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

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

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

$\sigma_{\mathrm{inel}} =$ 100 mb, $\sigma_{\mathrm{b\overline{b}}} =$ 500 μb

$\longrightarrow 10^{12}\ \mathrm{b\overline{b}}$ produced per LHC year (10^7 s)

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

Experimental needs:

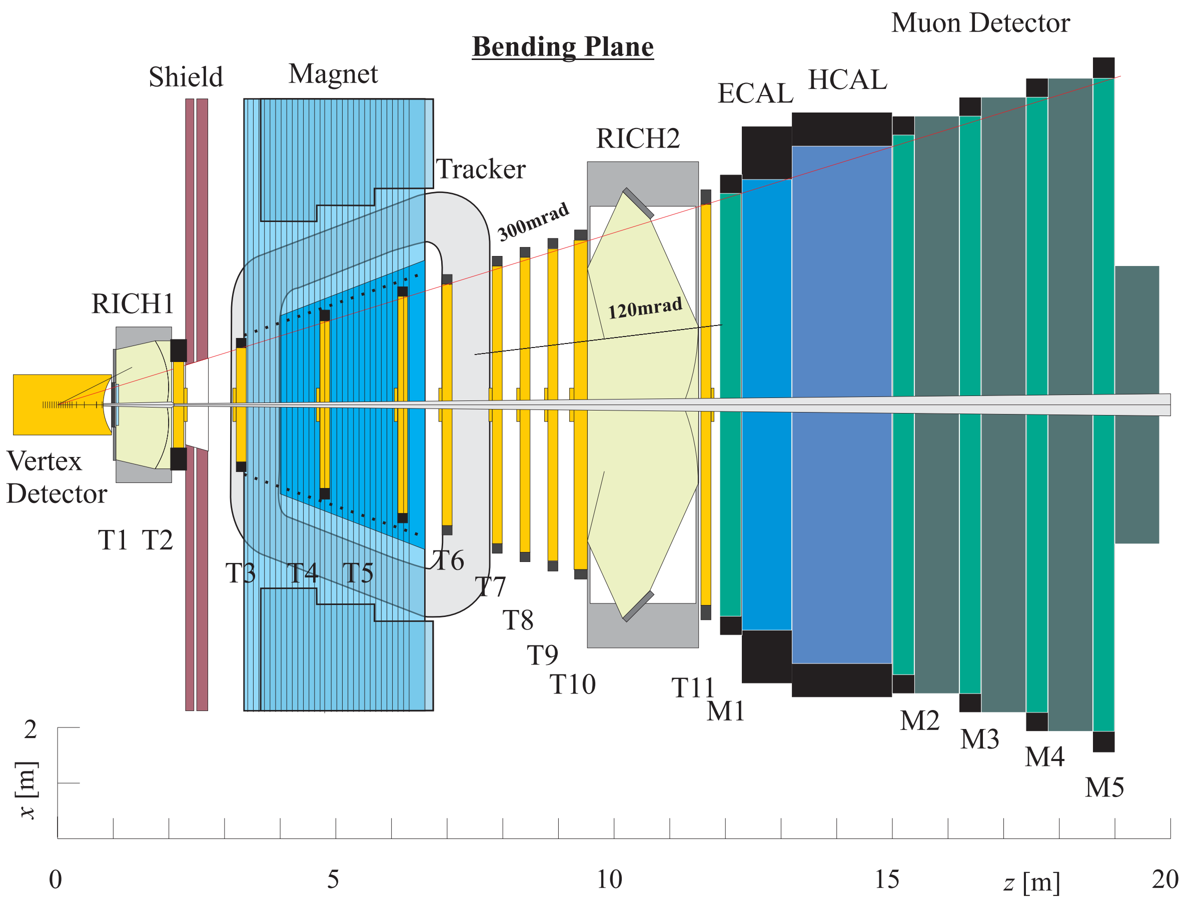
a) efficient trigger for leptons, hadrons and displaced vertices (B meson selection)

b) particle ID (π/K separation, flavour tagging)

c) good mass resolution (background rejection)

d) good decay time resolution ($\Delta \mathrm{m}_s$, $\Delta\Gamma_s$)

