

The Vertexing package and its application in the τ -tagging

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Abstract

A package for the vertex reconstruction (*Vertexing*) has been developed in the ATLAS offline software. It consists of an Object Oriented interface to an existing fitting routine and of a set of test algorithms. The code is described in the first part of this note. In the second part, the *Vertexing* algorithms are applied to the identification of the hadronic τ decays. A 44.1% efficiency has been achieved in $A \rightarrow \tau\tau \rightarrow \text{hadrons}$ ($m_A = 800$ GeV/ c^2) events. The jet-rejection has also been estimated in QCD events with high- p_T jets.

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1 The Vertexing package

1.1 Introduction

The Vertexing is a set of packages which performs the reconstruction of primary and secondary vertices. It is part of the ATLAS software official release since that tagged 2.4.0, and it has been implemented as a sub-package of the Reconstruction container package. The algorithms have been created to work properly in the Athena [1] framework.

The vertex fit is performed by an external Fortran routine which has been wrapped into an Object Oriented C++ interface.

The Vertexing internal structure is the following:

- VertexFit: the mere interface;
- SimpleVertex: the object containing the vertex information;
- VertexPrimary: the primary vertex fitting algorithm;
- VertexExampleSecSeed: an example about how to reconstruct secondary vertices, starting from a seed;
- VertexExampleSecUserTracks: an example about how to reconstruct secondary vertices, using a user-defined track list;
- VeretxExampleScheme: a dummy example which summarizes the example code structure.

1.2 The fitting routine

The main fitting routine was written for the CDF experiment Run I and its I/O was later adapted to the ATLAS standards [2]. By default it performs geometrical vertex fits, but kinematical and mass constraints can also be imposed to perform constrained fits.

The fit is based on on χ^2 minimization method. The minimization starts from the point which is the intersection of the first two tracks to fit. Its position is found projecting the two helices onto the r, ϕ plane: if the resulting circles intersect, the point with the smaller z difference between the two helices (extrapolated to the intersection point) is chosen (see fig. 1); if they do not intersect, the vertex approximation is taken as the point of closest approach of the two circles.

The routine finds an initial approximation to the track parameters and adjust them in order to minimize the χ^2 . The minimization proceeds by expanding the equations in a Taylor series around the last approximation, keeping only the linear terms and solving the resulting linear equations. The expansion and solution are

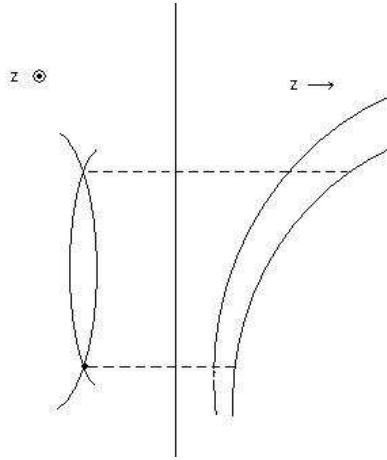


Figure 1: *First vertexing approximation from two tracks.*

iterated several times. The iteration is repeated until the linear terms become negligible small [3].

1.3 The interface

The interface is aimed to allow C++ algorithms to communicate with the fitting routine. Since the fit I/O is managed by mean of Fortran common blocks, C structures and access methods have been provided.

The interface sets the fit options and store in the C structures the track parameters extracted by a standard SimpleTrackCollection object[4]. The fitted vertex and the recalculated tracks are respectively stored in a SimpleVertex object and in a new SimpleTrackCollection.

The possibility of evaluating the single track contribution to the vertex χ^2 is provided as well. The track with the highest χ^2 can be spotted, marked and, if the case, excluded from the new list of tracks to be fitted. This procedure can be iterated until at least one track exceeds a previously set χ^2 limit. If less than two tracks are left, the fit is aborted.

The interface can operate in three different modes:

- **mode 1:** only the primary vertex is fitted. All the reconstructed tracks which satisfy a few basic quality cuts are passed to the vertexing; the χ^2 control provides a further selection to eliminate tracks emerging from secondary vertices.
- **mode 2:** only the secondary vertices are fitted; the primary vertex position and error matrix are hardwired.

- **mode 3**: both primary and secondary vertices are reconstructed.

