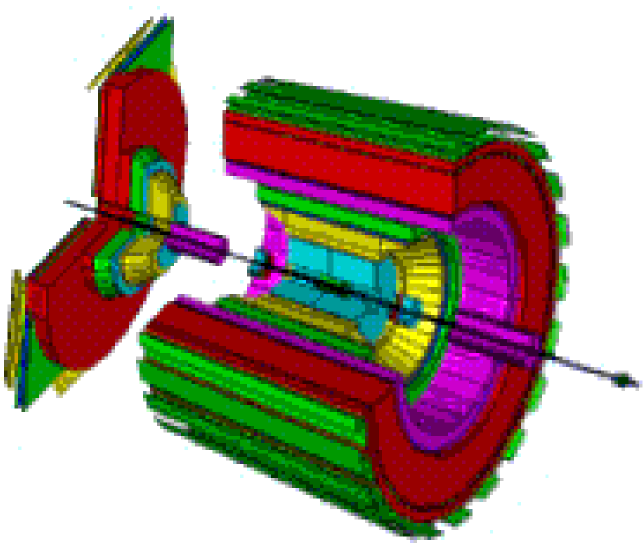

SUISSE
FRANCE
LHCb
CERN Meyrin
ATLAS
CERN
Prévessin
ALICE
CMS
LHC 27 km

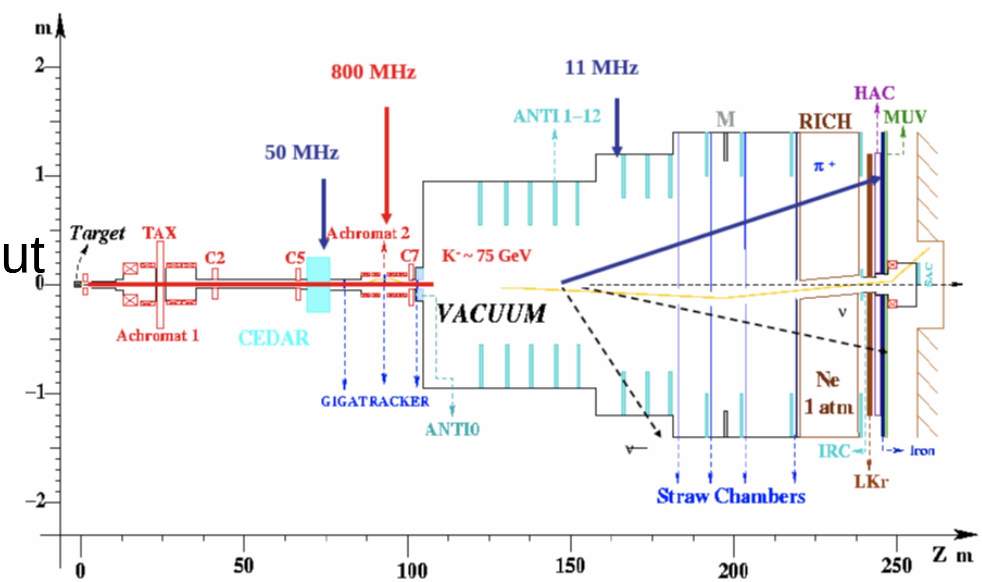
How to measure and identify particles?

- Ideally we would like to measure the position, charge, speed, mass and energy of all particles produced in the collisions.
- The particle detector is made up of several layers which all play a role in particle detection



Traditionally colliding beam experiments have this kind of layout

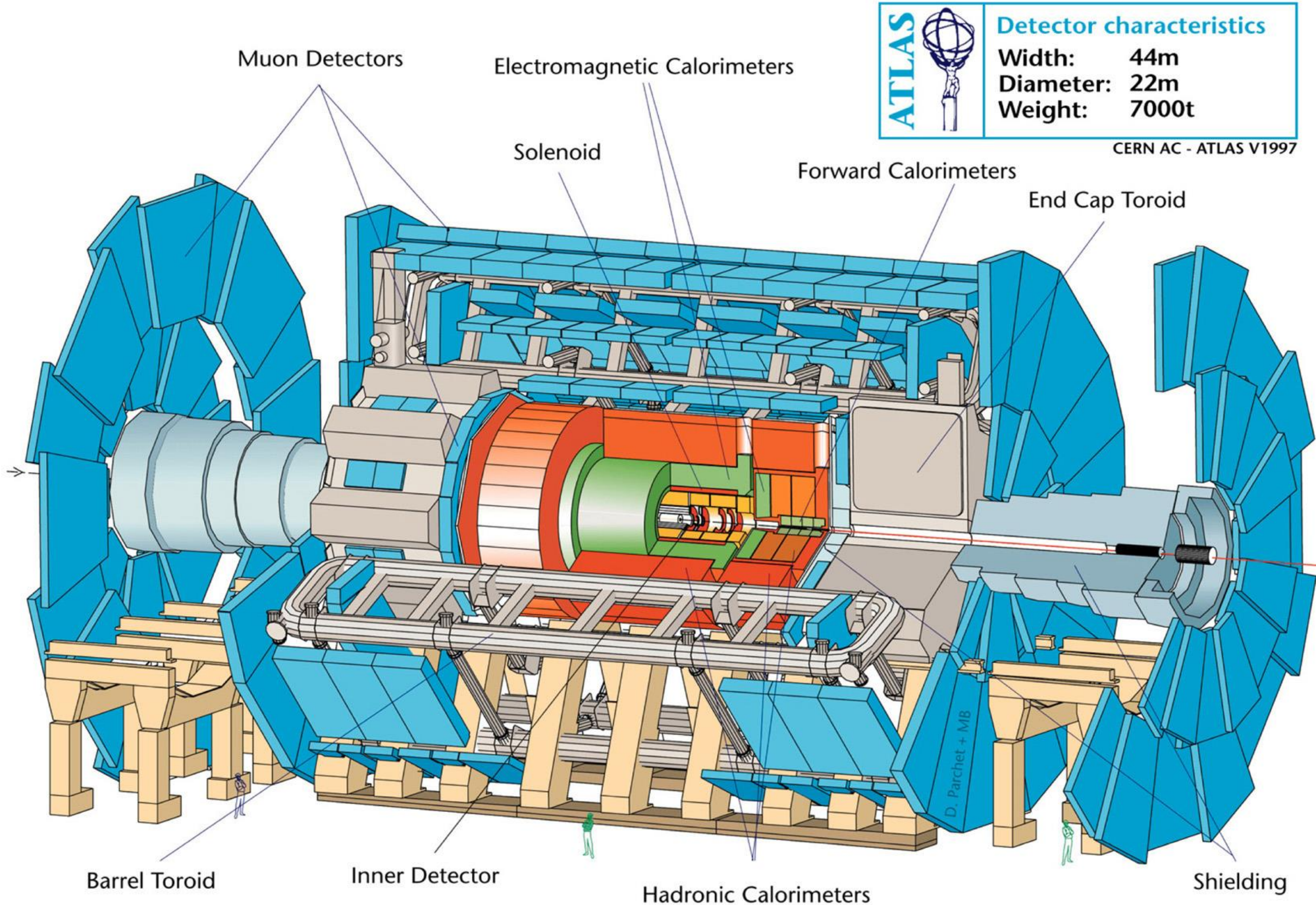


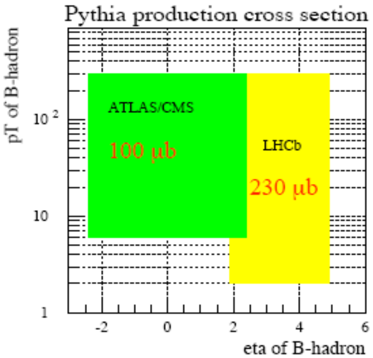


while fixed target experiments have a forward geometry

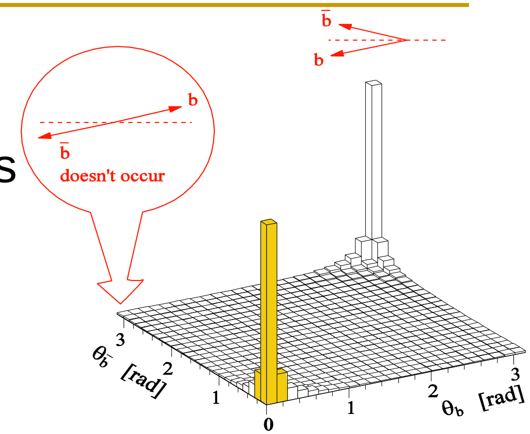
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

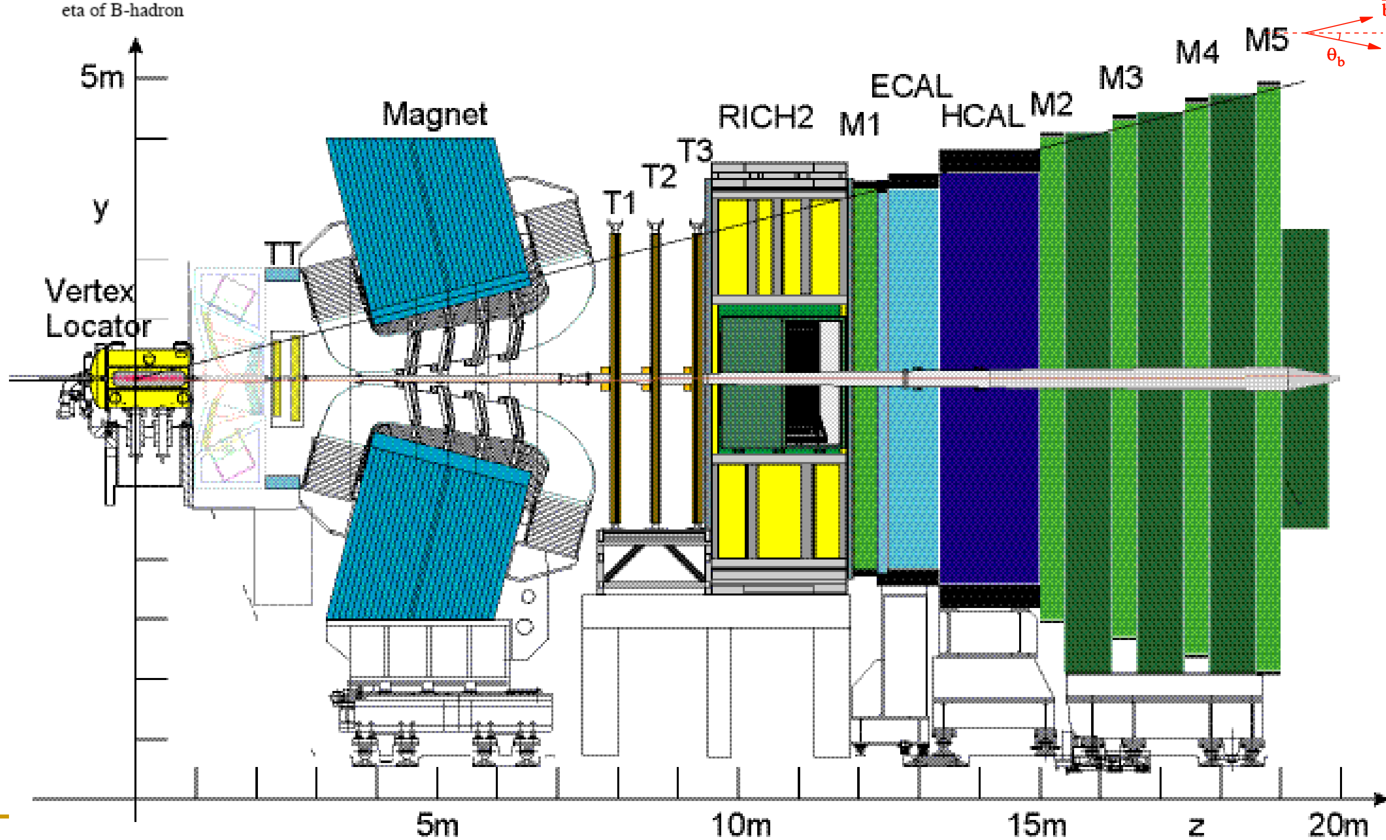
Particle production roughly constant in units of rapidity


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
D. Parchet + MB
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

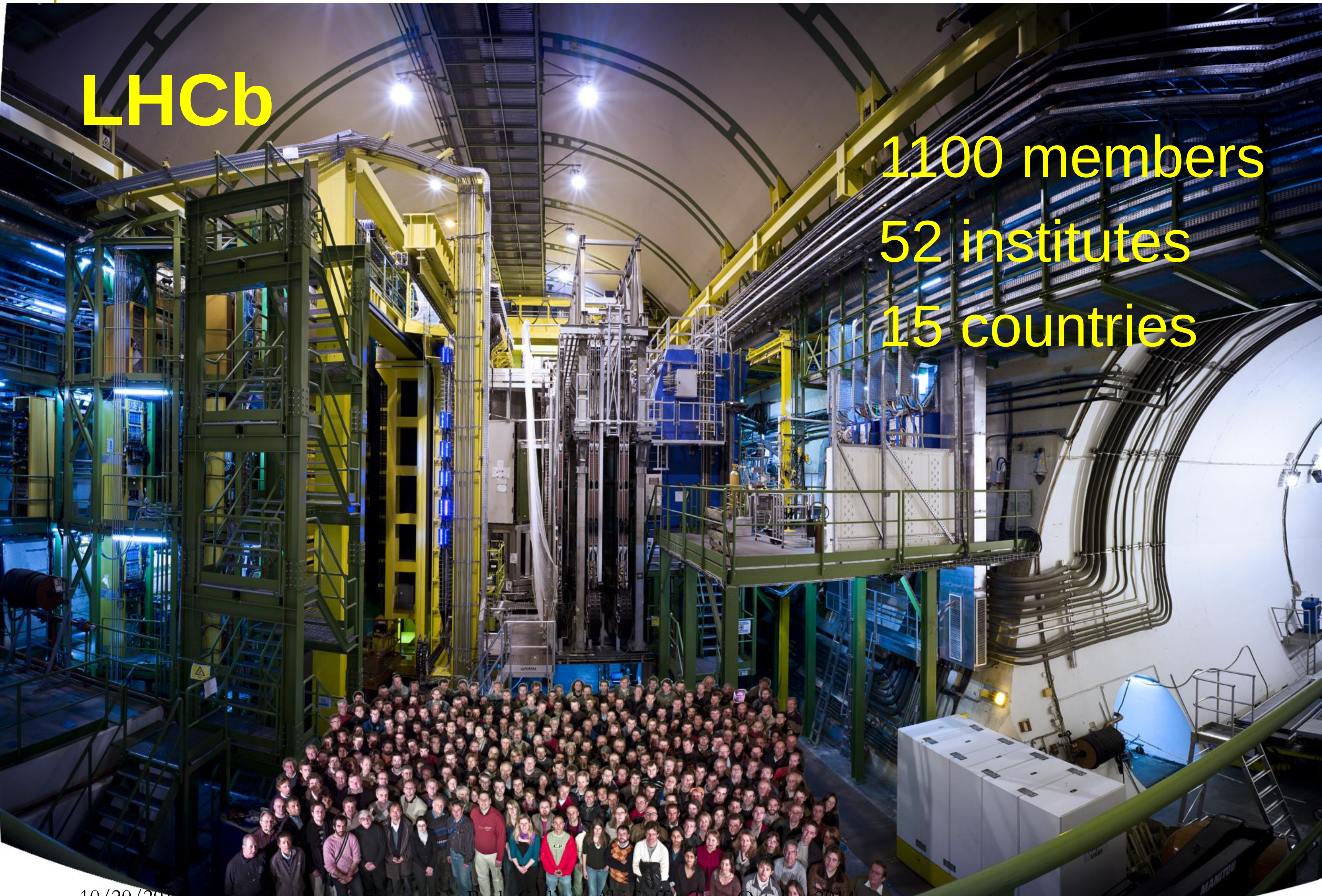


Angular distribution of b and b quarks forward (backward) and correlated





LHCb

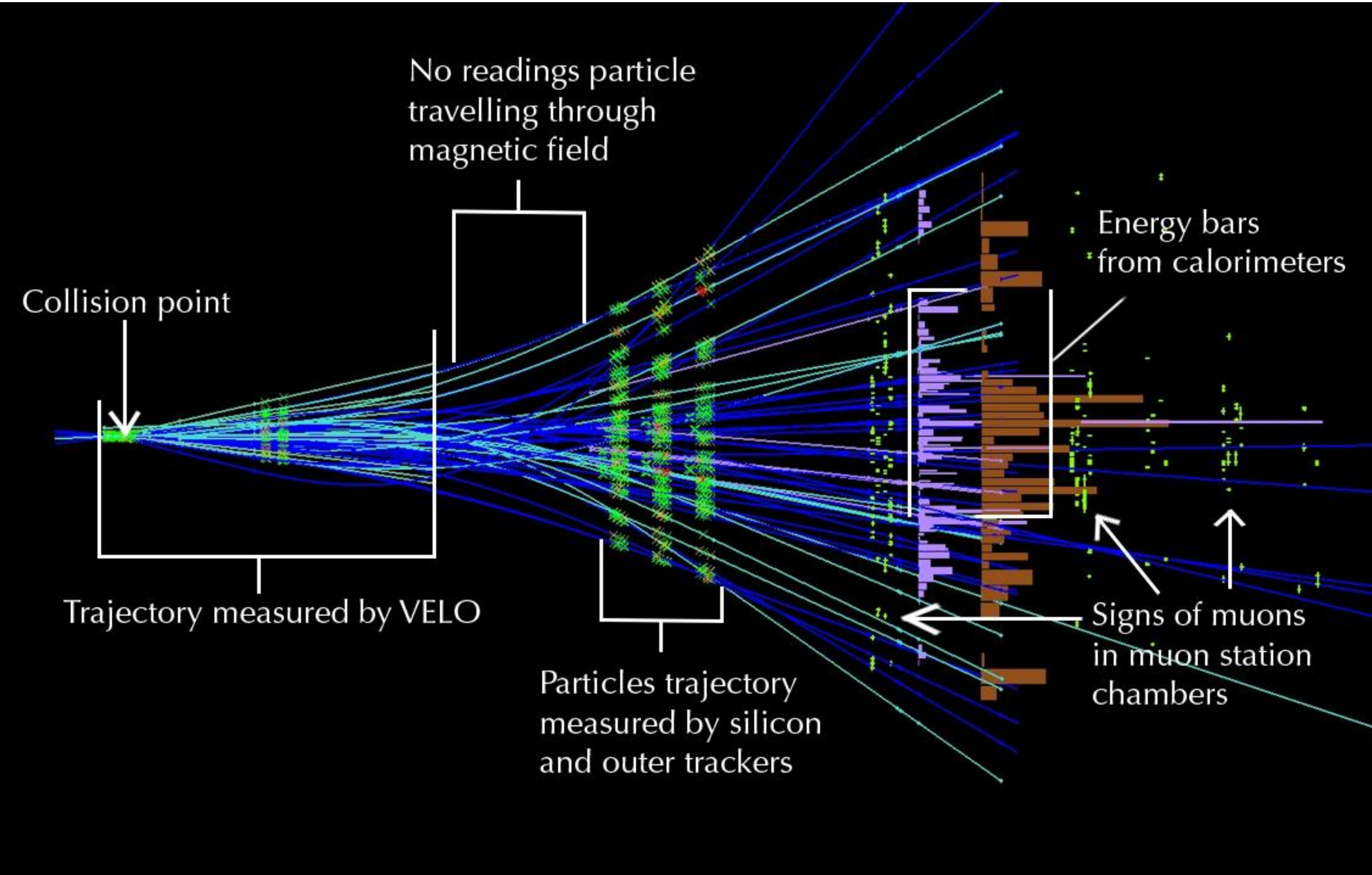


1100 members

52 institutes

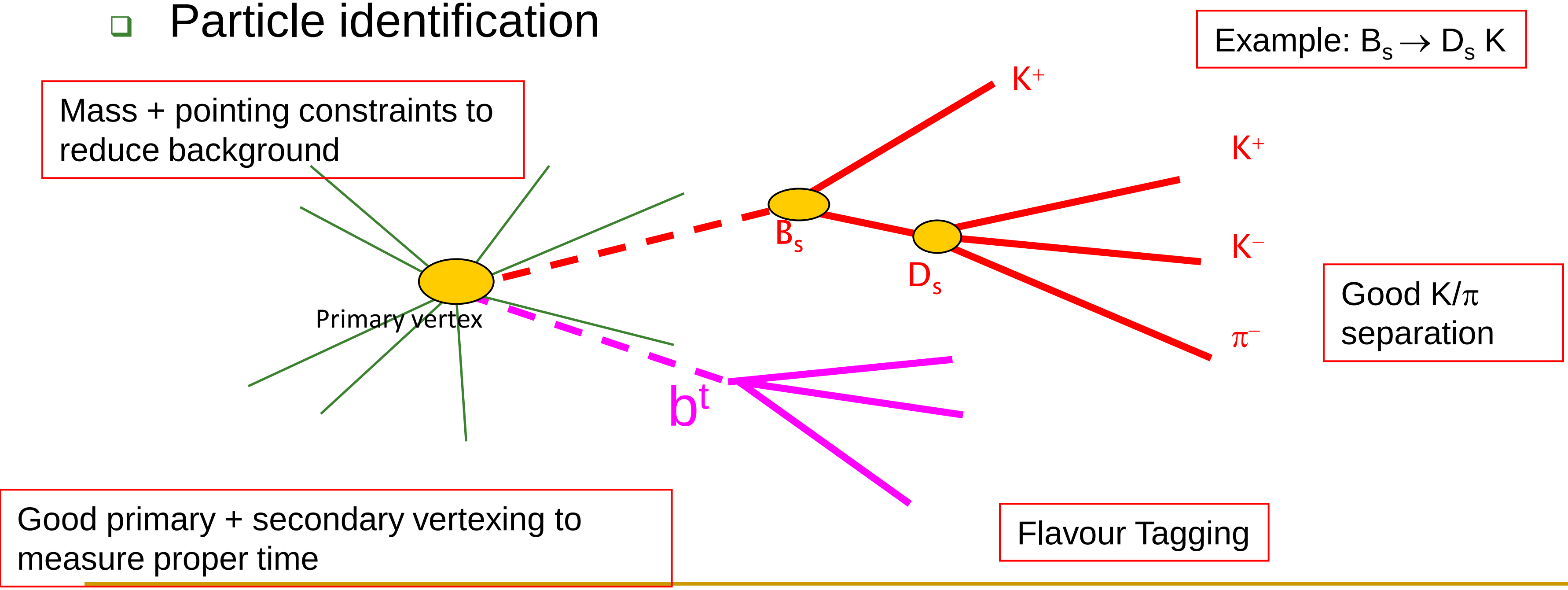
15 countries

How to measure and identify particles?



