LHCb experiment : Detector and Physics program

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B Physics and CP violation at proton collider

Detector for B meson physics at LHC : LHCb experiment

Main role of the Trigger system

Optimization of the detector and Physics performance

B Physics and CP violation at proton collider

Why choosing a *hadron collider* at $\sqrt{s} = 14$ TeV to study $B(\bar{B})$ physics ?

⋆ Main production process : Gluon-Gluon fusion

⋆ $\sigma(pp \to b\bar{b} + X) \approx 0.5 \;\; mb$

⋆ Comparing to e^+e^- machine :

$$\frac{\sigma(pp \to b\bar{b} + X)}{\sigma(e^+e^- \to Y(4S))} \geq 4.3 \times 10^5$$

$\Longrightarrow$ Expected number of $b\bar{b}$ pairs in one year data taking (10^7 s/y) :

$$N_{b\bar{b}} \sim 10^{12}$$

⋆ Multiple hadronic flavours in final states :

$$B_d^0(40\%),\ B_s^0(10\%),\ B_u^{\pm}(40\%),\ B_c^{\pm},\ \Lambda_b, ...(10\%)$$

$\Longrightarrow$ Many open channels available for **CPV** processes with $B(\bar{B})$ mesons.

⋆ Standard B Physics

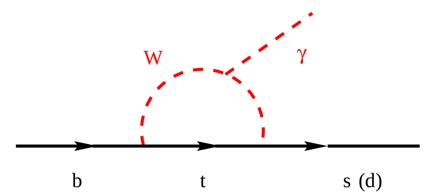
• High precision measurement of the unitarity triangles (UT) angles :

$$\alpha, \beta, \gamma, \delta\gamma$$

• Exhaustive study of $B_s^0 - \bar{B}_s^0$ system :
Mixing , Oscillations, x_s

⋆ Modern B Physics

• Radiative B decays



$\Longrightarrow$ Electroweak Penguin:

Measurement of some poorly known **CKM** matrix elements :

V_{td} related to : $B \to \gamma\ \rho^0$

V_{ts} related to : $B \to \gamma\ K^{*0}$

• Search for Rare Decays :

$$B_s{}^0 \to \mu^+\mu^- \ , \ \ B^0 \to \ell^+\ell^- X \ ...$$

which SM branching ratios $\sim 10^{-7} - 10^{-9}$

• Channels forbidden by the S.M. like :

$B^0{}_{d,s} \to e^{\pm}\mu^{\mp}$

$\Rightarrow$ Opportunity to search for **New Physics** beyond the SM like FCNC or SUSY processes

⋆ Old-New items with B Physics

⋆ Search for a **direct CPV** in charged $B^{\pm}$ decays :
Very small according to the S.M, but $\Rightarrow$ New path to understand the mechanism of CPV

⋆ Exhaustive study of **CPV with mixed eigenstates :**

$$B^0_{d,s} \to V_1^0 V_2^0 \quad \Rightarrow CP = (-1)^{\ell}$$

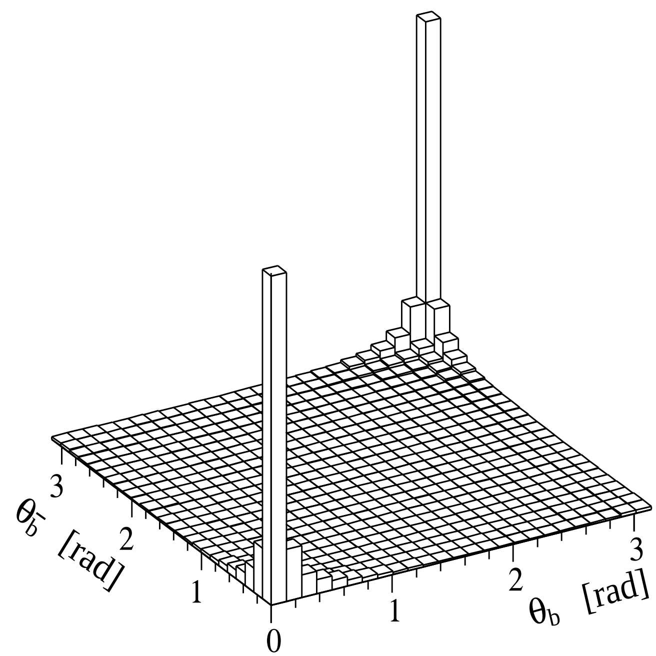
with ${J_V}^{PC} = 1^{--}$ and $\ell = 0, 1, 2$

$\Rightarrow$ Angular analysis performed in a **model independent** way

Detector for B Physics at proton collider : LHCb

- $b\bar{b}$ pairs produced by *gluon fusion*

$\Rightarrow$ B mesons very peaked in the forward direction :



$$\Theta_B \leq \quad 200\ mrad$$

- Mean momentum of the B meson, $< P_B > \; = 80 \;\; GeV$

$\Rightarrow$ Particles coming from B decays must be detected at *very small angles* according to the beam axis :

$$15 \; mrad \leq \theta_i \leq 300 \; mrad$$

$\Longrightarrow$ LHCb detector very similar to a fixed target experiment

$\Longrightarrow$

Open detector : easy for the installation and maintenance of the subdetectors

Other characteristics of B mesons at LHC

- Mean path length of a B meson : $\ell = \; 7mm$

- Mean nominal luminosity : $\mathcal{L} = 2 \times 10^{32} cm^{-2} s^{-1}$
Optimized luminosity with *single pp interaction*

- Important background :

