SAND2015-10444PE

# Measuring hydrogen-bearing and nuclear materials in containers

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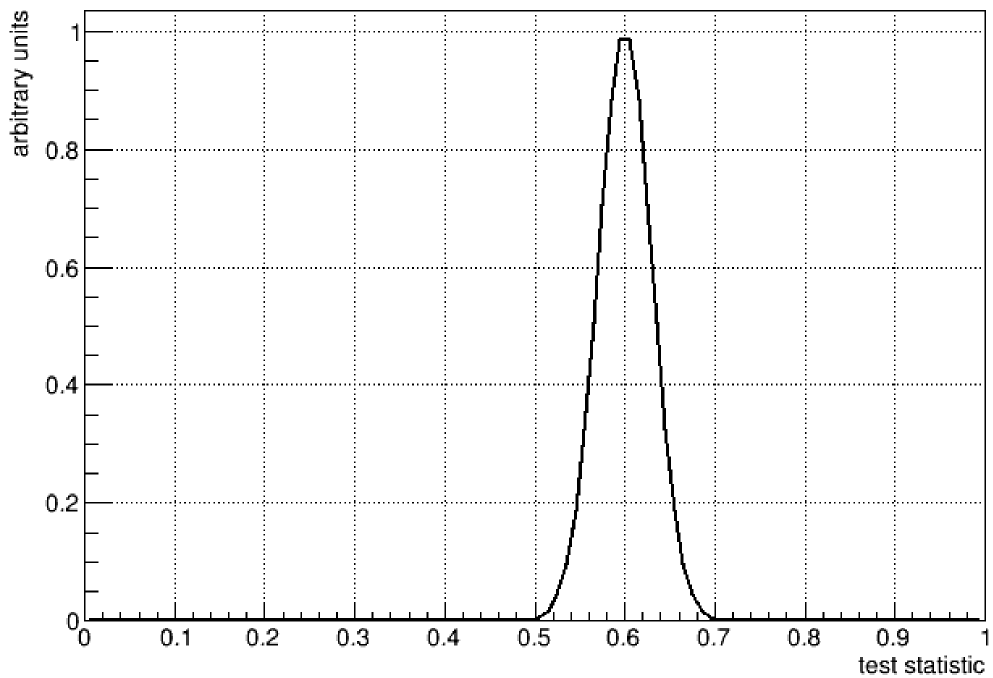
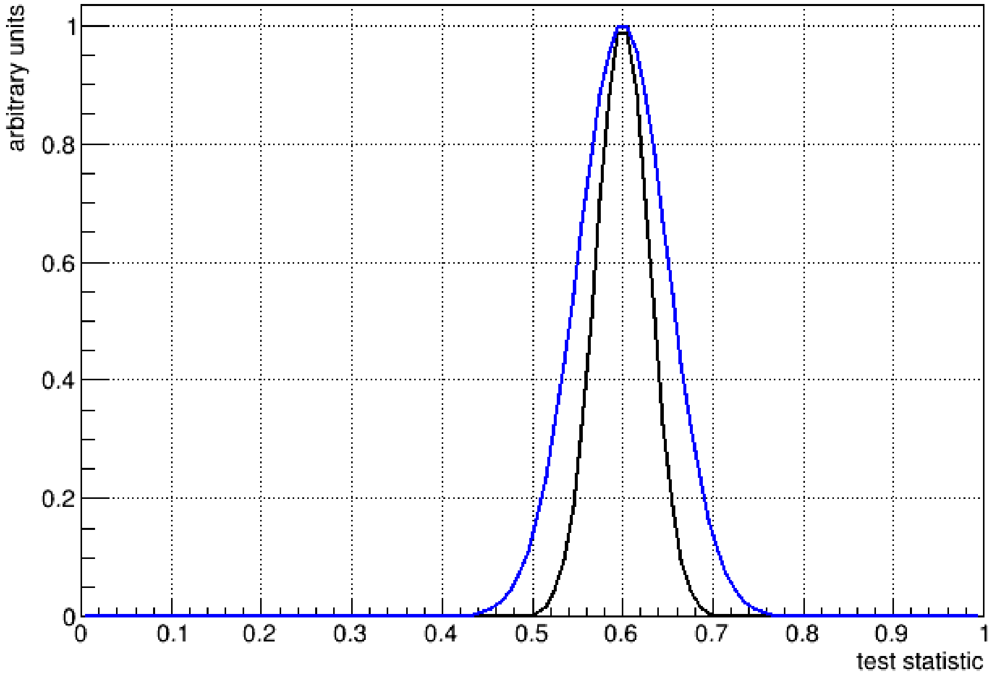
# Test Statistic Distribution




Whether it represents an ***attribute*** or a ***template*** comparison metric, verification performance always comes down to a test statistic distribution.