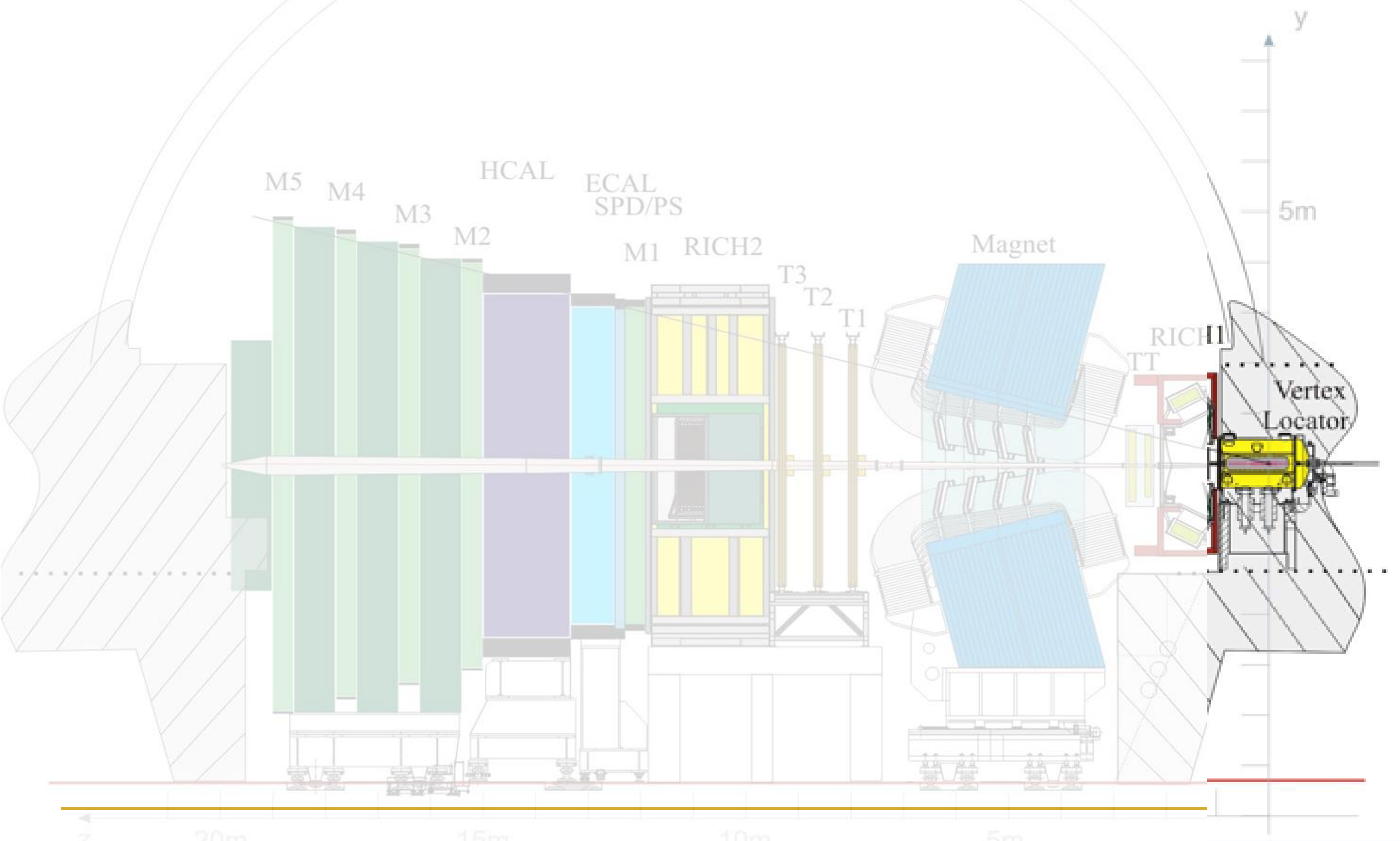
Detector Requirements

- Key features:
  - Highly efficient trigger for both hadronic and leptonic final states to enable high statistics data collection
  - Vertexing for secondary vertex identification
  - Mass resolution to reduce background
  - Particle identification




M5
M4
M3
M2
HCAL
ECAL
SPD/PS
M1
RICH2
T3
T2
T1
Magnet
RICH1
TT
Vertex
Locator
5m
20m
15m
10m
5m

VErtex LOcator



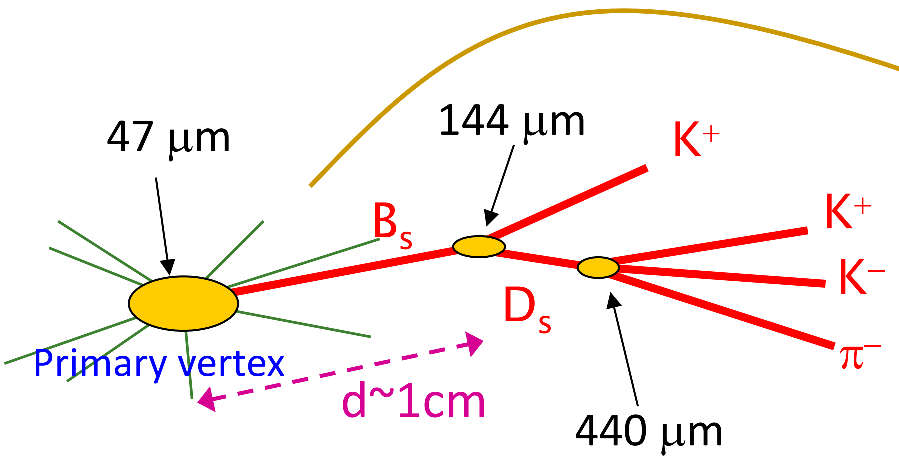
Vertex Locator (Velo)

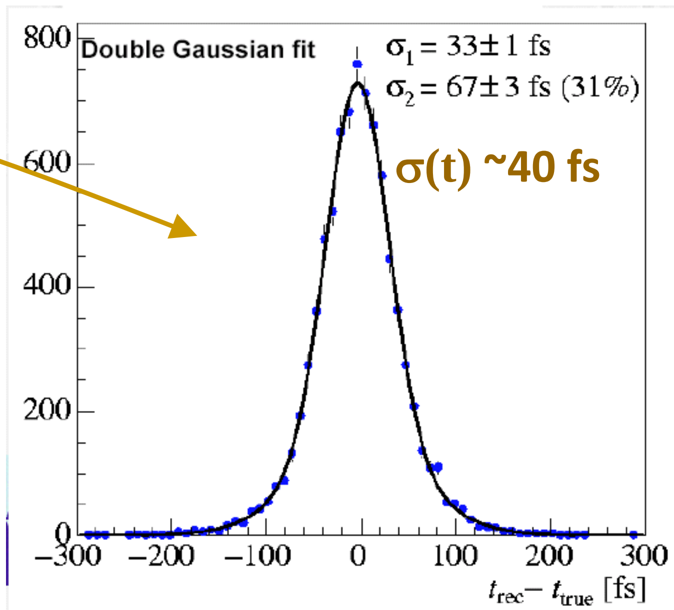
21 stations of silicon strip detectors (r-ϕ)

~ 4 μm hit resolution

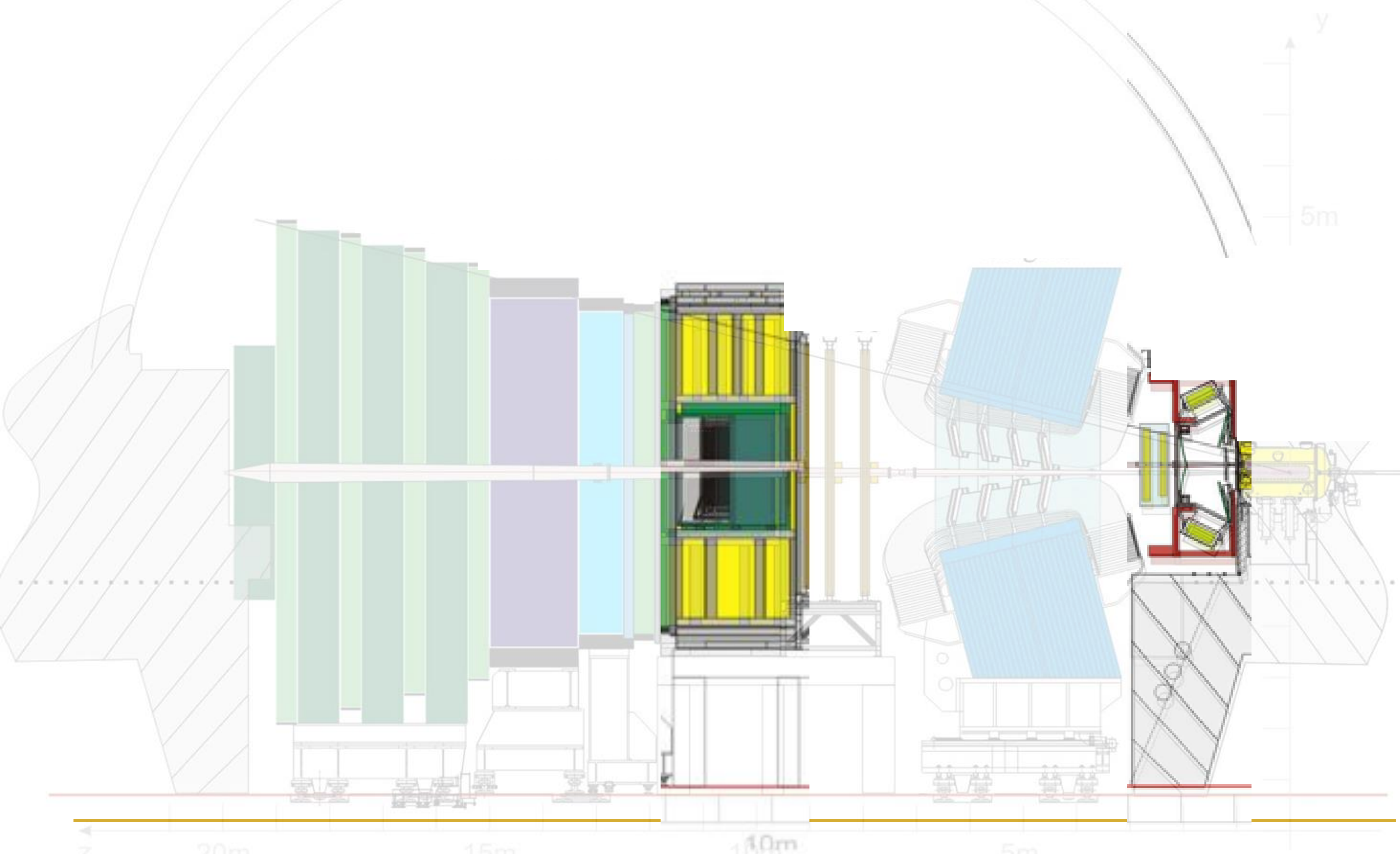
- Trigger on large IP tracks
- Measurement of decay distance (time)

Example: $B_s \rightarrow D_s K$





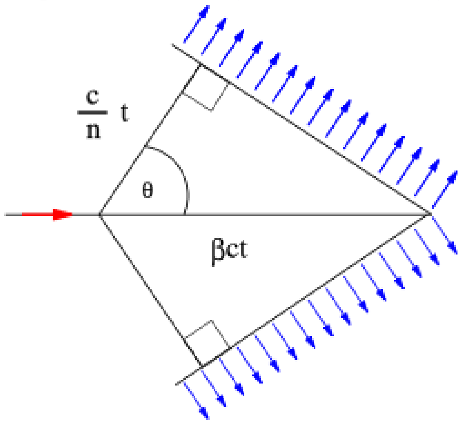
Cherenkov Detectors



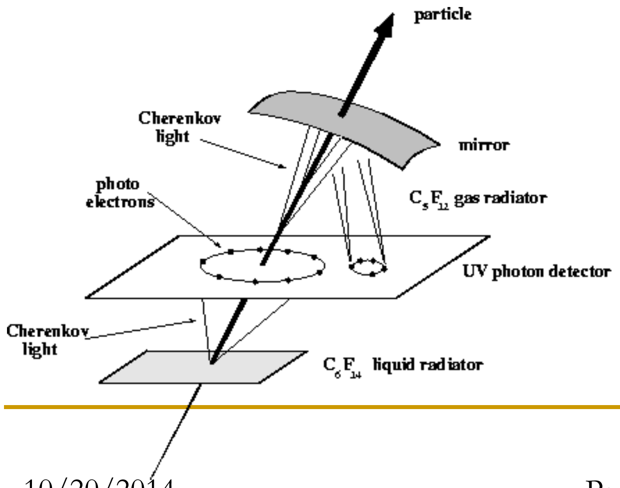
Cherenkov Detectors

Cherenkov light

- Radiation produced when a charged particle travels faster than the speed of light in the medium it is passing through ($\beta c > c/n$, with n=refractive index)

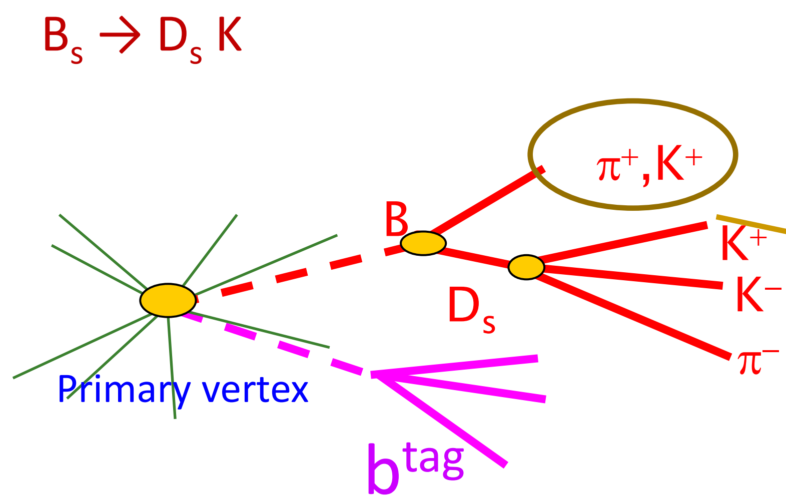


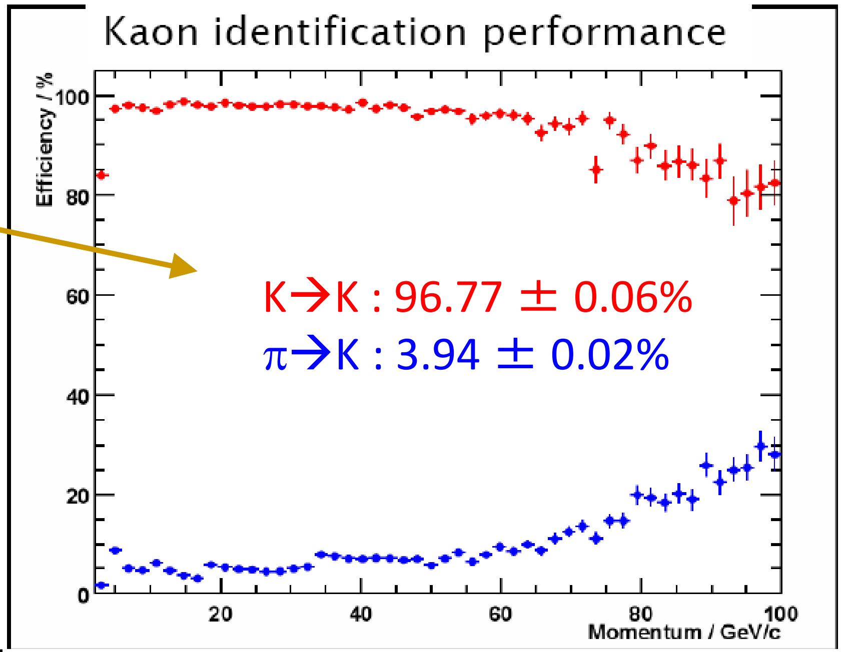
- Light produced in a cone with $\cos\theta_c = 1/\beta n$ can be detected as a ring image



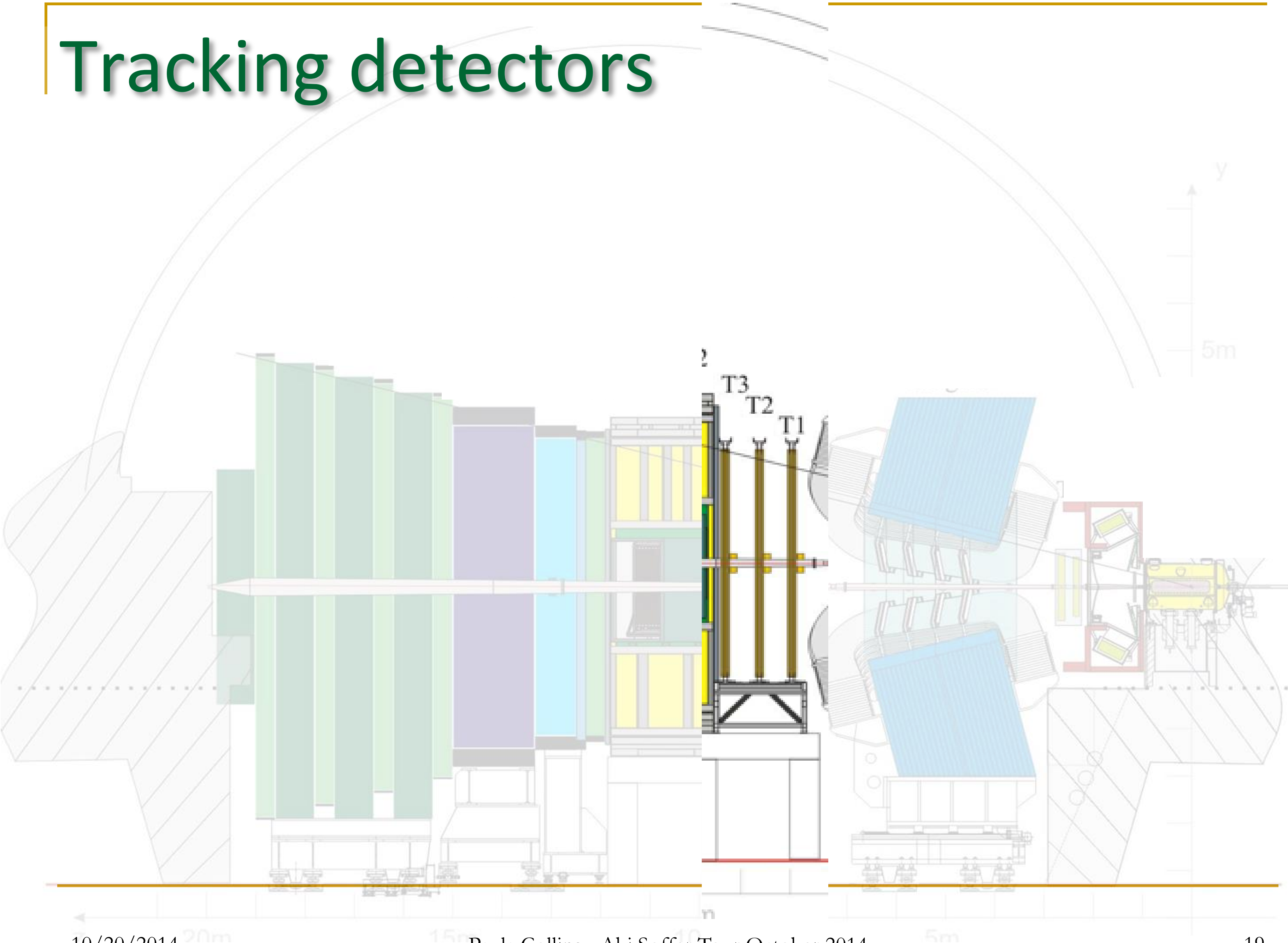
- By measuring θ_c ($\propto$ radius of ring) the velocity β of the particle is found Then with knowledge of its momentum the mass of the particle can be found

Cherenkov Detectors





Tracking detectors

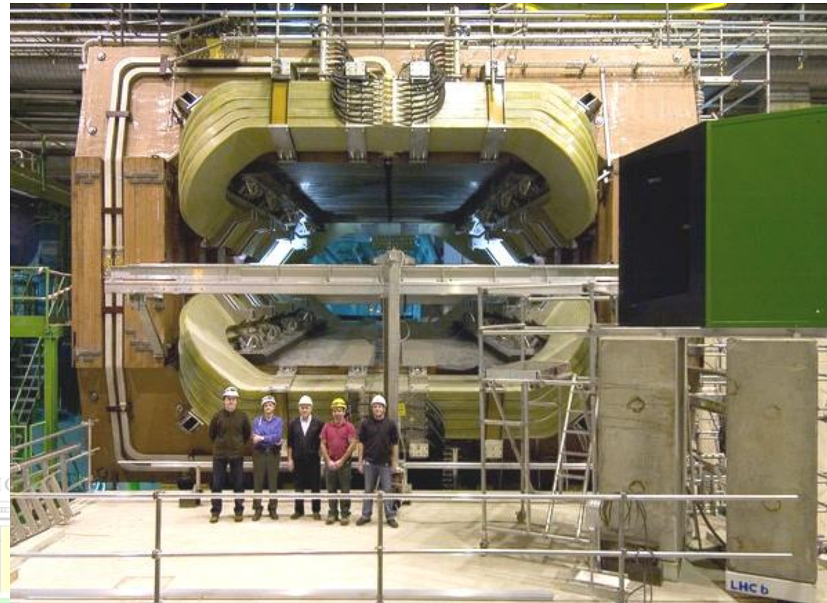


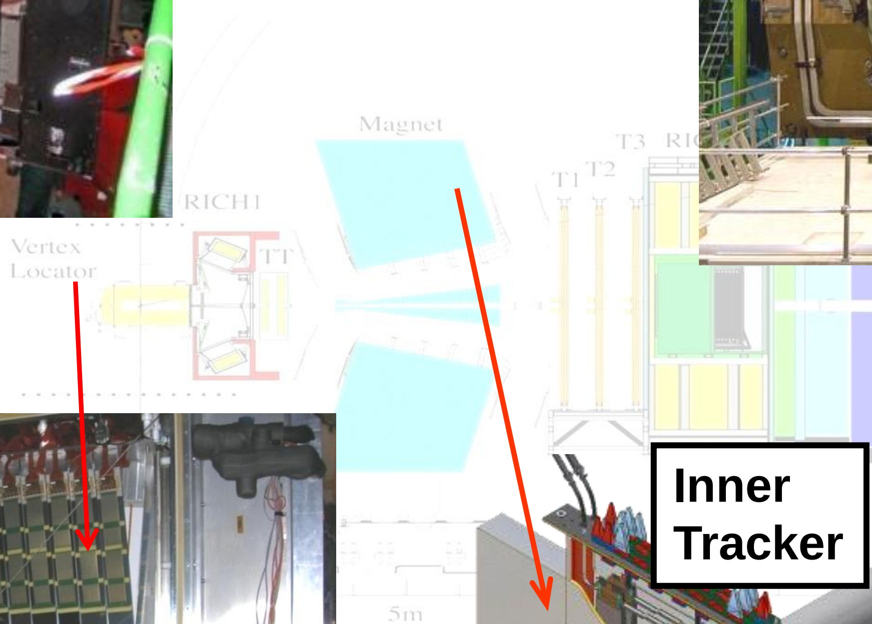
Momentum measurement

$\sigma_p/p \sim 0.5\%$

Outer Tracker

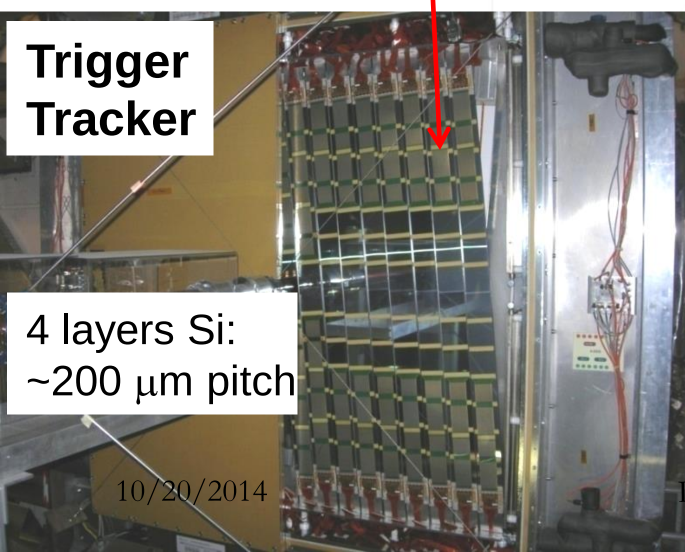
24 layer Straws
$\sigma_{hit} \sim 200\mu m$



