Lecture 11, 18.03.2020

Tracking detectors

Olaf Steinkamp

University of Zurich & NUST MISiS

`olafs@physik.uzh.ch`

FROM MGA TO NUST MISIS 100 YEARS 1918-2018 OPENING A NEW CENTURY

MISIS National University of Science and Technology

SHiP Search for Hidden Particles

LHCb

University of Zurich UZH

Particle Physics Experiments

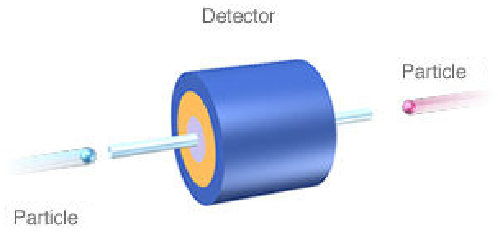
Accelerate a beam of (stable & charged) particles to high energies

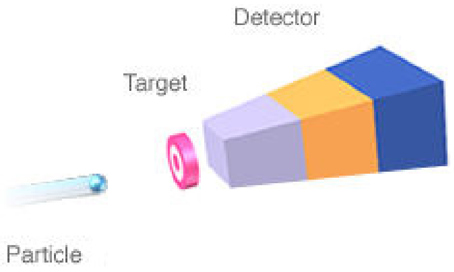
→ electrons/positrons, protons/antiprotons, heavy ions

Bring them into collision with

another beam of particles:
“collider experiment”
e.g. ATLAS, CMS

a target at rest:
“fixed-target experiment”
e.g. SHiP





Measure the properties of the long-lived particles that are created in the collision

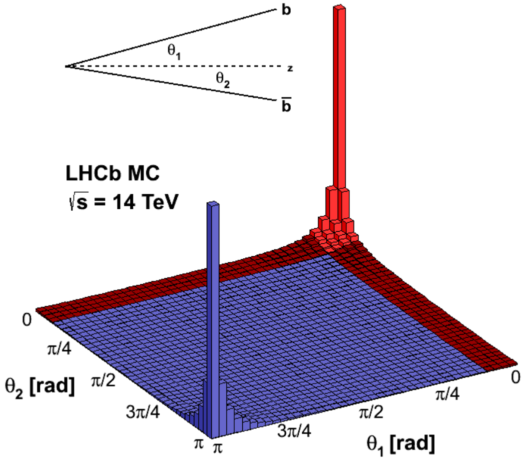
Reconstruct short-lived particles using relativistic kinematics

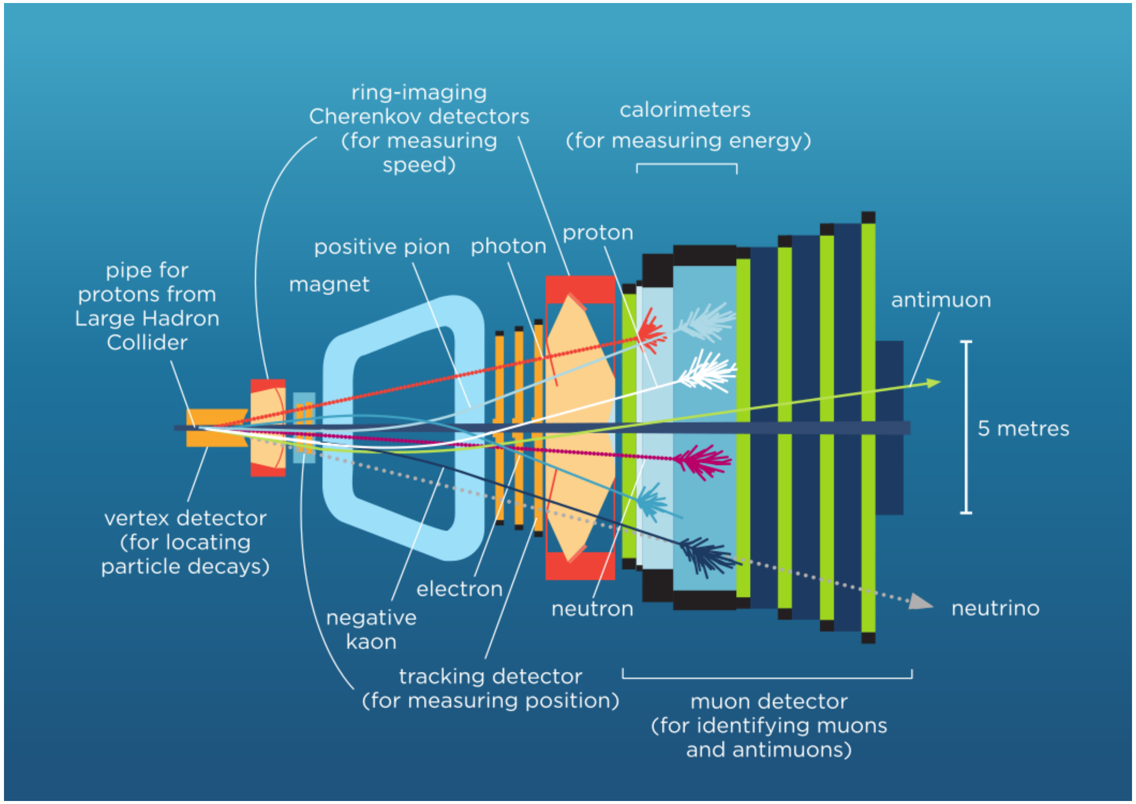
LHCb Experiment

A collider experiment that looks like a fixed target experiment

Main goal is to study
***b* and *c* hadrons**

→ are produced mostly at small angles wrt beam axis





Detector Components

Position-sensitive detectors

→ production vertices and flight path of charged particles
→ decay vertices of short-lived particles

Position sensitive detectors in a magnetic field

→ momenta of charged particles

Calorimeters

→ energy of charged and neutral particles

Cherenkov counters, Transition radiation counters, Time-of-flight counters, …

→ speed of charged particles
(momentum + speed → mass → particle type**)**

Momentum measurement

Moving charge in magnetic field → Lorentz force

$$\vec{F}_L = q \cdot \vec{v} \times \vec{B}$$

→ forces particle onto circular trajectory around field lines

$$\frac{m \cdot v^2}{r} = q \cdot v \cdot B$$

$$p = q \cdot B \cdot r$$

→ measure bending radius of particle trajectory in a known magnetic field

→ for a particle with $q = \pm e$

$$p\,[\mathrm{GeV}] \approx 0.3 \cdot B\,[\mathrm{T}] \cdot r\,[\mathrm{m}]$$

Momentum measurement

Typical collider experiment: solenoid or toroid magnet

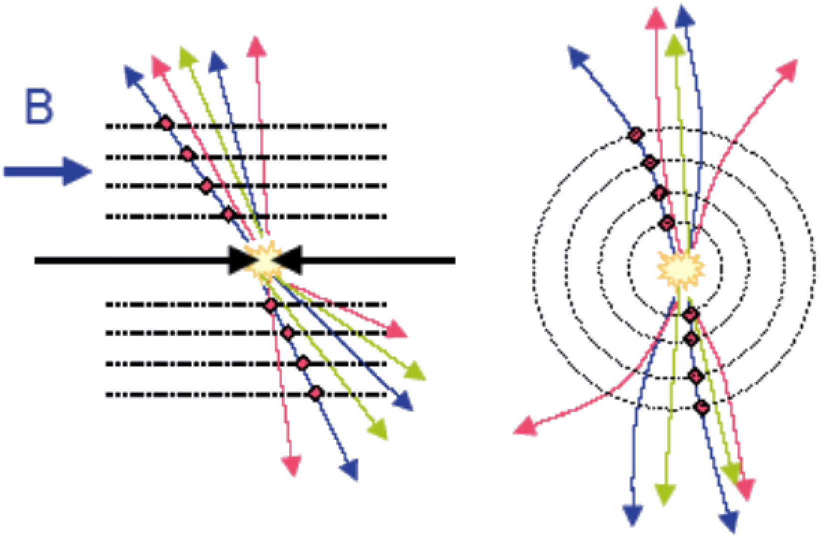
→ field lines parallel to beam

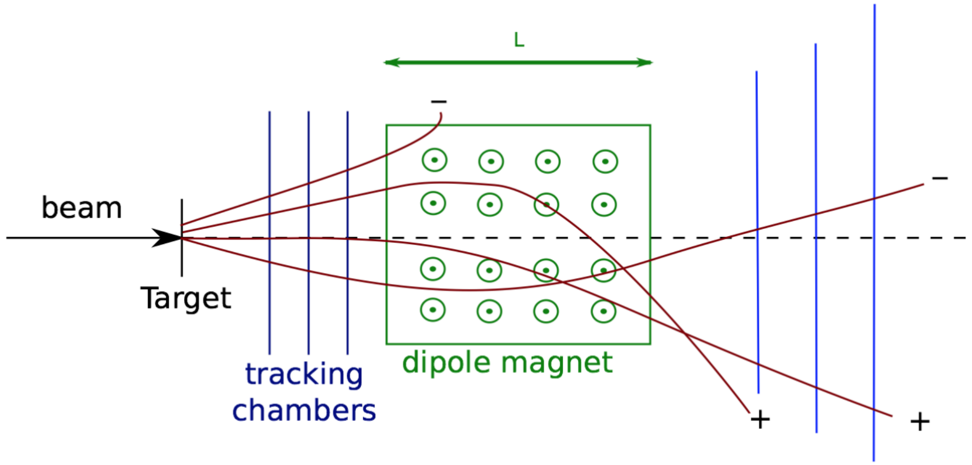
cylindrical tracking layers inside the magnet

Typical fixed-target experiment: dipole magnet

→ field lines orthogonal to beam

planar tracking detectors before and after the magnet





Momentum resolution (I)

“Gluckstern equation” for *N* equidistant measurements:

$$\frac{\sigma(p)}{p} = \sqrt{\frac{720}{N+4}} \cdot \sigma_x \cdot \frac{p}{0.3\, B\, L^2}$$

[NIM24(1963)381]

Relative momentum resolution

→ degrades linearly with increasing momentum

→ improves linearly with spatial resolution of the detector

→ improves linearly with the strength of the magnetic field

→ improves **quadratically** with the length of the measured track segment

Main reason for the large size of high-energy physics experiments

FROM MGA TO NUST MISIS 100 YEARS 1918-2018 OPENING A NEW CENTURY

MISIS National University of Science and Technology

SHiP Search for Hidden Particles

LHCb

University of Zurich^{UZH}

Momentum resolution (II)

Particle trajectory disturbed due to multiple scattering in the material of the detector

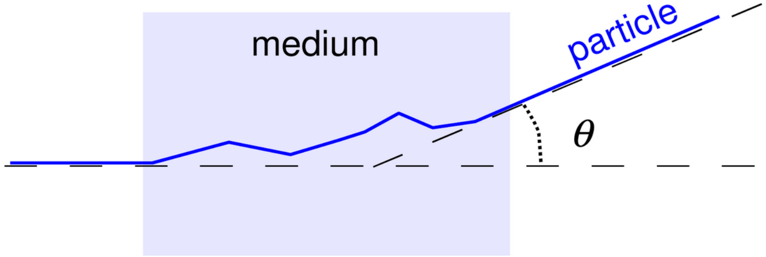
Causes deterioration of momentum resolution

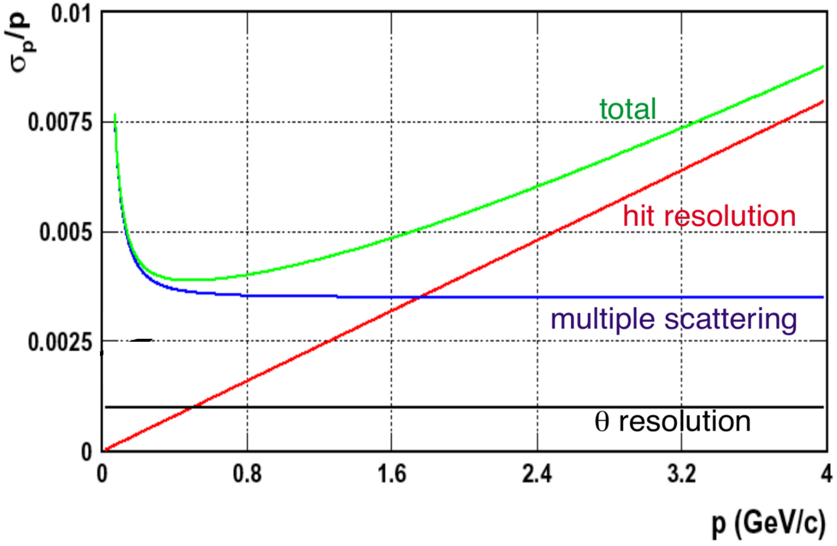
$$\frac{\sigma(p)}{p} = \frac{0.2 \cdot \sqrt{L/X_0}}{\beta \cdot B \cdot L}$$

→ limits momentum resolution at low momenta (small β)

→ material often dominated by supports, cables, etc

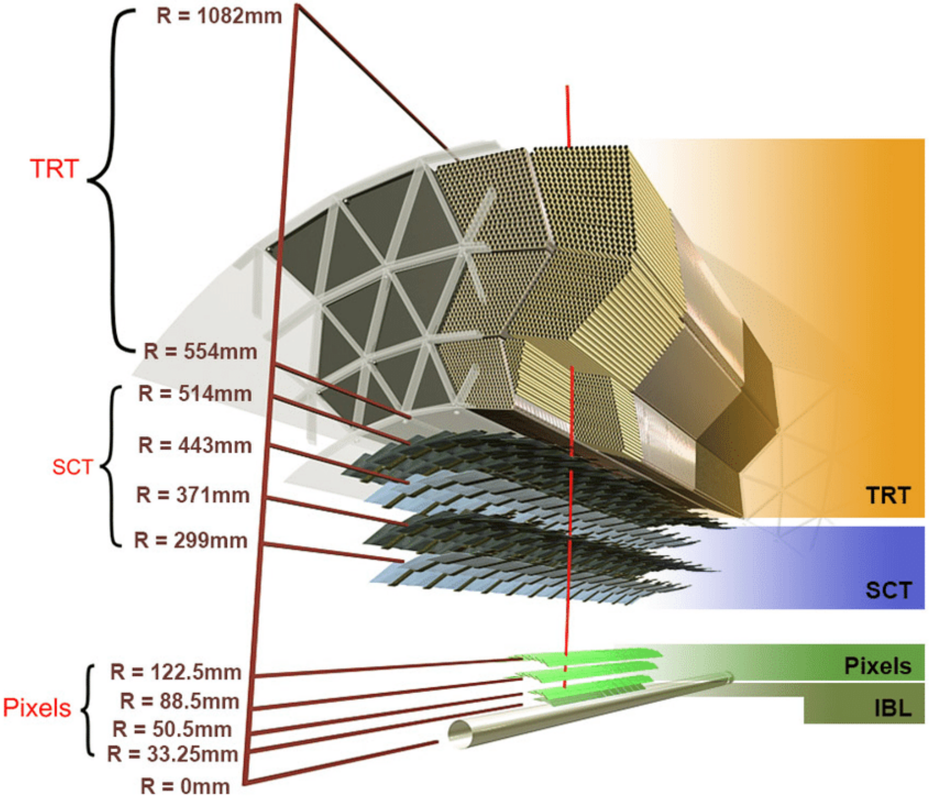
(“dead material”)



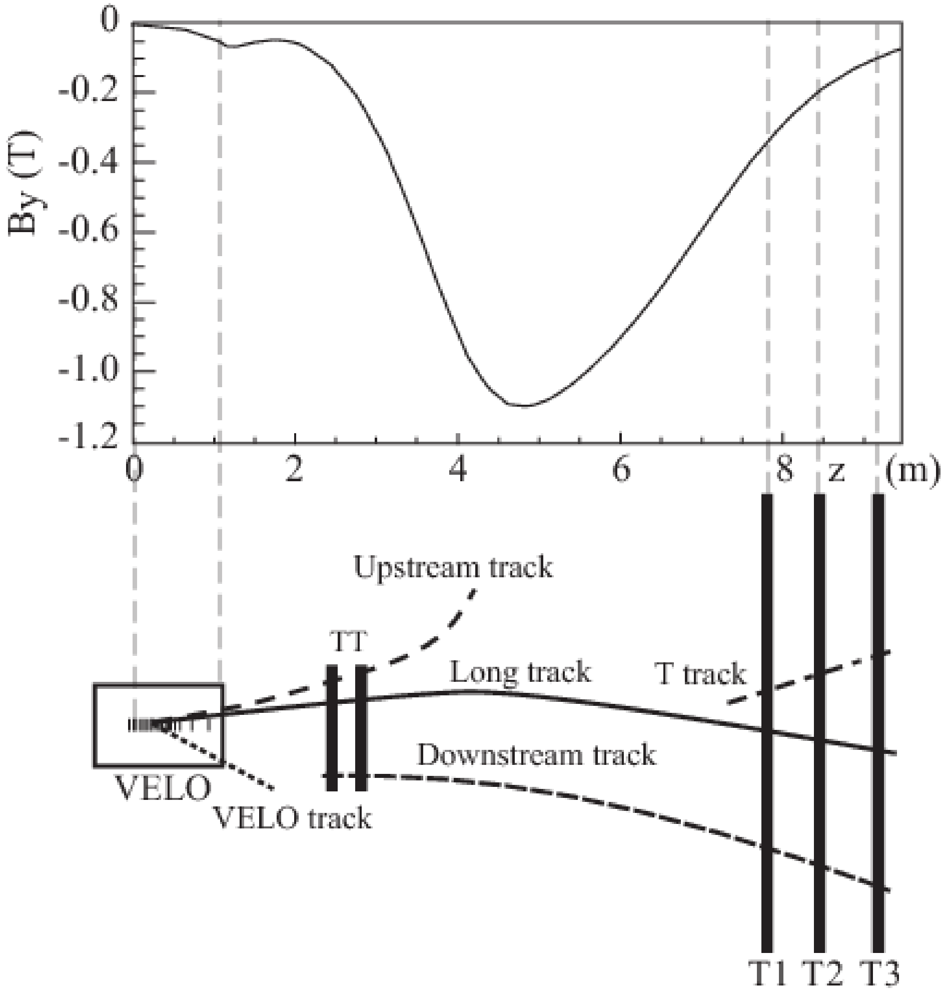


Momentum resolution (III)

ATLAS tracking system

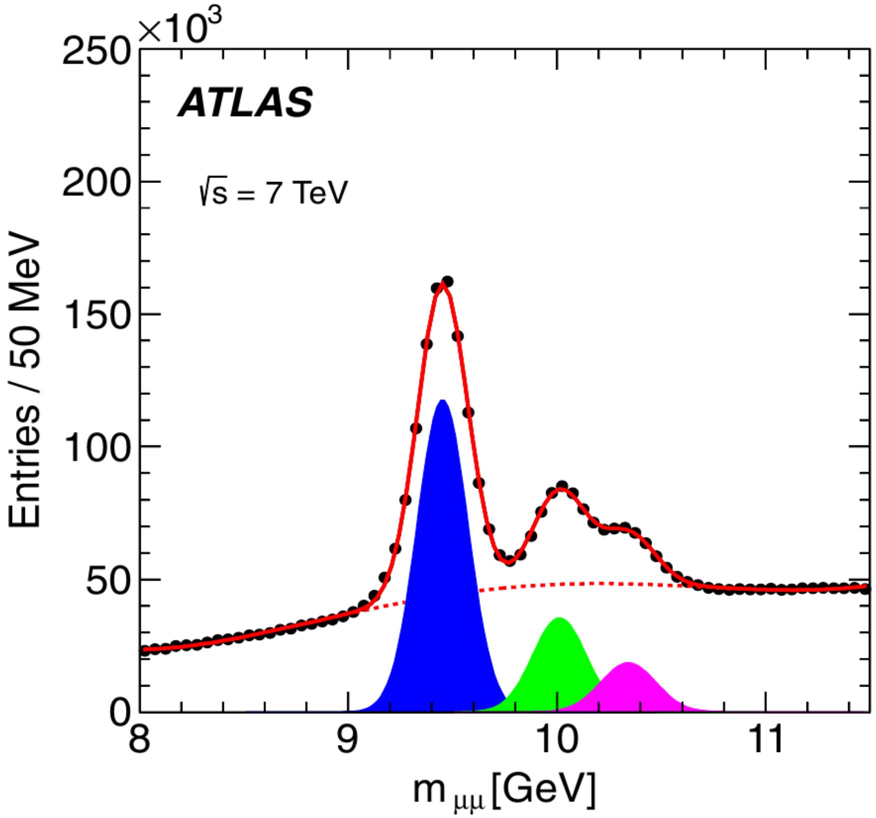


LHCb tracking system



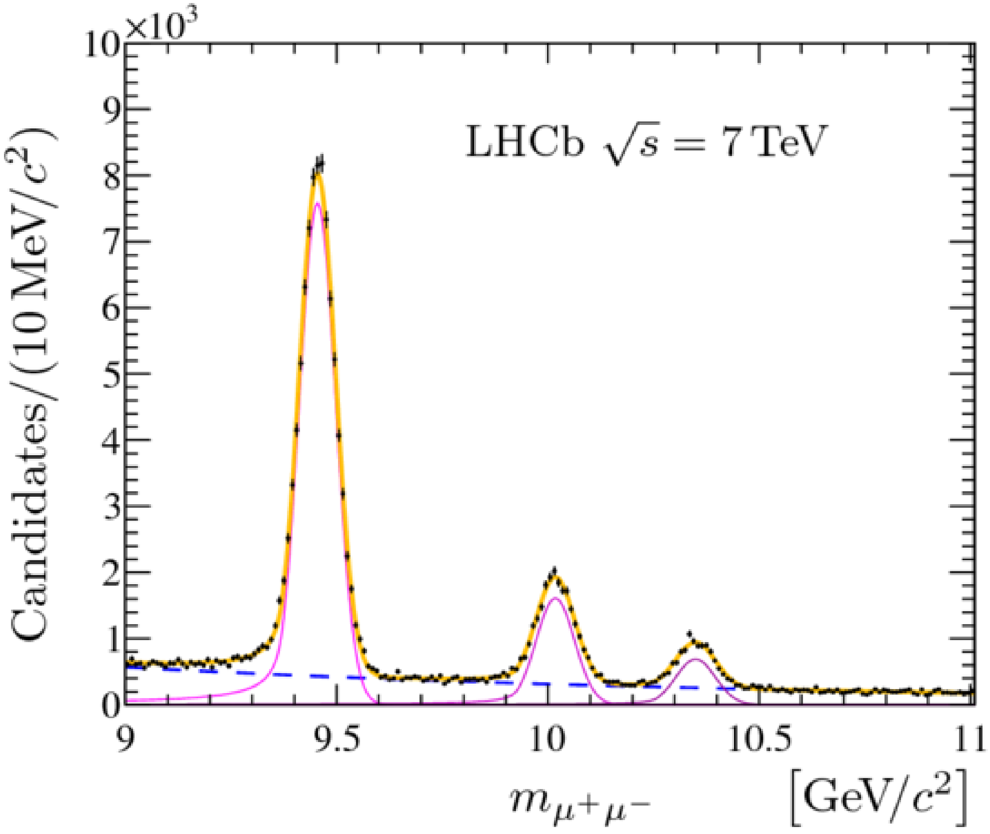
Momentum resolution (IV)

