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Reconstruction of $\mathbf{K}_s^0$ and $\mathbf{\Lambda}^0$ Mesons with the CMS Silicon Tracker

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Abstract

A study of the reconstruction of V0 meson decays in the CMS silicon tracker is presented. Since the baseline track reconstruction in CMS uses pixel seeds, it is not well suited for reconstructing K_s^0 or Λ^0 meson decays occurring far away from the primary event vertex. Novel seeding algorithms, using e.g. TOB and TEC layers have been implemented, and a selection strategy for K_s^0 and Λ^0 mesons has been developed. A strategy to reduce the CPU requirements for high multiplicity events is proposed, using a seed cleaning based on dedicated discriminating variables.

1 Introduction

The term "V0" is given to neutral particles which have a long lifetime and, in the case of proton-proton collisions, will decay far away from the primary vertex, such as K_s^0 and Λ^0 mesons [1]. Such particles are expected to be copiously produced in LHC pp collisions and can be reconstructed in the CMS tracker using their decays into two charged particles. The reconstruction and study of V0's will play an important role in the calibration of the CMS detector. For instance, they can be used to improve the jet energy measurement in the context of energy flow algorithms. Using their invariant mass distribution, they can also be used to perform a magnetic field mapping or to check the tracker alignment. Their decay position in the detector can also be used to provide an estimate of the tracker material budget.

In this note, a method to reconstruct and select K_s^0 and Λ^0 mesons with the CMS detector is presented. Three Monte Carlo samples are used for most of the studies presented here:

- A K_s^0 particle gun sample. K_s^0 mesons are generated with a flat momentum distribution in the range $2 < p < 30$ GeV and $|\eta| < 2.5$;
- A standard minimum bias QCD sample;
- A QCD jets sample, where $50 < \hat{p}_T < 80$ GeV.

This note is structured as follows: In section 2 the basic properties of K_s^0 and Λ^0 mesons are discussed. Section 3 gives a brief summary of the CMS standard track seeding and reconstruction algorithm. Dedicated seeding algorithms for V0 reconstruction are presented in section 4, and a selection strategy for K_s^0 and Λ^0 mesons is developed in section 5. In Section 6 a strategy to implement a dedicated two-step V0 track reconstruction with seed cleaning is proposed. Open issues and ideas for future improvements are discussed in the concluding section 7.

2 V0 Physics Properties

The K_s^0 has a mass of 498 MeV, a $c\tau$ of 2.7 cm and its charged decay branching ratio into $\pi^+\pi^-$ is 67%, versus 30% for the neutral decay into $\pi^0\pi^0$. The Λ^0 has a mass of 1115 MeV, a $c\tau$ of 7.8 cm and its branching ratio for the charged decay into $p^\pm\pi^\mp$ is 64%, versus 34% for the neutral decay into $n\pi^0$.

In minimum bias events, about 5 V0's are produced per event, with a mean p_T of 0.8 GeV. For QCD jet events, where the jets are produced with 50 GeV $< \hat{p}_T < 80$ GeV, there are in total about 20 V0 mesons per event, with a slightly harder p_T spectrum of 1.8 GeV on average. Figure 1 (left) shows the generated p_T spectrum for V0's for a minimum bias sample, as well as for two QCD jet samples with different $\hat{p}_T$ ranges.

With the standard track reconstruction algorithm of CMS, charged particles can be reconstructed if they have a p_T larger than 0.9 GeV and $|\eta| < 2.5$. This means that only 3% of the V0's will be observable in minimum bias events and 12% in QCD jet events where the jets are produced with $50 < \hat{p}_T < 80$ GeV.

Figure 1 (right) shows the decay vertex radial position r_{vtx} of the V0 mesons for various p_T regions. With increasing p_T the V0's tend to decay further away from the nominal interaction vertex. By default, the starting point for track finding in CMS is based on seeds defined in the pixel detector, which consists of three layers located at a radius of 4.3, 7.2 and 10.1 cm, respectively. V0's decaying at a radius beyond the coverage of the pixel layers will not be reconstructed with the standard track seeding and reconstruction algorithm.

In order to obtain an efficient V0 selection, two complementary paths can thus be taken. The first one consists in developing algorithms that are able to reconstruct particles at low p_T. This approach has been already documented in [2]. A second idea, which is explored in this note, is to develop a tracking algorithm that allows to reconstruct particles decaying far away from the primary vertex, allowing to recover high p_T V0 meson decays.

3 Standard Track Seeding and Reconstruction in CMS

In order to realize the challenges connected to reconstructing V0 mesons in CMS, it is important to understand the way the standard track reconstruction works. Therefore, we give in the following a brief summary of the current baseline tracking software in CMS.

The baseline algorithm for track reconstruction [3] in CMS is the Combinatorial Kalman Filter. After the tracker hits have been reconstructed (clustering and position estimation), track reconstruction proceeds through the following four stages:

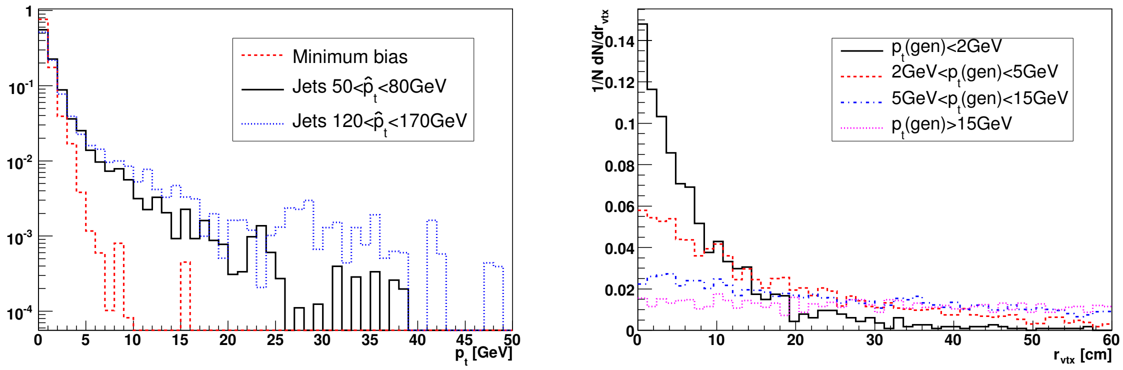

Figure 1: Left: The p_T spectrum of generated V0 mesons in a minimum bias sample (red dashed line), a QCD jets sample with $50 < \hat{p}_T < 80$ GeV (black solid line), and a QCD jets sample with $120 < \hat{p}_T < 170$ GeV (blue dotted line). Right: The radial position of the decay vertex r_{vtx} for $p_T(V0) < 2$ GeV (black solid line), $2 < p_T(V0) < 5$ GeV (red dashed line), $5 < p_T(V0) < 15$ GeV (blue dashed-dotted line) and $p_T(V0) > 15$ GeV (pink dotted line). All distributions are normalized individually.

- Trajectory seeding;
- Pattern recognition;
- Trajectory cleaning;
- Track fitting and smoothing.

3.1 Trajectory Seeding

Seed generation provides initial trajectory candidates for the full track reconstruction. A seed must define initial trajectory parameters and errors. Hence, five parameters are needed to start trajectory building. Therefore, the standard trajectory seeds in the CMS tracker are constructed from pairs of hits in the pixel detector and a vertex constraint. The pixel detector is well suited for seeding due to its low occupancy, its proximity to the beam spot and due to the 2D measurement capability in both $r\phi$ and rz. The seed finding efficiency is $> 99\%$, and the seed generation takes approximately 10% of the total CPU time needed for track reconstruction.

3.2 Pattern Recognition and Track Fitting

Trajectory building is based on a combinatorial Kalman filter method. The filter proceeds iteratively from the seed layer, starting from a coarse estimate of the track parameters provided by the seed, and including the information of the successive detection layers one by one. With each included layer, the track parameters are better constrained. In the extrapolation of the trajectory from layer to layer, the effects of energy loss and multiple scattering are accounted for. Trajectory candidates are added for each compatible hit (including an additional trajectory without a measured hit in order to account for inefficiencies), and the trajectory parameters are updated according to the Kalman filter formalism. The best trajectory candidates are grown in parallel up to the outermost layers.

