μ/π Separation in LArTPCs Using Optimal Transport-Based ML

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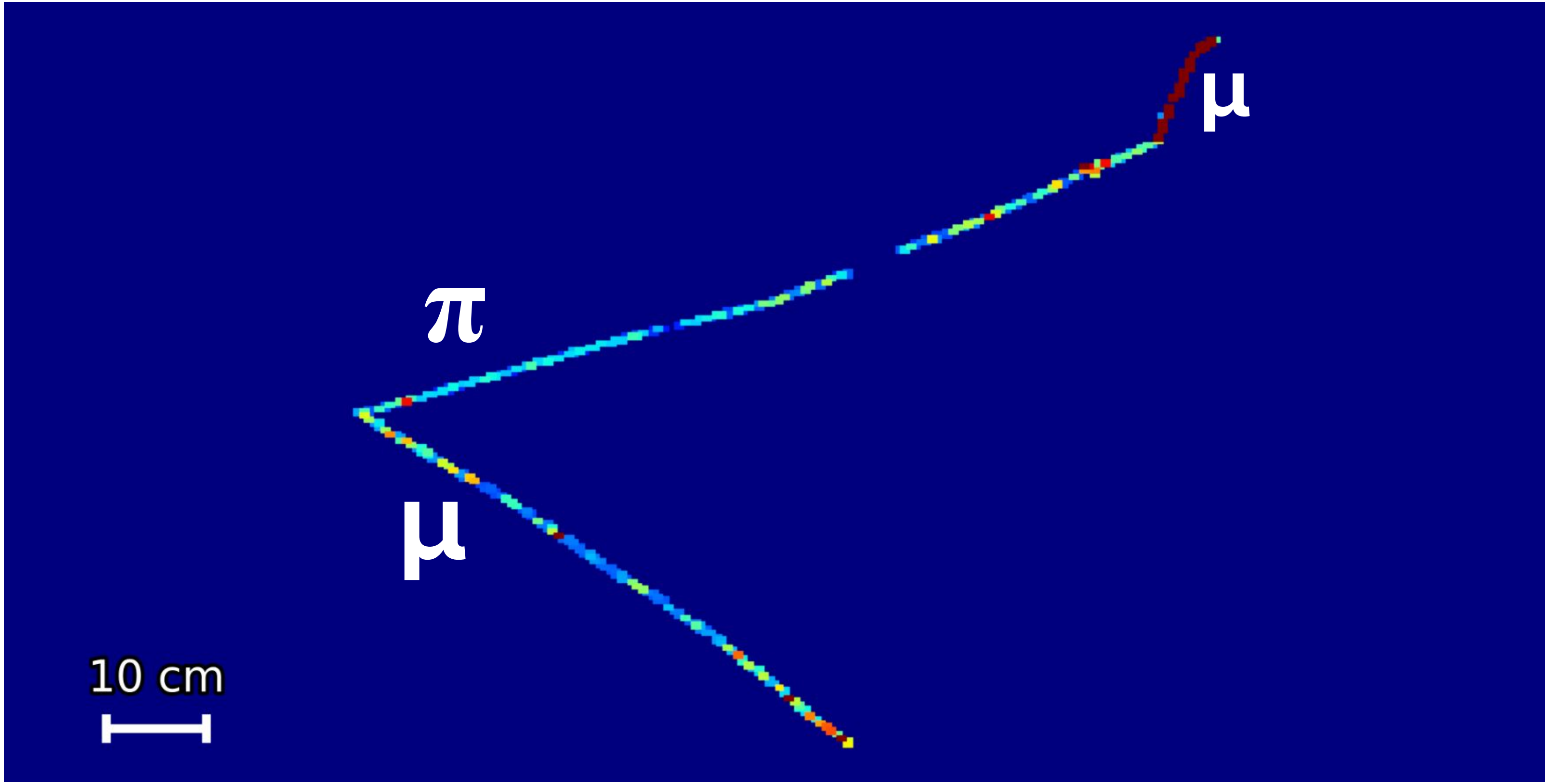


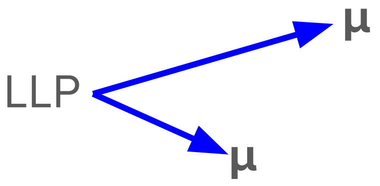
Motivation: CC1π Backgrounds Fake Dimuon Signals

Signal

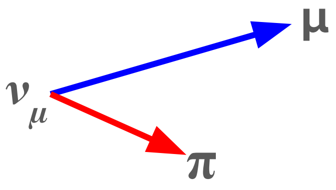
- ❖ Long-lived beyond standard model particle → $\mu^+ \mu^-$
- ❖ Two muon-like tracks from a common vertex
- ❖ Dimuon acceptance scales approximately as the squared muon efficiency

Background

- ➔ ν_μ CC1π event → μ + π + X
- ➔ μ and π tracks are MIP-like, with similar dE/dx over their trajectories
- ➔ Misid pion can fake a dimuon event
- ➔ Searches rely on a high muon purity to reduce the CC1π background



Goal: Improve muon efficiency at a fixed high muon purity



Optimal Transport Compares Track Topology

- OT computes the minimum cost to move weight from one distribution P(x) to another Q(y)
- Finds the transport plan $\mathbf{T}_{ij}$ with minimum total cost
- We compute the discrete 2-Wasserstein distance between spacepoint distributions for tracks
- **Smaller OT distance → more similar charge-weighted topology**

$$W_2^2 = \min_T \sum T_{ij} d(x_i, y_j)^2$$

Simulated Data Sample

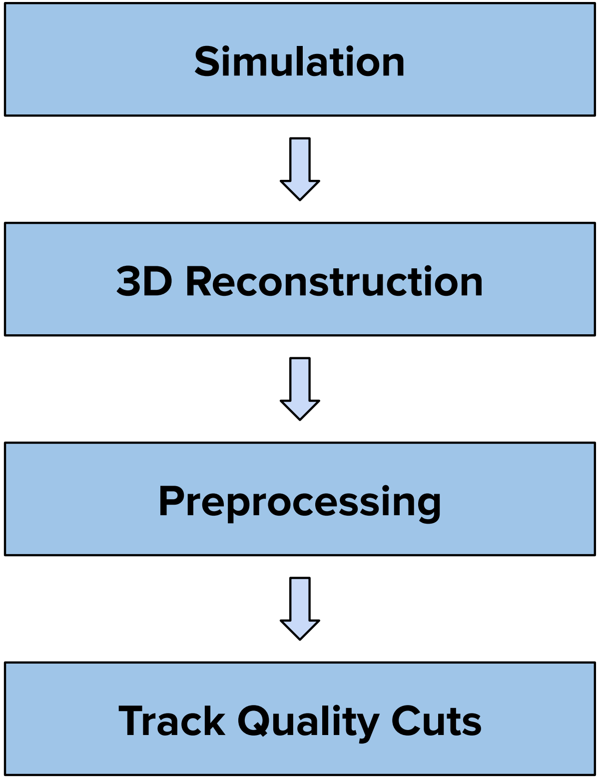
MicroBooNE Public Dataset — BNB Inclusive Overlay

MicroBooNE Public Data

- **~753k simulated events** (NoWire sample)
- Simulated BNB inclusive neutrino interactions sample
- Overlaid on Cosmic-ray data

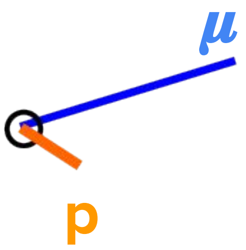
Reconstruction

- Pandora Reconstruction produces **3D spacepoint-based tracks** (~750 spacepoints per track)
- Reconstructed objects can be matched to true events



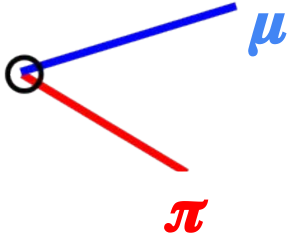
Samples Include Multiple Neutrino Topologies

