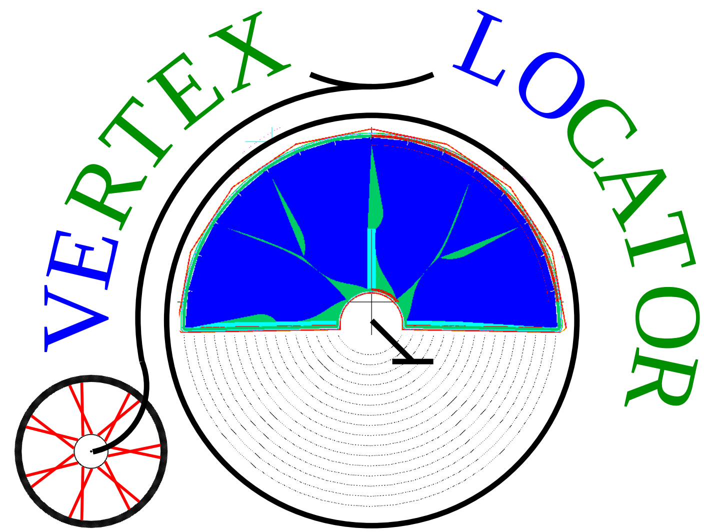
VELO: the LHCb Vertex Detector

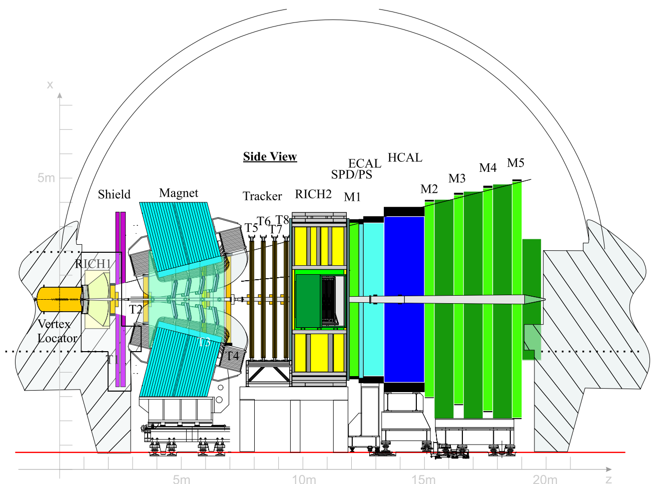
Jim Libby, CERN

- The tasks of the LHCb VErtex LOcator
- The VELO design:
  - Mechanics and LHC integration
  - Silicon sensor design and R&D
- The VELO in the trigger



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

The tasks of the LHCb VELO

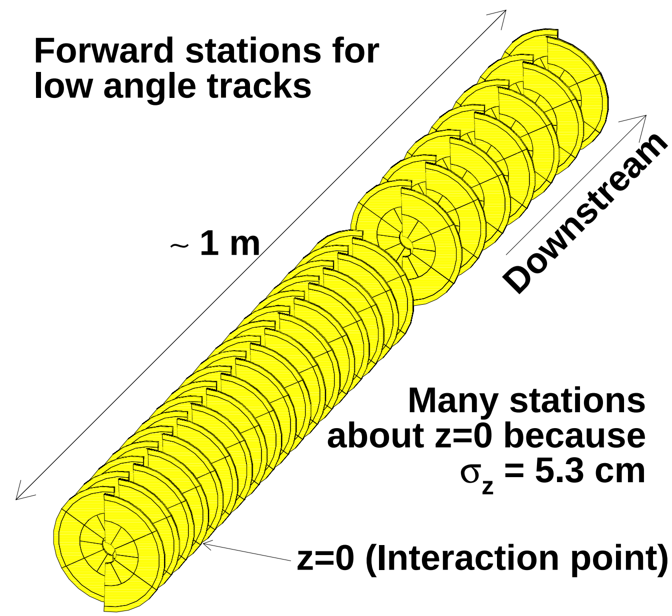


he 3 main tasks for the VELO are:

- 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

hese criteria motivate the design choices for the ELO 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 $\Rightarrow$ improved primary vertex reconstruction

Design of the VELO

rtexing precision is best achieved with:

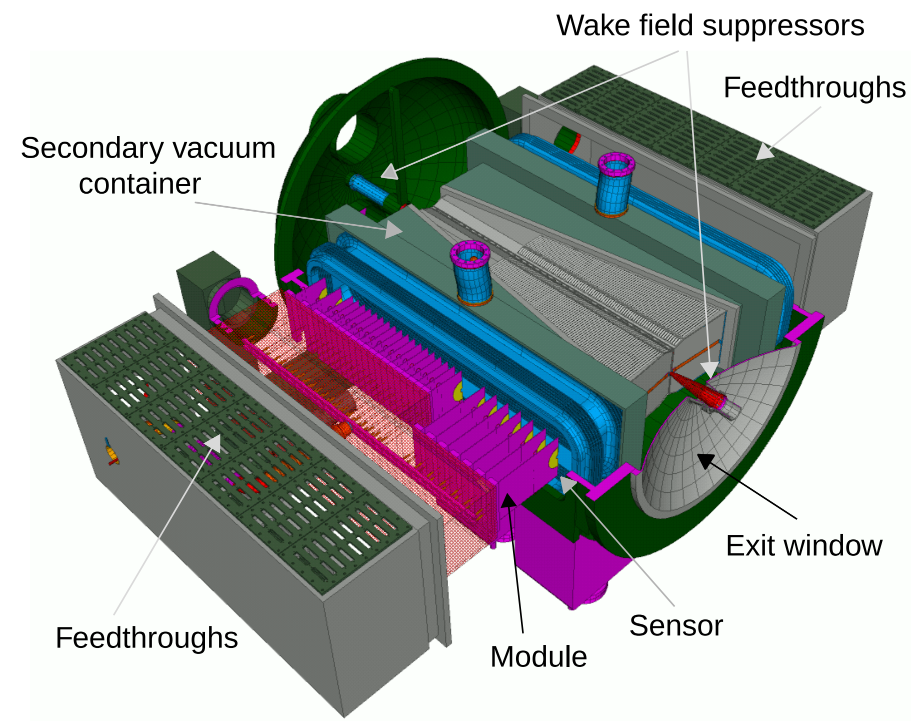
- Short extrapolation distances ⇒ measurements at small radius
- Minimal multiple scattering ⇒ little material between interaction and measurement points

th have important consequences on the mechanical sign of the VELO

place sensors very close (7 mm) to the beam line quires the VELO to be integrated with LHC vacuum stem:

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

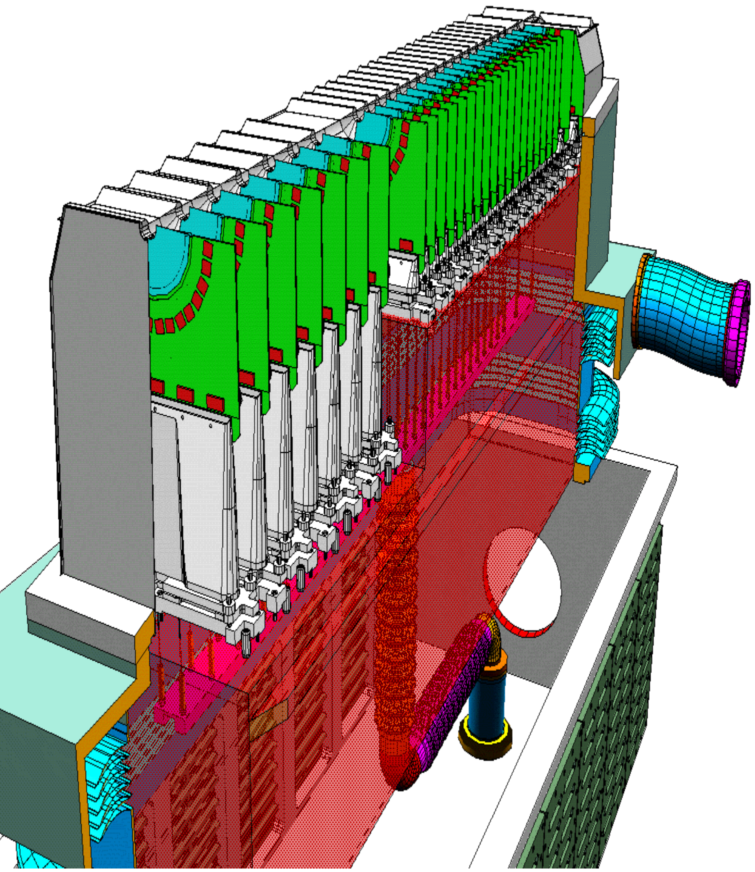
Therefore, the sensors are placed inside a secondary vacuum isolated from the LHC (primary) vacuum ⇒ Roman pots

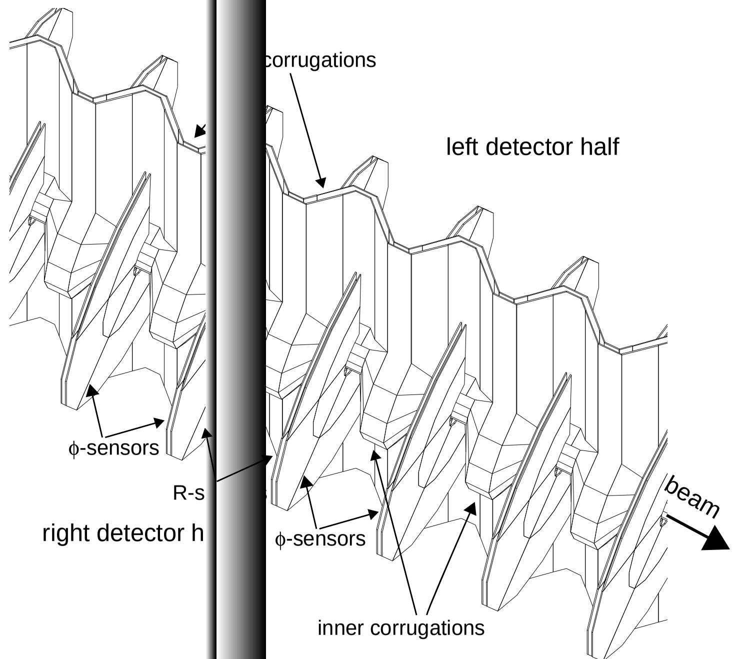


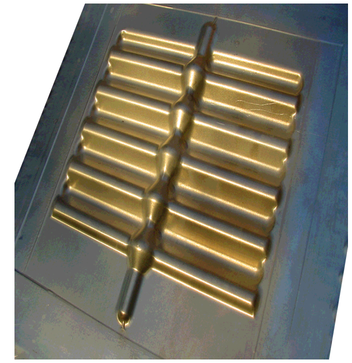
RF–foil is made from $250\ \mu m$ thick Al

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

The mechanics and HC integration







sverhplastichnost (Bochvar and Sviderskaya in 1945)

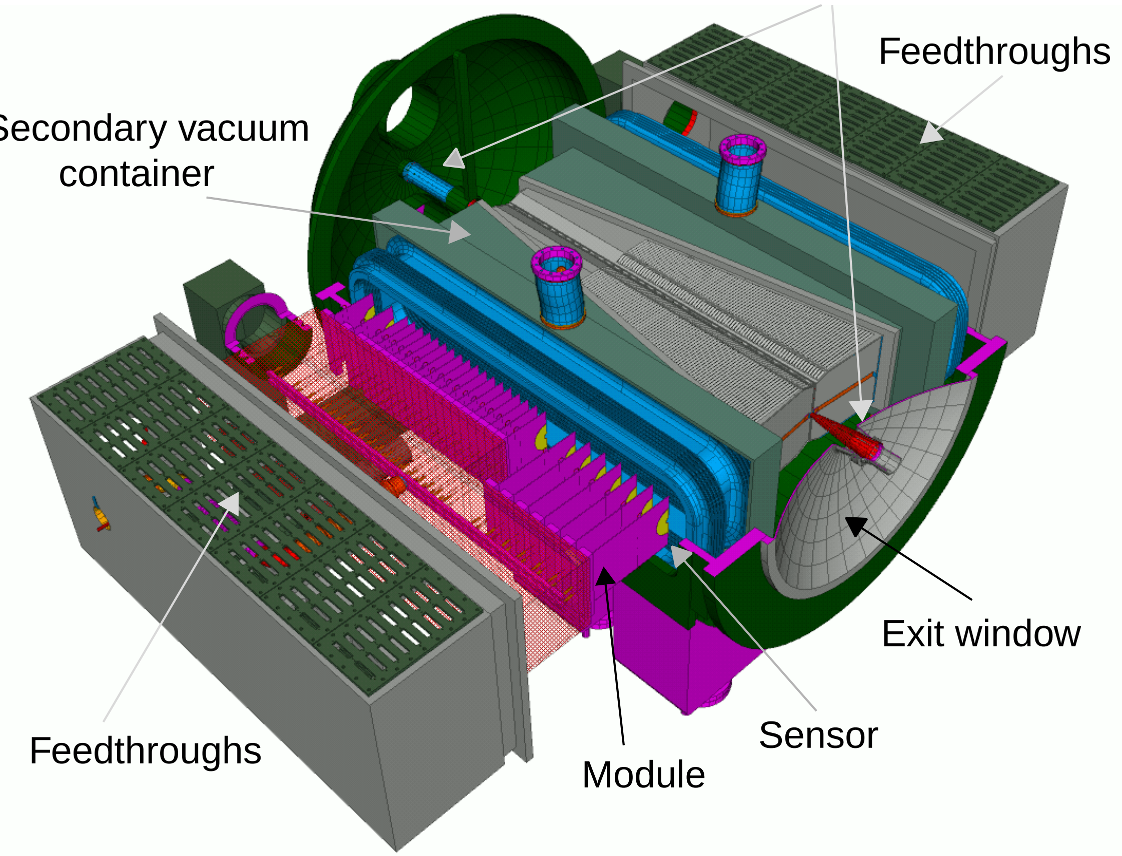
Outer corrugations for overlap of the two halves:

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

Inner corrugations to minimise material before first measured point:

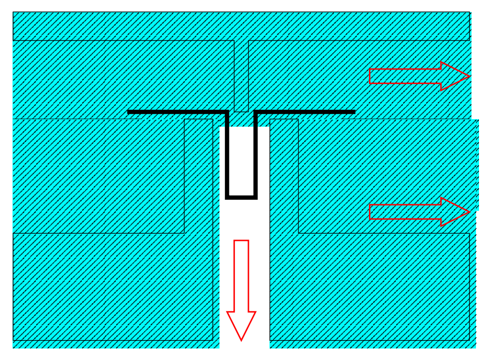
- with corrugations: 3.2% X_0
- without corrugations: 12.0% X_0

The mechanics and LHC integration

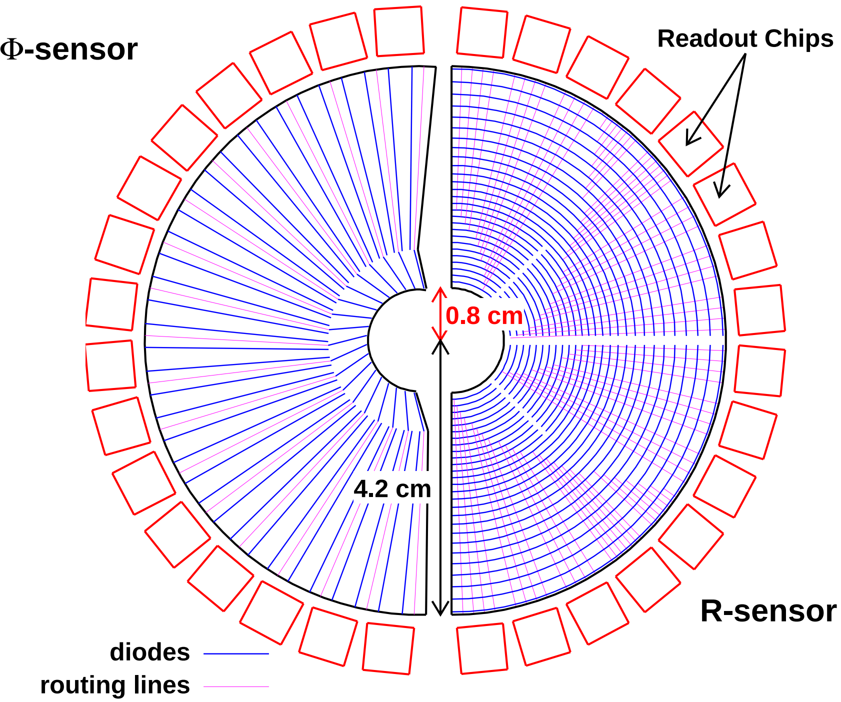


Mechanical design approved by LHC machine and prototyping and test of components going well
See poster

- 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 and radiation environment

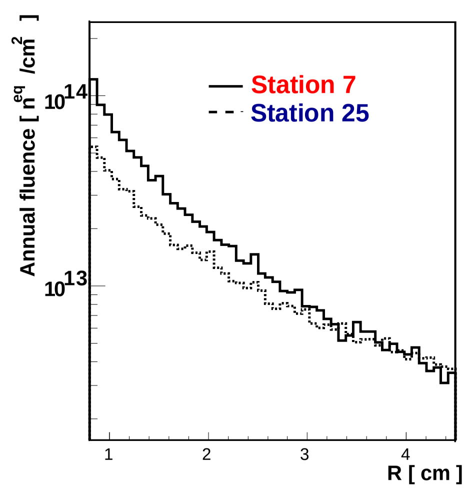


Φ–measuring sensor has inner and outer regions to balance occupancy

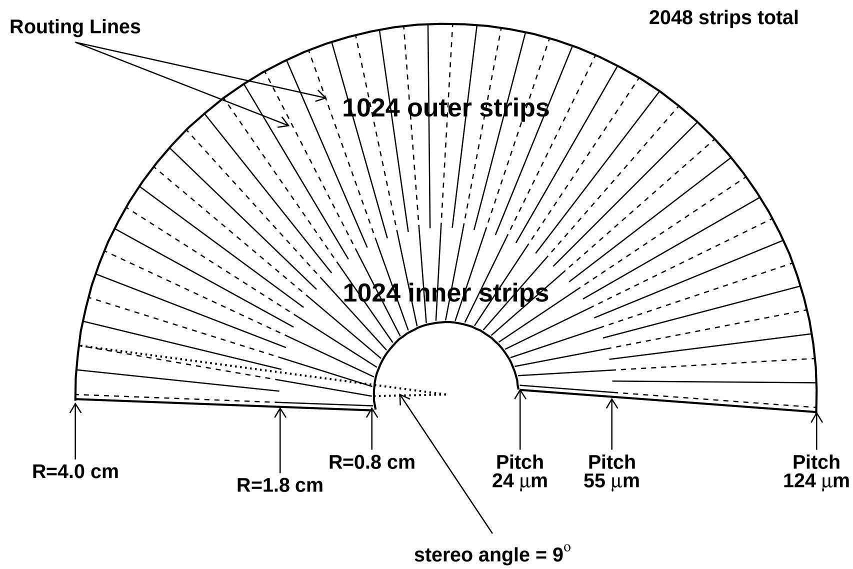
R–measuring sensor has different azimuthal segmentation in inner and outer regions for occupancy and trigger