ϒ resonances in ATLAS



[PRD87(2013)052004]

ϒ resonances in LHCb



[JHEP(2015)103]

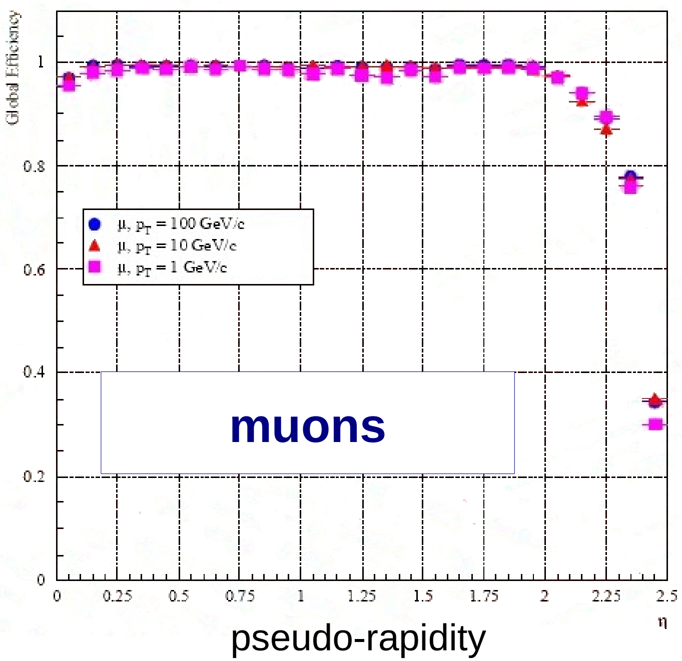
Hadronic Interactions

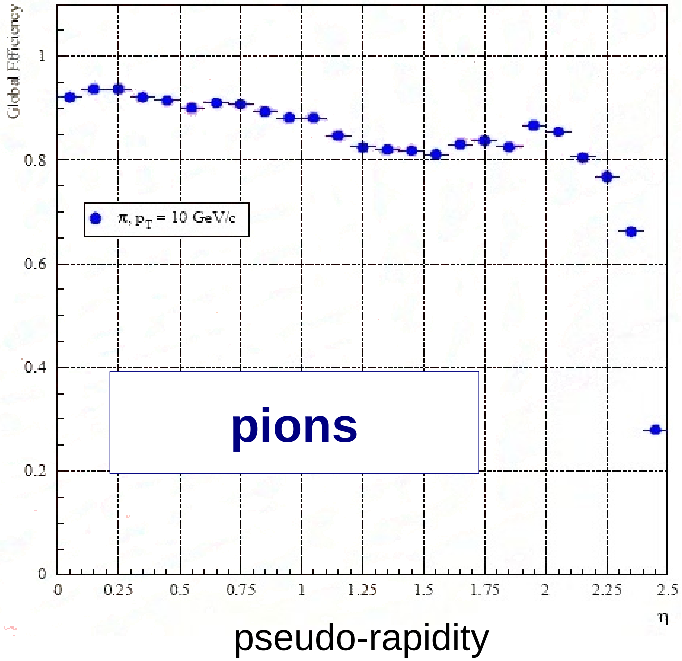
Hadrons also undergo nuclear interactions in detector material

→ large kink in trajectory or shower of secondary particles

→ loss in reconstruction efficiency

Example CMS:





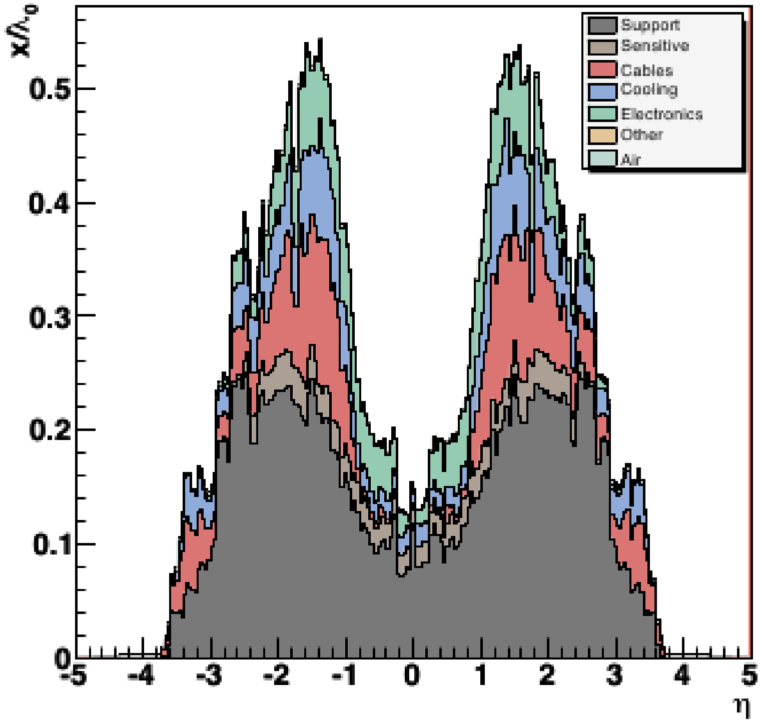
Hadronic Interactions

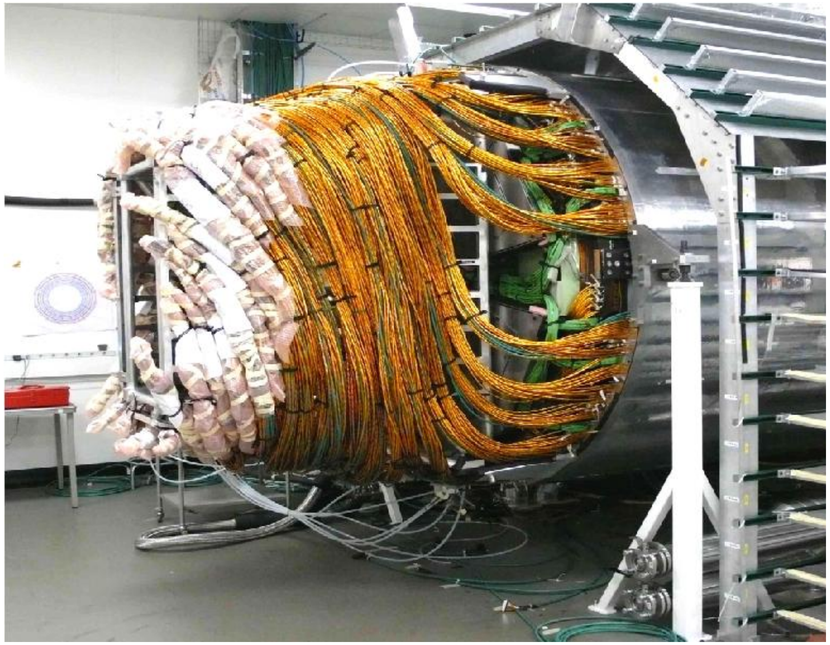
Hadrons also undergo nuclear interactions in detector material

→ large kink in trajectory or shower of secondary particles

→ loss in reconstruction efficiency

Example CMS:





Requirements

Spatial hit resolution

→ vertex resolution, momentum resolution, …

Granularity

→ ability to separate two particles that pass the detector close in space

Rate capability

→ ability to separate two particles that pass the detector close in time

Material budget

→ minimize multiple scattering, hadronic interactions

Radiation hardness

→ performance degradation from degradation of detector material

Cost !!!

→ often dominated by readout electronics

(number of channels, amount of information per channel)

Requirements

Close to interaction point: highest particle density …

→ need fine granularity, excellent position resolution, radiation hardness

… but small tracking volume

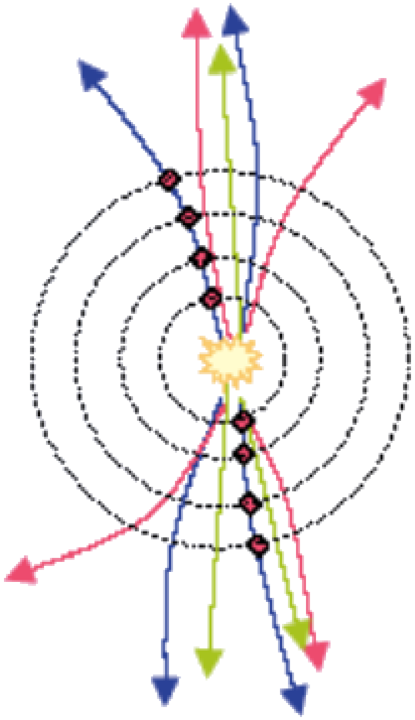
→ can afford expensive detectors with fine granularity, many readout channels

Further away: large tracking volume …

→ need cost effective detector

… **but lower particle density**

→ can afford coarser granularity, lower position resolution



Early tracking detectors

E.g. cloud chamber (Wilson, 1912**):**

Vessel filled with supersaturated water vapour

→ charged particle creates ionisation clusters

→ ionisation clusters act as condensation nuclei

→ trail of water droplets along particle trajectory

Photograph trails through windows in the vessel

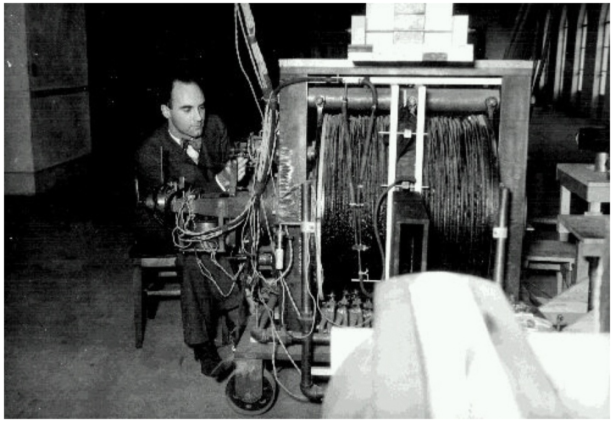
→ spatial resolution ~ 100 µm

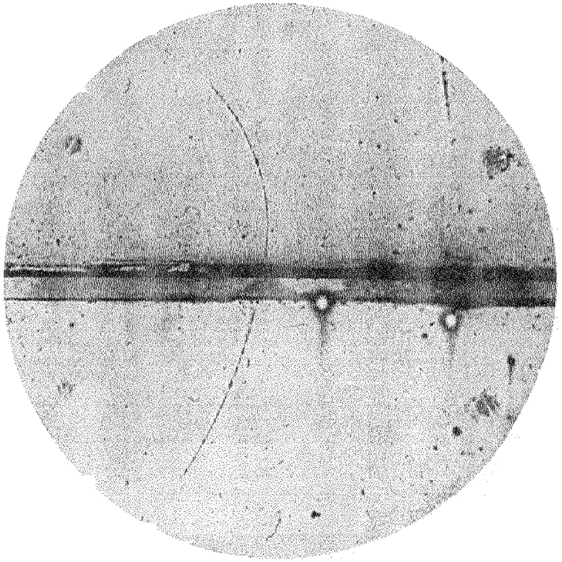
→ estimate particle energy from density of droplets

Most important experimental tool until 1950s, but

→ low rate capability

→ tedious manual analysis of photographs





discovery of positron (Anderson, 1932)

Modern tracking detectors

Charged particle interacts with detector material

→ creates free charge carriers (e.g. by ionization)

Apply electric field across detector volume

→ collect charges on segmented electrodes

Electronically amplify & shape signal pulse

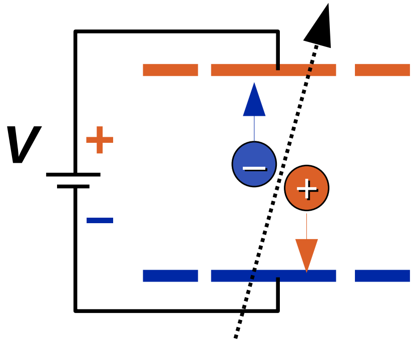
Digitize the signal

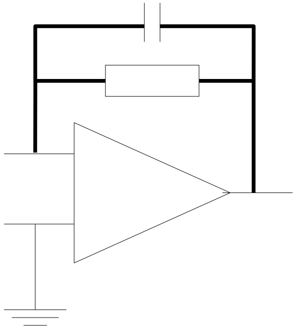
→ discriminator: hit / no hit

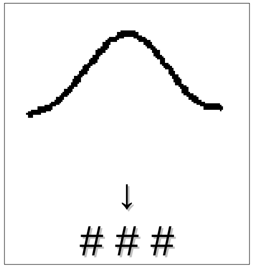
→ ADC: encode pulse height

→ TDC: encode signal arrival time

Transfer digital data to a computer farm for processing and storage







Gaseous tracking detectors

Cylindrical tube, filled with gas mixture, thin wire strung along its centre

High voltage (typically 1– 2 kV**) between wire and outer wall**

Charged particle ionizes gas atoms

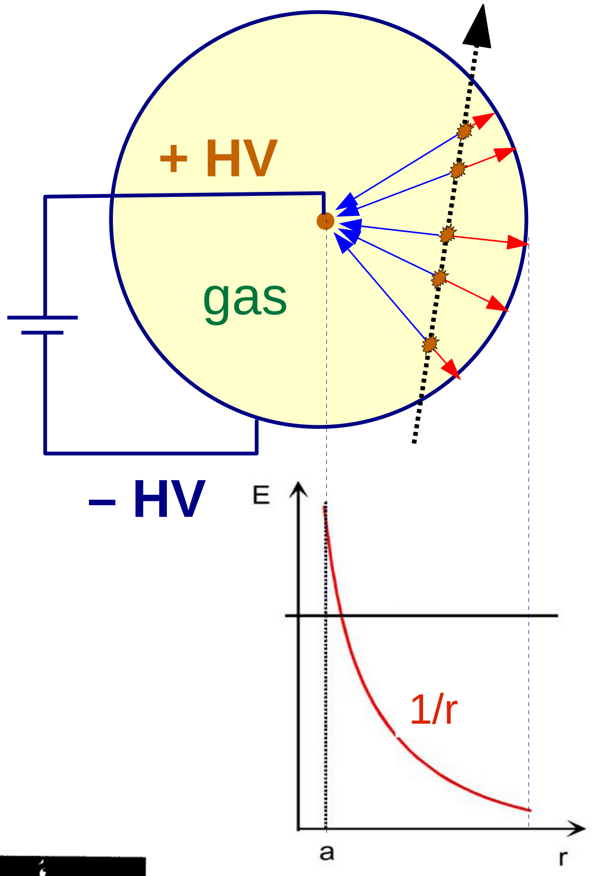
→ electrons drift towards the wire

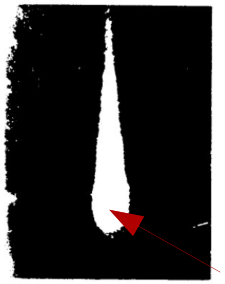
Very high electric field close to the wire

→ electrons gain enough energy to ionize secondary atoms

→ charge avalanche

→ measurable voltage pulse on wire

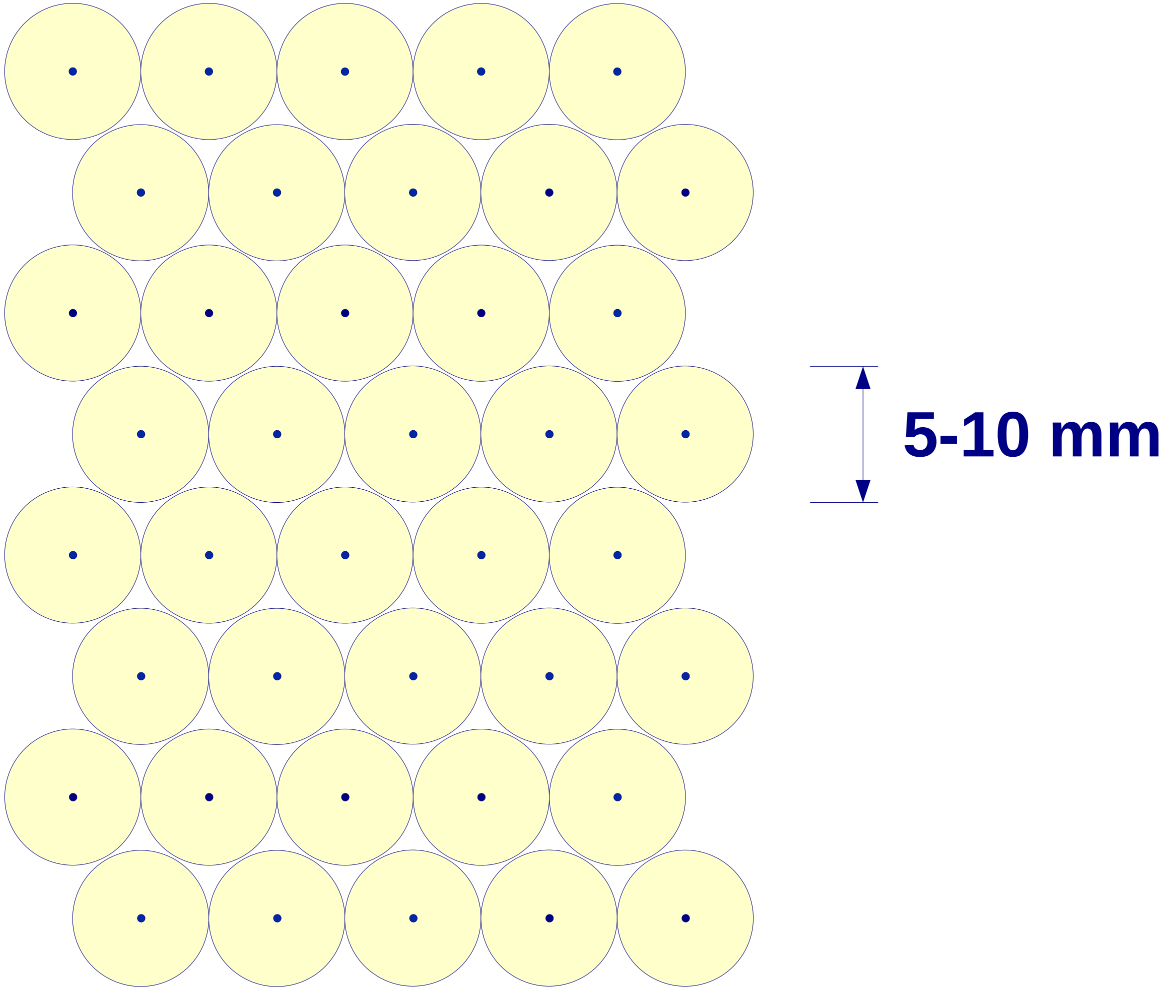




photograph of a charge avalanche

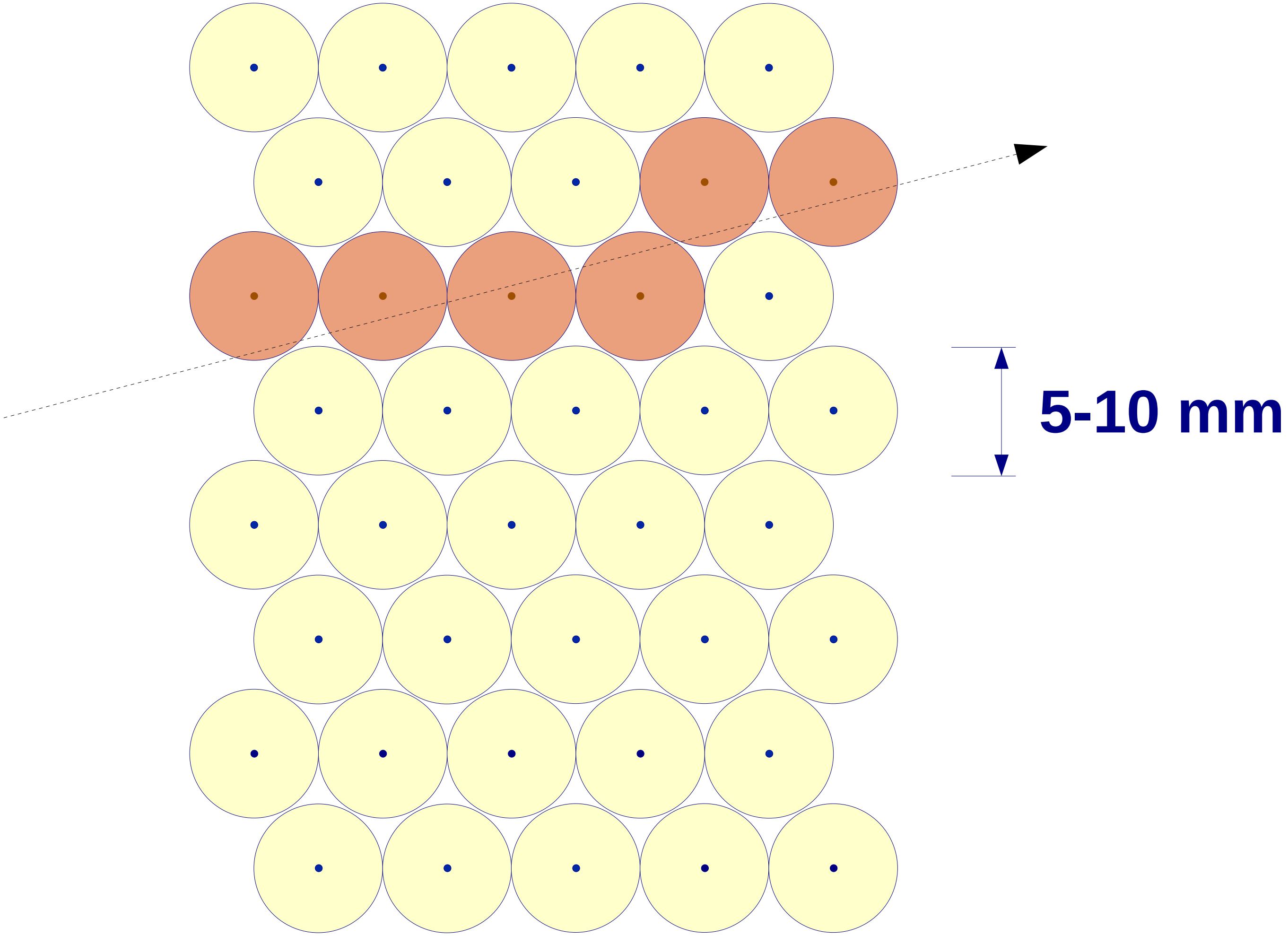
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



