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

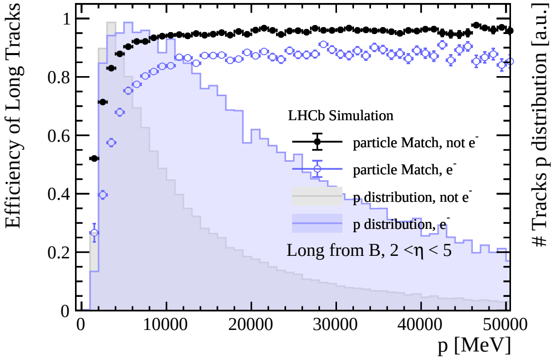

Figure: Match track efficiency of electrons and other particles.

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**

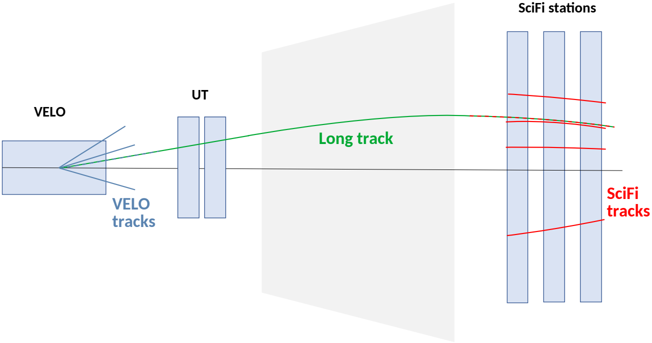

Figure: Sketch of LHCb track types in the x-z plane.

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

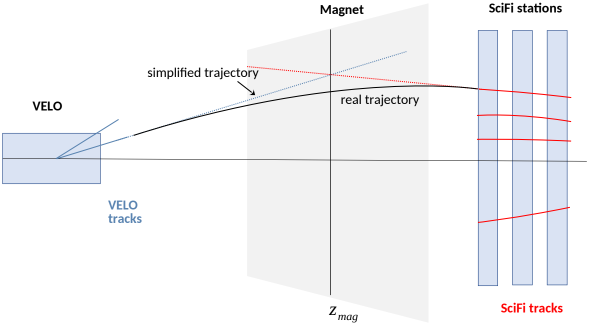

Figure: Basic idea of the Matching algorithm in the x-z plane.

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

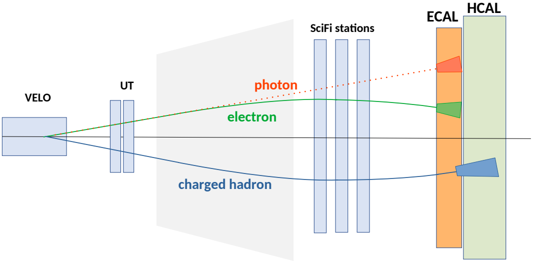

Figure: Different particle signatures in the LHCb detector.

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:

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

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

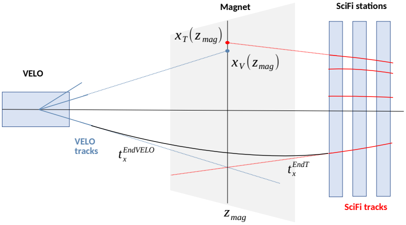

Figure: Bending plane.

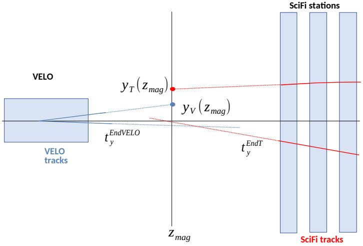

Figure: Non-bending plane.

Parameter Tuning

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

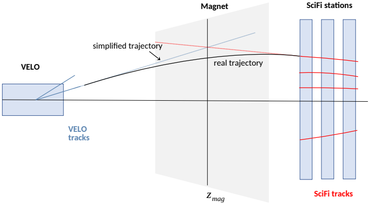

Figure: Magnet kick position z_{mag}.

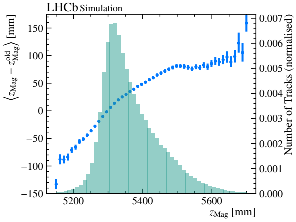

Figure: Old z_{mag} parameterisation for electrons.

