EIC Tracking Update

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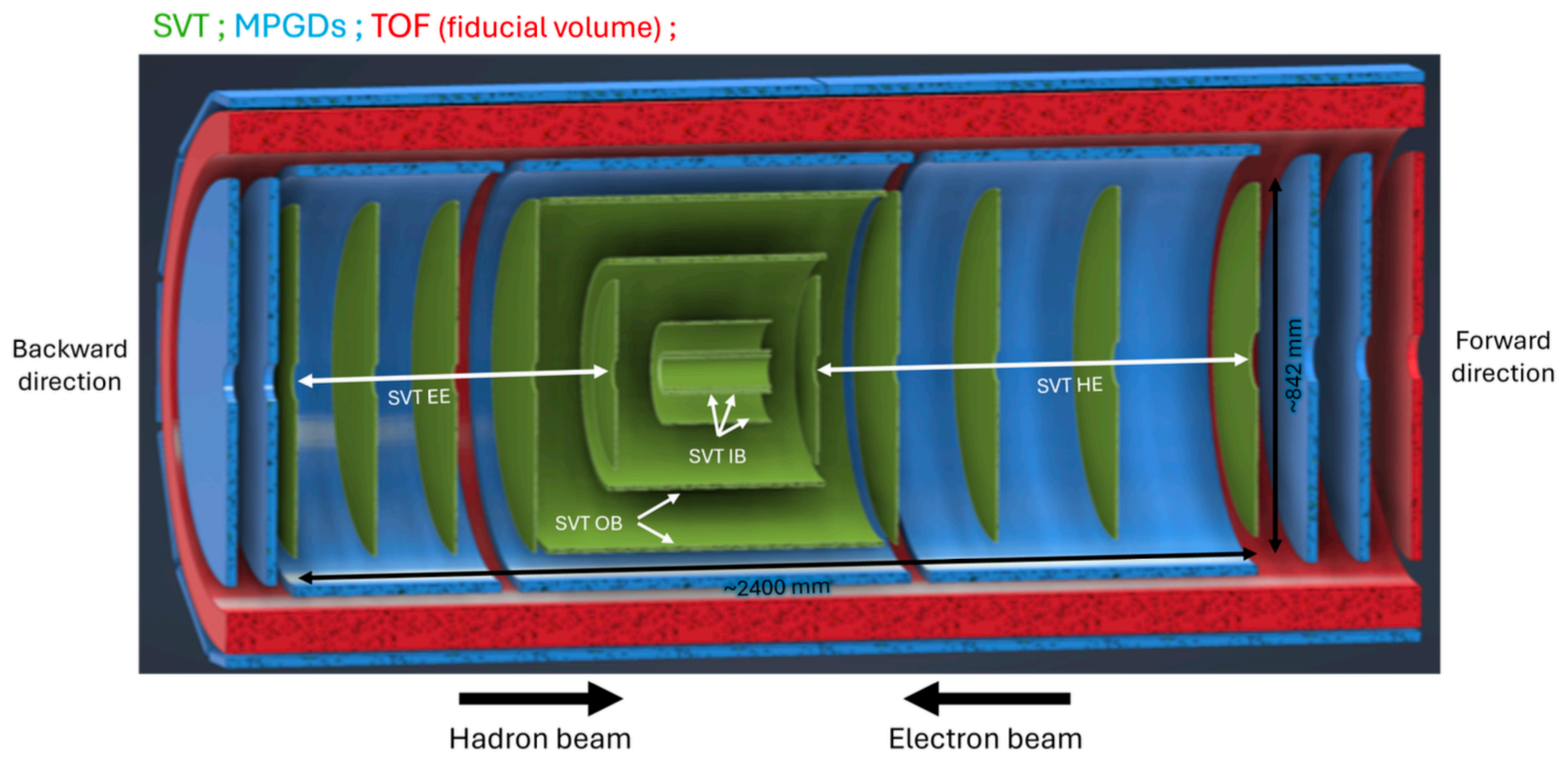
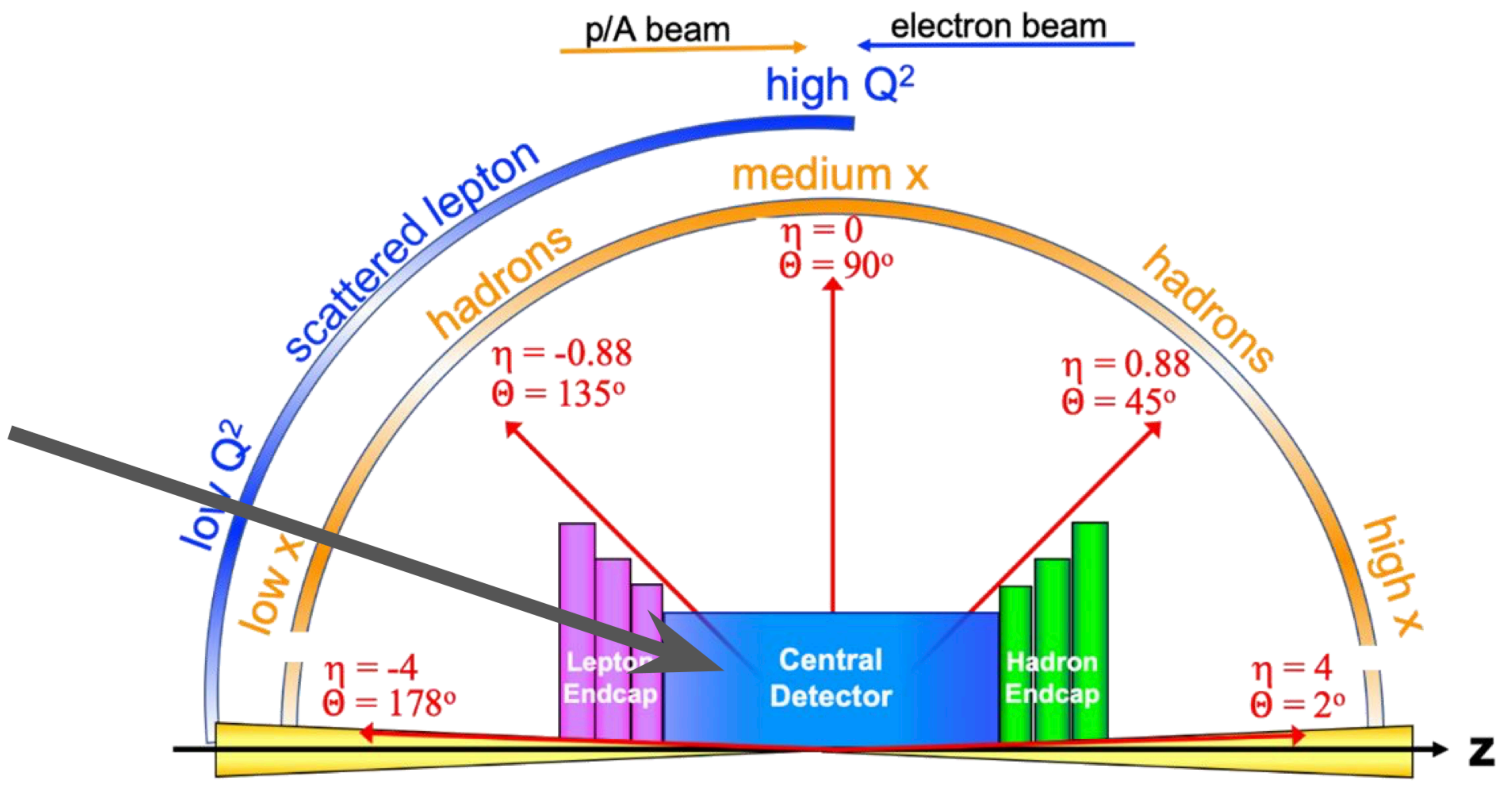
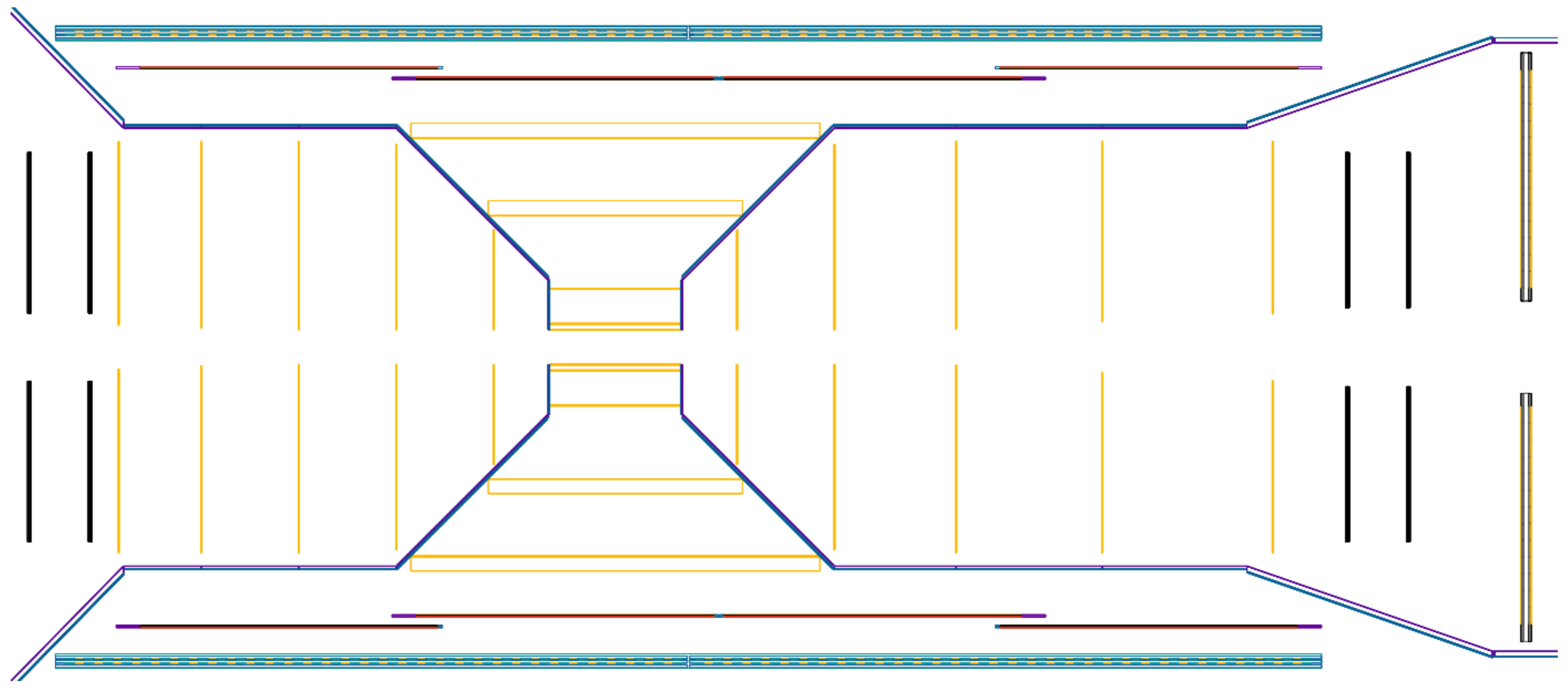




- ACTS(A Common Tracking Software) is mainly developed by folks at ATLAS and a few other collaborations.
- Designed to be experiment independent.
- sPHENIX is using it and we plan to use it for EIC as well.



Cross sectional View

Conceptual Overview of Tracking

Build the seeds (tracklets) : Seeds are made from three space points that can be in any of the 5 SVT Layers. Why 3 space points? : Because in a homogeneous magnetic field, 3 measurements perfectly describe the helical path of a charged particle.

- The seed tells the tracking algorithm where to look for additional measurements or space points to create a track spanning the whole detector.
- As you can imagine we can define a helix with any 3 measurements..combinatorial in nature! We need some constraints or cuts
- One such loose cut is the Min/Max z for the primary vertex (± 250 mm). The middle space point of a given seed can not be shared by any other seed.

ACTS seed finder and filter parameters

Parameter	Description	Value
bFieldInZ	z component of magnetic field	1.7 T
rMax	Maximum r value to look for seeds	440 mm
rMin	Minimum r value to look for seeds	33 mm
zMin	Minimum z value to look for seeds	-1500 mm
zMax	Maximum z value to look for seeds	1700 mm
beamPosX	Beam offset in x	0
beamPosY	Beam offset in y	0
deltaRMinTopSP	Min distance in r between middle and top SP in one seed	**10 mm**
deltaRMinBottomSP	Min distance in r between middle and bottom SP in one seed	**10 mm**
deltaRMaxTopSP	Max distance in r between middle and top SP in one seed	**200 mm**
deltaRMaxBottomSP	Max distance in r between middle and top SP in one seed	**200 mm**
collisionRegionMin	Min z for primary vertex	-250 mm
collisionRegionMax	Max z for primary vertex	250 mm
cotThetaMax	Cotangent of max theta angle	**27.29**
minPt	Min transverse momentum	100 MeV/cotThetaMax
maxSeedsPerSpM	Max number of seeds a single middle space point can belong to - 1	0
sigmaScattering	How many standard devs of scattering angles to consider	5
radLengthPerSeed	Average radiation lengths of material on the length of a seed	0.1
impactMax	Max transverse PCA allowed	3 mm
rMinMiddle	Min R for middle space point	20 mm
rMaxMiddle	Max R for middle space point	400 mm
bFieldMin	min B field	0.1

Conceptual Overview of Tracking

- The track seeds are then projected onto the tracking layers to pick up additional hits.
- Particle propagation through the magnetic field requires solving the corresponding differential equations of motion using numerical integration techniques. ACTS uses Runge-Kutta 4th order method.

Position Vector

$$\frac{d^2\vec{r}}{ds^2} = \frac{q}{p}\left(\frac{d\vec{r}}{ds} \times \vec{B}(\vec{r})\right) = f(s, \vec{r}, \vec{T}), \qquad \vec{T} \equiv \frac{d\vec{r}}{ds},$$

Path element

Tangent Vector

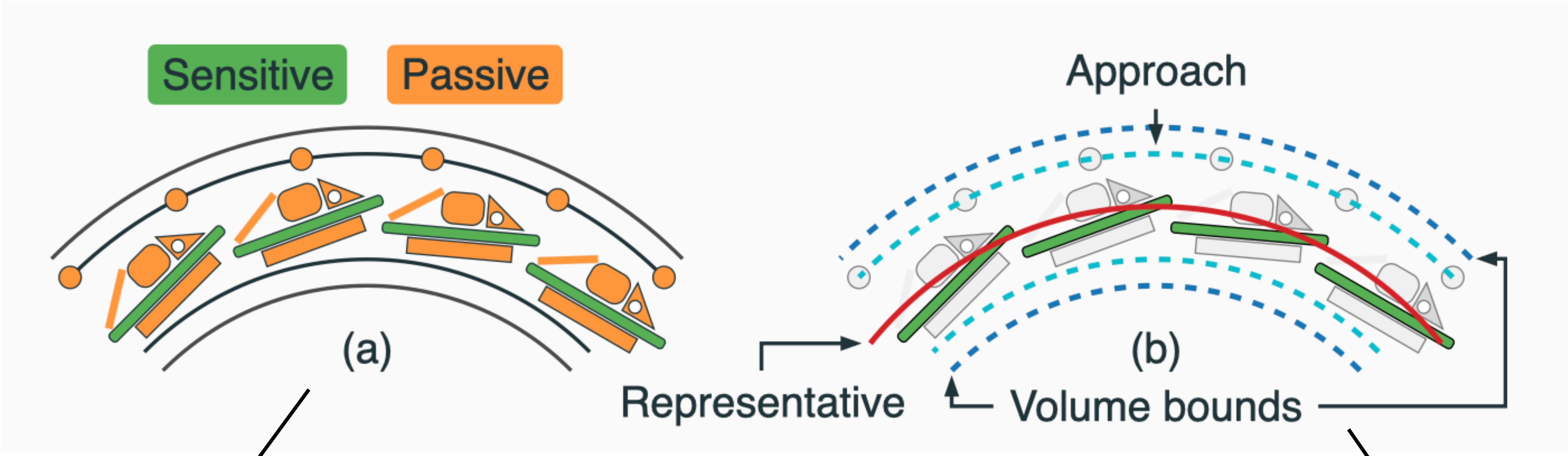
Numerically solving this equation requires initial conditions.