$$\sigma(b\bar{b})/\sigma_{Inelastic} \approx 0.006$$

Main requirements for LHCb detector

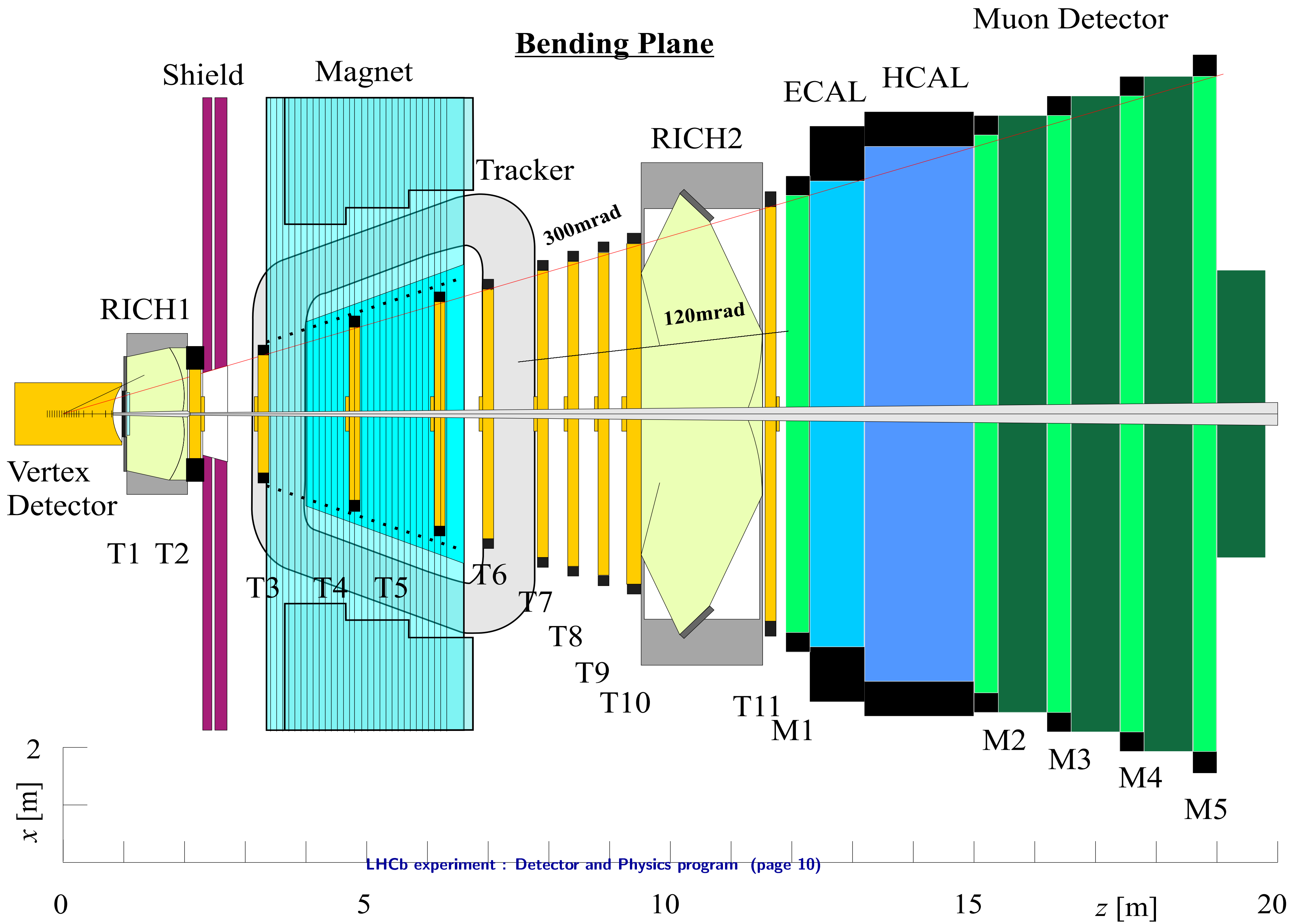
- Vertex detector
- Particle identification : $\gamma/e/\mu/\pi/K/p$
- Very accurate track reconstruction and momentum resolution
- High selective and fast trigger system to select both :

Semi-leptonic channels and purely hadronic ones

Subdetectors

- Magnet
- Vertex locator (VELO)
- Two ring imaging Cherenkov : RICH1 and RICH2
- Tracker system : Inner tracker and Outer tracker
- Calorimetric system : SPD, Preshower, ECAL, HCAL
- Muon system

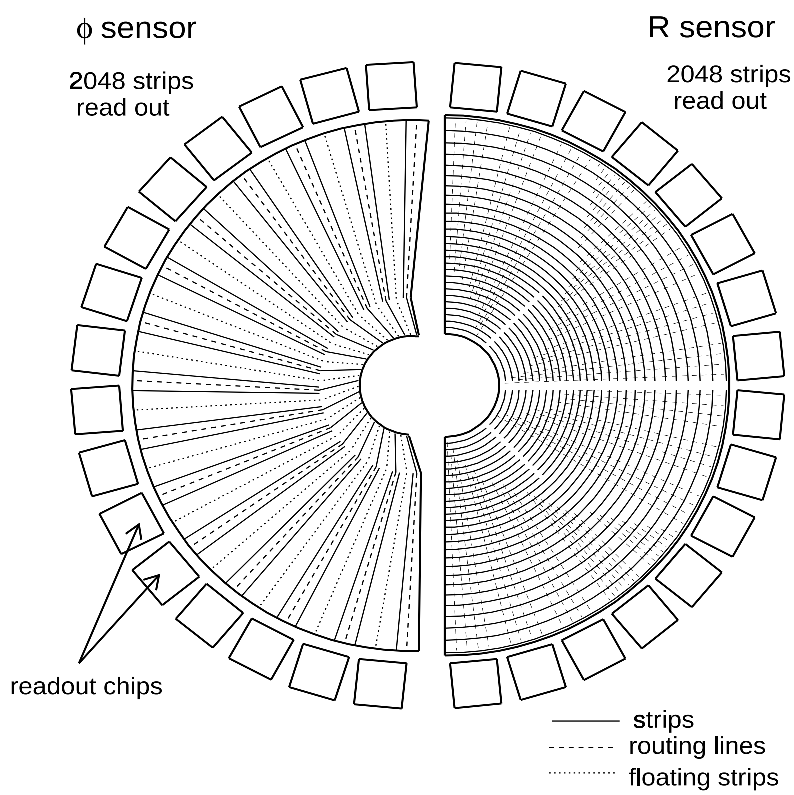
- Total "length" ≈ 20 meters


Bending Plane
Muon Detector
Shield
Magnet
RICH1
Tracker
ECAL
HCAL
RICH2
300mrad
120mrad
Vertex
Detector
T1 T2
T3
T4
T5
T6
T7
T8
T9
T10
T11
M1
M2
M3
M4
M5
2
x [m]
0
5
10
15
z [m]
20

VErtex LOcator (VELO)

- Silicon vertex detector made out of **21** stations
- Each station contains **2** discs divided into sectors :

One disc with *radial* strips for ϕ angle measurement
Other disc with *circular* strips for r coordinate measurement



- With 200,000 electronic channels and a total silicon area of $0.32m^2$, the primary vertex resolutions are the following :
  - Beam direction, $\sigma_z = 42 \pm 1 \ \ \mu m$
  - Perpendicular to the beam, $\sigma_\perp = 10 \pm 1 \ \ \mu m$
  - Time resolution for $B_s \to D_s \pi$: $\sigma_t = 42 fs$

Tracking system

Stations involving two main technologies :

⋆ *Inner tracker* : Silicon sensors

⋆ *Outer tracker* : Drift cells of 5 mm diameter made out of straw tubes

• Average reconstruction efficiency for an individual track coming from B decays :

$$\epsilon_{tracking} = \quad 96\% \pm 1\%$$

• Momentum resolution : $\sigma_p/p \quad = \quad 0.4\%$

In the Technical Proposal, 11 stations were foreseen.

