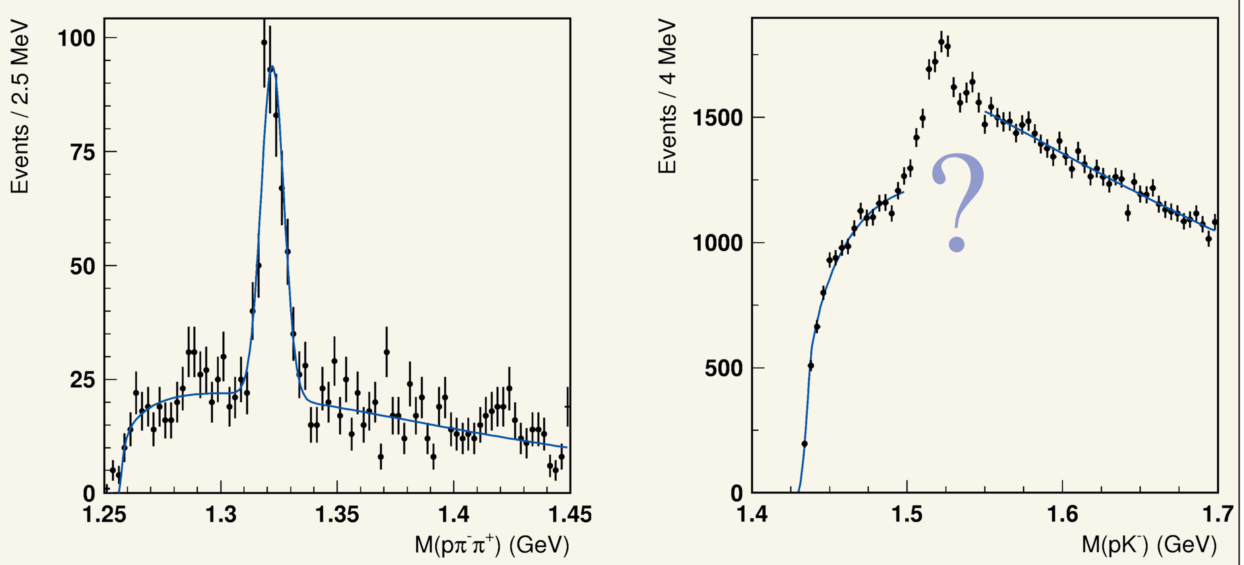
Experimental Techniques in Hadron Spectroscopy

Wouter Deconinck
University of Michigan

Introduction

In hadron spectroscopy the **distribution of the invariant mass M** is commonly used to determine the energy and width of hadronic resonances. For events that satisfy the selection criteria defined by the physical process under study (*e.g.* particle identification, vertex separation) the invariant mass of the resonant state is calculated from the four-momenta and the rest masses of the detected decay products.

In the figures below the distributions for the hyperon decays $\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ (left panel) and $\Lambda(1520) \to pK^-$ (right panel) are shown using events collected at the HERMES experiment [1] on the HERA electron collider at DESY, Germany.

