

CERN-THESIS-2024-042

**Electron track reconstruction studies and improvement for
LHCb's real-time analysis trigger**

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Motivation

tracking at LHCb:

- tracks of charged particles are reconstructed with efficiencies well above 90%
- **but:** electron tracking underperforms significantly compared to other particles
- due to bremsstrahlung

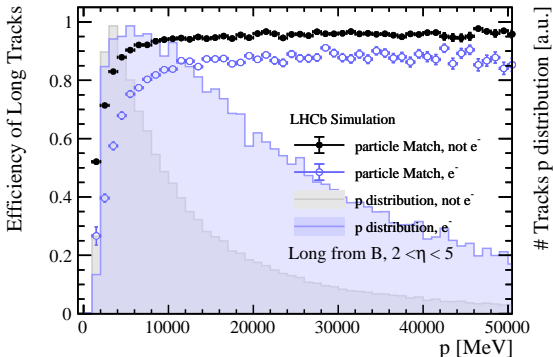


Figure: Match track efficiency of electrons and other particles.

Improving Electron Reconstruction

currently, all track-reconstruction tuning explicitly excludes electrons

idea:

- run dedicated electron reconstruction sequence in HLT2

explored solution:

- identify electron tracks using the ECAL filter: TrackBasedElectronShowerAlg [Rec!2319]
- expand the Matching algorithm
 - must be computationally cheap to be run in the trigger
- tune parameterisations to electrons
- upper limit for the efficiency around 93%, determined by the VELO and SciFi track efficiency

Tracking of Charged Particles

- **Long tracks** offer the highest relative momentum resolution with 0.5%
- main type used in physics analyses
- reconstructed via two methods: Forward tracking and **Track Matching**

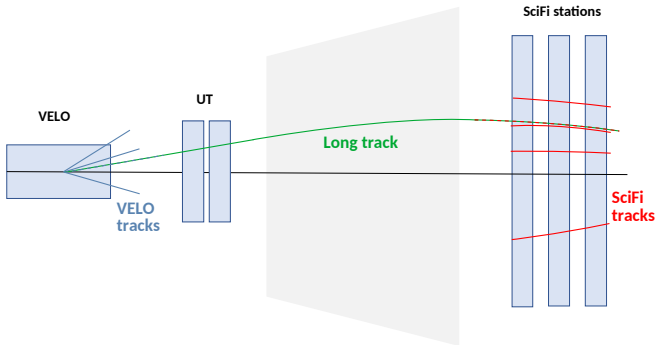


Figure: Sketch of LHCb track types in the x - z plane.

The Matching Algorithm

Basic idea:

- combine VELO and SciFi tracks of same particle to create Long tracks
- quantify the level of agreement, *i.e.* a match, between reconstructed VELO and SciFi tracks
- evaluate a neural network to obtain a combined estimate of being correctly matched

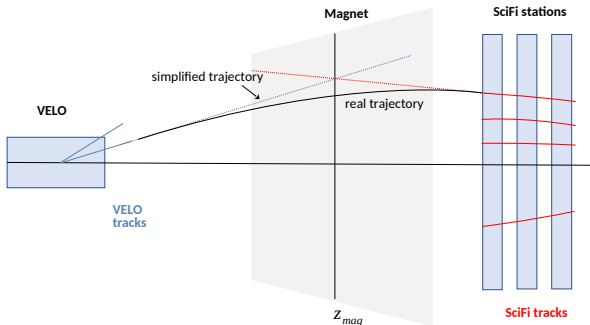


Figure: Basic idea of the Matching algorithm in the x - z plane.

Track Preselection

electron track identification:

- tracks can be extrapolated to the ECAL and matched to EM-showers:
 - VELO tracks are matched to the EM-showers of photons emitted by electrons in the VELO (not available for tracking yet, currently using MC information to simulate a perfect filter)
 - SciFi tracks are matched to the EM-showers of the electrons directly
- [[Rec!3738](#), [Rec!2319](#)]
- the performance of the ECAL filter has not been studied in detail

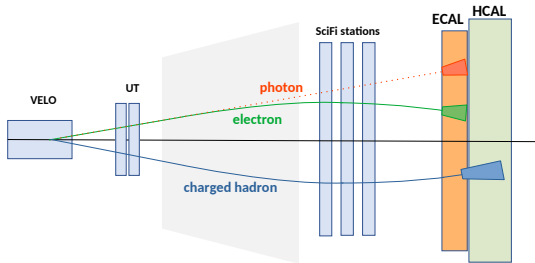


Figure: Different particle signatures in the LHCb detector.