- An initial position vector
- The tangent to the initial position vector
- The momentum magnitude

SEED!

Conceptual Overview of Tracking

- Track propagation also requires taking into account any material effects i.e. Energy Loss, Multiple scattering etc!
- ACTS uses a simplified geometry modeling for the passive elements.



Passive elements could be the readout or the cooling elements that accounts for the material effects

This detailed geometry modeling is absolutely necessary for simulations using tools like Geant4

For reconstruction frameworks: A detailed geometry for sensitive elements is still required (to perform a transformation from the local measurements coordinates to the global ones) but a detailed modeling of passive elements is unnecessary. Geometry for the passive elements is approximated instead!

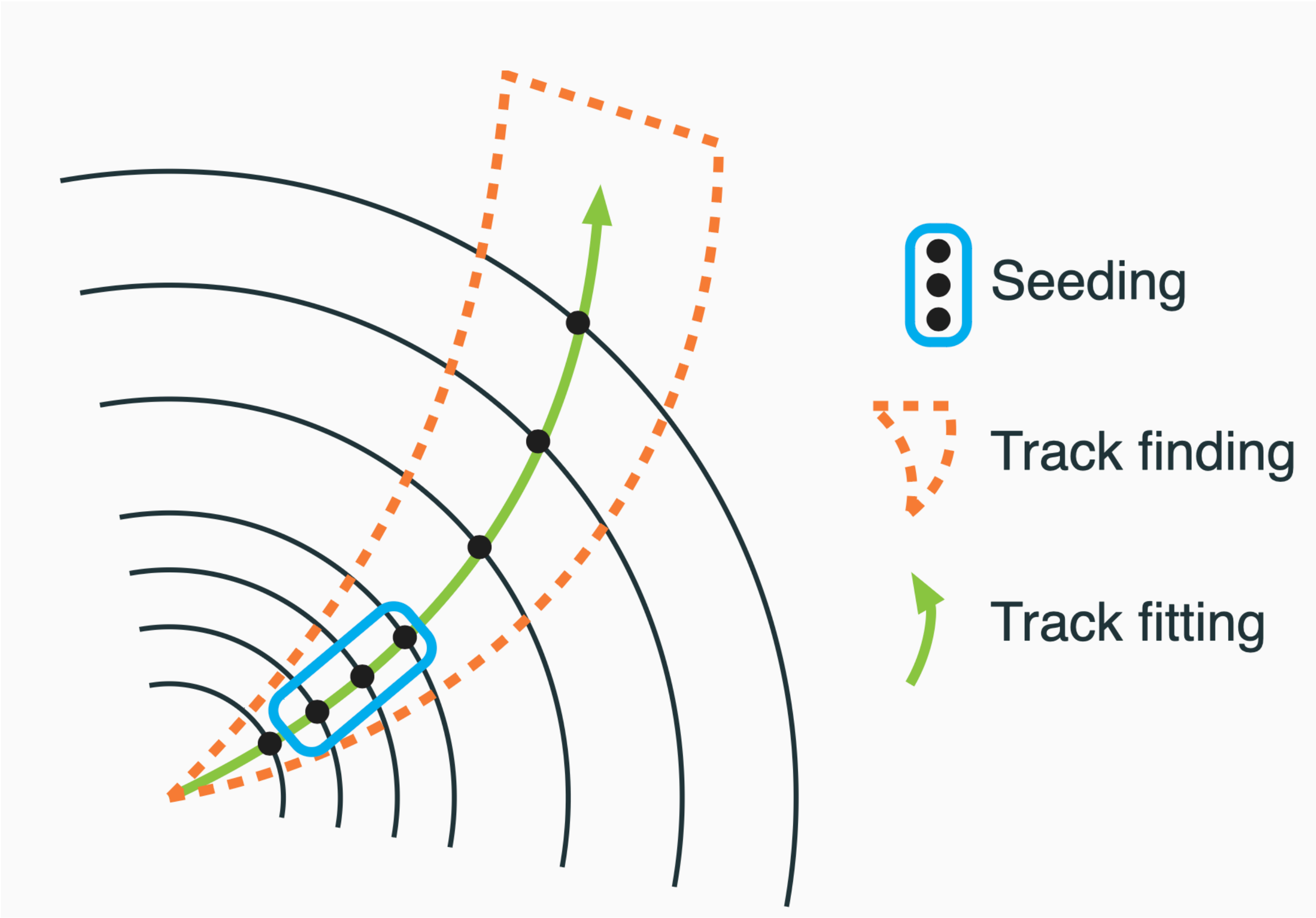
- Suppose your track state is represented by the vector $\vec{x}$. The corresponding uncertainties and correlations also need to be taken into account which can be represented by a covariance matrix.

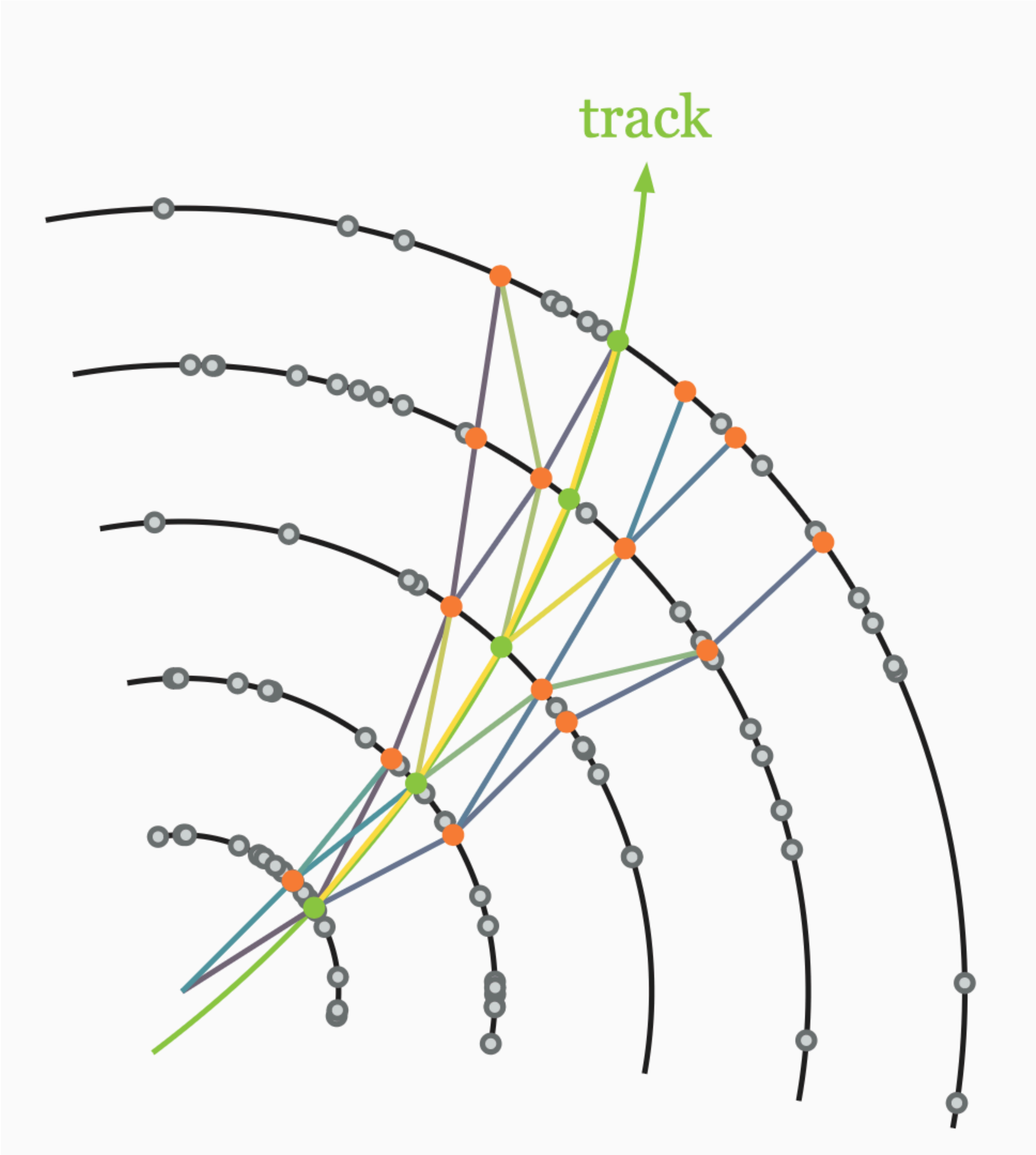
- In going from one detector surface to the next both the track state and the covariance needs to be transformed (taking into account any material effects if any).

- ACTS uses a Combinatorial Kalman formalism where the prediction (with the RK method) at each detector surface is smoothened or filtered with the measurement at that detector surface.

- It's combinatorial in nature: The CKF explores the event starting from an initial track seed. It does this by considering not only a single sequence of measurements, but allowing the branching of the fit at each sensitive surface that is encountered.

- To choose between a set of measurements at a given detector surface that might fall within the search window (defined by the covariance evolution from the previous step) we use a χ^2 cut.





χ^2 Evaluation in the ACTS code (used as a plugin for EICRecon)

This is just a projection matrix

Defined here

```
// Get the residuals
ParametersVector res =
    calibrated - subspaceHelper.projectVector(predicted);

// Get the chi2
return (res.transpose() *
        (calibratedCovariance +
         subspaceHelper.projectMatrix(predictedCovariance))
            .inverse() *
        res)
    .eval()(0, 0);
```

```
template <typename Derived>
Vector projectVector(const Eigen::DenseBase<Derived>& fullVector) const {
  assert(fullVector.size() == kFullSize && "Invalid full vector size");
  Vector result = Vector::Zero();
  for (auto [i, index] : enumerate(*this)) {
    result(i) = fullVector(index);
  }
  return result;
}

template <typename Derived>
SquareMatrix projectMatrix(
    const Eigen::DenseBase<Derived>& fullMatrix) const {
  assert(fullMatrix.rows() == kFullSize && fullMatrix.cols() == kFullSize &&
         "Invalid full matrix size");
  SquareMatrix result = SquareMatrix::Zero();
  for (auto [i, indexI] : enumerate(*this)) {
    for (auto [j, indexJ] : enumerate(*this)) {
      result(i, j) = fullMatrix(indexI, indexJ);
    }
  }
  return result;
}

private:
 Container m_indices{};
};
```

- Code location on ACTS GitHub: Acts/Core/src/TrackFinding/MeasurementSelector.cpp
- CKF Code on ACTS Github: Acts/Core/include/acts/TrackFinding/CombinatorialKalmanFilter.hpp
- Value for the χ^2 cutoff used for EIC is defined in EICRecon/src/algorithms/tracking/CKFTrackingConfig.h

MCRecoTrackParticleAssociationCollection

CentralCKFTrackAssociations
(Performs associations between Monte-Carlo Tracks and Reconstructed tracks)

```
CentralCKFTrackAssociations = (vector<edm4eic::MCRecoTrackParticleAssociationData>*)0x5629b01c0950
CentralCKFTrackAssociations.simID = 0, 0, 0, 0
CentralCKFTrackAssociations.recID = 0, 0, 0, 0
CentralCKFTrackAssociations.weight = 1.000000, 1.000000, 1.000000, 1.000000
_CentralCKFTrackAssociations_rec = (vector<podio::ObjectID>*)0x5629b020a310
_CentralCKFTrackAssociations_rec.index = 0, 1, 2, 3
_CentralCKFTrackAssociations_rec.collectionID = 530999115, 530999115, 530999115, 530999115
_CentralCKFTrackAssociations_sim = (vector<podio::ObjectID>*)0x5629b020b2f0
_CentralCKFTrackAssociations_sim.index = 2, 3, 5, 7
_CentralCKFTrackAssociations_sim.collectionID = 2714477136, 2714477136, 2714477136, 2714477136
```

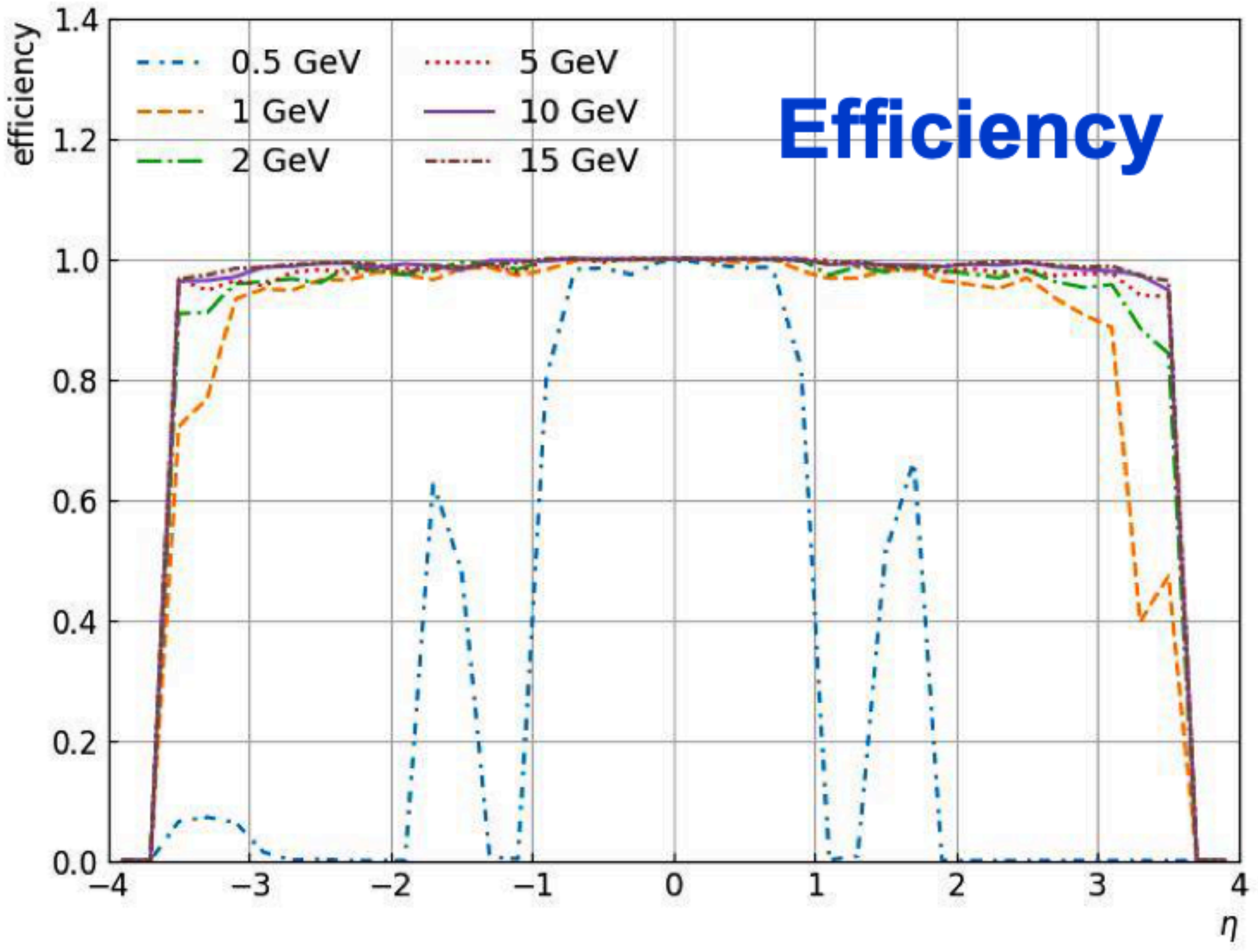
This is what we need to use instead.

```
edm4eic::MCRecoTrackParticleAssociation:
  Description: "Association between a Track and a MCParticle"
  Author : "S. Joosten"
  Members:
    - uint32_t          simID             // Index of corresponding MCParticle (position in MCParticles array)
    - uint32_t          recID             // Index of corresponding Track (position in Tracks array)
    - float             weight            // weight of this association
  OneToOneRelations:
    - edm4eic::Track    rec               // reference to the track
    - edm4hep::MCParticle sim             // reference to the Monte-Carlo particle
```

These associations are performed between Monte Carlo tracks and reconstructed tracks irrespective of the generator status. It's possible that in an event all your reconstructed tracks are secondaries and none of those correspond to the primary track.

