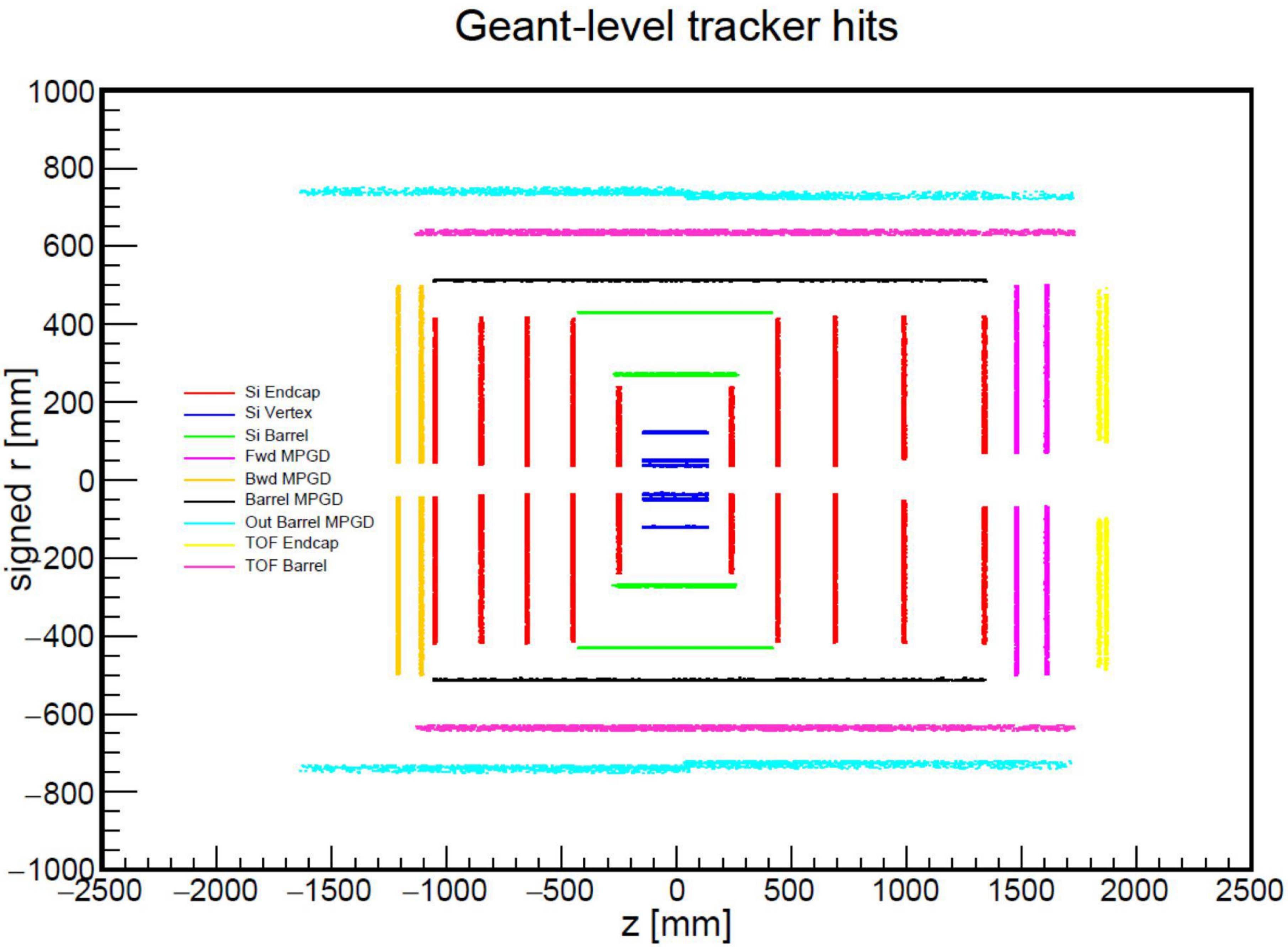
Single-particle track reconstruction status in ePIC

Barak Schmookler



Geant-level tracker hits
signed r [mm]
z [mm]
Si Endcap
Si Vertex
Si Barrel
Fwd MPGD
Bwd MPGD
Barrel MPGD
Out Barrel MPGD
TOF Endcap
TOF Barrel
1000
800
600
400
200
0
−200
−400
−600
−800
−1000
−2500
−2000
−1500
−1000
−500
0
500
1000
1500
2000
2500

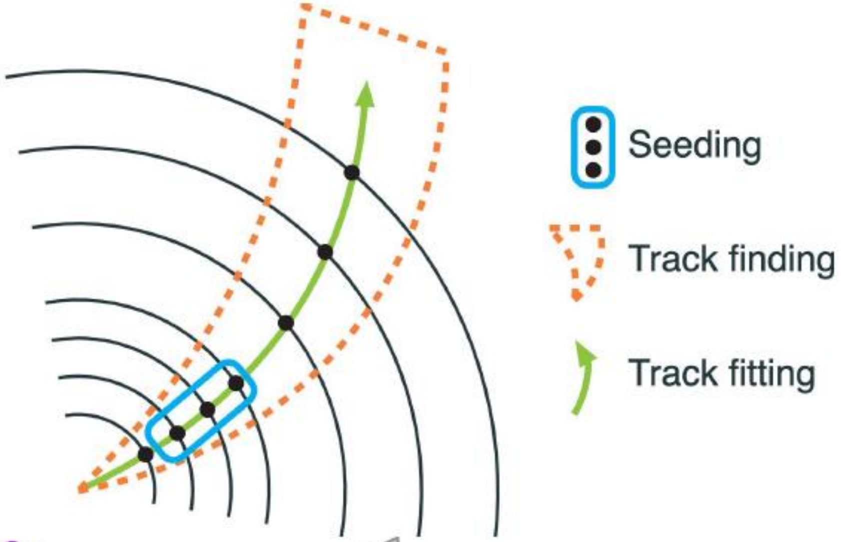
Track reconstruction framework

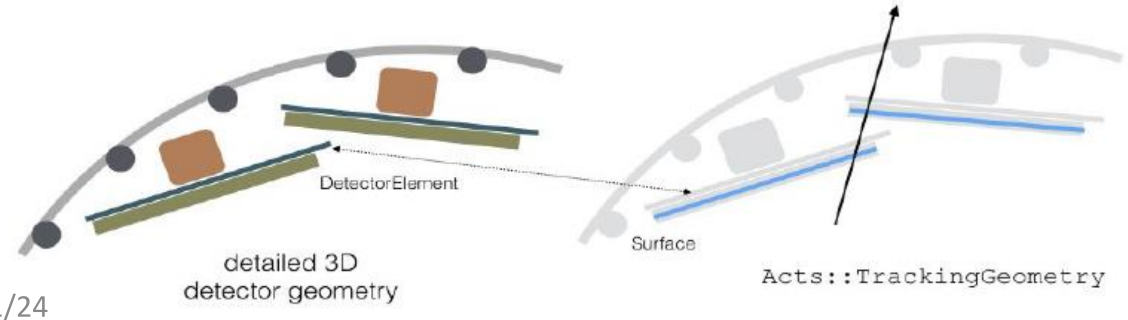
- Reconstruction Framework (**EICrecon** http://eicrecon.epic-eic.org/)
  - Hits digitization
  - Track finding/fitting:

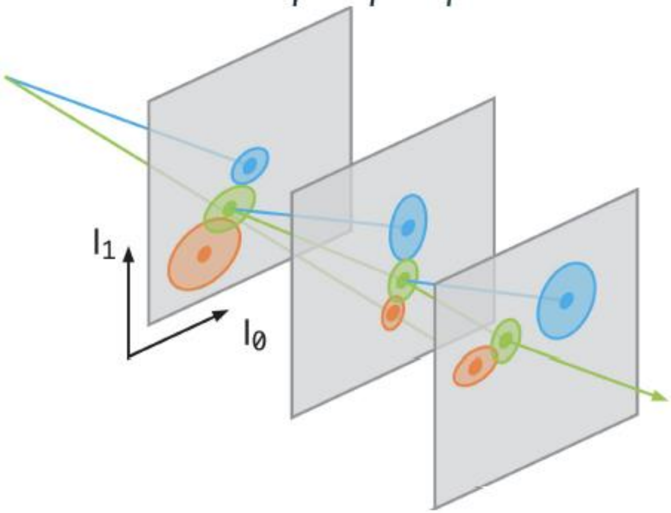
arXiv:1910.03128

A Common Tracking Software

- **Combinatorial Kalman Filter (CKF)**
  - Combined track finding and fitting
  - Realistic seeder to provide initial guess







Track reconstruction workflow

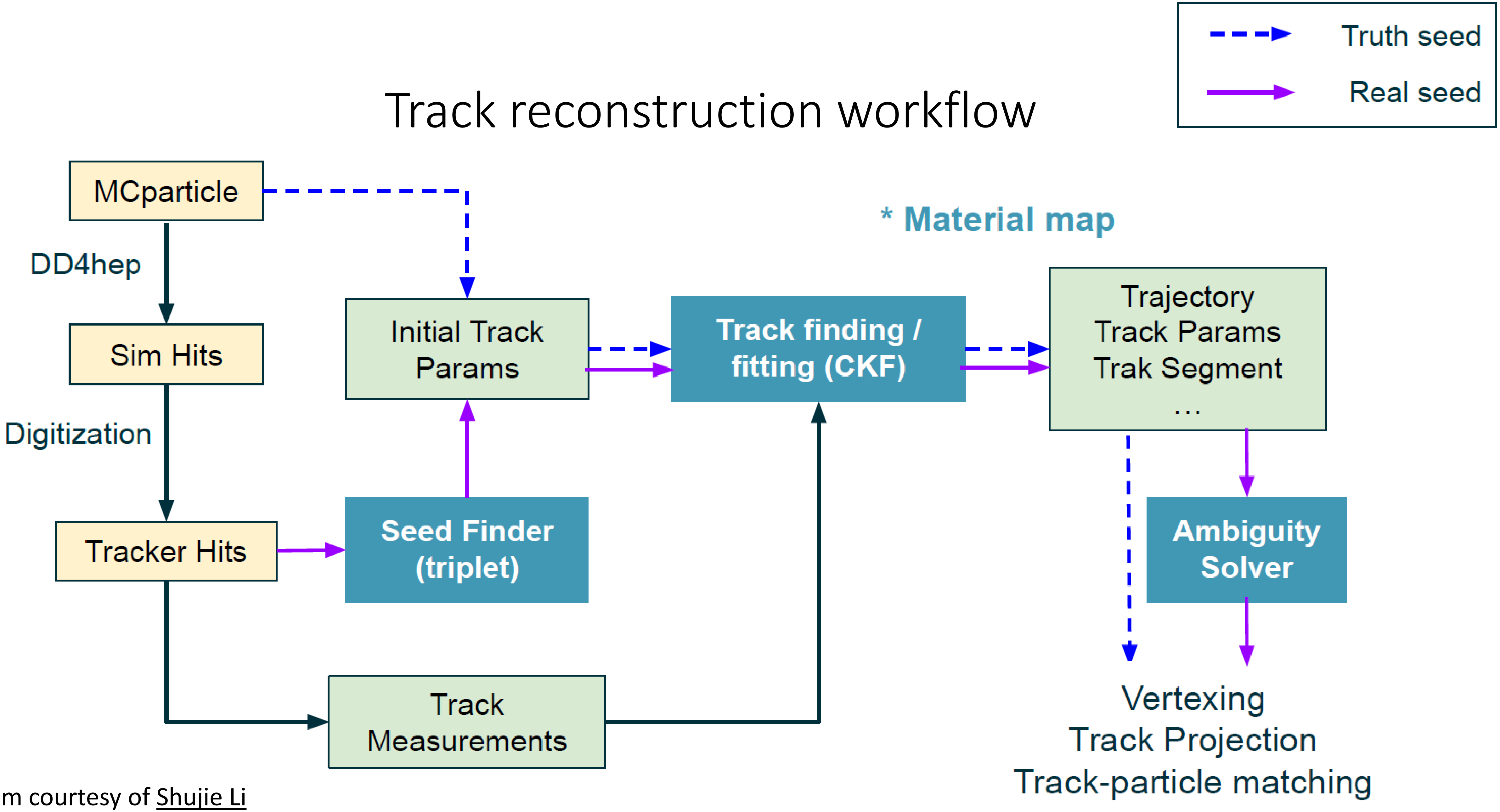


Diagram courtesy of Shujie Li

Seeding and tracking

<u>Seeding implementations</u>

Truth (Ideal) seeding: For every generated, final-state (i.e. status = 1) charged particle, we use the true charge, q/p, theta, phi, and generation vertex to form the seed. Option to smear the initial parameters is included.

Real seeding: The ACTS orthogonal seeder outputs a set of seeds, with each seed consisting of 3 space points. The seeds need to fulfill certain expectations for a particle moving in a uniform magnetic field. The seed finder and seed filter settings configure the allowed search region and tolerances. We then fit the seed space points to determine the charge, q/p, theta, phi, and the initial position coordinates.

A given seed is then passed into the ACTS CKF for track finding and fitting. At the acceptance edges, the truth-seeded tracks can sometimes have fewer than 3 hits. For real seeding, we can have seed duplicates.

We don't currently have an implementation where we separate track finding and fitting. For example, we don't use Geant information to send the true hits for a given particle to a KF.

https://acts.readthedocs.io/en/latest/tracking.html
https://acts.readthedocs.io/en/latest/core/seeding.html#seeding-core

Truth-seeded tracking Status

Track reconstruction workflow

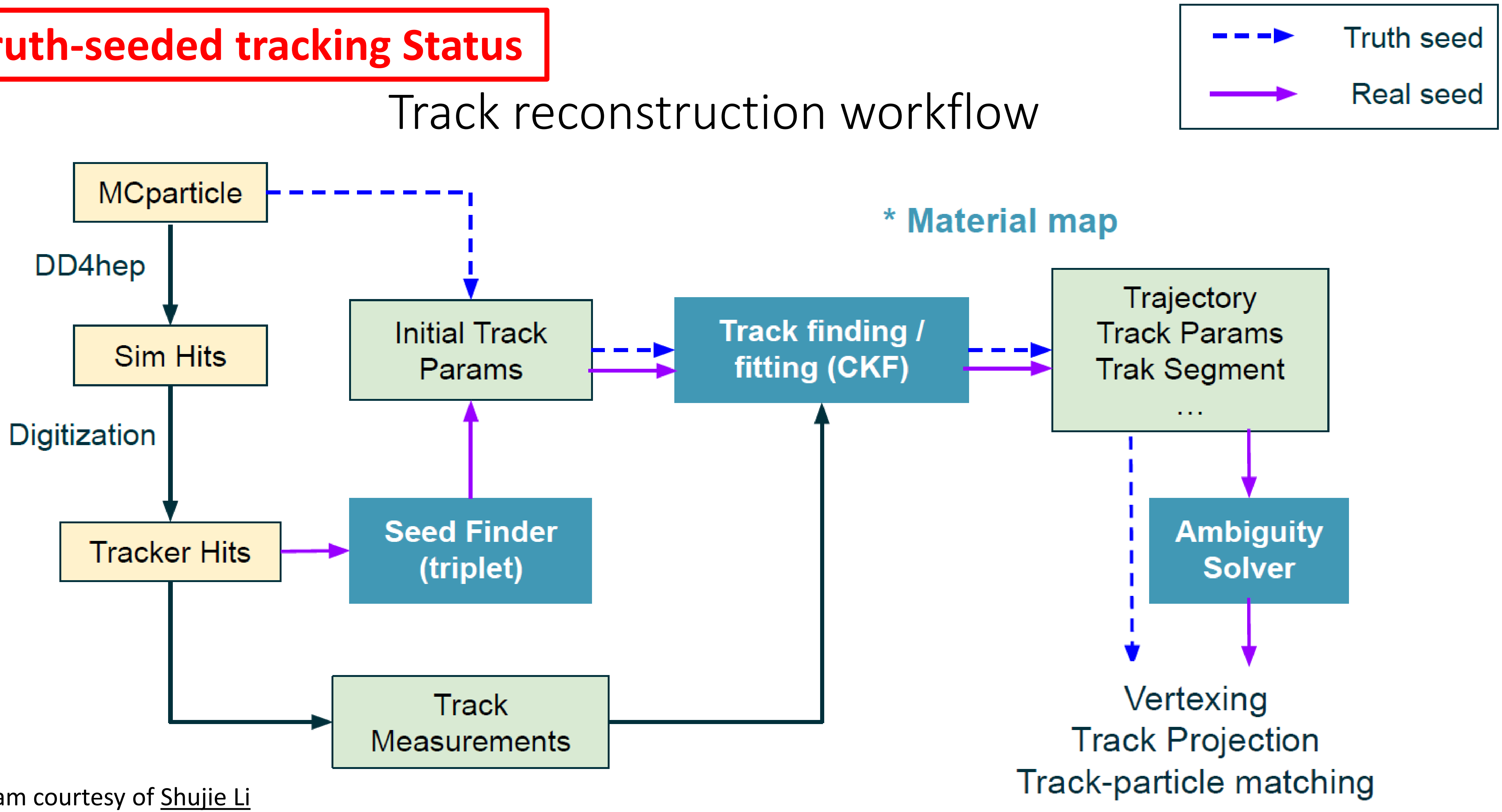


Diagram courtesy of Shujie Li

Single-particle studies over entire beam-spot range

https://github.com/eic/documents/blob/master/reports/general/Note-Simulations-BeamEffects.pdf

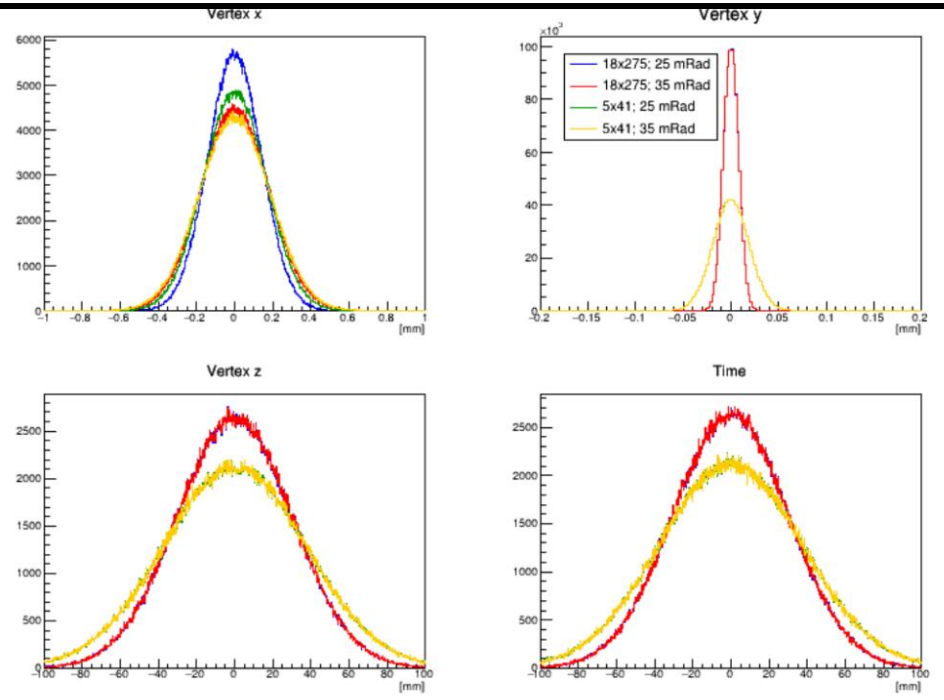


Figure 4: Detector frame vertex position and time distributions for beam energies of 18x275 GeV and 5x41 GeV and crossing angels of 25 and 35 milliradians.