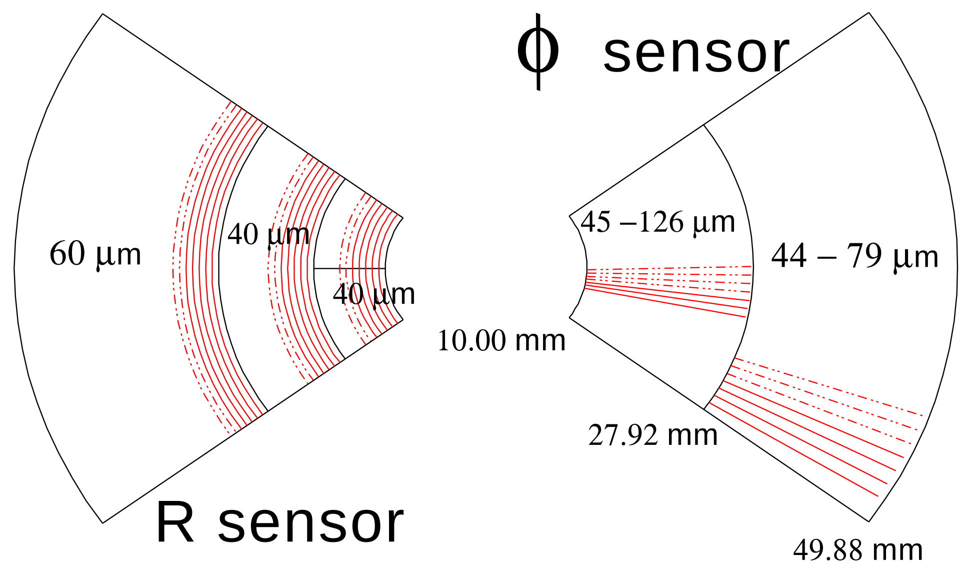
Common to both is a **double metal layer** used to route the signals from the inner region to the readout electronics situated around the outer radius

- Maximum station irradiation $0.5 - 1.3 \times 10^{14}\ n_{\mathrm{eq}}/\mathrm{cm}^2/\mathrm{year}$
- 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



Prototype detectors

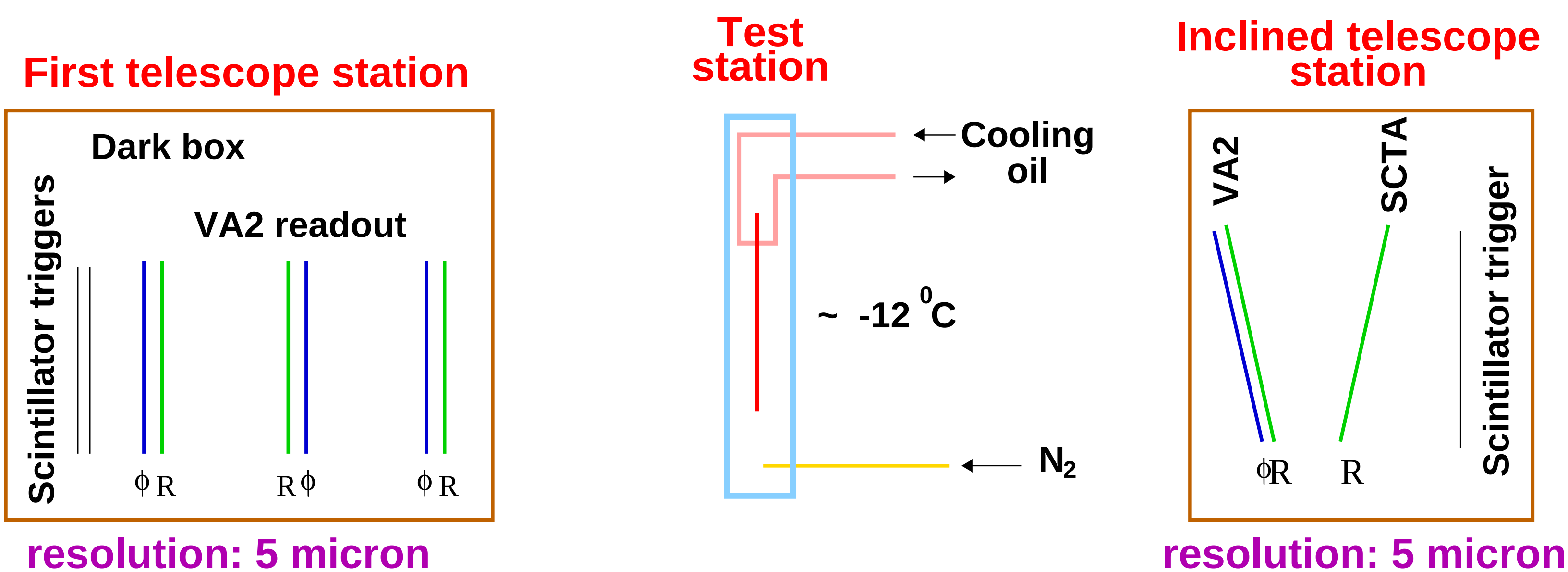




Manufactured by MICRON
p–on–n
$200\ \mu m$ thick
Pitch: $24 - 124\ \mu m$
Range of fluence: $0 - 6.4 \times 10^{14}\ n_{eq}/cm^2$

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

Silicon R&D

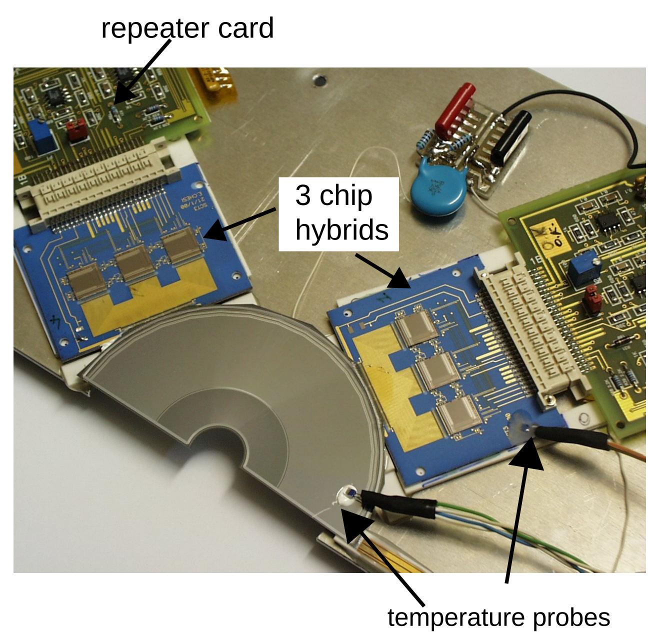


Test–beam take place at the CERN SPS (120 GeV π and μ)