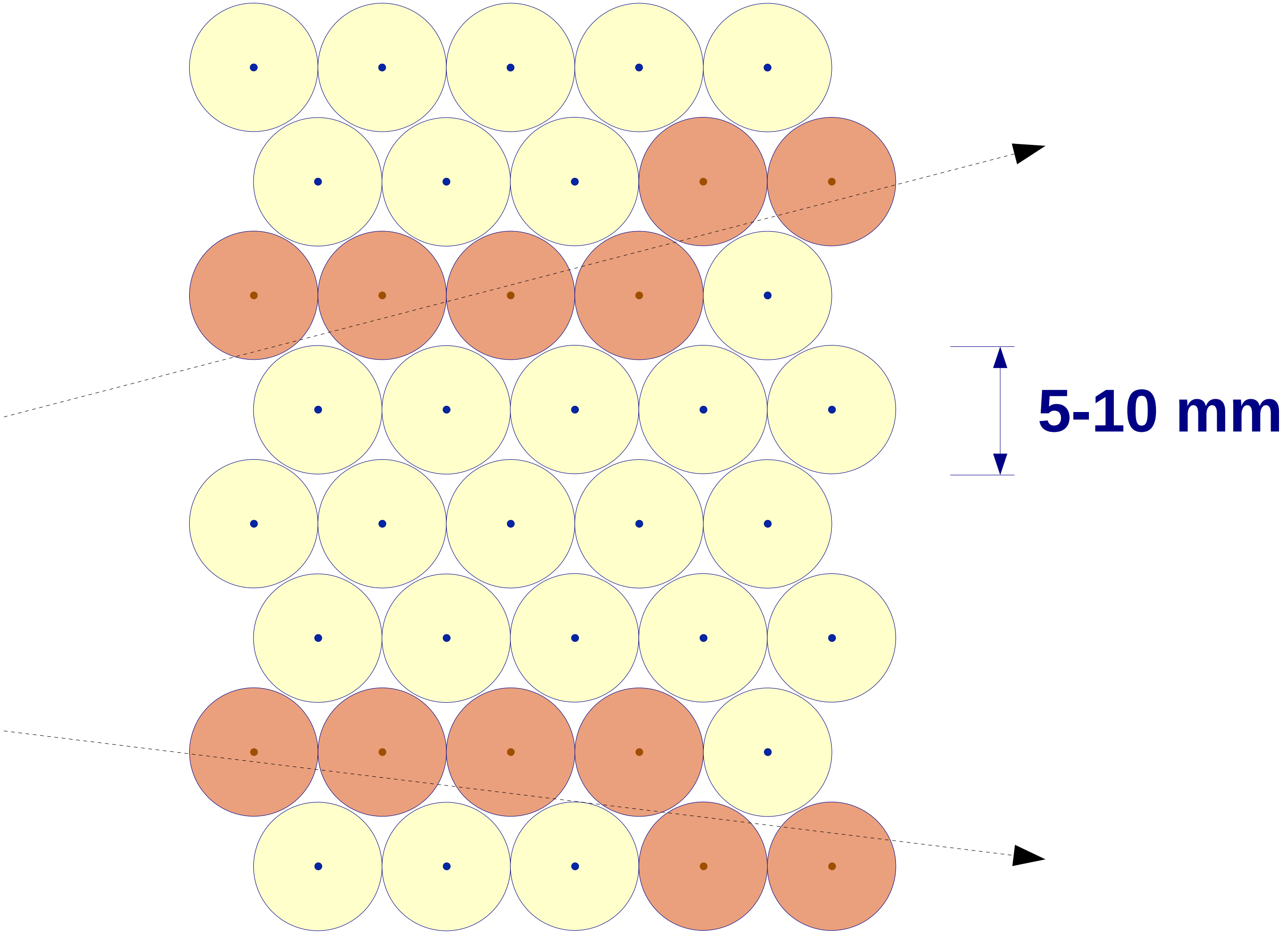
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes



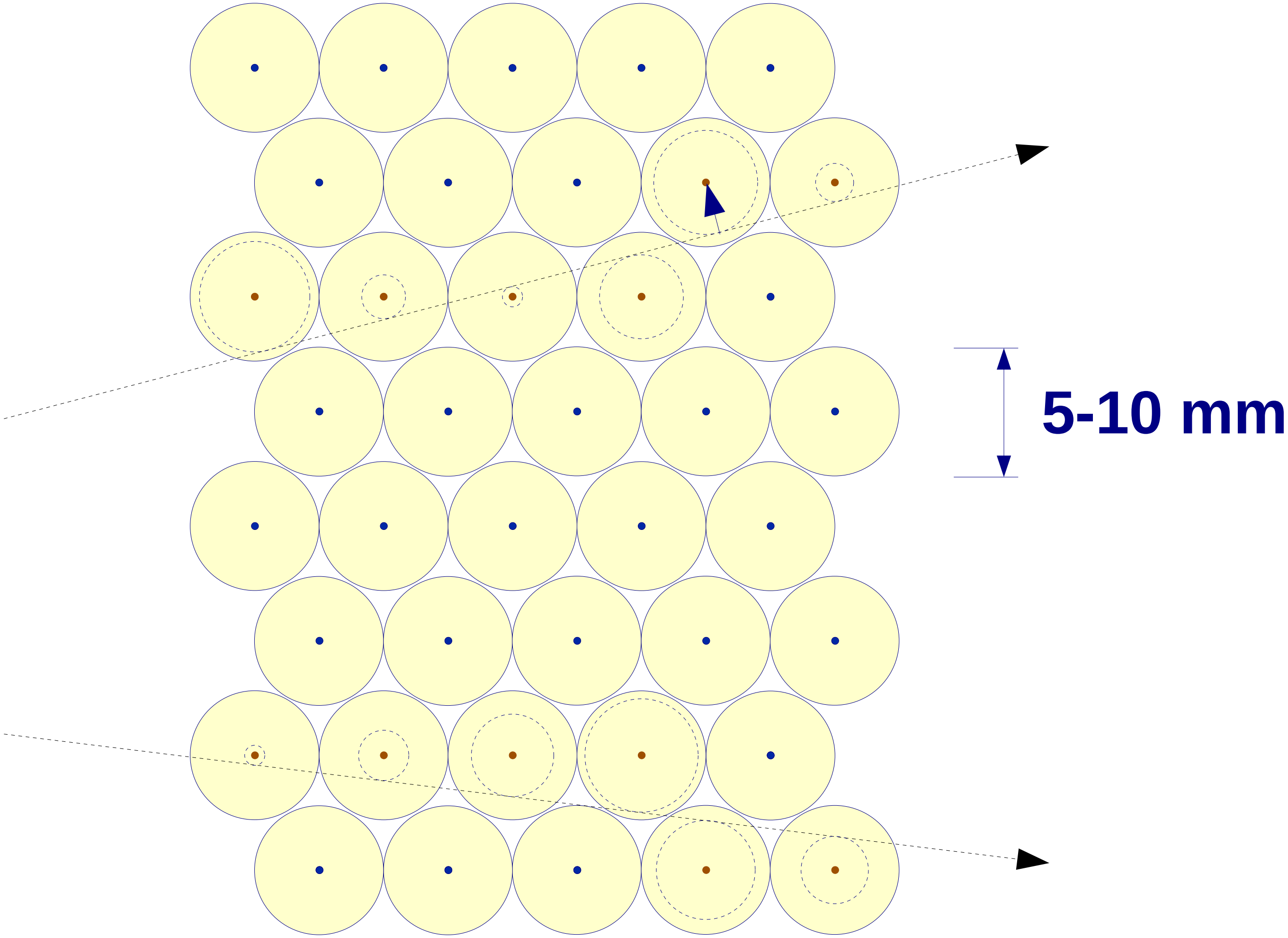
Gaseous tracking detectors

Tracking detector: several layers of such drift tubes

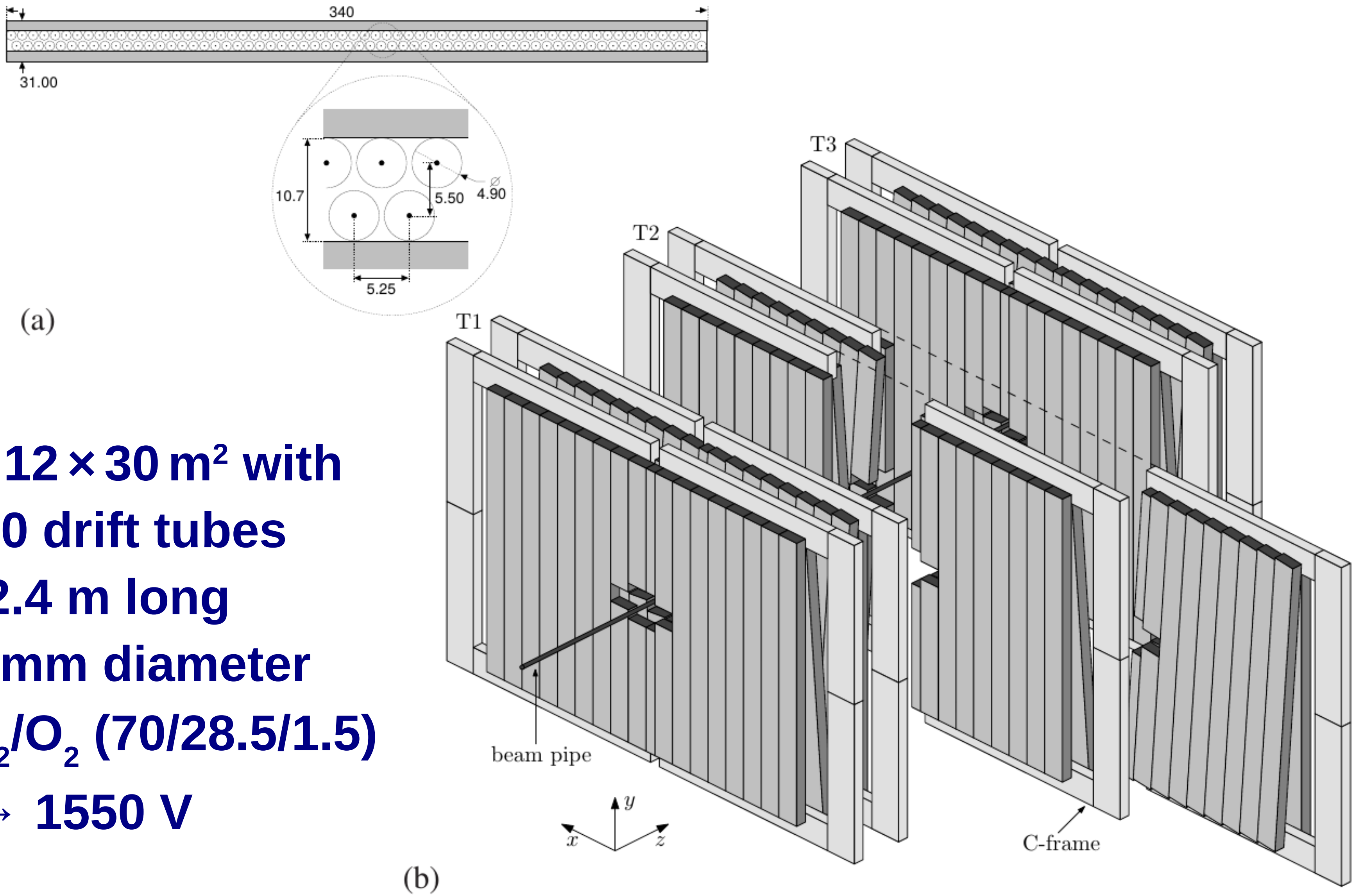


Gaseous tracking detectors

Measure drift time of electrons → < 200 μm spatial resolution



LHCb Outer Tracker



Covers 12 × 30 m^2 with 53’760 drift tubes

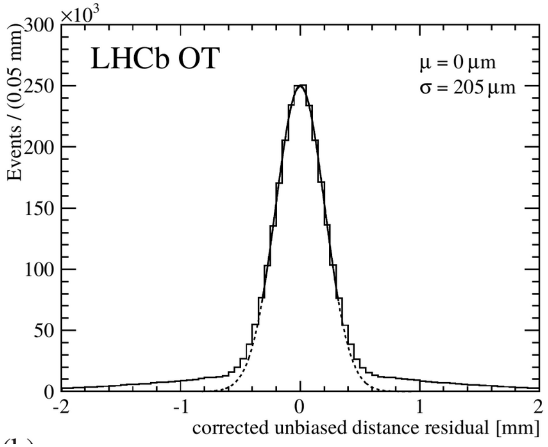
→ 2.4 m long

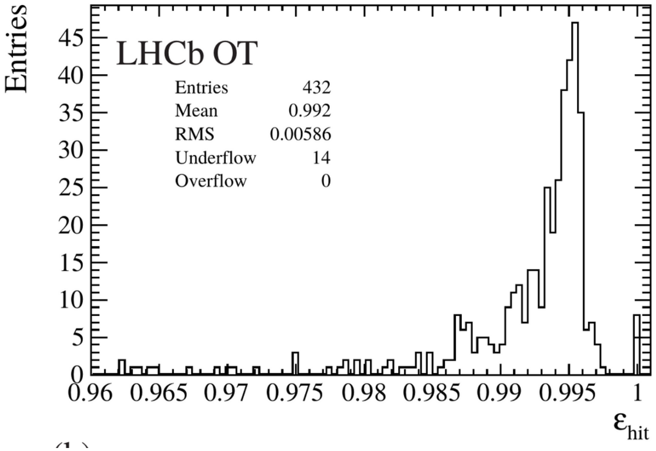
→ 4.9 mm diameter

→ Ar/CO$_2$/O$_2$ (70/28.5/1.5)

→ 1550 V

Gaseous tracking detectors





→ operated reliably

→ good spatial resolution ≈ 200 μm

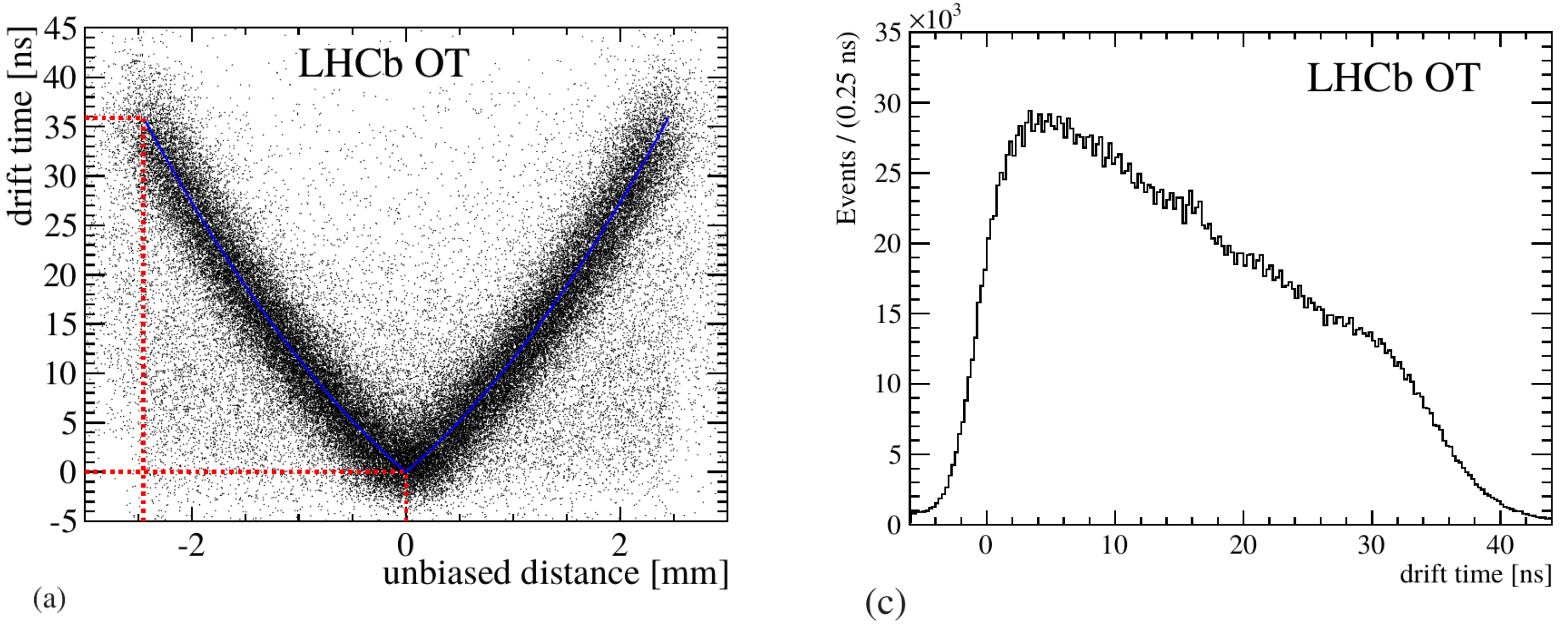
→ good hit efficiency > 99 %

→ is being replaced by a scintillating fibre tracker in the ongoing LHCb upgrade

LHCb Outer Tracker

Drift time of electrons up to ≈ 40 ns,
but bunch crossings at the LHC every 25 ns

→ read out overlapping events

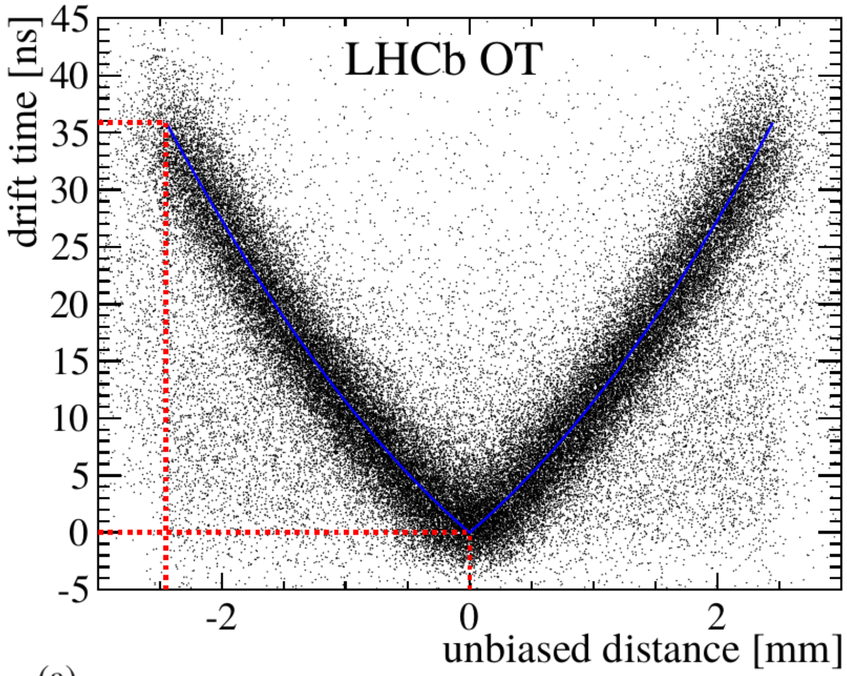


[JINST9(2014)P01002]

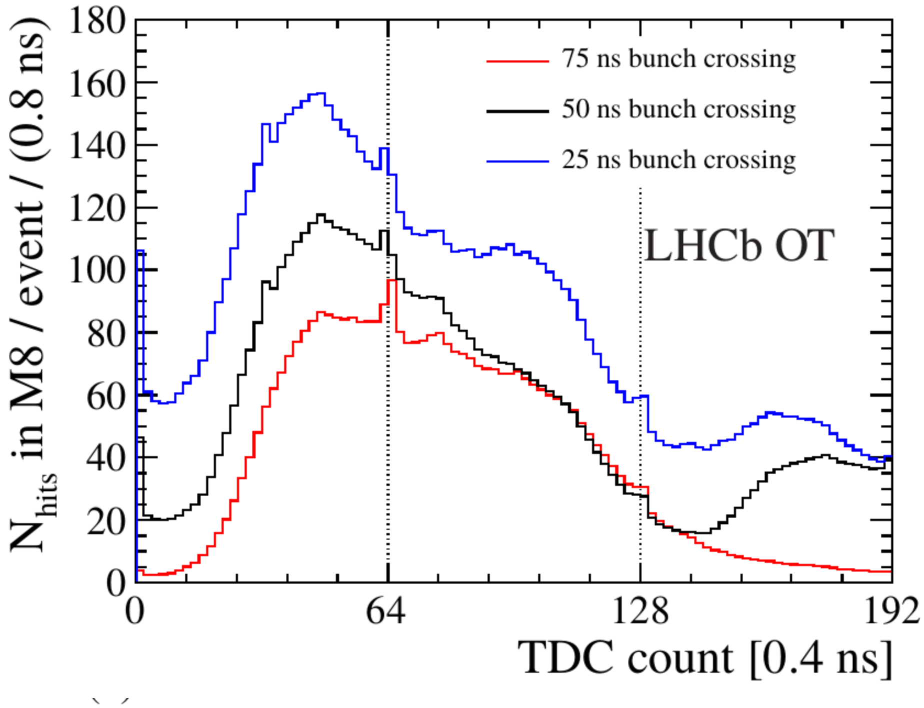
LHCb Outer Tracker

Drift time of electrons up to ≈ 40 ns,
but bunch crossings at the LHC every 25 ns

→ read out overlapping events



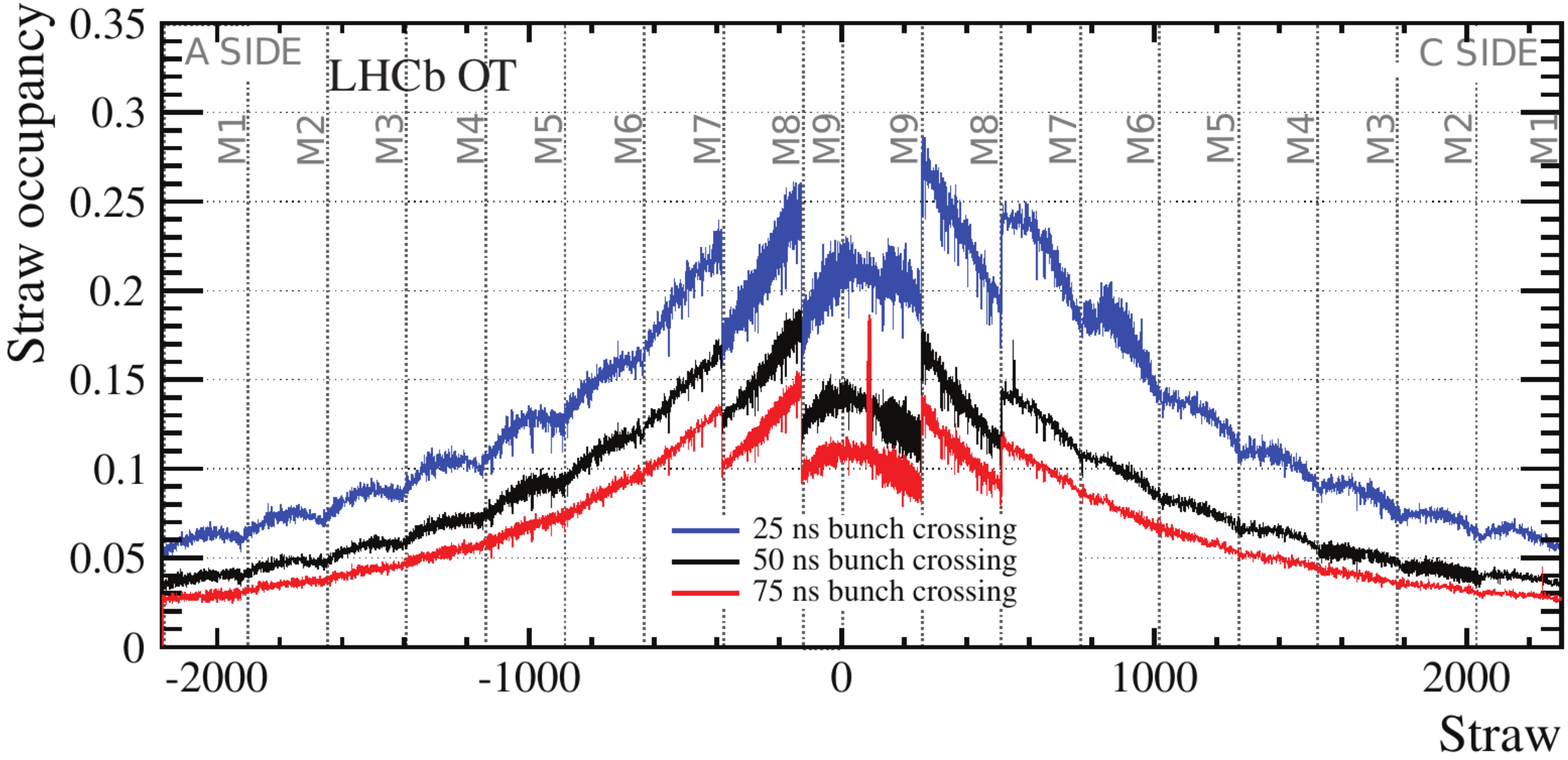
(a)



[JINST9(2014)P01002]

LHCb Outer Tracker

Occupancy in the inner part of the detector
→ up to one in 4 straws is hit on average
→ at the limit for efficient track reconstruction



[JINST9(2014)P01002]

MISIS National University of Science and Technology

SHiP

LHCb

University of Zurich

LHCb Outer Tracker

Primary ionization is a statistical process, discrete ionization clusters generated along the particle trajectory

Number of clusters for a given pathlength follows a Poisson distribution

$$P(k\,|\,\mu) = \frac{\mu^k}{k!} \cdot e^{-\mu}$$

→ probability to create at least one cluster

$$\varepsilon = 1 - P(0\,|\,\mu) = 1 - e^{-\mu}$$

→ for detection efficiency $\varepsilon > 99\%$ need $\mu \geq 5$

Gas	Density ρ [g/cm³]	I_0 [eV]	W [eV]	n_P [cm⁻¹]	n_T [cm⁻¹]
H_2	8.99×10^{-5}	15.4	37	5.2	9.2
He	1.78×10^{-4}	24.6	41	5.9	7.8
N_2	1.23×10^{-3}	15.5	35	10	56
O_2	1.43×10^{-3}	12.2	31	22	73
Ne	9.00×10^{-4}	21.6	36	12	39
Ar	1.78×10^{-3}	15.8	26	29	94
Kr	3.74×10^{-3}	14.0	24	22	192
Xe	5.89×10^{-3}	12.1	22	44	307
CO_2	1.98×10^{-3}	13.7	33	34	91
CH_4	7.17×10^{-4}	13.1	28	16	53
C_4H_{10}	2.67×10^{-3}	10.8	23	46	195

For Argon (at 1 bar**):** μ **= 29 primary clusters / cm**

→ need ≥ 1.7 mm path length to reach $\varepsilon \geq 99\%$

→ need drift cell with ≥ 5 mm diameter

Wire Ageing

Creation of chemical radicals in the charge avalanche close to the wire

→ polymerization of carbohydrates

Formation of deposits on wires

→ loss of gas gain

Formation of whiskers

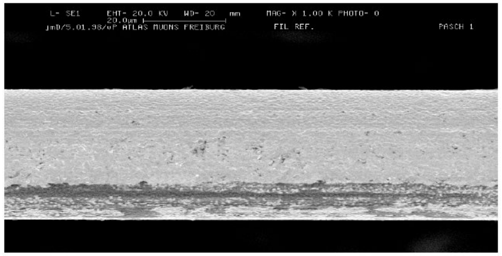
→ discharges, noise, HV breakdown

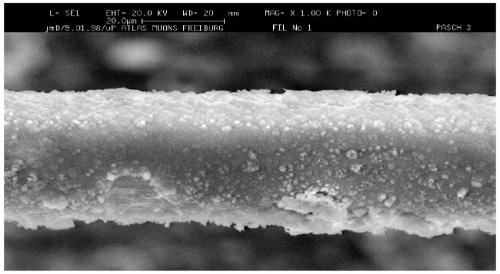
Very small contamination of the drift gas can have disastrous consequences

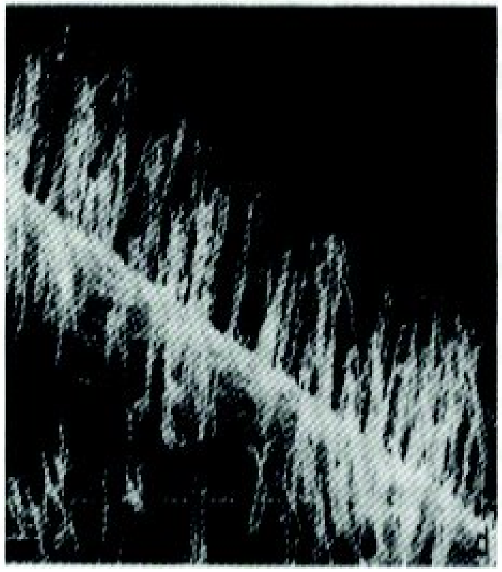
→ typical problem: outgassing of glues

Extensive studies, lists of “allowed” materials

→ but one mistake can destroy the detector







Micro-Pattern Gaseous Detectors

Gas Electron Multiplier (“GEM”**):**

Thin Kapton foil

(electrically insulating polyimide film **)**

with copper coating on both sides

Regular array of fine holes

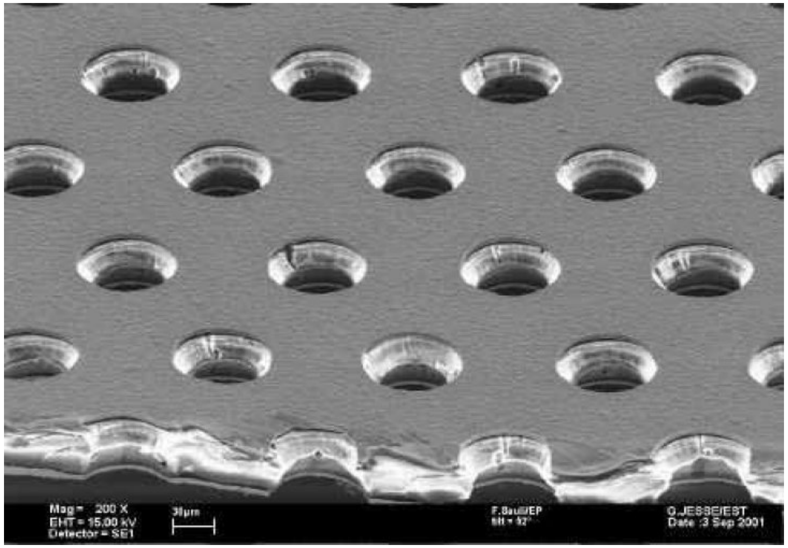
(75 μm Ø, 140 μm distance **)**

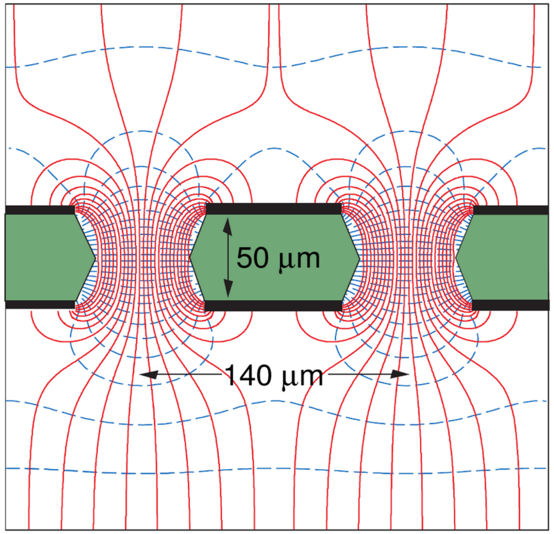
etched through the foil

Voltage applied between the two sides

→ high electric field inside the holes

→ gas amplification





Micro-Pattern Gaseous Detectors

Readout granularity independent of the thickness of the gas layer

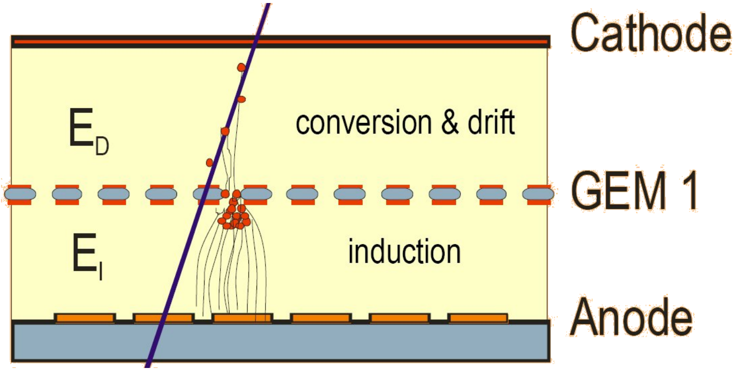
No wires → no wire ageing

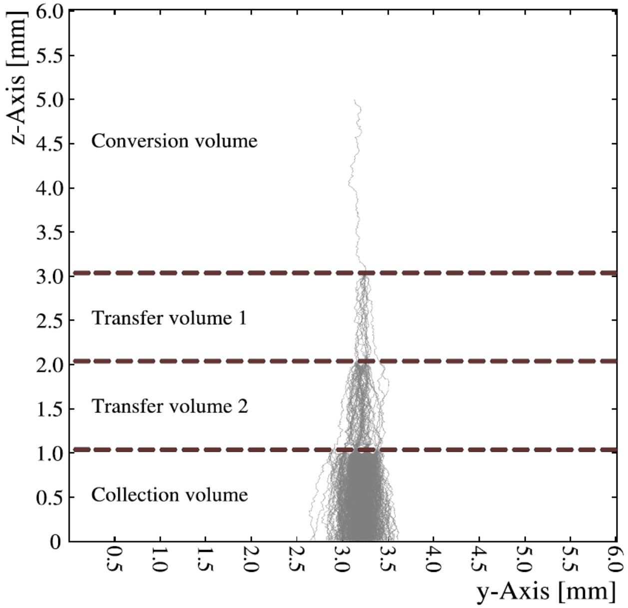
Usually stack several GEM foils to obtain high gas gain with low voltage

Triple-GEM detectors e.g. employed in inner part of LHCb muon system

415 V per GEM foil → total gain ~ 4’300

Disadvantage: inclined tracks can give signals on many readout strips





gas gain, e.g.

~ 20

~ 20

~ 20

~ 8000

Silicon tracking detectors

Segmented reverse biased *p*–*n* junction (diode)

Simplest device: *n*–doped monocrystalline silicon wafer, *p*–doped implants at surface

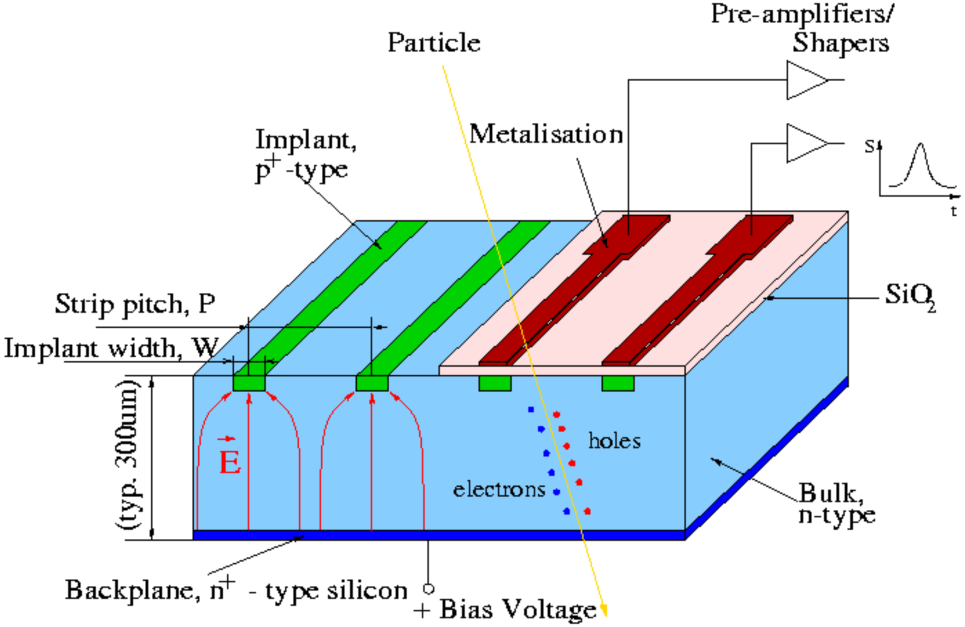
→ strips with pitch 250 – 20 µm

→ resolution 50 to a few µm

→ or pixels for even finer granularity

Apply reverse bias voltage

→ electric field through the wafer



Ionizing particle creates electron-hole pairs in the silicon lattice

→ electrons and holes drift to surface

→ induce signals on the *p*-doped implants

p-*n* Junction

***n*-side: doping with Group-V elements**

→ loosely bound electrons (*e*) in silicon lattice

***p*-side: doping with Group-III elements**

→ loosely bound “holes” (*h*) in silicon lattice

e/h density gradient across the junction

→ diffusion across the junction

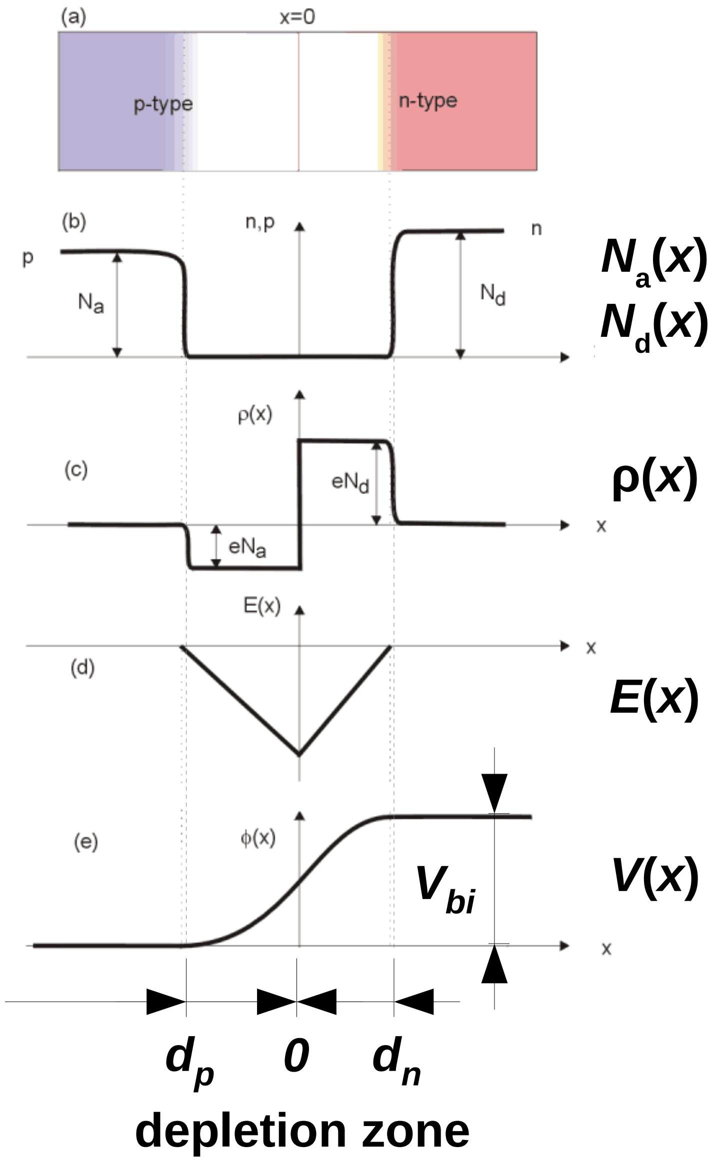
Depletion zone without free charge-carriers

→ *p*-side: *e* absorbed by acceptor atoms

→ *n*-side: *h* absorbed by donor atoms

Movement of electric charge

→ electric field across the junction



p-n Junction

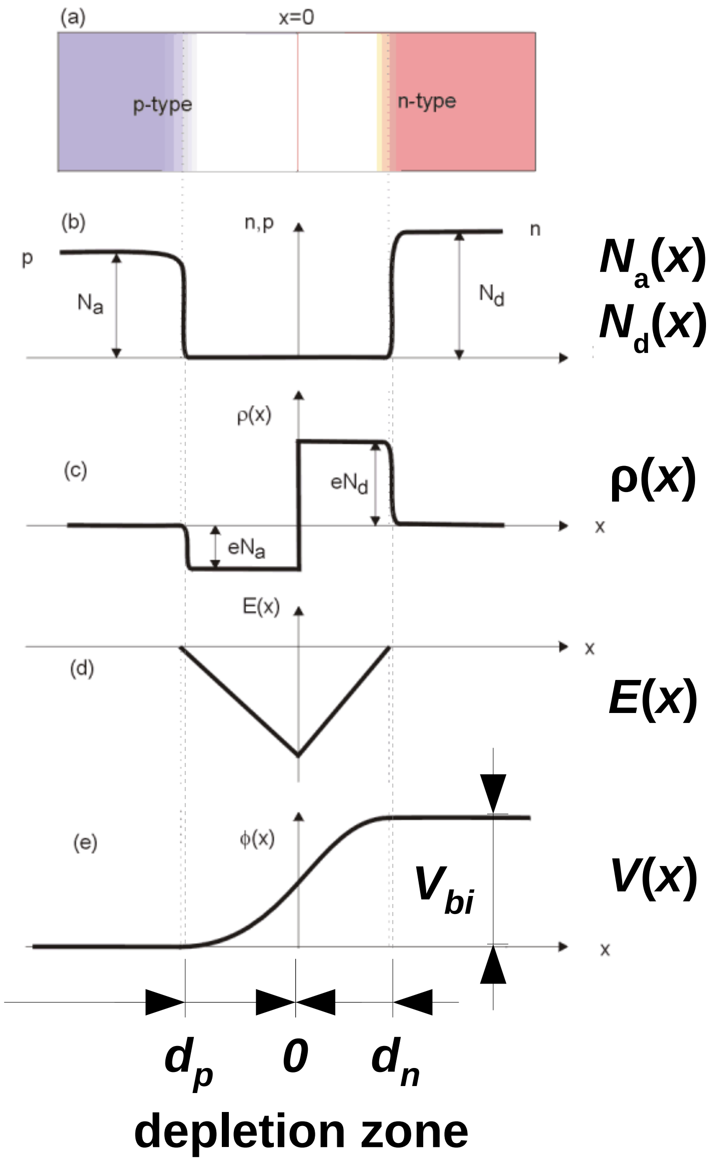
Equilibrium between diffusion and Coulomb force

Electric field and potential barrier from Coulomb equation

$$-\frac{d^2V}{dx^2} = \frac{dE}{dx} = \frac{\rho(x)}{\varepsilon}$$

→ intrinsic potential barrier and thickness of depletion zone:

$$V_{bi} = \frac{e}{2\varepsilon} \cdot \left(N_d\, d_n^2 + N_a\, d_p^2\right)$$



Asymmetric Junction

In a silicon detector, junction is between

→ bulk: few 100 μm thick

→ implants: few μm thin

Want depletion zone to extend into bulk

$$d_n\,(\text{bulk}) \gg d_p\,(\text{implant})$$

To achieve this, use charge conservation

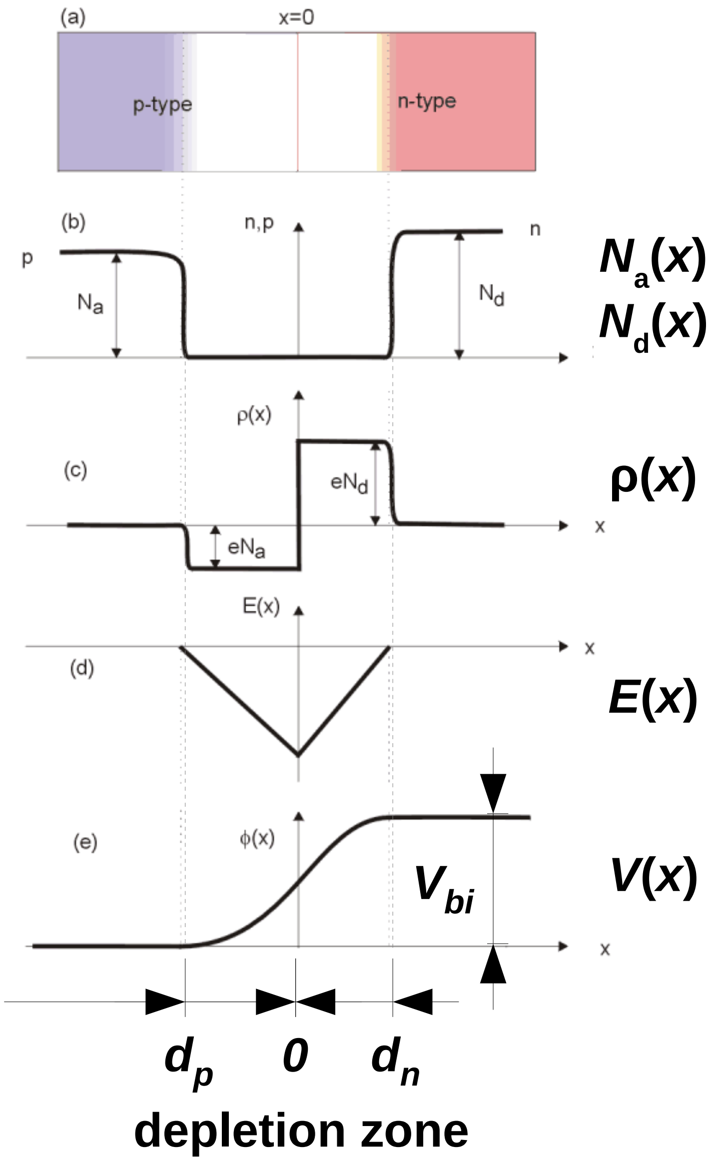
$$N_d\, d_n = N_a\, d_p$$

and make

$$N_a\,(\text{implant}) \gg N_d\,(\text{bulk})$$

For $d_n \gg d_p$:

$$V_{bi} = \frac{e}{2\varepsilon}\cdot N_d\, d_n^2 \;\Leftrightarrow\; d_n = \sqrt{\frac{2\varepsilon\, V_{bi}}{e}\cdot\frac{1}{N_d}}$$



Reverse-Biased Junction

Example: $N_d \approx \text{few} \times 10^{12}\,/\,\text{cm}^3$

$\rightarrow V_{\text{bi}} = 0.65\ \text{V},\ d_n \approx 25\ \mu\text{m}$

Apply an external voltage to increase the thickness of depletion zone

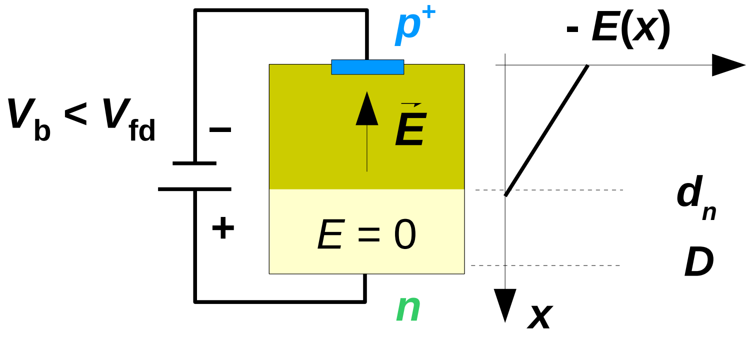
$$d_n = \sqrt{\frac{2\varepsilon\,(V_b + V_{\text{bi}})}{e} \cdot \frac{1}{N_{\text{d}}}}$$

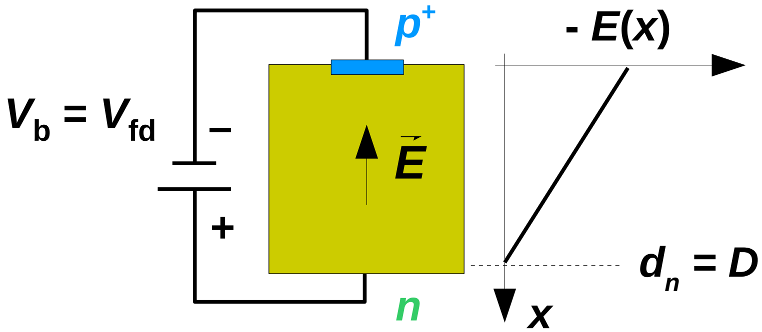
To fully deplete a detector of thickness *D*

$$V_{\text{fd}} = \frac{e}{2\varepsilon} \cdot N_{\text{d}} \cdot D^2$$

Example: $D = 300\ \mu\text{m},\ N_d \approx \text{few} \times 10^{12}\,/\,\text{cm}^3$

$$V_{\text{fd}} \approx 100\ \text{V}$$





Charge Collection

Drift velocity of charge carriers proportional to electric field *E*(*x*)

$$v(x) = \mu \cdot E(x)$$

with μ ≡ charge carrier "mobility"

≈ 1500 cm2 / Vs for electrons

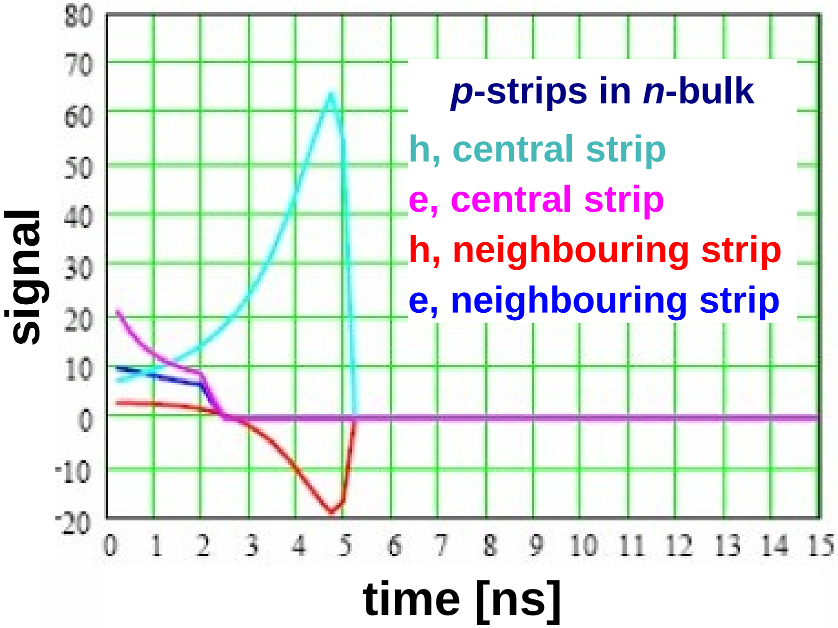
≈ 450 cm2 / Vs for holes

Maximum drift time (for $V_b \gg V_{fd}$ **)**

$$t_{\max} = \frac{D^2}{2\mu \cdot V_b}$$

Example: D = 300 µm, V_b = 200 V

$$t_{\max} \approx \begin{cases} 3.5\text{ ns for electrons} \\ 11\text{ ns for holes} \end{cases}$$



Signal on readout strips
induced by moving charge carriers
→ *h* drift towards the implant,
→ *e* drift towards backplane

Signal and Noise

“Signal” from charged particle

→ Landau distribution

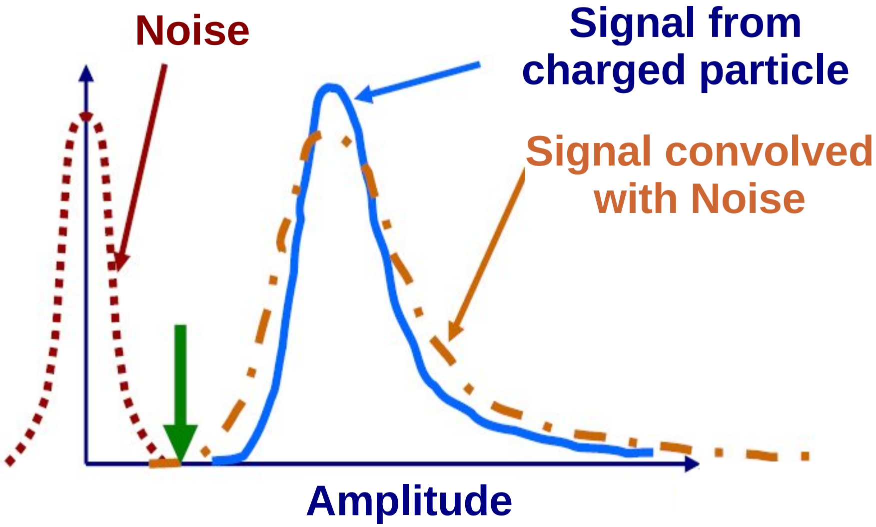
“Noise”, e.g. from electronics

→ Gaussian with mean zero

→ broadens also signal distribution

Cut on the measured amplitude

to select signal and suppress noise



For high detection efficiency at low rate of “noise hits” need clean separation between the distributions

Figure of merit: $S/N \equiv \dfrac{\text{most probable signal for mip}}{\text{rms of noise distribution}}$

Rule of thumb: need *S / N* > 10 for a working detector

Signal and Noise

Signal determined by $dE\,/\,dx$ of particle
and thickness of depletion zone

→ e.g. most probably signal of 22’500 *e*/*h* pairs
for a minimum-ionizing particle in a 300 µm thick detector

Various noise sources:

Fluctuations in leakage currents

→ operate at low temperature

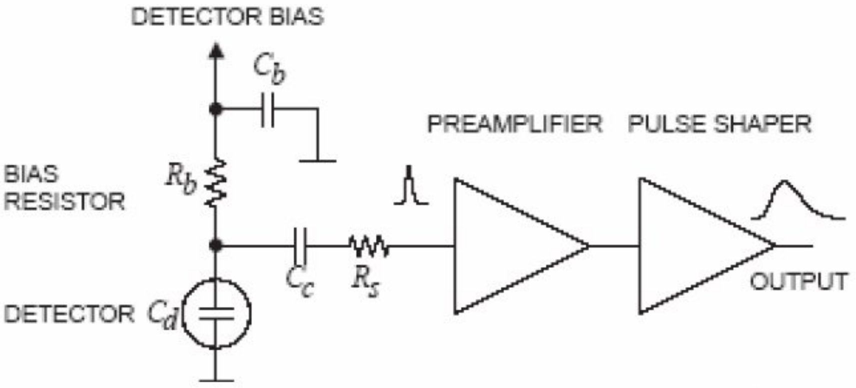
Voltage fluctuations in resistors

→ R_s as small as possible

→ R_b as large as possible

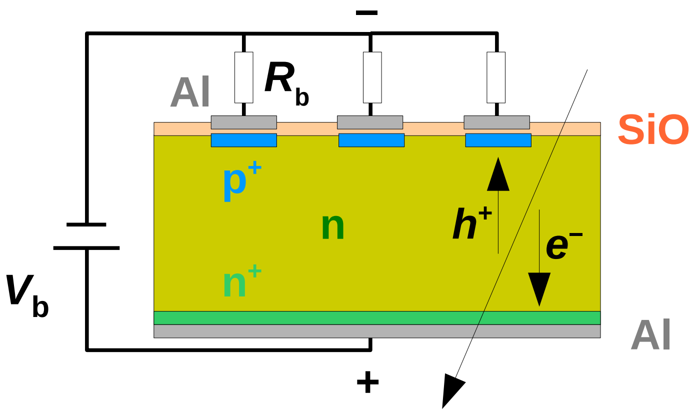
Detector capacitance

→ strip / pixel size



C_d: sensor capacitance to ground
R_b: bias resistor
C_C: AC coupling capacitance
R_s: serial resistance on signal path

Silicon Strip Detector



Basic features of a *p*-in-*n* strip sensor

metallization of readout strips and backplane

reduce electric resistance (R_s) along signal path

thin SiO layer between implants and metal strips

isolate readout amplifier from leakage currents through detector bulk (“AC coupled readout”)

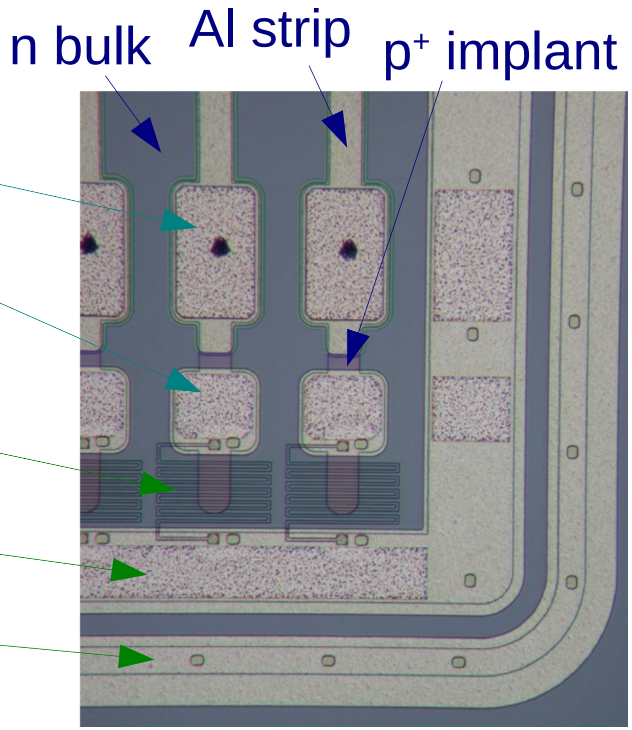
bond pads: connect metal strip to readout electronics

DC pads: ohmic contact to p^+ implant, for test purposes

bias resistors: connect p^+ implants to bias ring, but insulate implants from each other

bias ring: connect to external bias voltage

guard ring(s): shape electric field close to the edge of the sensor, avoid discharges to backplane



Pixel Detectors

Readout implants segmented into pixels (typically $\approx 50 \times 500\,\mu m^2$ **)**

Finer segmentation

→ higher rate capability

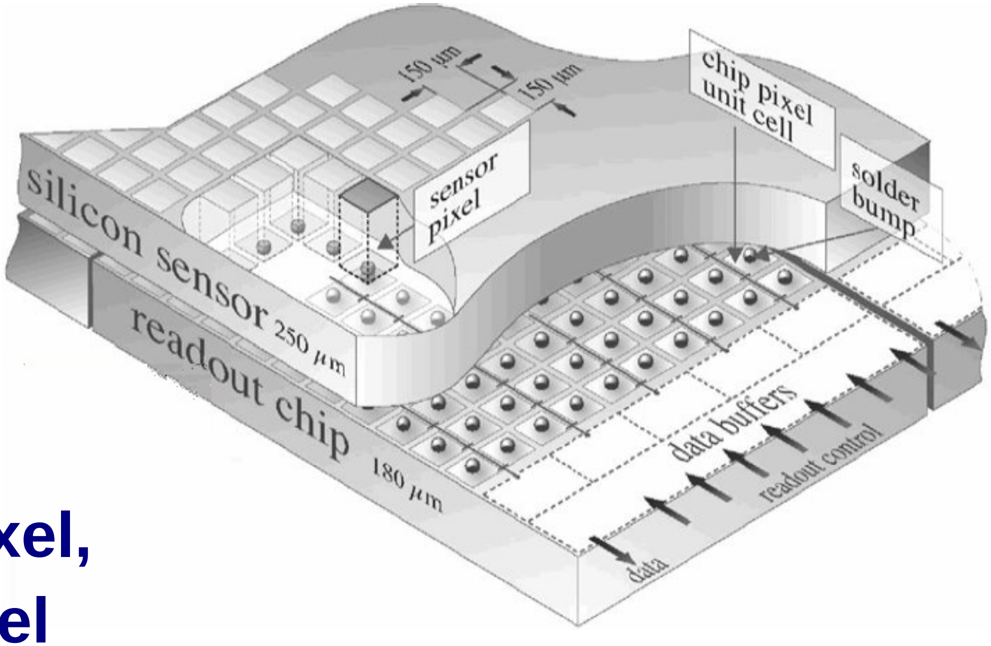
Smaller cell size

→ lower noise

Measure both coordinates

→ easier for track reconstruction

Need readout amplifier for each pixel, located directly on top of the pixel



Hybrid detector: two wafers mounted back-to-back

1st wafer: pixel sensor, 2nd wafer: readout electronics

electrical connection by “bump bonding”

Monolithic Pixels

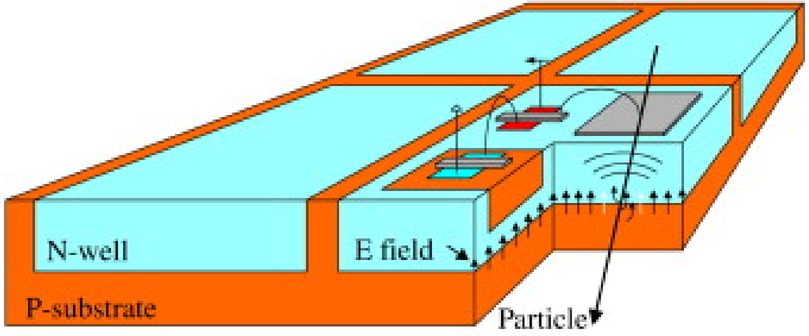
Integrate detector and front-end electronics in one wafer