Charged Current Quasi-Elastic



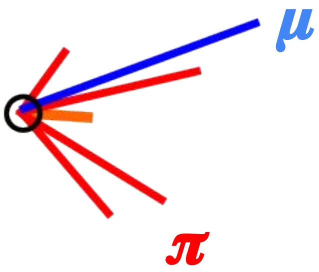
$$\nu_\mu + n \rightarrow \mu^- + p$$

Resonant Pion Production



$$\nu_\mu + N \rightarrow \mu^- + \pi + N'$$

Deep Inelastic Scattering



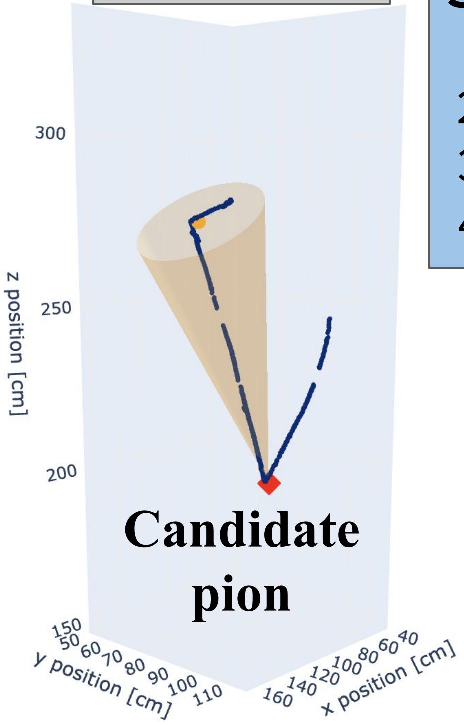
$$\nu_\mu + N \rightarrow \mu^- + X$$

Neutral Current Pion Production

$$\nu_\mu + N \rightarrow \nu_\mu + \pi + X$$

Preprocessing: Standardizing Tracks for OT Comparisons

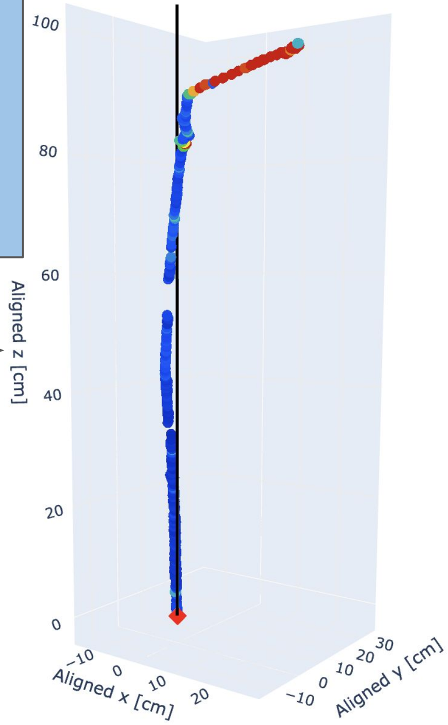
Initial



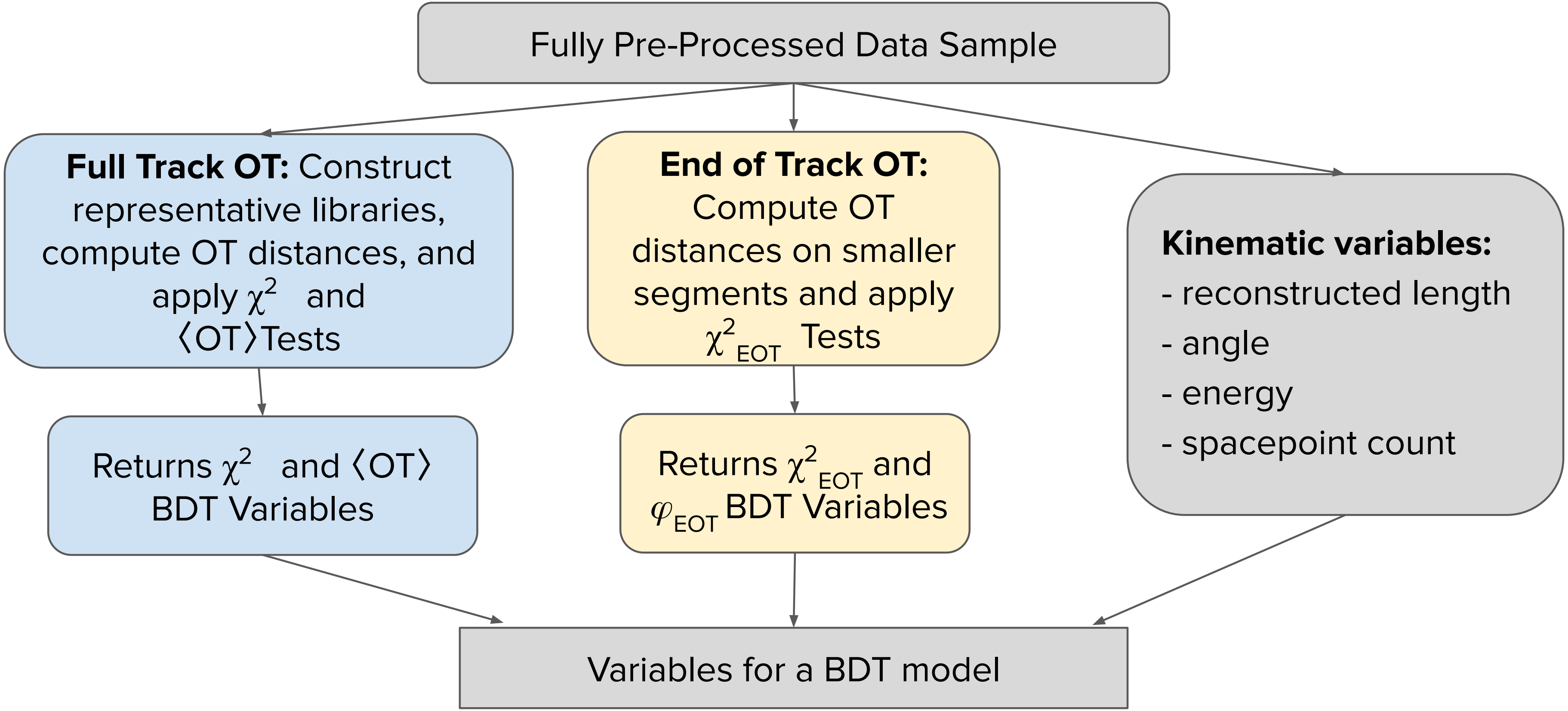
Stages:
1. Select candidate track spacepoints
2. Align track origin
3. Rotate track to the beam direction
4. Assign normalized charge weights

Track Quality Cuts:
- ➢ Fully contained
- ➢ > 50 spacepoints
- ➢ > 30 cm length
- ➢ No large wire gaps

Final



Applying OT to mu/pi Separation



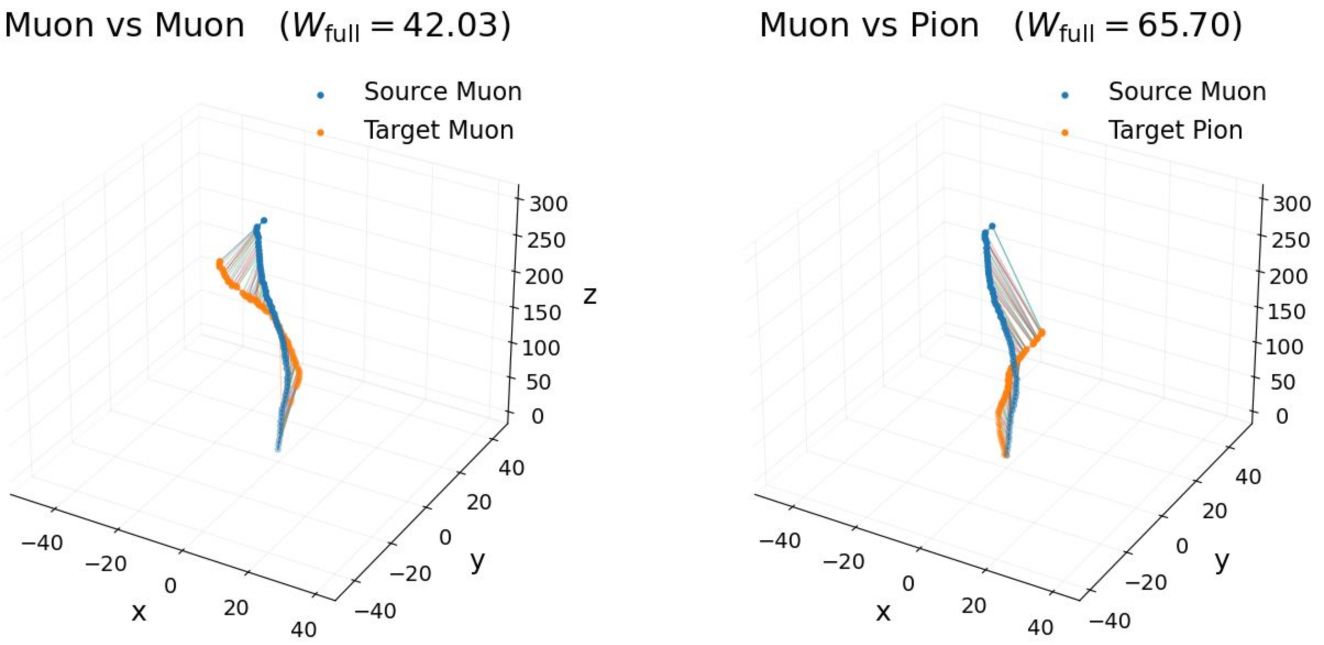
Track-to-Track OT Distances Measure Similarity

Pairwise Comparison:

- ❖ Source track
- ❖ Target track
- ❖ Smaller OT distance

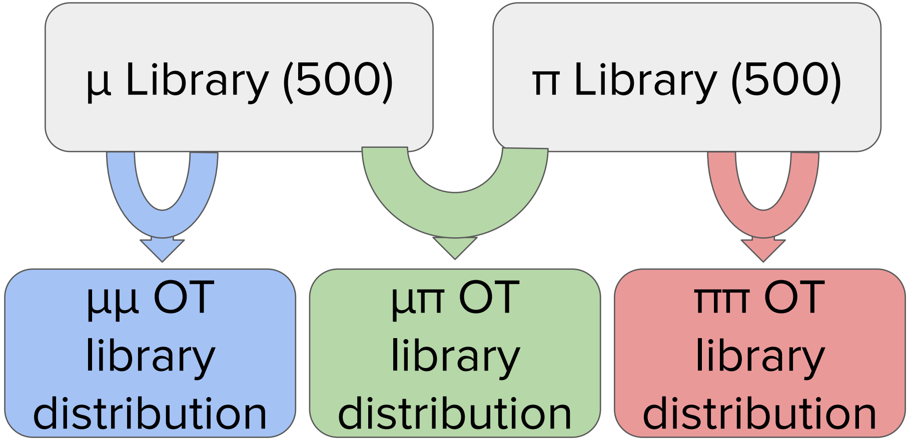
  ➔ more similar

  topology

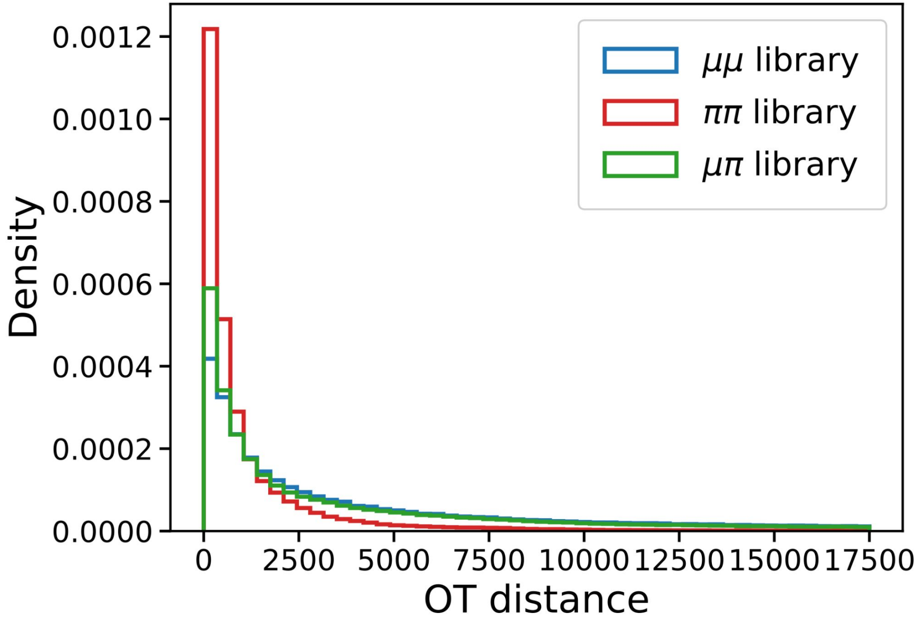


A single comparison is not enough.
We compare each test track to libraries of muon and pion tracks.

Building Library distributions



We construct **3 template distributions** that are **compared to a single test track's** performance



pi and mu libraries are constructed by interlibrary OT comparisons
mu/pi library constructed by cross comparisons between libraries

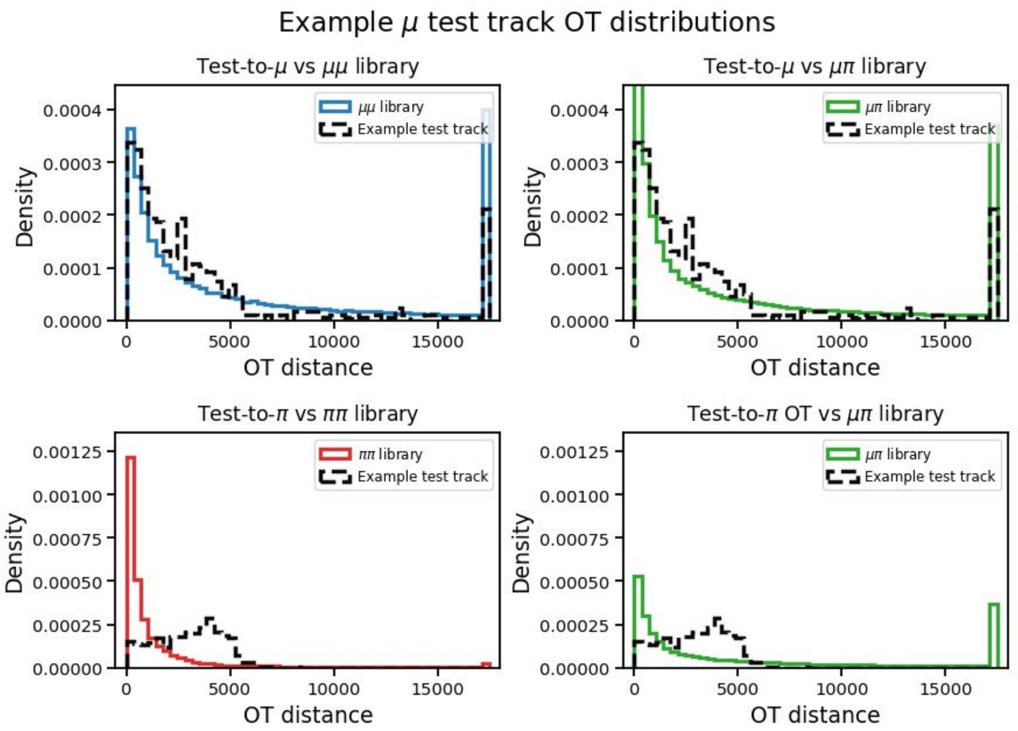
Test Distributions Compare to Libraries

- Compute 2 distributions by comparing an individual track to all 500 tracks in each respective library

- We compare these distributions to the library distributions using a Weighted Pearson χ^2 Test:

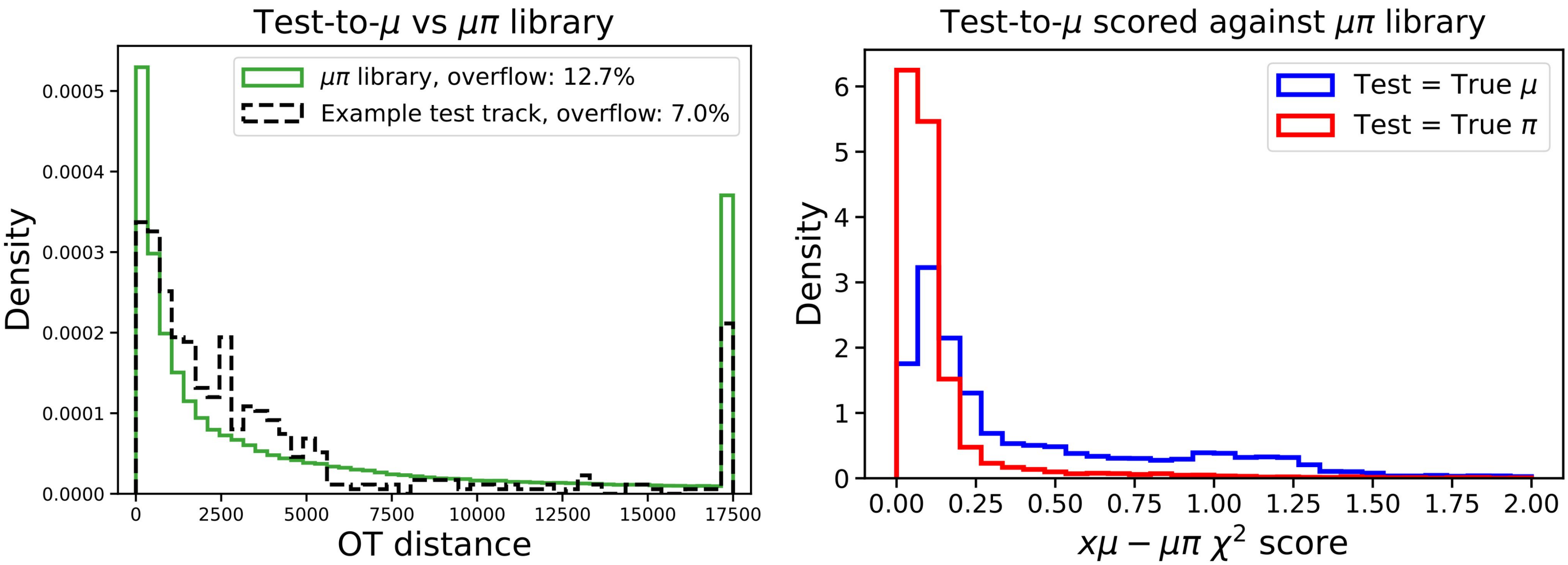
$$\chi^2 = \sum_i w_i \frac{(T_i - L_i)^2}{L_i + \epsilon}$$

Results for a sample test muon track:



Scoring Test Tracks with Library Distributions

Each test-track distribution is scored against a library template.
Repeating this over many test tracks gives χ^2 variables for classification.