LHCb-light optimization : 11 stations replaced by 4 stations giving the same resolution

RICH detectors

Need to identify and to separate Π/K in a wide momentum range : 1-150 GeV/c

$\Longrightarrow$ Measurement of the **angles α and γ**

$\star$ Main signals involving pion(s) and kaon(s)

$$B_d^0 \to \pi^+\pi^-$$
$$B_s^0 \to K^+K^-$$
$$B_s^0(\bar{B}_s^0) \to D_s^+K^-(D_s^-K^+)$$

Important backgrounds from other B decay channels and beauty hadrons :

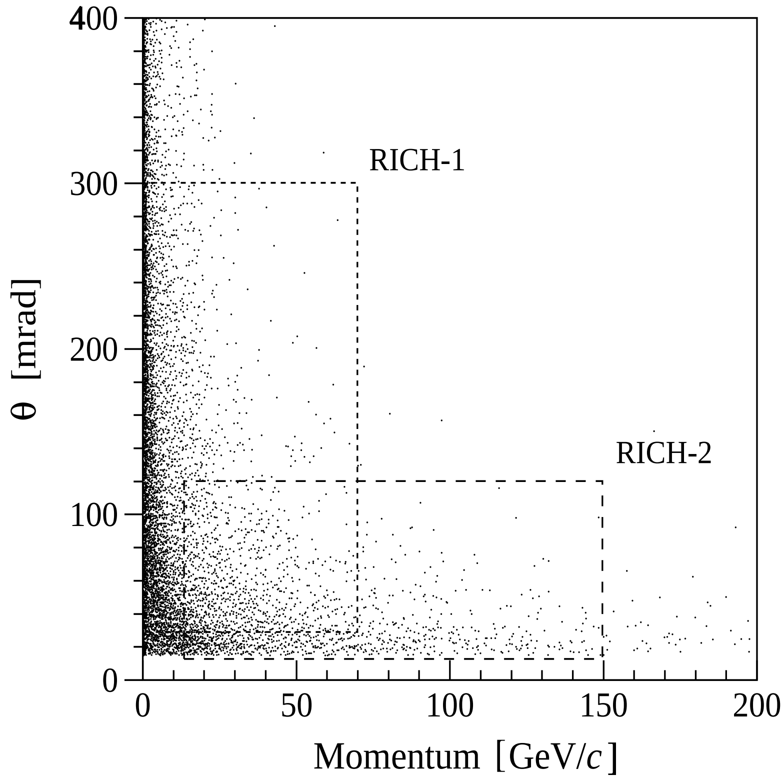
$${B^0}_{d,s} \to \pi K$$
$$\Lambda_b \to pK \quad , \quad p\pi$$

Kinematic conditions

i) $\approx 90\%$ of $\pi^\pm$ coming from $B_d^0 \to \pi^+\pi^-$ have momentum ≤ 150 GeV/c.

ii) Kaons from high multiplicity B decays : momentum down to 1GeV/c.

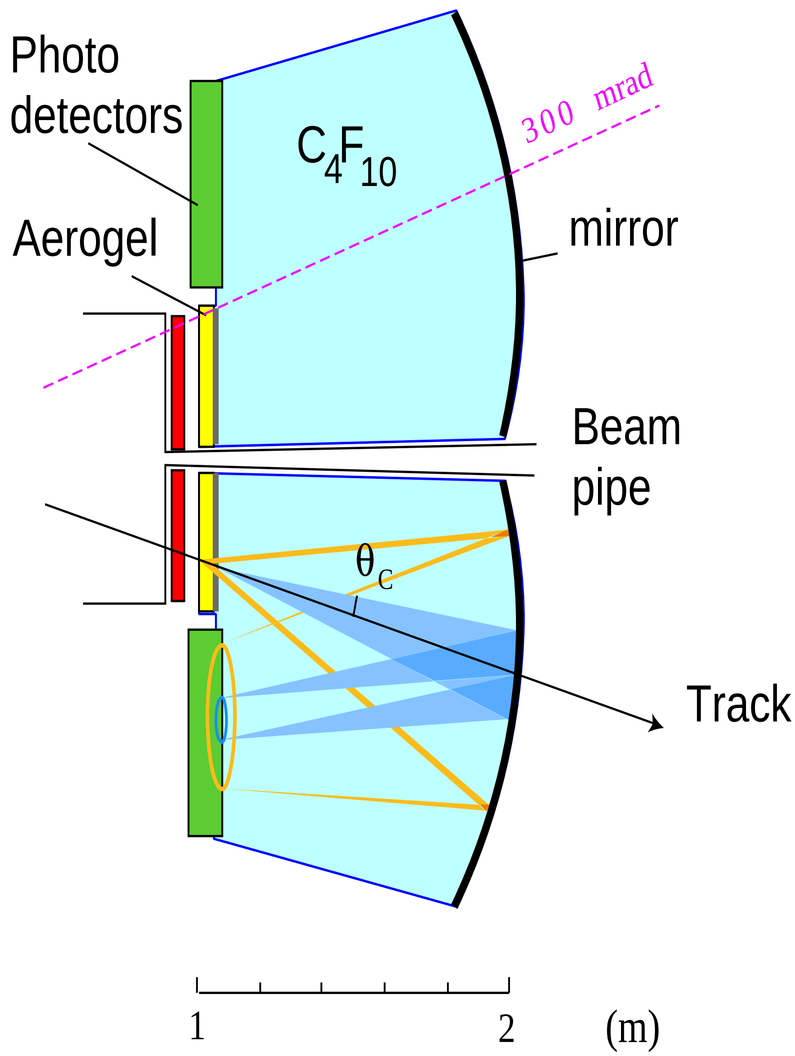
⋆ Momentum and Angular acceptances of the B tracks



⟹ Three kinds fo radiators with different indices in *two separated RICH detectors*

