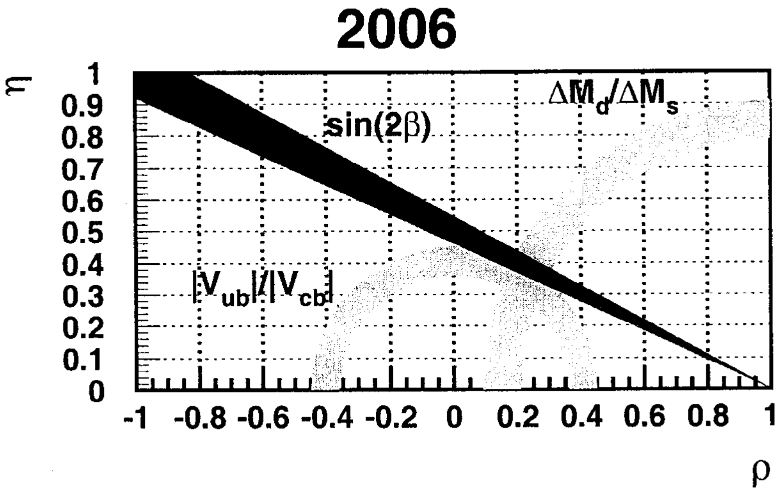
VELO: the LHCb Vertex Detector

Jim Libby, CERN

- B–physics in 2006 and the LHCb detector
- The VELO in the LHCb trigger
- Some LHCb physics
- The tasks of the LHCb VErtex LOcator
- The VELO design:
  - Mechanics and LHC integration
  - Silicon sensor design

The VELO group: CERN, Glasgow, Heidelberg-MPI, Lausanne, Liverpool and NIKHEF

B–physics in 2006

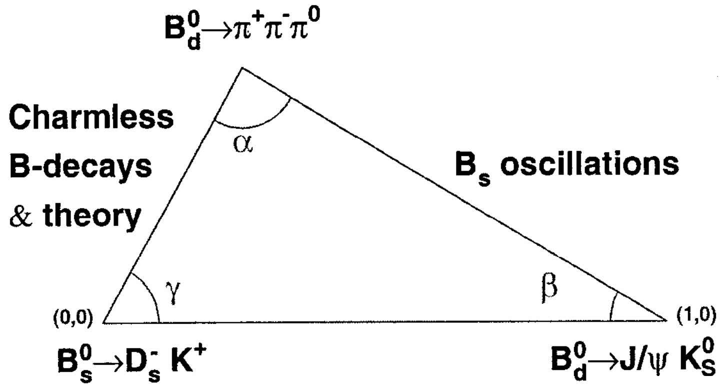


In 2006 the allowed region of the (ρ, η) plane will be reasonably well constrained.

$|V_{ub}|/|V_{cb}|$ will be limited to $\sim 10\%$ by theoretical uncertainties

$\Delta M_s/\Delta M_d$ will be limited to $\sim 7\%$ by theory, assuming a measurement of $\mathrm{B_s^0}$ oscillations at the Tevatron

$\sin(2\beta)$ will be measured to an accuracy of 0.04–0.03 by BaBar, Belle, CDF and D0



However, not all constraining measurements of the unitarity triangle will have been made to similar precision

Measurements of the angle γ will have been made, but not in theoretically clean modes or with large data sets

CP–violation in $\mathrm{B_d^0} \rightarrow \pi^+\pi^-$ and $\mathrm{B_d^0} \rightarrow \rho\pi$ may have been observed but will not be well measured

LHCb designed to make precision measurements of CP–violation, in particular angles γ and α

The LHCb detector

There are 2 advantages for B–physics at the LHC:

- The 5 orders of magnitude enhancement of $\sigma_{b\bar{b}}$, b–pair production cross–section, compared with the $\Upsilon(4s)$, and
- the production of B_s^0 mesons

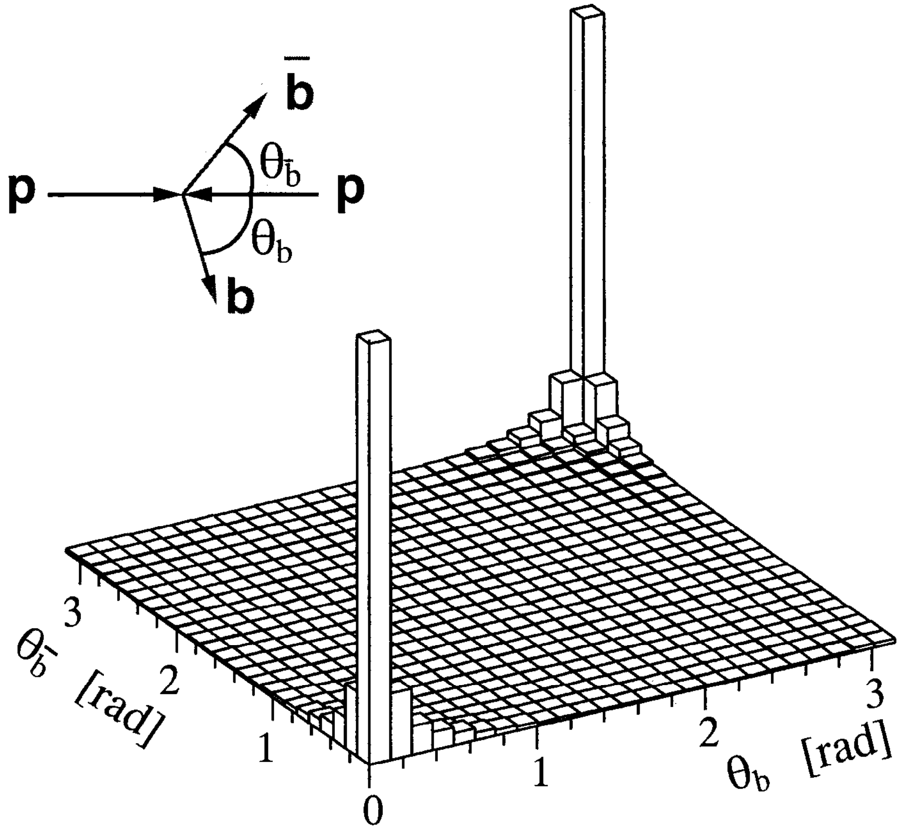
pp collisions at the LHC with:

- energy $= 14$ TeV
- instantaneous luminosity $= 2 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

leads to ⇒ $10^{12}\ \mathrm{b\bar{b}}$/**year**

The main disadvantage is the inelastic cross–section is ~ 160 times greater than $\sigma_{b\bar{b}}$, compared to a factor 3.5 at the $\Upsilon(4s)$ ⇒ sophisticated and efficient trigger

Also, non–coherent production of B–mesons allows oscillations before tagging ⇒ dilution of CP–measurements



Enhancement of correlated $b\bar{b}$ production at angles close to the beam direction
⇒ **Forward spectrometer**

The LHCb luminosity

The LHC will deliver an instantaneous luminosity of $10^{33} - 10^{34}$ cm^{-2}s^{-1} to ATLAS and CMS

However, LHCb will have its luminosity detuned by a factor between 5 and 50 to:

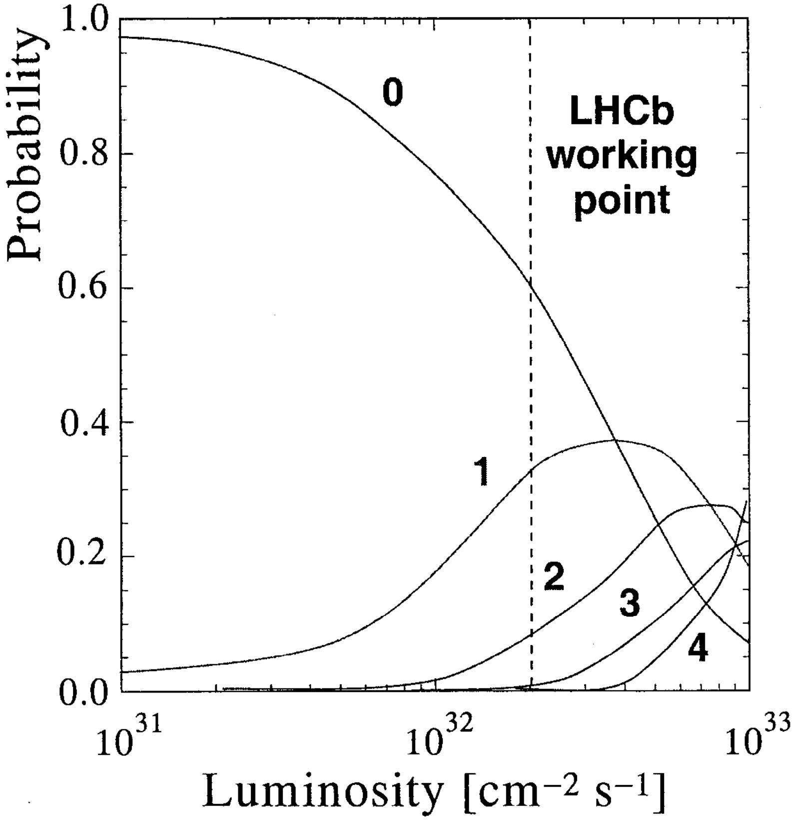
$$2 \times 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Optimises the number of single interactions while minimising the number of multiple interactions ⇒ less ambiguities in vertex association

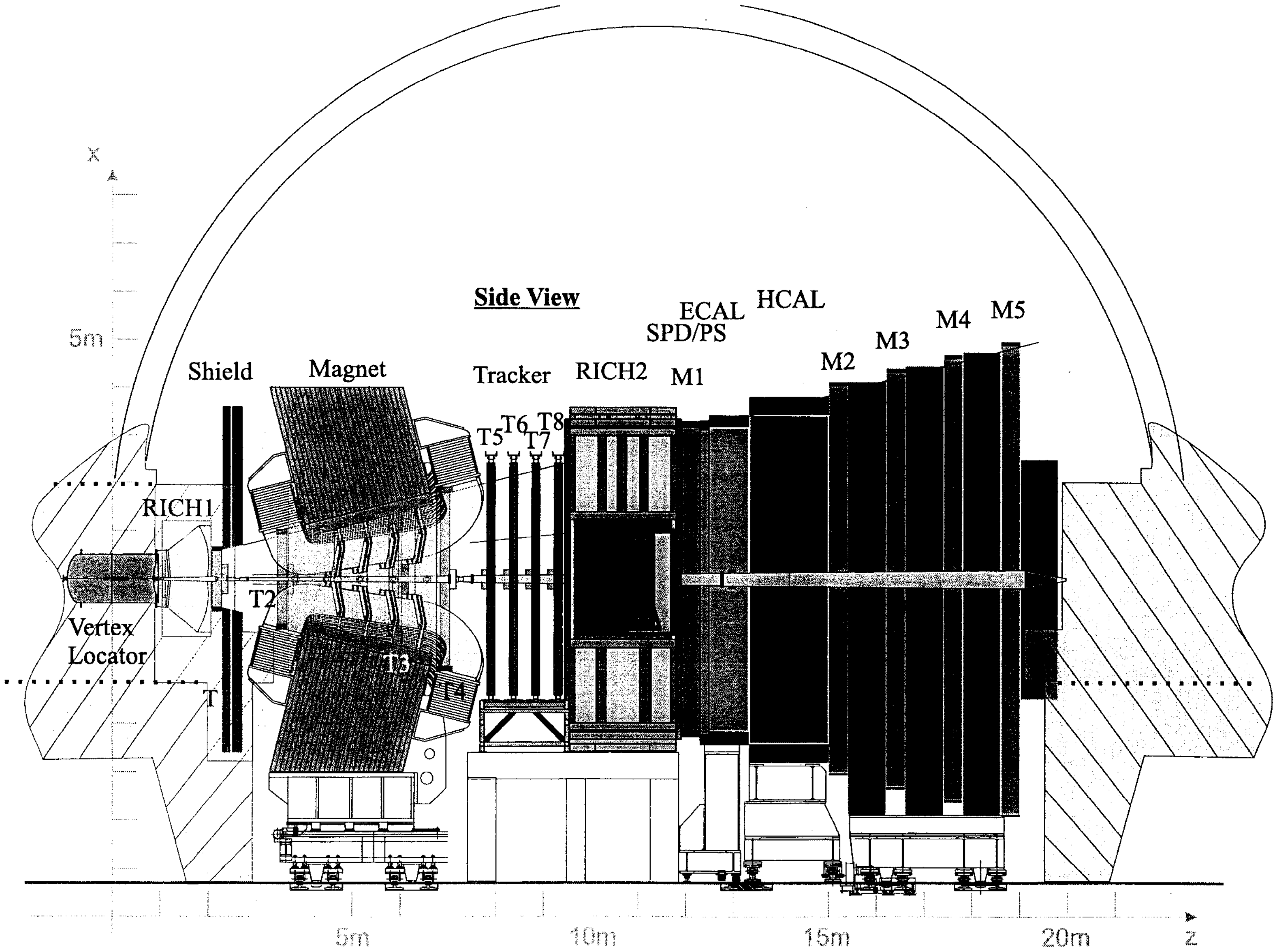
Also, prevents multiple interactions saturating bandwidth of the lower level triggers