<u>Particle Generation</u>

Single negative muons

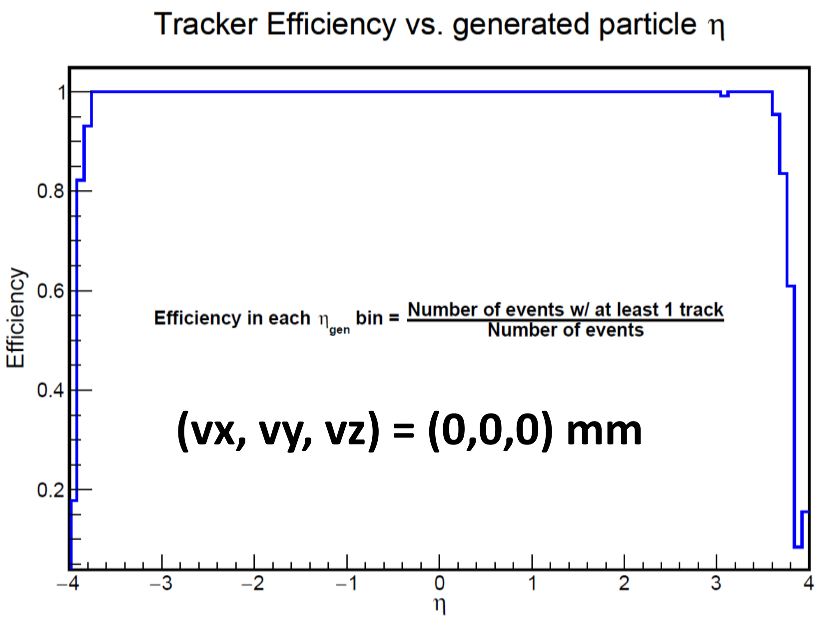
Uniform momentum [0.5,20] GeV/c

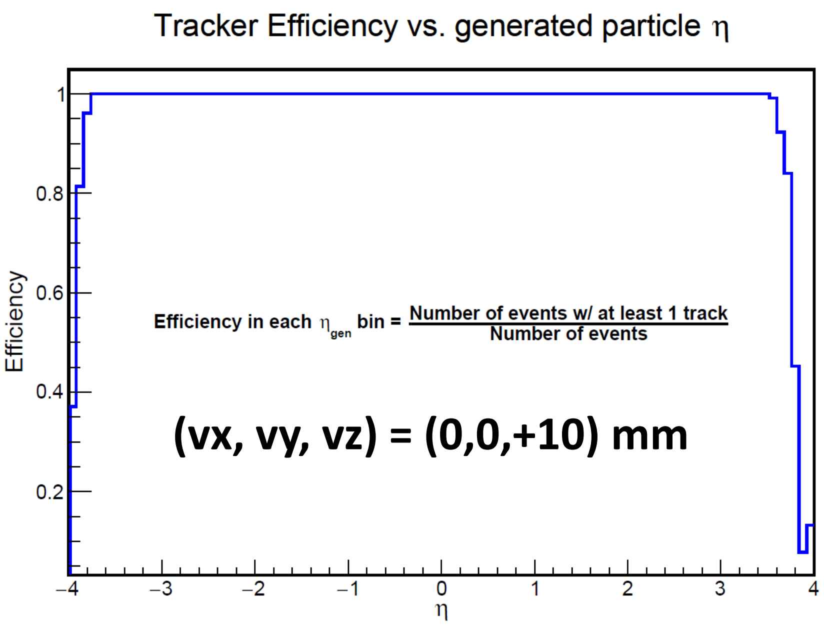
Uniform eta [-4,4]

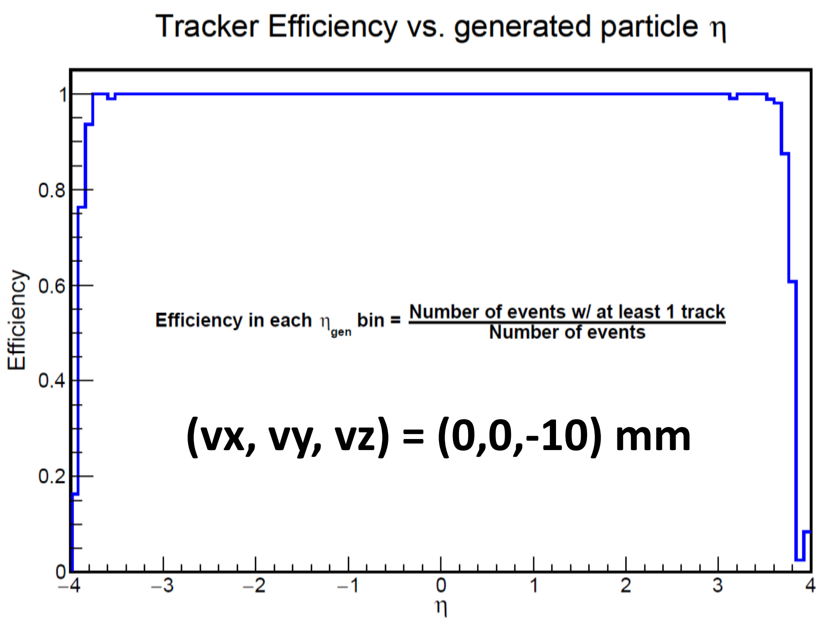
Uniform phi [0,2Pi]

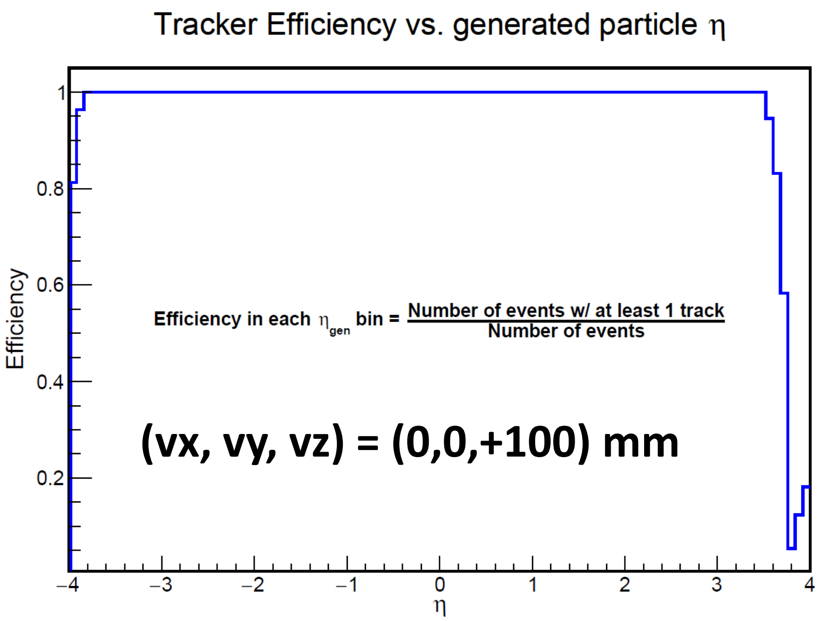
<u>Generation Vertex</u>

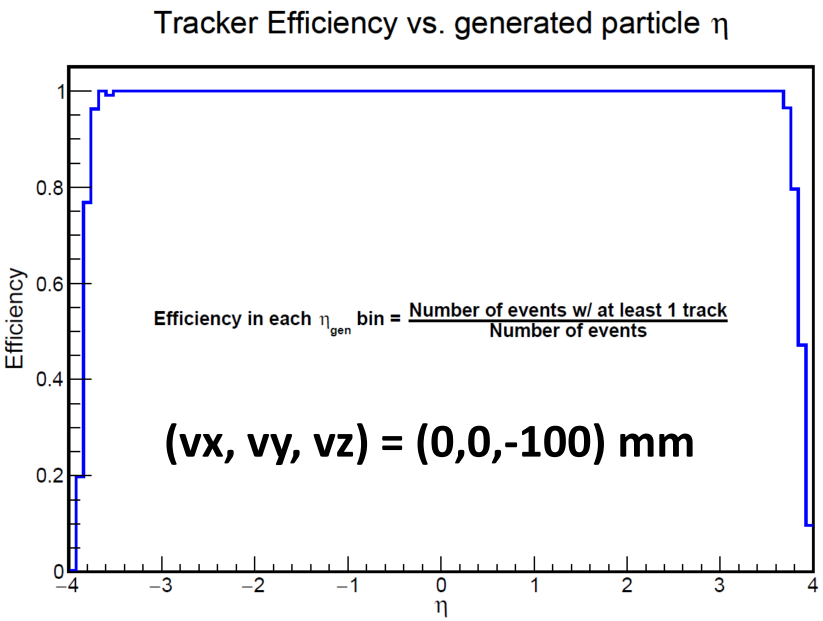
1. (vx, vy, vz) = (0,0,0) mm
2. (vx, vy, vz) = (0,0,10) mm
3. (vx, vy, vz) = (0,0,-10) mm
4. (vx, vy, vz) = (0,0,100) mm
5. (vx, vy, vz) = (0,0,-100) mm



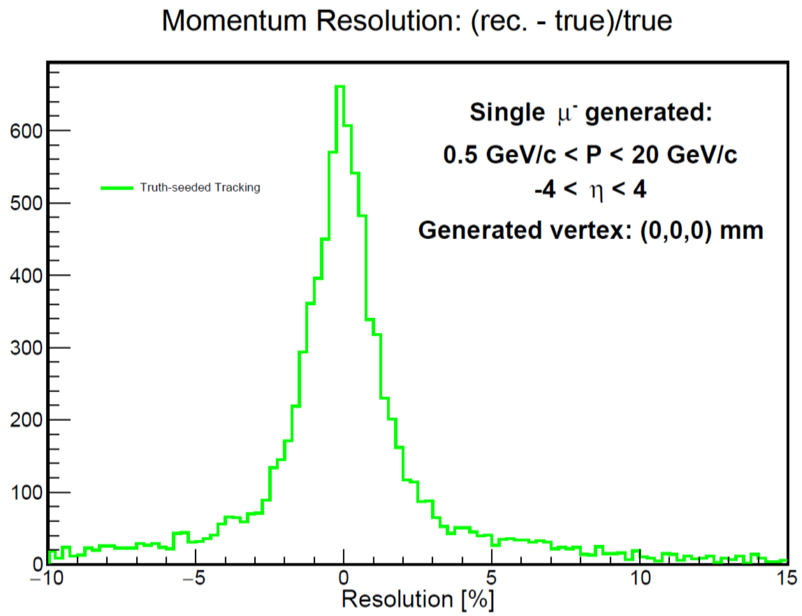


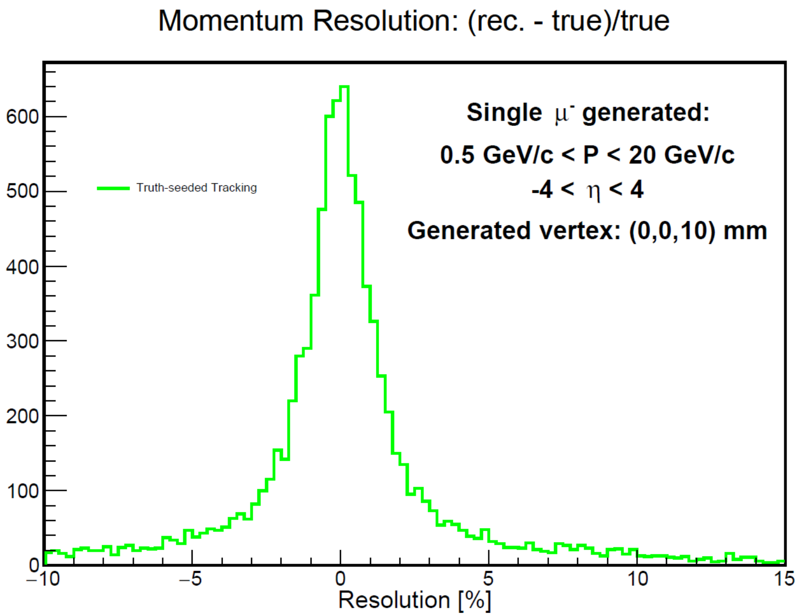


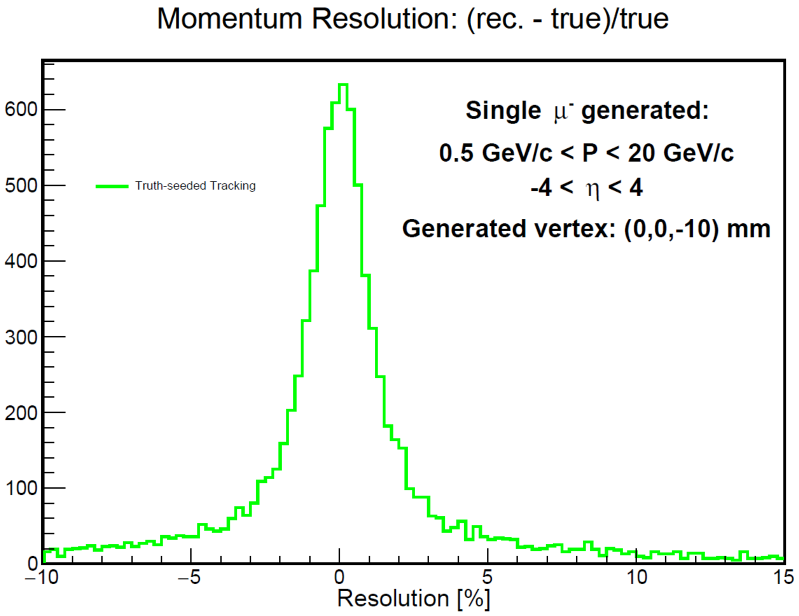


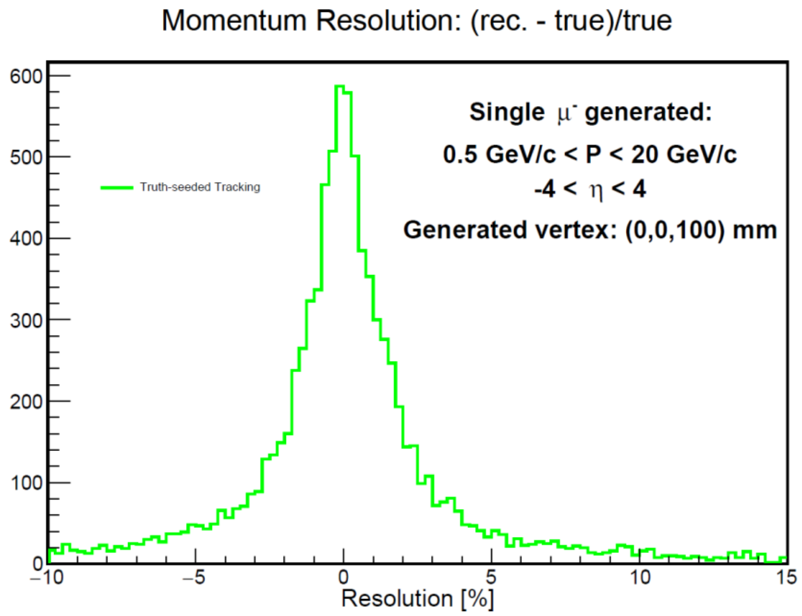


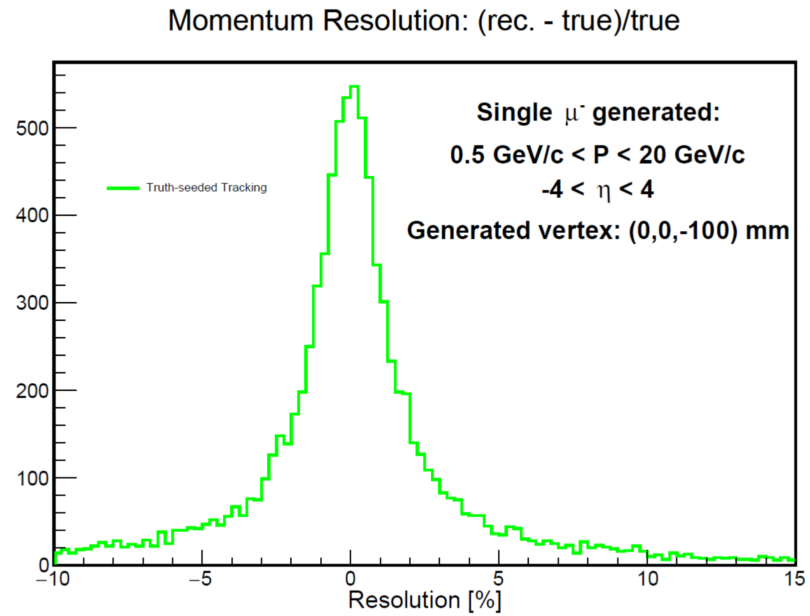
Efficiency as a function of pseudo-rapidity for <u>truth-seeded</u> tracking.











Momentum resolution for <u>truth-seeded</u> tracking.

Results for theta, phi, position parameters, and charge identification also look reasonable. Plots can be found here.

Plan is to repeat previous more-differential studies of the resolution and incorporate all this into the official detector benchmarks repository.

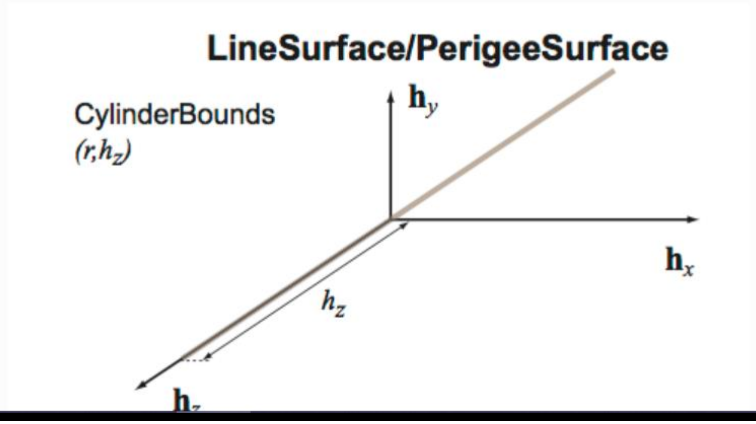
Truth seeding: Initial position parameters

- We set the initial track parameters based on the generated particle's momentum vector, charge, and creation point. This information is then fed into the CKF in addition to a line surface (perigee surface) along the z axis through (0,0,0).
- Since the generated particle's momentum vector may not be tangential to the cylinder surrounding the line surface when its creation point is not at (x,y) = (0,0), we should not pass the particle's creation point as (Loc_a, Loc_b).
- Instead, we should track the particle back to its point of closest approach to (x,y) = (0,0), and calculate the corresponding z value. This is now implemented correctly in EICRecon ([PR #1291](PR #1291)).