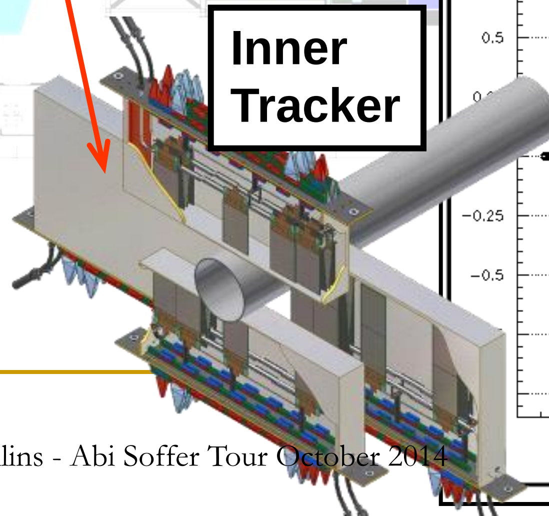


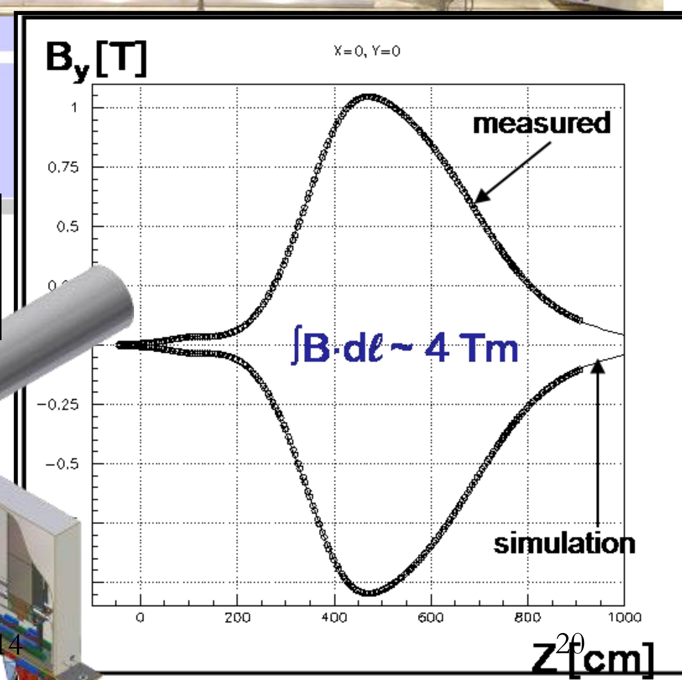
Trigger Tracker

4 layers Si:
~200 μm pitch



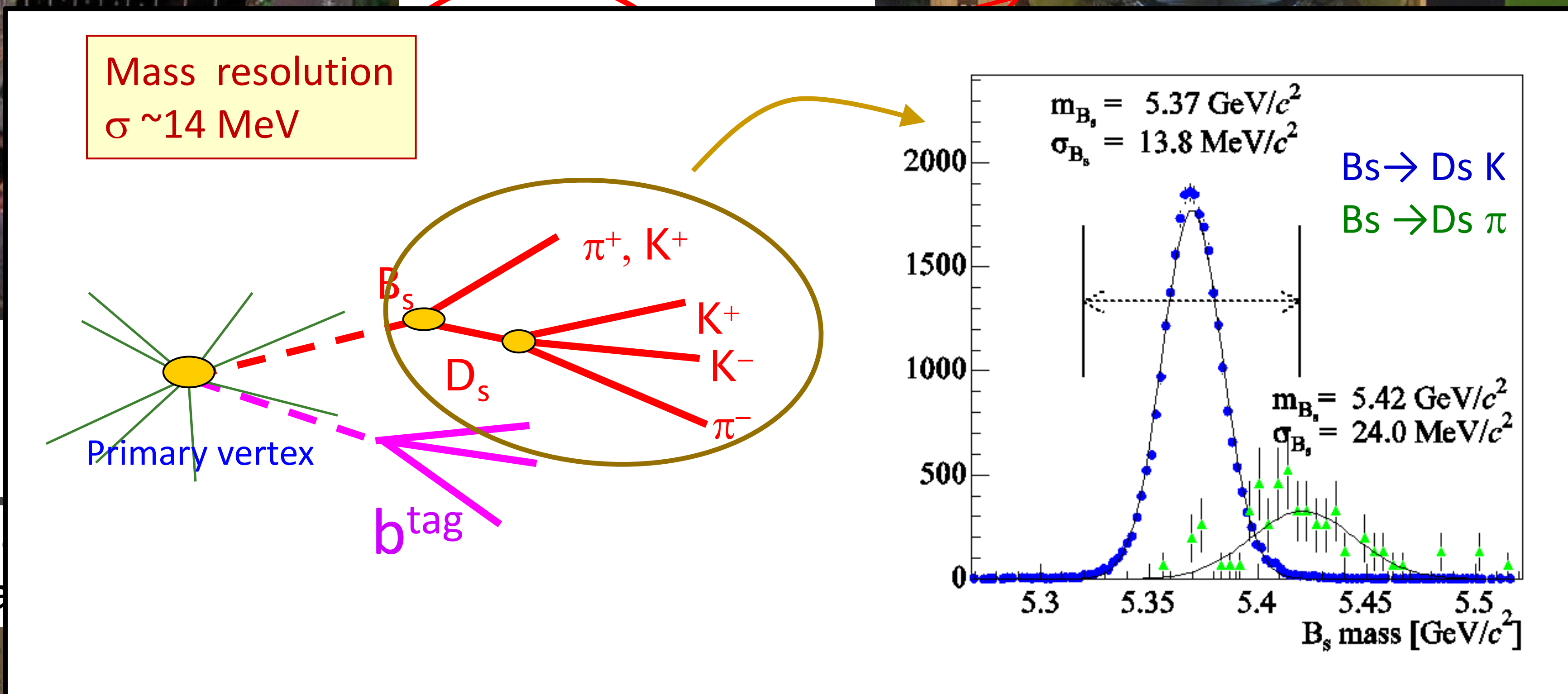
Inner Tracker

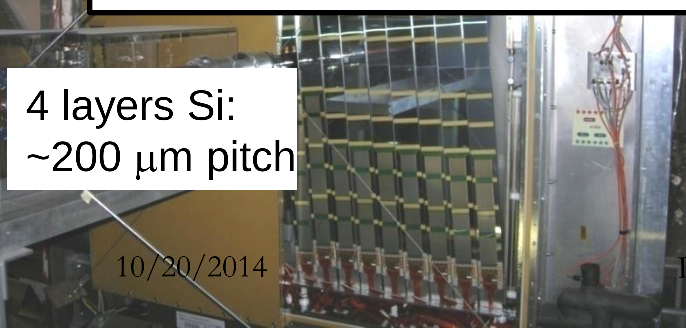


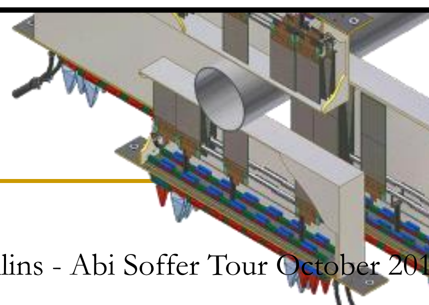


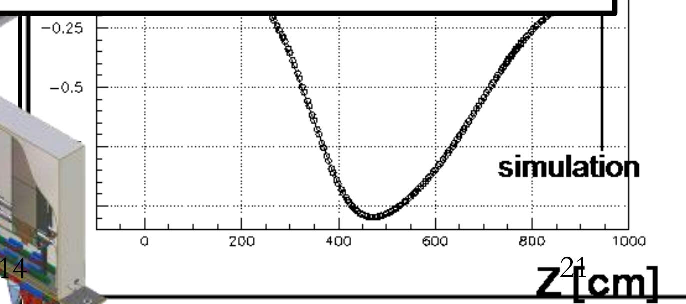
Momentum measurement

σ_p/p~0.5%

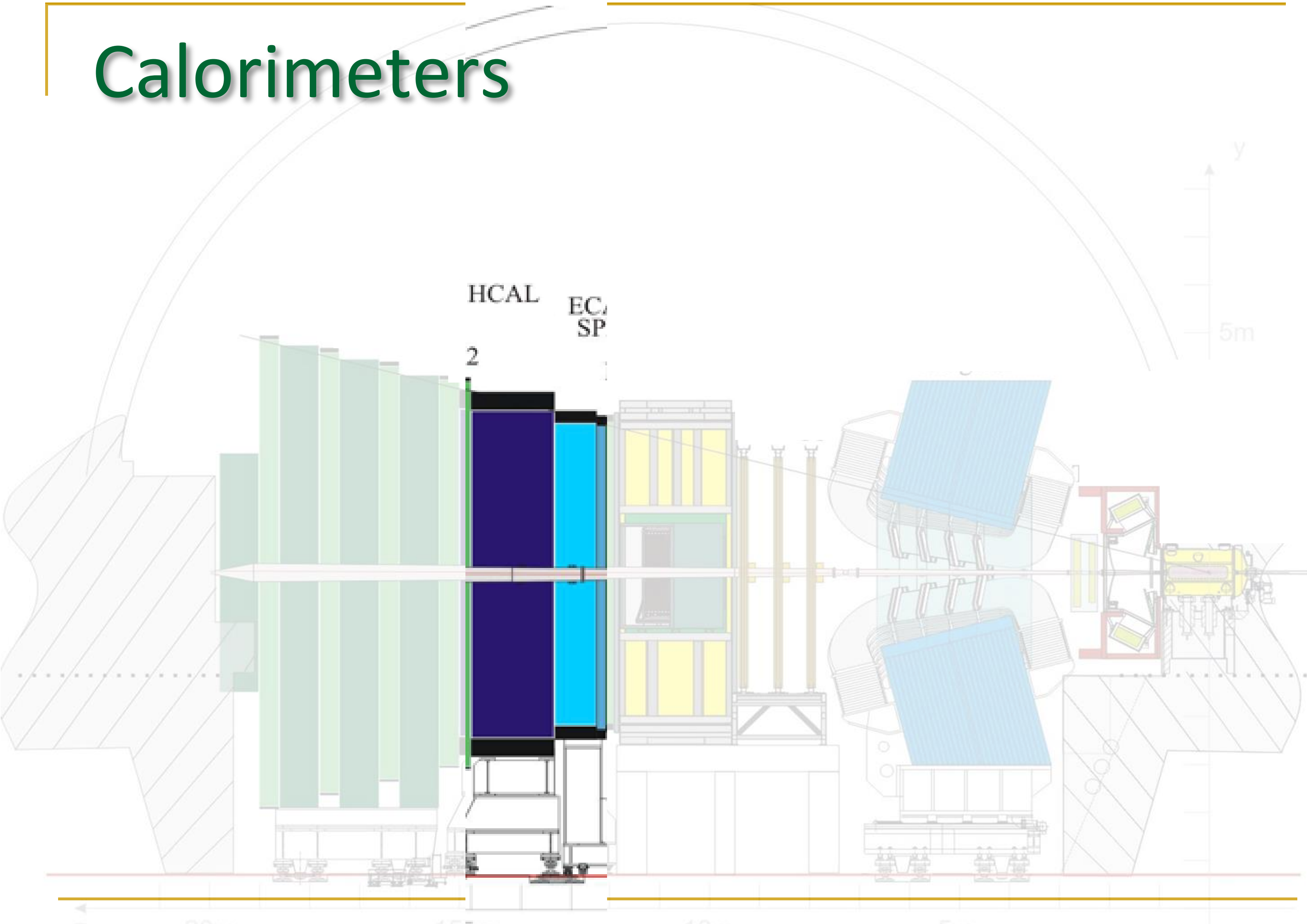




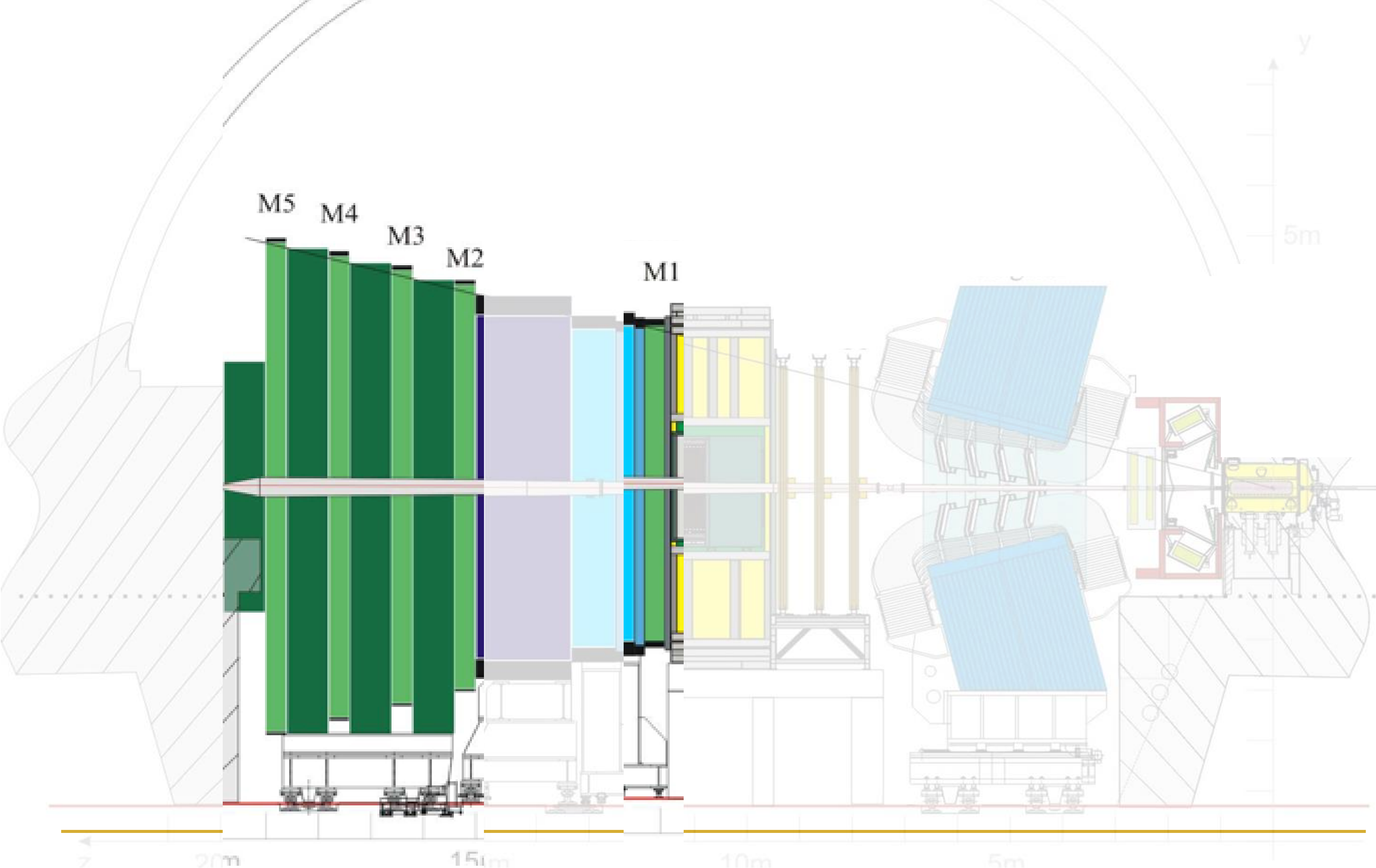




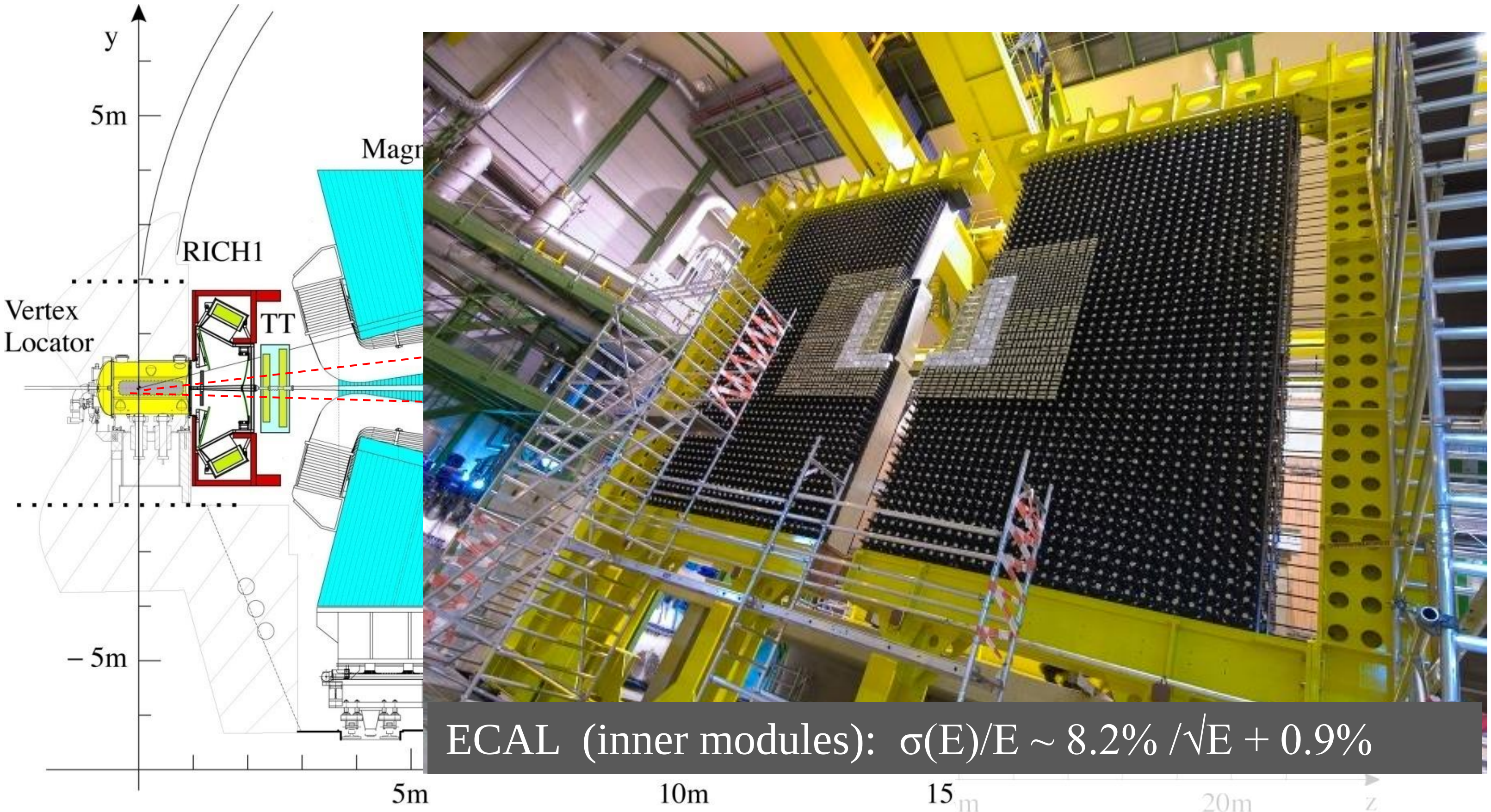
Calorimeters



Muon Detectors

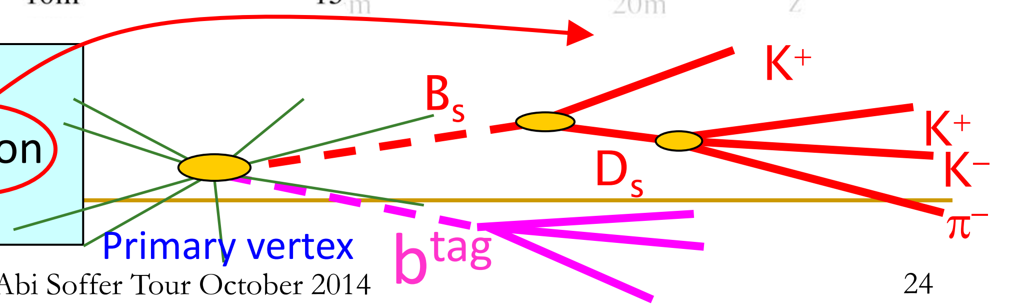


Particle identification and L0 trigger

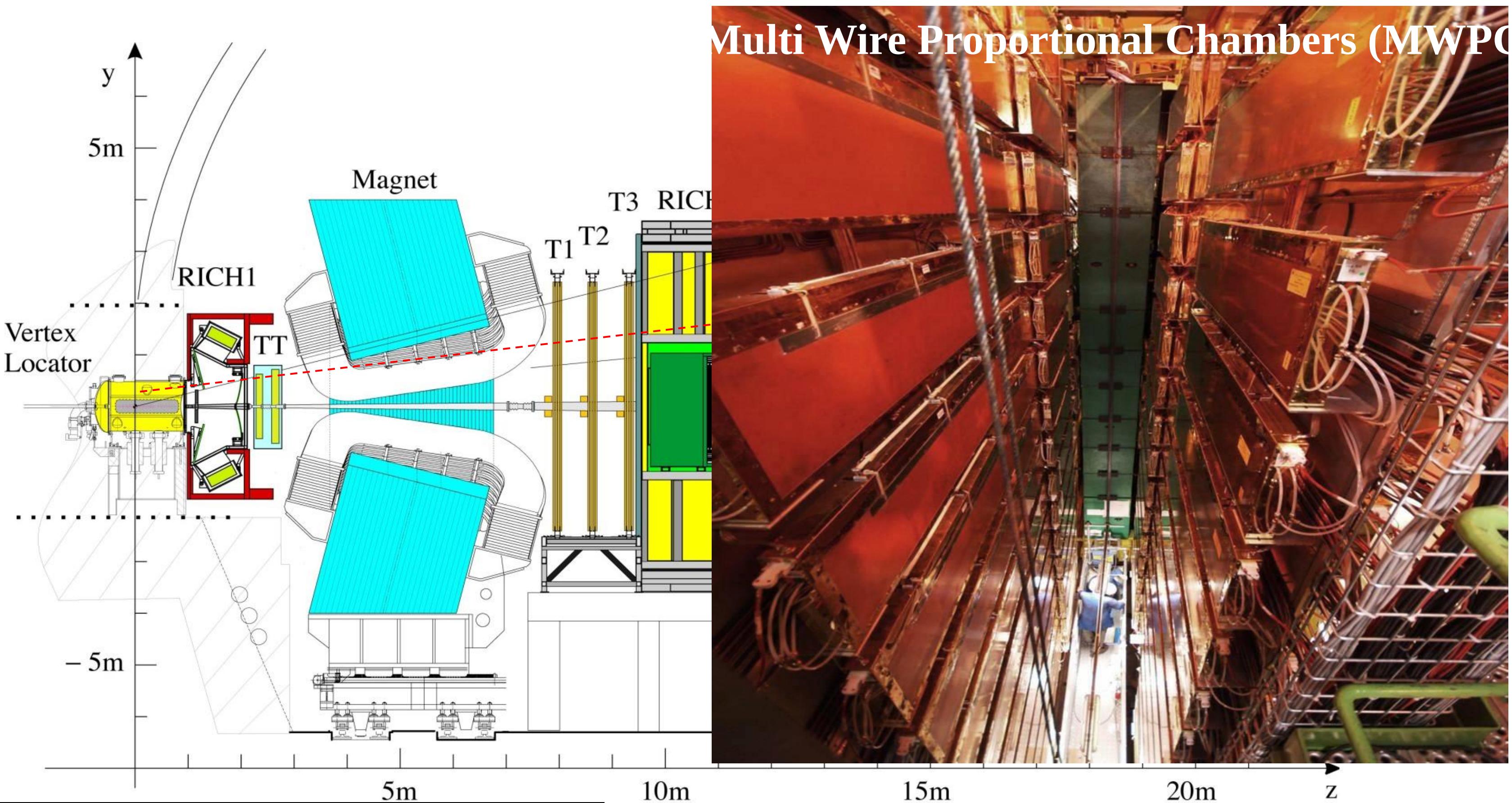


Calorimeter system :

- Level 0 trigger: high E_T electron and hadron
- Identify electrons, hadrons, π^0 ,γ

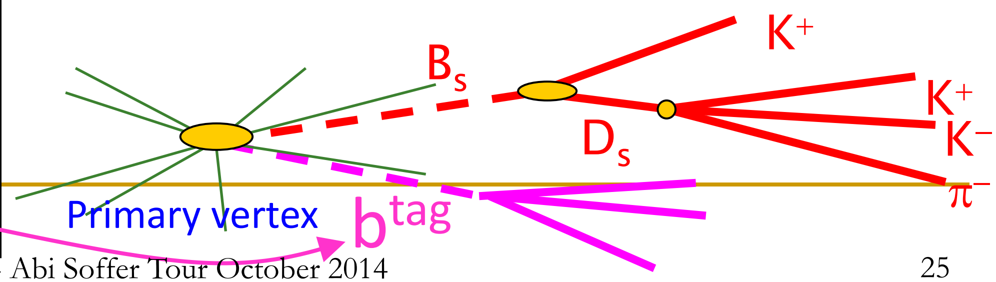


Particle identification and L0 trigger



Muon system:

- Level 0 trigger: High P_t muons
- Identify muon
  (also important for flavour tagging)



LHCb Trigger

- Trigger is crucial as σ_{bb} is less than 1% of total inelastic cross section and B decays of interest typically have BR < 10^{-5}
- b hadrons are long-lived →
  - well separated primary and secondary vertices
- have a ~large mass→
  - decay products with large p_T

LHCb trigger

The tracking and particle ID systems of the detector can only be read out at 1 MHz : must therefore start with Calorimeter/Muon based hardware trigger

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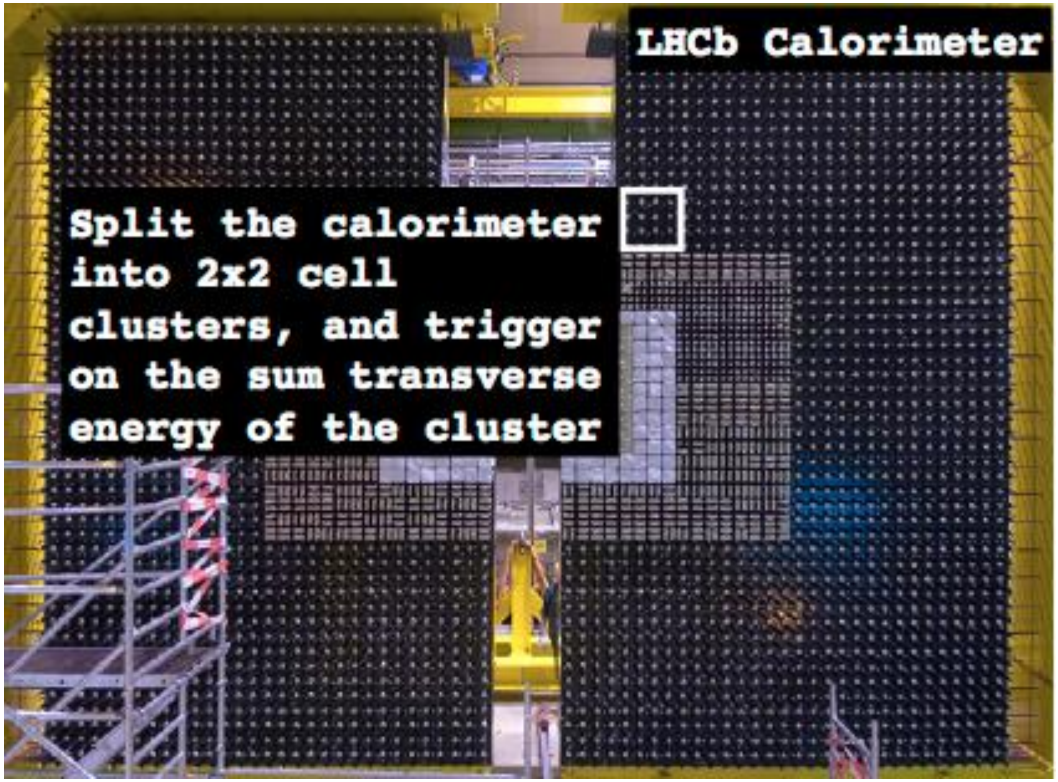
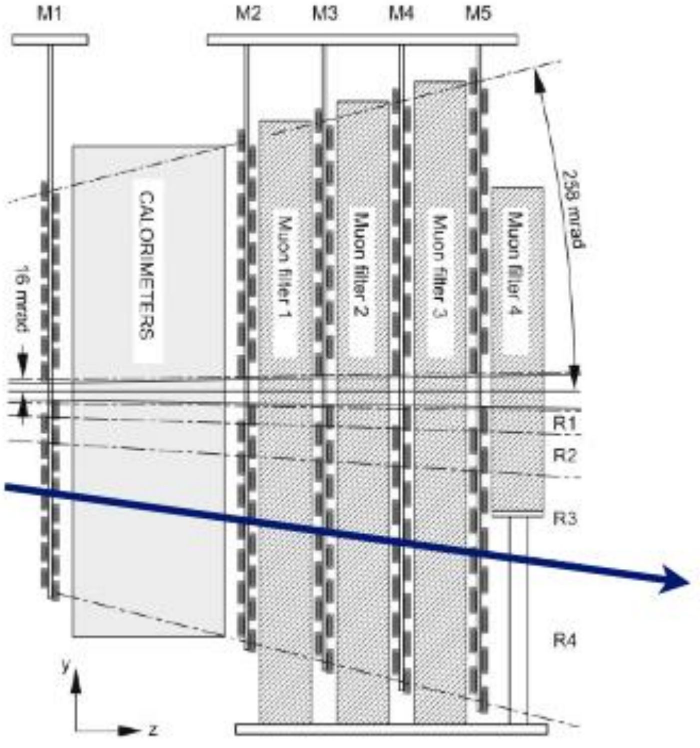


