Reconstruction of Multiple-Interaction Events

Rainer Mankel
Humboldt University Berlin

Institute Seminar, Zeuthen, 7-Jan-98
**HERA-B Challenges**

**Hardware:**
- New detector technologies
- Complexity & size
- Radiation hardness
- Rate capability
- Alignment
- Readout
- DAQ
- Triggering

**Software:**
- Complexity
- Detector material
- Track/Hit densities
- Online reconstruction (farm)
- Distributed code development
- Dedicated reconstruction techniques
Outline

• CP violation
• HERA-B detector
• Reconstruction concept
• Methods & performance
  – Track Reconstruction
  – RICH
  – Muon System
• Summary

Note: all performance figures are preliminary
Weak Flavour Mixing

Charged hadronic current (V-A structure)

\[ \sim \left( \bar{u}, \bar{c}, \bar{t} \right)_L \gamma_\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{td} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \]

CKM matrix (Cabbibo-Kobayashi-Maskawa)

Unitarity Triangle

B \rightarrow \pi\pi
B \rightarrow \pi l\nu

\[ V_{ub}^* \]
\[ |\lambda V_{cb}| \]

\[ V_{td} \]

\[ B \rightarrow D^* l\nu \]

\[ \mathcal{L} \rightarrow B \rightarrow K_S \rho \]

\[ \mathcal{L} \rightarrow B \rightarrow J/\psi K_S \]

HERA-B: Reconstruction of multiple-interaction events 7-Jan-98
Status of the Unitarity Triangle

\[ V_{ub} = A\lambda^3 (\rho - i\eta) \]
\[ V_{td} = A\lambda^3 (1 - \rho - i\eta) \]

- CP-violating $K^0K^0$ mixing ($\rightarrow \varepsilon$):
  - $V_{cd} = -\lambda - A^2\lambda^5(\rho + i\eta)$

- non-degenerate triangle ($\eta > 0$) likely, but not certain
\textbf{CP in the B system?}

\[ \Gamma(B^0 \rightarrow f) \neq \Gamma(\bar{B}^0 \rightarrow f) \rightarrow \text{CP violation} \]

\textbf{CP in the standard model:}

CKM phase measurement: Interference between $b \rightarrow c$ transition amplitude and $B^0\bar{B}^0$ mixing amplitude.

“Golden decay mode” \( B \rightarrow J/\psi K^0_S \)

\[ \frac{N(B^0 \rightarrow f) - N(\bar{B}^0 \rightarrow f)}{N(B^0 \rightarrow f) + N(\bar{B}^0 \rightarrow f)} \sim \sin \left[ \arg \frac{V_{td} V_{cb}}{V_{td}^* V_{cb}^*} \right] \sim -\sin 2\beta \]
HERA-B: a hadronic B Factory

- Idea: convert the HERA proton ring into a B factory
- suspend wire target in halo of proton beam

- 40 MHz interaction rate possible without disturbing the other HERA experiments
- 820 GeV protons $\rightarrow$ huge Lorentz boost $\rightarrow$ forward spectrometer
- $\sigma_{bb} / \sigma_{inel} \sim 10^{-6}$
  $\rightarrow$ 4…5 superimposed interactions
Principle of the (dedicated) Hadronic B Factory

Determination of $B$ initial state:

- $\bar{B} \to e^- \ldots, \mu^- \ldots$ Lepton tag
- $\to K^- \ldots$ Kaon tag

→ Forward spectrometer
→ excellent track and vertex reconstruction
→ particle identification ($e, \mu, K/\pi$)
The Detector Simulation

B → J/ψ K^0_S only

plus 5 interactions

(S. Nowak)
The Detector Simulation (cont’d)

- crucial for detector design & SW development
- based on Geant 3.21
- ~18000 detector volumes
- integrated into HERA-B software frame
- common geometry definition for simulation and reconstruction

Testrun 1997:

OT occupancy compared to HBGEAN
→ agreement data/MC within 10…15%
→ similar for other devices
Geometry Generation (OT)

