Tracking Simulation & Reconstruction

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(including work by Jeremy McCormick)

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Geant4: MCS Fix

- Geant4 versions prior to version 8 had ~30% variation in energy deposition in thin layers depending on the production cut for secondaries.
- The version 8 stepping model changed this.
- Now a series of steps of decreasing size is taken as the particle approaches a volume boundary.
  - Seemed to fix or at least drastically reduce problems with varying energy deposition.
- It may have also introduced bugs / problems …
- Number of steps per layer seems to scale
  - e.g. 40-50 micron steps in tracker layer and 4-5 micron steps in vertex layer

SLIC: SimTrackerHit Updates

- Momentum added to SimTrackerHit
  - For single step, current particle momentum.
  - For multiple steps, average of particle momenta.
  - Implemented in org.lcsim interface / implementation and Event Browser.
- Path length added to SimTrackerHit
  - For single step, distance from pre to post step point
  - For multiple steps, distance from entry to exit point
    - Or in case of interaction, multiple tracks are produced, so it is start of new track to exit point
  - Also implemented in org.lcsim
- Entry and exit point from path length and momentum
  - Not yet in org.lcsim interfaces (but trivial)
- Released with LCIO version 1.7 (Cambridge)

LCSim Event

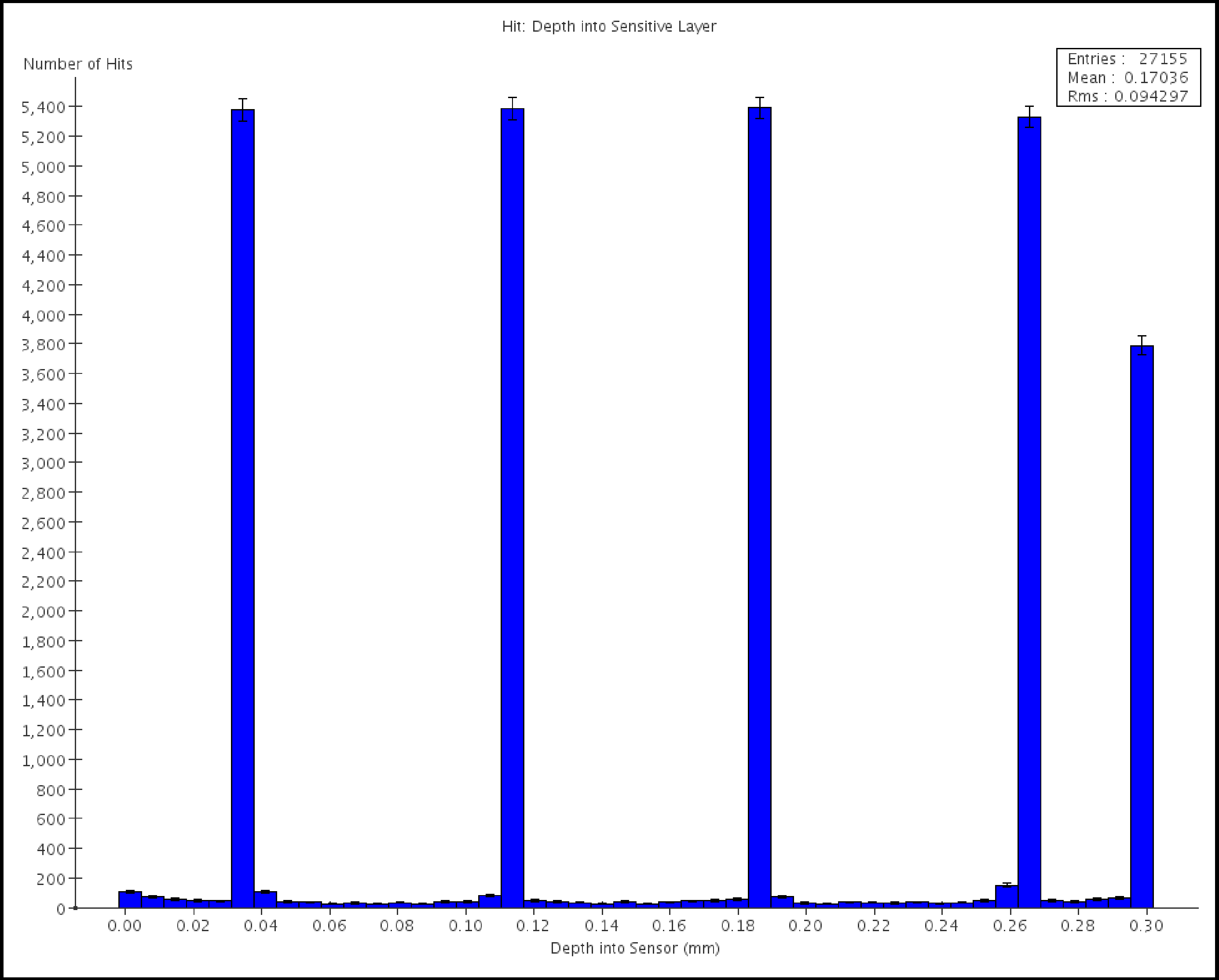
Run:0 Event: 0

- Event
  - EcalBarrHits
  - EcalEndcapHits
  - ForwardEcalEndcap
  - HcalBarrHits
  - HcalEndcapHits
  - LuminosityMonitorH
  - MCParticle
  - MCParticleEndPoin
  - MuonBarrHits
  - MuonEndcapHits
  - TkrBarrHits
  - TkrEndcapHits
  - VtxBarrHits
  - VtxEndcapHits
  - MCParticleTree

Collection: TkrBarrHits size:377 flags:c0000000

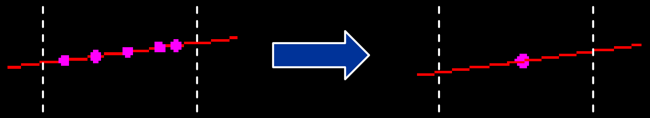
id: syst...	id: layer	id: barr...	x (mm)	y (mm)	z (mm)	dEdx (GeV)	time (ns)	px (GeV)	py (GeV)	pz (GeV)	pathLength (mm)
13	3	0	-516.62	-819.72	866.59	1.0882E-4	8.0703	3.5049E-4	-6.4218E-5	-.0010064	.13482
13	4	0	-517.28	-819.35	862.99	1.5041E-4	10.507	-6.3473E-5	-1.9939E-4	-1.7364E-5	.098904
13	4	0	-215.77	-1205.8	1423.8	9.2928E-5	8.2888	5.6848E-5	2.1151E-4	-2.3349E-4	.18280
13	0	0	-202.07	2.4258	-18.814	8.4814E-5	9.5180	-11.697	.29396	-1.0905	.30133
13	1	0	-457.90	13.054	-42.673	1.6052E-4	1.5360	-11.680	.67765	-1.0907	.30143
13	2	0	-712.37	32.008	-66.471	8.7739E-5	2.3916	-11.652	1.0592	-1.0902	.30161
13	3	0	-967.26	59.408	-90.353	8.7814E-5	3.2513	-11.610	1.4406	-1.0911	.30188
13	4	0	-1221.4	95.182	-114.29	1.0079E-4	4.1118	-11.556	1.8205	-1.0914	.30223
13	0	0	-201.74	-11.778	-62.498	1.2659E-4	100.66	-1.5041	-.23680	-.47600	.31585
13	1	0	-450.28	-84.197	-143.62	9.6445E-5	1.6173	-1.3959	-.60743	-.47540	.32244
13	2	0	-677.93	-221.13	-226.98	9.0348E-5	2.5505	-1.1889	-.94994	-.47503	.33569
13	3	0	-870.86	-425.13	-314.66	1.6222E-4	3.5367	-.88361	-1.2387	-.47394	.35747
13	4	0	-1008.3	-695.87	-409.72	1.2459E-4	4.6038	-.47876	-1.4434	-.47492	.39374
13	0	0	14.209	201.44	245.25	4.1456E-5	.67684	-1.6908E-4	-1.3521E-4	1.6649E-4	.055816
13	3	0	-502.00	-829.09	-411.88	7.2626E-6	5.3418	-4.4560E-4	-4.8823E-4	1.7634E-4	.026753
13	3	0	-501.99	-829.11	-411.98	1.3489E-4	11.637	-1.1307E-4	2.4991E-4	-1.8961E-4	.15763
13	4	0	-502.01	-829.07	-412.08	9.5562E-5	11.638	-8.0698E-5	1.4025E-4	-2.2725E-5	.059711
13	4	0	-522.72	-1107.8	308.98	1.6136E-5	5.3875	-1.6609E-4	-1.3280E-7	-7.7428E-5	.012591
13	1	0	450.39	-83.670	-277.66	1.1618E-4	5.4579	.60880	-.11152	-.37334	.31528
13	2	0	711.64	-45.324	-439.01	1.4746E-4	2.8322	.55160	.28038	-.37190	.40679
13	3	0	932.81	262.66	-676.38	3.1136E-4	4.3661	.089296	.61067	-.37179	.86054
13	3	0	656.72	712.63	-1021.3	2.9856E-4	6.5973	-.58402	.19678	-.37198	.86028
13	2	0	710.23	-62.015	297.64	8.8848E-5	16.662	-6.0126E-5	-1.0705E-4	1.8854E-4	.11730
13	3	0	284.65	1191.7	-707.28	2.2920E-4	15.751	-1.2470E-4	1.5541E-4	1.7885E-4	.13612
13	2	0	-620.81	350.84	678.55	.0046407	6.5994	-.081992	.021597	.063570	.39588
13	4	0	-552.72	-795.84	-709.98	3.8797E-5	7.6193	-.0088544	-.018904	.0083445	3.8274E-5
13	4	0	1202.9	-231.75	-1038.4	3.6846E-5	42.817	-.020545	.0095953	2.5424E-4	3.5348E-5
13	4	0	969.75	748.85	74.800	2.6749E-4	196.57	.0017414	-.0019064	-.0011791	.76857
13	4	0	969.38	749.34	75.657	3.3350E-4	56.105	8.5247E-4	-.0010166	.0016451	.96327
13	4	0	968.38	750.63	79.249	1.9381E-4	56.131	.0010754	-.0016248	8.6281E-4	.72866
13	4	0	967.98	750.90	78.103	2.6077E-4	56.160	2.7965E-5	-.0017679	-5.1162E-4	.61755
13	4	0	968.83	749.80	77.435	1.1268E-4	56.167	7.2861E-4	7.2312E-4	-6.6238E-4	.34782
13	4	0	968.84	749.94	76.883	6.5261E-4	56.170	-4.2154E-4	1.2642E-5	-3.0880E-4	.38377
13	4	0	959.08	139.48	400.38	3.0113E-5	111.85	-5.6859E-5	6.7751E-5	-9.8716E-6	.0032125
13	3	0	1016.4	-683.83	411.76	4.9751E-5	13.180	9.7038E-5	-6.2164E-5	-7.0181E-6	.0077151

SLIC: SimTracker Hit Depth Plot



SLIC: Combining Hits

- Used to consistently have O(1) hit per track crossing per layer in silicon tracker
  - Except in case of interactions (fairly rare)
- Geant4 MCS fix changed this to O(4) hits / layer.
- Always possible to combine hits in SLIC (TPCS)
  - combine_hits flag
- Now an option to combine hits in the compact description
  - This will become the default in MC production runs.
  - Can still turn on for high precision studies, debugging, accuracy checks, etc.
- Sim code is a lot more complicated than single hits per step so bugs potentially exist.
  - We need to study new SLIC output thoroughly.



