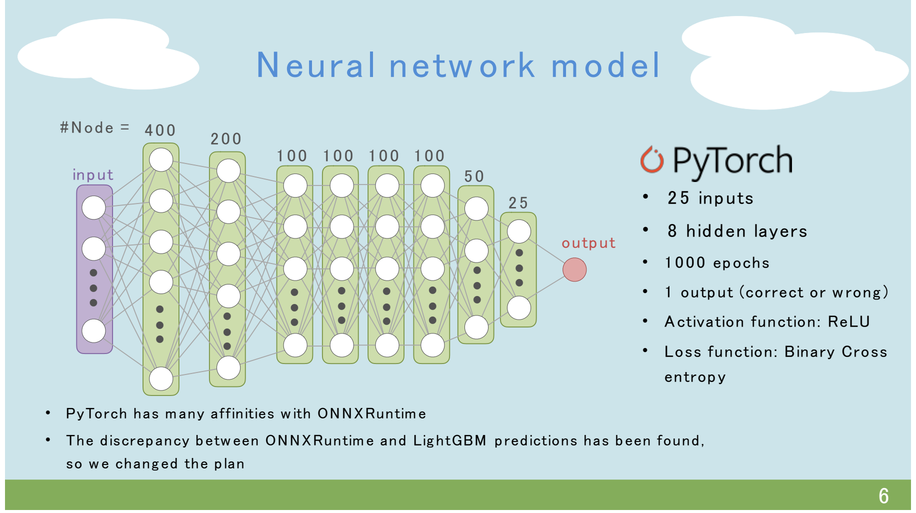
MFT-MUON track Matching with ML

Satoshi YANO
(Hiroshima University)

How to Proceed with Today's Meeting

- Basically, this meeting will proceed based on the following slides (13/07/2022)
  - https://indico.cern.ch/event/1176563/contributions/4941919/attachments/2479224/4255672/0713_MFT.pdf
- I added some comment slides to the original

Original slide



Additional slide

Next Steps for ML Matching

- The priority of retrieving training sample from real data is the highest for the ML matching
- The software preparation for the ML matching (MC□ Real Data)
  1. Retrieve training sample from real data (C++ in O2/O2Physics)
  2. Convert ROOT base file to Python readable format (Python)
  3. Building model (Python)
  4. Convert model into onnx readable format (Python)
  5. Matching (inference) code with ONNXRuntime reading onnx file (C++ in O2Physics)

(My) Matching Philosophy

- The presentation was made three years ago!
  - The situation has been changing dramatically
- However, my own philosophy has not changed and still can be applicable to the current situation
  - The matching should be done by AO2D analysis level
  - Training parameters should be retrieved from real data
  - Extrapolating MFT to MCH side is better than vice versa (MCH side matching plane)
- At that time, there were not sufficient data to study the matching parameters in real
  - The presentation used only simulation data → ideal environment
    - Now we already know the condition is not ideal environment
  - Now we have huge statistics and knowledge about the detectors, so it is the time to study data driven training sample → realistic environment

MFT-MCH track matching

Satoshi Yano
Hiroshima University

What I would like to show today

- MFT-MCH track matching performance
  - Performance of global muon track reconstruction
  - Performance of J/ψ and ϕreconstruction with global muon tracks

- Collision system
  - pp @ 13.6 TeV and PbPb @ 5.5TeV

- Comparable matching methods
  - Matching-chi2 with all parameters @ z=-77.5 cm
  - ML @ z=-77.5 cm
  - ML @ z=-505 cm

MFT-MCH track matching flowchart

- Export ROOT file with O2 format
- Convert the O2 format into a “pure” ROOT TTree object

- Create ML mode and train it with the TTree object
- Export the model with ONNX format

- Load the model by ONNXRuntime in O2

Simulation condition

proton-proton

- proton-proton collisions @ 13.6 TeV
  - Signal: J/ψ and ψ(2s) with O2DPG ~ 30,000 events
    - 12 x J/ψ + 6 x ψ(2s) per event
  - Background: pythia8 (default setting of O2DPG)
  - Collisions rate: 500k Hz
- proton-proton collisions @ 13.6 TeV
  - Signal: ϕ with O2DPG ~ 30,000 events
    - 10 x ϕ per event
  - Background: pythia8 (default setting of O2DPG)
  - Collisions rate: 500k Hz

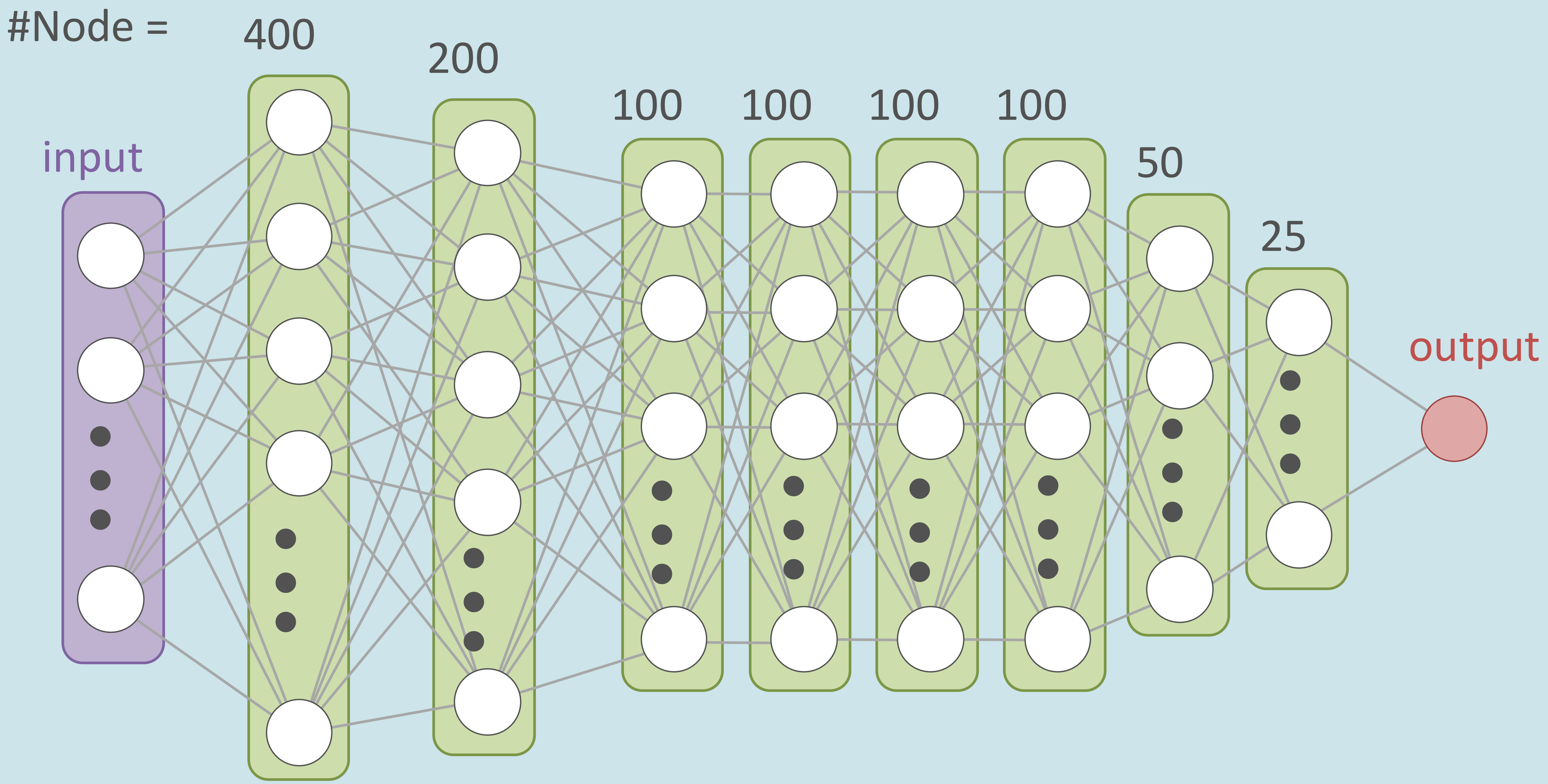
Pb-Pb

- Pb-Pb collisions @ 5.5 TeV
  - Signal: J/ψ and ψ(2s) with O2DPG ~ 13,000 events
    - 12 x J/ψ + 6 x ψ(2s) per event
  - Background: pythia8hi (default setting of O2DPG)
  - Collisions rate: 50k Hz
- Pb-Pb collisions @ 5.5 TeV
  - Signal: ϕ with O2DPG ~ 10,000 events
    - 10 x ϕ per event
  - Background: pythia8hi (default setting of O2DPG)
  - Collisions rate: 50k Hz

Variable / word in this presentation

- Global muon track
  - The reconstructed track by MFT+MCH+MID
- Pairable muon
  - The muon track reconstructed by both MFT and MCH within the same ROF
- Purity
  - The fraction of global muon tracks with correct MFT-MCH matching out of all global muon tracks
- True pairing efficiency
  - The fraction of reconstructed pairable muons with correct MFT-MCH matching out of all pairable muons

Neural network model



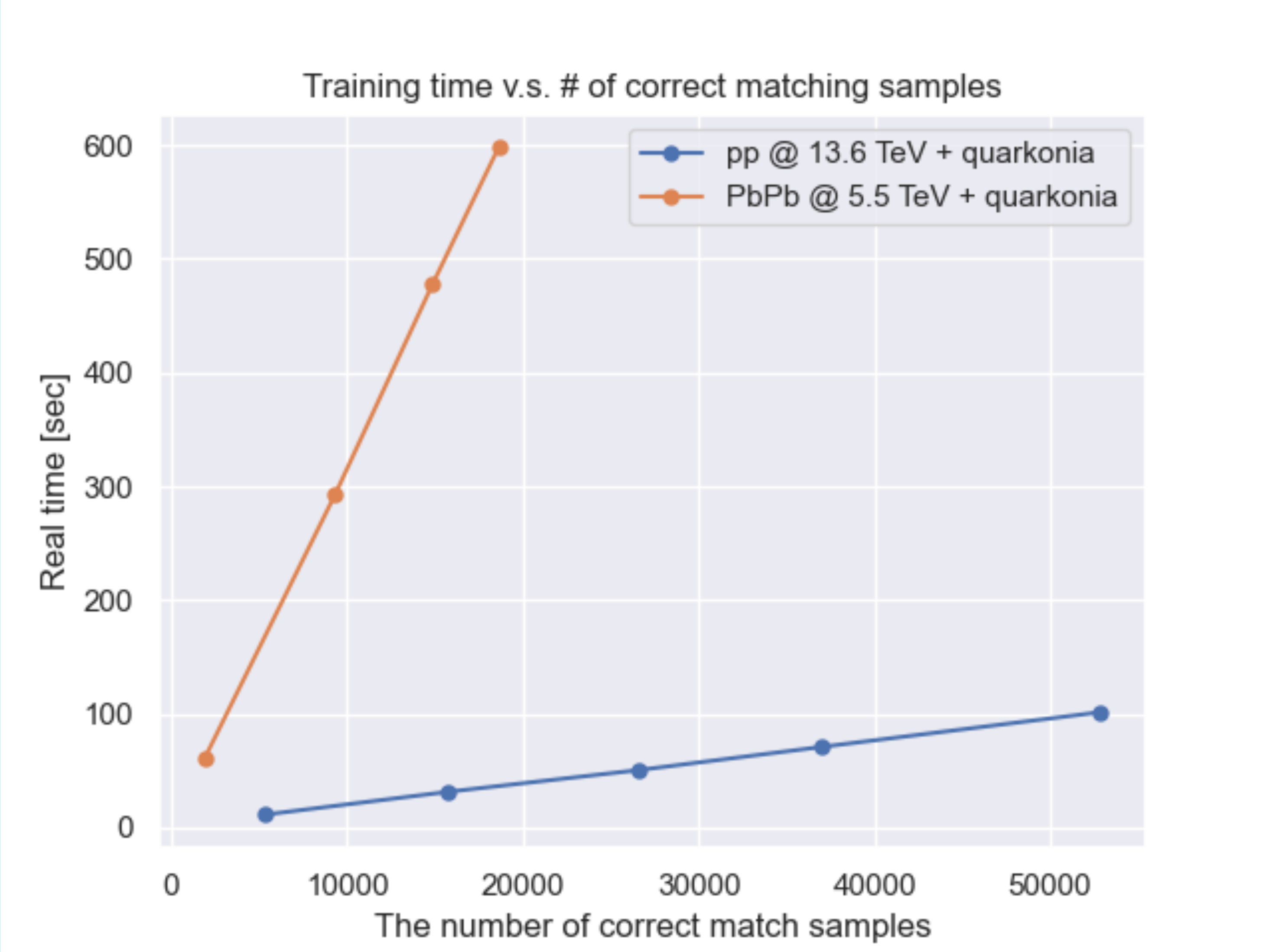
PyTorch

- 25 inputs
- 8 hidden layers
- 1000 epochs
- 1 output (correct or wrong)
- Activation function: ReLU
- Loss function: Binary Cross entropy

- PyTorch has many affinities with ONNXRuntime
- The discrepancy between ONNXRuntime and LightGBM predictions has been found, so we changed the plan

Training time

- Training time is measured by the following GPU
  - NVIDIA RTX 3090: 10496 cuda cores (1400MHz, 24GB RAM)



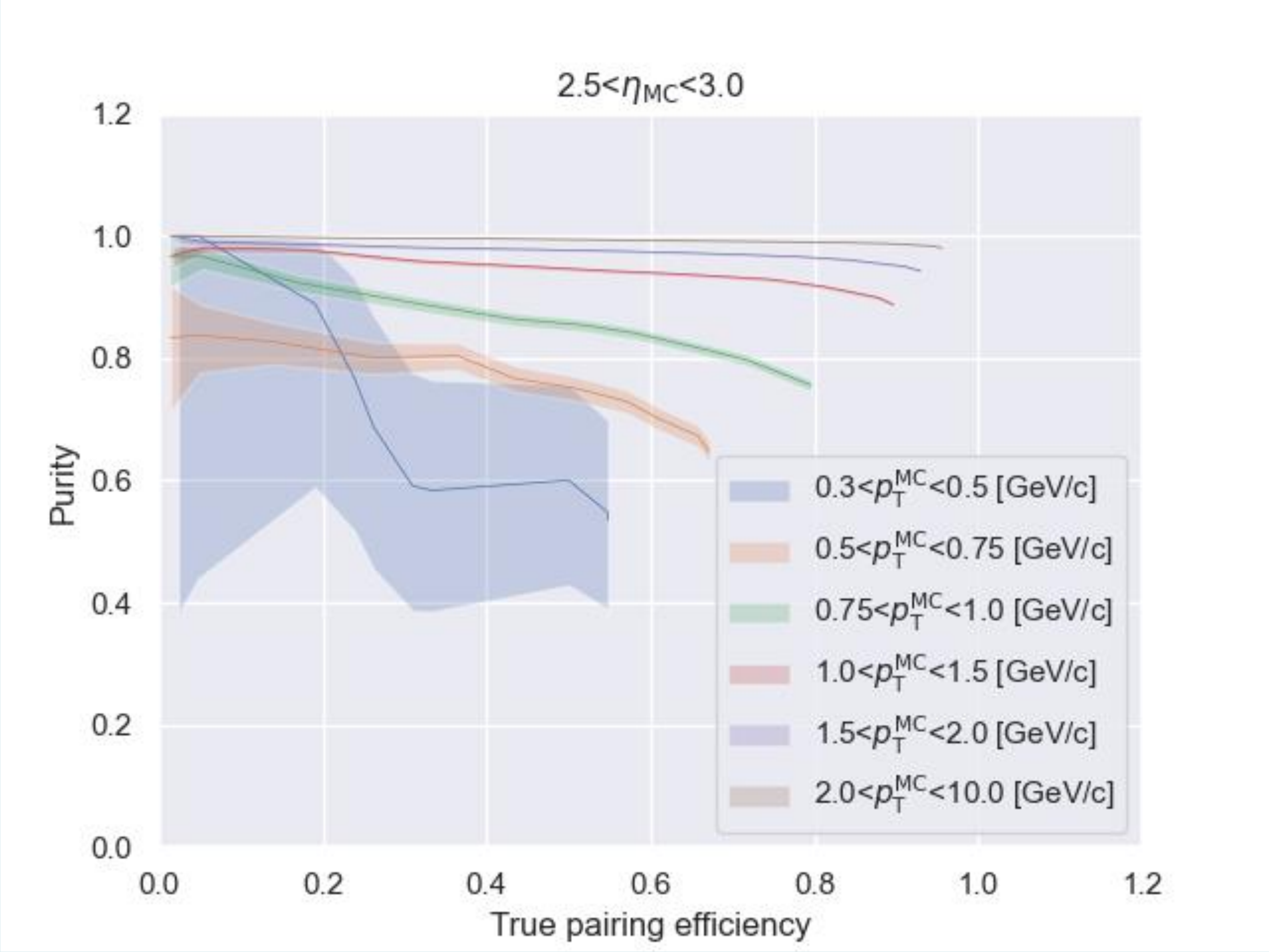
- Dependence of collision systems has been observed
  - Linear correlation in the same system
  - Not easy relationship between the number of samples and training time ⇨ need to investigate the reason
  - If the sample size is larger than ~3.5 M, the model exceeds the memory capacity limit ⇨ need to use mini-batch system

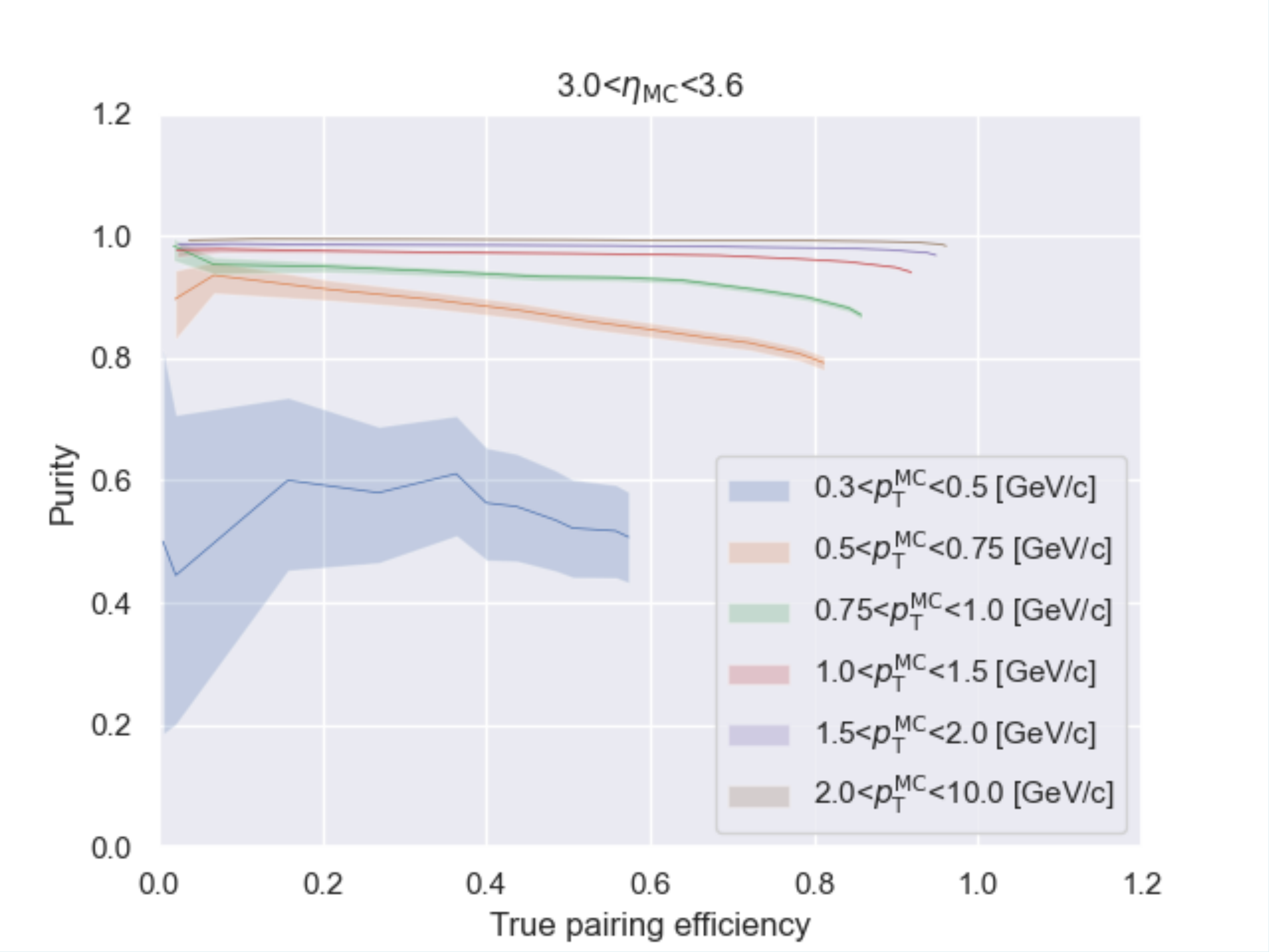
Matching-chi2 (all params)
for performance baseline

proton+proton collisions

Performance of muon track
pp @ 13.6 TeV (MB) + Quarkonia data

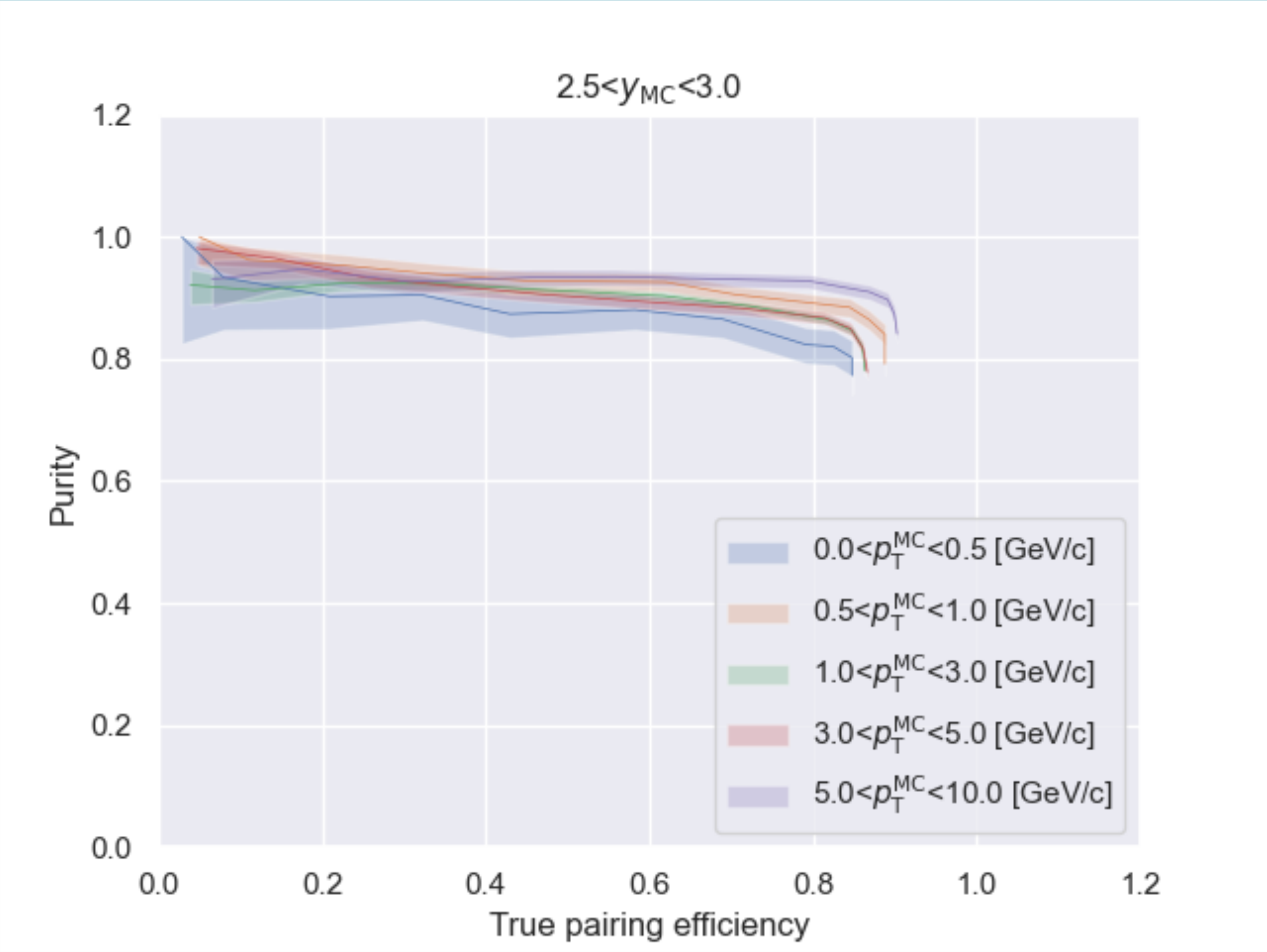
- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

