Detecting Nuclear Materials from Muon-Scattering Data

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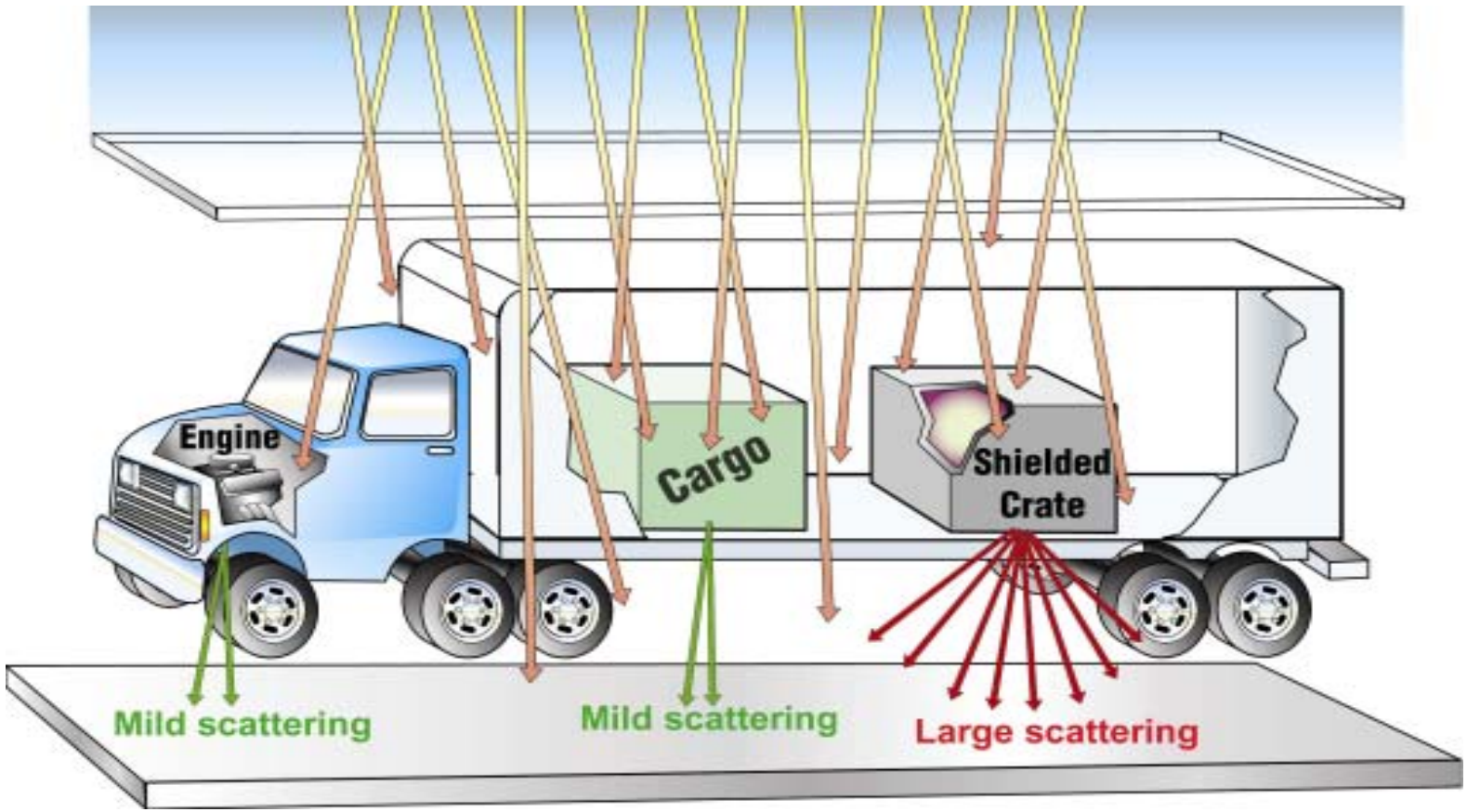
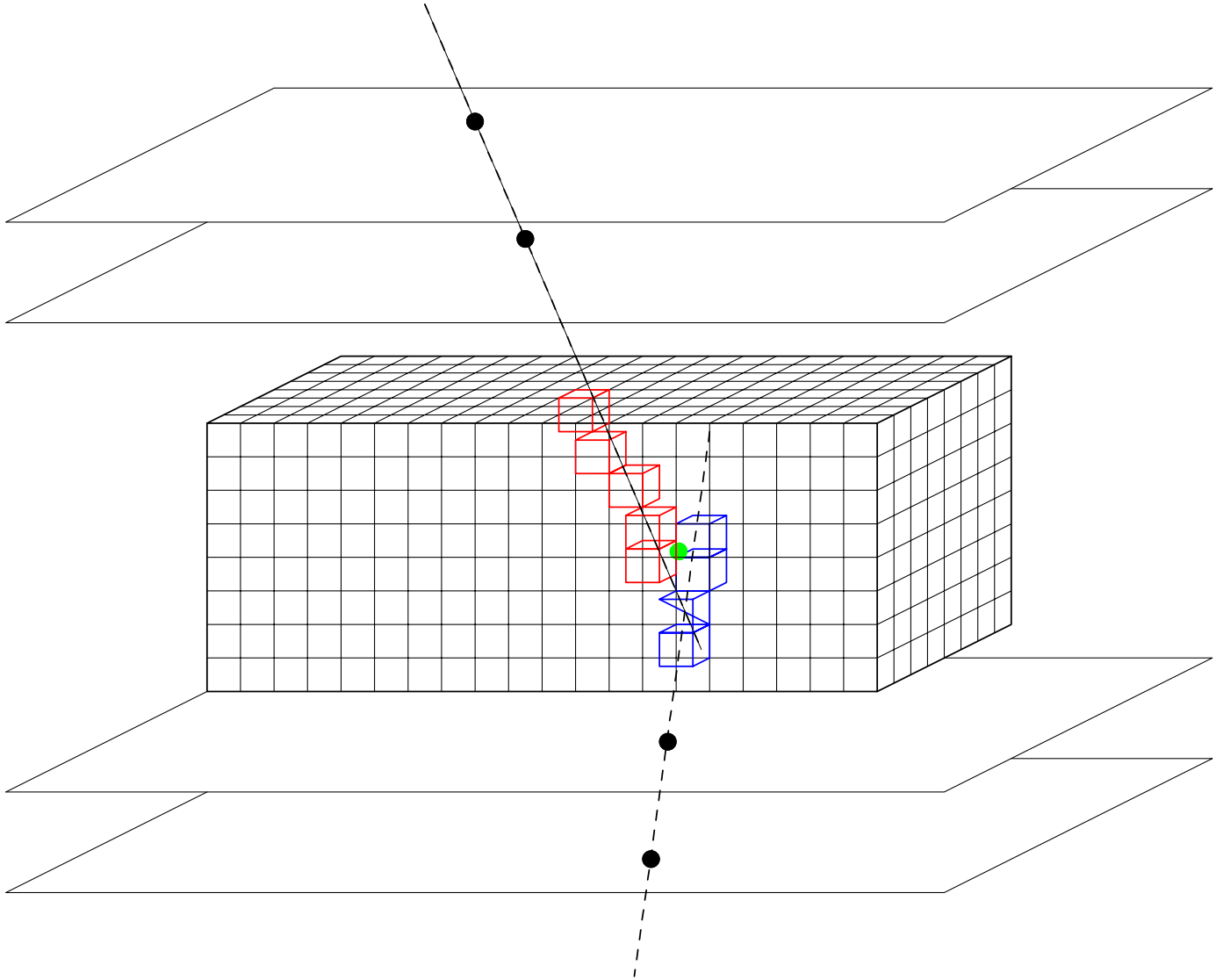
Muon Radiography Operational Concept