LHCb trigger

The tracking and particle ID systems of the detector can only be read out at 1 MHz : must therefore start with Calorimeter/Muon based hardware trigger

For muons search for a track in all 5 muon system stations
(also momentum estimate from first two stations)

Trigger limitation comes from ability of front-end boards to collect and process information in time



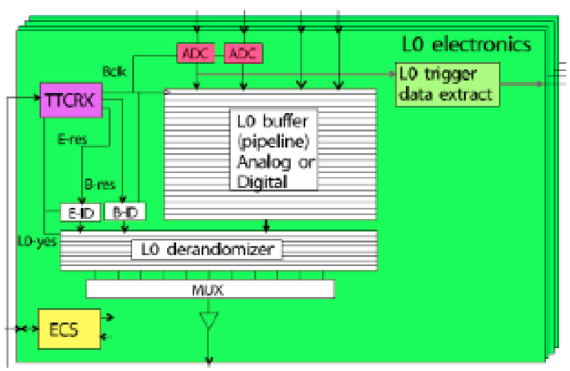
Trigger Latency

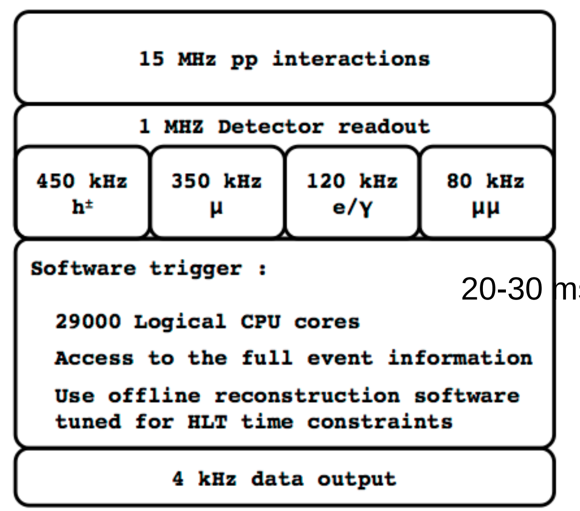
Maximum latency of L0 trigger is 4 μs

Half of this is time for particles to travel to the detector, and their signals to travel throught the cables in the readout system – the other half the time needed to make a decision

Need to be able to process 80 events in parallel

- Muon(s) with high transverse momentum
- Hadrons with high transverse energy etc..





ATLAS/CMS triggers vs LHCb

	Rate of bunch crossings	Mean interactions per bunch crossing	Mean event size
ATLAS/CMS	20 MHz	> 30	1500 kB
LHCb	20 MHz	2	100 kB

The data rates at ATLAS and CMS are 15 times greater than at LHCb. This drives a design in which much more work is done by hardware triggers which make their decisions based on information from only a part of the detector.

Focus on RICH

Cherenkov Radiation in a Nutshell

Fundamental Cherenkov relation:

$$\cos\theta_C = \frac{1}{n\beta}$$

Both a *threshold* and thereafter, an *angular dependence* up to *saturation* ($\cos\theta = 1$)

Frank-Tamm relation:

$$\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 \, L \, \sin^2\theta_C$$

So number of photons will also increase with velocity (up to saturation)

History of Cherenkov Radiation

- Prediction of Cherenkov radiation: Heaviside 1888
- Discovery (by accident) : Pavel Cherenkov 1936

Cherenkov: 1905-1990

Radiation seen when uranyl salts exposed to radium source.

Sergey Vavilov was Cherenkov's supervisor, and hence Russians refer to Vavilov-Cherenkov radiation

- Explanation: Tamm and Frank 1937
- Experimental exploitation in HEP pioneered by Cherenkov himself

(Cherenkov, Tamm, Frank: Nobel Prize 1958)

Fathers of the RICH

Cherenkov :
1936 – discovery

1905-1990

Arthur Roberts: 1960 - first to propose exploiting □$_c$

1912-1994

Tom Ypsilantis: 1977- driving force behind practical RICH

1928-2000

What is a RICH ?

$$\cos\theta_C = \frac{1}{n\beta}$$

Measurement of cosθ from RICH, together with p, from tracking system, allow mass, and hence PID to be determined.

This is an excellent way of separating cosθ from kaons and protons

The simplest way to exploit Cherenkov radiation is to choose n such that heavy particles do not emit light. This works OK if p range narrow.

→Cherenkov counter (not a RICH!)

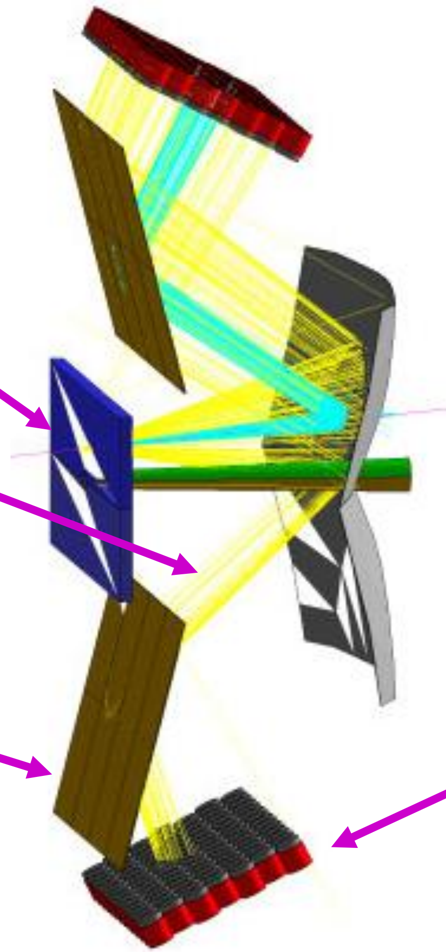
But if we want to do better, or if momentum is far from monochromatic, then we need to measure $\cos\theta_C$. We have to image the ring. This is a RICH!

LHCb RICH 1: a two-in-one detector

Spherical Mirror, tilted at 0.3 rad to keep photodetectors outside acceptance

Aerogel

Gas volume



Flat Mirror

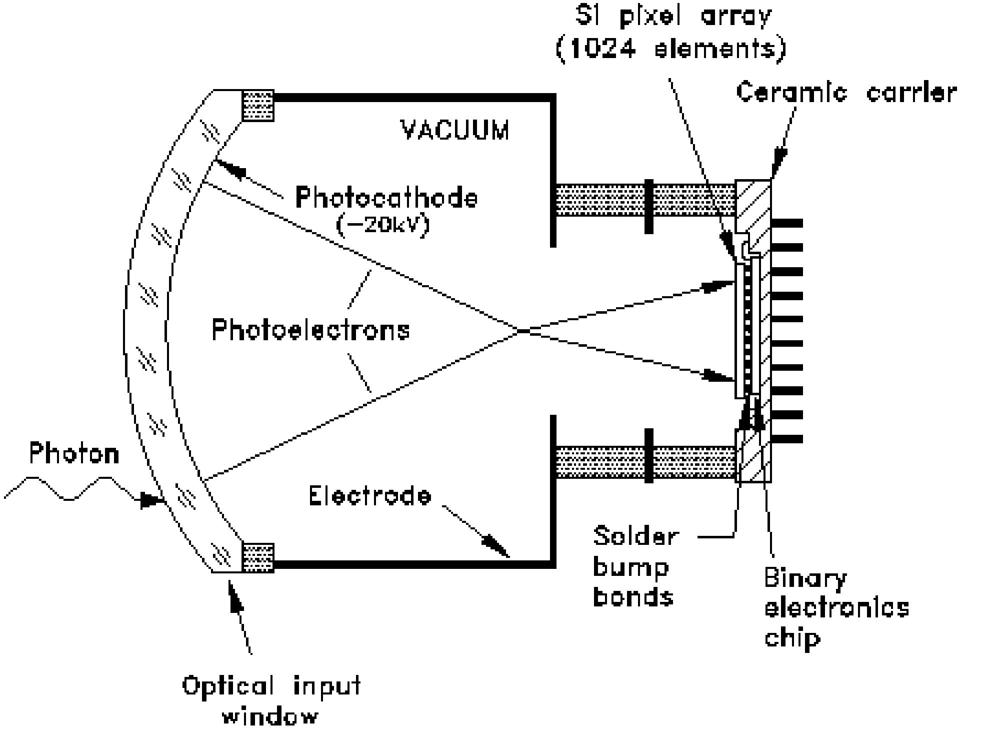
Photodetectors, enclosed in magnetic shielding box (not shown) to protect vs fringe field of dipole magnet

Hybrid Photo-Diodes (HPDs)

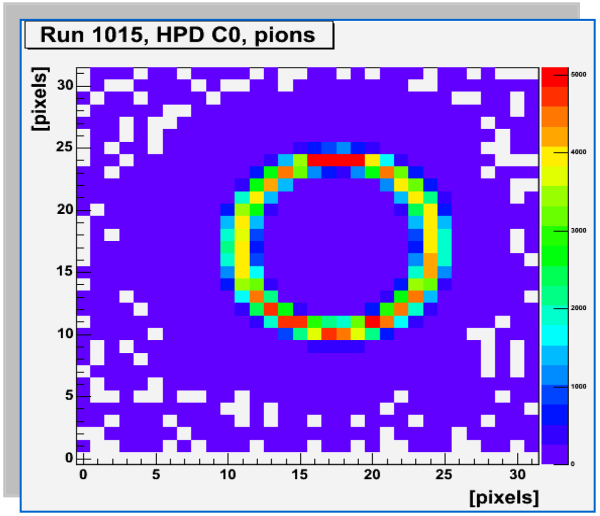
What kind of photodetector do we need for high performance PID at the LHCb? Requirements:

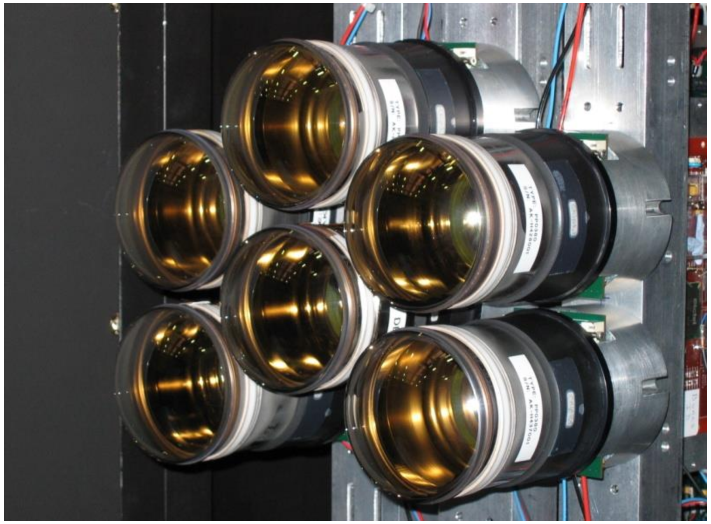
- Good single photon efficiency
- Sensitivity in visible
- Capacity to cover large area (several m^2)
- Good spatial resolution (order mm^2)
- High rate capabilities

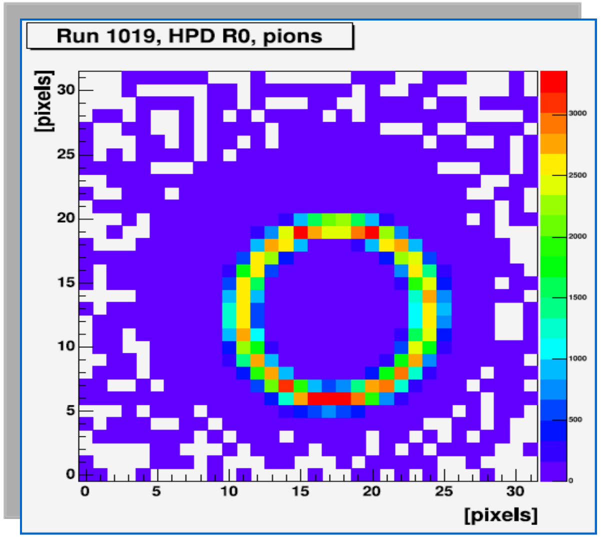
Solution – the HPD:



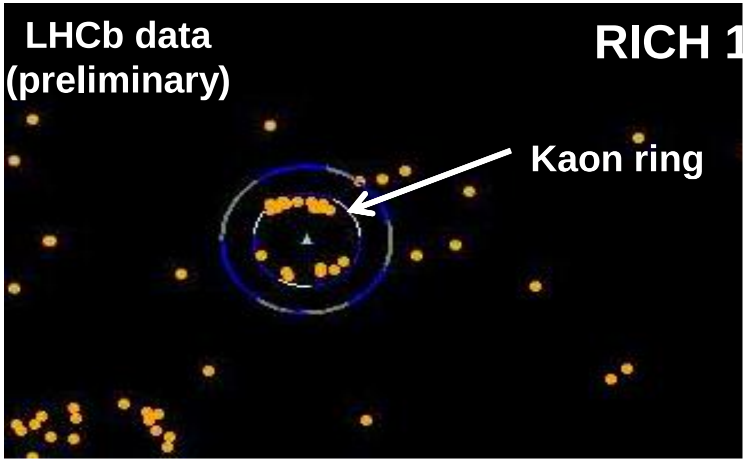
HPDs and Testbeam Results

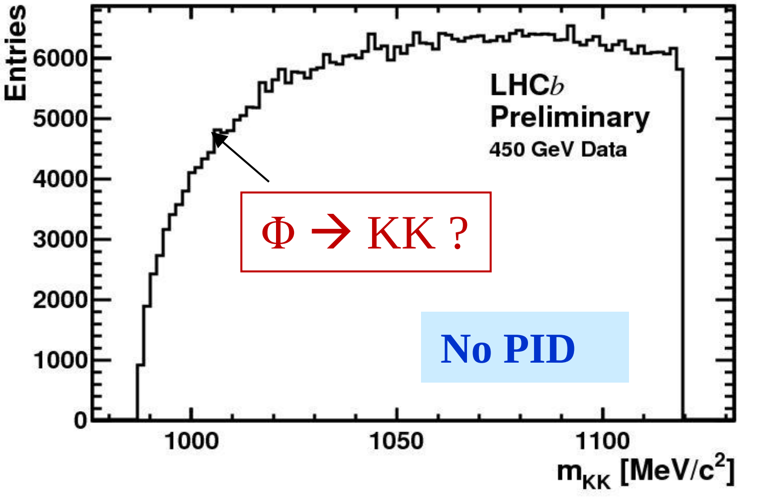


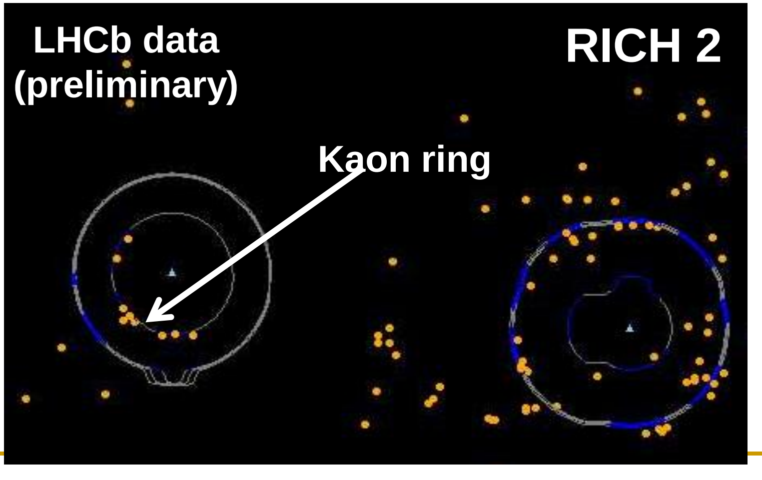


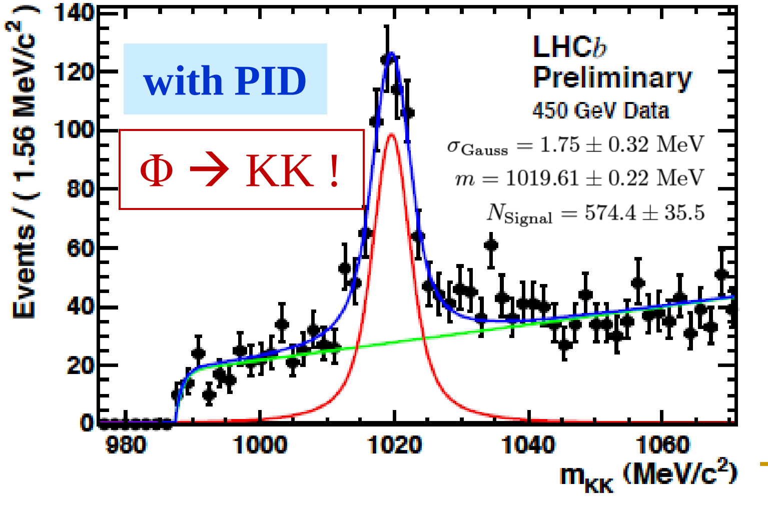


LHCb RICH already performed well with very first (2009) collision data

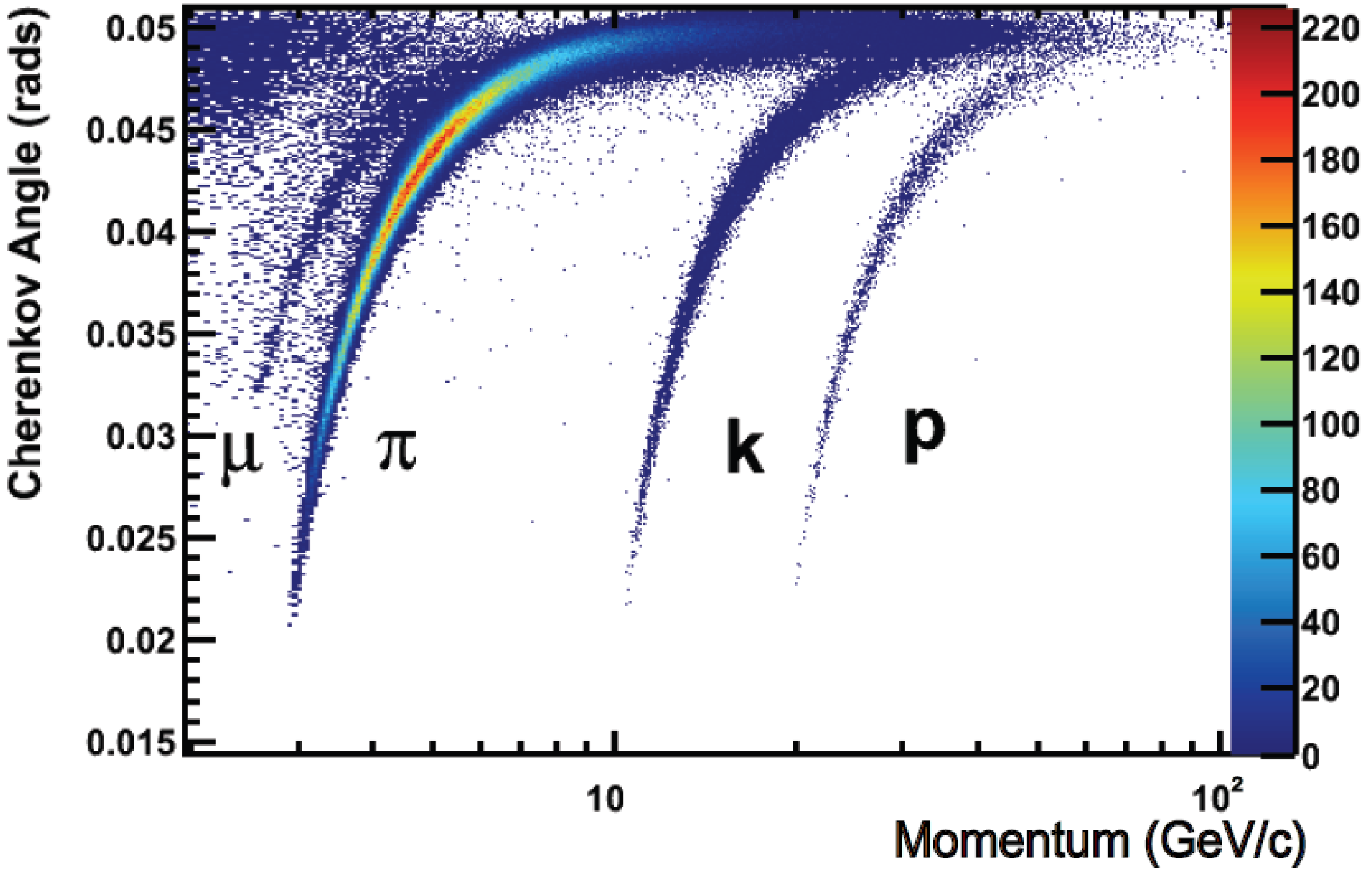




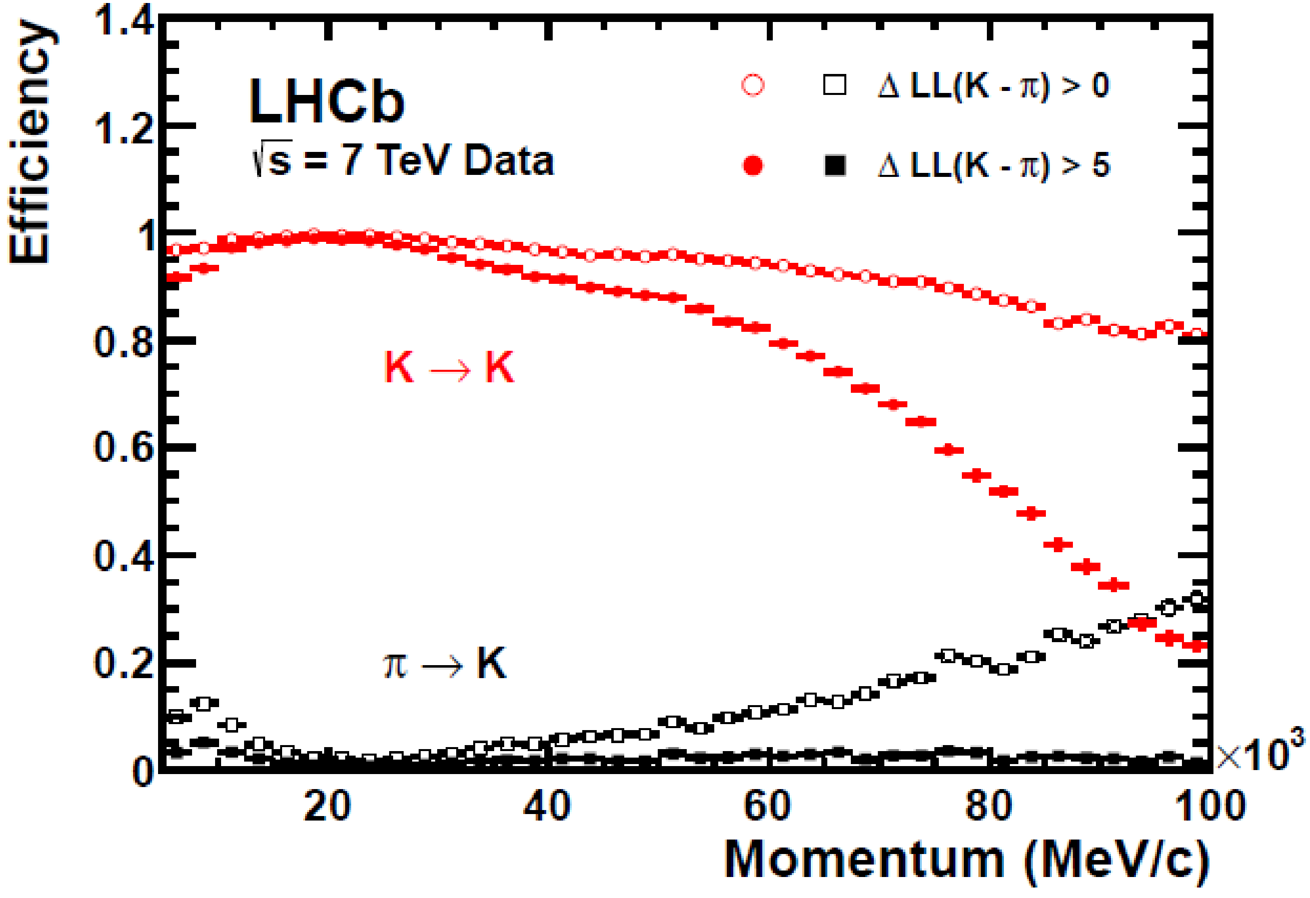




Reconstructed Cherenkov angle vs momentum



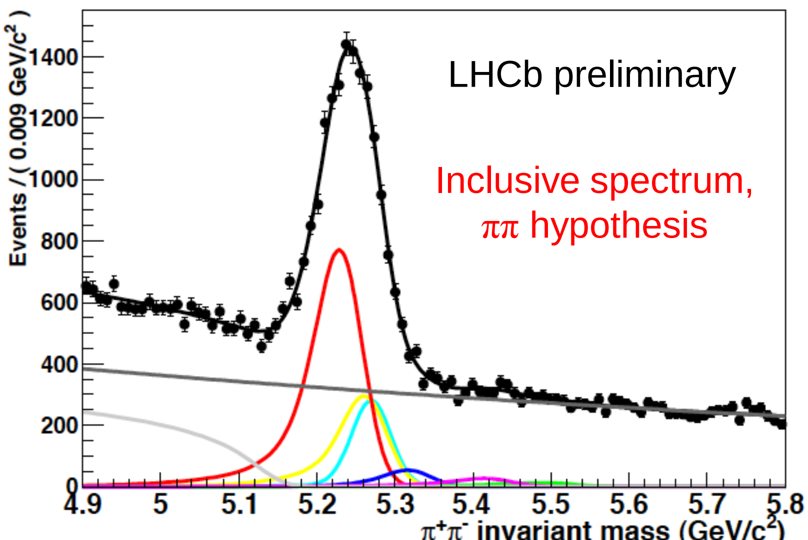
A performance plot



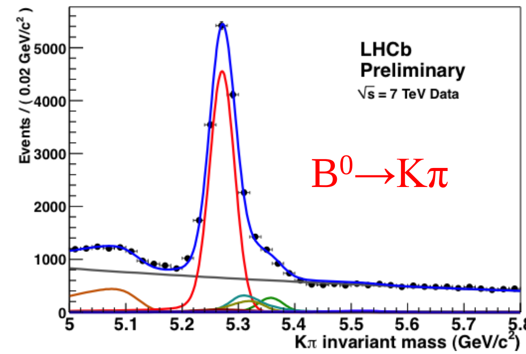
LHCb RICH: performance on ‘B→hh’