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 $\longrightarrow$ 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

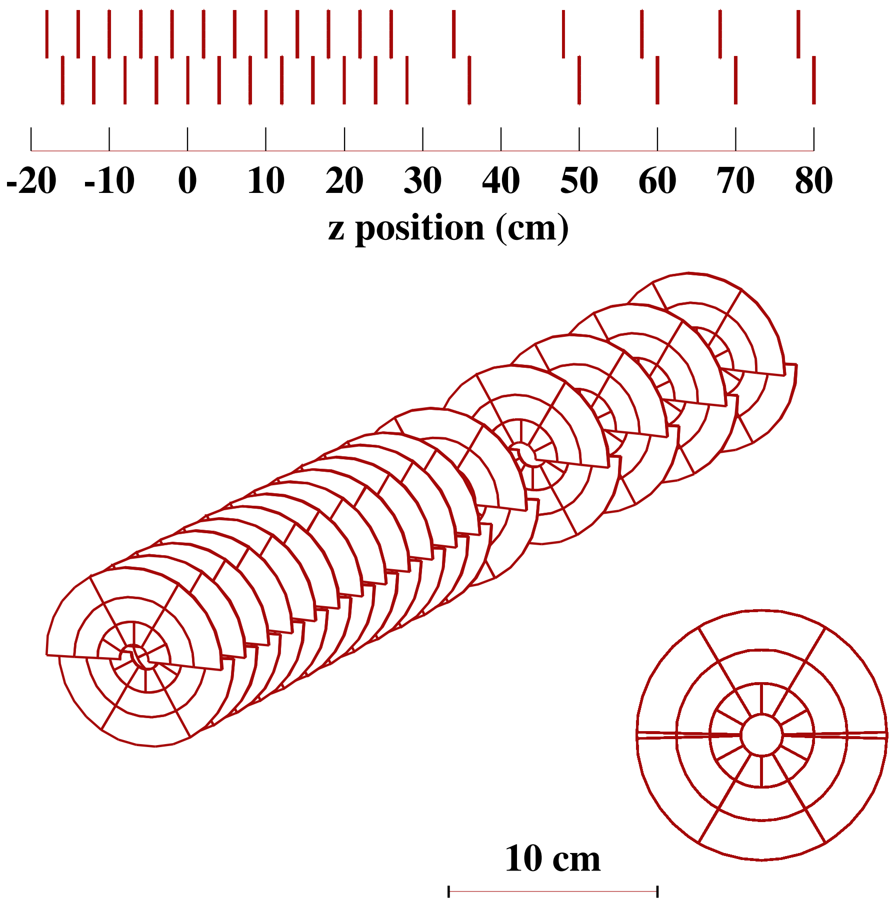
L1: input rate 1 MHz, output rate 40 kHz

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)...