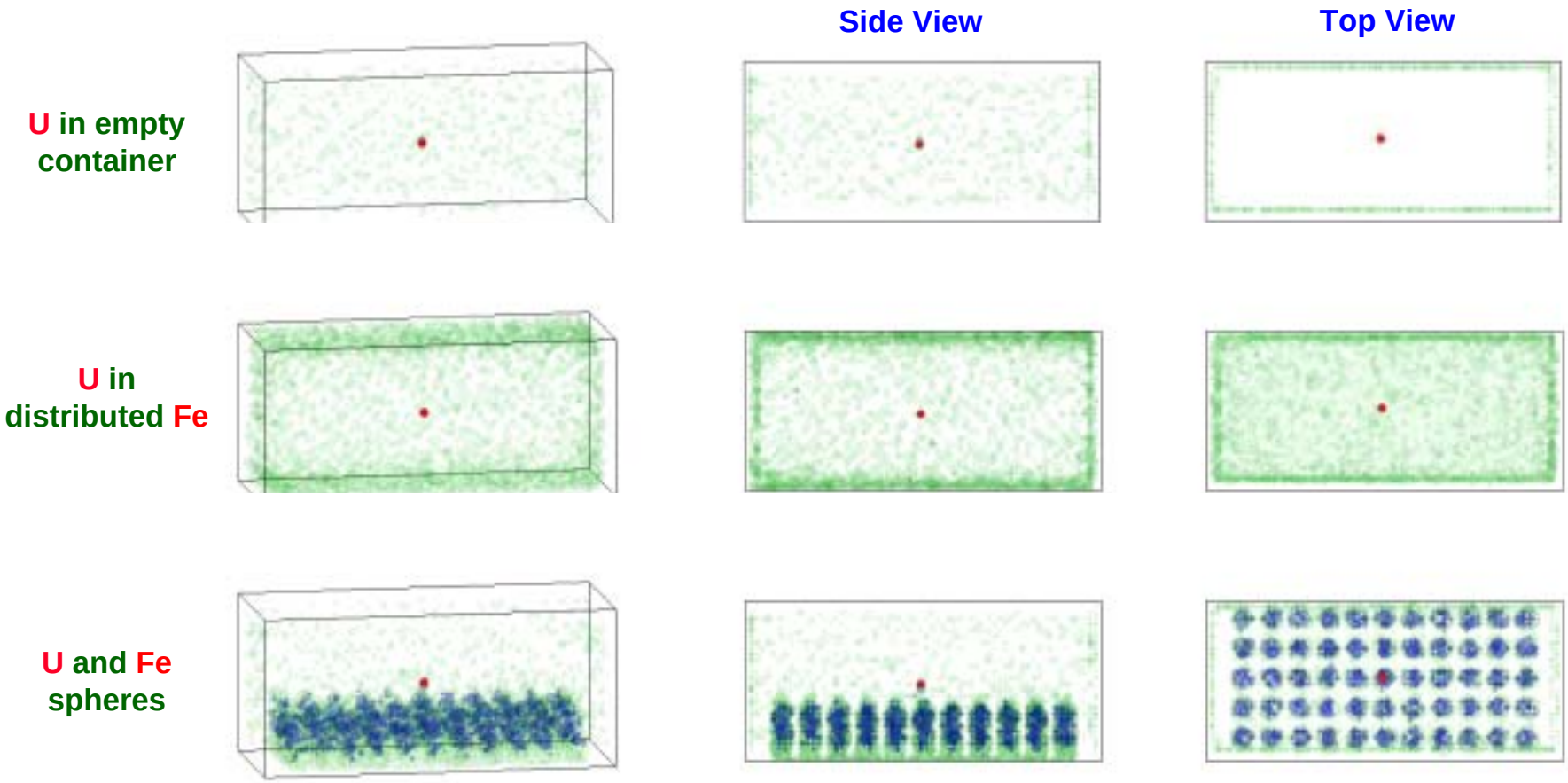
Expected muon scattering increases with increasing atomic number, due to the electric charge of muons.