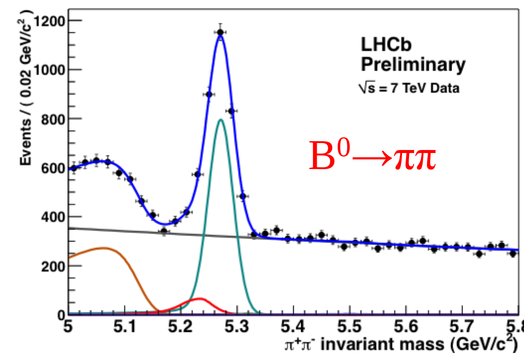
Two-body charmless B decays are central goal of LHCb physics. Significant contribution of Penguin diagrams provides entry point for New Physics

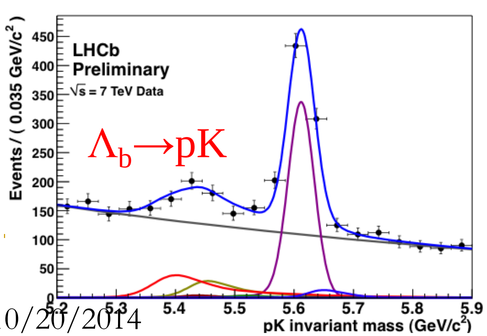
RICH needed to dig out contributing modes !

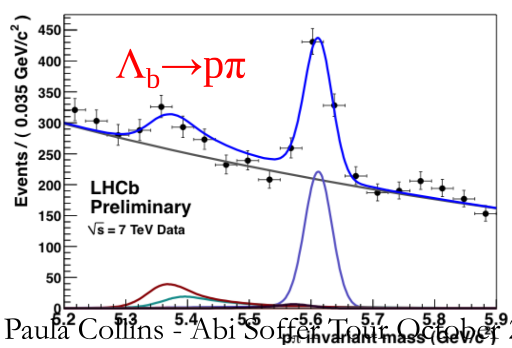


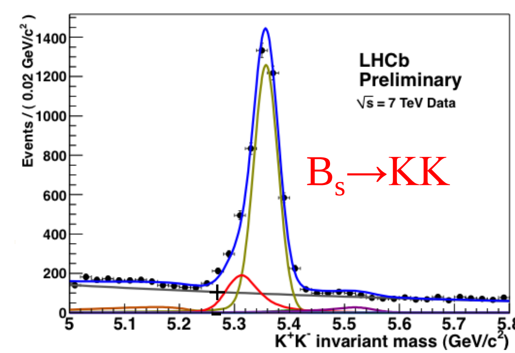
Deploy RICH to isolate each mode !







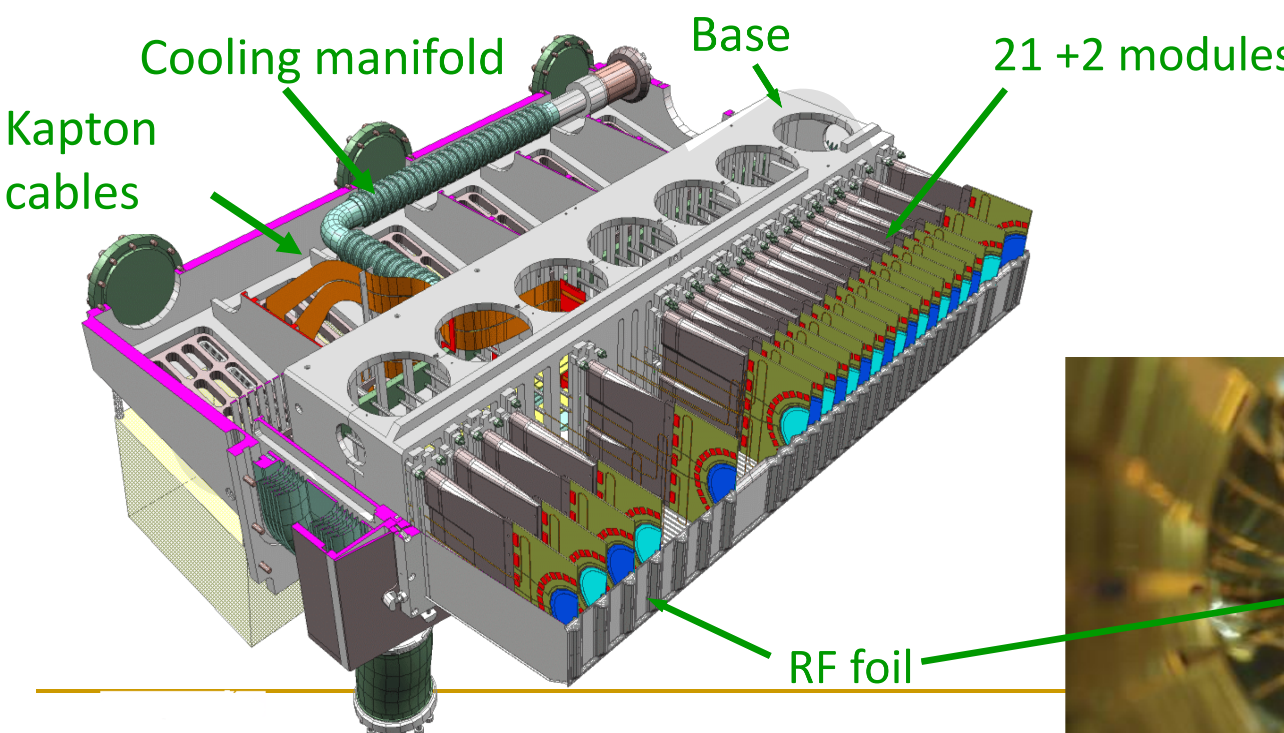


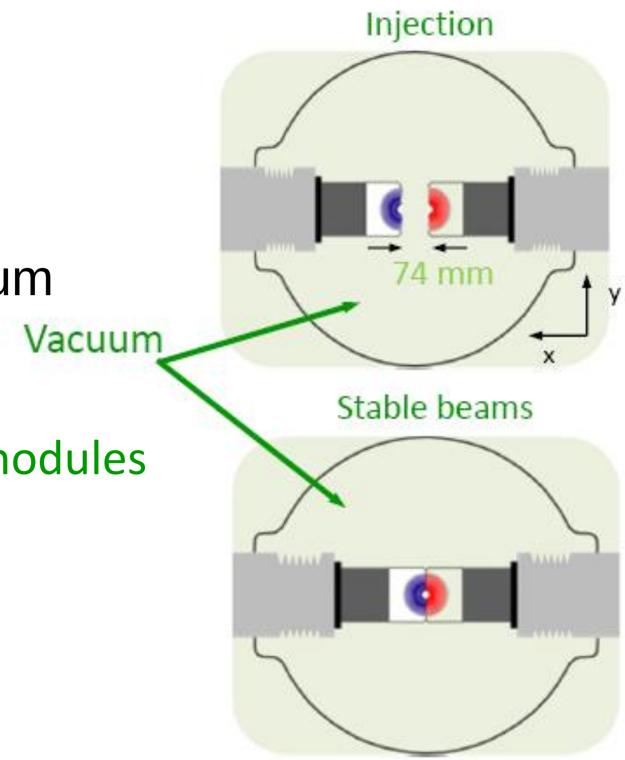


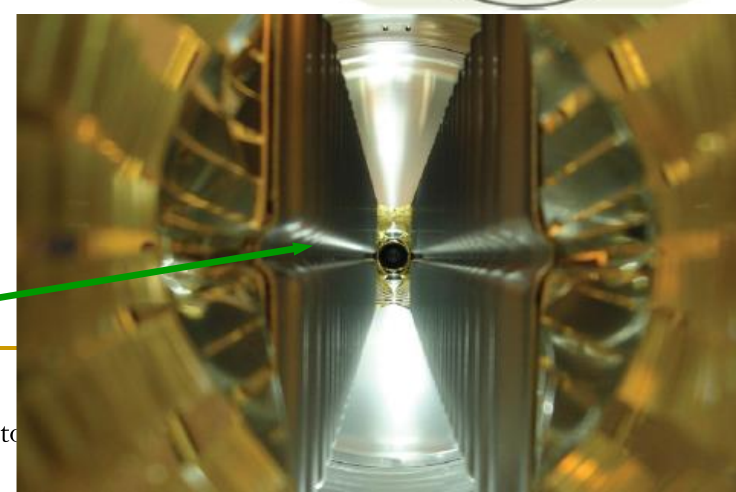
Focus on VELO

VELO: Current Design

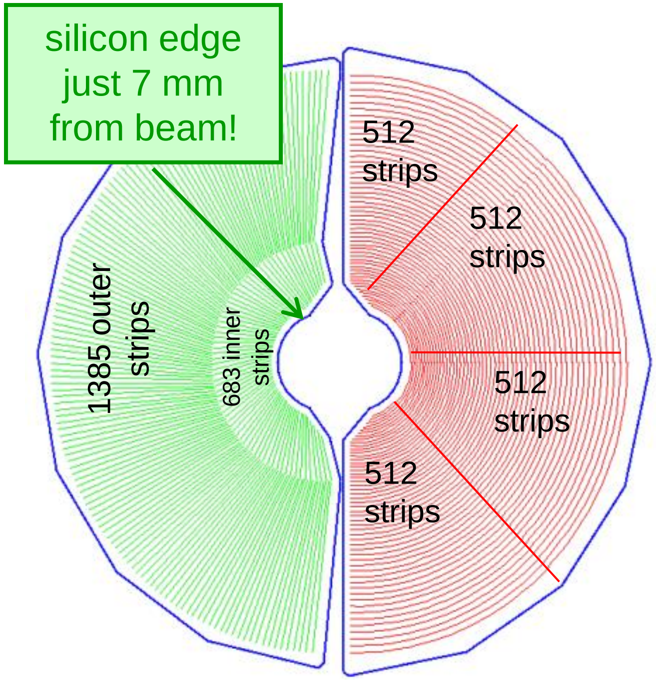
- 2 retractable detector halves:
  - 7 (37) mm from beam when closed (open)
- 21 stations per half with an R and ϕ sensor
- Operated in secondary vacuum
- 300μm Al foil separates detector from beam vacuum
- Bi-phase CO_2 cooling system







VELO sensors



Φ measuring sensors:
- 2 regions
- Short/long strips
- Pitch=36-97μm
- Stereo angle.

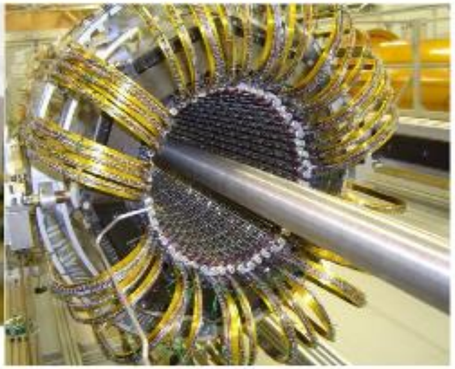
R measuring sensors:
- 45^{o} quadrants
- Pitch=40-102μm

- 300 μm n in n strip sensors (Micron Semiconductor)
- Double metal layer for signal routing

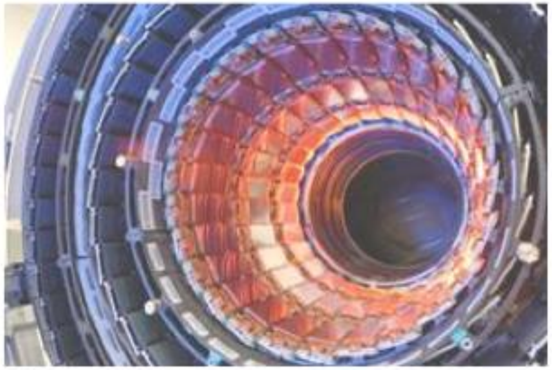
Silicon very popular in HEP

ALICE Pixel Detector

LHCb VELO



ATLAS Pixel Detector

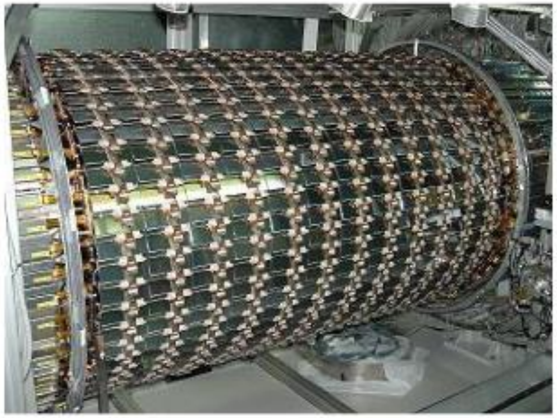


CMS Strip Tracker IB

CMS Pixel Detector

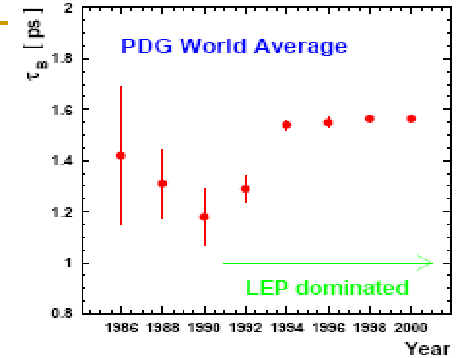
ALICE Drift Detector

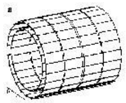
ALICE Strip Detector



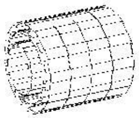
ATLAS SCT Barrel

Large Systems

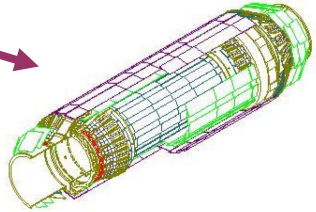




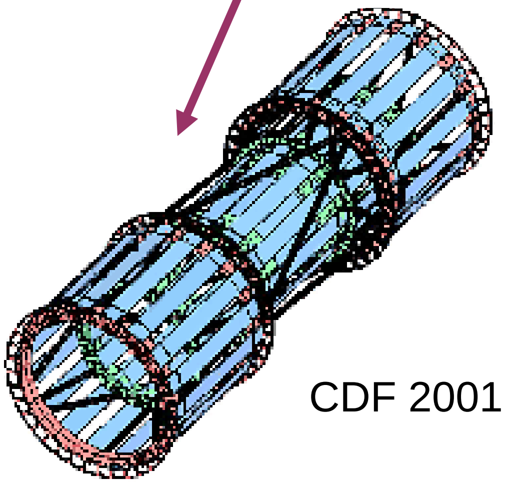
DELPHI
1990



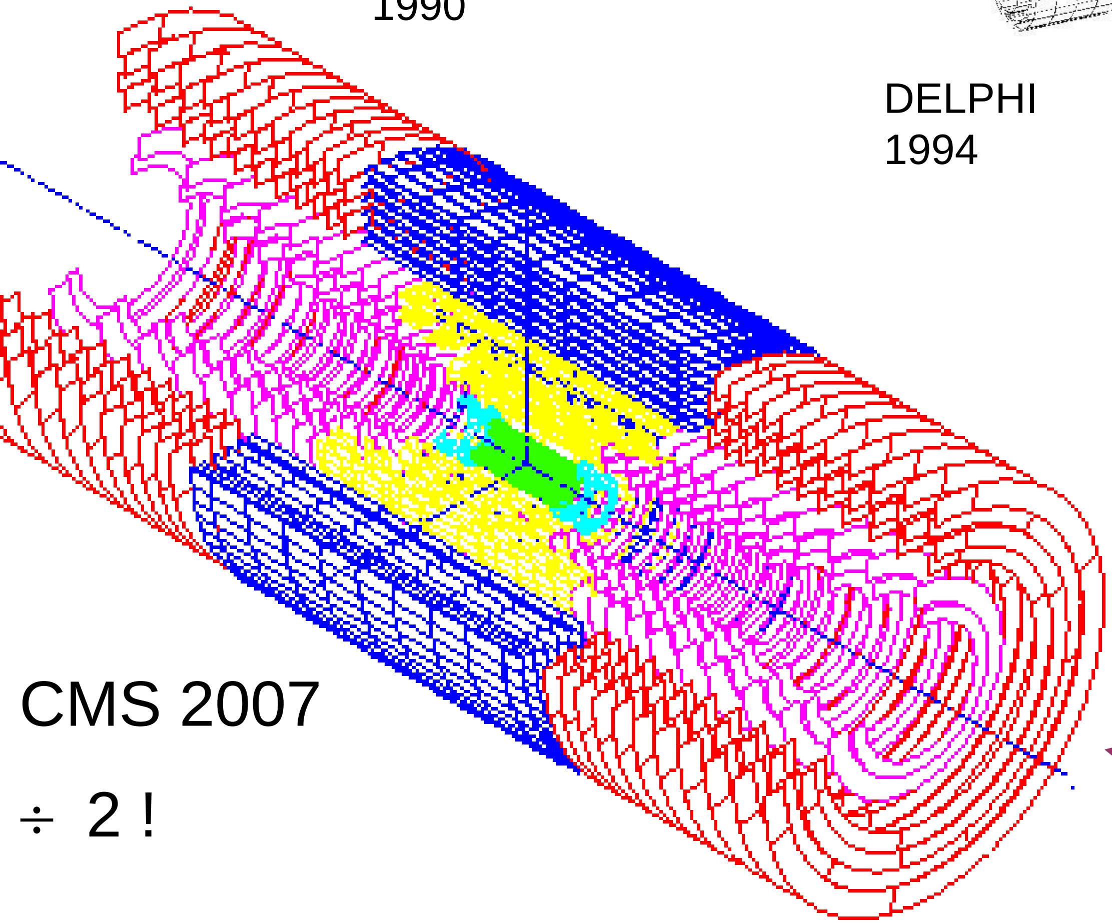
DELPHI
1994



DELPHI
1996



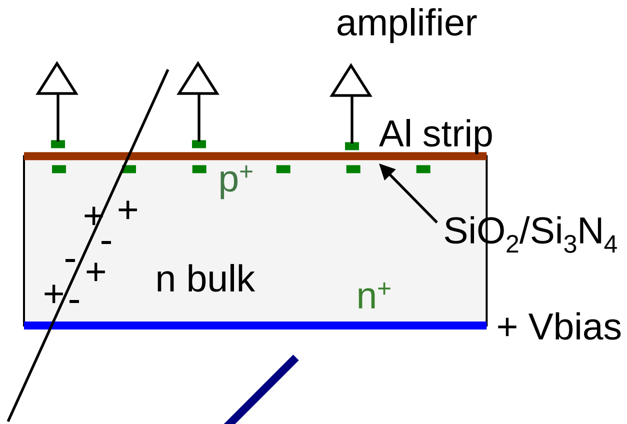
CDF 2001



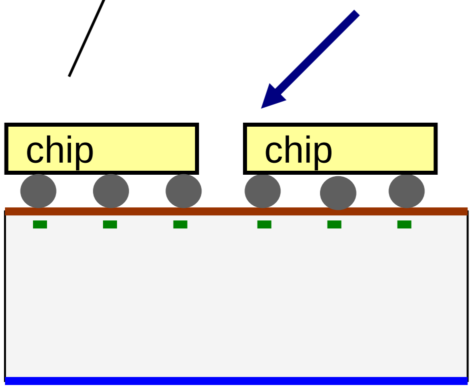
CMS 2007

÷ 2 !