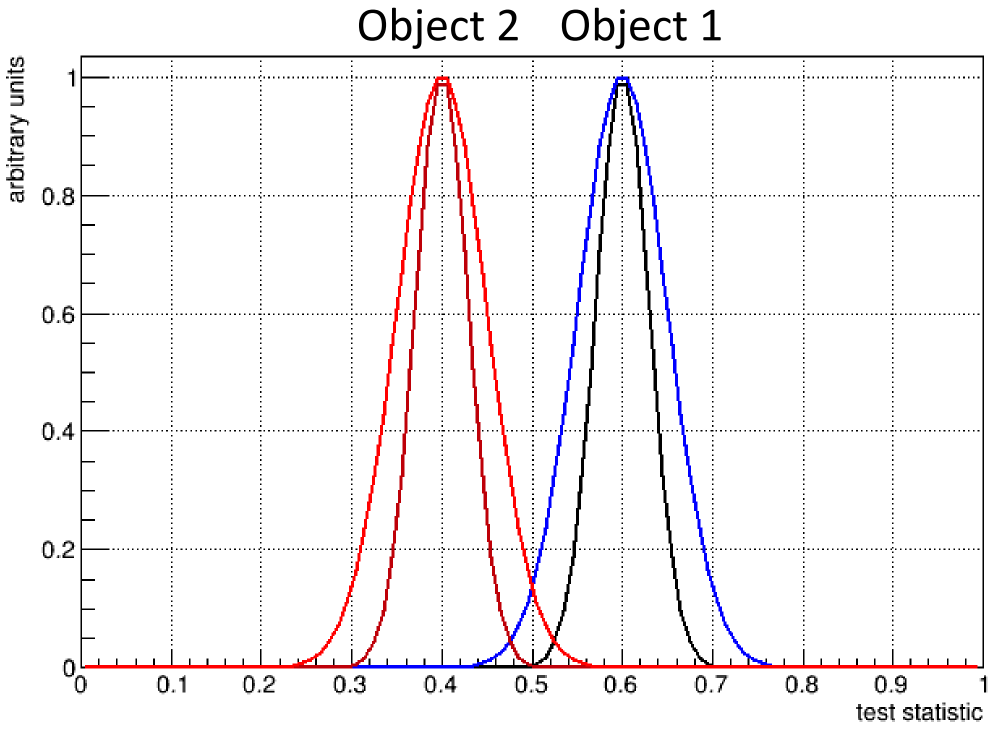
# Test Statistic Distribution: statistics + systematics




The width is determined by:

1. Statistical variation (take more data).
2. Uncontrolled systematic variation (nuisance terms).

# Test Statistic Distribution: discrimination




The ability to discriminate between two objects is determined by:

1. The difference in mean values (sensitivity of the measurement system to relevant characteristics).
2. The widths of the distributions (control those uncertainties).

# Generic Nuisance Terms

Detection system

Hydrogen-bearing + nuclear material in container

- Some generic nuisance parameters:
  - Environment
    - Background
    - Variability in container
    - Walls/floor, other scatterers
    - Nearby sources
  - Detector characteristics
    - Response drifts
    - Temperature effects, etc.

# Nuisance Terms – gamma-based

Detection system

Hydrogen-bearing + nuclear material in container

| Detection System | Relevant Characteristics | Nuisance Terms |
|---|---|---|
| Gamma spectroscopy | Presence and isotopics of fissile material, mass (with assumptions) | Shielding (high-Z), self shielding, unknown configuration, |
| Gamma imaging | Configuration of fissile material (by isotope), configuration of intervening material (high-Z) | Position and orientation, shielding (high-Z), self shielding |

# Nuisance Terms – neutron-based

Detection system

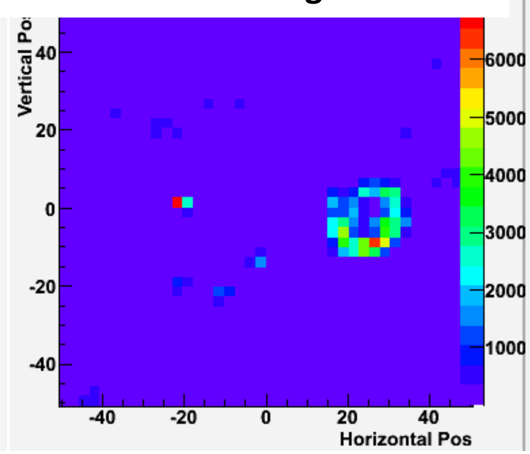
Hydrogen-bearing + nuclear material in container

| Detection System | Relevant Characteristics | Nuisance Terms |
|---|---|---|
| Fast neutron multiplicity | Presence of fissile material, fission rate, multiplication | