Objective 1: V^0 And Bremsstrahlung Finding And Reconstruction

Requirement capture, review of existing strategies and initial design for V^0 and bremsstrahlung fitting AlgTools

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Review of current reconstruction strategies in the ATLAS Inner Detector

Currently there are two ATLAS reconstruction packages, iPatRec [1] and xKalman [2], running within the ATHENA framework.

In iPatRec the track finding starts by forming track candidates using space-point combinatorials subject to criteria on maximum curvature and crude vertex region projectivity. A track-fit procedure gives the track parameters with covariance at the perigee. A track-follower algorithm propagates them to each layer in turn. Good quality track candidates are extrapolated to the TRT using a histogramming technique. In a final fit energy loss and Coulomb scattering are taken into account. Accepted tracks are required to have at least 6 silicon clusters and a fit probability greater than 0.001. Tracks with clusters in the 2 innermost pixel layers plus TRT association are termed primary tracks and are permitted a maximum of 3 holes. Otherwise a maximum of 1 hole is allowed. Truncated tracks have hits starting in the innermost layer but have not been successfully followed to the outermost layers or TRT. Secondary tracks start further out and are required to have TRT association. A track is not allowed to share more than 3 silicon clusters with any other track.

xKalman starts the reconstruction from three space-points in the silicon detector layers to define primary trajectories and perform a local pattern recognition in the precision layers. It is possible to investigate all 3-space-point combinations or only some of them. xKalman has nine levels of selectivity. By increasing the level of selectivity xKalman will decrease the number of 3-space-point combinations it uses for local pattern recognition. A Kalman filter smoother formalism is used to pick up all consistent clusters along the track in the silicon layers. The track is then extrapolated into the TRT. All TRT straw and drift time hits found within a narrow road are added for the final track finding and track fitting steps. Multiple scattering and energy loss are taken into account in the predictive equations of a Kalman filtering procedure by adding ”noise” terms to the covariance matrix of the track parameters at each measurement step. Accepted tracks are required to have at least 7 silicon clusters and 9 TRT clusters, less than 3 silicon holes and a maximum silicon gap of 2. The maximum number of all holes allowed is 22. The ratio of TRT hits to crossed straws is required to be greater than 0.7 and a track should have at least 5 uniquely assigned clusters. Only primary tracks are currently reconstructed with xKalman.

Both iPatRec and xKalman store their tracks as TrkTrack. This class is not intended for use in physics analysis and is instead optimised for reconstruction. The diagram in Figure 1 shows the current Post-Processing chain for the Inner Detector.

The V^0 finding and bremsstrahlung fitting AlgTool proposed here have to work with TrkTrack. Any output tracks will also be stored as TrkTrack objects.

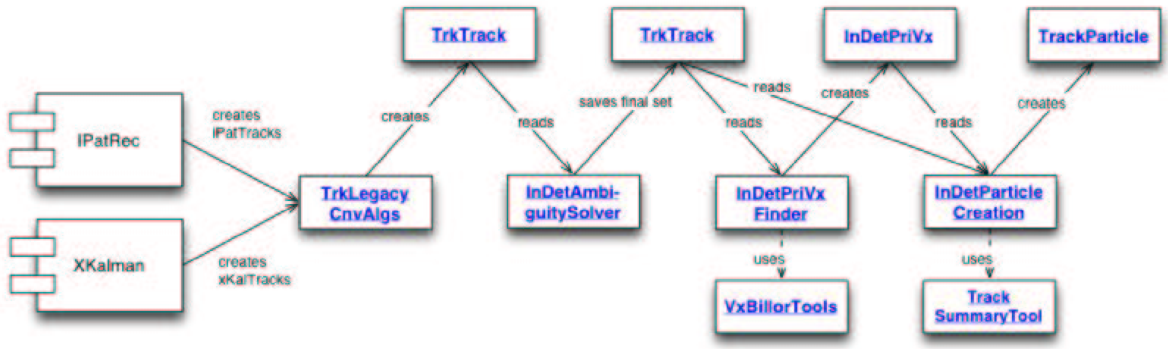

Fig. 1: Post-Processing chain for the Inner Detector.