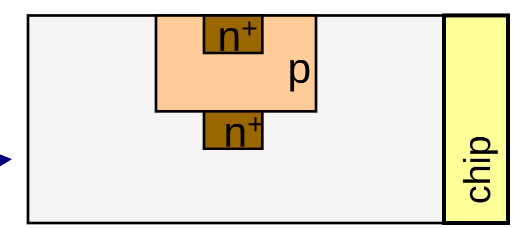
Silicon sensors for HEP



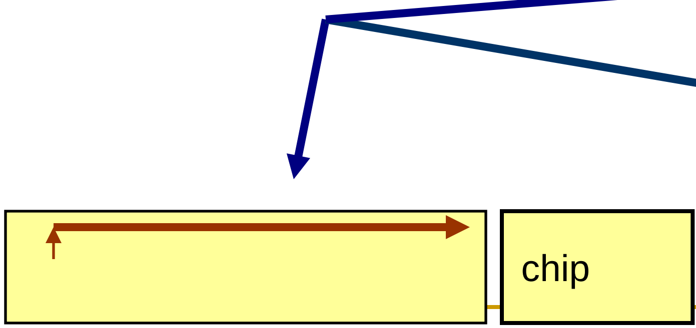
Start with high resistivity silicon
More elaborate ideas:
- n+ side strips – 2d readout
- Integrate routing lines on detector
- Floating strips for precision
- make radiation hard



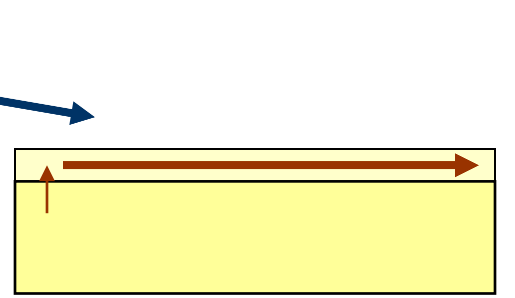
Hybrid Pixel sensors
Chip (low resistivity silicon)
bump bonded to sensor
Floating pixels for precision



DEPFET:
Fully depleted sensor
with integrated preamp



CCD: charge collected in thin layer
and transferred through silicon



MAPS: standard CMOS wafer
Integrates all functions

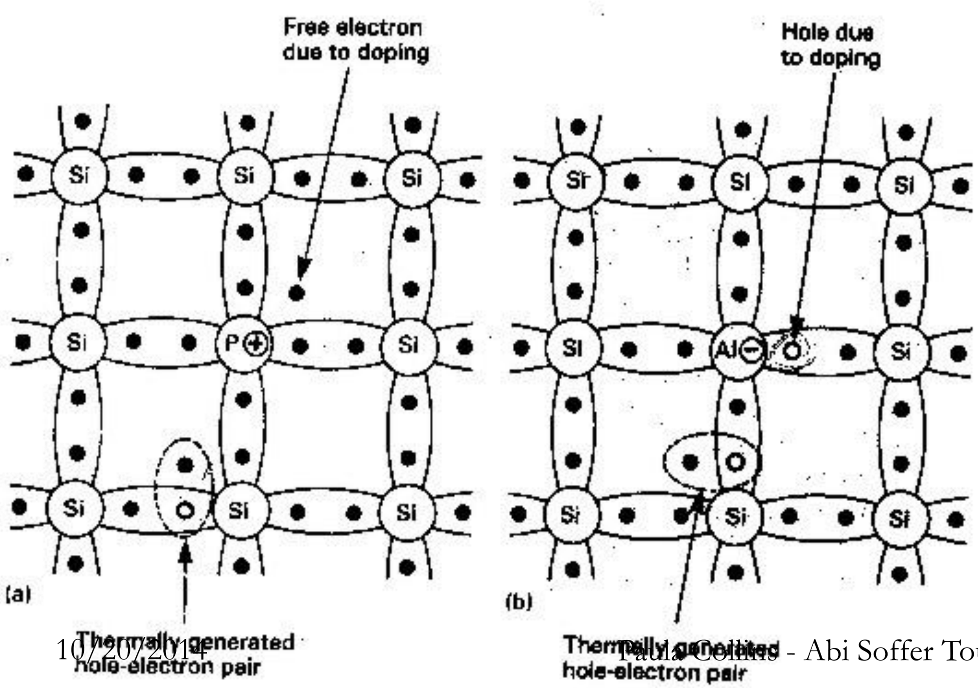
Basic Principles (1)

The probability of an electron jumping from the valence band to the conduction band is proportional to

$$e^{\frac{-E_g}{kT}}$$

where E_g, the band gap energy is about 1.1 eV and kT=1/40 eV at room temperature

- Next step is to dope the silicon with impurities



Phosphorus doping: electrons are majority carriers
Boron doping: holes are majority carriers

Some numbers:

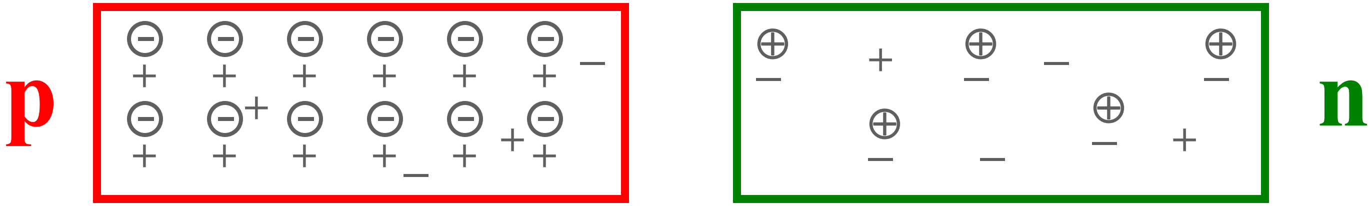
Intrinsic carriers: $10^{10}cm^{-3}$

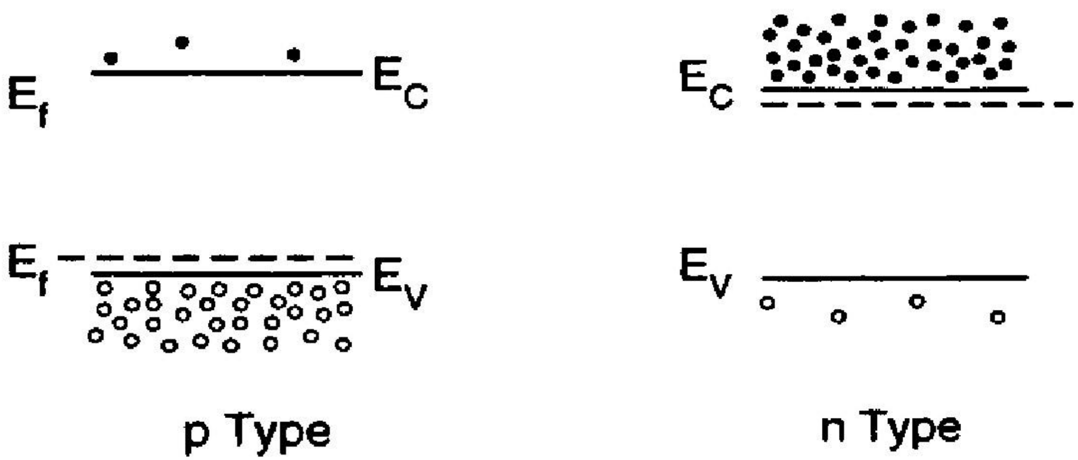
Doping concentration: $10^{12}cm^{-3}$

Silicon Density: $5 \times 10^{23}cm^{-3}$

Basic Principles (2)

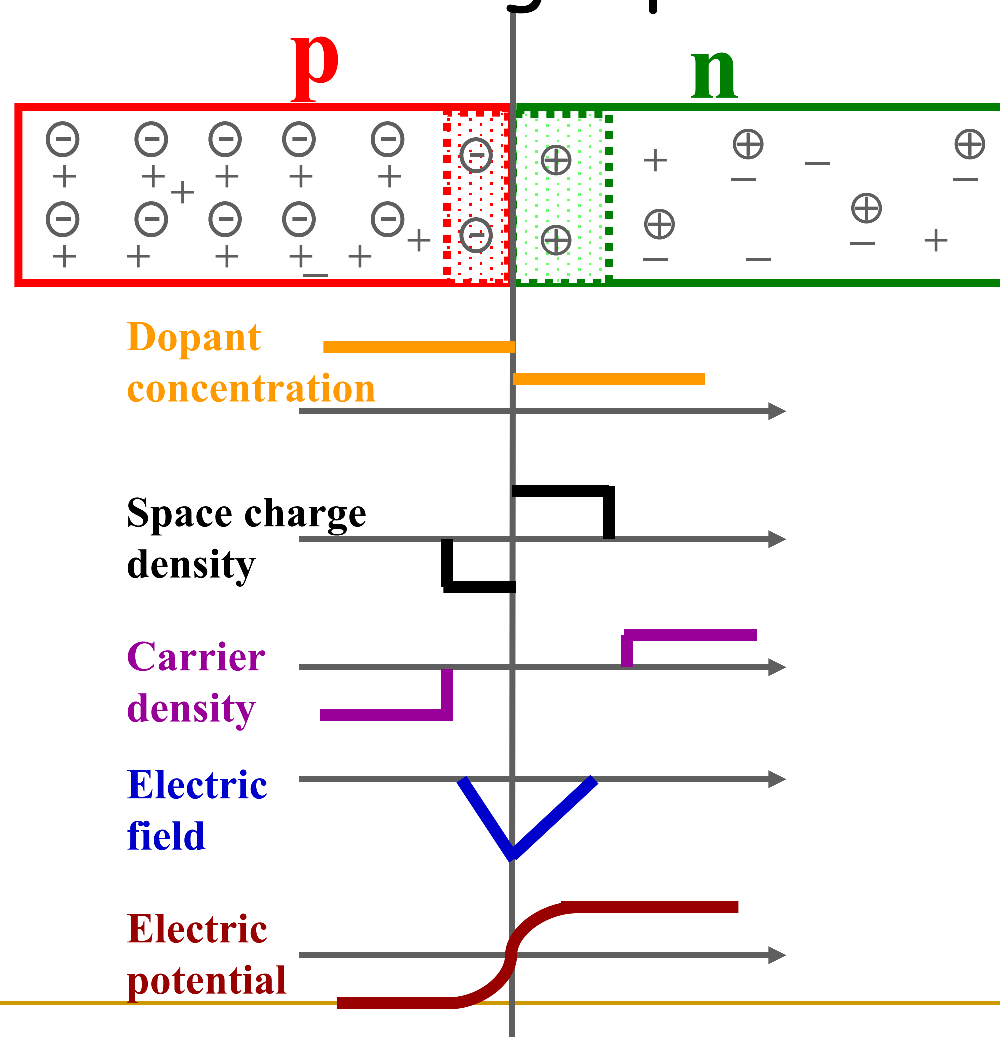
Now we can construct a p-n junction





Basic Principles (3)

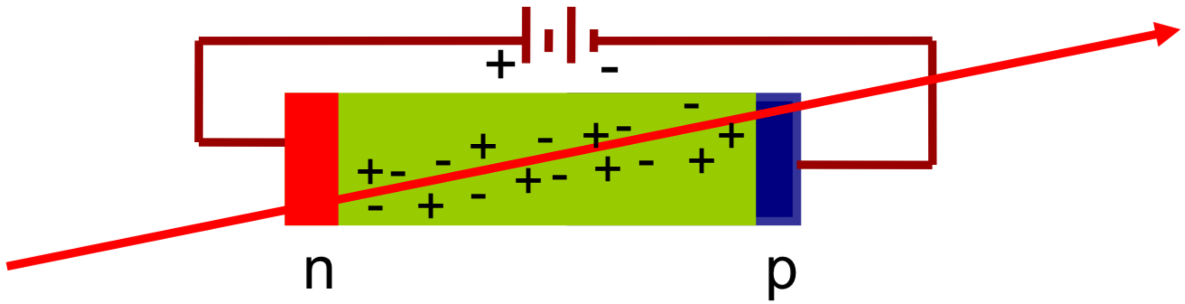
Now for the magic part!

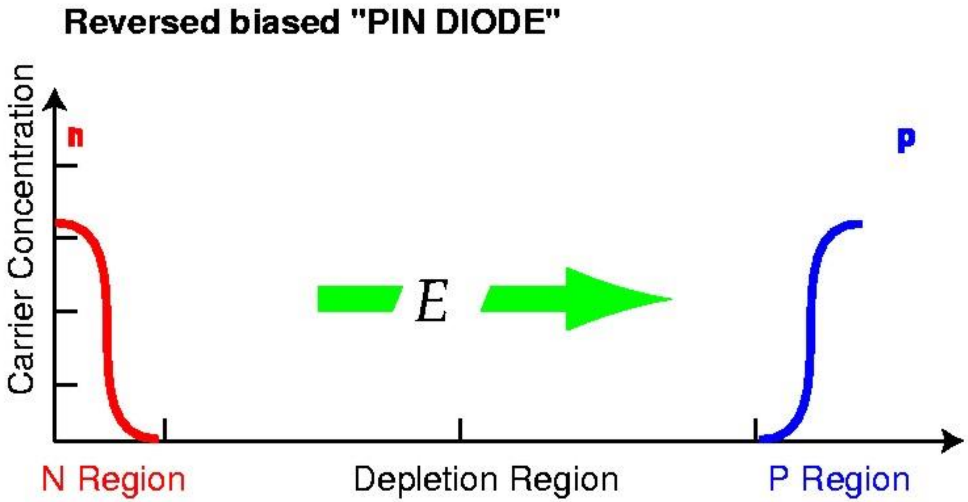


When brought together to form a junction, the majority diffuse carriers across the junction. The migration leaves a region of net charge of opposite sign on each side, called the space-charge region or depletion region. The electric field set up in the region prevents further migration of carriers.

Basic Principles (4)

The depleted part is very nice, but very small
Apply a reverse bias to extend it



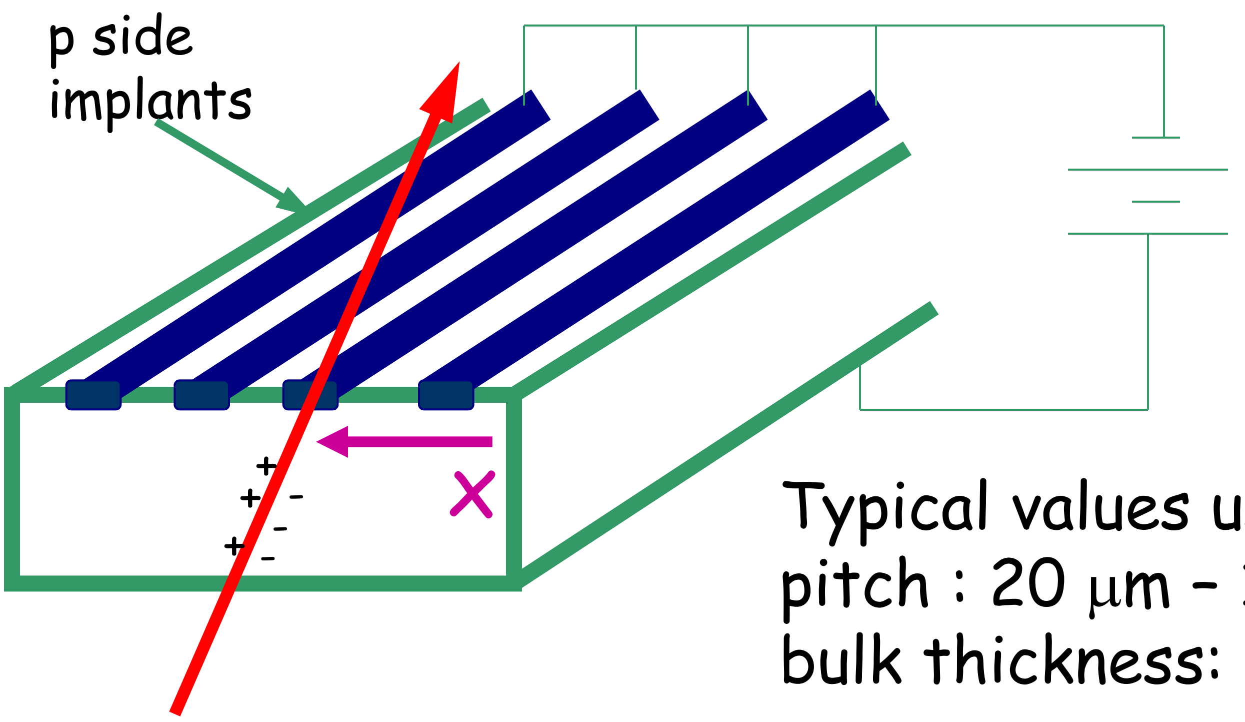


Electron-hole pairs created by the traversing particles drift in the electric field

$V_d = d^2 / (2\varepsilon\rho\mu)$

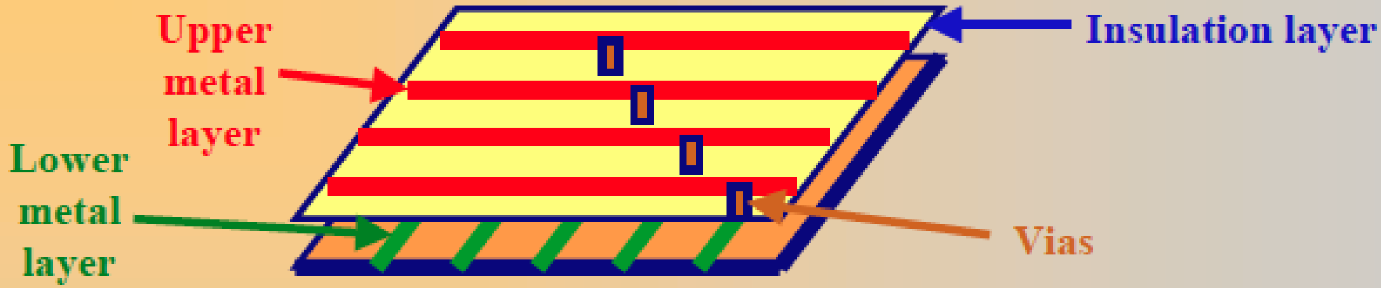
Basic Principles (5)

By segmenting the implant we can reconstruct the position of the traversing particle in one dimension



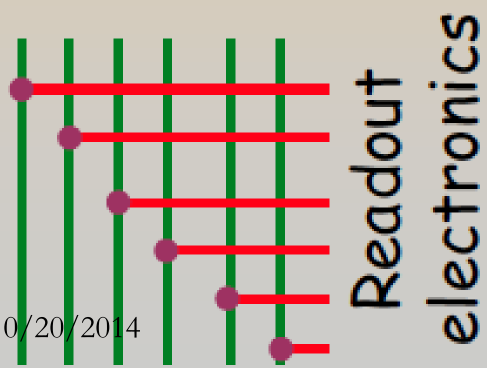
Typical values used are
pitch : 20 μm – 150 μm
bulk thickness: 150 μm – 500 μm

Double Metal Technology

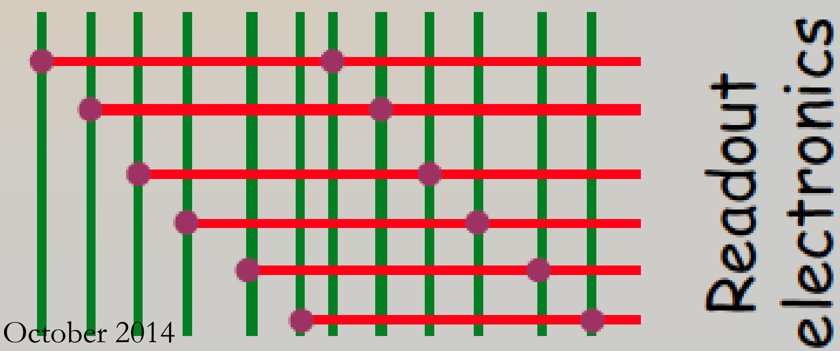


Add an insulation layer, and above that add another layer of strips which are going in the right direction – the direction of the readout electronics. This might be orthogonal to the strips and might not – many weird and wonderful patterns are possible

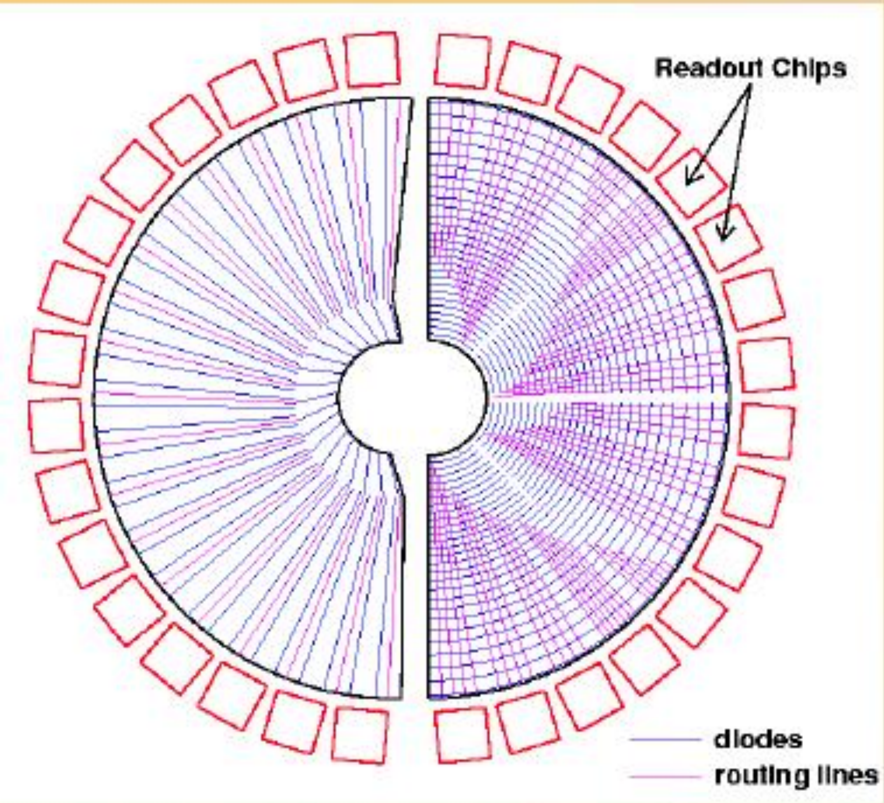
a simple solution..



.... a solution with multiplexing



Challenging, but elegant



The LHCb sensors must measure R and Phi and must keep the electronics on the outside - an obvious application for double metal technology!

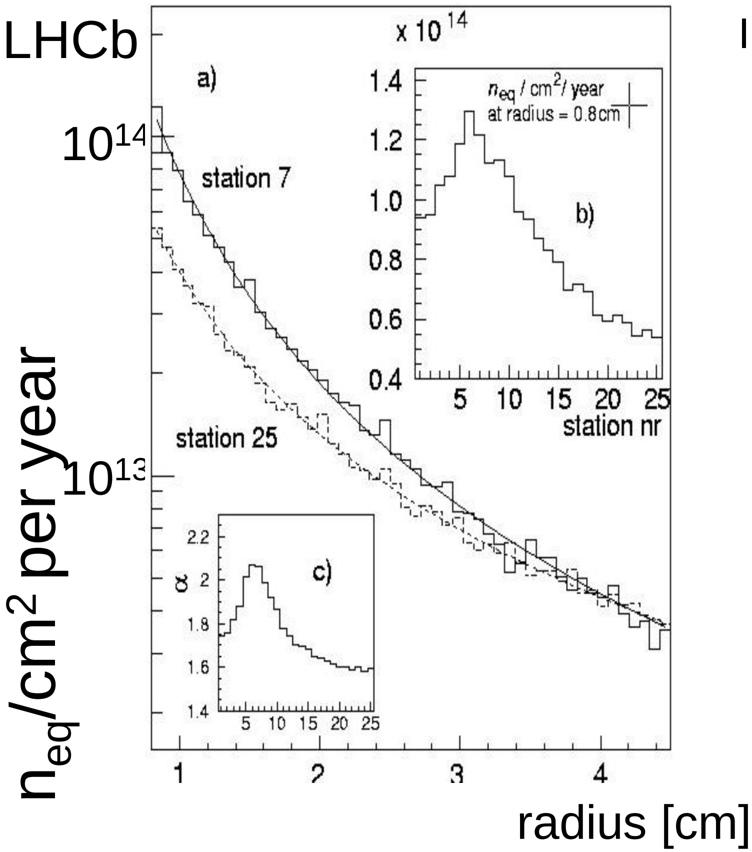
These detectors are single sided and n-on-n

Irradiation –
LHCb VELO most irradiated silicon so far at LHC

- Good testing ground for future upgrades
- Change of depletion/operation voltage
  - Due to defect levels that are charged in the depleted region -> time and temperature dependent, and very problematic!
- Increase of leakage current
  - Bulk current due to generation/recombination levels
- Damage induced trapping centers
  - Decrease in collected signal charge

Irradiation: strips for LHCb

High and strongly non uniform irradiation



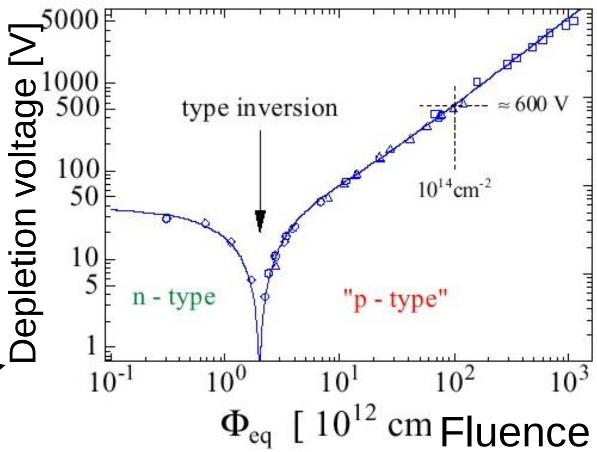
We expect the classic bulk damage effects

