Measurement of γ_s from B^+ to D^0 K^+ and reconstruction of K_s decays

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The (b,s) unitarity triangle

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Six triangular relations from unitarity of V_{CKM} .
Among them : the "(b,s)" triangle.

At FCC-ee, all angles of the (b,s) triangle can be measured directly

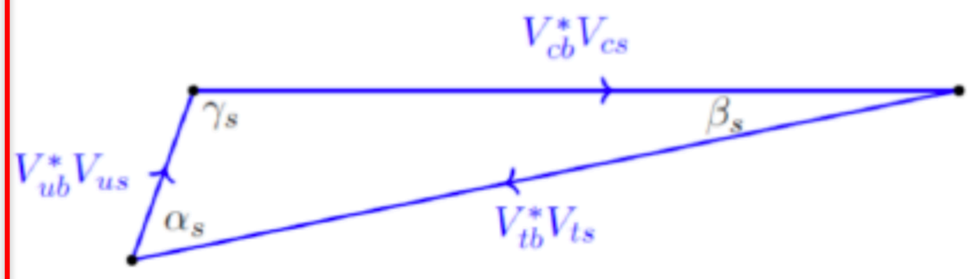
β_s : via $B_s \rightarrow J/\psi\ \phi$

α_s : B_s to D_s K

γ_s : B^+ to D^0 K+

See R. Aleksan, L. Oliver, E.P: 2107.02002 and 2107.05311

$$V^*_{ub} V_{us} + V^*_{cb} V_{cs} + V^*_{tb} V_{ts} = 0$$



$(\alpha_s, \beta_s, \gamma_s) \sim (67^o, 1^o, 111^o)$

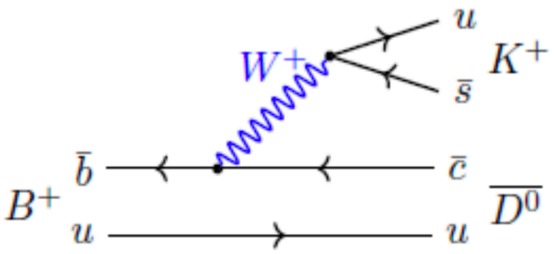
These processes provide good benchmarks for detector performance:

- Excellent tracking performance (mass resolutions)
- Excellent EM resolution (modes with neutrals)
- K/Pi separation in a wide p range
- Ks reconstruction (crucial for many flavour analyses)
  - Crucial for many flavour analyses
  - For example for measuring γ_s

Measurement of γ_s : B^+ to D^0 K+

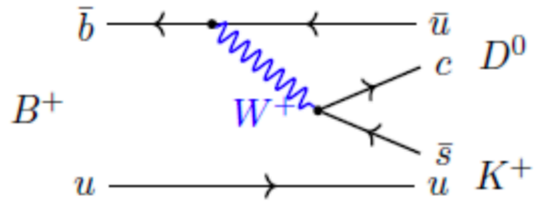
$$\gamma_s = \arg\left(-\frac{V_{cb}^* V_{cs}}{V_{ub}^* V_{us}}\right)$$

Direct CP violation in decays of B+ to D^0 ($\overline{D}^0$) K^+ : well-known method to measure the γ angle of the "usual" UT. Can be applied too to measure γ_s.



$B^+ \to \overline{D}^0 K^+$

$V_{us} V^*_{cb}$



$B^+ \to D^0 K^+$

$V_{cs} V^*_{ub}$

With a final state f that is accessible to both D^0 and $\overline{D}^0$: interference, and CPV.

D^0 ($\overline{D}^0$) $\to$ $K^+ K^-$ ($\eta_{CP} = 1$) or $K_s \pi^0$ ($\eta_{CP} = -1$) : $\Phi_{CKM} = \pi + \gamma_s$

$\Gamma (B^+ \to f_{(D)} K^+) \neq \Gamma (B^- \to f_{(D)} K^-)$. Asymmetry $\mathcal{A}_{CP}$ given by :

$$\frac{\pm 2\mathcal{R} \sin\Delta \sin\gamma_s}{1 + \mathcal{R}^2 \mp 2\mathcal{R}\cos\Delta\cos\gamma_s}$$

$$\mathcal{R}^2 = \frac{Br(B^+ \to D^0 K^+)}{Br(B^+ \to \overline{D^0} K^+)}$$

R already known to 5%, can be much improved with D0 semi-leptonic decays

Δ = strong phase difference. PDG: -130° ± 5°

Combination of $\mathcal{A}^+_{CP}$ ($K^+ K^-$) and $\mathcal{A}^-_{CP}$ ($K_s \pi^0$) gives Δ and γ_s (8-fold ambiguity)

Expected sensitivities

BR ($B+ \to \overline{D}^0 K+$) ~ $3.6\ 10^{-4}$
BR ($B+ \to D^0 K+$) ~ $3.6\ 10^{-6}$
BR ($D^0 \to K^+ K^-$) ~ $4.1\ 10^{-3}$
BR ($D^0 \to K_s \pi^0$) ~ $1.2\ 10^{-2}$

Indicative # of B+ decays

150 ab^{-1} at FCC-ee at the Z peak.

$\overline{D^0} K^+$	$\overline{D^0} \to K^+ K^-$	$\sim 5.8\ 10^5$
$D^0 K^+$	$D^0 \to K^+ K^-$	$\sim 5.7\ 10^3$
$\overline{D^0} K^+$	$\overline{D^0} \to K_s \pi^0$	$\sim 1.2\ 10^6$
$D^0 K^+$	$D^0 \to K_s \pi^0$	$\sim 1.2\ 10^4$

Asymmetries are sizable. E.g. with $\Delta = -130^o$ and $\gamma_s = 108^o$:

$\mathcal{A}^+_{CP} (K^+ K^-) \approx -15\%$ and $\mathcal{A}^-_{CP} (K_s \pi^0) \approx 14\ \%$

with expected statistical uncertainties of ~ 0.1% (absolute, accounting for approx. acceptance and efficiencies), which corresponds to $\sigma (\gamma_s)$ of 2.8^o

(uncertainty on γ_s depends on the value of Δ – ranges between < 1^o to a few deg.)

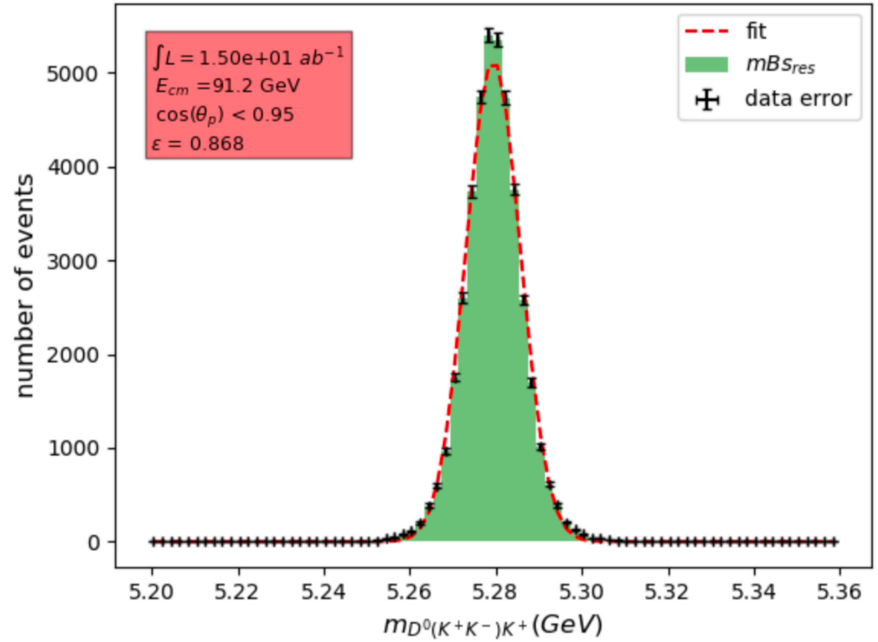
Possible improvements with additional modes, e.g. $D \to K_s \eta$, $B^+ \to D K^{*+}$

Measurement of γ_s to $1^o - 2^o$ within reach.

Signal reconstruction

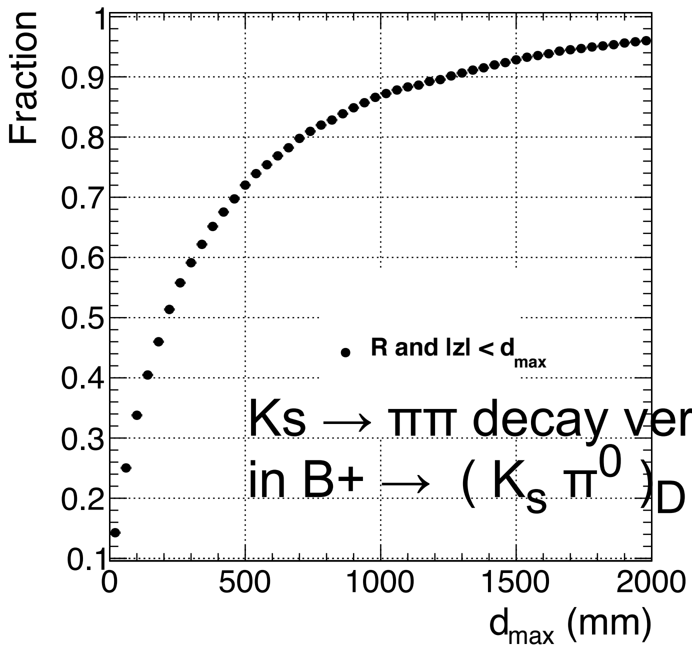
- $B^+ \to (K^+ K^-)_D K^+$: should be quite easy thanks to excellent mass resolution

  σ ~ 6 MeV on the B+ mass



- $B^+ \to (K_S \pi^0)_D K^+$: much more challenging

  - Worse mass resolutions
  - Displaced pion tracks from K_S decay



Ks → ππ decay vertex in $B+ \to (K_S \pi^0)_D K^+$

30% of the K_S decay at > 50 cm from the IP

Need to reconstruct the Ks up to O(1m) from the IP:
ε (acceptance) x ε (fiducial) = 85% x 87% = 74%

With acceptance = | cos theta | < 0.95

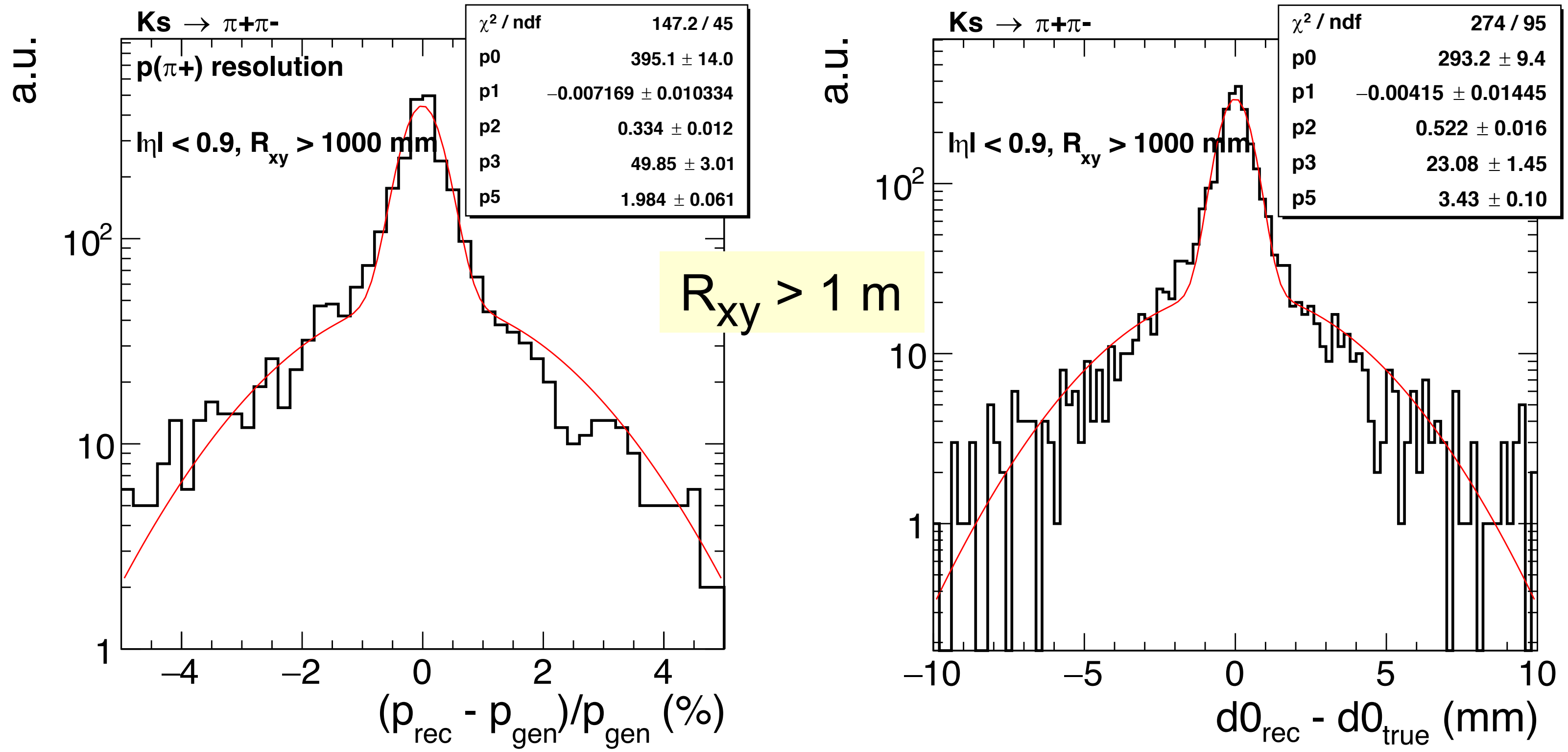
E.Perez

Simulation setup

Signal events $B^+ \rightarrow (K_s \pi^0)_D K^+$: (EvtGen + Pythia) passed through Delphes