Radiator	Index	Momentum range
Silica aerogel	1.03	low
Gaseous C_4F_{10}	1.0014	intermediate
Gaseous CF_4	1.0005	high

RICH1

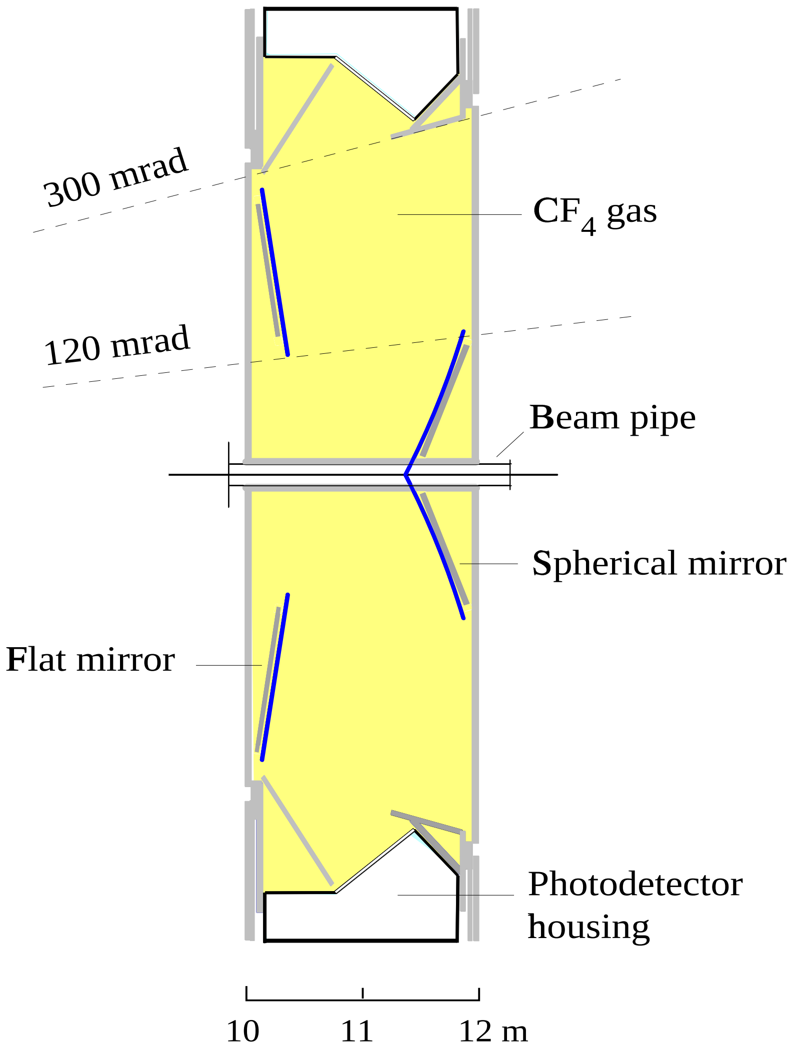


Very close to the Vertex detector :
$\Theta_H \leq 300$ mrad , $\Theta_V \leq 200$ mrad
Radiators : Aerogel + C_4F_{10} with a volume $2.4 \times 2.4 \times 1 \ \ m^3$

Radiation length $\approx 14\%X_0$

Momentum range for Π/K separation : 1 - 100 GeV/c

RICH2



Placed downstream with smaller angular acceptances :
$\Theta_H \leq 120$ mrad , $\Theta_V \leq 100$ mrad

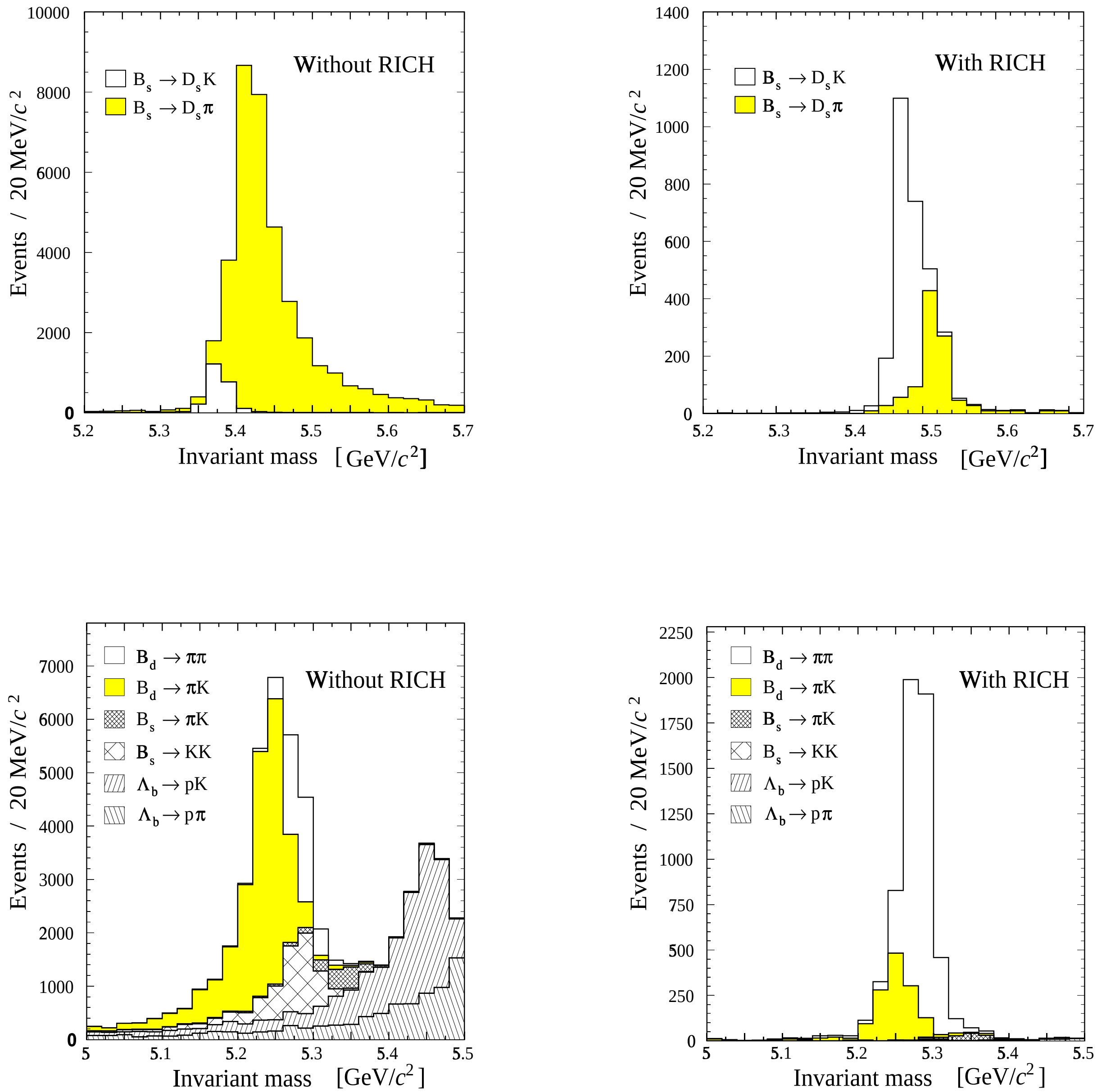
Radiator : CF_4 with a volume $7 \times 7 \times 2.45 \ \ m^3$