V^0 Finding

High-level use cases and review of existing strategies

V^0 finding is an essential part in the reconstruction of exclusive B decay modes. Efficient reconstruction of K_S^0 would provide an increase in statistics necessary for the extraction of $\sin 2\beta$ from $B_d \to J/\psi K_S^0$ decays. Similarly, polarisation measurements in $\Lambda_b \to J/\psi \Lambda$ decays rely on finding Λ up to large decay radii.

Another use case for V^0 finding is b-tagging, where the standard procedure for b-jet identification is track impact parameter based and only recently new strategies utilising secondary vertices reconstruction inside jets have been proposed [3].

A V^0 finder can also be an useful tool for energy flow reconstruction and studies of strangeness production. The creation of a dedicated V^0 package will hopefully trigger more interest in this area.

For the purposes of designing a V^0 AlgTool we have studied in detail the requirements of the B-physics group but our plan is to design the tool in as general way as possible.

For the reconstruction of decay vertices the B-physics group until now has used a Fortran program CTVMFT [4], adapted from CDF code. The vertex algorithm uses a uniform magnetic field of 2T. Although the plan is to use VxBillorTools in the V^0 tool, we used CTVMFT on the $B_d \to J/\psi K_s^0$ events generated for the TDR studies [5] to study the current K_s^0 reconstruction efficiency and identify the area where additional effort is needed.

The events were simulated, reconstructed (with xKalman) and analysed with the 6.5.0 atrecon and 7.0.0 Athena releases both with Initial and Complete layouts. For the Initial layout the best performance was achieved with selectivity level 4, which was also used for the Complete layout. The minimal number of uniquely assigned clusters was changed from the default to 4 (TDR value). The reconstruction was done with a minimum of 7 and 6 precision hits required in the pattern recognition. The reconstruction procedure followed closely that described in the TDR [6]. Table 1 summarizes the K_S^0 efficiencies after various cuts and for the different detector layouts and reconstruction strategies investigated.

Figure 2 shows the effect of the number of precision hits on the total reconstruction efficiency as a function of the decay radius for Initial and Complete layout and the result from the TDR study (6 pre-

K_S^0 eff. %	TDR	Initial Layout			Final Layout		
	tdr-xKalman	atrecon 7 pr.hits	atrecon 6 pr.hits	Athena 6 pr.hits	atrecon 7 pr.hits	atrecon 6 pr.hits	Athena 6 pr.hits
fiducial region	68.6	66.1	66.1	64.7	66.1	66.1	64.7
Kine match	52.8	41.5	44.5	46.5	42.9	45.4	47.4
after χ^2 cut	43.6	33.0	34.7	36.8	34.1	35.4	37.7
after all cuts	41.1	28.0	29.2	30.8	28.9	29.7	31.2

Table 1: Fraction of K_S^0 generated within the fiducial region (1 cm $< R(K_S^0) <$ 37 cm, $|z| <$ 210 cm), of reconstructed K_S^0 where both pions have been reconstructed by xKalman and the fraction of successfully fitted K_S^0 after the χ^2 cut and after all selection cuts were applied for the different detector layouts and reconstruction strategies.

cision hits). The results are in agreement with the TDR conclusion that relaxing the requirement on the number of precision hits increases the acceptance but also reduces the quality of the reconstruction, resulting in similar overall efficiency (see Table 1). Clearly just modifying the default xKalman parameters is not the right strategy. Optimisation of xKalman seems to be necessary for improving the efficiency and quality of the primary tracks reconstructed with the new detector layouts. But as is obvious even from the TDR results alone additional secondary tracks need to be provided from the pattern recognition so that better efficiency is achieved at decay radii greater than 10 cm. An increase in the fiducial volume by reconstructing tracks in the TRT + SCT and TRT only would be desirable if V^0 with radii greater than 40 cm are to be found.

Although we have not studied the performance of iPatRec, the results are not expected to be significantly different as both packages have been shown to produce similar efficiency and quality of the reconstructed tracks. iPatRec also lacks a TRT based pattern recognition.

Requirements for an initial design

We propose a V^0 AlgTool, InDetV0 Finder, which can be run after the InDetPriVx Finder, with the proposed structure repeating the InDetPriVx structure of Figure 1, eg InDetV0 Finder reads TrkTrack, uses VxBillorTools and creates InDetV0 objects. It should contain the following components:

- Secondary track finding

  After removing/masking the digitizations included in tracks found by the standard procedures (iPatRec/xKalman) a secondary tracking procedure will be developed based in the TRT straw detectors. Separate technique will probably have to be developed for the barrel and end cap straw sections. Having formed tracks in the TRT an attempt will be made to unambiguously add any precision points which may be available, and more tentatively any calorimeter information. Tracks found by this methods will be saved as TrkTrack and subsequently combined with previously found tracks to attempt to form a V^0 candidate.