Increased Leakage Current

- Noise
- Hard to bias

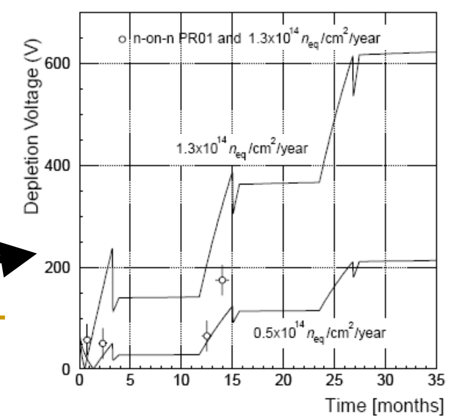
Effective Doping Changes

- Depletion growing from n^+ side

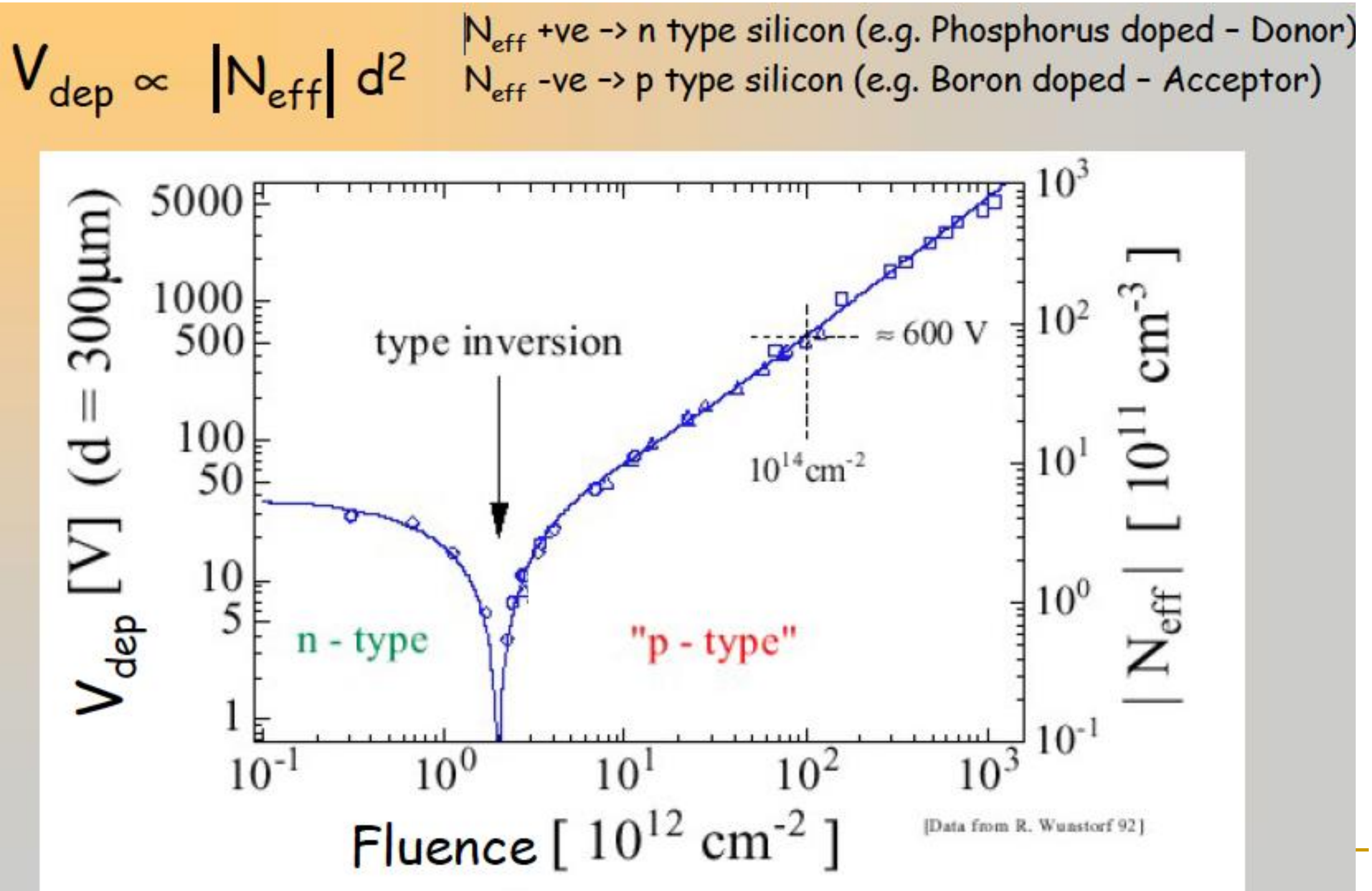


Annealing effects

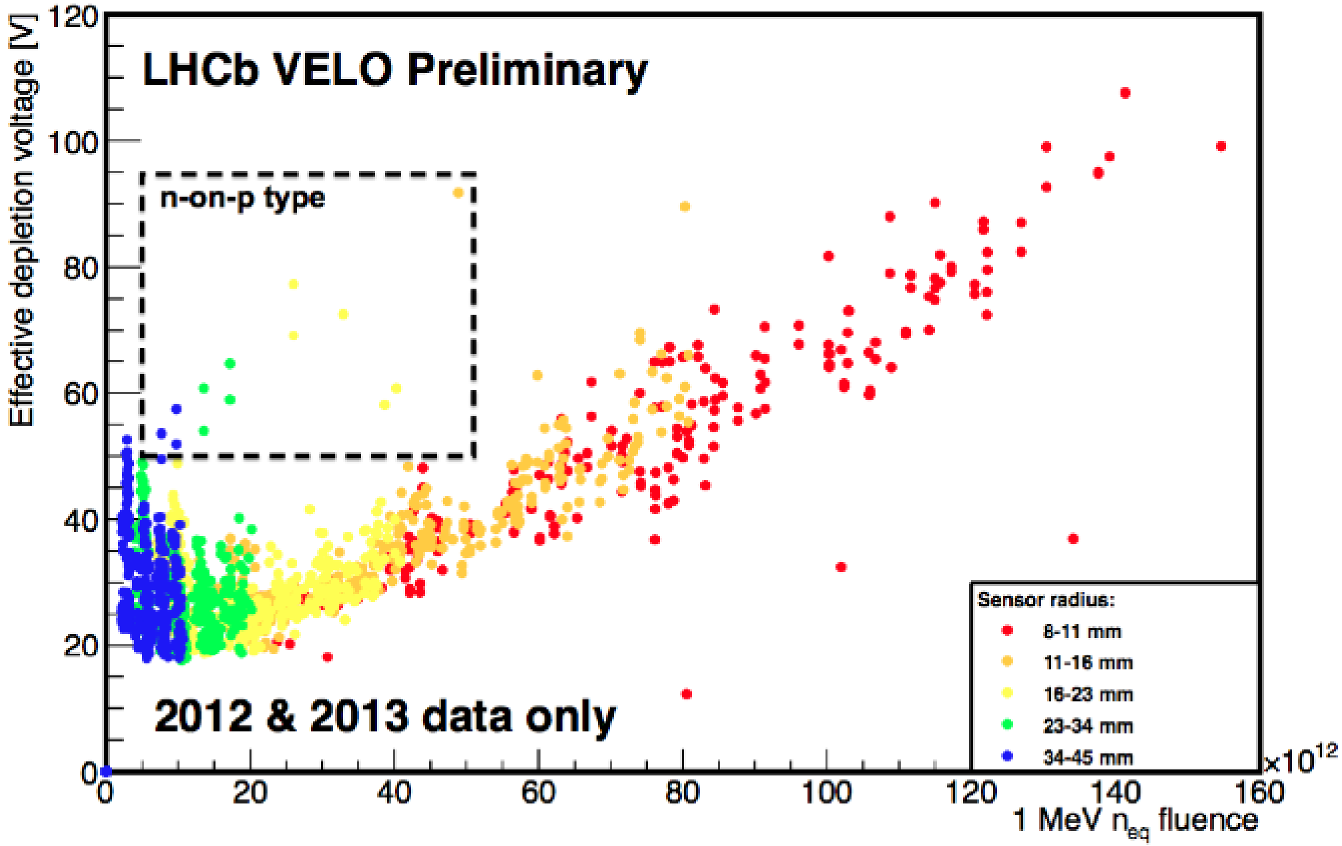
- Buildup of negative space charge worsening in time
- Strongly temperature dependent



Changes in depletion voltage

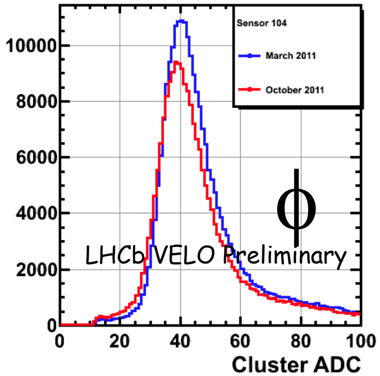


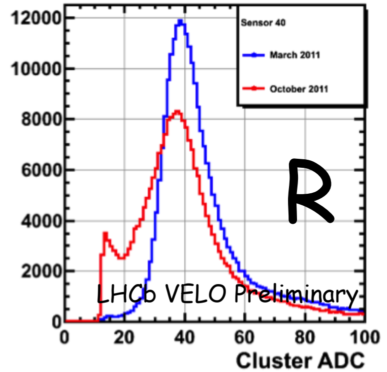
LHCb textbook



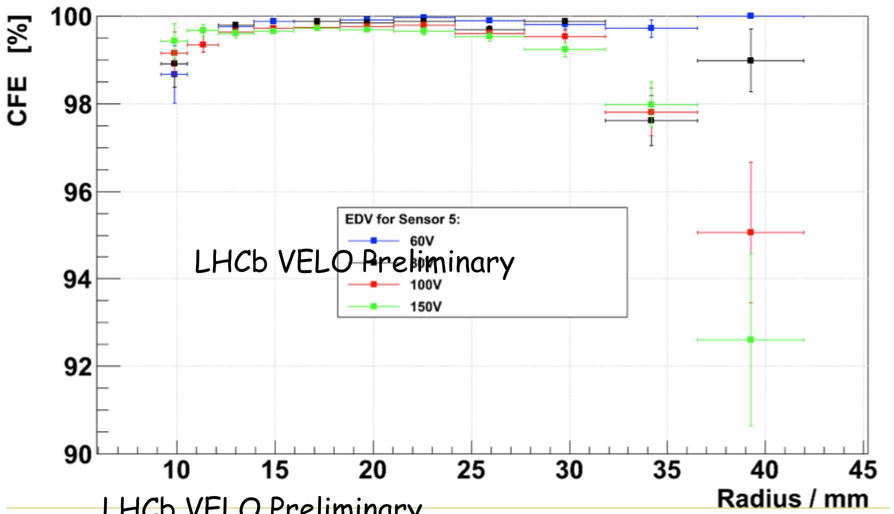
LHCb – new textbook

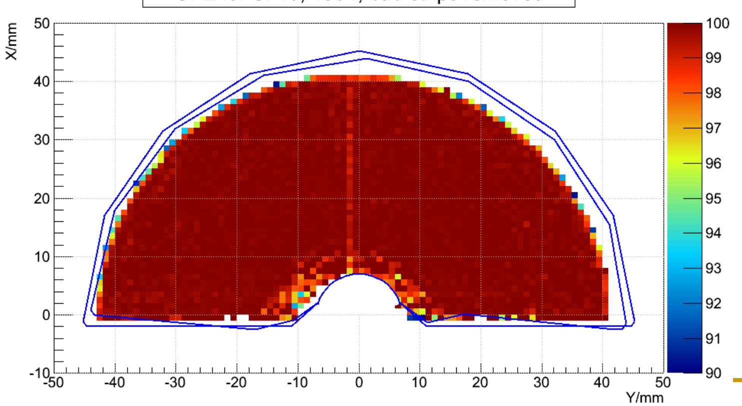
Landau shapes of R sensors are deteriorating



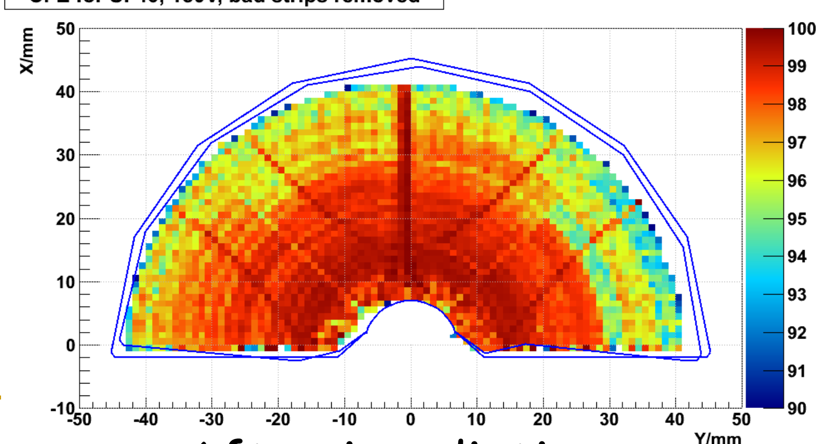


R sensors are showing inefficiencies at the outer parts which are inversely dependent on HV





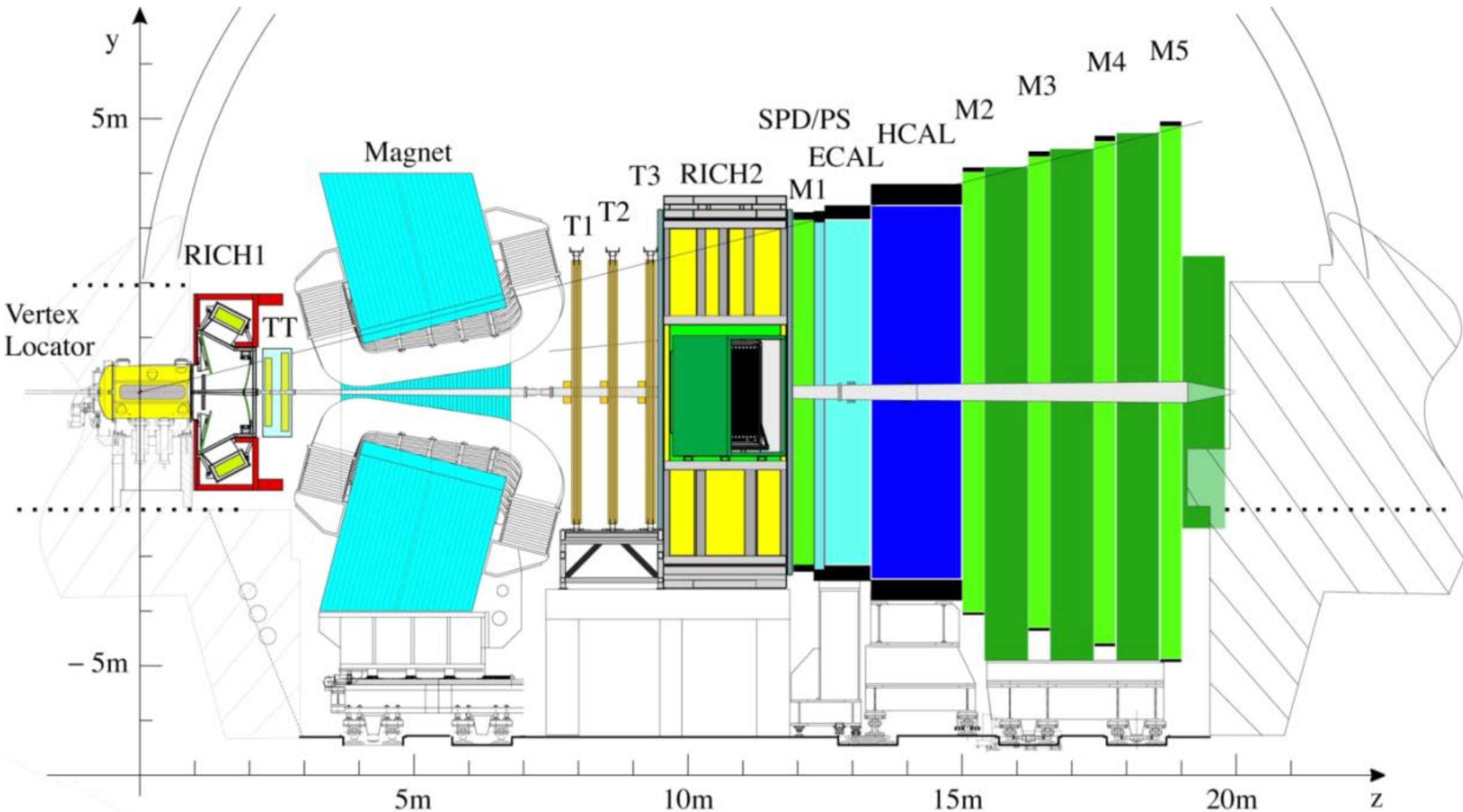
Before irradiation



After irradiation

LHCb and VELO Upgrade

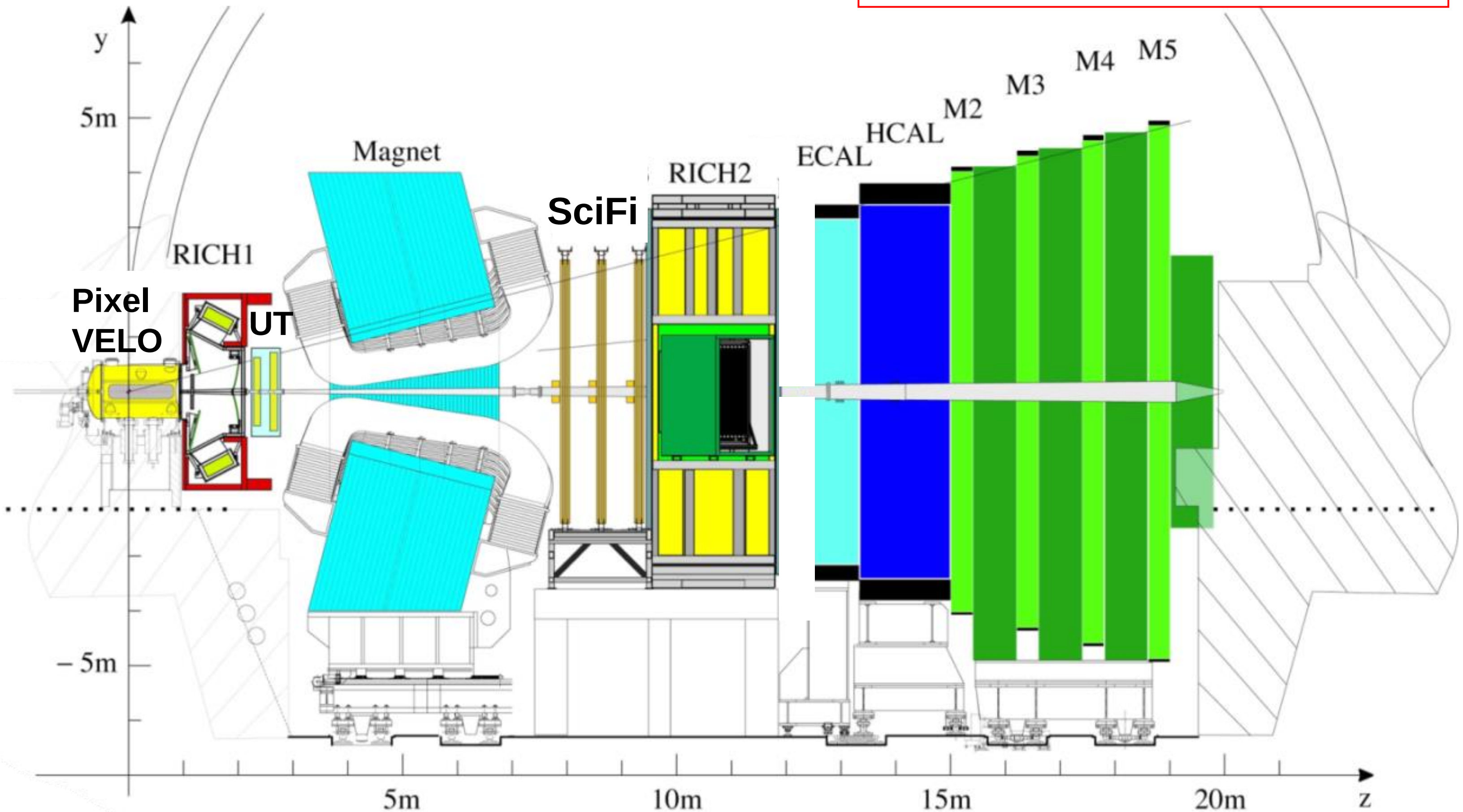
Current detector



Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger



Upgrade overview

Current detector → upgraded detector

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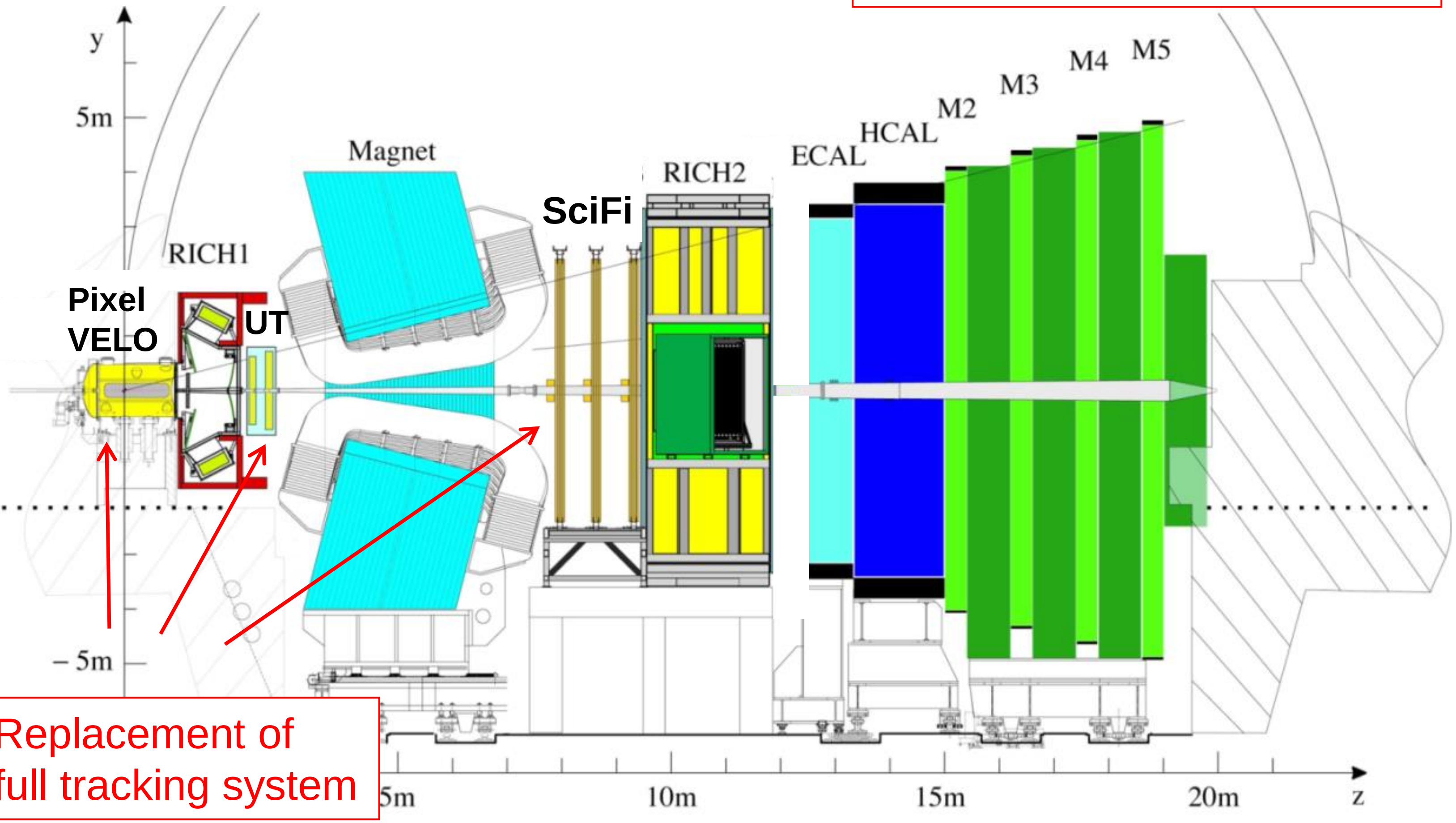