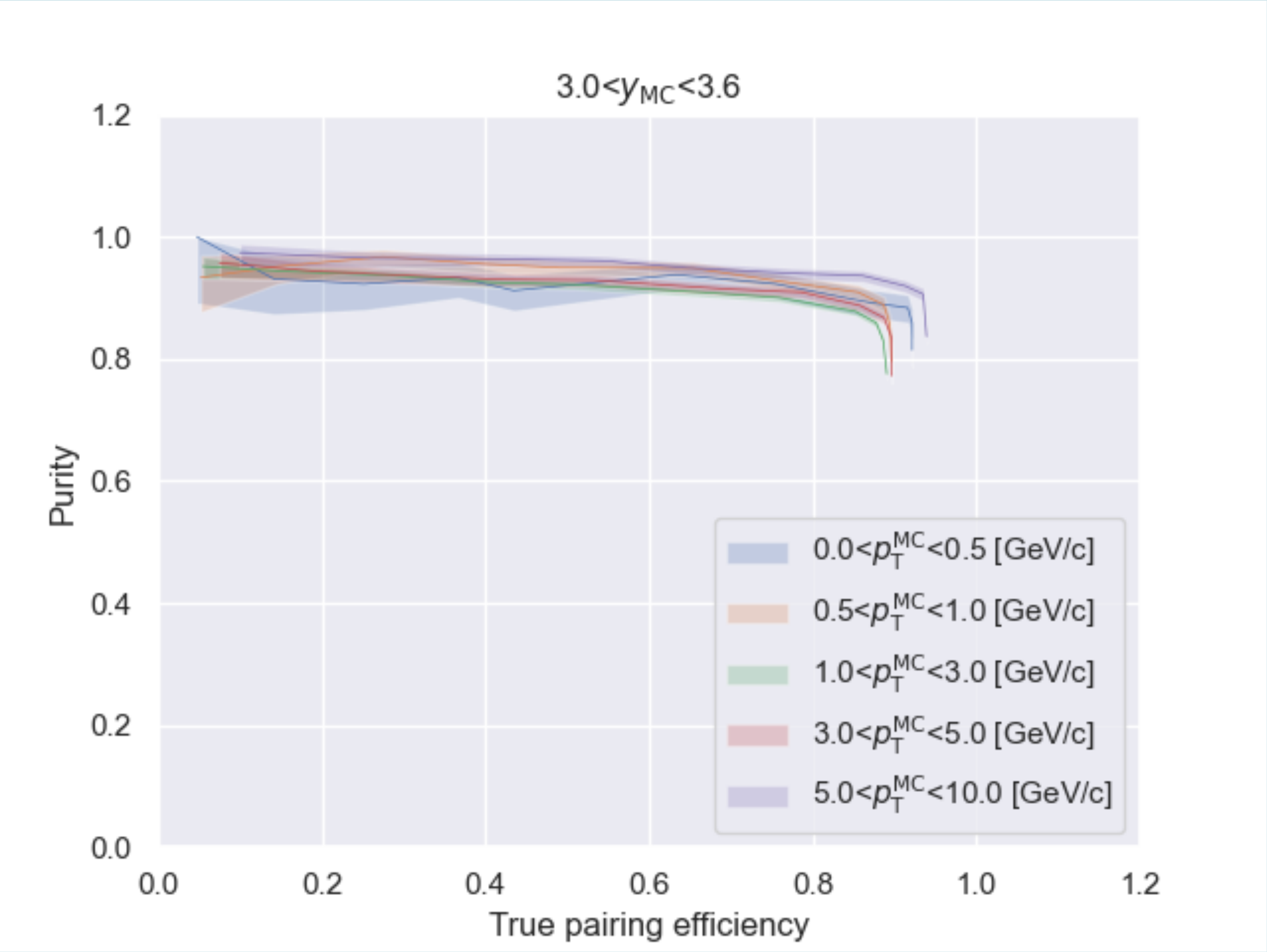




Performance of J/ψ reconstruction pp @ 13.6 TeV (MB) + Quarkonia data

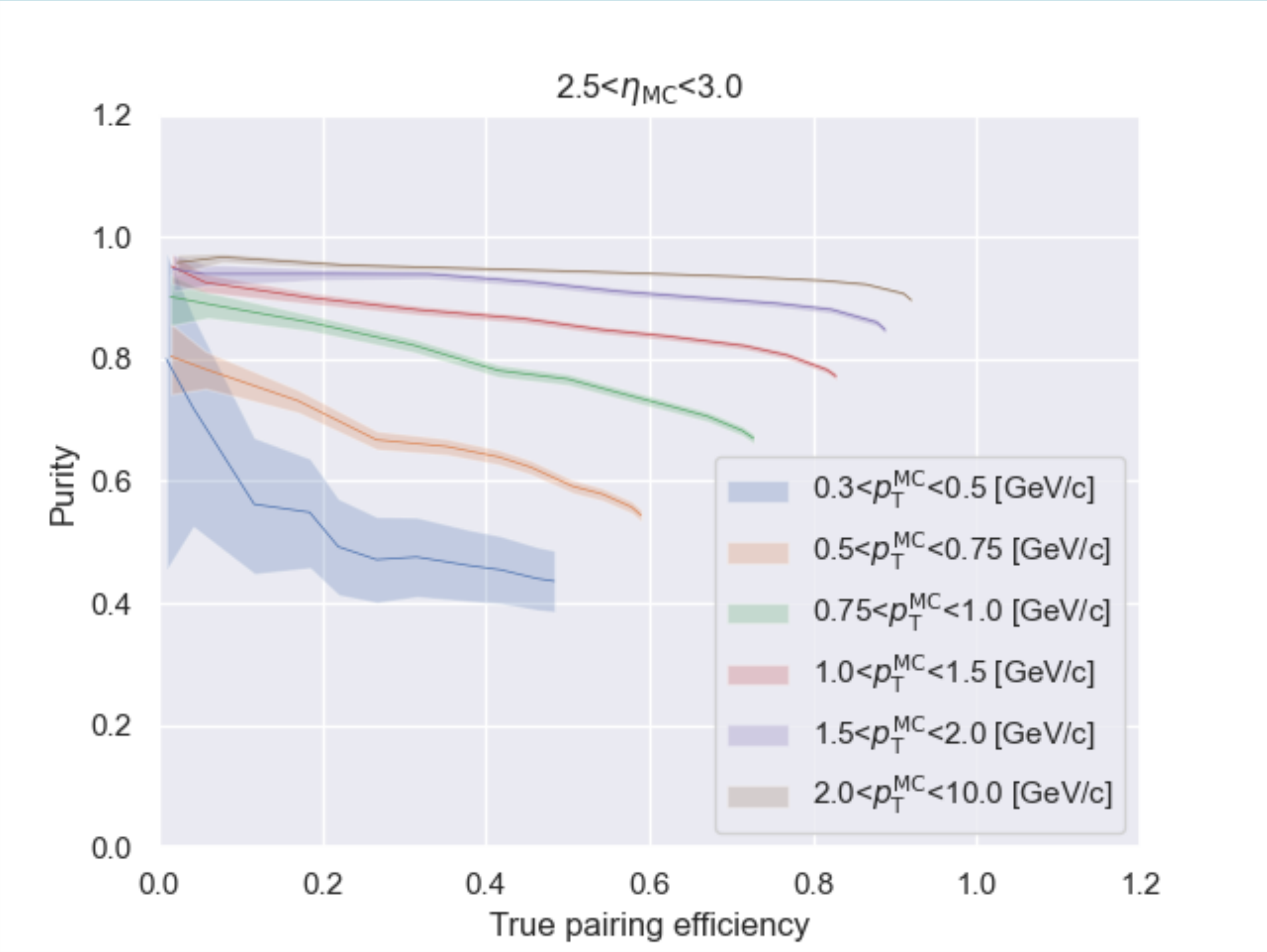
- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

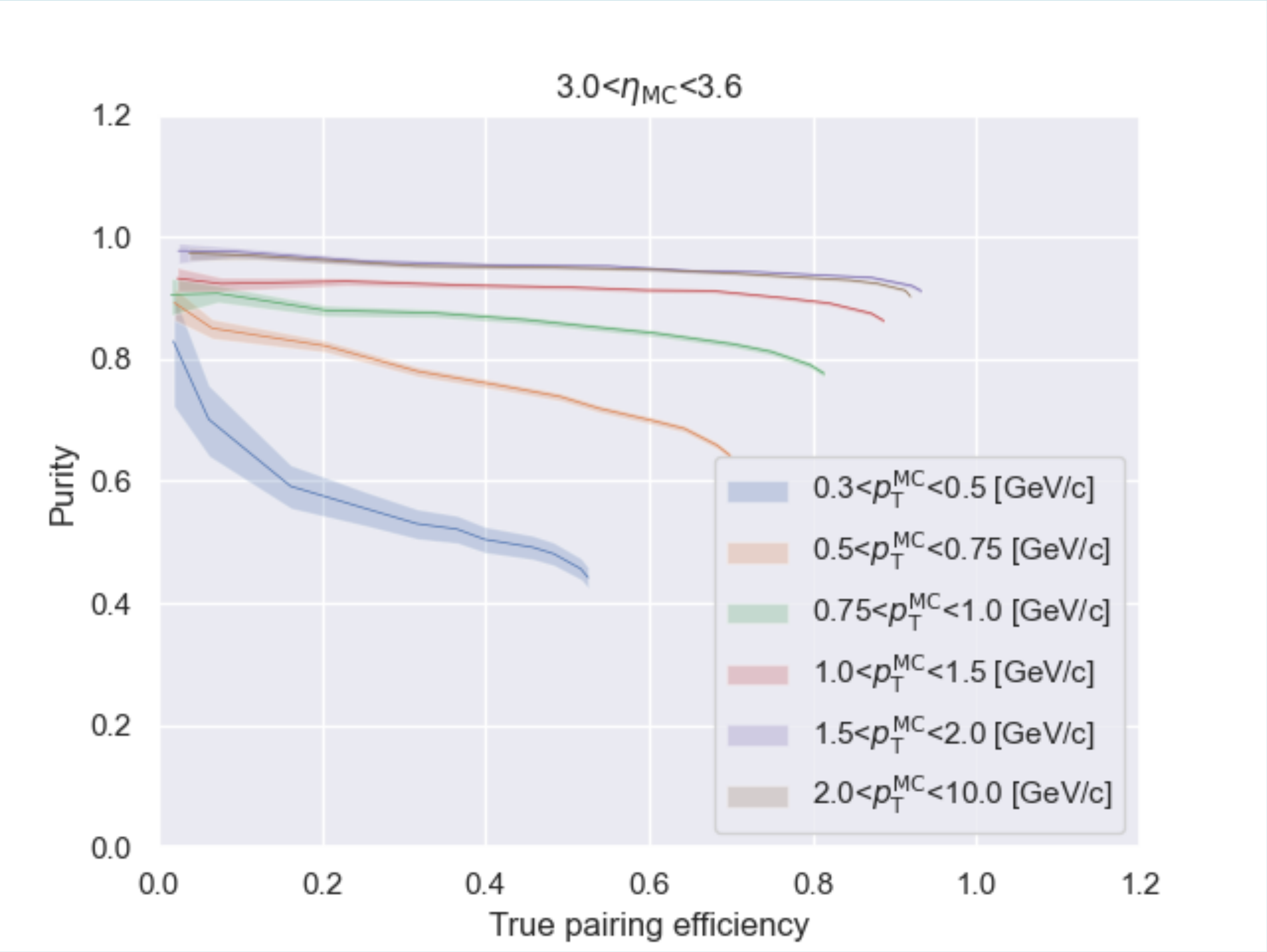




Performance of muon track pp @ 13.6 TeV (MB) + ϕ-meson data

- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

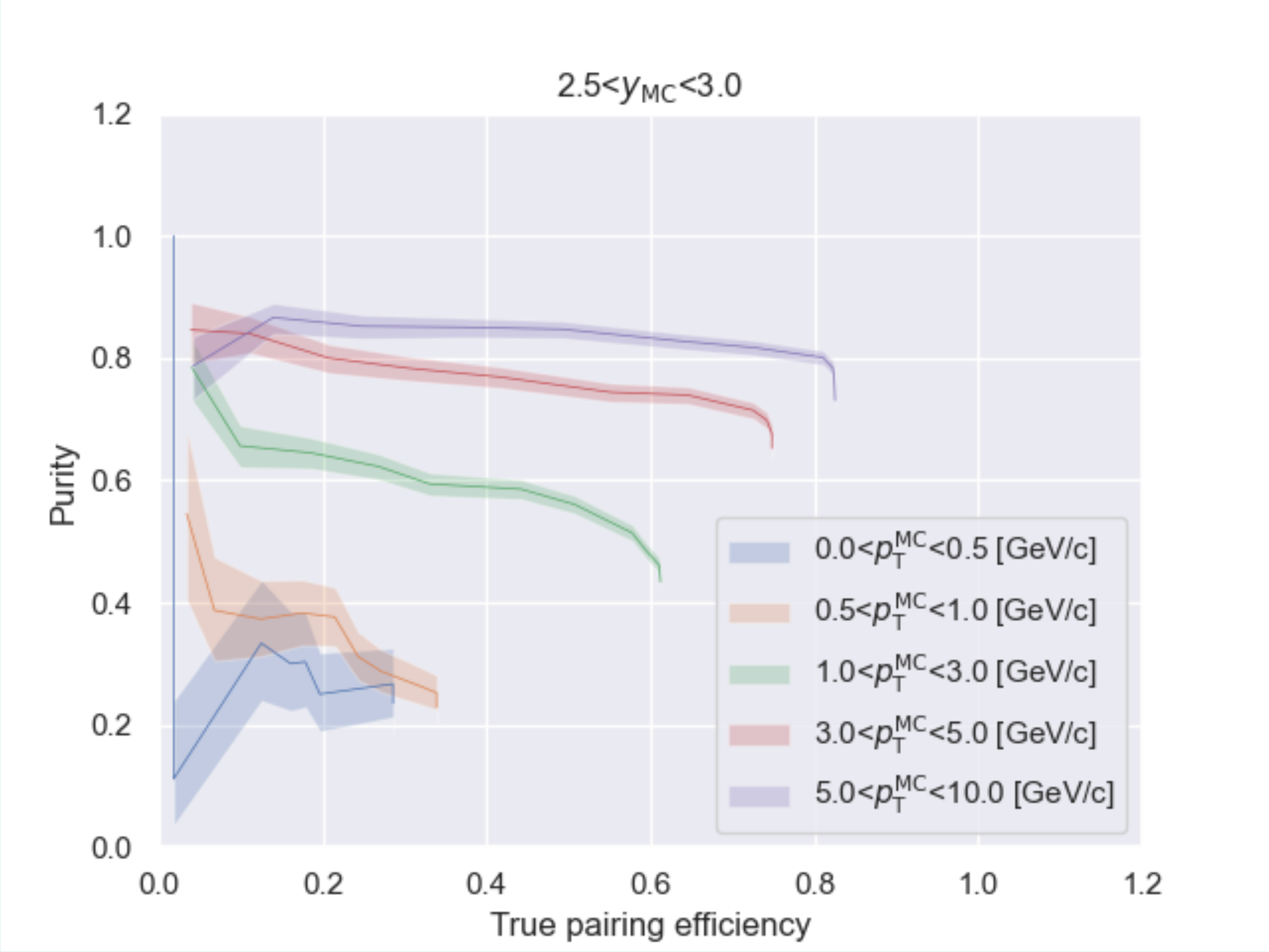


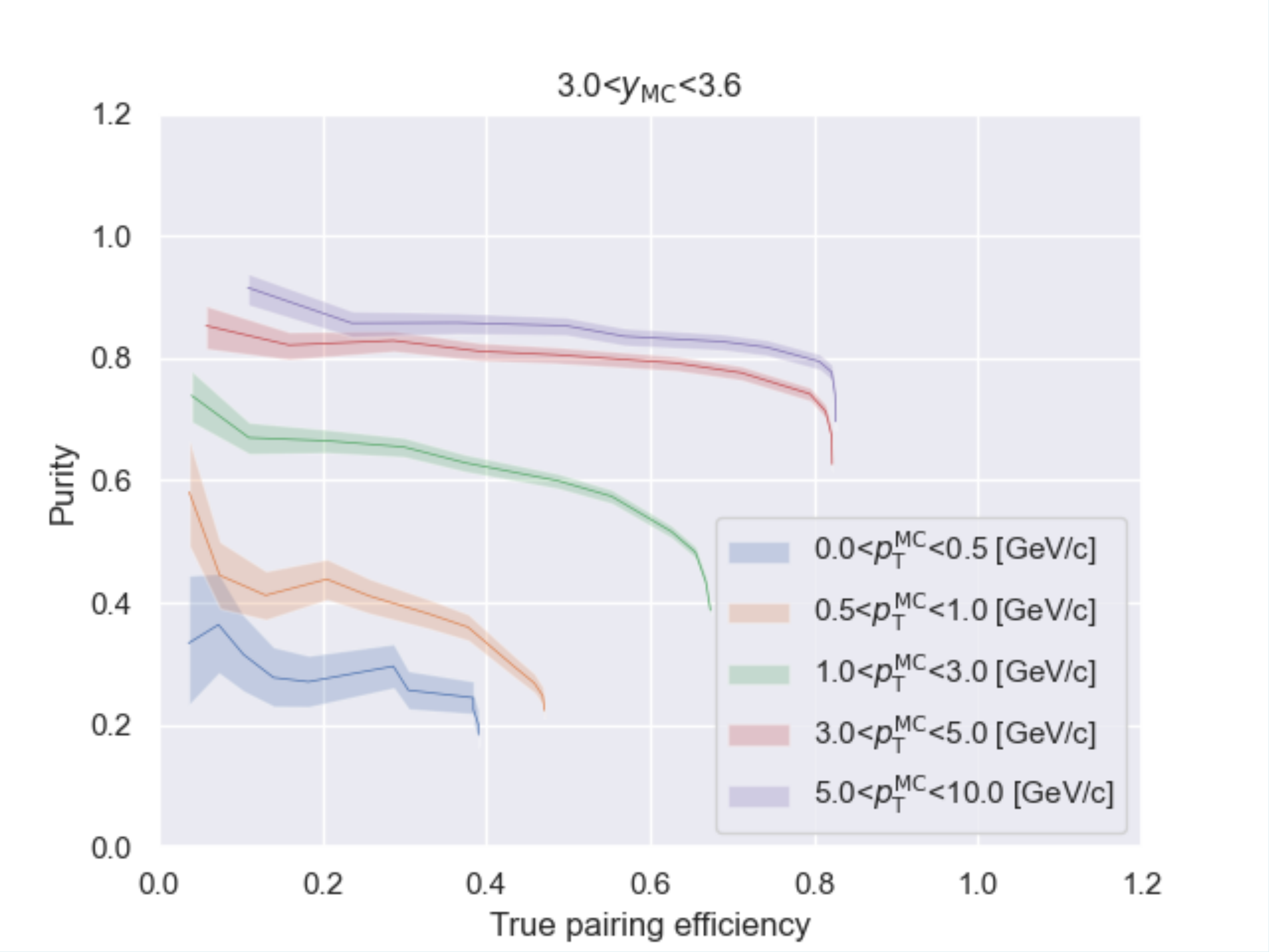


- Purity and efficiency are not the same as quarkonia data sample case, (due to p_T shape?)

Performance of ϕ-meson reconstruction pp @ 13.6 TeV (MB) + ϕ-meson data

- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

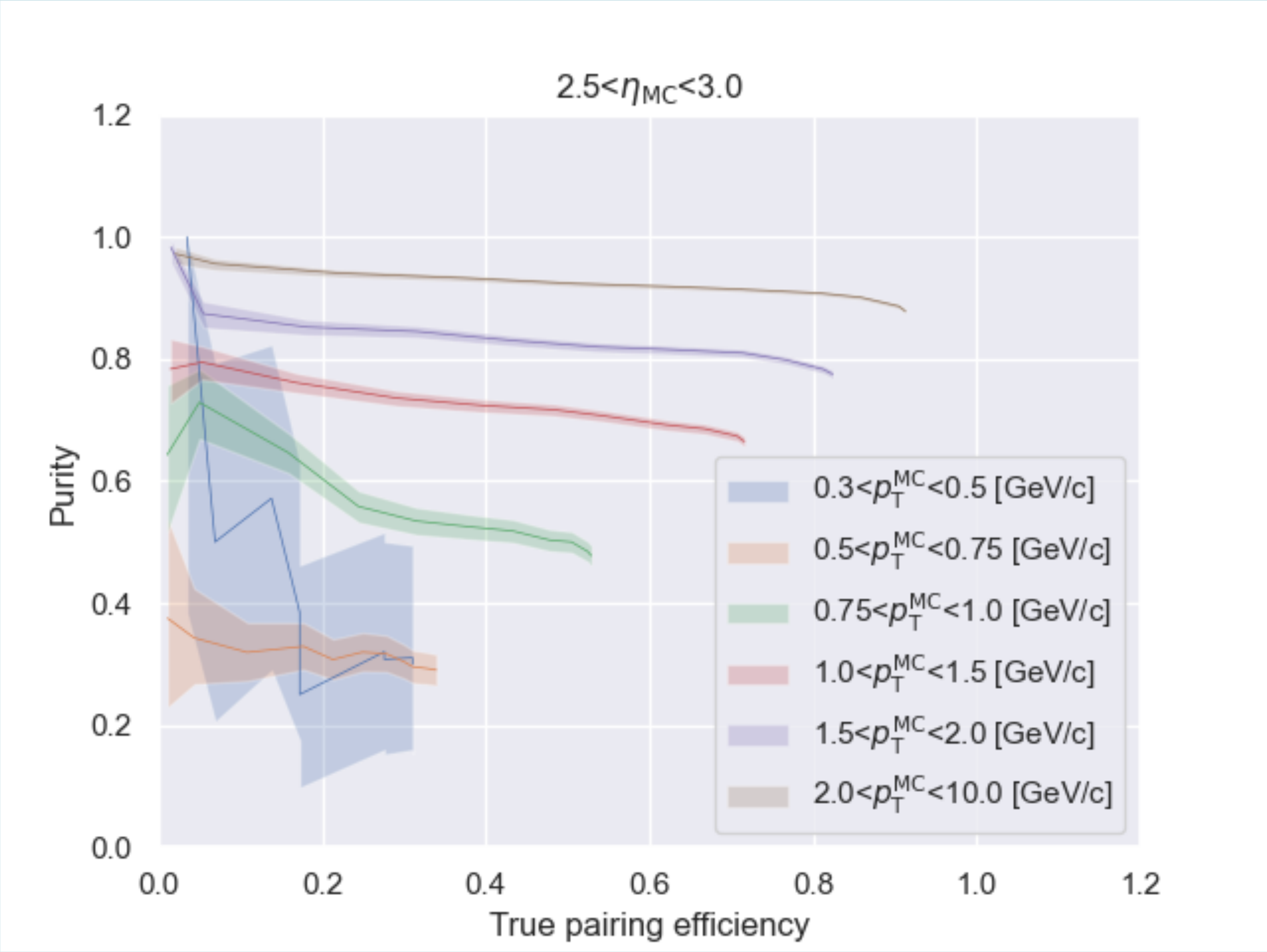


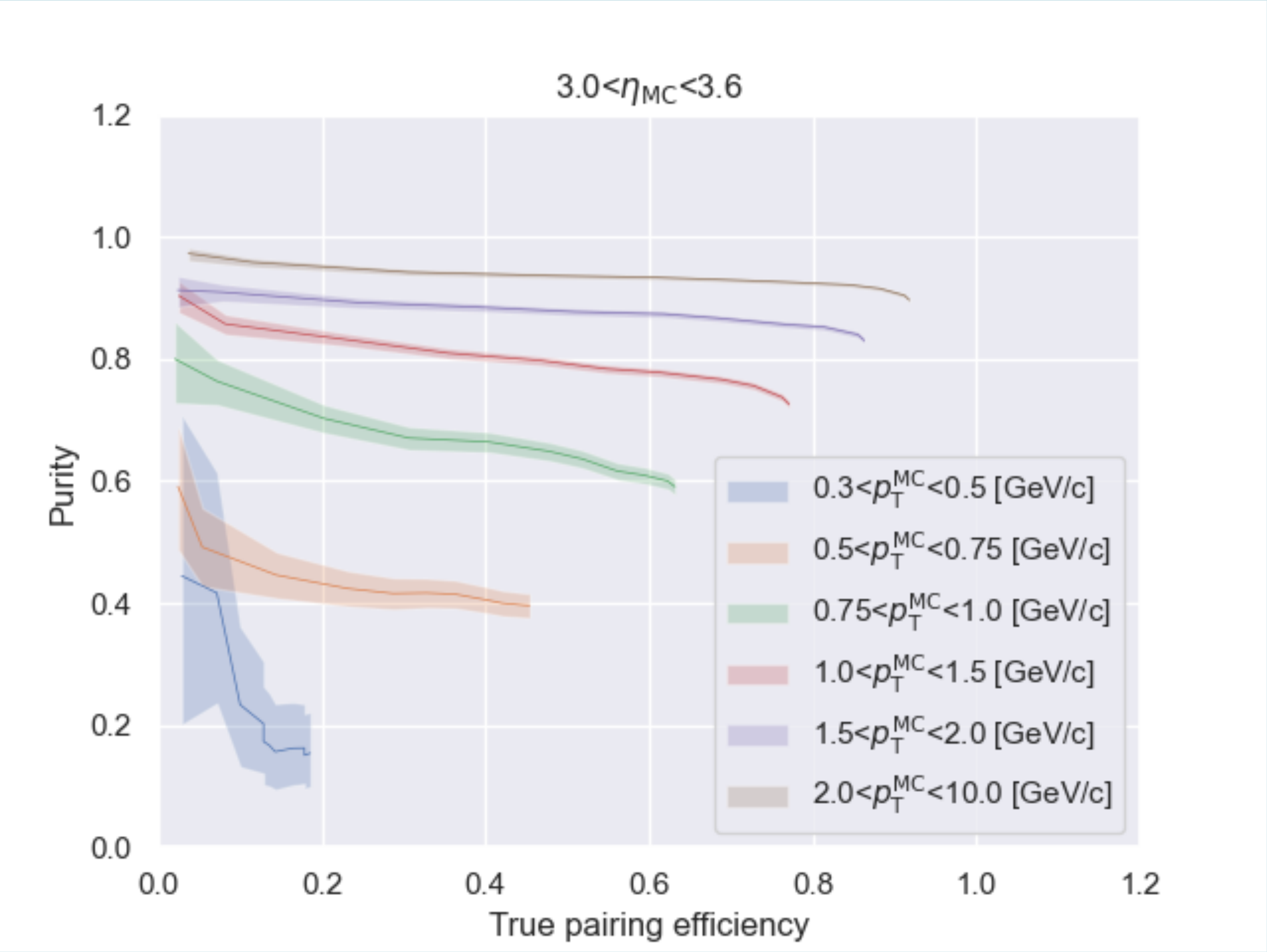


PbPb collisions

Performance of muon track
PbPb @ 5 TeV (MB) + Quarkonia data

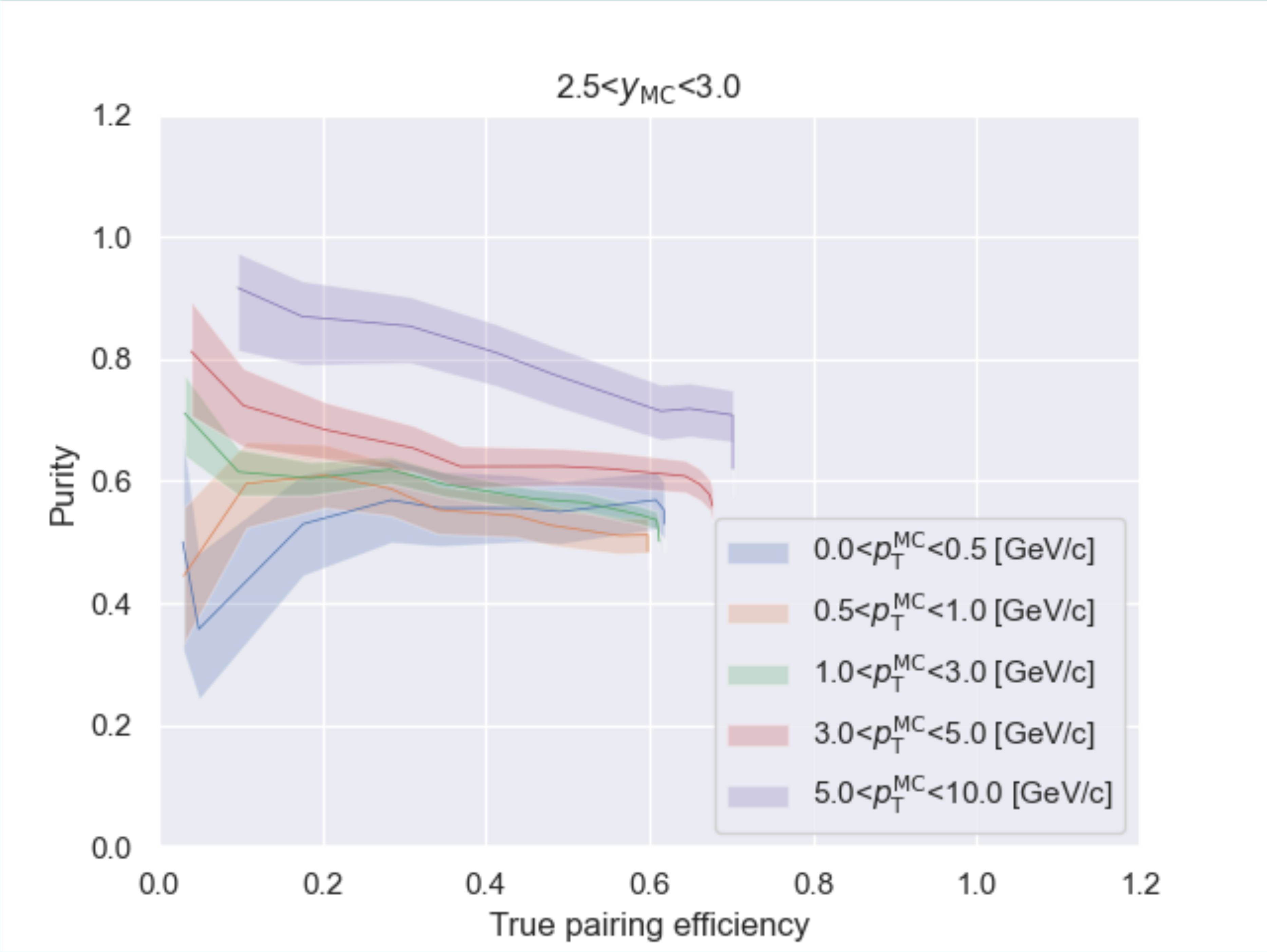
- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