The overall vertexing procedure is shown in fig. 2.

1.4 The algorithms

Three algorithms, to be run in the Athena framework, have been included in Vertexing: VertexPrimary, VertexExampleSecSeed, and VertexExampleSecUserTracks.

In VertexPrimary all the reconstructed tracks which satisfy a few quality cuts are used to fit the primary vertex. By default the iteration to delete the track with the highest χ^2 is also enabled.

A sample of about 800 events with a 100 GeV/c² SM Higgs decaying into $b\bar{b}$ has been used to test the algorithm. The resolution is improved using the loop, since, at the end of the iteration, most of the tracks emerging from the B secondary vertices have been dropped.

The resulting RMS's are summarized in table 1.

RMS's (μm)			
	x	y	z
Loop enabled	24	24	48
Loop disabled	37	38	61

Table 1: *Primary vertex resolutions ($H \rightarrow b\bar{b}$ events).*

The *VertexExampleSecSeed* algorithm has been used to test the interface technicalities when reconstructing secondary vertices and has been roughly tuned to search for B decay vertices. A b quark is looked for in the Pythia simulated data (GENZ) and its direction is used as a seed. The resolution is shown in table 2. A rough estimation of the B mean free path has been performed (see fig. 3). The fitted value of $\gamma c\tau$ is (3.3 ± 0.3) mm (the error is underestimated since the vertexing resolution is not included), to be compared with the expectation for a B mixture: $\gamma c\tau \simeq 4.3$ mm (an average transverse B momentum of 50 GeV/c has been considered).

