Reconstruction of decay vertex for long-lived particles

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2nd Workshop on Electromagnetic dipole moments of unstable particles

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Motivation

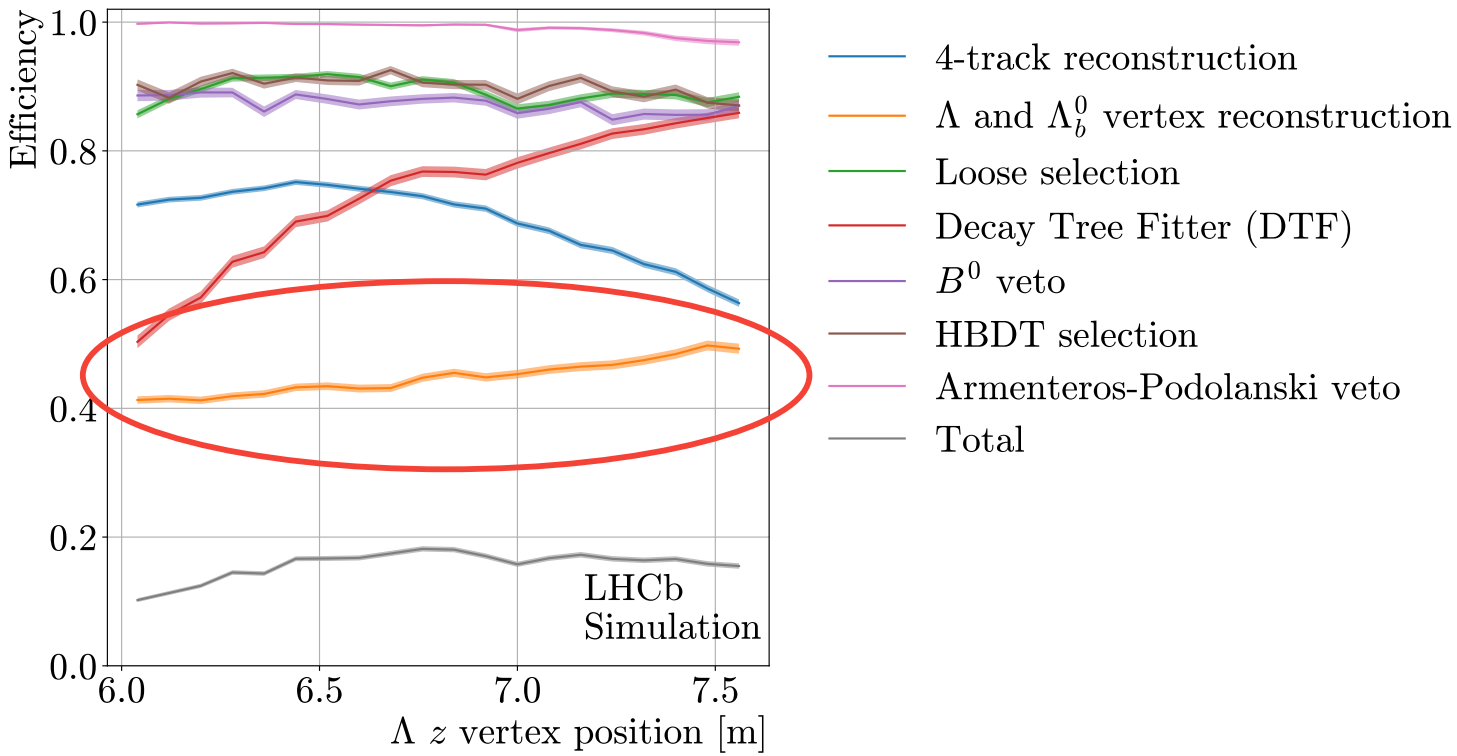
In $\Lambda_b \to J/\Psi\Lambda$ analysis we observe three issues when applying the vertexing algorithm to T tracks:

- Efficiency ($\approx 50\%$) $\to$ lower statistics
- Decay topology ("ghost vertex") $\to$ affects angular resolution
- Vertex bias $\to$ affects proper-time measurements

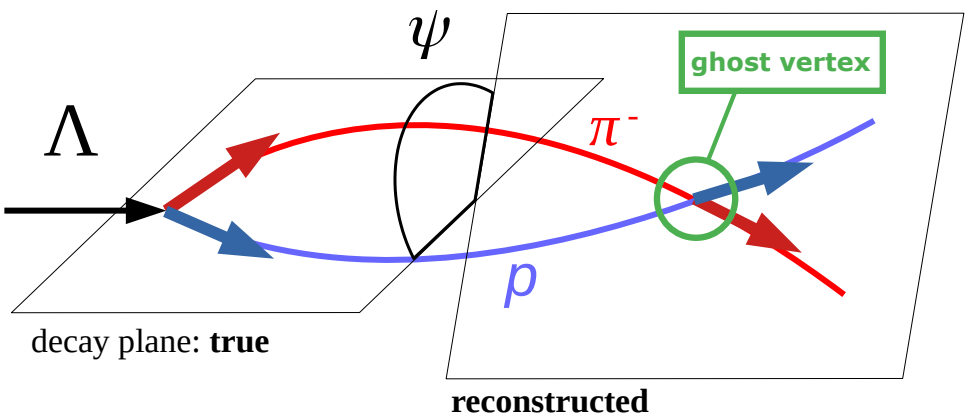
$\to$ impact on polarization measurement

Efficiency

The bottleneck of $\Lambda_b \to J/\Psi\Lambda$ analysis efficiency is the vertex reconstruction for Λ and Λ_b^0 (LHCb-DP-2022-001)



"Ghost" vertex and closing tracks topology

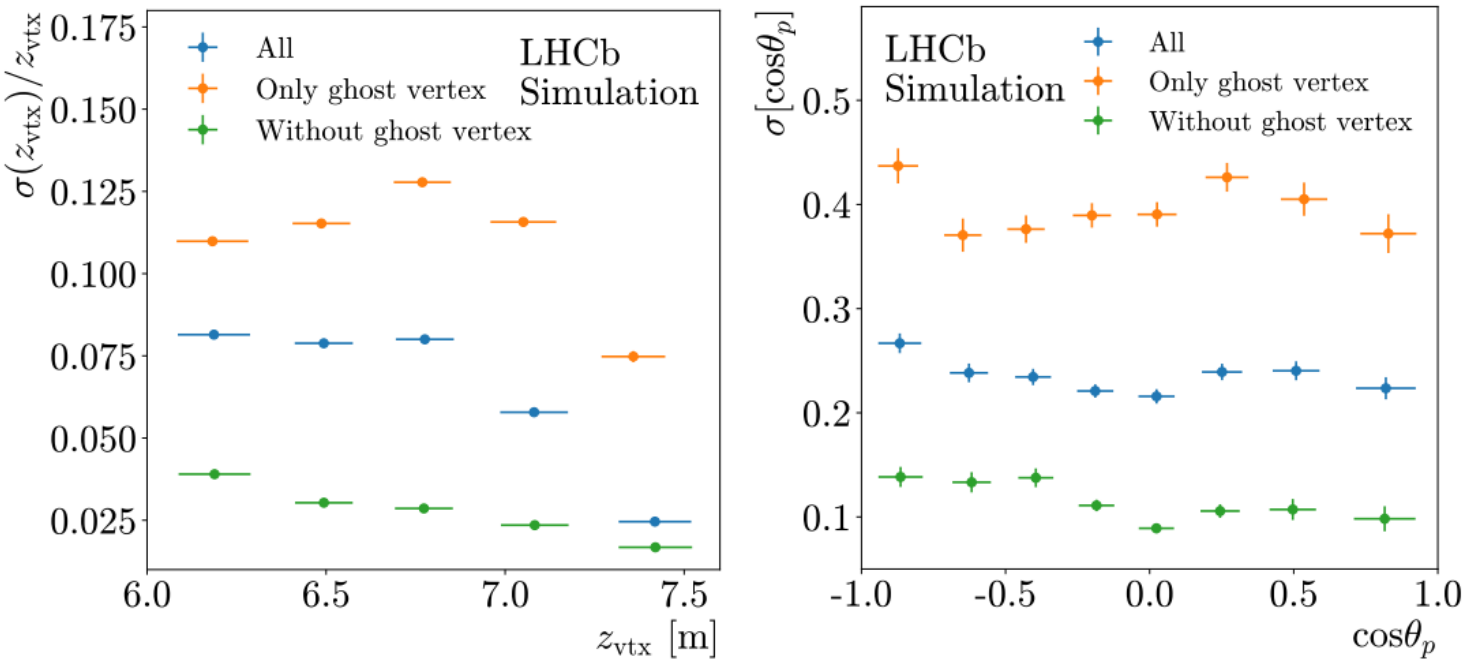


Closing tracks topology due to

- poor spatial resolution
- poor momentum resolution
- low Q-value $\rightarrow$ small opening angle

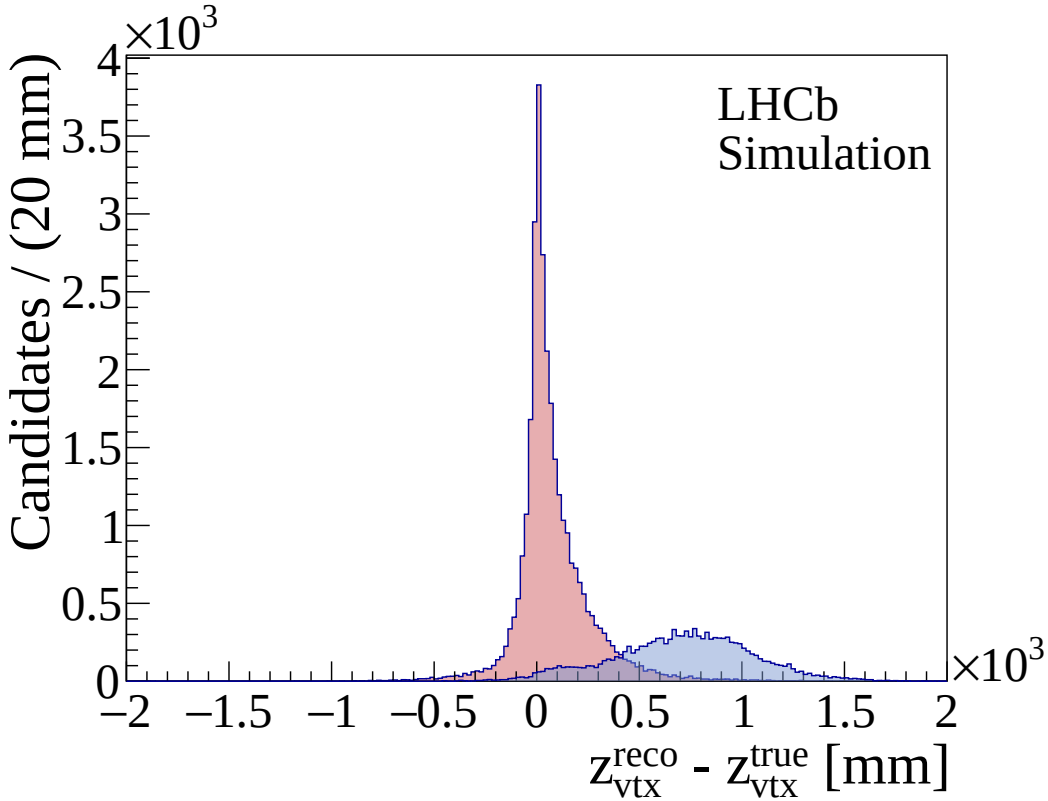
Current vertexing algorithm cannot discriminate between the two vertices

Closing tracks topology and "ghost" vertex



Ghost vertex topology plays a major role in the reported resolution plots: for events without ghost vertex, the average resolutions improve by about a factor 2.5