- latest version of Delphes: uncertainties of track parameters are determined also for displaced tracks (TrackCovariance module, Franco Bedeschi)
- Detector = baseline IDEA unless specified otherwise
- Edm4hep events, FCCAnalysis framework

Validation: take the reco'ed tracks that are MC-matched with the two pions from the Ks decay. For central tracks (| η | < 0.9), look at the resolution of track parameters in bins of Rxy, the MC radial position of the Ks decay vertex. Examples:



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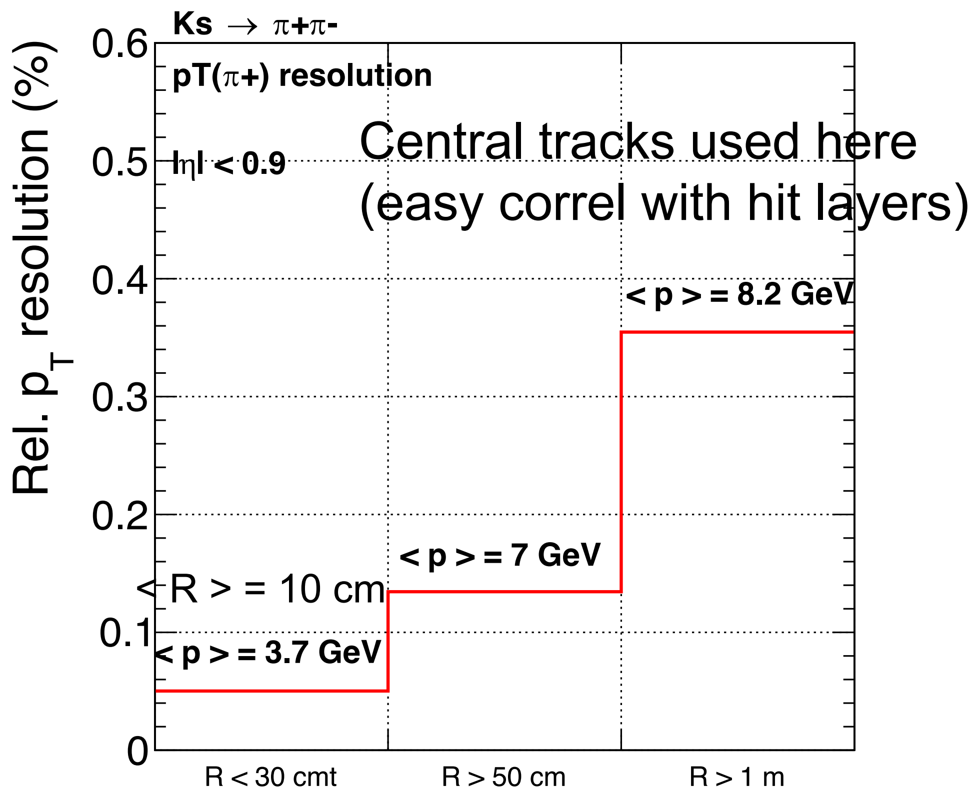
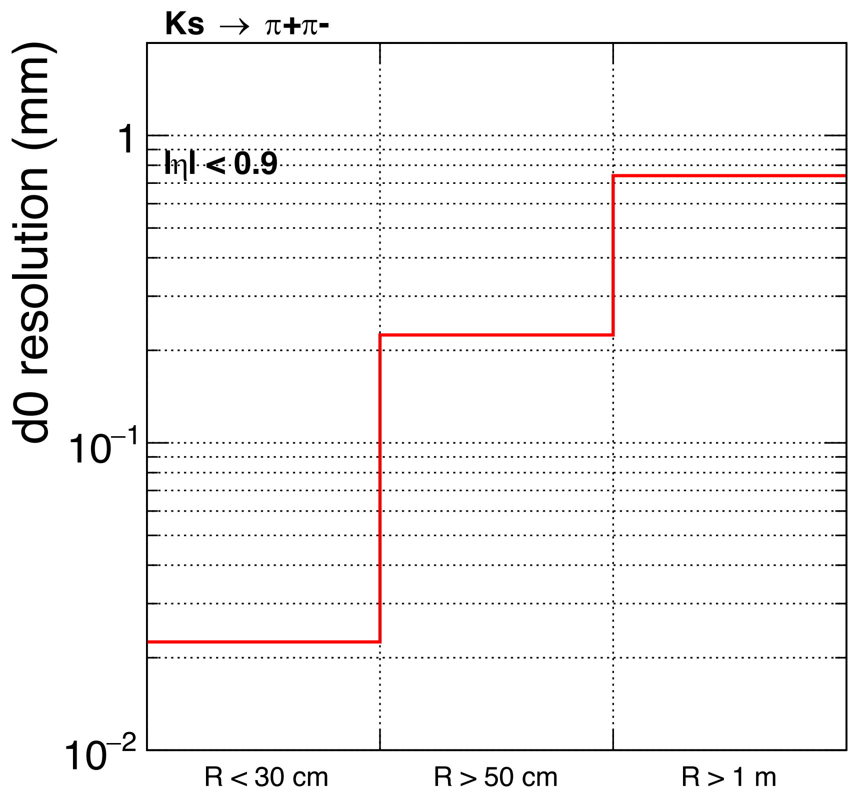
Resolutions for displaced tracks



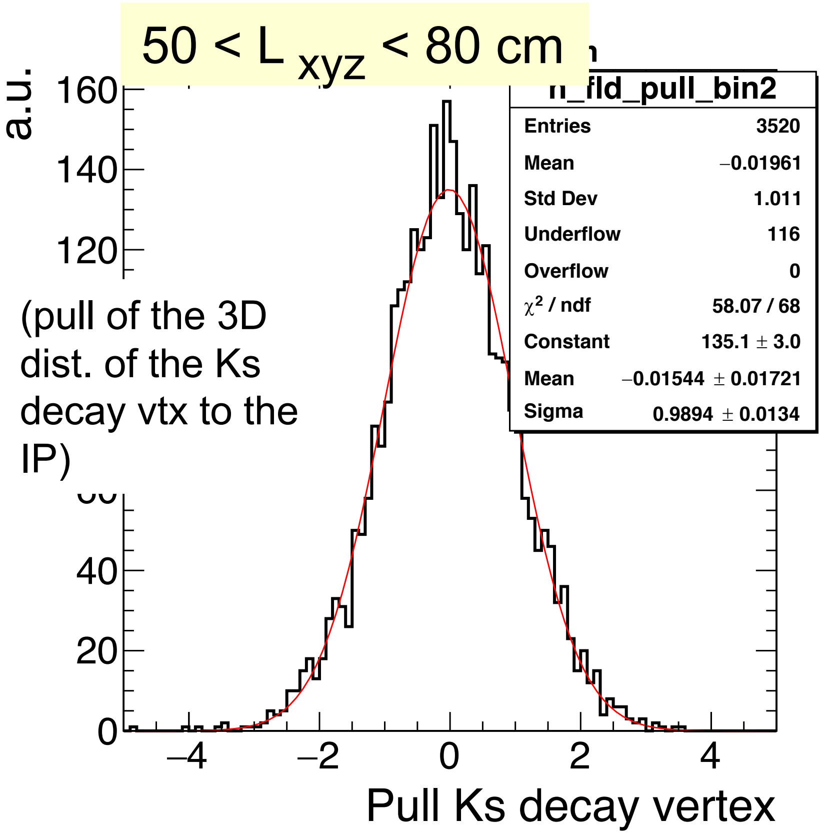


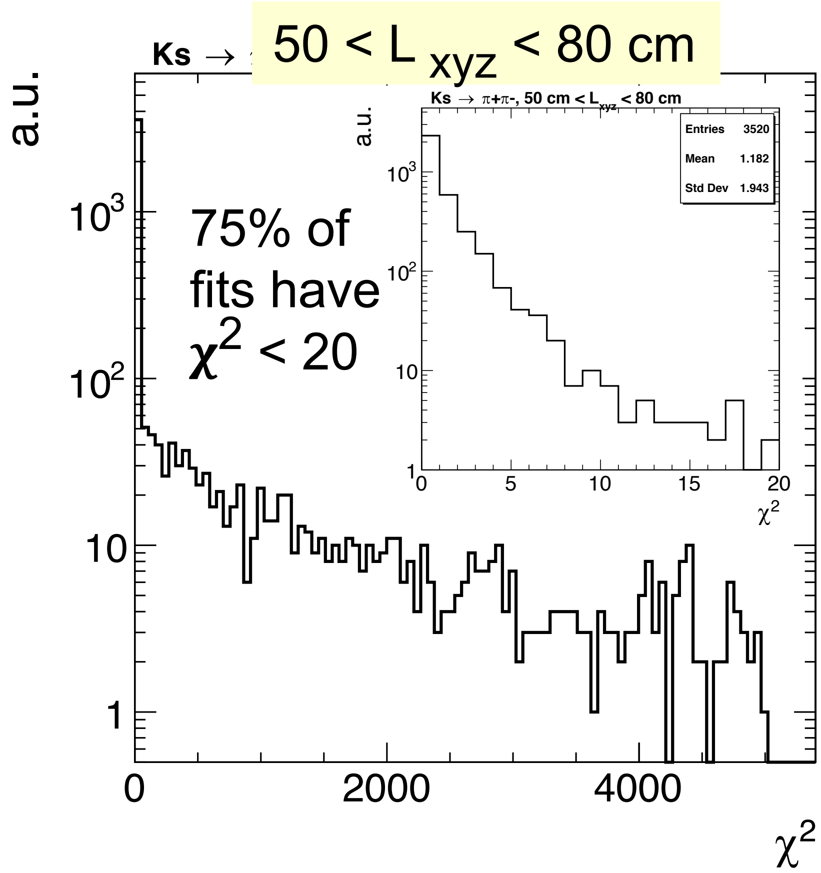
- Momentum resolution worsens by O(3) between “R > 50 cm” and “R > 1 m”, and by O(7) between “prompt” (R < 30 cm) and “R > 1 m”
  - Note large MS component in “prompt” bin
- Resolution on d0 or z0 : worsens dramatically as soon as the track makes no hit in the Si layers (single hit resolution 3 μm -> 100 μm)
- Qualitatively consistent with expectations (e.g. Drasal/Riegler, NIM A910, 127)

$K_s \to \pi^+\pi^-$ vertex reconstruction (perfect seeding)

Vertex fit from the two reco'ed tracks that are MC-matched with the pion tracks.
Vertex fitter: code from Franco Bedeschi (in Delphes and in FCCAnalyses).

- As soon as no VXD hit on the track: distribution of the χ^2 of the vertex fit has large tails. Suspect that the starting value of the fit is badly off.