RMS (cm)		
x	y	z
0.32	0.41	0.56

Table 2: *B vertex resolution.*

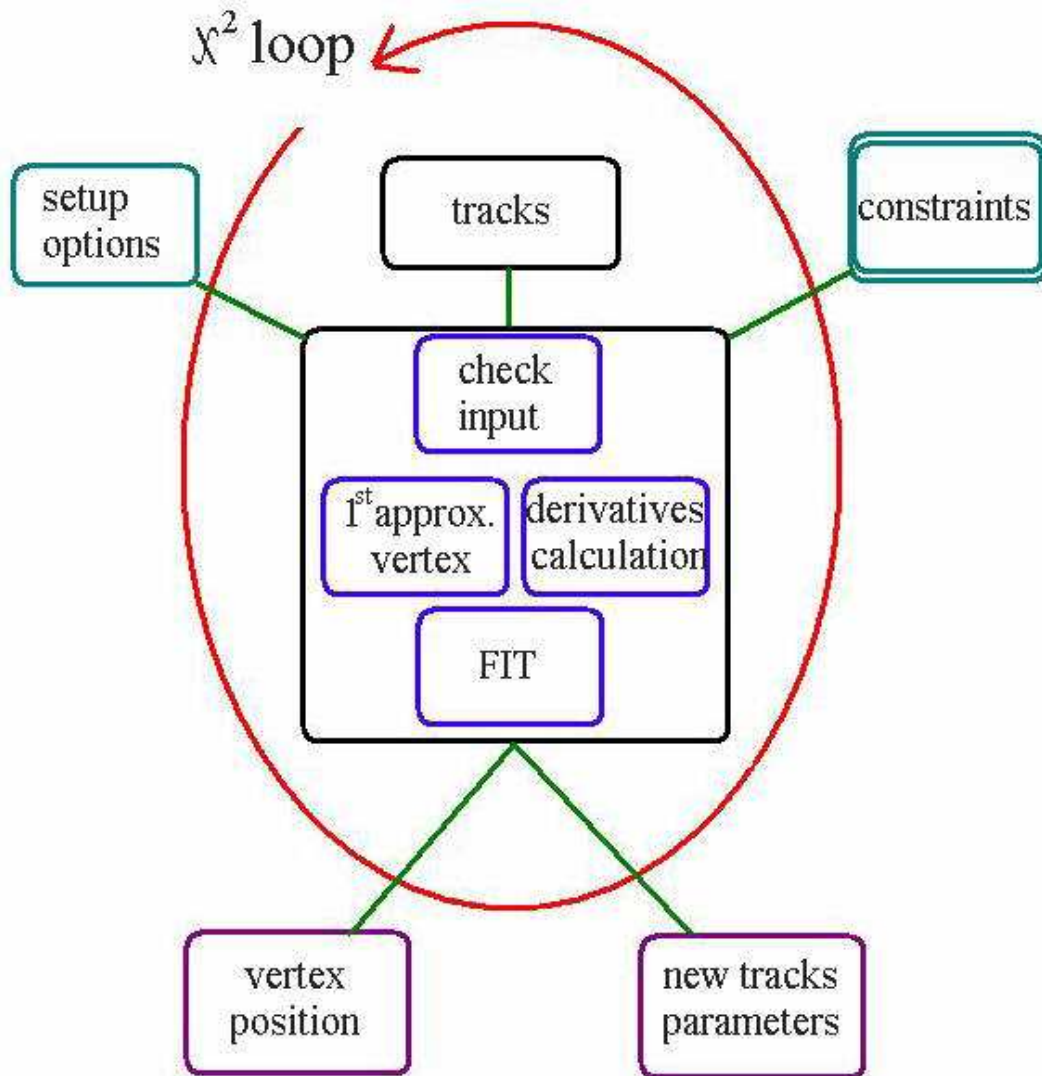


Figure 2: A summary of the vertexing procedure.

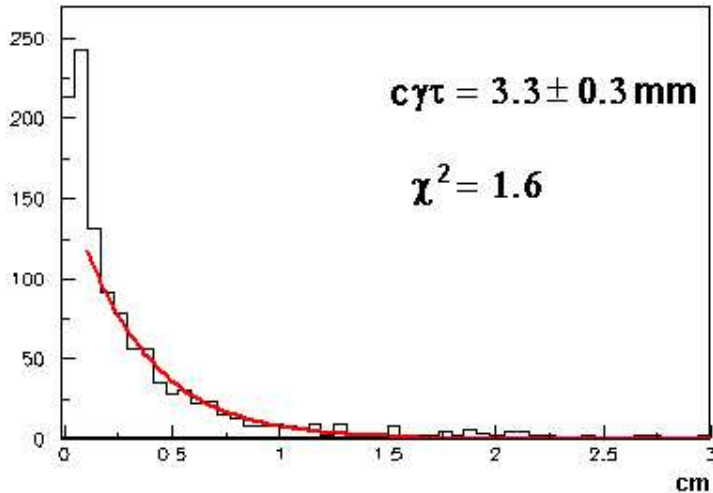


Figure 3: $\gamma c\tau$ for B 's (the vertexing resolution is not included in the error estimation).

To test *VertexExampleSecUserTracks* algorithm, a sample of about 5000 $A \rightarrow \tau\tau$ events have been analyzed.

The track list for the τ vertex fit has been created storing the tracks associated to a three prongs hadronic τ decay. The τ vertex resolution is shown in table 3.

RMS (cm)		
x	y	z
0.40	0.40	0.51

Table 3: τ vertex resolution.

An approximated mean free path estimation has been performed (fig. 4). It is in fair agreement with the expectation ($\gamma c\tau \simeq 20$ mm, for 400 GeV/c average transverse τ momentum).

2 Hadronic τ -tagging

In this part of the note, it is described how the *Vertexing* can be used in the τ -identification, which is extremely important in the study of several physics channels (e.g. $A/H \rightarrow \tau\tau$).

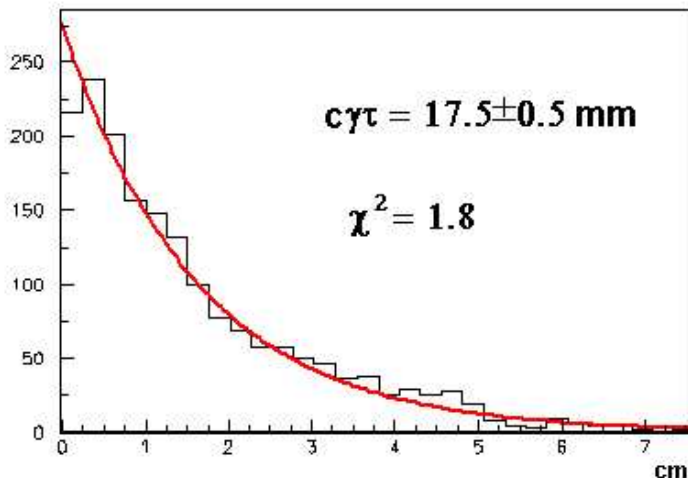


Figure 4: $\gamma c\tau$ for τ 's (the vertexing resolution is not included in the error estimation).