Ambiguities in track finding arise because a given track may be reconstructed starting from different seeds, or because a given seed may result in more than one trajectory candidate. These ambiguities must be resolved in order to avoid double counting of tracks. The ambiguity resolution is based on the fraction of hits that are shared between two trajectories. It is applied twice: the first time on all trajectories resulting from a single seed, and the second time on the complete set of track candidates from all seeds.

For each trajectory, the building stage results in a collection of hits and an estimate of the track parameters. However, the full information is only available at the last hit of the trajectory, and the estimate may be biased by constraints applied during the seeding stage. Therefore the trajectory is refitted using a least squares approach, implemented as a combination of a standard Kalman filter and smoother. While the filter runs inside-out, in the smoothing step a second filter is run outside-in. In both cases, the initial covariance matrix of the track parameters is scaled by a large factor to avoid possible biases. At each hit the updated parameters of the smoothing filter are combined with the predicted parameters of the first filter. The combination yields optimal estimates of the track parameters at the surface of each hit.

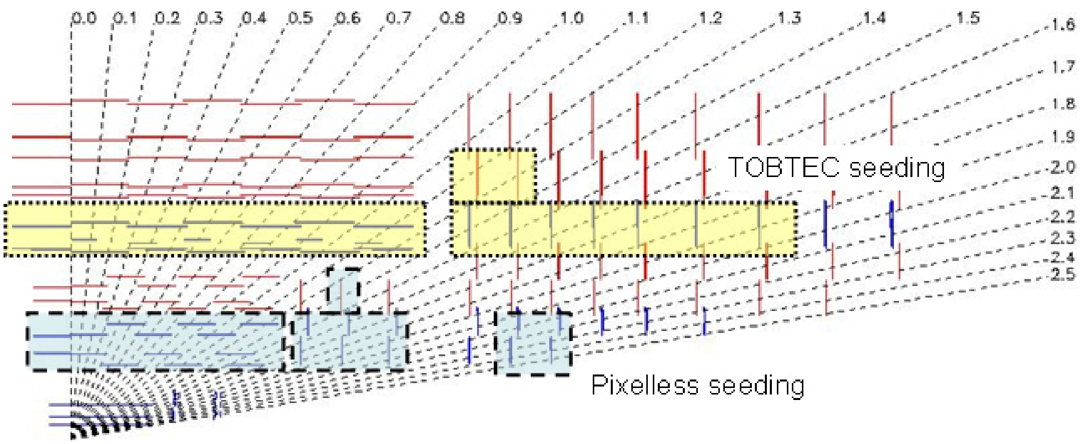

Figure 2: Illustration of one quarter of the CMS tracker in the rz-view. The layers used for the pixelless and TOBTEC seeding are indicated by the blue (dashed) and yellow (dotted) shaded areas, respectively.

	Seed layer pairs
Barrel	TOB1+TOB2
Barrel-Endcap	TOB1+TEC1 , TOB1+TEC2
Endcap	TEC1+TEC2 , TEC1+TEC3 TEC2+TEC3 , TEC2+TEC4 TEC3+TEC4 , TEC3+TEC5 TEC4+TEC5 , TEC4+TEC6 TEC5+TEC6 , TEC5+TEC7 TEC6+TEC7

Table 1: Combination of layers used to construct seeds in the TOBTEC seeding.

4 Seeding Algorithms for the Reconstruction of V0 Mesons

As explained in section 3.1, the baseline CMS seeding is aimed at reconstructing tracks originating from the primary vertex as it uses pairs of hits in the pixel detector and a tight vertex constraint of $r < 1$ mm. Since V0's can decay into charged particles far away from the primary vertex, alternative seeding methods have to be developed, using strip tracker layers at larger radii.

4.1 Pixelless Seeding

The pixelless seeding [4, 5] was developed in order to facilitate track reconstruction during the early running of the CMS experiment, when the pixel detector will not yet be installed. Seeds are constructed from hit pairs in the two innermost layers of TIB, which are built from double sided modules, and hence provide 2D coordinate measurement. In addition, the two innermost rings of TID (and the third ring of the second disk in order to increase acceptance), as well as rings 1 and 2 of TEC disks 2 and 3 are used (see Figure 2).

Using this seeding, V0 mesons decaying at a radius of approximately $r < 20$ cm, i.e. before the first TIB layer, can be reconstructed.

4.2 Seeding in TOB and TEC

In order to reconstruct V0's decaying further outside than $r \sim 20$ cm, a novel seeding algorithm using TOB and TEC modules has been developed. In the barrel, seeds are constructed from pairs of hits in TOB layers 1+2 (Figure 2), which are built from double sided modules. In the endcap region, TEC ring 5 is used, which also uses double sided modules. To increase acceptance in the transition region between barrel and endcap, TEC ring 6 of disks 1 and 2 is also used. The pairs of layers considered in order to construct seeds are listed in Table 1.

Using the TOBTEC seeding, V0 decay vertices up to approximately $r < 60$ cm, the radius of the first TOB layer, can be reconstructed.

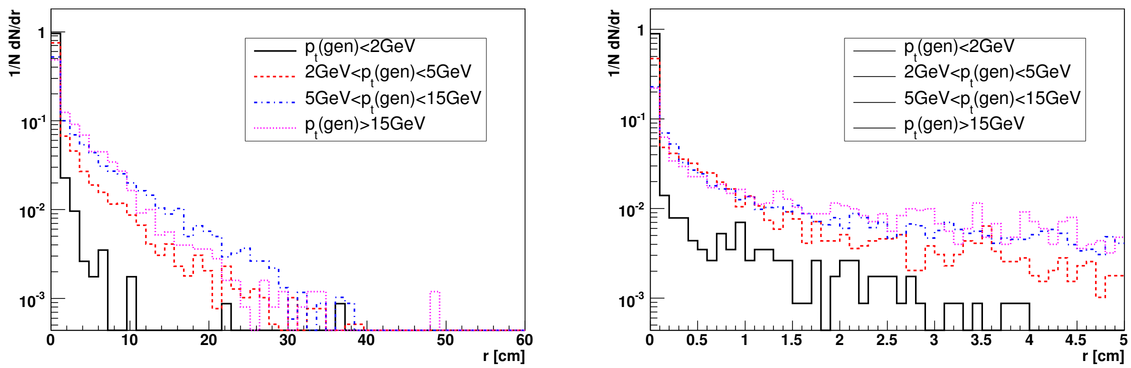

Figure 3: Particle Gun sample. The track impact parameter r of the V0 decay particles is shown for various $p_T(V0)$ intervals for $r < 60$ cm (left) and $r < 5$ cm (right).

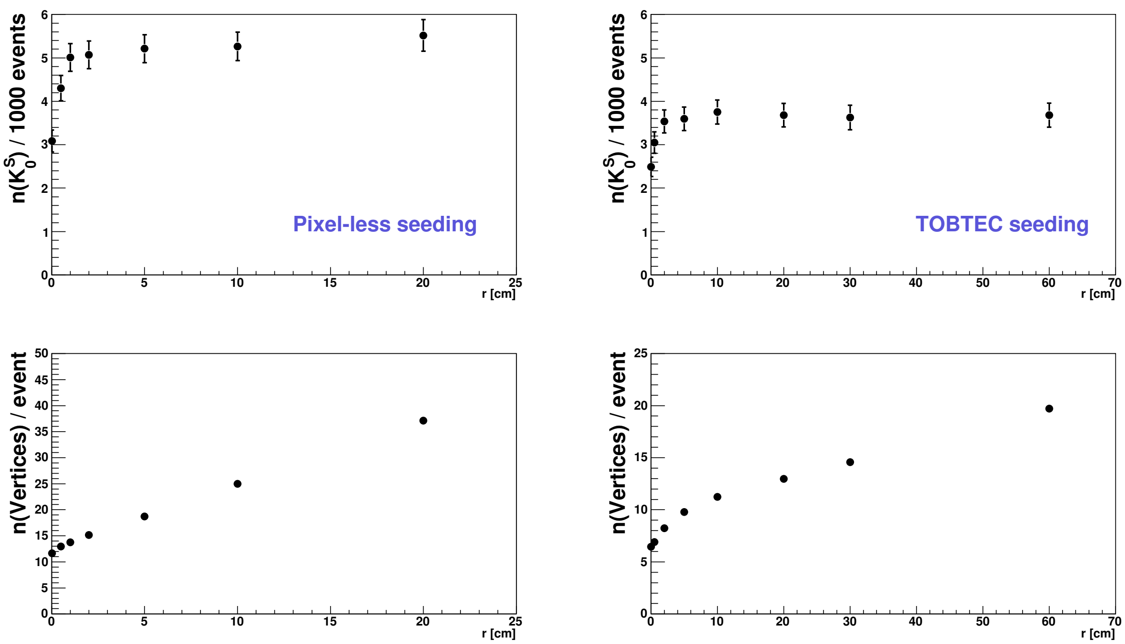

Figure 4: Minimum bias sample. K_s^0 yield as a function of the vertex radius cut imposed in the seeding algorithm (top) and the number of reconstructed vertices per event (proportional to algorithm speed, bottom), shown for pixelless seeding (left) and TOBTEC seeding (right).

4.3 Combined V0 Seeding

A seed generator which combines the pixelless and TOBTEC seeding methods described in sections 4.1 and 4.2 as also been implemented. Technically, the pixelless and TOBTEC seed generators are run consecutively, and the seeds are simply added afterwards.

4.4 Relaxed Vertex Constraint

All seed generators use a vertex constraint in order to define valid seeds. In the default seeding, this constraint is based on the impact parameter of the track, r, requiring $r < 1$ mm, in order to constrain reconstructed tracks to originate close to the nominal interaction vertex. Note however that in the seeding phase the uncertainties on the track parameters are still quite large. Figure 3 shows the impact parameter distribution, in cm, for tracks coming from a V0 in different p_T regions.

In order to retain high efficiency for tracks originating from a V0 decaying far away from the nominal vertex, this vertex constraint has to be relaxed. On the other hand, the number of reconstructed seeds is strongly correlated with the vertex constraint. Therefore, an optimal value must be found which retains high V0 efficiency without

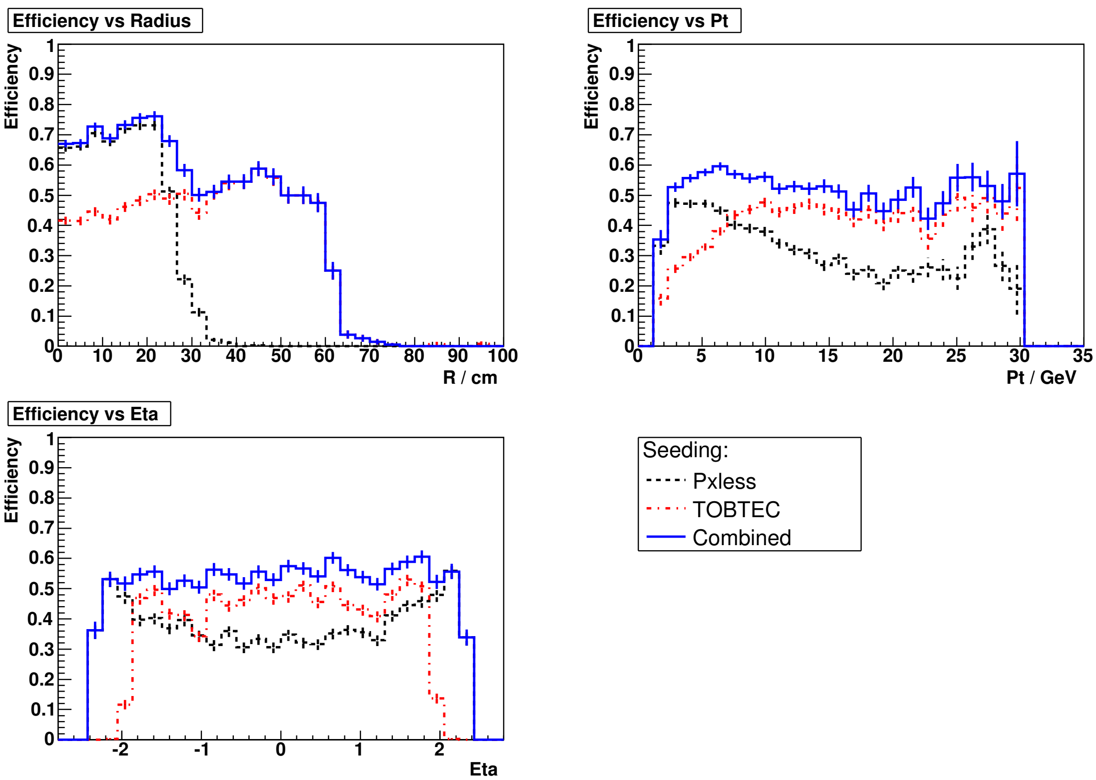

Figure 5: K_s^0 meson reconstruction efficiency, estimated using particle gun events, shown as a function of the radius of the decay vertex, the transverse momentum and the pseudo-rapidity of the generated K_s^0 .

increasing too much the CPU budget. This dependency is illustrated in Figure 4. Using a minimum bias sample and the selection procedure that will be discussed in detail in section 5, the number of reconstructed K_s^0 mesons is shown as a function of the vertex constraint radius cut used in the seeding, for both pixelless as well as TOBTEC seeding. The number of reconstructed vertices is also shown, which scales with the number of seeds and the used CPU time. As can be seen, a cut value of $r = 2$ cm (5 cm) for the pixelless (TOBTEC) seeding gives a good V0 efficiency while keeping the CPU requirements under control. This value is also compatible with the $c\tau$ of the K_s^0 .

4.5 Performance

The efficiency of the different seeding methods described above has been evaluated using the K_s^0 particle gun sample. Figure 5 shows the reconstruction efficiency for the pixelless, TOBTEC and combined V0 seeding methods as a function of the radius of the simulated decay vertex, transverse momentum and pseudo-rapidity of the K_s^0 . The efficiency is defined as the ratio of the number of reconstructed K_s^0 divided by the number of simulated K_s^0 , where at least two simulated K_s^0 tracks with $p_T > 0.9$ GeV are present in the event. In this sense, it represents an *algorithmic* efficiency.

The efficiency of the pixelless seeding is around 70% for $r < 25$ cm, corresponding approximately to the first TIB layer. It decreases with increasing p_T, ranging from 45% at $p_T = 2$ GeV to 20% at 30 GeV. On the other hand, the TOBTEC seeding extends the acceptance significantly towards larger radii. It varies between 40% at small radii and 50% at $r = 60$ cm. The efficiency also increases with p_T, reaching a plateau of 45% at $p_T = 10$ GeV. The combined V0 seeding shows the features of combining pixelless and TOBTEC seeding, as expected.

The obtained K_s^0 efficiencies (for reconstructing two tracks) are consistent with the single pion track reconstruction efficiency documented in the CMS Physics TDR [5], which is in the range $75 \ldots 90\%$ for pions with $p_T = 1 \ldots 10$ GeV.

Finally, it should be mentioned that the `GroupedCombinatorialTrajectoryBuilder` should be used for V0 track reconstruction, since it allows to grow trajectory candidates both outwards as well as inwards, starting from the seed. This way, tracks from V0 decays can be fully reconstructed by picking up eventual hits from *inside* the seeding layers.