A. Lanyov

Example: Outer tracker
• Geometry constants for O(1000) outer tracker modules needed
→ automatic conversion from engineer’s data sheets to experiment data model

Engineers/CAD ➔ Arte tables ➔ GEANT volumes
Comparing Event Topologies

ARGUS/CLEO, $\sqrt{s} = 10.45$ GeV  
LEP, $\sqrt{s} = 90$ GeV

HERA-B, $E_p = 820$ GeV

→ high demands on event reconstruction!
Track Reconstruction Concept

- Magnetic field very inhomogeneous
  → start pattern recognition in field-free area
- "Pattern tracker" = field-free area of main tracking system
**The HERA-B Main Tracker**

- **Outer tracker (d>20cm):**
  - Honeycomb Drift Chambers (75 μm Pokalon-C)
  - Ø 5 and 10 mm
  - resolution < 200 μm
  - peak occupancy < 20 %

- **Inner tracker (6cm < d < 20cm):**
  - Micro-Strip Gaseous Chambers (MSGC)
  - Pitch 300 μm
  - resolution < 80 μm
  - peak occupancy ~ 3 %

**Note:** stereo angles 0°, ±5°
Pattern Recognition

- complicated geometry
- mix of different detector technologies
- high occupancy, frequent track overlap

=> Full exploitation of track model
=> Kalman filter technique
=> Triplet seeding
=> Concurrent track evolution
Concurrent Track Evolution

**Challenge:**
- Occupancy ⇒ Track following confused by many available paths
- Vast combinatorics
- Delicate optimization process

**Solution:** Concurrent Track Evolution
- combines virtues of track following and combinatorial approaches
- propagate all branches in parallel, but inferior branches ‘die out’
- maximize quality estimator

$$Q = \text{#Steps} - \text{#Faults} - w\chi^2 \sum \chi_i^2$$

- Kalman filter
Accept from seed
Simulated Event

• $p\text{Al} \rightarrow B^0+X$ superimposed with 6 inelastic interactions

$\Rightarrow$ good track separation through efficient use of track model
Detail

- reconstruction of pion from the golden decay $B^0 \rightarrow J/\psi K_S$
Mean efficiency for tracks from the golden B decay (5 superimposed interactions) $> 96\%$

fraction of “ghost” tracks $< 8\%$

in spite of high track density high track finding efficiency feasible

ultimately limited by track overlap in drift chamber cells
Influence of Resolution and Hit Efficiency in Outer Tracker

.resolution $\sigma \leq 200\mu m$ important for suppression of ghosts

.hit efficiency should be in 90\% area
  - 98\% (outer tracker)
  - >95\% (inner tracker)

fault tolerance is important parameter of algorithm
Geometrical Acceptance

- Acceptance defined by pattern tracker:
  - 88% for leptons from golden B decay
  - 78% “ pions “ “ “ “ “
Resolution and Granularity of Inner Tracker

Resolution and Double track separation

- resolution $O(100\mu m)$ sufficient for pattern recognition
- double track resolution crucial
- ideal hardware solutions:
  - micro strip gaseous chambers (MSGC)
  - scintillating fibres

R. Nahnhauer et al.
Magnet Tracking

- magnetic field measured and parametrized with polynomials in boxes
  A. Spiridonov

- 3D Kalman filter propagation
- treat inhomogeneous field with 5th order embedded Runge-Kutta method
  $\rightarrow \varepsilon_{\mu(B)} \sim 92\%$ (still preliminary)
Pattern Recognition Toolkit

- Track Following (Kalman filter)
- Space points, master planes
- Track segment following
- Template matching
- Hough Transform (Histogramming)
- Hough transform (MST)
- Fuzzy Radon transform
- Hopfield neural net
- Elastic Arms (Deformable Templates)

Established Avantgarde
Hough Transform

(T. Schober)

Pattern Space

Feature Space

Simple model
detector,
12 layers,
no stereo views,
no left/right
ambiguity

- high efficiency only with complicated cluster search
- memory & cpu time demands (~36s)
- left/right ambiguity additional challenge
- 3D generalization?