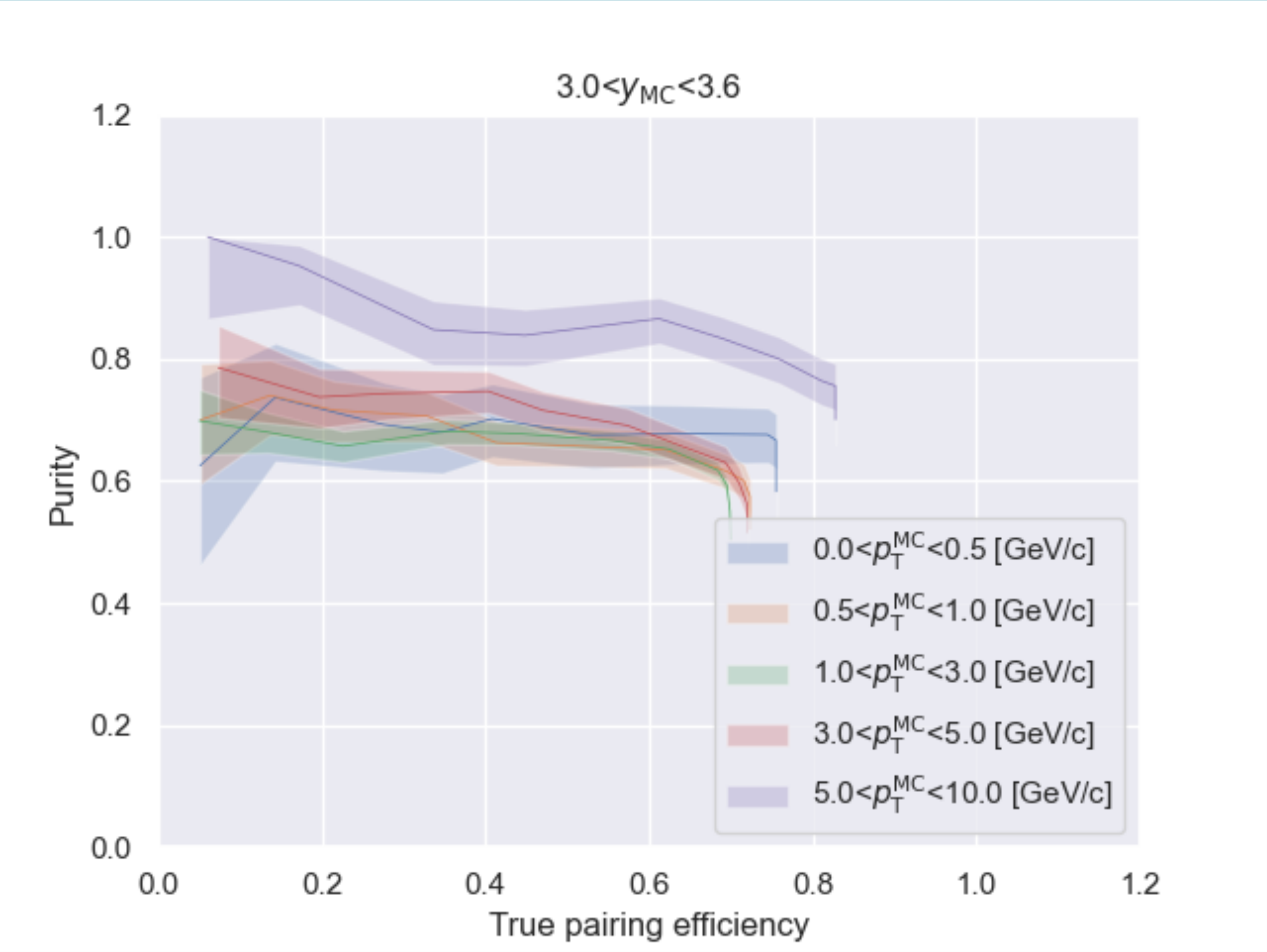




Performance of J/ψ reconstruction PbPb @ 5 TeV (MB) + Quarkonia data

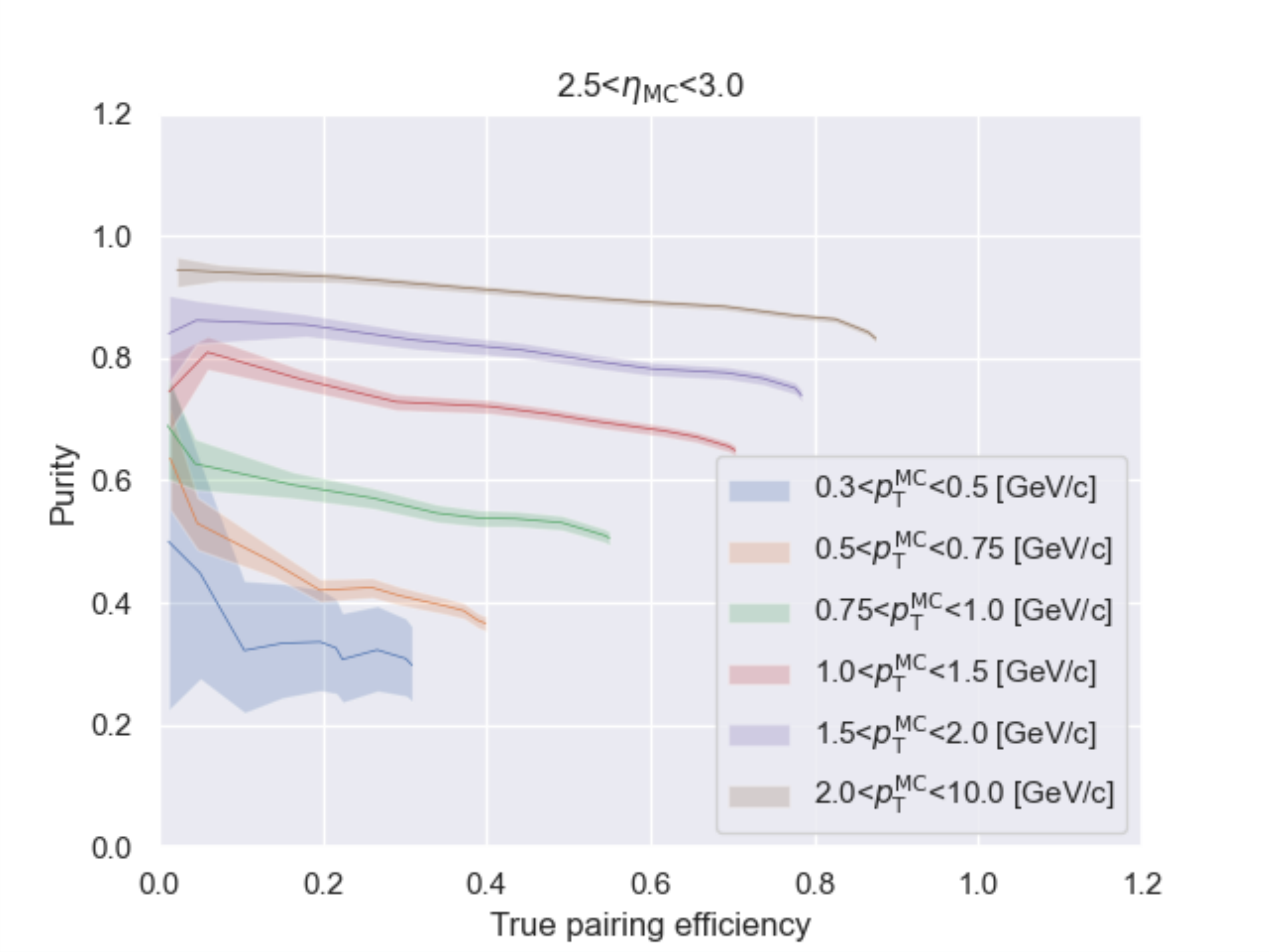
- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

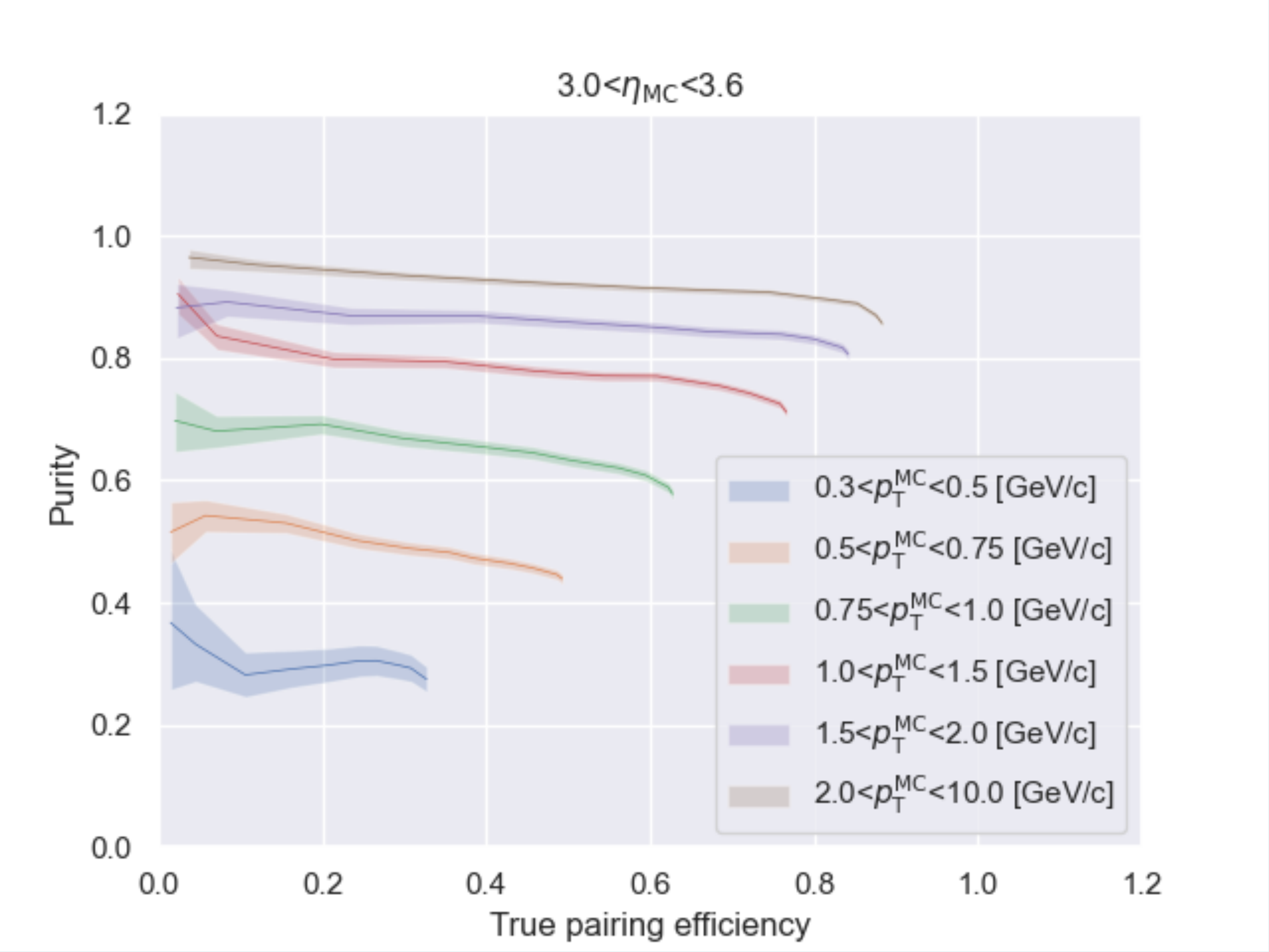




Performance of muon track PbPb @ 5 TeV (MB) + ϕ-meson data

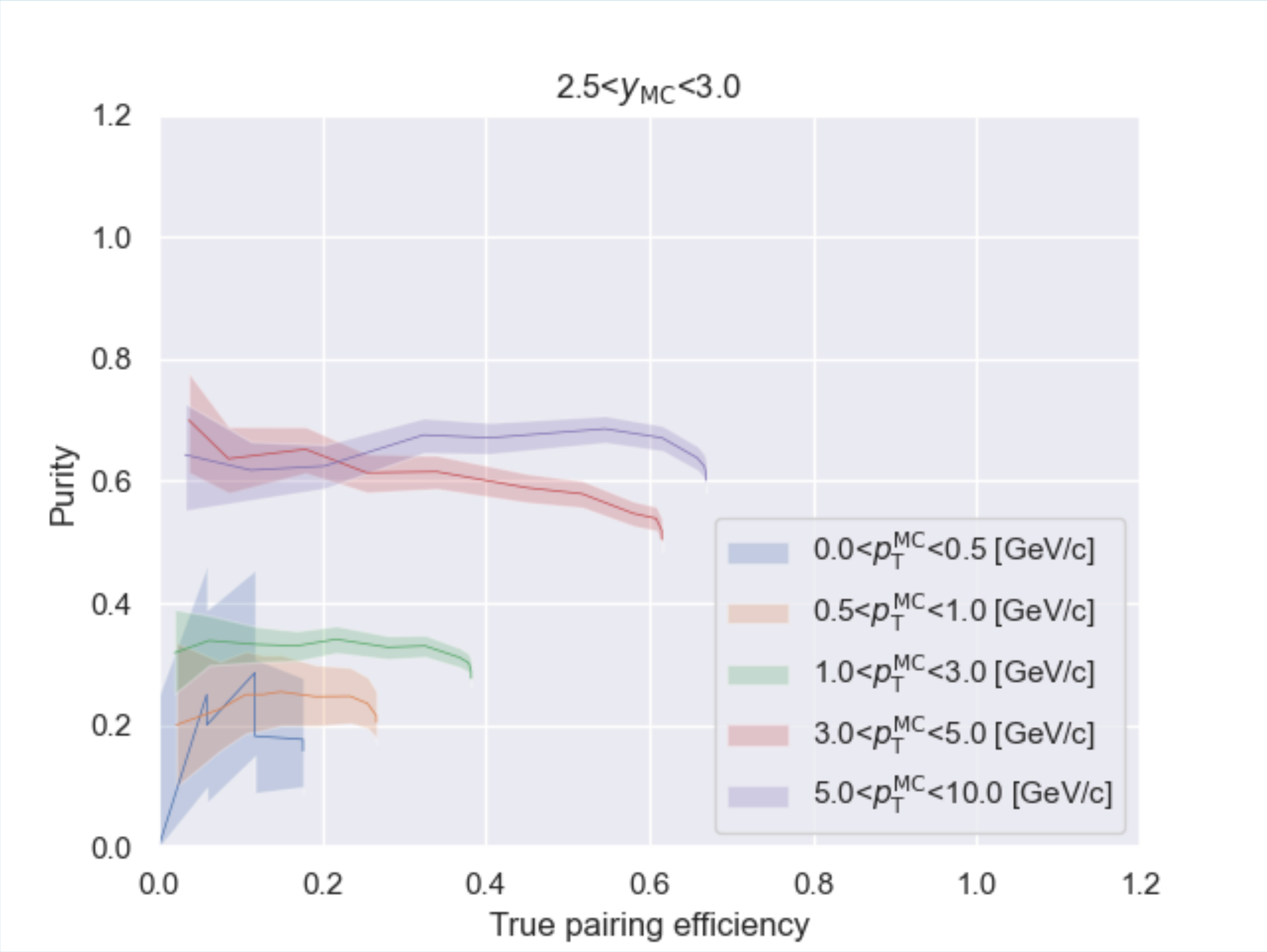
- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm

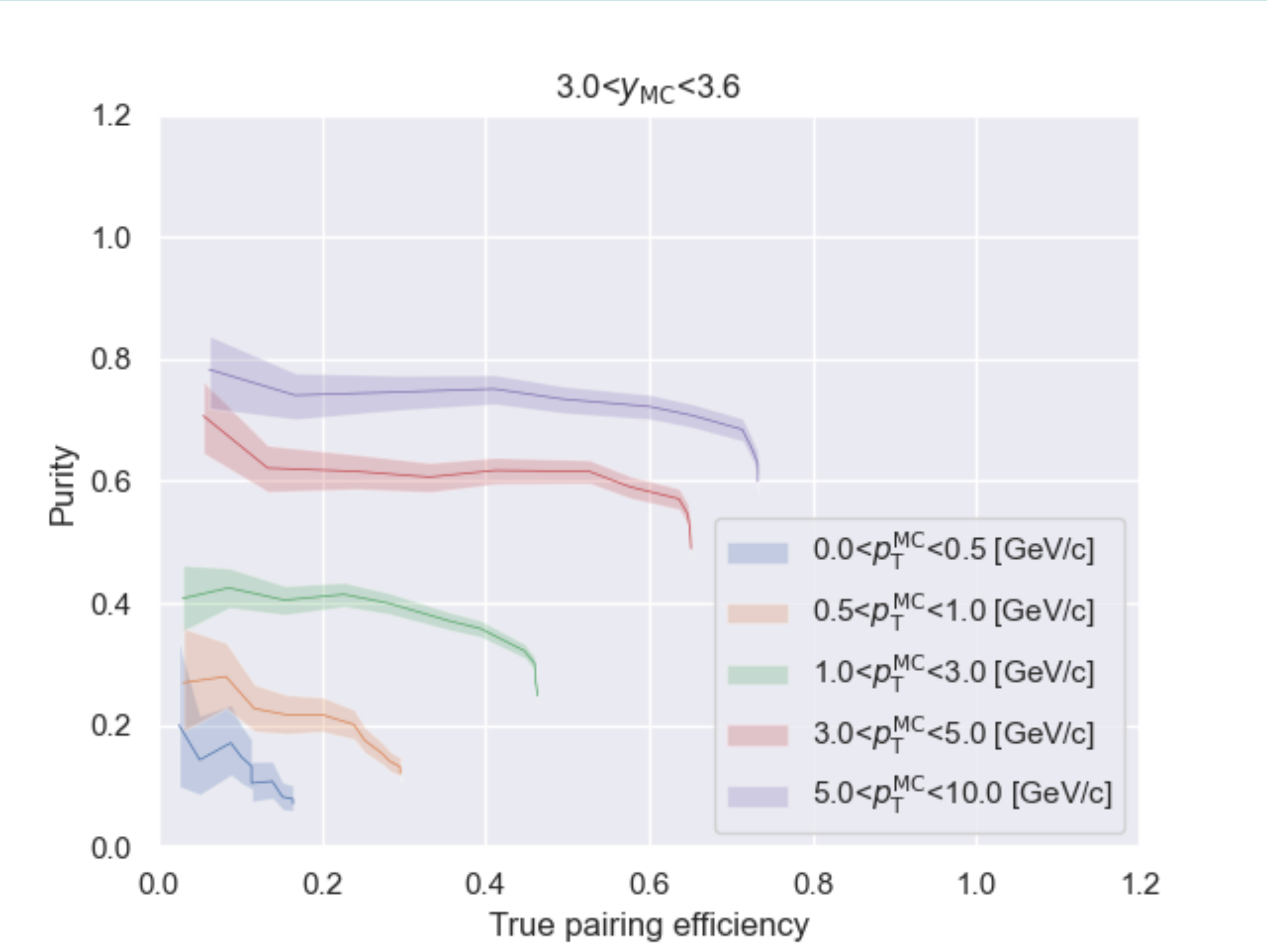




Performance of ϕ-meson reconstruction PbPb @ 5 TeV (MB) + ϕ-meson data

- Matching-chi2 with all parameters (matchALL)
- Matching plane z = -77.5 cm



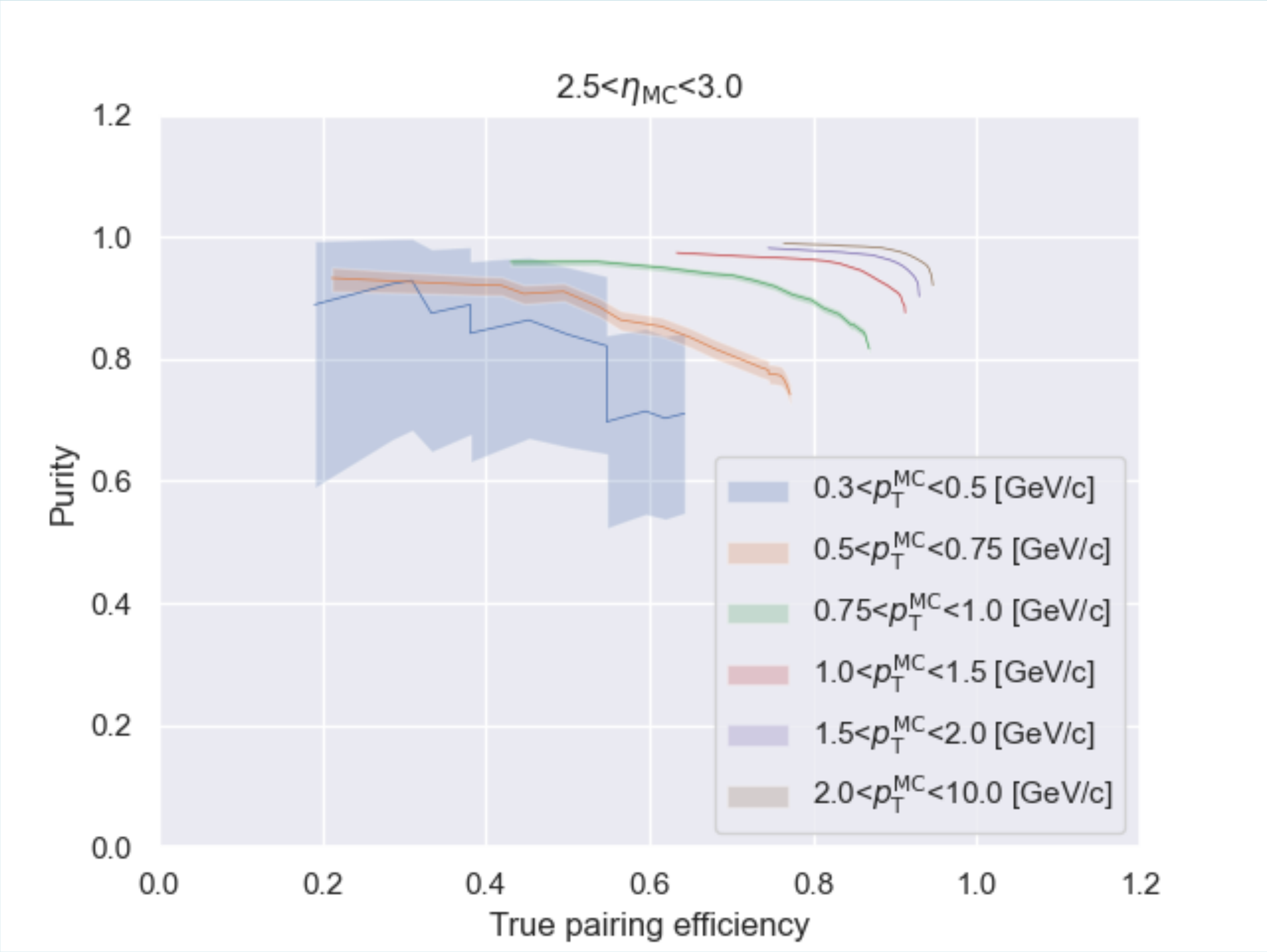


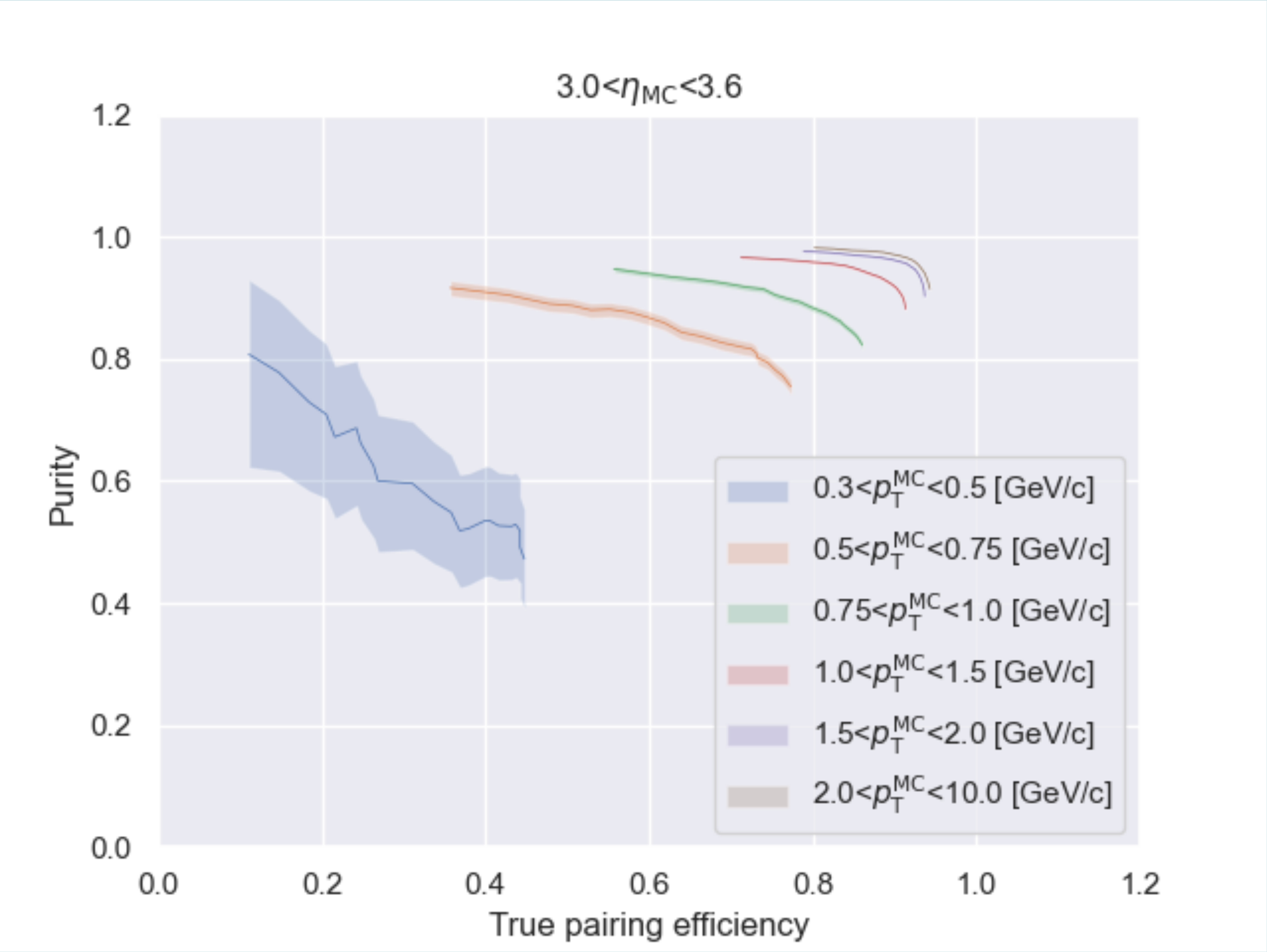
ML performance

Matching plane $z = -77.5$ cm

Performance of muon track
pp @ 13.6 TeV (MB) + Quarkonia data

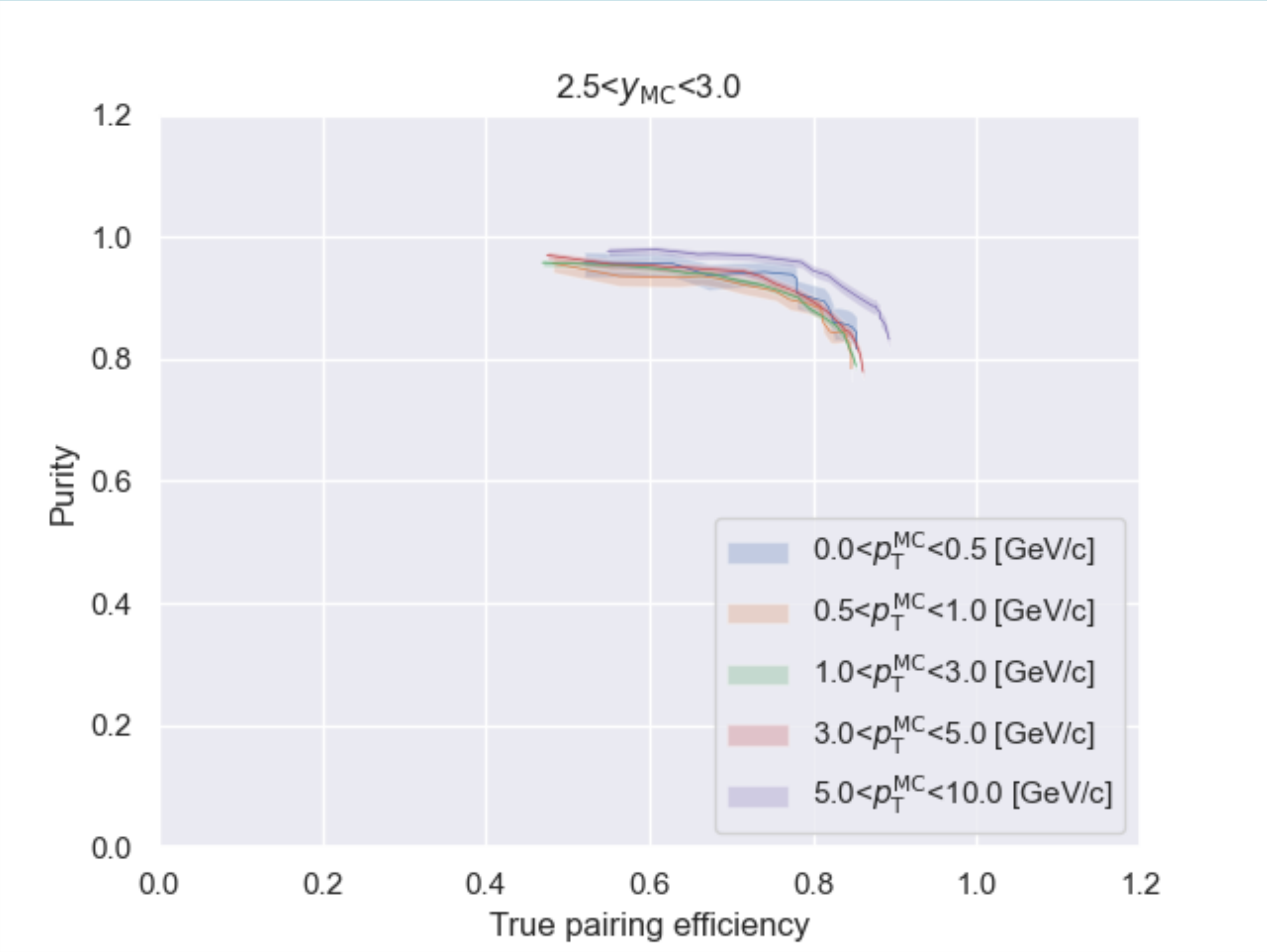
- NN with 8 layers (1000 epochs)
- Trained with 984607 samples, correct : wrong = 23910 : 960697
- Matching plane z = -77.5 cm