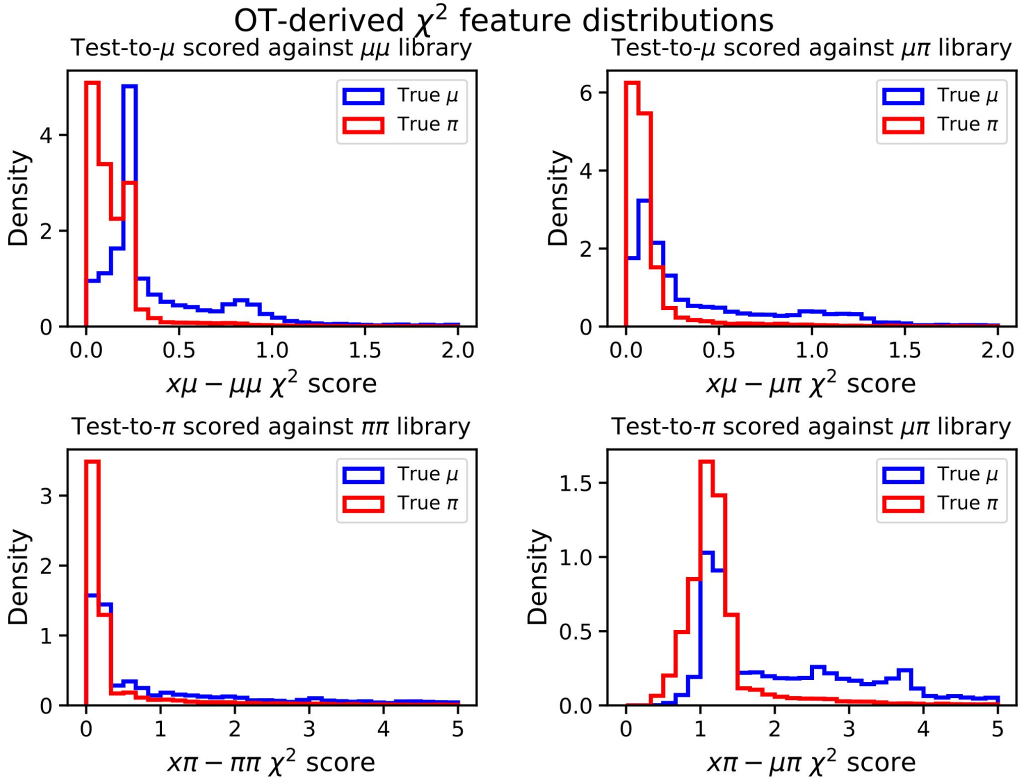


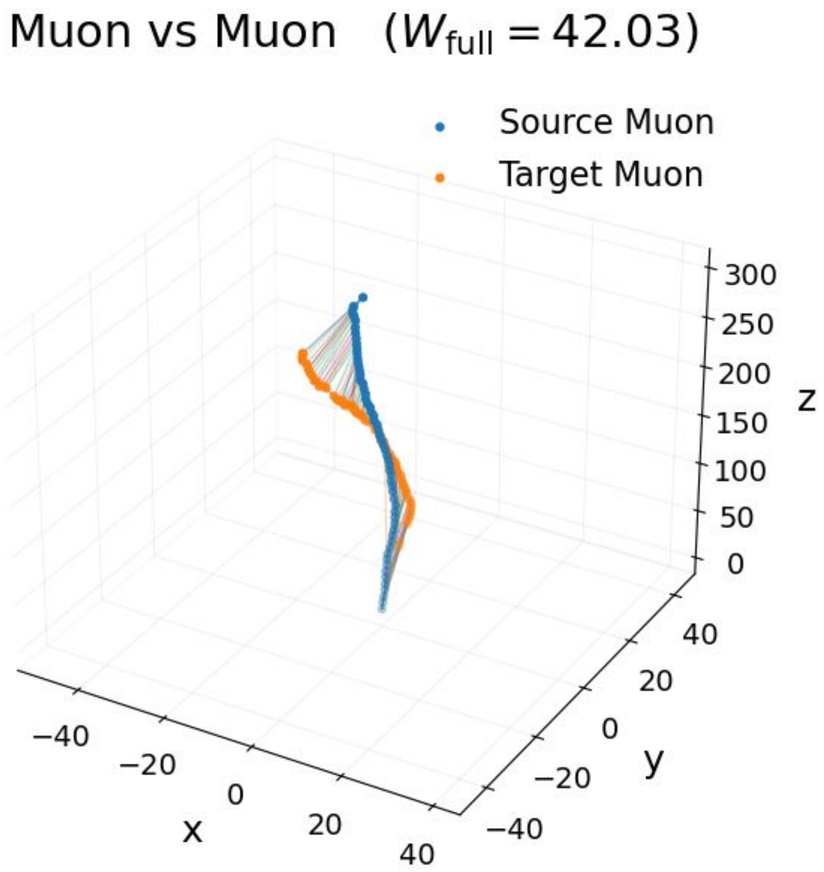
χ^2 Comparisons Produce Four OT-based BDT Variables

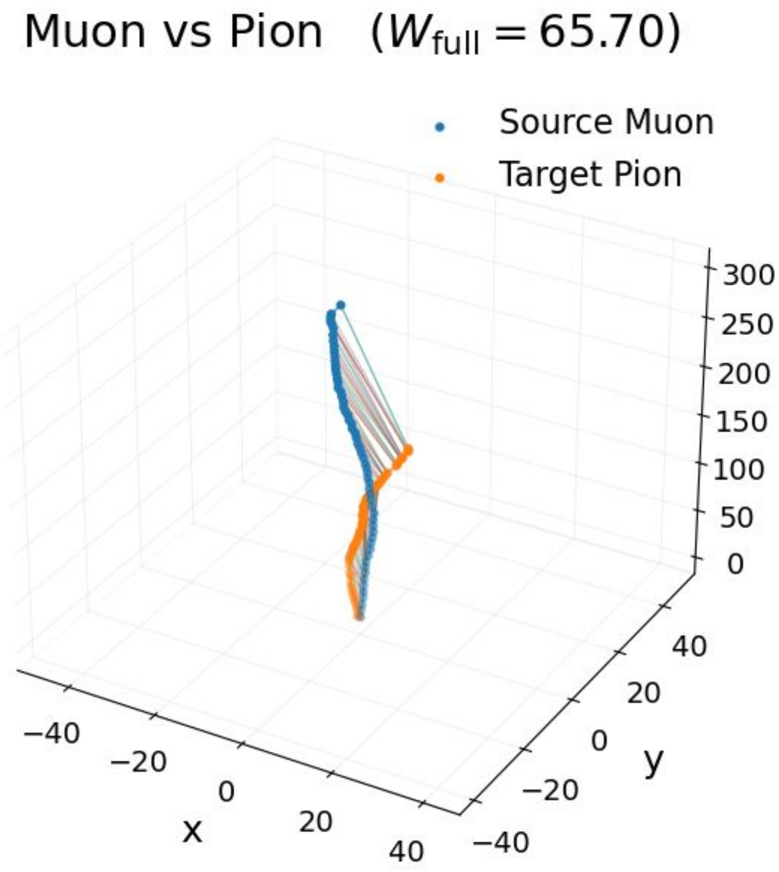
- Relevant comparisons for a test track t:
  - test-to-μ vs μμ library
  - test-to-μ vs μπ library
  - test-to-π vs ππ library
  - test-to-π vs μπ library

- This produces **4 scores to be used in a BDT model** for classification

- χ^2 captures distribution shape, but not all useful library-distance information.

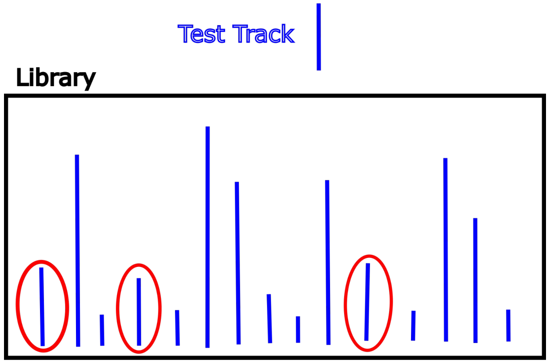



Muon vs Muon ($W_{full} = 42.03$)
Source Muon
Target Muon
x
y
z
−40
−20
0
20
40
0
50
100
150
200
250
300

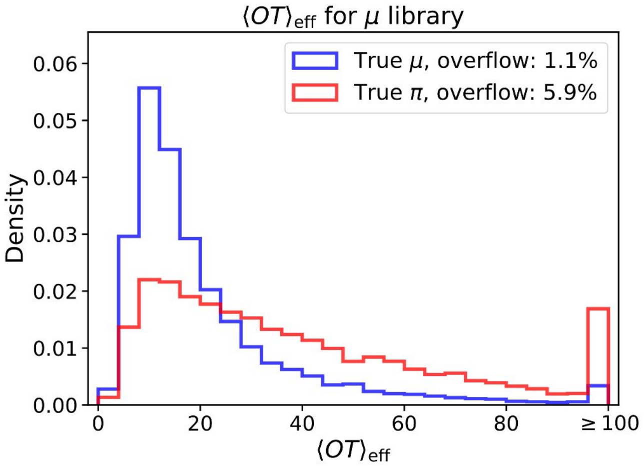

Muon vs Pion ($W_{full} = 65.70$)
Source Muon
Target Pion
x
y
−40
−20
0
20
40
0
50
100
150
200
250
300

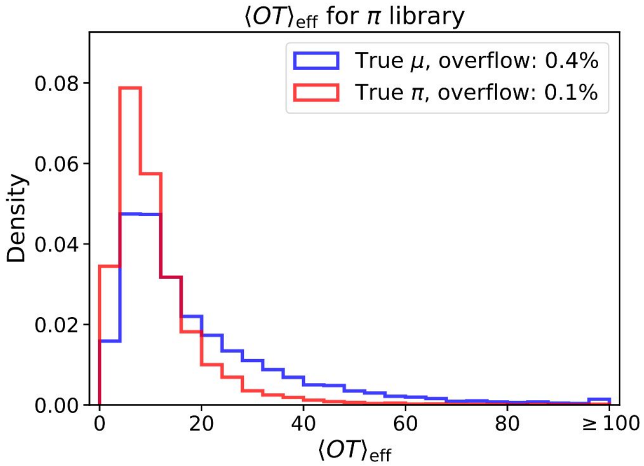
Effective Average OT

To use library information beyond χ^2 scores, we compute an average OT distance by comparing to tracks of similar spacepoint count



Produces: **2 OT-Based BDT variables**





- Select N = 10 nearest neighbors from each library
- Find average OT distance of comparisons to these 10 tracks, divide by Test Track length

$$\langle \mathrm{OT}\rangle_{\mathrm{eff}} = \frac{1}{L}\left(\frac{1}{N}\sum_{i=1}^{N} d_{\mathrm{OT}}^{(i)}\right)$$

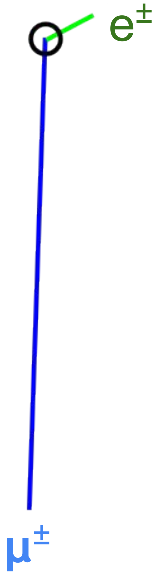
End of Track (EOT) Motivation

Decay occurs for both pi$^{\pm}$ and mu$^{\pm}$

Capture occurs only for pi^{-} and mu^{-}

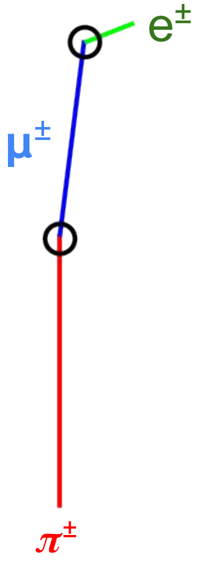
Charged Muon Decay

$\mu^{\pm} \rightarrow e^{\pm} + \nu + \nu$



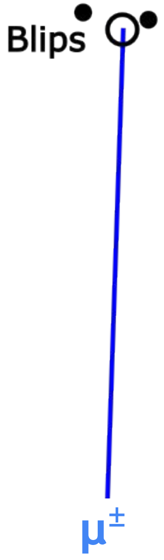
Charged Pion Decay

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu \rightarrow e^{\pm} + \nu + \nu$



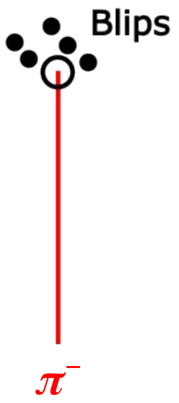
Charged Muon Capture

$\mu^{-} + Ar \rightarrow \nu + \gamma + Cl$

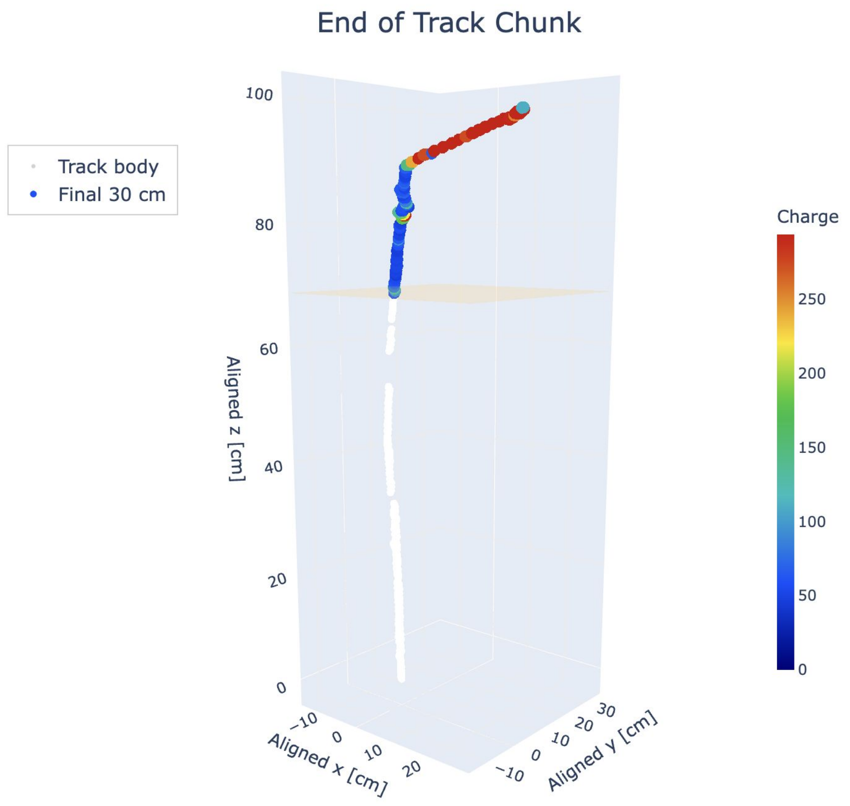


Charged Pion Capture

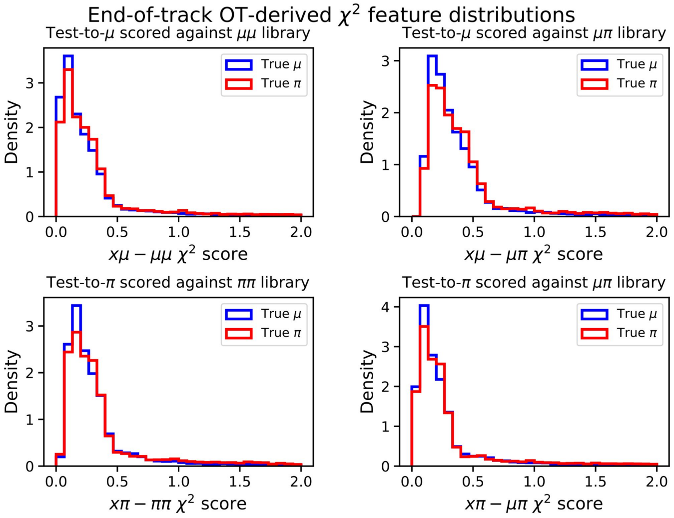
$\pi^{-} + Ar \rightarrow \gamma + Cl + n/p$



End of Track OT Method



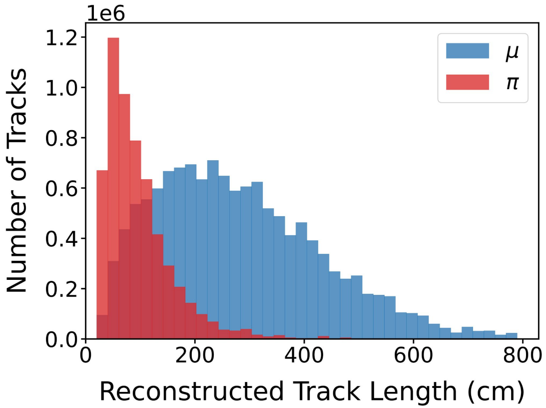
OT tests computed for libraries and test samples on the EOT segment using the same OT + χ^2 test method used for full track OT produces **4 more OT-based BDT variables**



BDT Input Variables

Kinematic Variables

- Reconstructed length
- Angle between track trajectory and beam
- Total charge deposition
- Spacepoint count



OT/EOT Based BDT Variables

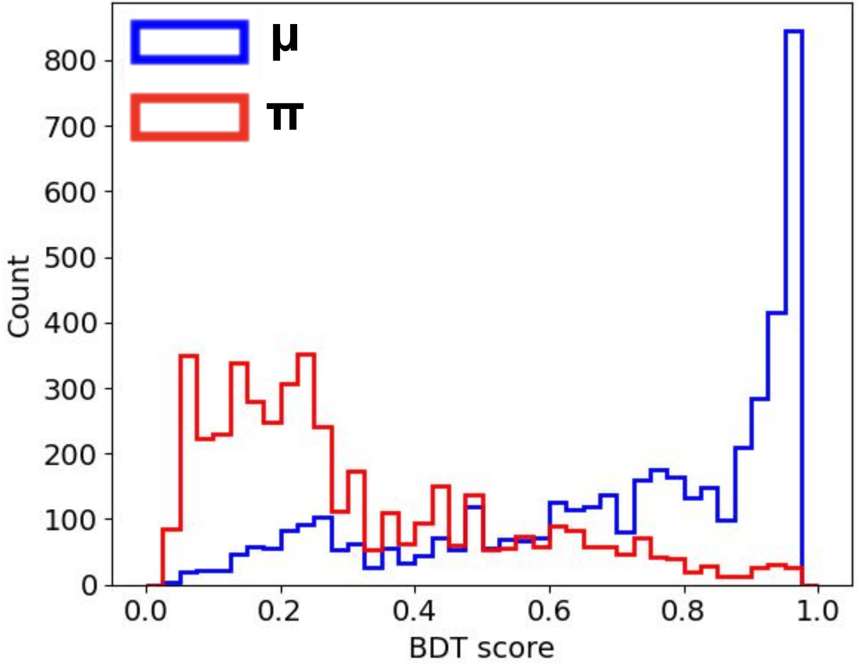
- 4 χ^2 scores derived from the full track OT distance distributions
- 2 Effective Average OT scores derived from nearest neighbor comparisons
- 4 χ^2 scores derived from the end of track OT distance distributions
- 1 EOT angle between initial and end track trajectories

We compare the performance of OT relative to a baseline BDT using only kinematic variables

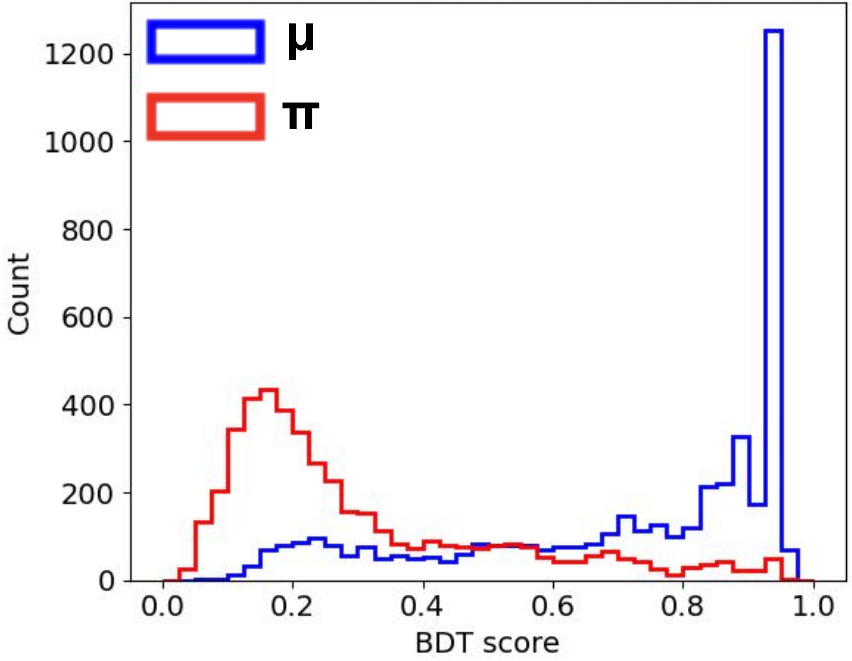
Overall Model Performance:

Apply a balanced 50% train/test split on 12000 tracks to train a BDT model

Kinematic Variables Only

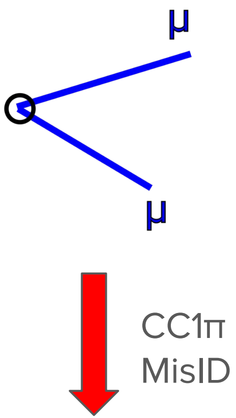


Adding OT-Based Variables



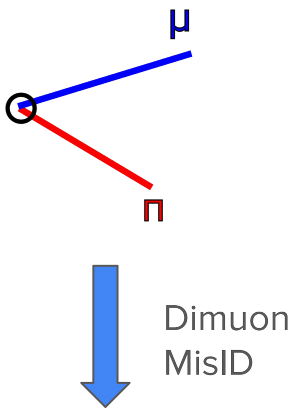
Maximizing Muon Purity for Dimuon Searches

Dimuon Signal



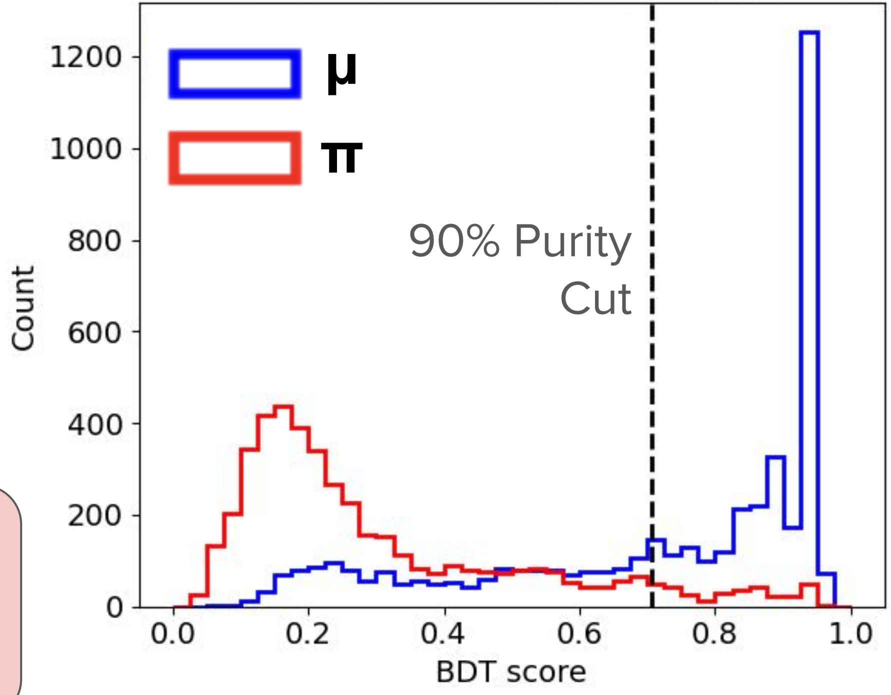
Signal loss reduces statistics but does not create background

CC1π Background



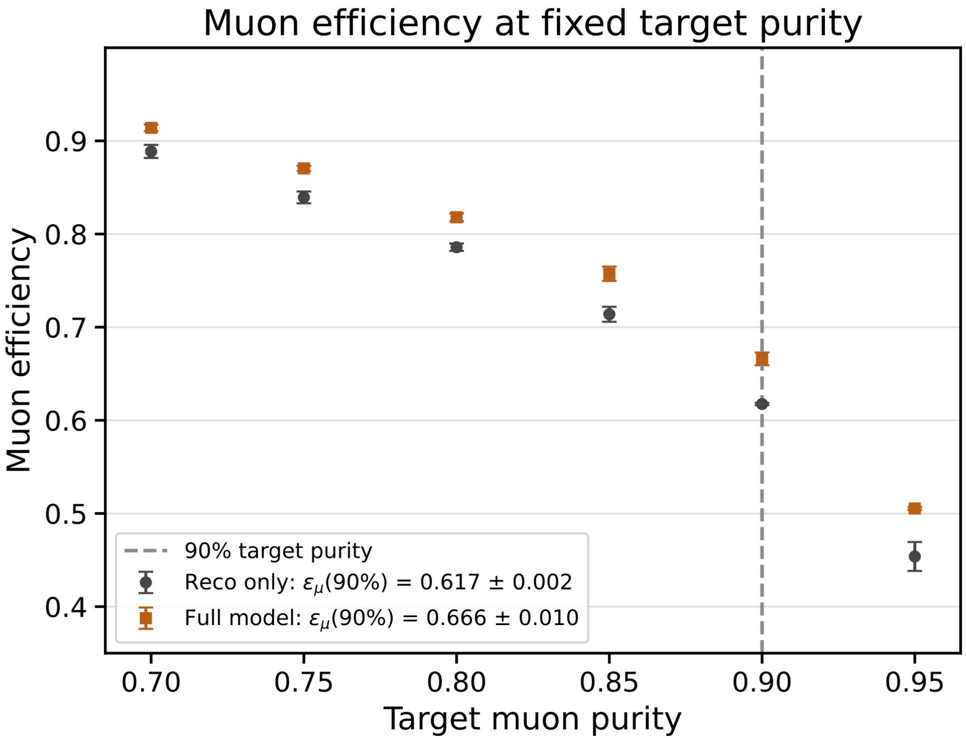
Background inflation directly reduces discovery sensitivity

OT Based BDT Score Distribution

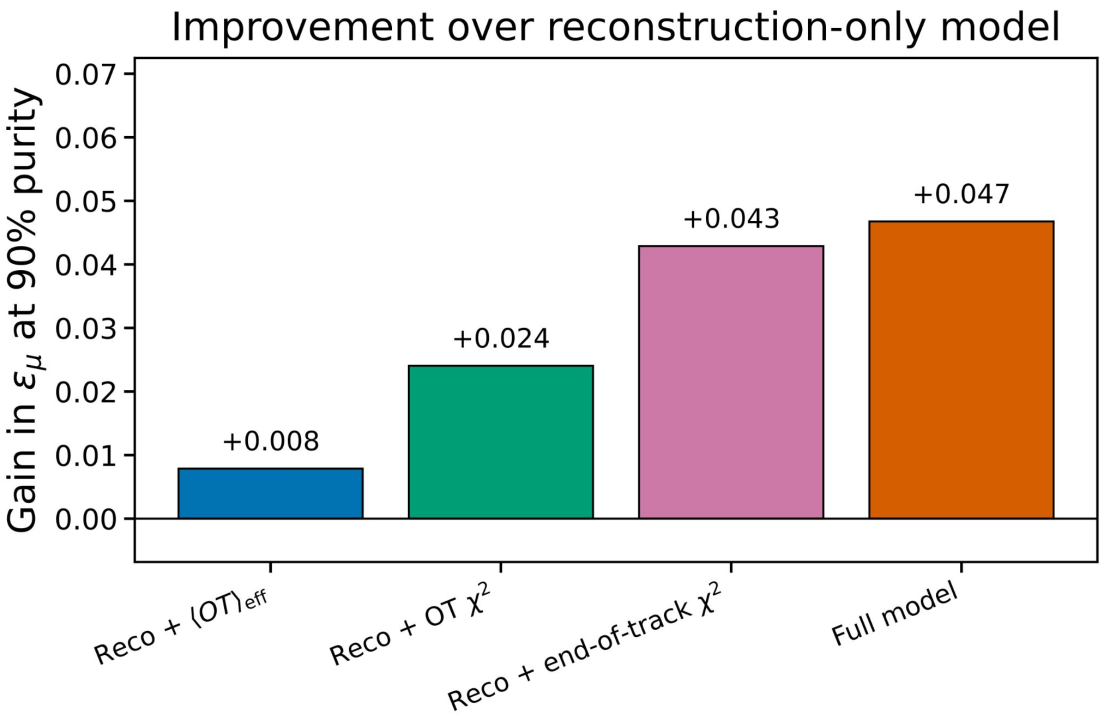


OT Improves Muon Efficiency at Fixed Muon Purity

- Averaged results over two runs with error bars displaying the spread in performance
- **Gain of 4.9% efficiency** by including the OT methods discussed at the 90% purity benchmark
- **All purity levels improved**, OT + EOT method provides meaningful benefits in mu/pi separation for dimuon searches



End-of-Track Variables Drive the Largest Gain



*Feature-ablation results averaged over 100 train/test split seeds.