(total radiation length $\approx 12.4\% X_0$)

Momentum range for Π/K separation : 100 - 150 GeV/c

$\star$ Electronic read-out : **HPD** $\rightarrow$ need to 450 HPD to cover all the photo-detector area ($2.6 \ \ m^2$)

$\Longrightarrow$ Performance of the two RICH : Π/K separation **greater than** 3σ



Calorimeter system

Made from 4 **subdetectors :**

- Scintillator Pad Detector (SPD), PreShower (PS), Electromagnetic Calorimeter (ECAL), Hadronic Calorimeter (HCAL)
- It provides *high transverse energy* hadron, electron and photon for the level $L0$ trigger

SPD and Preshower

• Lead wall of $12\ mm$ thickness sandwiched by two scintillator planes :

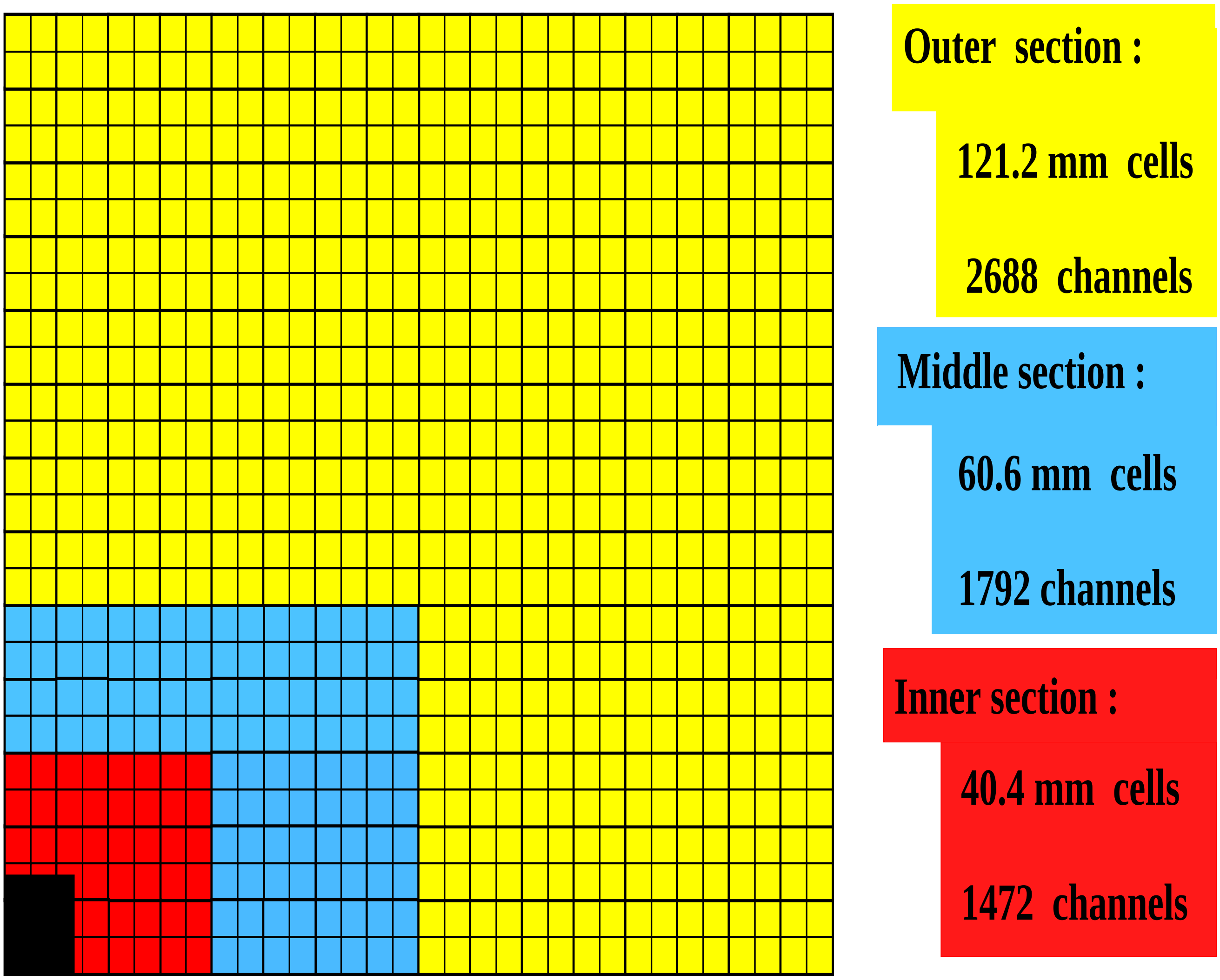
⋆ First plane or SPD signals the passage of charged particles :
$\rightarrow$ discriminates between γ and $e^{\pm}$

⋆ Second plane or PS located after the lead : discriminates between $e^{\pm}$ and $\pi^{\pm}$

• Total radiation length $= 2X_0$

• Light collection is transmitted by wavelength shifting fibers (WLS)

ECAL



- **Shashlik** technology : 2mm lead $\oplus$ 4mm scintillator plates
- Thickness of $25X_0$ for an optimal energy resolution for $e^\pm$ and γ
- Variable cell sizes : 4x4 cm^2 , 6x6 cm^2 , 12x12 cm^2