EDM4EIC documentation will say that association has a corresponding index in the reconstructed tracks array as well as the MC array and that you can access that index via simID and recID, but that is not correct

Previous Track Reconstruction Efficiency Results



*These plots were made with the requirement of 3 minimum hits on the track.

The reconstruction efficiency for low-momentum tracks can be improved, particularly in the transition and end-cap regions.
Possible contributing factors include:

1. The **χ^2 cut** applied on a layer-by-layer basis may be rejecting valid hits in certain layers.

3. The **track seeds** for these low-momentum tracks may not be forming at all, possibly due to restrictive cuts applied during the seeding stage.

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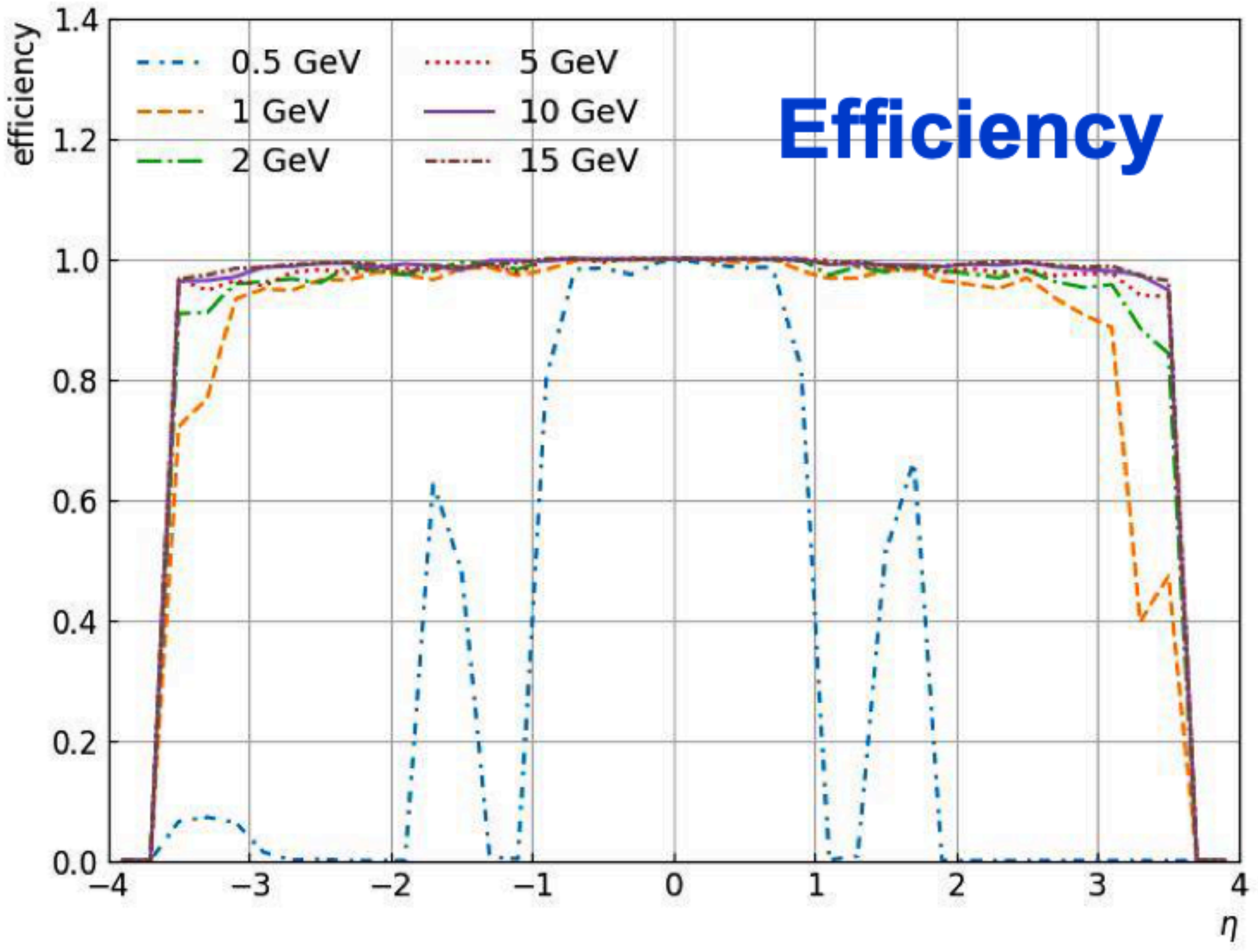

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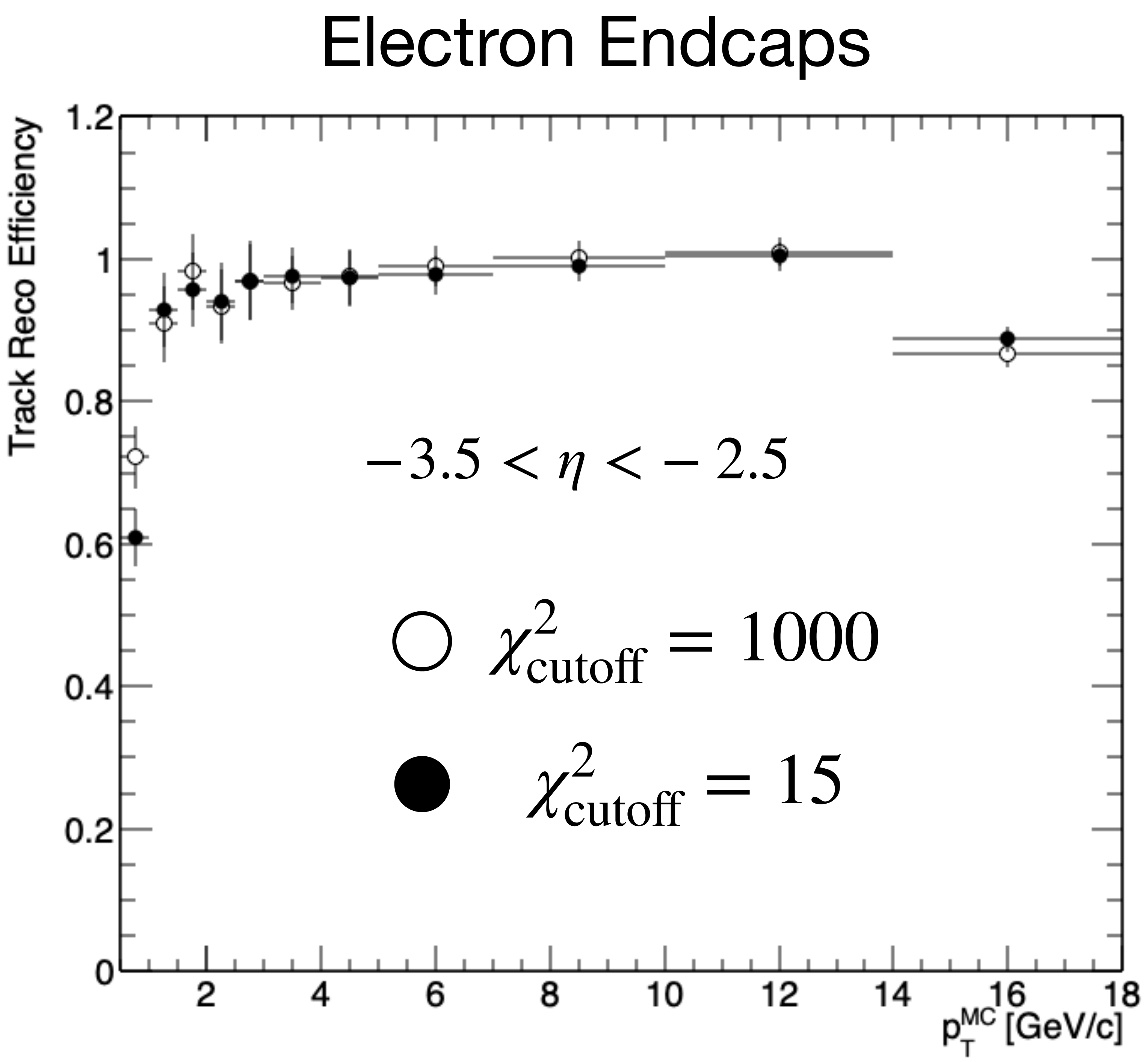
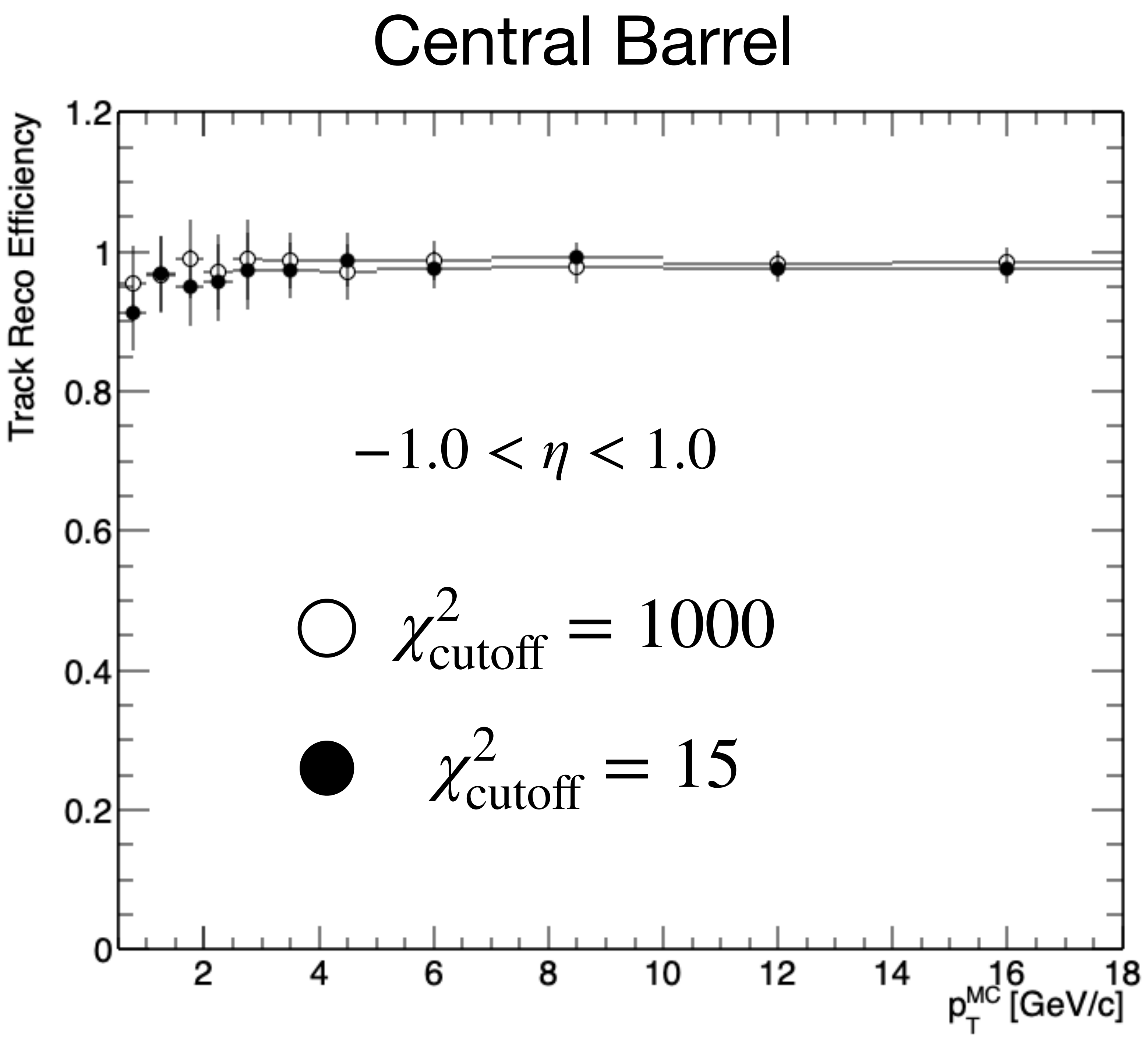
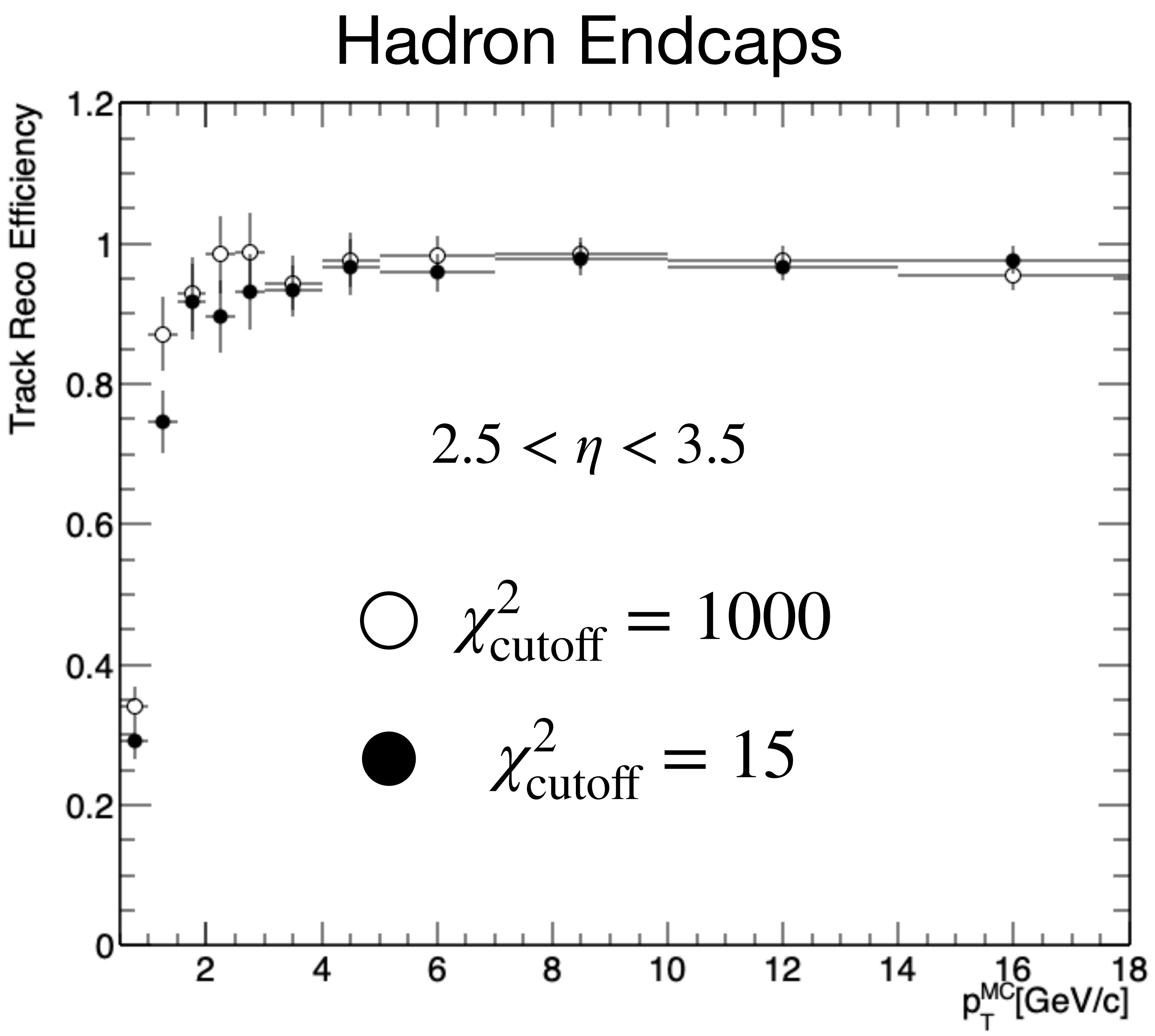
3. The **track seeds** for these low-momentum tracks may not be forming at all, possibly due to restrictive cuts applied during the seeding stage.

