6.6 Vertexing and impact parameter measurement

An example of a fully reconstructed B-meson decay in the ALEPH experiment

Track measurements with a precision of a few µm near the interaction point improve the momentum measurement and allow to determine the decay vertex. This is especially important for B-hadrons

(typical lifetime of about 1.5 ps)
The life time of B-mesons can be measured from the decay length L, if the momentum of the B-meson (γ-factor) is measured as well.
Impact parameter measurement

The innermost silicon detector must provide the required $b$-tagging efficiency.

Good vertex resolution is achieved by placing the innermost ($B$) layer close to the beam pipe, and the next layer farer to it (lever arm), and by an excellent $B$-layer resolution.

Small multiple scattering term: $\sigma_{MS} \sim \frac{1}{p} \sqrt{x/X_0}$

Expected transverse IP resolution $\sim 13 \mu m$ for 100 GeV track.

Decay length significance

$R_{q\text{-light}} \sim 600$ for $\varepsilon_b = 0.5$
Estimation of the impact parameter resolution (2-point approximation):

\[ \sigma_b = \frac{r_2}{r_2 - r_1} \]

\[ \sigma_1 = 0 \]

\[ \sigma_2 = 0 \]

\[ \sigma_1 > 0 \]

\[ \sigma_2 > 0 \]

\[ \sigma^2 = \left( \frac{r_1}{r_2 - r_1} \sigma_2 \right)^2 + \left( \frac{r_2}{r_2 - r_1} \sigma_1 \right)^2 + \sigma_{MS}^2 \]

\[ \sigma_{MS} \sim \frac{1}{p} \sqrt{\frac{x}{X_0}} \]
More general case of N measurement points:

- N points,
- precision $\sigma_{\text{mess}}$ at each point

To optimize the impact parameter resolution:
- High precision measurement, small $\sigma_{\text{mess}}$
- Large lever arm (L)
- Place first detector plane as close as possible to the interaction point $\Rightarrow$ small $x$
- Gain with number of layers, however, only $\sim 1/\sqrt{N}$

$\Rightarrow$ Silicon strip and pixel detectors are essential!
Example: ATLAS pixel detector *

\[ N = 3, \quad \sigma = 10 \mu m, \]
\[ x_1 = 4.7 \text{ cm}, \quad x_2 = 9.1 \text{ cm}, \quad x_3 = 13.5 \text{ cm} \]
\[ L = 8.8 \text{ cm}, \quad r = x_2/L = 1.03 \]
\[ \sqrt{1 + \frac{12(N-1)}{(N+1)} r^2} = 2.65 \]

Impact parameter resolution

\[ \sigma_{d_0} = 15.7 \mu m \quad \text{(linear, i.e. no field)} \]
\[ \sigma_{d_0} = 45.5 \mu m \quad \text{(extrapolation with B-field)} \]

Note

- if curvature is used for extrapolation with N=3 the error on \( d_0 \) gets larger by a factor \( \sim 2.9 \).
- however, curvature is measured by the entire inner detector => error on \( d_0 \) similar to linear case

* from N. Wermes, Lectures at BND School 2015
Impact parameter resolution, including multiple scattering *)

- For **low momentum** tracks the momentum resolution and the impact parameter resolution are **dominated by multiple scattering**.
- The amount of **material** actually traversed by the particles depends on the polar angle:
  \[
  \frac{x}{\sin \theta}
  \]
- The momentum resolution tends to:
  \[
  \frac{\sigma_p}{p^2} \rightarrow k_p \frac{\sqrt{x/X_0}}{p\sqrt{\sin \theta}}
  \]
- The impact parameter resolution tends to:
  \[
  \sigma_{d_0} \rightarrow k_{d_0} \frac{\sqrt{x/X_0}}{p\sqrt{\sin \theta}}
  \]
- Since the MS error and the point measurement error are **independent of each other**, the total error is the sum in quadrature of the 2 terms with and w/o MS.
- For the **ATLAS** detector Monte Carlo studies have shown that the resolutions on momentum and impact parameter can be parametrized as:
  \[
  \frac{\sigma_{p_T}}{p_T^2} = 0.00036 \oplus \frac{0.013}{p_T \sqrt{\sin \theta}} \text{(GeV)}^{-1}
  \]
  \[
  \text{or}
  \]
  \[
  \frac{\sigma_{p_T}}{p_T} = 0.04\% p_T \oplus \frac{1.3\%}{\sqrt{\sin \theta}} \text{(GeV)}^{-1}
  \]
  \[
  \sigma_{ip} = \begin{cases} 
    11 \mu m & \frac{73 \mu m}{p_T \sqrt{\sin \theta}} 
  \end{cases}
  \]

* from N. Wermes, Lectures at BND School 2015
6.7 The ATLAS and CMS Central Tracking Detectors
The ATLAS Inner Detector (one end-cap)
The ATLAS Inner Detector

![Diagram of the ATLAS Inner Detector]

<table>
<thead>
<tr>
<th></th>
<th>R- $\phi$ accuracy</th>
<th>R or z accuracy</th>
<th># channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>10 $\mu$m</td>
<td>115 $\mu$m</td>
<td>80.4M</td>
</tr>
<tr>
<td>SCT</td>
<td>17 $\mu$m</td>
<td>580 $\mu$m</td>
<td>6.3M</td>
</tr>
<tr>
<td>TRT</td>
<td>130 $\mu$m</td>
<td></td>
<td>351k</td>
</tr>
</tbody>
</table>

$\sigma/p_T \sim 0.05\% \ p_T \oplus 1\%$
Example: ATLAS Si-Tracker SCT

4 cylindrical barrels with 2112 modules

Endcaps: 1976 modules on 2.9 disks

Only Silicon shown

5.6m x 1.04m