- V^0 candidate finding

These are formed using pairs that have:

- a positive and negative charge hypothesis
- their first measured points within a certain tolerance of each other (eg 3 layers)
- an invariant mass hypothesis within some loose tolerance of a V^0 mass candidate (K_s^0, Λ, γ)
- other possible kinematic cuts

- Secondary vertex fitting

  A secondary vertex finder is needed, probably based on the Billoir fitting package, that can cope with combinations of the following categories of tracks:

  - standard primary tracks (found by xKalman or iPatRec)
  - TRT + precision points
  - TRT alone.

  V^0 candidates after this stage would only be considered if they have formed a good vertex (eg have a good χ^2/n.d.f.)

- Kinematic fitting

  Provide a tool for doing a kinematic fit to a given V^0 production vertex and/or a mass constraint.

- Create a V^0 object which must be capable of holding the following information

  - used track information
  - fitted vertex information (not kinematic fit)
  - mass hypotheses and χ^2 information

  and any number of the following (in the case of kinematic constraints):

  - kaon mass hypothesis tracks/vertex/and χ^2 information
  - Λ mass hypothesis tracks/vertex/and χ^2 information
  - $\bar{\Lambda}$ mass hypothesis tracks/vertex/and χ^2 information
  - γ mass hypothesis tracks/vertex/and χ^2 information

- Create a tool for resolving any V^0 ambiguities (eg where V^0s share a track)

- Provide analysis tools to facilitate the selection of certain types of V^0 candidate.

The InDetV0 Finder should provide the user with the option to select all or any subset of the above at run time by means of setting flags in the jobOptions (python script) provided.

Bremsstrahlung Recovery

High-level use cases and review of existing strategies

$Z \to e^+e^-$ and $J/\psi \to e^+e^-$ decays are not only important part of many physics studies (Higgs, SUSY, QED, B-physics, charm etc.) but they are also an invaluable tool for calibrating the detectors, and in particular the electromagnetic calorimeter. The reconstruction of electrons is more problematic than the reconstruction of other charged tracks, since in addition to ionisation energy loss and multiple Coulomb scattering, electrons suffer from large energy losses due to bremsstrahlung.

The fraction of energy lost to bremsstrahlung depends on the thickness, t, of material traversed by the electron in units of radiation length, X_0 and is given by [8]:

$$f(z) = \frac{(-\ln z)^{t/\ln 2 - 1}}{\Gamma(t/\ln 2)}, \tag{1}$$

where z is the fraction of energy remaining after the material layer is traversed.

The material distribution in the Inner Detector is shown in Figure 3, where it can be seen that the combined radiation length of all detectors is around $0.3X_0$ at $\eta = 0$ and $1.0X_0$ at $|\eta| = 2$ for the DC1 layouts (a) while for the TDR layout the values were around $0.28X_0$ at $\eta = 0$ and $0.6X_0$ at $|\eta| = 2$ (b).

Therefore there is a sizable probability for an electron to lose a significant fraction of its energy in the Inner Detector. Although much of the bremsstrahlung radiation will be collected by the EM Calorimeter, the track in the ID can be seriously affected, resulting in a poorly reconstructed p_T, or even in a failure to reconstruct the track altogether.

In the Inner Detector, bremsstrahlung recovery for electron tracks can be done in two complementary ways:

- at the track level, making corrections which allow for bremsstrahlung when material is traversed

  Both iPatRec and xKalman have implemented such a strategy.
  For tracks where the fraction of TRT hits exceeds 15%, xKalman attempts to recover the energy loss by incorporating an additional noise term in the Kalman Filtering formalism. The modified track fit is retained if the track quality, measured by the number of precision hits, is improved. xKalman is sensitive to hard bremsstrahlung since this is treated as continuous noise and not as a point-like break in the track curvature.

- by including the position of the associated EM cluster as an external point in the track fit (no use is made of the measured energy of the cluster).

  In both iPatRec and xKalman such a correction is automatically attempted in the case of seeding from a Calo cluster.

In iPatRec there is also a possibility to fit the track in just the first few silicon layers, thereby reducing the sensitivity to bremsstrahlung. Giving more weight to the earlier part of the track reduces the sensitivity to bremsstrahlung but at the cost of reduced p_T resolution.

Since the reconstruction of the low p_T electrons coming from a J/ψ decay can give us a good idea of the performance of the existing brem recovery options in iPatRec and xKalman, we decided to re-simulate, using DC1 software, the $B_d \to J/\psi K_s^0$, $J/\psi \to e^+4e^-4$ events used for the TDR studies. The events were reconstructed with Athena 6.0.3 using both xKalman and iPatRec, followed

	Brem. Rec.	$\lvert\eta\rvert$ range	Δm_0, MeV	$\sigma_{\rm left}$, MeV	$\sigma_{\rm right}$, MeV	ε_R, %	ε_W, %
TDR	Yes	< 0.7	-14 ± 5	94 ± 5	42 ± 4	79.4	66.6
	No	< 0.7	-17 ± 5	97 ± 5	41 ± 4	74.1	62.8
NEW	Yes	< 0.7	-21 ± 5	117 ± 6	38 ± 4	76.4	58.6
	No	< 0.7	-27 ± 5	119 ± 6	36 ± 3	71.6	55.1
TDR	Yes	> 0.7	-24 ± 6	141 ± 8	46 ± 5	74.5	58.5
	No	> 0.7	-42 ± 6	128 ± 8	50 ± 4	64.1	50.4
NEW	Yes	> 0.7	-80 ± 13	130 ± 17	80 ± 10	69.1	45.6
	No	> 0.7	-101 ± 9	128 ± 19	82 ± 6	57.9	39.3
TDR	Yes	All	-18 ± 2	122 ± 3	43 ± 2	75.9	61.0
	No	All	-27 ± 3	118 ± 4	45 ± 3	67.2	54.2
NEW	Yes	All	-39 ± 6	140 ± 7	52 ± 4	71.3	49.6
	No	All	-42 ± 3	157 ± 9	47 ± 3	62.1	44.1

Table 2: Asymmetric Gaussian fit results to the reconstructed electron-positron invariant mass distributions from $J/\psi \to e^+e^-$ decays, in the mass interval between 2.85 and 3.15 GeV.

by egammaRec. In order to achieve full compatibility of TDR and DC1 physics analyses, the TDR detector-simulated events were reconstructed in this study again, using the data-cards requiring the TDR geometry and uniform magnetic field. The CTVMFT secondary vertex code was used to reconstruct the $J/\psi \to e^+e^-$ decay.

In the setup for xKalman track reconstruction, two separate values of the parameter BREMOPT were used: BREMOPT=0 (default), meaning that no bremsstrahlung recovery attempt is made, and BREMOPT=61, recommended by the author for maximum (best) brem recovery.

The analysis was kept as close as possible to the one described in the TDR [5]. The identification of electrons from J/ψ decays was made based on the MC truth information. The J/ψ reconstruction efficiency was assessed separately for the barrel and the end-cap regions. In order to calculate the J/ψ reconstruction efficiency within a mass window, ε_W, cuts were applied to the invariant mass of the electron-positron pair, with an asymmetric window around the nominal J/ψ mass, $M_{J/\psi} = 3096$ MeV.

The resulting efficiencies of J/ψ reconstruction for various layouts, brem recovery options and pseudorapidity ranges, are presented in Table 2. The electron pair invariant mass distributions for all these cases are shown in Figure 4, where the solid lines correspond to the brem recovery option switched on, while the dashed lines describe the same distributions without brem recovery.

All shown distributions were fitted using an asymmetric Gaussian function with different values of σ, $\sigma_{\rm left}$ and $\sigma_{\rm right}$, either side of the fitted peak mass m_0. The parameter $\sigma_{\rm right}$ characterizes the effective resolution in the invariant mass of the pair, while $\sigma_{\rm left}$ is a measure of the deterioration of this resolution due to bremsstrahlung. The fits were performed in a narrow mass interval, between 2.85 and 3.15 GeV. The fit quality was generally good, and the fitted values for the parameters $\Delta m_0 \equiv m_0 - M_{J/\psi}$, $\sigma_{\rm left}$ and $\sigma_{\rm right}$ are also shown in Table 2.

As seen from Figure 4 and confirmed by Table 2, at this level of statistical precision there seems to be no significant difference in the effective resolutions between the TDR and the new layout at the higher mass slope, but the deterioration of resolution due to bremsstrahlung, clearly visible at the lower mass tail, is more significant with the new detector geometry. Compared to the TDR, there is a noticeable increase in the low mass tail, resulting in the overall broadening and shifting of the J/ψ peak, which is linked to the increase of material inside the detector, especially at high η values.

The use of the brem recovery option allows to recover the $J/\psi \rightarrow e^+e^-$ decays in some cases, but the low-mass tail still remains visibly larger than in the TDR. The brem recovery option gives some improvement in the shifts of the peak mass from its nominal value, but the shifts themselves are significantly bigger in the new layout. In both layouts, the use of the brem recovery option results in a modest ($\sim 10\%$) improvement in the J/ψ reconstruction efficiency. However, the efficiency in the new layout is about 20% lower, than in the TDR.

A comparative study of xKalman vs iPatRec was also performed. On the whole, the two reconstruction packages were well consistent with each other, with iPatRec being slightly more efficient in the barrel area, while the brem recovery option in xKalman allowed to achieve small improvements in the endcap region (see Figure 5).

The use of electron identification by egammaRec package was also attempted at the analysis stage. It was noted that the J/ψ reconstruction efficiency was somewhat higher when using iPatRec/egammaRec tracks, probably due to Ecal cluster information being used to re-fit some tracks. However, a detailed comparison of the reconstructed and re-fitted J/ψ invariant mass distributions was not possible due to the absence of a full covariance matrix information in the Combined Ntuple for egammaRec tracks.

It is quite clear that the existing strategies for bremsstrahlung recovery fall short of achieving a satisfactory electron track reconstruction. More effort can be put into re-optimising the performance of the tools but it is not clear if the increased material content of the new ID layouts would allow a significant improvement.

The non-optimal performance of the brem recovery algorithms, especially in the case of Kalman filters is due to the assumption of Gaussian probability density distributions for the electron energy loss. A non-linear estimator, which would take into account the actual shape of distribution (1), can be expected to perform better. A non-linear generalisation of the Kalman filter, the Gaussian-sum filter (GSF), has been proposed recently [9] and has been implemented by CMS [8].

In the GSF the distributions of all state vectors are Gaussian mixtures, i.e. weighted sums of Gaussians. The different components of the mixture model different degrees of hardness of bremsstrahlung in each detector layer. The strict application of the GSF algorithm leads very quickly to a prohibitively large number of components due to the combinatorics involved at each layer of material traversed. Therefore the number of components has to be repeatedly reduced to a predetermined number, N. As was shown by CMS, keeping the N components with the largest weights does not result in a good parameter fit. A more successful approach is to merge the components into clusters until the required number is reached. Once the infrastructure for a GSF is implemented in Athena, studies will have to be performed to determine the best approach, suitable for the Atlas Inner Detector.

Requirements for an initial design

A GSF AlgTool, InDetGsf, will read a TrkTrack object, and provided that a bremsstrahlung fit is required, will produce a modified TrkTrack, which will be passed to the InDetAmbiguitySolver, see Figure 1.

InDetGsf should consist of the following components:

- pre-selection process

  needed to determine if a brem fit is suitable (could also take a user-defined pointer to a track)

- a Gaussian sum filter

  the parameters (N, the number of Gaussians and the values of the parameters that define them) should be set to optimised default values with the possibility of changing these in the jobOptions (python scripts) provided
- decision making process

  to determine if the brem recovery was successful
- storing the new re-fitted track as TrkTrack