The approach would be to simply remove the **χ²** cut .

Track Reconstruction Efficiency: 4 Hits Requirement





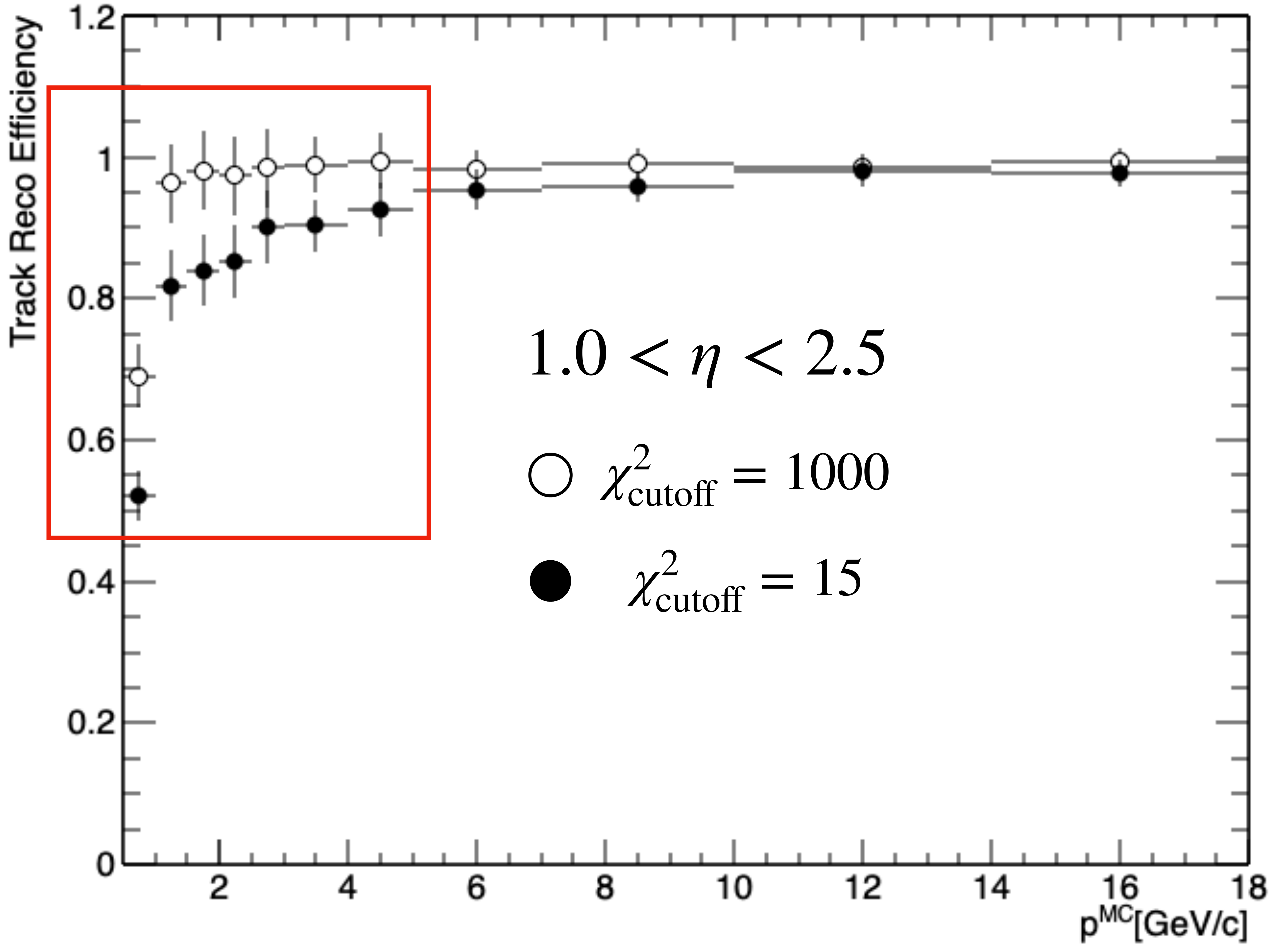


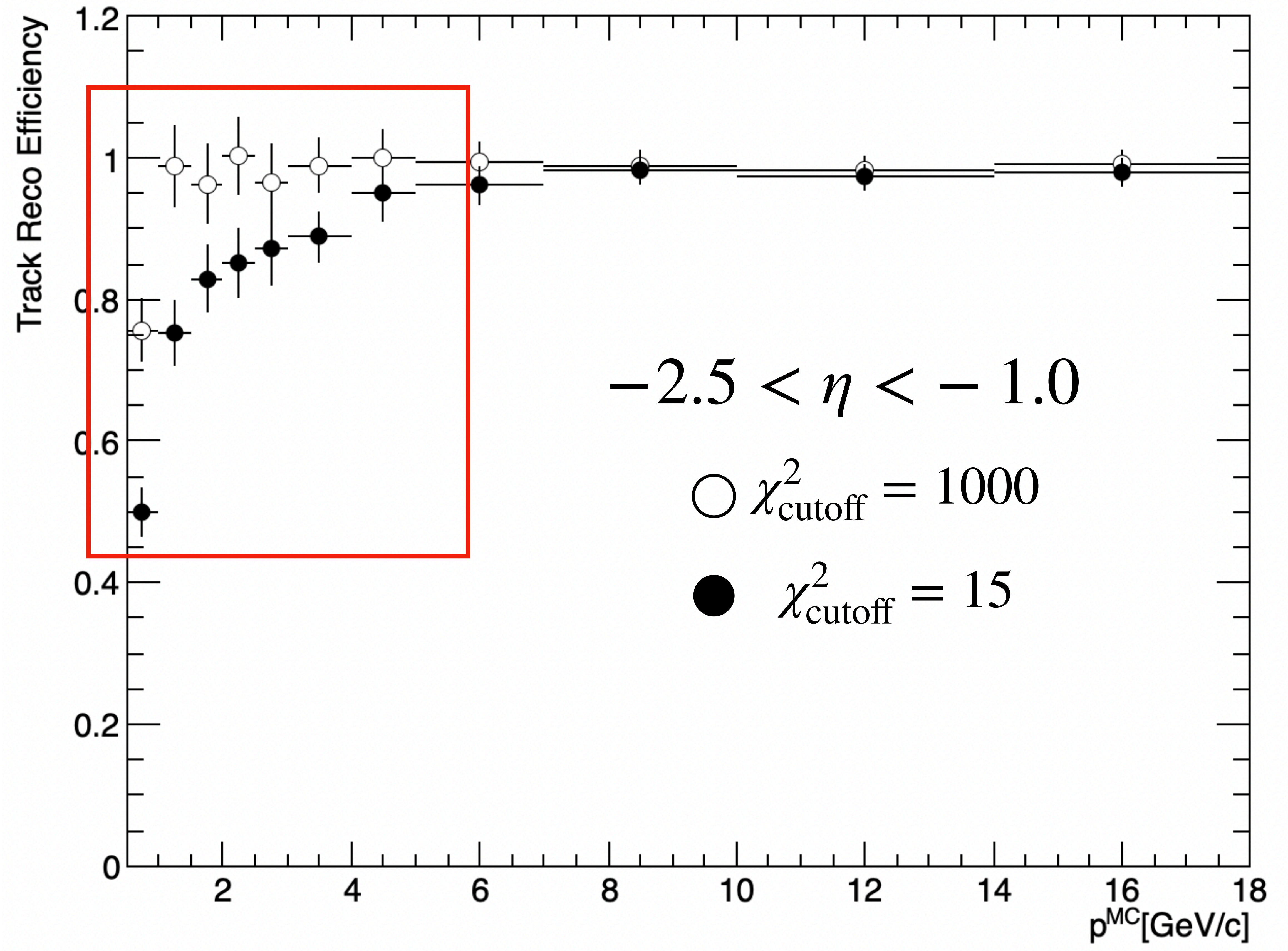
Some improvements in the low momentum region

The χ^2 selection does not really affect the central barrel region

Some improvements in the low momentum region

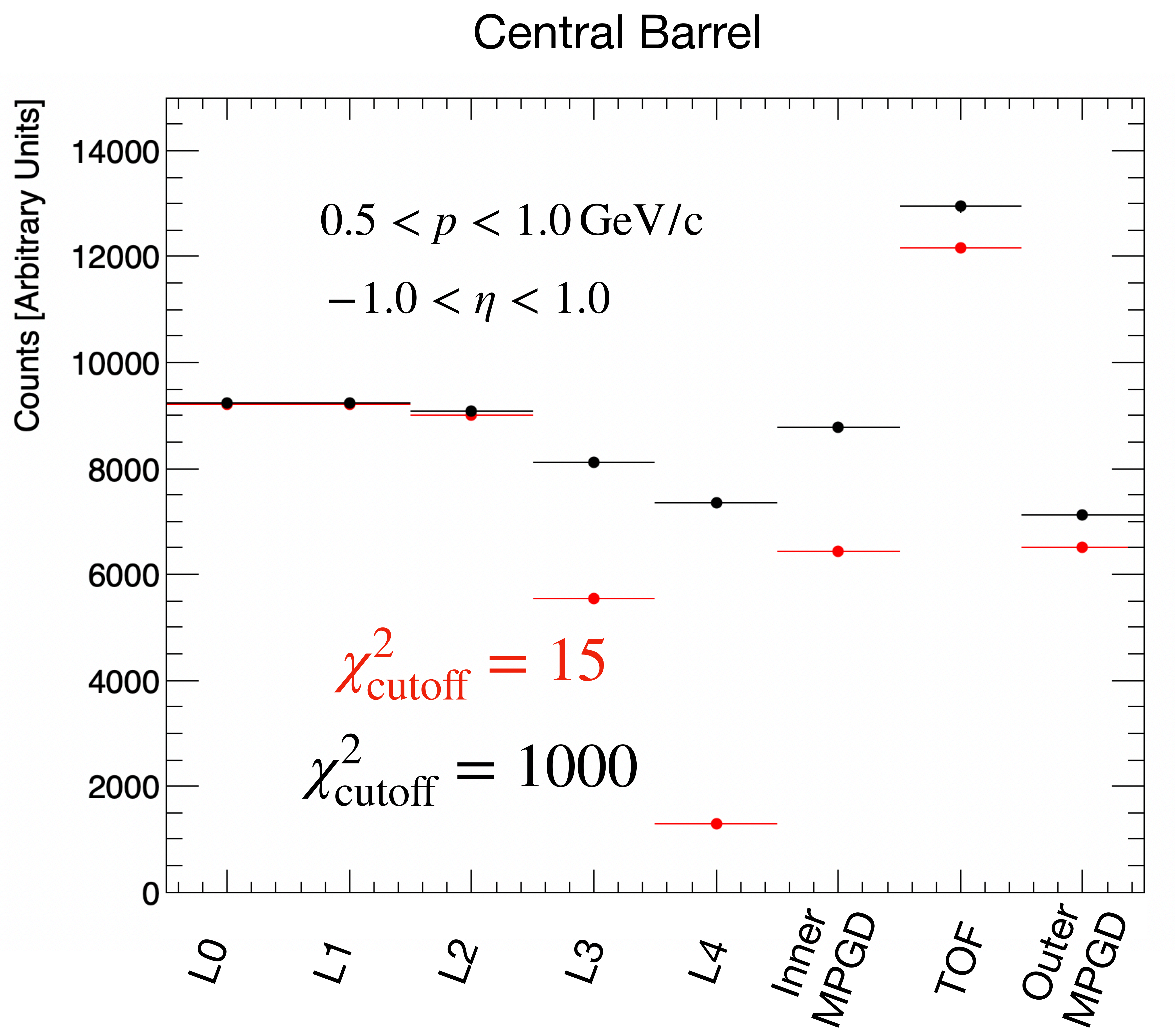
Track Reconstruction Efficiency: 4 Hits Requirement



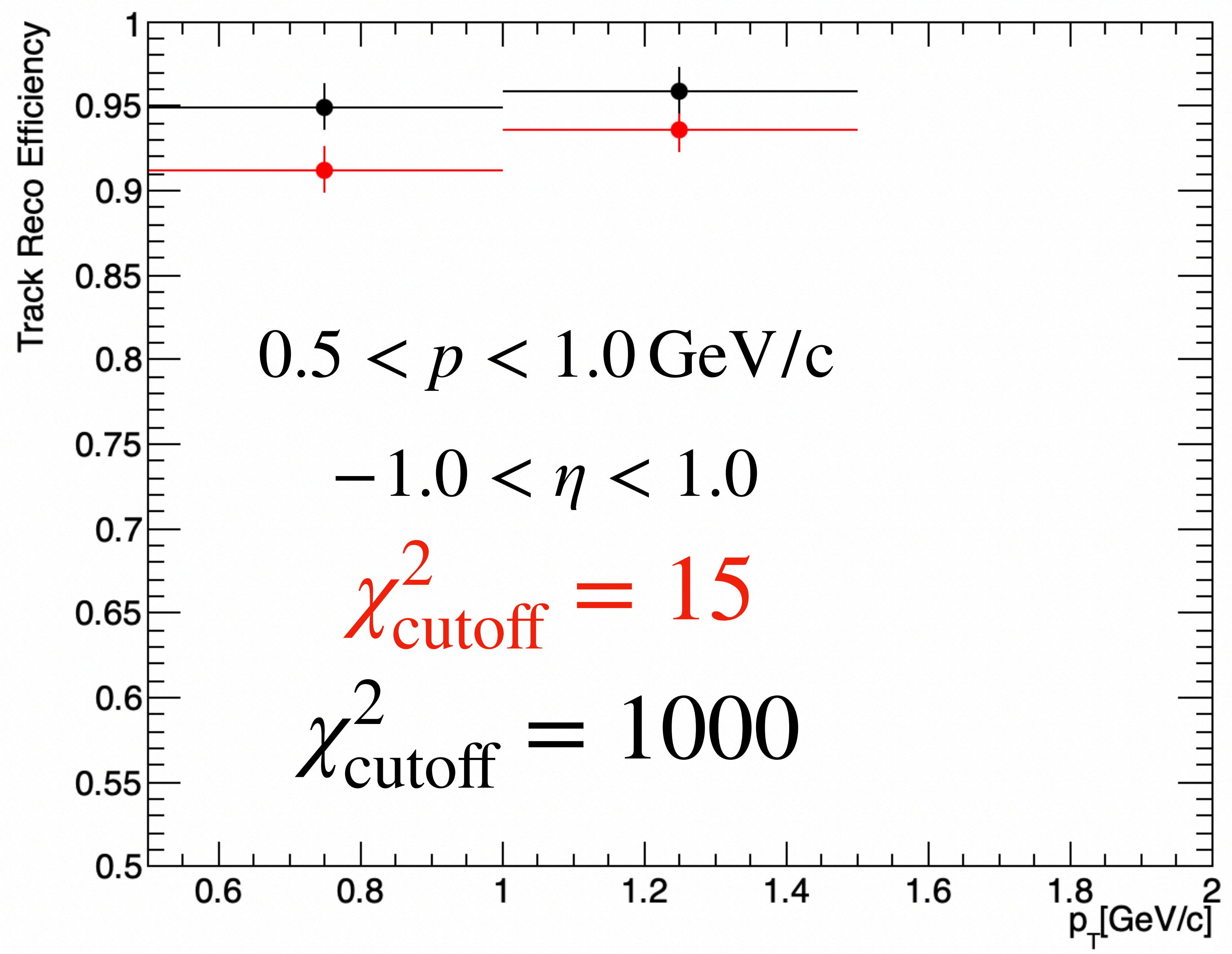


A significant effect in the transition region!