Input Variables

- six input variables
- most important:

$$D_x = |x_V(z_{\text{mag}}) - x_T(z_{\text{mag}})|$$

$$D_y = |y_V(z_{\text{mag}}) - y_T(z_{\text{mag}})|$$

- used to define a combined quality measure, mimicking a χ^2 :

$$\chi_{\text{match}}^2 = \frac{D_x^2}{\sigma_x^2} + \frac{D_y^2}{\sigma_y^2} + \frac{|\Delta t_y|^2}{\sigma_{t_y}^2}$$

using other variables as input for the NN, such as

- the radiation length fraction x/X_0
- the pseudorapidity η
- the azimuthal angle ϕ

does not offer significant improvements

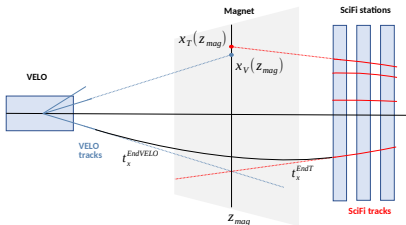


Figure: Bending plane.

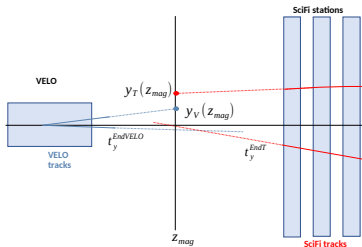


Figure: Non-bending plane.

Parameter Tuning

tune all approximations and estimates used during the reconstruction to electrons, e.g. the z_{mag} parameter in the optical model

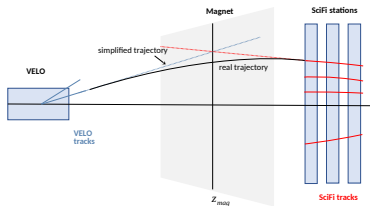


Figure: Magnet kick position z_{mag} .

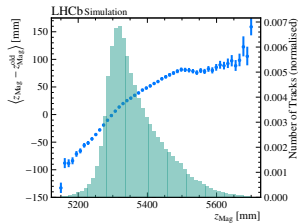


Figure: Old z_{mag} parameterisation for electrons.

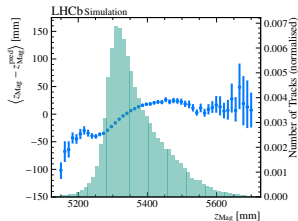


Figure: New z_{mag} parameterisation for electrons.

Test on Electron Tracks

- new Matching algorithm tested on **only** electron tracks
- efficiencies above 90%
- low ghost rate

Table: Integrated Matching efficiencies using perfect track selection.

Category	Old ε [%]	New ε [%]
Long	64.02	78.33
Long from B	83.46	87.90
$p > 5 \text{ GeV}$	86.22	90.05
$p > 3 \text{ GeV } p_T > 0.5 \text{ GeV}$	87.72	90.86
Ghost rate	17.44%	13.96%

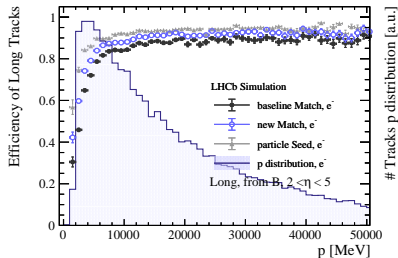


Figure: Efficiency using perfect selection.

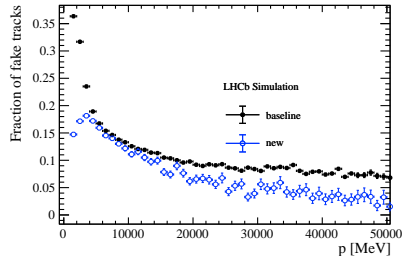


Figure: Ghost rate.

Improved Electron Reconstruction Efficiency

- new Matching algorithm + TrackBasedElectronShowerAlg performs best using a combination of DLL and E/p
- also tested: ClusterMatch and ElectronMatch
- efficiency increases by 3%
- higher ghost rate

Table: Integrated Matching efficiencies using ECAL filtered tracks.