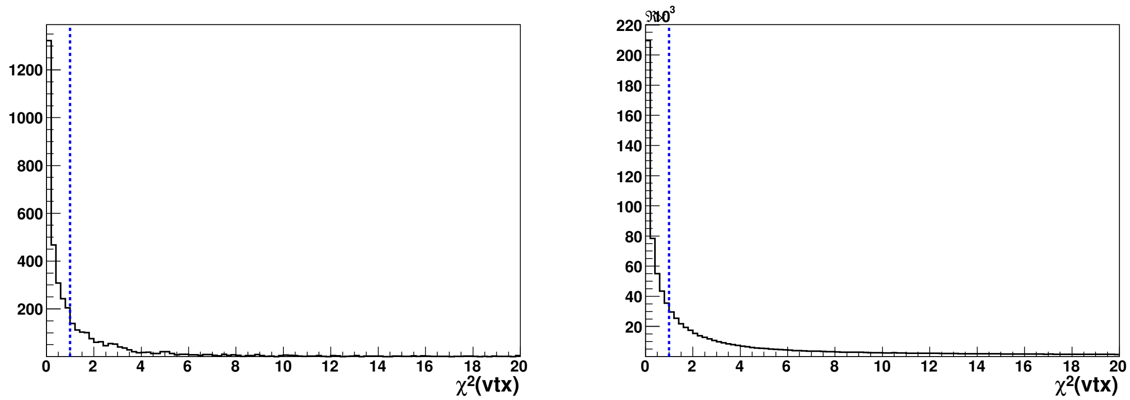

Figure 6: The χ^2 of the secondary vertex for the K_s^0 particle gun sample (left) and QCD jets (right).

5 Selection of K_s^0 and Λ^0 Mesons

The selection of V0 mesons was studied using the three simulated event samples mentioned in section 1, namely K_s^0 particle gun, minimum bias and QCD jet events. ORCA_8_13_3 was used to simulate the detector response and reconstruct the events.

V0 candidates are built starting from all possible combinations of positive and negative tracks. These track pairs are then fitted to a common vertex using the standard Kalman vertex fitter. Only vertices with a χ^2 smaller than 20 are kept. The following selection variables were then used in order to select V0 decays among all candidates.

- First, a stronger cut can be applied on the χ^2 of the secondary vertex. Figure 6 shows the vertex χ^2 distribution for a K_s^0 particle gun sample (left) and for QCD jets sample (right), which contains mainly background. A cut $\chi^2 < 1$ is applied on the V0 candidates.
- Since V0's are expected to decay away from the primary interaction point, a cut can be applied on the radius of the reconstructed secondary vertex r_{vtx}, requiring $r_{vtx} > 0.1$ cm. Figure 7 shows r_{vtx} after the cut on χ^2 is applied, for the K_s^0 particle gun sample (left) and the QCD jets sample (right).
- Finally a cut on the vertex significance, defined as $r_{vtx}/\sigma(r_{vtx})$, is applied, requiring it to be larger than 22. Figure 8 shows the vertex significance for a K_s^0 particle gun sample (left) and for QCD jets sample (right), after the cuts on χ^2 and r_{vtx} are applied.
- To select more specifically Λ^0 mesons, an additional cut is applied on the particle collinearity requiring it to be smaller than 0.02. The collinearity is defined as the angle between the reconstructed V0 direction and the direction between the primary vertex and the secondary vertex. It should be small for particles coming from the primary vertex. Figure 9 shows the collinearity distribution for the QCD jets sample.

Figure 10 (left) shows the reconstructed pion-pion invariant mass distribution for all secondary vertices found (top), after requiring $\chi^2 < 1$ and $r_{vtx} > 0.1$ cm (middle) and finally after all cuts applied (bottom), where the K_s^0 peak is clearly visible. Similarly, Figure 10 (right) shows the reconstructed pion-proton invariant mass distribution for all secondary vertices found (top), after requiring $\chi^2 < 1$ and $r_{vtx} > 0.1$ cm (middle) and finally after all cuts applied (bottom), where the Λ^0 peak can be seen around $m_{p\pi} = 1.1$ GeV. The second broad peak around $m_{p\pi} = 1.4$ GeV is originating from K_s^0 reflections. Both mass peaks were obtained using the pixelless seeding with relaxed vertex constraint (2 cm).

Figure 11 (left) shows the K_s^0 peak after all selection cuts are applied. The 2% resolution obtained is compatible with the tracking resolution. Figure 11 (right) shows the Λ^0 peak after all selection cuts applied. The resolution for this peak of about 0.5% is much smaller than for the K_s^0 peak. This is due to the fact that the resolution is dominated by the proton mass.

In order to quantify the cut selection efficiency, two samples were selected starting with the reconstructed vertices from the QCD jet sample. A "signal" sample was selected by requiring that the reconstructed K_s^0 candidate is matched to a generated K_s^0 within $\Delta R < 0.02$. In addition, a loose mass cut is added, asking 0.4 GeV $< m_{\pi\pi} <$ 0.6 GeV. A "background" sample is defined from all events in the sample, which are mostly not V0s.

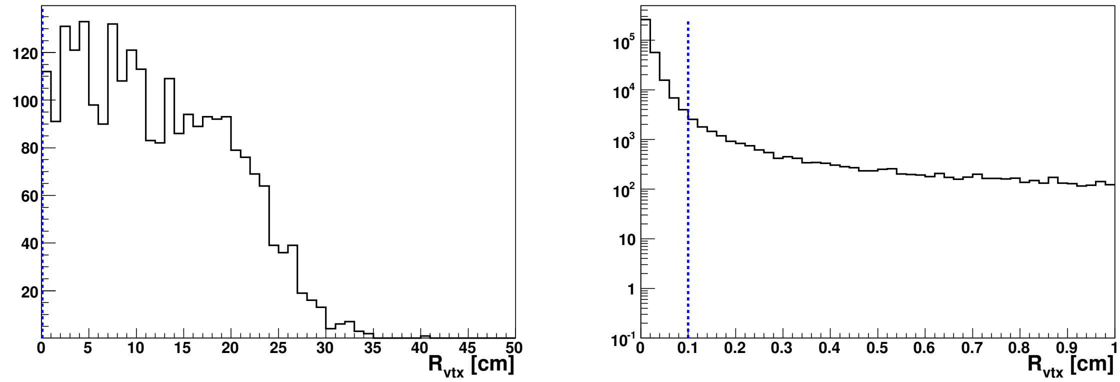

Figure 7: The r_{vtx} distribution of the secondary vertex for the K_s^0 particle gun sample (left) and QCD jets (right), after cutting on χ^2 .

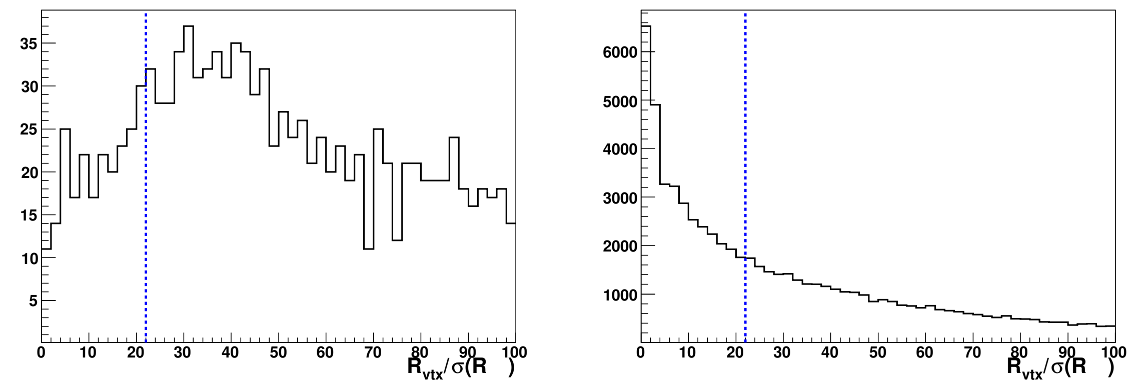

Figure 8: The vertex significance for the K_s^0 particle gun sample (left) and QCD jets (right), after cutting on χ^2 and r_{vtx}.

Table 2 shows the cut efficiency for the QCD jet sample for the signal and background samples. The efficiency is calculated with respect to the number of reconstructed vertices. With a total cut efficiency of roughly 40% on signal events, a background reduction of 5000 is achieved with the pixelless seeding. As can be seen in Figure 11 (left) these selection cuts allow to reach a signal over background ratio of 2.5. For the TOBTEC seeding, a total cut efficiency of 43% is observed on signal events against a reduction of roughly 3000 on background events, leading to a signal over background ratio of 2.8.