Ghost vertex effect on vertex bias



Ghost vertices in blue, closing track topology in red

Ghost vertices fraction is about 30% after the selection

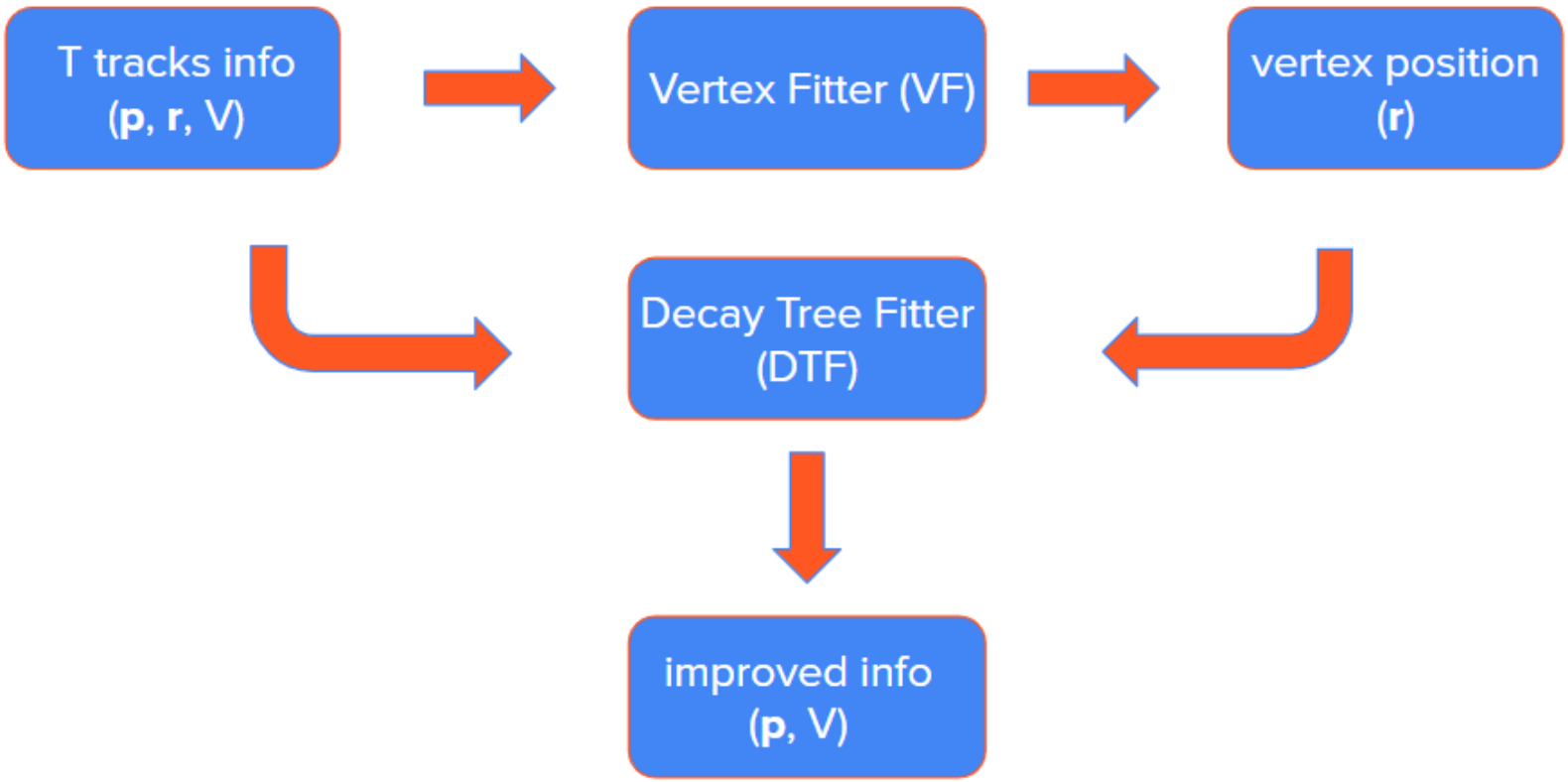
Removing the ghost vertex events does not completely remove the bias

Vertexing algorithms

In order to solve the problems presented, we try to change the vertexing algorithms for T tracks

- Overview of the current LHCb algorithms
- Our ideas to improve the algorithms

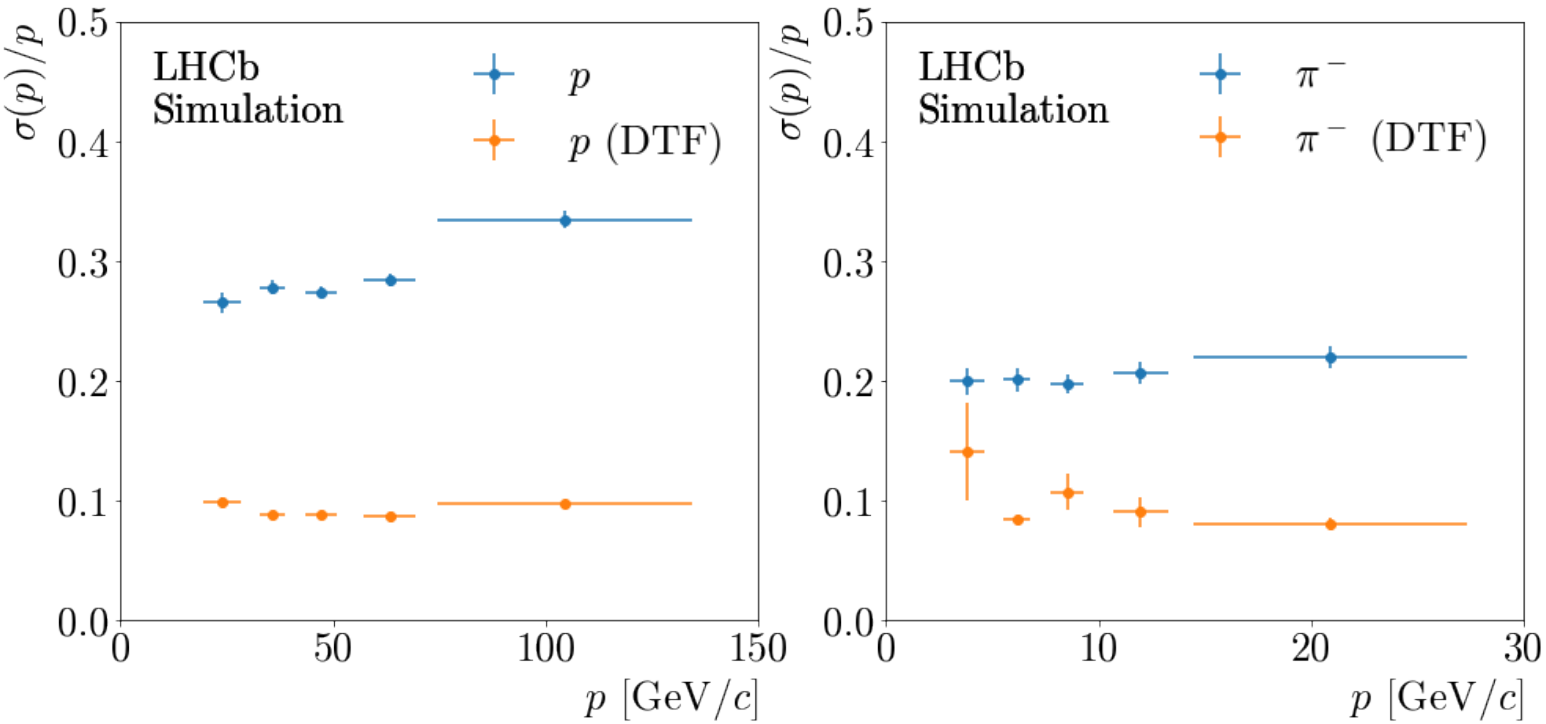
Vertexing strategy for T tracks



Info: momenta ($\mathbf{p}$), position ($\mathbf{r}$) and covariance matrix (V)

DTF: vertexing algorithm with constraints

$\Lambda_b^0 \to J/\Psi\Lambda$ momenta resolutions and DTF effect

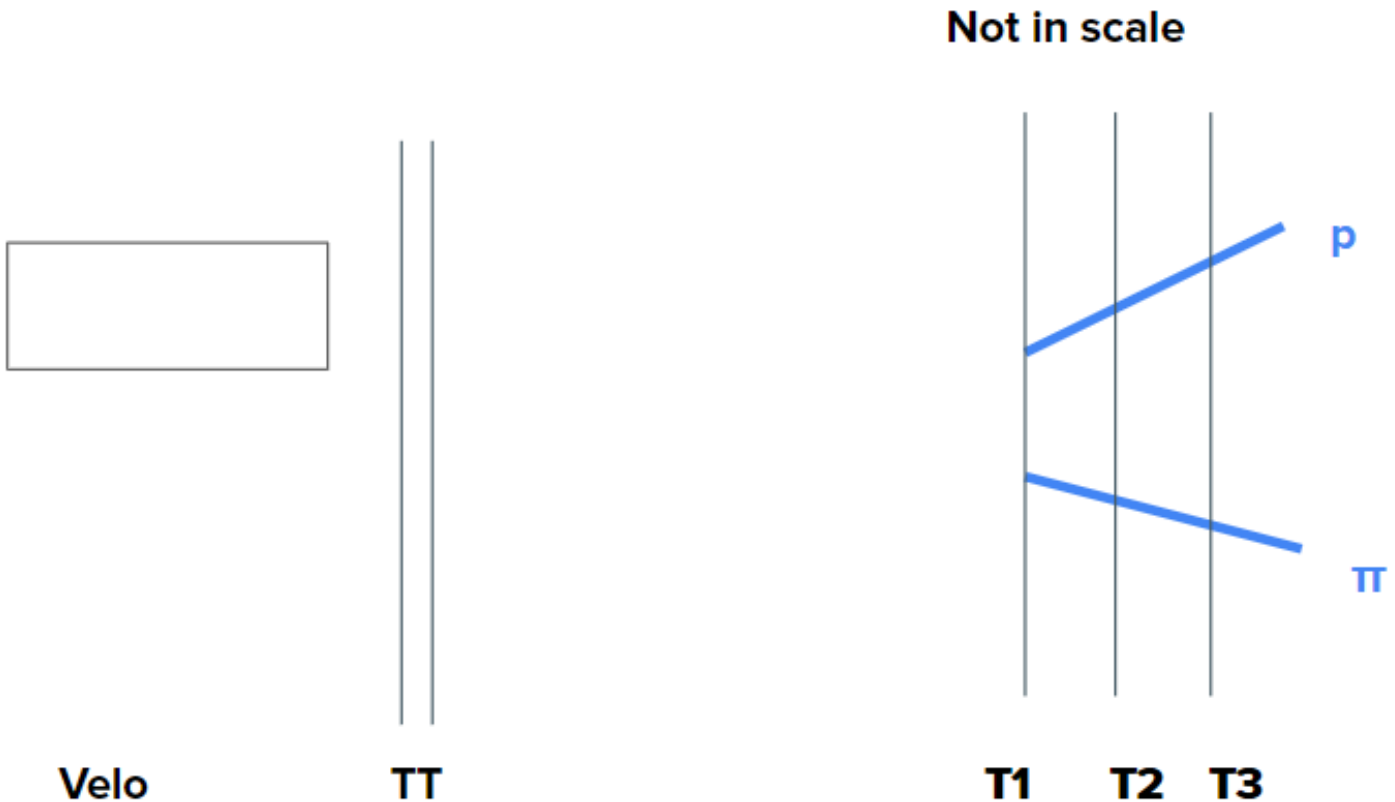


Low magnetic field in T track region $\to$ large bending radius, poor momentum resolution.

It improves using DecayTreeFitter with primary vertex + J/Ψ and Λ invariant mass constraints.