Smaller capacitance → lower noise

→ do not need large signal

→ can make detectors very thin

→ do not need large bias voltage



Example: High-Voltage CMOS

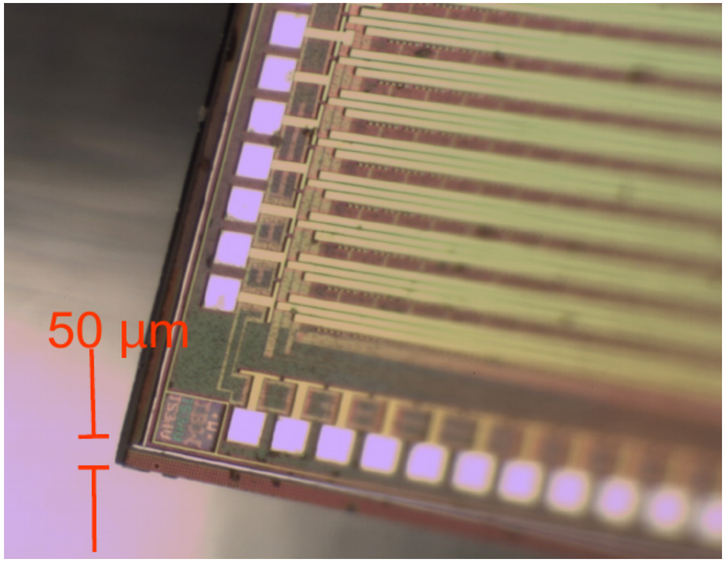
→ process developed for automobile industry

→ allows to apply voltages up to 100 V

Developed for µ3e experiment at PSI:

→ thickness 50 µm, pixels ≈ 80 × 80 µm^2

Envisaged for LHCb upgrade 1b and 2



Low-Gain Avalanche Detectors

Thin, highly doped “gain layer” underneath each readout implant

→ high electric field
→ charge avalanche

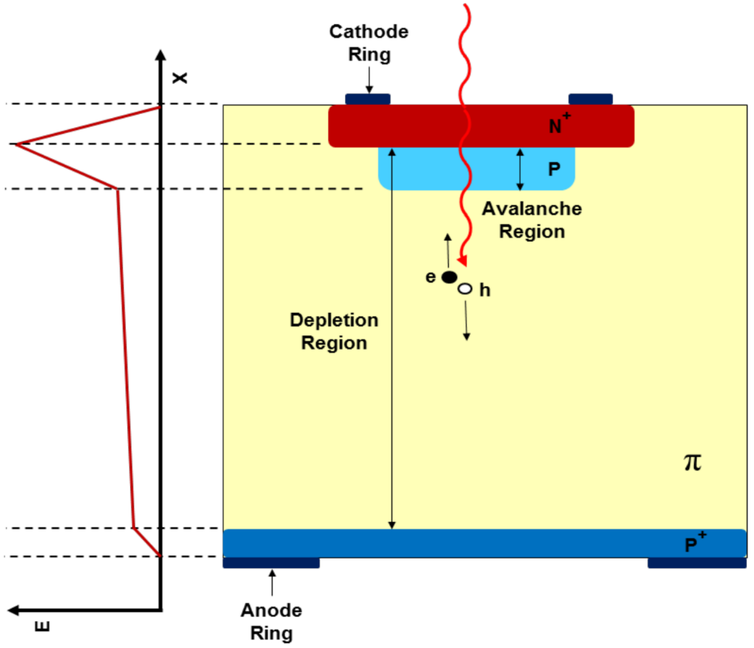
Large signal despite thin sensor

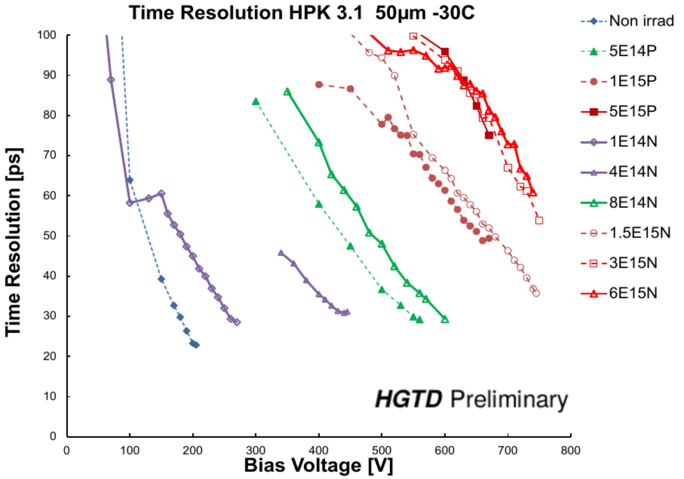
→ fast signal collection
→ time resolution of 30 ps
for large pixels (1.3 × 1.3 mm^2)

Time resolution for small pixels ?

→ non-uniform electric field
→ non-uniform drift velocity

Radiation hardness ?





[Giovanni Pellegrini @ 23rd RD50]

“4D” Tracking

Measure position and time of hit

Can help with pattern recognition:

→ assigning hits to tracks

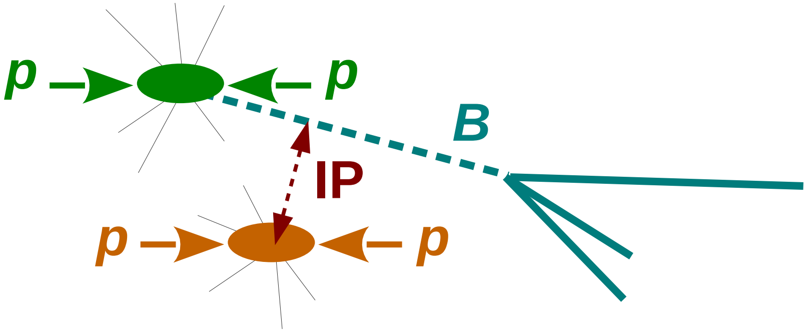
→ assigning tracks to vertices

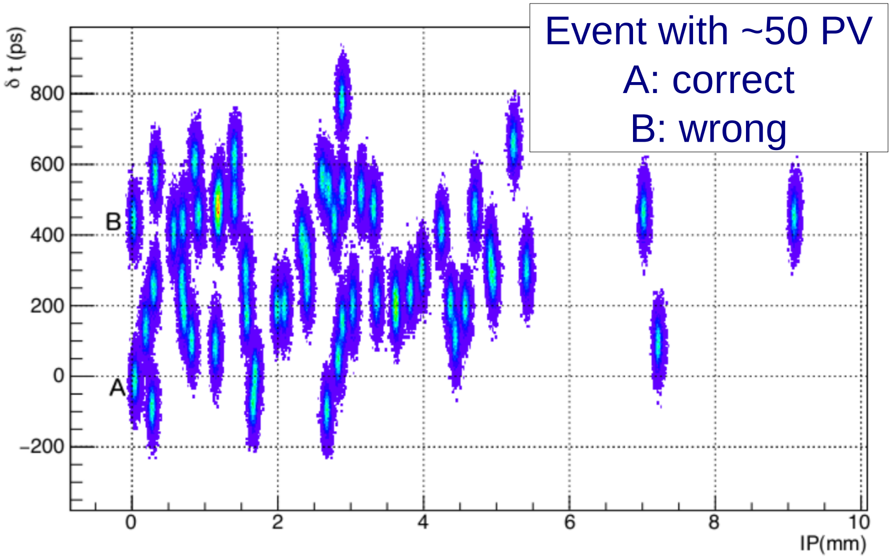
E.g. LHCb measures *B* mesons

→ travel ~ 1 cm before they decay

LHCb Upgrade 2: around 50 *pp* interaction vertices for each LHC bunch crossing

→ lower risk of assigning *B* meson to a wrong *pp* vertex if precise timing information is available





[LHCb-PUB-2019-001]

“4D” Tracking

Measure position and time of hit

Can help with pattern recognition:

→ assigning hits to tracks

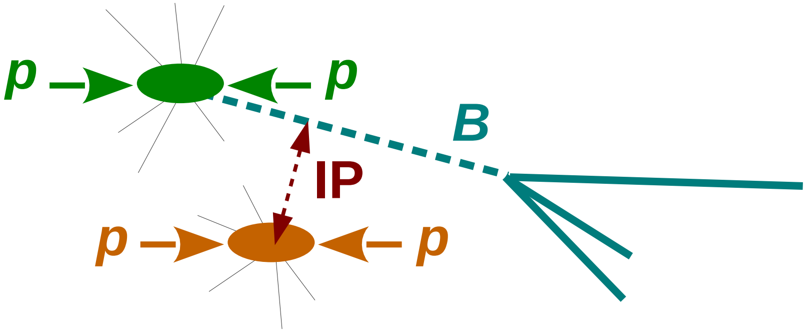
→ assigning tracks to vertices

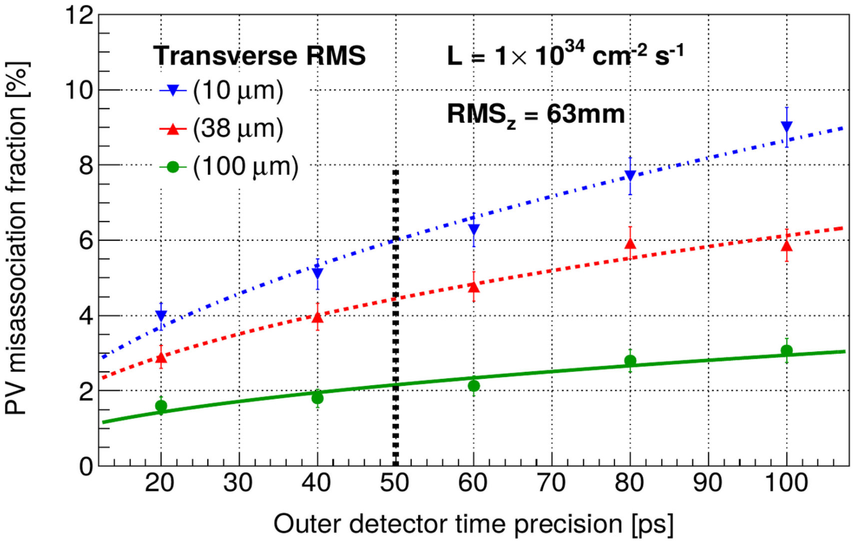
E.g. LHCb measures *B* mesons

→ travel ~ 1 cm before they decay

LHCb Upgrade 2: around
50 *pp* interaction vertices for
each LHC bunch crossing

→ lower risk of assigning *B* meson to a wrong *pp* vertex if precise timing information is available





[LHCb-PUB-2019-001]

Radiation Damage

Most critical: bulk damage from Non-Ionising Energy Loss (NIEL)

Displacement of atoms in the lattice

→ increase of leakage current, noise

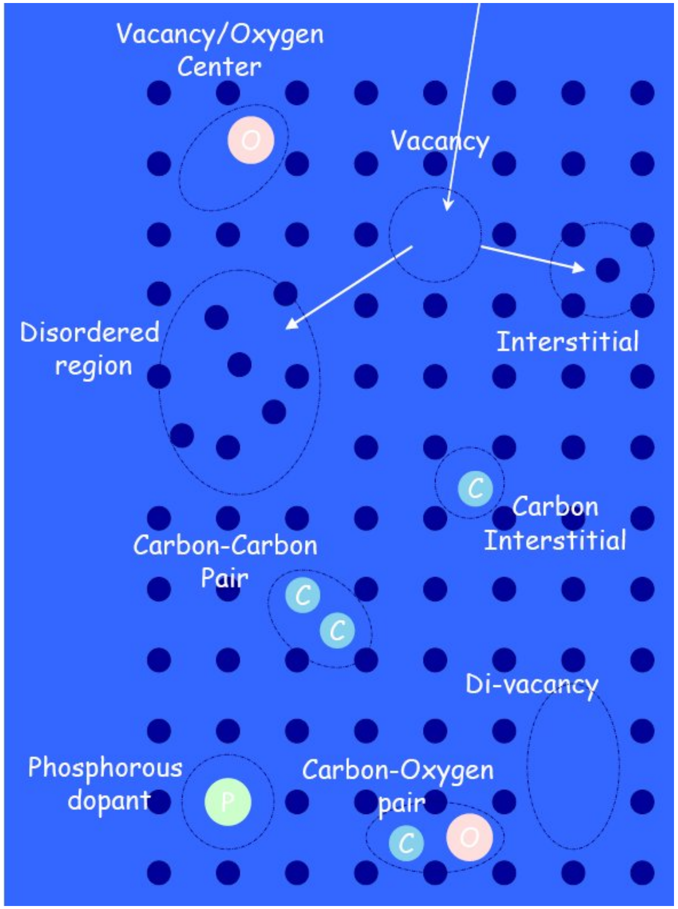
Defects act like acceptor atoms

→ “effective dopant concentration” of the silicon bulk changes

$$N_d \rightarrow N_{eff} = N_d - N_a$$

→ “Type inversion”: bulk becomes effectively *p*-type as number of defects keeps increasing with received fluence

Defects can trap drifting charge carriers



Radiation Damage

Full depletion voltage changes with effective dopant concentration

$$V_{\mathrm{fd}} = \frac{e}{2\varepsilon} \cdot |N_{\mathrm{eff}}| \cdot D^2$$

→ keeps increasing after type inversion

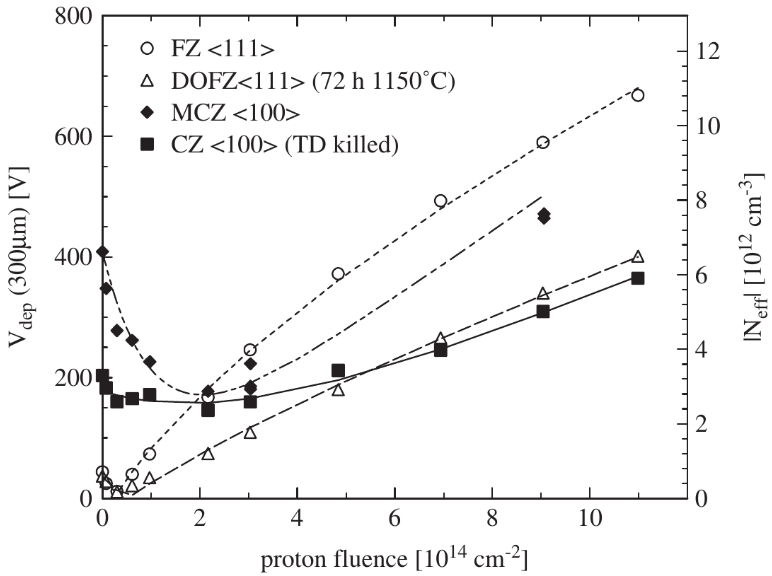
→ eventually exceeds breakdown voltage

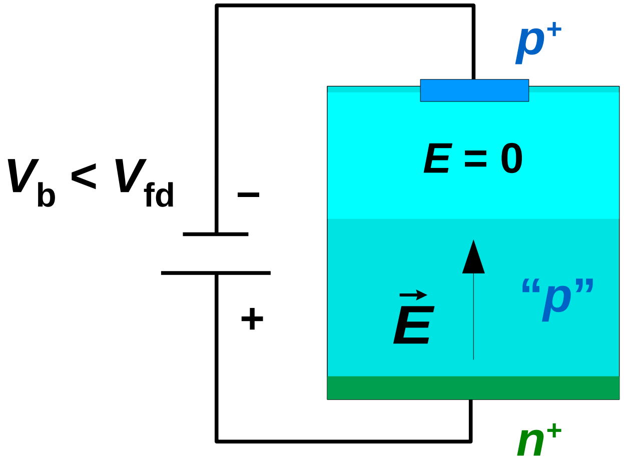
→ cannot fully deplete the detector

After type inversion, depletion zone grows from backplane of the sensor

→ field-free region on the strip side if the detector is not fully depleted

→ rapid loss of efficiency, spatial resolution





Radiation Damage

Operate detectors at low temperatures

→ suppresses leakage currents

→ slows down change in N_{eff}

Use *n*-type implants in *p*-type bulk:

→ depletion zone grows from readout side before and after irradiation

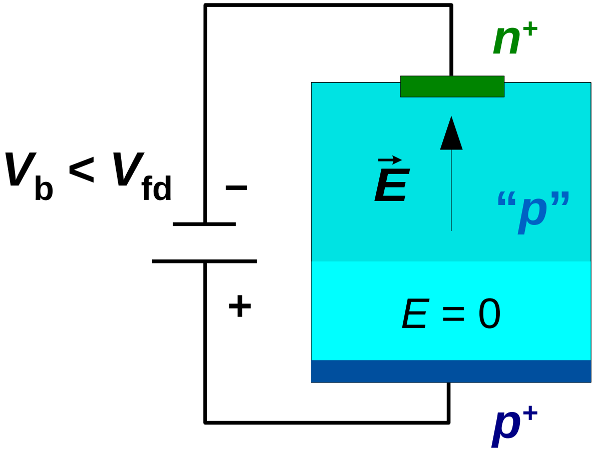
→ slow, gradual loss of efficiency as V_{fd} exceeds maximal bias voltage

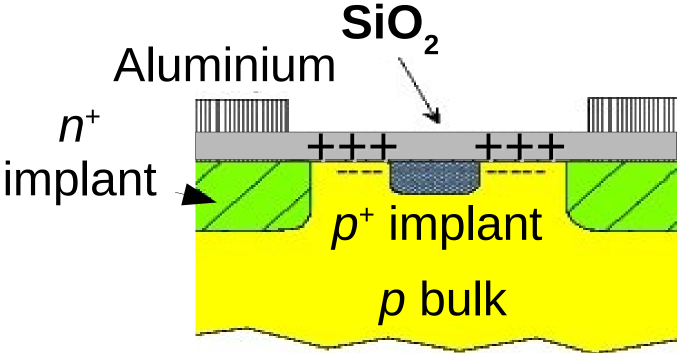
But: trapping of e^- at Si/SiO$_2$ interface:

→ causes short between readout strips

→ need to add p$^+$-type implants to insulate *n*-type implants from each other

→ additional production step, higher cost





“3D Detectors”

Manufacture implants through the bulk

→ decouple drift distance from detector thickness

Higher rate capability

→ faster charge collection

Better radiation hardness:

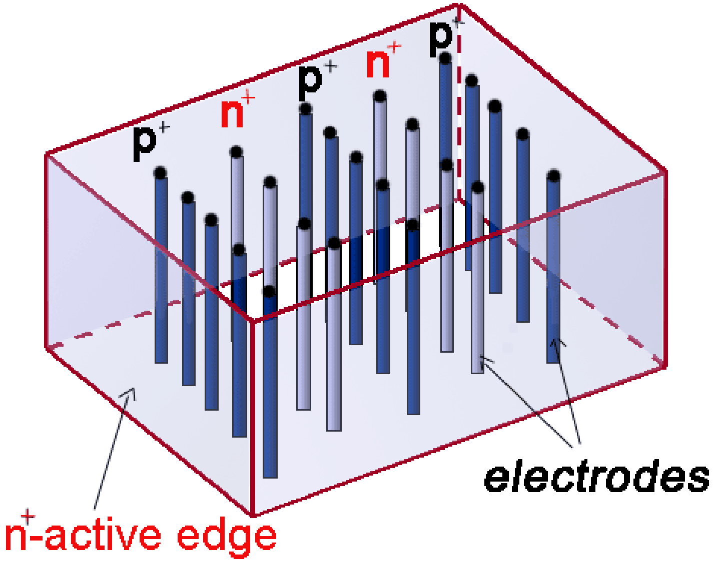
→ lower bias voltages

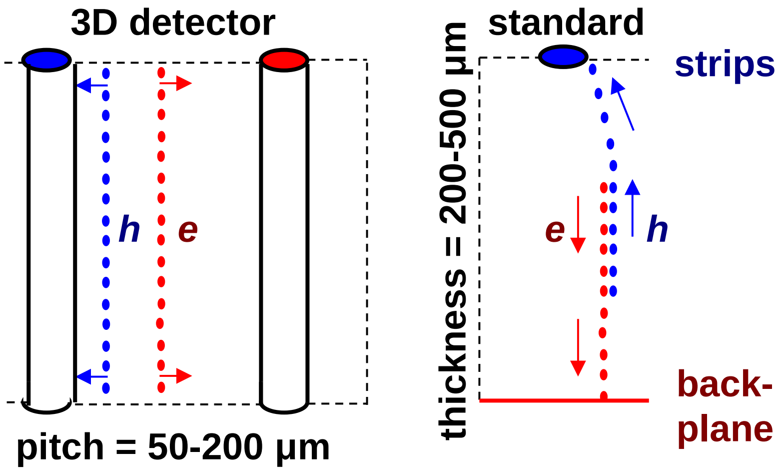
→ smaller losses from charge trapping

Production expensive

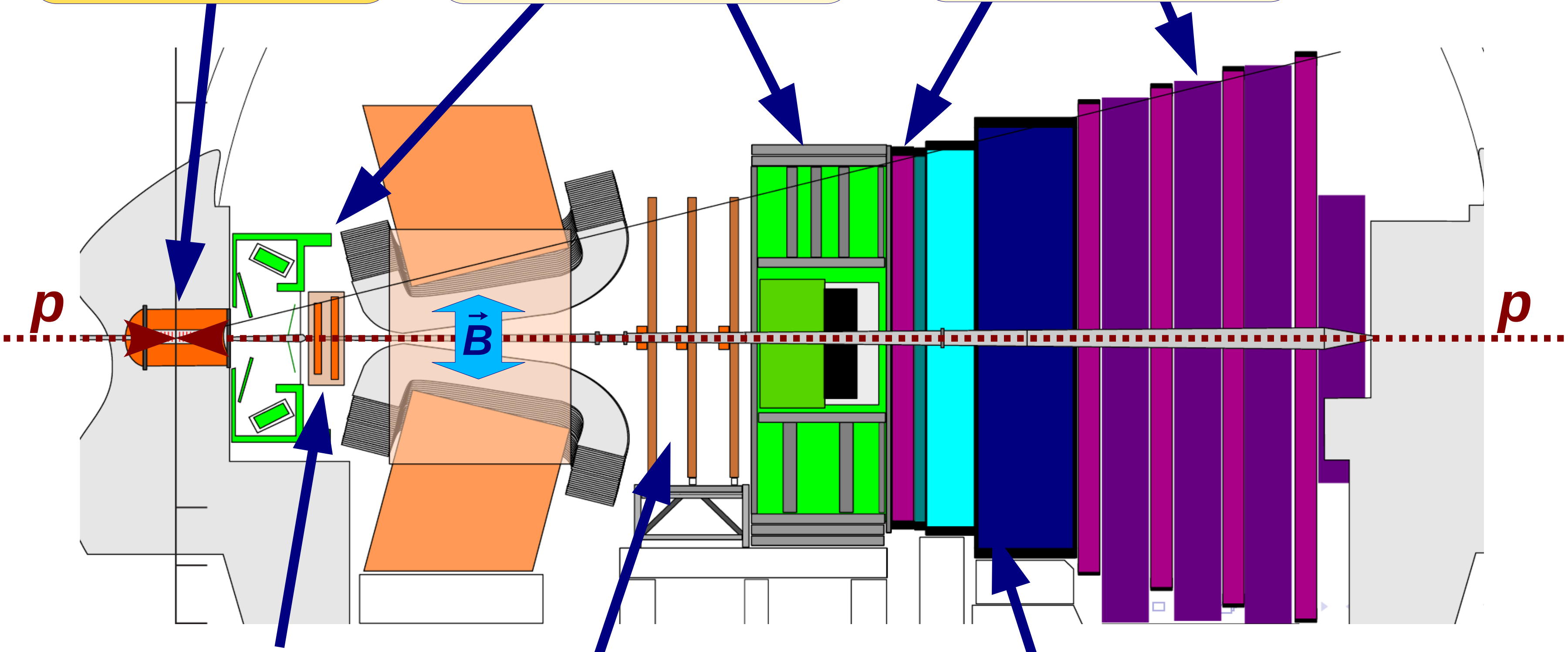
→ laser drilling or etching

First employed in ATLAS Inner Barrel Layer, installed in 2013/2014





LHCb Detector: 2010-2018



Vertex locator
(silicon strips)

