3D-Triplet Tracking for LHC and Future High Rate Experiments

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Overview

• 3D-tracking and multiple scattering
• Motivation for triplet layer designs
• General design studies:
  ➔ track resolution
  ➔ track linking
• Triplets and track triggers
• Conclusions
Motivation for 3D Triplet Tracking

- High-Lumi-LHC (>2025) or Future Circular Hadron Colliders (>2035-2040):
  - ~ 150 Pileup Events (L=5 \cdot 10^{34}) → \( O(3000) \) tracks @25ns

- **Physics benefit** depends crucially on the performance of detectors
  - high precision (offline)
  - fast selectivity (online filtering / trigger)

- The **combinatorial problem** is main problem for fast track reconstruction
  → can be tackled by:
  - fast algorithms
  - optimised tracker designs

- Opportunities with new detector technologies (CMOS sensors)
  - build a **full pixel tracker**?
  - potential and possibilities exploiting **3D tracking**?
Three Dimensional (3D) Tracking

Free particle in homogenous solenoidal magnetic field

- Helix described by 6 parameters +1 (end point)
- Need to know **three** 3D space points to provide enough parameters!

For symmetry reasons “2.5D tracking” is sufficient:

- \( R_{3D} \sin \Theta = R \)
- \( \tan \Phi_0 = \left. \frac{dy}{dx} \right|_0 \)
- \( \tan \Theta = \frac{s}{z} \)

**Problem**: Position measurement interferes with particle trajectory (multiple scattering)
Three Dimensional (3D) Tracking

Multiple Scattering:

- Two helix segments described by 10 parameters (assuming energy conservation)
- But three 3D space points provide only 9 parameters!

3D view:

Need external constraints → scattering theory!

Fitting is required!
Three Dimensional (3D) Tracking

- Hit uncertainties (@high momentum)
- Multiple scattering uncertainties (@low momentum)

Standard implementations for track fitting:
- Kalman-Filter
- 3D Broken Line Fit

→ both time consuming (matrix inversion, iterative, complex, ...)

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Modern solid state tracking detectors allow for (almost) infinite precision → small pixel size

- hit resolution becomes negligible at low momentum where most particles are!

Fast and precise reconstruction of low momentum tracks is important for good detector performance:
- pile up
- track isolation
- particle flow concept → improves jets, MET, ...

→ neglect hit uncertainties and consider multiple scattering only (for the moment)
Simple Multiple Scattering Fit

→ neglect hit uncertainties

Track fit model:

\[ \chi^2(R_{3D}) = \frac{\Theta_{MS}(R_{3D})^2}{\sigma^2_\theta} + \frac{\Phi_{MS}(R_{3D})^2}{\sigma^2_\phi} \]

→ \( \chi^2 \) minimisation

Calculation:

\[ R_{3D} = -\frac{\kappa \tilde{\Phi}_C + \beta \tilde{\Theta}_C}{\kappa^2 + \beta^2} \]

FAST!

used in Mu3e experiment (filter farm)

→ presentation by Alex Kozlinskiy
Feature of 3D Triplet-Fit

Track Resolution from multiple scattering

only slightly improved performance at low polar angles
Tracking with Triplets

Idea:

Possible advantages:
- standalone tracking in triplet layers possible
- no beamline constraint needed (helps to suppress BG)
- little combinatorics
- one triplet layer might be sufficient for triggering?

How does it compare with other (more standard) design options in terms of
- track resolution?
- high momentum behaviour?

→ study and compare different geometries
Optimal Geometry

Basics:

\[ \sigma(p) = \frac{2b}{B L} \] independent of position of scattering layer!

\[ \frac{\sigma(p)}{p} = \sqrt{2} \frac{b}{B L} \] two independent measurements

Optimal geometry:

However, such a geometry cannot be used for high track multiplicity environments!
Tracker Geometry & Resolution

multiple scattering only:

\[ \frac{\sigma(p)}{p} = w_{\text{geom}} \frac{2b}{B \cdot L} \]

\( b \) = scattering parameter (layer material)

\( w_{\text{geom}} = 0.96 \)

\( w_{\text{geom}} = 0.71 \)

\( w_{\text{geom}} = 1.38 \)

\( w_{\text{geom}} = 0.99 \)

\( w_{\text{geom}} = 1.51 \)

\( w_{\text{geom}} = 1.25 \)

(assuming infinitesimal small distances in pairs and triplets)
Basic simulation parameters:

- All pixel (perfect hit information)
- Instrumentation: $R = 20 - 100$ cm
- Distance between stacked layers $\Delta = 10$ mm
- Magnetic field: $B = 2T$
- Layer thickness: $X = 0.01X_0$
- Energy loss: 0
- Only barrel type of detector with cylindrical symmetry

Multiple scattering simulated using Highland formula (PDG)
Results for Multiple Scattering (Only)

Z0 (at beamline)

uncertainty mostly determined by scattering at innerst layer

Distance of Closest Approach to beamline

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Results for Multiple Scattering (Only)

Polar angle at beamline

Azimuthal angle at beamline

geometries with large bending distances improve measurement precision for $\Phi$

best

worst
Comparison: MS with Helix Fit

Azimuthal angle at beamline

![Graph showing comparison between MS and Helix Fit](image)
Comparison: MS with Helix Fit

Azimuthal angle at beamline

In general:
MS-fit about 2 times better than helix fix!

- small differences for regular designs
- large differences for irregular designs

→ Triplet geometry with MS-fit provides best resolution
Relative Momentum Resolution

multiple scattering only

\[ \text{constant up to very high } p_T \]
Relative Momentum Resolution

multiple scattering only

finite pixel size*: 40 μm x 40 μm

- constant up to very high $p_T$
- finite pixel size destroys good momentum resolution at high $p_T$ (as expected)
- regular geometry more robust

* 40x40 μm² motivated by Mu3e (80x80 μm²)
Momentum Resolution with Pixel Errors
Momentum Resolution with Pixel Errors

- Loss of resolution recovered with “right” fitting model
- Triplet designs beneficial at small $p_T$ (as expected)
- No “recovery” possible for “triplet 6” design
Summary of Resolution Studies

Triplet 9

Vector 10

Equi 9

Triplet 6

Vector 6

Equi 6
Track Reconstruction +Linking

... and the combinatorial problem
Extrapolation of Track Uncertainties

Track uncertainties determine the combinatorial problem in track linking!

Extrapolation uncertainty for triplets: $\Delta = 10$ mm

![Graph showing extrapolation uncertainty for different parameters](image)

Remark:
- reduced uncertainty if momentum known!

uncertainty $\sim 25$ mm at $d=40$ cm
Extrapolation of Track Uncertainties

Track uncertainties determine the combinatorial problem in track linking!

Extrapolation uncertainty for triplets: $\Delta = 10$ mm

- A) hit errors
- B) scattering errors

Uncertainty $\sim 600 \, \mu m$ at $d=40$cm
Extrapolation of Track Uncertainties

Track uncertainties determine the combinatorial problem in track linking!

Extrapolation uncertainty for triplets: \( \Delta = 10 \text{ mm} \)

- A) hit errors
- B) scattering errors

very precise in longitudinal direction!

\( \rightarrow \) fine z-segmentation
\( \rightarrow \) pixel detectors

\[ \Phi \]

\[ z/\theta \]

\[ \sigma_{\text{hit}} = 12 \mu m \quad (a_{\text{pixel}} = 40 \mu m) \]

\[ \sigma_{\text{scatt}} = 1 \text{ mrad} \]

overlay: x-y plane & s-z plane

position uncertainty envelop
General Design Linking Study

Methodology

- Generation of minimum bias events
- Track multiplicity 250 - 64000 per event for $|\eta|<1.5$
- Simulation: scattering and hit errors
- Single hit efficiency 100%
- Hits required in all planes
- Linking based on track fit (chi2-cut based on MS&hit error) → 99.5% track finding efficiency

Linking speed depends also on linking strategy

- **strategy A: inside out**
- strategy B: vector tracking (first form pairs)
- strategy C: triplet tracking (first form triplets)

Figures of merit:

- number of triplet fits → *speed performance*
- hit ambiguities (fake track) rate → *physics performance*
Track Linking Results

number of (triplet) fits for linking

ambiguous tracks (fake candidates)

Best performance achieved for:
- triplet 9 \(\rightarrow\) smallest number of fits
- vector 6,10 \(\rightarrow\) least ambiguities
Summary of Linking Studies

Triplet 9

Vector 10

Equi 9

Triplet 6

Vector 6

Equi 6
Triplets for Track Triggers

- Independent track reconstruction (local) in triplets
- Goal: reject low momentum tracks

Performance of inner triplet (3A)
\[ \sigma(DCA) = 5-8 \text{ mm (w/o additional constraints)} \]
\[ \sigma(Z0) = 5-15 \text{ mm (w/o additional constraints)} \]
\[ \sigma(p)/p = 4\% \text{ @ } p_T=2 \text{ GeV} \]

Conclusion:
triplets are very robust against BG from
• low momentum tracks
  → secondary (tertiary) interactions

Note: precision could be further improved by increasing the layer stacking

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HV-MAPS Triplets & Online Reconstruction

- stitched CMOS chips
- module width 4cm
- 5% readout strip at both sides
- power and control via flex prints
- wire bonding between sensors and to flex prints
- readout chain
- push hit address and timestamp

MU3e HV-CMOS developments

- 50µm glass on 25µm kapton

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2x2 cm² CMOS sensors
wire bonds

MU3e HV-CMOS developments

50 µm glass on 25 µm kapton

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HV-MAPS Triplets & Online Reconstruction

Rate Estimates for HL-LHC $|\eta|<3$

<table>
<thead>
<tr>
<th>triplet radius</th>
<th>#ladders</th>
<th>data rate/module (Gbit/s)</th>
<th>#hits per halfladder</th>
<th>#GPUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 cm</td>
<td>36</td>
<td>120</td>
<td>1.2 \cdot 10^9/s</td>
<td>72</td>
</tr>
<tr>
<td>60 cm</td>
<td>100</td>
<td>40</td>
<td>0.4 \cdot 10^9/s</td>
<td>200</td>
</tr>
<tr>
<td>100 cm</td>
<td>164</td>
<td>24</td>
<td>0.24 \cdot 10^9/s</td>
<td>328</td>
</tr>
</tbody>
</table>

GPU solution - processing all hits for every event - technically feasible
Conclusions

- Pixel tracker with triplet layer geometry proposed for tracking in hadron colliders (LHC, …) with highest multiplicities
- Triplet of pixels provide full track information, beneficial for fast and robust track reconstruction (trigger)
- Resolution for low momentum tracks can be even improved with the three triplet design

Results obtained so far are promising and motivate more detailed studies…