References

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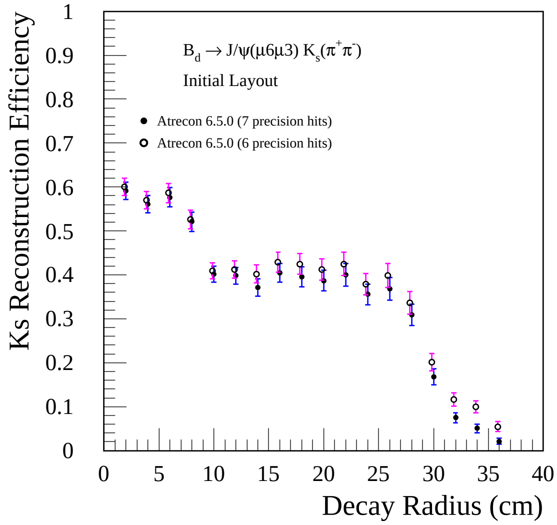
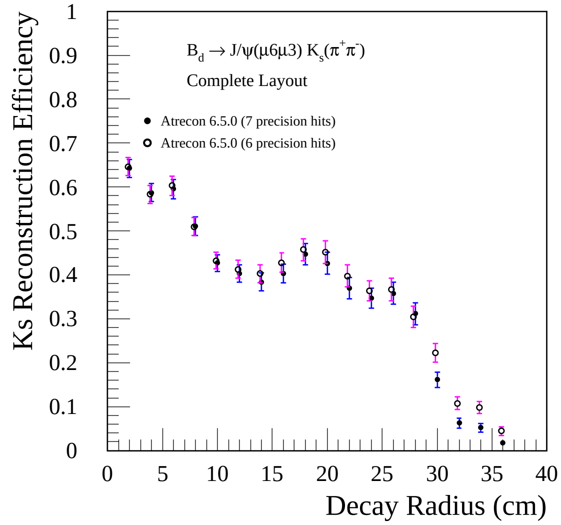


(a)



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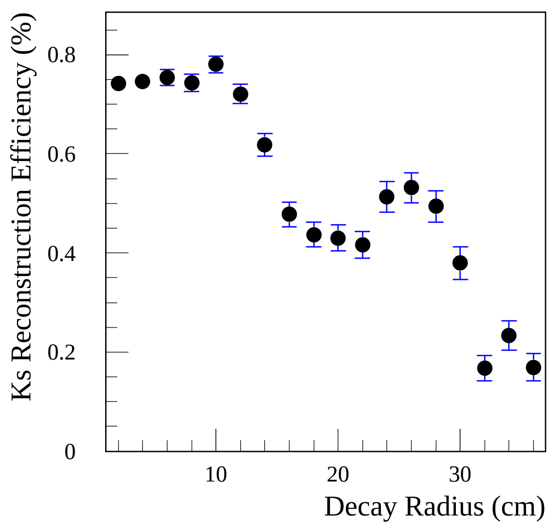
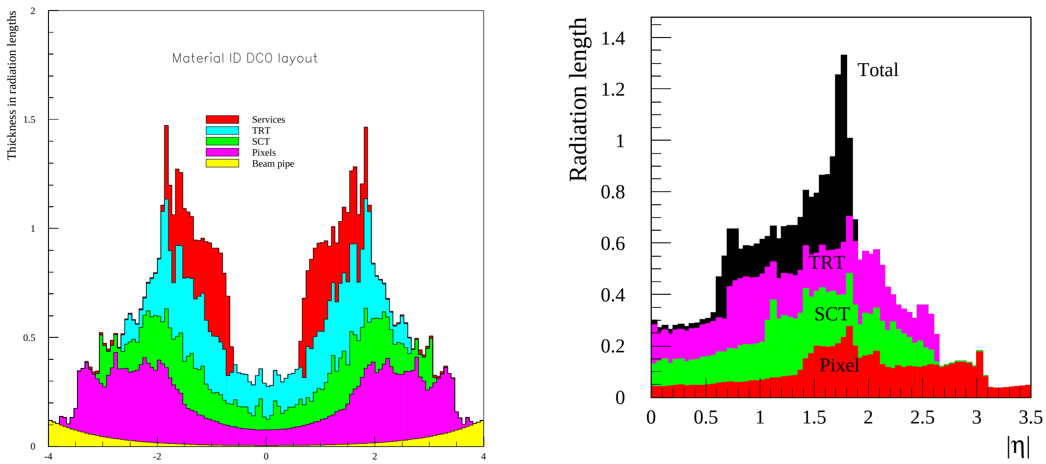


(c)

Fig. 2: K_S^0 reconstruction efficiency as a function of the decay radius in atrecon with a minimum of 7 and 6 precision hits for (a) Initial, (b) Complete layout and (c) TDR.