Voxels, Rays, and Point of Closest Approach



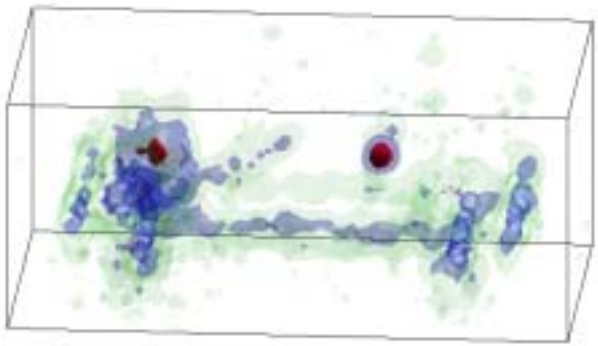
Maximum-Likelihood Reconstruction

Cargo container, 60 seconds of muon exposure



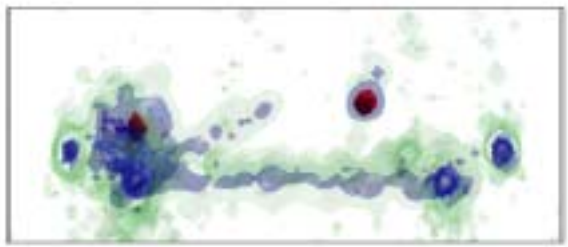
Maximum-Likelihood Reconstruction

Passenger car, 60 seconds of muon exposure

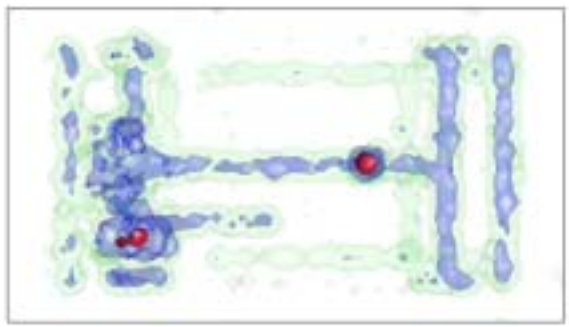


Two 20-kg U spheres

Side View



Top View



Classification

- Interpreting images can be difficult, and requires human involvement.
- Instead of using the data to create images, we sought to determine directly from the data whether a threat object is present.
- Instead of trying to determine how to get an answer from 800,000 detector coordinates, we used *machine learning* techniques.
- A computer algorithm is “trained” using many examples of datasets where the answer is known and provided to the algorithm.
- The algorithm “learns” how to discern the answer from the data.

Machine Learning Implementation

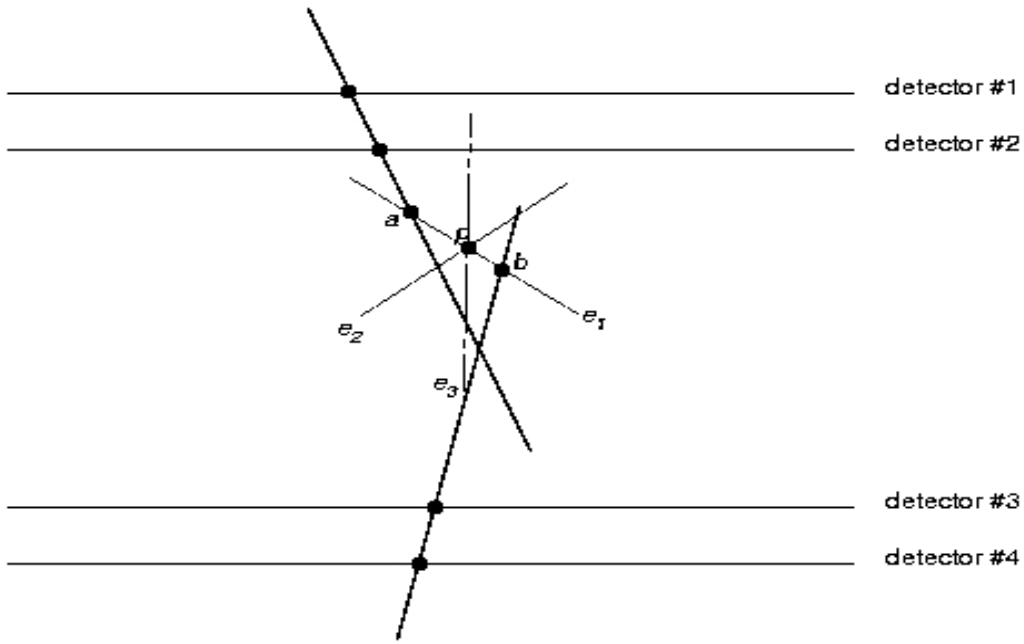
- The classifier is trained using muon-scattering data generated by computer simulations of cargo containers or passenger cars containing a variety of materials, some with a threat object and some without.