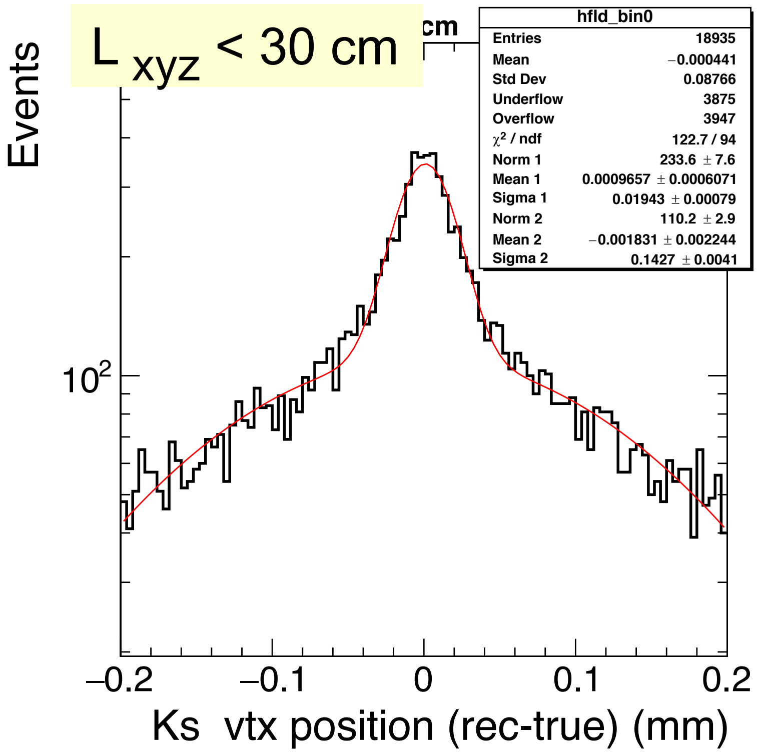


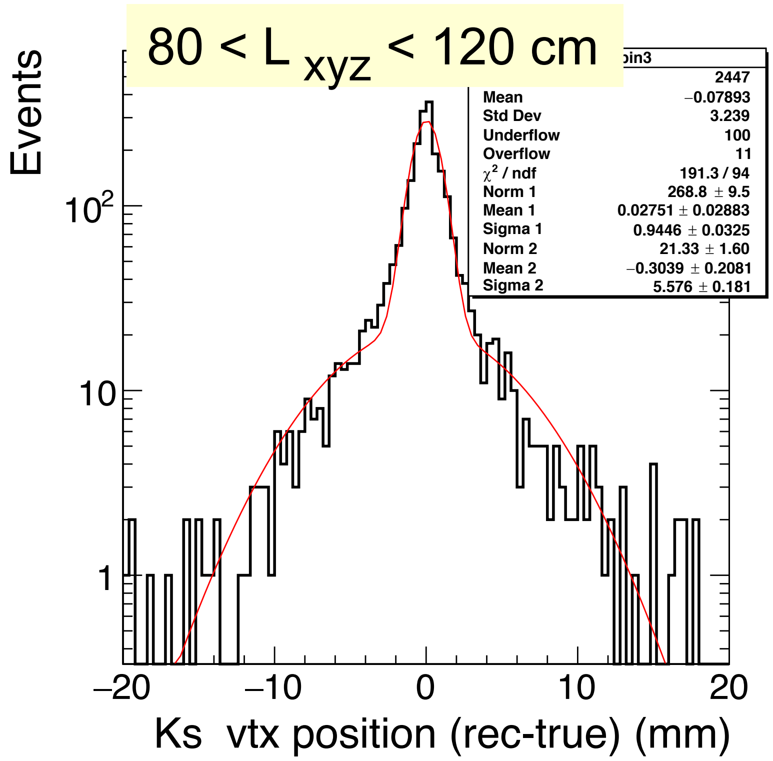
- After cutting out the tail (e.g. $\chi^2 < 20$): pulls of the fitted vertex are nicely Gaussian with $\sigma \approx 1$ in all displacement bins.

Ks -> pi pi vertex reconstruction (perfect seeding)

Vertex resolution when $\chi^2 < 20$.

Red curve = fit by a sum of two Gaussians



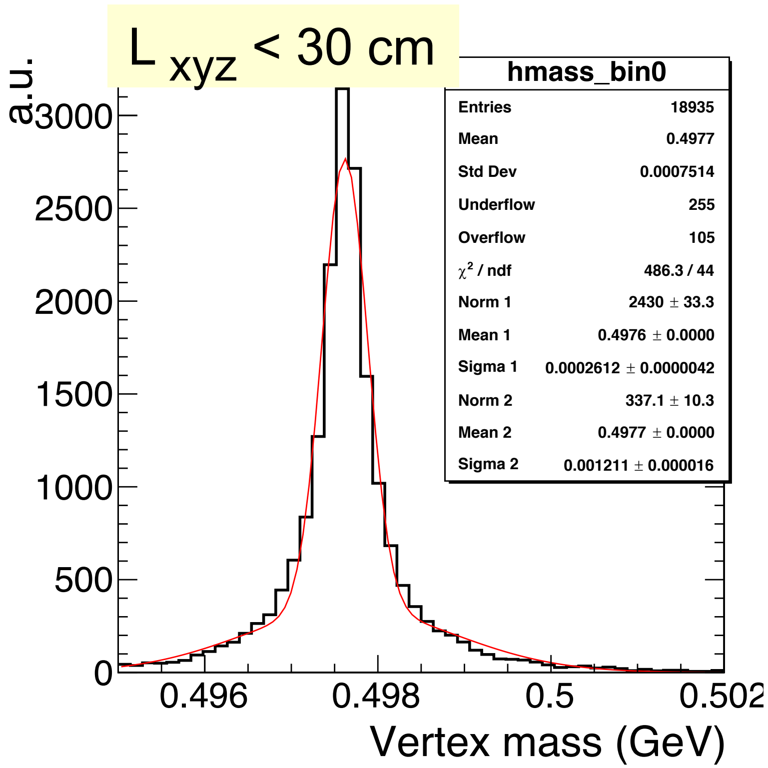


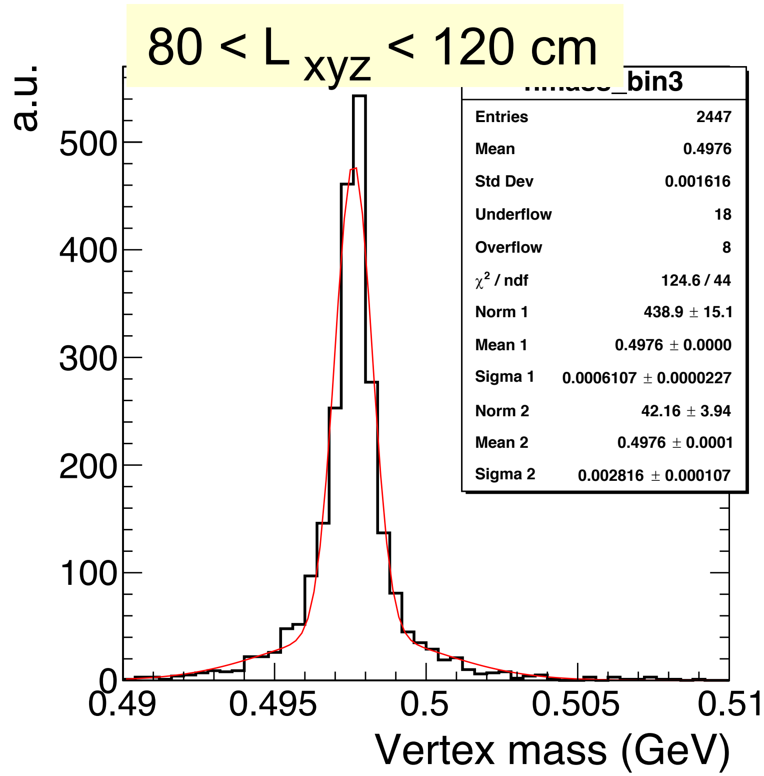
L_{xyz} bin	< L >	Average σ
L < 30 cm	12 cm	48 mum
50 < L < 80 cm	63 cm	0.85 mm
80 < L < 120 cm	1 m	1.25 mm
120 < L < 160 cm	1.4 m	1.92 mm

Average sigma = weighted average of the sigma's of the two Gaussians, weights = normalisations.

Vertex mass of Ks -> pi pi (perfect seeding)

Vertex mass from the track momenta at this vertex, assigned mass = pion mass





L_{xyz} bin	< L >	< p >	Average σ(M)
L < 30 cm	12 cm	3.7 GeV	0.38 MeV
50 < L < 80 cm	63 cm	6.1 GeV	0.5 MeV
80 < L < 120 cm	1 m	7.1 GeV	0.8 MeV
120 < L < 160 cm	1.4 m	7.8 GeV	1.3 MeV

Reconstruction of K_S decays

1st version of K_S reconstruction algorithm developed in FCCAnalyses, based on DELPHES samples. Two main steps :

- Identify the non-primary tracks
  - Some details on next slide

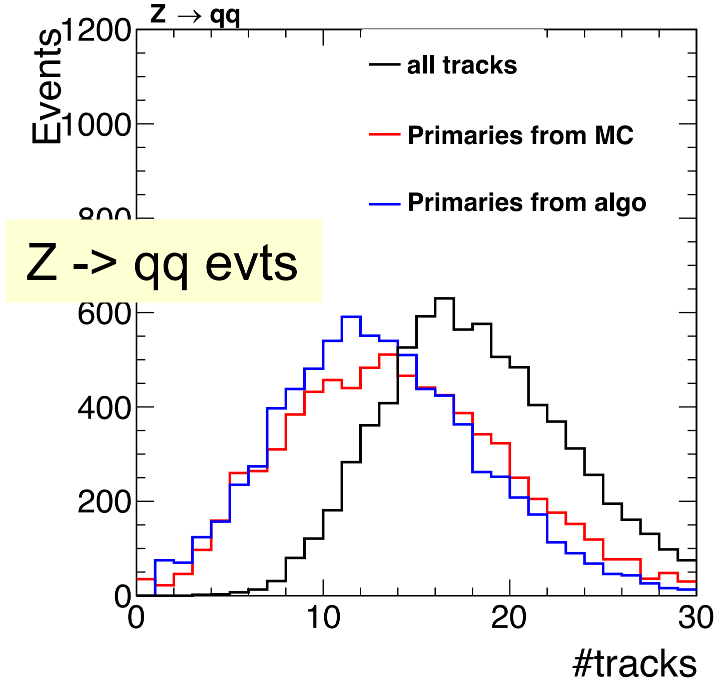
- Using the non-primary tracks: build all 2-track combinations (no PID used so far) and select combinations consistent with a Ks decay :

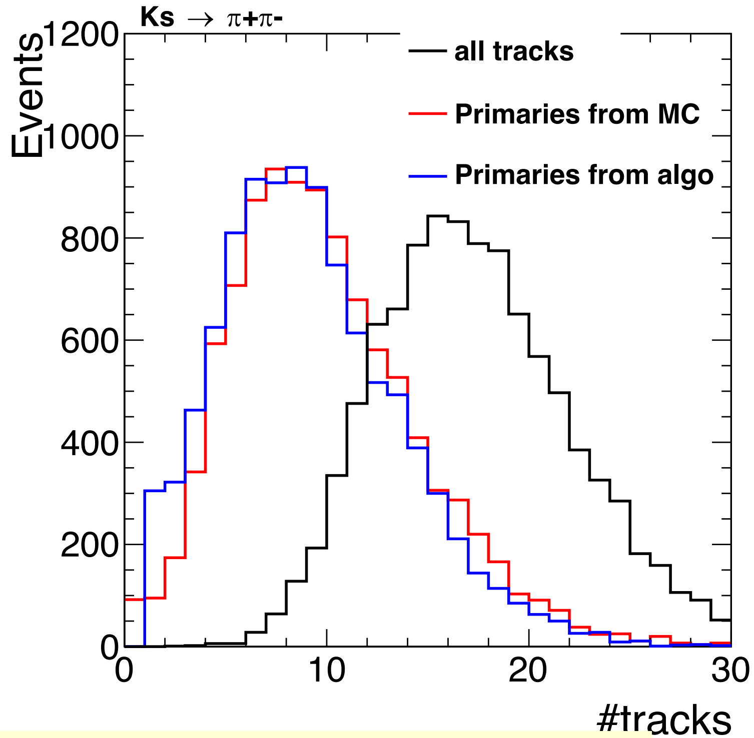
  - Fit the 2 tracks to a common vertex
  - Propagate the tracks to this vertex
  - Build the vertex mass, using m = pion mass for each leg
  - Restrict to opposite-sign pairs and apply some cuts on the vertex χ^2 and on the vertex mass, based on what is seen from perfect seeding :