(a) (b)

Fig. 3: Cumulative distribution of material distribution in number of radiation lengths as a function of η for pixels, SCT, TRT and external services. (a) New detector (DC1) layout [7] ; (b) TDR layout [6]

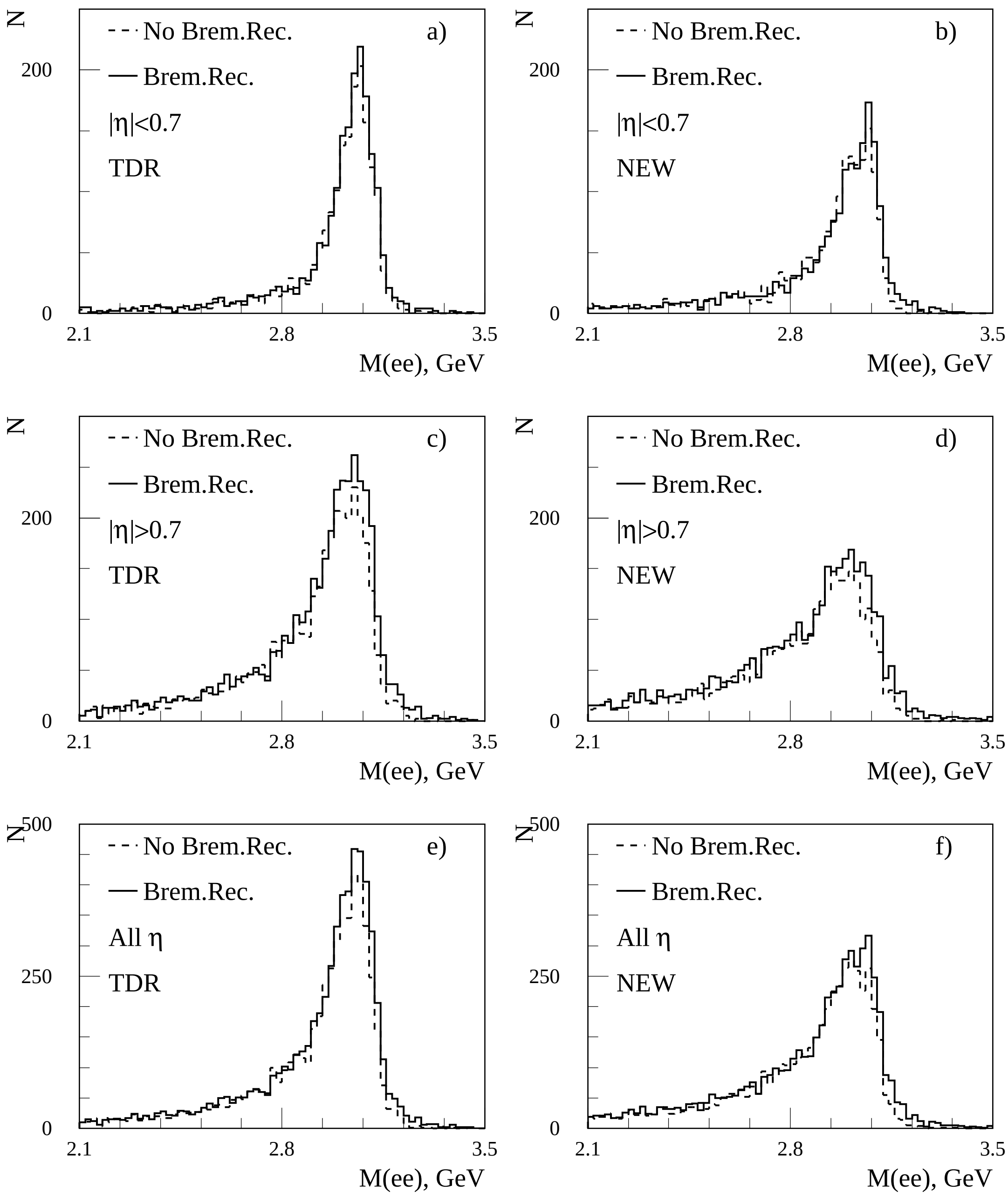


Fig. 4: The electron-positron pair invariant mass distributions with the TDR layout (a,c,e) compared to the same distributions with the new layout (b,d,f): (a,b) both electrons have $|\eta| < 0.7$; (c,d) at least one electron has $|\eta| > 0.7$; (e,f) full η range. The dashed lines describe the spectra without brem recovery, while the solid lines describe the distributions with the brem recovery option.