Energy resolution :

$$\sigma_E/E = 10\%/\sqrt{E} \oplus 1.5\% \quad (GeV)$$

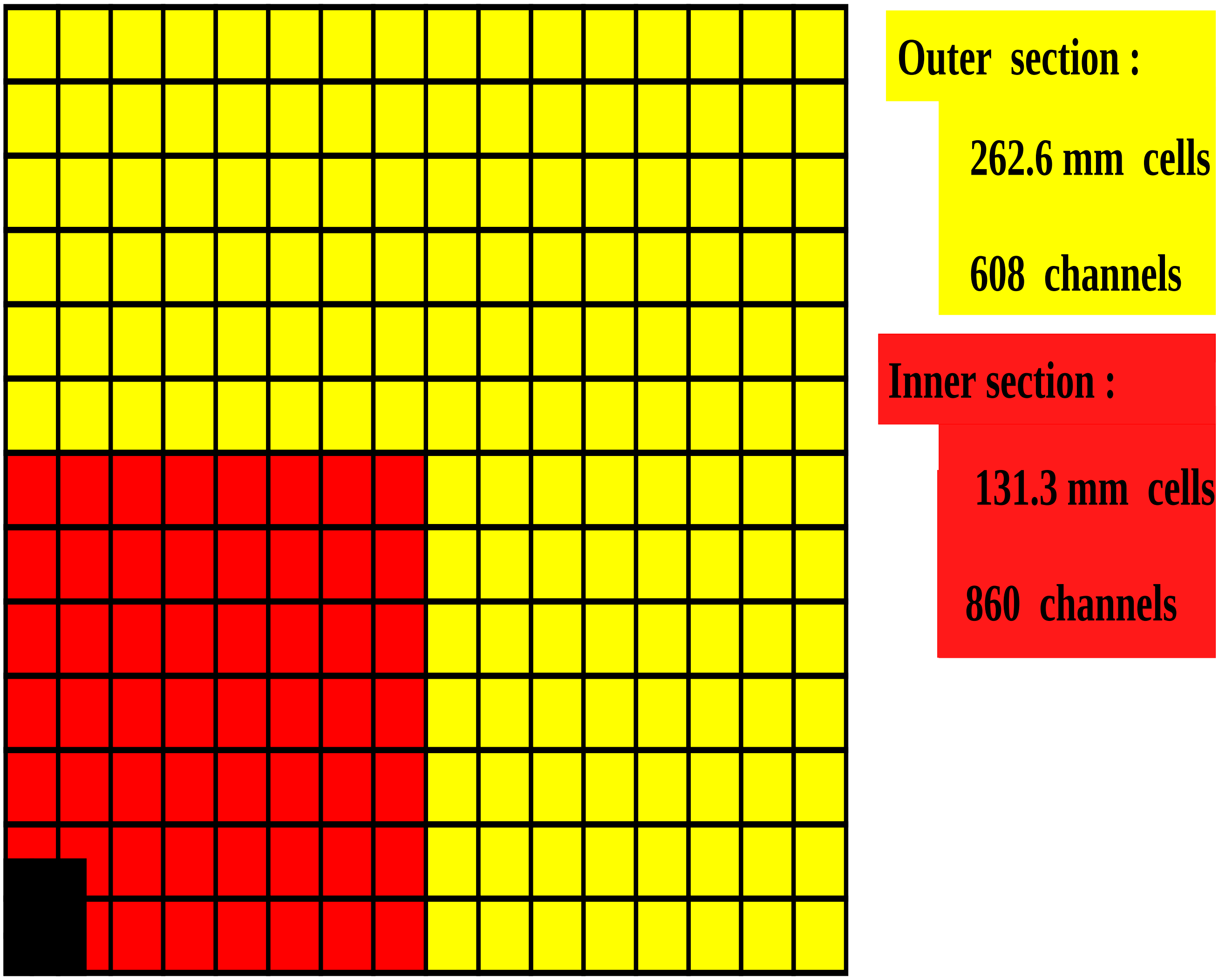
- Both SPD, PS and ECAL have each ~ 6000 channnels.

Readout system

WLS fibers connected to PMT :

- Multianode PMT with 64 anodes for SPD/PS
- Monoanode PMT for ECAL

HCAL



- Sampling structure :
Iron/Scintillator tile 16mm Iron $\oplus$ 4 mm scintillator
- Two cell sizes : 13x13 cm^2 and 26x26 cm^2
- ~ 1500 channels readout by WLS and monoanode PMT
- Thickness $= 5.6\lambda_I$

• Energy resolution :

$$\sigma_E/E = 80\%/\sqrt{E} \oplus 10\% \quad (GeV)$$

Muon system

⋆ Main channels :

$$B_d{}^0 \to J/\Psi(\mu^+\mu^-)K_s{}^0 \quad , \quad B_s{}^0 \to \mu^+\mu^-$$

• 5 muon stations : 1 station located after RICH2 and 4 stations after the HCAL

Two kinds of technology are used :

• MWPC for the Inner detector

• RPC for the Outer detector

⇒ Provides a muon signal for the level **L0 trigger**
$p_T \geq 1 \;\; GeV/c$

Trigger system for LHCb

Main requirements for the trigger system :

- ✥ Rejecting the huge inelastic backgrounds, $\sigma_{Inelas} = 80.0 \ \ mb$
- ✥ Selecting the signal
- ✥ Reconstructing the B mesons *online*

$\Longrightarrow$ Four levels for the Trigger :

- L0 : p_T of the photon or the charged particle
- L1 : **Vertex** informations
- L2 and L3 : Event reconstruction at the **software** level

$\Downarrow$

⋆ Reducing the high rate of the incident beam particles from **40 MHz** to **200 Hz**

L0 Trigger

• Detecting high transverse momentum or transverse energy hadron, electron and/or photon with the **calorimeter system**

$$E_T(\gamma) \geq 4\ GeV, \quad E_T(h) \geq 2.4\ GeV, \quad E_T(e) \geq 2.4\ GeV, \quad P_T(\mu) \geq 1\ GeV$$

⇒ L0 output rate $= 1\ MHz$

⋆ Important improvement since the Technical Proposal (Feb. 1998) :

→ Conception and realization of a Π^0 trigger

$$B_d^0 \to \pi^0\pi^0\ ,\ \ B_d^0 \to \rho^\pm\pi^\mp\ ,\ \ B_d^0 \to \rho^\pm\rho^\mp$$