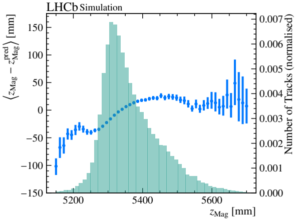

Figure: New z_{mag} parameterisation for electrons.

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 $\varepsilon[\%]$	New $\varepsilon[\%]$
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%

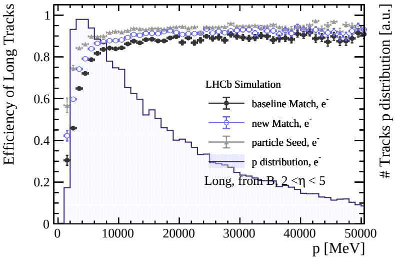

Figure: Efficiency using perfect selection.

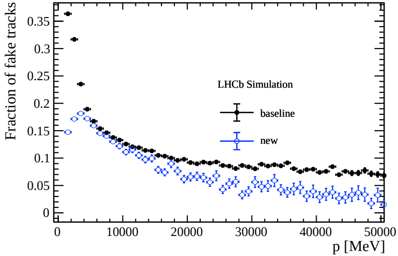

Figure: Ghost rate.

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

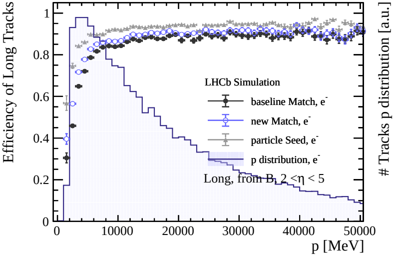

Figure: Matching efficiency using ECAL filter.

Table: Integrated Matching efficiencies using ECAL filtered tracks.

Category	Old $\varepsilon[\%]$	New $\varepsilon[\%]$
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%

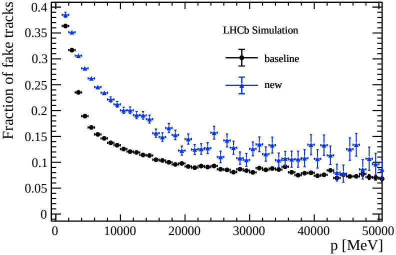

Figure: Ghost rate.

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

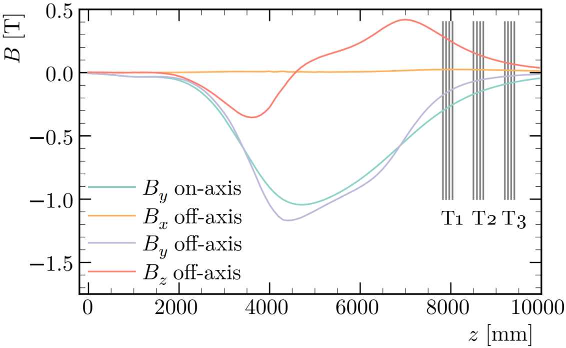

Figure: Magnetic field strength components as functions of z[1].

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[1] CERN-THESIS-2023-097

Performance Metrics

two main performance indicators for track reconstruction with pattern recognition:

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

   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

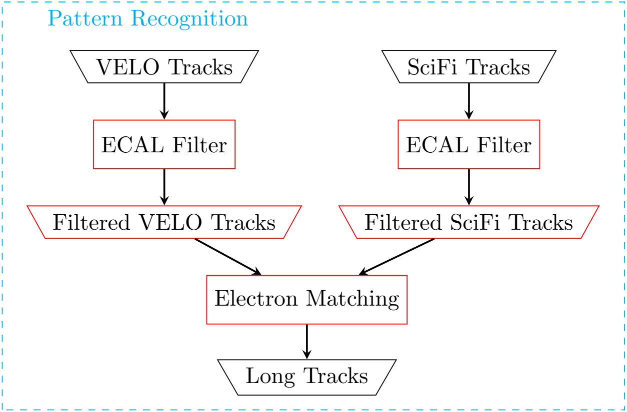


Figure: Electron reconstruction sequence.

