Optimization of the B meson vertex resolution for the Belle II experiment

Christian Roca Catalá

Max-Planck Institut für Physik - Belle Group

crisroc@mpp.mpg.de

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Belle II experiment at SuperKEKB

New Tracking System
- Pixel Vertex Detector (PXD)
- Silicon Vertex Detector (SVD)
- Central Drift Chamber (CDC)

Instantaneous luminosity
- KEKB: $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- SuperKEKB: $8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
CP violation and time dependent analysis

\[ \Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow f_{CP} f_{tag} ; \quad f_{CP} \rightarrow J/\psi K_S, f_{tag} \rightarrow \text{all modes} \]

Asymmetry in the B/\bar{B} decay to f_{CP}

\[ A_{CP} = \frac{\Gamma(\bar{B}^0 \rightarrow f_{CP}, \Delta t) - \Gamma(B^0 \rightarrow f_{CP}, \Delta t)}{\Gamma(\bar{B}^0 \rightarrow f_{CP}, \Delta t) + \Gamma(B^0 \rightarrow f_{CP}, \Delta t)} \]

\[ A_{CP} \cos(\Delta m_d \Delta t) + S_{CP} \sin(\Delta m_d \Delta t) \]

- A_{CP}: direct $CP$; $S_{CP}$: mixing induced $CP$

- Kinetic reconstruction
  → CP side
- Flavour ID
  → tag side

* PRL 108, 171802 (2012)*

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What is the contribution of the Vertex resolution?

- **Time-dependent analysis** depend on the good measurement of $\Delta t$ - obtained from $\Delta z$
- Belle: $B_{\text{tag}}$ resolution (89 $\mu$m) $\sim$ 30% **worse** than $B_{\text{CP}}$ resolution (63 $\mu$m)
- $B_{\text{tag}}$ resolution depends heavily on the fitting **algorithm**.
- The **contribution** for $\Delta z$ that needs to be specially **optimized** is the $B_{\text{tag}}$ vertex

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Vertex resolution of the CP side

\[ B^0(\bar{B}^0) \rightarrow f_{CP} = [J/\psi \rightarrow \mu^+ \mu^-]K_S \]

Legend
- Resolution distr. = vertex - MC vertex
- 3 Gaussian fit with std. dev \( \sigma \)
- Resolution = weighted avg. \( \sigma \)

Observations
- \( \mu \) tracks \( \geq 1 \) PXD hit
- Resolution improvement from Belle (63 \( \mu \)m) - factor 2.7
- Small Shift of 1.8 \( \mu \)m (under investigation)

Belle II simulation using PXD

\[ J/\psi \rightarrow \mu^+ \mu^- \text{ VertexZ Resolution} \]

\( \sigma = 22.5 \mu \text{m} \)
How is the fit performed?

1. $B_{\text{tag}}$ vertex fit uses the **tracks remaining** after the reconstruction of the CP side

2. **No** $B_{\text{tag}}$ reconstruction is performed (**loss of statistics**)

3. **Algorithm:** RAVE Adaptive Vertex Fit (AVF)* with spatial constraints

RAVE Adaptive Vertex Fit (AVF) with constraints

All tracks are used and weighted following two criteria:

1. Outlying and isolated tracks are down-weighted
2. Tracks weighted according their position with respect to the constraint

Weighting works iteratively

What is the constraint?

- A spatial constraint is defined within which the B is expected to decay
  - Ellipsoid of 600 µm long axis
  - Centered in the Beam Spot
  - Along the boost direction

Standard 600µm long constraint Centered in the BeamSpot
Belle II $B_{\text{tag}}$ vertex Resolution - Standard algorithm

In comparison with BELLE:
- Resolution $= 89 \, \mu m$ - factor 1.5

- Improvement in the $B_{\text{tag}}$ vertex resolution lower than for $B_{\text{CP}}$
- Dominated by the algorithm! PXD precision not fully used.

- Can we do better than this? New algorithm
New Algorithm: Using Flavor Tagging Information

Flavor Tagging Algorithm:

- Take all the **remaining** tracks after the reconstruction of the CP side.
- Find the tracks best suited for **Flavor Tagging**
- Extract **probabilistic** information from those tracks
  - Prob. of being a **daughter** from $B_{tag}$
  - Prob. of belonging to a given decay mode/category
- Finally return a **parameter** $\in [-1, 1]$ that reflects how good the **flavor** can be identified
- **Flavor id. crucial to measure** $\mathcal{C}/\mathcal{P}$

<table>
<thead>
<tr>
<th>Categories</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$, $e^+$</td>
</tr>
<tr>
<td>(Intermediate Electron)</td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^-$, $\mu^+$</td>
</tr>
<tr>
<td>(Intermediate Muon)</td>
<td></td>
</tr>
<tr>
<td>KinLepton</td>
<td>$e^-$</td>
</tr>
<tr>
<td>Kaon</td>
<td>$K^-$</td>
</tr>
<tr>
<td>KaonPion</td>
<td>$K^-$, $\pi^+$</td>
</tr>
<tr>
<td>SlowPion</td>
<td>$\pi^+$</td>
</tr>
<tr>
<td>FastPion</td>
<td>$\pi^-$</td>
</tr>
<tr>
<td>MaximumP</td>
<td>$\ell^-$, $\pi^-$</td>
</tr>
<tr>
<td>FSC</td>
<td>$\ell^-$, $\pi^+$</td>
</tr>
<tr>
<td>Lambda</td>
<td>$\Lambda$</td>
</tr>
</tbody>
</table>

Total = 10 (12)
New Algorithm: Single Track Fit (STF)

Constraint of New Algorithm

Secondary tracks are not used in the fit, and therefore:

- **Constraint** centred at the BS is no longer down weighting secondary tracks
- B-meson **decays** in average $\sim 120 \mu m$
- If the **constraint** remains centred at BS, **large bias** appears ($\sim 15 \mu m$)

**Why do we move the constraint?**

If this does not converge...

**EXTRA:** If possible: perform fit removing tracks with NO hits on the PXD
New algorithm: $B_{\text{tag}}$ vertex resolution

Events with successful single track fit

All events

In comparison with Belle:

Resolution = 89 $\mu$m
- Single Track Fit Factor 2.2
- STF + Standard Alg. Factor 1.9

In comparison with Standard Algorithm:

Resolution = 56 $\mu$m
- Single Track Fit Factor 1.4
- STF + Standard Alg. Factor 1.2

- Single Track Fit triggered $\sim$ 15% of all $B_{\text{tag}}$ cases
- Resolution improvement with respect to Belle almost reached CP side.
  - CP side - factor 2.8
  - Tag side - factor 2.2 (Single Track Fit), factor 1.9 (Combined)
New algorithm: $\Delta t$ distribution

Events with successful single track fit

All events

In comparison with Belle:

Resolution = 0.92 ps
- Single Track Fit Factor 1.6
- SFT + Standard Alg. Factor 1.4

In comparison with Stand. alg.:

Resolution = 0.78 ps
- Single Track Fit Factor 1.3
- SFT + Standard Alg. Factor 1.2

- Single Track Fit triggered $\sim$ 15\% of all $B_{\text{tag}}$ cases

- Resolution improvement with respect to Belle almost reached CP side.
  - CP side - factor 2.8
  - Tag side - factor 2.2 (Single Track Fit), factor 1.9 (Combined)
### Vertex resolution and optimization using PXD

<table>
<thead>
<tr>
<th>B&lt;sub&gt;CP&lt;/sub&gt; Vertex resolution (23 µm):</th>
<th>improved a factor 2.7 with respect to Belle (63 µm).</th>
</tr>
</thead>
<tbody>
<tr>
<td>B&lt;sub&gt;tag&lt;/sub&gt; Vertex resolution with Standard Algorithm (57 µm):</td>
<td>improved a factor 1.5 with respect to Belle (89 µm).</td>
</tr>
<tr>
<td>Improvement in Tagged side do not scale as in Reconstructed side</td>
<td></td>
</tr>
<tr>
<td>New algorithm performs a single track fit with higher resolution (39 µm) with 15% efficiency, improvement by a factor 2.2 with respect to Belle.</td>
<td></td>
</tr>
<tr>
<td>B&lt;sub&gt;tag&lt;/sub&gt; Vertex resolution with Standard Algorithm + Single Track Fit (47 µm):</td>
<td>improved a factor 1.9 with respect to Belle (89 µm).</td>
</tr>
</tbody>
</table>

### Outlook

- Understand the small shift on the CP side vertex
- Improve the single track selection criteria in order to increase the efficiency.
- Improve the B<sub>tag</sub> vertex fit constraint’s parameters to reduce the bias in the resolution
THANKS FOR YOUR ATTENTION!

MASCARA

APPROVES
Preliminary analysis - semileptonic decay

$B_{tag} \rightarrow \mu^- \bar{\nu}_\mu D^{(*)} +$ and conjugate

**USING ALL TRACKS**

**USING MC MATCHED MUONS**

TagVz Resolution

![Graph](image1)

- Fit Shift = -0.7 ± 0.4 µm
- Res = 61.3 ± 0.7 µm

![Graph](image2)

- Fit Shift = -15.2 ± 0.5 µm
- Res = 52.5 ± 0.6 µm

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Cut analysis - Generic decay (work still on progress)

\[ B_{tag} \rightarrow \text{generic} \]

**Purity analysis**

- Perform several **cuts** on the variables of the **tracks**
- Compare with **Monte Carlo** information
- Aim: Kill the **bad** ones and keep the **good** ones!
- **High purity** acquainted after selection

![Normalized distribution of Purities](image-url)

- **Initial purity**
- **Purity after the 8th Cut**
TagVz Resolution

- Fit: Shift = 3.4 ± 0.8 μm
- Res = 56.6 ± 1.3 μm
- Efficiency 78
B_{tag} Vertex Resolution using only tracks not coming from B

TagVz Resolution

Events

Shift = 3.4 ± 1.4 μm
Res = 97.6 ± 2.4 μm
Efficiency 54