The τ lepton has a 15.2% probability of decaying hadronically into three prongs. In this case, the τ secondary vertex can be spotted by mean of the *Vertexing* tools. Moreover, the recalculated track parameters and their χ^2 contribution to the vertex can be used to establish τ -identification criteria.

2.1 Generalities

In order to optimize and test the hadronic τ identification, signal and background events have been generated with PYTHIA 6.203[5] and simulated with ATLSIM[6]:

- signal: $bbA \rightarrow bb\tau\tau \rightarrow hadrons$ with $m_A=800$ GeV/ c^2 ;
- background: QCD di-jets (with three different cuts on minimum p_T : 50, 100, 200 GeV/ c).

The particle level filter was set requiring $|\eta| < 2.7$ and at least one parton with $p_T > 17$ GeV/ c (see table 4).

2.2 Event reconstruction and τ vertex resolution

The event reconstruction has been done using the Athena framework. The software used is that inside the release 4.0.1. A complete reconstruction inside the Inner Detector (ID) and the calorimeters has been performed. The pattern

Channel	Generated events	Filtered events	Acceptance	Rejection
Signal	25000	24125	96.5 %	-
QCD 50	50000	40910	-	1.222
QCD 100	50000	48348	-	1.034
QCD 200	50000	49950	-	1.001

Table 4: *Data filtering.*

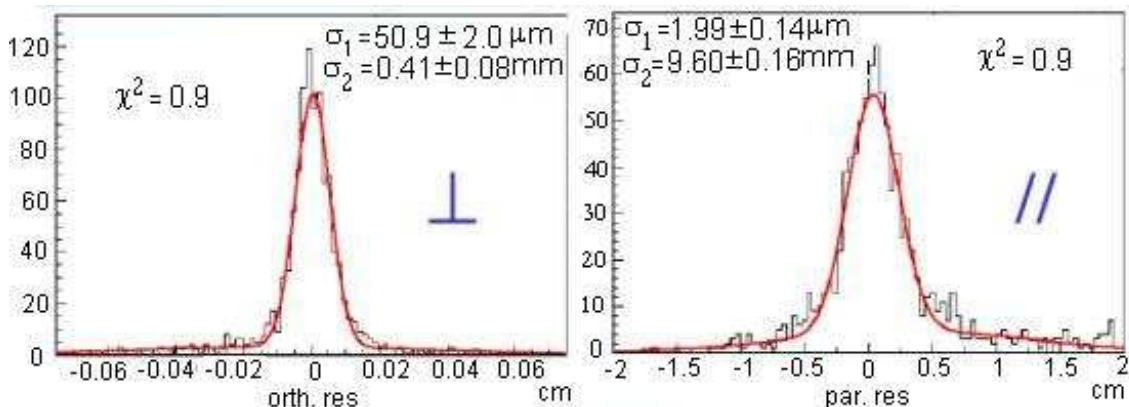


Figure 5: τ vertex resolution.

recognition algorithm *xKalman*[7] has been used to reconstruct tracks inside the ID, while the primary and secondary vertex spotting has been done using the *Vertexing* algorithms. *tauRec*[8] program (with the parameters opportunely tuned) has been used both as a mere jet-finding algorithm and to get the τ candidate parameters useful for the τ identification. An estimation of the τ vertex resolution, in the directions parallel and orthogonal to the τ -jet axis, has been performed fitting the tracks coming out from a three-prong decaying τ (see fig. 5).

2.3 τ tagging

τ identification has been developed in the studies published in [9], in [10] and [11], where mainly the information coming from the calorimeters have been used and where only the *1-prong* decays were selected. In this note it is shown that the τ identification of the *3-prong* τ -decays can be done more performant exploiting the Inner Detector precise track measurements. Since in this study hadronic τ decays are looked for, all the reconstructed jets are considered as candidates to the analysis. These are pre-selected using *tauRec* (its parameters have been tuned

to make it work as a high efficiency jet finding algorithm).