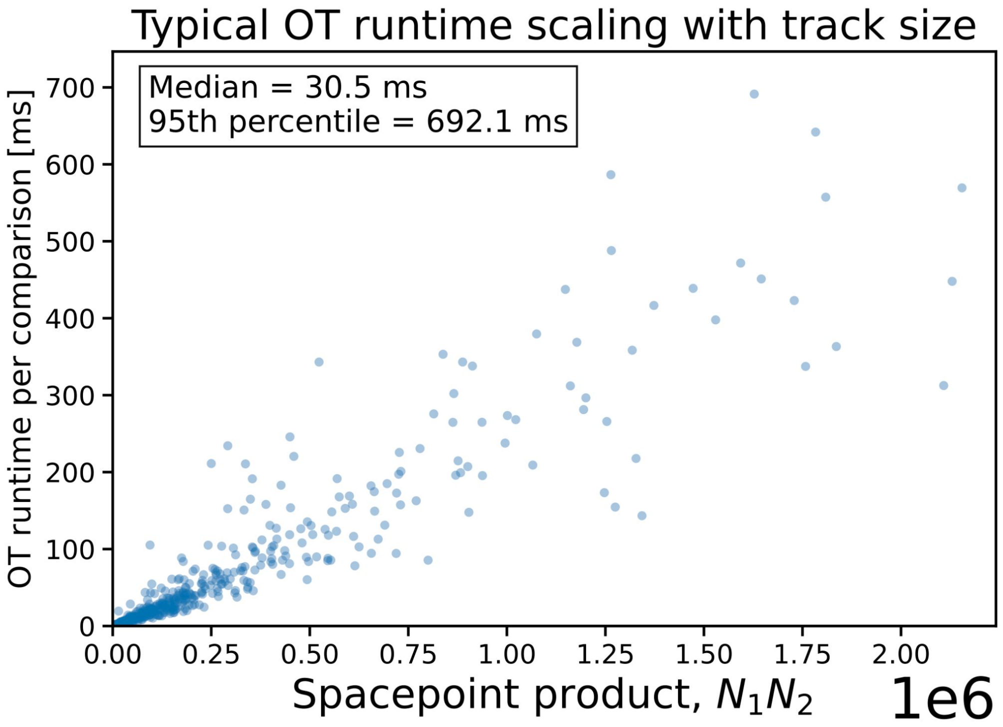
- Variable importance study compares OT variable groups against the kinematic only baseline
- **End-of-track χ^2 variables provide the largest individual gain**
- Full model gives the largest total improvement

Implications for a Dimuon Search

- We estimate a **12% increase in sensitivity** to dimuon events achieved by OT above standard reconstruction variables

- 10^{21} POT → ~2.2 x 10^5 tracks. Using a library size of 500 this workflow takes **~2000 CPU hours.**

- OT computation is parallelizable which can drastically reduce compute time



Conclusion:

- Developed OT-based μ/π separation using charge-weighted 3D LArTPC tracks
- OT-based BDT variables add separation relevant information beyond the standard kinematic variables
- End of track variables provide the largest individual gain
- Improved μ efficiency increases dimuon acceptance and expected sensitivity

μ efficiency at 90% μ purity:

Full model:

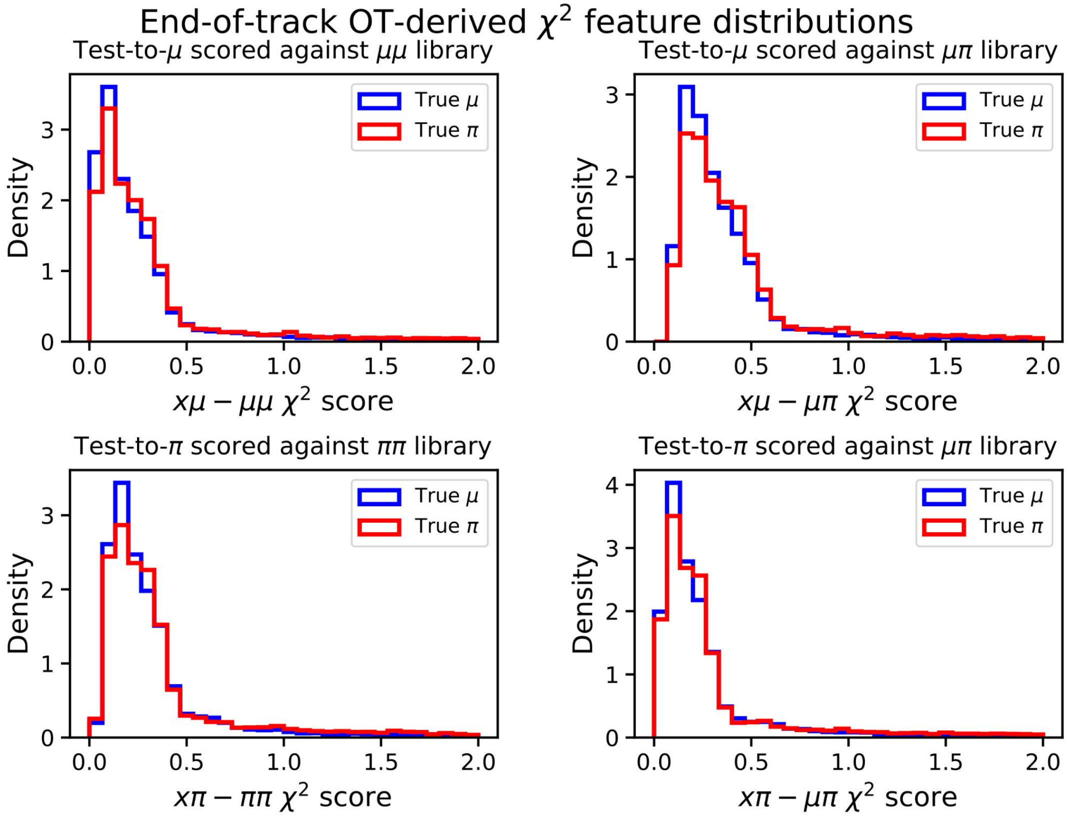
$\boldsymbol{\varepsilon_{\mu} = 66.6 \pm 1.0\ \%}$

Gain:

$\boldsymbol{\Delta\varepsilon_{\mu} = 4.9 \pm 1.0\ \%}$

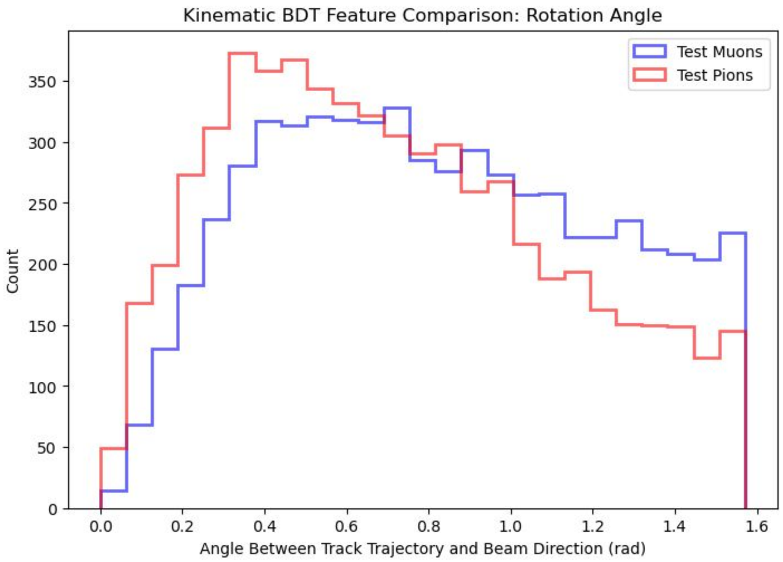
Backups

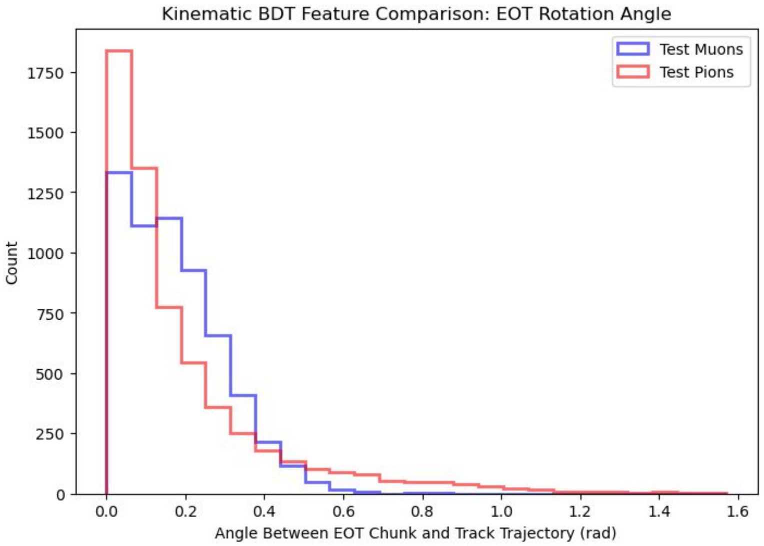
χ^2 EOT Test Results



- Same Pearson Chi-squared procedure produces 4 new features for the BDT
- EOT comparisons demonstrate in general less separation at the feature level
- When implemented into the BDT EOT improves performance by larger margins than chi2 distributions imply