- The features for each sample are the mean squared scattering (angle times energy) for each 10-cm voxel in a 3-voxel cube surrounding the sample location.

- A muon's scattering can assigned to voxels in several ways:
  - Assign to the voxel containing the point closest to the incoming and outgoing ray tracks
  - Assign to every voxel the incoming and outgoing ray tracks pass through
  - Weight the assignment according to some measure of distance from a voxel to the point of closest approach

Physics-Based Distance Function

- Uses the single-scatter approximation to associate a point with each muon.
- Choice of weights incorporates the uncertainty of this approximation.
- Orthonormal coordinate vectors for each muon:
  - e_1: orthogonal to both paths
  - e_2: in direction of the deflection
  - e_3: follows tracks most closely

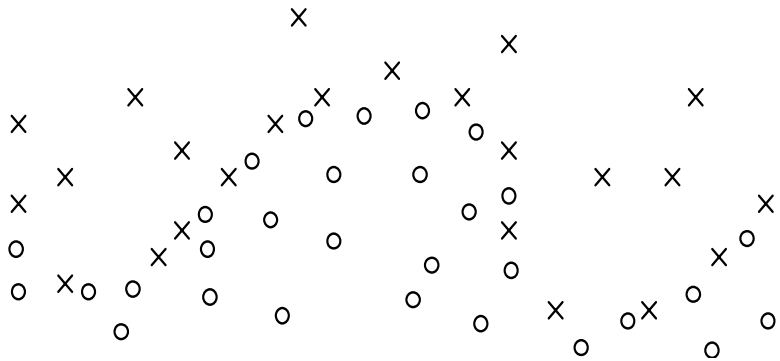


$$d_j(s) = \sqrt{\sum_{i=1}^{3} \left(\alpha_{ji}\left(s - p_j\right) \cdot e_{ji}\right)^2}$$

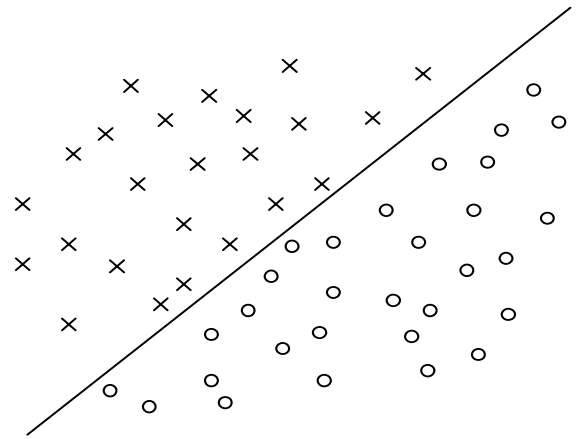
$$\alpha_{j1} = \alpha_{j2} \propto \left(\left|a - b\right| \cdot \Delta\theta\right)^{-1},$$

