Tracking and alignment performance of LHCb silicon detectors

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LHCb is an experiment dedicated to heavy flavour physics at the LHC.
Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons.

(bb) - pairs produced predominantly close to beam direction \(\Rightarrow\) Forward spectrometer: \(1.9 < \eta < 4.9\)

Requirements:
- High precision measurement of primary and secondary vertex \(\Rightarrow\) proper time
- Good momentum resolution \(\Delta p/p = 0.4\% - 0.55\%\)
- Good particle ID
Main detector requirements
- Good vertex resolution [proper time]
- Momentum resolution (MC): $\Delta p/p = 0.4\% - 0.55\%$
- Good particle identification [K/\pi separation]
Main detector requirements

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- Warm Magnet integrated magnetic field of 4 T \cdot m
**Silicon Vertex and Tracker detectors**

**Vertex detector**
- 21 silicon micro-strip stations with r-\(\phi\) geometry
- 2 retractable detector halves:
  - 8.2 mm from beam with stable beam condition,
  - 30mm from beam during injection and MD
- 300\(\mu\)m foil separates detector vacuum from beam vacuum and constitutes beam-pipe in VELO region

[More details in K. Akiba talk]

**Silicon tracker**
- Track Turicensis (TT) detector
  - Upstream of the magnet
  - Four planes of silicon micro-strip (p on n) sensors (0\(^\circ\), +5\(^\circ\), -5\(^\circ\), 0\(^\circ\))
  - Readout pitch 183\(\mu\)m pitch
  - 500\(\mu\)m thickness
  - strip length from 9 to 37 cm
  - Area of 8.2 m\(^2\) covered by Silicon, 143360 strips

**Inner Tracker (IT) detector**
- Downstream of the magnet
- 3 stations with 4 layers (0\(^\circ\), 5\(^\circ\), -5\(^\circ\), 0\(^\circ\))
  - Readout pitch 198\(\mu\)m
  - 320/410\(\mu\)m thickness for 1/2 sensor ladders
  - Area of 4.2 m\(^2\) covered 129024 readout strips
LHCb Tracking

- **VELO tracking using r and $\phi$ hits**
  - Same tracking in trigger and in offline data processing
  - No momentum information for backward tracks $\Rightarrow$ needed for improving PV resolution

- **Long tracks**
  - Extrapolate VELO tracks and associate hits in T-stations
  - Combine VELO tracks with seeds from T-station
  - Add TT hits for resolution

- **Track fitting with bi-directional Kalman filter and detailed material map**
Efficiency of VELO tracking:
- Using Tag and Probe method with $J/\psi \rightarrow \mu\mu$ sample

Good agreement between data and MC

Similar method can be used to evaluate the efficiency of the tracking system
- Selecting $K \rightarrow \pi\pi$ or $J/\psi \rightarrow \mu\mu$
Alignment
First method
- Module and 2 half alignment by method based on Millepede
- Sensor alignment by an histogram method, used also for monitoring

Second method
- Global $\chi^2$ minimisation based on Kalman track fit residuals.

Sensor alignment better than 4 $\mu$m
VELO centred around the beam for each fill when the beam declared stable

PV method:
- Reconstruct PV using tracks in left or in the right side
- Evaluation of misalignment by the distance between the 2 vertices

Stability of 2 half alignment by PV method:
- within ± 5 μm for Tx
- within ± 2 μm for Ty
**ST: alignment**

- **Method:**
  - Global $\chi^2$ minimisation based on Kalman track fit residuals
  - track t residual
  - applying also mass constraints ($J/\Psi$ and $D^0$ masses)
  - No sensitive to Ty alignment

- **Alignment precision evaluated by the bias of the residuals**
  - IT Misalignment 11.1 $\mu$m
  - TT Misalignment 17.7 $\mu$m
- ST modules have gaps due to insensitive Guard Rings and edges in Y hits distributions.
- Extrapolation VELO tracks to the IT and TT stations
  - evaluation of y misalignment
  - To disentangle y misalignment and effect due the magnetic field
    - magnet off data for alignment
    - magnet on data for validation
Hit resolution
Main dependence:
- strip pitch
- projected angle (the angle between the track and the strip in the plane perpendicular to the sensor).

Other factors:
- Charge sharing as function of fractional strip position ($\eta$)
  - work on progress for $\eta$ correction implementation

Hit resolution:
- Best hit resolution $4 \ \mu m$
- Good agreement with MC
- Improvements expected with $\eta$ correction
ST: hit resolution

- **Dependency:**
  - Strip pitch
  - Charge sharing
  - Cross talk due to capacitive coupling between the strips
  - Lorentz angle: bias of cluster position due to the presence of $B_{\text{field}}$

- Tuning of Monte Carlo with the measured parameters

\[
tan(\theta) = -0.0163
\]
Hit resolution
- IT: 58 μm, strip pitch 190 μm
- TT: 62 μm, strip pitch 183 μm

The difference with respect to Monte Carlo due to:
- some difference in the gain
- status of the alignment
Primary Vertex Resolution

- **Vertex resolution**
  - Measure resolutions by randomly splitting track sample in two
  - Compare split vertices of equal multiplicity
  - Method validated with MC

- **PV resolution (x,y,z) with 25 tracks:**
  - Data (13.0, 12.5, 68.5) μm
  - MC (10.7, 10.9, 58.1) μm

- Room for improvement
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- Room for improvement
**Impact Parameter resolution**

- **IP resolution**:
  - defined as the closest distance of each track to the primary vertex
  - Measure x and y component of impact parameter
  - Assume all tracks originate from primary interaction point
  - Measure resolution as spread of IP distribution

- **IP resolution down to 13 \( \mu \)m for high \( p_T \)**
**Impact Parameter resolution**

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- **IP resolution down to 13 μm for high \( p_T \)**

- **MC resolution down to 11 μm**

- **Possible cause of discrepancy**
  - Alignment effect
  - Material description
Alignment effect:
- Improving alignment closed the gap between data & MC at high $p_T$.
- Difference between gradients remains roughly constant.

Material effect:
- RF foil thickness 250 $\mu$m instead of 300 $\mu$m
  $\Rightarrow$ small change in the slope
- Missing other material?
  $\Rightarrow$ detailed material scan study by vertex interaction
Material study

- Use detector model in simulation to estimate material budget
  - Largest contribution from RF foil (~42%)
- Use vertices of hadronic interactions with material to map VELO
  - \#interaction(Si) has good agreement between data and MC
  - Good description of total material
- Changing the Geant setting, size of multiple scattering is changing
IP resolution:
- Impact Parameter (IP) is defined as the closest distance of each track to the primary vertex:
- Measure x and y component of impact parameter
- Assume all tracks originate from primary interaction point
- Measure resolution as spread of IP distribution
- IP resolution up to 13 µm for high $p_T$
- MC resolution up to 11 µm
- Still under investigation the discrepancy between data and Monte Carlo
Mass measurement

- Very precise momentum and mass resolution
- Mass measurement:
  - world best measurements for $B_u, B_d, B_s$ and $\Lambda_b$ after one year of data taking
Proper time resolution

Proper time resolution ~50 fs

Many physics results, one example:

- Competitive measurement of $B_s^0 - \bar{B}_s^0$ mixing frequency
  $\Delta m_s$ with $36 \text{ pb}^{-1}$
  $\Delta m_s = 17.63 \pm 0.11 \text{ (stat.)} \pm 0.04 \text{ (syst.) ps}^{-1}$
Conclusion

- Excellent performance of the vertex and tracker detectors in LHCb experiment:
  - Good understanding of tracking and alignment
  - High track efficiency
  - Hit resolution for VELO down to 4 $\mu$m and for ST $\sim$190 $\mu$m
  - PV resolution at $\sim$13 $\mu$m
  - IP resolution down to 13 $\mu$m
  - Good momentum and mass resolution
  - Proper time resolution 50 fs

- Given a powerful tool to obtain a lot of new physics results ...
  and maybe also observation of New Physics!
Backup
VELO: Cluster finding efficiency

- Evaluation of efficiency in the test module, not used in the tracking
  - 1 module test each 5 modules
  - Same method as Charge Collection Efficiency

- Extrapolate each track to the test sensor
- If the extrapolated point in the sensitive area
- Check the cluster in the neighboring strip

- Overall efficiency is 99.5% including the known bad and dead strips
**ST: Hit efficiency**

- Measure efficiency with tracks $p > 10$ GeV:
  - Isolation criteria to reject ghosts.
  - Efficiency varies as function of window size: 2.5 mm (TT) and 1 mm (IT).

  \[
  \text{Efficiency} = \frac{\text{Num. found hits}}{\text{Num. expected hits}}
  \]

- Noise cluster rate: $O(10^{-5})$

- Overall efficiencies:
  - IT: 99.7 %.
  - TT: 99.3 %.
VELO: 2 half alignment

- Velo centred around the beam for each fill when the beam declared stable.
- Special Data taking condition at beam energy below 7 TeV:
  - at 0.9 TeV → Velo at ± 10mm
  - at 2.8 TeV → Velo at ± 5mm
- Motion system high precision for opening distance < 5 mm
  - Not foreseen other positions than fully closed
  - Observed large misalignment
- Calibration of resolver position using PV method

 Fully open

 Closed pos.

Scale factor of 0.57%

\[
\text{Misalign.(mm)} = (0.0057 + 0.0001) \times \text{OpenDistance}
\]
VELO: sensor module alignment

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Vertex2011, 24 June 2011
Material study

- Material budget
- Use detector model in simulation to estimate material budget
- Average particle leaving VELO sees 0.217 $X_0$ material for $1.6 < \eta < 4.9$
- Largest contribution from RF foil (~42%)
Cluster size as function of the projected angle

- LHCb Preliminary

![Graph showing cluster size as a function of the projected angle with different pitch bins.](image-url)