

# Optimising the LHCb VELO detector

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## Outline:

- LHCb overview
- VELO tasks
- VELO layout
- Required VELO performance
- Updates to VELO design
- Simulation of new VELO designs
- Outlook

## LHCb overview

**Aim:** study CP violation in  $B$  meson decays

**LHC:**  $pp$  collisions at c.o.m. energy **14 TeV**

$$L = 2.0 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

bunch-crossing (interaction) rate **40 (15) MHz**

$$\sigma_{\text{inel}} = 100 \text{ mb}, \sigma_{b\bar{b}} = 500 \mu\text{b}$$

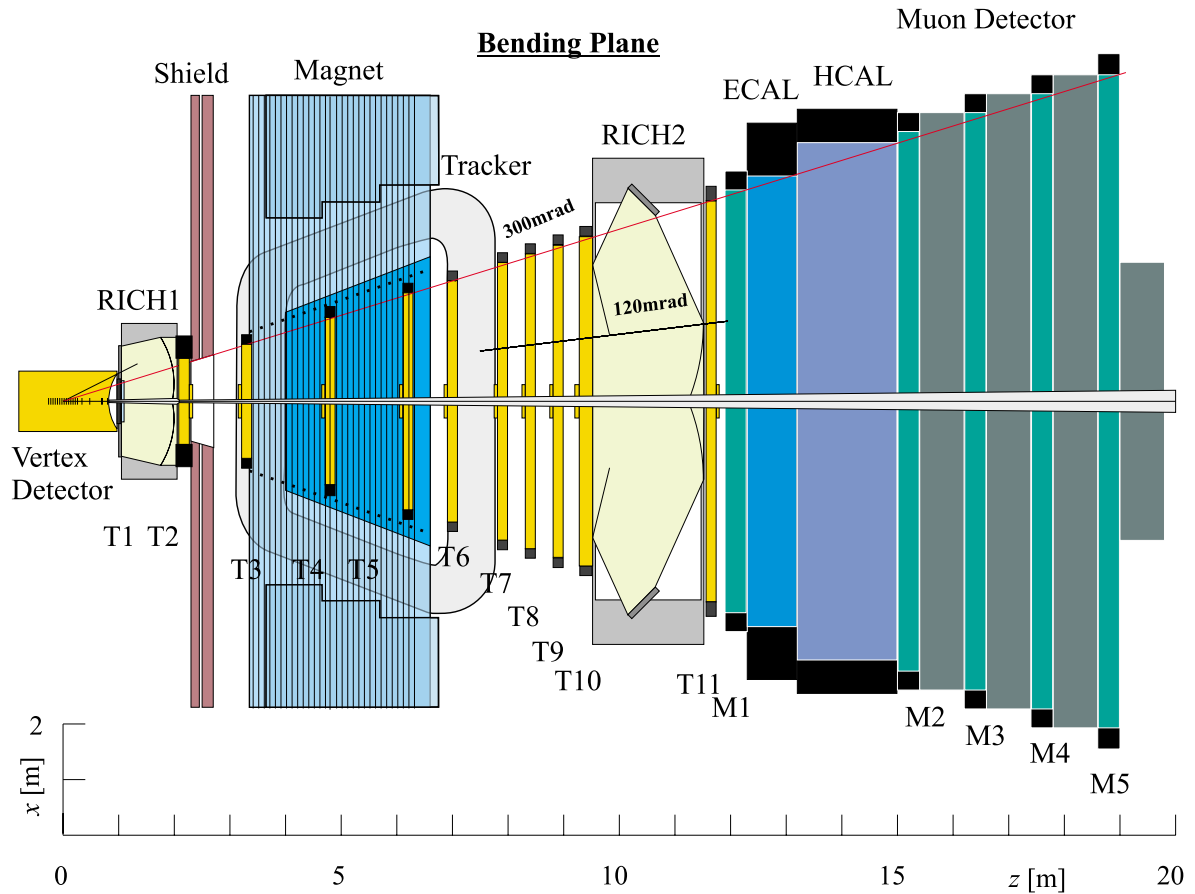
→  $10^{12}$   $b\bar{b}$  produced per LHC year ( $10^7$  s)

→ **high statistics** samples for precision measurements of CP asymmetries,  $B$  oscillations and rare  $B$  decay studies

**Experimental needs:**

- a) efficient trigger for leptons, hadrons and displaced vertices ( $B$  meson selection)
- b) particle ID ( $\pi/K$  separation, flavour tagging)
- c) good mass resolution (background rejection)
- d) good decay time resolution ( $\Delta m_s, \Delta \Gamma_s$ )

## LHCb overview (cont'd)



Single-arm spectrometer covering  $\theta =$   
 15 mrad to 300 mrad ( $\eta = 1.88$  to 4.89)

**Main features:**

**VERtEX LOcator (VELO)** — vertex detector

usual complement of tracking chambers, RICH,  
 ECAL, HCAL, muon chambers and magnet