$$\alpha_{j3} \propto \left|a - b\right|^{-1}$$

Support-Vector Machines



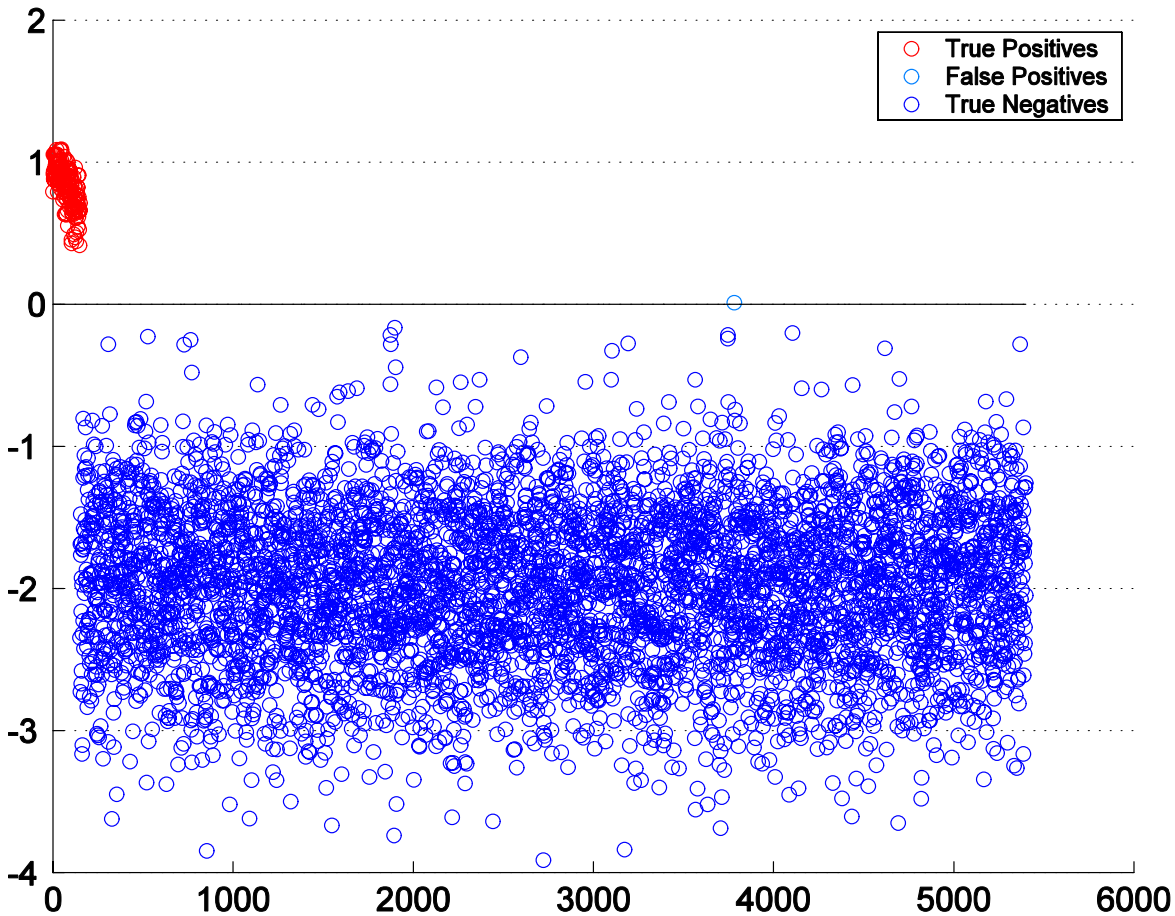
Thousands of points in 27-dimensional space



Thousands of points in infinite-dimensional space

- Linear classification is made possible by nonlinearly embedding the data into an infinite-dimensional function space.
- Given a kernel $k(x, y)$, the embedding maps y to $x \mapsto k(x, y)$.
- For $k(x, y) = e^{-\Gamma \|x-y\|^2}$, the data is mapped to a simplex; any two subsets can be separated by a hyperplane.

Results---Test Data



Positive samples have 20-kg U sphere centered on the central voxel.