How are the hits distributed across various tracking layers?



- 4th hit requirement is most likely fulfilled by the TOF. Tho we do see slight differences between the two choices of χ^2.
- Running more statistics particularly in the low momentum region, we do see differences in the track reconstruction efficiency.



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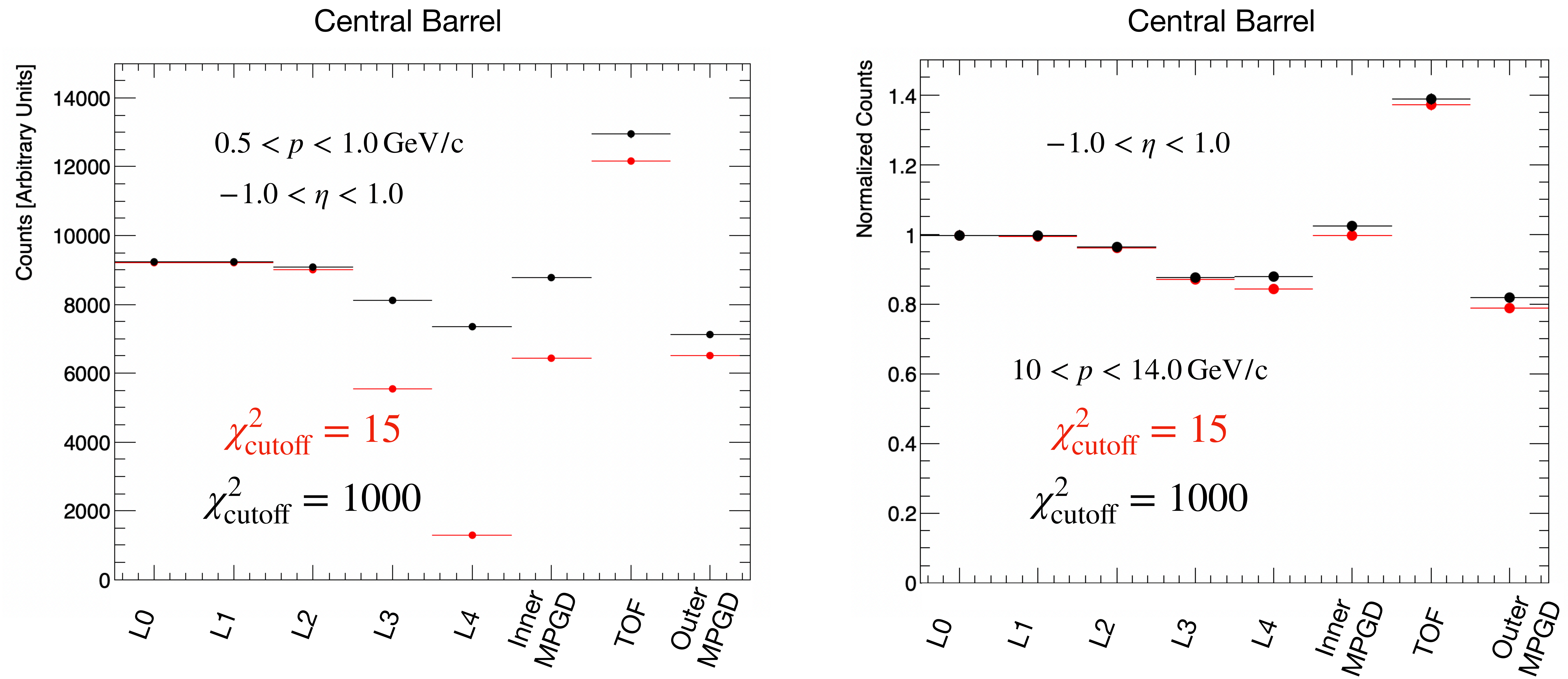
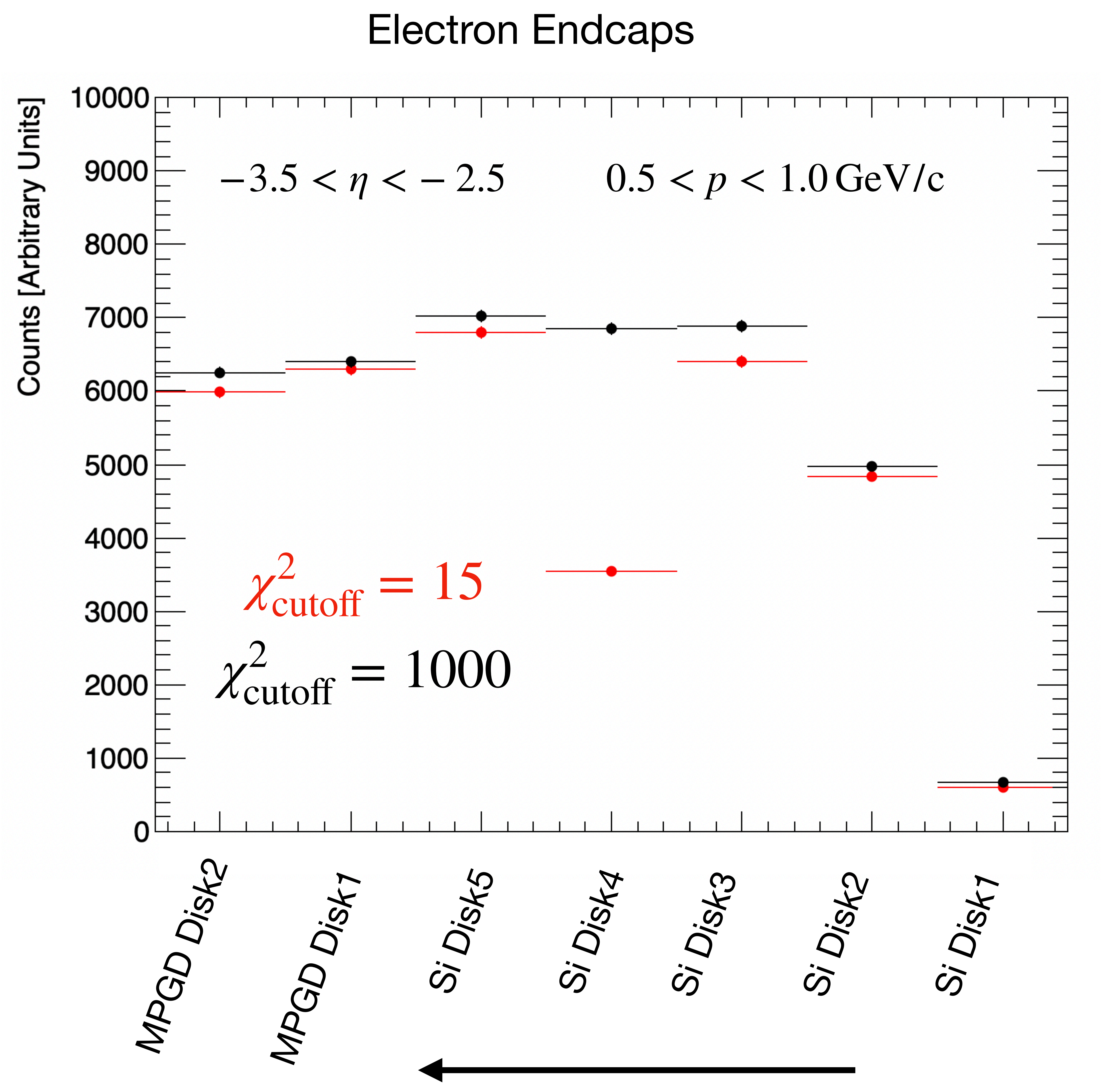
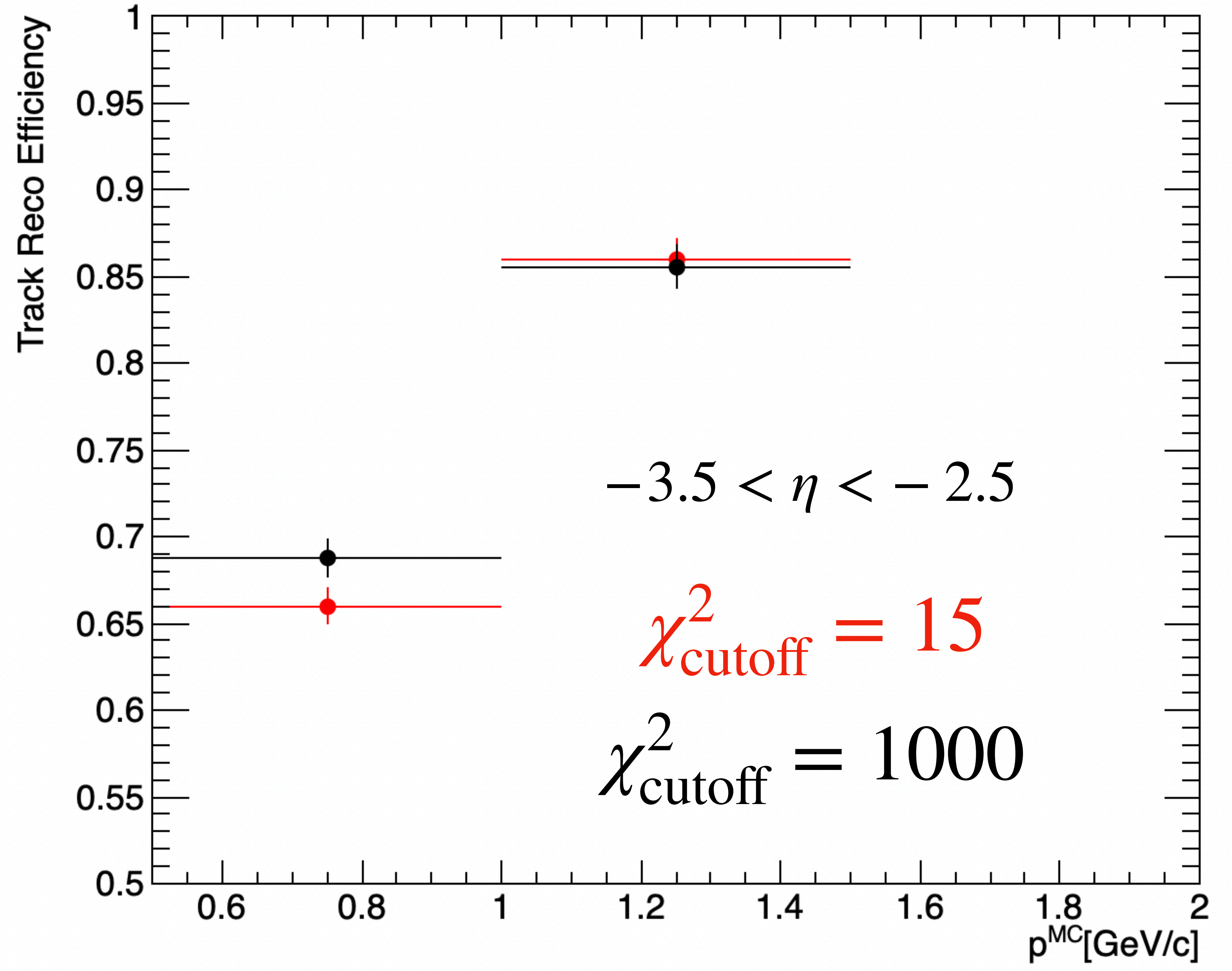
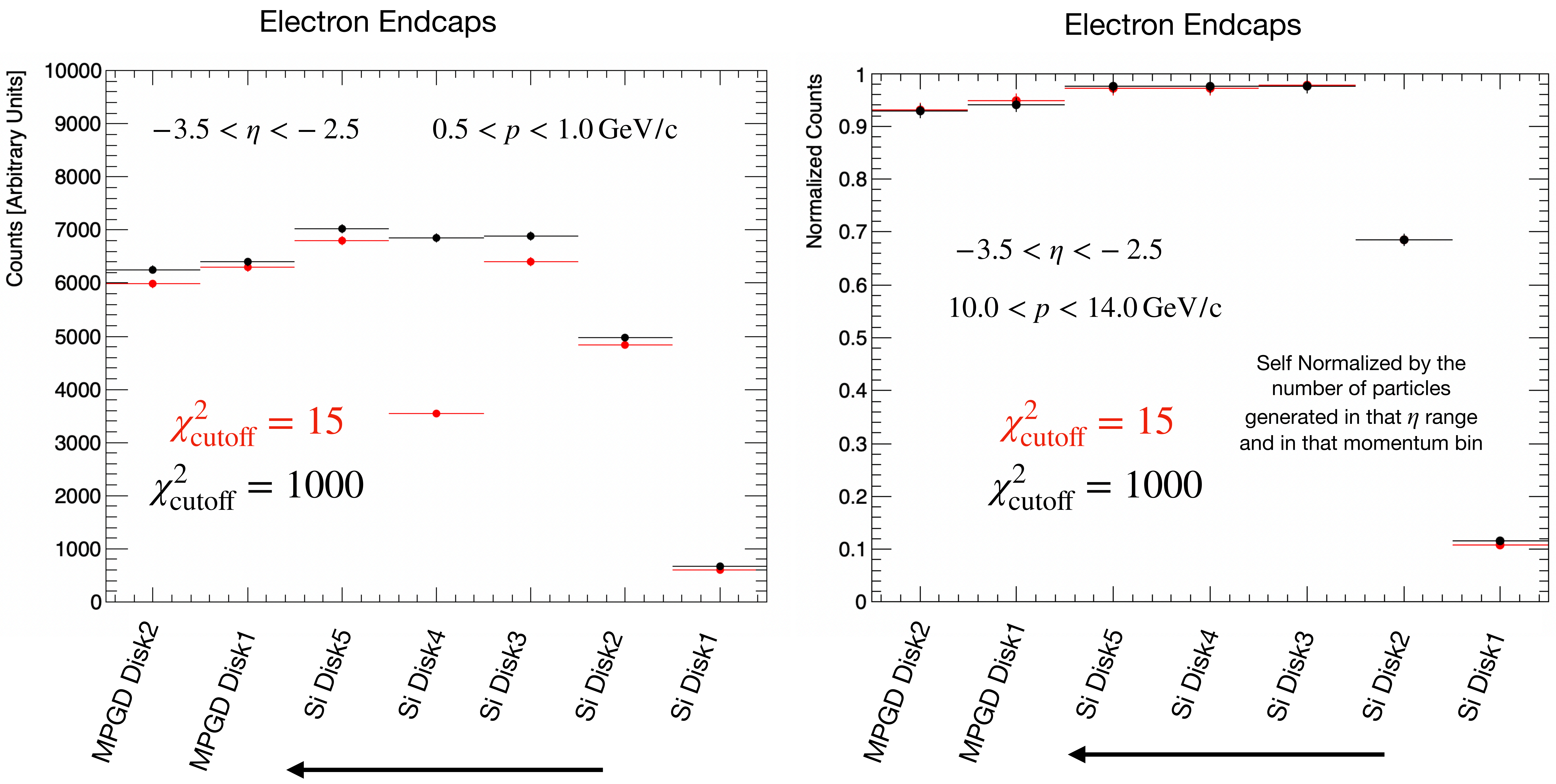