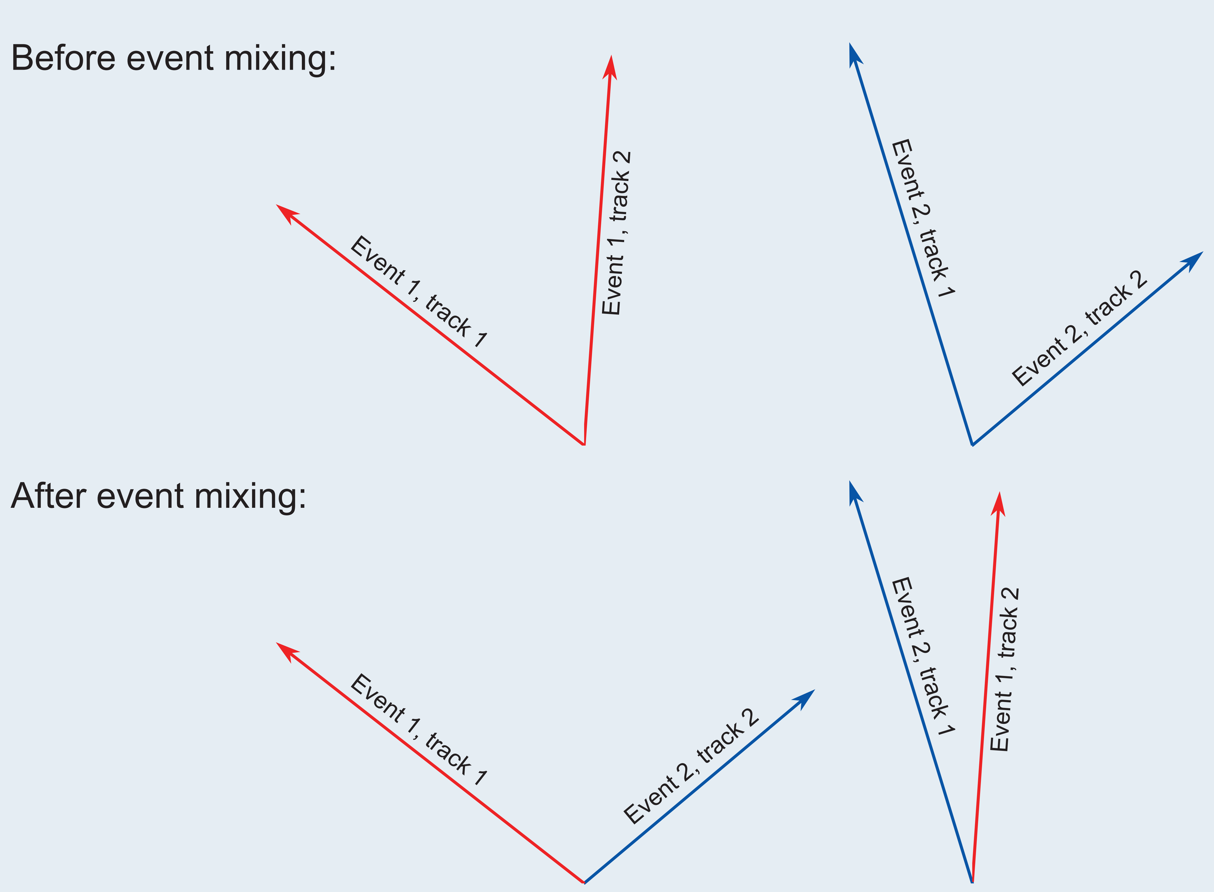


An accurate description of the **invariant mass distribution of background events** is important for the determination of the resonance position and width, and for the calculation of cross sections. Monte Carlo simulations are not always available and sometimes unable to describe the background distributions, in particular when poorly known resonances or non-trivial detector acceptance effects are involved. The shape of the background distribution is therefore commonly obtained by **fitting a smooth function** to the invariant mass distribution in a region where there are no resonances. This function is then extrapolated to the resonance region and a Gaussian or Lorentzian function is added to describe the resonance, as illustrated above left for the Ξ^- hyperon.

However, in the case of the $\Lambda(1520)$ hyperon above right the background shape seems **different on either side of the resonance** and no Monte Carlo simulation is available. A different approach to determining the background distribution is needed.

Event Mixing

An entirely different approach to determining the background distribution is the method of event mixing [2,3]. When the detected **tracks from different events are combined** as if they were from the same event, resonances and more generally all statistical correlations will be removed from the final mixed event distribution. In the figure below this is illustrated schematically for two events.