## VELO tasks

VELO has 2 main tasks:

a) precise track measurement near interaction region → good resolution on track impact parameters (IP), primary (PV) and secondary (SV) vertices and  $B$  decay length

b) use in LHCb trigger to enrich  $B$  sample

**L0:** input rate 40 MHz, output rate 1 MHz

based on high  $p_t$  leptons, hadrons and photons  
+ “pile-up” veto

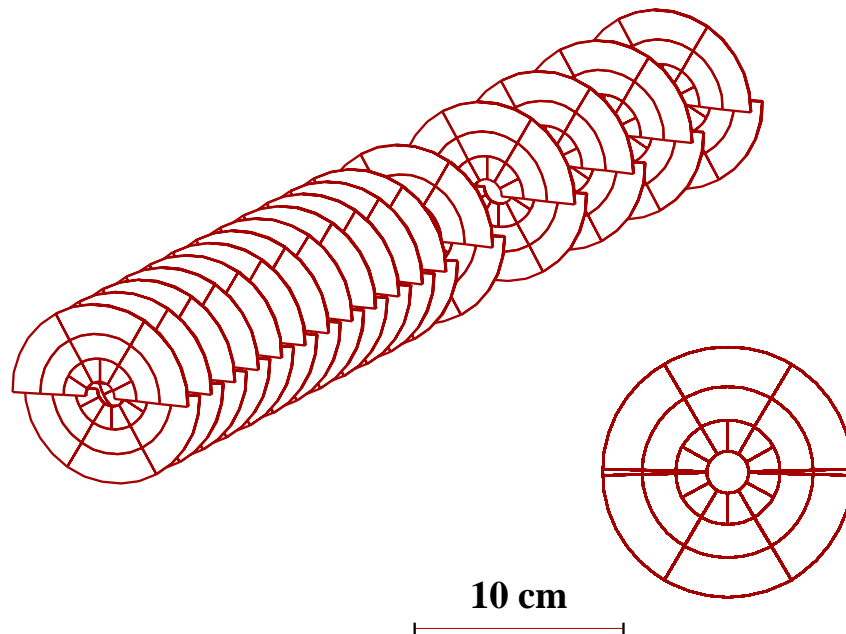
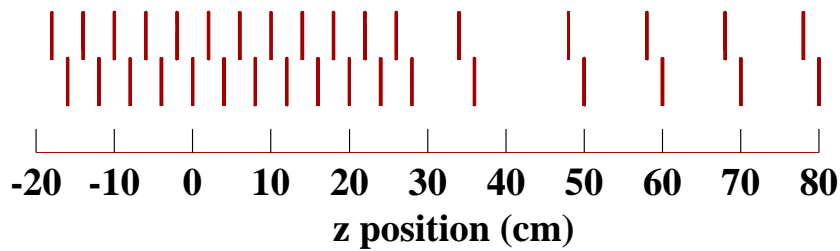
**L1:** input rate 1 MHz, output rate 40 kHz

based on vertex (VELO) and track triggers

**L2 and L3** reduce rate to 200 Hz (final sample mostly  $b\bar{b}$ ,  $c\bar{c}$  events)

## VELO layout

At time of Technical Proposal (1998)...



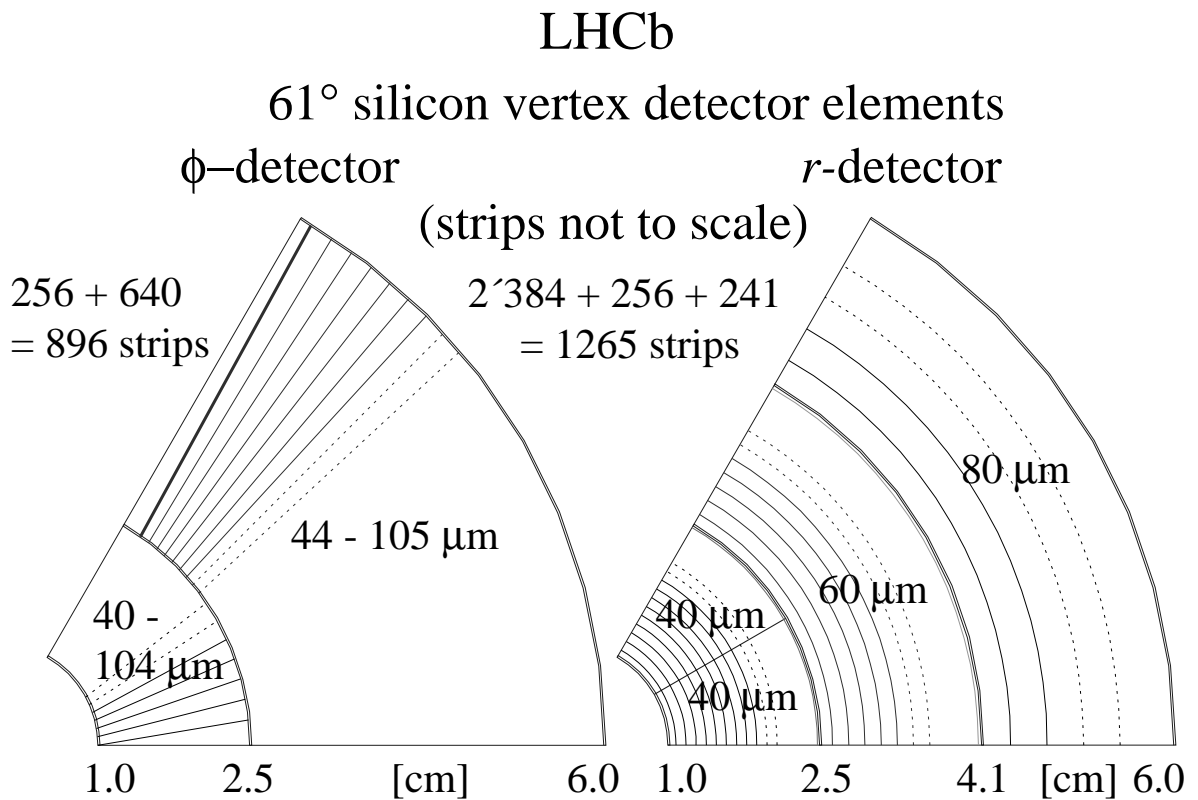
17 disks (stations) of  $r$  and  $\phi$  detectors