HERA-B: Reconstruction of multiple-interaction events
Neural Network Methods

- Dynamic systems of (non-linearly) interacting units (neurons)
- Neuron ‘active’ or ‘inactive’
- Goal: intrinsically simple methods, flexible & robust

Hopfield neuron: Denby-Peterson

Potts neuron:

Elastic arms (Ohlsson-Peterson)
Denby-Peterson Algorithm

(C. Borgmeier)

- Hopfield net implementation
- no explicit track model
- assign neuron to every possible \textit{connection} of 2 hits

\begin{equation}
S_{ij} = \begin{cases} 
1, & \text{segment part of a track} \\
0, & \text{otherwise} 
\end{cases}
\end{equation}

- Activation

- Define interaction

\begin{itemize}
  \item \textit{wrong} \textit{wrong} \sim \textit{OK}
\end{itemize}
Energy Function

- suppress both large angles and large distances

\[ \Theta_{ijkl} \]

- Update Rule

\[
S_{ij} = \Theta \left( \sum_{kl} \left( - \frac{\partial E_{ij;kl}}{\partial S_{ij}} \right) \right)
\]

First Iteration:

36 Iterations (convergence):

HERA-B: Reconstruction of multiple-interaction events 7-Jan-98
Results (Denby-Peterson)

- 2D model detector

![Graph showing peak occupancy vs. peak occupancy]

- Many ghosts consist of improperly merged track fragments ⇒ recoverable?
- Computing time ~500s for $\rho=20\%$
- 3D implementation non-trivial
- Need track model to resolve close tracks
Elastic Arms

(C. Borgmeier)

- Let ‘track templates’ search their hits
- Explicit track model

\[
E = \sum_{\text{Hits}} \sum_{\text{Templ}} S_{iu} M_{iu} \text{ with gradient descent & simulated annealing}
\]

\[= 1 \text{ if hit assigned to template}
\]
\[= 0 \text{ otherwise}
\]
Elastic Arms (cont’d)

- Initialize templates with local Hough transform

- 2D pattern recognition efficiency

- Works nicely, but considerable computing effort for HERA-B occupancies (~3000s for $\rho=0.17$)
Elastic Arms (cont’d)

A. Paus

• “Real” 3D tracker requires a more sophisticated template initialization:
  – 0° triplets in each superlayer
  – two triplets define 0° segment
  – stereo superlayer triplets
  – full candidate seed

• Acceleration of convergence:
  – lower initial temperature (better initialization)
  – early weedout of far-off hits
  – resilient propagation instead of gradient descent
  ➔ ~1000 times faster!
Elastic Arms (cont’d)

Pattern recognition efficiency

ε relative to initialization:

- ~100s/evt cpu time
- ~92% of all hits correctly assigned
- efficiency governed by initialization
Elastic Arms (cont’d)

- Expect: global algorithm more stable against hit inefficiencies, failed modules etc

**Elastic arms efficiency**

- Potential of robustness & independence of complicated detector structure already visible
- Track following methods are still ahead, but:
- Performance approaches regime of practical useability
Track Fit

- Track fit has to provide the best possible estimate of particle parameters
- should include various kinds of detector information as
  - 1D coordinates (strips, drift distances)
  - 2D coordinates (pads, pixels)
  - cluster information (x,y,E) from ECAL
  - photon radiation ($\delta E$)
- substantial multiple scattering effects (~ 60% of a radiation length)
The Kalman-Filter Method

- Progressive least-squares fitting of parameters of a trajectory
- Iterative cycle prediction/filter

- include stochastic perturbations
  - multiple scattering (Molière theory)
  - energy loss (dE/dx, Bremsstrahlung)
- Kalman-Filter is most effective method of Least Squares Fit in presence of multiple scattering
Prediction

Filtering of k-th point
multiple scattering  prediction

filtering of k-th point
Object-oriented Implementation (C++)

- track consists of “nodes”
- filter formalism in each node depends on type of node