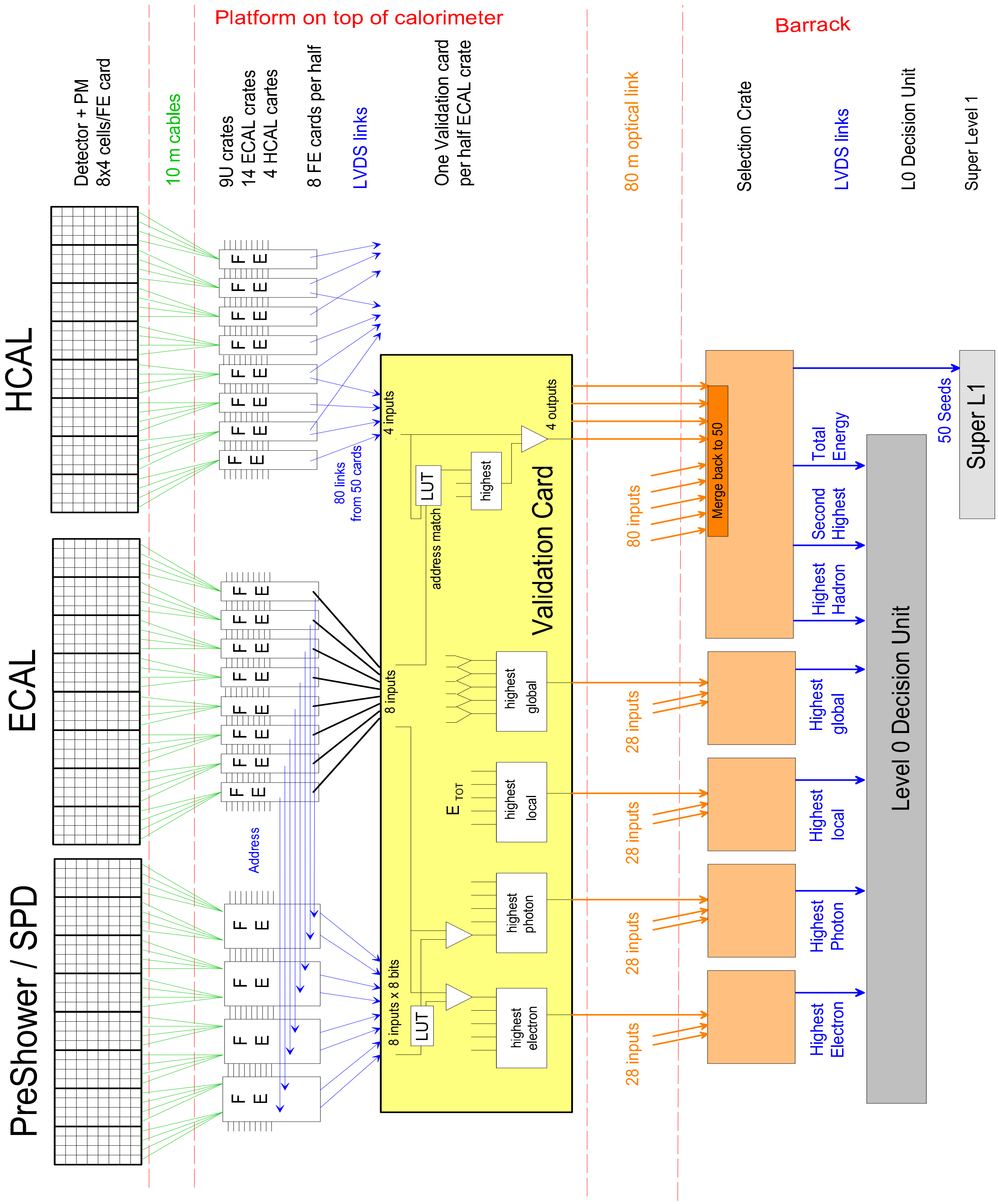
Main characteristics :

• Π^0 trigger concerns 15% to 45% of the unconverted photon pairs

• Very elaborate algorithm for the cluster topology in the ECAL :

$E_{T1} + E_{T2} \geq 3\ \ GeV$

⇒ Improvement of the performance of the L0 trigger : Relative efficiency increases from 10% to 20% according to the channels


HCAL
ECAL
PreShower / SPD
Platform on top of calorimeter
Barrack
Detector + PM
8x4 cells/FE card
10 m cables
9U crates
14 ECAL crates
4 HCAL cartes
8 FE cards per half
LVDS links
One Validation card
per half ECAL crate
80 m optical link
Selection Crate
LVDS links
L0 Decision Unit
Super Level 1
80 links
from 50 cards
Address
4 inputs
4 outputs
LUT
highest
address match
Validation Card
8 inputs
highest global
E_{TOT}
highest local
highest photon
highest electron
8 inputs x 8 bits
LUT
80 inputs
28 inputs
28 inputs
28 inputs
28 inputs
Merge back to 50
Total Energy
Second Highest
Highest Hadron
Highest global
Highest local
Highest Photon
Highest Electron
50 Seeds
Super L1
Level 0 Decision Unit

L1 Trigger

• It uses informations from the vertex detector and the hits in the stations to reconstruct the primary and secondary vertices.

Input rate for **L1 : 1 Mhz** $\Rightarrow$ Output rate : $40\ KHz$
$\Longrightarrow$ Towards the Data Acquisition system **(DAQ)**

L2 Trigger

Refines the vertex positions and the track reconstruction by using partial informations from the different subdetectors
$\rightarrow$ Output rate : $5\ KHz$

L3 Trigger

Uses complete data for B meson reconstruction
$\rightarrow$ Output rate : $200\ Hz$

Total trigger efficiency : • Depends on the channel • Mean value $\approx\ 30\%$ (**Tech.Prop.**) • Important improvements since the T.P. especially for the hadronic channels

Reoptimization of LHCb : LHCb-light

⋆ Material thickness up to the RICH2 : $60\%\ X_0$ and $20\%\ \Lambda_I$

⇒ Need to reduce the material for several purposes :
- Reducing the absorption of hadrons
- Improving their momentum resolution
- Good efficiency for γ and $e^{\pm}$ reconstruction

VELO

⋆ Minor change : 21 stations instead of 25

Tracking System

Important reduction of the number of stations :

11 (Tech.Prop.) $\Longrightarrow$ 4

With :

⋆ Removing the stations in the magnet
⋆ New tracking algorithm
⋆ New configuration of the tracking stations

New locations of the stations :

- TT1 before the Magnet
- ST1-ST3 after the Magnet and identical design than T7-T9

$\Longrightarrow$ Promising results :