LHCb Vertex fitter algorithm

- Loki analysis toolkit
- bottom-up decay tree fit via a 'leaf-by-leaf' approach



- daughter particle: 7-dim vector $(\vec{r}, \vec{q})$ with reference point position and 4-momentum + covariance matrix V

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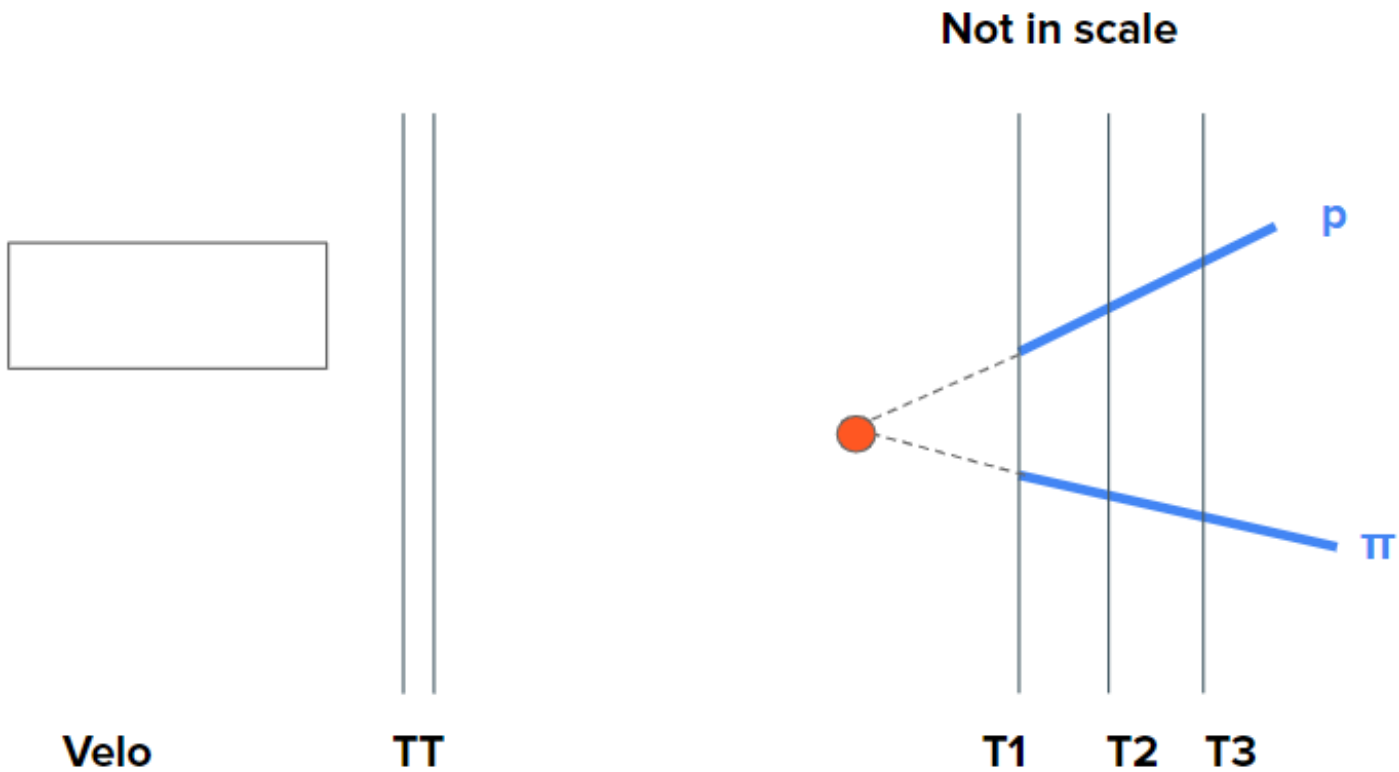

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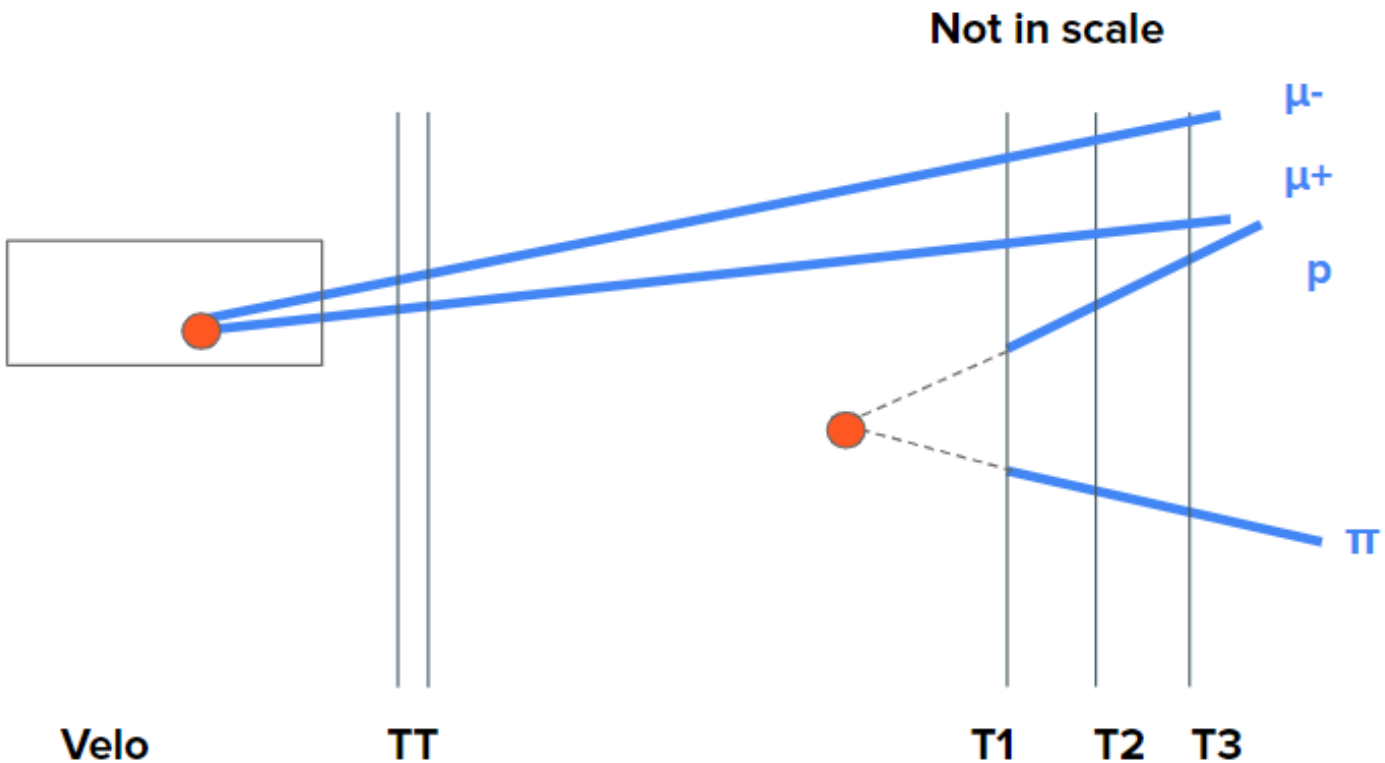

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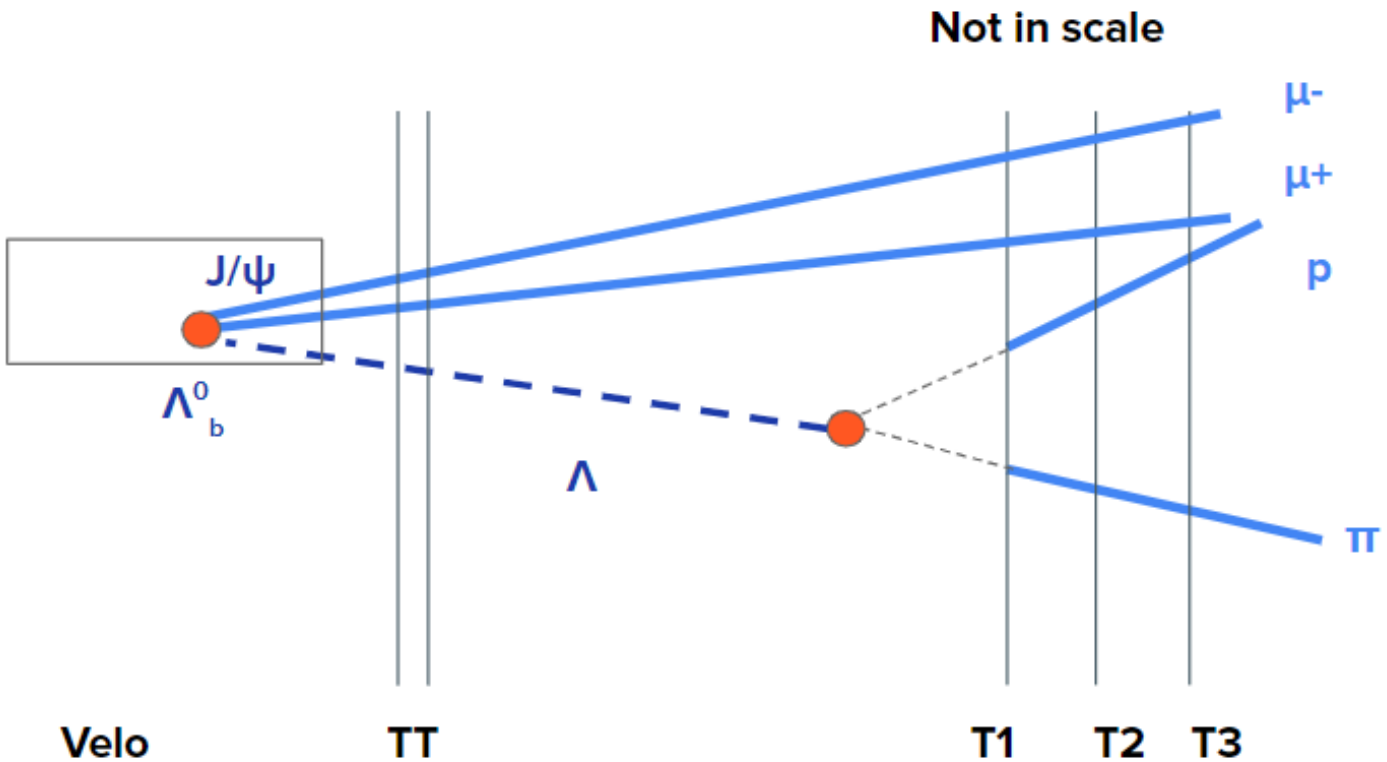