    - $\chi^2 < 20$
    - Loose mass cut: $0.48 \text{ GeV} < M < 0.52 \text{ GeV}$

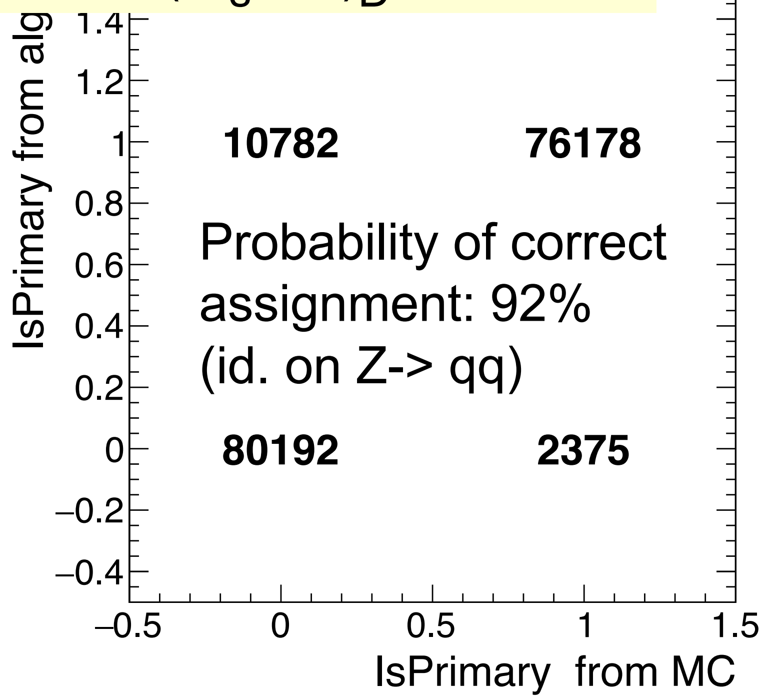
Selection of non-primary tracks

- Fit a primary vertex with all tracks
- Remove the track with the highest χ^2 if this χ^2 is > some cut (25)
- Run the fit again, iterate





$B^+ \rightarrow (K_s \pi^0)_D K^+$ events

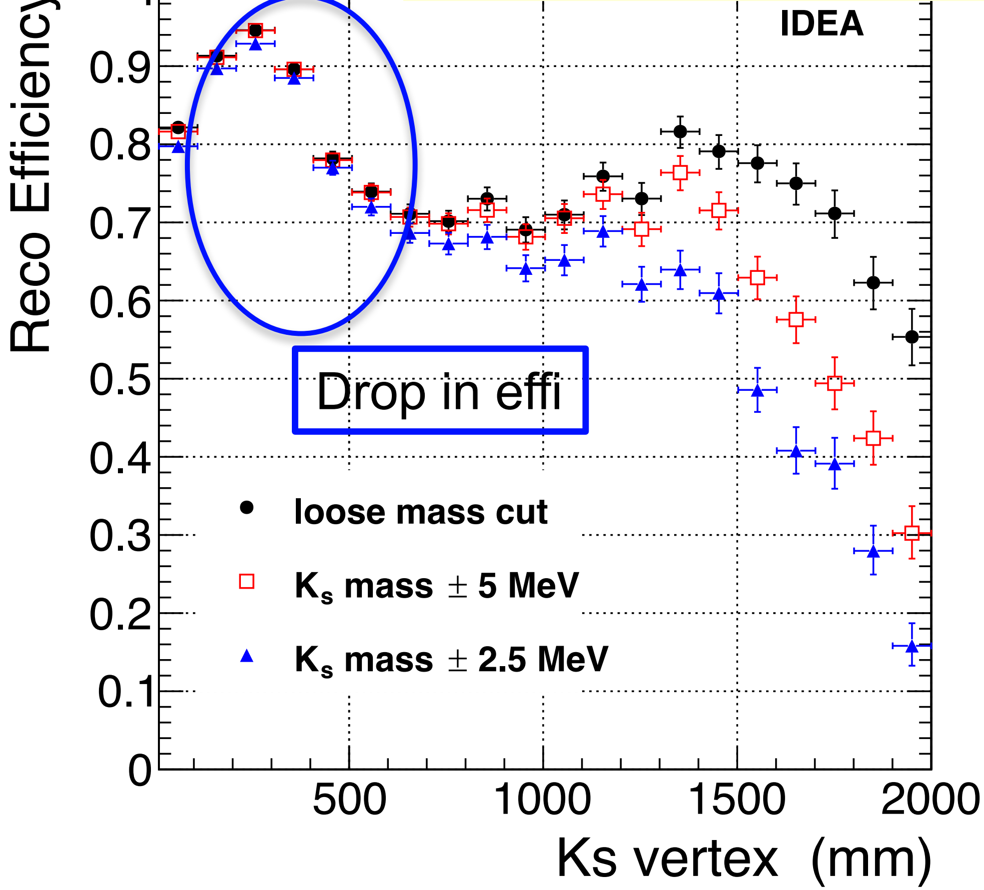


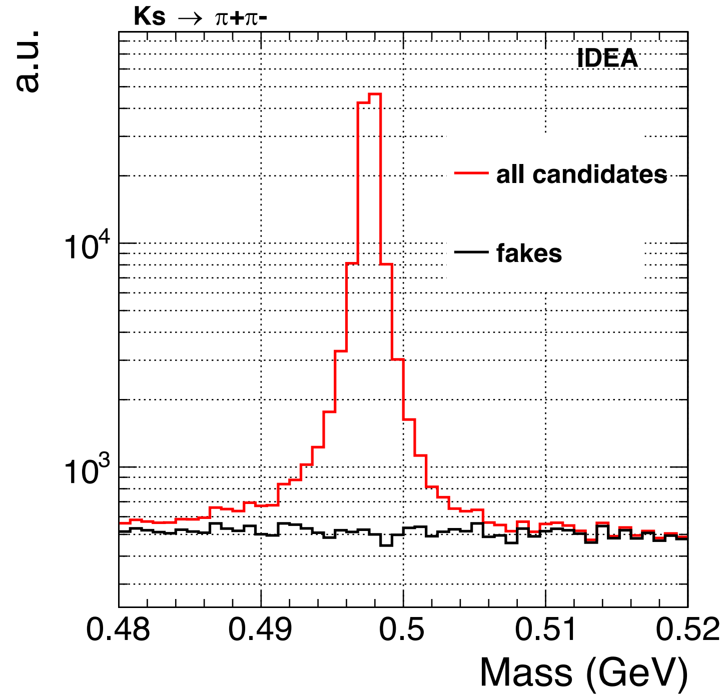
Decent selection of non-primary tracks.

Performance of the Ks reconstruction: efficiency

Use the association of the reco'ed legs to the MC particle to determine whether the K_S candidate is matched or not to a MC $K_S \rightarrow \pi\pi$. Non-matched candidates = fakes.

$B^+ \rightarrow (K_S \pi^0)_D K^+$ events



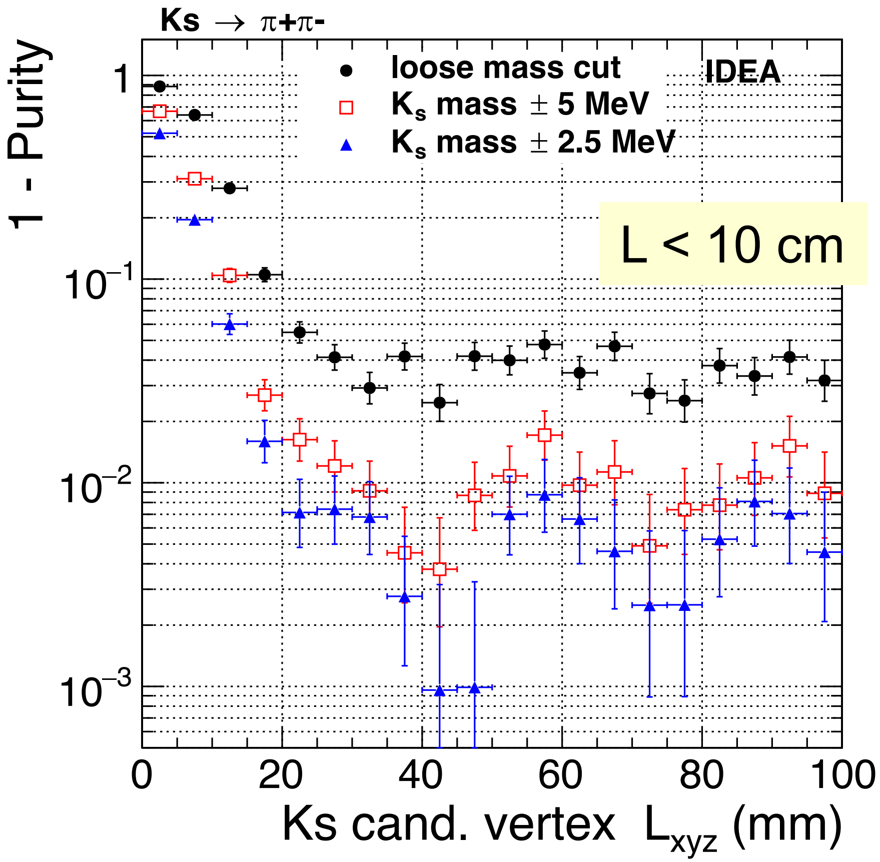


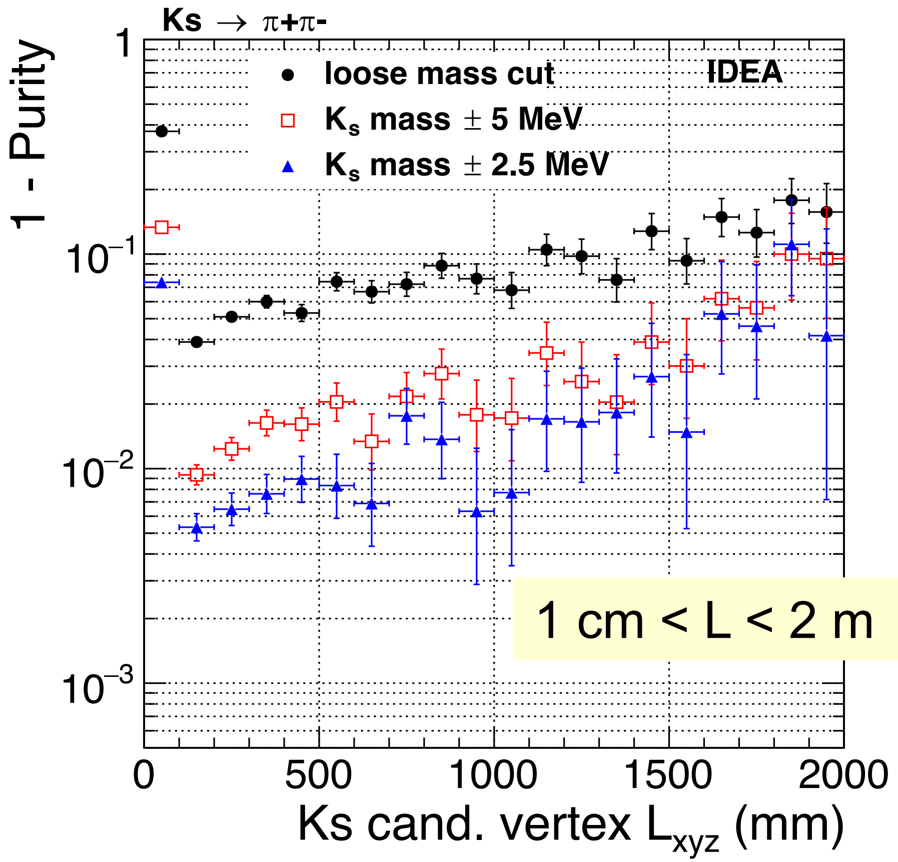
Drop in efficiency in L = 35 cm (last VXD barrel) - 70 cm (last VXD disk): when one looses hits in VXD. Cut on χ^2 less efficient.