Angular Kinematic Variable Plots



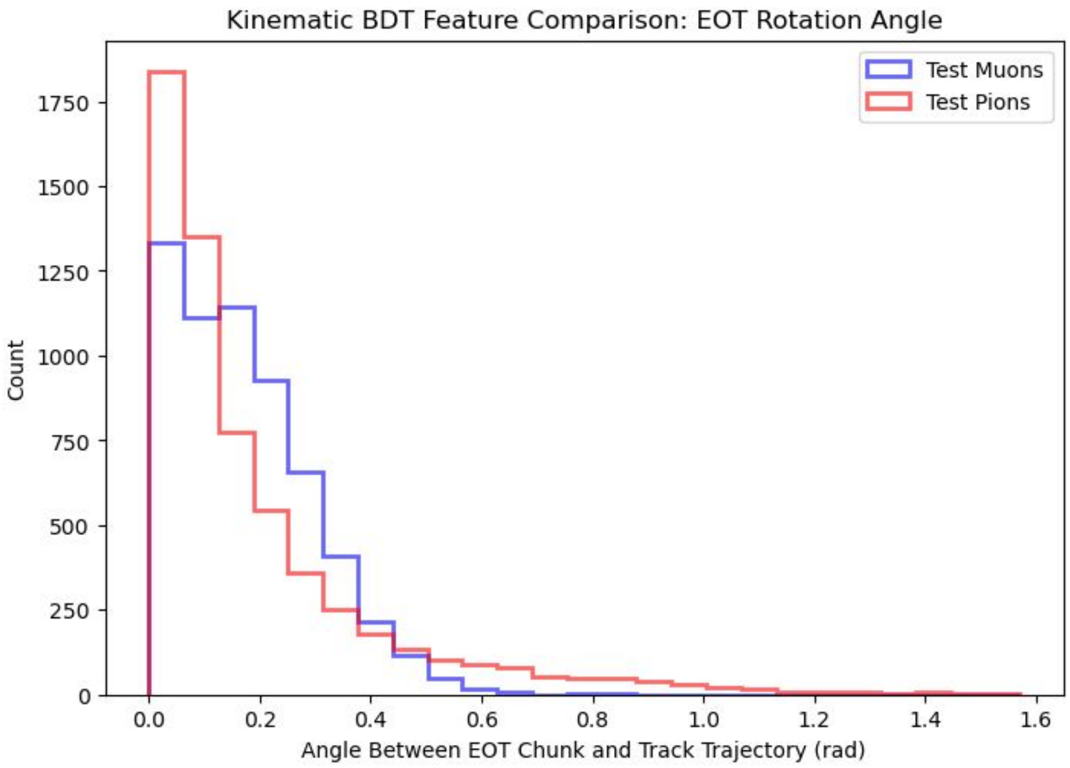


SP Count and Total Energy distributions are nearly identical to track length distribution

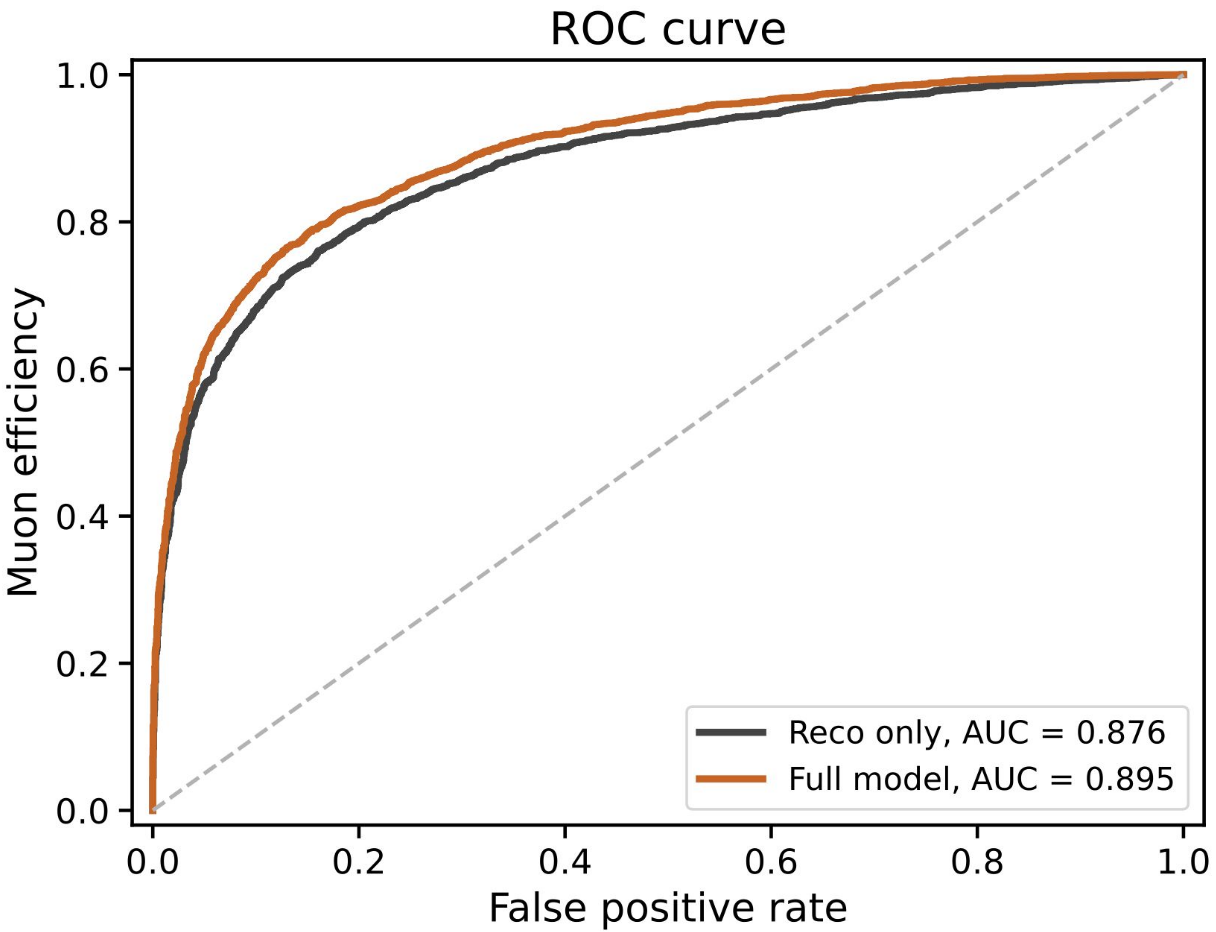
EOT Angle

- Computed angle between EOT chunk and track trajectory

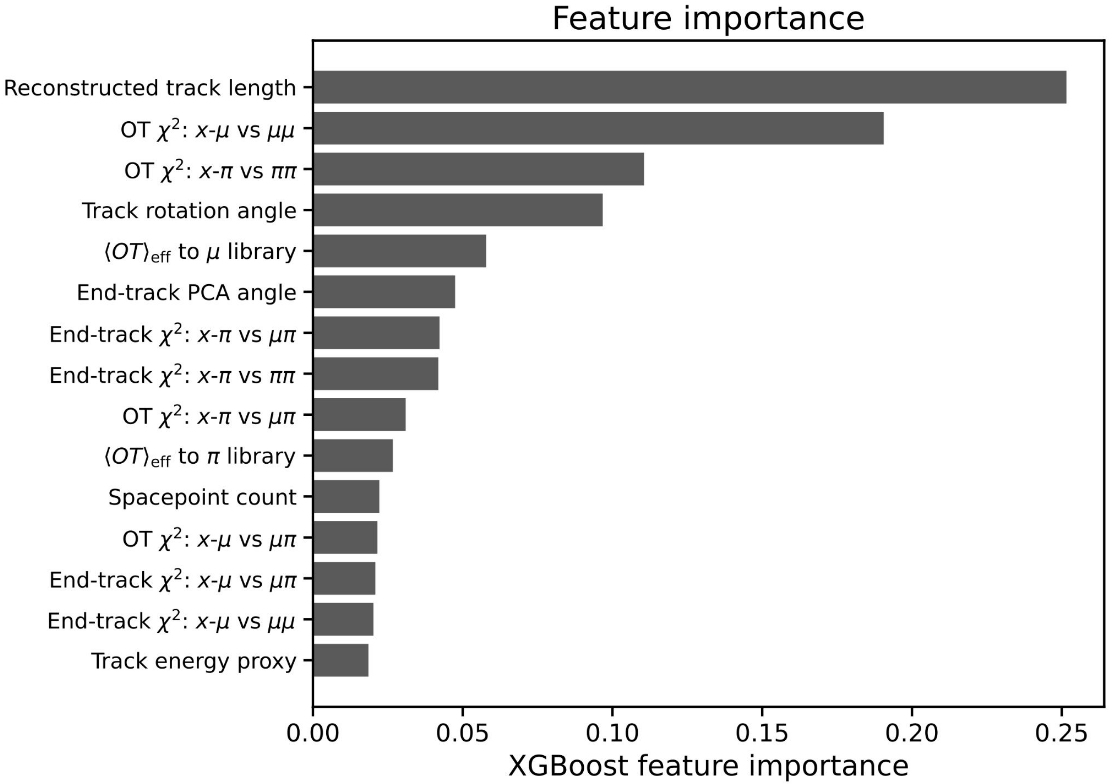
- Alleviates angular bias in OT distance testing at the BDT level



ROC AUC


ROC curve
Muon efficiency
False positive rate
0.0
0.2
0.4
0.6
0.8
1.0
Reco only, AUC = 0.876
Full model, AUC = 0.895

Feature Importance



Muon efficiency → Dimuon Sensitivity

$$Z \propto \frac{S}{\sqrt{B}}$$

$$Z \propto \frac{\epsilon_\mu^2}{\sqrt{\epsilon_\mu f_{\pi\to\mu}}} \propto \epsilon_\mu^{3/2}$$

$$\frac{Z_{\mathrm{OT}}}{Z_{\mathrm{baseline}}} = \left(\frac{0.666}{0.617}\right)^{3/2} \approx 1.12,$$