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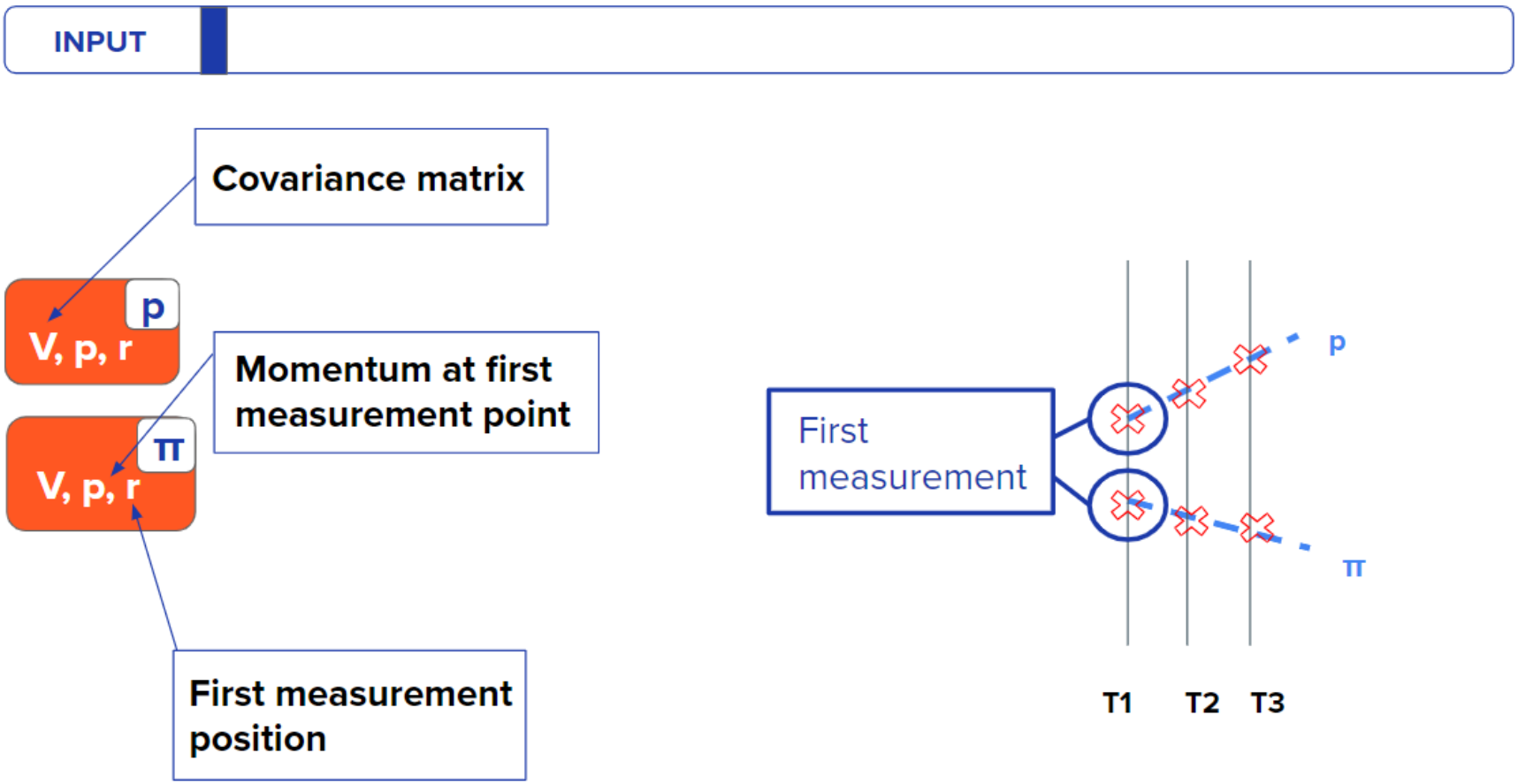

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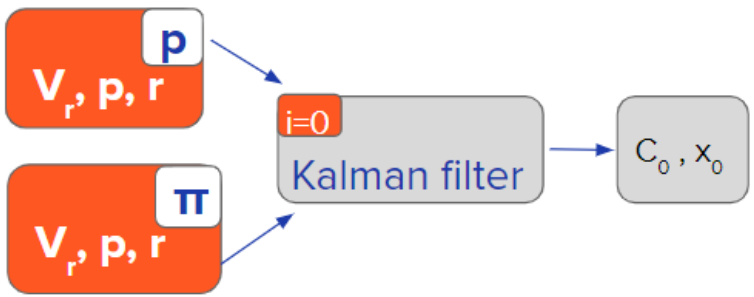

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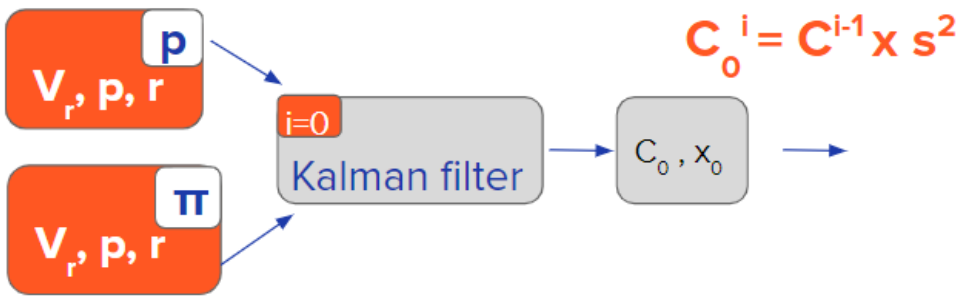

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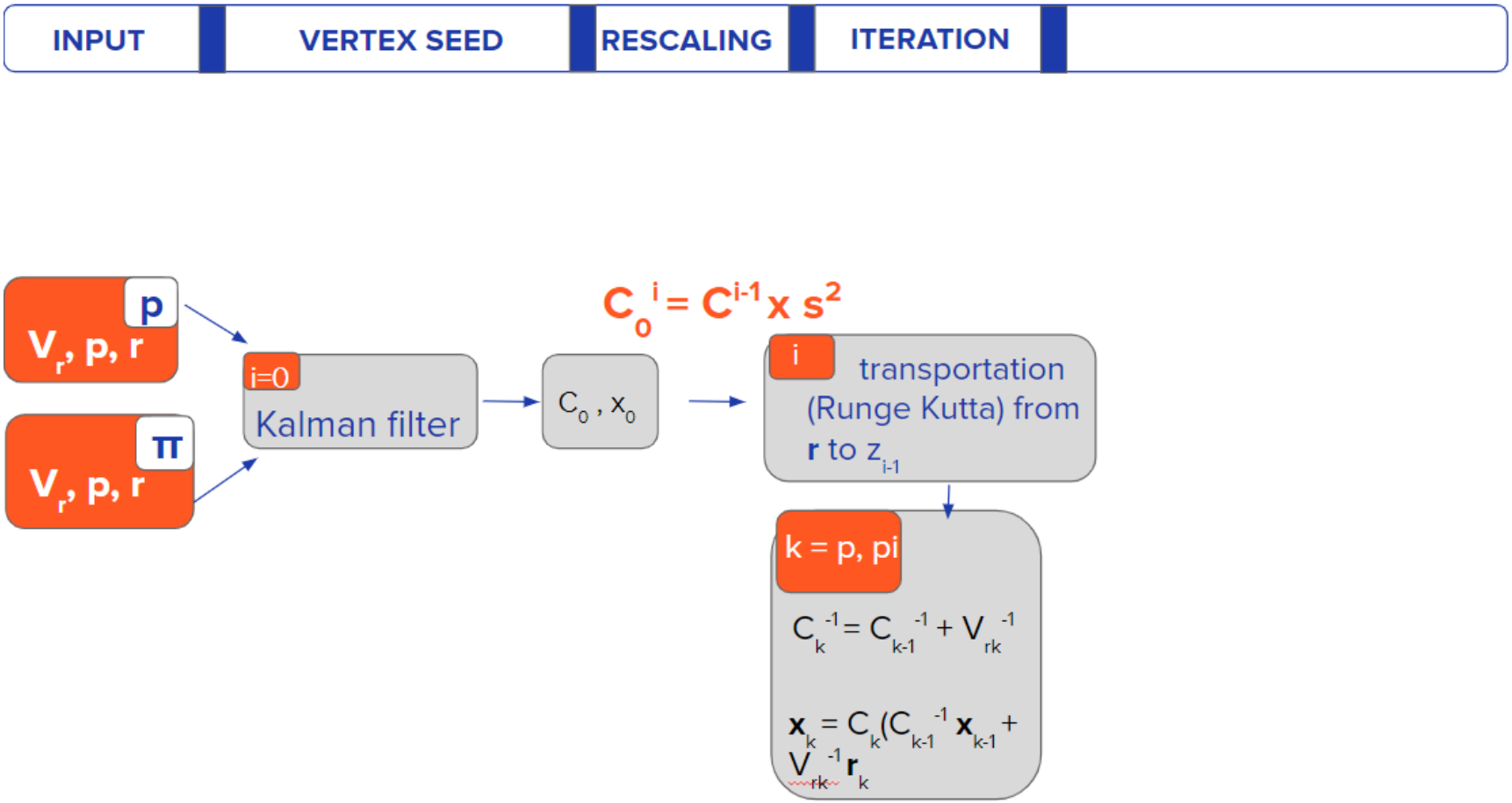

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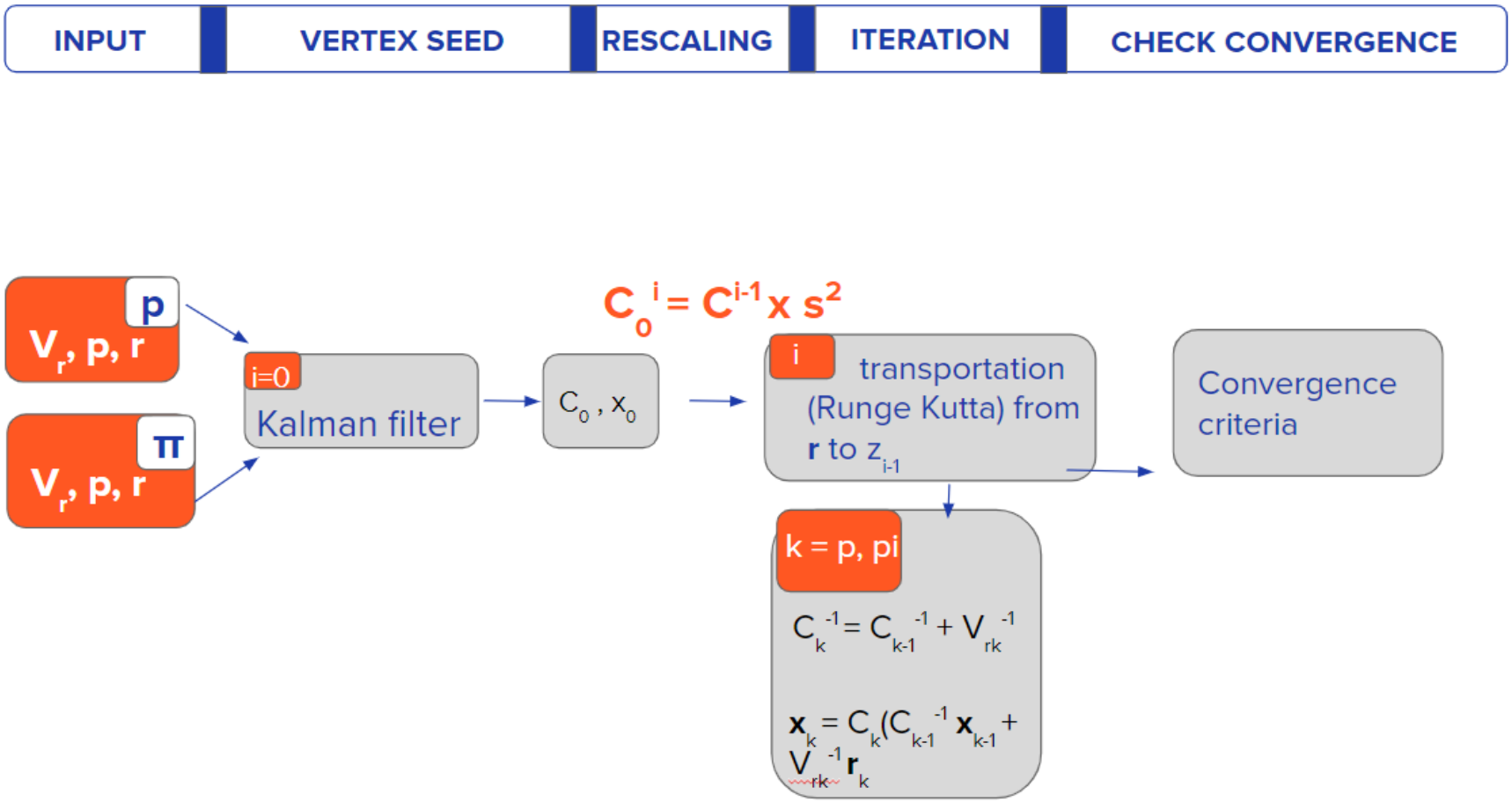