Selection efficiency :
78% - 82% of the $K_S \rightarrow \pi\pi$ decays (from B+) that are inside the acceptance, depending on the mass cut.

Performance of the Ks reconstruction: fakes (in inclusive Z -> had sample)

1 – purity : fraction of the identified Ks that are not matched to a MC.





- As expected, many fakes in the vicinity of the IP
- Above 3-4 cm: Fake fraction per-cent level up to about 1m, dominated by $\Lambda \rightarrow \pi\, p$
  - Lifetime (Λ) ~ 3x larger than that of the Ks
  - Should be easily reduced by PID, or by rejecting candidates with mass close to M(Λ) when one leg is assigned the proton mass.

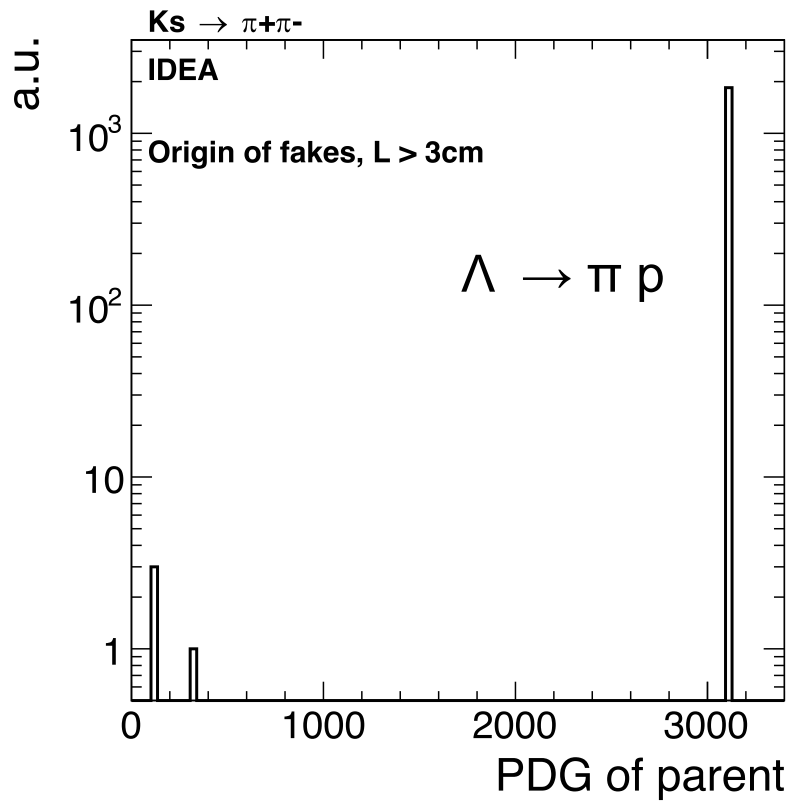
Origin of fakes

Fakes at distance < 3 cm from the IP

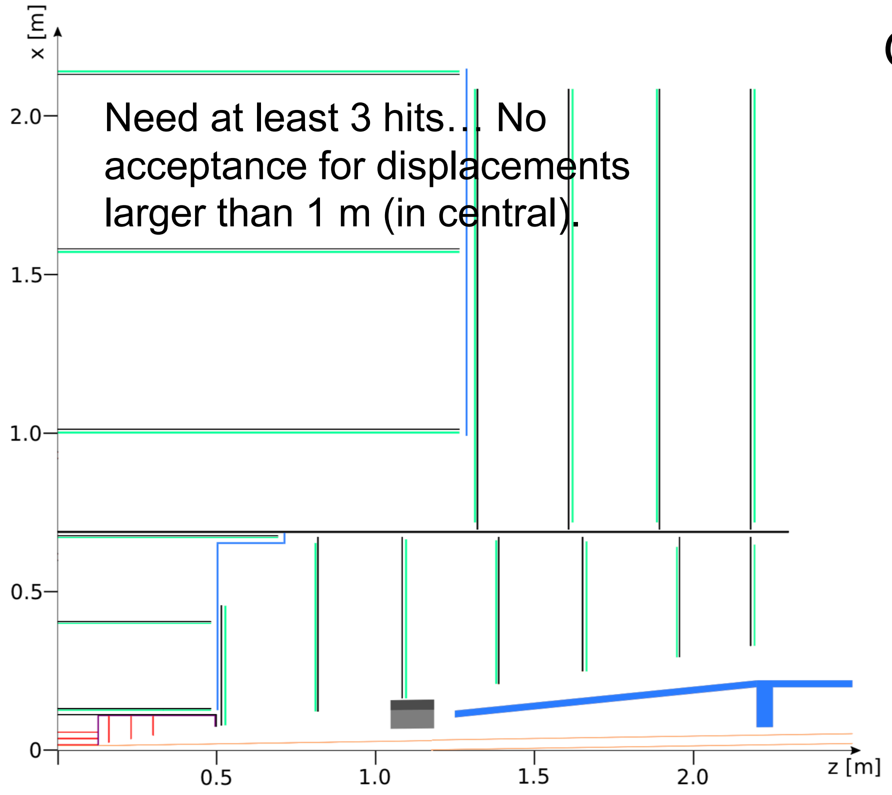
- In 70% of cases, the two legs do not come from the same paren
- Random combinations of pions or K tracks from the decays of rhos, omegas, Ds, etc

Fakes at distance > 3 cm from the IP :

- In 85% of cases, the two legs do come from the same parent (98% at L > 50 cm)
- Usually (p, pi) pairs from Lambda decays
- And a few Ks -> Pi e/mu nu
- Note: I chose to not count as "fakes" the decays Ks -> Pi+ Pi- gamma that pass the selection cuts.



Alternative tracker choice: CLD



Need at least 3 hits… No acceptance for displacements larger than 1 m (in central).

Only 6 layers in R range 12.7 cm – 2.1 m

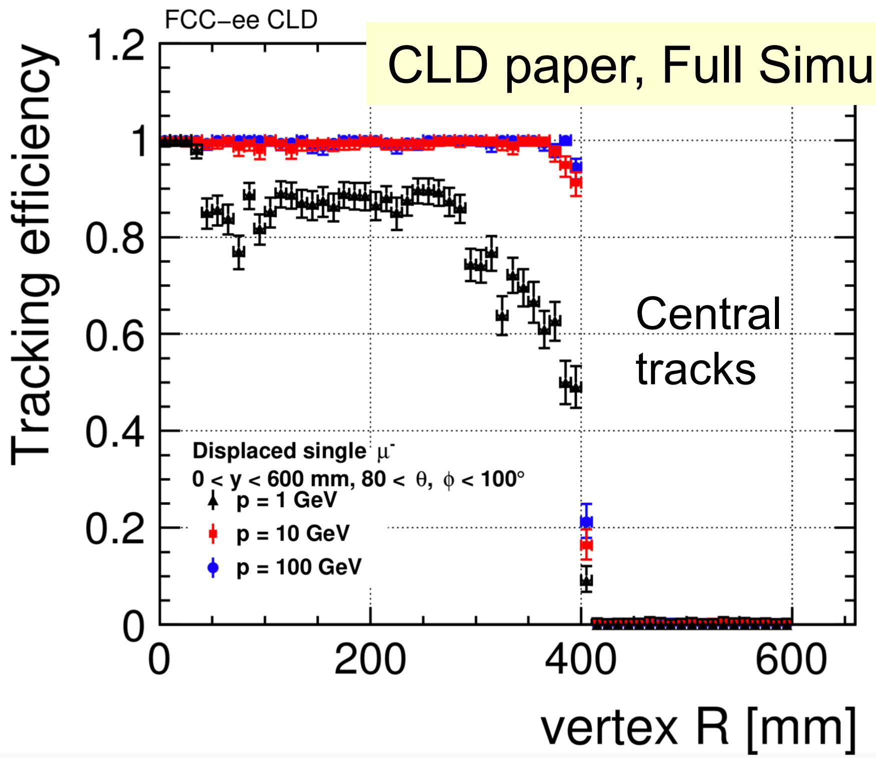
Default Delphes CARD: demands at least 6 hits for a track to be accepted.

Results in zero efficiency for central tracks, for displacements > 13 cm.

Similar cut (5 hits) in the track reconstruction in CLD Full Simulation.

Determine performance for tracks with Nhits ≥ 4 and Nhits ≥ 5.

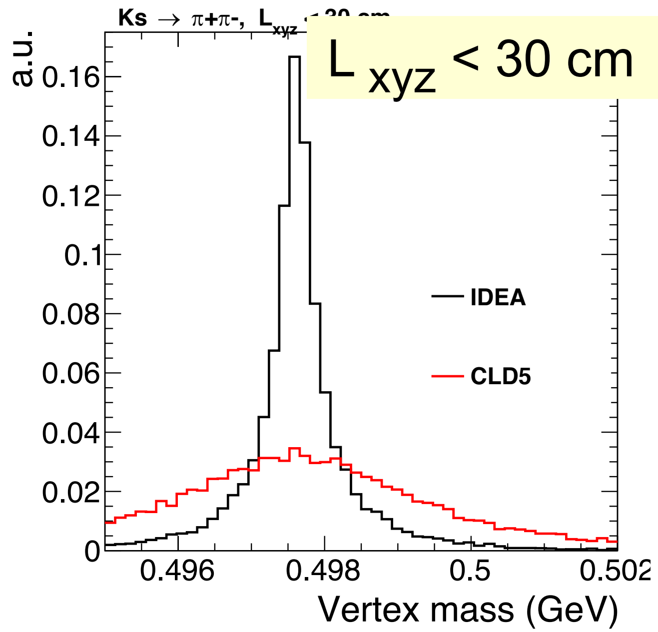
CLD paper, Full Simulation



Alternative tracker choice: CLD, demand 5 hits on the tracks

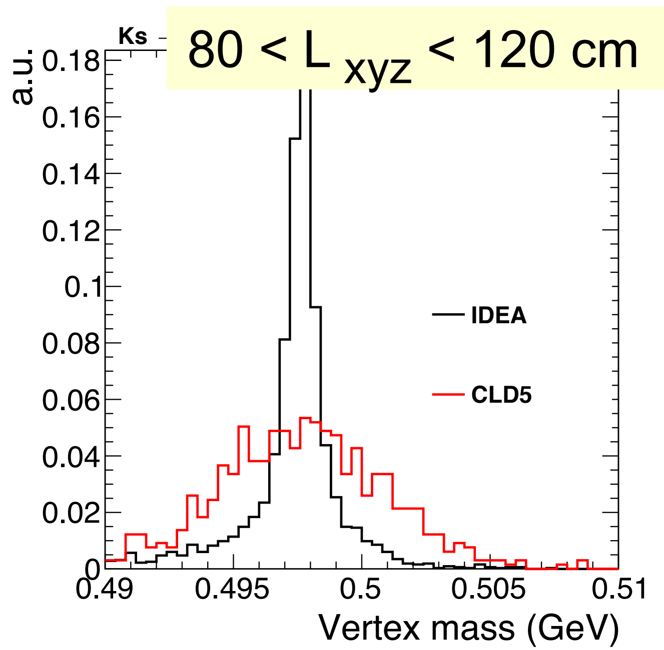
Vertex resolutions (with $\chi^2 < 20$) and effi. of χ^2 cut:

Lxyz bin	IDEA	CLD	IDEA	CLD
L < 30 cm	48 mum	60 mum	100%	100%
50 < L < 80 cm	0.85 mm	1.3 mm	75%	95%
80 < L < 120 cm	1.25 mm	1.5 mm	74%	92%