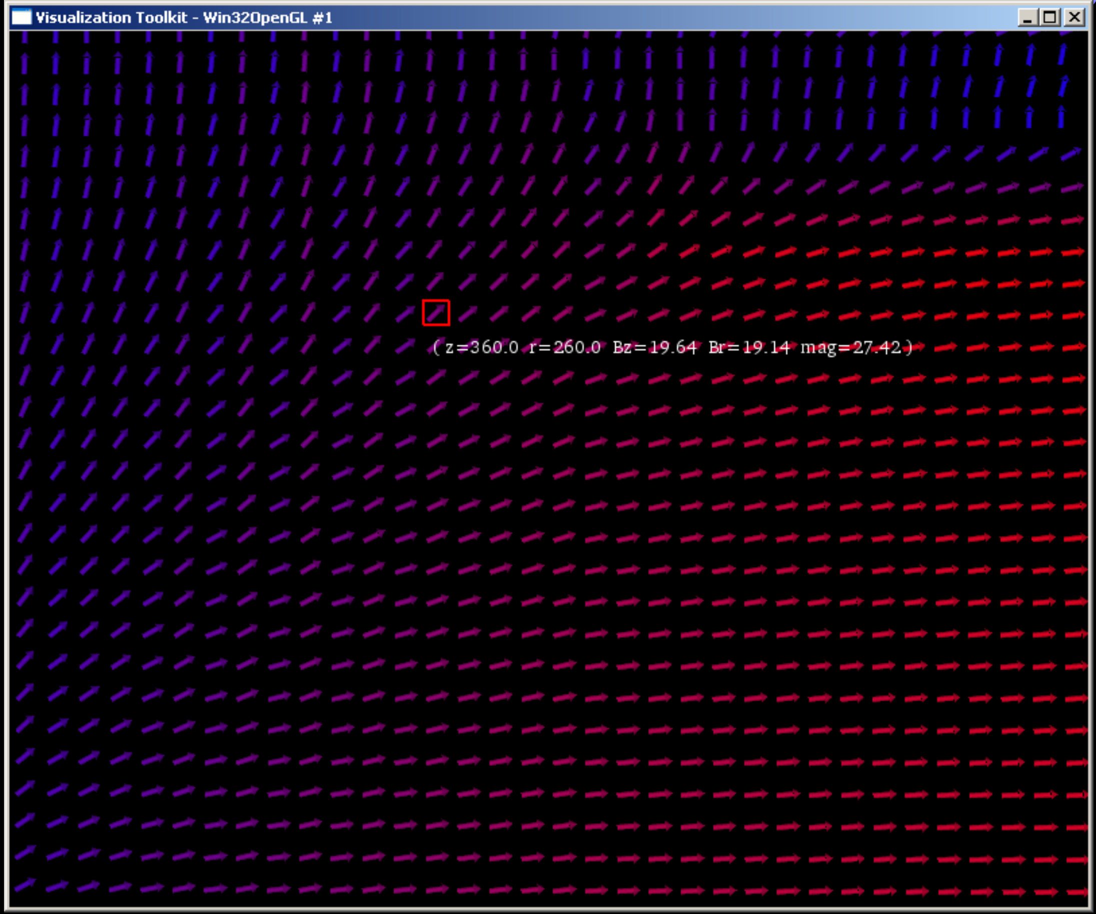
<detector id="11" name="VertexBarrel" type="MultiLayerTracker" readout="VtxBarrHits" combineHits="true">

(compact)

<tracker name="TrackerBarrel" hits_collection="TkrBarrHits" combine_hits="true"> (lcdd)

SLIC: Magnetic Field Map

- SLIC and org.lcsim support an RZB field map
  - format from Takashi Maruyama's FORTRAN code
  - C++ interpolation code from Norman
- data is single quadrant
- symmetric in phi
- visualization with VTK (python)
- Working on implementation of DID/DIDn't
- Working on arbitrary field map.



- To study effect of non-uniform field, do not need to include in reco (yet).
- Put field in simulation, analyze with perfect field. Difference gives maximum bound on the size of the effect. (Have Runge-Kutta propagators, but very slow.)

Compact: Regions and Limits

- Regions can be used to set production cuts in compac
  - limits production of secondaries (e+-, gamma)
    - potential distance < cut → not produced
      - particle dEdX - E(secondary)
  - also called “range cut”
  - different from setting physics limits

```
<regions>
   <region name=“EcalRegion” cut=“0.5” lunit=“mm” />
</regions>
…
<slice region=“EcalRegion” … />
```

- physics limits
  - set minimums and maximums
    - step length max
    - track length max
    - time max
    - kE min
    - range min (not same as production cut)
  - step length useful for calorimeters
    - particle goes across > 1 pad

```
<limits>
   <limitset name=“TrackerLimits”>
      <limit name=“step_length_max”
              value=“1.0” unit=“micrometer”
              particles=“*”
   </limitset>
</limits>
…
<slice limits=“EcalLimits” … />
```

Infrastructure components

- **Hit**
  - **Defined at a surface.**
  - **Provides a measurement and associated error**
  - **Provides a mechanism to predict the measurement from a track fit**
  - **Provides access to underlying cluster and/or digits**

Surfaces

- Surfaces generally correspond to geometric shapes representing detector devices.
- They provide a basis for tracks, and constrain one of the track parameters.
- The track vector at a surface is expressed in parameters which are "natural" for that surface.

Cylinder

- **Surface defined coaxial with z, therefore specified by a single parameter r.**
- **Track Parameters: (ϕ, z, α, tanλ, q/p_T)**
- **Bounded surface adds z_{min} and z_{max}.**
- **Supports 1D and 2D hits:**
  - **1D Axial: ϕ**
  - **1D Stereo: $\phi+\kappa z$**
  - **2D Combined: (ϕ, z)**

XY Plane

- **Surface defined parallel with z, therefore specified by distance u from the z axis and an angle ϕ of the normal with respect to x axis.**
- **Track Parameters: (v, z, dv/du, dz/du, q/p)**
- **Bounded surface adds polygonal boundaries.**
- **Supports 1D and 2D hits:**
  - **1D Stereo: w_v*v + w_z*z**
  - **2D Combined: (v, z)**

Z Plane

- **Surface defined perpendicular to z, therefore specified by single parameter z.**
- **Track Parameters: (x, y, dx/dz, dy/dz, q/p)**
- **Bounded surface adds polygonal boundaries.**
- **Supports 1D and 2D hits:**
  - **1D Stereo: $w_x*x + w_y*y$**
  - **2D Combined: (x,y)**

Hits

- **Cylinder**
  - 1D Axial: ϕ (for convenience)
  - 1D Stereo: $\phi + \kappa z$
  - 2D Combined: (ϕ, z)
- **XY Plane**
  - 1D Stereo: $w_v * v + w_z * z$
  - 2D Combined: (v, z)
- **Z Plane**
  - 1D Stereo: $w_x * x + w_y * y$
  - 2D Combined: (x, y)

Hit Interface

Hit	TrackerHit
HitVector measuredVector();	double[] getPosition();
HitError measuredError();	double[] getCovMatrix();
HitVector predictedVector();	double getdEdx();
HitError predictedError();	double getTime();
HitDerivative dHitdTrack();	int getType();
HitVector differenceVector();	
Cluster cluster()	List getRawHits();

Saving Hits in LCIO

- **Must be able to write out and read back these hits.**
- **One solution is to simply define these as LCIO objects and implement the classes.**
- **Another is to try to shoe-horn the data into TrackerHit and use the type attribute to covariantly return the correct hit type when read back from disk.**
- **Investigating these possibilities is a high-priority task.**

Base Classes

- A number of base class implementations of org.lcsim.event interfaces have been implemented and can be found in org.lcsim.event.base
  - BaseTrackerHit (and BaseTrackerHitMC)
  - BaseTrack
  - BaseReconstructedParticle
  - BaseMCParticle
- Comments and suggestions are welcomed.

Track Finding

- **Implemented a conformal mapping technique**
  - Maps curved trajectories onto straight lines
  - Simple link-and-tree type of following approach associates hits.
  - Once enough hits are linked, do a simple helix fit
    - circle in rPhi
    - straight line in s-z
  - Use track parameters to predict track and pick up hits.
  - Currently outside-in, but completely flexible.

Track Finding

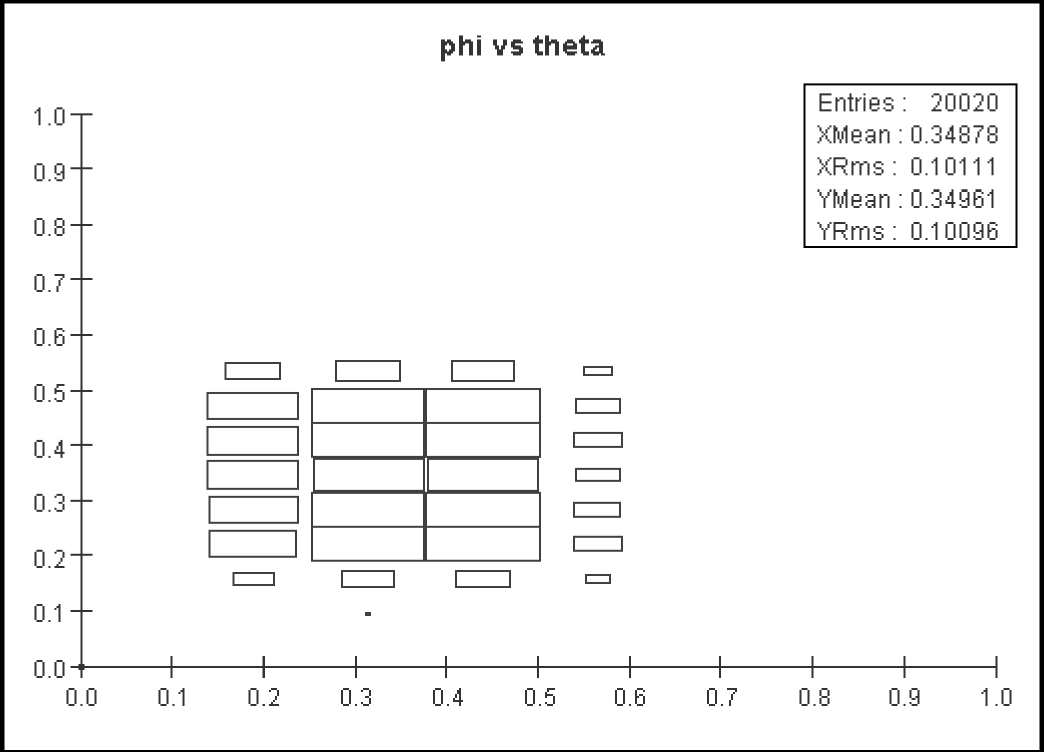
- ❖ **Currently using vertex detector hits and forward tracker disk hits.**
  - **VTX hits are pixels, so give 2D hits.**
  - **FWD hits are assumed to be double layer of stereo strips, giving 2D hits (+ ghosts).**
  - **Currently not handling ghosts, coming soon.**
  - **Currently not extrapolating into barrel tracker (soon)**
- ❖ **5 hits in the central region.**
- ❖ **9+ hits in the forward region.**

Data Samples

- **Single muons**
  - simple sanity check
- **Multiple muons**
  - next step in complexity, known momentum, acceptance and number of tracks to find.
- **$t\bar{t} \rightarrow$ six jets**
  - reasonably tough real physics environment. Challenge is to define the denominator, i.e. which tracks should have been found.