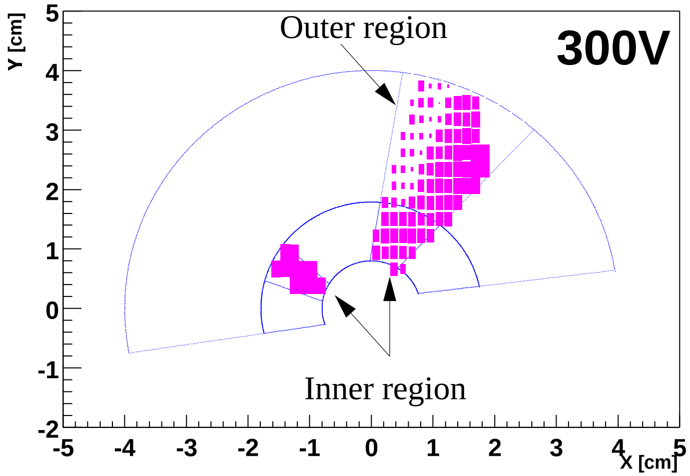
Test detectors equipped with SCT128A electronics sampling at 40 MHz

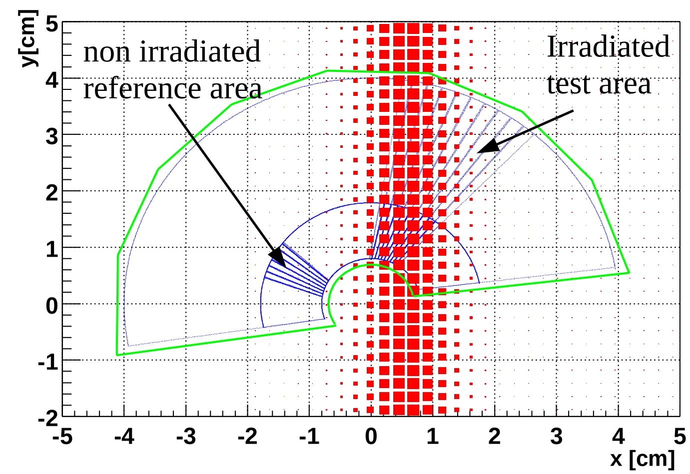
Additional non–irradiated detector equipped with SCT128As to to select tracks in time

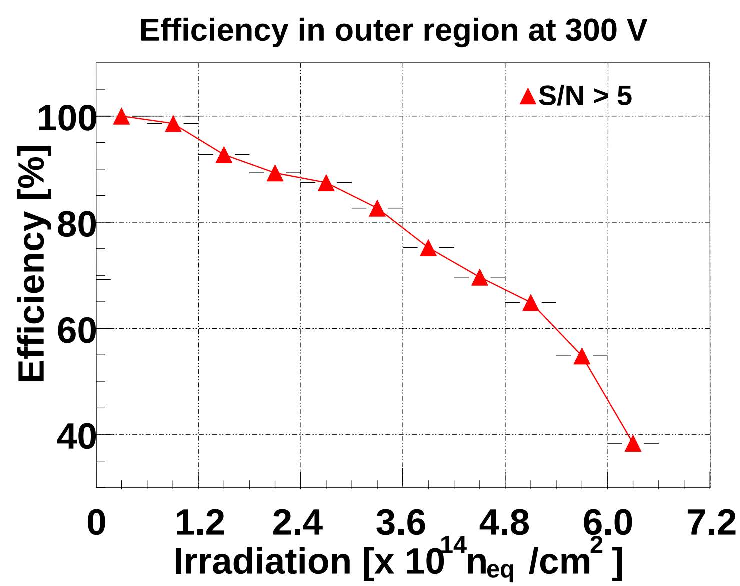
Track extrapolation error at test detector $\sim 4\ \mu$m



Measurements of the p–on–n prototype



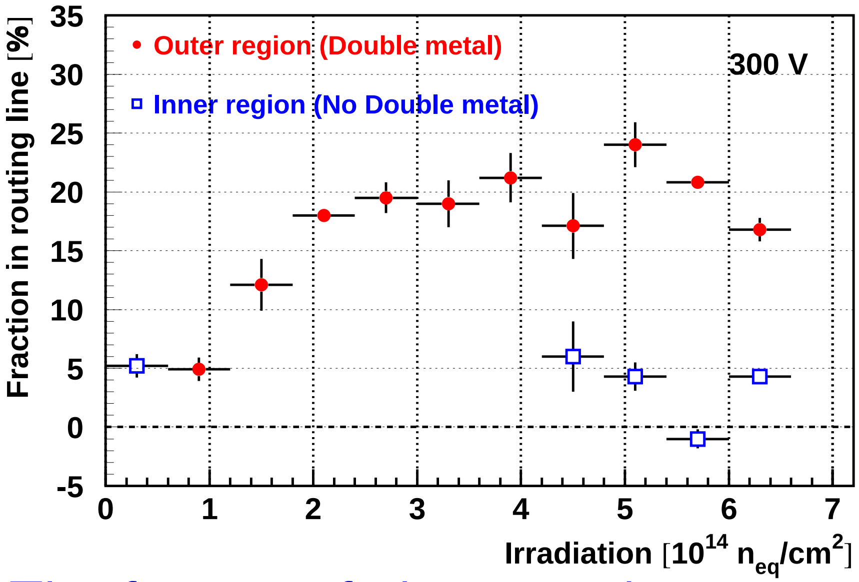




- Efficiency of reconstructing cluster near an extrapolated track
- Two features:
  - Irradiated region less efficient
  - Inner region more efficient than outer

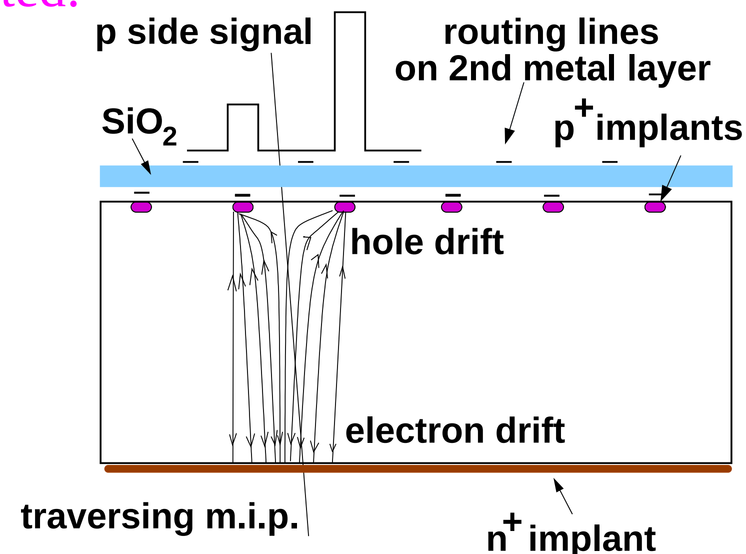
HCb desires an efficiency of 99% with a gnal–to–noise cut of 5