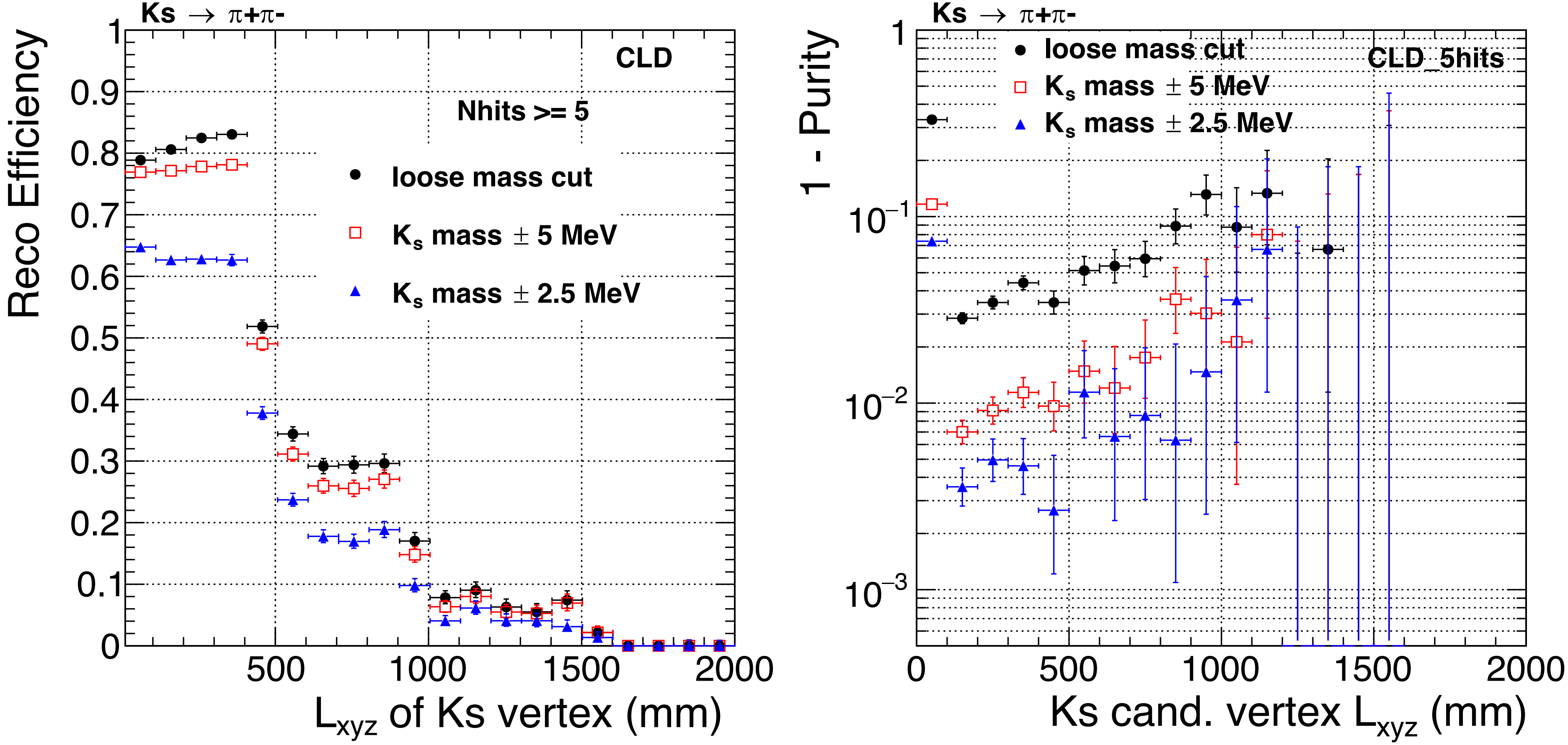
Mass resolutions:

Lxyz bin	IDEA	CLD
L < 30 cm	0.38 MeV	1.8 MeV
50 < L < 80 cm	0.5 MeV	2.5 MeV
80 < L < 120 cm	0.8 MeV	3.3 MeV



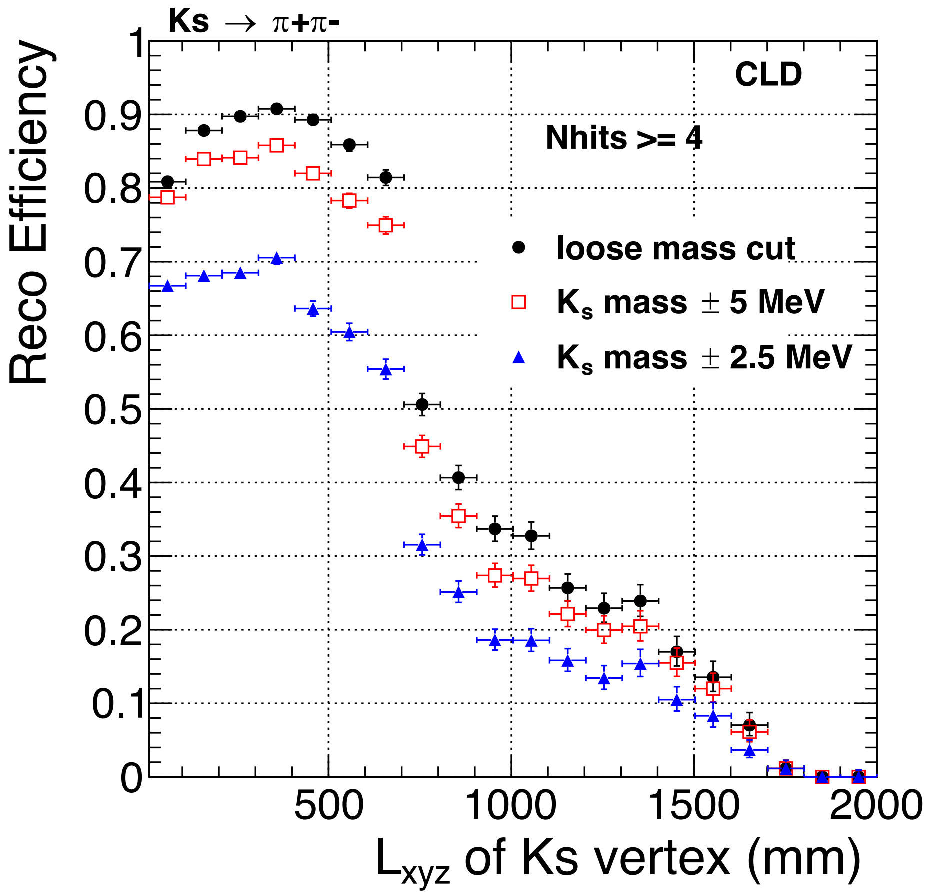
Vertex resolutions are comparable. IDEA: tails in χ^2 of the vertex fit when no VXD hit. CLD mass resolution worse by a factor of 3-4.

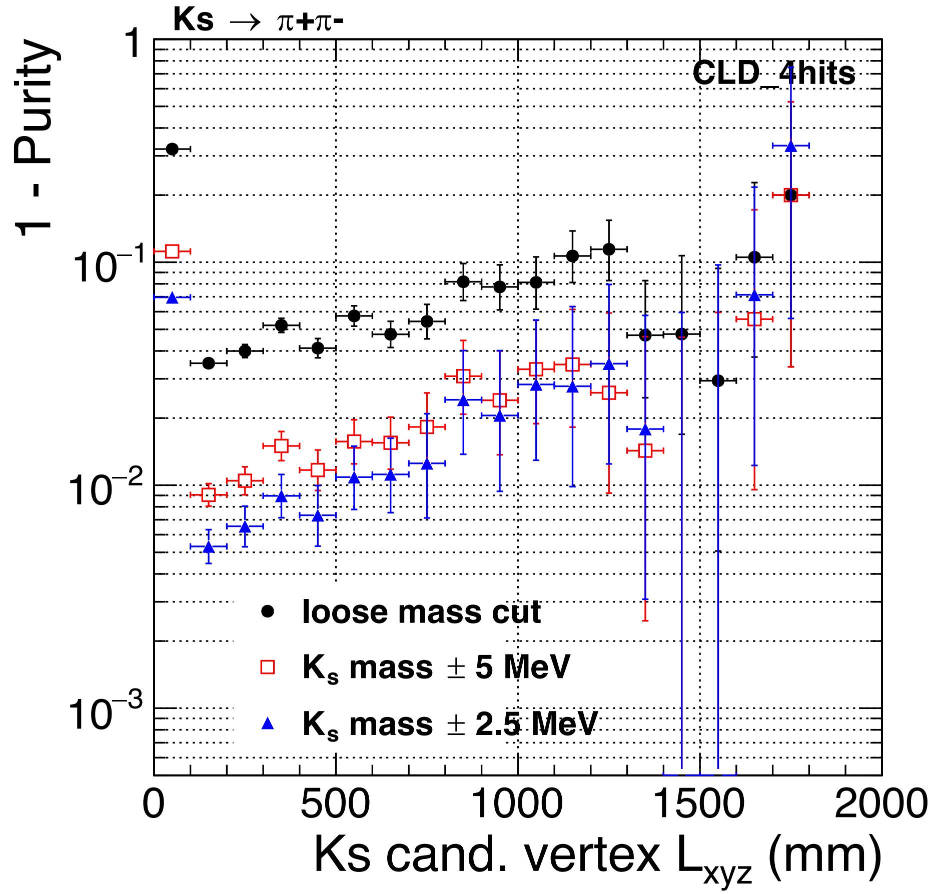
Performance, CLD (5 hits tracks)



- Clear steps in efficiency when one looses a layer
- Efficiency for a fake fraction at the percent level: 47% (blue) or 58% (red).

Performance, CLD (4 hits tracks)





- Efficiency for a fake fraction at the percent level: 56% (blue) or 70% (red).

Conclusions

- Latest version of Delphes allows far displaced tracks and vertices to be studied.

- Baseline IDEA detector provides an efficiency of O(80%) to reconstruct the K_s to ππ decays in the $B^+ \rightarrow (K_s \pi^0)_D K^+$ decay chain.
  - Confirms the assumption that was made in the preprint

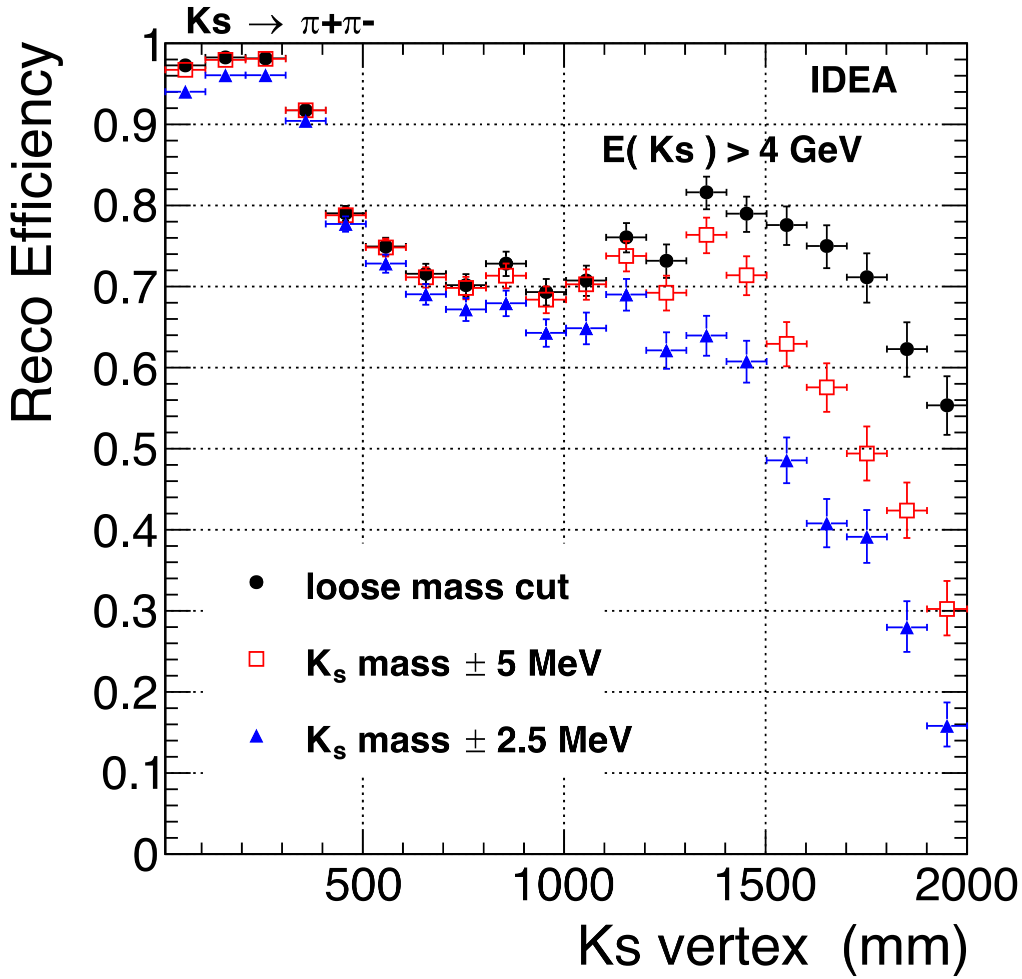
- Baseline IDEA detector can reconstruct Ks with an efficiency > 50% for displacements up to 1.5 m from the IP
  - L > 1 m : very relevant also for e.g. LLPs. Indicative performance from Ks study (but depends on #tracks, their momentum, opening angle, etc). Code developed for the Ks can probably be re-used to study other cases.