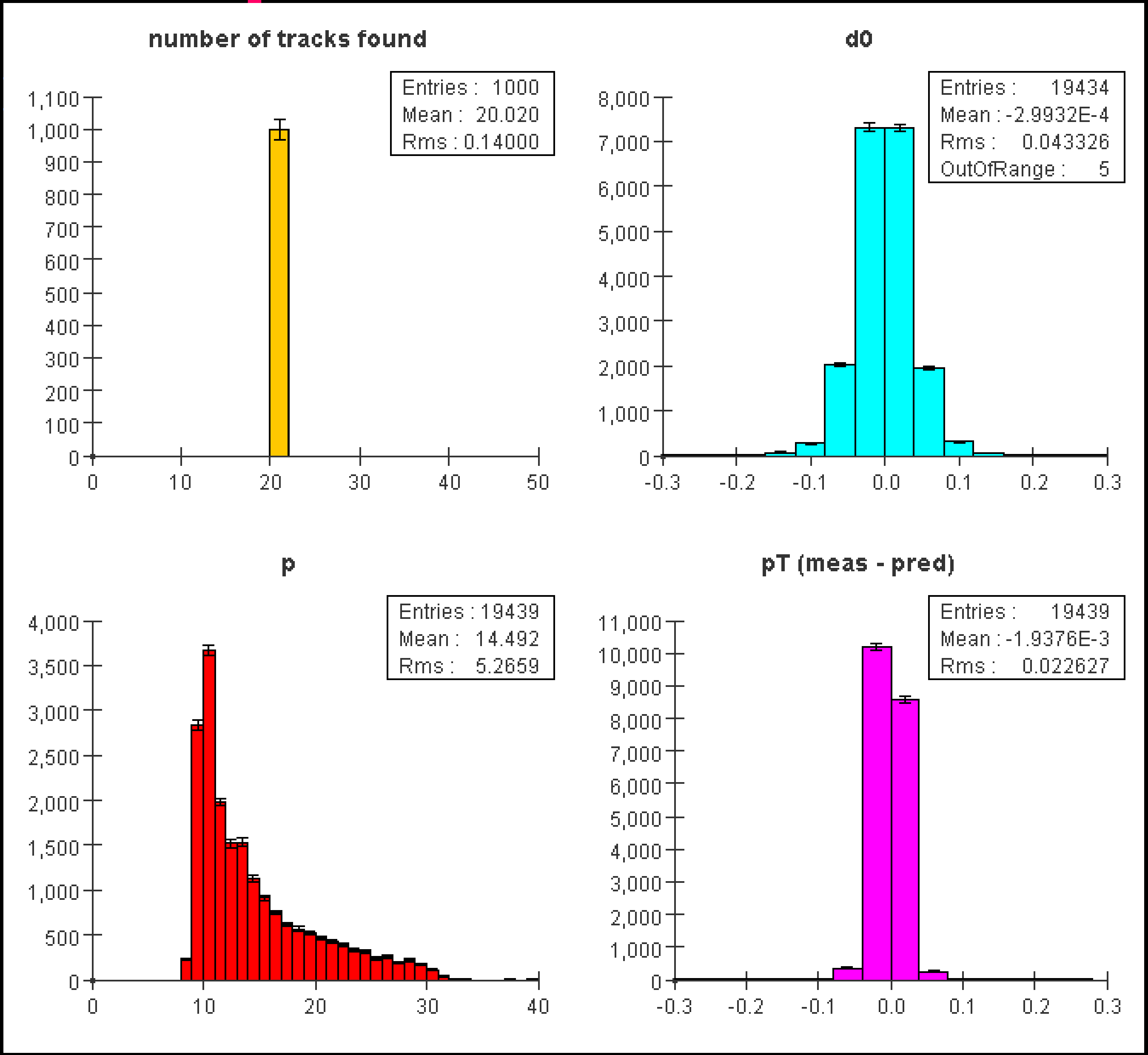
Multiple Forward Muons

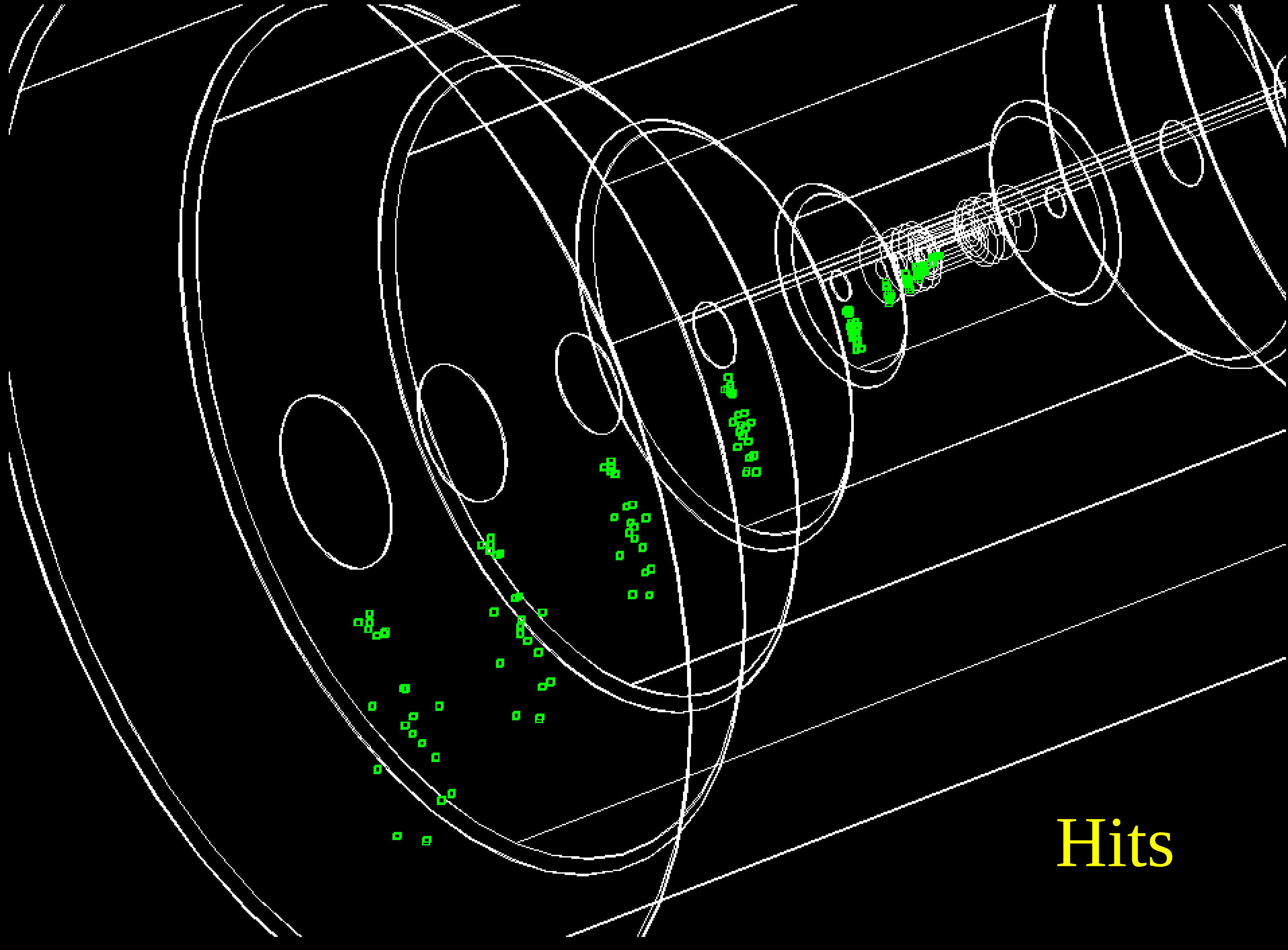
- Generate 20 muons into the forward tracking region.
- Always find 20 muons.