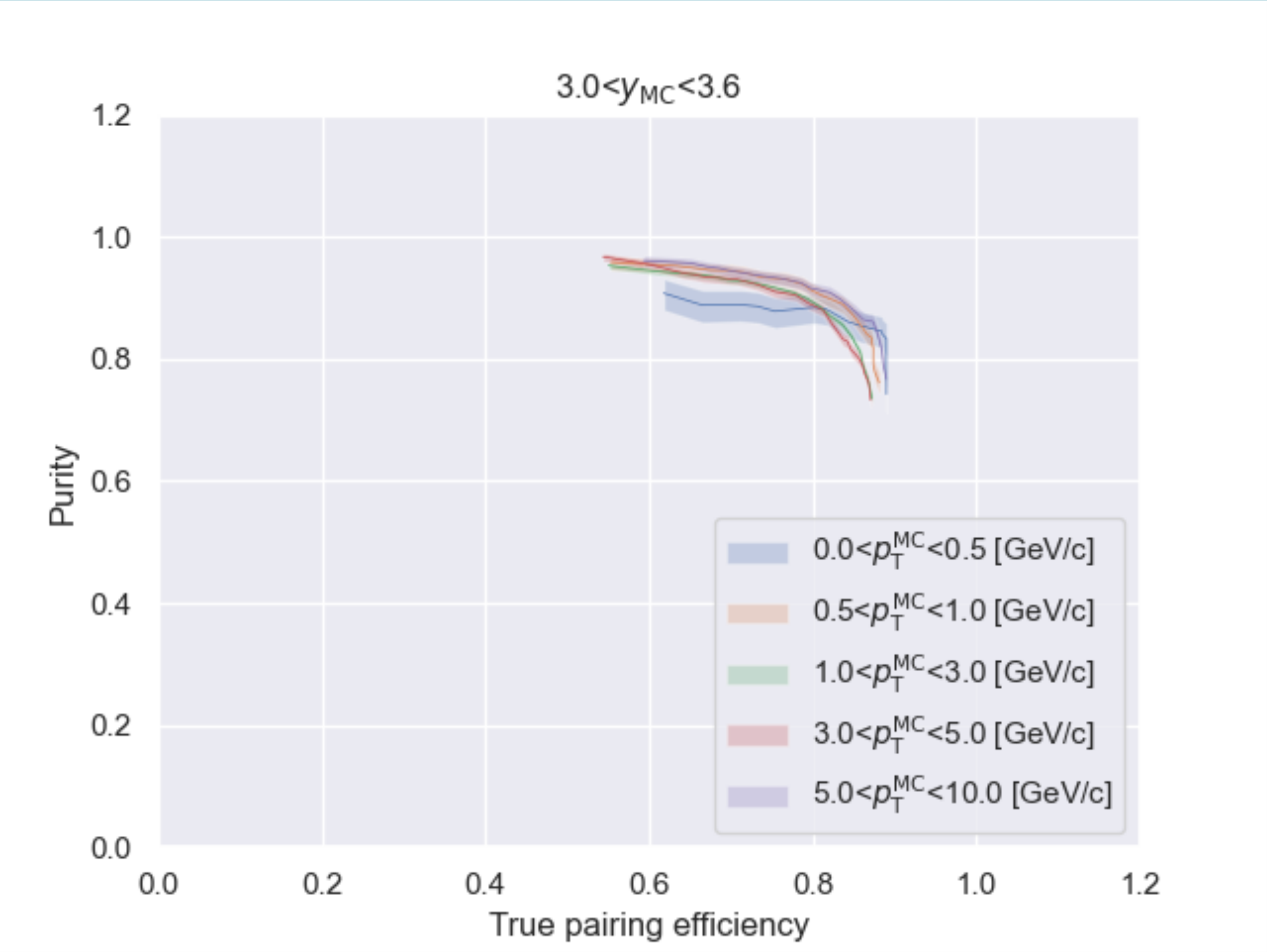




Performance of J/ψ reconstruction pp @ 13.6 TeV (MB) + Quarkonia data

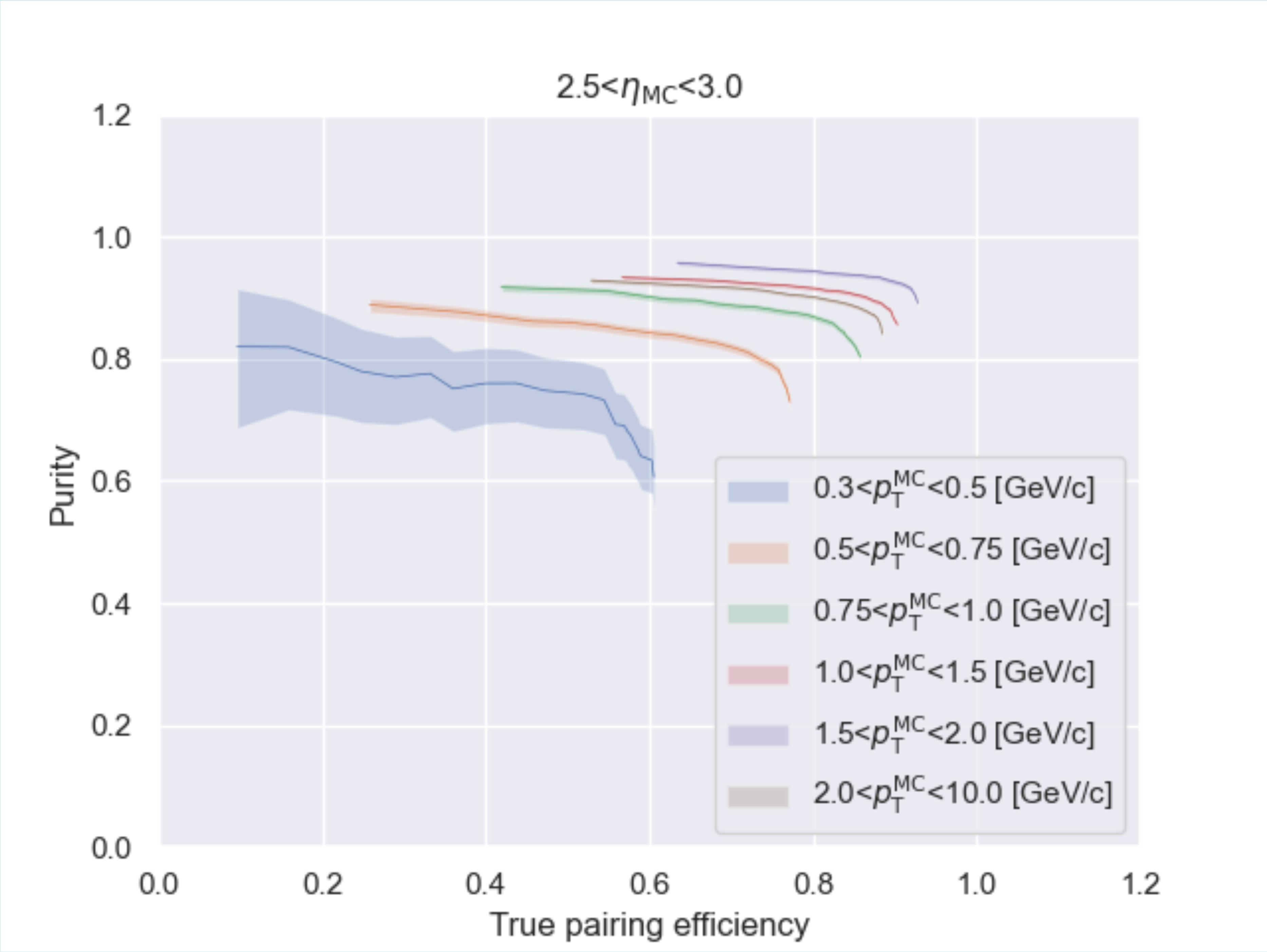
- NN with 8 layers (1000 epochs)
- Trained with 984607 samples, correct : wrong = 23910 : 960697
- Matching plane z = -77.5 cm

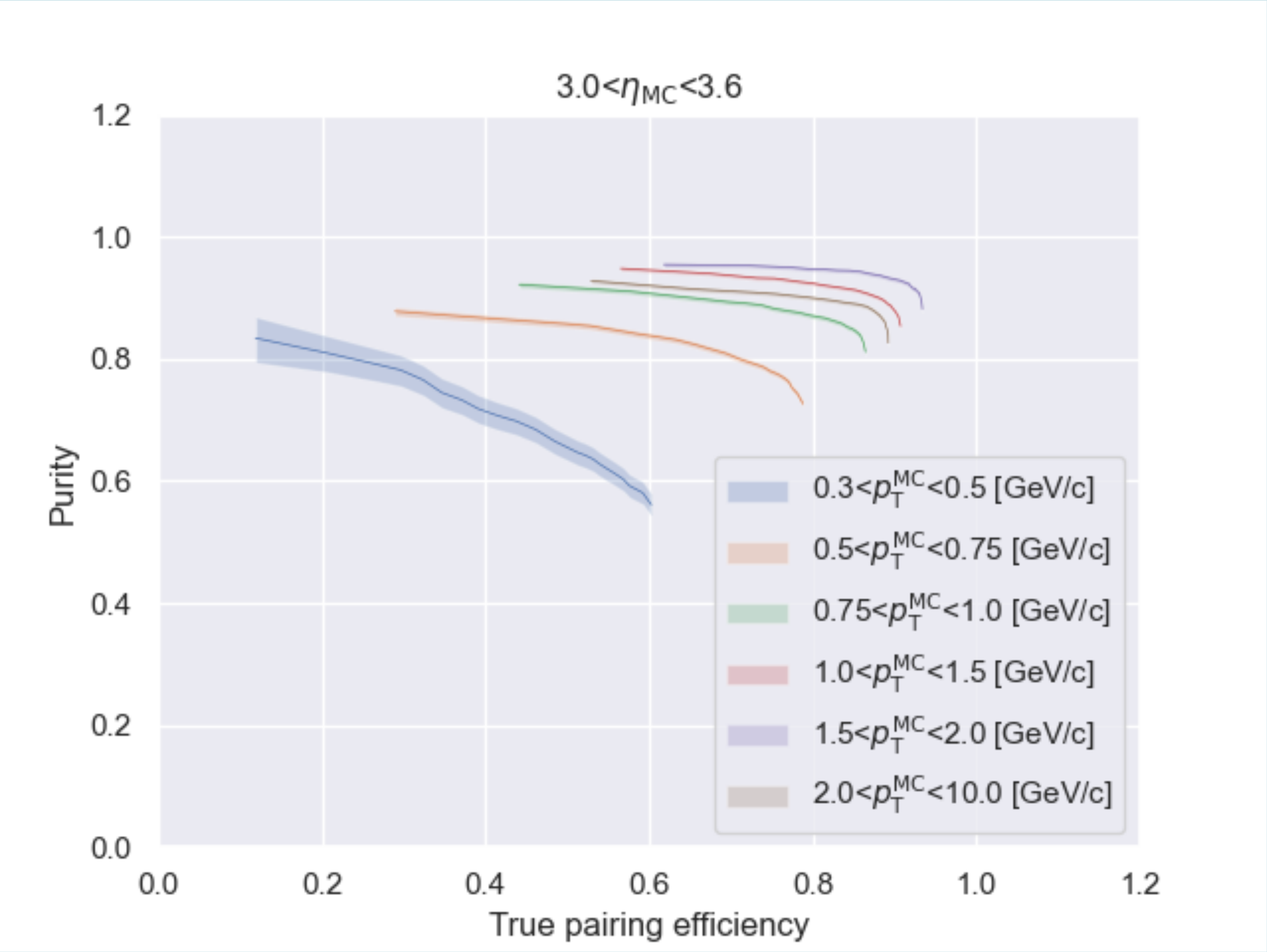




Performance of muon track
pp @ 13.6 TeV (MB) + ϕ-meson data

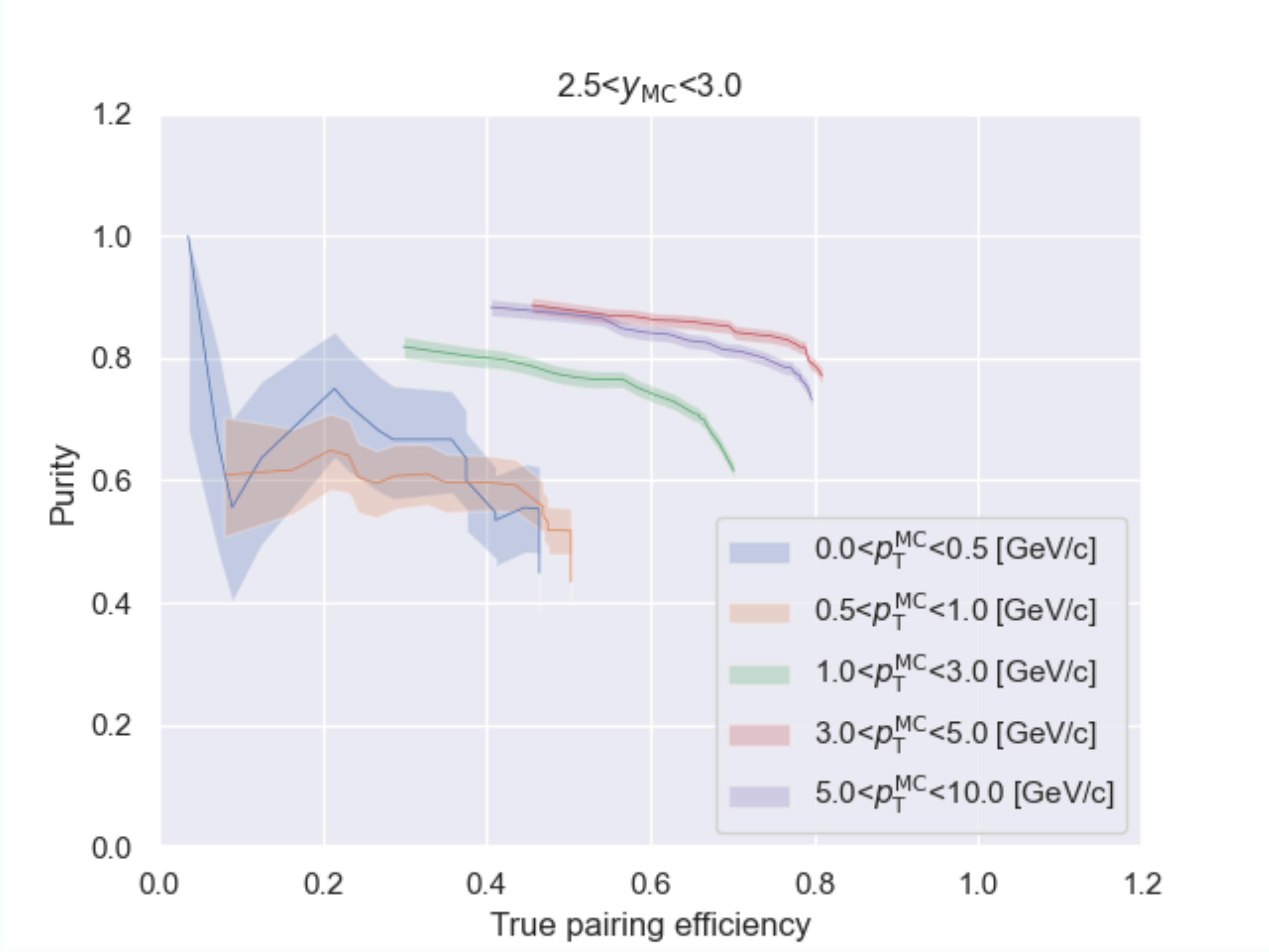
- NN with 8 layers (1000 epochs)
- Trained with 3084736 samples, correct : wrong = 32474 : 3052262
- Matching plane z = -77.5 cm

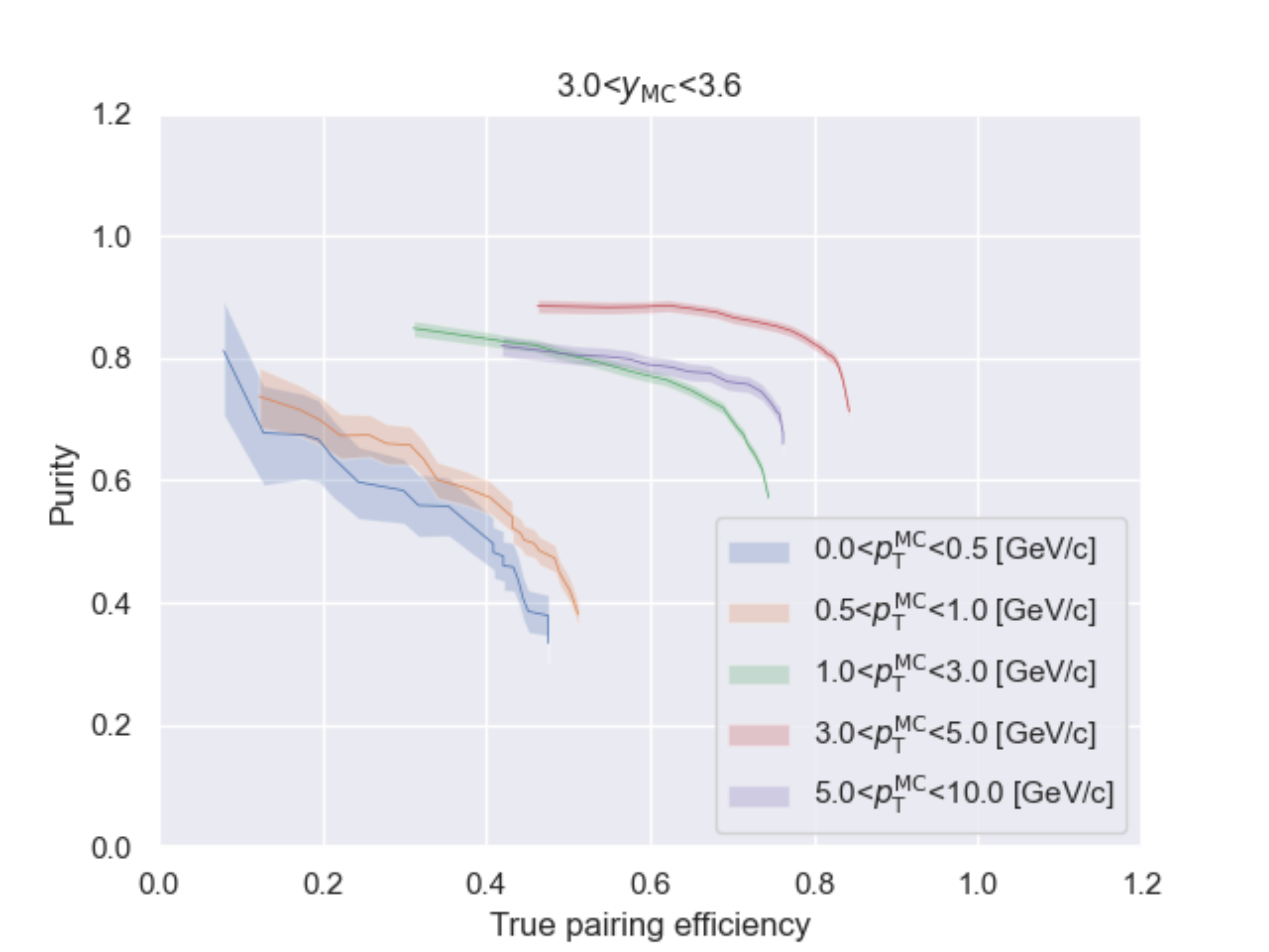




Performance of ϕ-meson reconstruction pp @ 13.6 TeV (MB) + ϕ-meson data

- NN with 8 layers (1000 epochs)
- Trained with 3084736 samples, correct : wrong = 32474 : 3052262
- Matching plane z = -77.5 cm