The *Vertexing* algorithms have been used to fit the primary vertex of the event and to fit the tracks inside the jets to spot a secondary vertex. Moreover, in order to minimize the contamination from particles not coming from the τ decay, the secondary vertex fit is performed using the (at most) three tracks with the highest p_T inside the jet. To select *1-prong* τ 's, it is required

- $R_{em} < 0.12$, where R_{em} is the jet radius computed in the EM calorimeter using only the electro-magnetic cells contained in the jet;
- one isolated track with $p_T > 40$ GeV/c within a cone of opening¹ $\Delta R < 0.1$ from the jet axis (as evaluated by *tauRec*) and no other track with $p_T > 1$ GeV/c in a cone of $\Delta R < 0.4$.

3-prong τ 's are pre-selected requiring

- *1-prong* selection failed;
- $R_{em} < 0.12$;
- one isolated track with $p_T > 40$ GeV/c within $\Delta R < 0.1$ from the jet axis (as leading track), at most two other tracks with $p_T > 1$ GeV/c in a cone of $\Delta R = 0.03$ around the leading track and no other track (*isolation cut*) with $p_T > 1$ GeV/c in an annulus of $0.03 < \Delta R < 0.4$ (see fig. 6);

The further *3-prong* τ -decay selection requires a successful decay vertex fitting.

3-prong τ candidates are eventually selected if they satisfy one of the following requirement sets (used in *OR*):

• **Set 1**

- the χ^2 contribution of the tracks fitted to the secondary vertex smaller than the contribution of the same tracks to the primary;
- the number of the tracks fitted to the vertex equal to 3;
- $p_{T3} > 7$ GeV/c (with p_{T3} the transverse momentum of the third most energetic track).

• **Set 2**

- 3 tracks fitted to the vertex;
- $p_{T2} > 40$ GeV/c (with p_{T2} the transverse momentum of the second most energetic track).