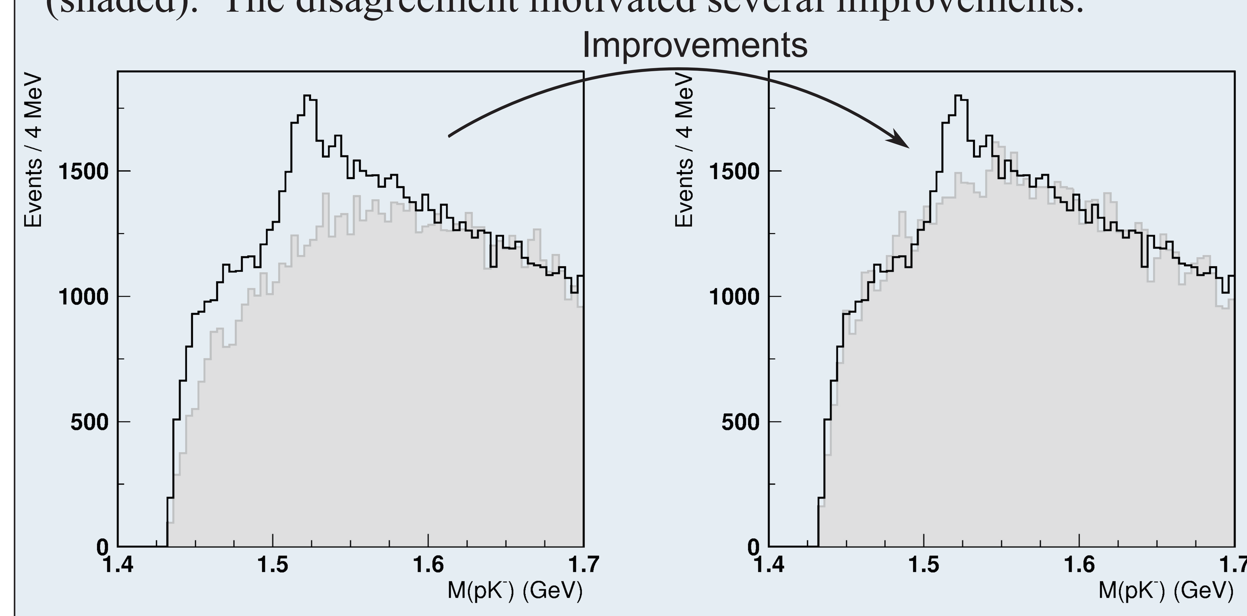


Advantages of Event Mixing

The **large number of possible combinations** grows as n^2, where n is the number of events. Even for a small number of detected events the background shape can be determined with an almost arbitrarily **high statistical precision** (at the expense of computing time).

Imperfections of Event Mixing

When the event mixing method is applied to the $\Lambda(1520)$ hyperon, the shaded distributions in the figures below are obtained. In the left panel the event mixing method is applied in its most simple form (shaded). The disagreement motivated several improvements.



After implementing the improvements to the event mixing method the background description in the right panel improves dramatically. The improvements are discussed in the following boxes.

Event Selection Criteria

- **Single-track selection criteria**, such as particle identification or momentum selection.
- **Multiple-track selection criteria** that combine the information of several tracks, such as vertex positions or the distance between two tracks,…

All track correlations are removed when information from different events is combined. The mixed events will therefore only satisfy the **multiple-track selection criteria** applied **after the event mixing**.

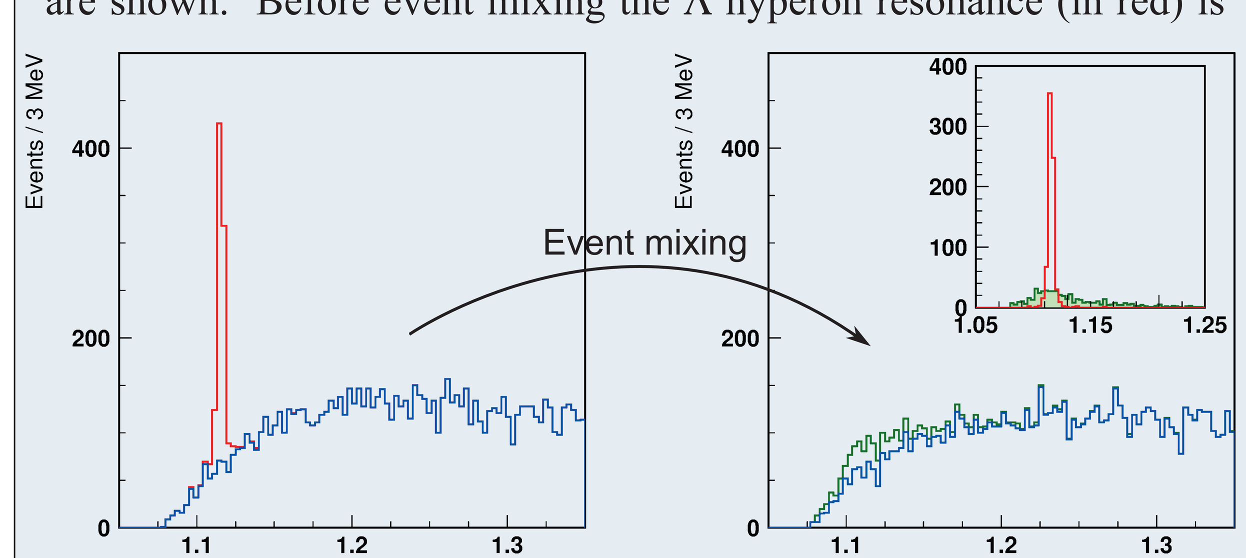
Recipe for Event Selection

- Select all event which satisfy the single-track selection criteria.
- Perform the event mixing.
- Select all event which satisfy the multiple-track selection criteria.