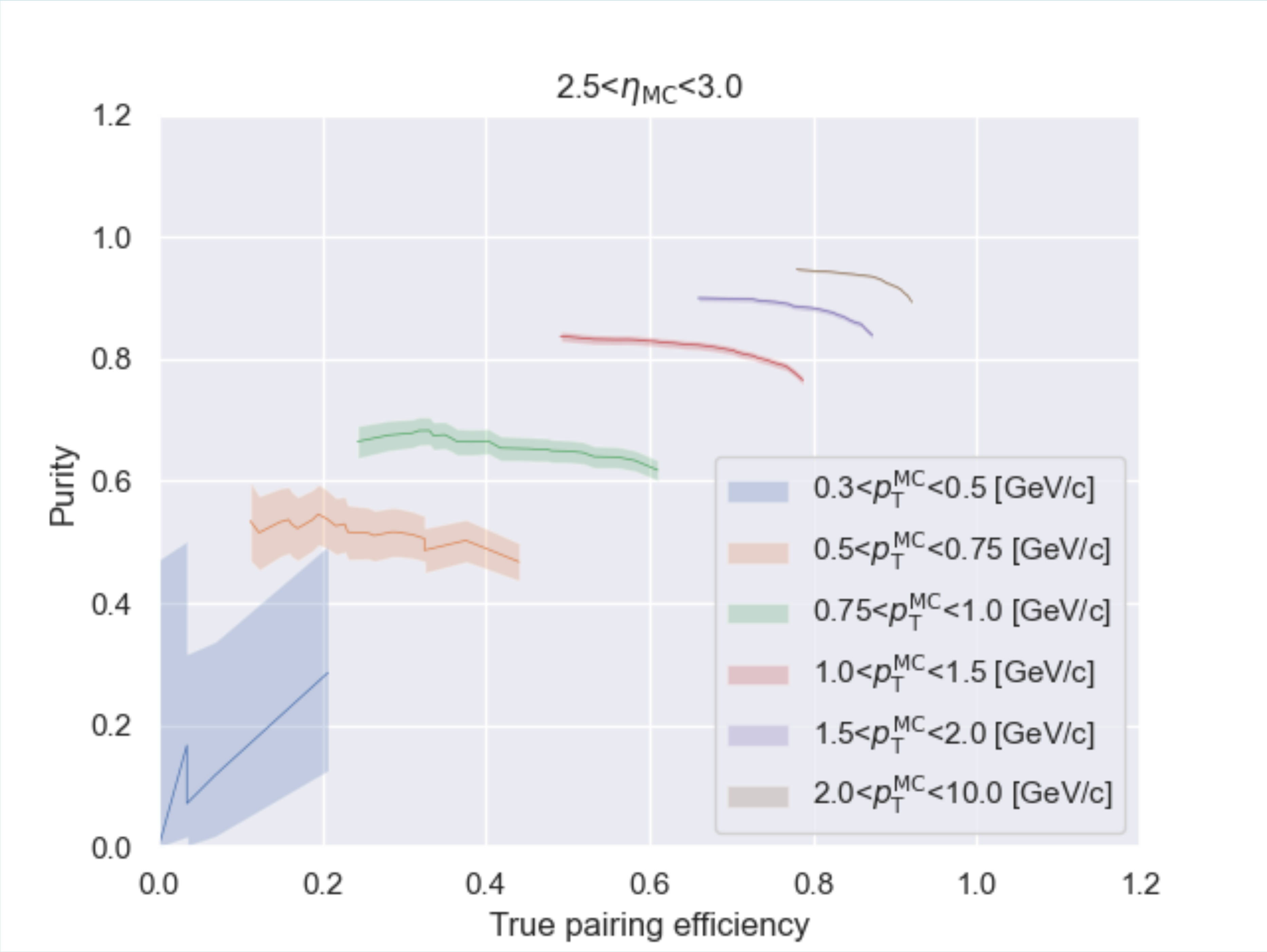


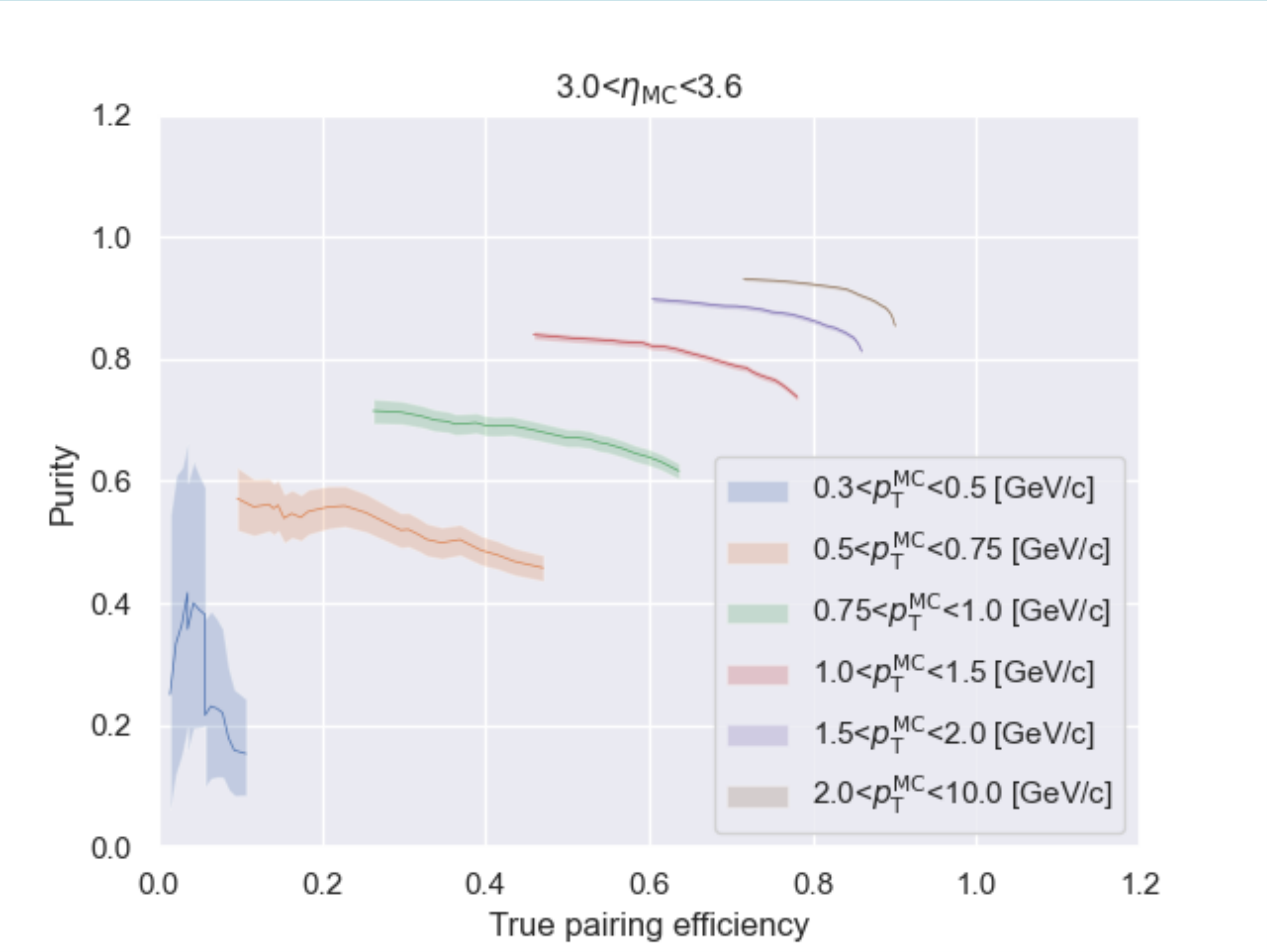


PbPb collisions

Performance of muon track
PbPb @ 5 TeV (MB) + quarkonia data

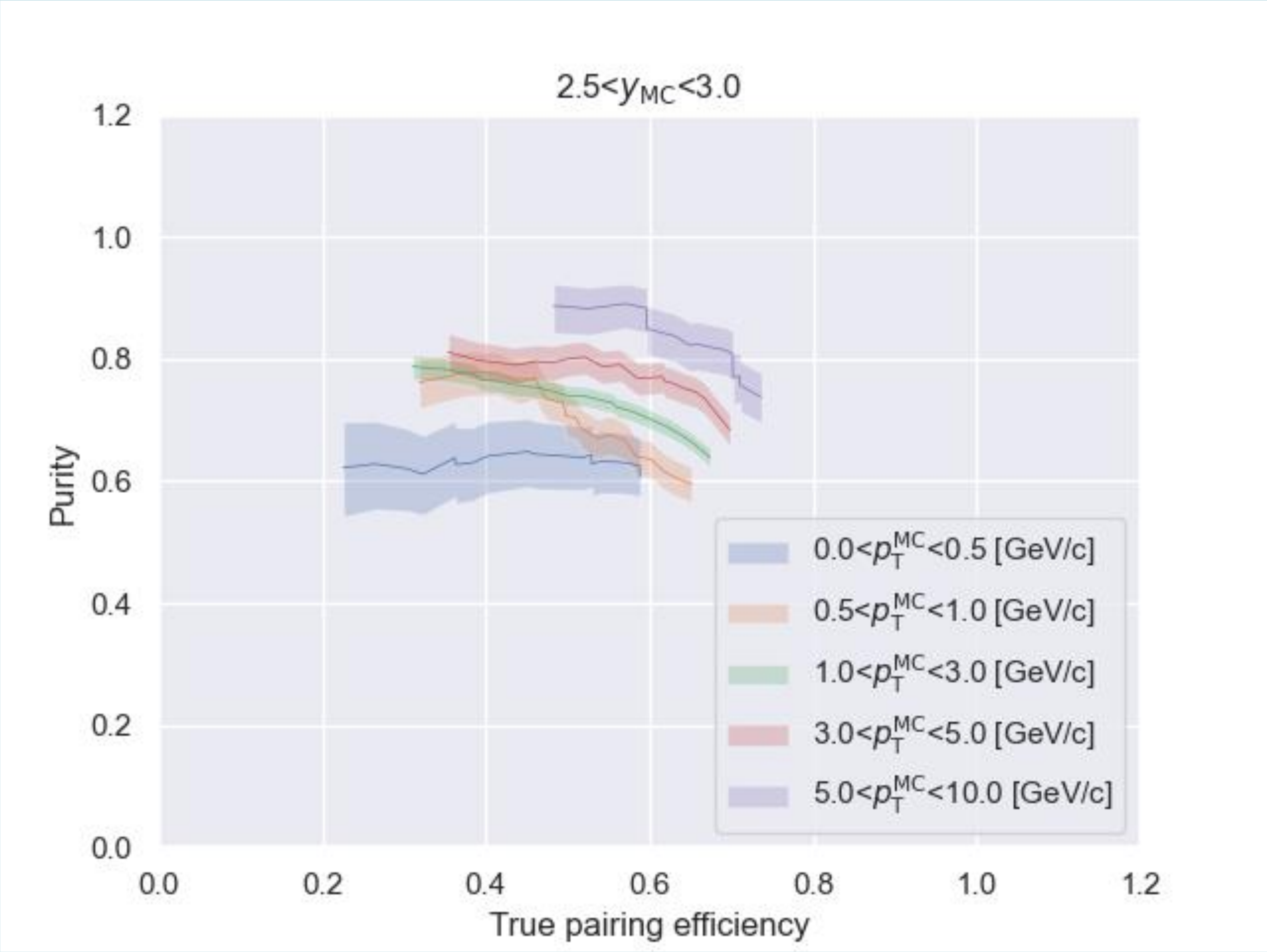
- NN with 8 layers (1000 epochs)
- Trained with 3499048 samples, correct : wrong = 4924 : 3494124
- Matching plane z = -77.5 cm

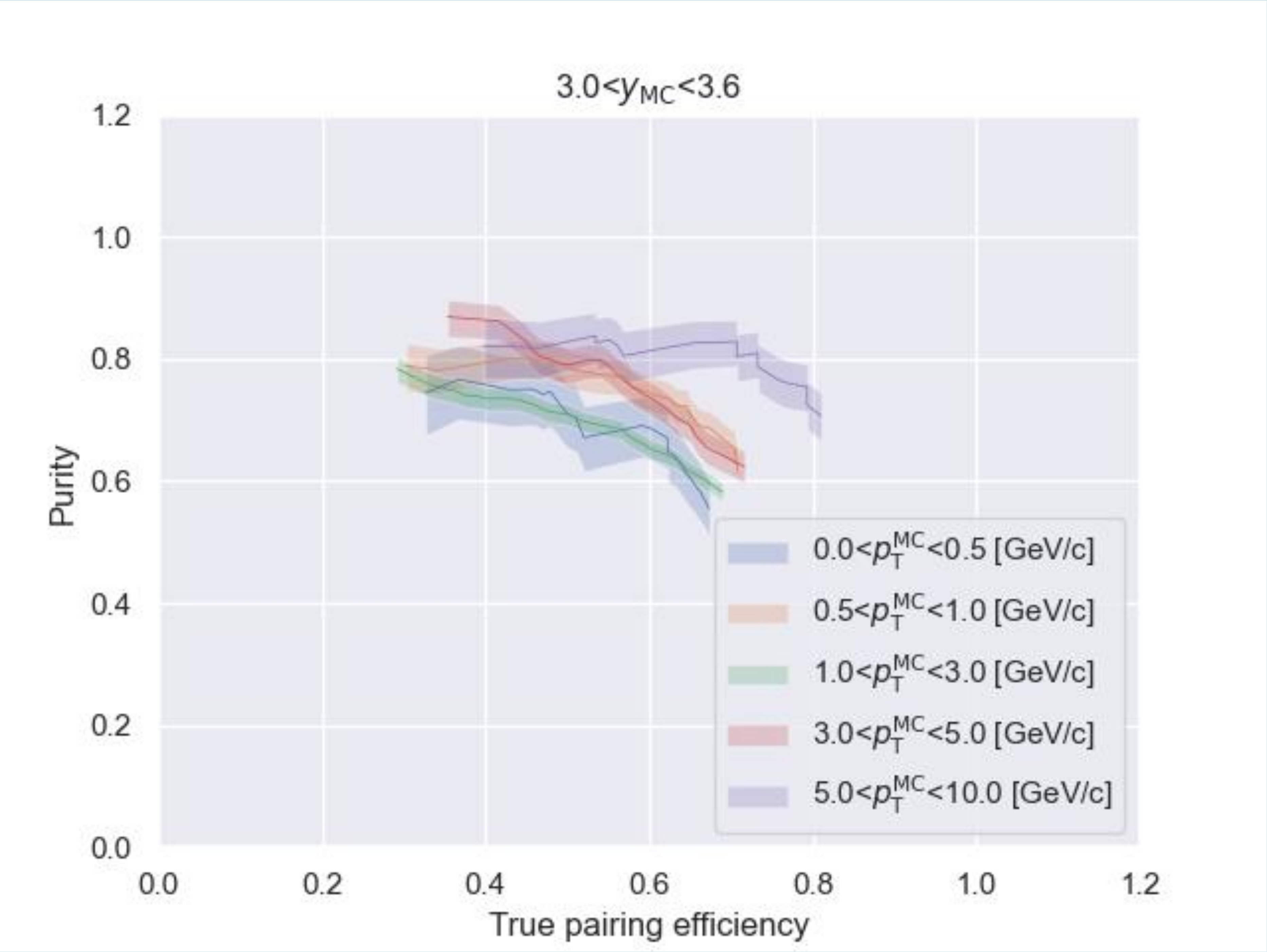




Performance of J/ψ reconstruction PbPb @ 5 TeV (MB) + Quarkonia data

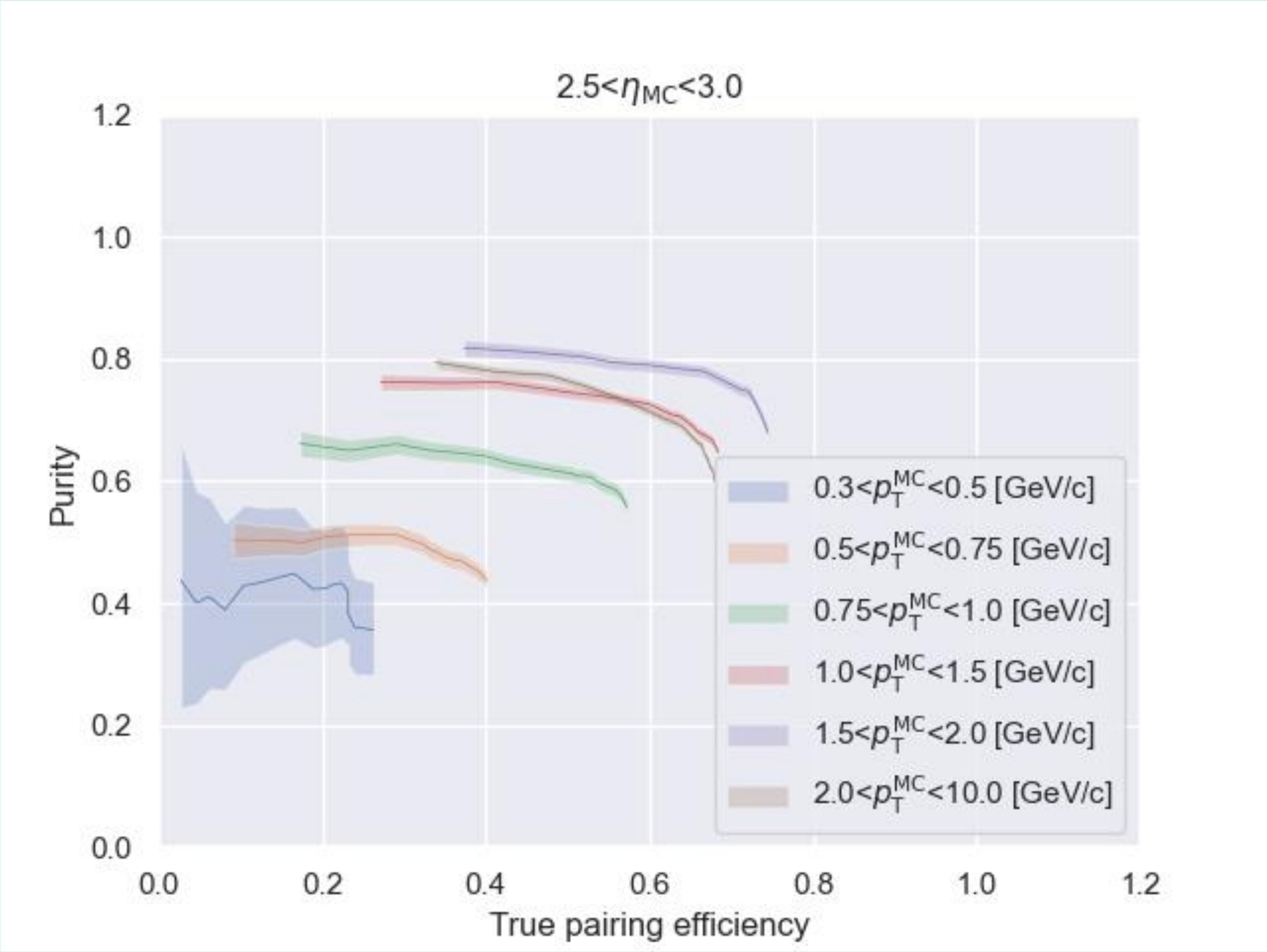
- NN with 8 layers (1000 epochs)
- Trained with 3499048 samples, correct : wrong = 4924 : 3494124
- Matching plane z = -77.5 cm

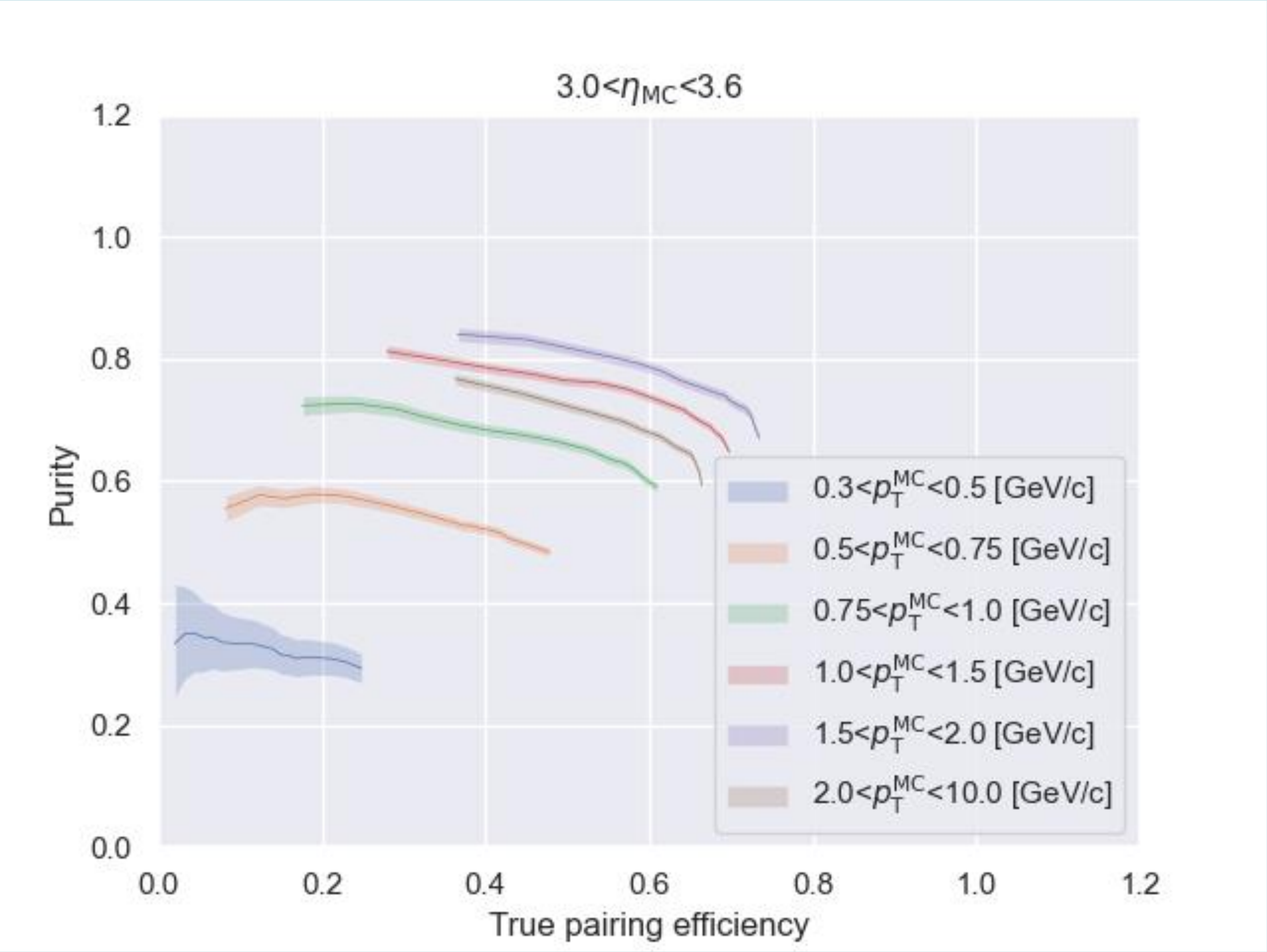




Performance of muon track
PbPb @ 5 TeV (MB) + ϕ-meson data

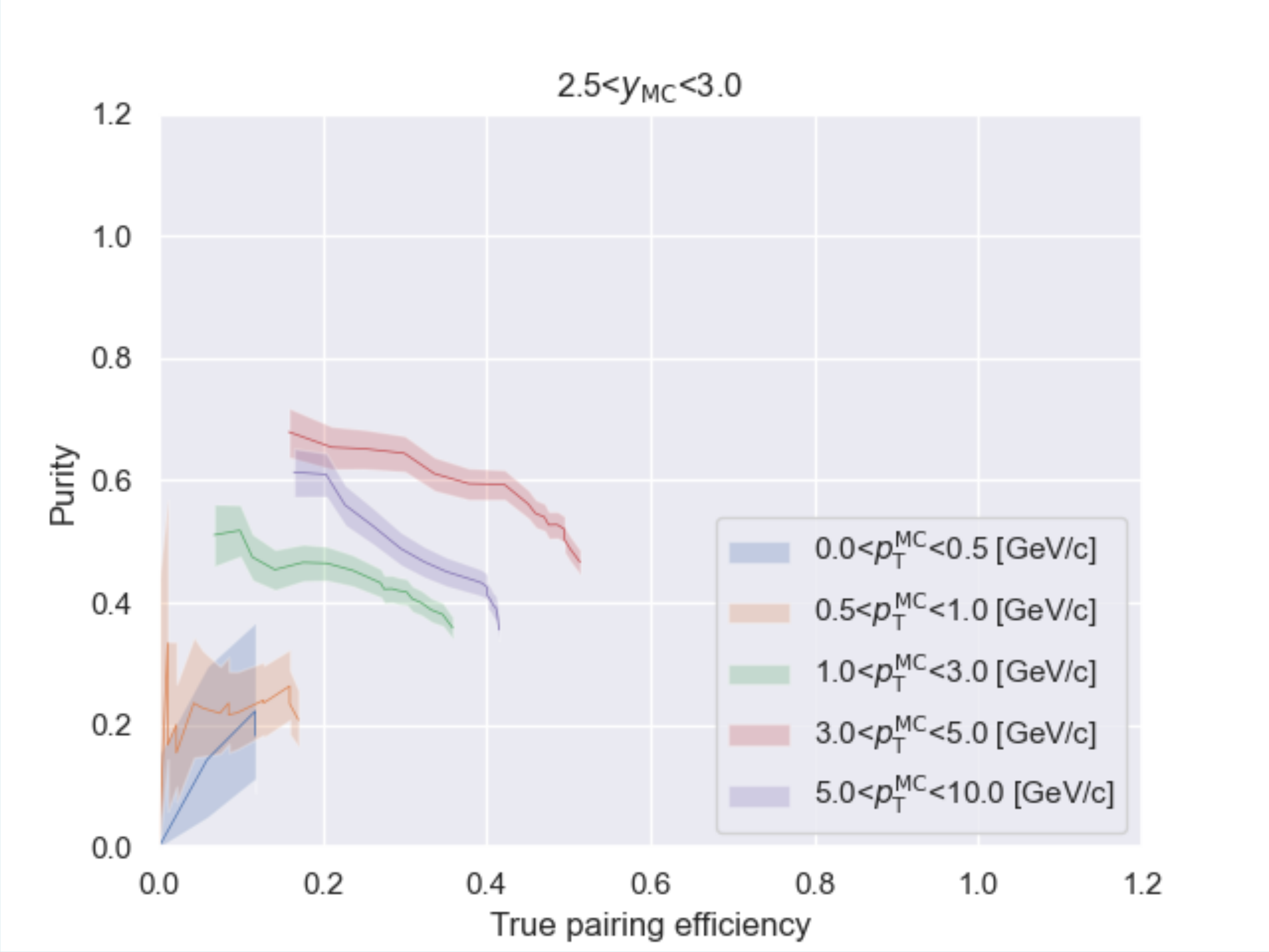
- NN with 8 layers (1000 epochs)
- Trained with 2800229 samples, correct : wrong = 5039 : 2795190
- Matching plane z = -77.5 cm

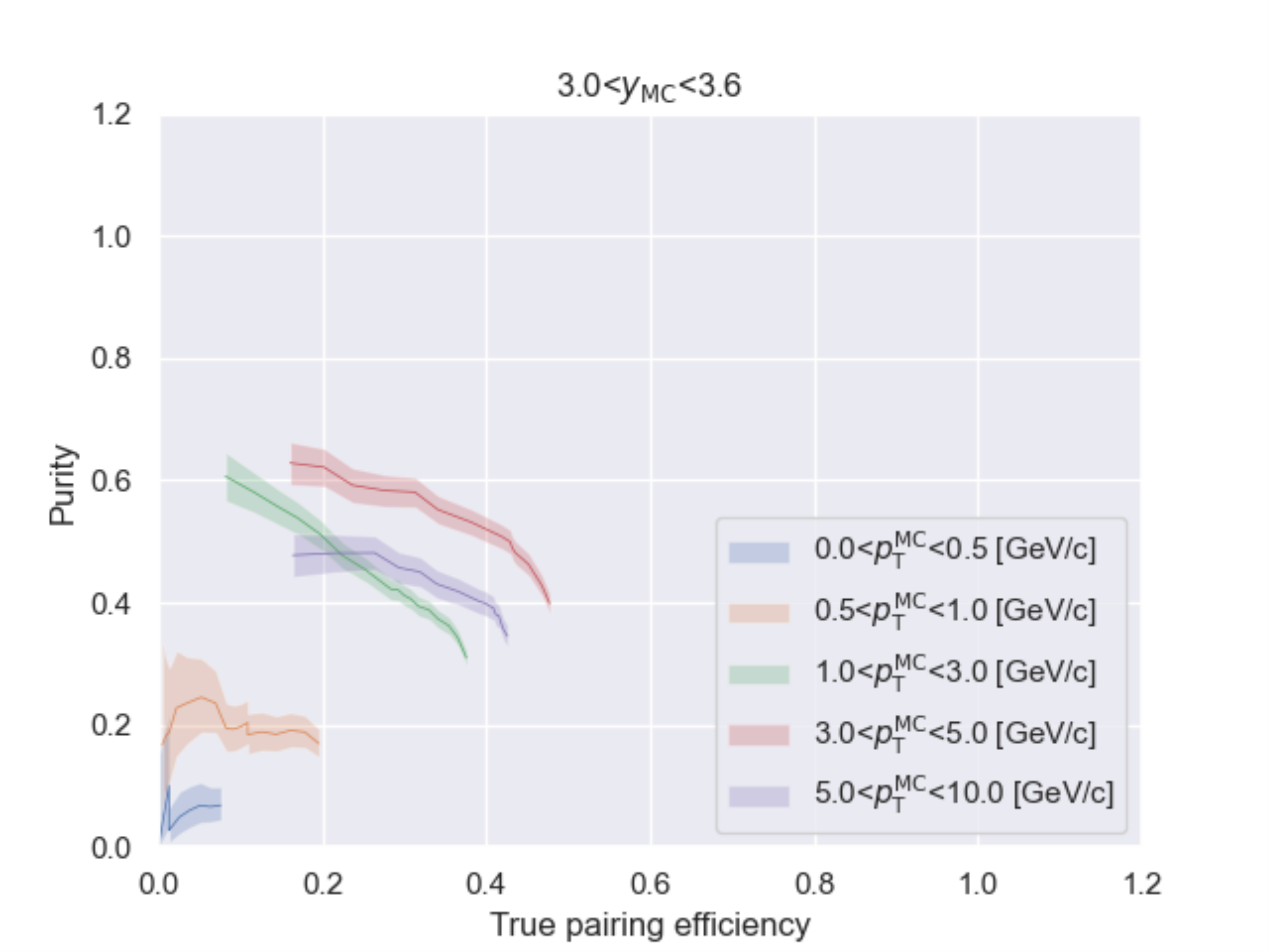




Performance of ϕ-meson reconstruction PbPb @ 5 TeV (MB) + ϕ-meson data

- NN with 8 layers (1000 epochs)
- Trained with 2800229 samples, correct : wrong = 5039 : 2795190
- Matching plane z = -77.5 cm

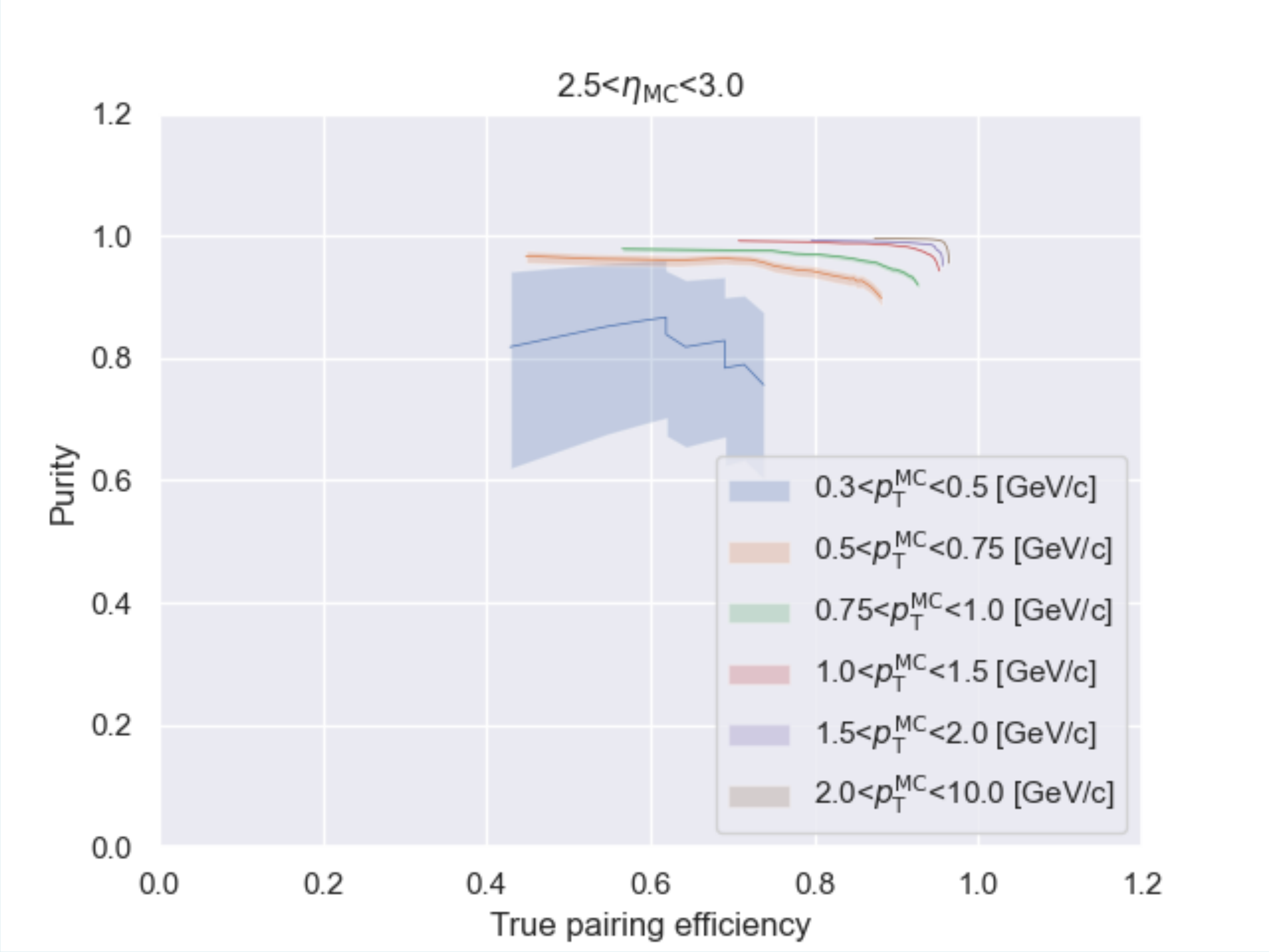


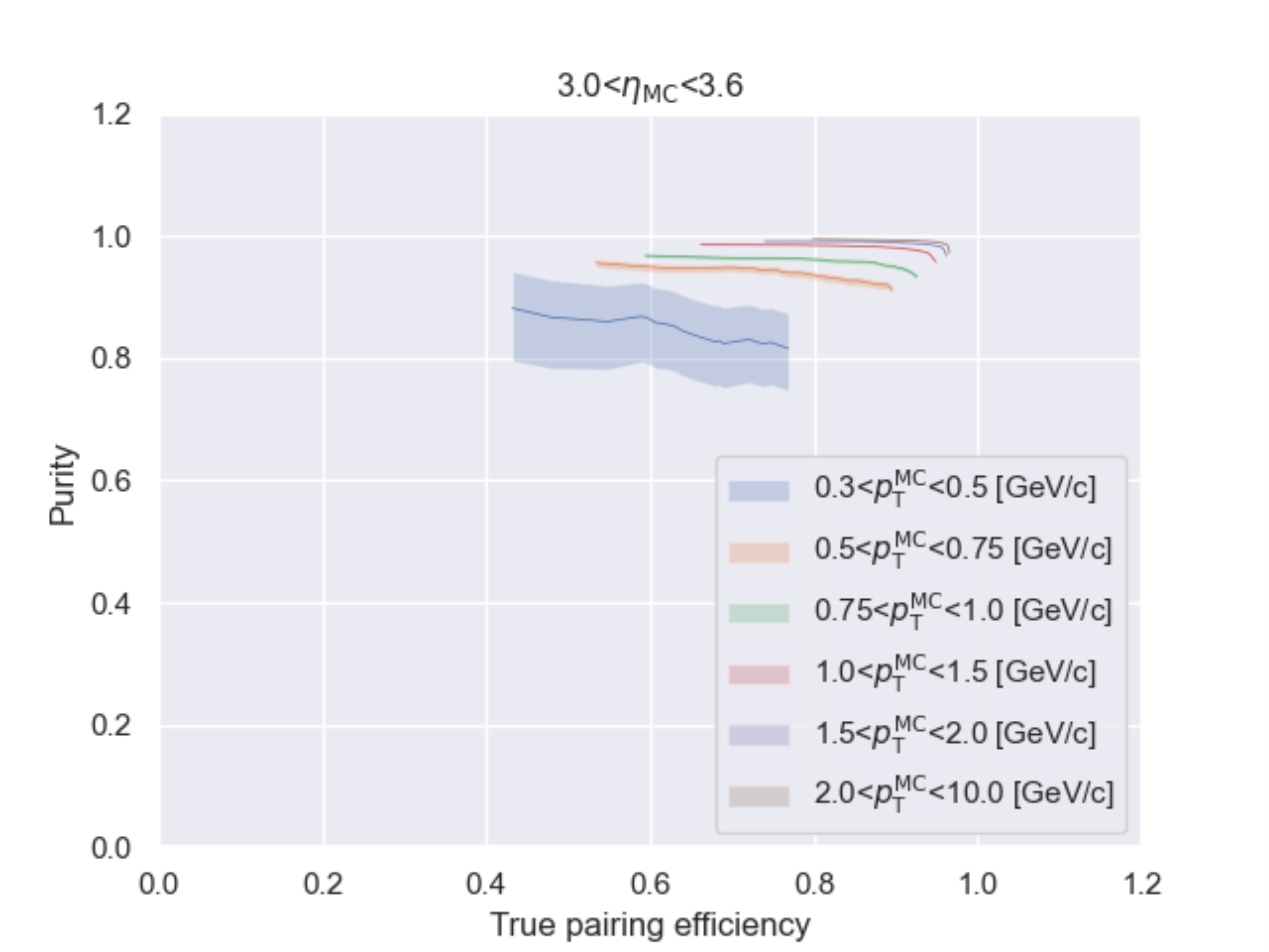


Matching plane $z = -505$ cm

Performance of muon track pp @ 13.6 TeV (MB) + Quarkonia data

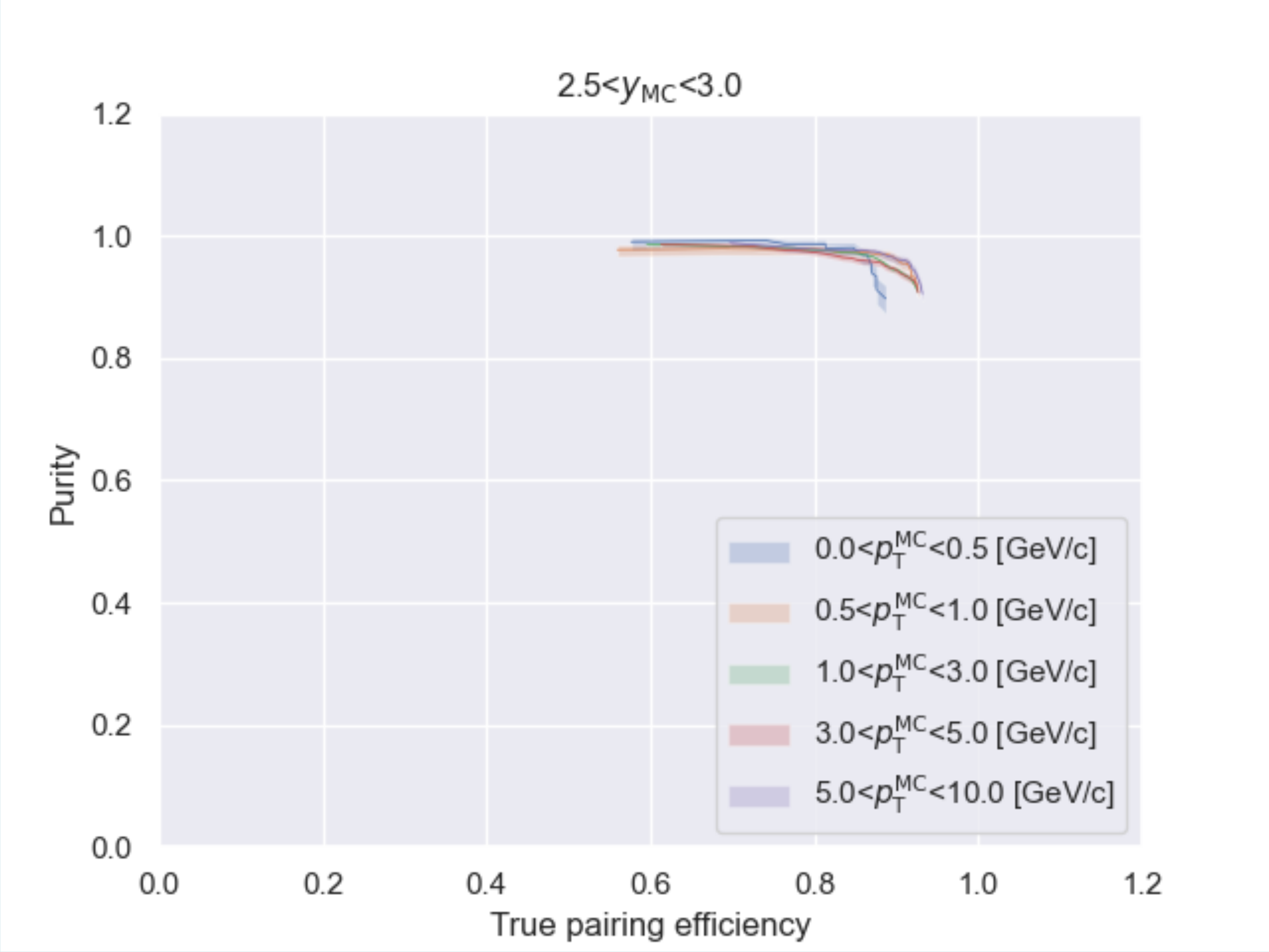
- NN with 8 layers (1000 epochs)
- Trained with 505447 samples, correct : wrong = 23681 : 481766
- Matching plane z = -505 cm

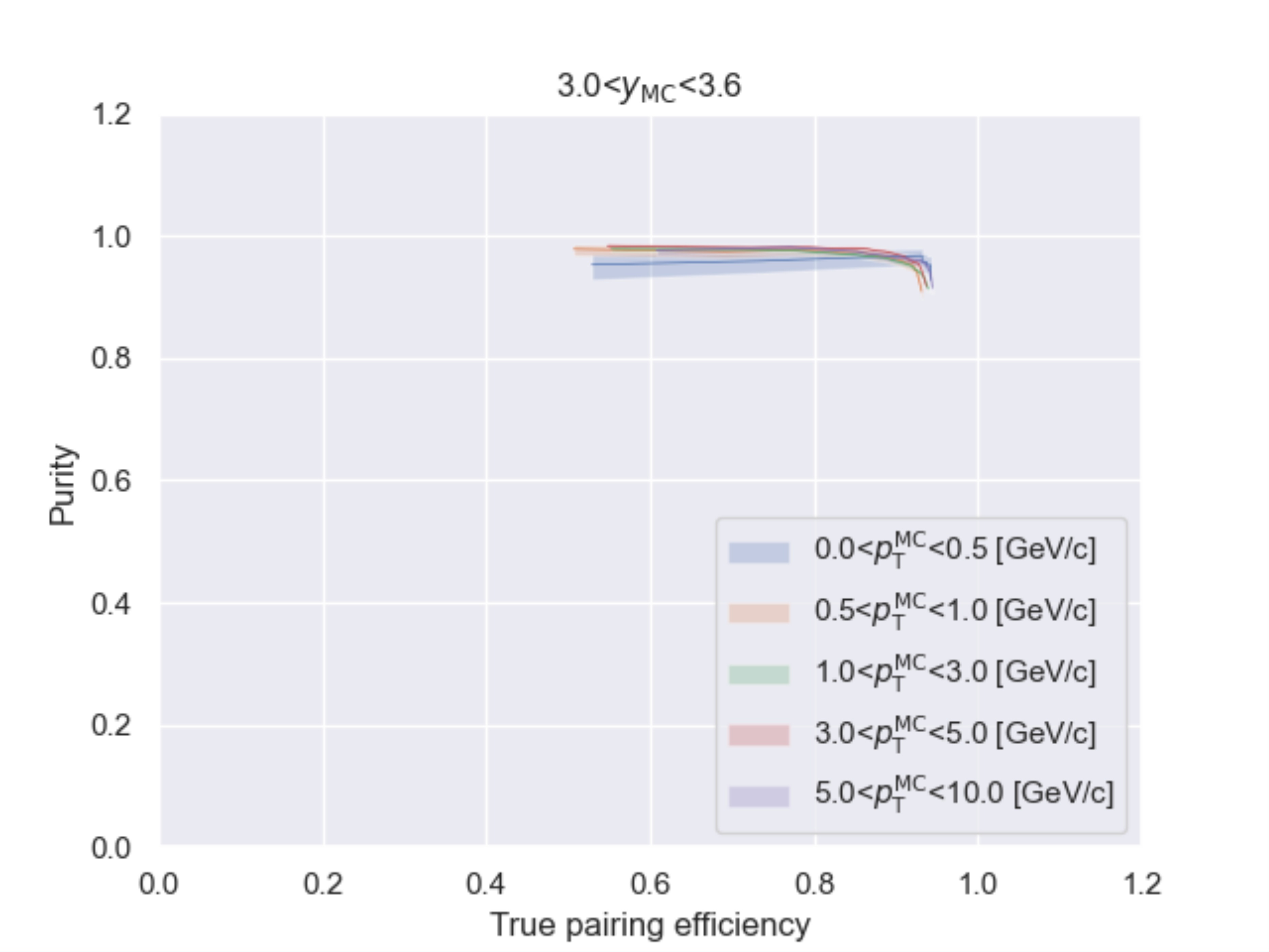




Performance of J/ψ reconstruction pp @ 13.6 TeV (MB) + Quarkonia data

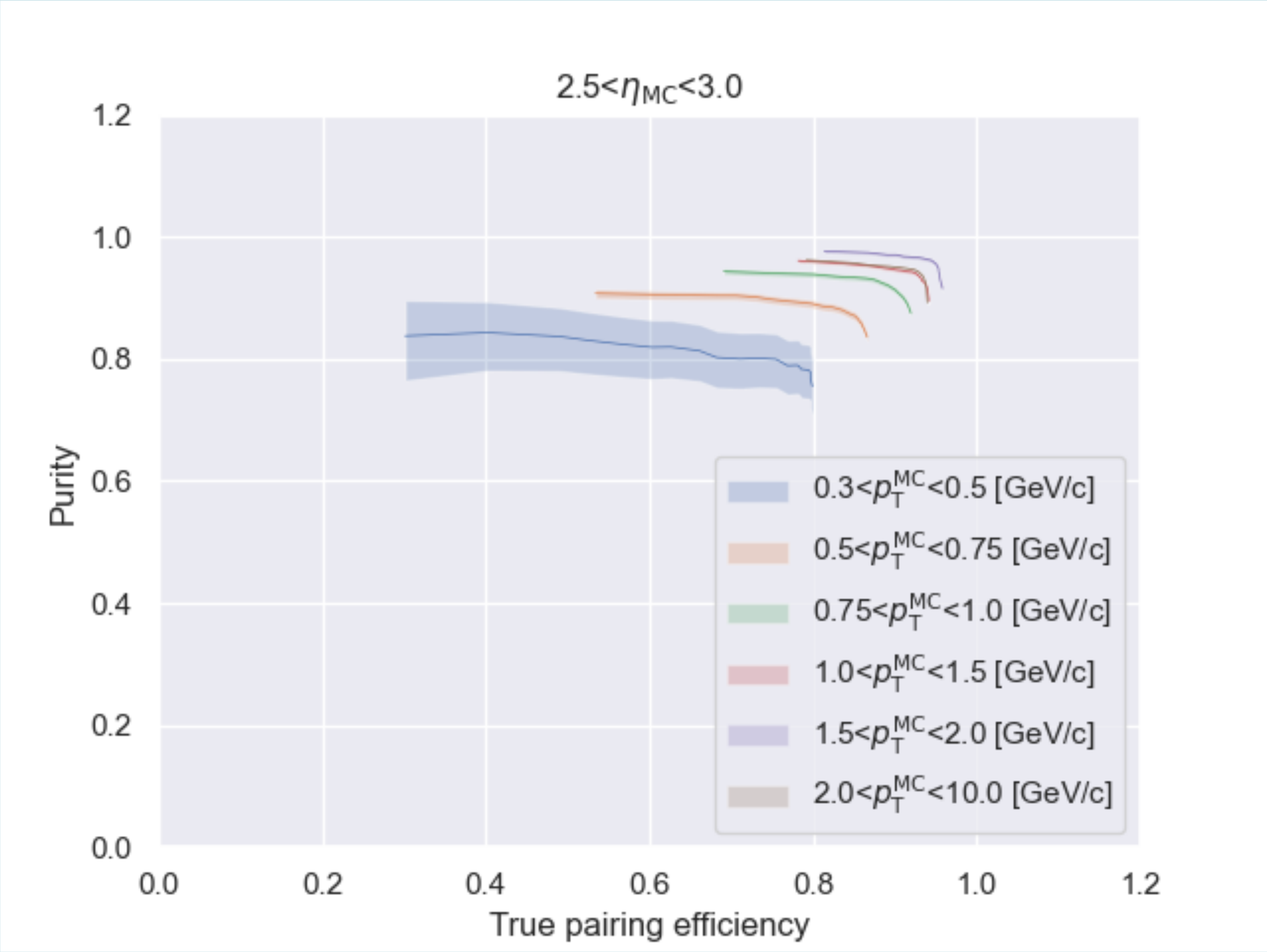
- NN with 8 layers (1000 epochs)
- Trained with 505447 samples, correct : wrong = 23681 : 481766
- Matching plane z = -505 cm

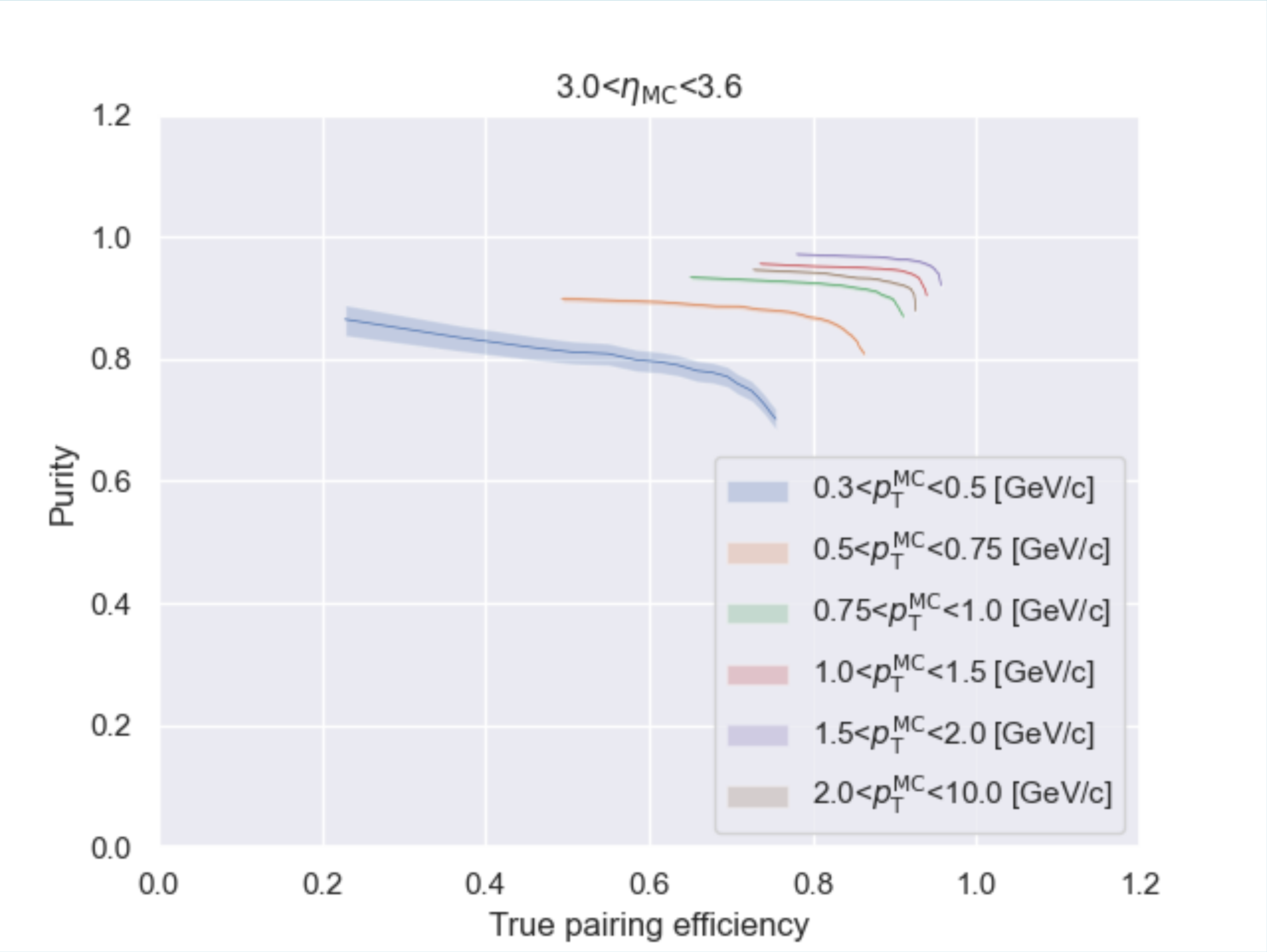




Performance of muon track
pp @ 13.6 TeV (MB) + ϕ-meson data

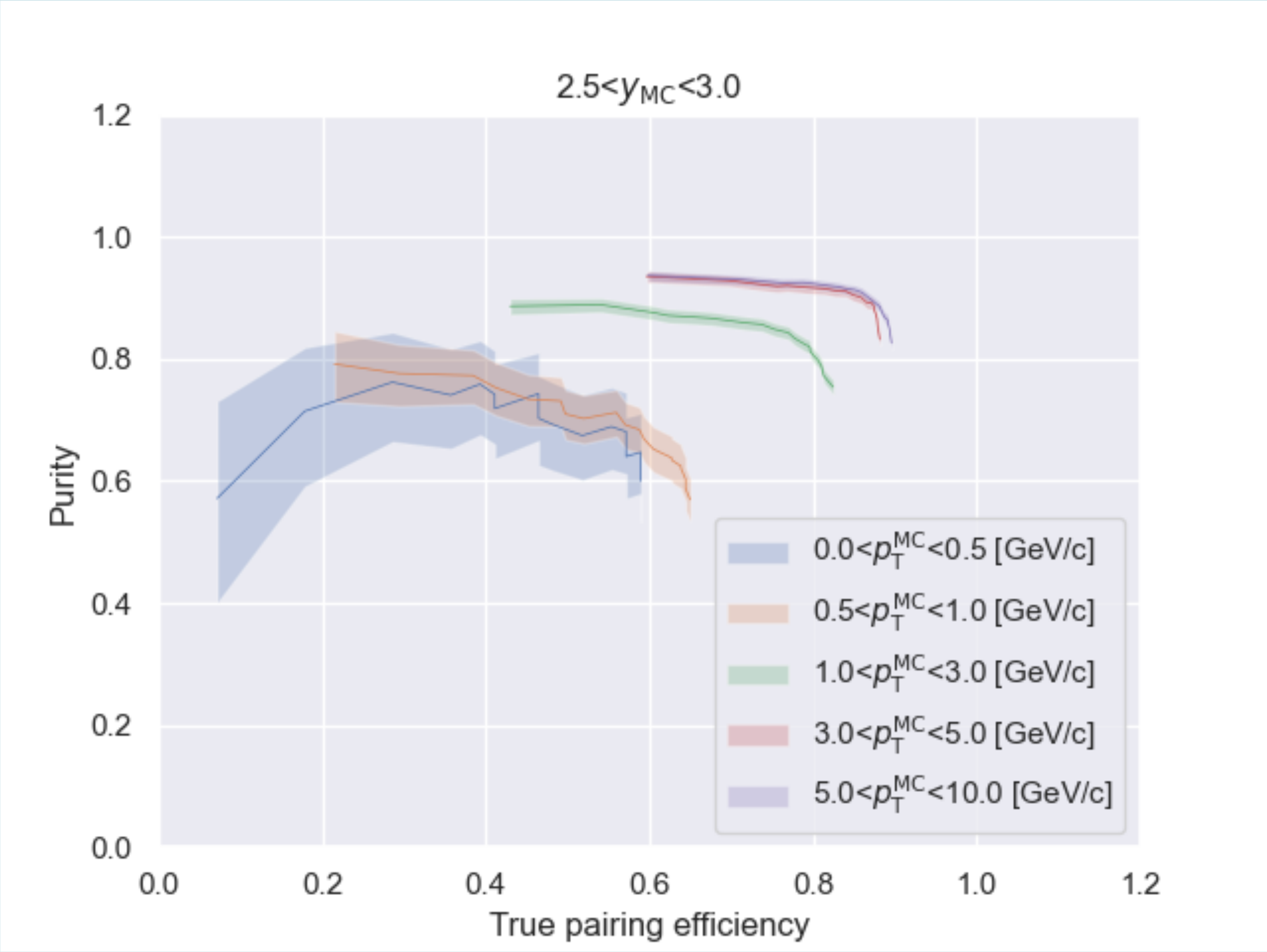
- NN with 8 layers (1000 epochs)
- Trained with 3127314 samples, correct : wrong = 58289 : 3069025
- Matching plane z = -505 cm

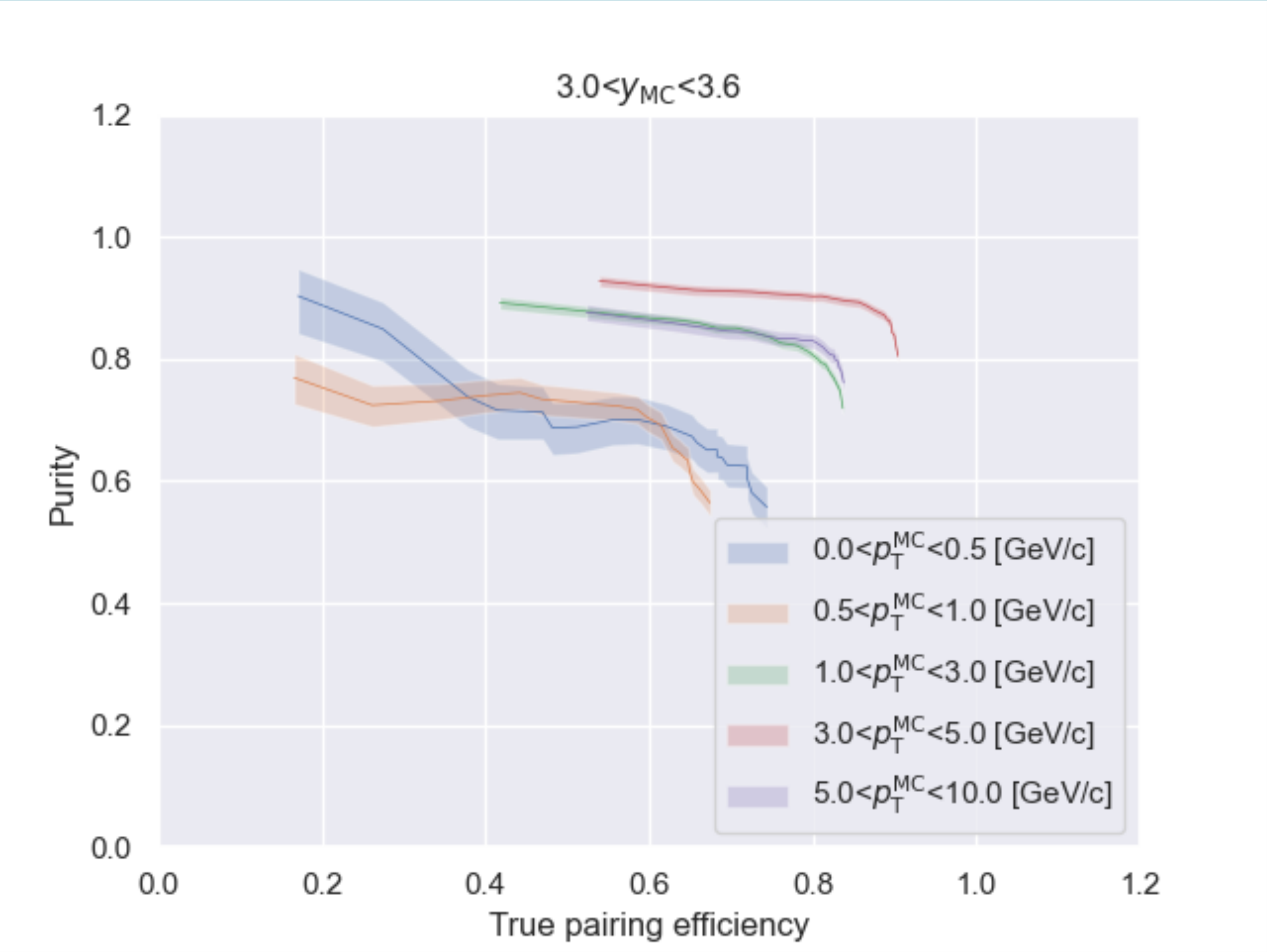




Performance of ϕ-meson reconstruction pp @ 13.6 TeV (MB) + ϕ-meson data

- NN with 8 layers (1000 epochs)
- Trained with 3127314 samples, correct : wrong = 58289 : 3069025
- Matching plane z = -505 cm