The dangers of p–on–n

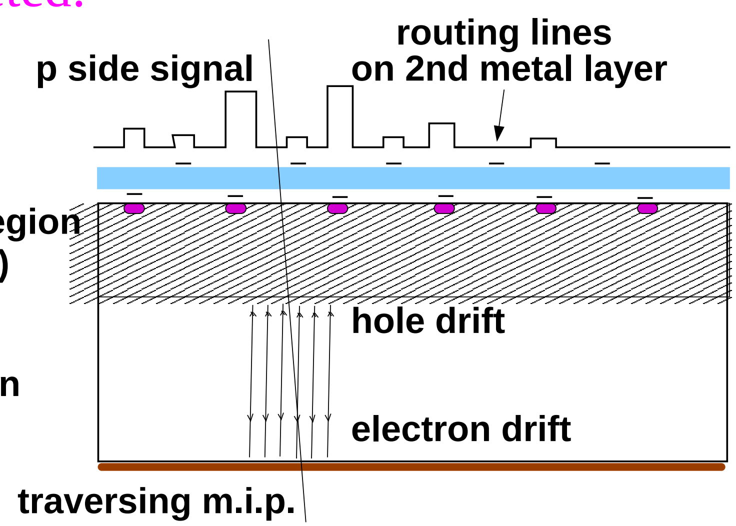


- The fraction of charge in the routing line $\sim 20\%$ for irradiations where the detector is underdepleted
- $\sim 5\%$ in inner region from capacitive coupling and/or electronic cross talk
- Charge loss explained by undepleted and **insulating** layer in irradiated silicon $\Rightarrow$

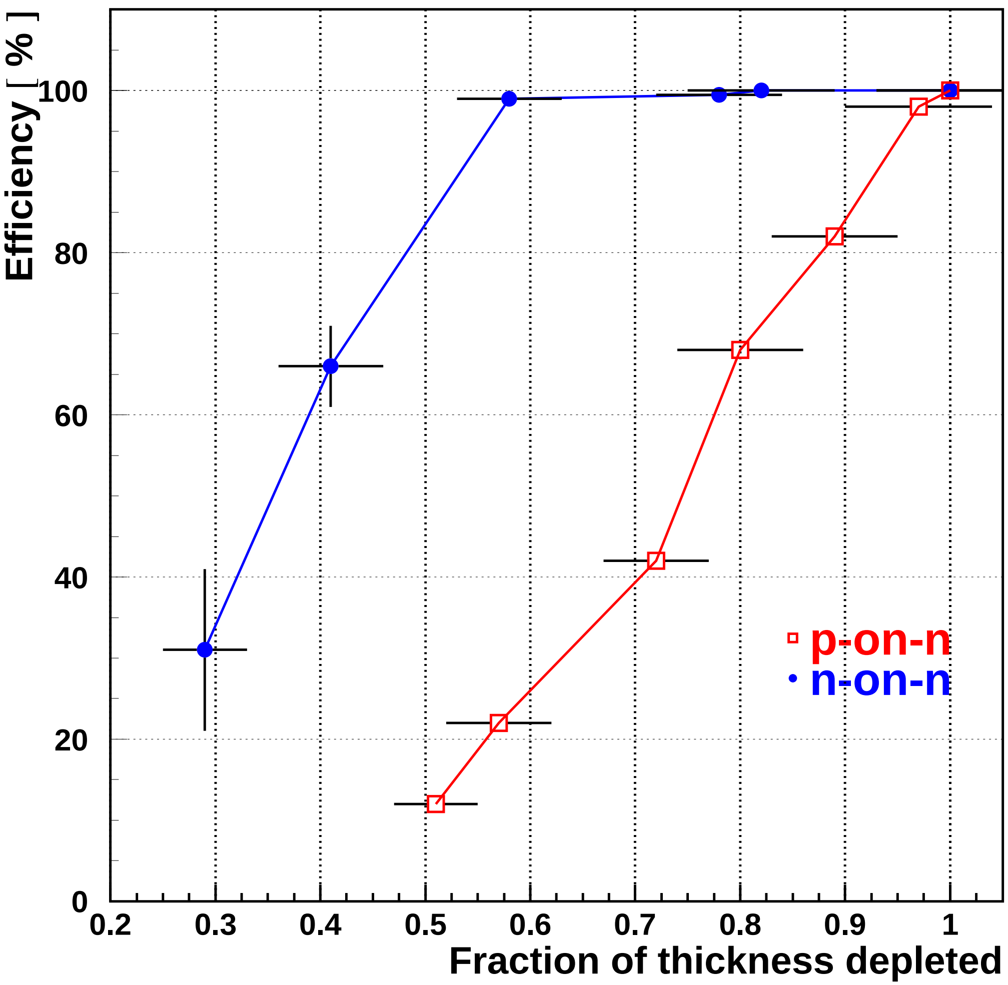
fully depleted:



underdepleted:



Comparison with n–on–n



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

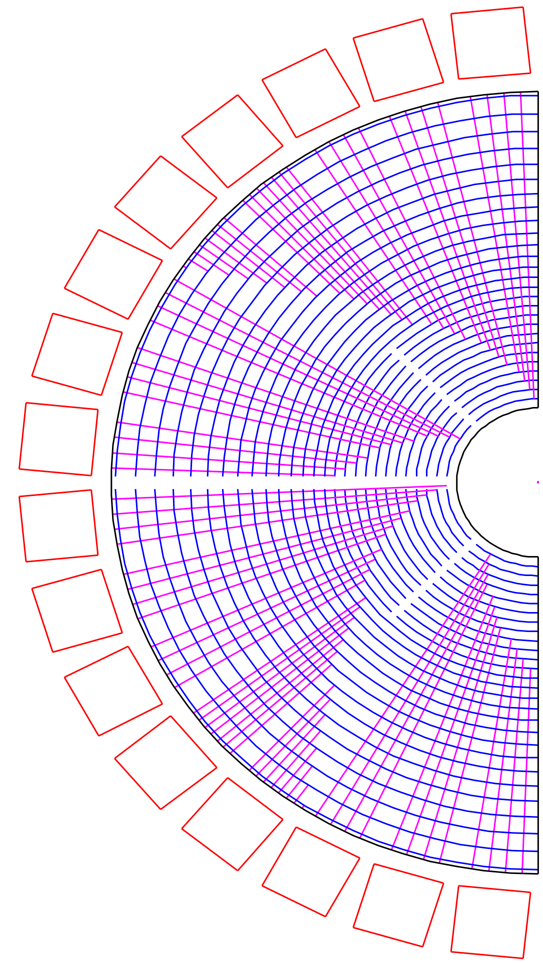
$$f = \sqrt{V_{\text{bias}}/V_{\text{dep}}}$$