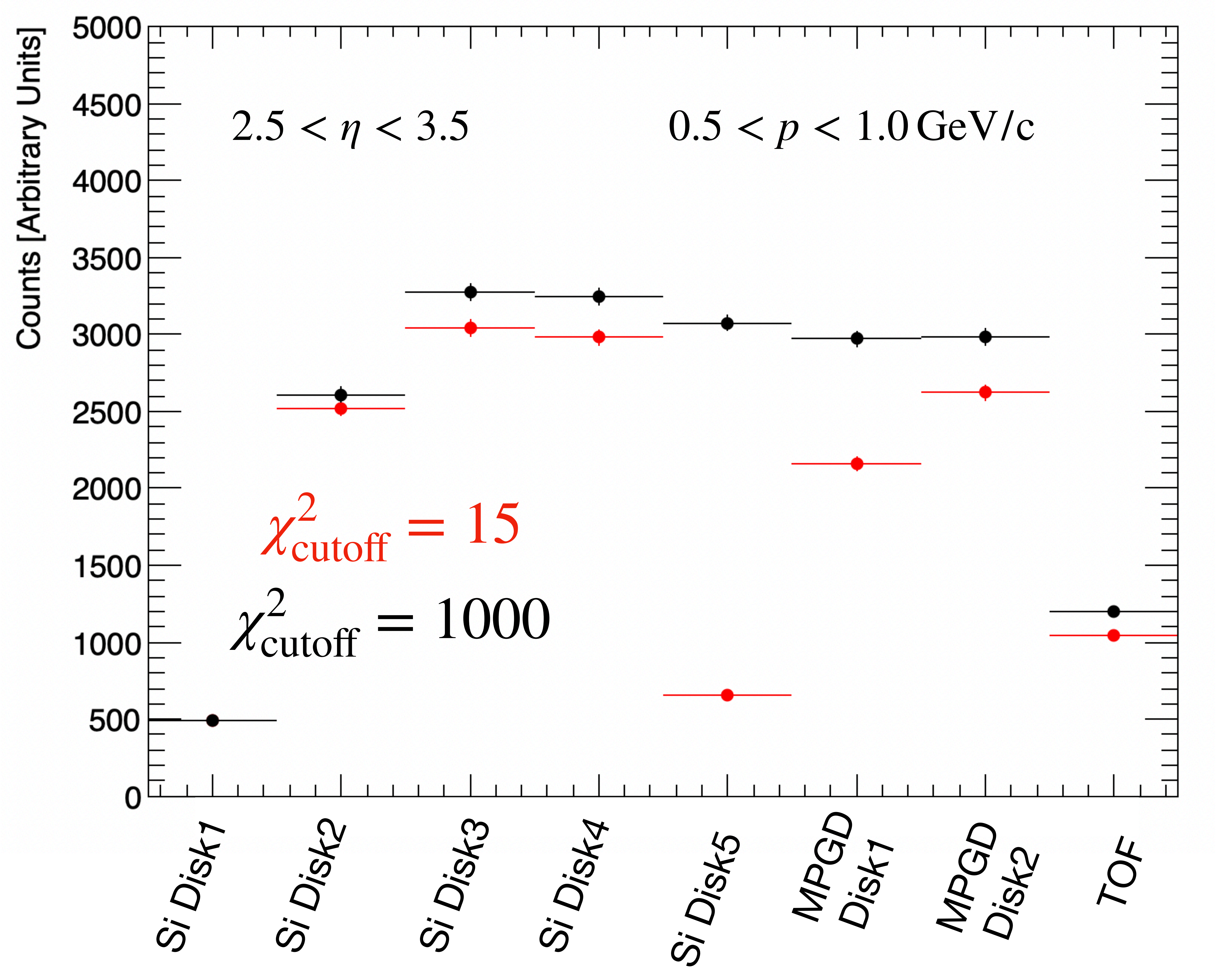
Track formation happens with hits in mostly the later tracking layers and except Silicon Disk 4 the differences between the two χ^2 options is not a lot.



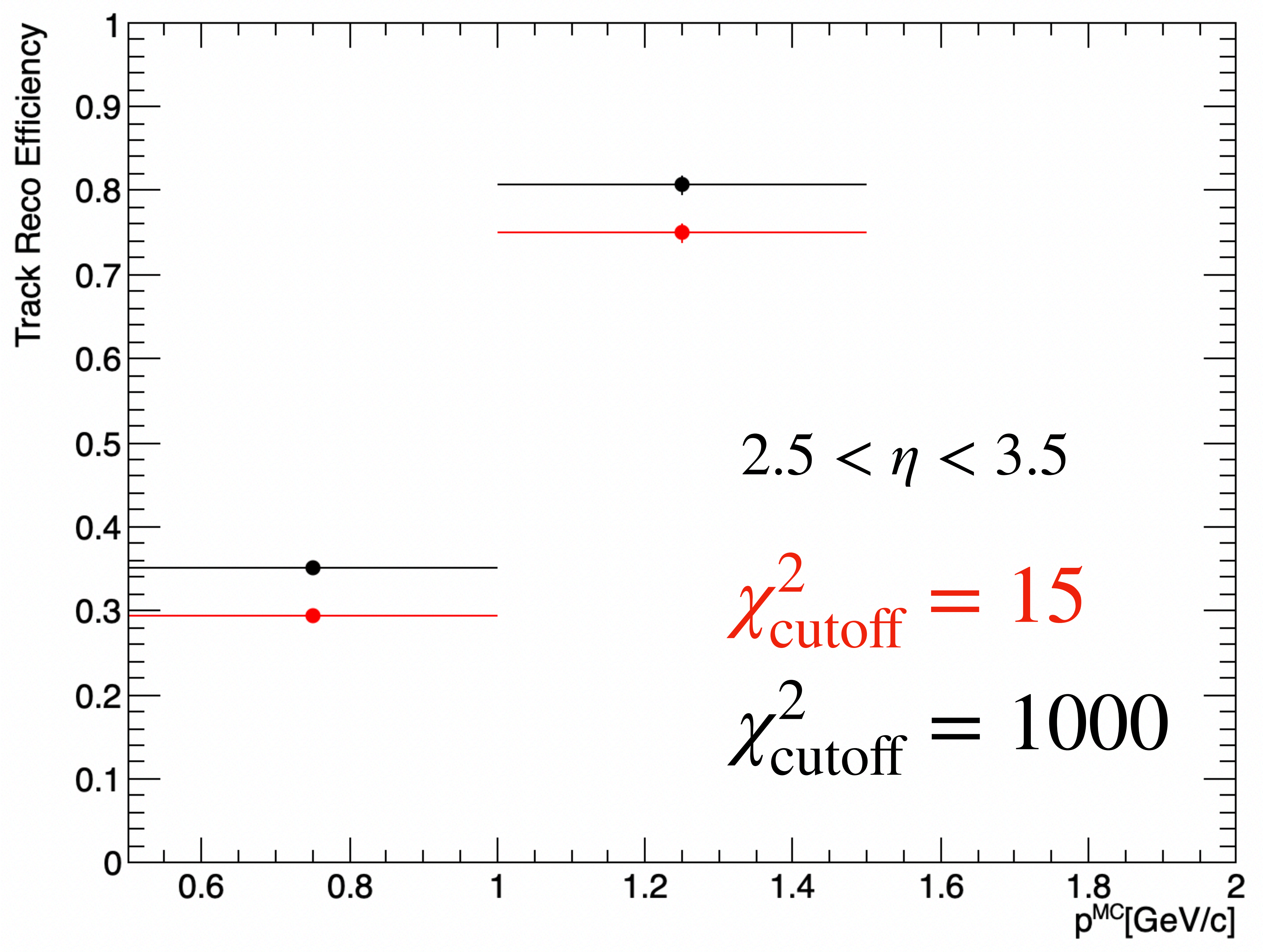


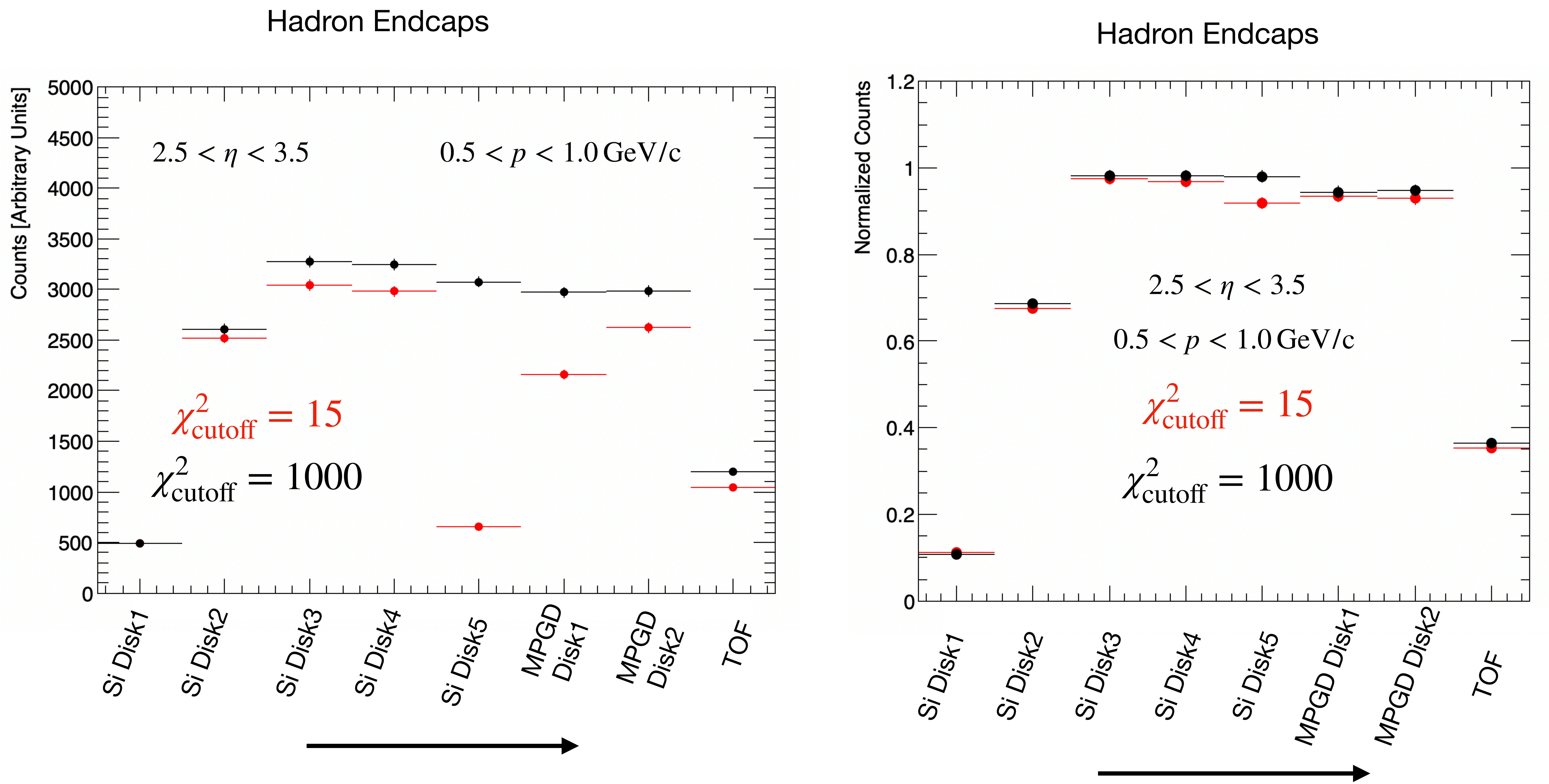
Electron Endcaps
Counts [Arbitrary Units]
$-3.5 < \eta < -2.5$
$0.5 < p < 1.0\,\mathrm{GeV/c}$
$\chi^2_{\mathrm{cutoff}} = 15$
$\chi^2_{\mathrm{cutoff}} = 1000$
MPGD Disk2
MPGD Disk1
Si Disk5
Si Disk4
Si Disk3
Si Disk2
Si Disk1
Electron Endcaps
Normalized Counts
$-3.5 < \eta < -2.5$
$10.0 < p < 14.0\,\mathrm{GeV/c}$
Self Normalized by the number of particles generated in that η range and in that momentum bin
$\chi^2_{\mathrm{cutoff}} = 15$
$\chi^2_{\mathrm{cutoff}} = 1000$
MPGD Disk2
MPGD Disk1
Si Disk5
Si Disk4
Si Disk3
Si Disk2
Si Disk1

Hadron Endcaps



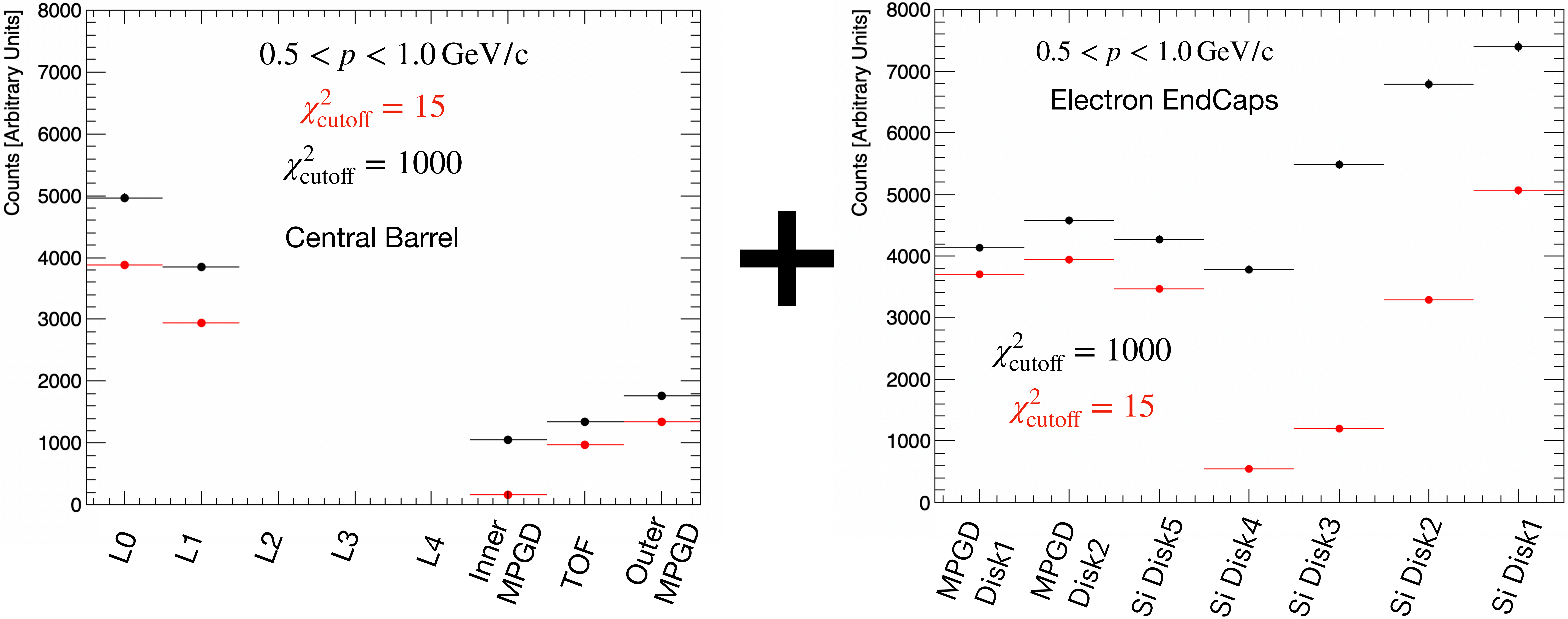
Track formation happens with hits in mostly the later tracking layers and except Silicon Disk 4 the differences between the two χ^2 options is more than it was for the electron end-caps.