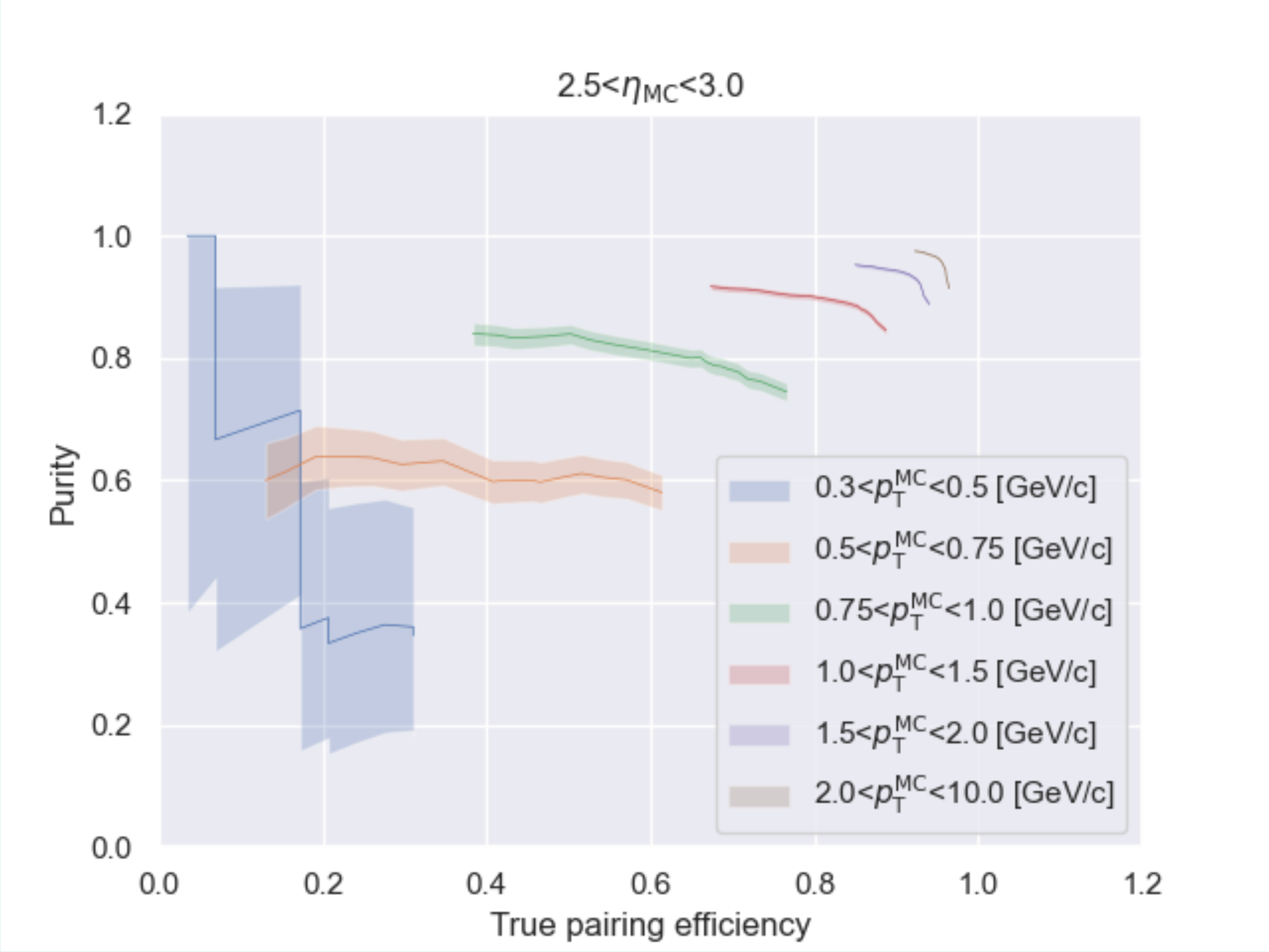


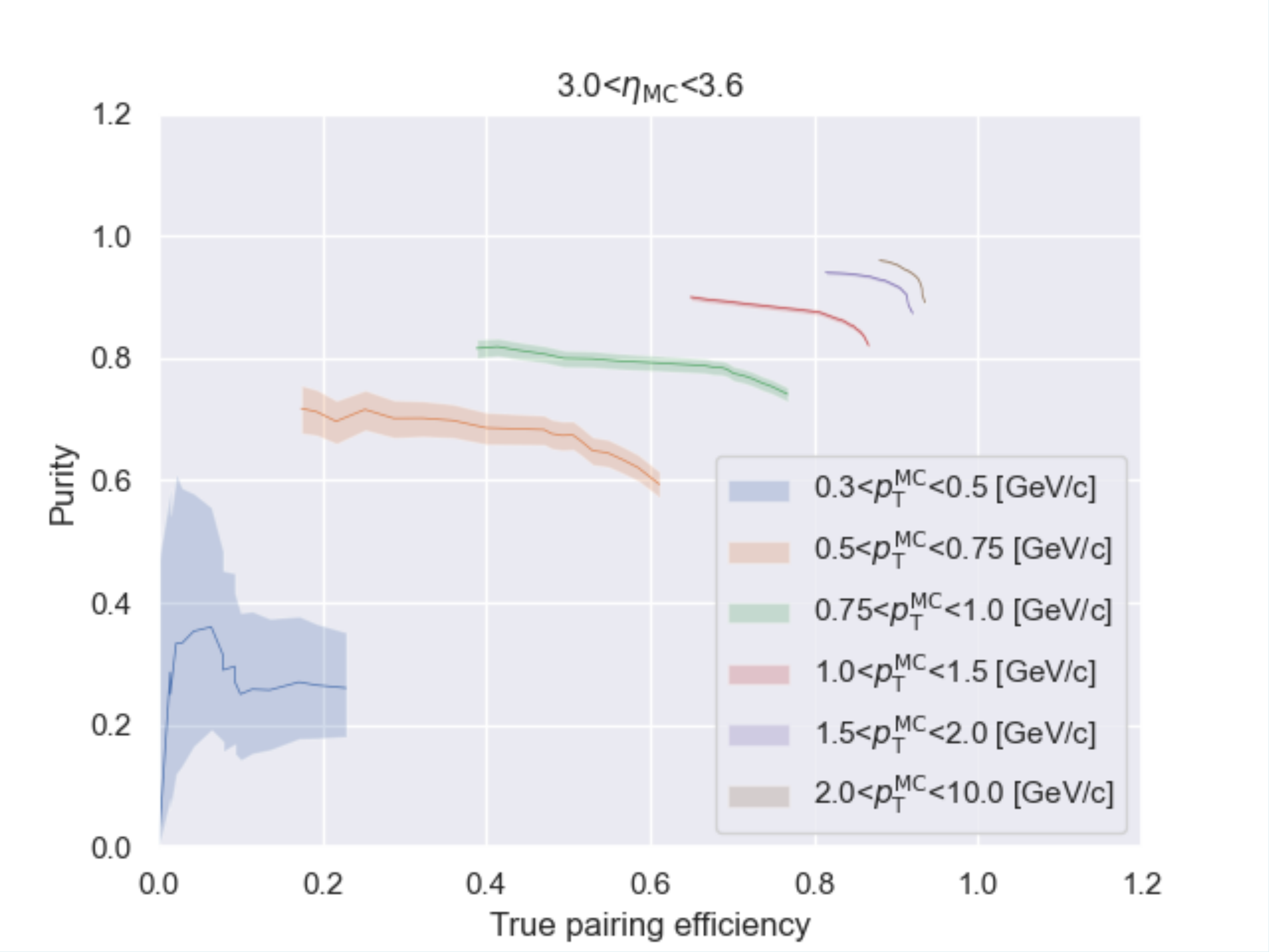


PbPb collisions

Performance of muon track
PbPb @ 5 TeV (MB) + Quarkonia data

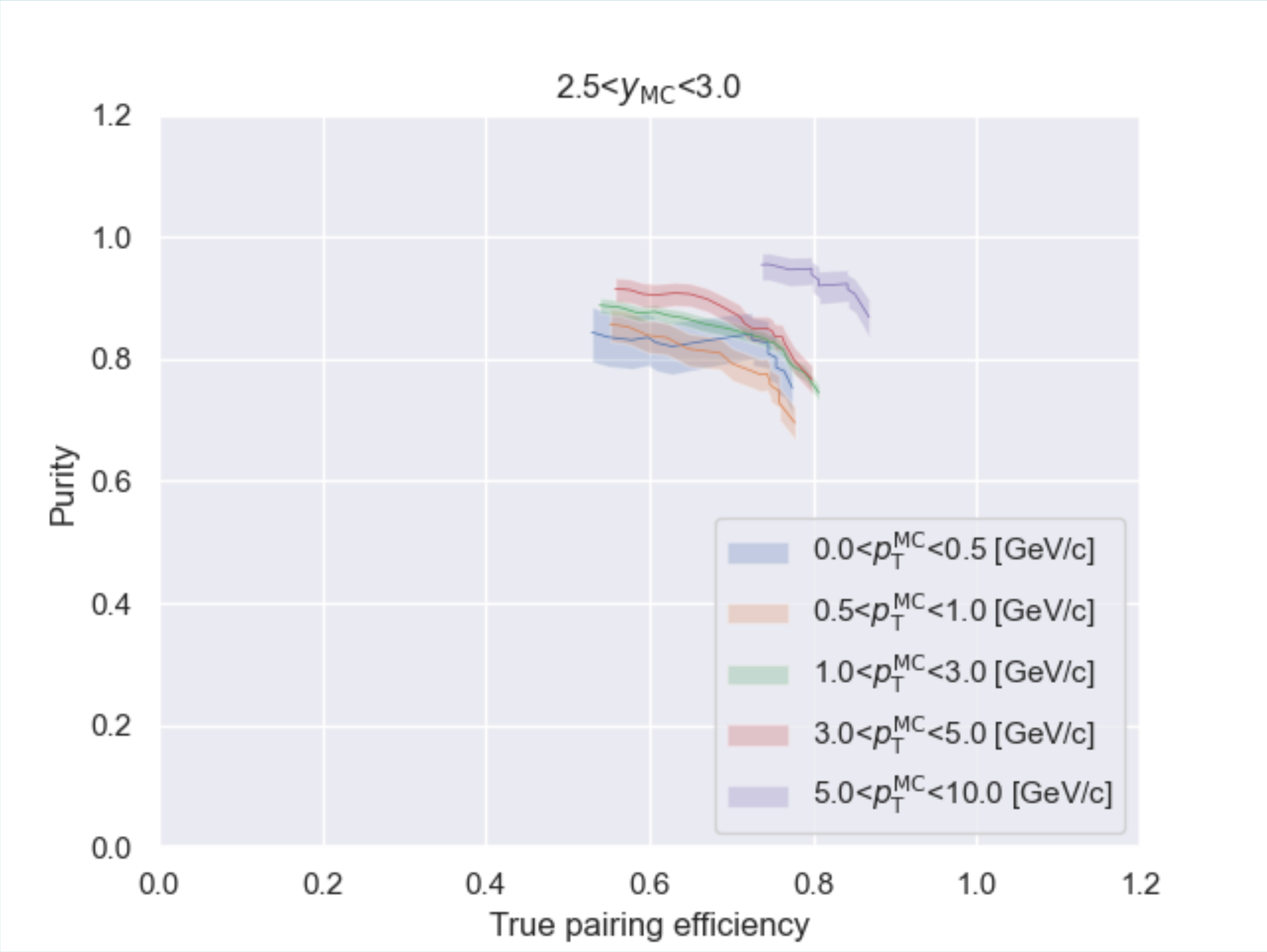
- NN with 8 layers (1000 epochs)
- Trained with 3094810 samples, correct : wrong = 13005 : 3081805
- Matching plane z = -505 cm

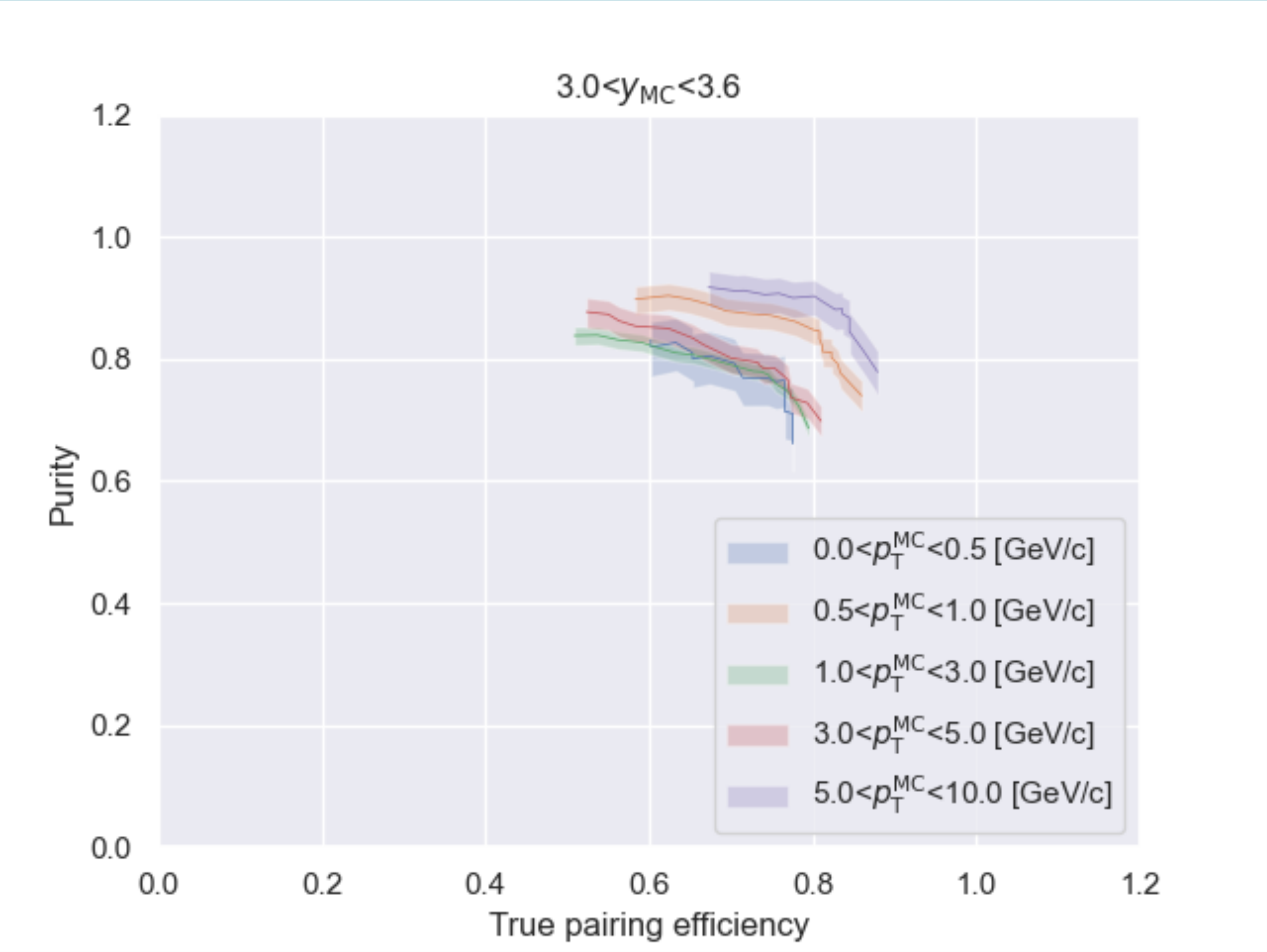




Performance of J/ψ reconstruction PbPb @ 5 TeV (MB) + Quarkonia data

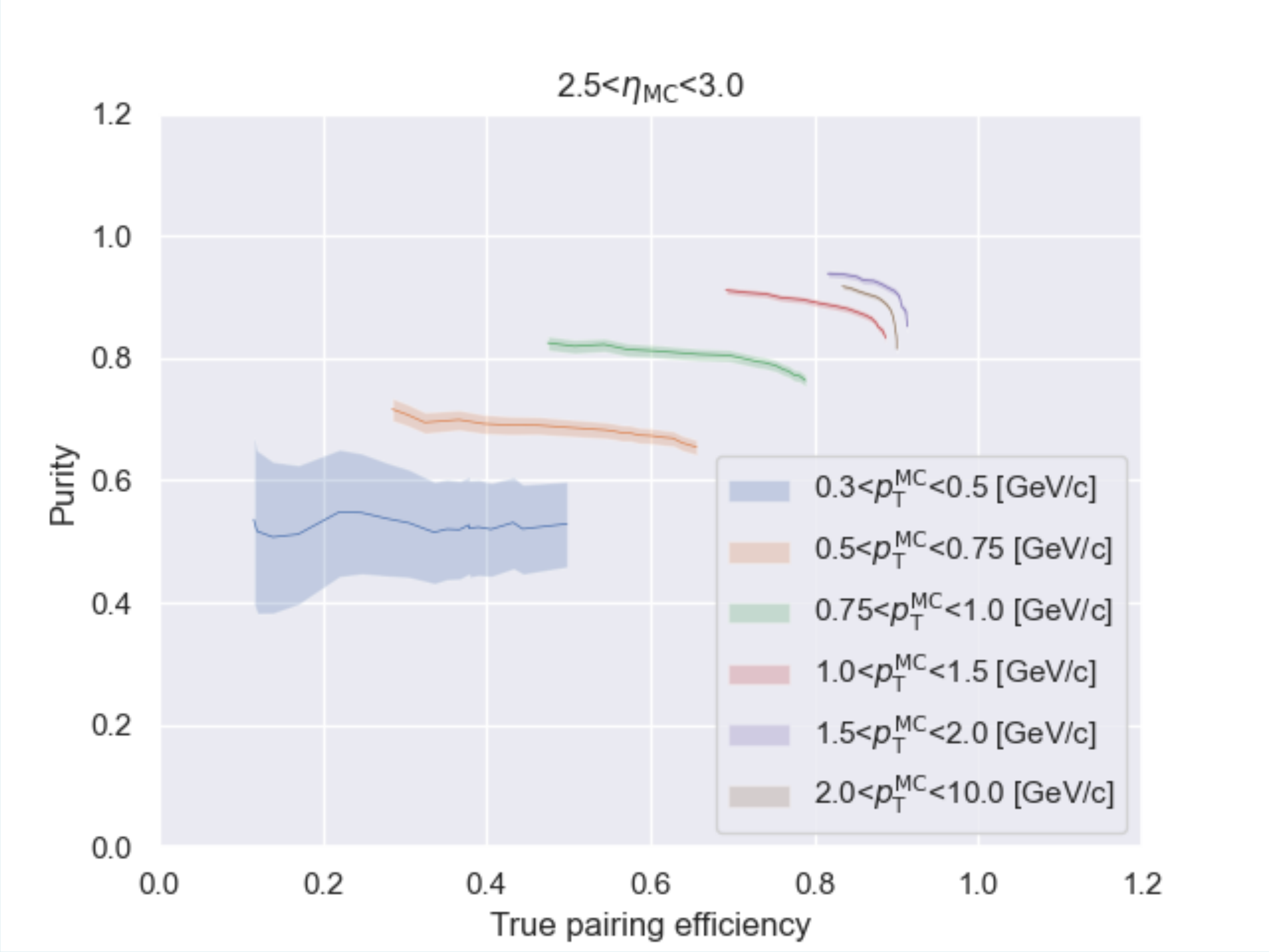
- NN with 8 layers (1000 epochs)
- Trained with 3094810 samples, correct : wrong = 13005 : 3081805
- Matching plane z = -505 cm

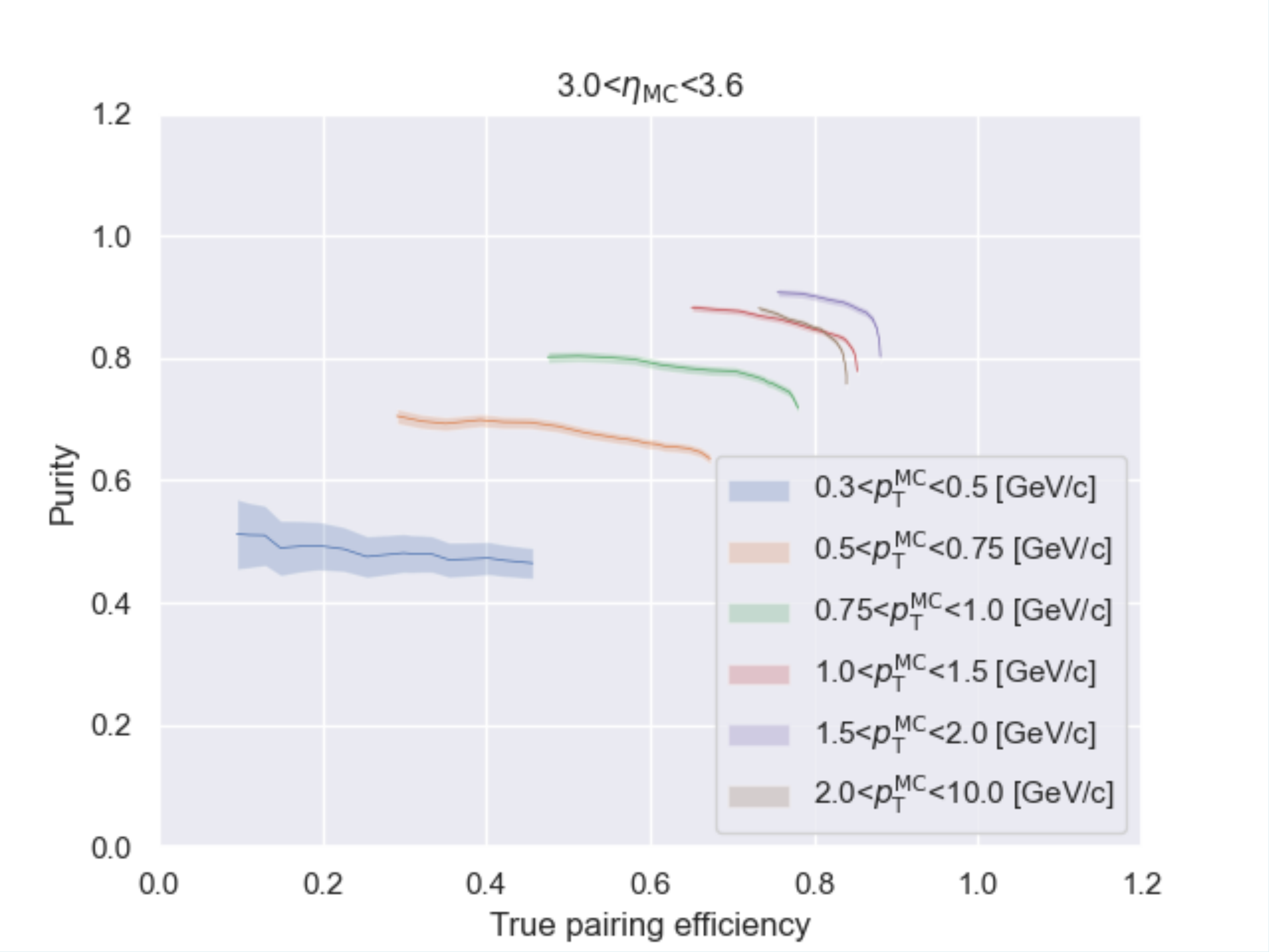




Performance of muon track
PbPb @ 5 TeV (MB) + ϕ-meson data

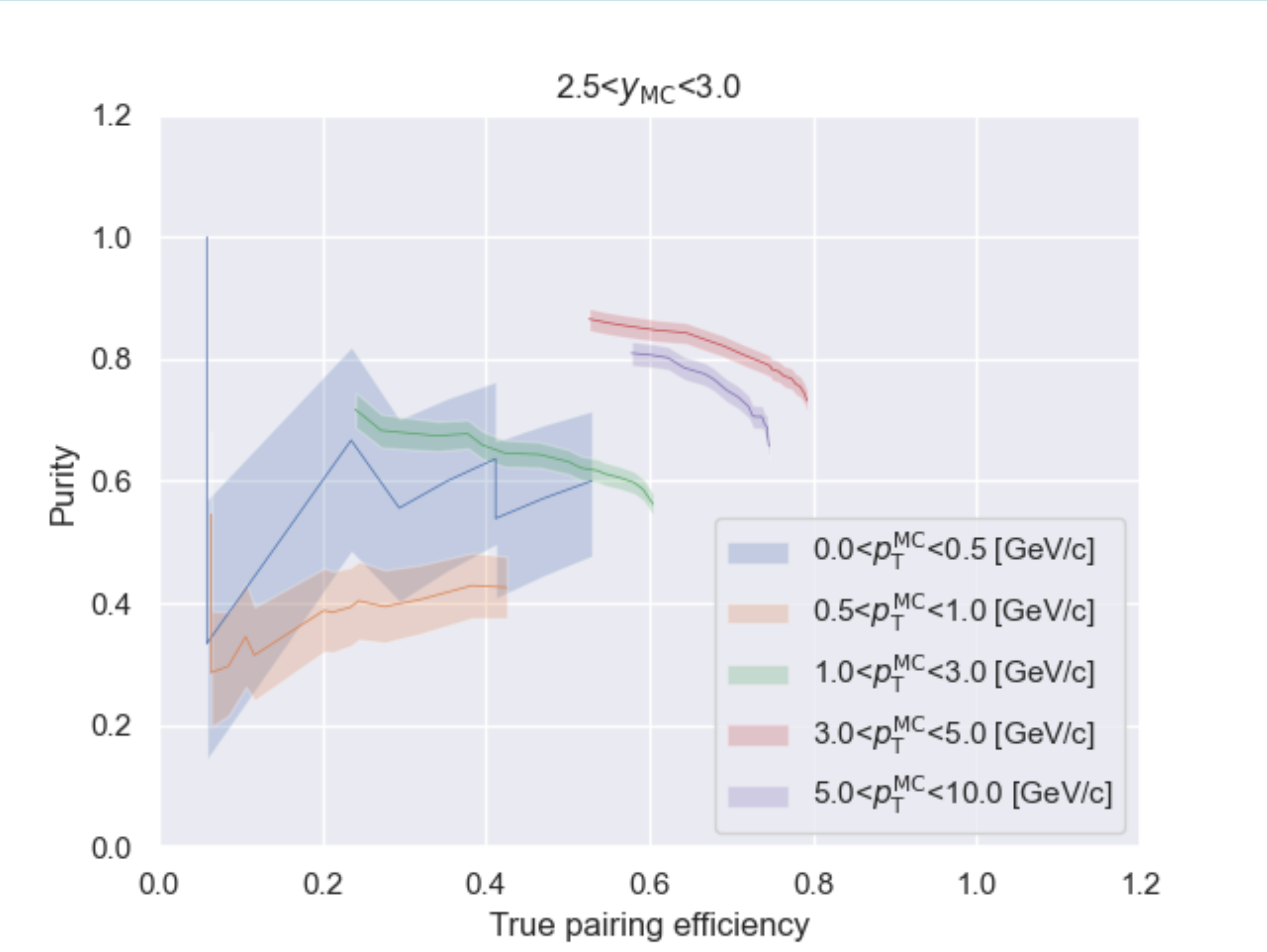
- NN with 8 layers (1000 epochs)
- Trained with 3115045 samples, correct : wrong = 12657 : 3102388
- Matching plane z = -505 cm