Relaxing the cut on the vertex constraint during the seeding phase of track reconstruction will significantly increase the CPU time needed to reconstruct an event. Table 5 shows the approximate CPU time in seconds needed to process 100 events on a 2.4 GHz PC for minimum bias and QCD jets events, using different values for the vertex constraint cut. For minimum bias events, relaxing the vertex constraint will not lead to a significant increase in the CPU time. However for QCD jets events, relaxing the vertex constraint to 2 cm will increase the time needed to process 100 events by a factor 2. In order to get a usable reconstruction algorithm, novel methods will have to be introduced in order to keep the CPU time under control.

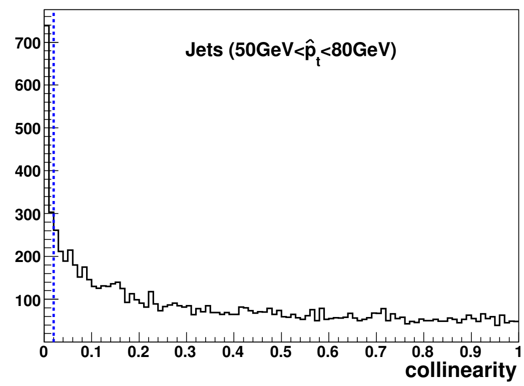

Figure 9: The collinearity of V0 candidates for the QCD jets sample after, all other cuts are applied.

Cut	Pixelless Seeding Signal	Pixelless Seeding Background	TOBTEC Seeding Signal	TOBTEC Seeding Background
$\chi^2 < 1$	0.50	0.18	0.52	0.12
$r_{vtx} > 0.1$ cm	0.46	0.028	0.52	0.028
$r/\sigma > 22$	0.40	0.013	0.48	0.020
$\lvert m_{\pi\pi} - 0.5\rvert < 0.05$ GeV	0.40	0.0002	0.43	0.0003

Table 2: Cut efficiency for the QCD jet sample. Signal candidates are required to be matched to a generated K_s^0 with $\Delta R < 0.02$. The efficiency is calculated with respect to the number of reconstructed vertices.

Sample	Standard (R<0.1cm)	Pixelless (R<0.1cm)	Pixelless (R<2cm)	Pixelless (R<25cm)	TOBTEC (R<5cm)	TOBTEC (R<60cm)
	Seeding algorithm					
Minimum bias	90	70	....	425	60	120
QCD 50-80	950	850	2000	90000	850	7000

Table 3: Approximate CPU time (in seconds) needed to process 100 events on a 2.4 GHz PC, without seed cleaning.

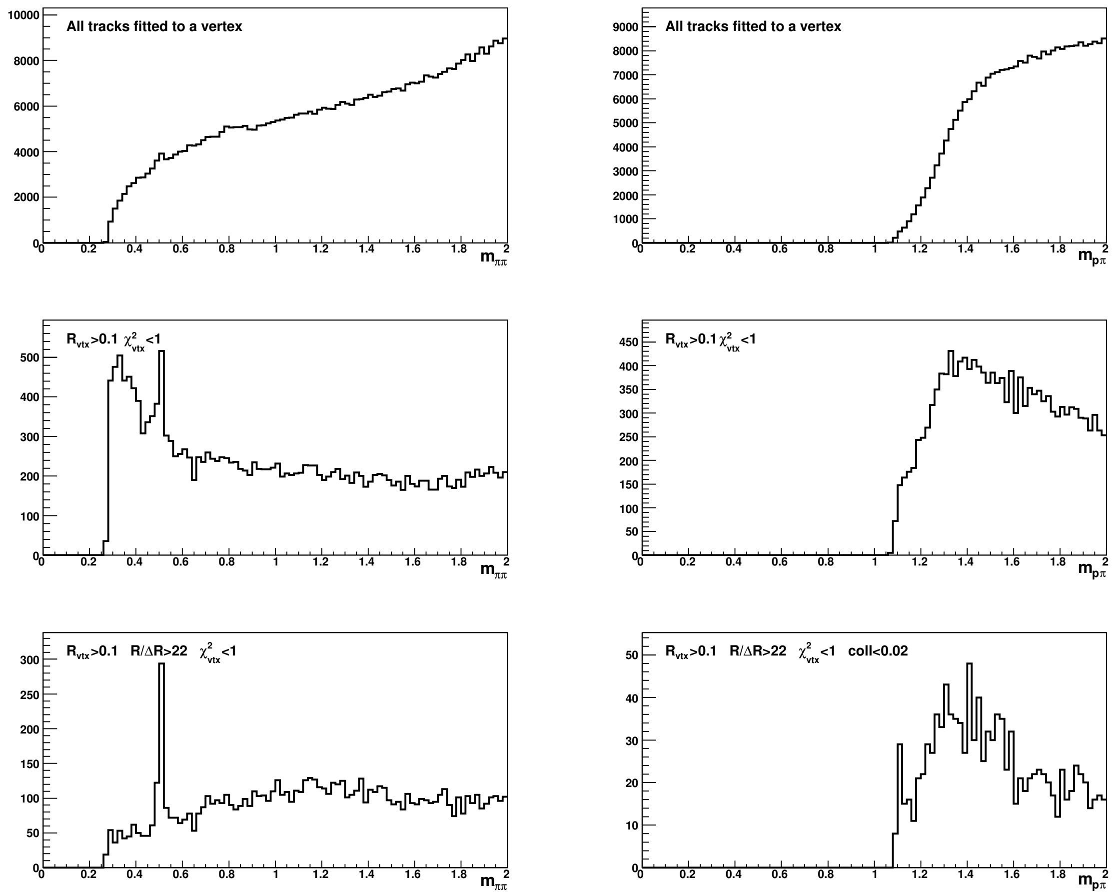

Figure 10: Pion-pion (left) and proton-pion (right) invariant mass distributions for the QCD jets sample, reconstructed using the pixelless seeding, shown for all secondary vertices found (top), after requiring $\chi^2 < 1$ and $r_{vtx} > 0.1$ cm (middle) and after all cuts have been applied (bottom).

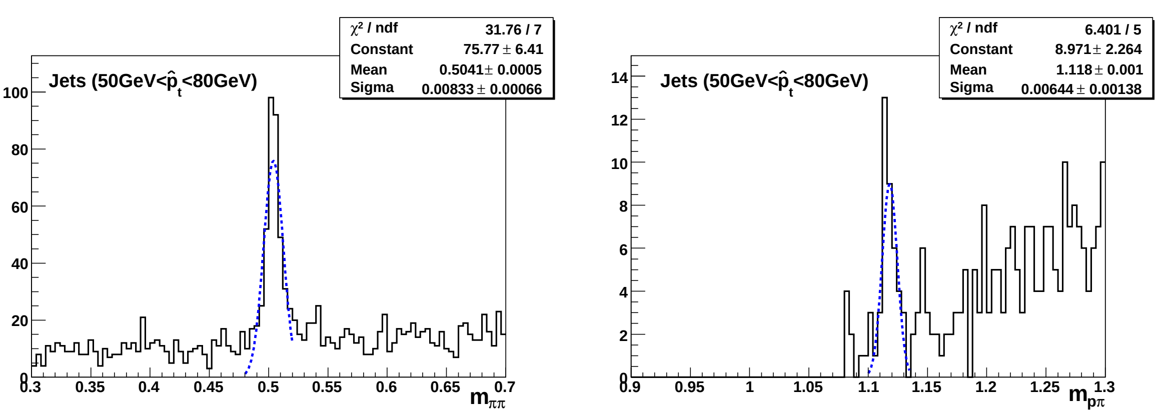

Figure 11: The pion-pion and proton-pion invariant mass distribution after all selection cuts have been applied, using the QCD jets sample.

6 Strategy for a Dedicated V0 Tracking with Seed Cleaning

As discussed in the previous section, using the pixelless seeding with relaxed vertex constraint significantly increases the CPU time needed to reconstruct high multiplicity events. Therefore, alternative track reconstruction algorithms have to be investigated. In the CMS tracking software, the CPU time needed for track reconstruction is dominated by the trajectory building (see section 3). The generation of the trajectory seeds takes only about 10% of the total time. Hence, in order to gain in terms of CPU performance it is vital to limit the number of seeds from which trajectory building is started.