Category	Old ε [%]	New ε [%]
Long	64.02	76.41
Long from B	83.46	86.40
$p > 5 \text{ GeV}$	86.22	88.55
$p > 3 \text{ GeV } p_T > 0.5 \text{ GeV}$	87.72	89.39
Ghost rate	17.44%	26.37%

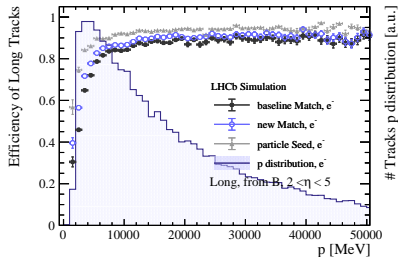


Figure: Matching efficiency using ECAL filter.

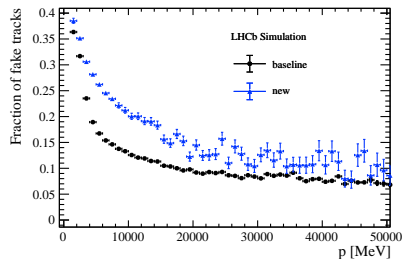


Figure: Ghost rate.

Conclusion

summary:

- slight improvements with new parameterisations and retraining of NN
- for major improvements in electron reconstruction
 - a high-performance preselection of electron VELO and SciFi tracks is needed to control the ghost rate
- efficiencies around 90% at the track-finding stage

next steps:

- ECAL filter ready for SciFi tracks, but not for VELO tracks
- study, how to integrate this into the current reconstruction
- use the electron track-finding for real data
- optimise track fit
 - Kalman Filter is suboptimal for electrons
 - possible alternative: Gaussian Sum Filter

BACKUP

Magnetic field at LHCb

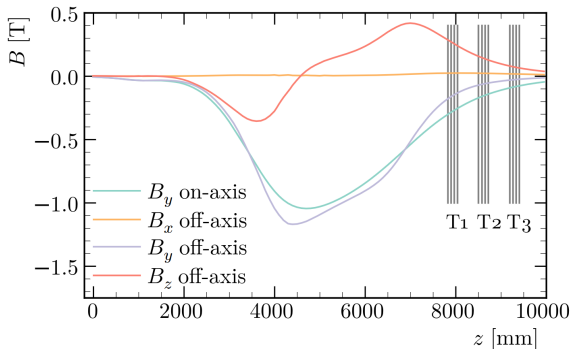


Figure: Magnetic field strength components as functions of z ¹.

¹CERN-THESIS-2023-097

Performance Metrics

two main performance indicators for track reconstruction with pattern recognition:

1. *track finding efficiency* $\varepsilon = \frac{N_{\text{reconstructible \& MC-matched}}}{N_{\text{reconstructible}}}$
2. *fake track fraction or ghost rate* $r_{\text{fake}} = \frac{N_{\text{fake}}}{N_{\text{total}}}$

where N is the number of tracks in the corresponding category

reconstructible:

- must pass through at least three VELO layers, leaving hits in each
- must leave a hit in at least one x and one stereo layer in each of the SciFi stations

MC-matched:

- more than 70% of the hits must originate from the same simulated particle

Electron Reconstruction Sequence

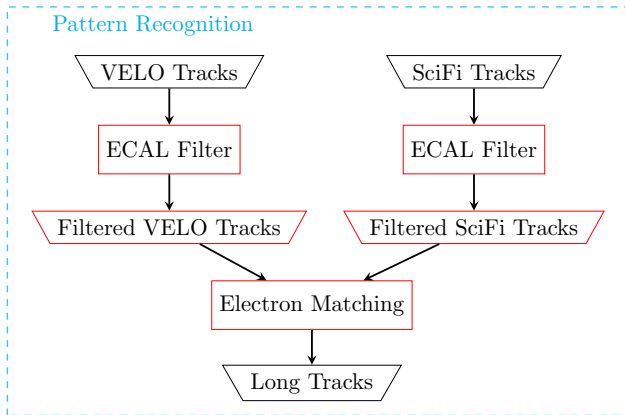


Figure: Electron reconstruction sequence.

Matching Variables

$$t_x^2 + t_y^2 = \left(\frac{dx}{dz}\right)^2 + \left(\frac{dy}{dz}\right)^2$$

$$|\Delta t_x| = |t_x^{\text{EndT}} - t_x^{\text{EndVelo}}|$$

$$|\Delta t_y| = |t_y^{\text{EndT}} - t_y^{\text{EndVelo}}|$$

$$D_x^{\text{match}} = \left| x_T - x_V + t_x^{\text{EndT}}(z_{\text{mag}}^{\text{match}} - z_T) - t_x(z_{\text{mag}}^{\text{match}} - z_V) \right|$$

$$D_y^{\text{match}} = \left| y_T - y_V + t_y^{\text{EndT}}(z_{\text{match}} - z_T) - t_y(z_{\text{match}} - z_V) - y_{\text{corr}}^{\text{match}} \right|$$

$$\chi_{\text{match}}^2 = \frac{D_x^2}{\sigma_x^2} + \frac{D_y^2}{\sigma_y^2} + \frac{|\Delta t_y|^2}{\sigma_{t_y}^2}$$

Input Variables

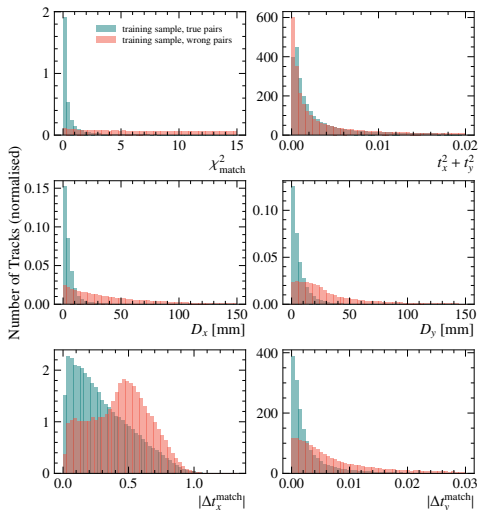


Figure: Matching MLP input variables.

some changes in the preselection cuts yield better performance

Table: Matching MLP input variables for electron Matching.

Variable	Preselection
χ^2_{match}	< 15
D_x	< 300 mm
D_y	< 300 mm
$ \Delta t_x^{\text{match}} $	< 2.0
$ \Delta t_y^{\text{match}} $	< 0.15
$t_x^2 + t_y^2$	

Input Variables

- six input variables

- most important:

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$$D_y = |y_V(z_{\text{mag}}) - y_T(z_{\text{mag}})|$$

- used to define a combined quality measure, mimicking a χ^2 :

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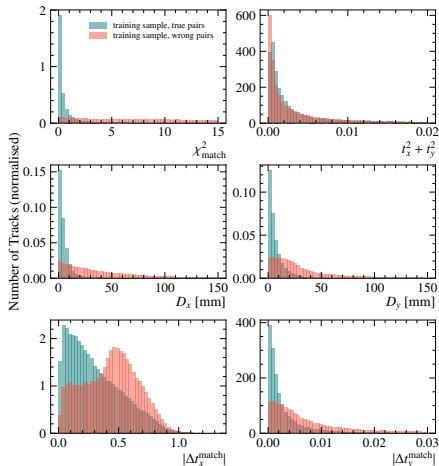
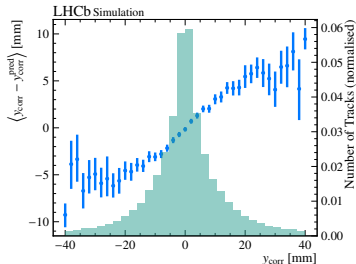
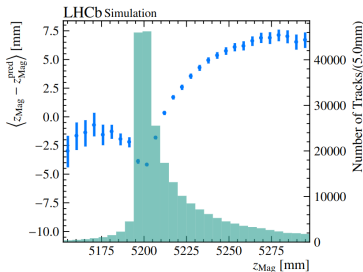


Figure: Matching MLP input variables.

Electron Matching Tuning



a: Old z_{mag} parameterisation for not-electrons^b.

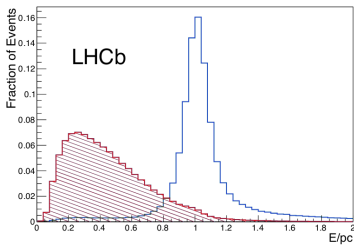
b: New y_{CORR} parameterisation for electrons.