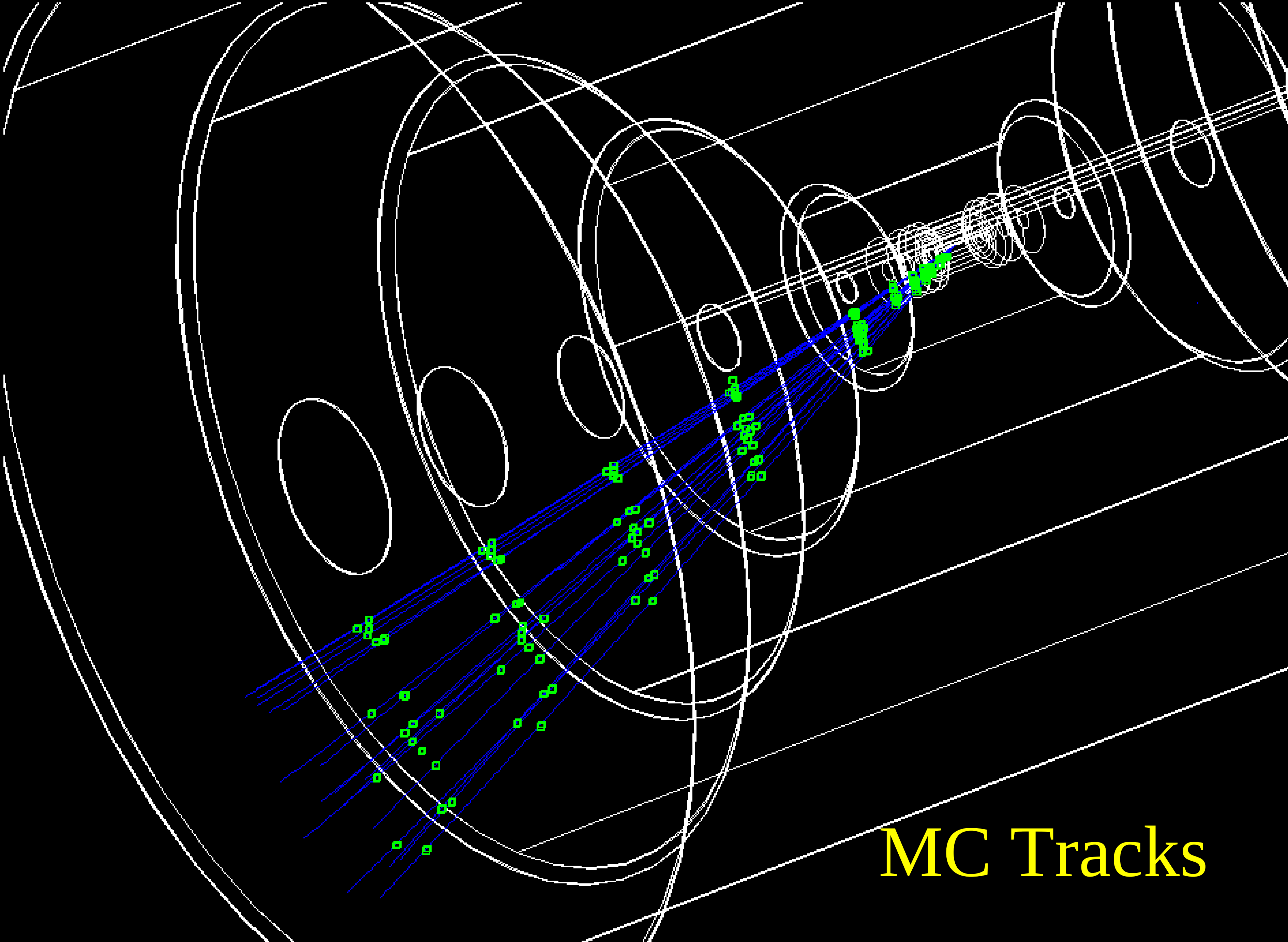


Multiple Forward Muons

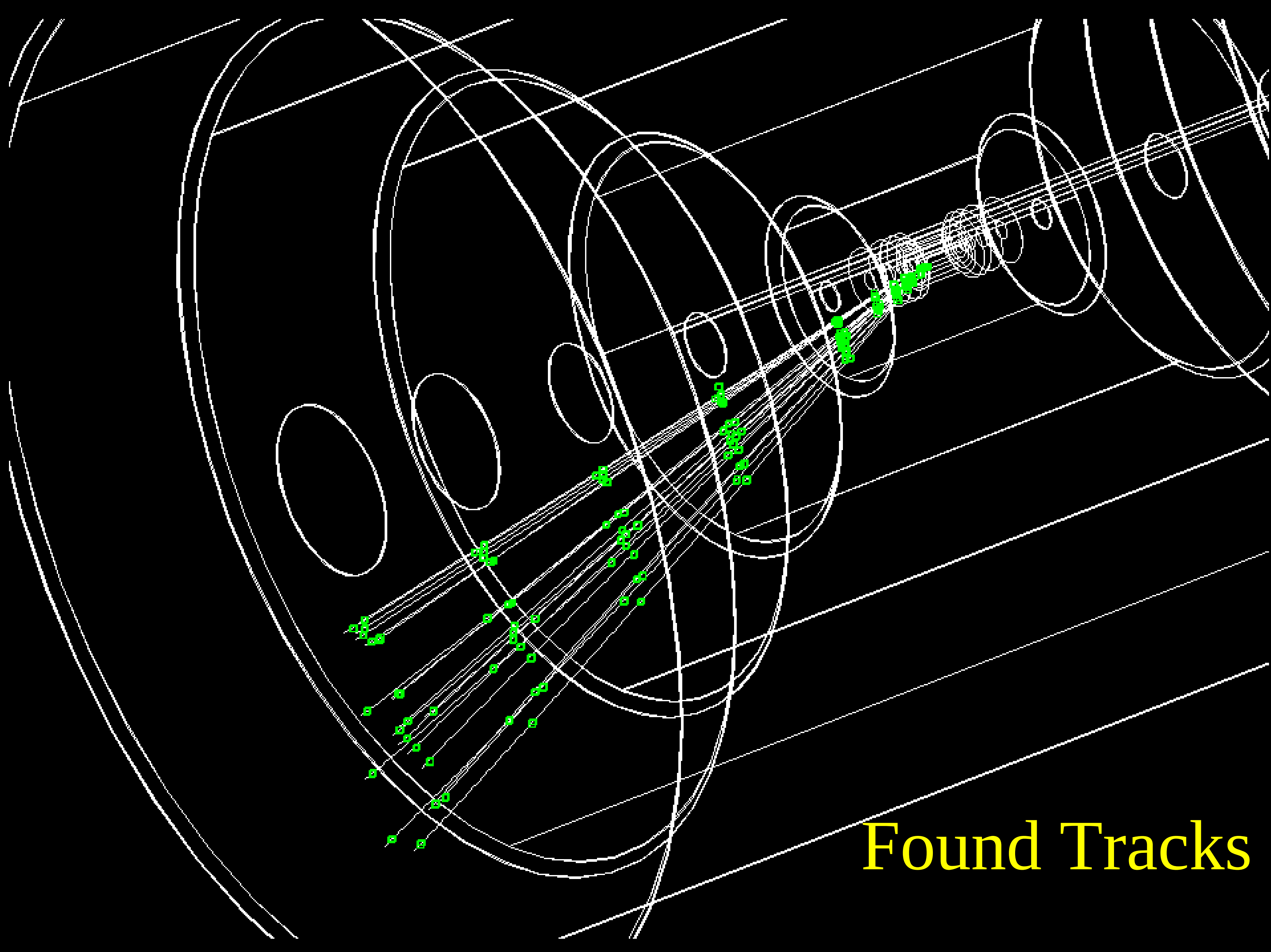
❖ Gene




Hits

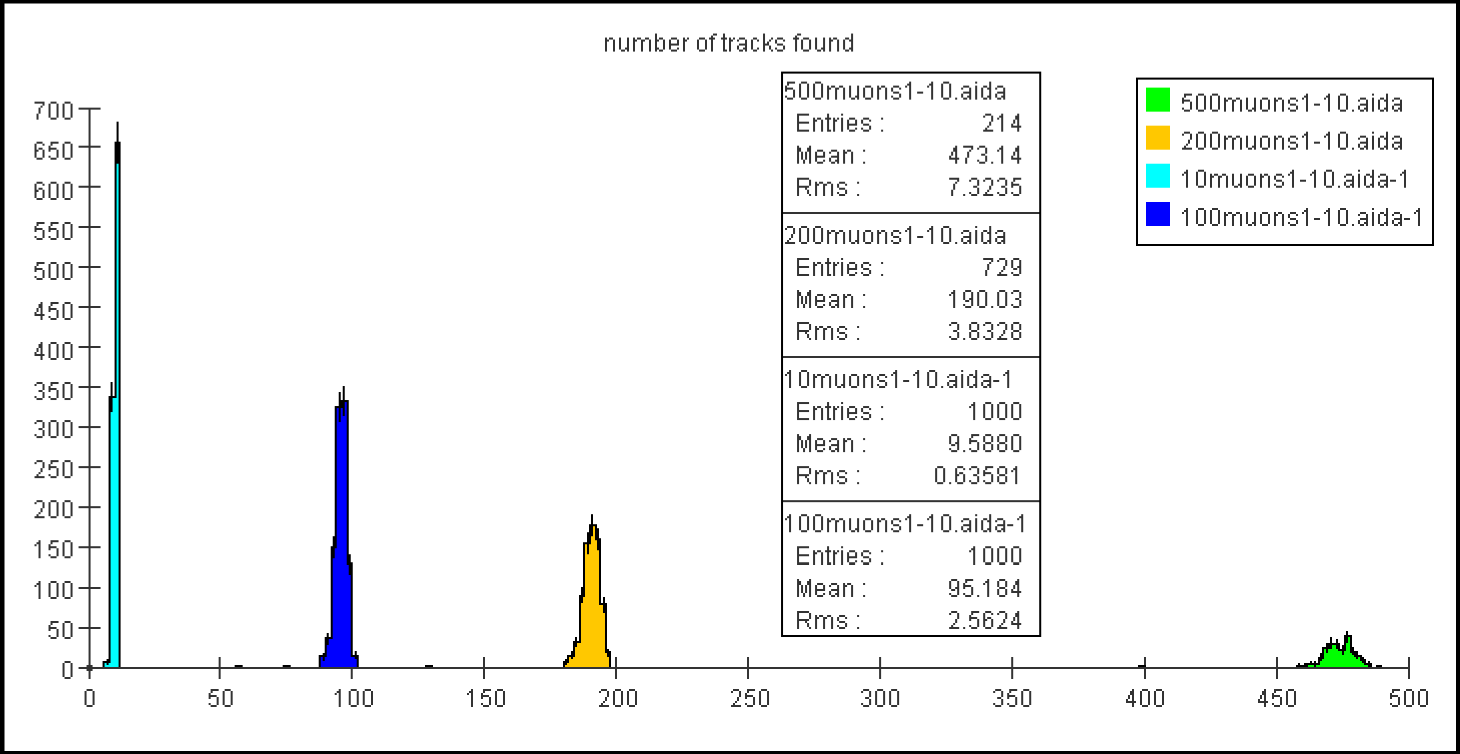


MC Tracks


Found Tracks

Multiple Isotropic Tracks

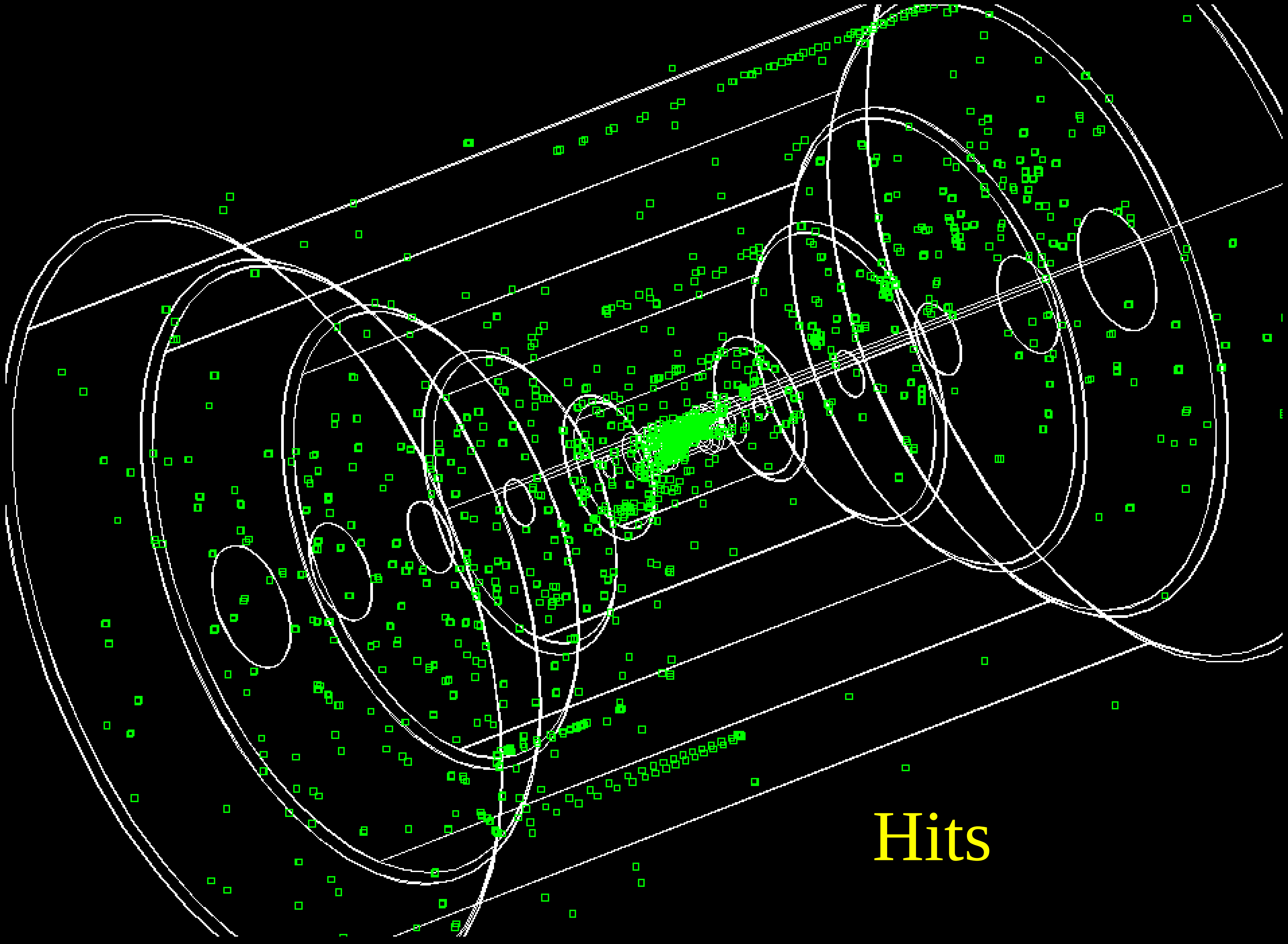
- Generate multiple (10, 100, 200, 500) muons isotropically between 1 and 10 GeV down to 4 degrees of the beam. Find ~95% out of the box.



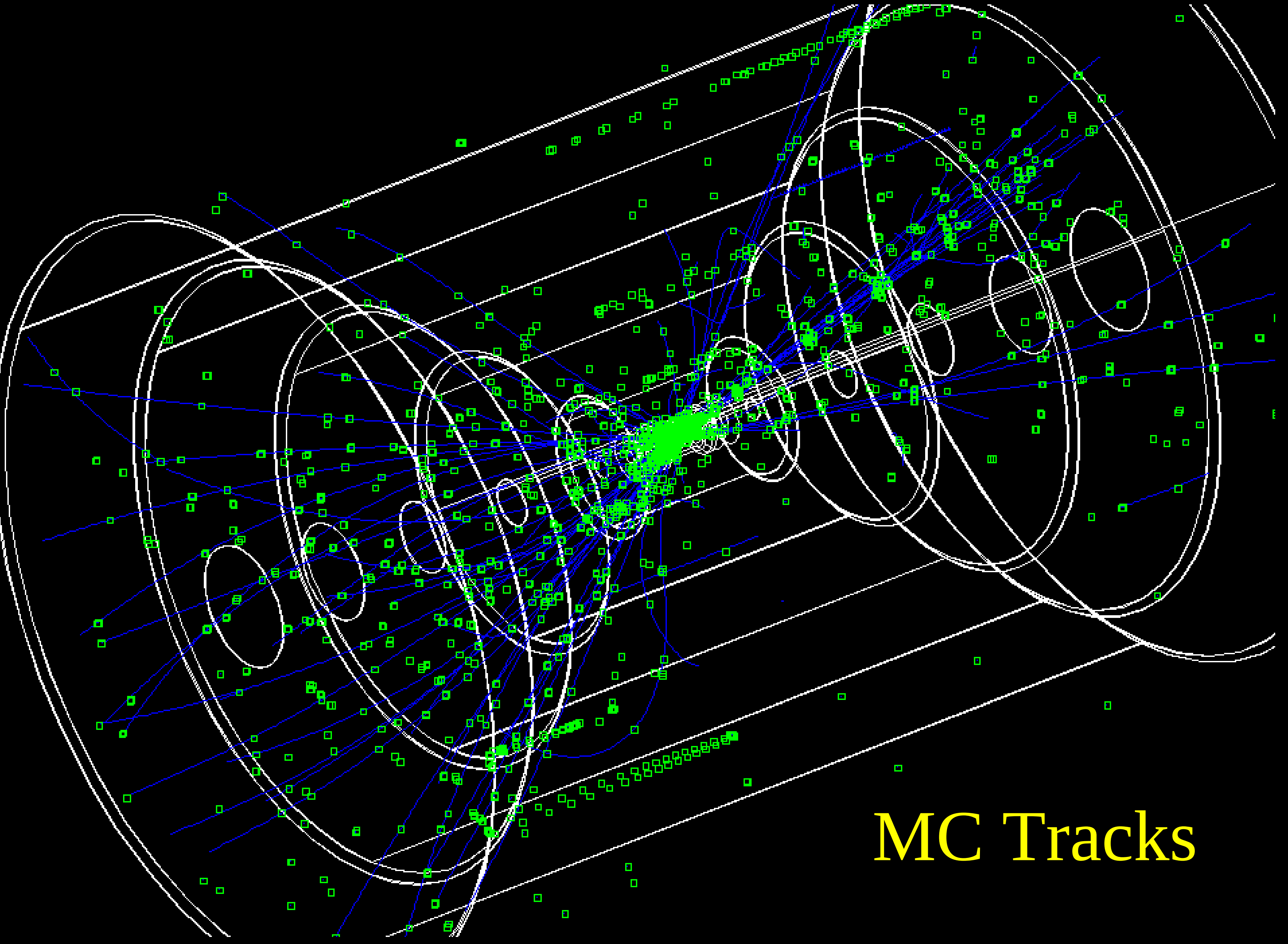
- n.b. some tracks are actually outside tracker acceptance.