Of those bunch crossings, at 2×10^{32} cm^{-2}s^{-1}, which have ≥ 1 interactions $\sim 25\%$ have ≥ 2 interactions

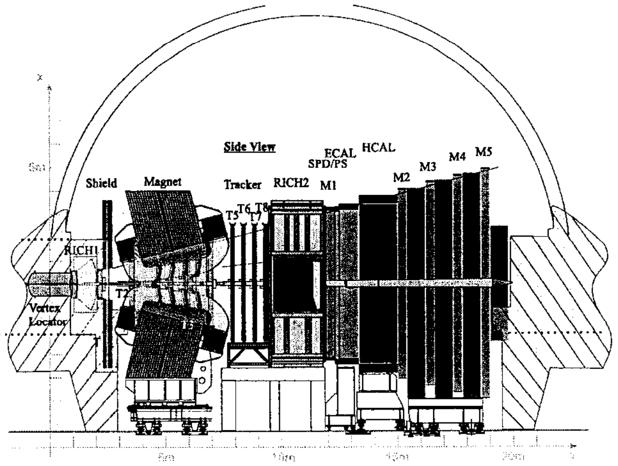
Silicon based trigger used to VETO multiple interactions at first stage of the trigger



The LHCb detector



The tasks of the LHCb VELO

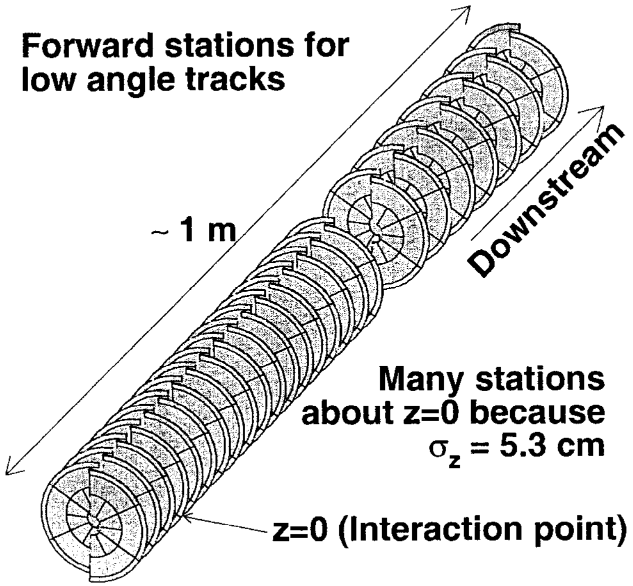


The 3 main tasks for the VELO are:

- Reconstruction of the pp interaction point (primary vertex)
- Reconstruction of secondary and tertiary decay vertices from beauty and charm decays
- Fast stand-alone tracking for impact parameter measurement and vertexing at the second level of the trigger

These criteria motivate the design choices for the VELO layout, mechanics and silicon sensors

- VELO consists of 25 Si stations placed along beam-line about the interaction point



- Provides at least **three** measurement points on tracks in range 15 mrad $\leq \theta \leq$ 390 mrad for $-2\sigma_z < z < 2\sigma_z$
- Stations upstream of interaction point used to measure backward tracks ⇒ improved primary vertex reconstruction

LHCb Trigger

The trigger is crucial for B–physics at hadron machines due to the large background and the high interaction rates

LHCb has a four–level trigger

Level	Signatures	Input rate	Output rate
0	High p_t hadrons, $e^{\pm}$, γ and $\mu^{\pm}$ Multiple interaction veto	40 MHz	1 MHz
1	Secondary vertices in VELO Linking to L0 high–p_t objects or some momentum information	1 MHz	40 kHz
2	Refined vertex trigger with p info	40 kHz	5 kHz
3	Streaming of most interesting channels using information from all subdetectors	5 kHz	200 Hz

Only Level 0 is hardware based (FPGA and DSP)

Levels 1–3 algorithms run on CPU farms

Level 1 special networked farm to process the VELO data

After a Level 1 Yes, all sub–detector's data are read–out and event building begins

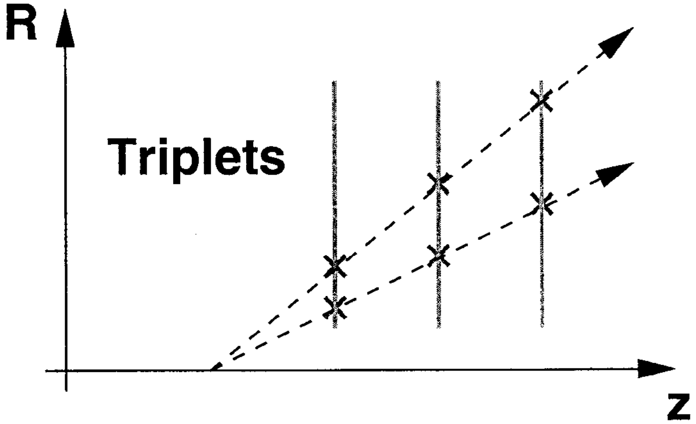
Second level vertex trigger

Second level of the trigger uses VELO to reconstruct tracks and find those with a large impact parameter with respect to the primary vertex

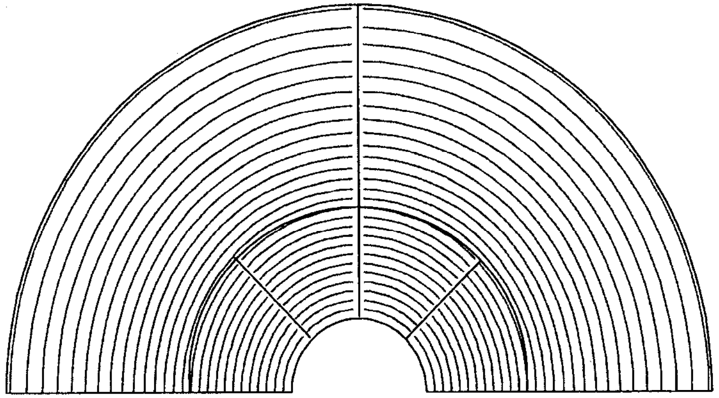
First step is tracking using R–measurements only

Triplets used to form tracks ⇒ 98%

Primary vertex position in z reconstructed from pairs of 2D—track crossings



From test–beam measurements using $\pi^{\pm}$ on Cu targets a 70 $\mu\mathrm{m}$ resolution on the PV is anticipated



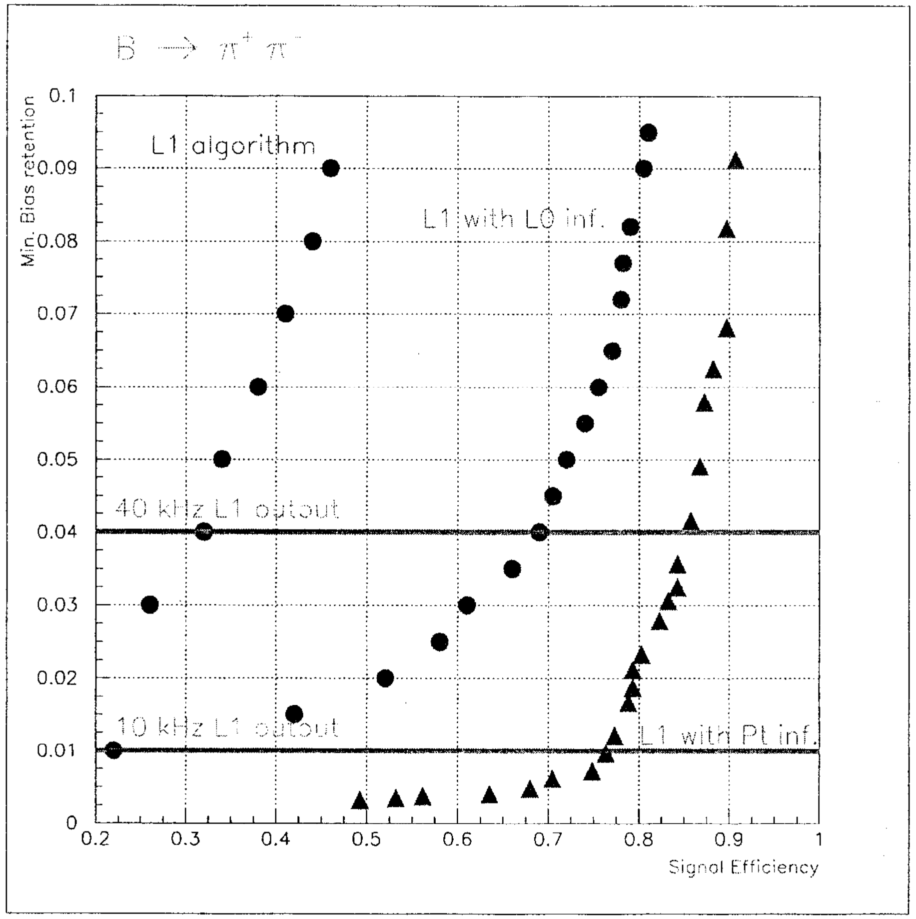
Trigger motivates R–**measuring detectors**

Azimuthal segmentation of $45°$ in the inner region of the R–detectors used to reconstruct position PV in plane $\perp$ to beam ⇒ $20\ \mu\mathrm{m}$ resolution

Impact parameter of all tracks then found and probability that it is not from the PV calculated

Tracks with a large probability are then reconstructed fully in 3D

Second level vertex trigger



L1 algorithm = two–track vertexing

Slightly reduced efficiency for L1 with p_t on $\mathrm{B_s^0} \rightarrow \mathrm{D}_s\pi$ at 4% minimum bias retention

Options for second level:

- find 3D two track vertices,
- associate with high p_t $\mu^{\pm}$, $e^{\pm}$ and hadrons found in the first stage of the trigger or
- measure p_t of the high impact parameter tracks

How can such a measurement be made in the $4.2\ \mu$s latency of the second–level of the trigger?
Ans. Introducing of B–field between VELO and an all/mostly Si first tracking station

$\frac{\delta p}{p} \leq 20\%$ achieves 85% efficiency with 4% minimum bias retention rate

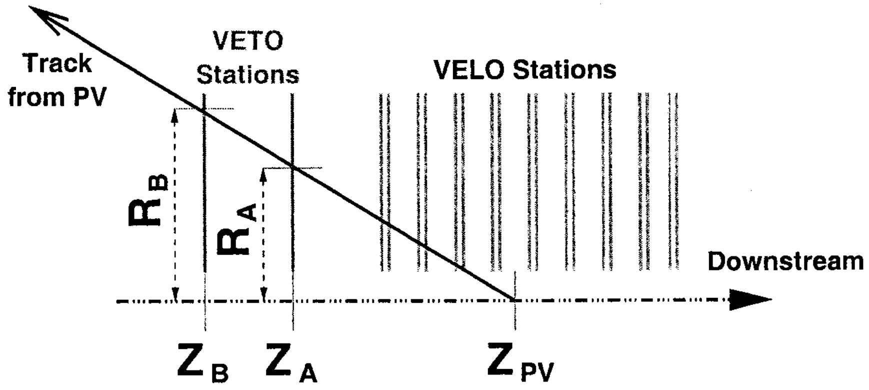
Under development at present ⇒ problem B–field around RICH1 photo–detectors

Vertex trigger to be finalised at the end of 2002

Level 0 pile-up veto

Rejecting multiple interactions at the first stage of the of the trigger is advantageous for two reasons

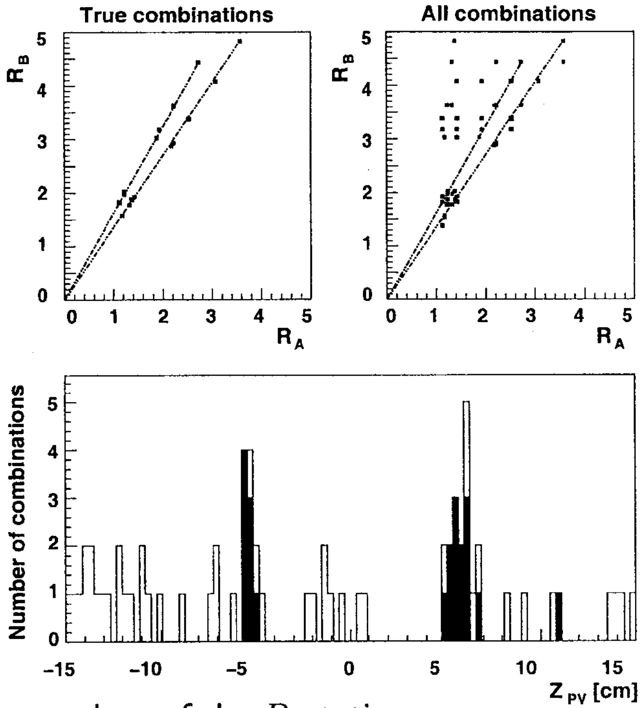
- single interactions are easier to reconstruct in the second trigger level, and
- reduce first level bandwidth taken by these events - $2\times$ higher probability of passing high p_t cuts



Two additional R–stations upstream of the luminous region

For tracks from the primary vertex:

$$\frac{R_{\rm B}}{R_{\rm A}} = \frac{Z_{\rm B} - Z_{\rm PV}}{Z_{\rm A} - Z_{\rm PV}} = \text{constant} \Rightarrow Z_{\rm PV}$$



- Binary readout of the R–stations
- FPGA builds histogram and searches for highest peak
- Hits in highest peak are masked and 2nd highest found
- If no. of hits in 2nd highest peak greater than a threshold $\Rightarrow$ event VETOed

Gain of 30 to 40% of single $b\bar{b}$ events

Measurements of γ

$\mathrm{B_s^0} \rightarrow \mathrm{D_s^{\pm}K^{\mp}}$ asymmetry measures $-\gamma + 2\delta\gamma$

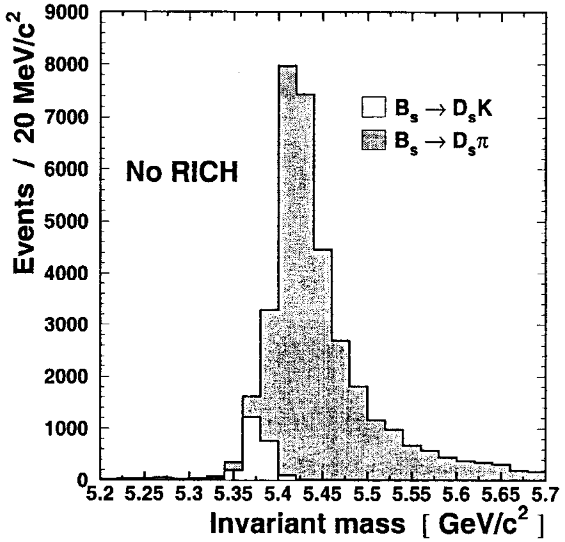
In combination with measurement of/limit on $\delta\gamma$ from $\mathrm{B_s^0} \rightarrow \mathrm{J}/\psi\phi \Rightarrow \sigma_\gamma \sim 10^\circ$

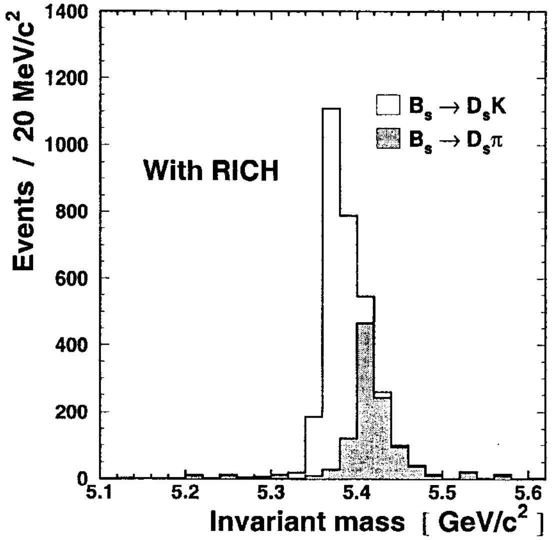
Measurement uses particle identification power of the RICHes

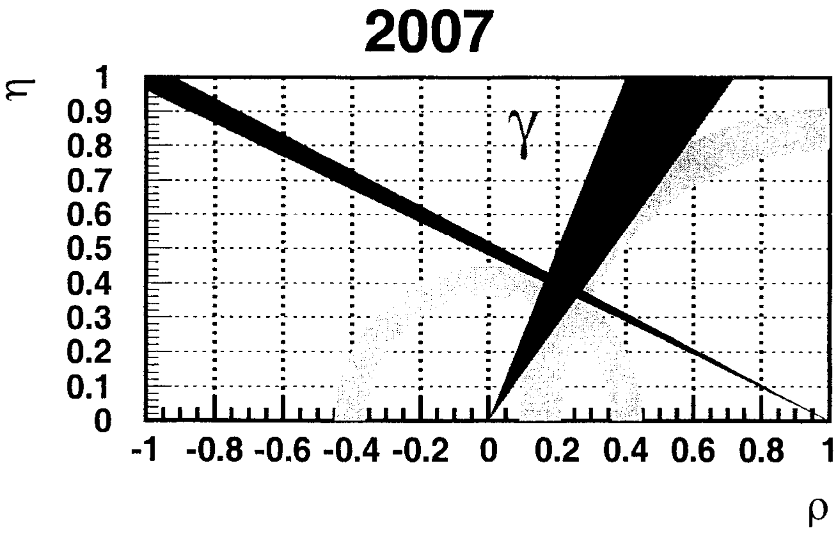
Excellent proper time resolution, σ_t, of 40 fs from the VELO resolves $\mathrm{B_s^0}$ oscillations and limits dilution of the CP–asymmetry

Measuring the asymmetries in $\mathrm{B_s^0} \rightarrow \mathrm{D}_s^+\mathrm{K}^-$ **and** $\mathrm{B_s^0} \rightarrow \mathrm{D}_s^-\mathrm{K}^+$ allows the strong phase contribution to be measured

Combined with analogous decay, $\mathrm{B_d^0} \rightarrow \mathrm{D}^*\pi$, one year error on γ of 7°

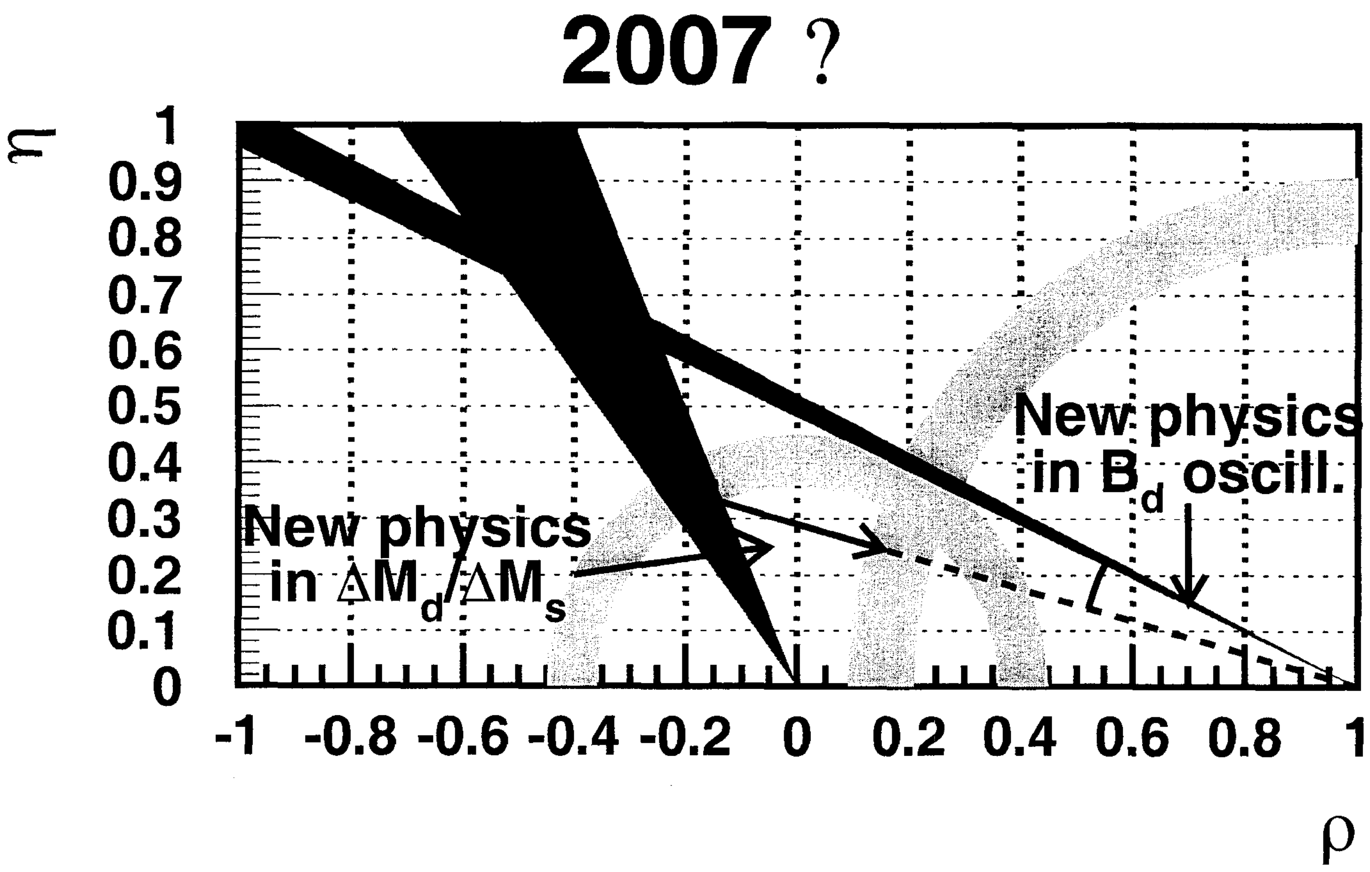






Measurements of γ

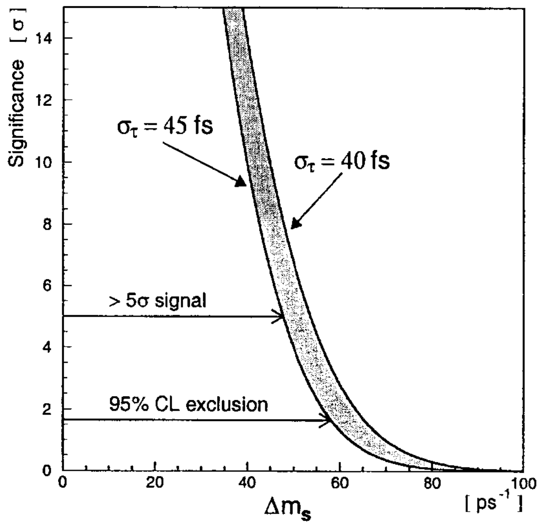
CKM + New Physics	CKM only
$\Delta M_d/\Delta M_s$	$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$
$\sin 2\beta$	γ from LHCb



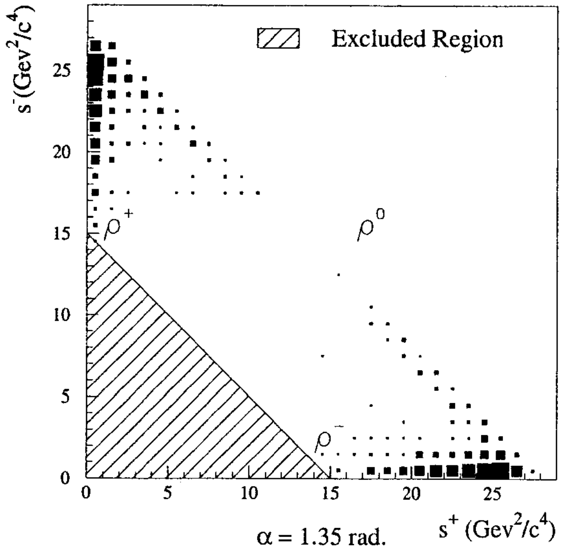
Other measurements

- $B_d^0 \to J/\psi K_s^0$ – 1 year $\sin 2\beta$ error ± 0.02 and sensitivity to direct CP–violation
- $B_s^0 \to J/\psi\phi$ – extract B_s^0 mixing phase which is predicted to be $\mathcal{O}(0.01)$ in SM. 5 year measurement of 0.02–0.03 sensitive to New Physics.
- $B_s^0 \to D_s\pi$ – Measurements of ΔM_s up to $54\ \mathrm{ps}^{-1}$ within 1 year
  - x_s up to 85
  - $\sigma_t \sim 40\ \mathrm{fs}$ from VELO
- $B_d^0 \to \rho\pi \to 3\pi$ – interference between three modes leads to measurement of α and strong phases
  - Time–dependent analysis of the $B_d^0 \to 3\pi$ Dalitz plot
  - LHCb expects 1.3k tagged events/year
  - Preliminary studies $\sigma_\alpha < 5^\circ$ in one year
  - VELO kills combinatoric background
  - A potential problem ρ' or scalar contributions

and much more$\Rightarrow$ B$\to h^+h^-$, B$\to$DD, Rare decays...



Dalitz Plot - $B_d^0 \to \pi^+\pi^-\pi^0$



Design of the VELO

Vertexing precision is best achieved with:

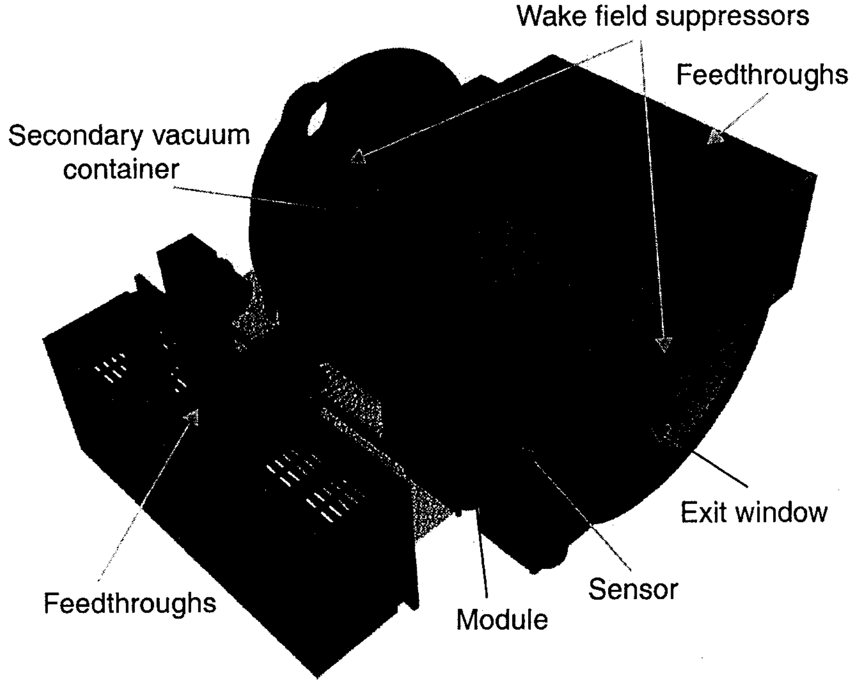
- Short extrapolation distances ⇒ measurements at small radius
- Minimal multiple scattering ⇒ little material between interaction and measurement points

Both have important consequences on the mechanical design of the VELO

To place sensors very close (7 mm) to the beam line requires the VELO to be integrated with LHC vacuum system:

- the sensors retract during injection as 3 cm beam aperture is required
- protection of the sensors from RF–pickup from the LHC bunches
- protecting the LHC vacuum from possible out–gassing of VELO modules ⇒ vacuum instabilities

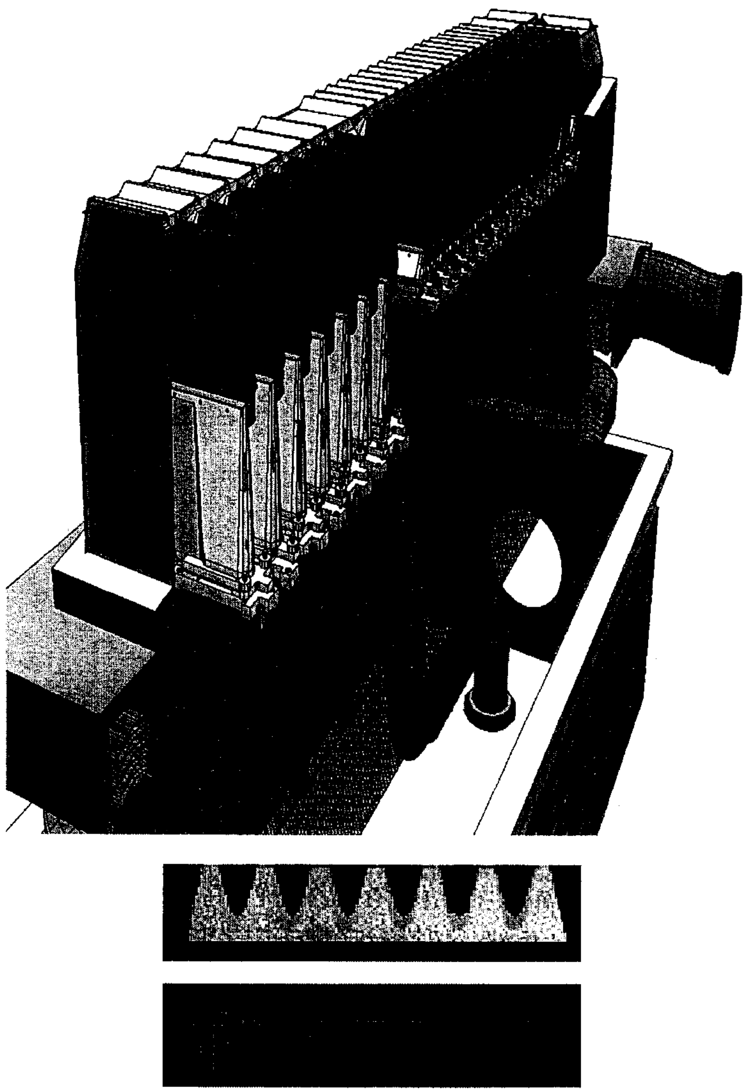
Therefore, the sensors are placed inside a secondary vacuum isolated from the LHC (primary) vacuum ⇒ Roman pots

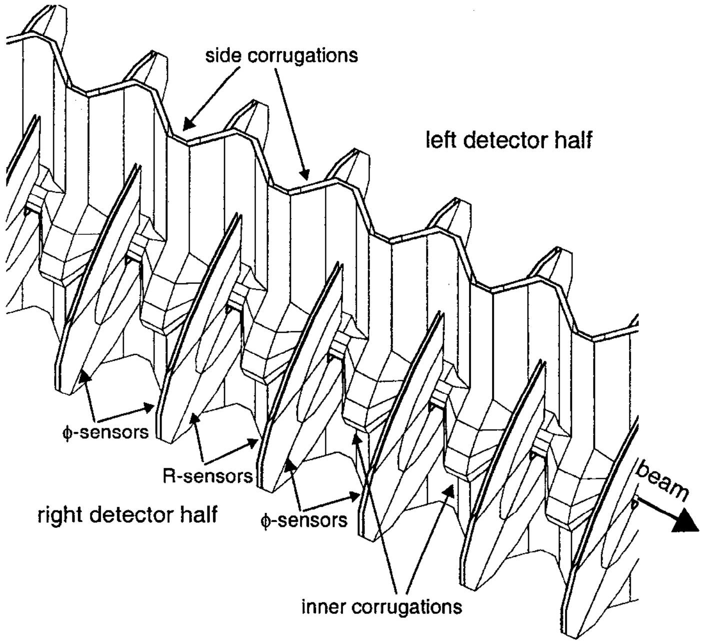


RF–foil is made from $250\ \mu\mathrm{m}$ thick Al

- enough skin–depths for RF–attenuation and,
- mechanical strength for up to 15 mbar pressure differential

The mechanics and LHC integration





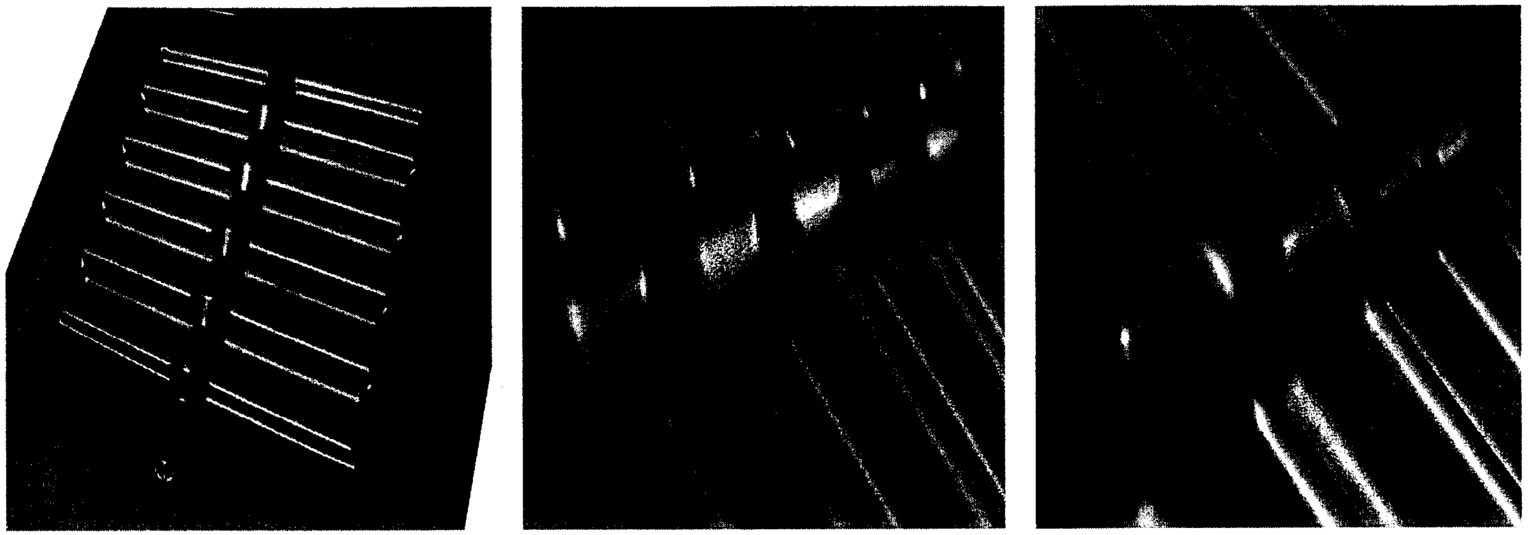
Outer corrugations for overlap of the two halves:

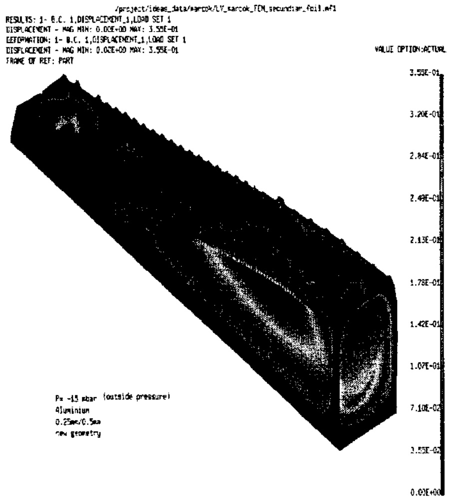
- full azimuthal coverage and
- tracks in both halves for alignment

Inner corrugations to minimise material before first measured point:

- with corrugations: 3.2% X_0
- without corrugations: 12.0% X_0

The mechanics and LHC integration



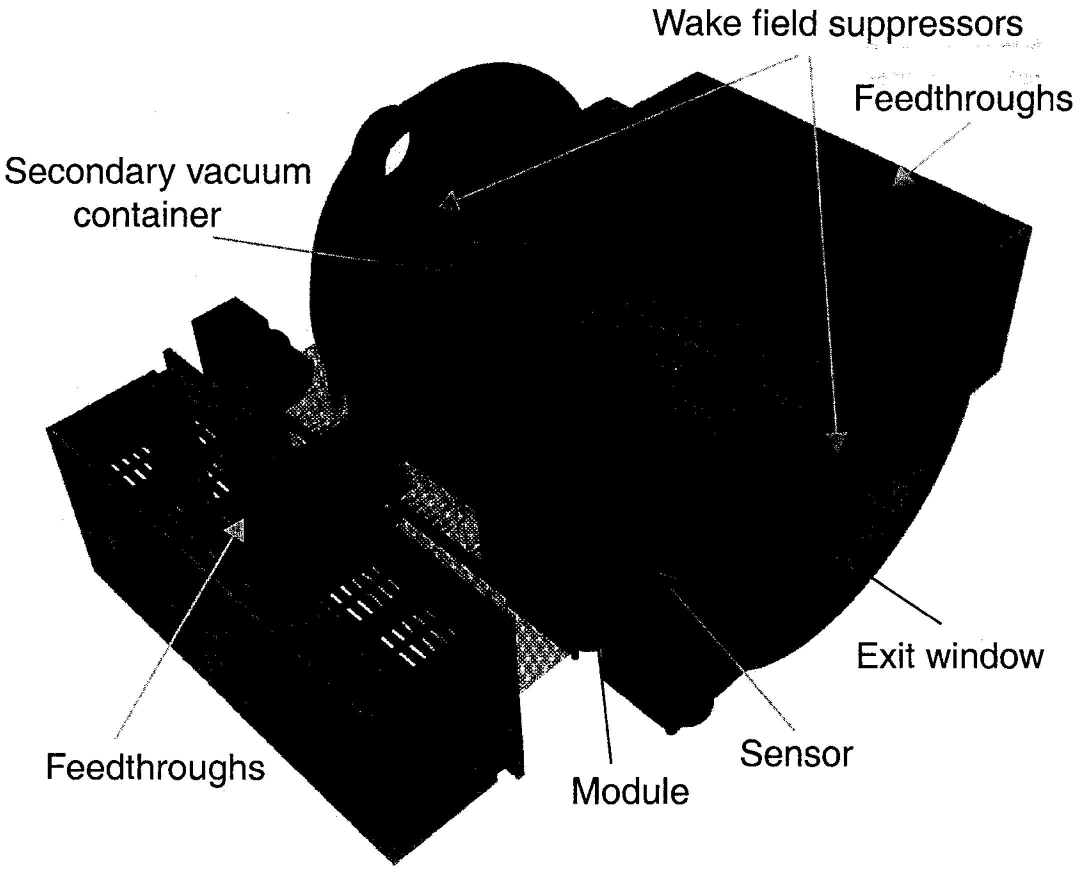


Prototype RF–foils have been produced that meet specifications using superplastic deformation molding

Leakage and rupture tests ongoing to compliment the FEA of the foil design

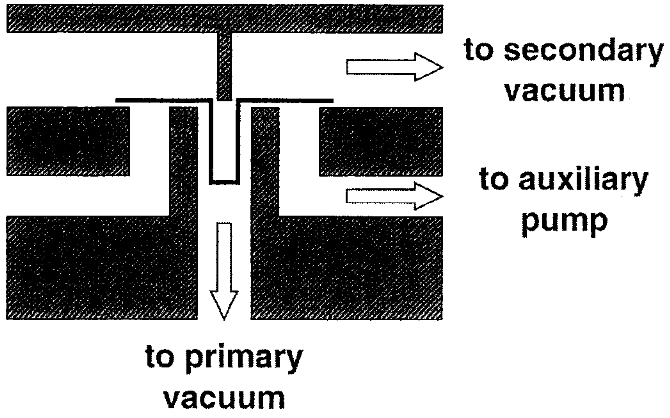
At 15 mbar pressure difference maximum displacement of 350 $\mu\mathrm{m}$ predicted

The mechanics and LHC integration



Mechanical design approved by LHC machine and prototyping and test of components going well

- Wakefield suppressors – continuous conducting bands connect to rest of LHCb vacuum pipe. Guides mirror charge from beams and prevents beam instabilities.
- Vacuum system – controls interaction between LHC, VELO primary and VELO secondary vacuums. Includes, procedures of *in-situ* bake-out of secondary vacuum box. Also, gravity valves for a non–external sensing or supply method of vacuum protection.



The sensors design

Azimuthal symmetry motivates measurements in $R - \phi$

Fast 2D–tracking can be performed in the trigger by using R–sensors alone impact parameter measurements in $R - z$ projection

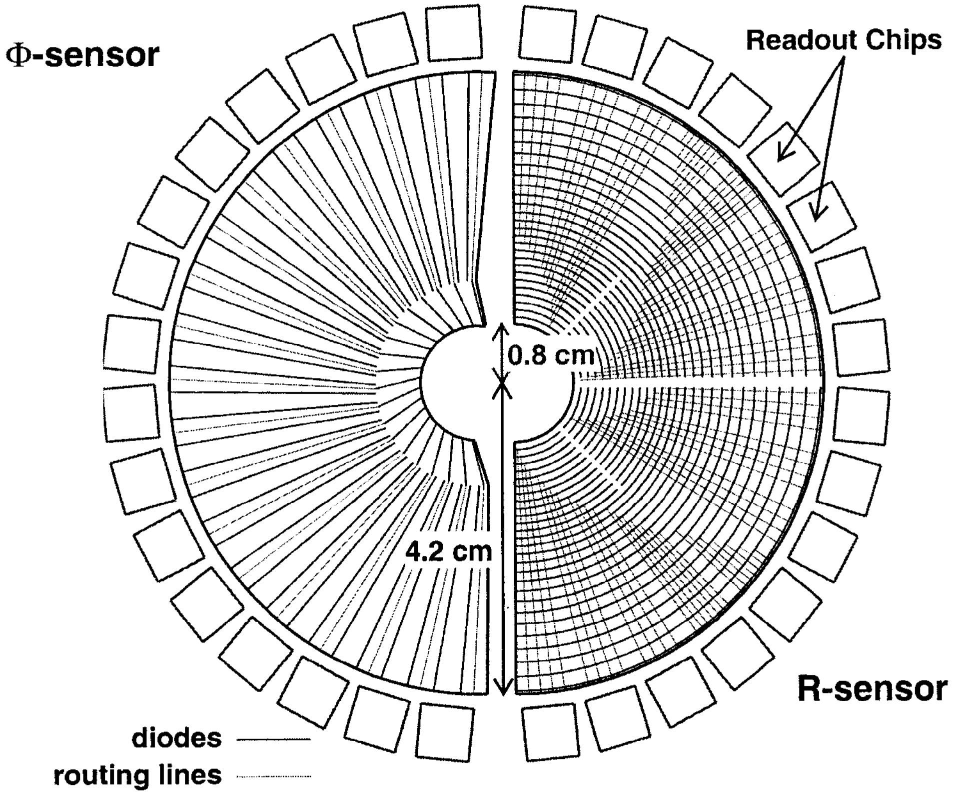
Designs of R and ϕ measuring sensors are segmented into inner and outer regions, and pitch increases with R:

- balanced occupancy
- short strips (minimum 6.2 mm) where radiation damage is greatest ⇒ low noise

$20°$ and $-10°$ stereo angle for strips on ϕ sensor. Ghost tracks suppressed with ϕ sensors reversed station–to–station.

Inner active radius of 8 mm limited by LHC machine aperture

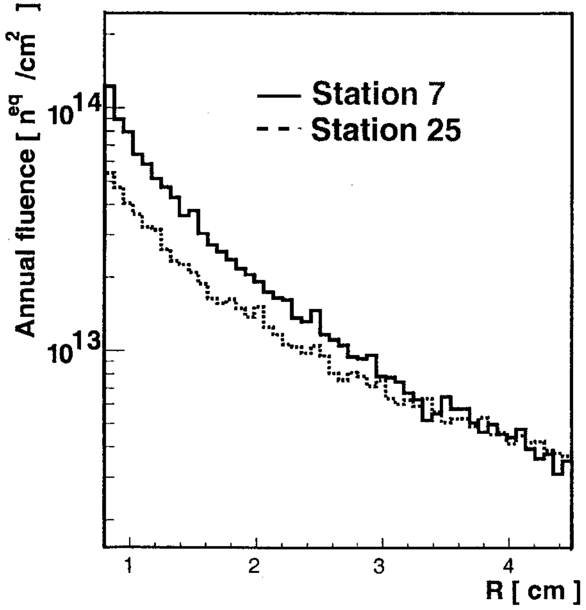
Outer radius of 42 mm from allows production $4''$ wafers

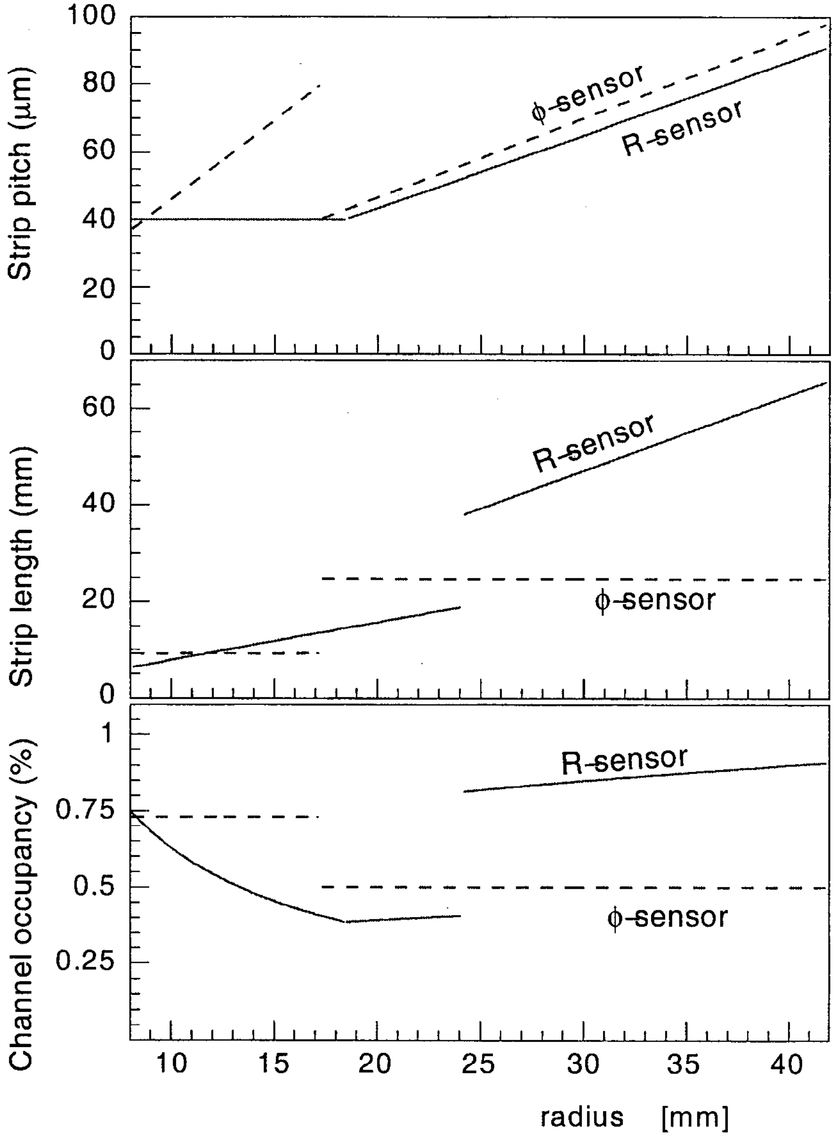


Common to both is a **double metal layer** used to route the signals from the inner region to the readout electronics situated around the outer radius

Radiation environment

- Maximum station irradiation
  $0.5 - 1.3 \times 10^{14}\ n_{\mathrm{eq}}/\mathrm{cm}^2/\mathrm{year}$
  $10 - 26$ MRad/year
- Irradiation dominated by $\pi^{\pm}$
- Irradiation level varies rapidly as $\sim R^{-2}$
- A factor of ~ 30 difference between R of 8 mm and 42 mm





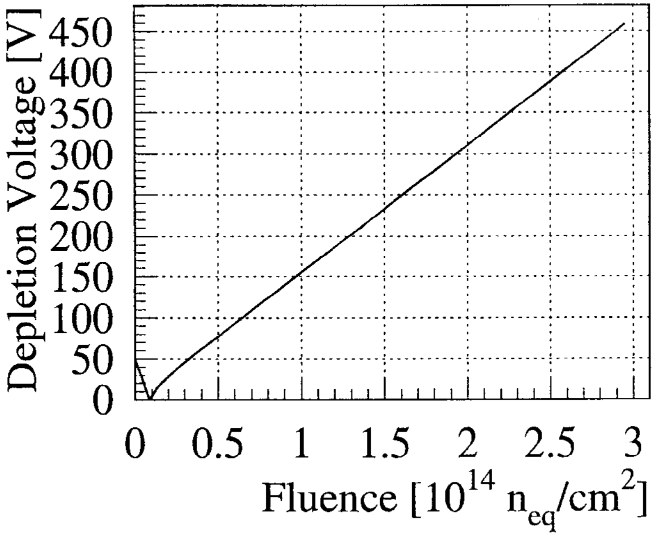
Radiation damage in silicon

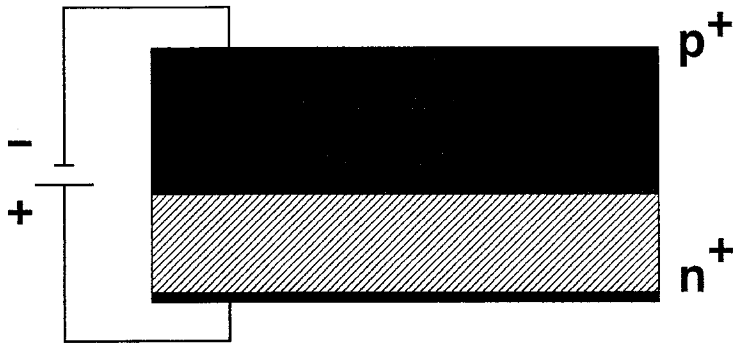
To obtain the maximum signal from a Si sensor it must be biased so that the bulk is fully depleted

The voltage required for this, V_{dep}, is proportional to the absolute value effective space charge, $|N_{eff}|$, in the Si bulk

Irradiation causes displacements of atoms in the Si lattice $\Rightarrow$ changes $|N_{eff}|$

Initial type inversion from n to p–type Si in bulk then V_{dep} increases





After type inversion

Leakage current of the detector increases with radiation $\Rightarrow$ higher noise

Behaviour changes with time after irradiation and is strongly temperature dependent $\Rightarrow$ annealing

Leakage current doubles ever $\approx$ 7°C

Cooling detectors below 0°C during operation suppresses the increase in leakage current due to irradiation $\Rightarrow$ minimises risk of thermal run–away

Silicon R&D

Extensive silicon micro–strip R&D programme for the LHCb VELO

Several differences with ATLAS and CMS experiments:

- Inhomogeneous and harsh radiation environment
- Fine pitch 40 μm or less (ATLAS 80 μm)
- Small Si area of 0.6 m^2 (CMS 240 m^2)

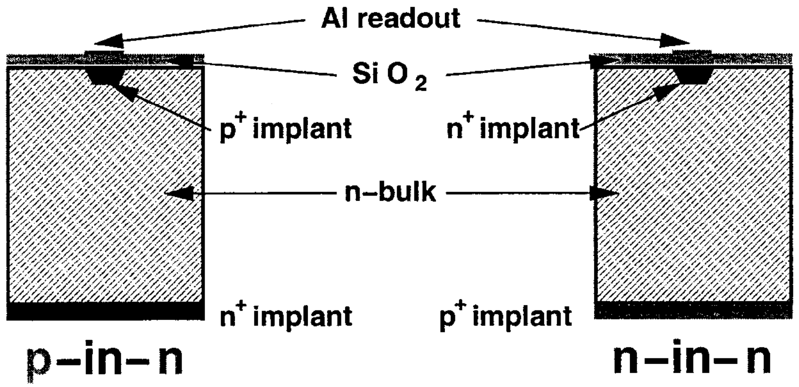
Pixel detectors were considered but:

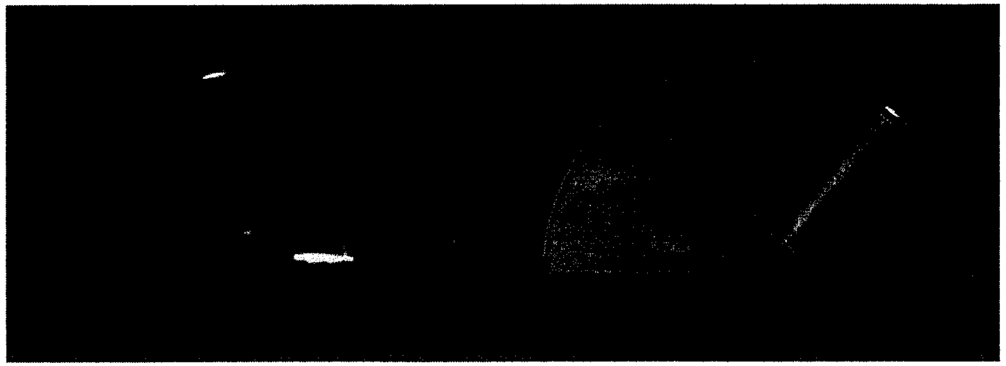
- Additional material
- Cooling problems, especially in vacuum
- No 2D tracking in the Level 1 trigger
- $< 1\%$ occupancy means no pattern recognition problems for VELO

Important decision is:

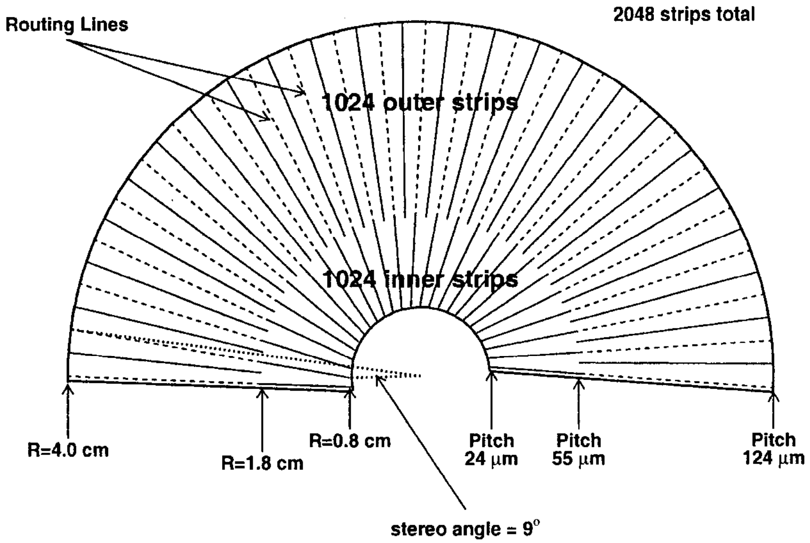
- p–on–n or,
- n–on–n – more complicated processing $\Rightarrow$ expense

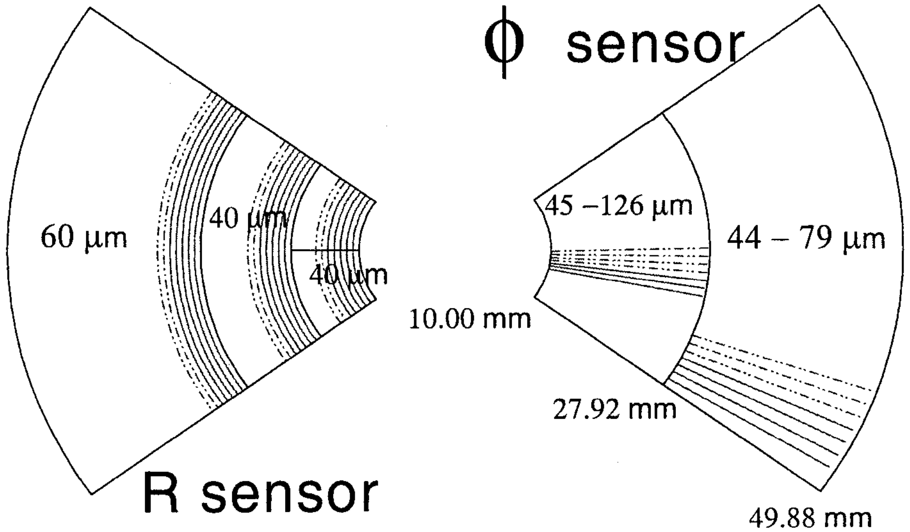
technology for sensors, based on performance after irradiation





Prototype detectors



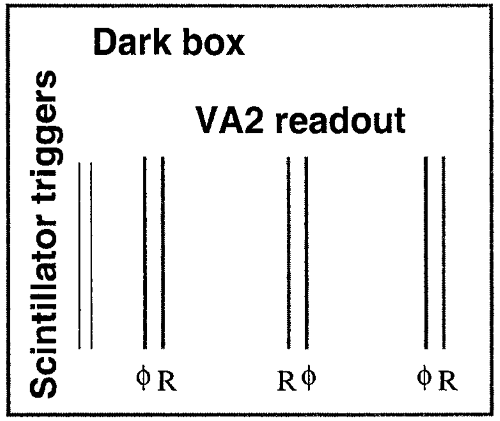


Manufactured by MICRON
p–on–n
$200\ \mu\mathrm{m}$ thick
Pitch: $24 - 124\ \mu\mathrm{m}$
Range of fluence: $0 - 6.4 \times 10^{14}\ n_{\mathrm{eq}}/\mathrm{cm}^2$

Manufactured by Hamamatsu
n–on–n
$300\ \mu\mathrm{m}$ thick
Pitch: $40 - 126\ \mu\mathrm{m}$
Range of fluence: $0 - 2.5 \times 10^{14}\ n_{\mathrm{eq}}/\mathrm{cm}^2$
(Phi detector only irradiated)

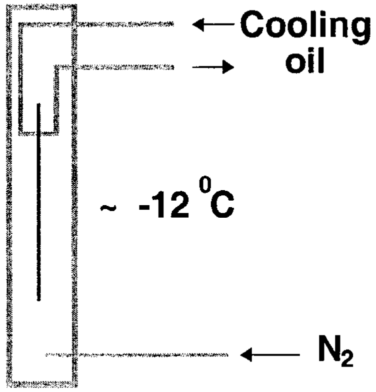
Silicon R&D

First telescope station

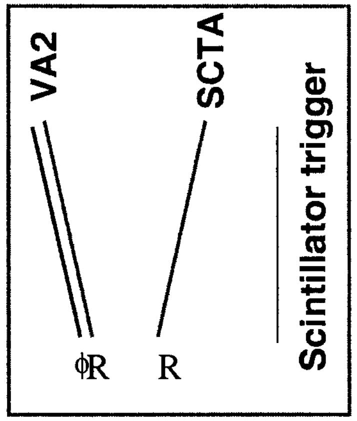


resolution: 5 micron

Test station

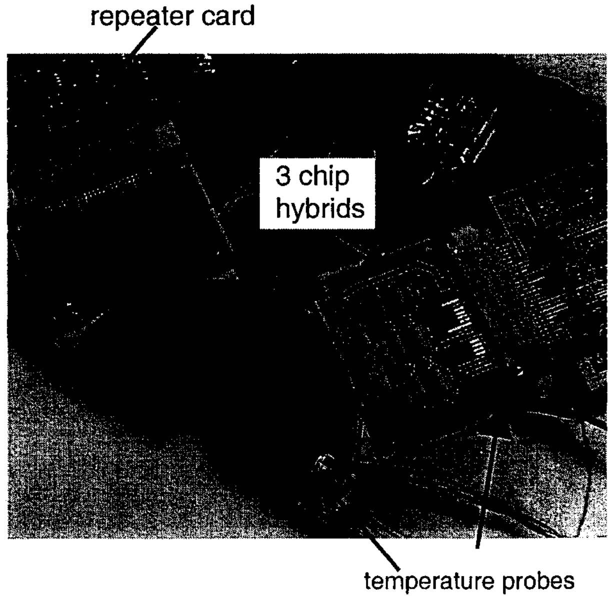


Inclined telescope station

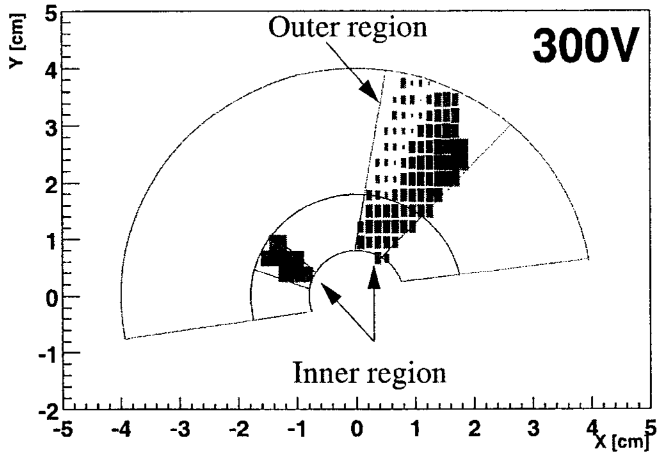


resolution: 5 micron

- Test–beam take place at the CERN SPS (120 GeV π and μ)
- Telescope of 8 Hamamatsu prototypes readout with VA2 electronics
- Test detectors equipped with SCT128A electronics sampling at 40 MHz
- Additional non–irradiated detector equipped with SCT128As to to select tracks in time
- Track extrapolation error at test detector $\sim 4\ \mu\mathrm{m}$