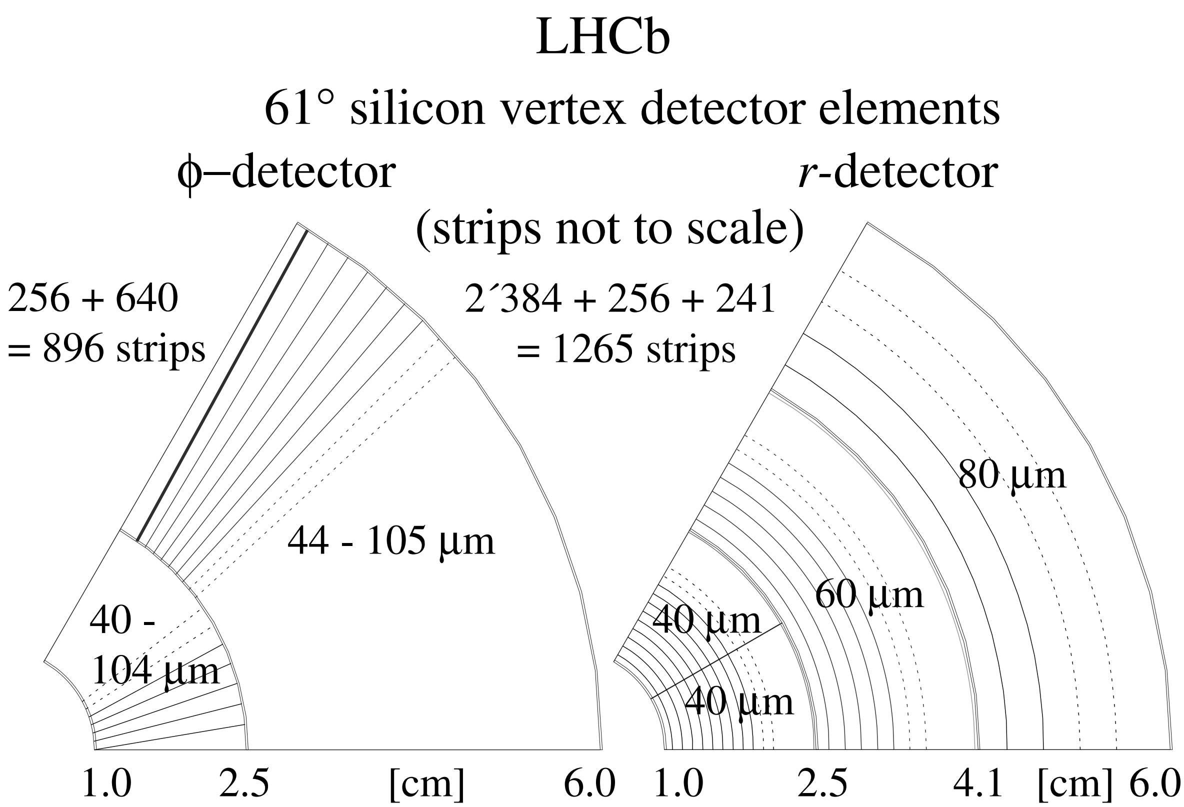
17 disks (stations) of r and ϕ detectors

upper-lower halves retract during LHC injection

upper-lower overlap for alignment

VELO layout (cont'd)

Strip layout:



Si thickness = 150 μm

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 μm thick) caps round Si

Al thick — withstand any differential pressure, provide enough shielding

Al thin — not degrade resolution

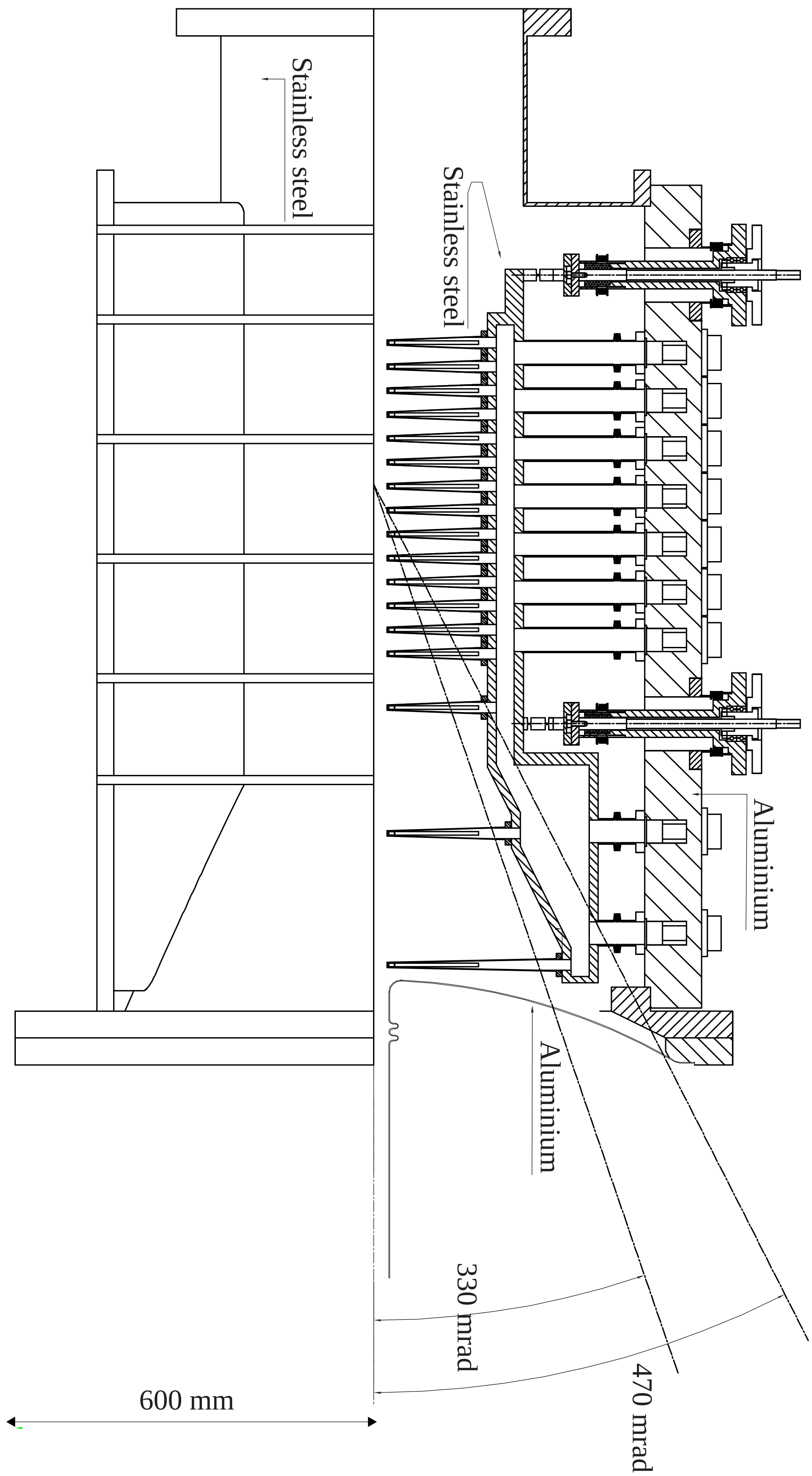
Vacuum tank:

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)

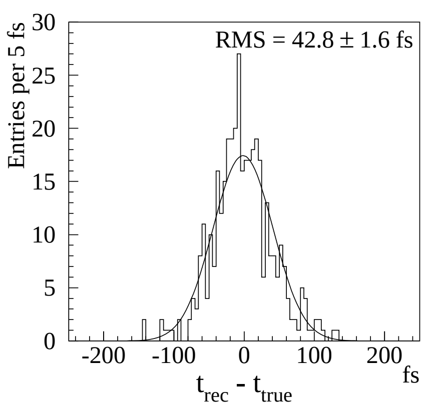


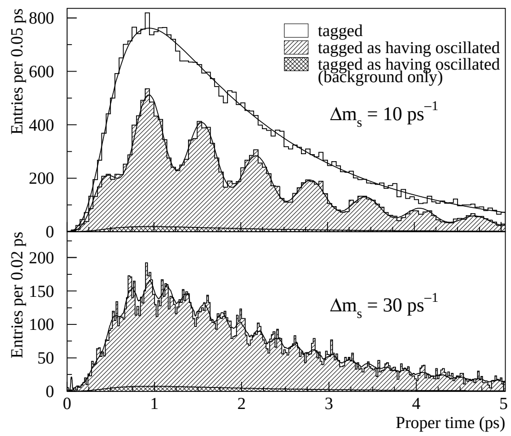
Required VELO performance

Simulated resolutions:

primary vertex — $\sigma = 40\mu$m

secondary vertex — $\sigma = 180\mu$m ($B \to \pi\pi$)





proper-time resolution for $B_s \to D_s^- \pi^+$ events = 43 fs $\longrightarrow$ 5σ measurement of $\Delta \mathrm{m}_s$ up to 48 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