Matching Variables

$$t_x^2 + t_y^2 = \left(\frac{\mathrm{d}x}{\mathrm{d}z}\right)^2 + \left(\frac{\mathrm{d}y}{\mathrm{d}z}\right)^2$$

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

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

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

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

$$\chi^2_{\mathsf{match}} = \frac{D_x^2}{\sigma_x^2} + \frac{D_y^2}{\sigma_y^2} + \frac{|\Delta t_y|^2}{\sigma_{t_y}^2}$$

Input Variables

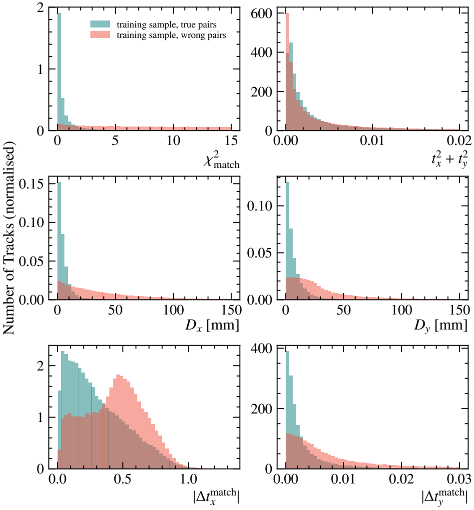


Figure: Matching MLP input variables.

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
$\left\|\Delta t_x^{\text{match}}\right\|$	< 2.0
$\left\|\Delta t_y^{\text{match}}\right\|$	< 0.15
$t_x^2 + t_y^2$	

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:

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

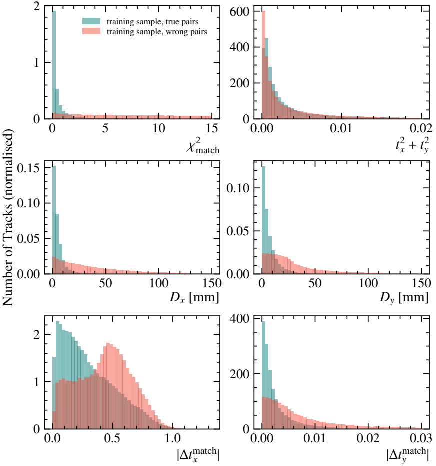
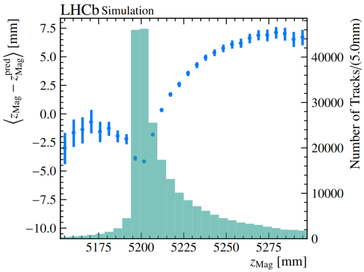
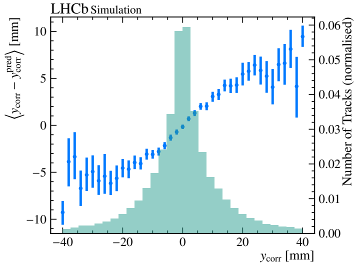


Figure: Matching MLP input variables.

Electron Matching Tuning



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



b: New y_{corr} parameterisation for electrons.

$$
\begin{aligned}
z_{\mathrm{mag}}^{\mathrm{match}} =& c_0 + c_3 t_x^2 + c_7 t_y^2 + |\Delta t_x| \left(c_1 + c_{11} t_y^2 \right) + \Delta t_x^2 \left(c_5 + c_{10} |x_T| \right) \\
& + \Delta t_x t_x \left(c_4 + c_9 |x_T| \right) + |x_T| \left(c_2 + c_8 t_x^2 + c_6 |x_T| + c_{12} |x_T|^2 \right)
\end{aligned}
$$

$$
y_{\mathrm{corr}}^{\mathrm{match}} = t_y \left(c_2 |\Delta t_x|^2 + c_3 |\Delta t_y|^2 \right) + \Delta t_y \left(c_0 + c_1 \Delta t_x \right)
$$

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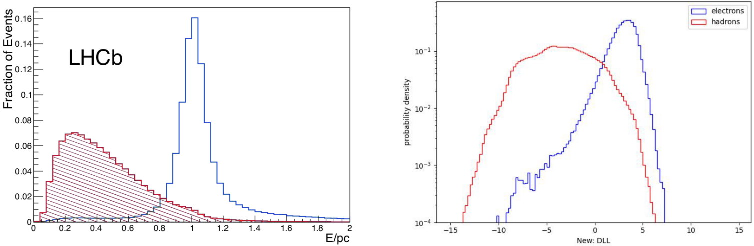
[b] CERN-THESIS-2023-097

ECAL Filter

SciFi track selection using the already implemented ECAL filter



a: E/p using Run 1 data[c].

b: DLL using simulated events[d].