upper-lower halves retract during LHC injection

upper-lower overlap for alignment

## VELO layout (cont'd)

Strip layout:



Si thickness = 150  $\mu\text{m}$

module overlap for alignment

channel occupancy less than 0.5%

## VELO layout (cont'd)

### RF shielding:

beam in primary LHC vacuum, detector and electronics protected from beam RF pick-up in secondary vacuum

Al (100  $\mu\text{m}$  thick) caps round Si

Al thick — withstand any differential pressure, provide enough shielding

Al thin — not degrade resolution

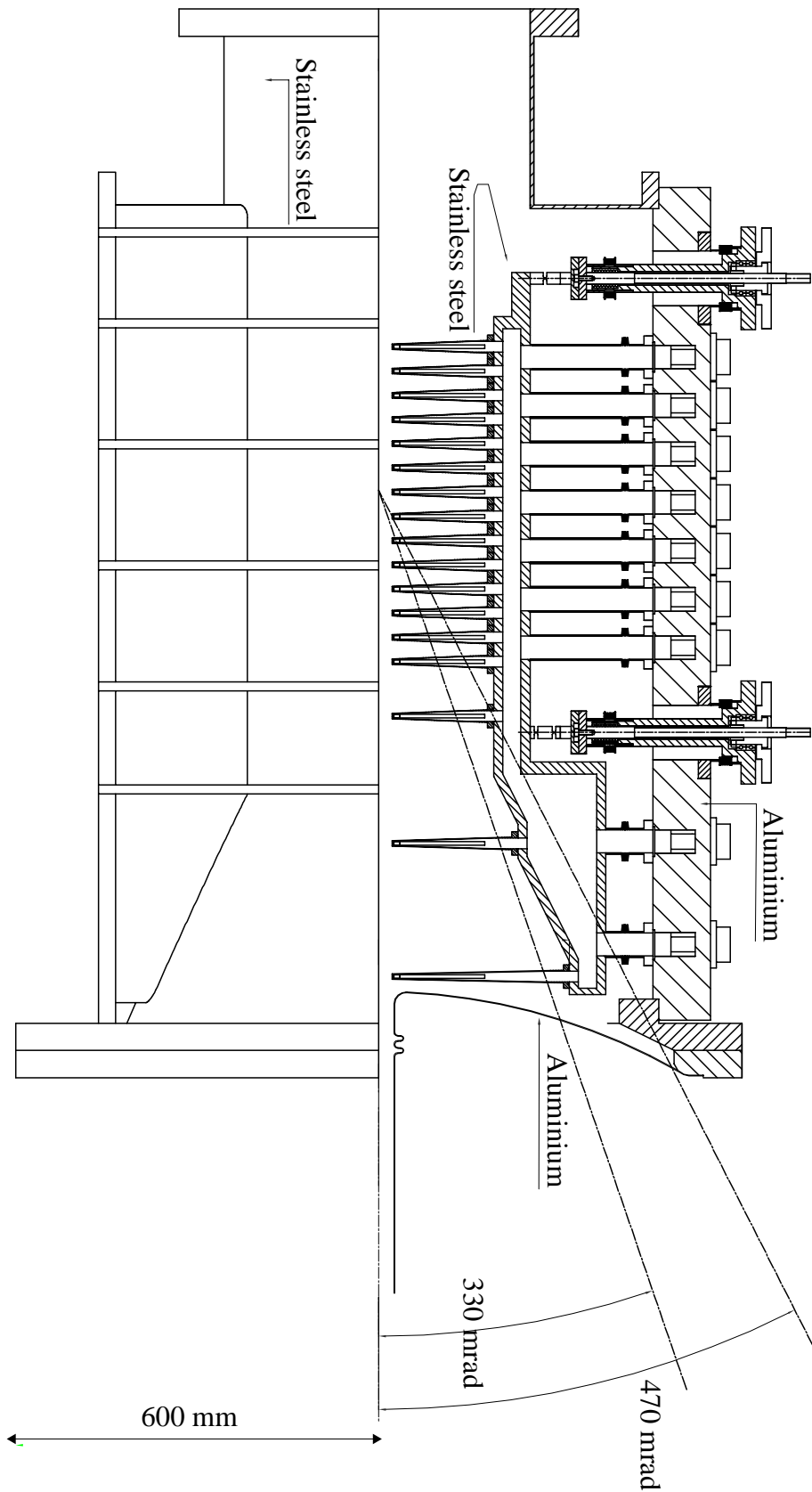
### Vacuum tank:

VELO mounted on support structures in cylindrical vacuum tank

alignment, retraction of VELO, mechanical stress from heat load, maintain vacuum with signal feed-throughs

low mass in acceptance region

# VELO layout (cont'd)

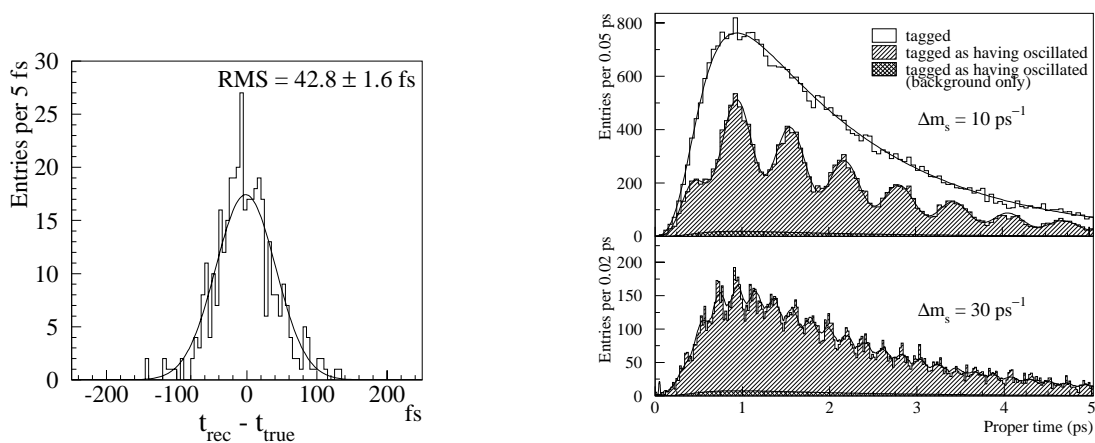


## Required VELO performance

Simulated resolutions:

primary vertex —  $\sigma = 40\mu\text{m}$

secondary vertex —  $\sigma = 180\mu\text{m}$  ( $B \rightarrow \pi\pi$ )



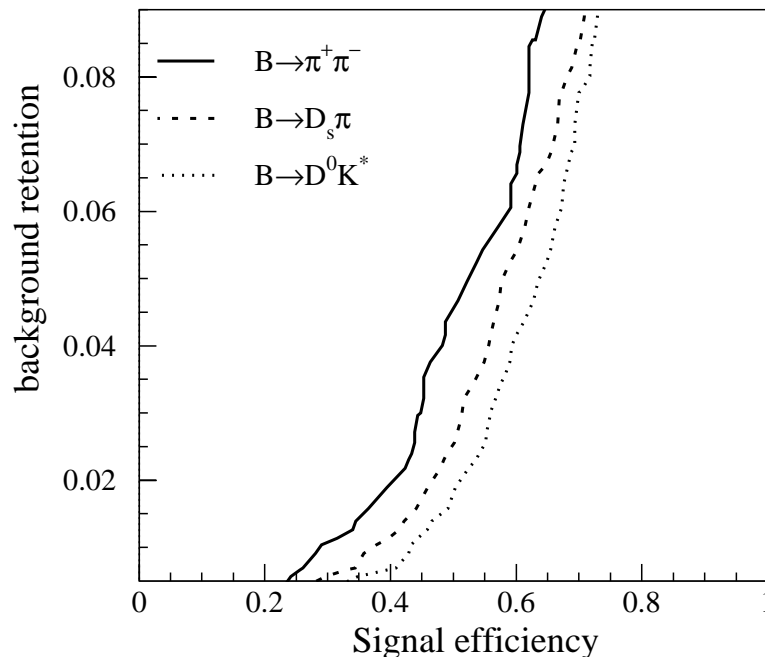
proper-time resolution for  $B_s \rightarrow D_s^- \pi^+$

events = 43 fs  $\rightarrow 5\sigma$  measurement of  $\Delta m_s$  up to  $48 \text{ ps}^{-1}$  (in one year)