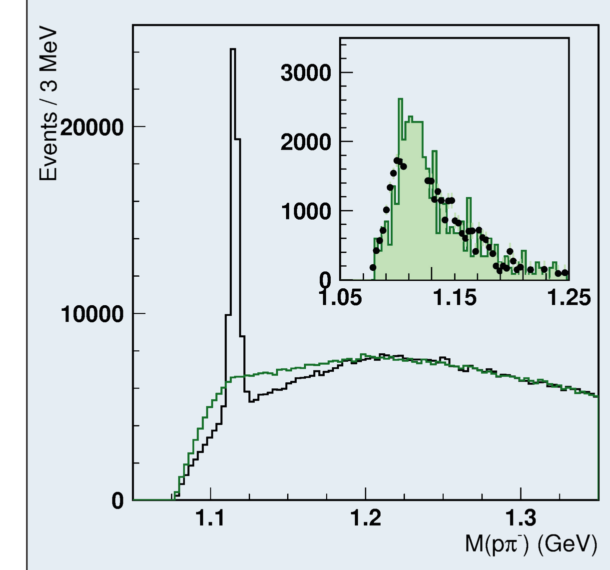
Mixed Resonance Events

The mixed event method is based on the assumption that the background distribution is identical before and after event mixing. However, when **resonance events are mixed** with each other they do not reproduce the background distribution but rather a different mixed resonance distribution.

The effect of the mixed resonance distribution can be demonstrated using PYTHIA Monte Carlo simulations. In the figures below the simulated invariant mass distributions for the hyperon decay $\Lambda \to p\pi^-$ are shown. Before event mixing the Λ hyperon resonance (in red) is

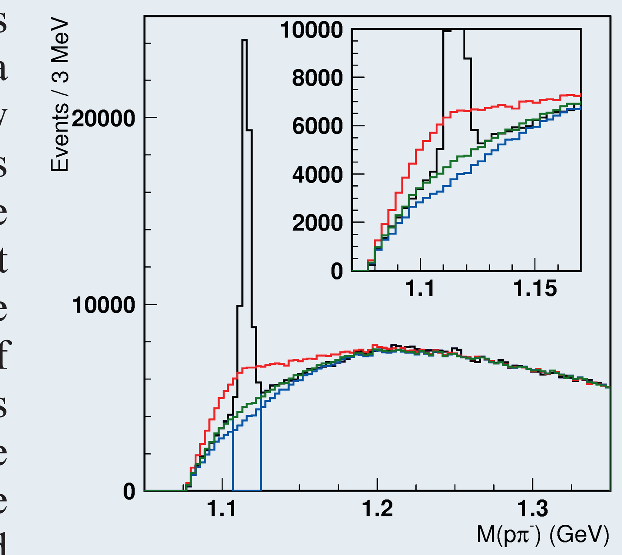


clearly visible above an uncorrelated background of $p\pi^-$ pairs created in separate physical processes. After event mixing the shape of this background distribution is unchanged, but the mixed resonance events (in green) are smeared out with a different shape than the background distribution. In the insert the original resonance shape and the mixed resonance distribution are compared.



In the figure on the left actual events collected at the HERMES experiment are shown before (in black) and after event mixing (in green). The mixed event distribution **overestimates** the background shape consistent with the contribution from the mixed resonance events. This is demonstrated in the insert where the difference (black points) is compared with the mixed resonance distribution from the Monte Carlo simulation (in green).