Hadron Endcaps
Counts [Arbitrary Units]
2.5 < η < 3.5
0.5 < p < 1.0 GeV/c
χ²cutoff = 15
χ²cutoff = 1000
Si Disk1
Si Disk2
Si Disk3
Si Disk4
Si Disk5
MPGD Disk1
MPGD Disk2
TOF
Hadron Endcaps
Normalized Counts
2.5 < η < 3.5
0.5 < p < 1.0 GeV/c
χ²cutoff = 15
χ²cutoff = 1000
Si Disk1
Si Disk2
Si Disk3
Si Disk4
Si Disk5
MPGD Disk1
MPGD Disk2
TOF

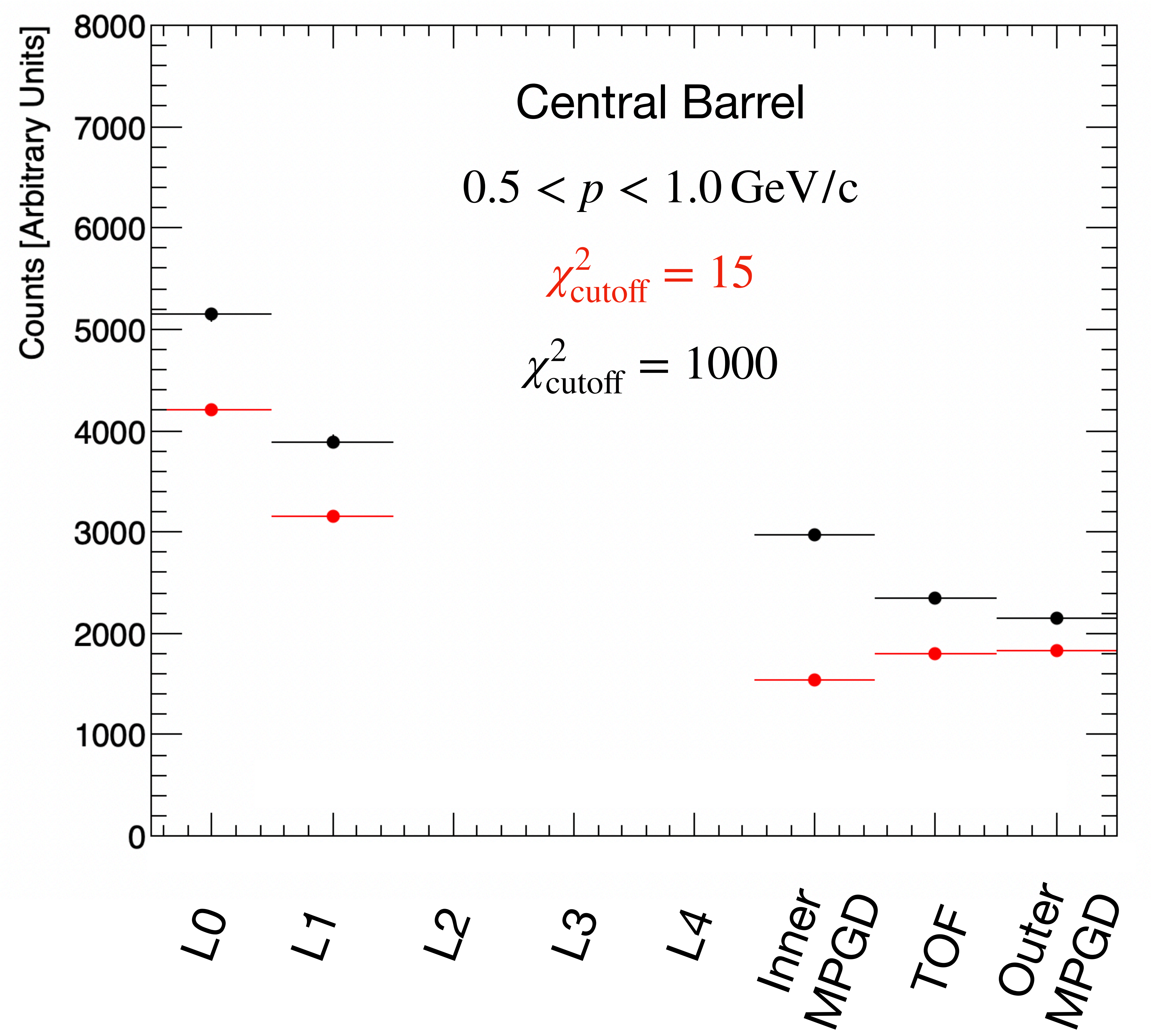
Backward Direction: We need to look at the combination of barrel and end-caps

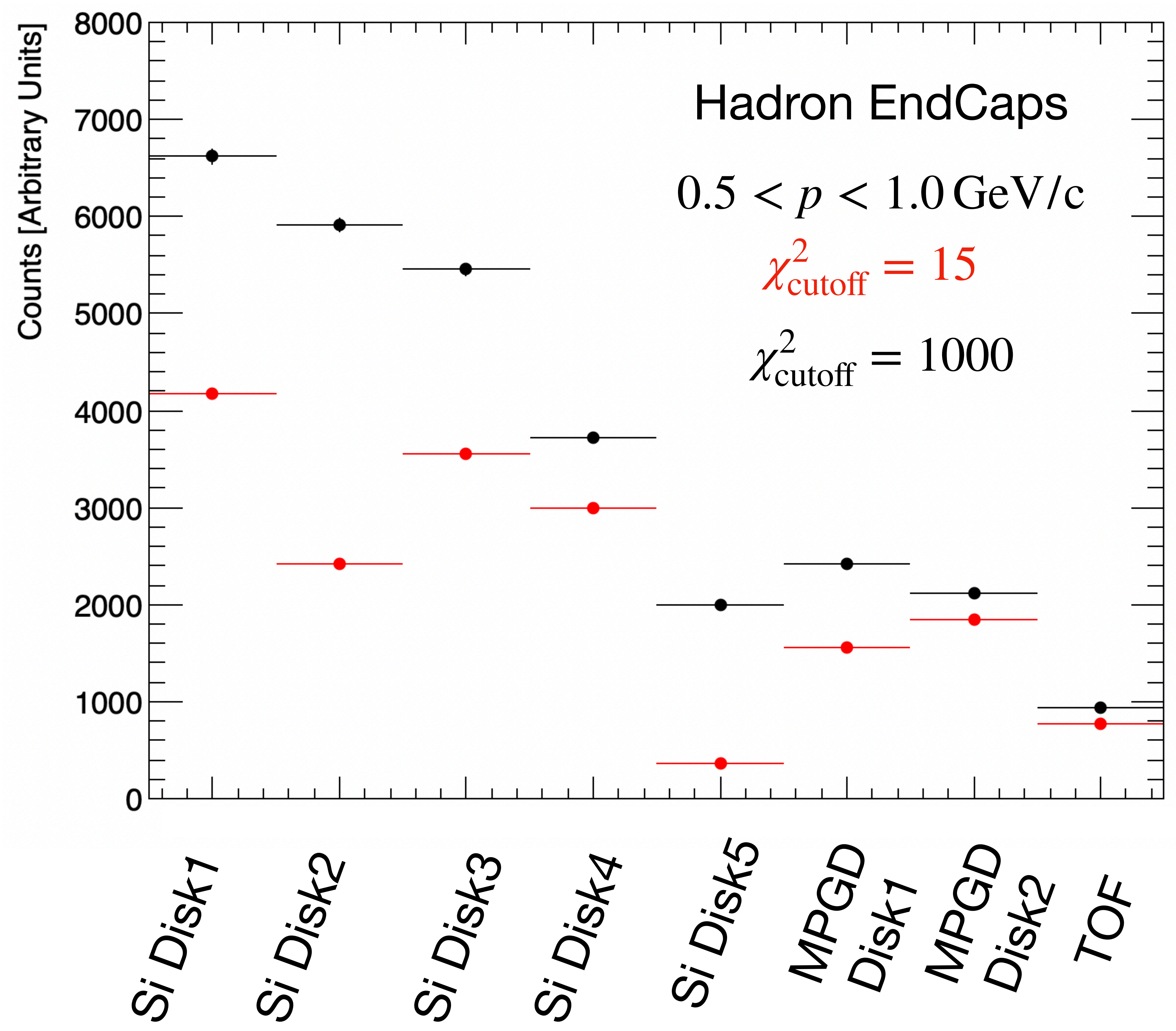
$-2.5 < \eta < -1.0$



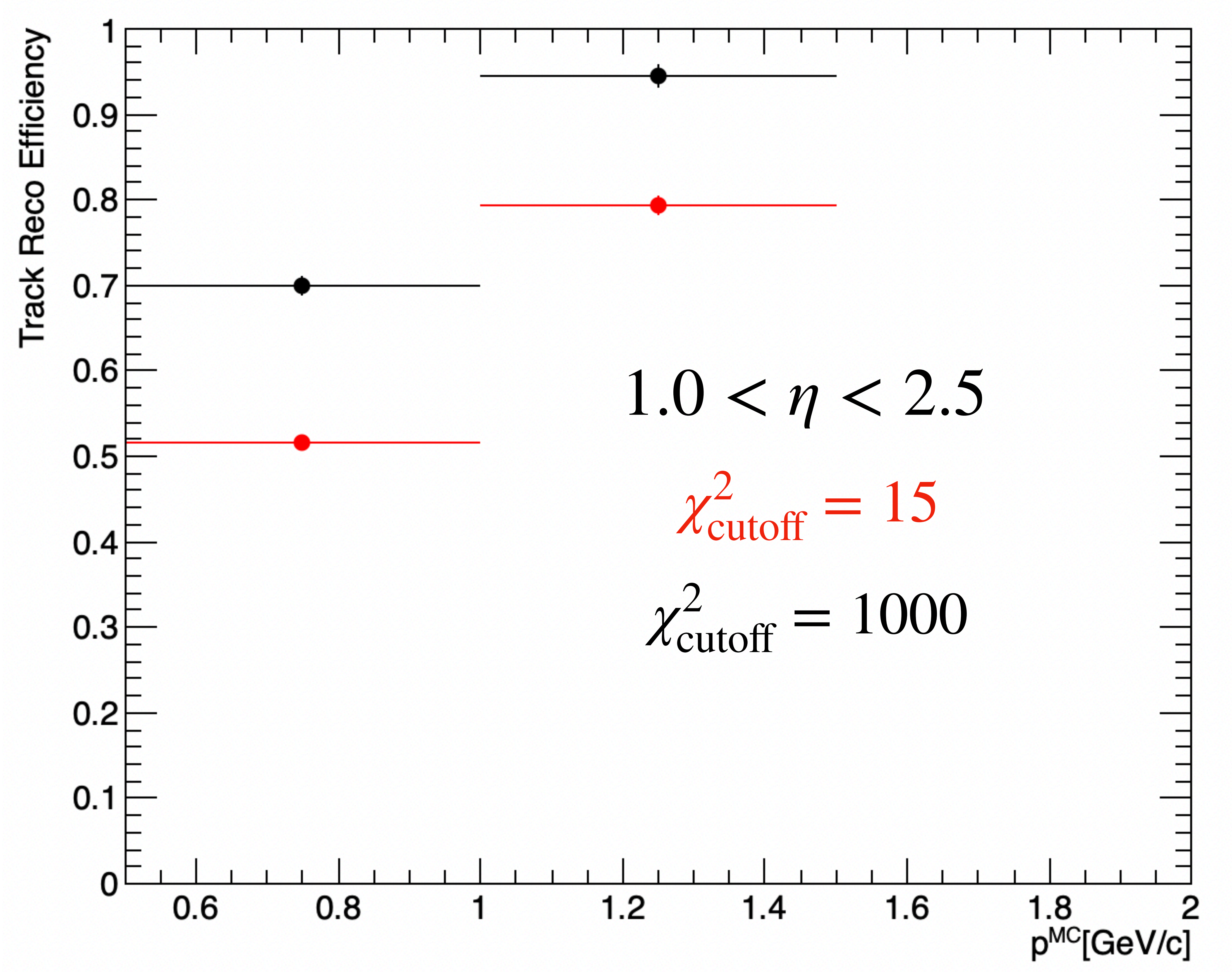
Forward Direction: We need to look at the combination of barrel and end-caps

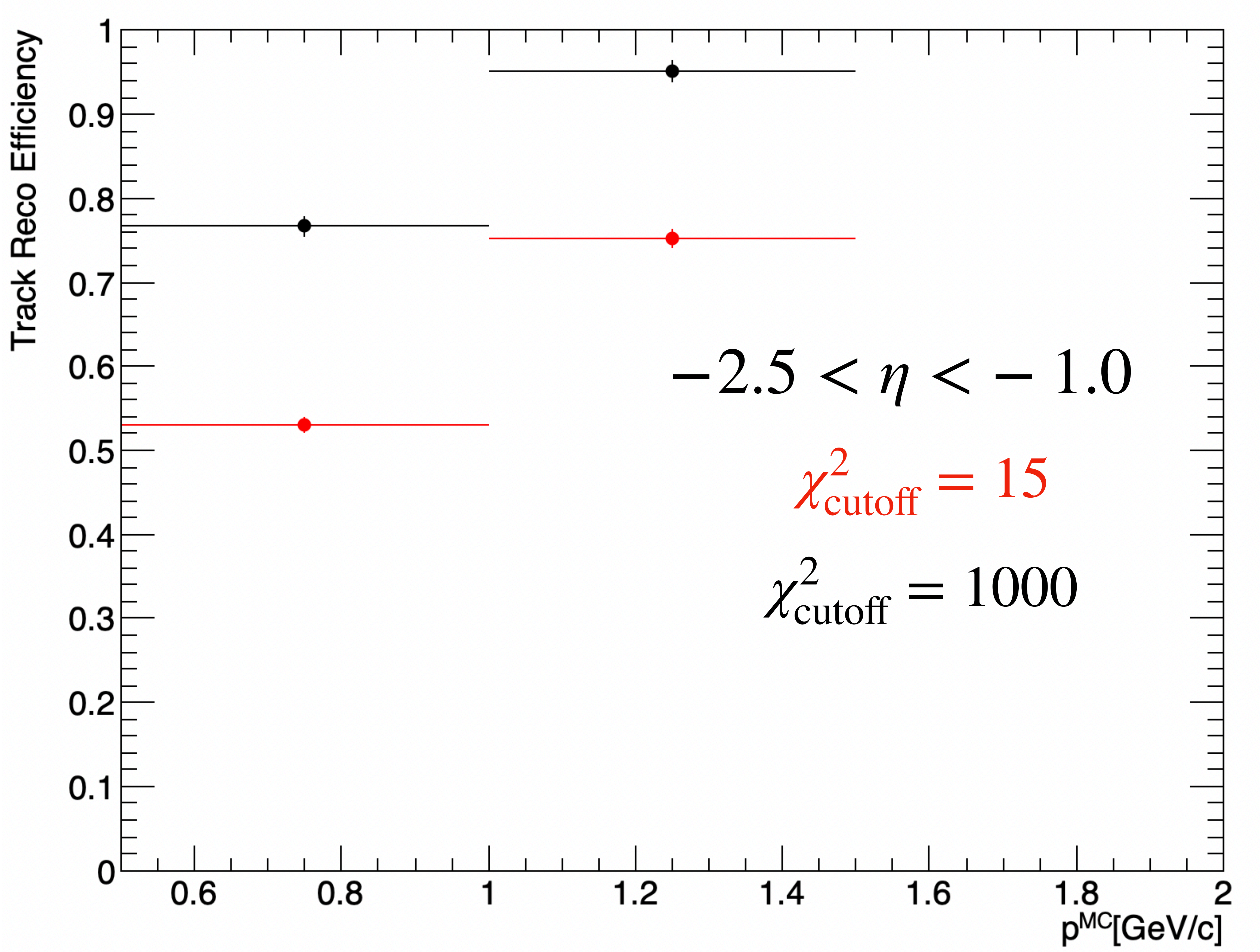
$1.0 < \eta < 2.5$





Track Reconstruction Efficiency (4 Hits Requirement)