`Acts::LineSurface` is a special kind of surface that depends on a reference direction, typically the unit momentum direction $\vec{d}$ of a particle. A point in space is considered *on surface* if and only if it coincides with the point of closest approach between the direction vector $\vec{d}$ and the line direction vector $\vec{z}$. As such, the function `Acts::LineSurface::globalToLocal()` can fail, if the argument position and direction do not fulfill this criterion. It is pure-virtual, meaning that it can not be instantiated on its own.

class `LineSurface` : *public* Acts::Surface

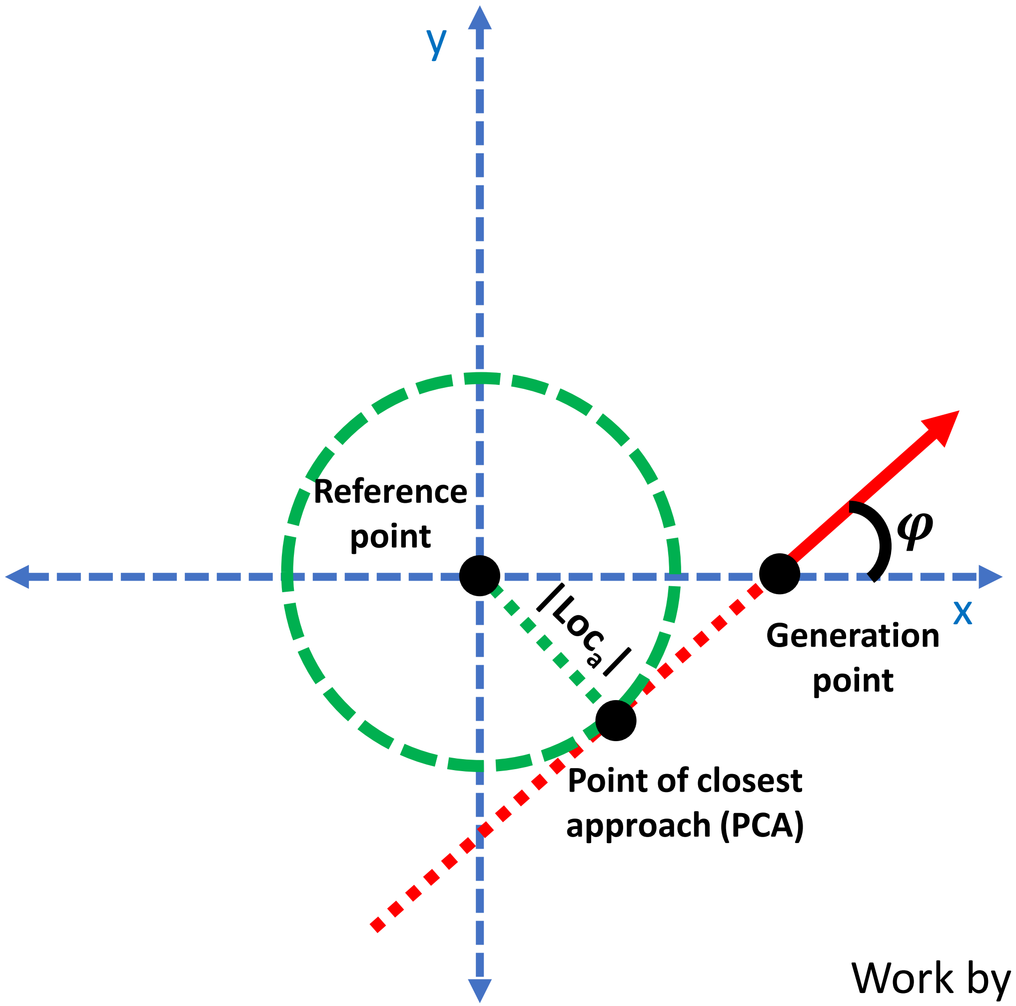
Base class for a linear surfaces in the TrackingGeometry to describe dirft tube, straw like detectors or the Perigee It inherits from Surface.



https://acts.readthedocs.io/en/latest/core/geometry/surfaces.html#line-surface

Work by Harsimran Singh

Truth seeding: Initial position parameters

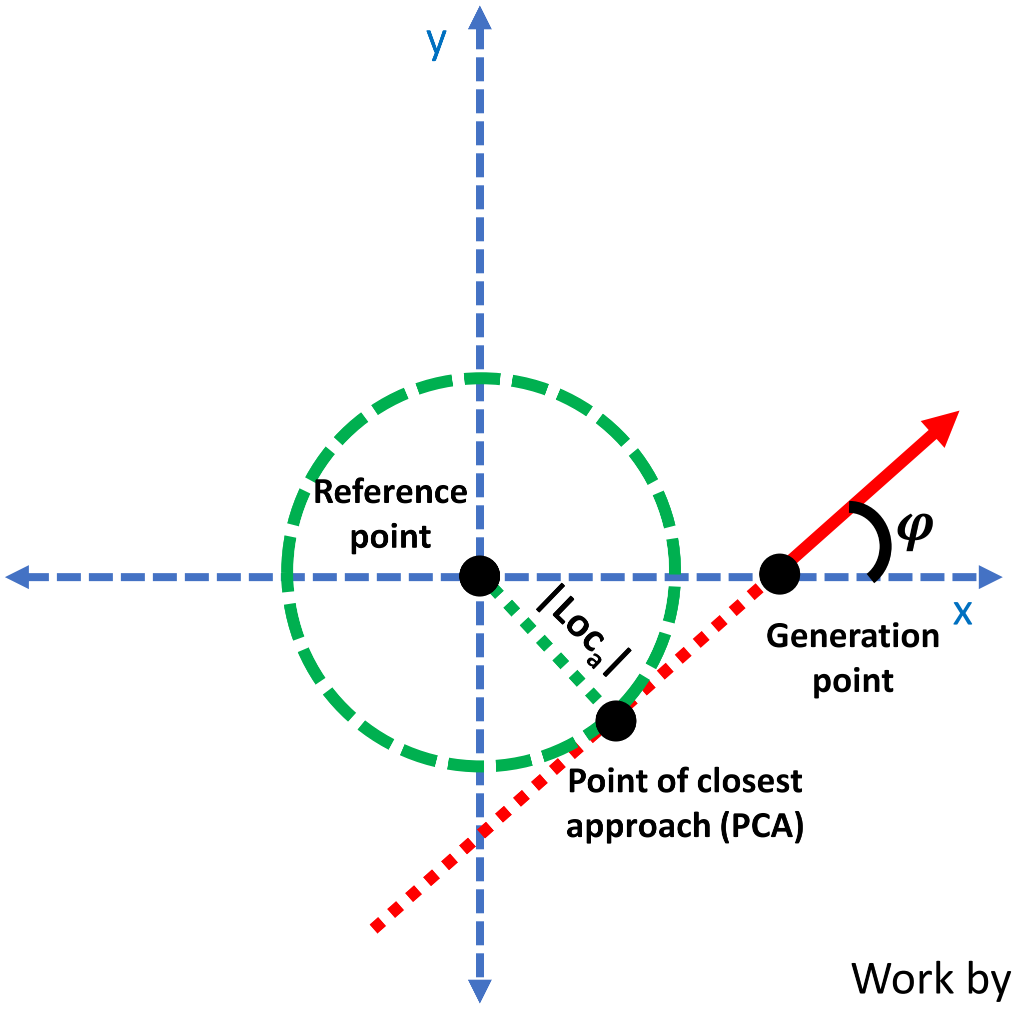


- Example: generation point at (x,y,z) = (+1,0,0) mm. $|Loc_a| = |\sin\varphi|$ under 'straight line' approximation.

- The sign of Loc$_a$ will be positive if the particle at the PCA transits clockwise around the line surface (reference point) through (x,y) = (0,0). It will be negative if it transits counterclockwise. See here: https://github.com/acts-project/acts/blob/main/Core/src/Surfaces/LineSurface.cpp#L80-L123.

Work by Harsimran Singh

Truth seeding: Initial position parameters



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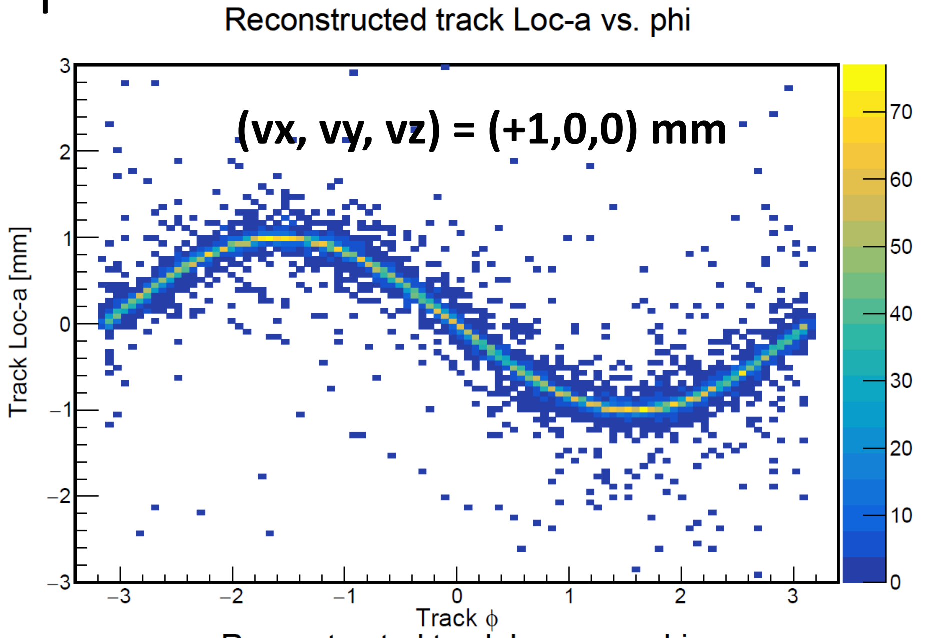
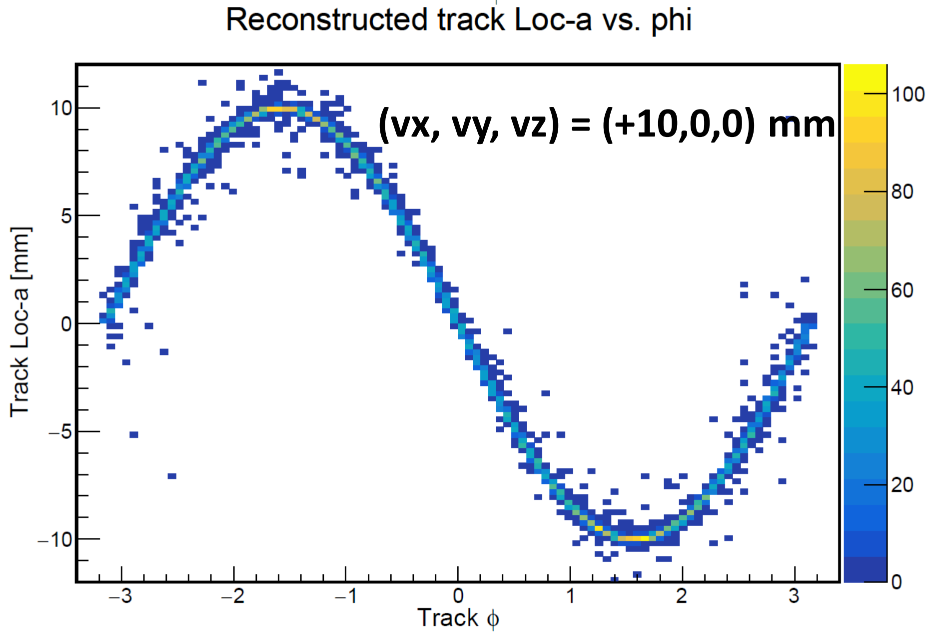
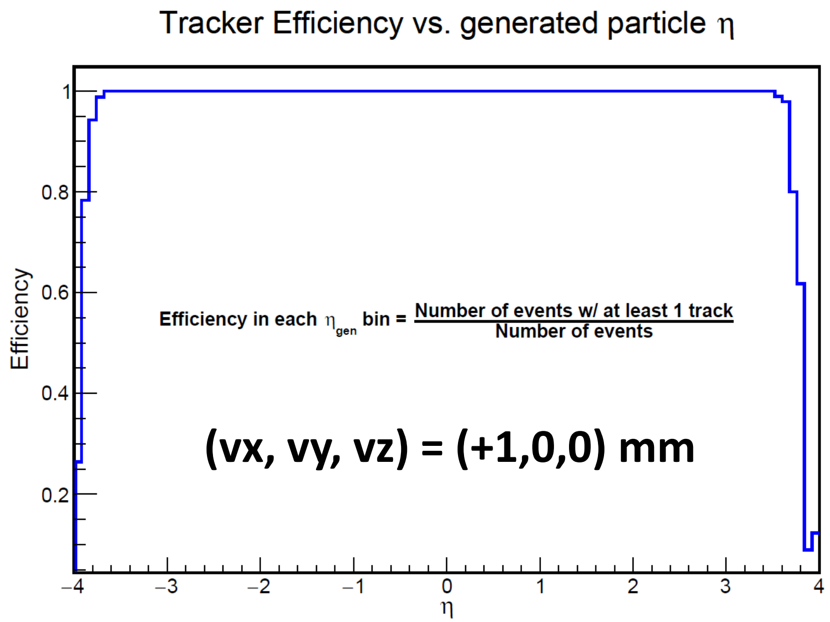
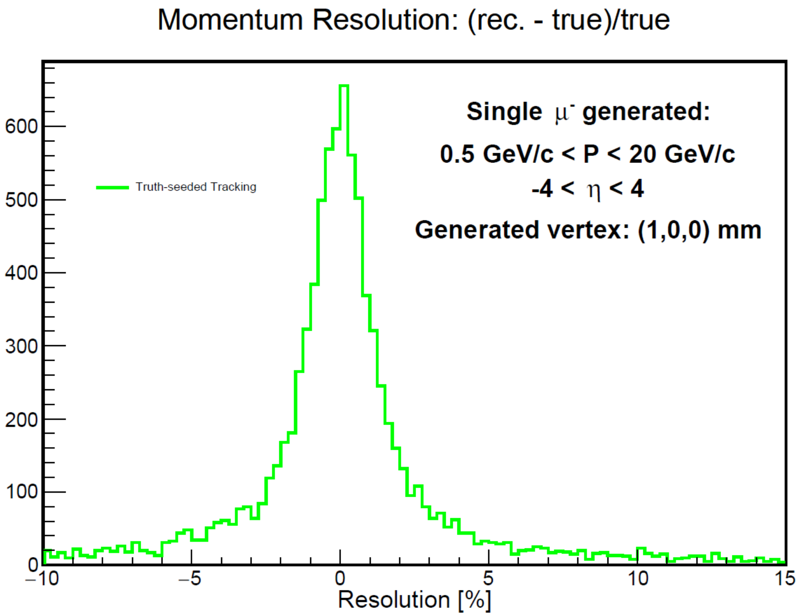
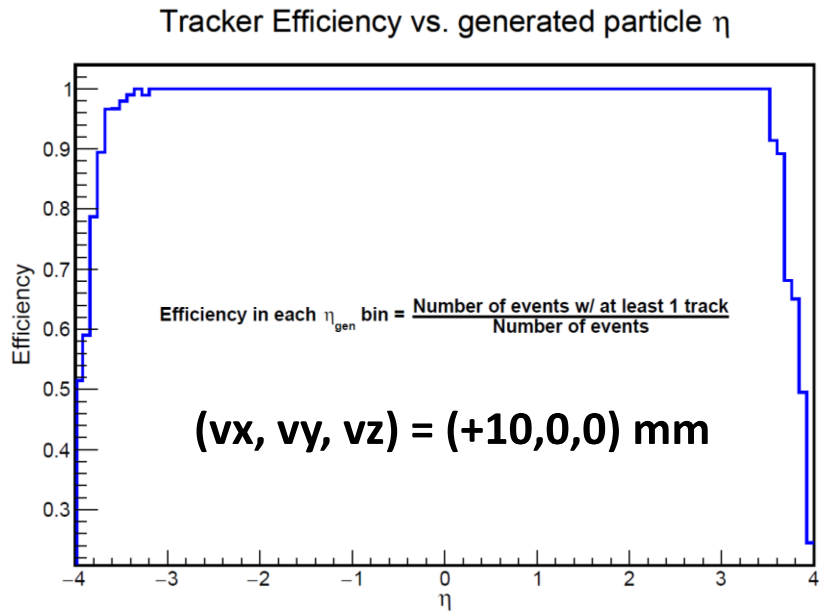


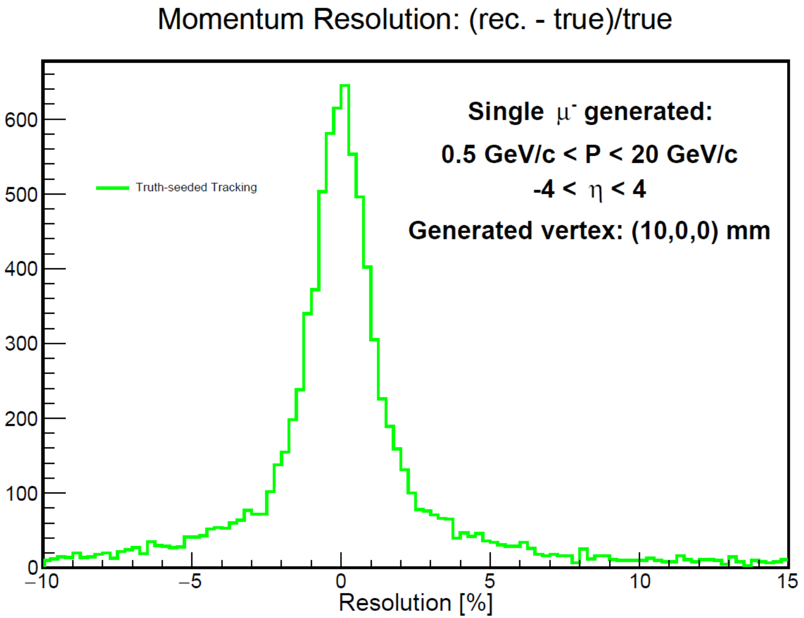


Truth-seeded tracking for off-beamline particles









Summary of truth-seeded tracking

- Single-particle truth-seeded tracking looks reasonable for particles generated both on and away from the z axis. Detailed performance studies need to be performed.
- With updated truth-seeding, studies of primary vertex finding and fitting performance is ongoing.

Real-seeded tracking Status

Track reconstruction workflow

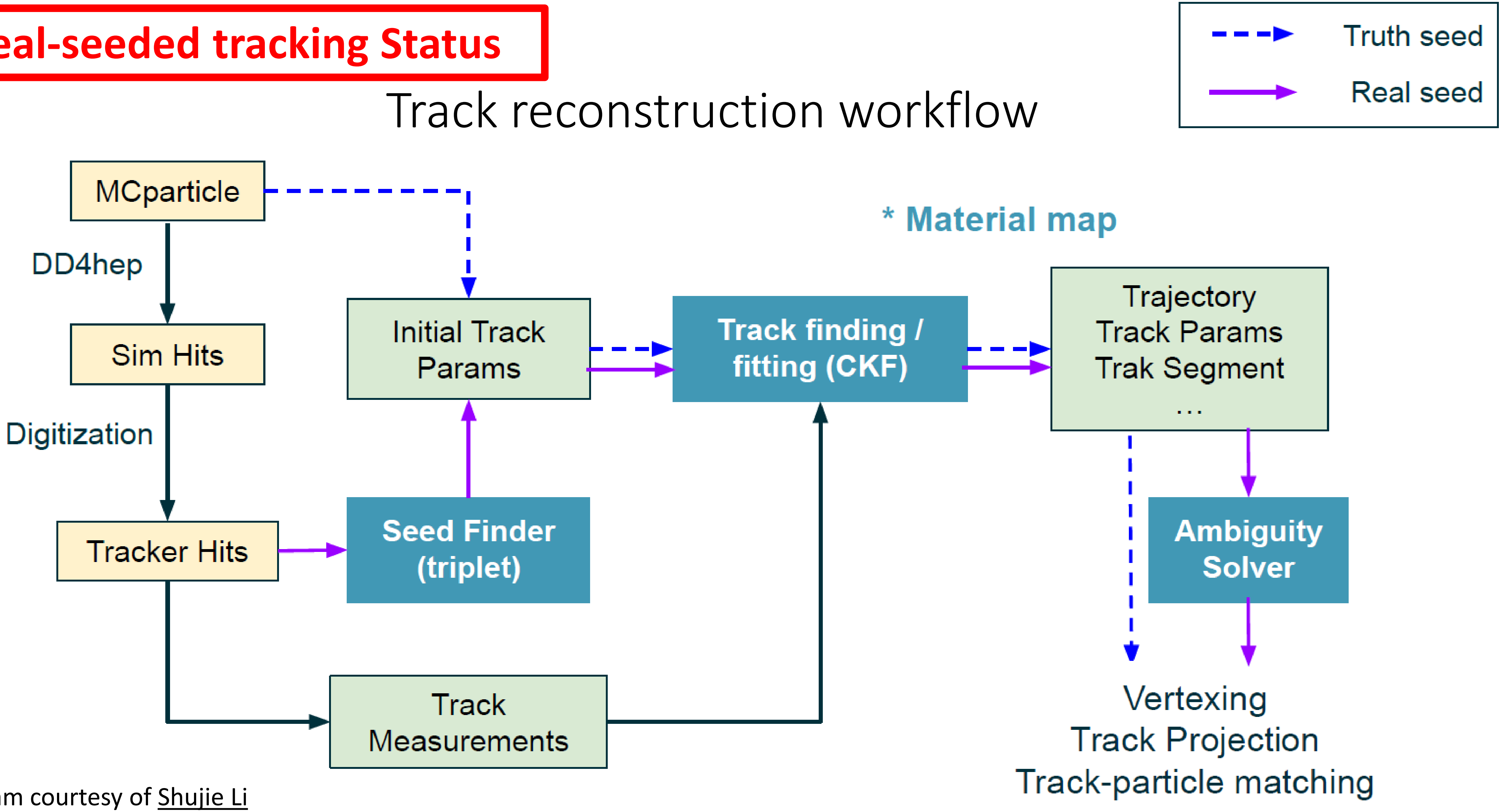
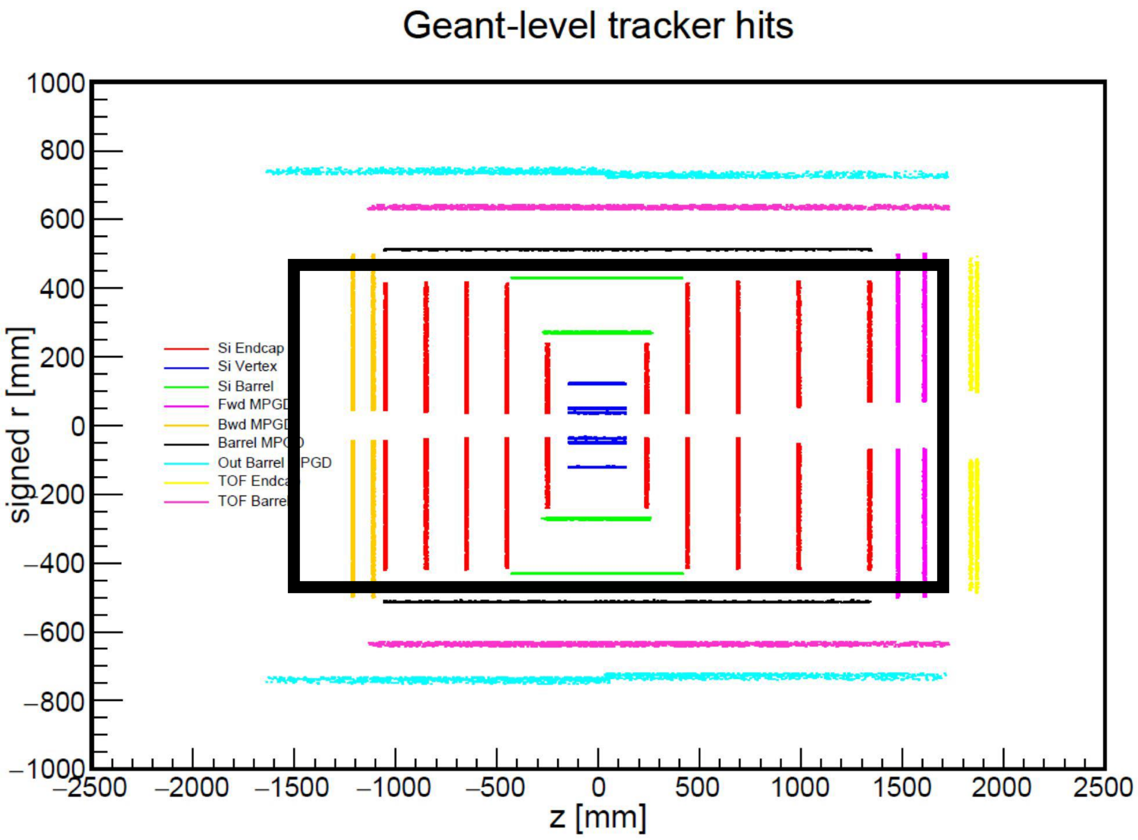


Diagram courtesy of Shujie Li

Seed finding using the ACTS orthogonal seeder

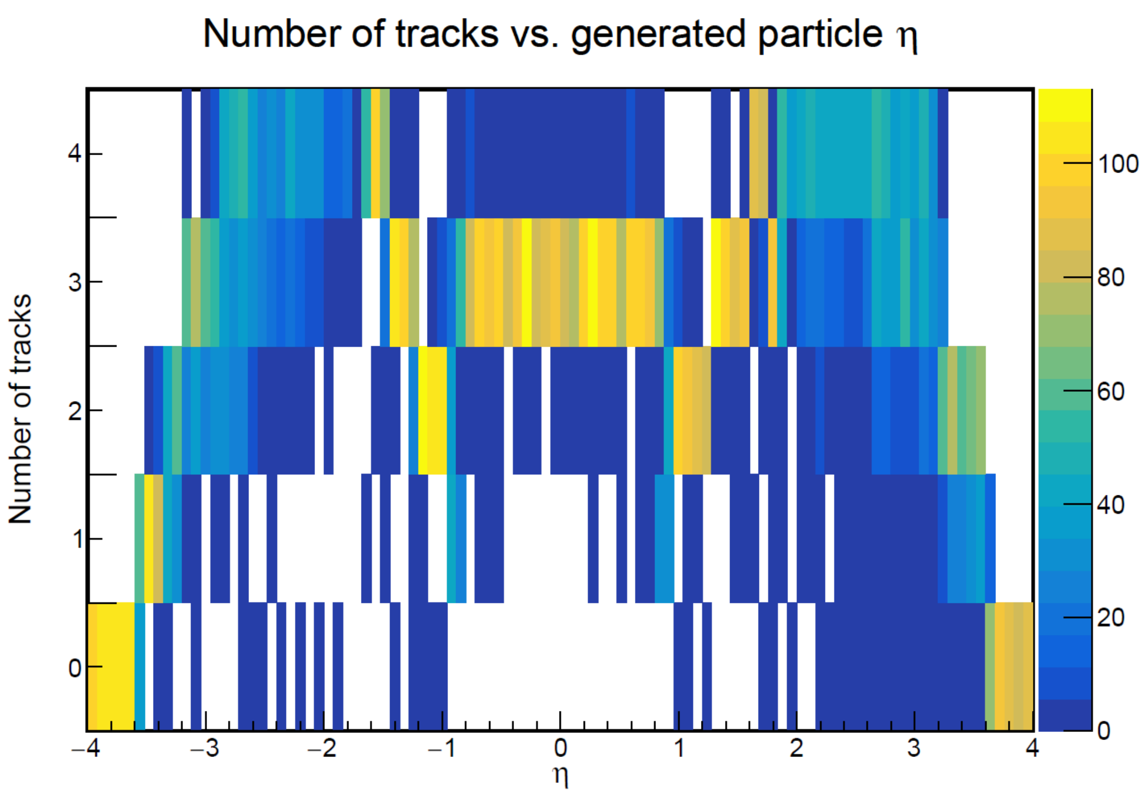
We search for seeds in part of our tracking volume – mostly in our MAPS silicon pixel detectors.



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

Single-particle tracking multiplicity



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Seed duplicates – particles have multiple seeds

If we have a particle at mid-rapidity which hits layers L0, L1, L2, L3, and L4, then we can make the following combinations:

1. L0,L1,L2
2. L0,L2,L3
3. L0,L3,L4
4. ✖ L0,L1,L3
5. ✖ L0,L1,L4
6. ✖ L0,L2,L4
7. ✖ L1,L2,L3
8. ✖ L1,L2,L4
9. ✖ L1,L3,L4
10. ✖ L2,L3,L4

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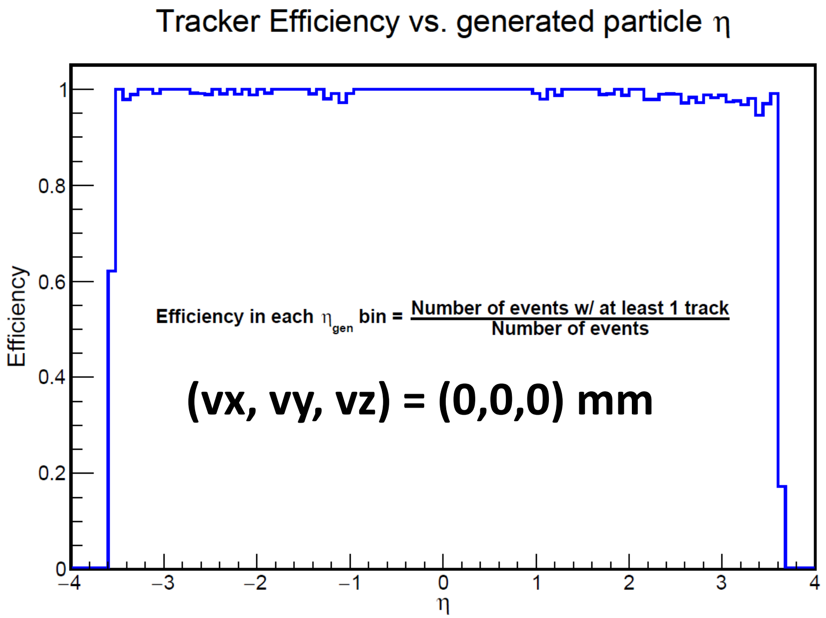
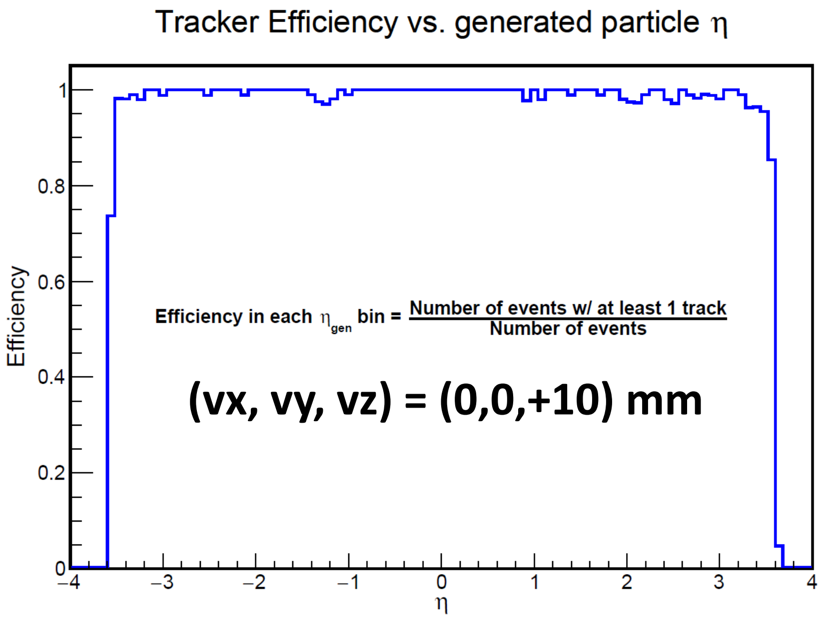
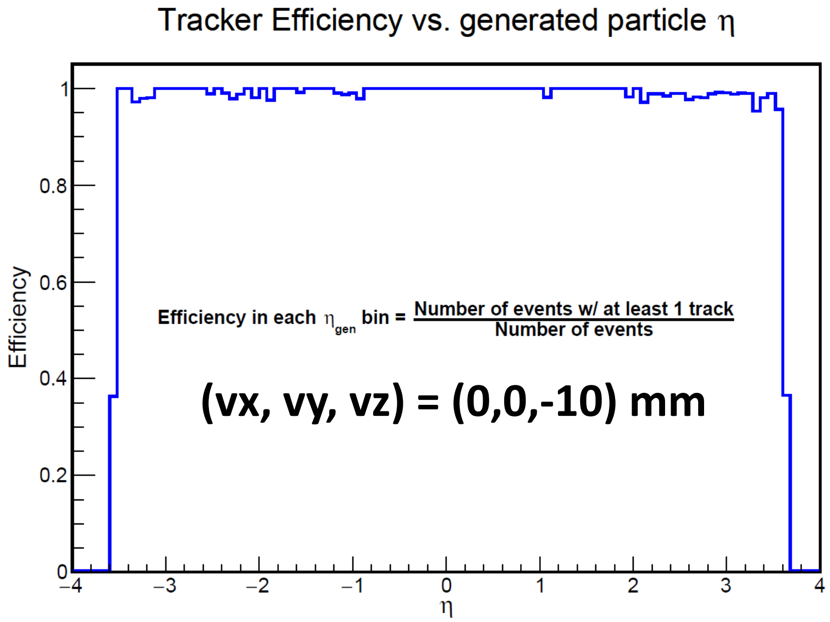
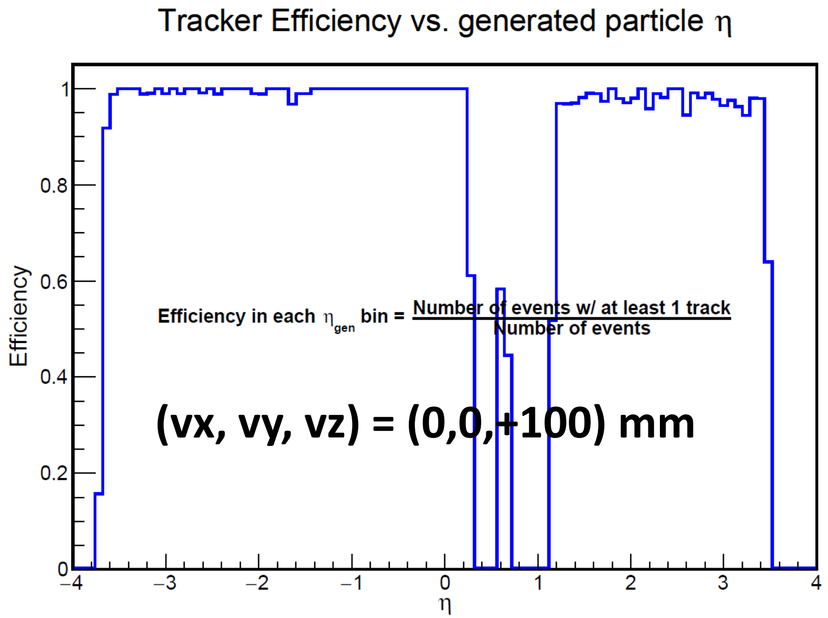
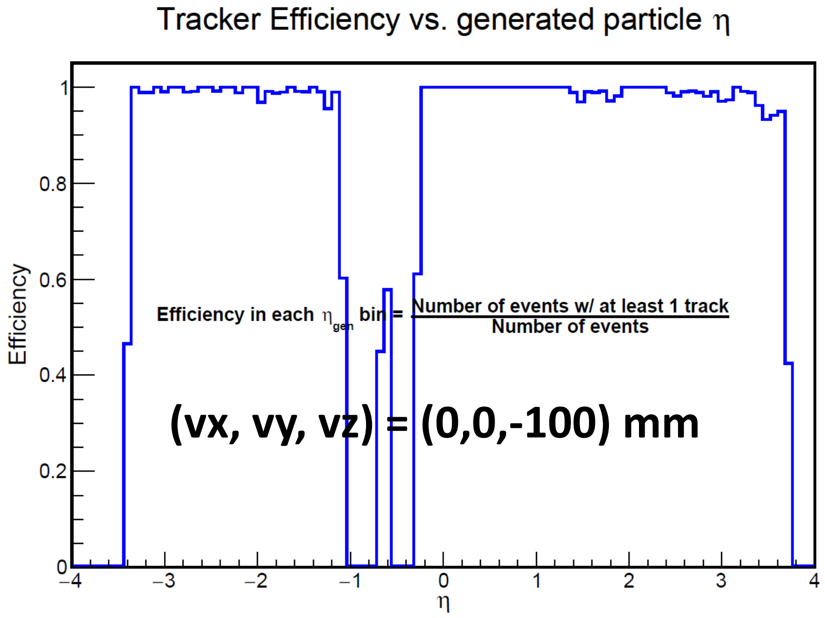