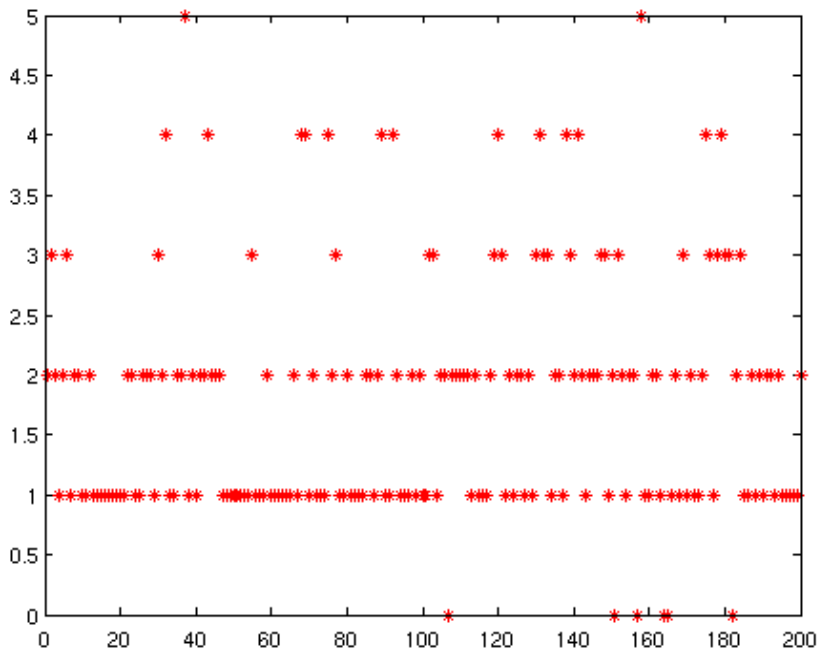
Likelihood Function for Locating Objects

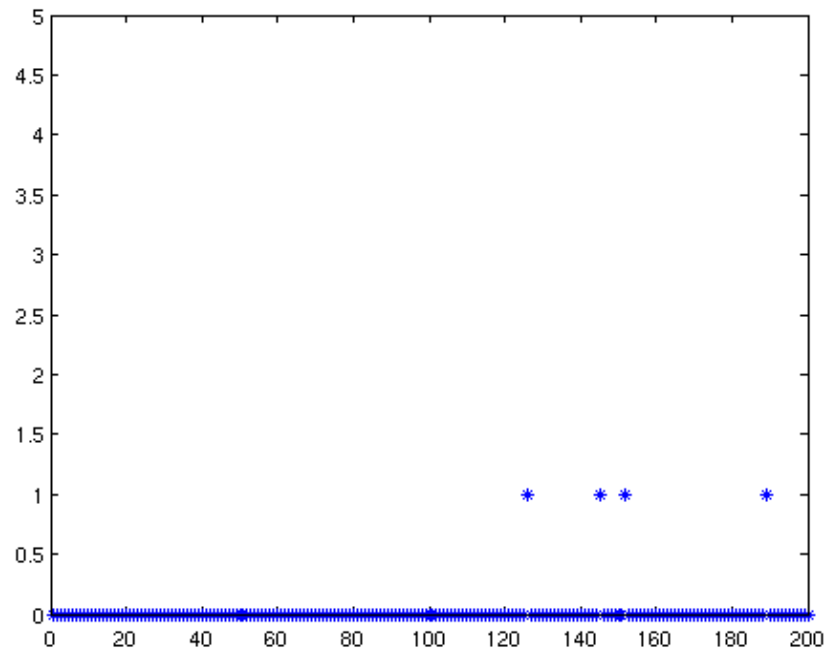
- The SVM works well for 3-voxel cubes; what about a whole container?
- Testing too many locations will allow test errors to accumulate.
- We identify a small number of locations to test by finding local minima of a likelihood function.

$$U(s) = \sum_j \frac{\Delta\theta_j E_j}{\max(d_j(s), a)}$$

Preliminary Results---Classifying Candidate Locations

Number of positively-classified samples per container





97% of containers with a threat object have at least one positive sample

98% of containers with no threat object have no positive sample

Summary

- We have demonstrated that we can reliably detect nuclear threat objects by processing scattering data from cosmic-ray muons, without the risk and expense of artificial radiation.
- After 60 seconds of muon exposure, the combined machine-learning classification/likelihood function approach detected all but 3% of tested cargo containers with a threat object.
- Only 2% of containers without a threat object were mistakenly flagged; these came from containers with atypical cargo.
- The majority of vehicles could be declared harmless with as little as 20 seconds of muon exposure.