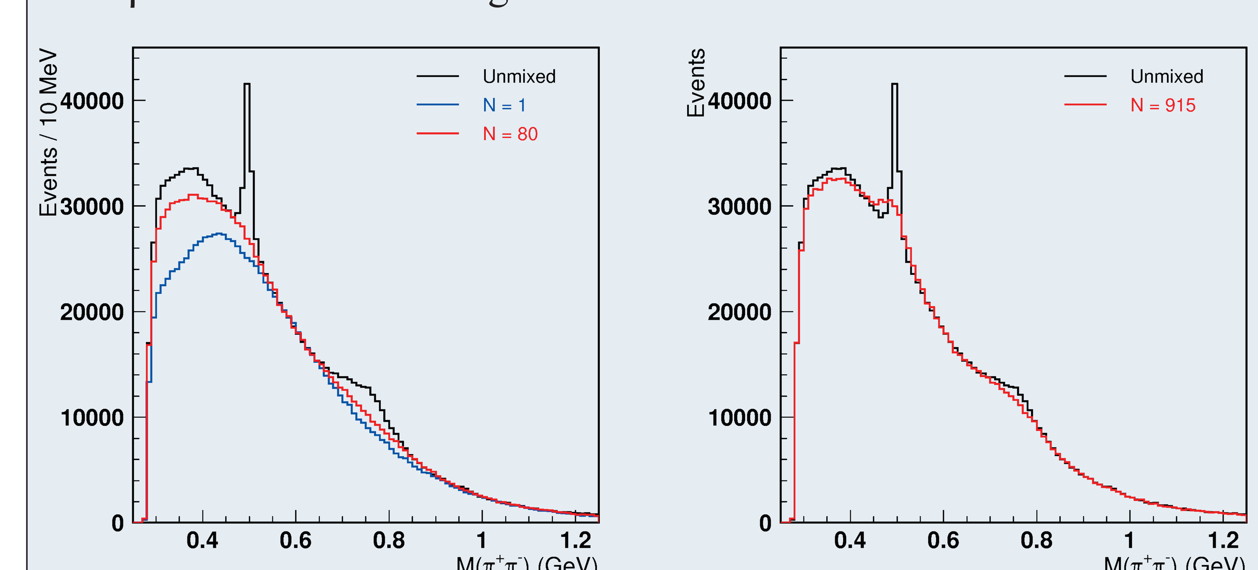
When Monte Carlo simulations are not available, events in a **narrow invariant mass window** can be **excluded**. This is demonstrated in the figure on the right. The mixed event distribution will underestimate the background. The fraction of background and resonance events is determined iteratively from the combination (green) of the underestimated (blue) and overestimated (red) backgrounds.



Momentum Mismatch

When events are mixed, the four-momentum vector of the replaced track is generally different from the original values. Uncommon or even **unphysical combinations** of the four-momentum vectors are disproportionally populated during the event mixing. This momentum mismatch distorts the mixed event invariant mass distribution. Tracks with similar four-momentum can be selected using a **buffer** with a sufficiently large size.

In the figures below the invariant mass distributions of the meson decay $K^0_S \to \pi^+\pi^-$ are shown for different values of the buffer size. In the left panel the improvement when increasing the buffer size to 80 events is visible. The remaining disagreement is due to the η, K^0_S and ρ resonances and in agreement with simulations.



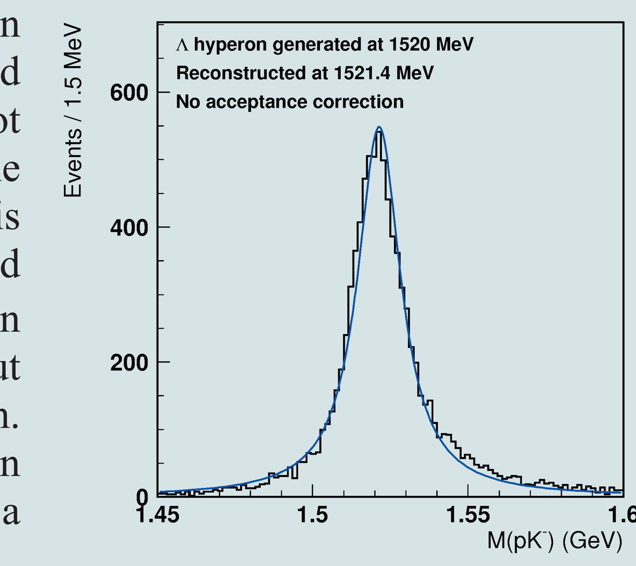
When the buffer size is chosen very large, for every four-momentum vector there can be found an almost identical candidate. The **mixed event distribution will then reproduce the resonances**, as illustrated in the right panel.