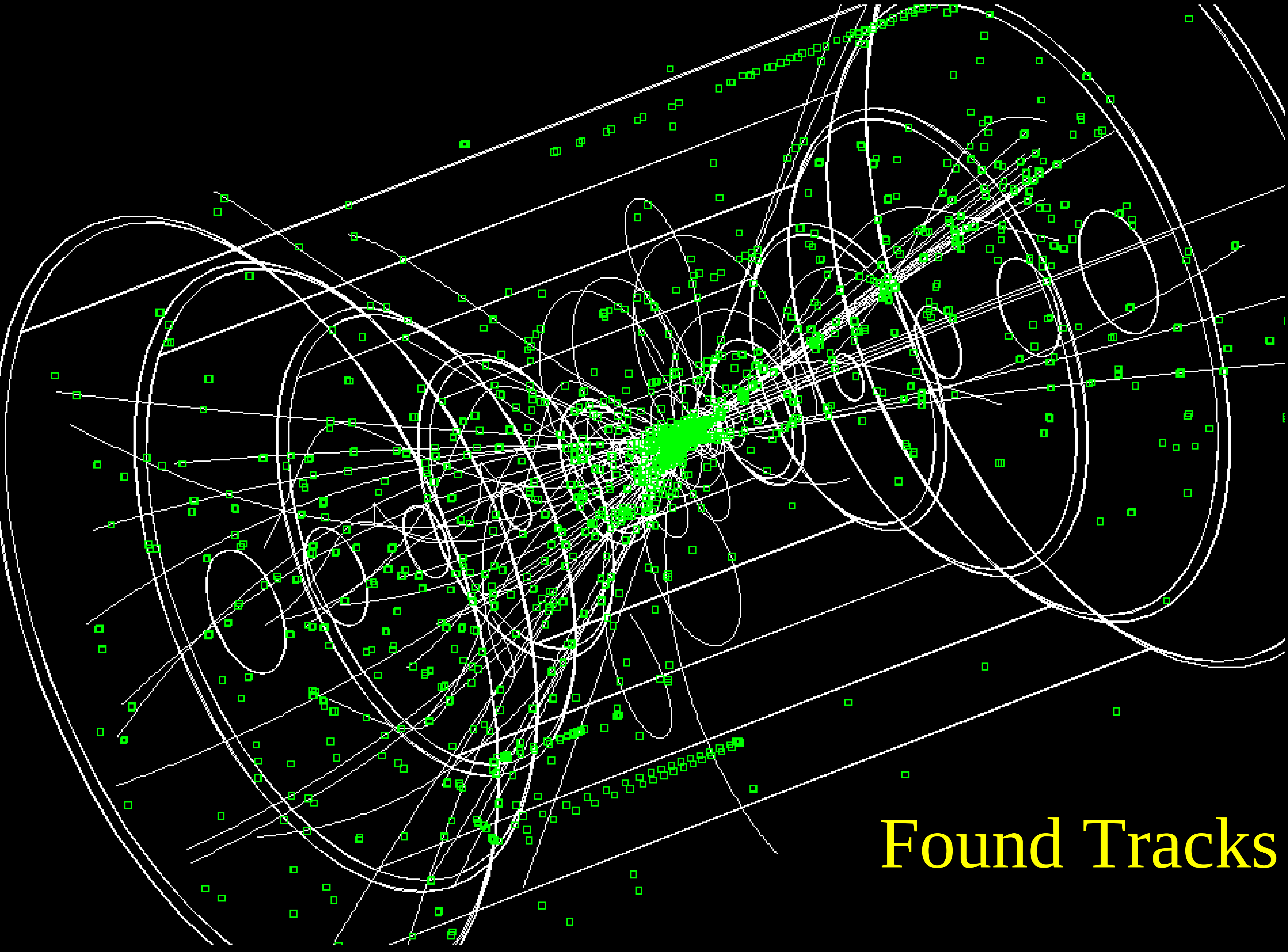
$t\bar{t} \rightarrow$ six jets

- Generate $e^+ e^- \rightarrow t\bar{t}$, $t\bar{t} \rightarrow$ six jets.
- Takes 3min to fully analyze 900 events on 1.7GHz laptop.
  - Open event, read in data.
  - Create tracker hits.
  - Find tracks.
  - Fit tracks.
  - Analyze tracks.
  - Write out histograms.