¹ $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

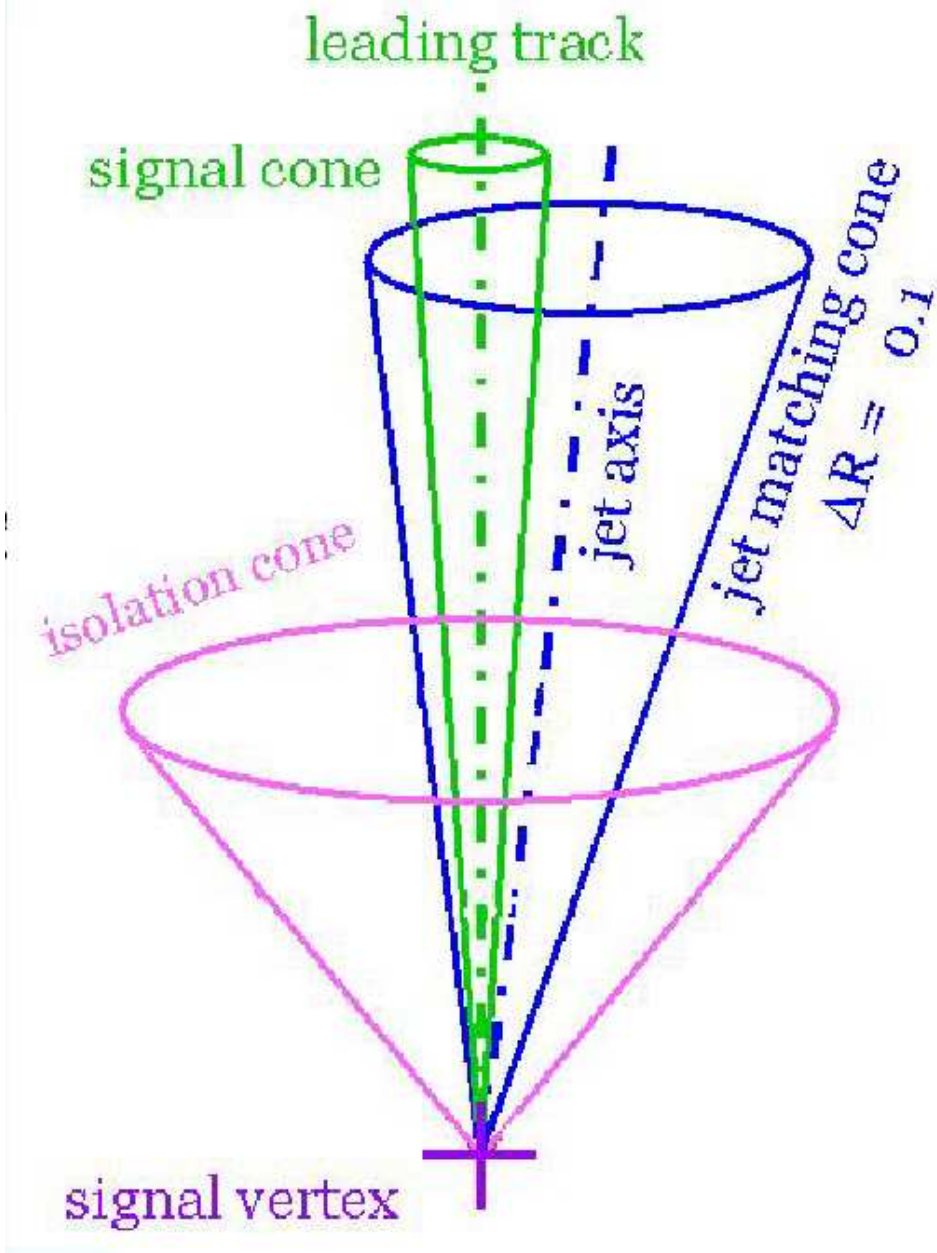


Figure 6: *Isolation criteria.*

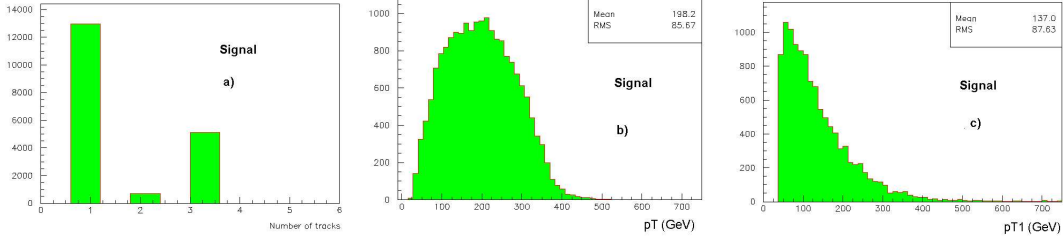


Figure 7: *Signal*: a) number of tracks to be fitted, b) p_T and c) p_T of the most energetic track.

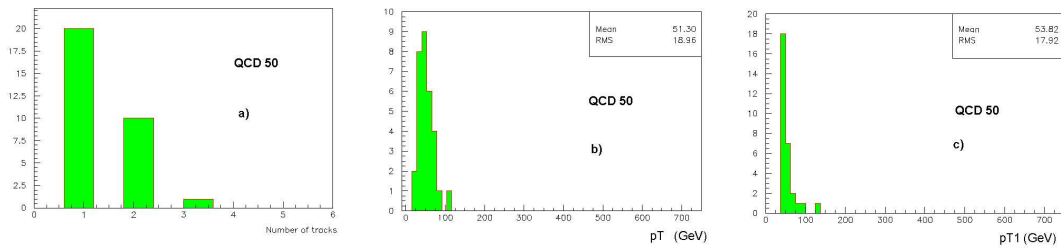


Figure 8: *QCD50*: a) number of tracks to be fitted, b) p_T and c) p_T of the most energetic track.