$\star$ B track efficiency $\approx 90\%$ in a wide momentum range

$\star$ Ghost rate $\leq 10\%$

RICH System

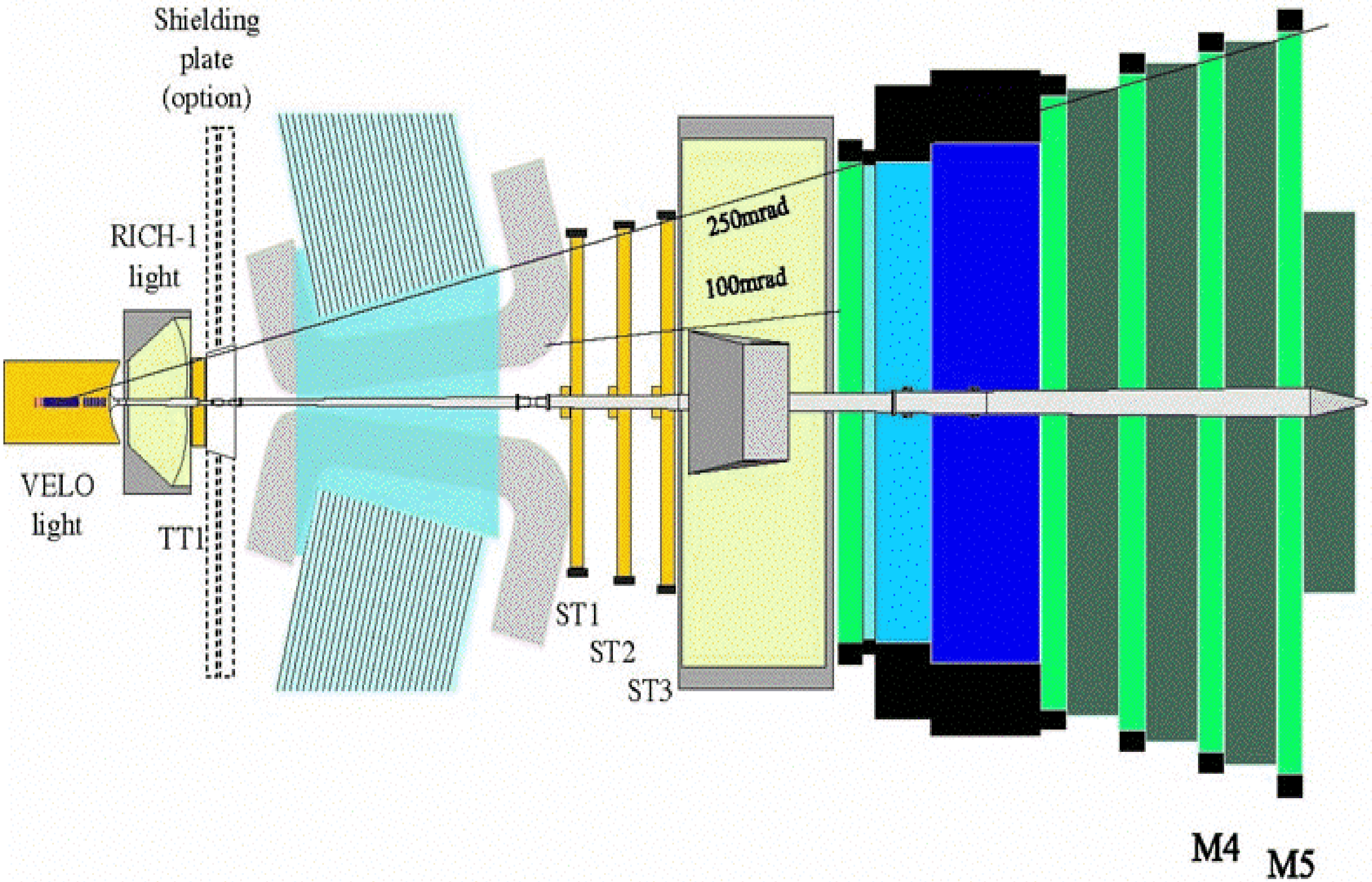
$\star$ Removal of the shielding plate of RICH-1
$\star$ New configuration and design of the spherical mirror in RICH-1

Improving the L1 trigger performance

LHCb-light final TDR in progress and submission in Autumn 2002.

Trigger TDR will be submitted early 2003

LHCb-light



Shielding
plate
(option)
RICH-1
light
VELO
light
TT1
250mrad
100mrad
ST1
ST2
ST3
M4
M5

Physics performance with LHCb

Many channels with high statistics $\Rightarrow$ Different ways to measure the UT angles

Angle β

$B_d \rightarrow J\Psi K_s^0 \Rightarrow$ 100K events/year, $\sigma(\sin 2\beta) = 0.02$

$B_d \rightarrow \Phi K_s^0 \Rightarrow$ Channel under study

Angle α

$B_d \rightarrow \pi^+\pi^- \Rightarrow$ 5K events/year, $\sigma(\sin 2\alpha) = 0.05$

$B_d \rightarrow \rho\pi \Rightarrow$ 1.3K events/year, $\sigma(\alpha) = 2.5^\circ - 5^\circ$

$B_d \rightarrow \pi^0\pi^0 \Rightarrow$ Channel under study

Angle γ

- Several channels to estimate the angle γ. Most important :

(i) $B_d \rightarrow D^{*\pm}\pi^{\mp}$ and (ii) $B_s \rightarrow {D_s}^{\pm}K^{\mp}$

(i) $\approx 340K$ events/year,
angle γ deduced from the measurement of $(\gamma + 2\beta)$
$\Rightarrow \sigma(\gamma) = 10^\circ$

(ii) $\approx 2.5K$ events/y $\Rightarrow$ measurement of $(\gamma - 2\delta\gamma)$
$\rightarrow \sigma(\gamma - 2\delta\gamma) = 6^\circ - 13^\circ$

- **"Fleischer method"** :

$SU(3)_f$ symmetry for the two conjugate channels :

$B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

$\Rightarrow$ Measuring both the two angles β and γ : Will be investigated

Angle $\delta\gamma$

- $B_s^0 \rightarrow J/\Psi\Phi \Rightarrow$ 80K events/y, $\sigma(\delta\gamma) = 2^\circ$

Channel where **New Physics** could be looked for

Conclusion

- LHCb provides a clean identification of the main B decay exclusive channels
- Many ways to measure the **UT angles** $\Rightarrow$ Possibility of over-constraining the **CKM** matrix

$\Longrightarrow$ Looking for a *deviation* from the SM

$\Rightarrow$ New Physics

$\Rightarrow$ Dynamical Origin of CP Violation

$\Downarrow$

Stopping the delay of LHC project...