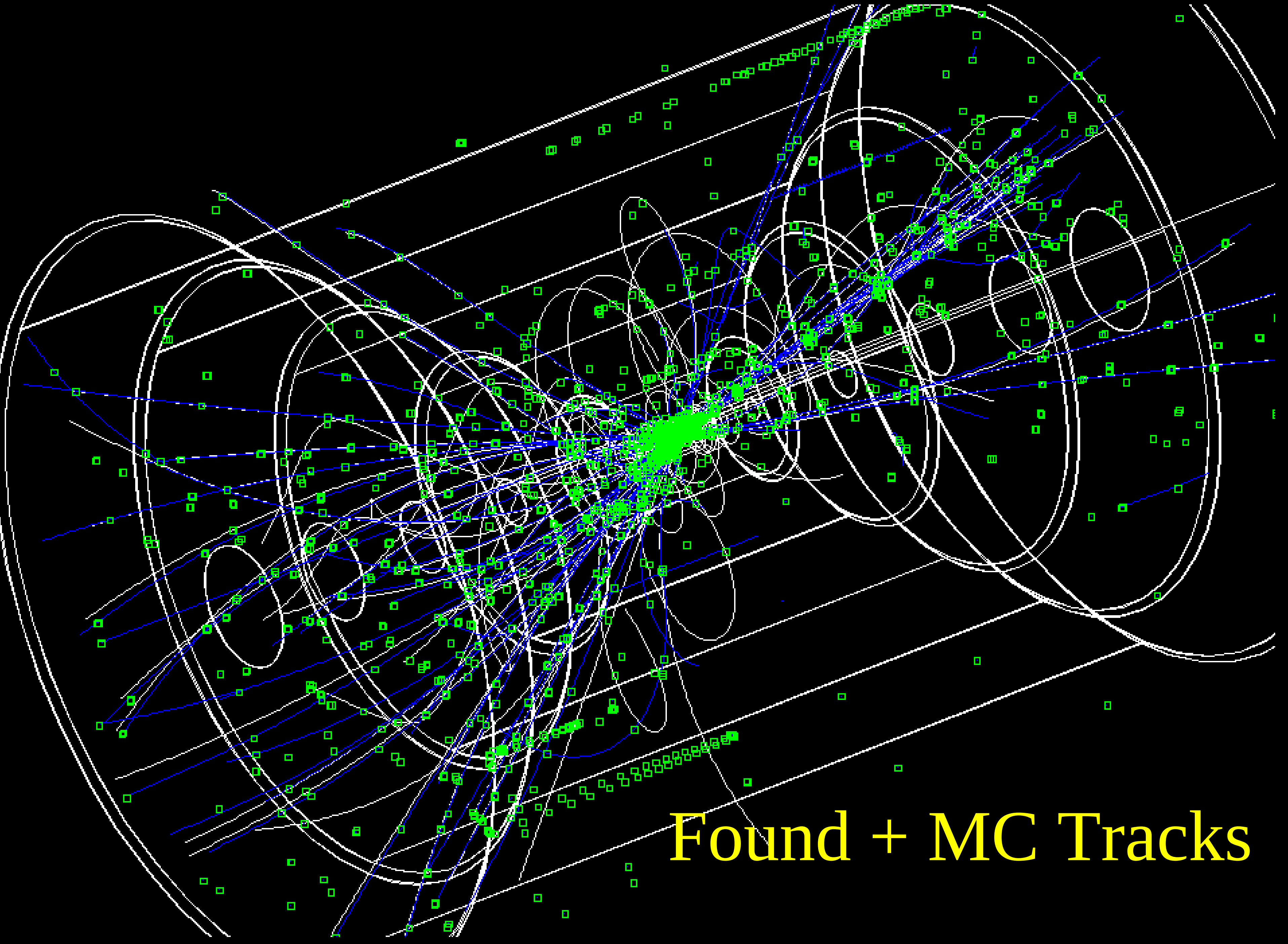


Hits

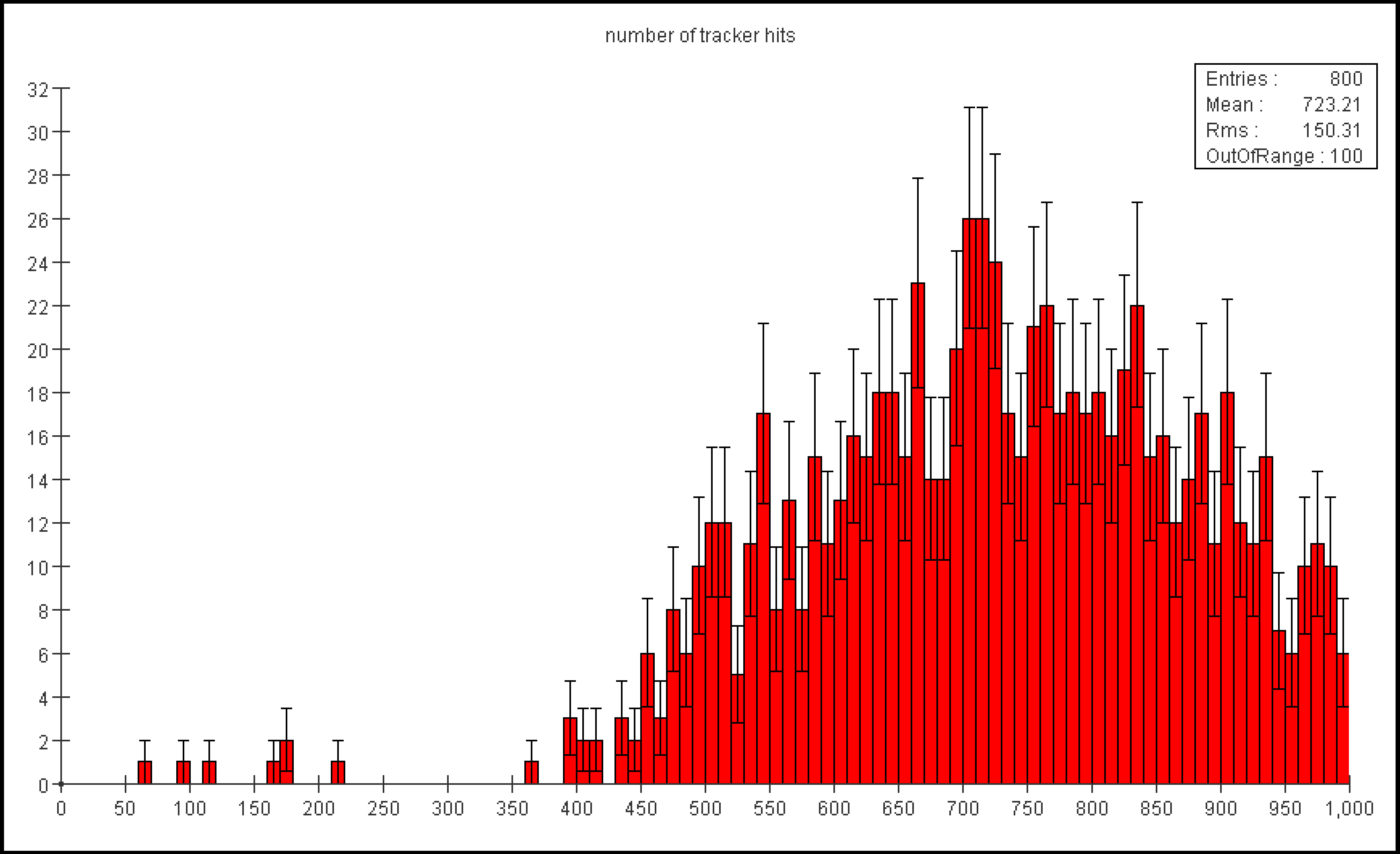

MC Tracks



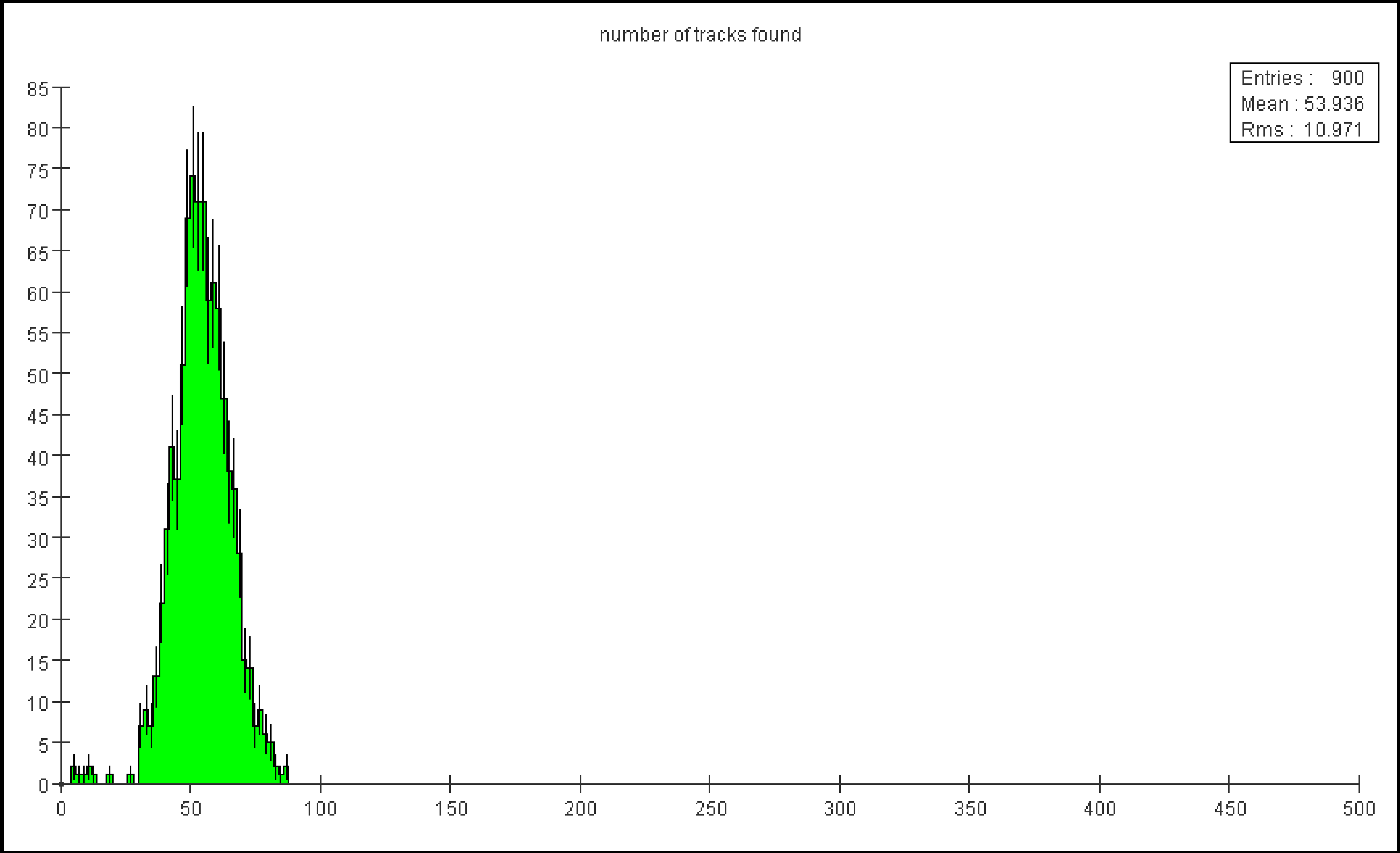
Found Tracks


Found + MC Tracks

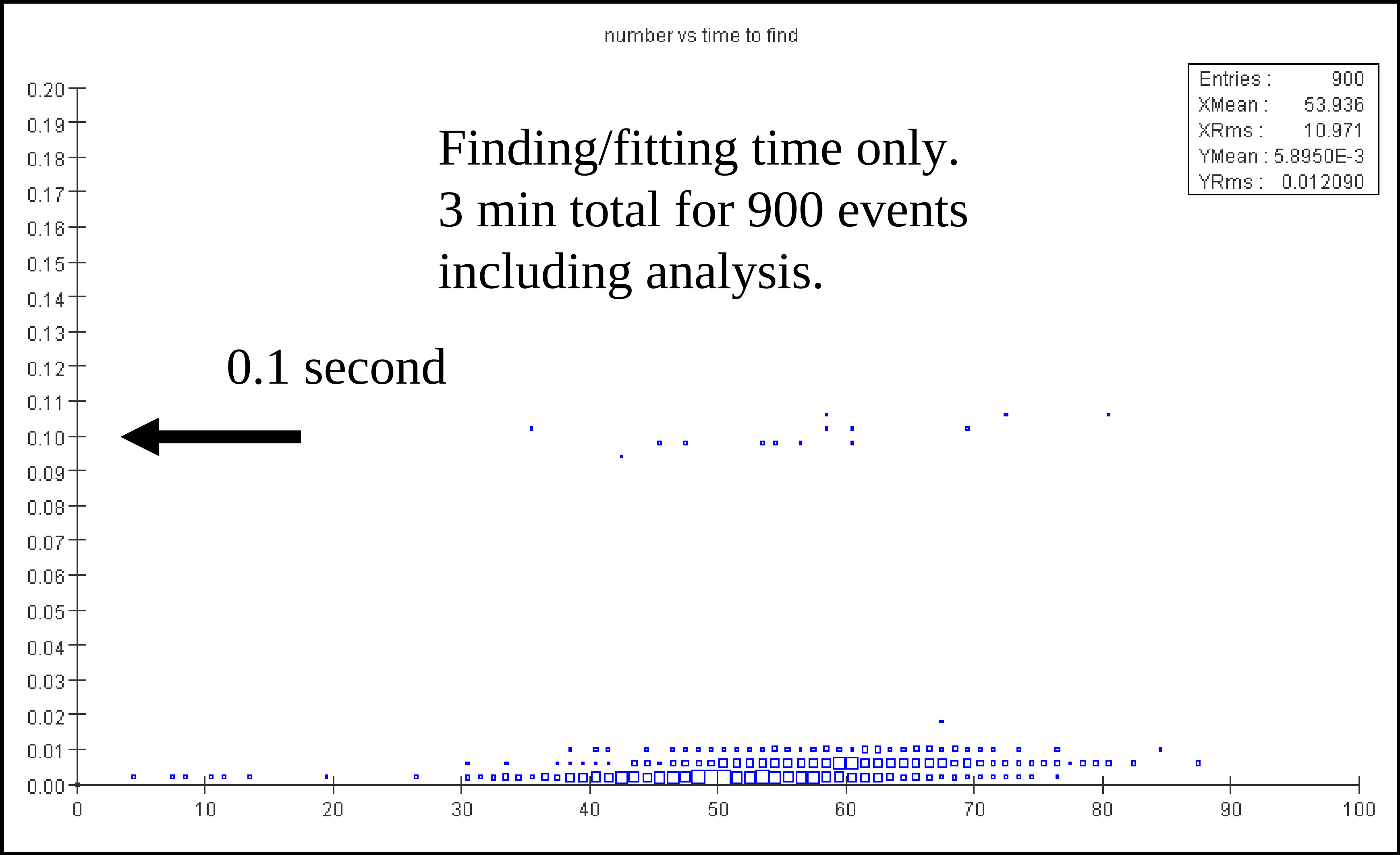
$t\bar{t}$ →six jets # of Hits



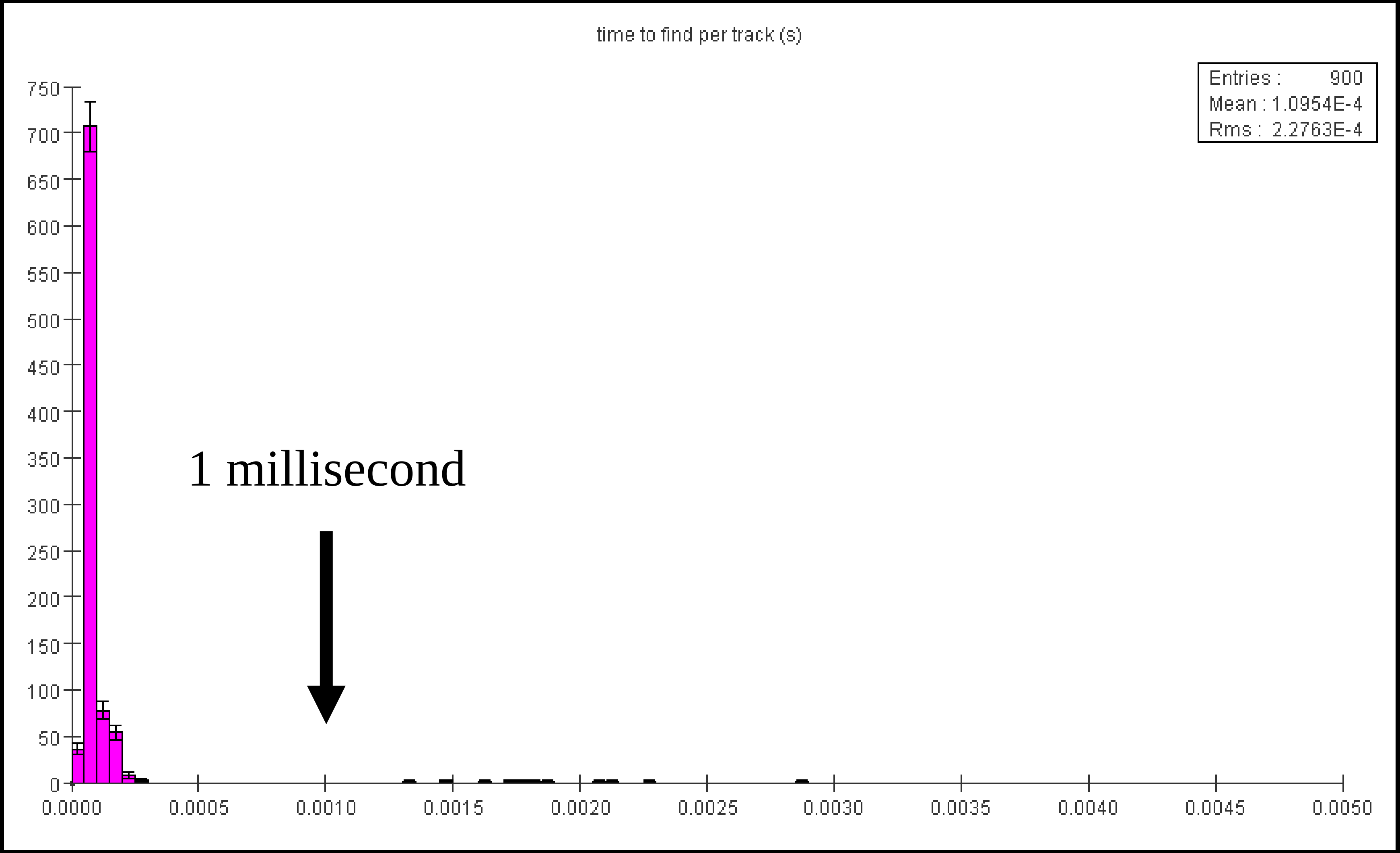
of tracks found



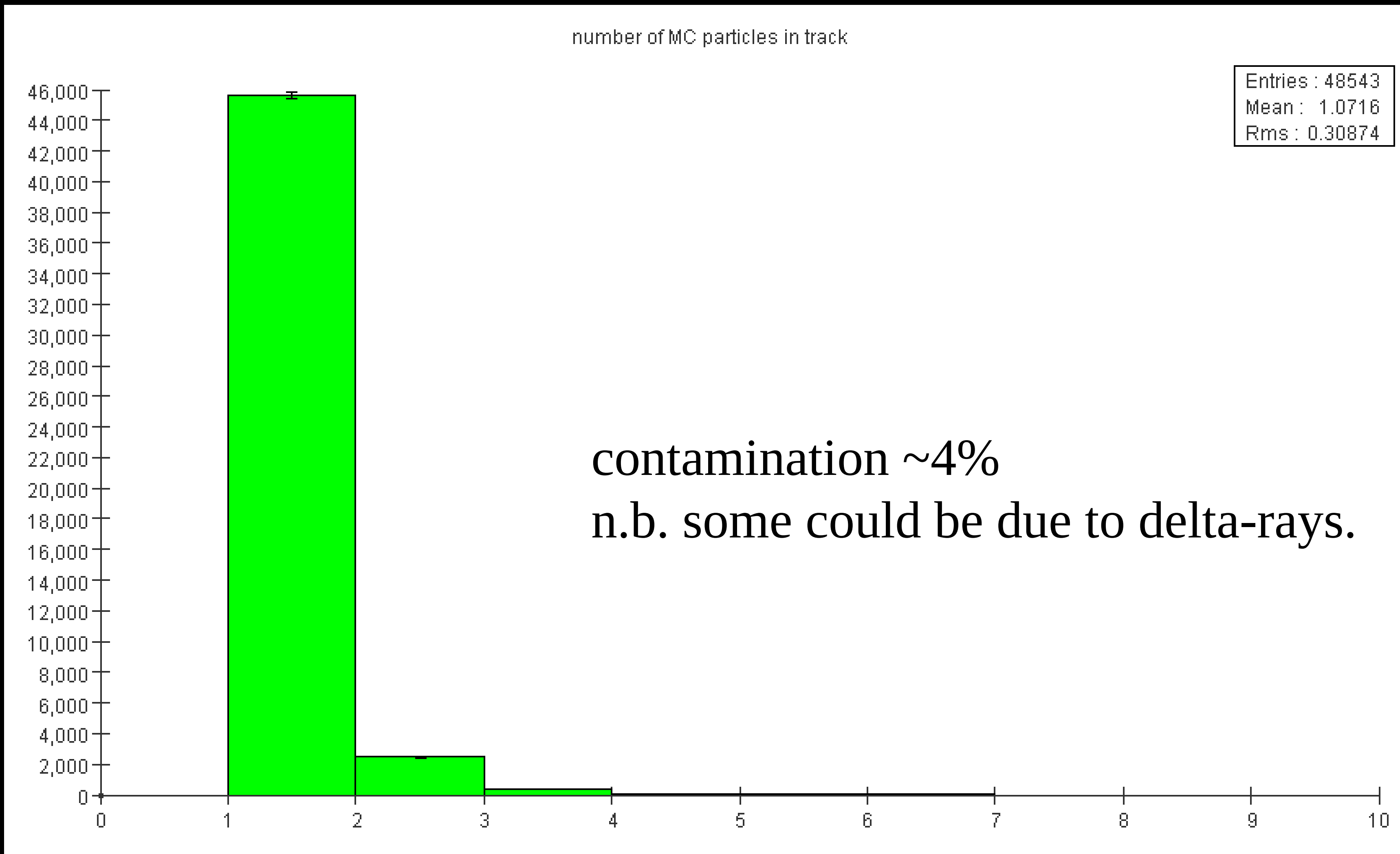
time (s) vs # tracks (1.7GHz)



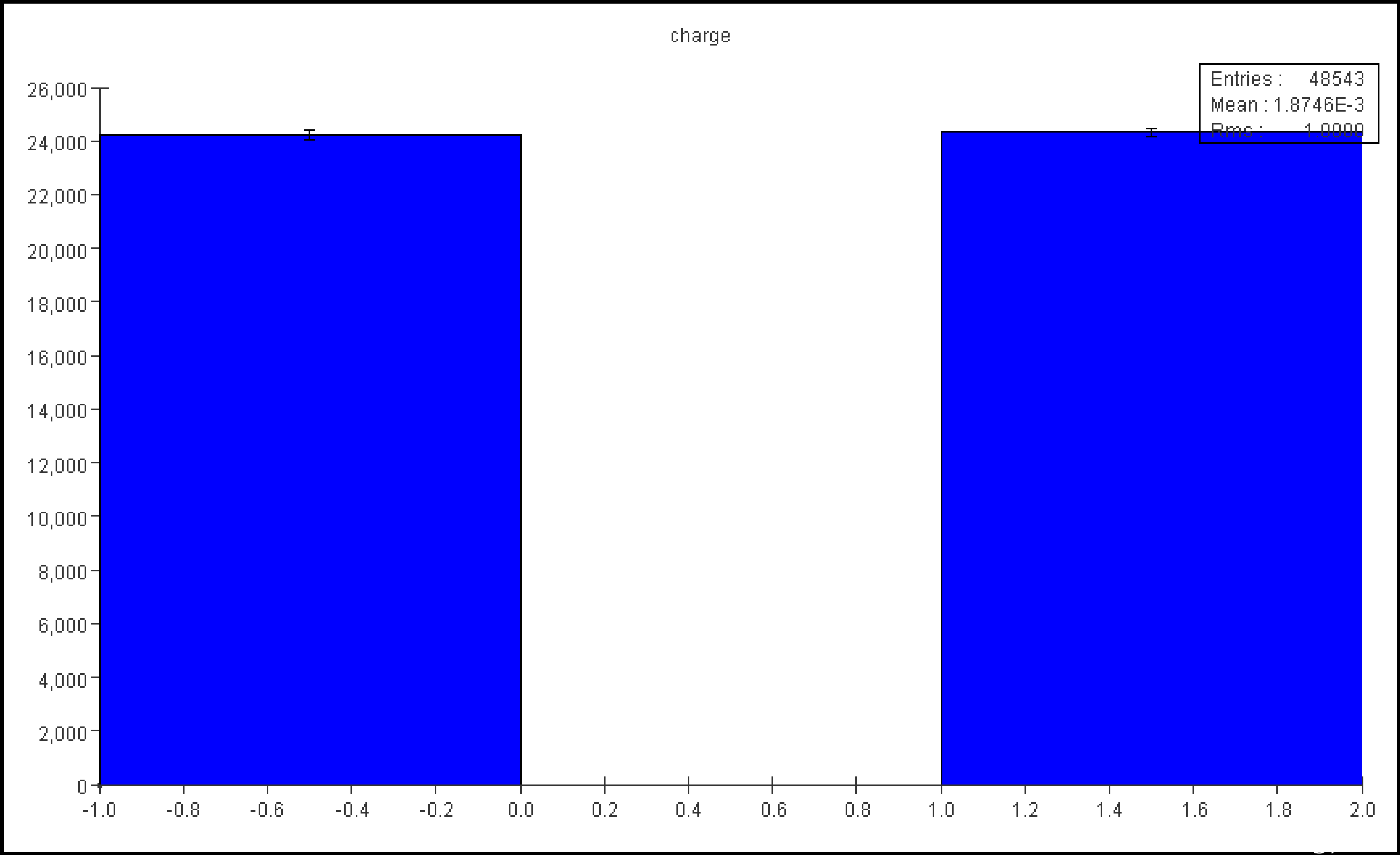
time(s) per track (1.7GHz)



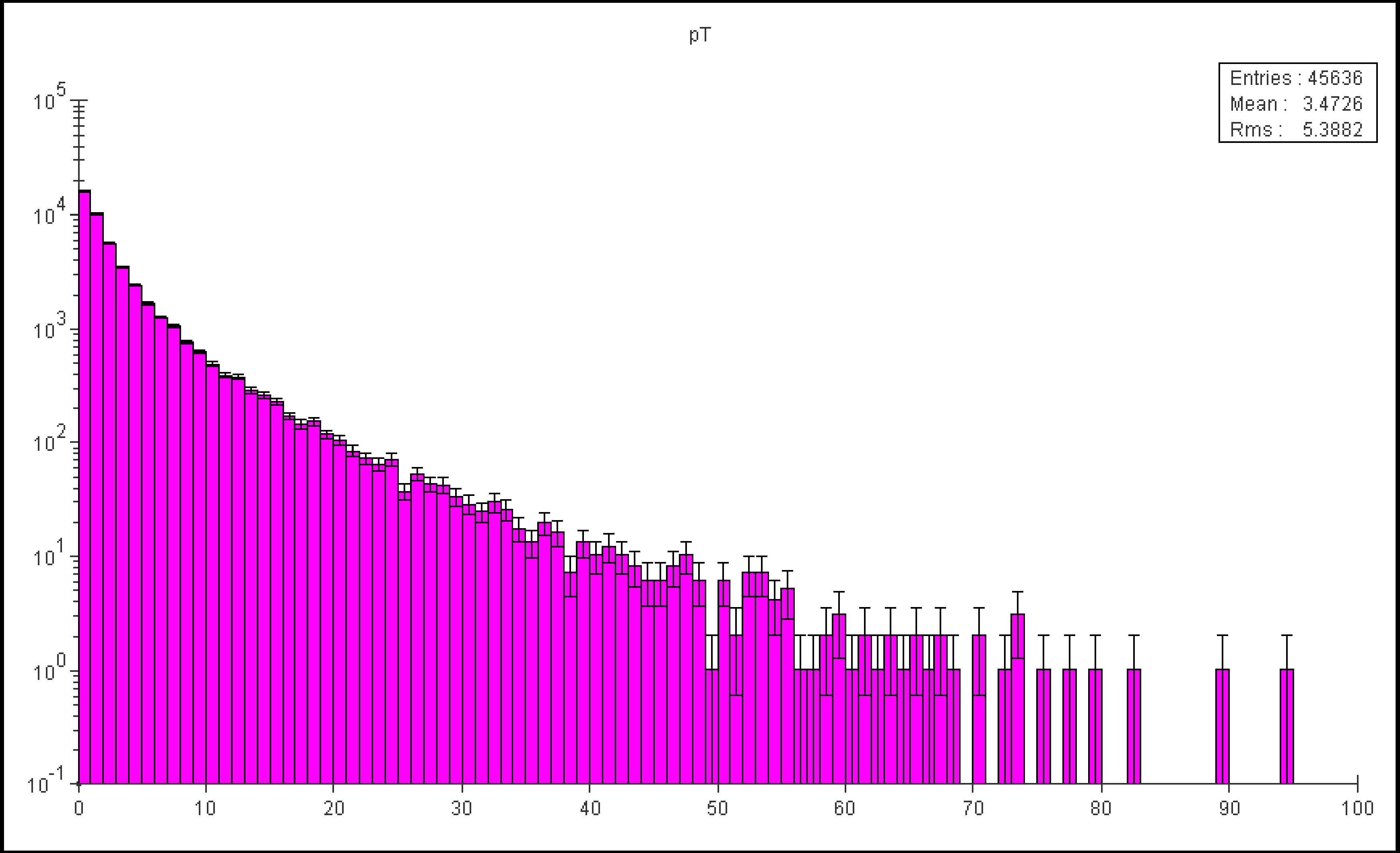
of MCParticles/track



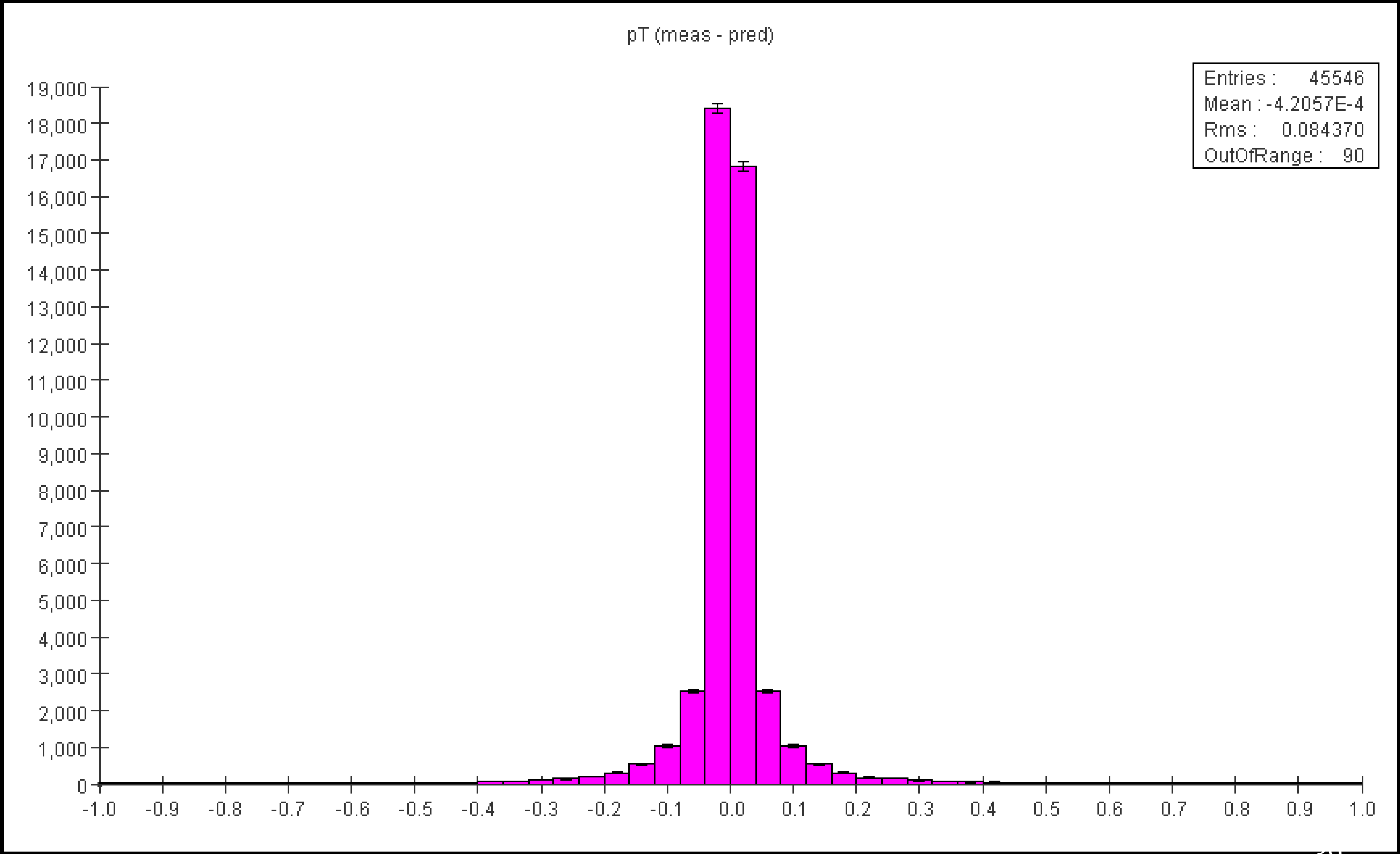
charge


charge
Entries : 48543
Mean : 1.8746E-3
Rms : 1.0000
26,000
24,000
22,000
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
-1.0
-0.8
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

$t\bar{t} \rightarrow$ six jets pT

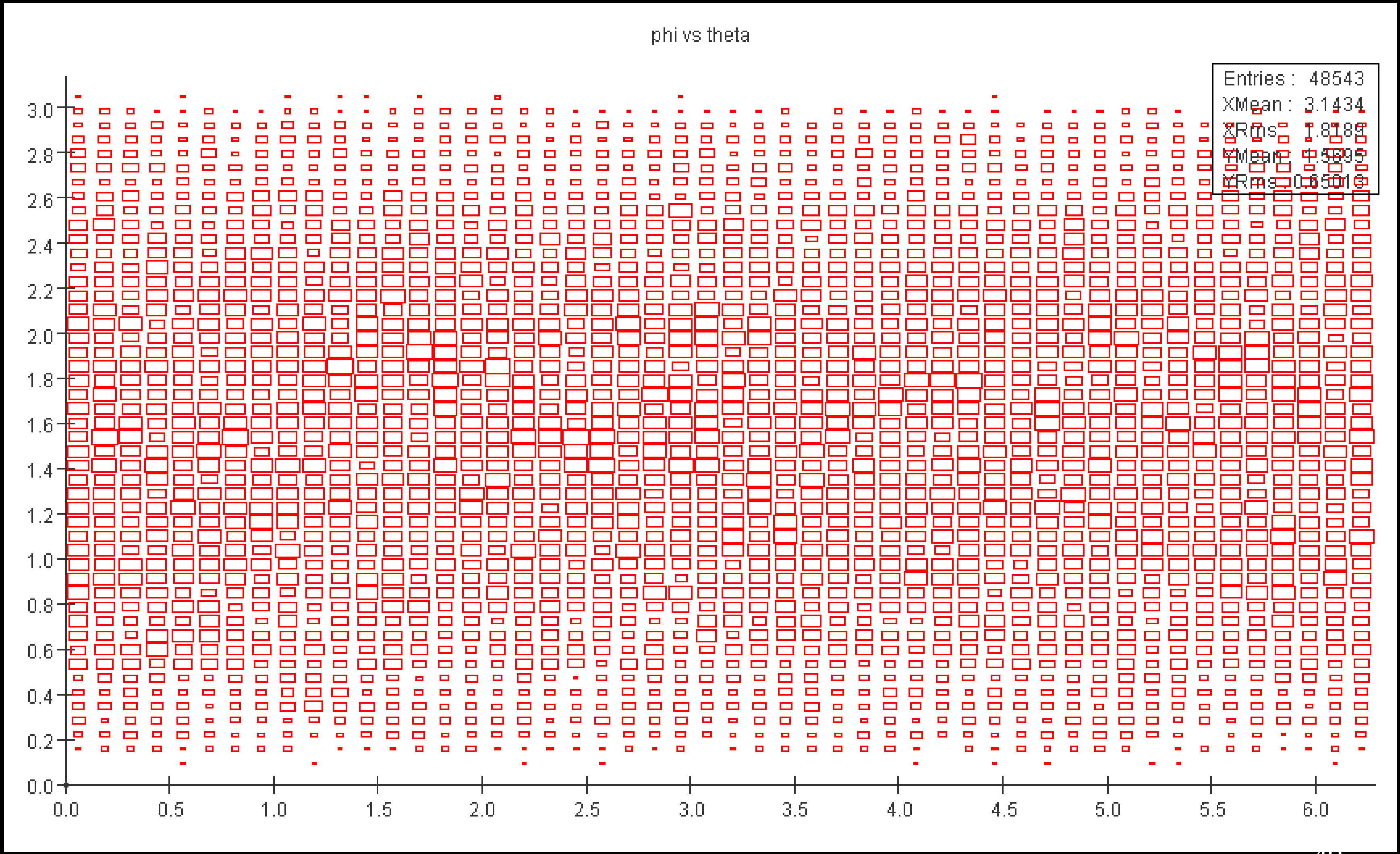


pT (meas-pred)



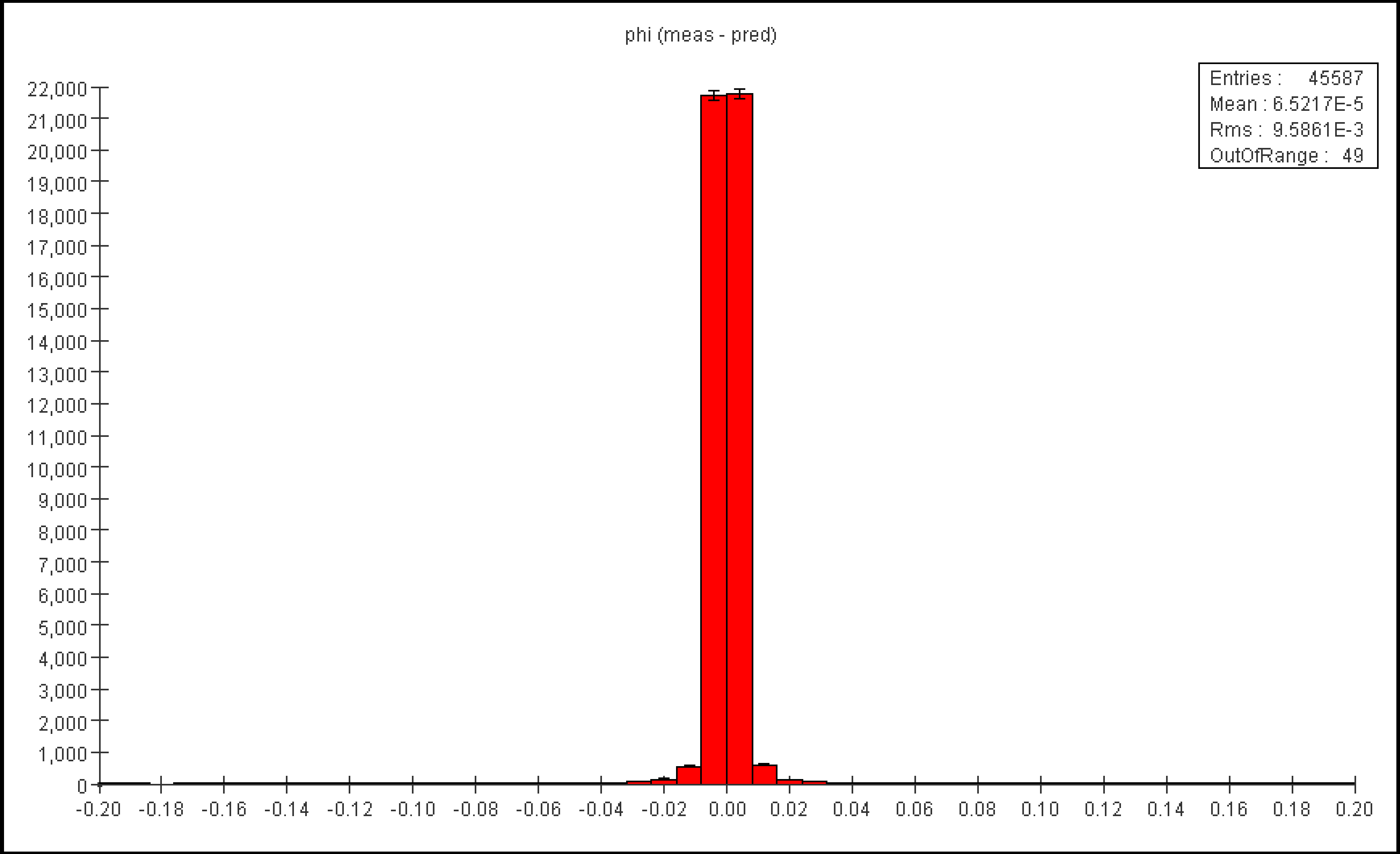
pT (meas - pred)
Entries : 45546
Mean : -4.2057E-4
Rms : 0.084370
OutOfRange : 90
19,000
18,000
17,000
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
-1.0 -0.9 -0.8 -0.7 -0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

φ vs θ

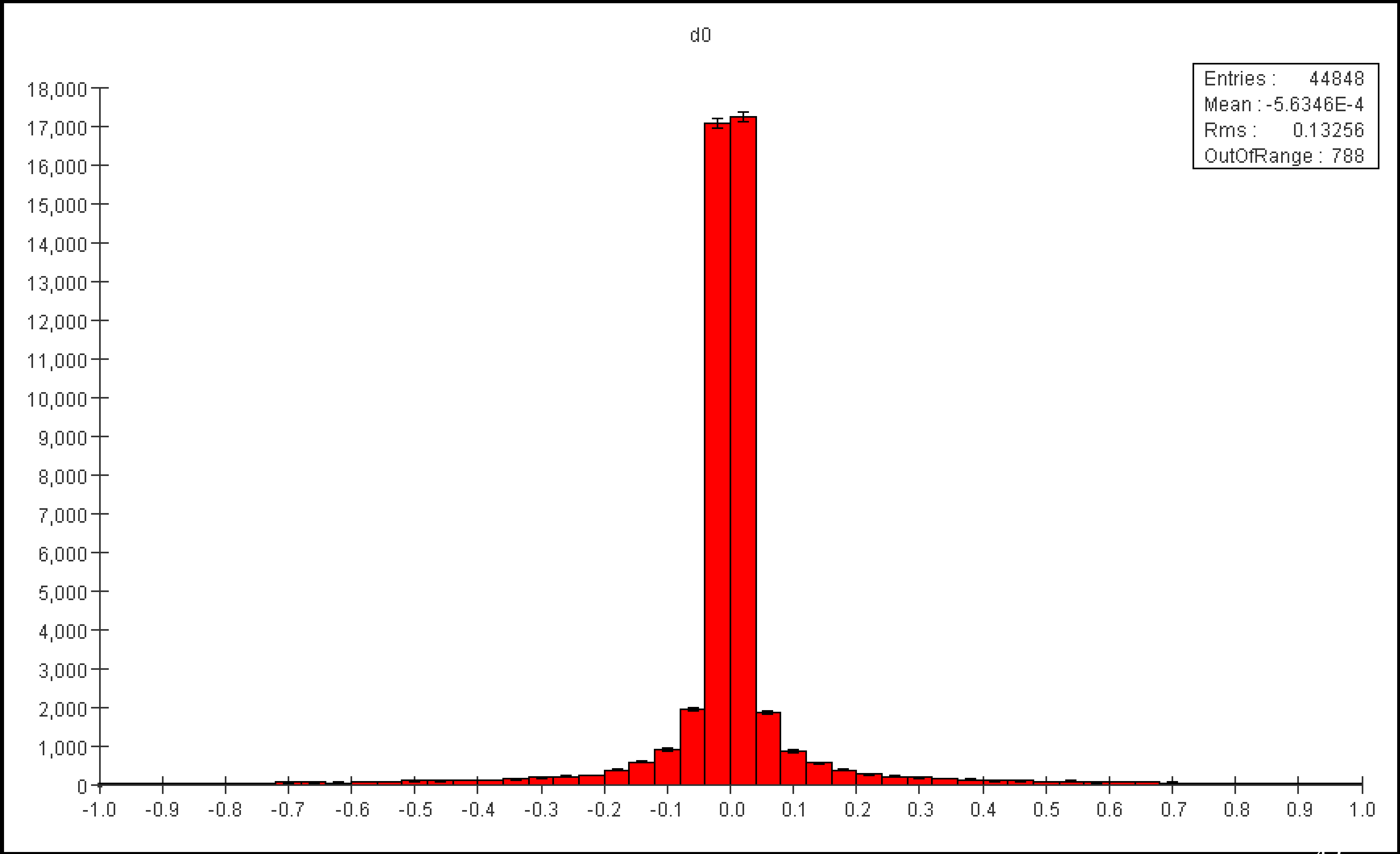


phi vs theta
Entries : 48543
XMean : 3.1434
XRms : 1.8189
YMean : 1.5695
YRms : 0.65013

phi (meas - pred)



impact parameter



Summary

- A number of improvements has been made to the Geant simulation package slic.
- Improvements are being considered for the tracker hit and track infrastructure.
- Pattern recognition based on 2-D measurements on surfaces is implemented.
- Fast, with high efficiency.
- Extrapolation into outer tracker and fitting with full Kalman filter soon.
- Lots of work ahead to characterize and improve.