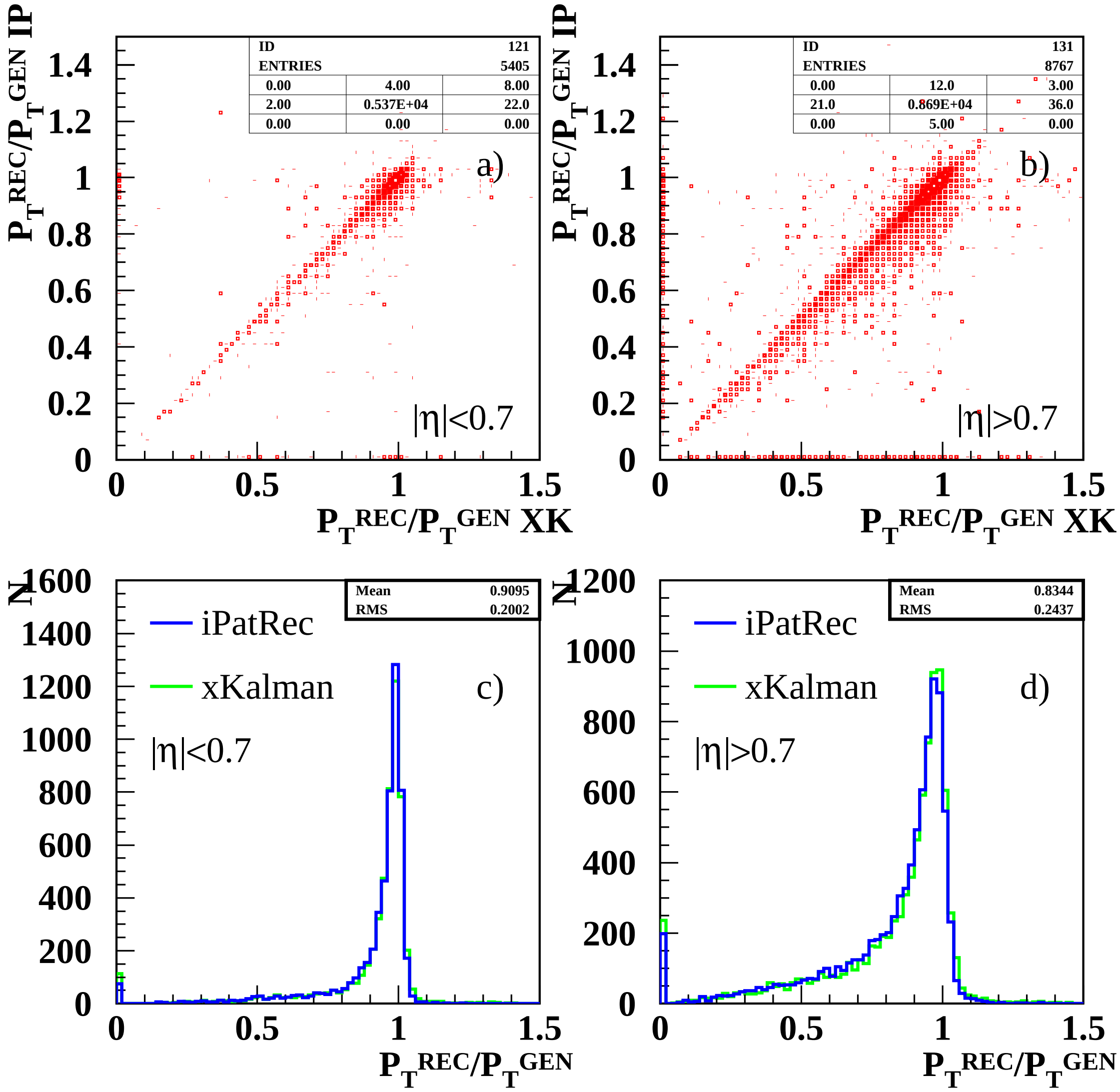


Fig. 5: The ratio of reconstructed and generated transverse momenta for electrons and positrons, as given by xKalman and iPatRec, in the barrel $|\eta| < 0.7$ and endcap $|\eta| > 0.7$ regions.