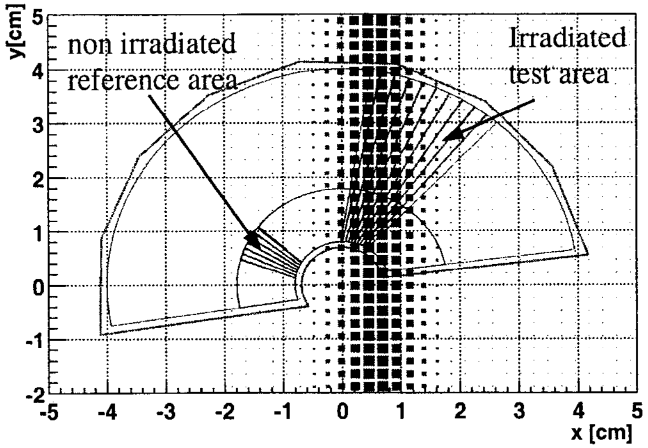


Measurements of the p–on–n prototype

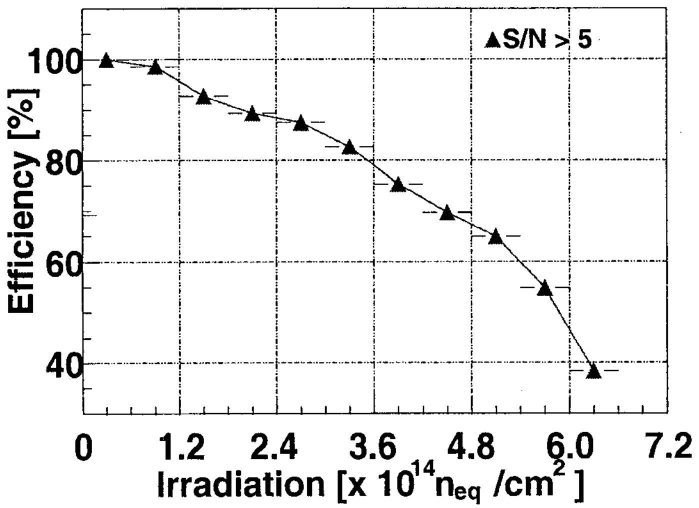


- Efficiency of reconstructing cluster near an extrapolated track
- Two features:
  - **Irradiated region less efficient**
  - **Inner region more efficient than outer**

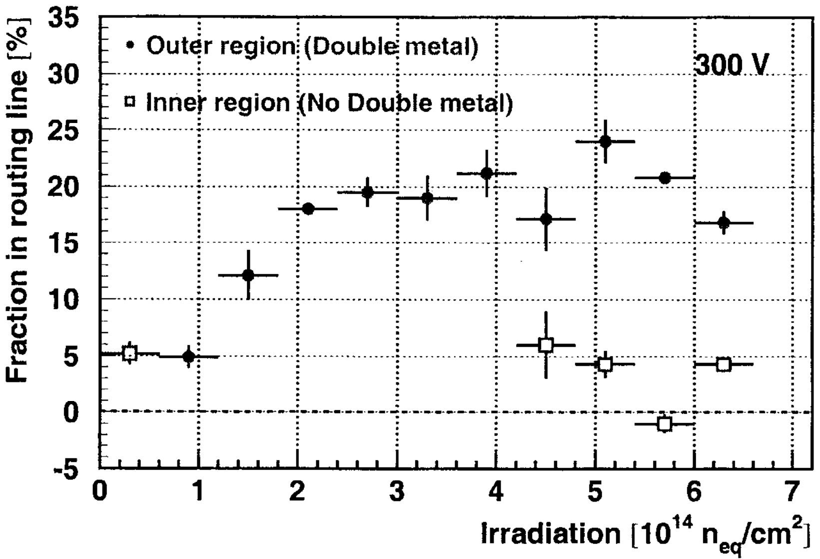
LHCb desires an efficiency of 99% with a signal–to–noise cut of 5



Efficiency in outer region at 300 V

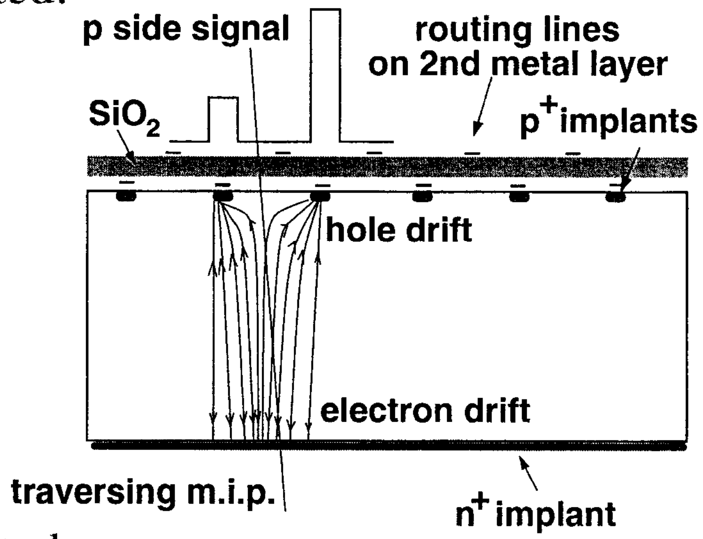


The dangers of p–on–n

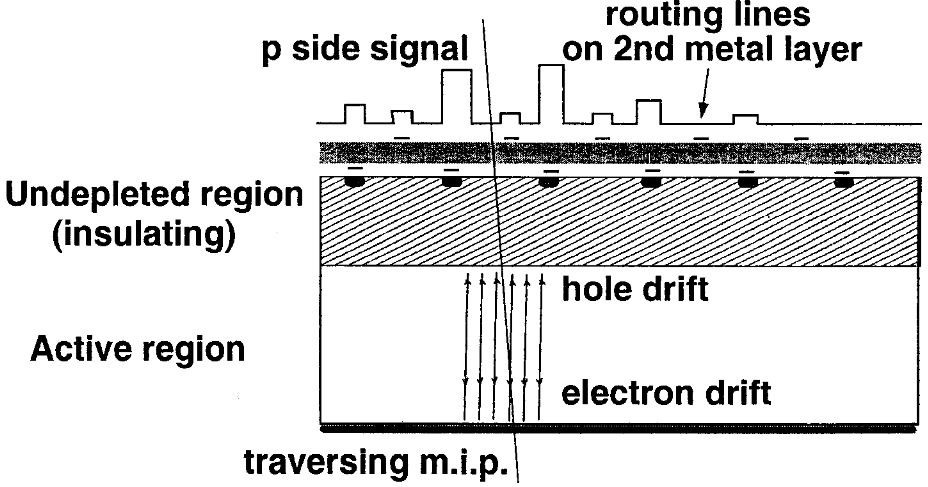


- The fraction of charge in the routing line $\sim 20\%$ for irradiations where the detector is underdepleted
- $\sim 5\%$ in inner region from capacitive coupling and/or electronic cross talk
- Charge loss explained by undepleted and **insulating** layer in irradiated silicon $\Rightarrow$

fully depleted:



underdepleted:

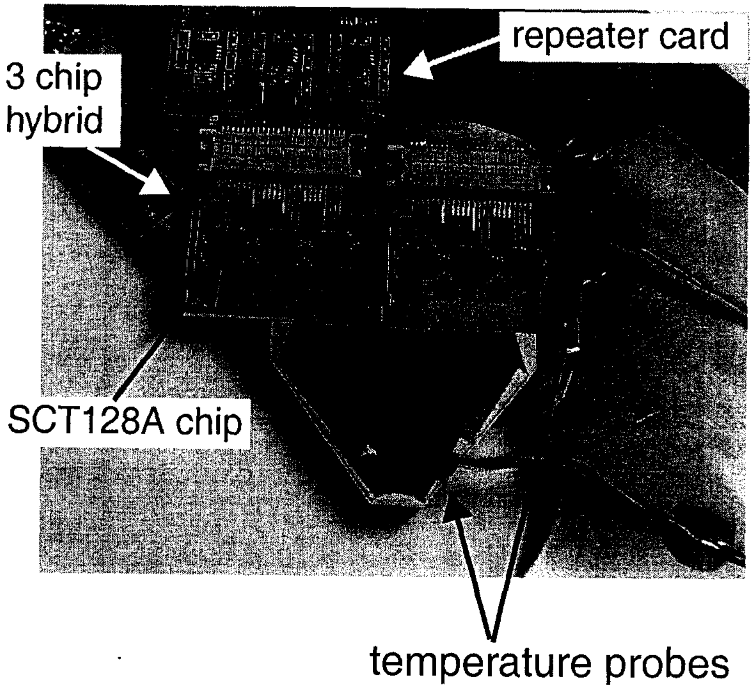


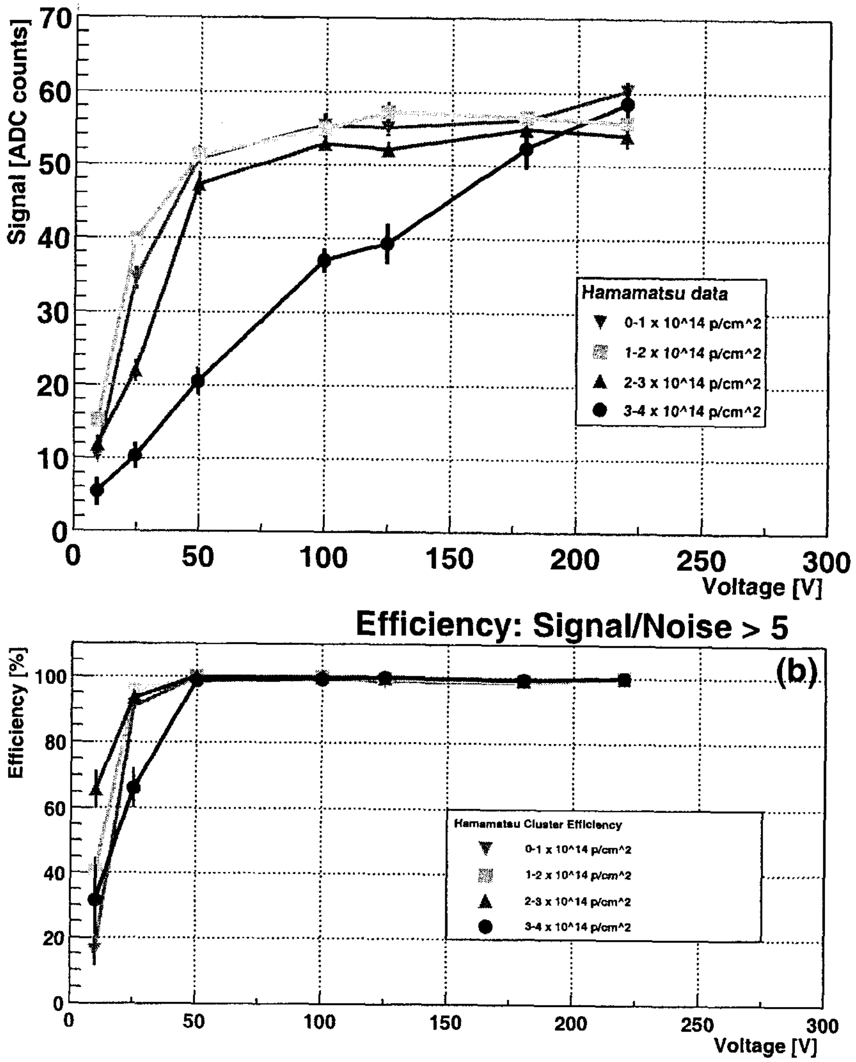
Measurements with n–on–n detectors

A similar set of efficiency measurements made with n–on–n irradiated sensor

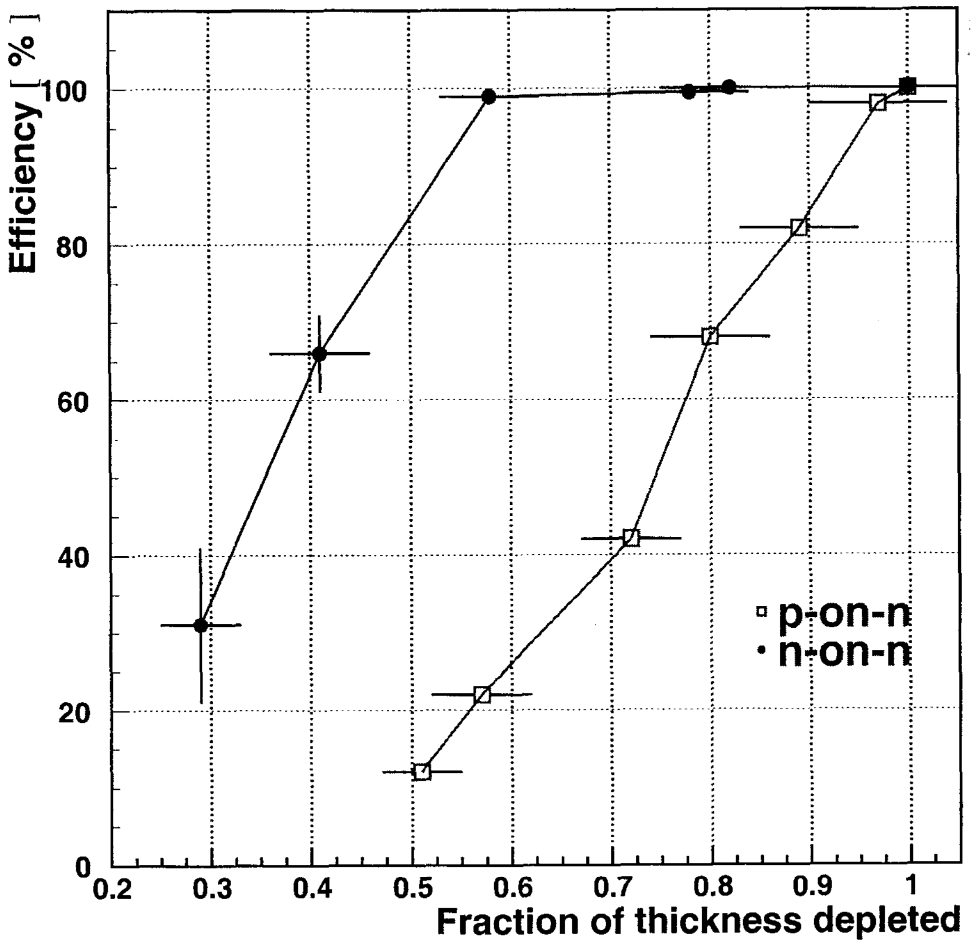
Depleted region develops from implant side. Therefore, no insulating layer around strip