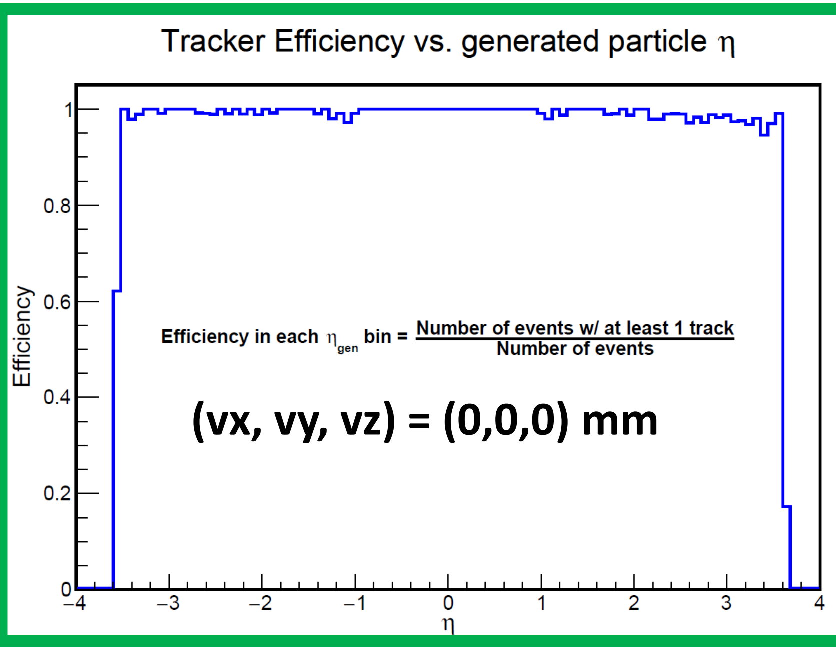


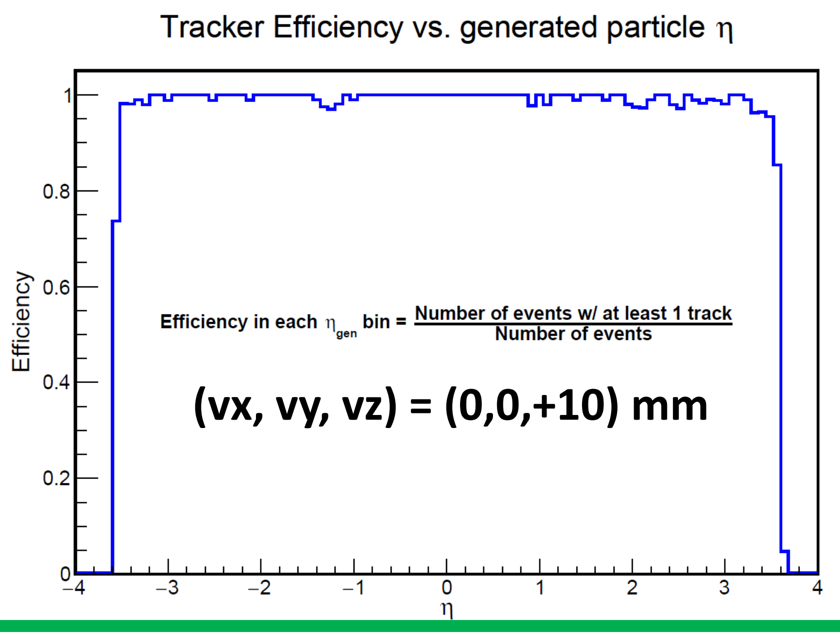


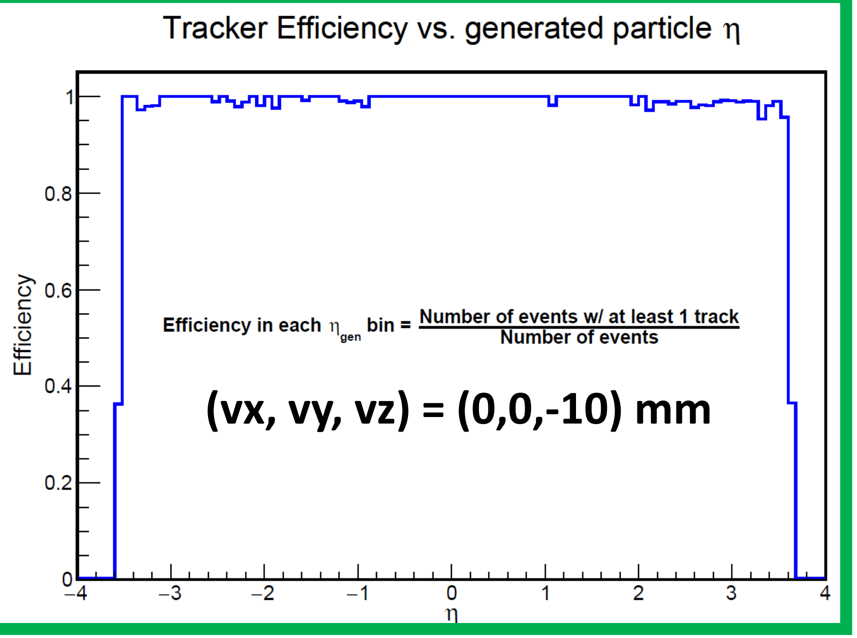


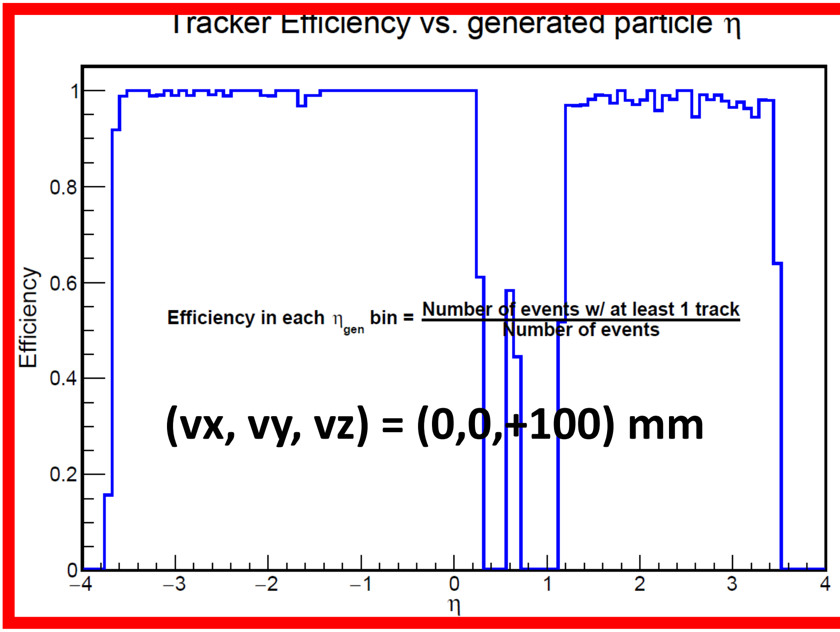


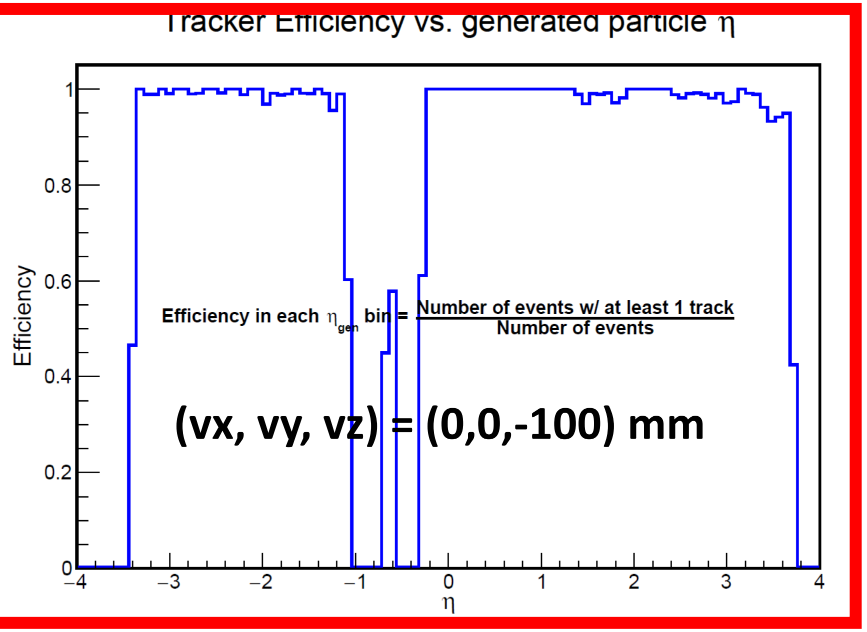
Efficiency as a function of pseudo-rapidity for real-seeded tracking.







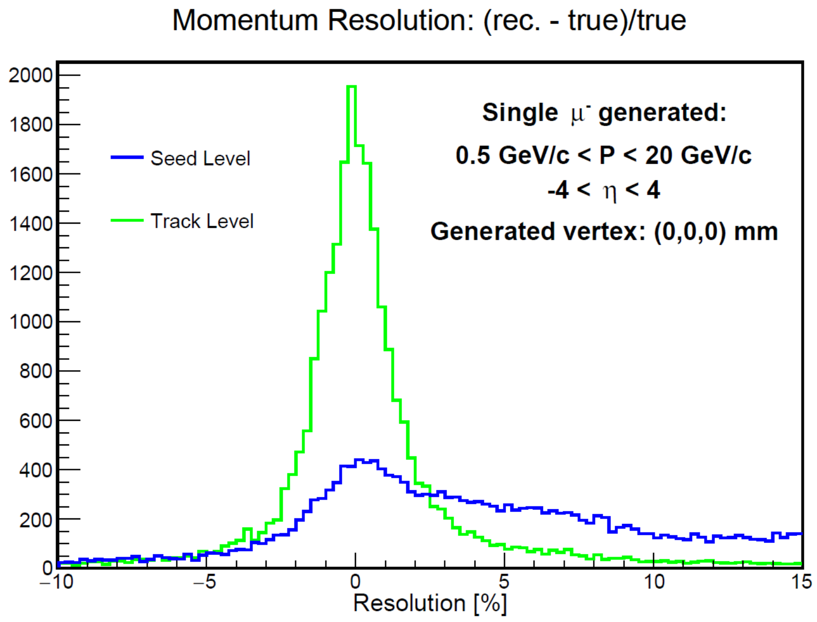


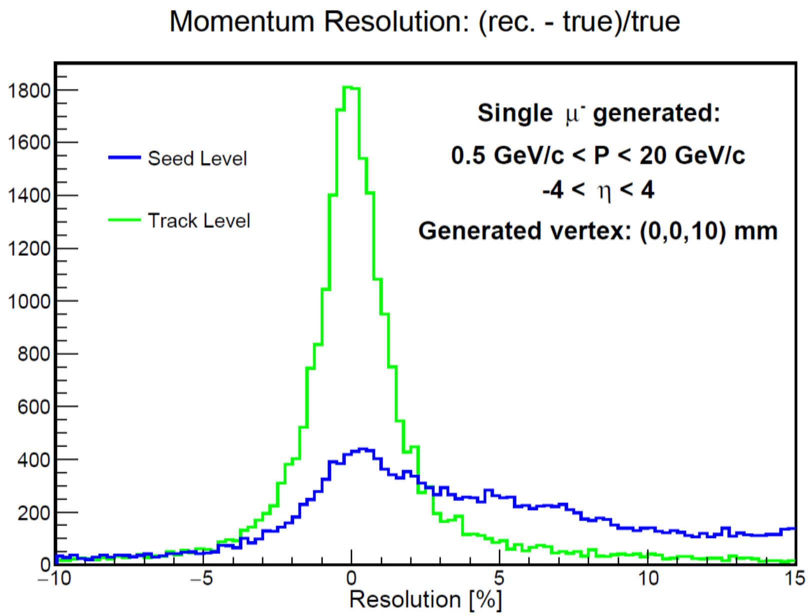


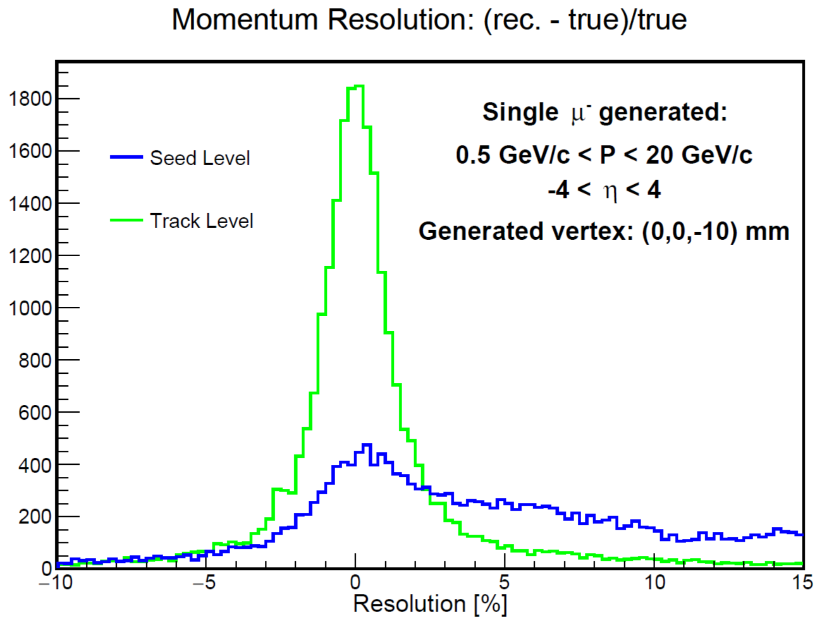
Efficiency as a function of pseudo-rapidity for real-seeded tracking.

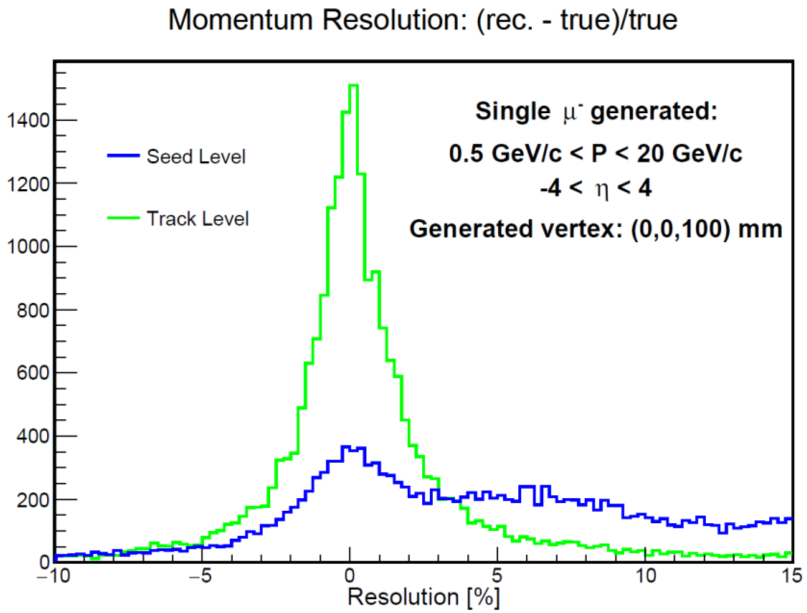
Efficiency looks good over the whole detector acceptance when |z| < 10 mm.

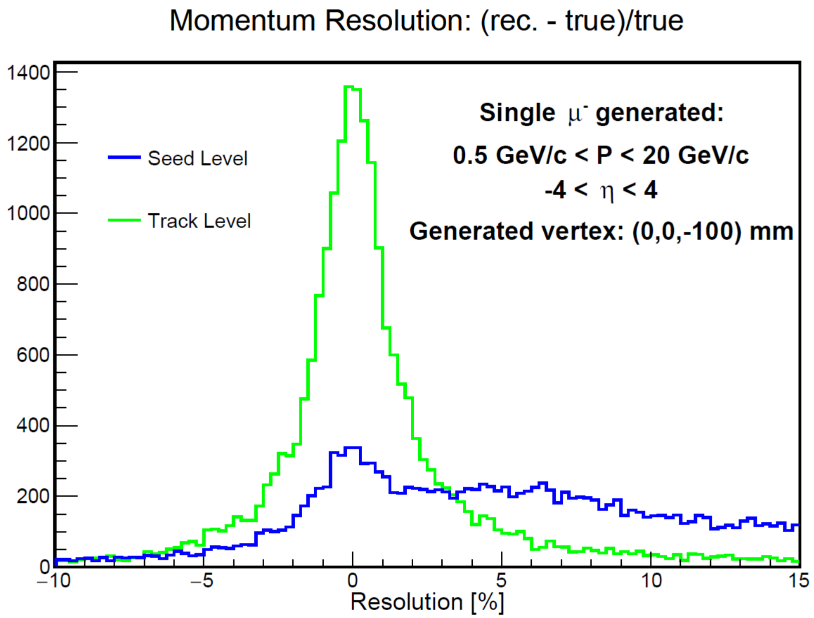
We see an acceptance gap for z = ±100 mm. We need to check our seed-finder parameters.











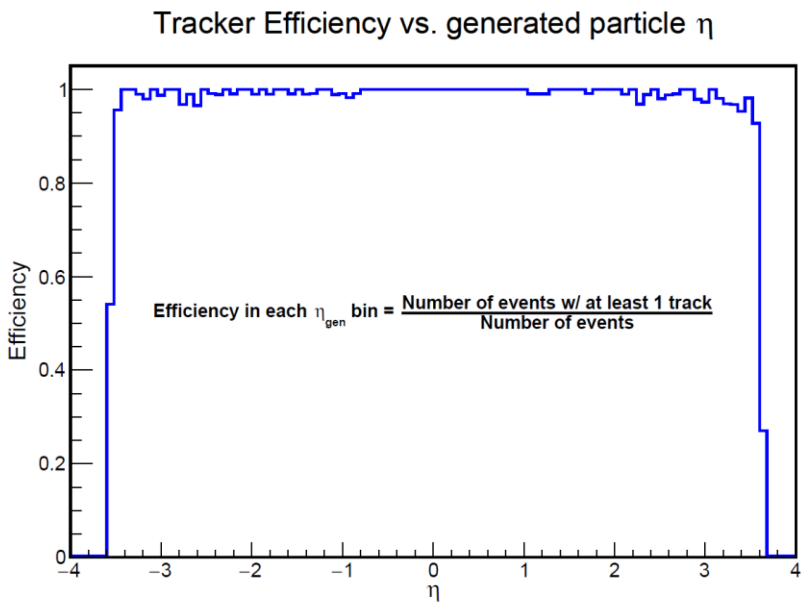
Momentum resolution for real-seeded tracking.

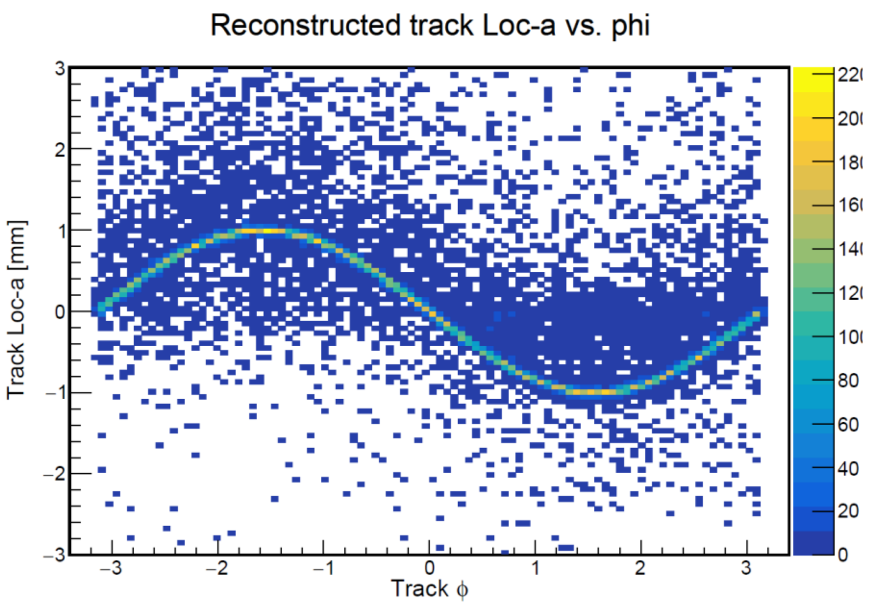
Results for theta, phi, position parameters, and charge identification also look reasonable. Plots can be found here.

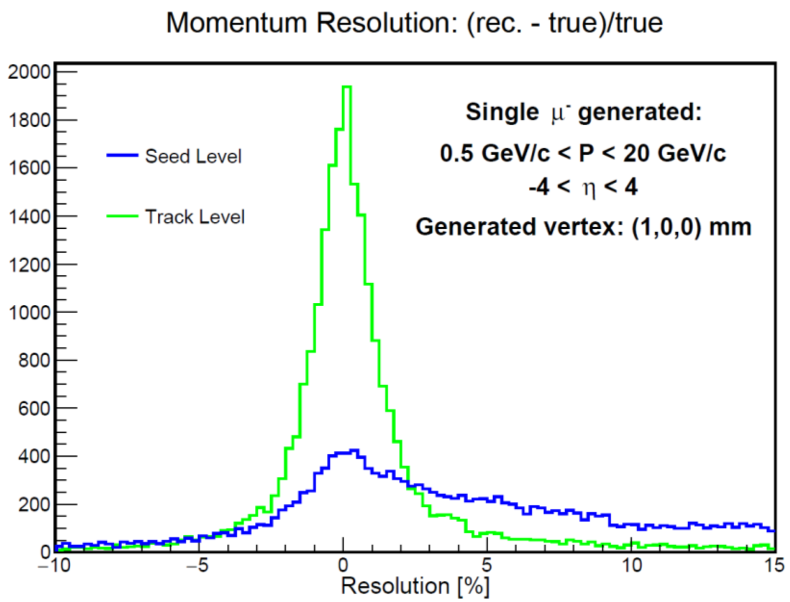
Plan is to repeat previous more-differential studies of the resolution and incorporate all this into the official detector benchmarks repository.

Real-seeded tracking for off-beamline tracking

(vx, vy, vz) = (+1,0,0) mm







Real-seeded tracking shows expected behavior for particles generated off the z axis.

We currently apply a beamline DCA cut of 3mm in the seed finder.

Ongoing work: how does initial error matrix affect our tracking?

Parameters Covariance matrix

$$C = \begin{bmatrix} \sigma^2(l_0) & \mathrm{cov}(l_0, l_1) & \mathrm{cov}(l_0, \phi) & \mathrm{cov}(l_0, \theta) & \mathrm{cov}(l_0, q/p) \\ . & \sigma^2(l_1) & \mathrm{cov}(l_1, \phi) & \mathrm{cov}(l_1, \theta) & \mathrm{cov}(l_1, q/p) \\ . & . & \sigma^2(\phi) & \mathrm{cov}(\phi, \theta) & \mathrm{cov}(\phi, q/p) \\ . & . & . & \sigma^2(\theta) & \mathrm{cov}(\theta, q/p) \\ . & . & . & . & \sigma^2(q/p) \end{bmatrix}$$

Evolution of parameters covariance

$$C^f = J \cdot C^i \cdot J^T,$$

$$J = \begin{bmatrix} \frac{\partial l_0^f}{\partial l_0^i} & \cdots & \frac{\partial l_0^f}{\partial (q/p)^i} \\ \vdots & \ddots & \vdots \\ \frac{\partial (q/p)^f}{\partial l_0^i} & \cdots & \frac{\partial (q/p)^f}{\partial (q/p)^i} \end{bmatrix},$$

Hit residual and chi-square

$$\mathrm{Res} = \vec{\mathrm{x}}_{\mathrm{calibrated}} - \mathrm{H}\vec{\mathrm{x}}_{\mathrm{predicted}}$$

$$\chi^2 = \mathrm{Res}^{\mathrm{T}}(\mathrm{C}_{\mathrm{calibrated}} + \mathrm{H}\mathrm{C}_{\mathrm{predicted}}\mathrm{H}^{\mathrm{T}})^{-1}\mathrm{Res}$$

H is observation matrix
$C_{calibrated}$ is measurement covariance
$C_{predicted}$ is predicted estimate covariance

Ongoing work: how does initial error matrix affect our tracking?

Parameters Covariance matrix

$$C = \begin{bmatrix} \sigma^2(l_0) & \mathrm{cov}(l_0, l_1) & \mathrm{cov}(l_0, \phi) & \mathrm{cov}(l_0, \theta) & \mathrm{cov}(l_0, q/p) \\ . & \sigma^2(l_1) & \mathrm{cov}(l_1, \phi) & \mathrm{cov}(l_1, \theta) & \mathrm{cov}(l_1, q/p) \\ . & . & \sigma^2(\phi) & \mathrm{cov}(\phi, \theta) & \mathrm{cov}(\phi, q/p) \\ . & . & . & \sigma^2(\theta) & \mathrm{cov}(\theta, q/p) \\ . & . & . & . & \sigma^2(q/p) \end{bmatrix}$$

Evolution of parameters covariance

$$C^f = J \cdot C^i \cdot J^T,$$

$$J = \begin{bmatrix} \frac{\partial l_0^f}{\partial l_0^i} & \cdots & \frac{\partial l_0^f}{\partial (q/p)^i} \\ \vdots & \ddots & \vdots \\ \frac{\partial (q/p)^f}{\partial l_0^i} & \cdots & \frac{\partial (q/p)^f}{\partial (q/p)^i} \end{bmatrix},$$

Hit residual and chi-square

$$\mathrm{Res} = \vec{\mathrm{x}}_{\mathrm{calibrated}} - \mathrm{H}\vec{\mathrm{x}}_{\mathrm{predicted}}$$

$$\chi^2 = \mathrm{Res}^{\mathrm{T}}(\mathrm{C}_{\mathrm{calibrated}} + \mathrm{H}\mathrm{C}_{\mathrm{predicted}}\mathrm{H}^{\mathrm{T}})^{-1}\mathrm{Res}$$

For Silicon endcap hits, for example, we have

$$\sigma_{xx} = \left(\frac{20\ um}{\sqrt{12}}\right)^2 = 0.000033\ mm^2$$

```
SiEndcapTrackerRecHits.position.x = 207.386734, 108.986137, 1
SiEndcapTrackerRecHits.position.y = -325.804352, -168.049530,
SiEndcapTrackerRecHits.position.z = 1349.864990, 699.864990,
SiEndcapTrackerRecHits.positionError.xx = 0.000033, 0.000033,
SiEndcapTrackerRecHits.positionError.yy = 0.000033, 0.000033,
SiEndcapTrackerRecHits.positionError.zz = 0.000000, 0.000000,
```

Ongoing work: how does initial error matrix affect our tracking?

https://github.com/eic/EICrecon/blob/main/src/algorithms/tracking/TrackSeeding.cc

```
trackparam.setLocError({0.1,0.1}); //covariance of location
trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```

These are the errors we currently set on the initial track parameters that go into the CKF from the seeder.

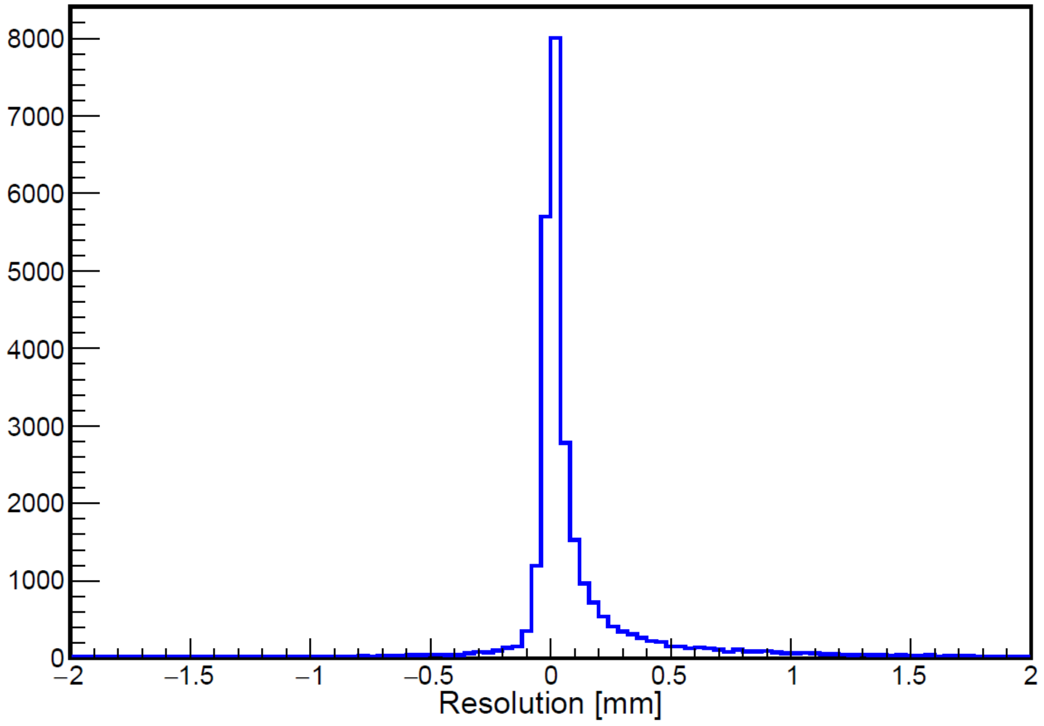
These values should be guided by the parameter resolutions *at the seed level*, and the effects of adjusting these parameters should be studied. We want to find the 'sweet spot' for these values.

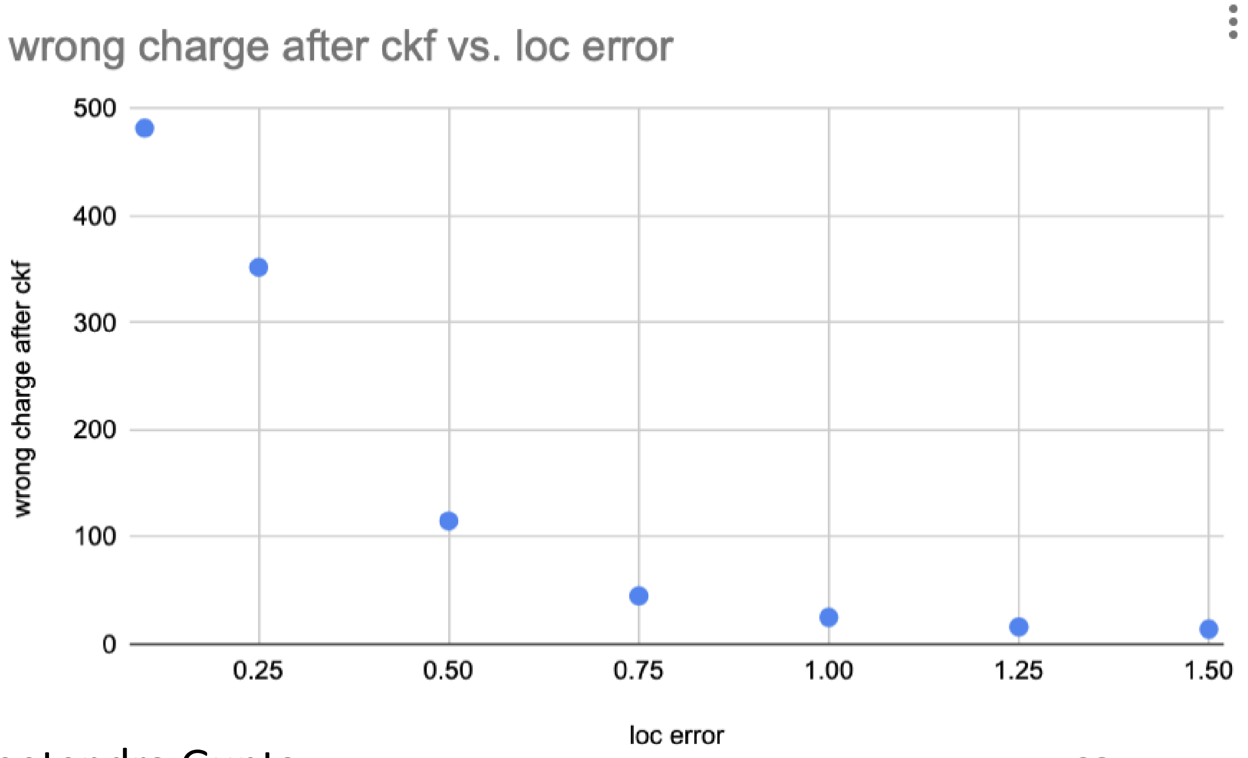
Ongoing work: how does initial error matrix affect our tracking?

Single μ^- generated:
0.5 GeV/c < P < 20 GeV/c
$-4 < \eta < 4$
Generated vertex: (0,0,0) mm

```
trackparam.setLocError({0.1,0.1}); //covariance of location
trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```

Seed ACTS loc-a Resolution: (seed - true)





Work by Jeetendra Gupta

Ongoing work: how does initial error matrix affect our tracking?

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Generated vertex: (0,0,0) mm

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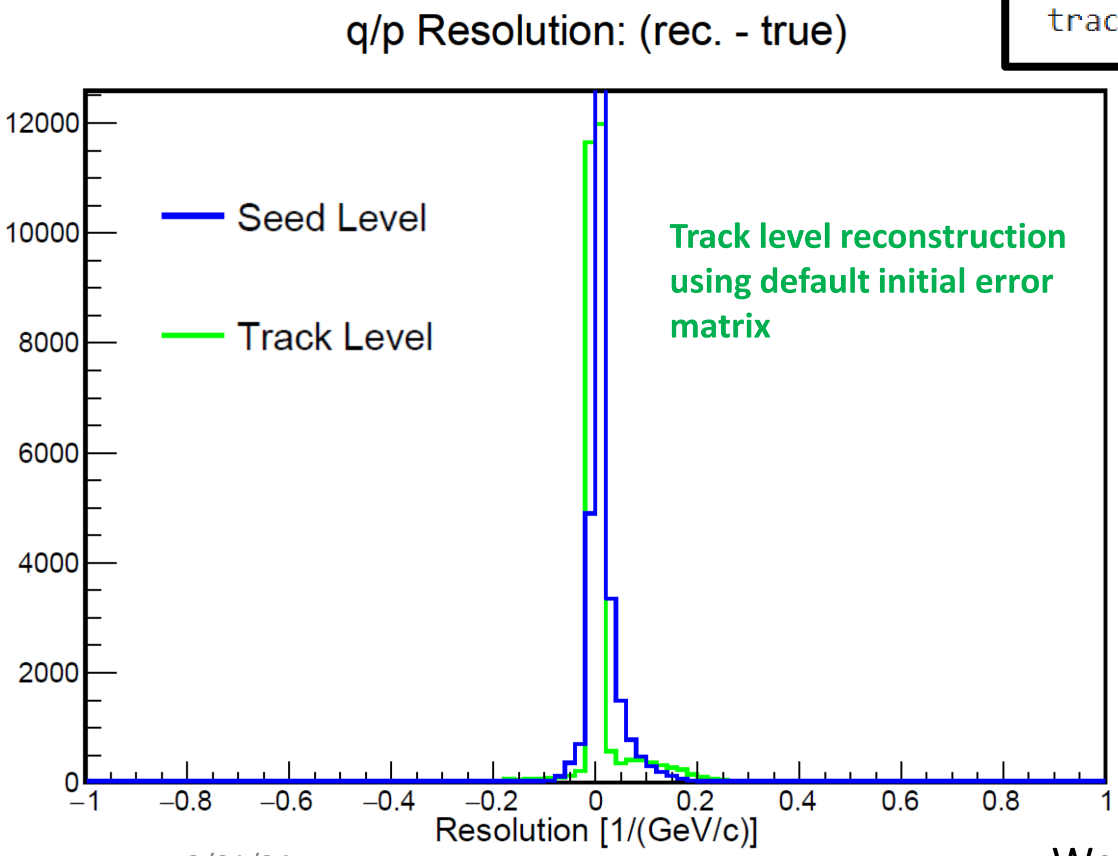
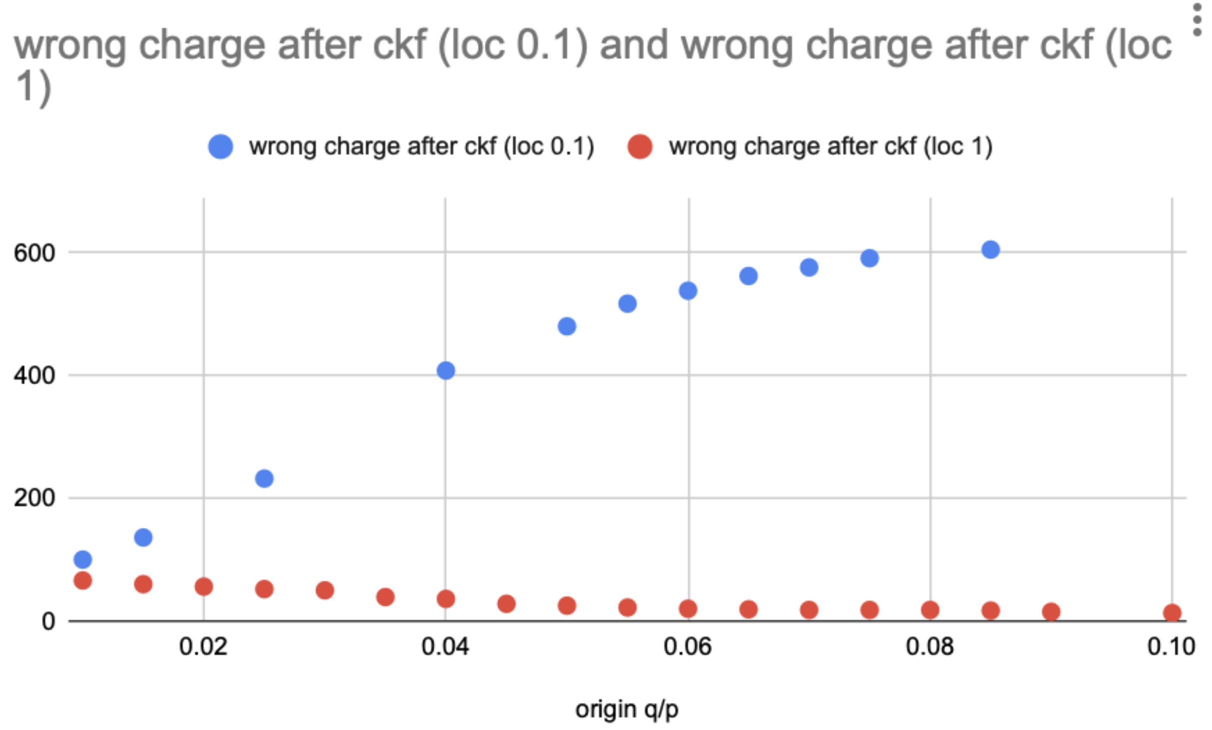
trackparam.setTimeError(0.1); // error on time
```





Work by Jeetendra Gupta

Ongoing work: how does initial error matrix affect our tracking?

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0.5 GeV/c < P < 20 GeV/c
-4 < η < 4
Generated vertex: (0,0,0) mm