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[c] arXiv: 2008.11556

[d] M. V. Veghel, personal communication, January 2024

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

Electron Matching Response

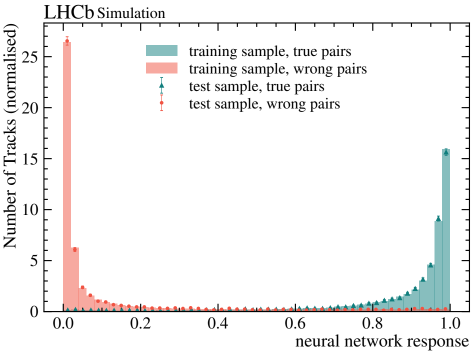


Figure: Output of the electron Matching MLP.

BestLong Efficiency

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

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

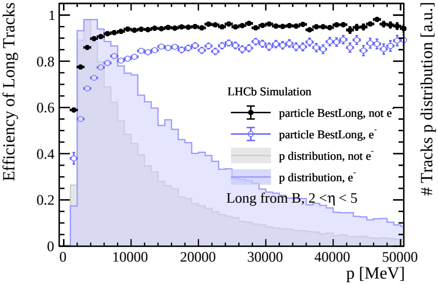
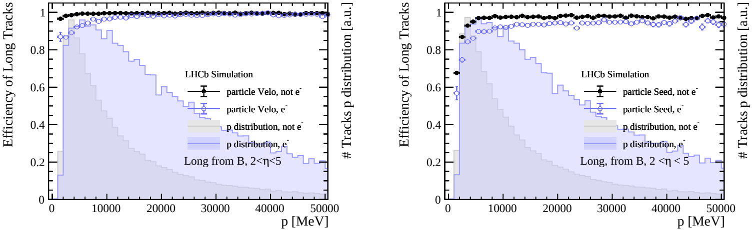


Figure: Long track efficiency of electrons and other particles, after Kalman filter.

VELO and T Track Efficiencies

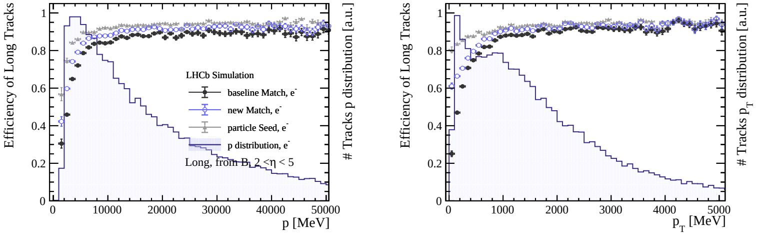


a: VELO Tracking efficiency.

b: Hybrid Seeding efficiency.

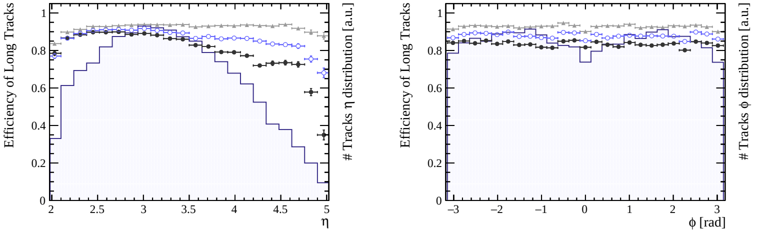
Figure: Reconstruction efficiency of (a) the VELO Tracking, and (b) the Hybrid Seeding algorithm.

New Matching Efficiencies - Long from B



a: Efficiency *vs.* momentum.

b: Efficiency *vs.* transverse momentum.