- Full Silicon tracker : performance is limited by the small number of layers. For Ks from B+ decays, efficiency of O(50-60%). Efficiency is limited to L < 50 – 70 cm, depending on the track criteria.

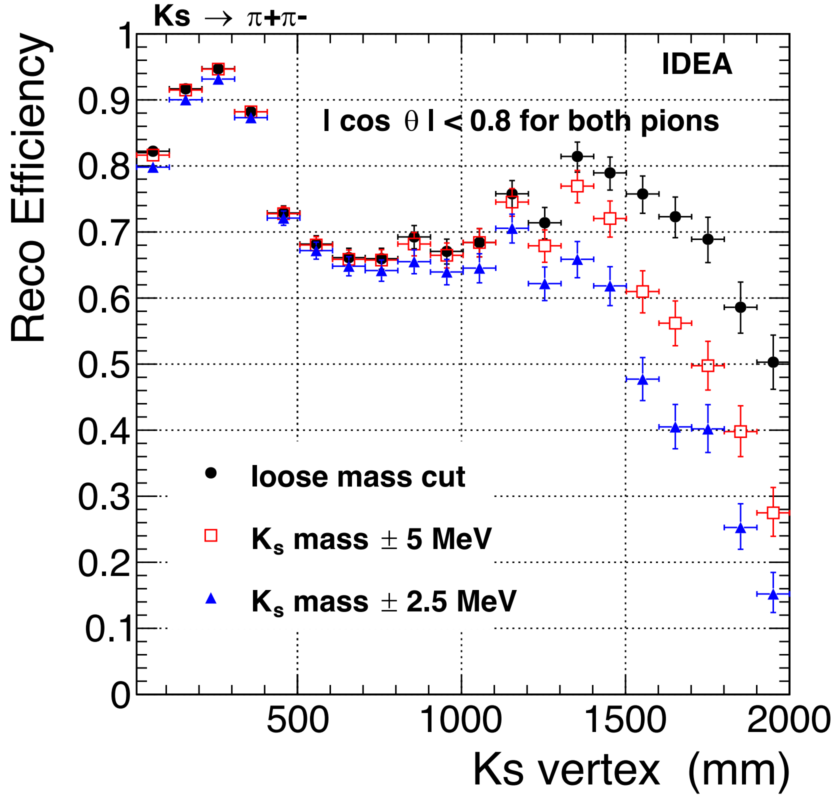
Backup

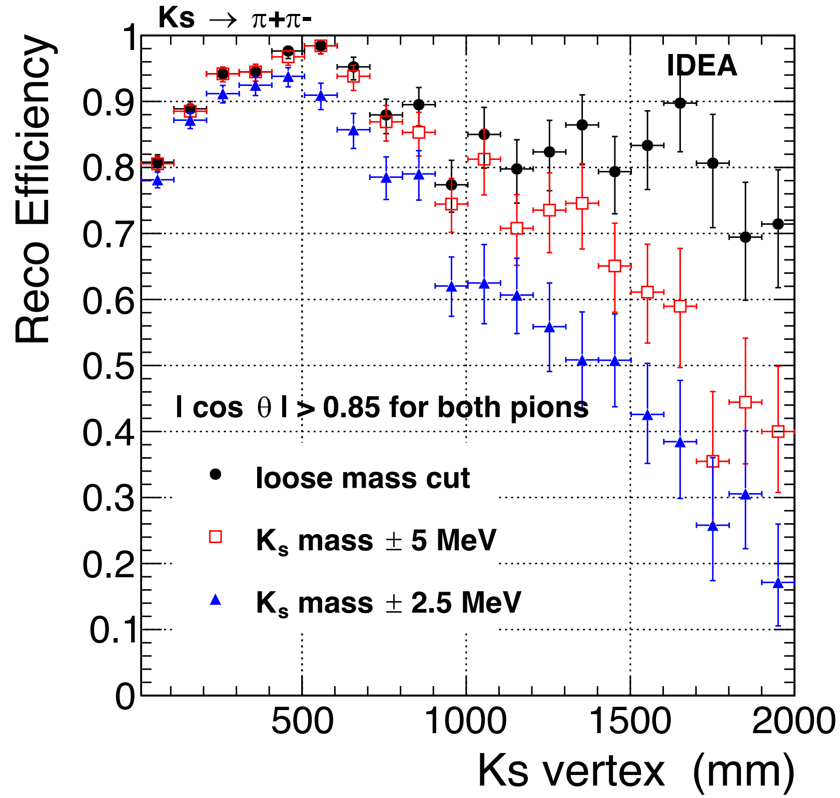
Inefficiency at small L

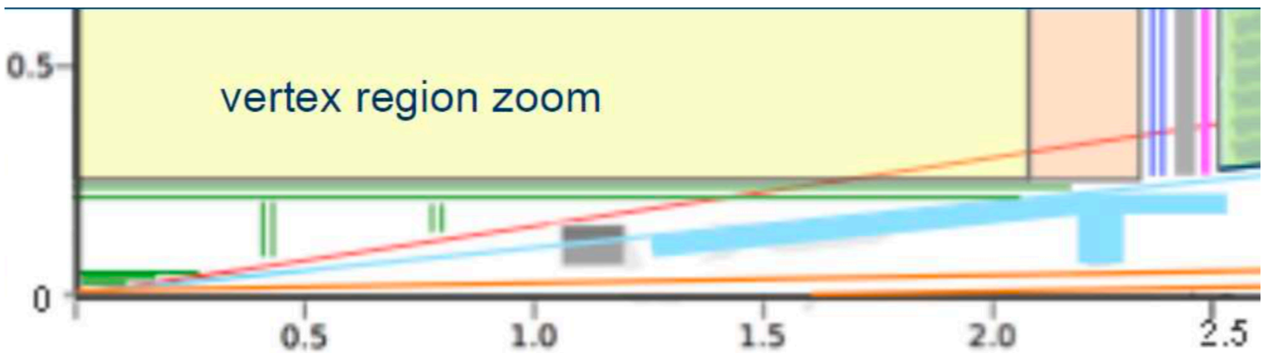
Is due to the correlation of L with the Ks energy. In the small L bins, the Ks have a lower energy, hence the pion tracks suffer more from multiple scattering.

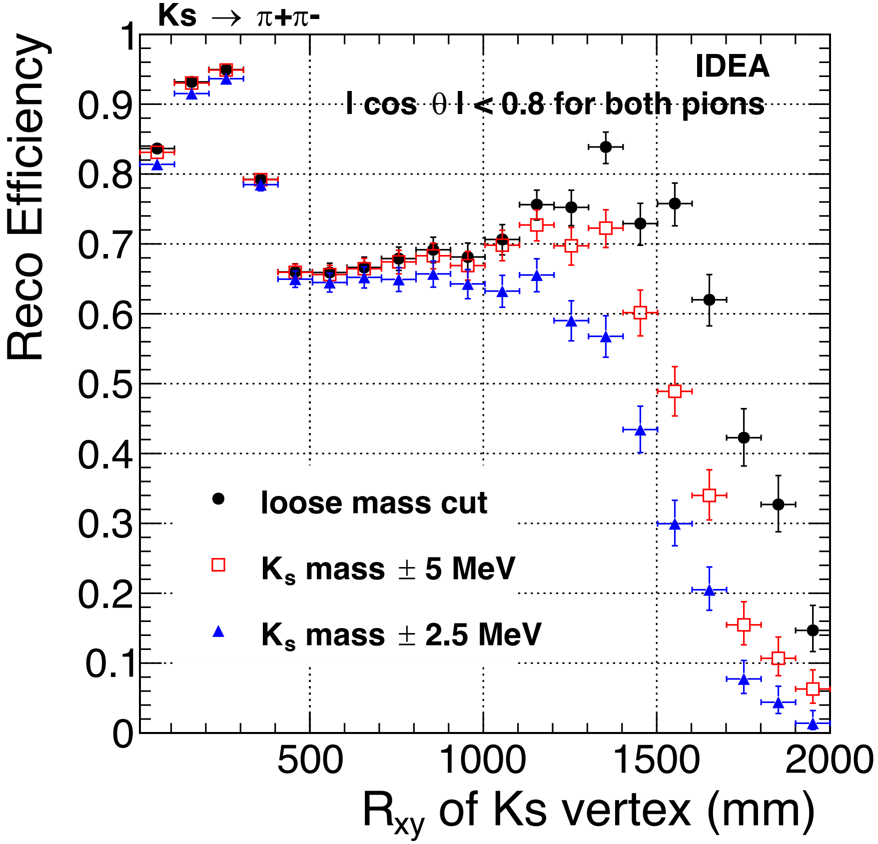


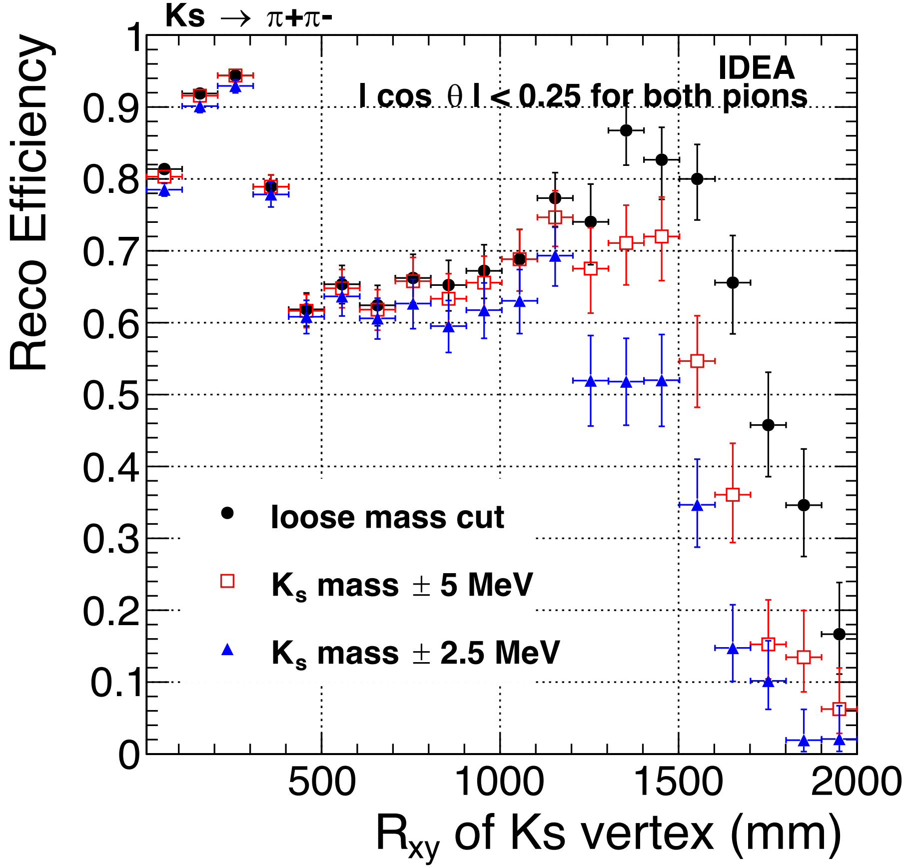
Increase of efficiency at L = 1 – 1.2 m ?