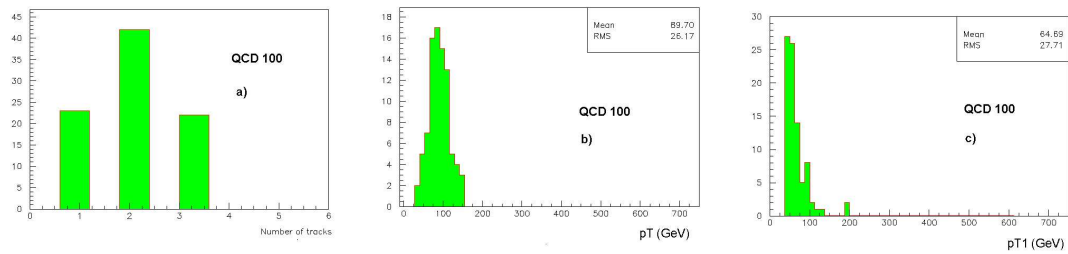


Figure 9: *QCD100*: a) number of tracks to be fitted, b) p_T and c) p_T of the most energetic track.

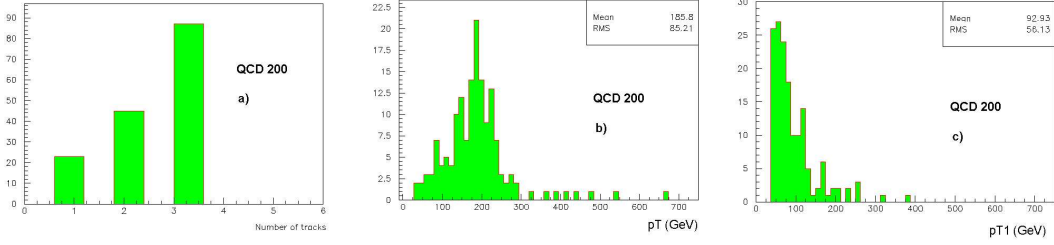


Figure 10: *QCD200*: a) number of tracks to be fitted, b) p_T and c) p_T of the most energetic track.

- **Set 3**

- $d_{r\phi}^{12} > 0.4$ cm (with $d_{r\phi}^{12}$ the distance, projected onto the $r\phi$ plane, between the primary and secondary vertex);
- 3 tracks fitted to the vertex;
- $p_{T1} > 50$ GeV/c (with p_{T1} the transverse momentum of the most energetic track);
- $p_{T2} > 25$ GeV/c.

- **Set 4**

- $d_{r\phi}^{12} > 0.4$ cm;
- 2 tracks fitted to the vertex;
- $p_{T1} > 50$ GeV/c;
- $p_{T2} > 35$ GeV/c.

The cuts have been optimized in order to achieve a high rejection rate on the background.

In figs. 7, 8, 9, 10 the number of tracks to be fitted, the τ candidate p_T and the most energetic track p_T are respectively shown for signal and background (the τ candidates are those selected after the isolation cut).

The same τ -tagging selection has been applied both on signal and background filtered events; the results are summarized in table 5. Single decay mode efficiency has also been calculated: *1-prong* efficiency is 34.4 % and *3-prong* one is 44.1 %, with a 10 % enrichment with respect to the previous analysis in [10].

<i>Data sample</i>	<i>Filtered τ/jets</i>	<i>1-prong</i>	<i>3-prong</i>	<i>tagged τ's</i>	<i>Efficiency</i>	<i>jet rejection</i>
Signal	48250	12932	4704	17636	36.6%	-
QCD50	81820	20	$< 2.4^\dagger$	$< 22.4^\dagger$	-	$> 3.7 \cdot 10^3$
QCD100	96696	22	10	32	-	$3.0 \cdot 10^3$
QCD200	99900	28	71	99	-	$1.0 \cdot 10^3$

Table 5: τ -tagging results for signal and QCD background. † Poissonian upper limits for a 90% confidence interval [12].

3 Summary

In the first part of the note, the Vertexing package, which aims to reconstruct primary and secondary vertices, has been described. It is an Object Oriented interface to an existing vertexing routine written in Fortran by the CDF experiment. A few tests of the package have been performed; they have given encouraging results.

In the second part, it is described how this tool has been used to develop an algorithm aimed to identify the hadronic τ decays. In particular, it has been useful in spotting the secondary vertices coming from three-prong τ decays.

About 150000 QCD and 25000 $A \rightarrow \tau\tau$ full simulated events have been produced and analysed, requiring an outstanding computing effort. An efficiency of 44.1% and a jet-rejection higher than 10^3 have been achieved in the τ -identification. The τ -tagging has been proved as an affordable and useful tool.

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