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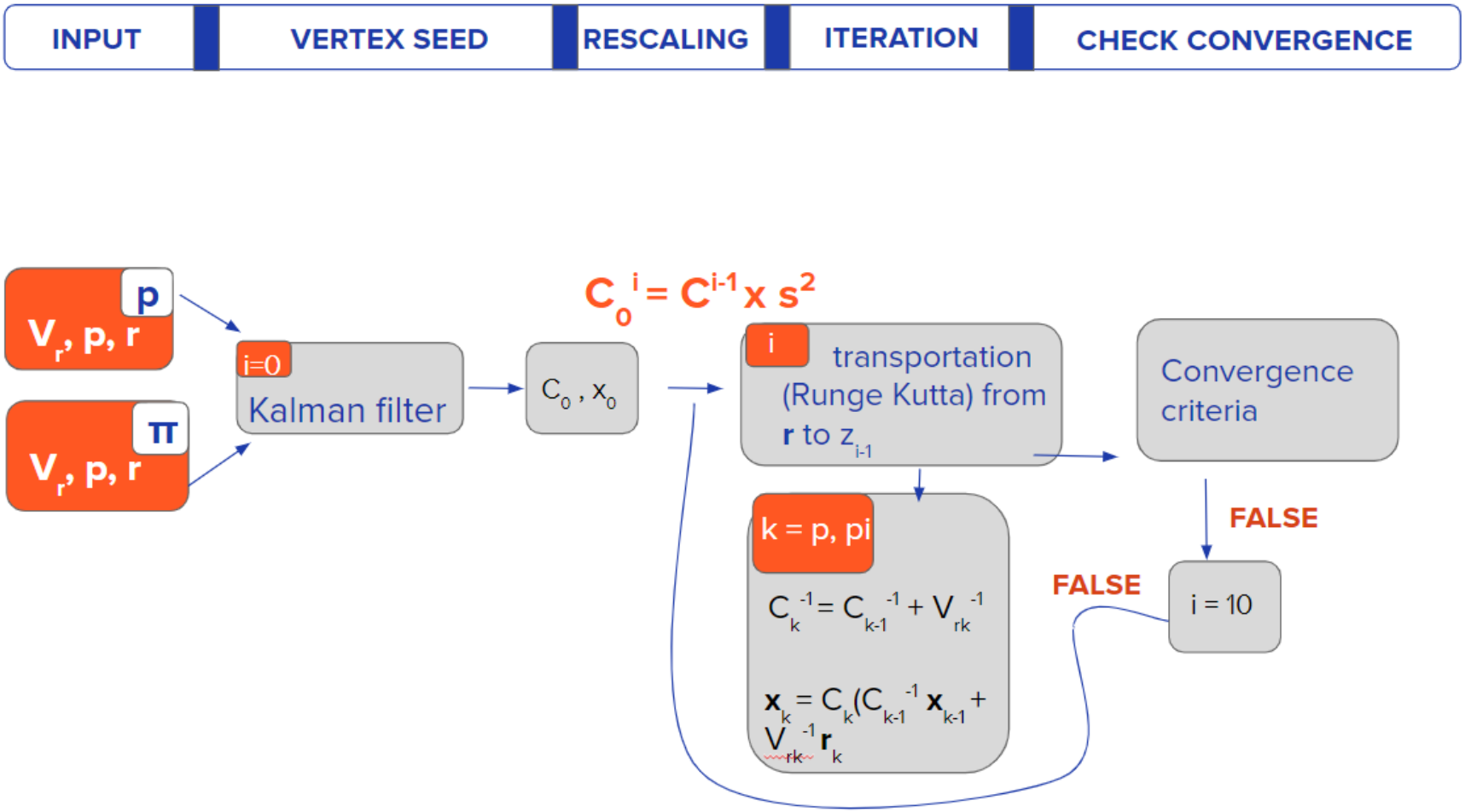

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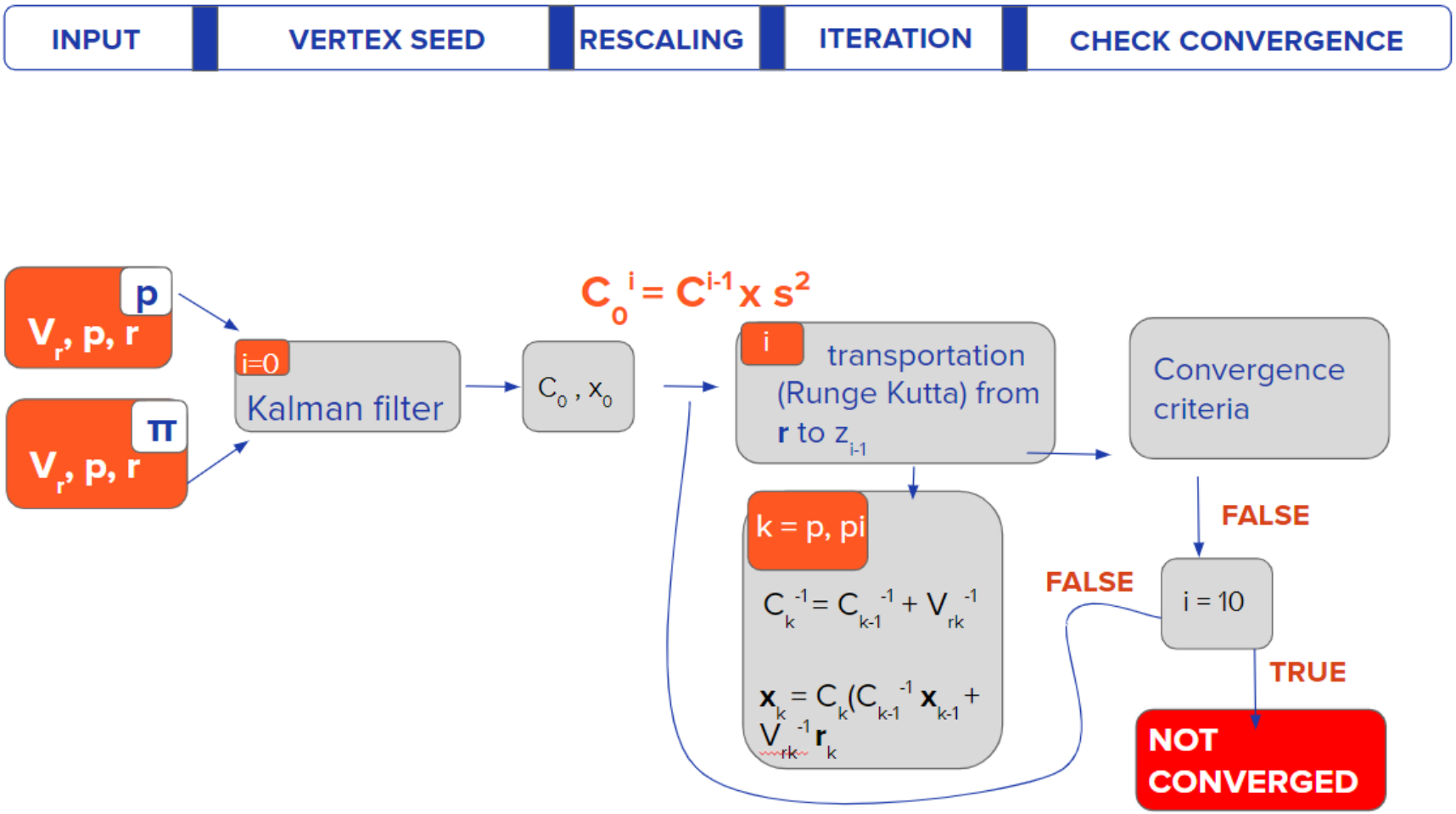