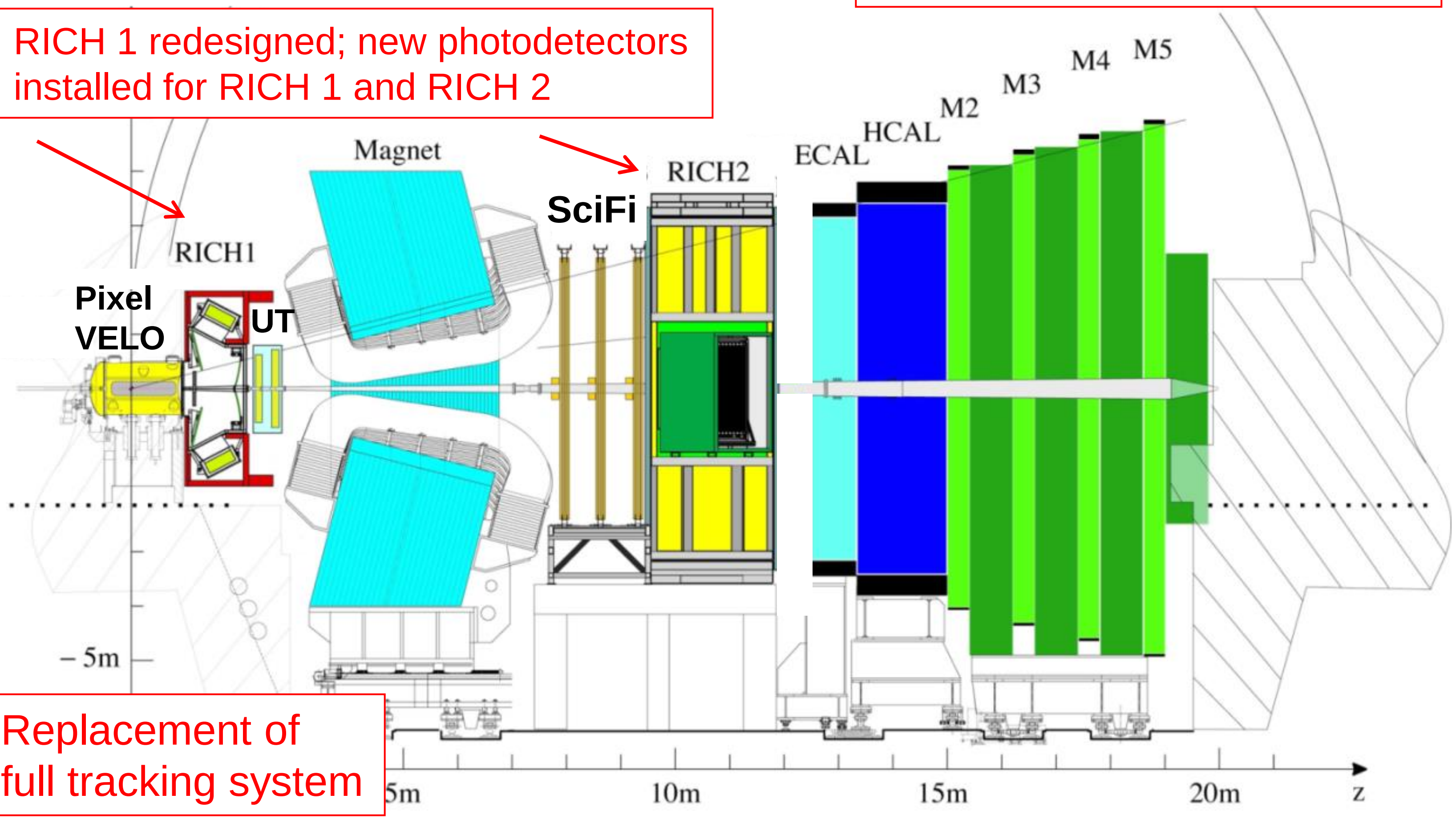
Replacement of full tracking system

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2



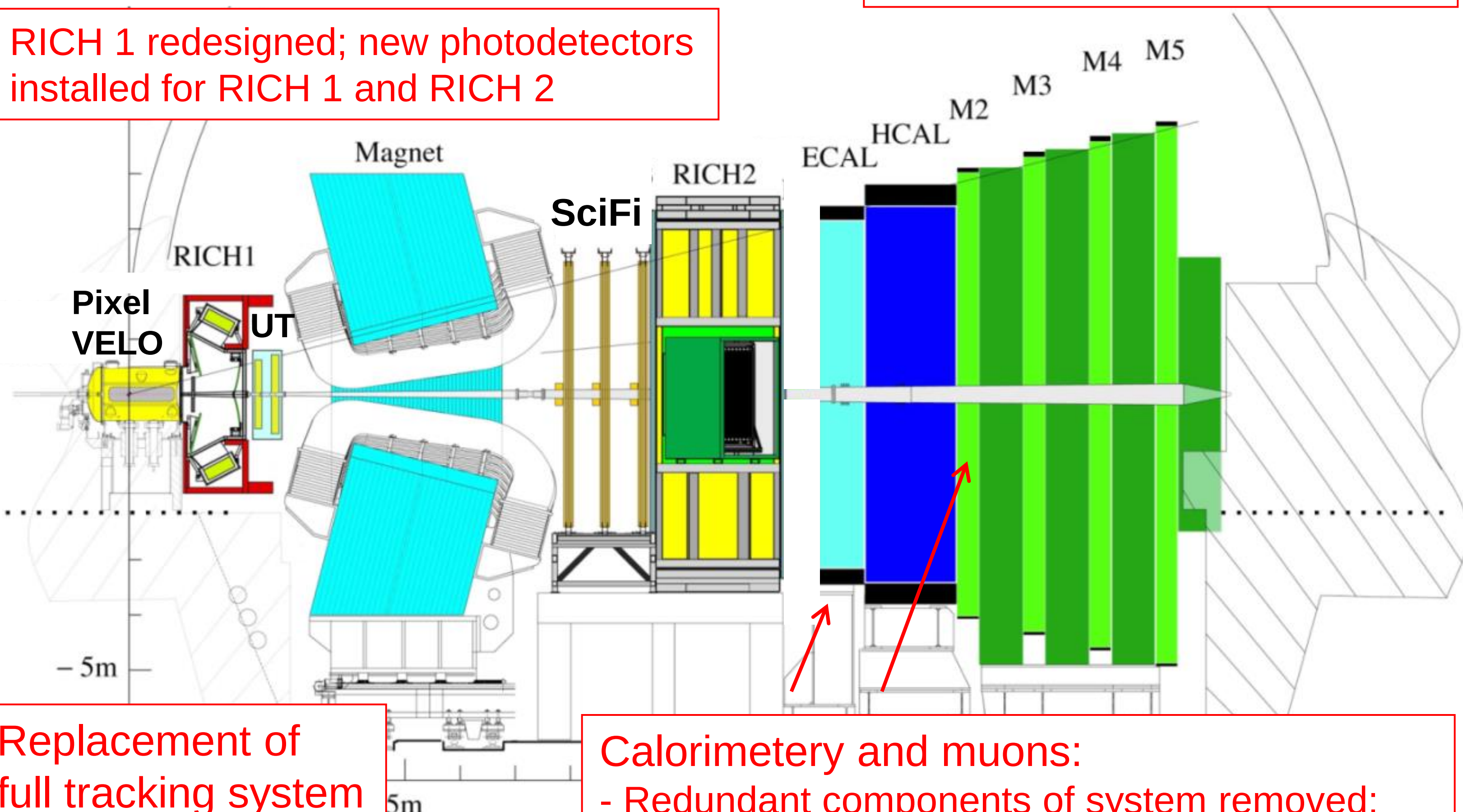
Replacement of full tracking system

Upgrade overview

Current detector → upgraded detector

All sub-detectors read out at 40 MHz for software trigger

RICH 1 redesigned; new photodetectors installed for RICH 1 and RICH 2

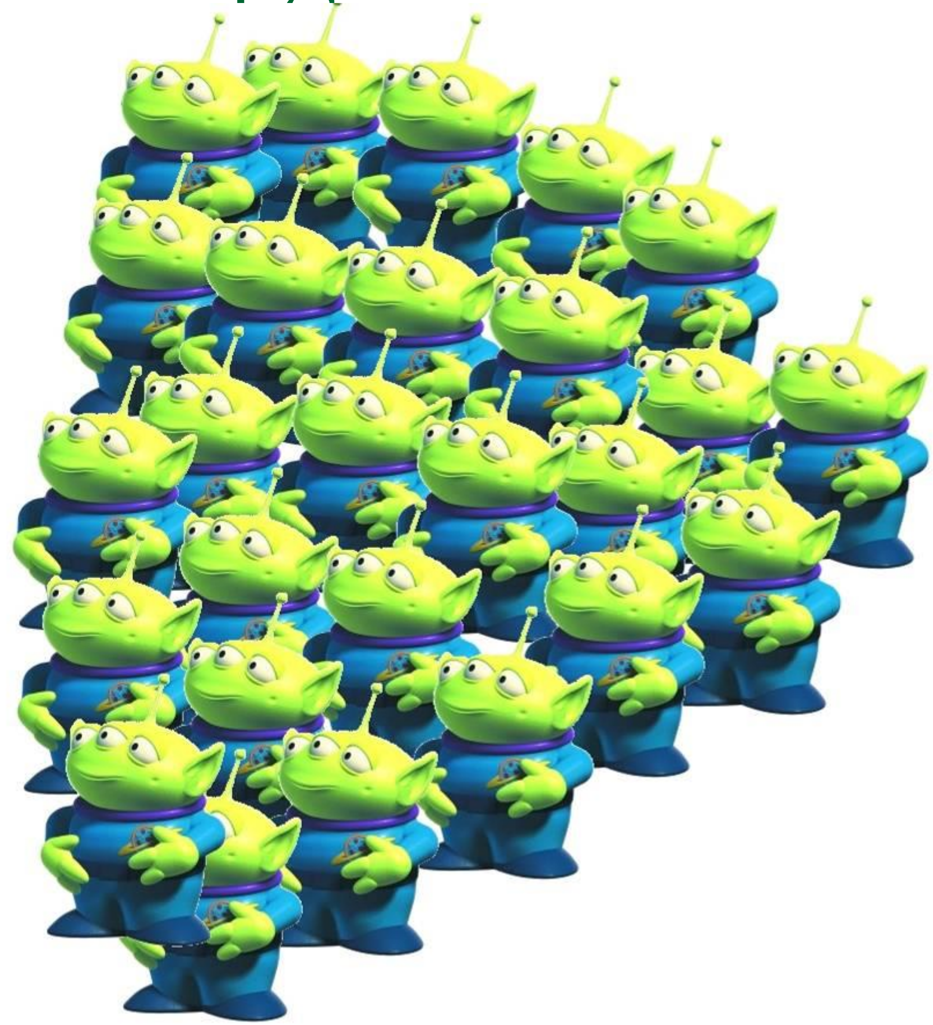


Replacement of full tracking system

Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

Challenges for VELO Upgrade

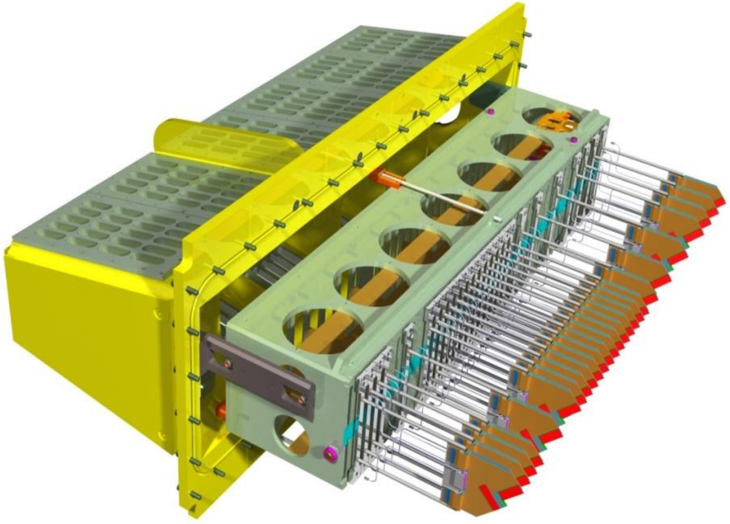
- 40 MHz readout (electronics)
- Pattern recognition and trigger capabilities
- Radiation hardness (and cooling)



How do I cope with having 10 quadrillion particles thrown at me?*

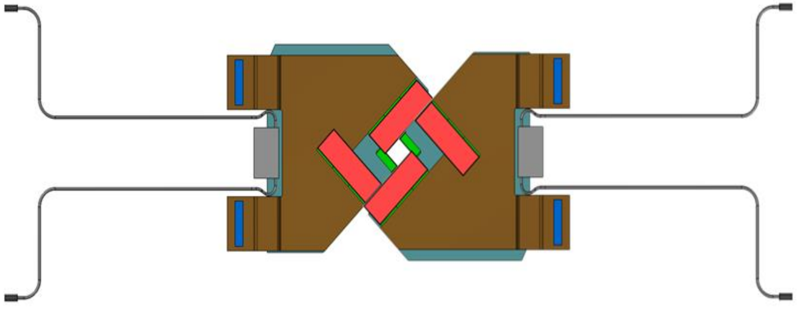
*10^{16} fluence / cm^2 at 4cm SLHC

VELO Upgrade

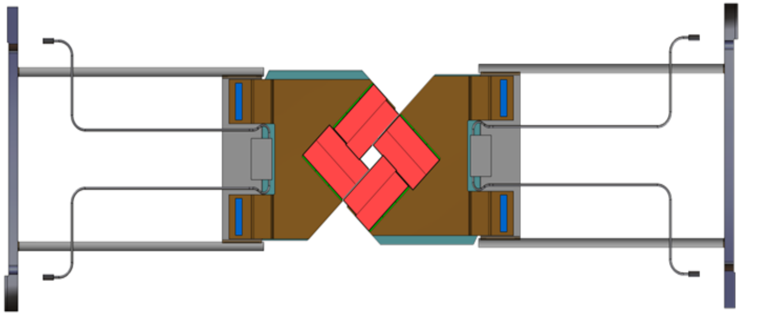


52 modules
Module pitch:
N*25 mm

VELO halves closed



front view

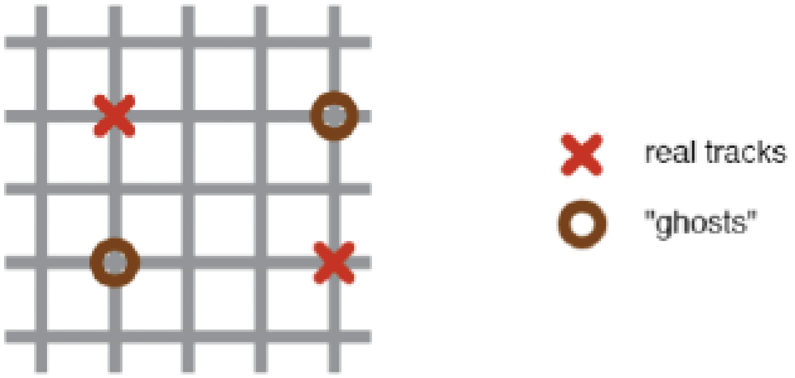


projected view of sensors

Hybrid Pixels

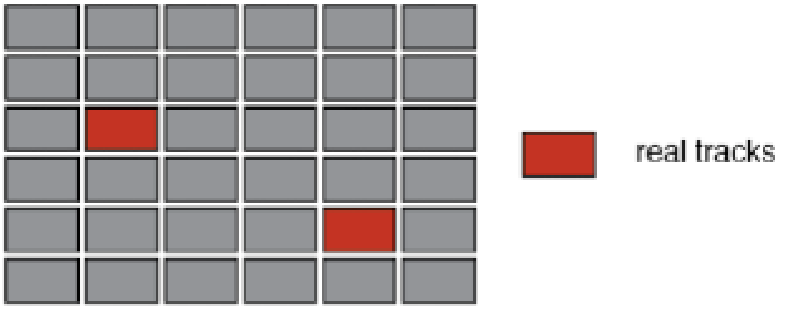
★ A strip detector measures 1 coordinate only. Two orthogonal arranged strip detectors could give a 2 dimensional position of a particle track. However, if more than one particle hits the strip detector the measured position is no longer unambiguous. "Ghost"-hits appear!

True hits and ghost hits in two crossed strip detectors in case of two particles traversing the detector:



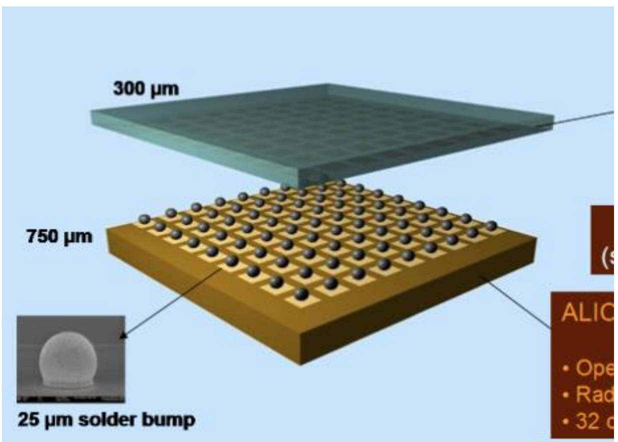
★ Pixel detectors produce unambiguous hits!

Measured hits in a pixel detector in case of two particles traversing the detector:



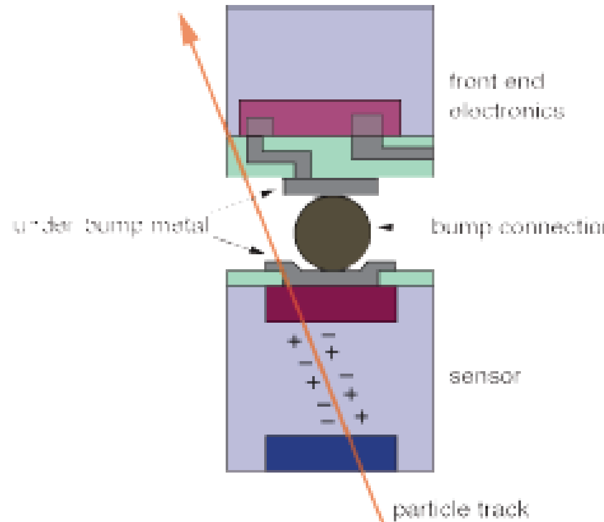
Hybrid Pixels

"Flip-Chip" pixel detector:
On top the Si detector, below the readout chip, bump bonds make the electrical connection for each pixel.



S.L. Shapiro et al., *Si PIN Diode Array Hybrids for Charged Particle Detection*, Nucl. Instr. Meth. A **275**, 580 (1989)

Detail of bump bond connection. Bottom is the detector, on top the readout chip:

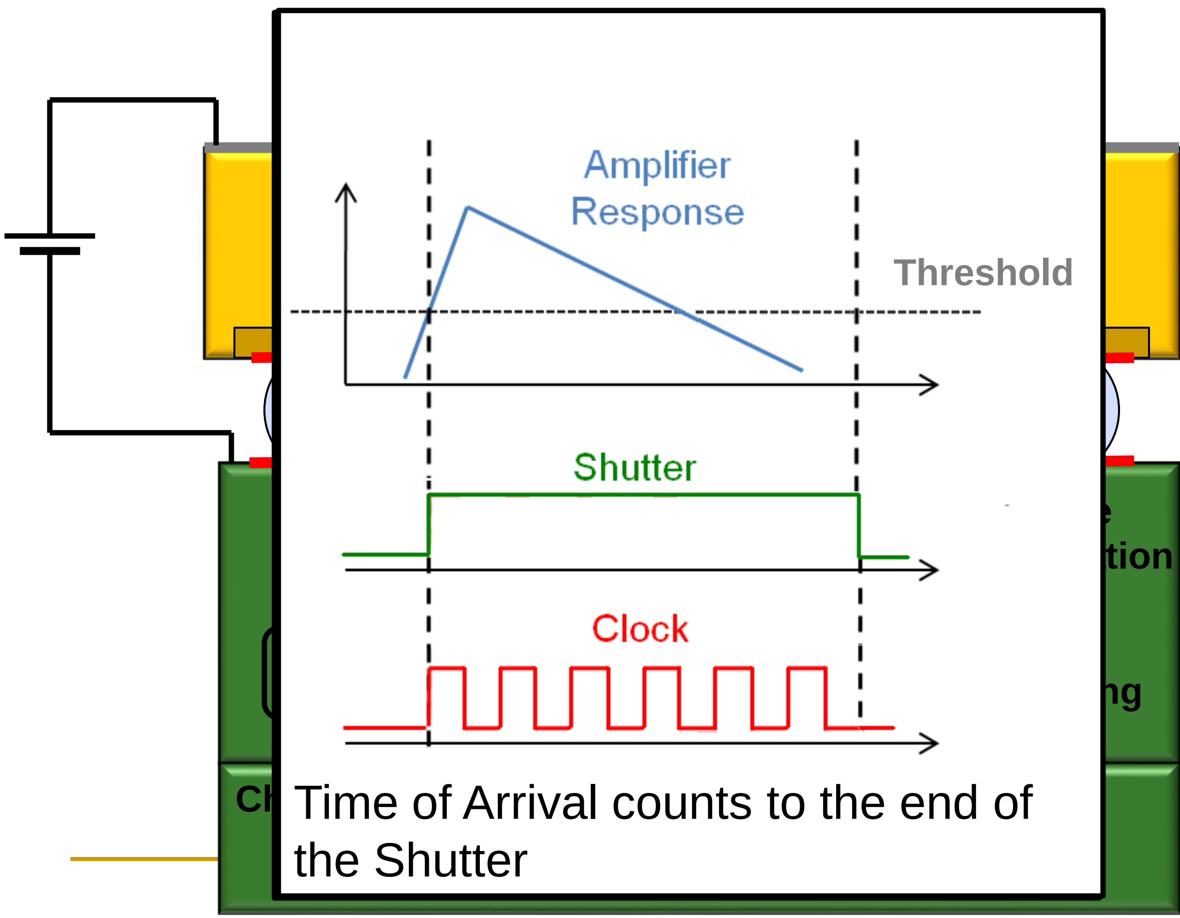


L. Rossi, *Pixel Detectors Hybridisation*, Nucl. Instr. Meth. A **501**, 239 (2003)

Drawback of hybrid pixel detectors: Large number of readout channels

→ Large number of electrical connections and large power consumption.

Intelligent Pixels 4 LHCb



Timepix design requestedand funded by EUDET collaboration

Conventional Medipix2 counting mode remains.

Addition of a clock up to 100MHz allows two new modes.

Time over Threshold

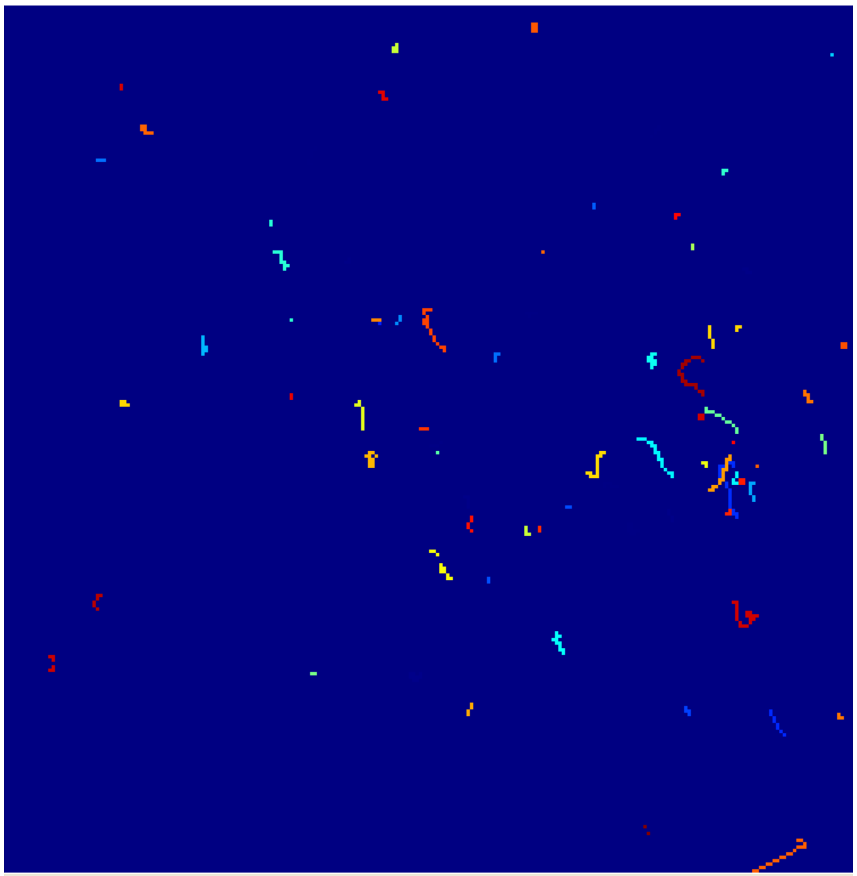
Time of Arrival

Pixels can be individually programmed into one of these three modes

Or As Results…

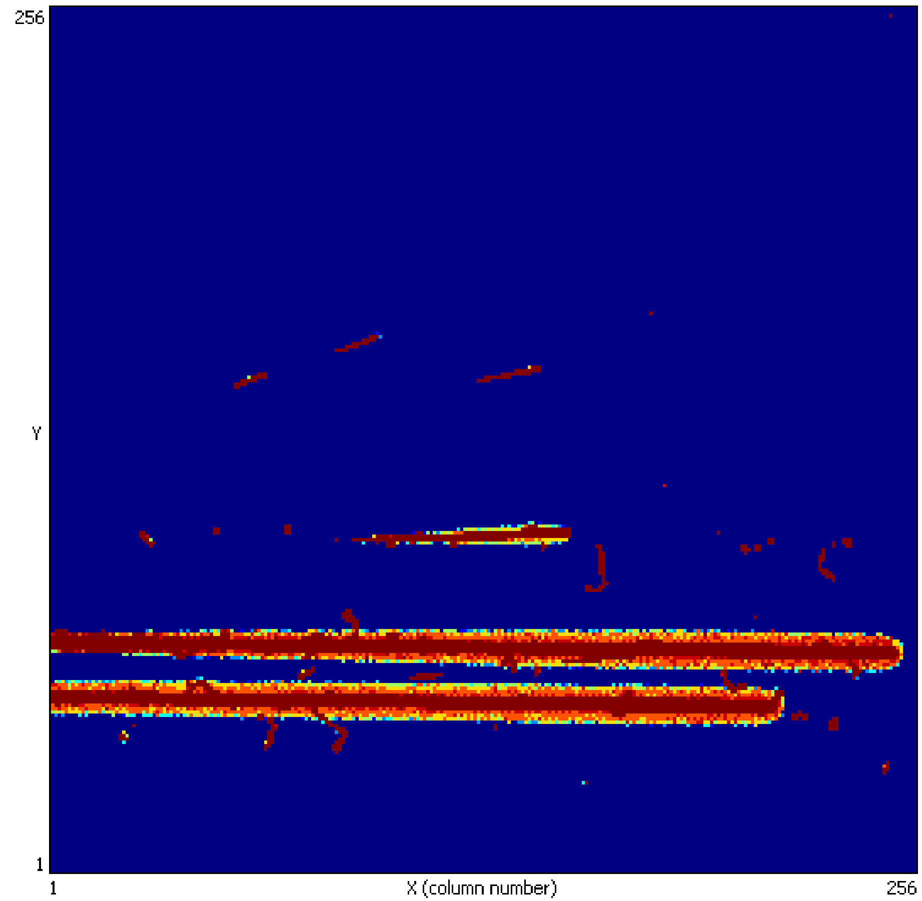
Time of Arrival

Strontium Source



Time over Threshold

Ion Beams at HIMAC



Charge deposition studies with various Isotopes
Space Dosimetry

Courtesy L. Pinsky, Univ. Houston

Summary

- LHCb is a very innovative, and so far very successful experiment with an exciting future
- I hope that in the future you may join us!

ברוכים הבאים!

ביקור נעים!