Good performance even when signal collected is below maximum (ie detector is underdepleted)





Comparison with n–on–n



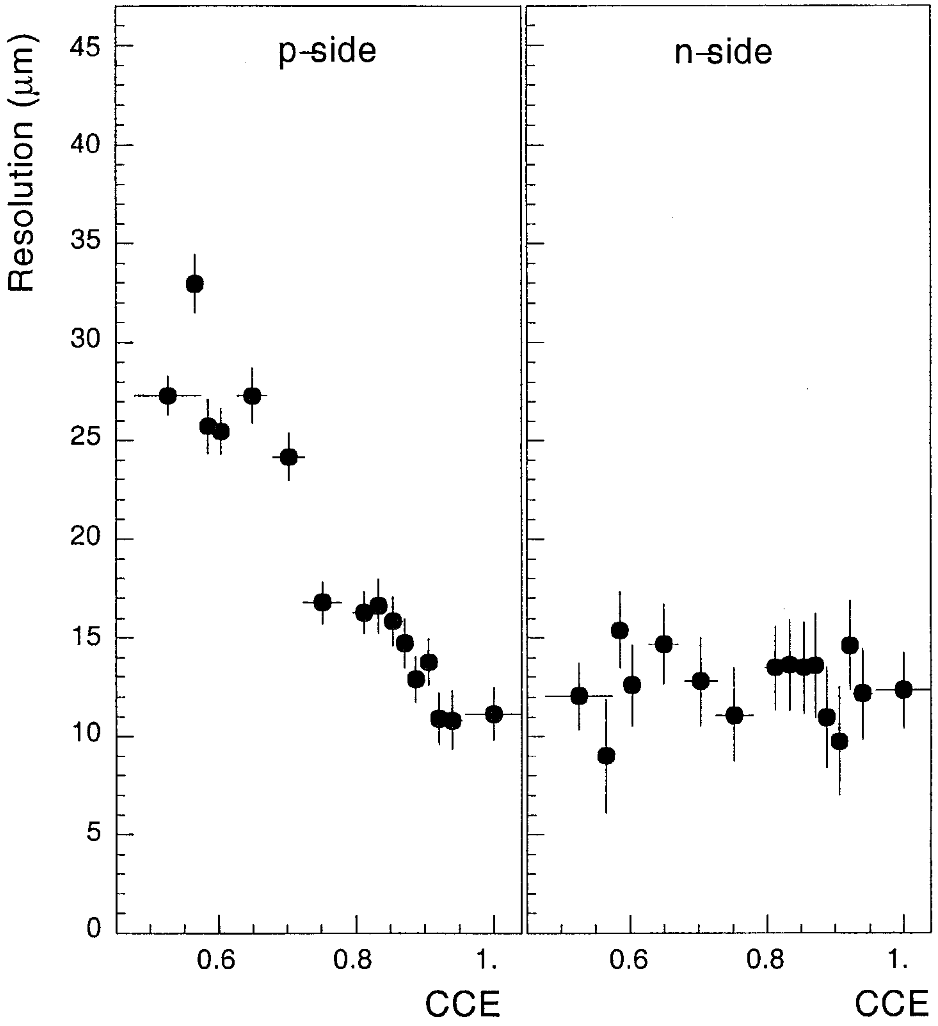
- Compare fraction depleted, f, versus efficiency for p–on–n and n–on–n

$$f = \sqrt{V_{\mathrm{bias}}/V_{\mathrm{dep}}}$$

V_{dep} from CCE

- Efficiency $\sim 100\%$ for only 60% depletion with n–on–n detector
- Efficiency only $\sim 80\%$ for only 90% depletion with p–on–n detector
- p–on–n efficiency **degrades** as soon as detector is underdepleted

Comparison with p–on–n



CCE=Charge Collection Efficiency

Another measurement has been made comparing the resolution of underdepleted and p–on–n and n–on–n detectors

Measurements with an irradiated double–sided micro-strip detector with (x, y) strips

Pitch 42 μm (n–side) and 50 μm (p-side)

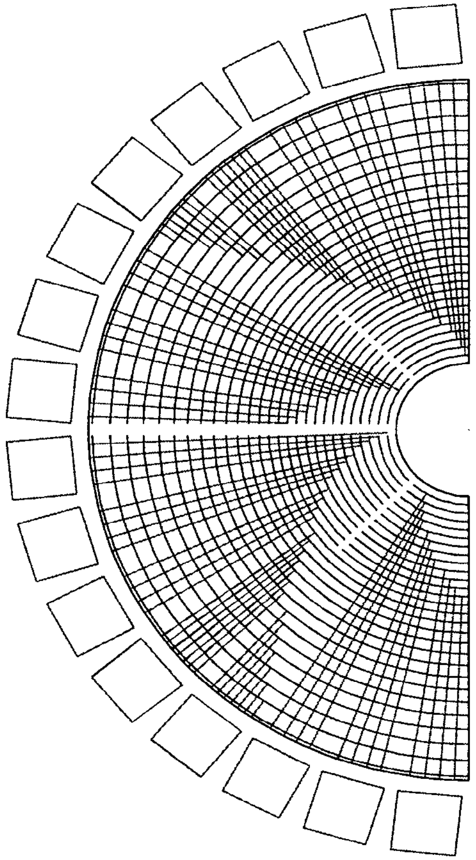
Slow electronics – $\sim 1.5\ \mu$s integration time

Depleted depth $\propto \sqrt{CCE}$ – for an irradiated sensor

Clear evidence on p–side of worsen resolution with increased underdepletion

Detector technology decision

- Due to the inhomogeneous irradiation a fully depleting detector in inner region ⇒ less irradiated outer region **overdepleted**
- Overdepletion can lead to increased noise due to micro–discharge in the Si–bulk about the strip
- If detectors have to be run underdepleted p–on–n will have charge loss to second metal layer ⇒ **impossible to recover** in R–detector where one strip is crossed by many routing lines



Therefore, to allow $\sim 100\%$ efficiency and best resolution even if parts of detector are underdepleted

And to avoid losses to the second metal layer

n–on–n the choice for LHCb

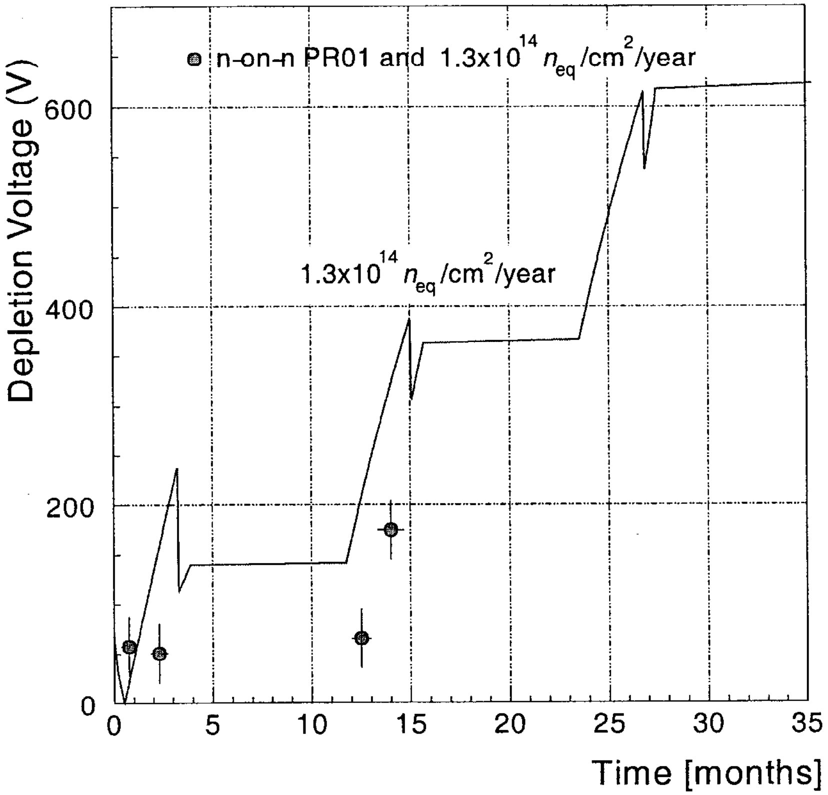
Detector technology decision

Model change in depletion voltage with time after start of the LHC

Prototype n–on–n detectors performance better than predicted$\Rightarrow$ Rose collab.

Depletion voltage $\sim$200 V after two years

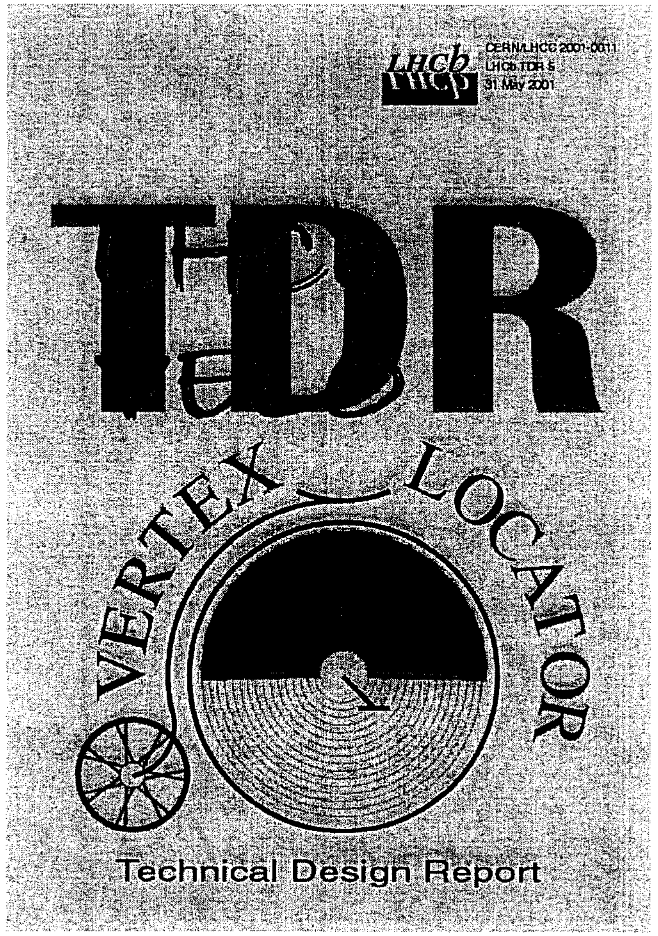
Should give reliable performance for 2 years $+$ before replacement of sensors



With a model of constant fluence for 100 days at T$=-5°$ C then 14 days at T$=22°$ C for reverse–annealing. Remainder of time T$<0°$ C.

Conclusions

- LHCb experiment designed to make precision measurements of the least well known aspects of the 'unitarity triangle' from 2006 onwards
- The VELO plays an integral part in making these
- VELO important part of the first and second–levels of the trigger
- Sophisticated mechanical system to allow measurements close to the interaction point
- Silicon sensor design must withstand harsh radiation environment ⇒ n–on–n technology



LHCb
CERN/LHCC 2001-0011
LHCb TDR 5
31 May 2001

TDR

VERTEX LOCATOR

Technical Design Report

Design approved last year
Technical Design Report CERN/LHCC-2001/0011