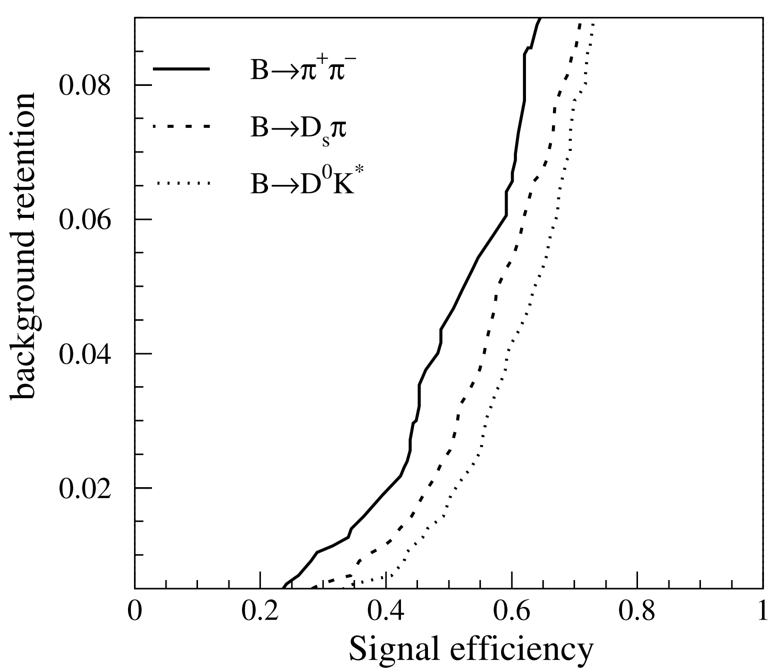
c) for 2D tracks not from PV add ϕ information

$\longrightarrow$ 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 $\longrightarrow$ breakdown, more heating

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

choice: 220 μm with 300 μm as backup

(TP: 150 μm)

Updates to VELO design (cont'd)

Strip pitch:

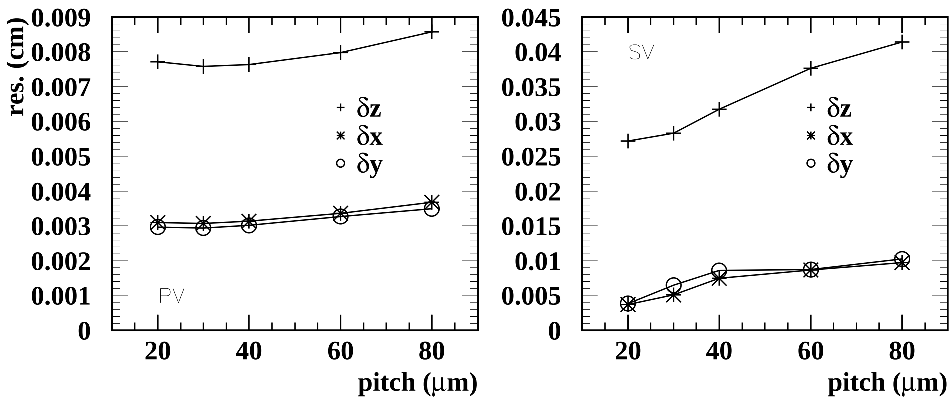
hit resolution $\approx$ SP/12 with low noise analog electronics and charge-sharing

technology choice affects SP —

n-strip with p-stops: min. 40μm

p-strip: min. 20-25μm

resolutions from simulation studies —



$\longrightarrow$ strip pitch important for SV resolution

choice: 20/30/40 μm for r detectors (backup as TP: 40/60/80 μm)

Updates to VELO design (cont'd)

Si inner/outer radius:

reducing inner radius improves IP resolution

$\longrightarrow$ 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)