RICH detectors

Muon system

Tracker Turicensis
(silicon strips)

Inner / Outer Tracker
(silicon strips / straws)

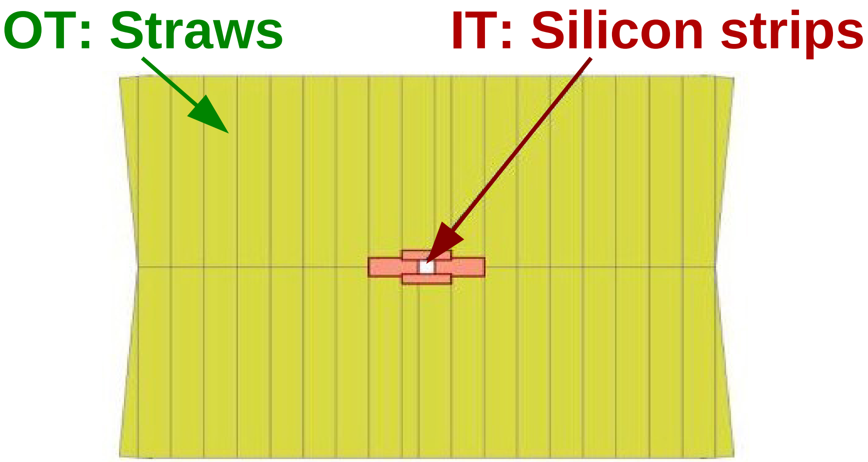
Calorimeters

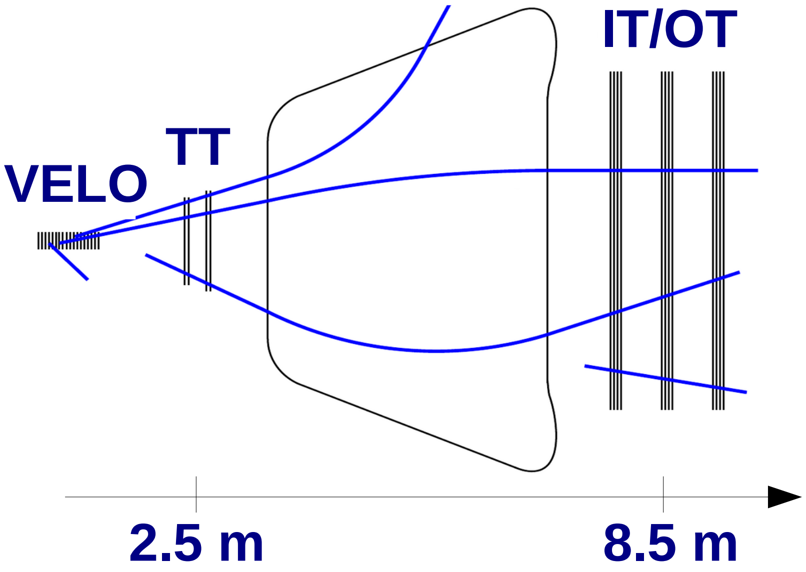
Tracking System: 2010-2018

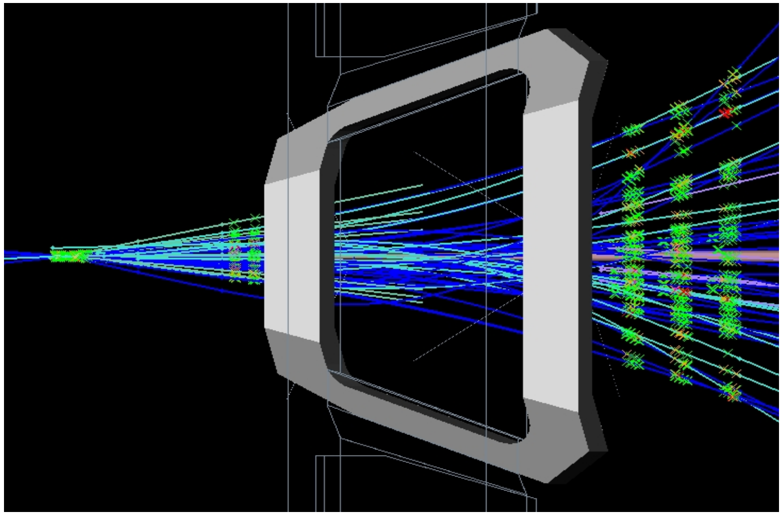
Particle density falls off rapidly with distance from the beam axis

→ finer granularity in inner region of each detector station, less fine granularity in outer regions

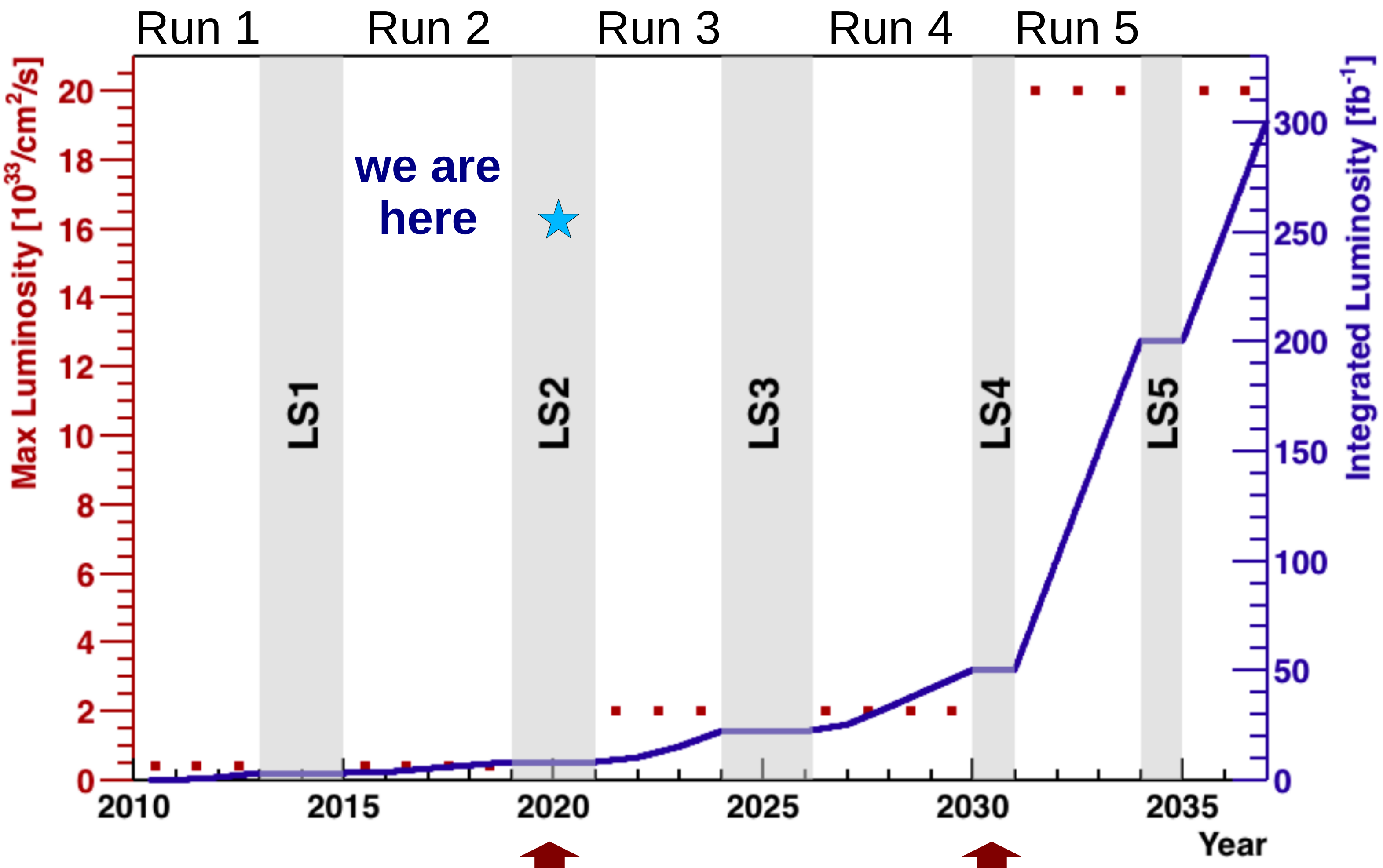
Downstream of magnet, two technologies in each station:







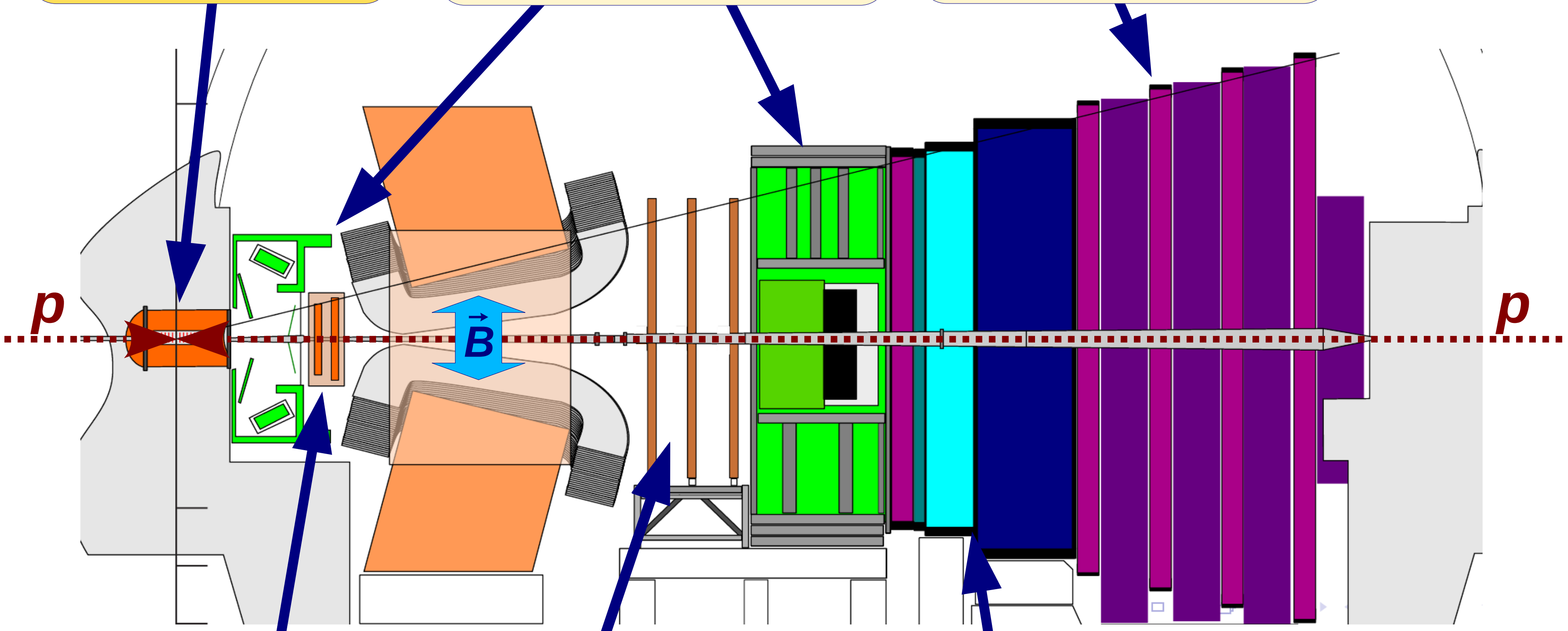
LHCb Upgrades



[arXiV:1808.08865]

Upgrade I II

Upgrade I (2021 ++)



Vertex locator
(silicon pixels)

New optics, photon detectors

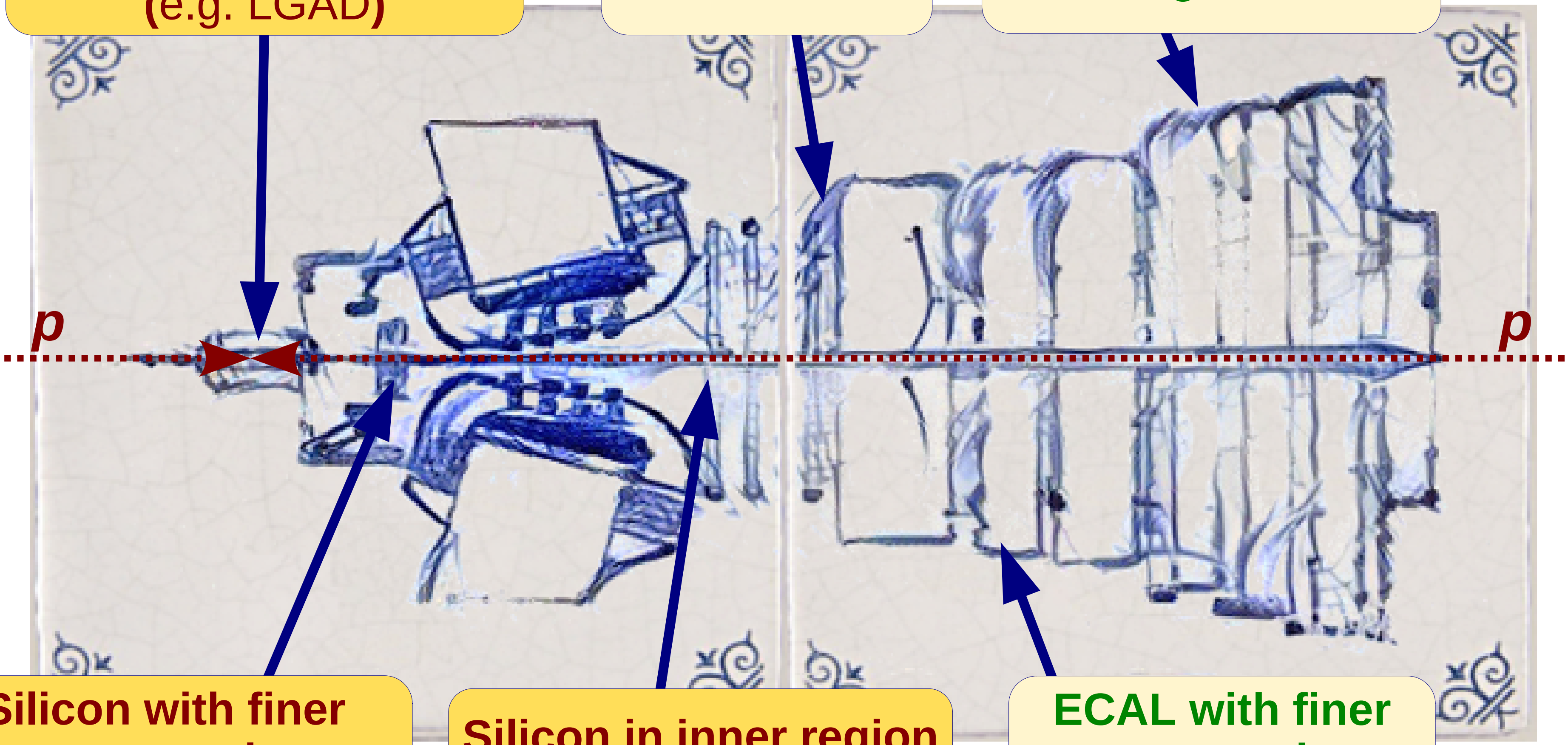
New electronics

Upstream Tracker
(silicon strips)

Scintillating Fibre Tracker

New electronics

Upgrade II (2030 ++)



Silicon pixels with timing resolution (e.g. LGAD)

New “TORCH” Detector

Muon detector with finer segmentation

Silicon with finer segmentation (timing resolution ?)