To address this problem, a dedicated track reconstruction optimized for reconstructing V0's could be developed, which would run in addition to the standard tracking. To limit CPU time, the following procedure could be implemented:

- Starting from the seeds, trajectory building is started with a cut on the maximum number of reconstructed hits N_{max} (*partial tracking*, also used at the High Level Trigger [6]). N_{max} should be small to limit CPU time, but large enough such that the track parameters are reasonably well defined.
- The partial trajectories are fed to a cleaning algorithm, which aims at retaining only pairs of seeds which are compatible with a V0 hypothesis.
- Only for the remaining seeds, trajectory building is resumed and the full tracks are reconstructed.

6.1 Cleaning Variables

The following variables could be used for cleaning the partial trajectories. They are calculated from all combinations of trajectory pairs with opposite charge:

- Using the first (1,3) and last (2,4) hit of the two partial trajectories, the `Planarity` can be calculated (see Figure 12) as
$$p = (\vec{p}_{12} \text{ x } \vec{p}_{34}) \cdot \vec{p}_{13} \; . \tag{1}$$
In case the four hits lie in a plane, which should be the case for a V0 decay, the planarity should be zero.
- The `VtxDistance` is defined as the distance of the plane used in Equation 1 from the primary vertex (defined using pixel hits only for speed). Seed pairs originating from a V0 decay away from the primary vertex should have on average larger values.
- The differences in pseudo-rapidity and phi of the trajectories, calculated at their innermost states and labeled as `DeltaEta` and `DeltaPhi`.
- The 3D distance of closest approach of the two trajectories, labeled `PairDistance`. The technical implementation uses the class `TwoTrackMinimumDistance`.

In addition, the trajectory pairs of opposite charge can be fitted to a common vertex using the standard `KalmanVertexFitter`, which would allow further discriminating variables to be defined:

- The invariant mass `FitMass`, calculated from the track parameters refitted to the common vertex.
- The radius `FitR` of the decay vertex.

Since the vertex fit is CPU time consuming and may fail in case the fitted trajectories are not well defined and/or inconsistent with a common vertex hypothesis, the cleaning procedure should be implemented such that first the simple variables defined in the first group are tested for V0 compatibility. Only if this first selection is passed, the vertex fit is initiated and used for further selection.

It must be evaluated how many hits need to be reconstructed in the first step of the trajectory building in order to have reasonably well defined trajectory parameters and hence discriminating power between V0 signal and background. Figure 13 shows distributions of `VtxDistance`, `Planarity`, `FitMass` and `FitR` for signal (K_s^0 particle gun) and background (minimum bias) using different cuts on the number of reconstructed hits N_{max}. As can be seen, already $N_{max} = 4$ ensures that the distributions are close to the ones using the full reconstruction. Hence this value is chosen for further studies.

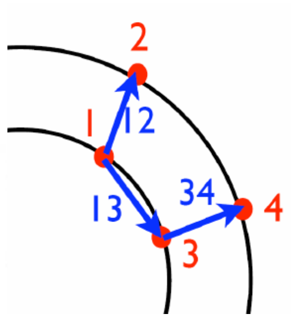

Figure 12: Definition of the `Planarity` variable. For details, see text.

Parameter	Seeding (K_s^0 eff.)					
	Pixelless		TOBTEC		Combined	
	(80%)	(90%)	(80%)	(90%)	(80%)	(90%)
V0SeedCleaner:maxVtxDistance	6.0	10.0	6.0	12.0	3.0	7.0
V0SeedCleaner:maxPlanarity	0.1	0.14	0.1	0.16	0.06	0.12
V0SeedCleaner:maxDeltaEta	0.2	0.4	0.2	0.4	0.3	0.5
V0SeedCleaner:maxDeltaPhi	1.0	1.5	1.1	1.6	1.1	1.5
V0SeedCleaner:maxPairDistance	2.0	4.0	2.0	4.0	1.5	3.0
V0SeedCleaner:maxFitMass	0.8	1.5	0.8	1.6	0.8	1.6
V0SeedCleaner:minFitR	14.0	8.0	14.0	8.0	10.0	5.0

Table 4: Cuts on trajectory cleaning variables for pixelless, TOBTEC and combined seeding. Two sets of cuts are quoted, optimized for 80% and for 90% K_s^0 signal efficiency per cut.

6.2 First Results

Distributions and cut efficiencies of the discriminating trajectory cleaning variables defined above are shown in Figures 14 and 15, using TOBTEC seeding and K_s^0 signal as well as minimum bias and QCD jet background samples. It can be seen that the distributions for the background samples are very similar, as expected. The dashed (dotted) vertical lines indicate the 80% (90%) efficiency for the K_s^0 signal. The resulting 80% and 90% efficiency selection cuts on the discriminating variables are summarized for pixelless, TOBTEC and combined seeding in Table 4.

A successful seed cleaning procedure will maintain a high V0 signal efficiency, while rejecting at the same time as much as possible seeds not consistent with a V0 hypothesis, keeping CPU time under control. The results of an initial study, using the 80% and 90% cut sets defined above, are summarized in Table 5. Using the 90% cut set, a reduction of 46% was found on K_s^0 that were selected using the variables defined in Section 5. If no vertex fitting is applied, the reduction is only 9%. Using the 80% cut set, a reduction of 74% (31%) was observed with (without) the vertex fitting. However, a significant reduction in the number of background seeds could only be obtained with the 80% cut set and using a vertex fit. Since performing a vertex fit for many pairs of tracks/vertices is time consuming, the presented strategy needs further development and improvement.

In addition, a further efficiency loss was observed related to the two-step trajectory building procedure, compared with the default one-step standard trajectory building. This aspect also needs further study.

7 Conclusions and Outlook

A study of the reconstruction of V0 meson decays in the CMS silicon tracker was presented. The reconstruction is based on novel seeding algorithms that enable to reconstruct high p_T V0's decaying far away from the primary interaction point. In particular, a seeding algorithm using TOB and TEC layers was developed. A set of V0 selection cuts was developed and optimized, which made it possible to extract K_s^0 and a Λ^0 peaks from the events.

The seeding algorithms used for V0 reconstruction significantly increase the CPU time required for track reconstruction. Therefore, the V0 signal selection procedure needs to be complemented by a seed cleaning technique. A strategy for the implementation of such a cleaning was proposed and studied. It consists of a two-step trajectory building procedure, in which partial trajectories are reconstructed, followed by a cleaning procedure and full reconstruction of the remaining trajectories. The cleaning algorithm tests pairs of oppositely charged trajectories

Sample	80% Cuts no Vertex fit	 with Vertex fit	90% Cuts no Vertex fit	 with Vertex fit
K_s^0 signal	0.69	0.26	0.91	0.54
min. bias	0.35	0.045	0.57	0.15
QCD jets	0.8	0.065	0.95	0.35

Table 5: Efficiencies of the studied seed cleaning procedure, using the 80% and 90% cut sets and with or without using the vertex fit. The numbers are quoted for a K_s^0 signal sample, as well as for min. bias and QCD jets background samples.

for a V0 hypothesis using a set of discriminating variables. In the future, it should be further optimized in order to enable an efficient reconstruction in the CMS tracker whilst keeping the CPU time to a manageable level.

Acknowledgments

We are grateful for many helpful suggestions by Wolfgang Adam and Gigi Rolandi.

References

[1] In 1947, G. D. Rochester and C. C. Butler published two cloud chamber photographs of cosmic ray-induced events, one showing what appeared to be a neutral particle decaying into two charged pions, and one which appeared to be a charged particle decaying into a charged pion and something neutral. The estimated mass of the new particles was very rough, about half a proton's mass. These new particles were given the nickname of "V particles" [from wikipedia].

[2] F. Sikler, "Reconstruction of V0s and photon conversions with the pixel detector", **CMS AN 2006/101** (2006).

[3] W. Adam et al., "Track reconstruction in the CMS tracker", CMS Note **2006/041** (2006).

[4] B. Mangano, private communication.

[5] CMS Collaboration, "Physics Technical Design Report Vol. 1: Detector Performance and Software", **CERN/LHCC 2006-001** (2006).