## Required VELO performance (cont'd)

### L1 vertex trigger:

- a) 2D track search in  $r - z$  projection
  - b) estimate of PV using 2D tracks
  - c) for 2D tracks not from PV add  $\phi$  information  
→ 3D tracks
  - d) search for SV using pairs of 3D tracks
- output** — probability based on number of SV  
and distance from PV



## Updates to VELO design

Si thickness:

**thin** — decrease depletion voltage, lower bulk leakage current (less cooling required), reduced signal and S/N needing better electronics

**thick** — increased multiple scattering, larger operating voltage → breakdown, more heating

**availability** (thickness) depends on technology and manufacturer — p-in-n generally thinner and cheaper than n-in-n

**choice:** 220  $\mu\text{m}$  with 300  $\mu\text{m}$  as backup

(TP: 150  $\mu\text{m}$ )

## Updates to VELO design (cont'd)

Strip pitch:

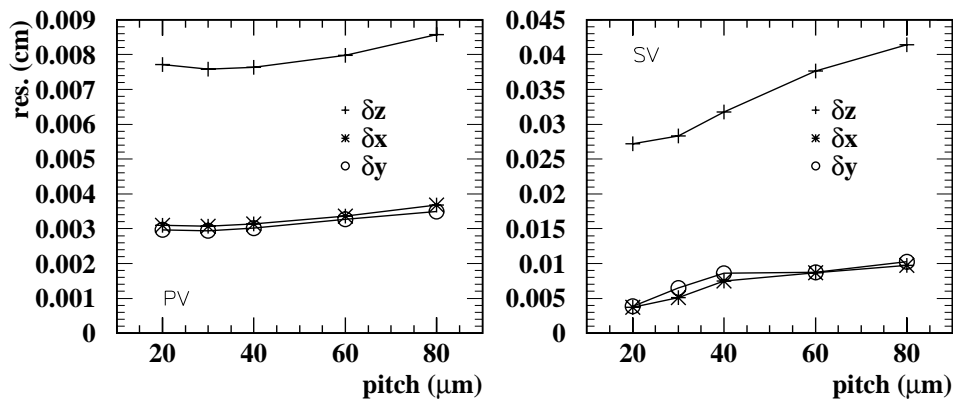
hit resolution  $\approx$  SP/12 with low noise analog electronics and charge-sharing

technology choice affects SP —

n-strip with p-stops: min.  $40\mu\text{m}$

p-strip: min.  $20\text{--}25\mu\text{m}$

resolutions from simulation studies —



→ strip pitch important for SV resolution

choice:  $20/30/40\mu\text{m}$  for  $r$  detectors (backup as TP:  $40/60/80\mu\text{m}$ )

## Updates to VELO design (cont'd)

Si inner/outer radius:

reducing inner radius improves IP resolution

→ reduce outer radius to maintain number of electronics channels

6"/4" facilities and flexibility of options —

180° sensors on 4" wafers: max. radius 4.5 cm

not all manufacturers moved to 6"

choice: IR 0.8 cm, OR 4.5 cm (TP: 1.0 cm and 6.0 cm)

## Updates to VELO design (cont'd)

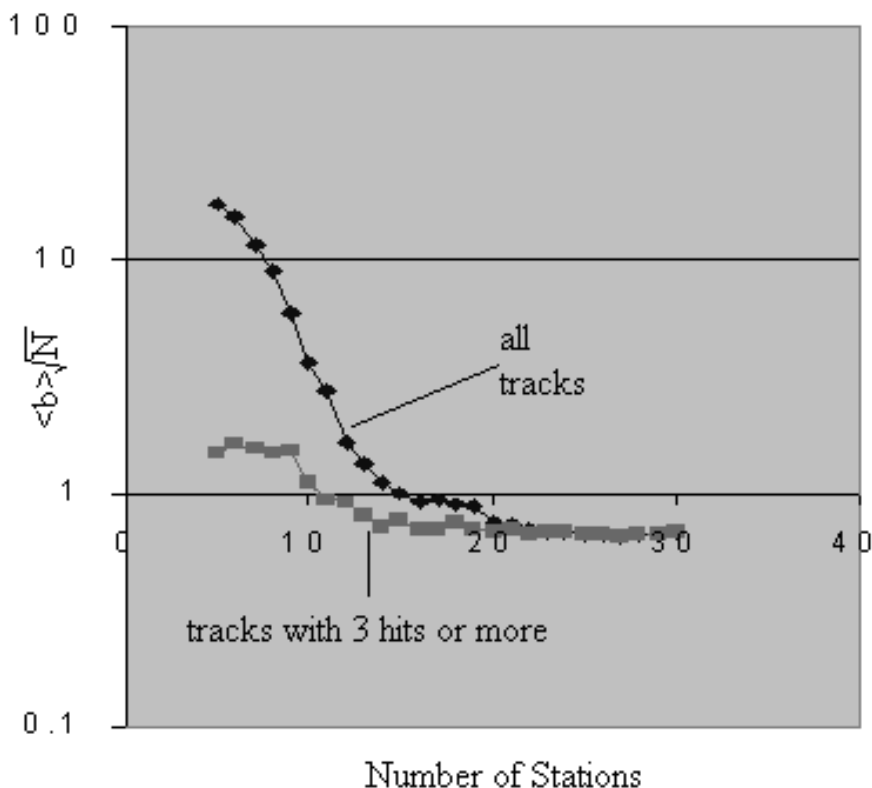
Number of Si stations:

tracks in LHCb — at least **VELO** 3 hits

**increase** from 17 — further improve tracking capabilities → cost, complexity, space

**fast optimisation** —

PYTHIA+beam-spot+MS+inefficiencies



**choice:** 25 stations (TP: 17)

## Updates to VELO design (cont'd)

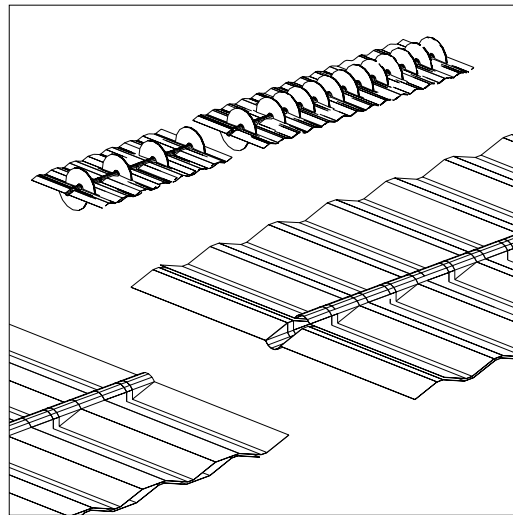
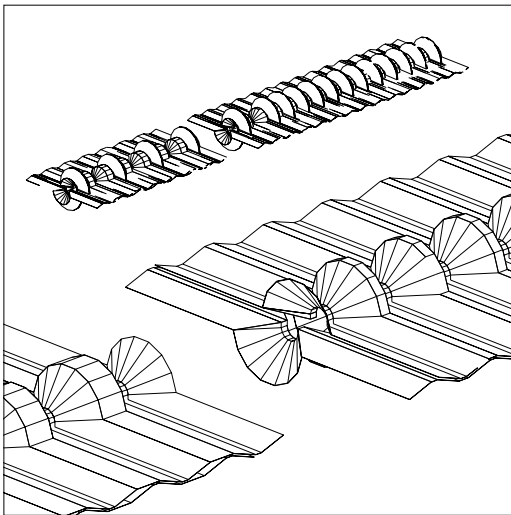
RF design:

TP shielding thickness not sufficient

wake field suppressors needed — 4 strips

along VELO length →

problems — thickness, cooling, mechanics



Al box acts as wake field suppressor

corrugation needed for upper-lower overlap

minimise multiple scattering

choice: “toblerone” design, Al  $250\mu\text{m}$  (TP:  
 $100\mu\text{m}$ )

## Updates to VELO design (cont'd)

Si radiation tolerance:

extreme environment — damage degrades performance

technology — n-in-n more “rad. hard”

results from irradiated detectors + work with oxygenated detectors, thinner detectors

→ better understanding of effects allowing Si closer to beam

Overall material budget:

minimise effect of changes on rest of LHCb

## Simulation of new VELO designs

Simulated new VELO design parameters with standard LHCb simulation (SICB: PYTHIA + GEANT)

Use MAP facility at Liverpool  
(<http://www.ph.liv.ac.uk/map/>)

Quantities investigated:

RMS distance between the true and reconstructed PV

RMS distance between the true and reconstructed SV

double-Gaussian fits to (true — rec.) decay lengths

*B* decay selection efficiencies and backgrounds

charged and neutral particle multiplicities

number of hits per event in other LHCb detectors

number of VELO hits per track

particle flux versus radius

L0 selection efficiency

number of high IP tracks — for L1

L1 efficiency versus min. bias retention

## Simulation of new VELO designs (cont'd)

Multiparameter problem — investigate performance for many combinations of VELO design parameters

→ large event samples used for this study:

study	event type	n. events
resolution	$B \rightarrow \pi\pi$	378k
	$B \rightarrow J/\psi(\mu\mu)K_s^0$	440k
event selection	$B \rightarrow \pi\pi$	771k
	$B \rightarrow J/\psi(\mu\mu)K_s^0$	730k
trigger, multiplicity	$B \rightarrow \pi\pi$	364k
and other	minimum bias	987k