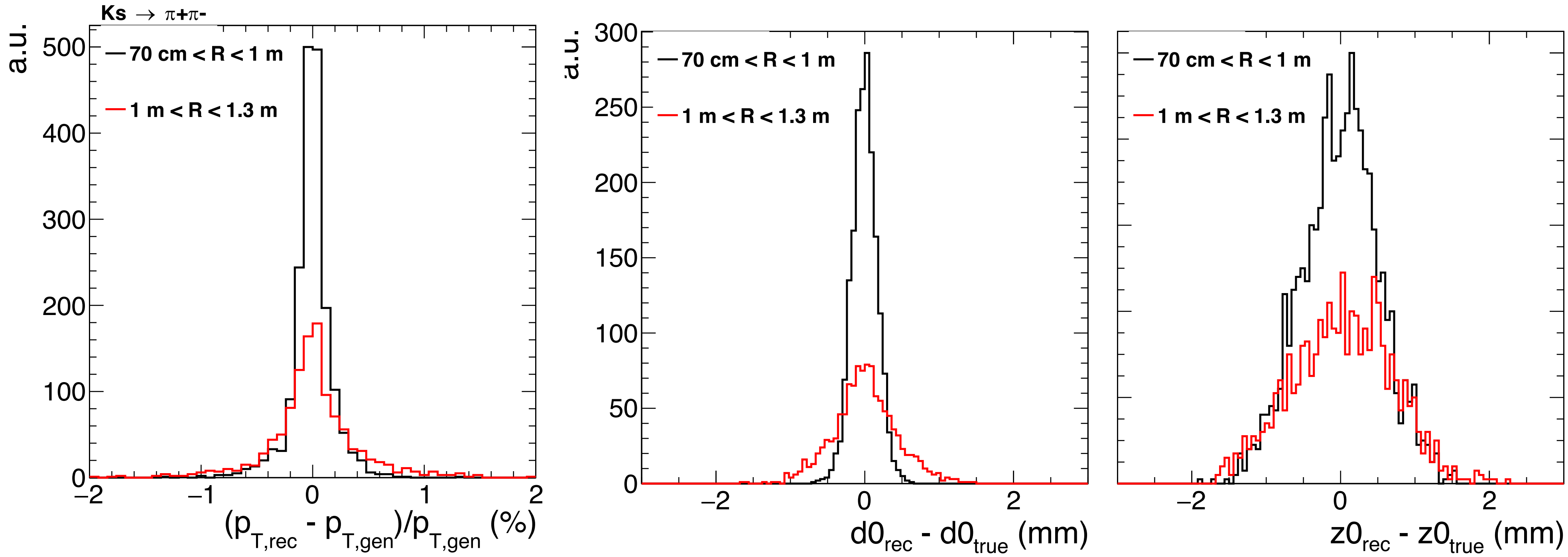




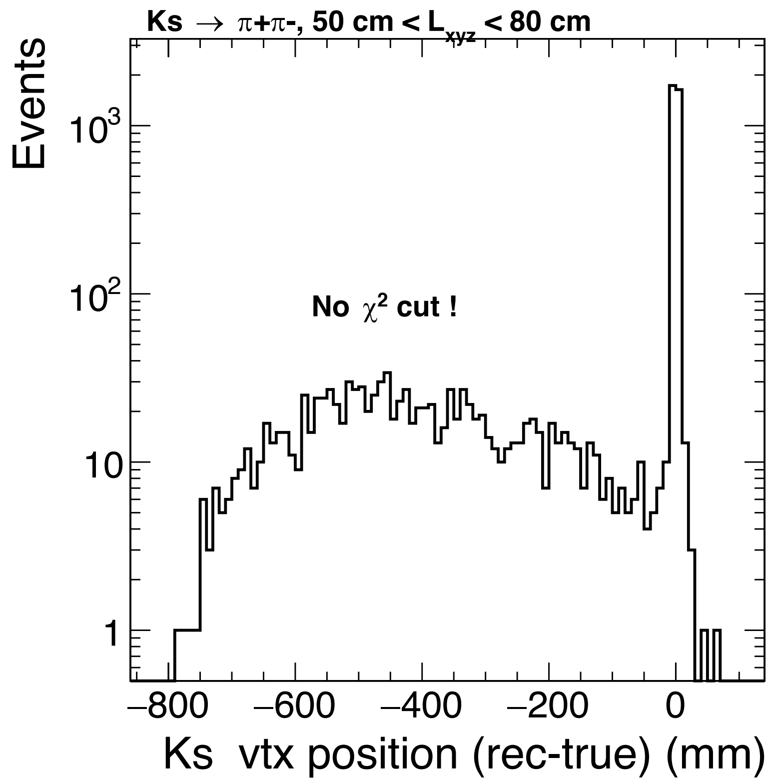

Ks → π+π-
IDEA
I cos θ I < 0.8 for both pions
loose mass cut
K_s mass ± 5 MeV
K_s mass ± 2.5 MeV
Reco Efficiency
R_{xy} of Ks vertex (mm)

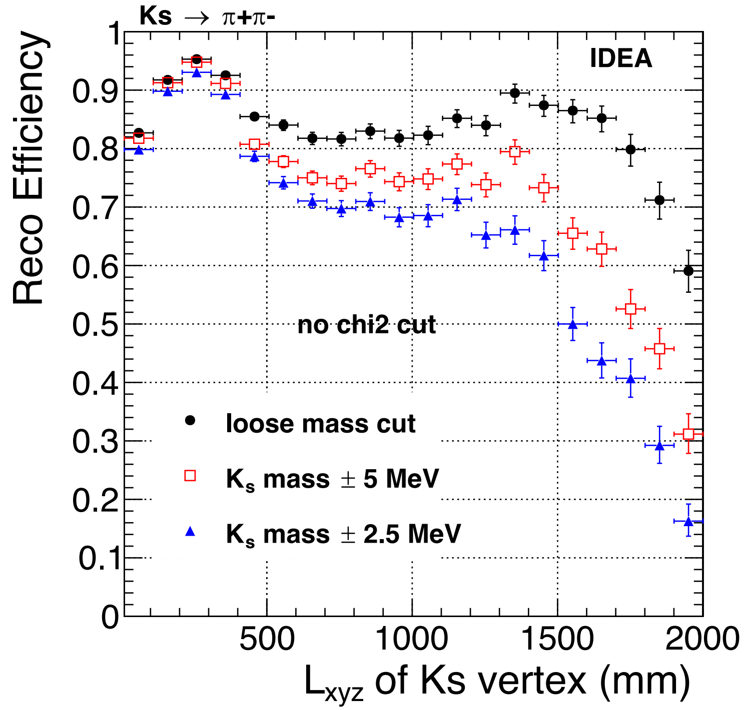

Ks → π+π-
IDEA
I cos θ I < 0.25 for both pions
loose mass cut
K_s mass ± 5 MeV
K_s mass ± 2.5 MeV
Reco Efficiency
R_{xy} of Ks vertex (mm)

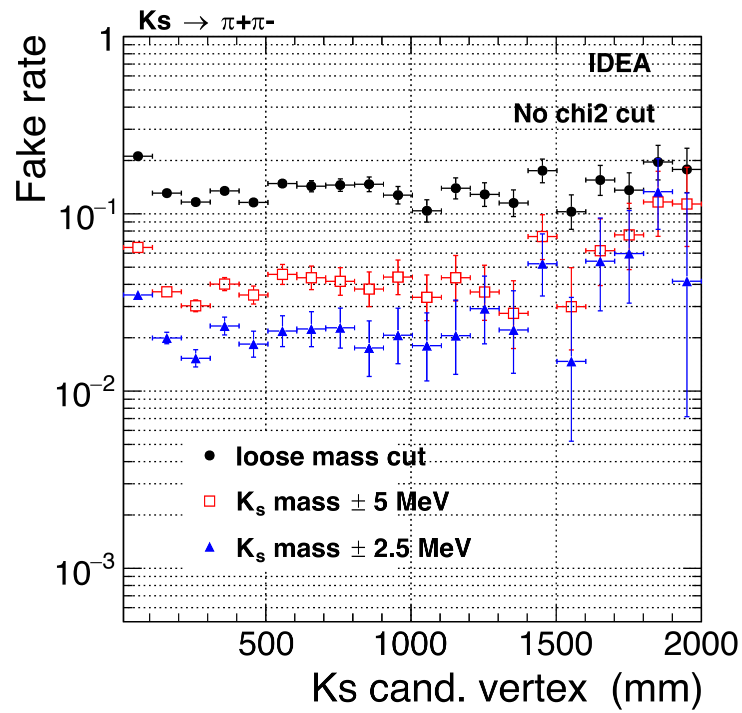
Track resolutions in 700 – 1000 vs 1000 – 1300, central tracks



IDEA, w/o any chi2 cut

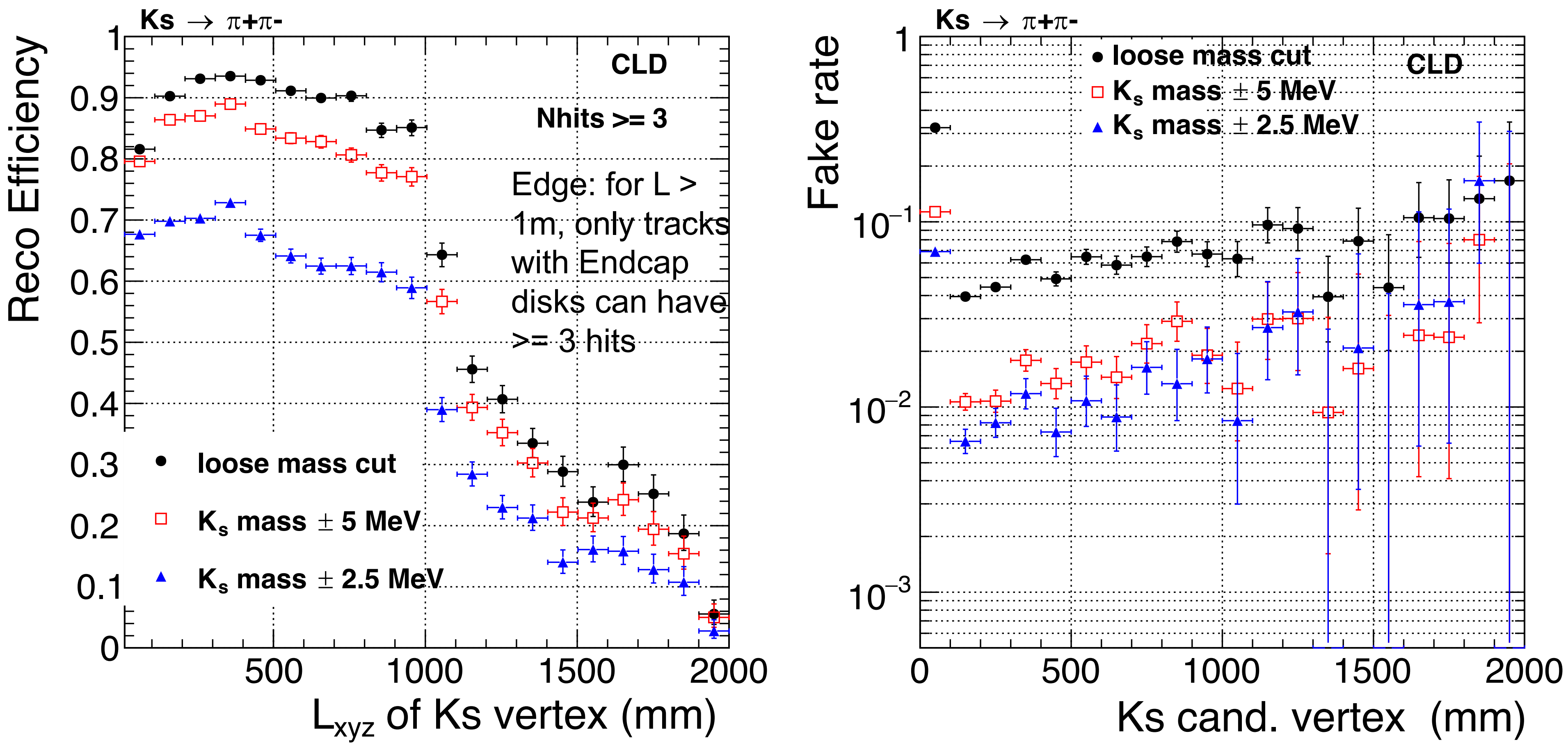






Relaxing the chi2 cut does not improve the efficiency when using a mass window that limits the fakes - fits with a very bad chi2 give a crazy vertex, hence the vertex mass can not be close to the Ks mass.
Leads to a lower purity.

Performance, CLD (3 hits tracks)



Overall efficiency for a fake rate at the percent level: 62% (blue), 78% (red)

But 3-hits tracks is probably not realistic, would have no redundancy, many fake tracks…