```
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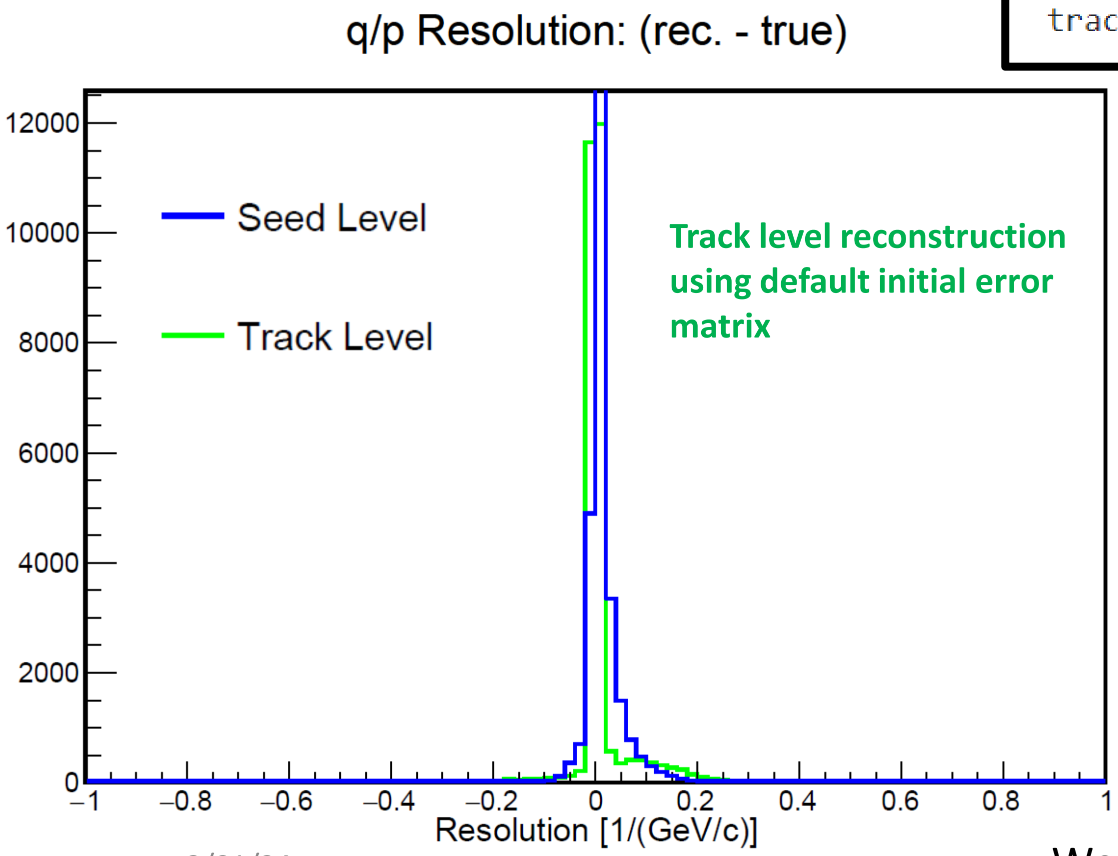
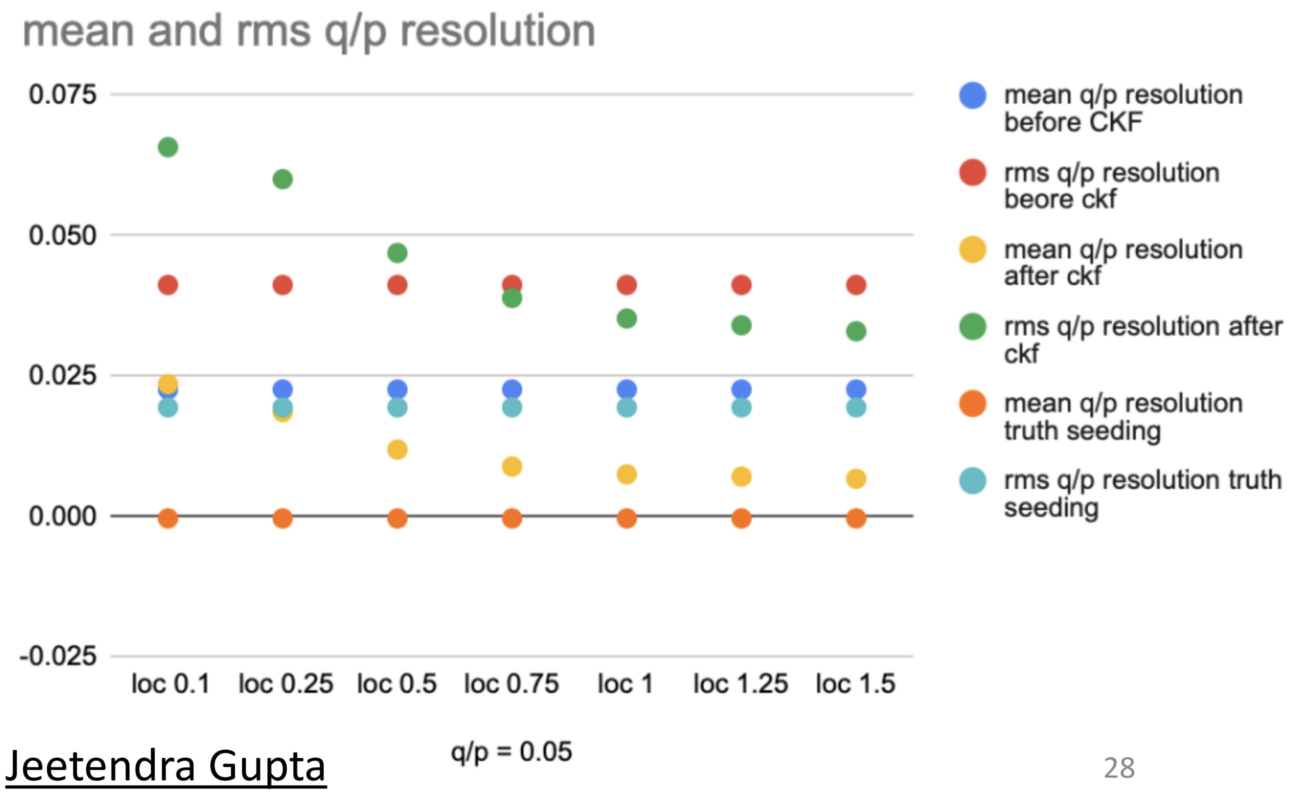
trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```





Work by Jeetendra Gupta

Ongoing work: how does initial error matrix affect our tracking?

Single μ^- generated:

0.5 GeV/c < P < 20 GeV/c

$-4 < \eta < 4$

Generated vertex: (0,0,0) mm

```
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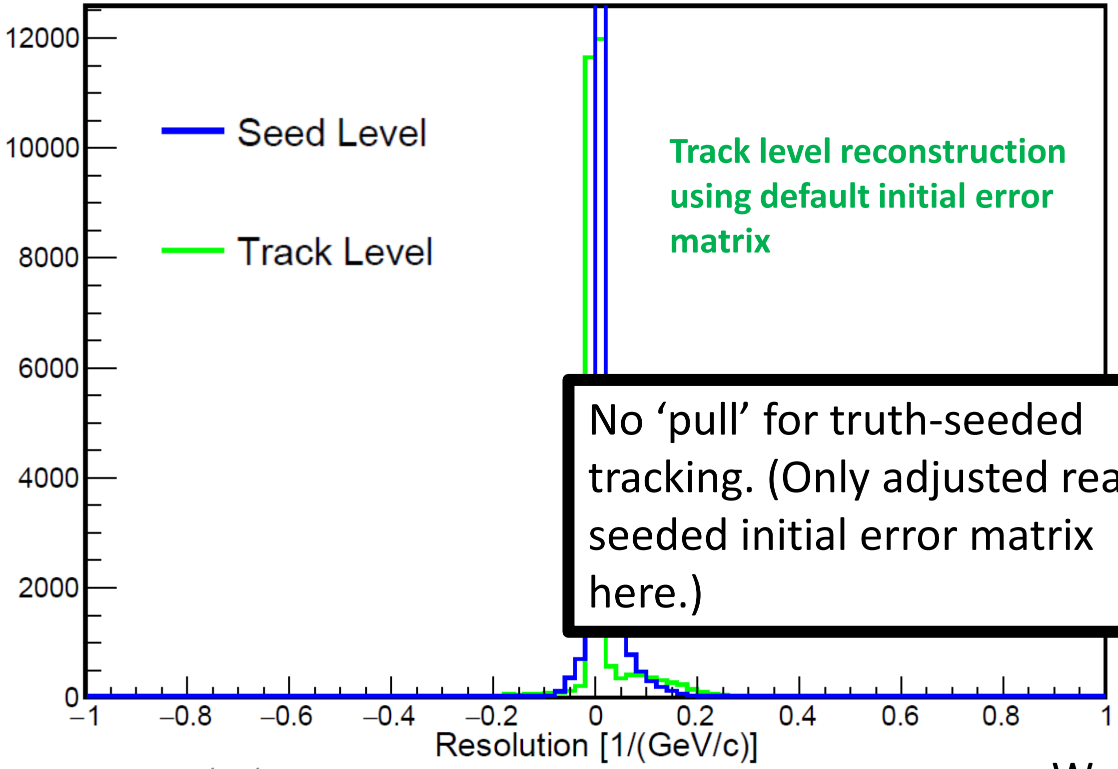
trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```

q/p Resolution: (rec. - true)



No 'pull' for truth-seeded tracking. (Only adjusted real-seeded initial error matrix here.)

q/p = 0.05

Work by Jeetendra Gupta

Ongoing work: how does initial error matrix affect our tracking?

Single μ^- generated:

0.5 GeV/c < P < 20 GeV/c

-4 < η < 4

Generated vertex: (0,0,0) mm

```
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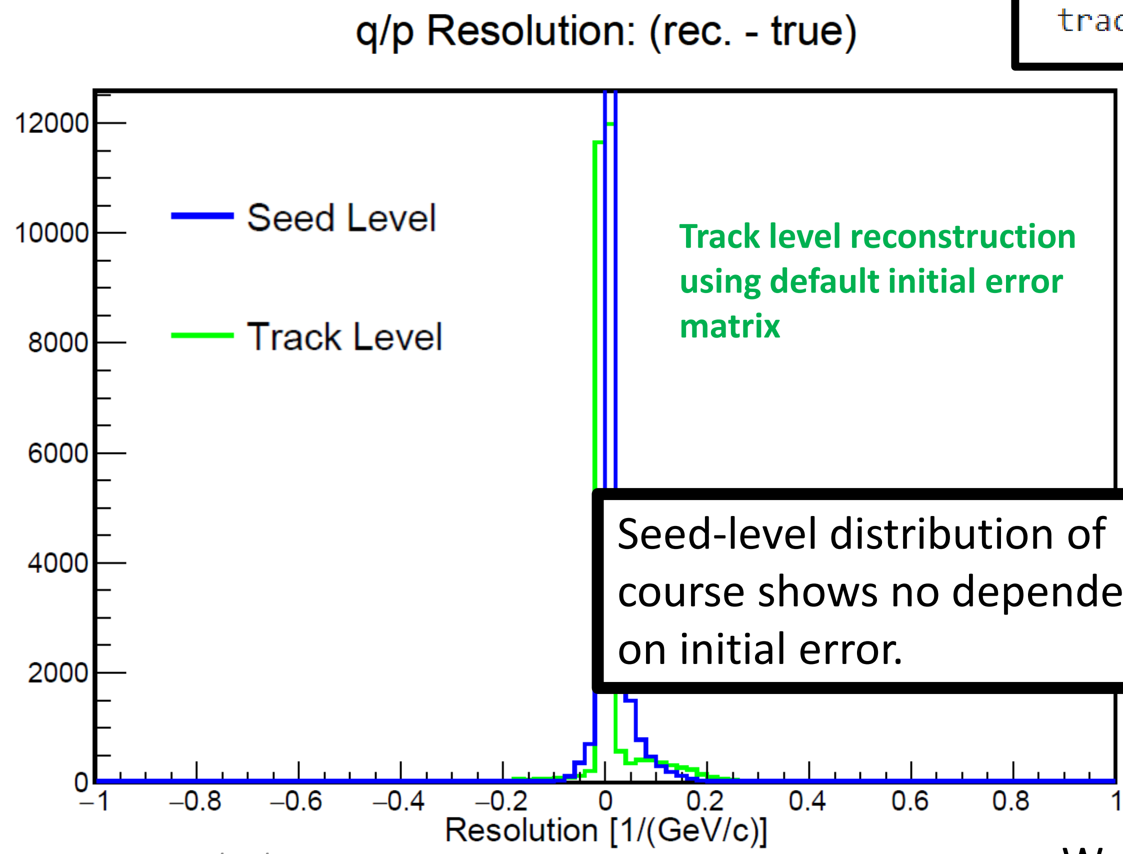
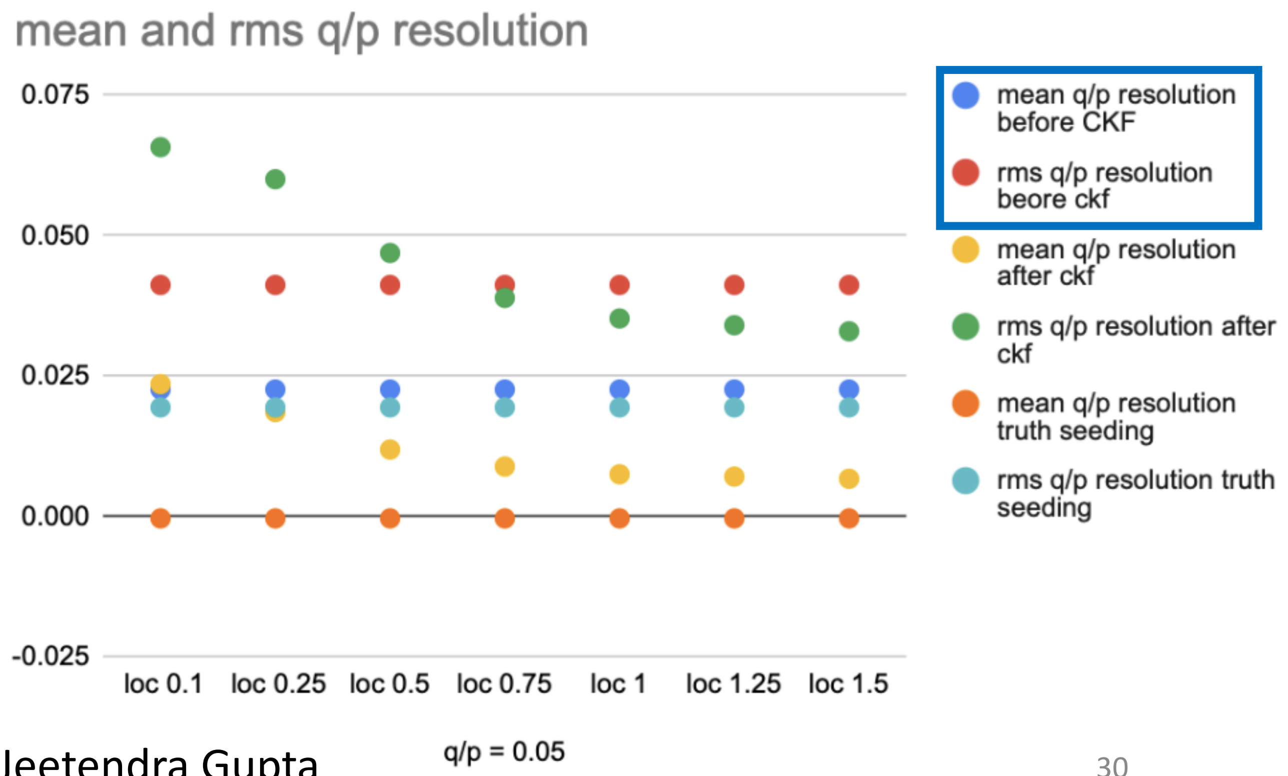
trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```



Seed-level distribution of course shows no dependence on initial error.



Work by Jeetendra Gupta

Ongoing work: how does initial error matrix affect our tracking?