^bCERN-THESIS-2023-097

$$z_{\text{mag}}^{\text{match}} = c_0 + c_3 t_x^2 + c_7 t_y^2 + |\Delta t_x| (c_1 + c_{11} t_y^2) + \Delta t_x^2 (c_5 + c_{10} |x_T|) \\ + \Delta t_x t_x (c_4 + c_9 |x_T|) + |x_T| (c_2 + c_8 t_x^2 + c_6 |x_T| + c_{12} |x_T|^2) \\ y_{\text{corr}}^{\text{match}} = t_y (c_2 |\Delta t_x|^2 + c_3 |\Delta t_y|^2) + \Delta t_y (c_0 + c_1 \Delta t_x)$$

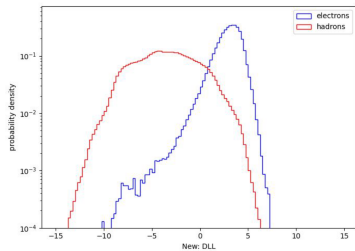
ECAL Filter

SciFi track selection using the already implemented ECAL filter



a: E/p using Run 1 data^c.

^carXiv: 2008.11556



b: DLL using simulated events^d.

^dM. V. Veghel, personal communication,
January 2024

Figure: Distributions of variables in the ECAL for electrons (blue) and hadrons (red).

Electron Matching Response

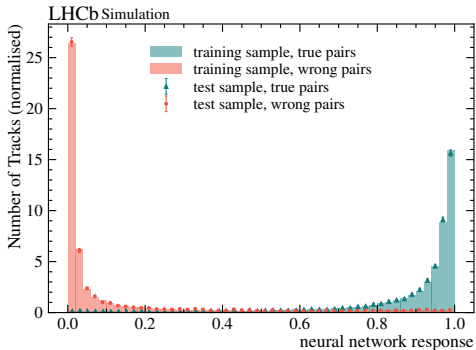


Figure: Output of the electron Matching MLP.

BestLong Efficiency

Table: Integrated Best Long efficiency of electrons and other particles.

BestLong	e^\pm ε [%]	not- e^\pm ε [%]
From B	82.04	91.08
$p > 5$ GeV from B	84.15	94.00
Ghost rate	10.26%	

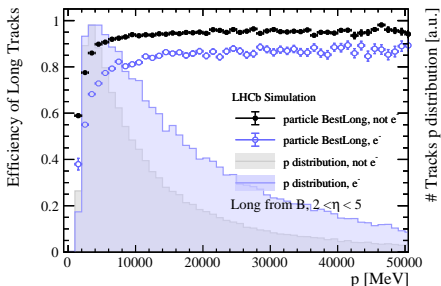
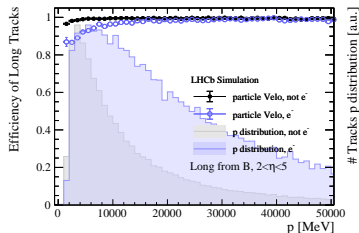
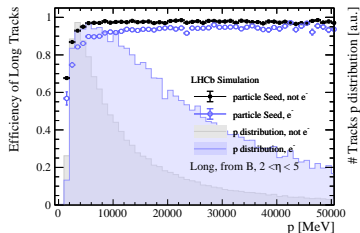


Figure: Long track efficiency of electrons and other particles, after Kalman filter.

VELO and T Track Efficiencies



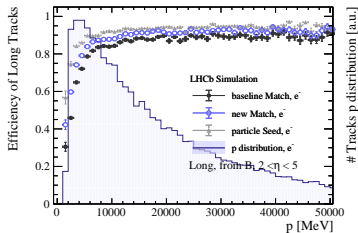
a: VELO Tracking efficiency.



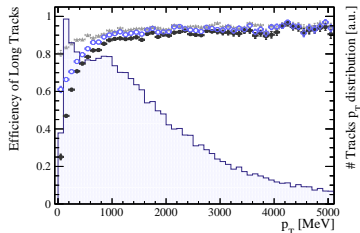
b: Hybrid Seeding efficiency.

Figure: Reconstruction efficiency of (a) the VELO Tracking, and (b) the Hybrid Seeding algorithm.

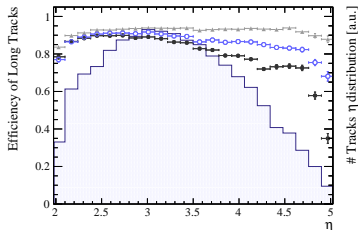
New Matching Efficiencies - Long from B



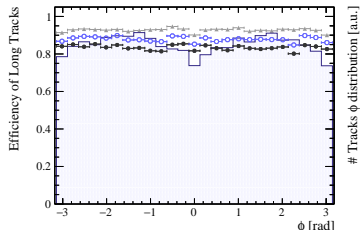
a: Efficiency vs. momentum.



b: Efficiency vs. transverse momentum.