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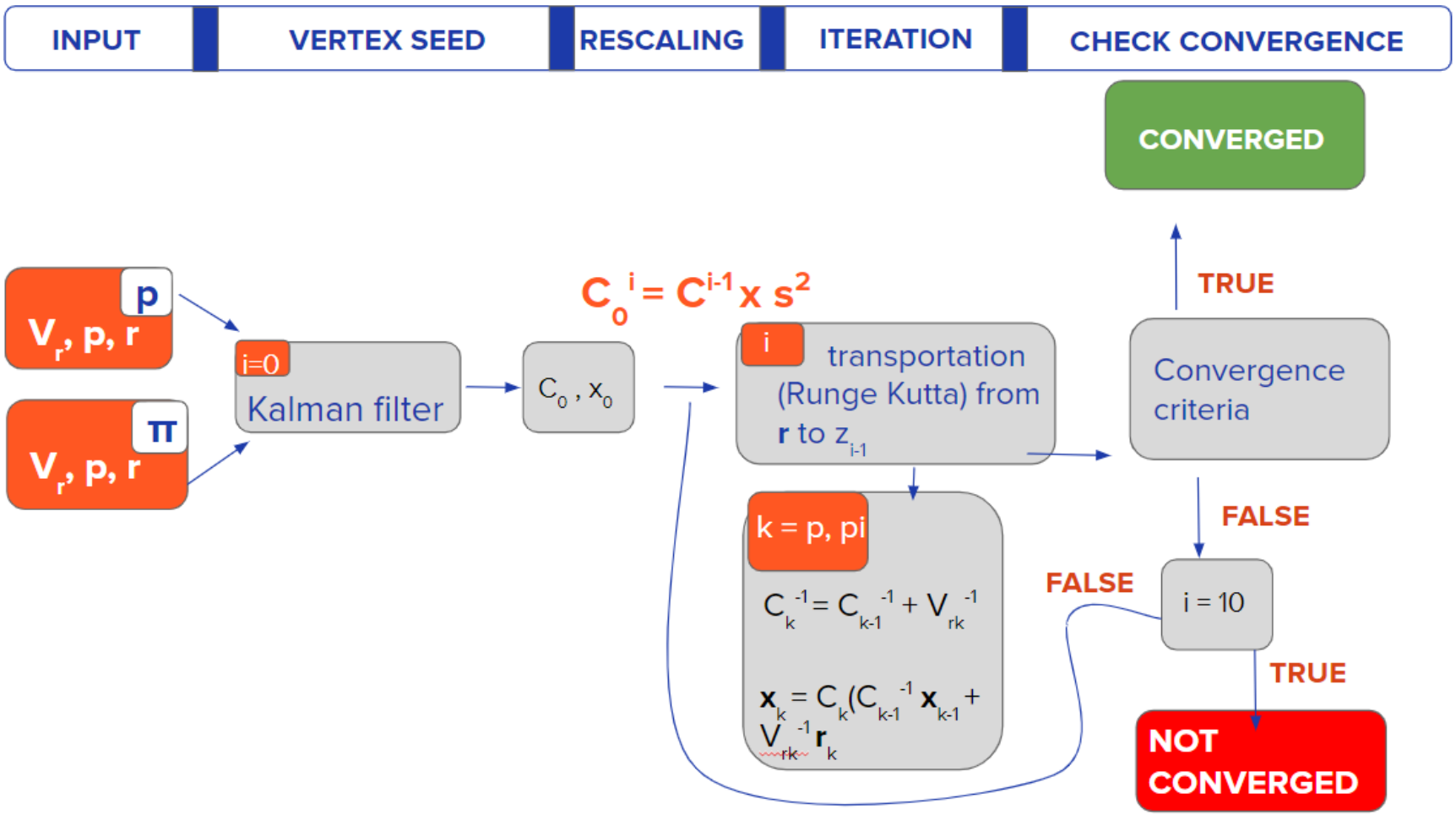
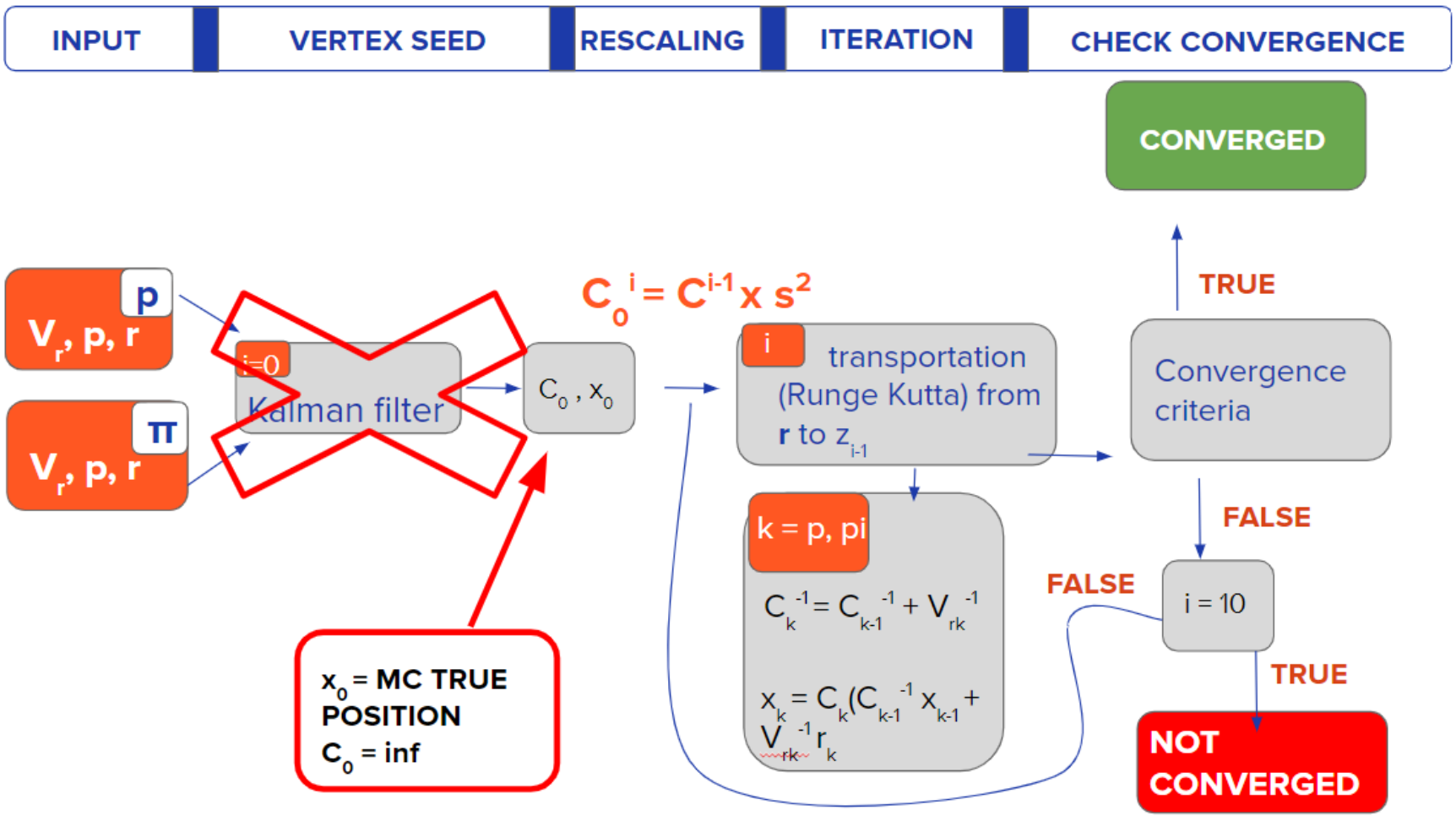
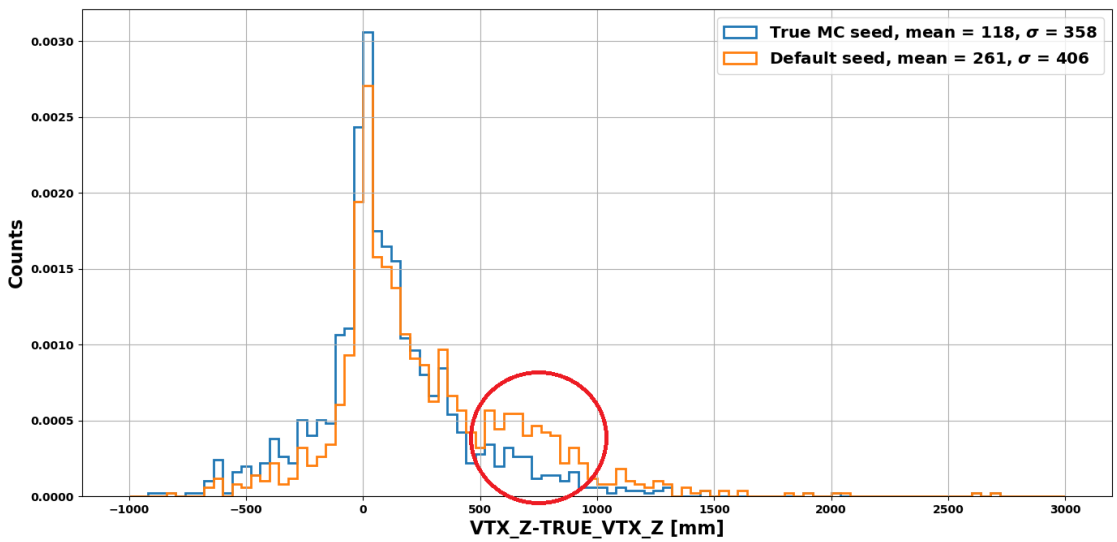


Our studies about the VF: bias on z vertex position due to ghost vertex



Our studies about the VF: bias on z vertex position due to ghost vertex

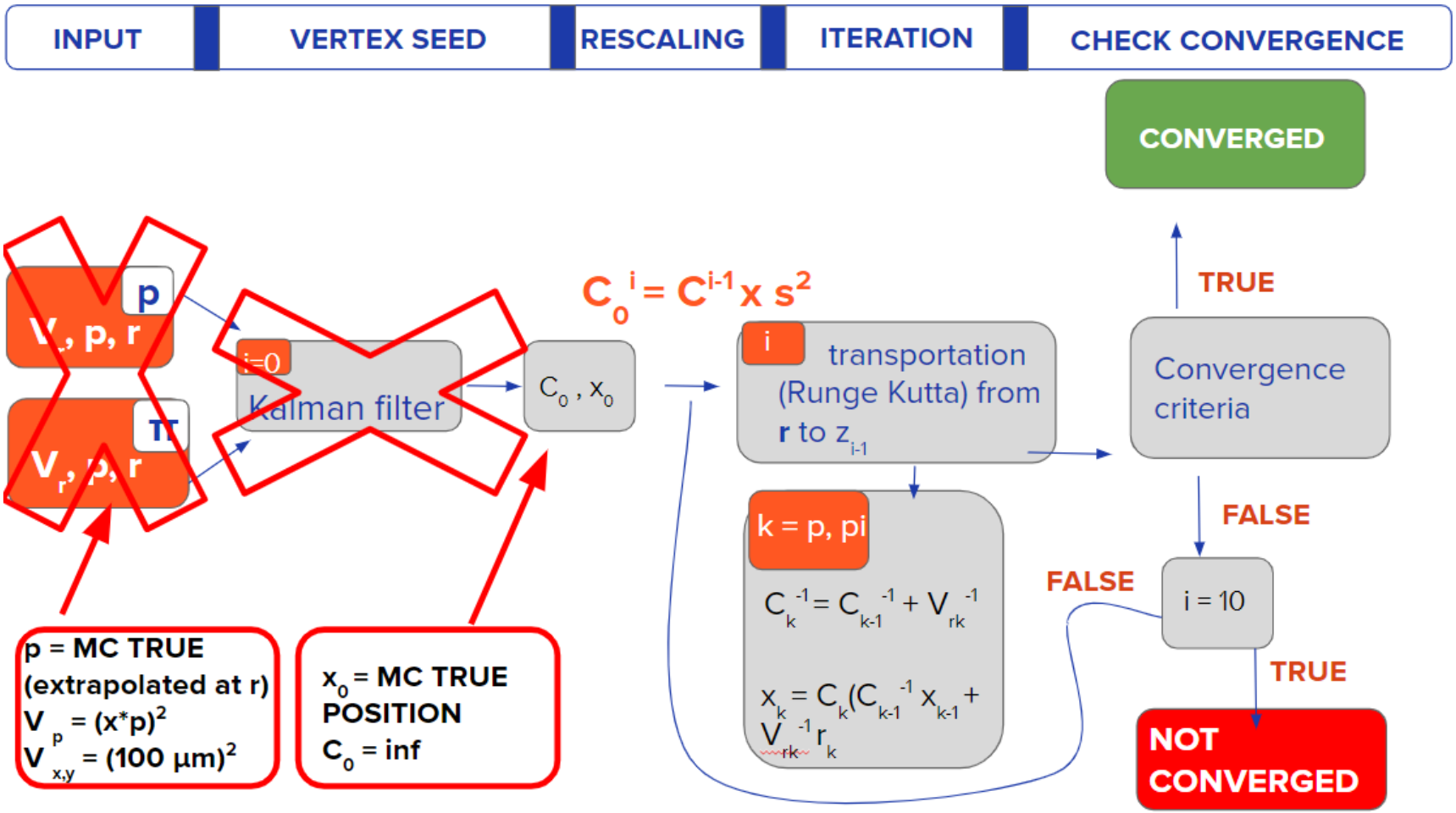
Reconstruction of Λ vtx with VF with simulation



Peak due to closing-track topology decreases if the seed is set to MC true vertex. Efficiency does not change

Bias remains due to low Q-value of the decay and limited momenta resolution

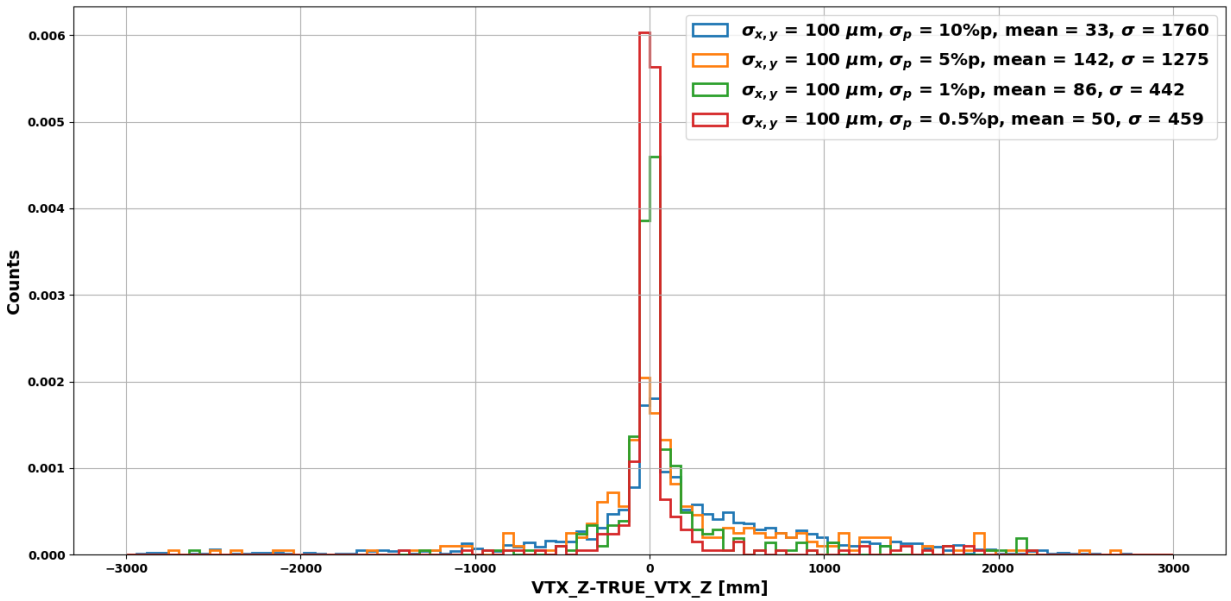
Our studies about the VF: momentum resolution



Our studies about the VF: momentum resolution

Seed = MC true vtx , $C_0 = inf$

True momenta at true vtx $\rightarrow$ transport at first measurement point (RK) $\rightarrow$ Gaussian smearing