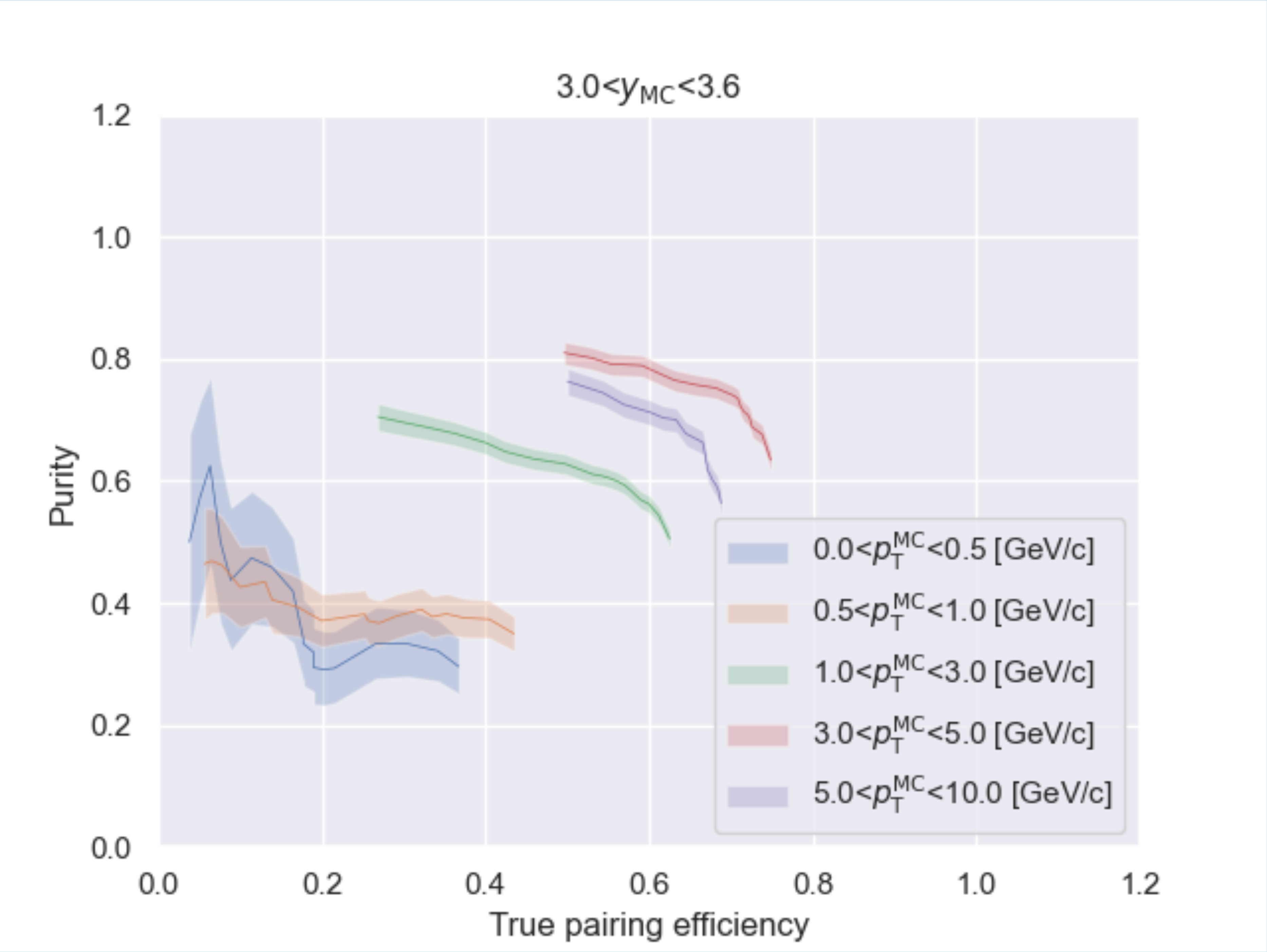




Performance of ϕ-meson reconstruction PbPb @ 5 TeV (MB) + ϕ-meson data

- NN with 8 layers (1000 epochs)
- Trained with 3115045 samples, correct : wrong = 12657 : 3102388
- Matching plane z = -505 cm

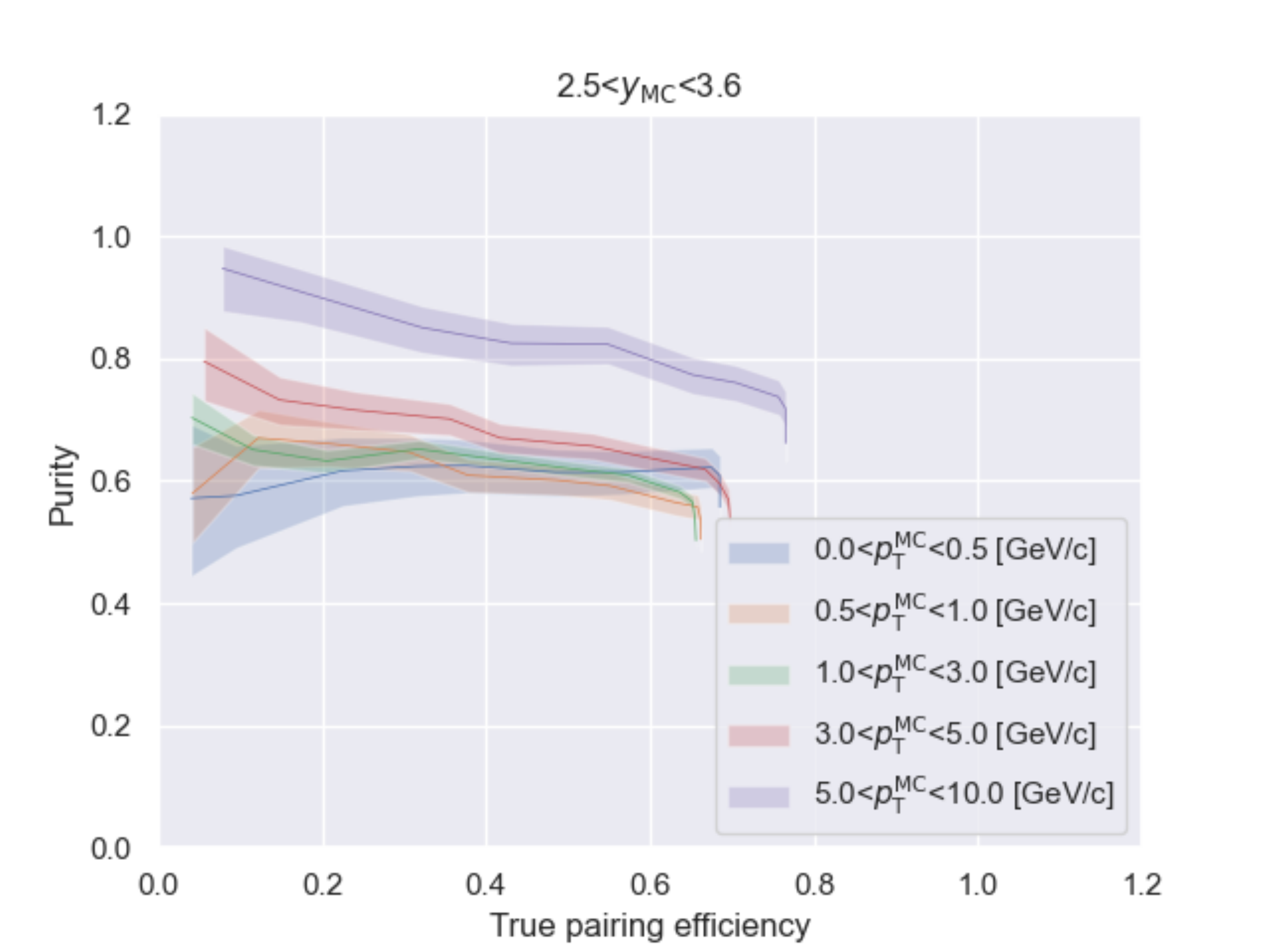




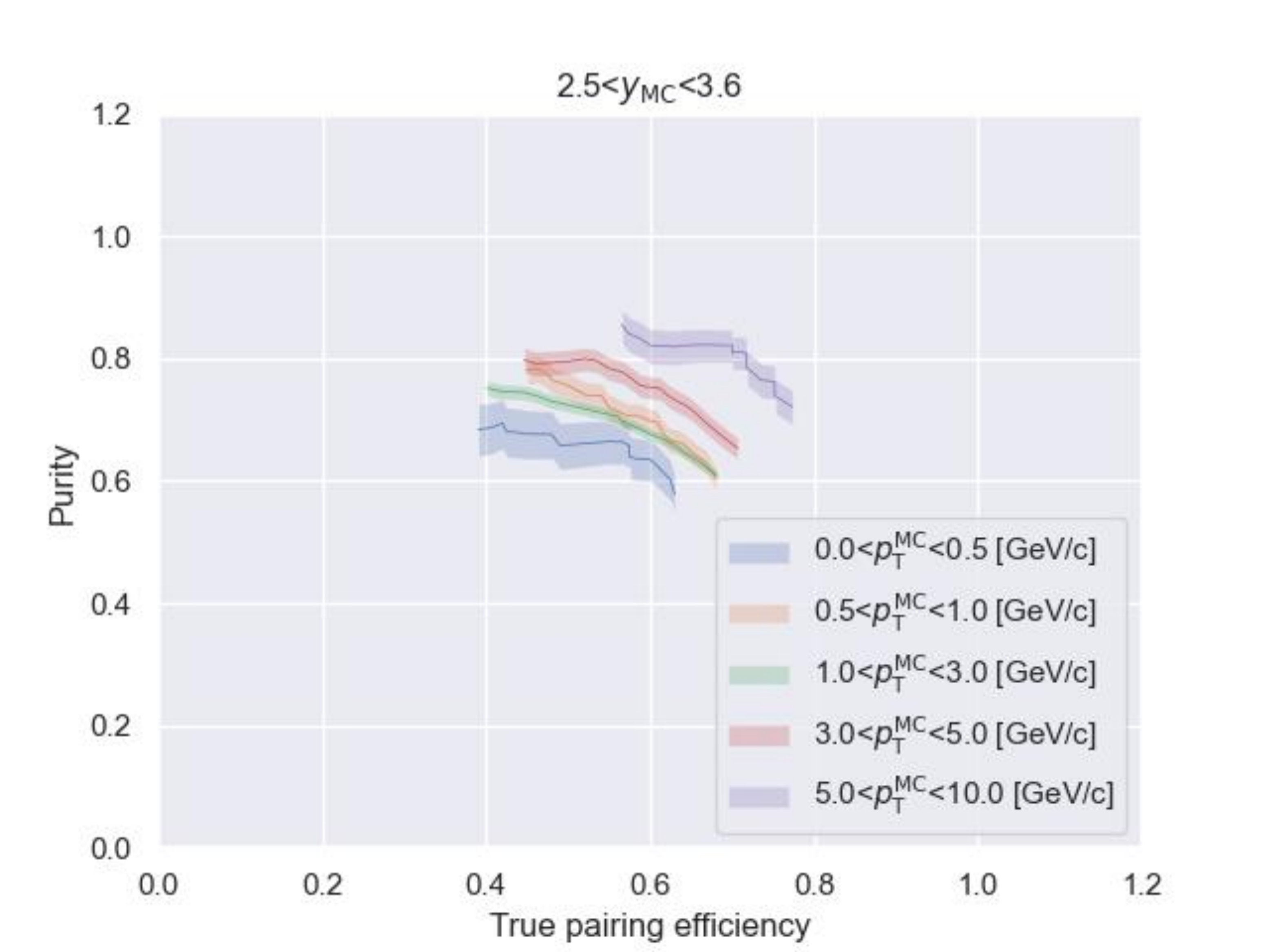
Comparison of J/ψ reconstruction performance PbPb @ 5 TeV (MB)

- The best ML performance is z=505 cm

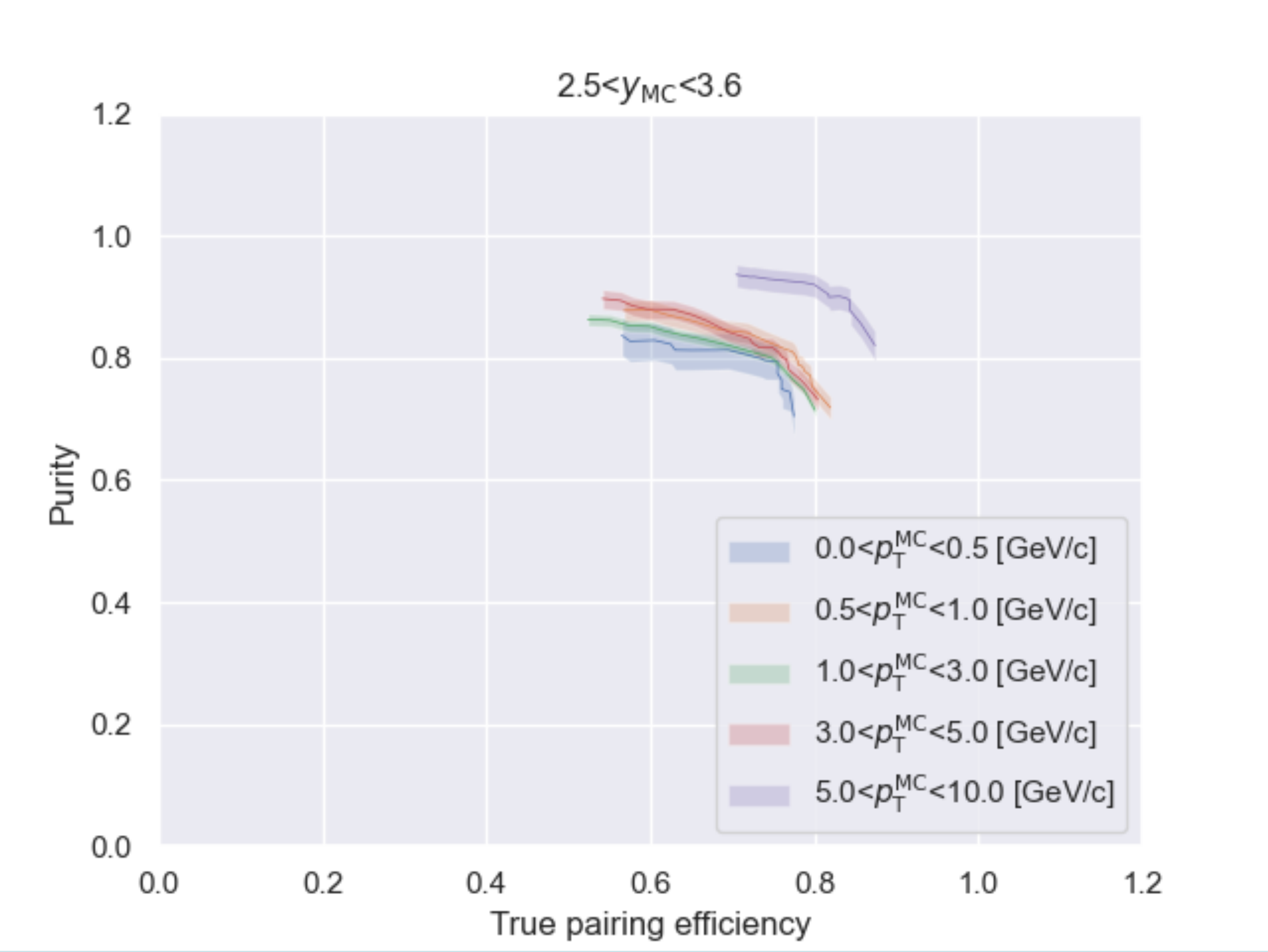
Matching-chi2 MatchALL @ z=77.5 cm



ML @ z=77.5 cm



ML @ z=505 cm

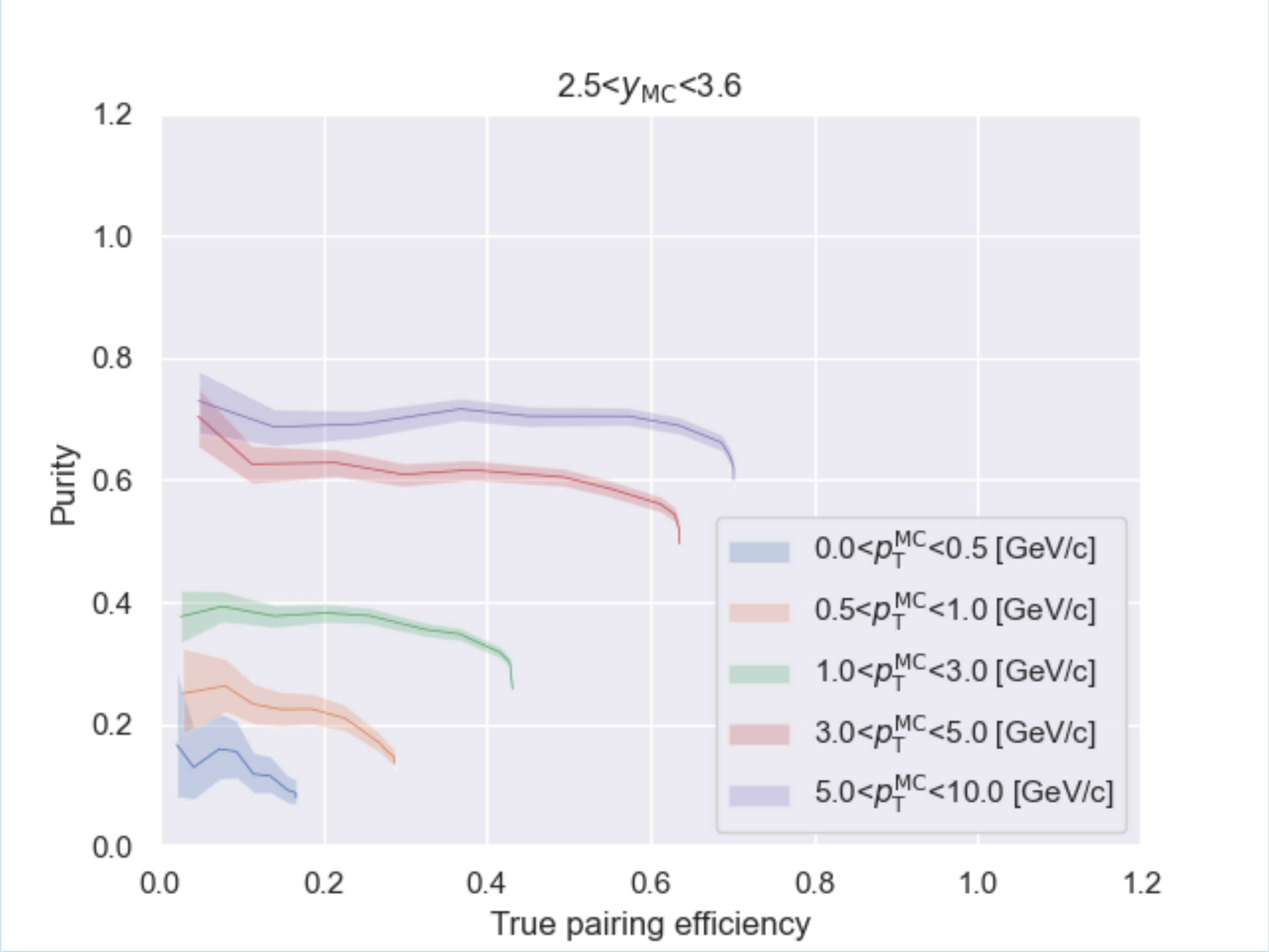


- Down to 0 GeV J/ψ can be measure with 80% purity and >75% efficiency by ML @ z=505 cm
  - Essential to measure B-meson energy loss and flow down to 0 GeV/c

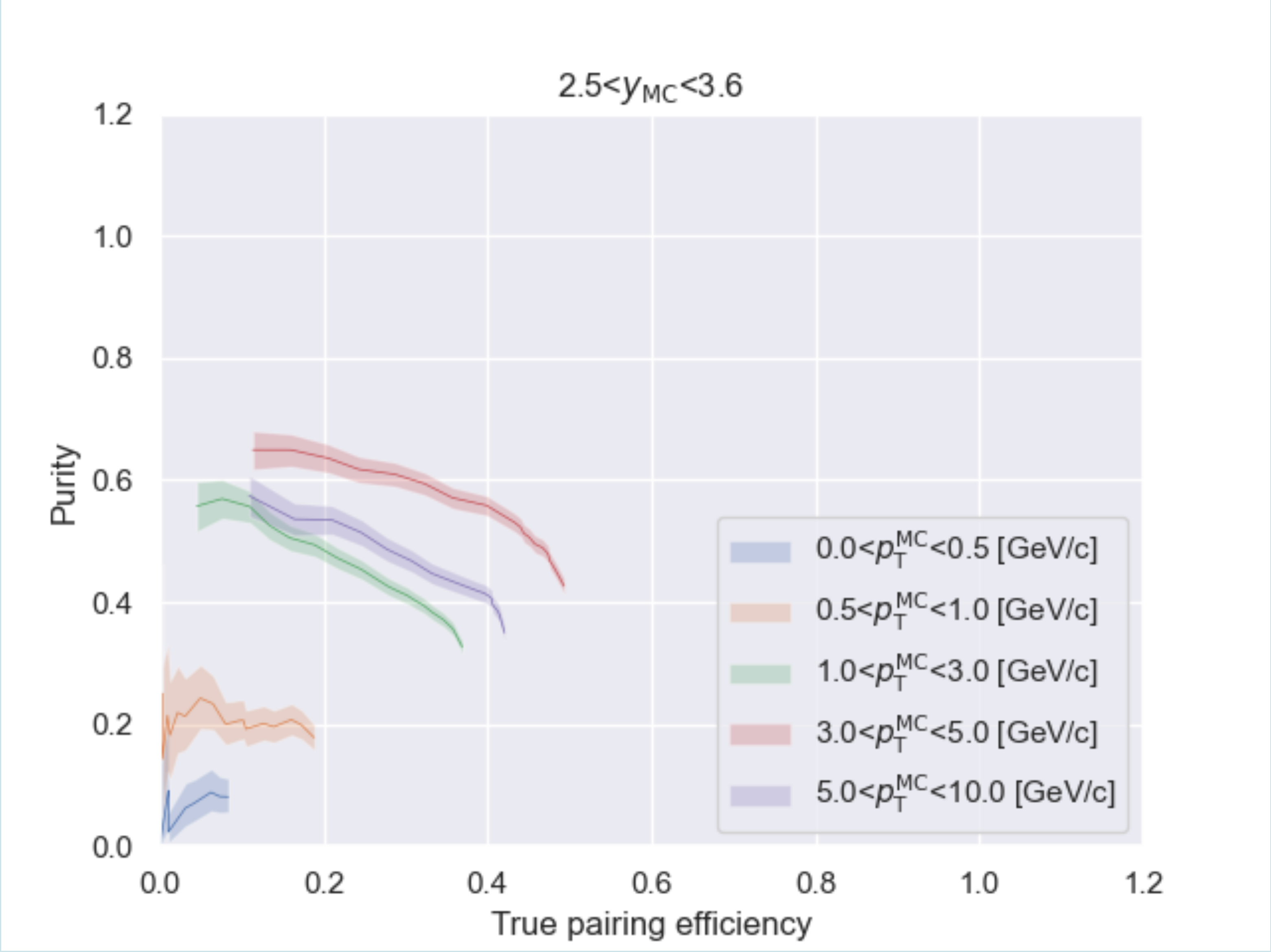
Comparison of ϕ-meson reconstruction performance PbPb @ 5 TeV (MB)

- The best ML performance is z=505 cm

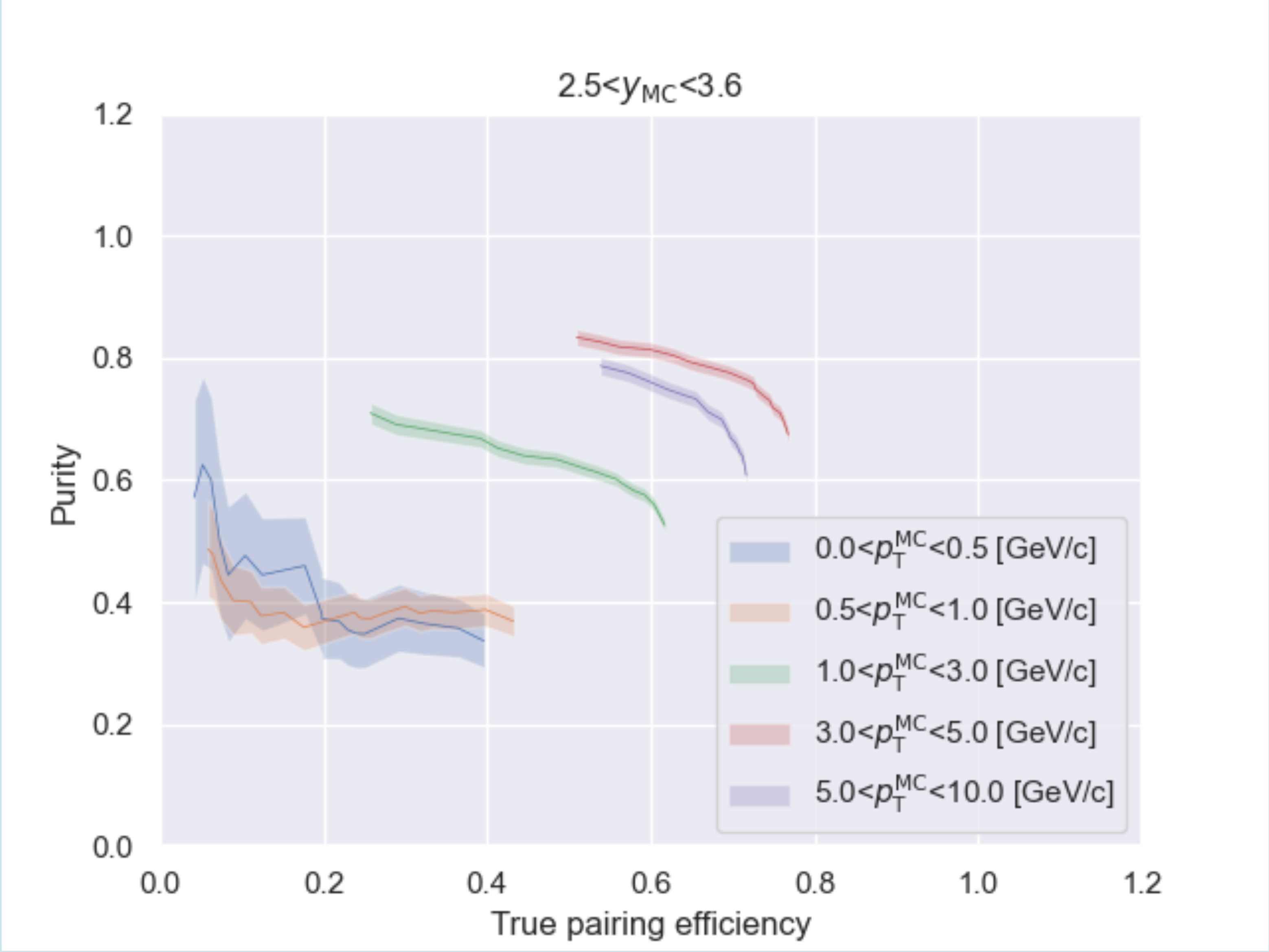
Matching-chi2 MatchALL @ z=77.5 cm



ML @ z=77.5 cm



ML @ z=505 cm



- Below 1 GeV/c ϕ-meson achieves 40% purity, but the other method is less than 20%
- It would be just barely good enough to observe ω and ϕ-meson CSR phenomena.

Summary and outlook

- NN on PyTorch has been applied to MFT-MCH track matching
  - Training time is not long when GPU is used
  - Mini batch training should be implemented to increase statistics
- Compared global muon track reconstruction performance (MFT-MCH track matching)
  - Matching-chi2 with all parameters @ -77.5 cm, Pytorch NN @ -77.5 cm and @ -505 cm
- J/ψ reconstruction
  - Matching-chi2 method is expected to be a good result in pp collisions
  - Matching-chi2 and NN @ -77.5 cm results are not sufficient for measuring down to 0 GeV/c (60% purity with 60% efficiency) in PbPb collisions
  - NN @ -505 cm is expected to be good results
- ϕ-meson reconstruction
  - Matching-chi2 and NN @ -77.5 cm results are not sufficient for measuring low-p_T region (less than 20% purity and efficiency) in both pp and PbPb collisions
  - NN @ -505. cm is mandatory to observe CSR phenomena with ω and ϕ
- What next?
  - How to estimate the effect of material budget and magnetic field discrepancy between real data and MC?
  - How to control ML performance?

Next Steps for ML Matching

- The priority of retrieving training sample from real data is the highest for the ML matching

- The software preparation for the ML matching (MC→Real Data)
  1. Retrieve training sample from real data (C++ in O2/O2Physics)
  2. Convert ROOT base file to Python readable format (Python)
  3. Building model (Python)
  4. Convert model into onnx readable format (Python)
  5. Matching (inference) code with ONNXRuntime reading onnx file (C++ in O2Physics)

Frameworks

Caffe2
Chainer
Cognitive Toolkit

mxnet
PyTorch
PaddlePaddle

ML.NET
MathWorks®
dmlc XGBoost

scikit learn
K