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

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



herefore, to allow $\sim 100\%$ efficiency and best resolution

en if parts of detector are underdepleted

nd to avoid losses to the second metal layer

n–**on**–n **the choice for LHCb**

LHCb Trigger

- e trigger is crucial for B–physics at hadron machines due to the large background and the
h interaction rates
- Cb 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

- ly Level 0 is FPGA based
- vels 1–3 algorithms run on CPU farms
- vel 1 special networked farm to process the VELO data
- ter a Level 1 Yes, all sub–detector's data are read–out and event building begins

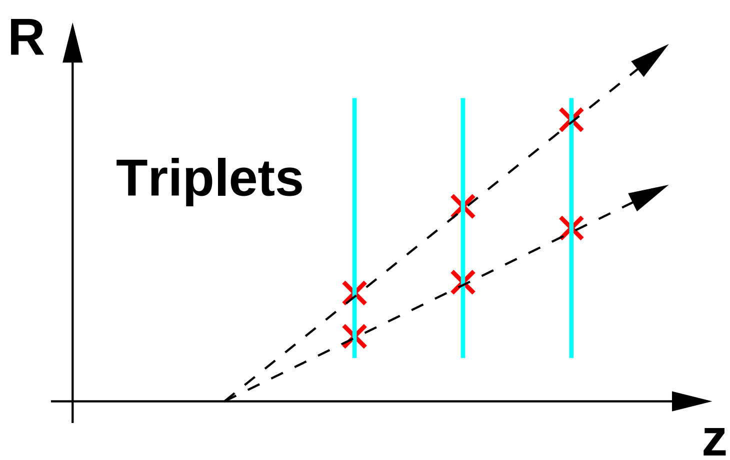
Second level vertex trigger

cond level of the trigger uses VELO to reconstruct cks and find those with a large impact parameter th respect to the primary vertex

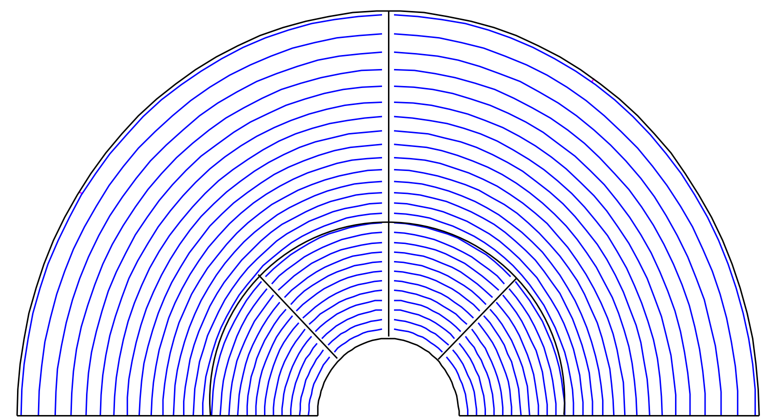
rst step is tracking using R–measurements only

iplets used to form tracks $\Rightarrow$ 98% efficient

imary vertex position in z reconstructed from pairs of)—track crossings



om test–beam measurements using $\pi^{\pm}$ on Cu targets 70 μm resolution on the PV is anticipated



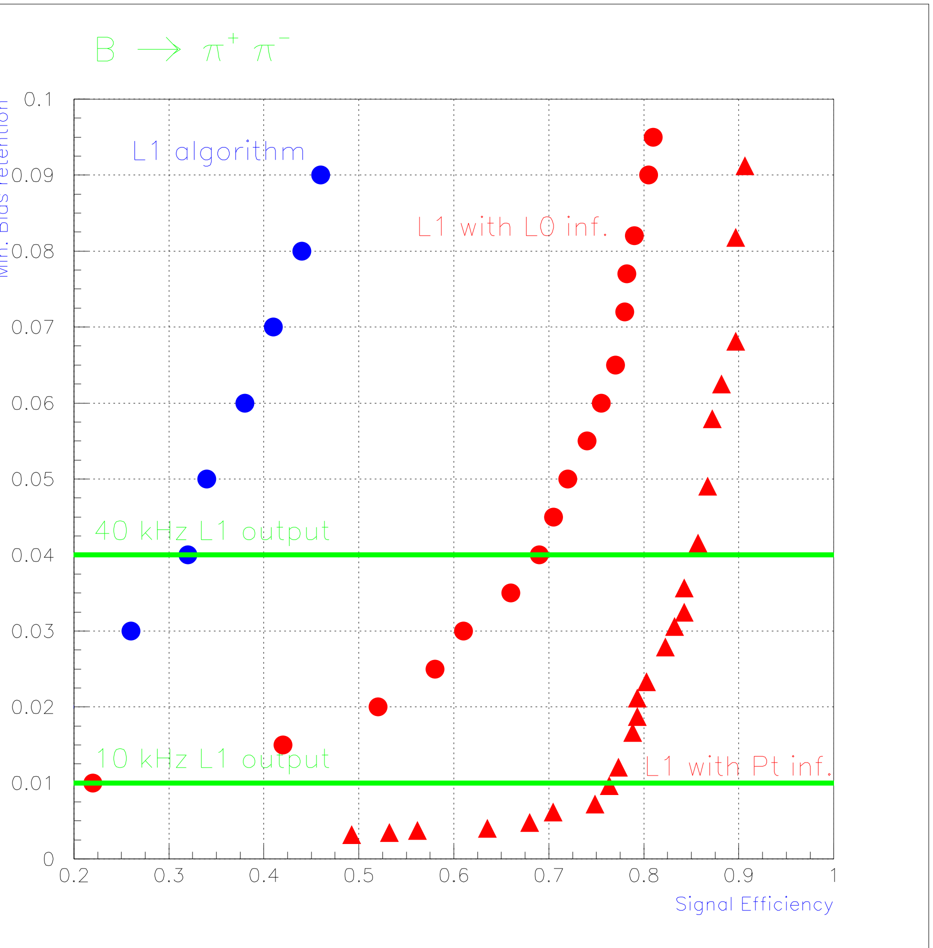
Trigger motivates R–**measuring detectors**