[6] CMS Collaboration, "Data Acquisition and High-Level Trigger: Technical Design Report", **CERN/LHCC 2002-026** (2002).

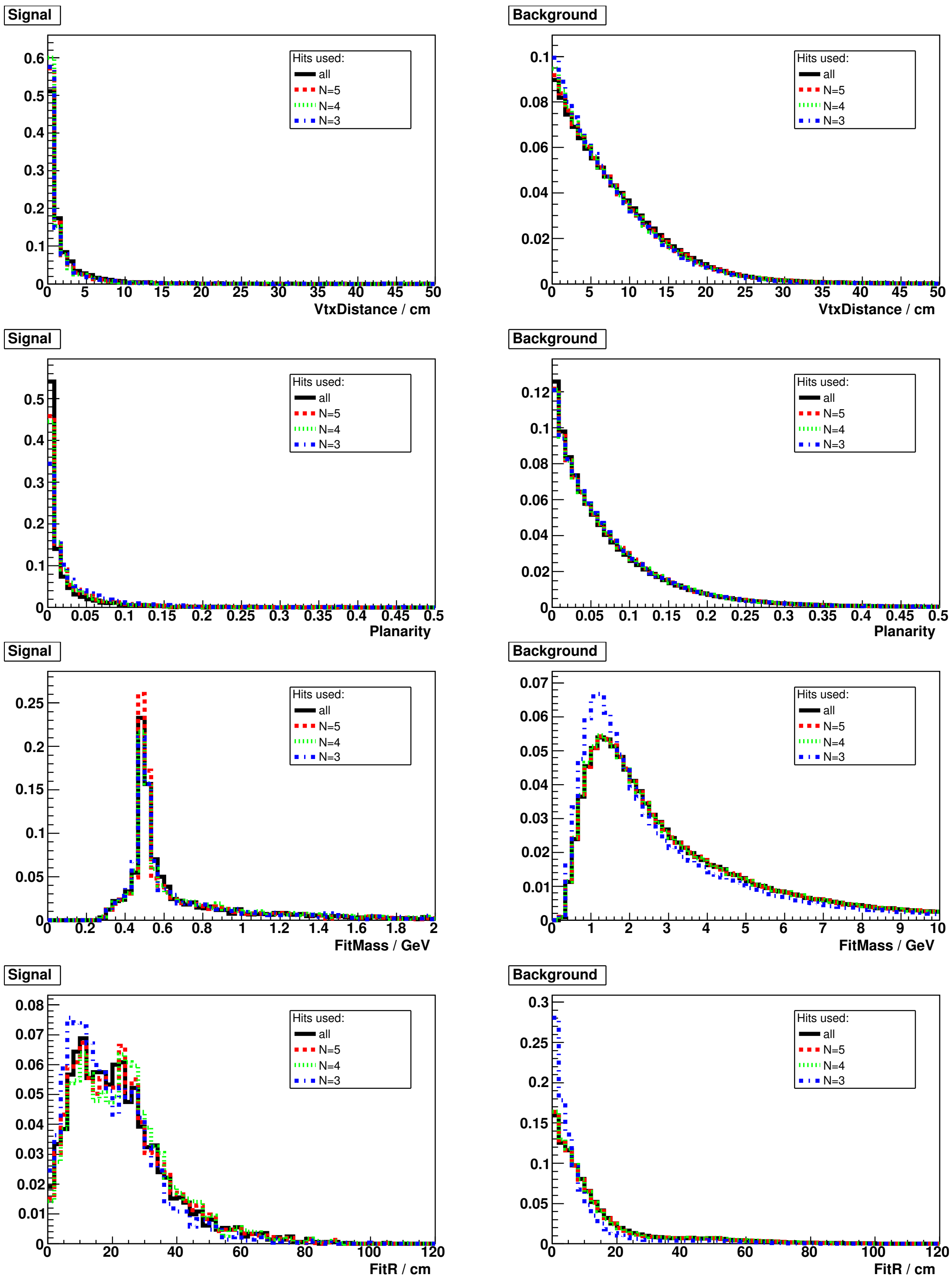

Figure 13: Trajectory cleaning variables for different settings of the maximum number of hits in the first stage of trajectory building. Shown are the distributions of `VtxDistance`, `Planarity`, `FitMass` and `FitR` for signal (K_s^0 particle gun, left) and background (minimum bias, right),using different cuts on the number of reconstructed hits N_{max}.

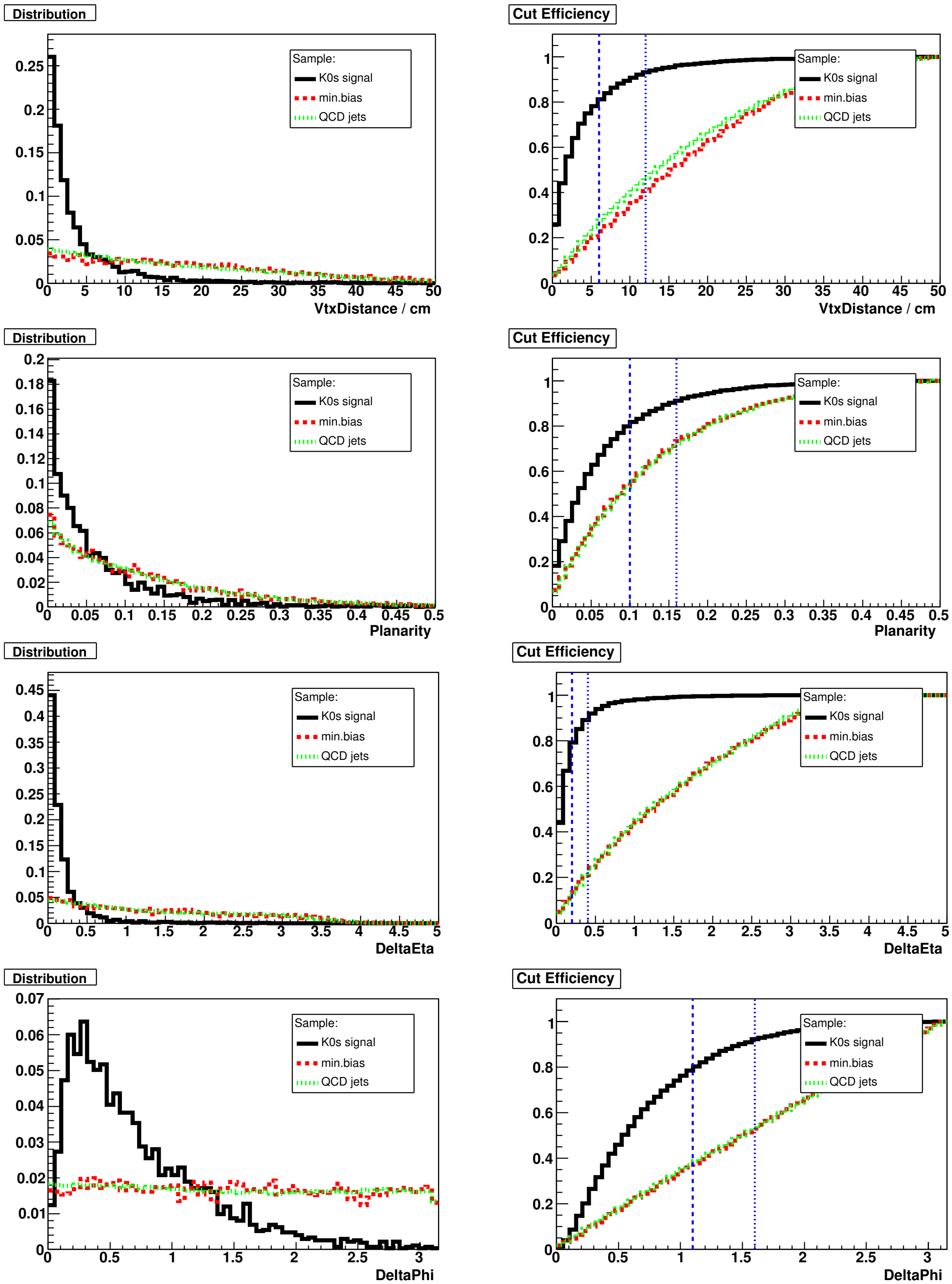

Figure 14: Trajectory cleaning variables: Shown are `VtxDistance`, `Planarity`, `DeltaEta` and `DeltaPhi` for K_s^0 signal, min. bias and QCD jet events as distributions (left), as well as in the form of cut efficiencies (right).