Track

- Node
  - Si hit
- Node
  - plane without hit
- Node
  - MSGC hit
- Node
  - wall
- Node
  - Pad hit
- Node
  - hard radiation
- Node
  - HDC hit
Node Classes

- inherent polymorphism
- implementation using inheritance & virtual functions
- hit type specific parts of filtering in derived classes
- flexible, scalable
Spatial & Angular Resolutions

- μ's traversing SiVD and outer tracker
- resolution at first point

Explained by
- coordinate resolution of SiVD
- multiple scattering
Momentum resolution

- μ’s traversing SiVD and outer tracker

\[ \frac{\Delta p}{p} \]

- Compensation of multiple scattering works
- Track fit reproduces design resolution
Interaction Time Shift

H. Deckers et al.

- HERA bunch length $\rightarrow$
  interaction $t_0 \neq$ time of bunch clock signal

- affects coordinate measurement in drift chambers
- widens residual distributions
- must be compensated in track fit
Interaction Time Shift (cont’d)

- introduce interaction time as additional (global) parameter
- test with 96/97 run geometry (9 HDC layers)

- track fit can “reconstruct” $t_0$ to a certain extent
- residual spread decreases 260µm → 190µm
* for multiple interactions: each interaction has its own $t_0$
Reconstruction in the RICH

- essential for K tagging
- high occupancy (< 10%)
- Principle: use tracking system information → center of ring known
- Standard method: calculate likelihood functions (signal + a linear background) for each hypothesis
- Main problem: ring overlap

RICH event display
Reconstruction in the RICH (cont’d)

M. Staric, P. Krizan

• “Background” is mainly due to other rings
• **Idea:** use iterative procedure to assign hits to rings
• Weight hit with \( w_i = \frac{y_i}{\Sigma y_i} \)
• ~20 iterations

![Graphs showing photon distributions](Image)
RICH reconstruction performance

$\epsilon_K \geq 90\%$ at 5\% misid for $p=10\ldots35$ GeV

- improvement over classical method
Muon Reconstruction

• Combines information from tube, pad and pixel chambers
Muon reconstruction (cont’d)

- Normally, track candidate from main tracker will be used as starting point
- for special studies (commissioning, partial detector setups) a standalone reconstruction method is needed
- use seed from pads/wires/pixels in superlayers 3 and 4 as starting point (no absorber in between)
- Kalman filter propagation into superlayers 1 and 2
- transport through first absorber shield
Performance of muon reconstruction

- reasonable performance even in standalone mode for moderate number of interactions
- efficiency limitation due to unknown momentum

> use of main tracker segments will improve further both efficiency and fake rate
CP Reach

<table>
<thead>
<tr>
<th>BABAR</th>
<th>HERA-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>P for $J/\psi K_S (\pi^+\pi^-)$</td>
<td>0.31</td>
</tr>
<tr>
<td>$J/\psi K_S$ events</td>
<td>1100</td>
</tr>
<tr>
<td>$\Delta \sin 2\beta$</td>
<td>$\pm 0.098$</td>
</tr>
<tr>
<td>All channels combined</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sin 2\beta$</td>
<td>$\pm 0.059$</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ events</td>
<td>400</td>
</tr>
<tr>
<td>$\Delta \sin 2\alpha$</td>
<td>$\pm 0.20$</td>
</tr>
<tr>
<td>$(1+B/S)$</td>
<td></td>
</tr>
<tr>
<td>$\rho\pi$ events</td>
<td>400</td>
</tr>
<tr>
<td>$\Delta \sin 2\alpha$</td>
<td>$\pm 0.11$</td>
</tr>
<tr>
<td>All channels combined</td>
<td></td>
</tr>
<tr>
<td>$\Delta \sin 2\alpha$</td>
<td>$\pm 0.085$</td>
</tr>
</tbody>
</table>

- attractive precision on $\sin 2\beta$ after 1 year of data taking
Summary

- HERA-B events hold many interesting challenges for reconstruction
- Suitable concepts have been/are being developed
- Performance in accord with design expectations
- Methods developed for HERA-B appear applicable in LHC environment (LHC-B)