Azimuthal segmentation of 45° in the inner region of the R–detectors used to reconstruct position PV in plane $\perp$ to beam $\Rightarrow$ $20\ \mu$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



algorithm = two–track vertexing

ghtly reduced efficiency for L1 with p_t on $\mathrm{B_s^0} \to \mathrm{D}_s\pi$
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 ≤ 1.7 ms 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

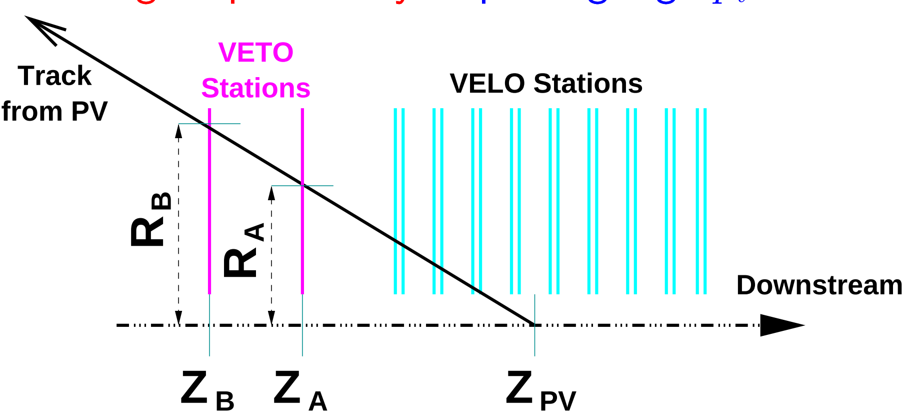
Under development at present ⇒ problem B–field around RICH1 photo–detectors

Vertex trigger to be finalised at the end of 2002

Level 0 pile-up veto

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

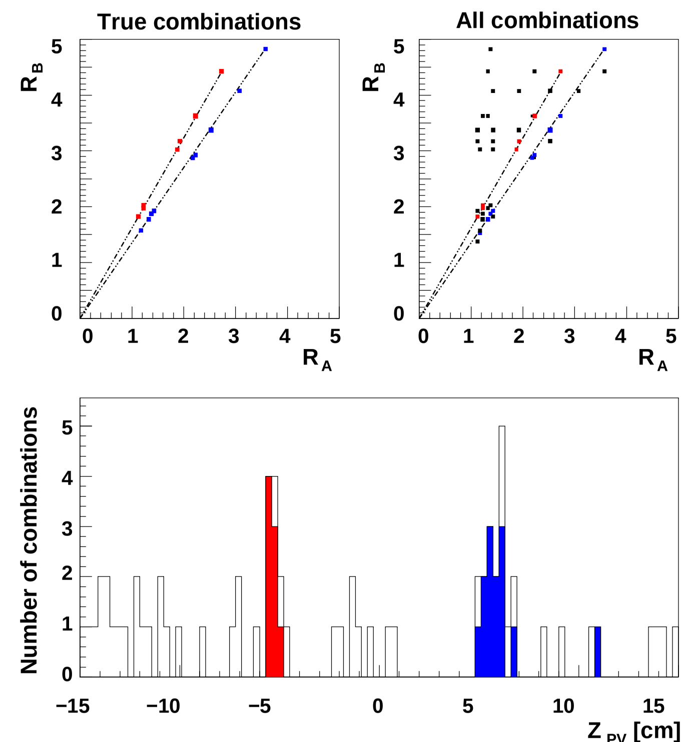
- single interactions are easier to reconstruct in the second trigger level, and
- reduce first level bandwidth taken by these events - $2\times$ higher probability of passing high p_t cuts



wo additional R–stations upstream of the luminous gion

r tracks from the primary vertex:

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

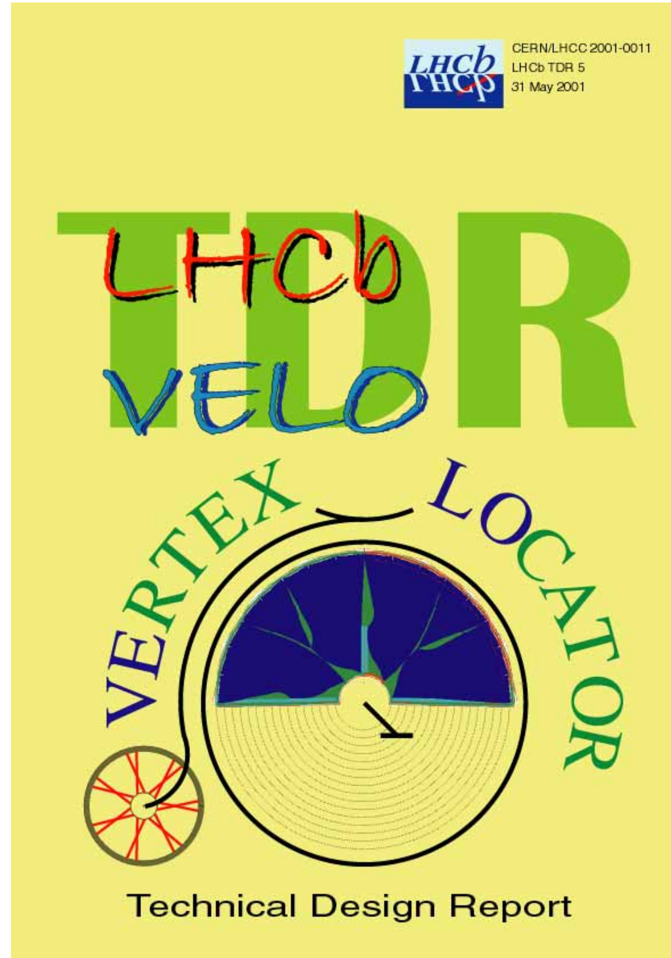


- Binary readout of the R–stations
- FPGA builds histogram and searches for highest peak
- Hits in highest peak are masked and 2nd highest found
- If no. of hits in 2nd highest peak greater than a threshold $\Rightarrow$ event VETOed

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

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
- Sophisticated mechanical system to allow measurements close to the interaction point
- Silicon sensor design must withstand harsh radiation environment $\Rightarrow$ n–on–n technology
- VELO important part of the first and second–levels of the trigger



Design approved last year

Technical Design Report CERN/LHCC-2001/0011