The PAX Toolkit and its Applications at Tevatron and LHC

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Abstract—At the CHEP03 conference we launched the Physics Analysis eXpert (PAX), a C++ toolkit released for the use in advanced high energy physics (HEP) analyses. This toolkit allows to define a level of abstraction beyond detector reconstruction by providing a general, persistent container model for HEP events. Physics objects such as particles, vertices and collisions can easily be stored, accessed and manipulated. Bookkeeping of relations between these objects (like decay trees, vertex and collision separation, etc.) including deep copies is fully provided by the relation management. Event container and associated objects represent a uniform interface for algorithms and facilitate the parallel development and evaluation of different physics interpretations of individual events. So-called analysis factories, which actively identify and distinguish different physics processes and study systematic uncertainties, can easily be realized with the PAX toolkit.

PAX is officially released to experiments at Tevatron and LHC. Being explored by a growing user community, it is applied in a number of complex physics analyses, two of which are presented here. We report the successful application in studies of $t\bar{t}$ production at the Tevatron and Higgs searches in the channel $t\bar{t}W$ at the LHC and give a short outlook on further developments.

Index Terms—particle physics analysis, reconstruction of complex events, event container model, C++ toolkit;

I. INTRODUCTION

PHYSICS analyses at modern collider experiments enter a new dimension of event complexity. At the LHC, for instance, physics events will consist of the final state products of the $O(20)$ collisions taking place during each readout cycle. In addition, a number of physics questions is studied in channels with complex event topologies and configuration ambiguities occurring during event analysis.

One item in the long list of examples is a channel of $t\bar{t}$-quark associated Higgs production, $t\bar{t}H$ with $H\to b\bar{b}$ (see Fig. 1a). The event topology of four $b$-jets, two light-quark-jets, an isolated muon, missing energy and possible additional jets from initial state radiation (ISR) and final state radiation (FSR) imposes highest demands on detectors and reconstruction algorithms. In addition, non-trivial ambiguities must be resolved during event analysis. Even if all final state products could be reconstructed perfectly (as illustrated in Fig. 1b) and no ISR or FSR effects occurred, at least 24 different configurations would be possible. Finite jet resolutions, limited efficiency and purity of the $b$-tagging as well as the presence of additional jets complicate ambiguity resolution and signal identification.

This task can be approached with a likelihood method based on characteristic event variables, where each possible event configuration is developed individually and rated with the likelihood function; the most probable of all interpretations finally is selected.

Such an approach can be implemented by object-oriented coding and suggests the use of a class collection, that provides event containers for the reconstructed objects (muons, jets, missing energy, vertices, collisions, etc.) and handles relations between the individual objects (as, for instance, vertex relations for particle decays). Due to the large number of ambiguities occurring during the reconstruction of $t\bar{t}H$ events, these classes are required to offer automated copy functionality for containers, objects and corresponding relations.

The application of a generalized event container comes with a number of desirable side-effects. If used to define an abstraction interface between the output of event generator, simulation or reconstruction software and the physics analysis code, the latter is protected from changes in the underlying software packages to a large extent. This reduces code maintenance and increases code lucidity. In addition, unnecessary duplication
of the analysis code can be avoided: so can the influence of
detector effects (studied by direct comparison of the results on
generator, simulation and on real data level) be investigated ad
hoc, i.e. with the same analysis source code.

Analysis factories, in which a number of analyses are ex-
ecuted at the same runtime, identifying and distinguishing
different physics processes or studying systematic uncertainties,
can easily be realized when using common physics objects and
a common event container model in each of the analyses.

Analysis environments based on a well-defined, generalized
event container also provide a basis for efficient team work.
Collaboration in (and supervision of) groups of students is facili-
tated, and knowledge transfer between subsequent generations
of analysts as well as between different experiments is fostered.

In this article, we present the Physics Analysis eXpert (PAX),
a C++ toolkit for particle physics analysis that provides such a
generalized event container together with various built-on functionalities.

II. The PAX class structure

The PAX kernel, introduced in the year 2002 [1] and released
at the CHEP03 conference in 2003 [2], is currently available
as 2.00 version. For the convenience of connecting to existing
software packages, PAX is realized in the C++ programming
language [3]. It provides additional functionality in top of the
vector algebra of the widely-spread libraries CLHEP [4] or
ROOT [5].\(^1\) The PAX container model as well as file I/O are
based on the C++ Standard Template Library (STL) [3].

The PAX toolkit provides three types of generalized physics
objects:

- particles (or reconstructed objects), i.e. Lorentz-vectors,
  represented by the class PaxLorentzVector,
- vertices, i.e. three-vectors, represented by the class PaxVer-
tex,
- and collisions, represented by the class PaxCollision.

These objects are able to establish relations, and can be
stored and managed in event containers, represented by the
PaxEventInterpret class.

A. Physics objects

The PaxFourVector class (see Fig. 2) represents particles or
reconstructed objects (such as muons, electrons, missing en-
ergy, jets etc.). It inherits its basic Lorentz-vector characteristics
from the well-known libraries CLHEP or ROOT. Commonly
needed, additional properties such as particle-id, status, charge
etc. can be stored in data members. Specific information (such
as b-tags, jet cone sizes or energy corrections, for instance)
can be stored in the so-called user records. User records
are collections of string-double pairs, meant to hold object
information complementary to data members.

\(^1\)At compile-time, the user can choose between the vector algebra packages
of CLHEP [4] (default) or ROOT [5]. Depending on a compiler switch, the
two type definitions PaxLorentzVector and PaxThreeVector are set to Hep-
LorentzVector and Hep3Vector of CLHEP or to TLorentzVector and TVector3
of ROOT.

All PAX physics objects own user records (instances of the
class PaxUserRecord) and provide methods for quick access
to individual user record entries. Each instance of a PAX
physics object carries an unique integer key (the so-called
PaxId) and a string name (the so-called PaxName). An integer
workflag facilitates tagging of individual objects. Print methods
are provided to allow monitoring of object state and established
relations on various verbosity levels. Copy constructors are
provided to perform deep copies of PAX physics objects.

The PaxVertex class, sketched in Fig. 3, represents the spatial
point of decays in particle reactions. Thus, in analogy with the
PaxFourVector, it obtains its basic three-vector characteristics
also from the CLHEP or ROOT package.

The PaxCollision class (see Fig. 4) allows the separation of
collisions in multicollision events, as they occur at high-rate
hadron colliders. It provides the relation management necessary
to associate PaxVertex and PaxFourVector objects with different
collisions in the event.

B. Access to primordial C++ classes

Each PAX physics object can record pointers to an arbitrary
number of instances of arbitrary C++ classes. This way, the
user can keep track of the data origin within the detector
reconstruction software, for instance. Access to the pointers

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{The PaxFourVector class extends the basic functionalities of the
PaxLorentzVector in order to represent particles in HEP decays.}
\end{figure}
is possible at the same runtime during any later stage of the analysis. A typical use case is the need to re-fit a track which requires access to the hits in the tracking chamber. The PAX object that represents this track, i.e. a `PaxFourVector` instance, provides the two template methods `addPointer< Type >( name, ID, pointer )` and `findPointer< Type >( name, ID )`. The argument `name` is supposed to correspond to the C++ class name, e.g. `Type`, the argument `ID` is a unique integer identifier for the referenced instance of the C++ class `Type`, and the third argument is a pointer to this instance.

The mechanism behind is sketched in Fig. 5. The class template `PaxExperiment< Type >` provides storage, access, and clone of the pointer of type `Type`. Its base class `PaxExperimentClass` is used as the interface to the PAX classes which are enabled to store and access the pointer through the C++ `dynamic_cast` operator.

When copying a PAX physics object, all pointers are copied as well by making use of the `clone()` method.

### C. Relation management

The principal duty of the PAX relation management is handling of decay trees. The manager is based on the Mediator design pattern, described in detail in reference [6]. In this design all relations are kept locally (i.e. every object knows about all their directly related objects), so that global relation directories can be avoided.