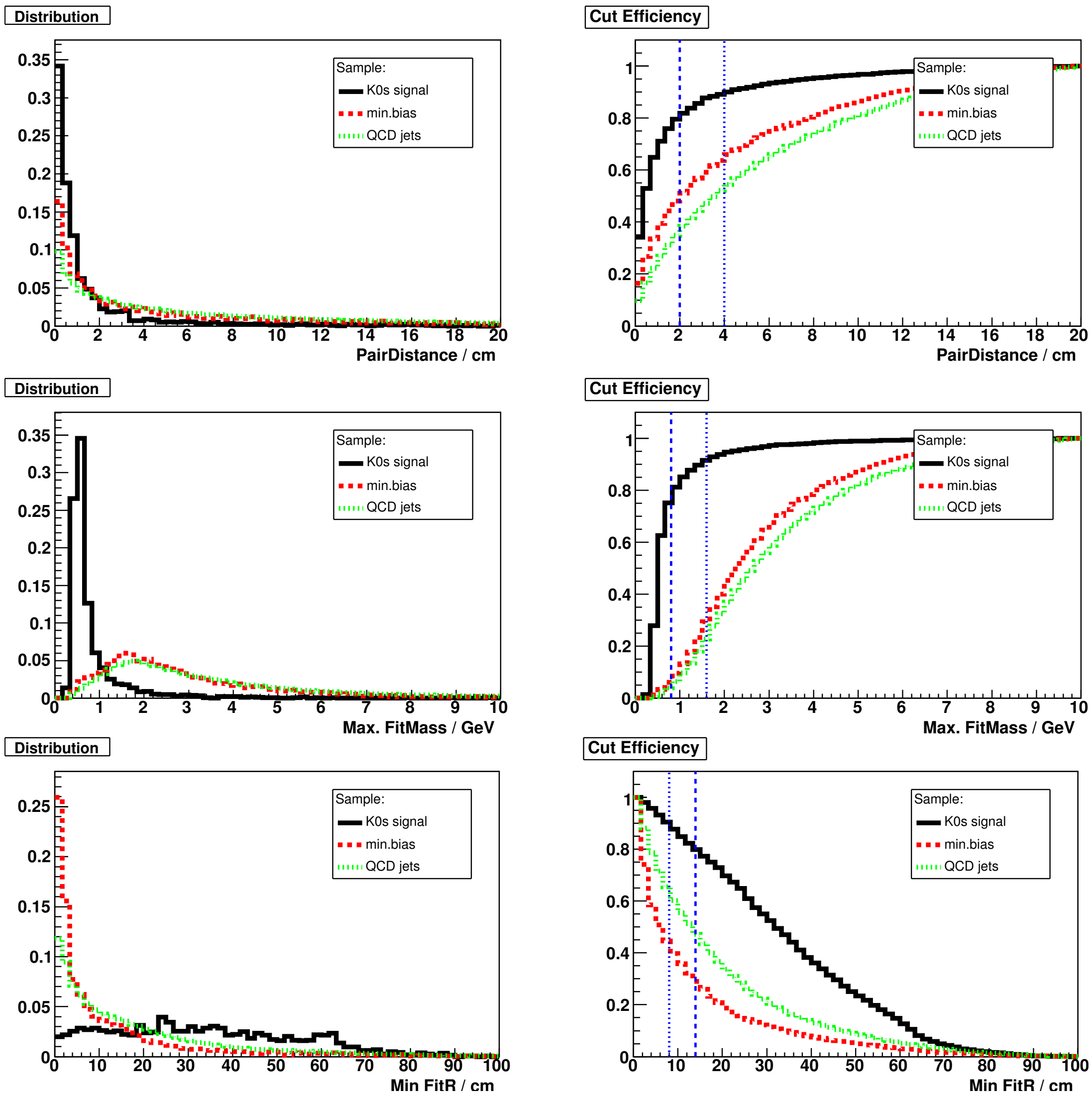

Figure 15: Trajectory cleaning variables: Shown are `PairDistance`, `FitMass` and `FitR` for K_s^0 signal, min. bias and QCD jet events as distributions (left), as well as in the form of cut efficiencies (right).

Appendix: TOBTEC and Combined V0 Seeding Code

In this appendix an overview of the code implemented for the TOBTEC seeding.is given. The code has been implemented in the ORCA reconstruction program, starting from the last version ORCA_8_13_3. It has been committed to the CVS HEAD. The following routines have been added or modified with respect to ORCA_8_13_3:

```
TrackerReco/TkHitPairs/interface/OuterSeedLayerPairs.h
TrackerReco/TkHitPairs/src/OuterSeedLayerPairs.cc
TrackerReco/TkSeedGenerator/interface/CombinatorialSeedGeneratorFromOuter.h
TrackerReco/TkSeedGenerator/src/CombinatorialSeedGeneratorFromOuter.cc
TrackerReco/TkSeedGenerator/interface/GlobalOuterSeedGenerator.h
TrackerReco/TkSeedGenerator/src/GlobalOuterSeedGenerator.cc
TrackerReco/TkDetLayers/interface/TkShortTECLayerBuilder.h
TrackerReco/TkDetLayers/src/TkShortTECLayerBuilder.cc
TrackerReco/TkSeedGenerator/interface/GlobalV0SeedGenerator.h
TrackerReco/TkSeedGenerator/src/GlobalV0SeedGenerator.cc
TrackerReco/GtfPattern/src/GroupedCombinatorialTrajectoryBuilder.cc
```

Remarks:

- `TkShortTECLayerBuilder` was modified in order to add the possibility to start short endcap layers in rings different from the innermost one
- In `GroupedCombinatorialTrajectoryBuilder`, a new steerable parameter was introduced:
  `GroupedCombinatorialTrajectoryBuilder:minNrOf2dHitsForRebuild`

Usage:

- Fast layers must be used:
  ```
  TkDetLayerFactory:TIB = FastTIB
  TkDetLayerFactory:TOB = FastTOB
  TkDetLayerFactory:TEC = FastTEC
  TkDetLayerFactory:TID = FastTID
  TkDetLayerFactory:BarrelPixel = FastBarrelPixel
  ```
- Pixelless seeding:
  `GlobalPixelLessSeedGenerator:originRadius=2.0`
- TOBTEC seeding:
  `GlobalOuterSeedGenerator:originRadius=5.0`
- Combined V0 seeding:
  ```
  GlobalV0SeedGenerator:MiddleSeedGenerator=GlobalPixelLessSeedGenerator
  GlobalV0SeedGenerator:OuterSeedGenerator=GlobalOuterSeedGenerator
  GlobalV0SeedGenerator:middleOriginRadius = 2.
  GlobalV0SeedGenerator:outerOriginRadius = 5.
  ```
- To use one of the above seed generators in place of the standard pixel seeding, for example with the standard `CombinatorialTrackFinder`, on needs to specify one of:
  ```
  CombinatorialTrackFinder:SeedGenerator = GlobalPixelLessSeedGenerator
  CombinatorialTrackFinder:SeedGenerator = GlobalOuterSeedGenerator
  CombinatorialTrackFinder:SeedGenerator = GlobalV0SeedGenerator
  ```
- The `GroupedCombinatorialTrajectoryBuilder` (GCTB) should be used in the tracking, in order to grow trajectories in both directions starting from the seed, e.g.
  `CombinatorialTrackFinder:TrajectoryBuilder=GroupedCombinatorialTrajectoryBuilder`
- The following parameters should be used for the GCTB with TOBTEC seeding, in order to avoid efficiency losses in the barrel-endcap transition region:
  ```
  GroupedCombinatorialTrajectoryBuilder:minNrOf2dHitsForRebuild = 1
  GroupedCombinatorialTrajectoryBuilder:minNrOfHitsForRebuild = 4
  GroupedCombinatorialTrajectoryBuilder:minimumNumberOfHits= 4
  ```