Single μ⁻ generated:
0.5 GeV/c < P < 20 GeV/c
-4 < η < 4
Generated vertex: (0,0,0) mm

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trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```
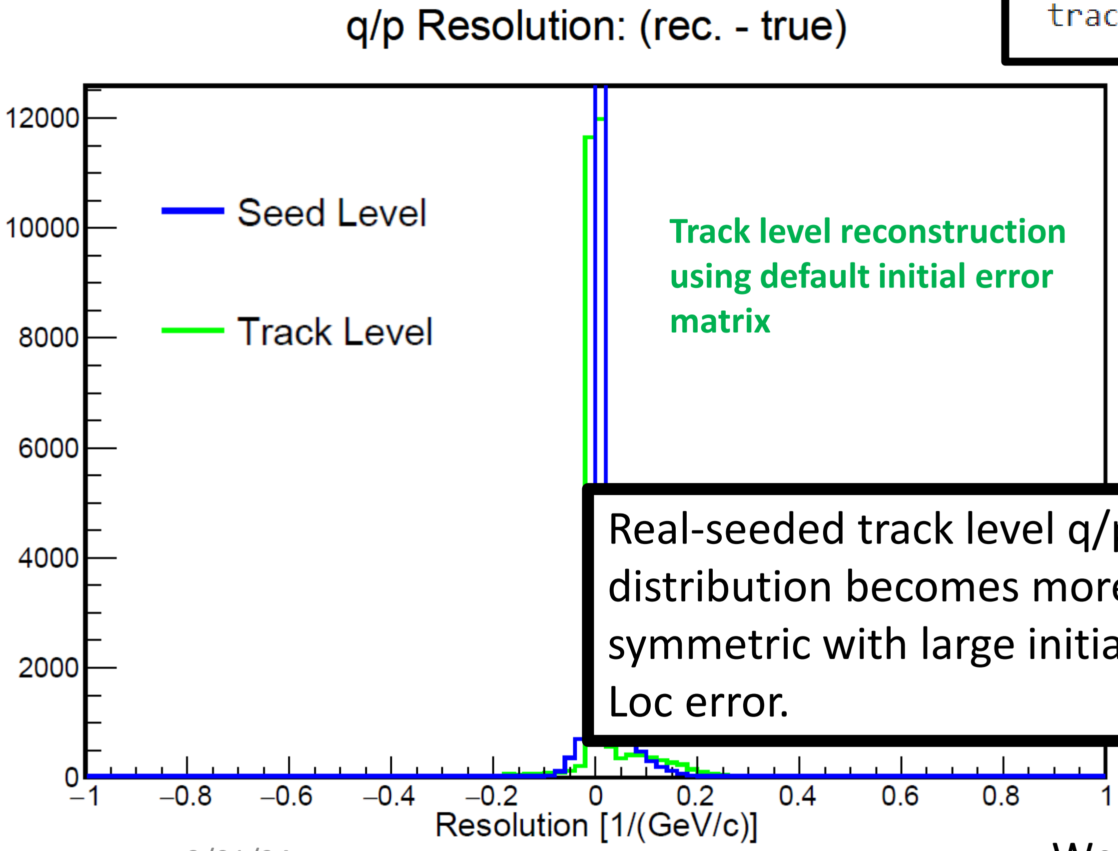
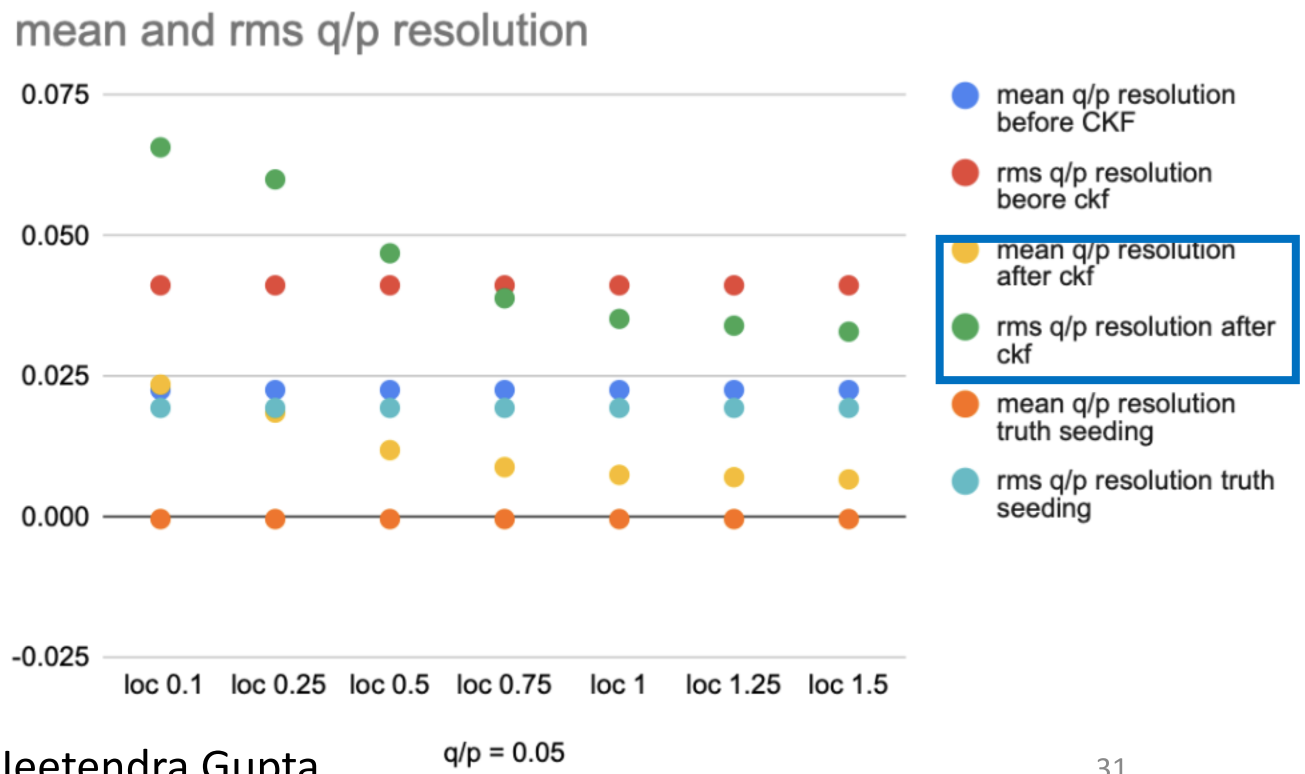



Real-seeded track level q/p distribution becomes more symmetric with large initial Loc error.



Work by Jeetendra Gupta

Ongoing work: how does initial error matrix affect our tracking?

Single μ^- generated:
0.5 GeV/c < P < 20 GeV/c
$-4 < \eta < 4$
Generated vertex: (0,0,0) mm

```
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trackparam.setMomentumError({0.05,0.05,0.05}); // covariance on theta/phi/q/p
trackparam.setTimeError(0.1); // error on time
```
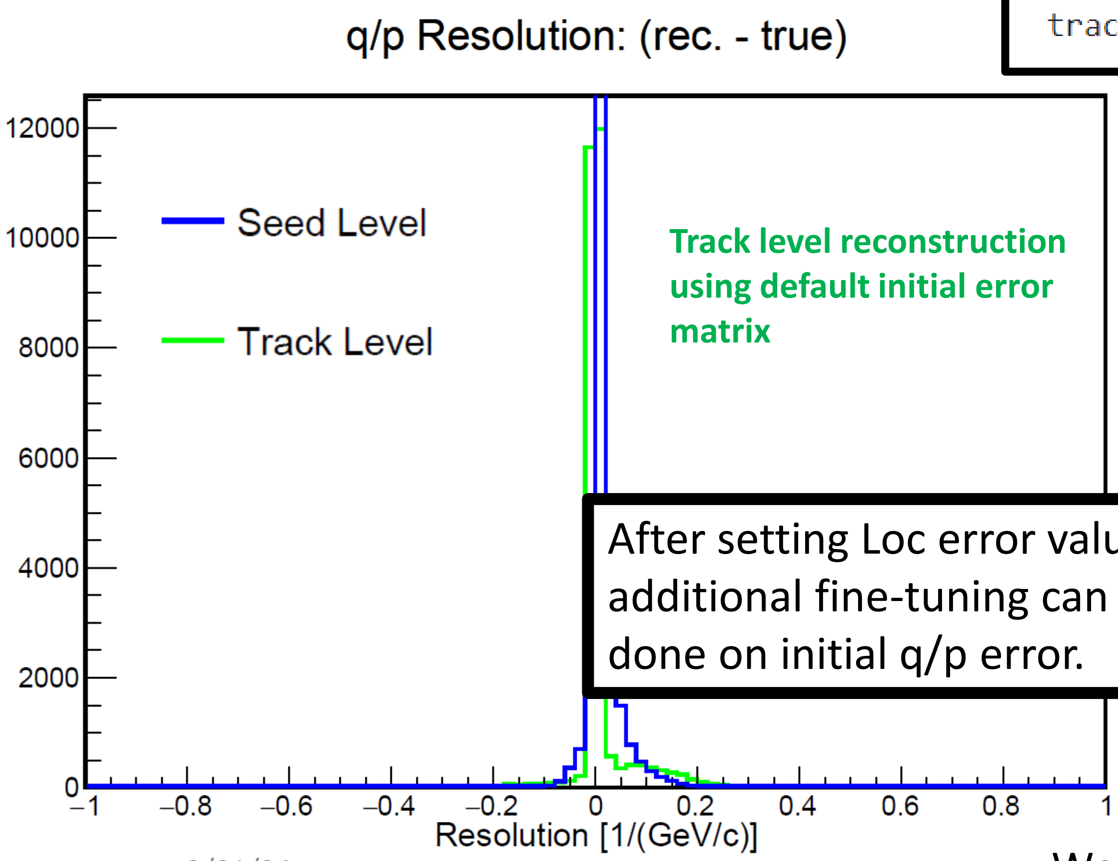
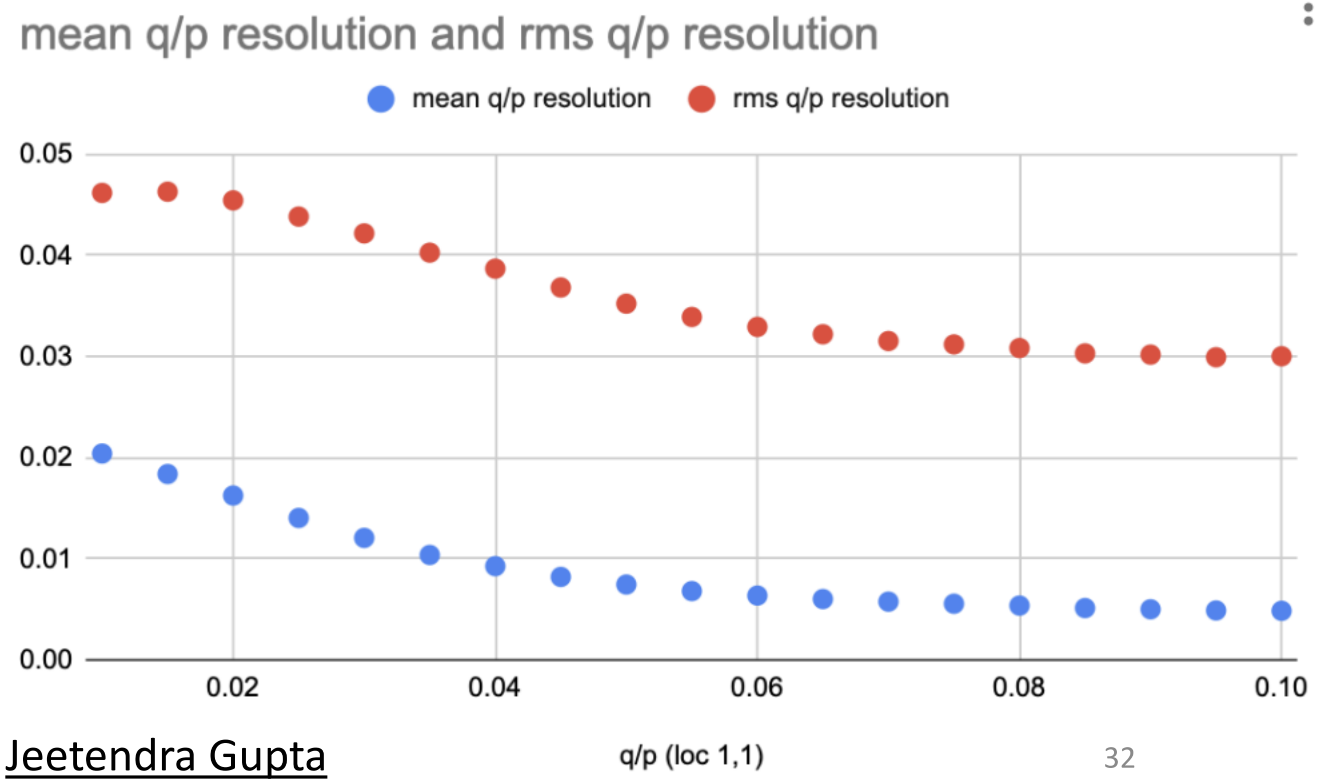



After setting Loc error value, additional fine-tuning can be done on initial q/p error.



Work by Jeetendra Gupta

Track duplicates – Acts ambiguity solver

Example single-muon event:

	Event #	Track #	# Meas.	Outliers	Total Chi2	Track Total Momentum [GeV/c]
*	0 *	0 *	5 *	0 *	10.844925 *	13.883998 *
*	0 *	1 *	5 *	0 *	10.843421 *	13.884253 *
*	0 *	2 *	5 *	0 *	10.828397 *	13.884164 *

These 3 real-seeded tracks share the same 5 measurements. The ambiguity solver will remove 2 of them.

Acts hits selection

For given track state, calculate chi2 of all hits on surface and rank, find $chi2_{min}$

- If no hit on surface → Hole
- If $chi2_{min}$ > $chi2_{cutoff}$ (default = 15) → Outlier
- If $chi2_{min}$ < $chi2_{cutoff}$ → Measurement (up to $numMeasurements_{CutOff}$ = 10 default)

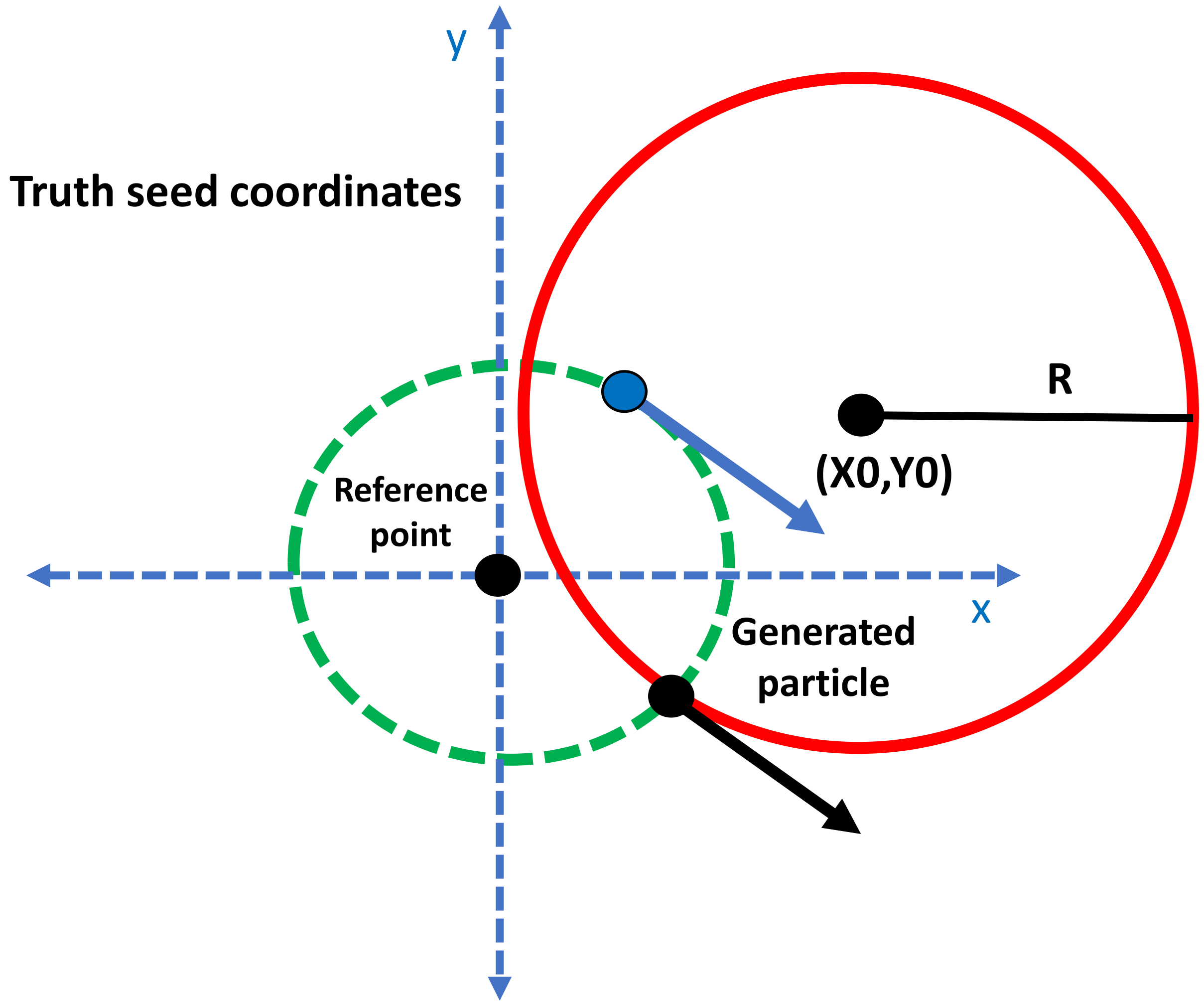
- Implementation of Acts ambiguity solver code EICRecon: https://github.com/eic/EICrecon/tree/tracking_ambiguity_resolution. Work by Minjung Kim.
- This code will remove tracks if they share several measurements with another track. The minimum number of measurements that need to be shared by the tracks is a tunable parameter.
- Some additional work on the output format needs to be done before a PR is made.

Summary of real-seeded tracking

- ➢Single-particle real-seeded tracking looks reasonable for $|z| < 10$mm, as well as for generation points up to 1 mm in the transverse plane.
- ➢For z values near the edge of the beam spot, we see efficiency holes. This first thing to check is the seed-finder parameters.
- ➢Ongoing effort to implement the Acts *ambiguity solver* into EICRecon. A PR should be made this week.
- ➢Ongoing study to understand the effect of initial error matrix on the input parameters that comes from the seeder.

Backup

Truth seeding: Initial position parameters before fix implemenation



Black arrow: Generated particle at its creation point

Blue arrow: Where the CKF will think the particle comes from in the pre-fix truth seeding implementation.