Speaking of PAX physics objects, this means, that each `PaxCollision` object owns relation managers (see Fig.6) that carry pointers to the related `PaxVertex` and `PaxFourVector` objects. At the same time, the `PaxVertex` objects hold pointers to their related `PaxCollisions` as well as to their incoming and outgoing `PaxFourVectors`. By the same token, `PaxFourVectors` know about their related `PaxCollisions` and about their begin and end `PaxVertex` objects. With this functionality, PAX allows to store complete multicollision events from parton to stable particle level, including four-momenta and spatial vertex information.

In addition, the PAX relation management is used to record analysis histories: each object, which is copied via copy constructors, keeps pointers to its original instances. This way the user may always go back and ask for original properties of
objects which might have changed during the development of the analysis.

A powerful feature, implemented by means of the relation management, is the so-called locking mechanism. It is implemented to enable the user to exclude parts of decay trees from the analysis (i.e. excluding a lepton from a jet finding algorithm, etc.). If one particle or vertex is locked, all the objects down the decay tree (and the history) will be locked, too. Locking and unlocking are realized by setting or removing the lock-flag owned by each PAX physics object.

**D. Maps & object containers**

The PAX kernel provides the base classes `PaxMap<key, item>` and `PaxMultiMap<key, item>`, which inherit from the STL classes `map<key, item>` and `multimap<key, item>`, respectively. The explicit inheritance has been chosen to provide the use of existing STL objects and methods with these PAX classes. This way, iterations of PAX maps can be performed by using either the PAX iterator classes (`PaxIterator`, `PaxMapIterator`, `PaxMultiMapIterator`) or the commonly known STL iterators. All PAX classes which serve as containers are based on the class `PaxMap` (see Fig. 7).

**E. Event container**

The `PaxEventInterpret` class, illustrated in Fig. 8, is the generalized event container provided by PAX. By incorporating the previously described functionalities, it is capable of holding the complete information of one multicollision event with decay trees, spatial vertex information, four-momenta as well as additional reconstruction data in the user records. Physics objects (i.e. instances of the classes `PaxFourVector`, `PaxVertex` and `PaxCollision`) can be added or created with the `PaxEventInterpret::add()` and `PaxEventInterpret::create()` methods. Depending on the object type, a pair of `PaxId` and Pointer to the individual object is stored in one of three maps (`PaxFourVectorMap`, `PaxVertexMap` or `PaxCollisionMap`). Access to these maps as well as direct access to the physics objects is guaranteed via methods such as `PaxEventInterpret::getFourVectors()` and `PaxEventInterpret::findFourVector()`. At deletion of a `PaxEventInterpret` instance, all contained physics objects will be deleted, too.

The `PaxEventInterpret` class is so named, because it is intended to represent a distinct interpretation of an event configuration (e.g. connecting particles to the decay tree according to one out of a number of hypotheses, applying different jet energy corrections, etc.). To facilitate the development of numerous parallel or subsequent event interpretations, the `PaxEventInterpret` class features a copy constructor, which provides a deep copy of the event container with all data members, physics objects, and their (redirected) relations.

**F. PAX file I/O**

The PAX toolkit offers a file I/O scheme for persistent storage of the event container, based on STL streams. It allows the user to write the contents of `PaxEventInterpret` instances with all contained physics objects as well as their relations to PAX data files. When restoring the data from file, an empty `PaxEventInterpret` instance is filled with the stored data and objects and all object relations are reproduced.

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2For obvious reasons, pointers recorded with PAX physics objects by means of the `PaxExperimentClass` functionality (as described in section II.B) are not stored to disk.
The PAX data file format provides multi-version and multi-platform compatibility. It is built of a hierarchy of binary data chunks: the top level unit is an event, which consists of an arbitrary number of event interpretations. The event interpretation chunk consists of data members, user records as well as chunks for each of the contained physics objects. Each chunk carries header information (one byte for unit type and four bytes for data amount information) and the actual binary data. This allows file structure checks and fast positioning. Therefore, the user can quickly skip arbitrary numbers of events in PAX data files, without having to sequentially read and discard.

PAX also provides the possibility to write event units to strings (and to restore the PaxEventInterpret instances from those strings). This way, the user can store PAX objects to any data format supporting strings or binary data fields (like databases or experiment specific data formats).