Over 10 million fully simulated LHCb events in total for this and other studies

## Simulation of new VELO designs (cont'd)

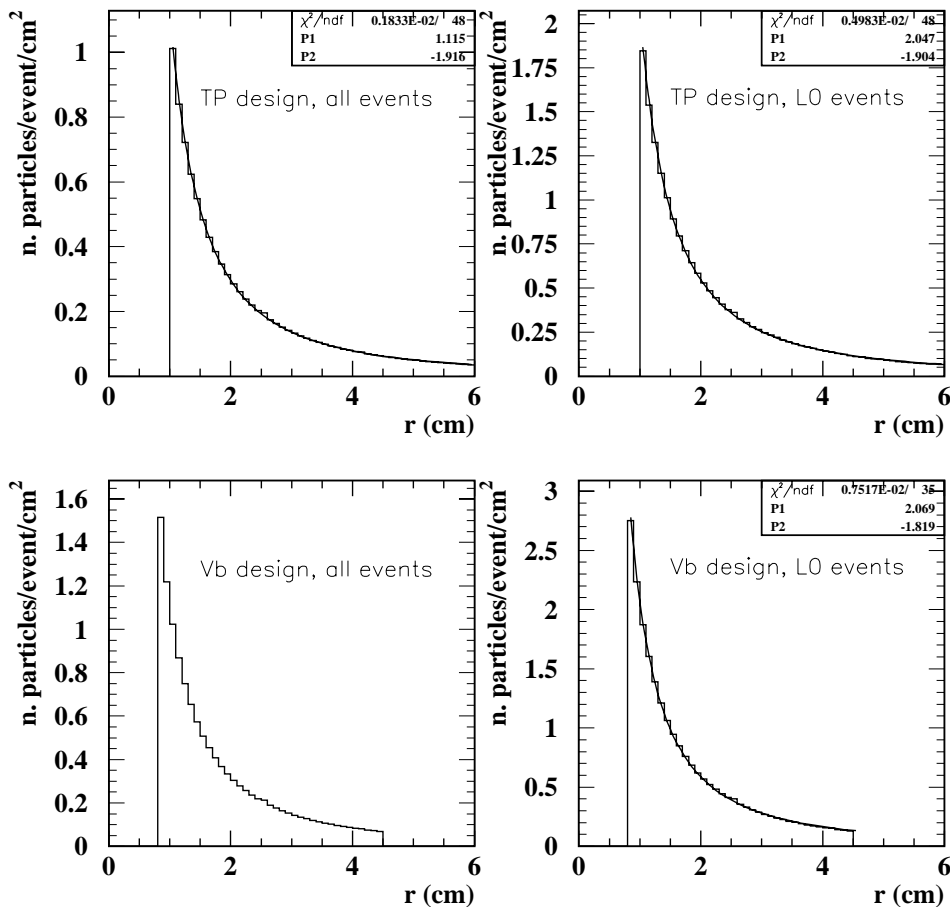
VELO design	number stations	Si parameters		strip-pitch SPir/SPmr/SPor ( $\mu\text{m}$ )	RF shield	
		d ( $\mu\text{m}$ )	IR/OR (cm)		design	ALth ( $\mu\text{m}$ )
TP	17	150	1.0/6.0	40/60/80	TP	100 250
I	25	220	1.0/4.5	40/60/80	TP	100 250
Ia	25	220	0.8/4.5	40/60/80	TP	100 250
II	17	220	1.0/6.0	40/60/80	tb	100 250
III	17	220	1.0/6.0	40/60/80	bp	100 250
IV	25	220	0.8/4.5	20/30/40	TP	100 250
Va	25	220	0.8/4.5	40/60/80	tb	250
Vb	25	220	0.8/4.5	20/30/40	tb	250
baseline	25	220	0.8/4.5	20/30/40	tb	250
backup	25	300	0.8/4.5	40/60/80	tb	250

tb — “toblerone” RF, bp — “beampipe” RF

+ TP with Si  $500\mu\text{m}$  thick

## Simulation of new VELO designs (cont'd)

### Particle fluxes for min. bias:



$\sigma_{\text{inel}}$ ,  $L$  and 1 LHC year as before:

$1.6 \times 10^{14} \text{ cm}^{-2}$  charged particles/year

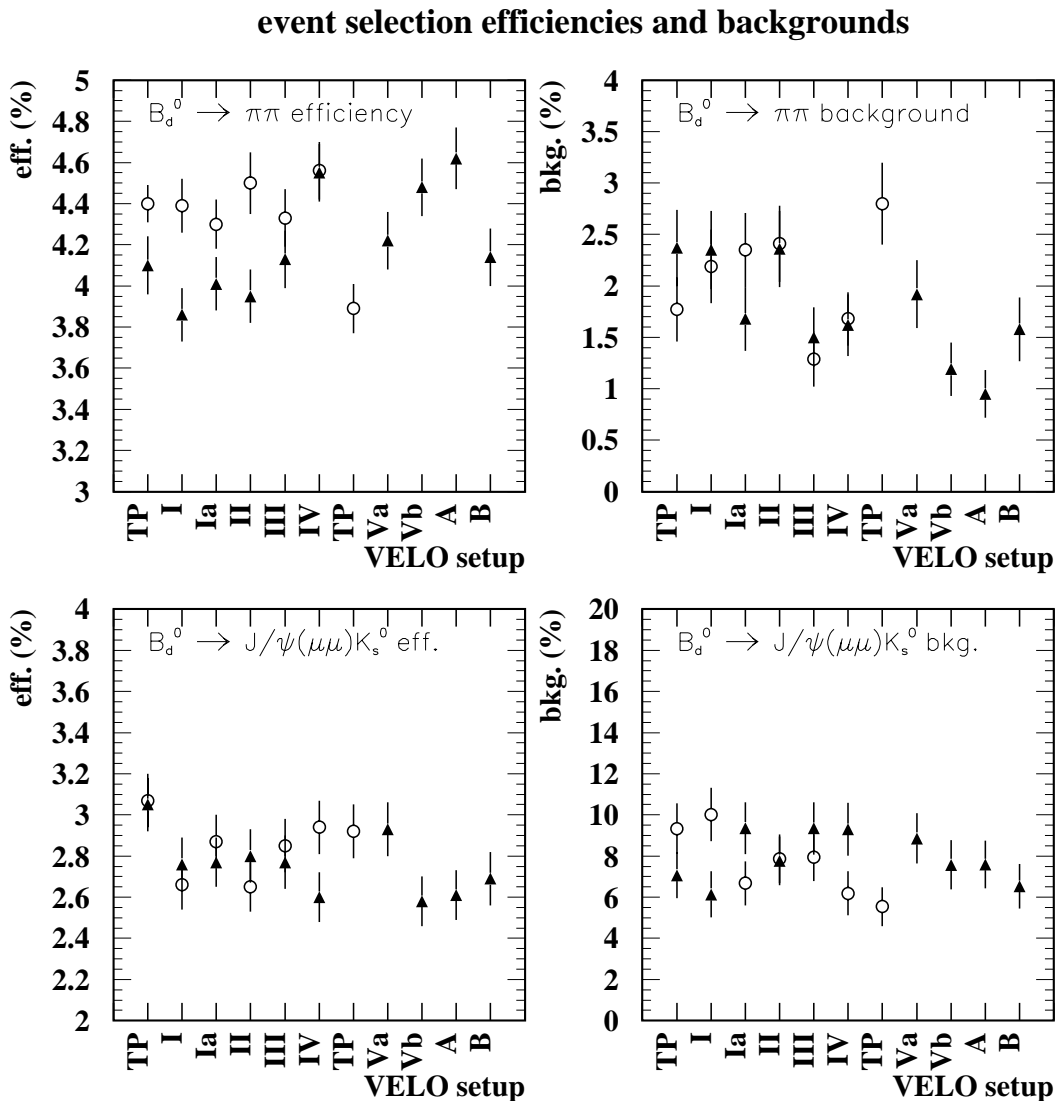
Mostly pions, fold with  $p$  and NIEL constants:

$0.6 - 1.1 \times 10^{14} \text{ cm}^{-2}$  1 MeV neutrons/year

(at  $r = 1 \text{ cm}$ , depending on  $z$ )

## Simulation of new VELO designs (cont'd)

Event selection **efficiencies** and **backgrounds**  
for  $B \rightarrow \pi\pi$  and  $B \rightarrow J/\psi(\mu\mu)K_s^0$ :



No large systematic effects, cuts not tuned for  
each design

## Simulation of new VELO designs (cont'd)

TP and baseline (backup) comparisons:

a) resolutions:

PV resolution — 5% worse

SV resolution — 15% better (no change)

decay length resolution —

20% better (no change)

- strip pitch, Si inner radius

+ Si thickness, RF thickness

b) multiplicities:

charged multiplicity up 7%

neutral multiplicity up 0.4%

number of hits in other dets. — up 5%

+ Si thickness, RF thickness

## Simulation of new VELO designs (cont'd)

c) number of high IP tracks (L1):

IP  $> 50,100\mu\text{m}$  up 10(20)% ( $B \rightarrow \pi\pi$ )

IP  $> 50,100\mu\text{m}$  up 20(40)% (min. bias)

+ Si thickness, RF thickness and design

- strip pitch, Si inner radius

d) number of VELO hits per track — up 50%

number of stations

e) L0 efficiency — down 7%

RF design

f) particle densities at min. radius — up 50%

Si inner radius

## Outlook

Chosen new design is “baseline”, with a conservative “backup” design (thicker Si, larger strip-pitch)

### Main points:

- a) need for increased RF shielding met
- b) number of stations increased to 25 — average number of VELO hits per track 50% higher → greater standalone tracking capability for the VELO
- c)  $B$  decay length resolution improved
- d) slight increase in material budget
- e)  $B$  decay selection performance maintained
- f) number of high IP tracks (for the L1 trigger) close to the TP values