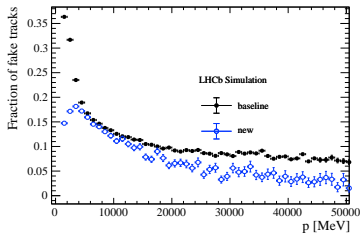
c: Efficiency vs. pseudorapidity.



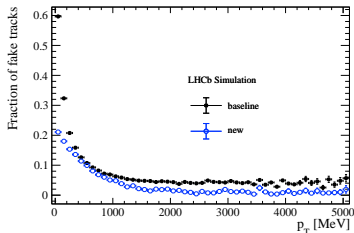
d: Efficiency vs. azimuthal angle.

Figure: Track finding efficiency of the electron Matching algorithm.

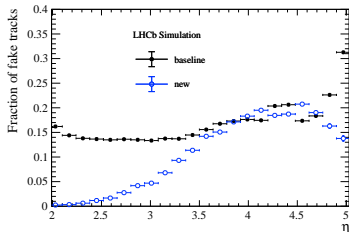
New Matching Fake Track Fraction - Long from B



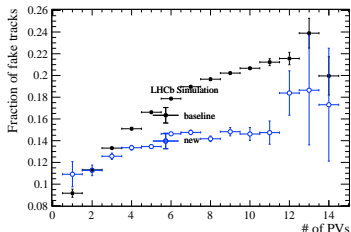
a: Fake track fraction vs. momentum.



b: Fake track fraction vs. transverse momentum.

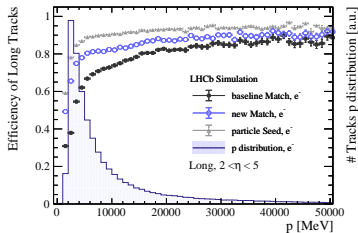


c: Fake track fraction vs. pseudorapidity.

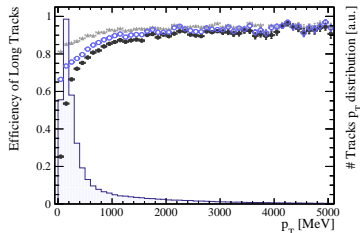


d: Fake track fraction vs. number of primary vertices.

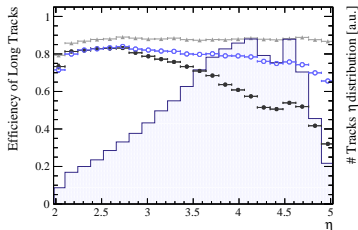
New Matching Efficiencies - Long



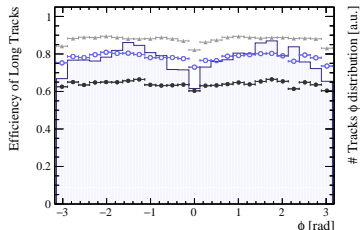
a: Efficiency vs. momentum.



b: Efficiency vs. transverse momentum.



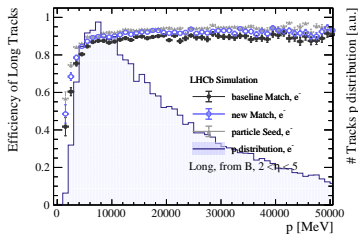
c: Efficiency vs. pseudorapidity.



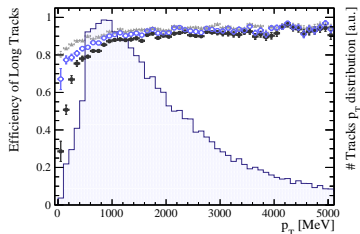
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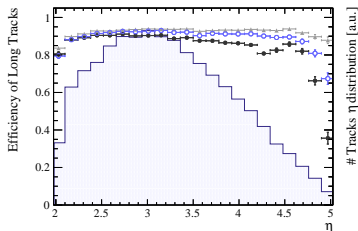
New Matching Efficiencies - Long from $B p > 3 \text{ GeV } p_T > 0.5 \text{ GeV}$



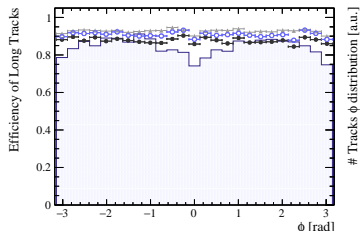
a: Efficiency vs. momentum.



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Figure: Track finding efficiency of the electron Matching algorithm.