G. Accessories and interfaces

As a complement to the PAX kernel, we released two accessory packages for reading standard event generator file formats. The PaxTuple package provides transfilling of decay trees stored in the HEPEVT or ROOT Ntuple data formats to PaxEventInterpret containers. Accordingly, the PaxHepMC package gives access to HepMC files.

In addition, interfaces developed and posted by PAX users, that fill PAX objects with specific data of HEP experiments, are available via the PAX web page [7].

H. Software development procedure

The PAX kernel and its officially supported accessories are coded and maintained by a core group of currently six developers at CERN and the Aachen and Karlsruhe universities. New developments and code modifications pass a certification procedure and are discussed and adopted in regular video meetings. As a guideline, new developments focus on aspects of performance improvement and on user feedback. New releases are to be backward compatible. Version management of the software project is handled with a web-browsable Version Control System (CVS) [8] [9].

I. Availability, documentation and support

The continuously updated PAX web page [7] provides download of the various versions of PAX kernel and accessories (based on the aforementioned web-browsable CVS repository). It also provides the PAX Users Guide [10], a comprehensive text documentation of the PAX toolkit, as well as class reference and fast navigator pages for download or online use. The web page also offers access to mailing lists, in which PAX users are informed about new developments and in which technical issues of PAX analyses can be discussed.

III. HOW PAX PHYSICS ANALYSES CAN BE STRUCTURED

To exploit the features offered by the PAX toolkit, physics analyses might be realized, for instance, according to the example structure illustrated in Fig. 9.

There, a dedicated, experiment-specific interface class for filling the PAX containers (i.e. PaxEventInterpret instances) represents the interface between detector reconstruction software and PAX-based physics analysis. The PAX persistency scheme is used to store the data to PAX data files for later use.

With an analysis consistently formulated with PAX objects, the filling class can be exchanged easily, and the identical analysis code can be applied, for instance, directly to the output of a Monte Carlo event generator or a fast simulation software, see Fig. 10a. Furthermore, the use of PAX data files, which provide the distilled experimental event information, allows fast analysis of the reconstruction data decoupled from the
IV. IMPLEMENTATION OF PAX INTO EXPERIMENT SPECIFIC SOFTWARE ENVIRONMENTS

PAX has been made available within the software environments of the experiments CDF, D0\(^3\) (both Tevatron) and CMS (LHC).

Following the same principles, the integration of PAX into the latter is described as a general example.

The PAX toolkit is provided by the CMS software environment as an external package [11], enabling the physicists inside the CMS collaboration to use PAX without having to care about installation or setup of the package.

An extensive example analysis for the use of PAX with the detector reconstruction software ORCA [12] is included in the CMS CVS repository [13]. In this example, the (ambiguous) reconstruction of the partonic process of the decay \(W\) is carried out by using reconstructed muons and missing transverse energy. The missing information about the longitudinal component of the neutrino momentum is obtained with a \(W\)-mass constraint, which yields (up to) two analytical solutions, and thus two possible event interpretations. Subsequently, both interpretations are developed in two separate \texttt{PaxEventInterpret} instances, and a number of example histograms is filled.

The class design of this example analysis is based on the structure described in the previous section, including interface classes for filling \texttt{PaxEventInterpret} containers with the reconstructed objects of ORCA.

To facilitate the start-up for new PAX users, a tutorial video for this example plus supplementary material can be found in the CMS section of the PAX web page [14].

V. PAX PHYSICS ANALYSES FOR TEVATRON AND LHC

Provided for the software environments of the CDF, D0 and CMS experiments, PAX is being explored by a growing user community. In the following, two successful applications of PAX in complex physics analyses are presented.

A. A PAX-based \(\tau\tau\) analysis for CDF

In this section, an analysis of top-antitop-quark events (\(\tau\tau\) events) with the CDF experiment at Tevatron is described [15]. As illustrated in Fig. 11, the electron-plus-jet decay channel shows similar combinatorial tasks as the aforementioned \(\tau\tau\) channel.

In this \(\tau\tau\) study, an analysis factory based on the PAX event interpretation concept is used to perform complete reconstruction of the partonic scattering process and to optimize the separation of signal and background processes.