- Λ vtx reconstruction efficiency = 83, 88, 94, 95% (σ_p=10, 5, 1, 0.5 %p)
- higher momenta resolution mitigates the bias

$\rightarrow$ effort in improving the momenta resolution (later in this presentation)

LHCb Decay Tree Fitter algorithm

- Complete decay chain fitted simultaneously
- Possibility to fix mass and primary vertex constraints
- Least square fit: minimization of the constraints ($\chi^2(\vec{x})$) to extract the parameters ($\vec{x}$)
- parameters $\vec{x}$:
  - 3/4 momenta (external/internal particle)
  - vertex position
  - decay time ($\theta = l/|\vec{p}|$)

LHCb Decay Tree Fitter algorithm

- Constraints $\chi^2(\vec{x})$:
  - measurement constraints with an associated error

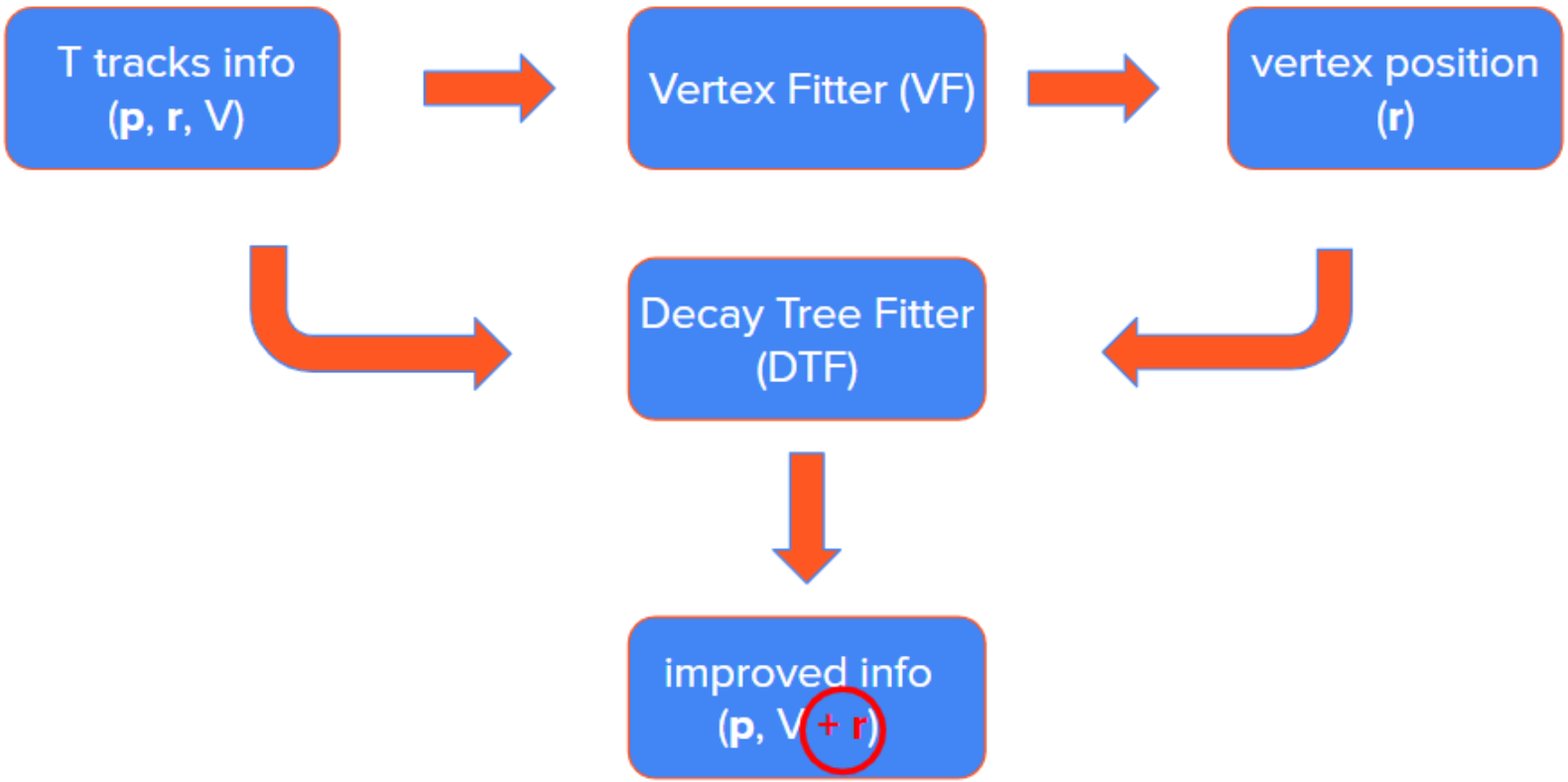
    $$\chi_i^2 = r_i^T(\vec{x}) V_i^{-1} r_i(\vec{x})$$

    with $r_i(x) = m_i - h_i(\vec{x})$ the constraint residual and V_i the constraint variance
  - exact constraints ($g_i(\vec{x}) = 0$) applied with Lagrangian multipliers (λ_i)

    $$\chi_i^2 = 2\lambda_i^T g_i(\vec{x})$$

- Kalman filter minimization to extract $\vec{x}$

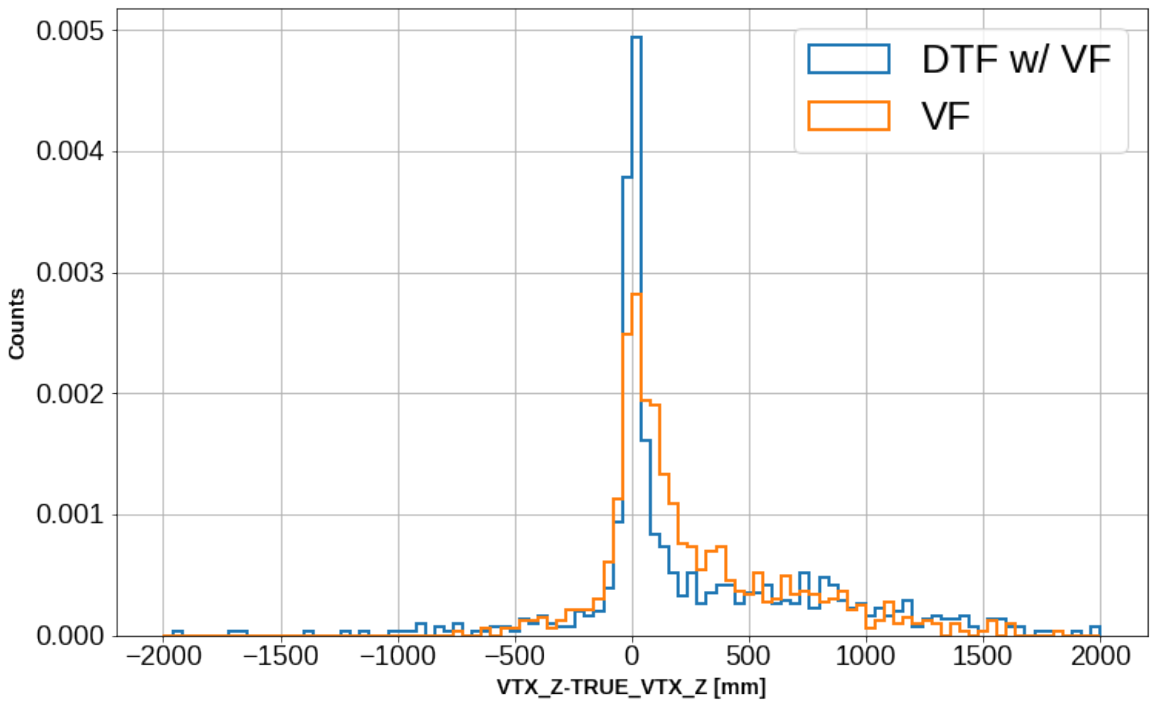
Our studies about DTF



Info: momenta ($\mathbf{p}$), position ($\mathbf{r}$) and covariance matrix (V)

Our studies about DTF

- DTF can be directly used as vertex finder $\rightarrow$ improvement, not final solution, a bias is still present



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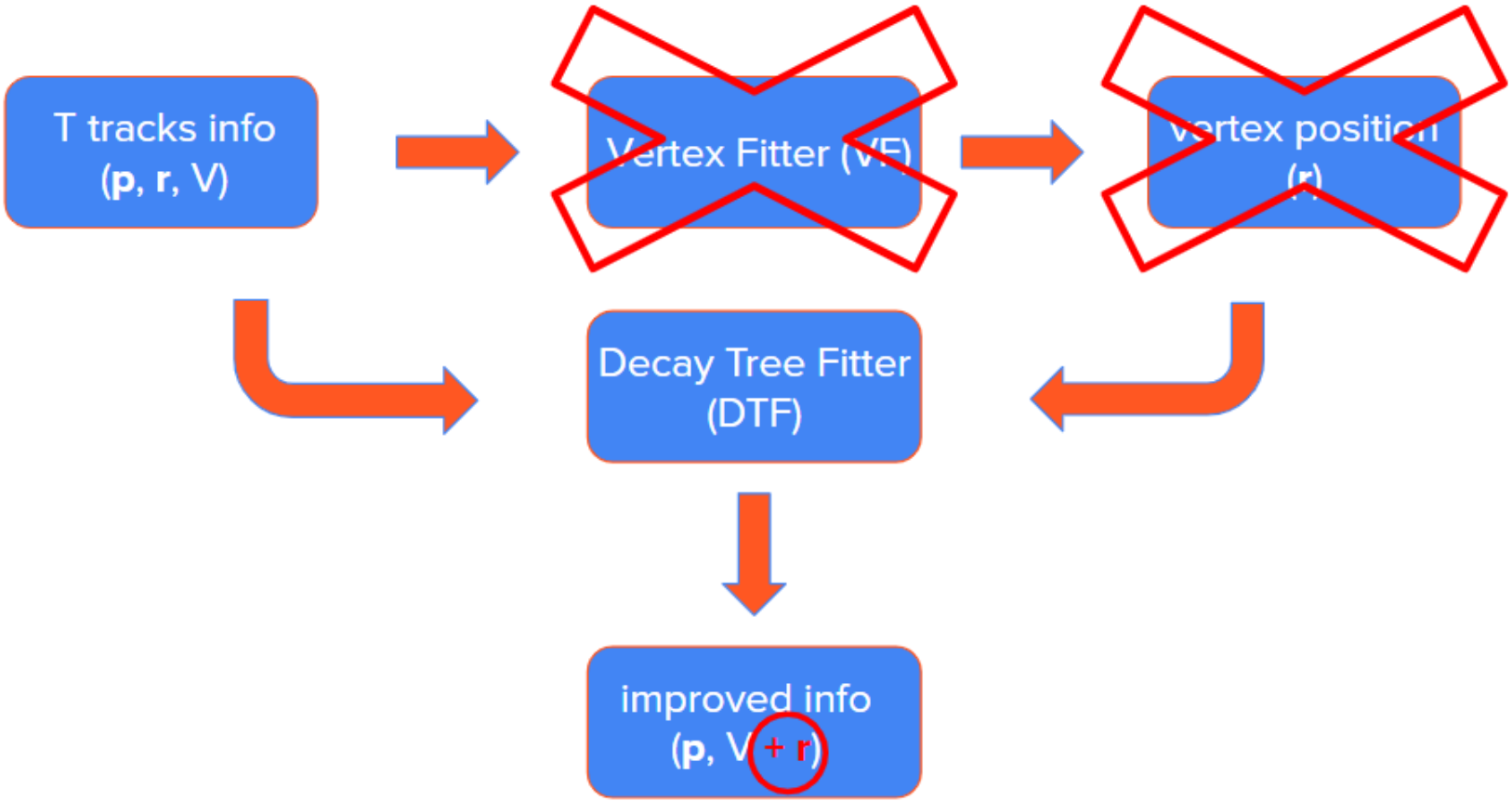
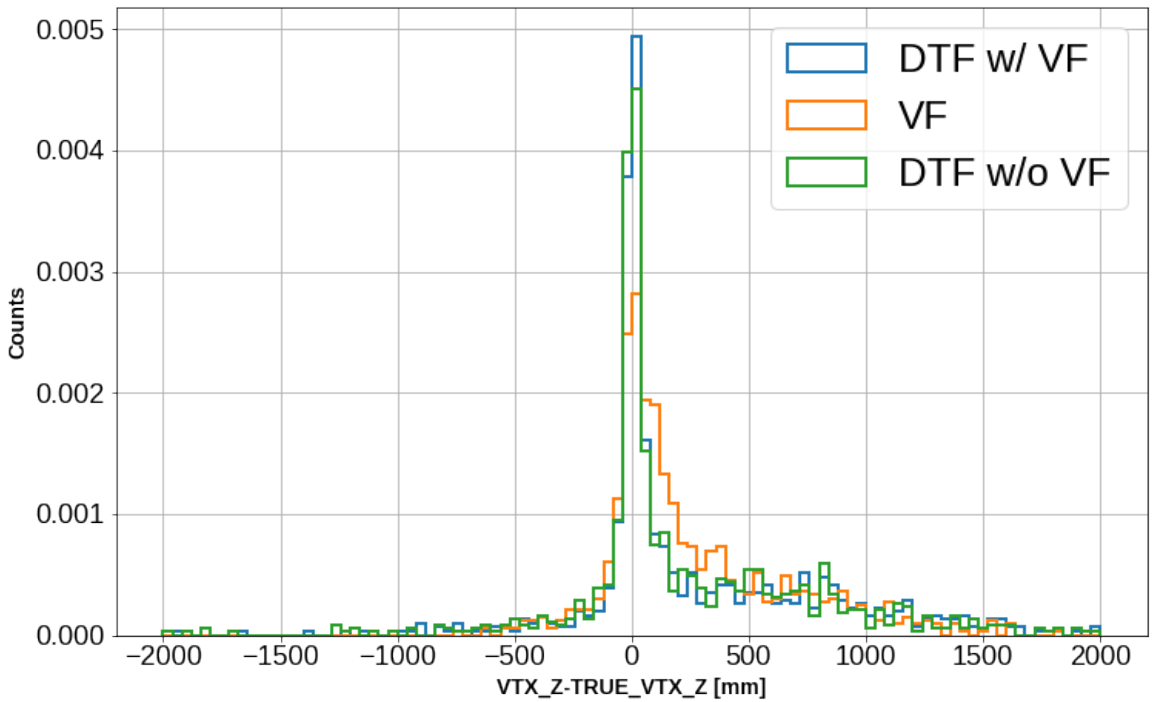