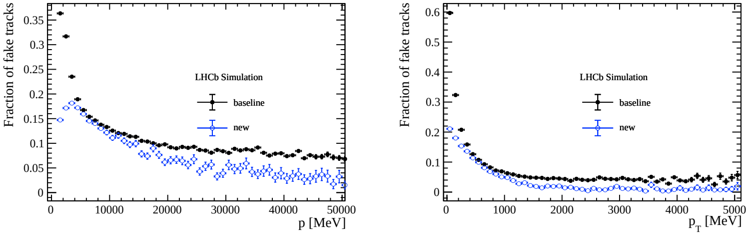


c: Efficiency *vs.* pseudorapidity.

d: Efficiency *vs.* azimuthal angle.

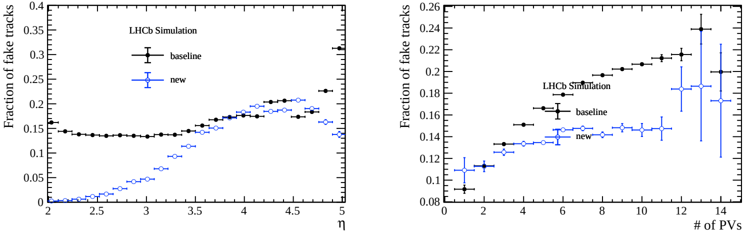
Figure: Track finding efficiency of the electron Matching algorithm.

New Matching Fake Track Fraction - Long from B



a: Fake track fraction *vs.* momentum.

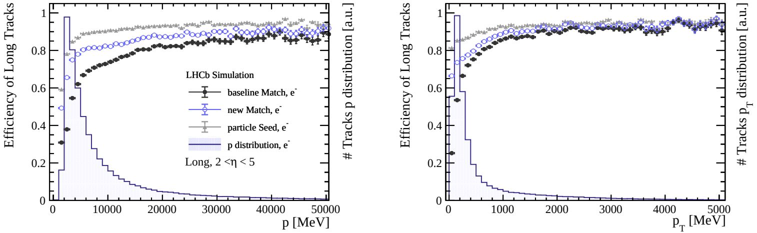
b: Fake track fraction *vs.* transverse momentum.



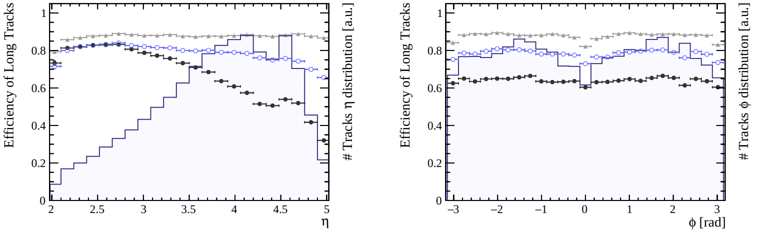
c: Fake track fraction *vs.* pseudorapidity.

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

New Matching Efficiencies - Long



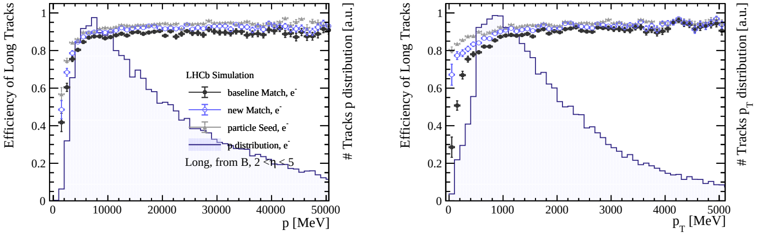
a: Efficiency *vs.* momentum. b: Efficiency *vs.* transverse momentum.



c: Efficiency *vs.* pseudorapidity. d: Efficiency *vs.* azimuthal angle.

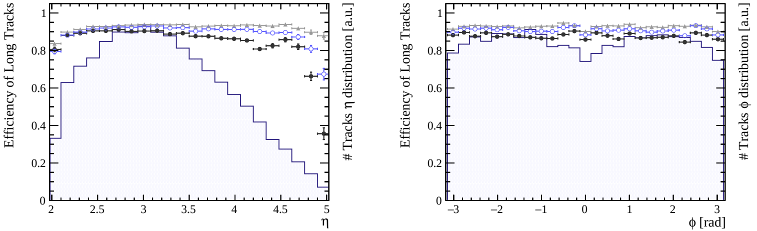
Figure: Track finding efficiency of the electron Matching algorithm.

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



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.