The partonic process of the decay \(\tau \rightarrow W b\) is reconstructed as follows. First, the W-boson decaying into electron and neutrino is reconstructed. From the W-mass constraint two possible solutions can be deduced for the longitudinal neutrino momentum. This results in two event interpretations for the W-boson. Combining each of those with one of the jets leads to the interpretations for the \(\tau\) quark (with different kinematics and reconstructed masses). The remaining part of the process, i.e. \(t \rightarrow W b\), is reconstructed from three of the remaining jets. Consequently, in a four jet \(t\bar{t}\) event, 24 interpretations can be constructed. The most likely \(t\bar{t}\) event interpretation is selected by first demanding non-zero \(b\)-probability for one of the jets of one of the \(\tau\) quark candidates. Finally, one of these solutions is selected by evaluating the most likely event interpretation based on kinematic properties, the reconstructed mass of the W boson decaying to \(\ell\ell\), and the mass difference of the two reconstructed \(\tau\) quarks. The resulting example plots are shown in Fig. 12.

B. A PAX-based \(\tau\tau\) analysis for CMS

The channel of associated Higgs production, \(\tau\tau\) with \(H\) is reconstructed by means of which the requirements to a particle physics analysis toolkit have been motivated in the introduction of this article, is studied in the CMS experiment at the LHC [18] [19], for instance.

The most recent of these studies makes use of the PAX event interpretation concept to develop possible event interpretations in a manner similar to the one described in the previous CDF example. After development of all interpretations, a likelihood function is used to select the most probable one by rating the different configurations on the basis of kinematics variables and masses of the two \(\tau\) quarks and their decay products.

Fig. 13 illustrates the performance of this method in simulations with and without detector effects. Please notice, that Fig. 13a and Fig. 13b have been produced with the identical analysis code, by simply exchanging the interface classes (compare Fig. 9 and Fig. 10). In this way, a good measure for how detector and reconstruction methods influence the results can directly be obtained – with almost no analysis code duplication.

VI. CONCLUSIONS

The PAX toolkit is designed to assist physicists at modern collider experiments in the analysis of complex scattering...
processes. PAX provides a generalized HEP event container with three types of physics objects (particles, vertices and collisions), relation management and file I/O scheme.

The PAX event container is capable of storing the complete information of multicollision events (including decay trees with spatial vertex information, four-momenta as well as additional reconstruction data). An automated copy functionality for the event container allows the user to consistently duplicate event containers with physics objects and relations. The PAX file I/O scheme can be used to write (and read) complete event containers to (from) disk file; this offers an easy realization of distilled experiment data streams. By structuring physics analyses based on PAX objects, the identical source code can be applied to various data levels. This adds a desirable aspect of flexibility to the software-side of particle physics analysis.

PAX is available within the software environments of experiments at Tevatron and LHC, where it is applied in a number of physics analyses. Two thereof are outlined in this article, demonstrating typical use cases and successful applications of the PAX toolkit. Evident advantages arising from the usage of the PAX toolkit are avoidance of code duplication, increased code lucidity, unified data model and nomenclature, and therefore more efficient team work in the complex physics analyses at modern HEP experiments.

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Verification of the $t$-$\bar{t}$ quark reconstruction in generated $t$-$\bar{t}$ events. The full histograms show reconstructed properties of the event interpretation which reproduces the partonic $t$-$\bar{t}$ state best. Further information results from the selection procedure using reconstructed quantities of the event only: the symbols represent the selected event interpretation, the dashed histogram summarizes the other possible interpretations. a) Reconstructed mass of the $t$-quark with a subsequent leptonic $W$-decay. b) Angular distribution of the $W$-boson in the rest frame of the $t$-quark. c) Angular distribution of the charged lepton in the rest frame of the $W$-boson. (For this study, the HERWIG Monte Carlo generator [16] and CDF detector simulation [17] have been used.)

Fig. 13
Reconstructed Higgs mass in the channel $t\bar{t} + H → Hb\bar{b}$ on generator (a) and full simulation level (b). The gray shaded area corresponds to the combinatorial background, i.e. to those events, in which a wrong $H → Hb\bar{b}$ configuration was selected. (For this study, the PYTHIA Monte Carlo generator [20] and CMS detector simulation [21] have been used.)