In practice the buffer size should be chosen small enough to generate differences between the original resonance and the mixed resonance distribution. With Monte Carlo simulations or invariant mass windows the mixed resonance contributions can then be removed.

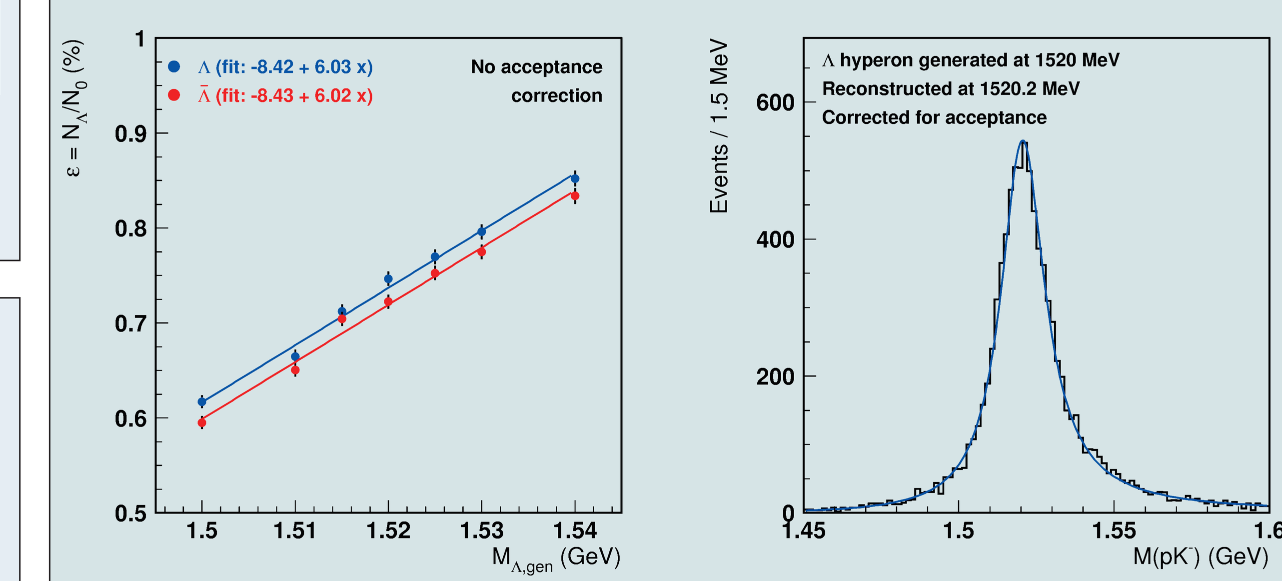
Effects of Acceptance on the Resonance Shape

The intrinsic Lorentzian resonance shape is often obscured by the effect of the **non-zero detector resolution**. This random smearing of the invariant mass can be modeled with a Gaussian function. When the resonance width and the detector resolution are comparable in size a good description of the observed resonance shape is only possible with the convolution of both functions.

Even when the detector resolution is taken into account the observed resonance shape is sometimes not sufficiently reproduced. In the figure on the right this is demonstrated for simulated decays of the $\Lambda(1520)$ hyperon without background events but with a full detector simulation. The convolution of a Lorentzian and Gaussian function results in a **misreconstruction of 1.4 MeV**.



Due to the large width of the $\Lambda(1520)$ hyperon there is a substantial change in the detector acceptance for decay events, illustrated in the figure below left. An additional convolution of the resonance shape has to be performed to take this effect into account. In the figure below right the invariant mass distribution for simulated $\Lambda(1520)$ hyperon decays is shown. It is well described when the variation of the acceptance is taken into account and the generated resonance position is correctly reconstructed.



Summary

The widely-used experimental technique of determining resonance parameters from invariant mass distributions by fitting a smooth background function and Gaussian peak has to be refined. The method of event mixing can be improved to obtain better approximations. Acceptance effects can still influence the shape of the observed resonance and should be taken into account.

Acknowledgements

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References

[1] K. Ackerstaff et al., Nucl. Instrum. Meth. A417, 230 (1998).

[2] H. G. F. D. Drijard and T. Nakada, Nucl. Instrum. Meth. A225, 367 (1984).

[3] T. Nakada, (1983), CERN-EP-IR/83-10.

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