Silicon in inner region (e.g. HV-MAPS)

ECAL with finer segmentation, timing resolution

FROM MGA TO NUST MISIS 100 YEARS 1918-2018 OPENING A NEW CENTURY

MISIS National University of Science and Technology

SHiP Search for Hidden Particles

LHCb

University of Zurich^{UZH}

Upgrade II (2030 ++)

Promising technology for inner part:
HV-CMOS pixel detectors

→ pioneered by mu3 experiment

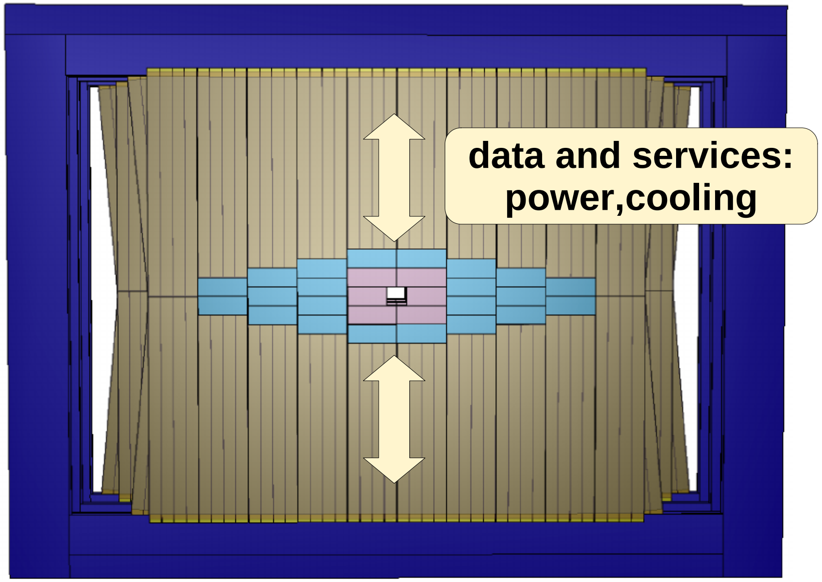
→ sufficiently radiation hard

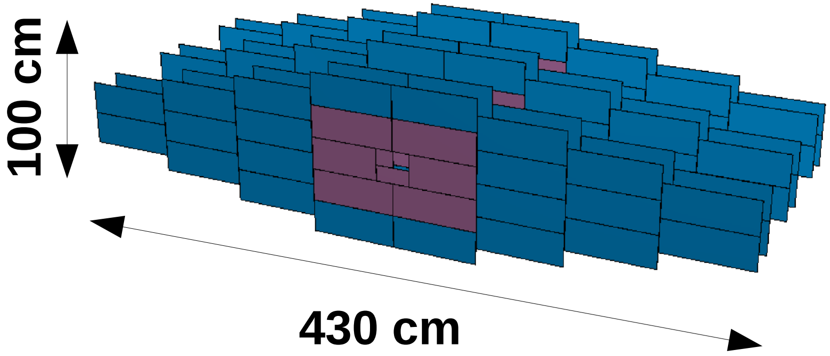
→ thin detectors = little material

→ low power consumption

→ details of chip design to be adjusted for LHCb needs
(pixel size, front-end data processing)

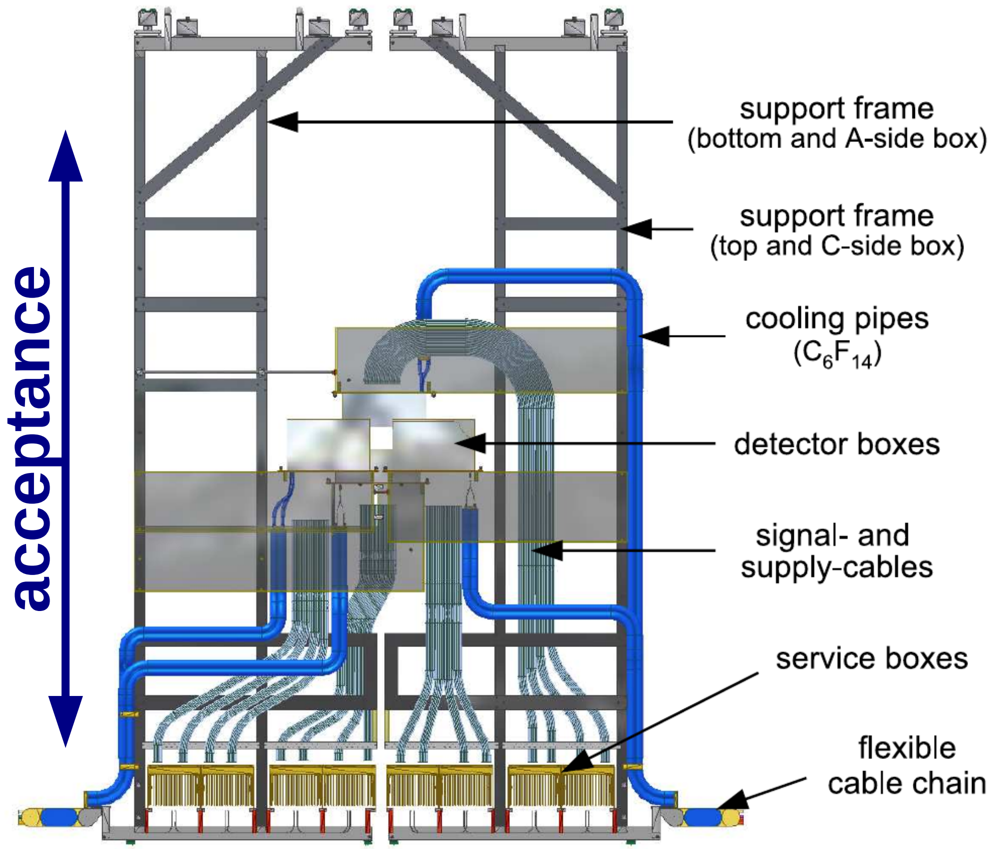
→ minimize dead material from cables, supports etc

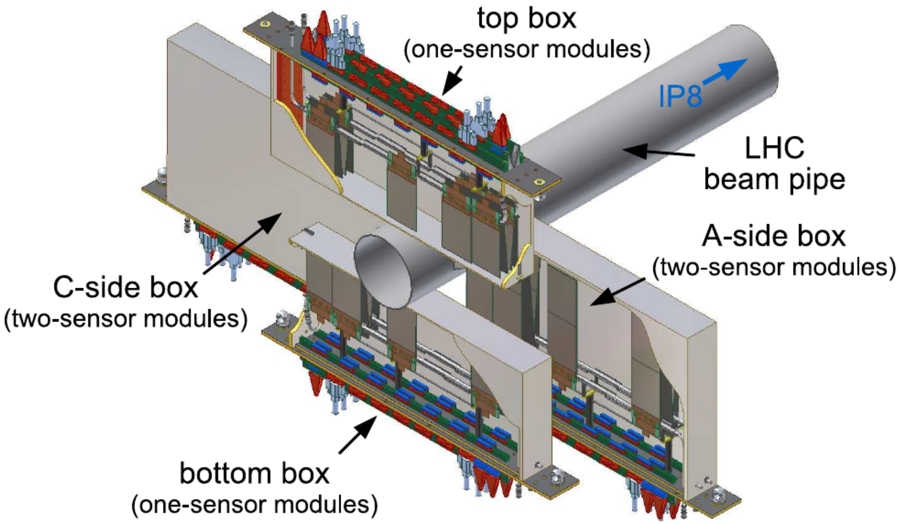


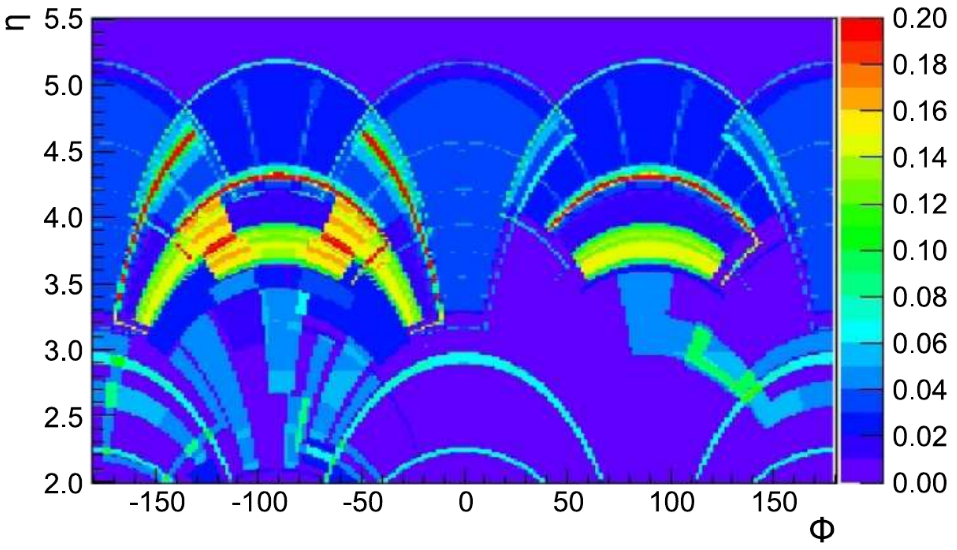


Inner Tracker (2010-2018)

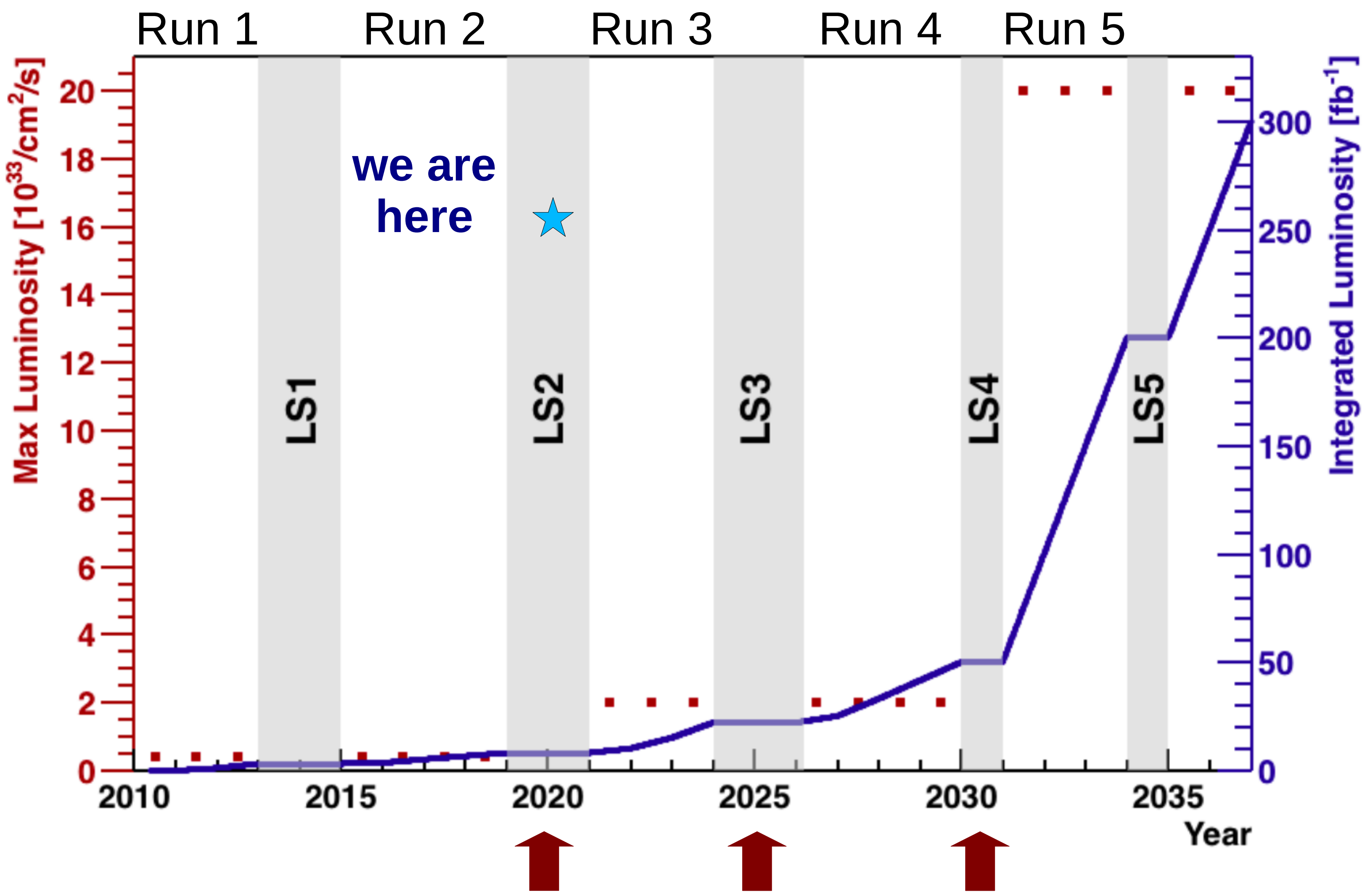
Material completely dominated by supports, cooling, cables







LHCb Upgrades



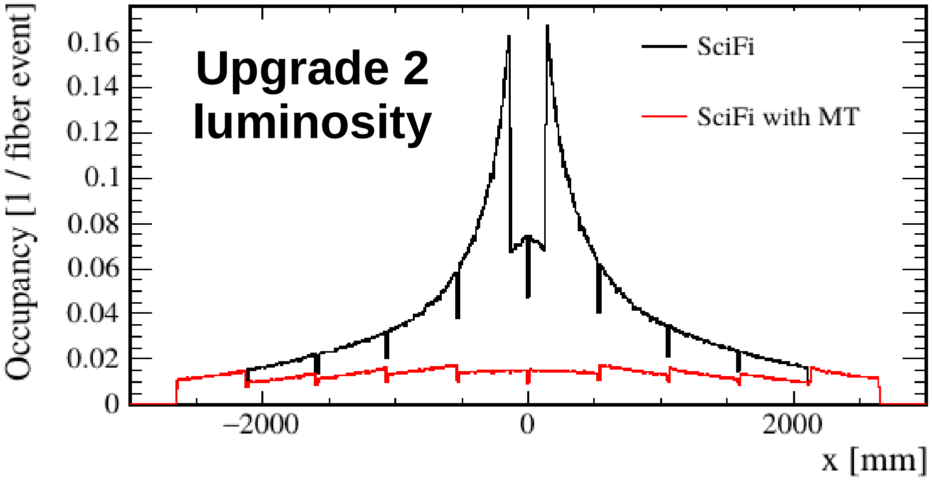
Upgrade I Ib II

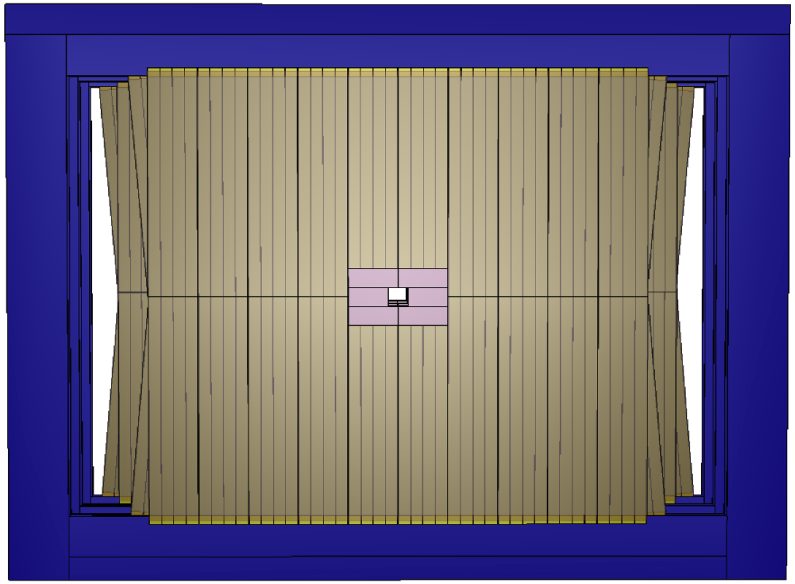
[arXiV:1808.08865]

Upgrade Ib (≈2025)

Size of the silicon tracker
for Upgrade 2:
keep the occupancy in the
scintillating fibre tracker
at an acceptable level
→ 3 m^2 per layer
→ 18 m^2 for 6 layers

Idea: install a smaller version of
the silicon tracker in Upgrade Ib
→ gain experience with the
new technology
→ improve track reconstruction
performance for LHC Run 4



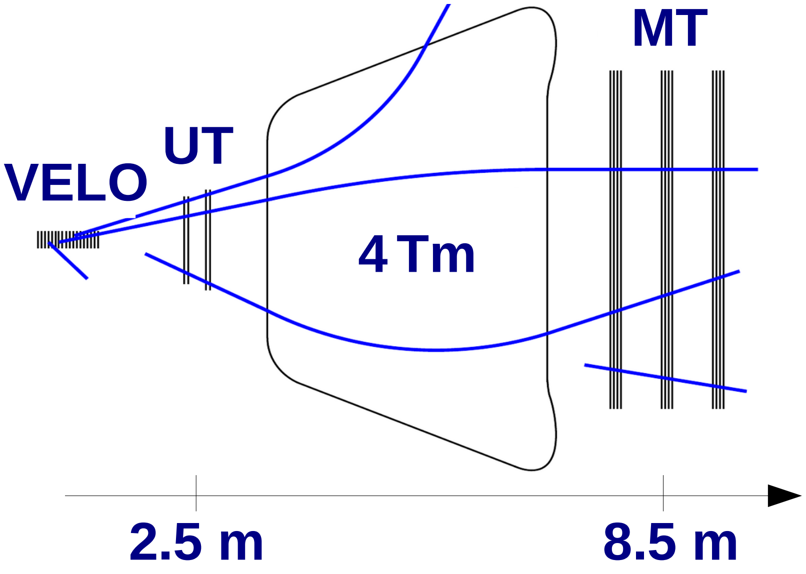


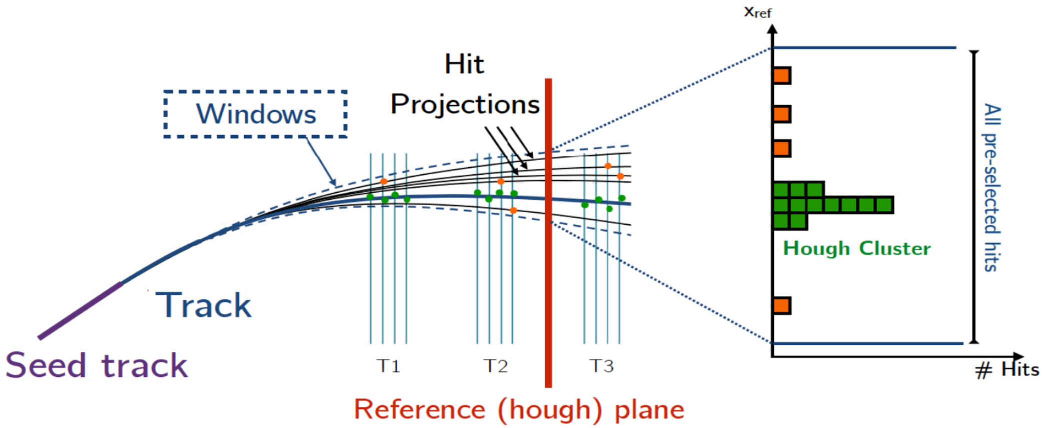
Track Reconstruction

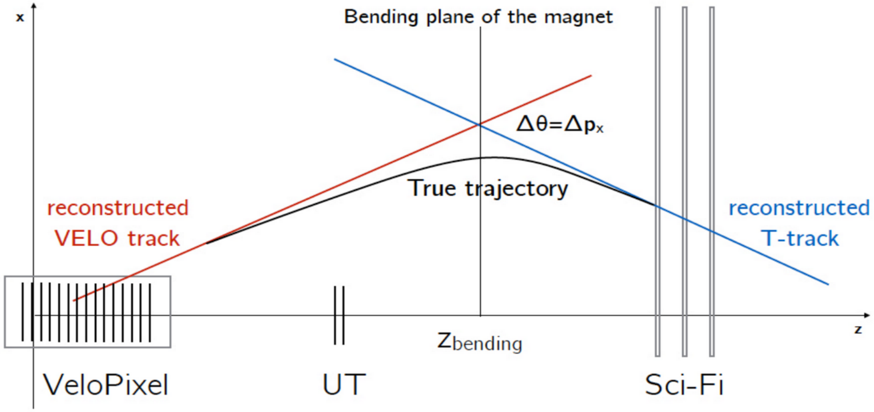
Expect biggest challenge to be matching between VELO/UT and MT

→ Upgrade 2: 2500 charged particles inside LHCb acceptance

→ need to extrapolate trajectories over 6 m through magnetic field, without any intermediate information







Summary

Efficient and precise tracking of charged particles is a crucial ingredient for almost all particle physics experiments

→ to determine production and decay vertices
→ to measure momenta

Detection based on interaction of particle with detector material, e.g.

→ ionisation of a gas
→ creation of electron/pair holes in a semiconductor

Apply electric field across detector volume, read out the signals induced by drifting charges on segmented electrodes

→ wires, strips, pixels

Many (sometimes conflicting) performance requirements
→ granularity, spatial resolution, rate capability,
radiation hardness, material budget, cost

New detector technologies to face new challenges

Summary

Did not talk about many, many very interesting things

e.g. use of scintillating fibres for tracking

e.g. Scintillators and scintillating fibres
play an important role in calorimetry,
I suspect this will be discussed in the lecture
by Giovanni de Lellis on 8th of April

The slides of this lecture are available at

http://www.physik.uzh.ch/~olafs/pdf/200318_MISIS.pdf

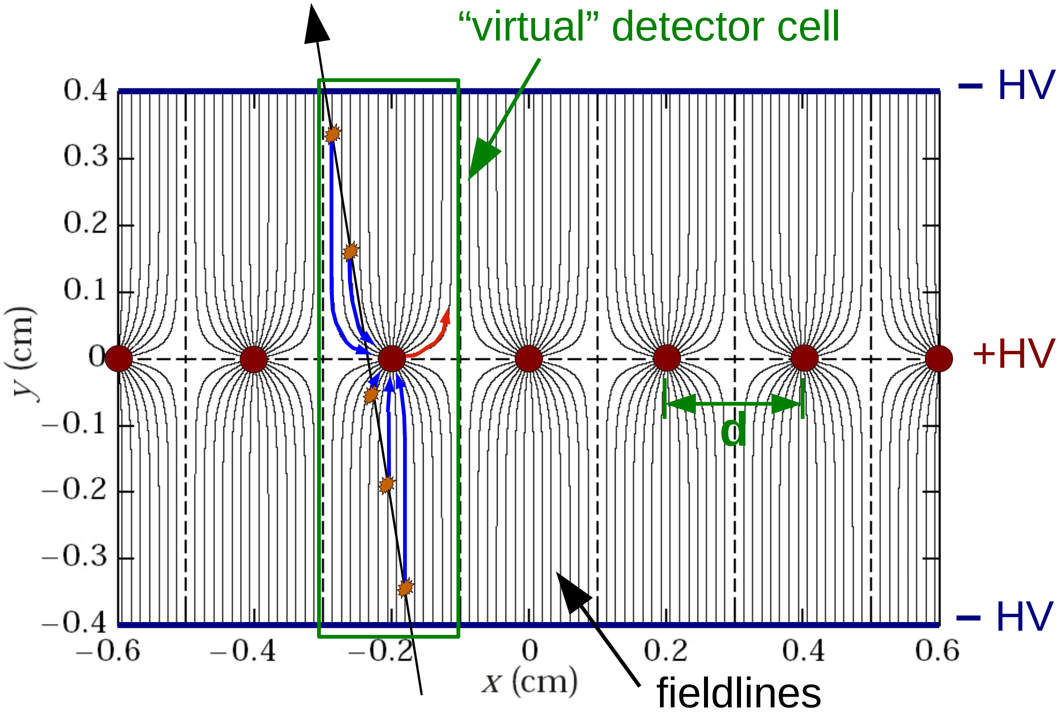
Multi Wire Proportional Chamber

<u>Array of signal wires in between two planar cathodes</u> (Charpak, 1968**)**

- **each wire connected to a readout amplifier and a discriminator**
    - register a “hit” if signal on the wire is above discriminator threshold
    - “binary readout” (hit or no hit)
- **spatial resolution given by distance *d* between wires**

$$\sigma \approx d / \sqrt{12}$$

- typically $d \approx 2$ mm ⇒ $\sigma \approx 600$ μm



- **rate capability up to 10^6 /s**