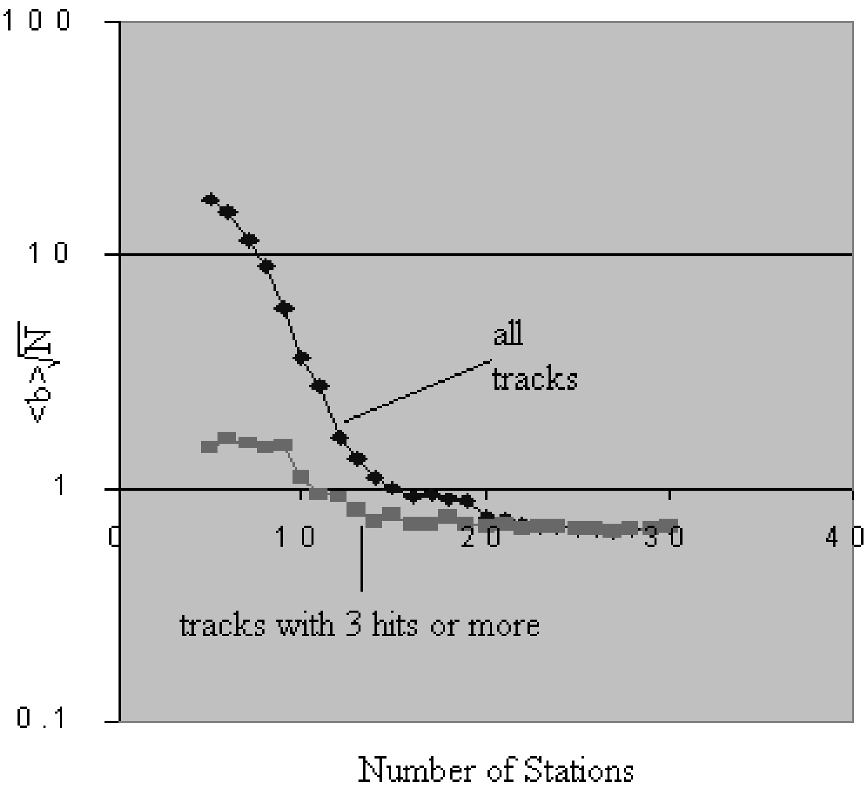
Updates to VELO design (cont'd)

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)

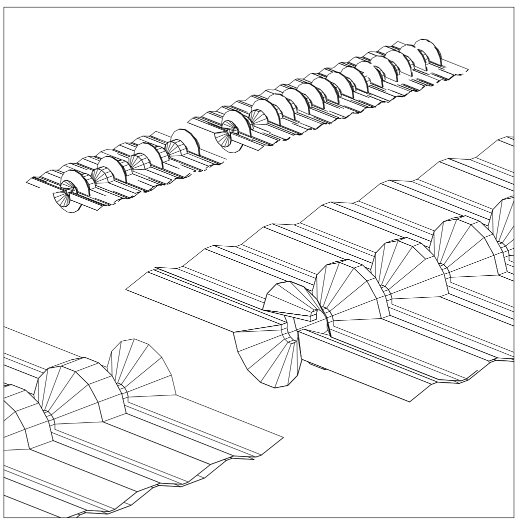
Updates to VELO design (cont'd)

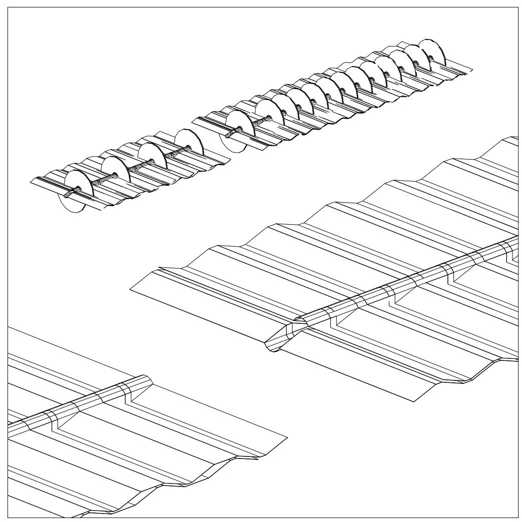
RF design:

TP shielding thickness not sufficient

wake field suppressors needed — 4 strips along VELO length $\longrightarrow$

problems — thickness, cooling, mechanics





Al box acts as wake field suppressor

corrugation needed for upper-lower overlap

minimise multiple scattering

choice: "toblerone" design, Al 250μm (TP: 100μm)

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

$\longrightarrow$ 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

$\longrightarrow$ 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)

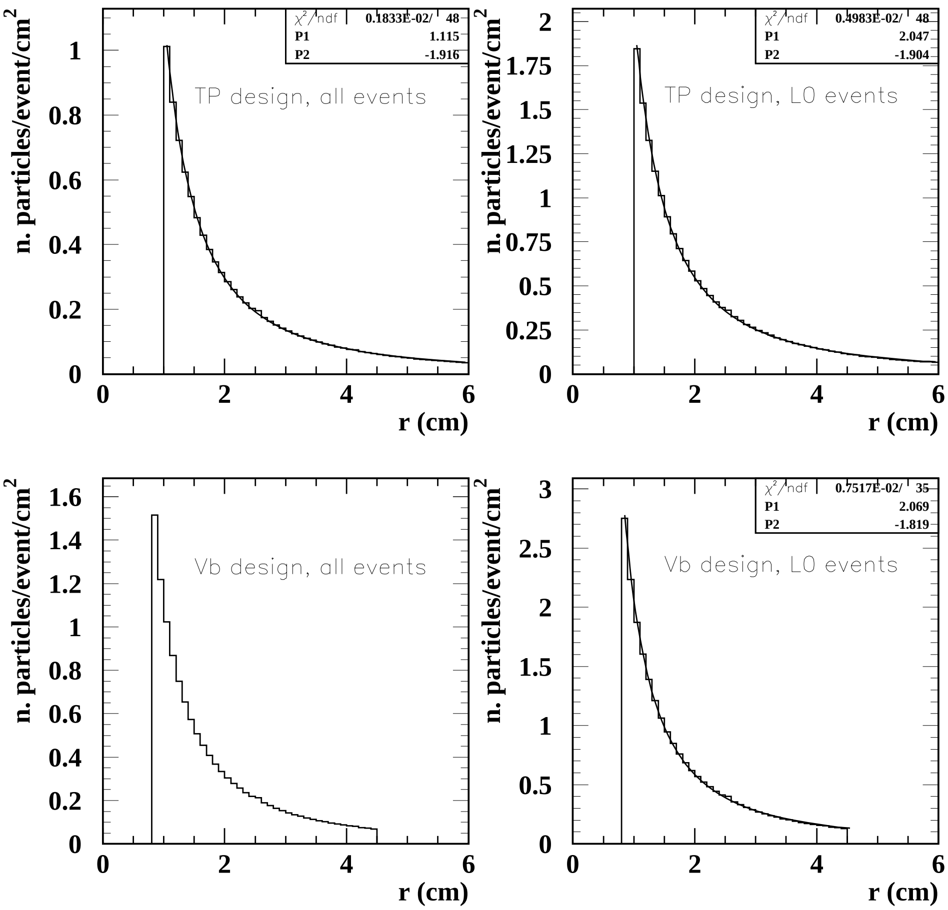
VELO design	number stations	Si parameters d (μm)	Si parameters IR/OR (cm)	strip-pitch SPir/SPmr/SPor (μm)	RF shield design	RF shield ALth (μm)
TP	17	150	1.0/6.0	40/60/80	TP	100
						250
I	25	220	1.0/4.5	40/60/80	TP	100
						250
Ia	25	220	0.8/4.5	40/60/80	TP	100
						250
II	17	220	1.0/6.0	40/60/80	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 500μm thick

Simulation of new VELO designs (cont'd)

Particle fluxes for min. bias:



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

1.6×10^{14} cm^{-2} charged particles/year

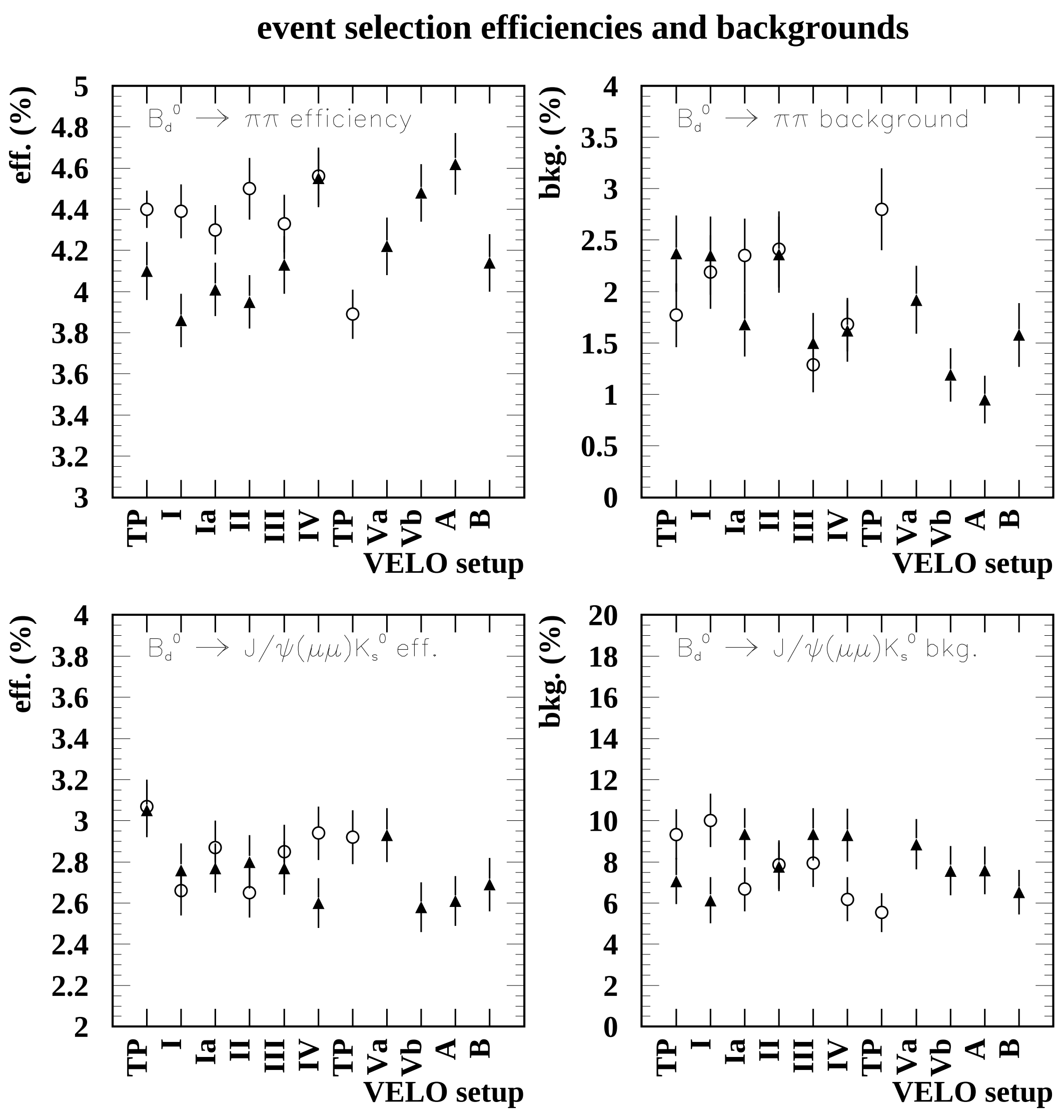
Mostly pions, fold with p and NIEL constants:

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

(at r = 1cm, depending on z)

Simulation of new VELO designs (cont'd)

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



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 $>$ 50,100μm up 10(20)$\%$ ($B \rightarrow \pi\pi$)

IP $>$ 50,100μm 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 $\longrightarrow$ 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