Info: momenta ($\mathbf{p}$), position ($\mathbf{r}$) and covariance matrix (V)

Our studies about DTF

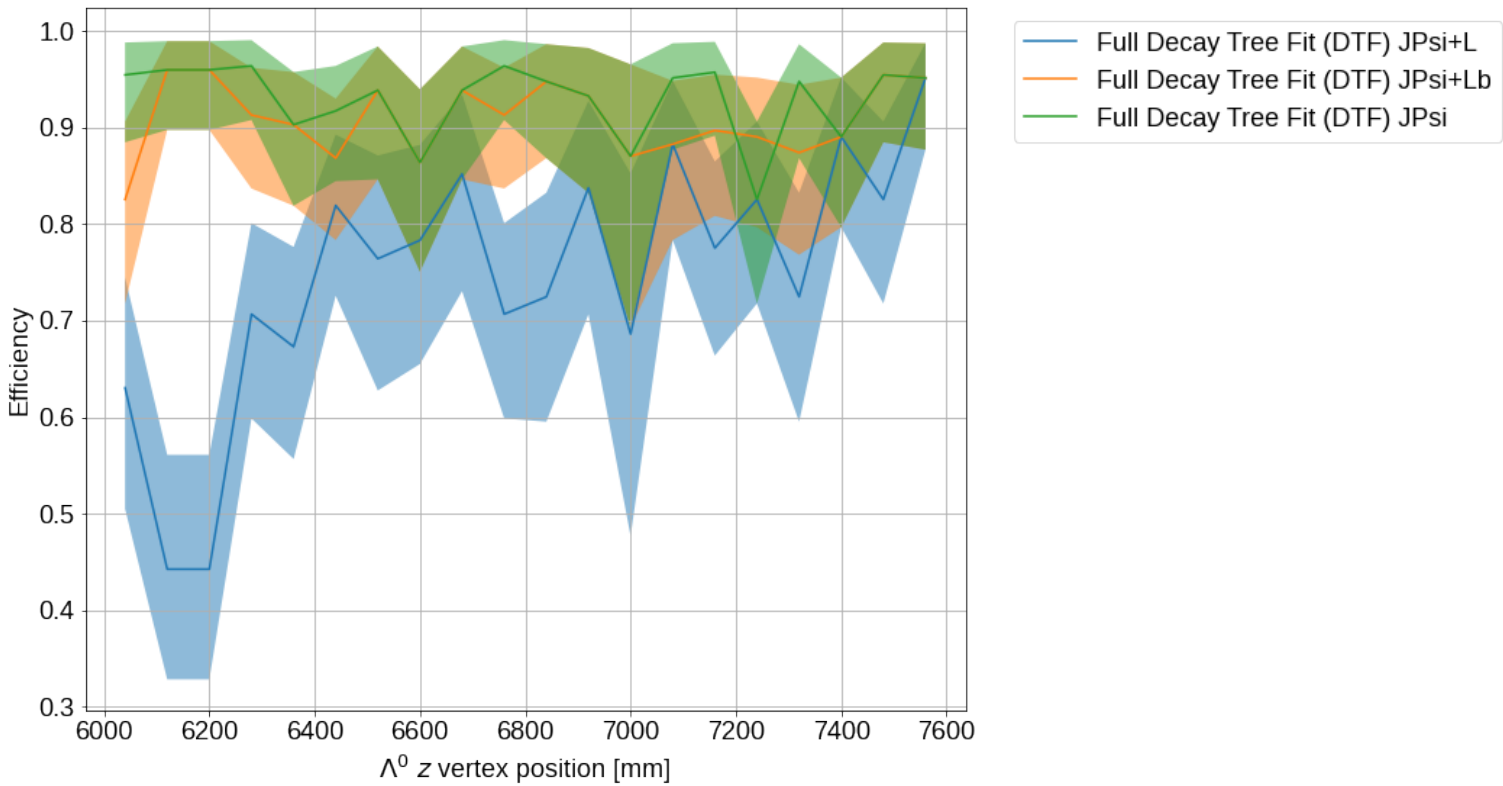
- Possibility to use directly the DTF, without the VF in the first step



$\rightarrow$ the bias is not improved, but recovery in the efficiency

Our studies about DTF

- Possibility to consider different mass constraints to recover efficiency



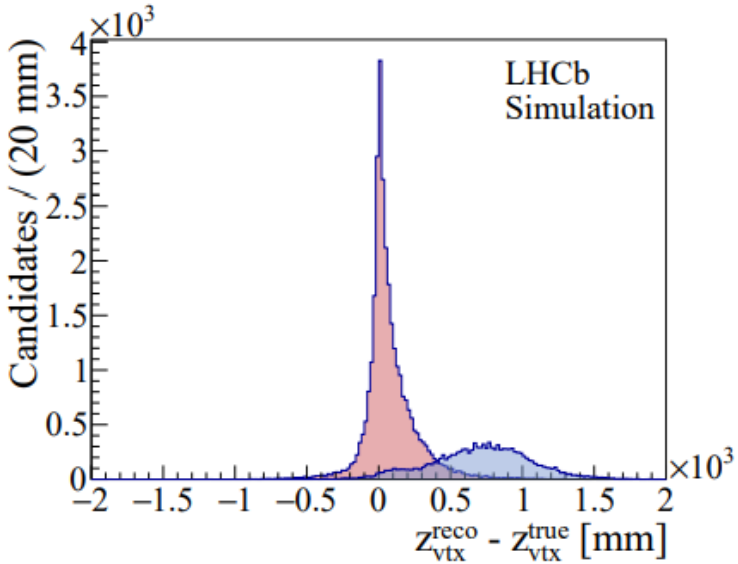
Impact on resolution without Λ mass constraint to be evaluated

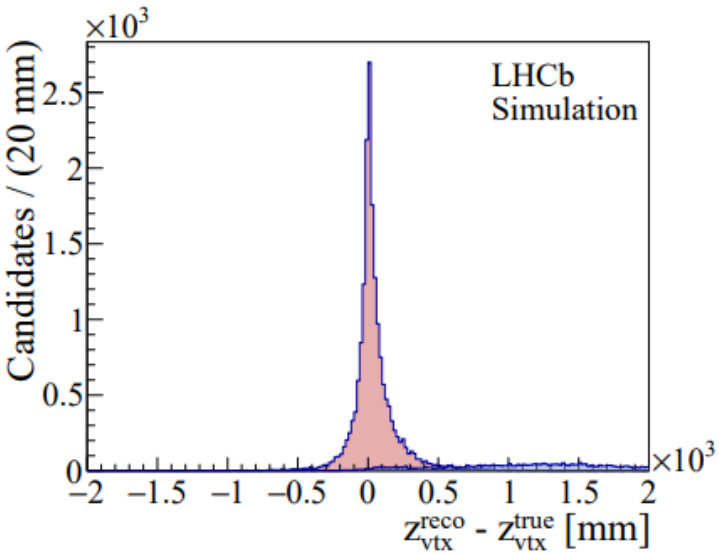
Conclusions

- Overview of the main vertexing algorithms used in LHCb
- Three problems linked to these algorithms emerge (efficiency, bias, ghost vertices) when dealing with T tracks
- Studies to improve vertexing with T tracks are ongoing
  - VF needs to have improved momentum resolution in input (ML regressor or RICH info see M. Wang talk)
  - DTF should be used directly instead of VF + DTF
- Resolution dilutes the sensitivity to EMDMs $\rightarrow$ need to quantify
  - removing ghost vertices could be a key in improving the resolution
- Vertexing is not a showstopper for the first measurement of dipole moments, but could really help in improving the analysis

Backup

Closing track topology: Λ vs K_s^0





Ghost fraction after the selection: 30% for Λ, only 1% for K_s^0

Different fraction of ghost vertex due to different Q-value of the decays: in K_s^0 case the angle between the daughters is larger, lower fraction of crossing tracks

LHCb Vertex fitter algorithm

Iterative algorithm

At each i-th iteration:

- initial rescaling of vertex covariance matrix $C_0^i = C_n^{i-1} \times s^2$, with $s^2 = 10^{-4}$
- transportation (Runge-Kutta method) of daughter particle from reference point $(\vec{r}) \rightarrow$ z component of $i-1$ vertex position

Within each iteration there are steps: addition of the k-th daughter

- vertex covariance matrix updated: $C_k^{-1} = C_{k-1}^{-1} + V_{rk}^{-1}$
- common origin vertex updated: $\vec{x}_k = C_k(C_{k-1}^{-1}\vec{x}_{k-1} + V_{rk}^{-1}\vec{r}_k)$
- momentum and χ^2 are updated accordingly

LHCb Vertex fitter algorithm

First step ($i = 0$) vertex seed: simplified step of the Kalman filter

Vertexing process is repeated until

- a convergence criterium is satisfied
  - $|\vec{x}^{(i-1)} - \vec{x}^{(i)}| < 1\ \mu m$
  - from i=2, $0 \leq (\vec{x}^{(i-1)} - \vec{x}^{(i)})^T C^{-1(i)} (\vec{x}^{(i-1)} - \vec{x}^{(i)}) \leq 1\%$

  $\rightarrow$ converged event

- the maximum number of iteration ($i = 10$) is reached $\rightarrow$ non-converged event $\rightarrow$ discarded

Our studies about the VF: change of parameters - not effective