Quantifying the Results

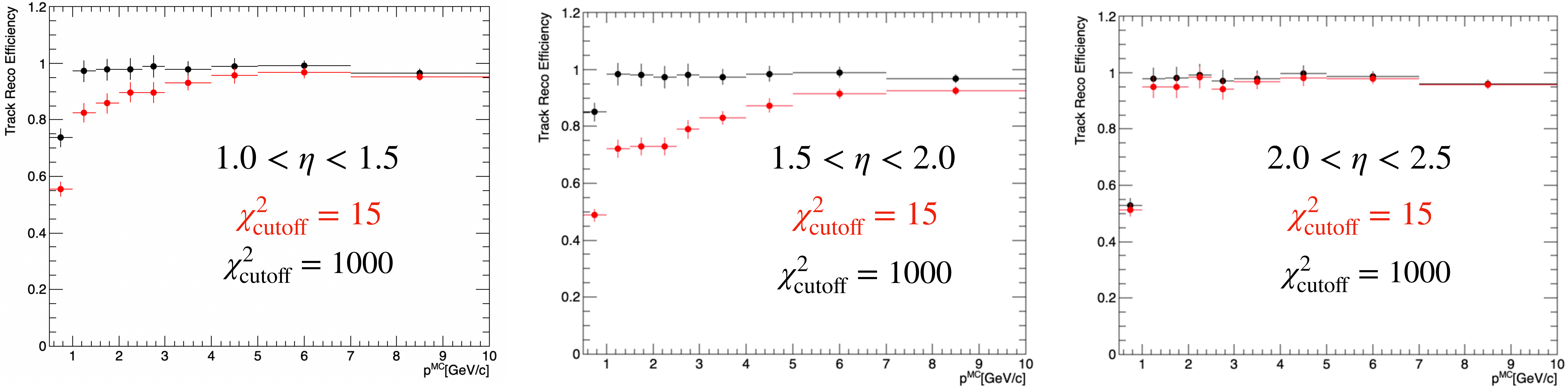
The effect of practically removing the χ^2 cut on the track reconstruction efficiency for low momentum (0.5-1.0 GeV/c) tracks.

$-3.5 < \eta < -2.5$	~3%
$-2.5 < \eta < -1.0$	~14%
$-1.0 < \eta < 1.0$	~4%
$1.0 < \eta < 2.5$	~18%
$2.5 < \eta < 3.5$	~6%

Transition regions are def getting affected a lot more

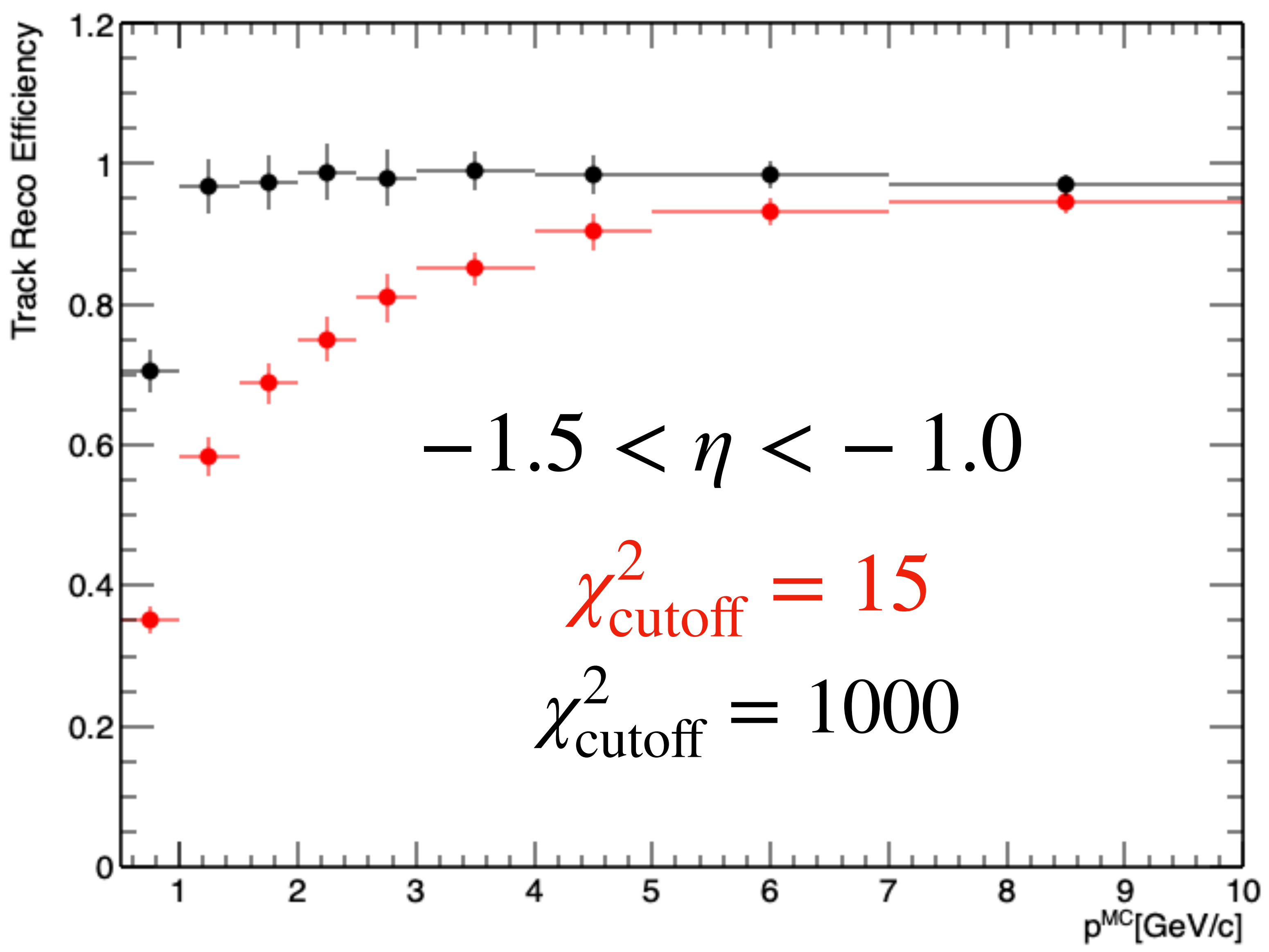
The effect is in general more in the forward than in the backward direction

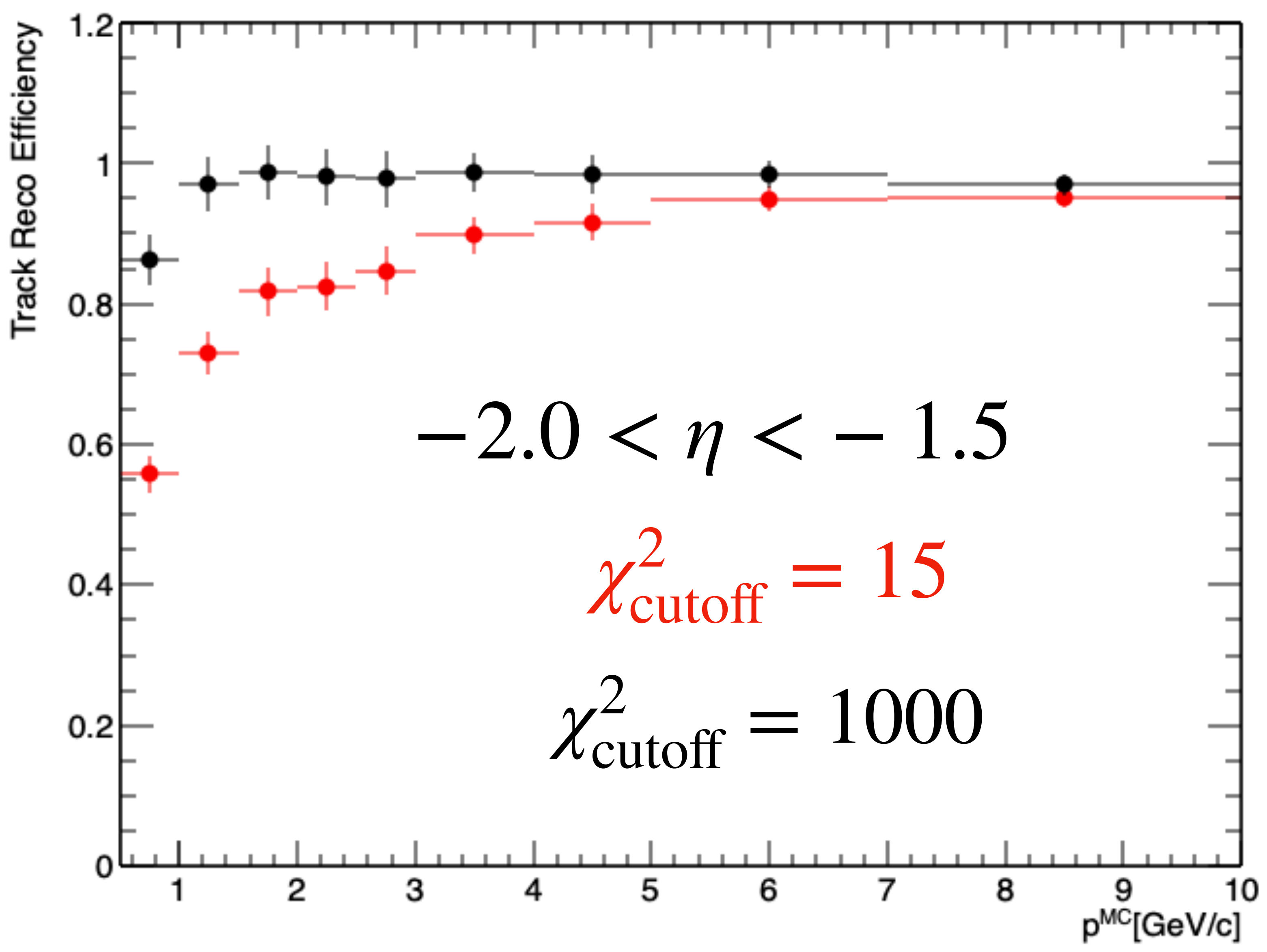
Looking More differentially in η

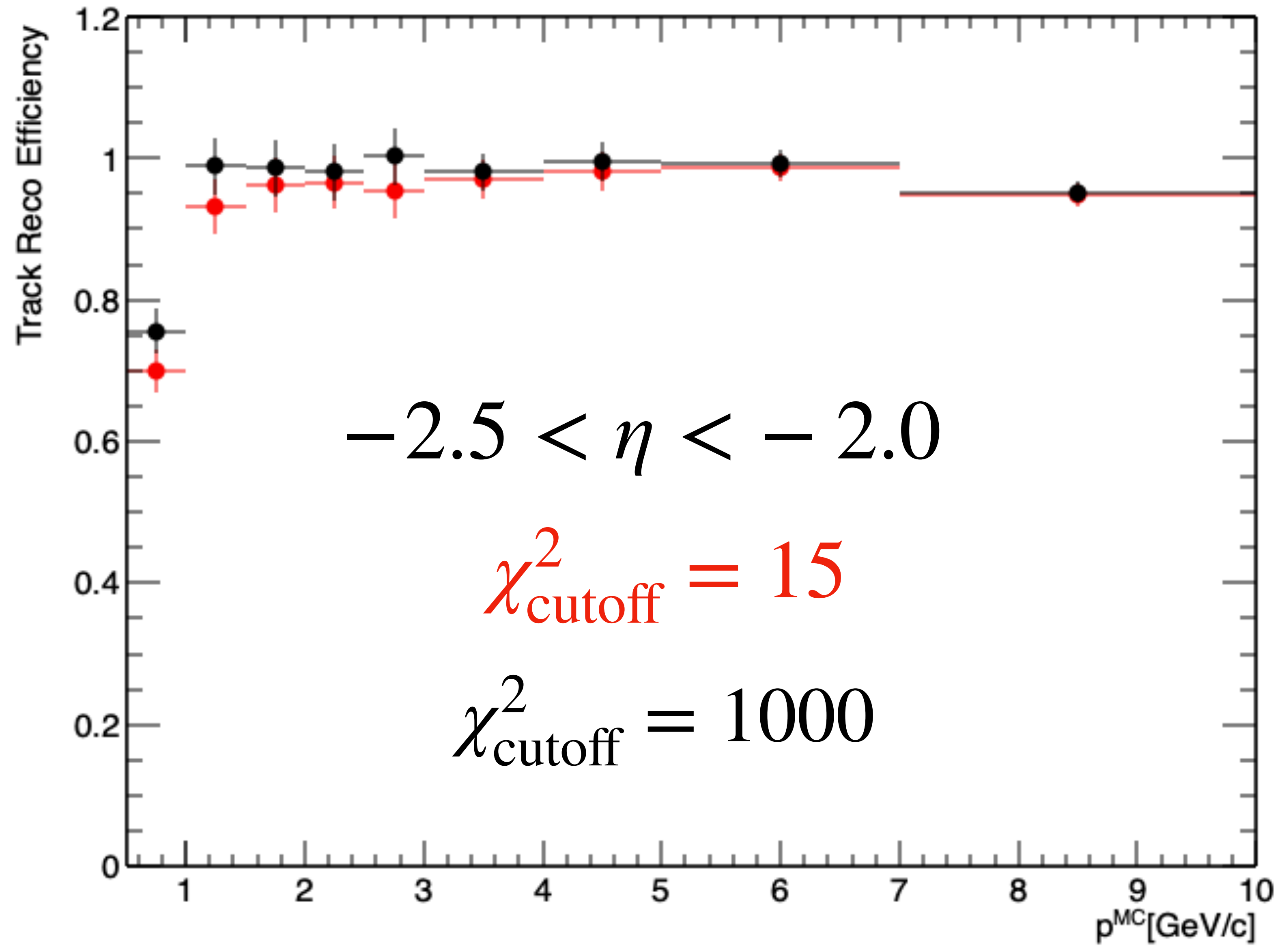


More of a difference between the two chi2 cut offs in these 2 regions

Looking More differentially in η







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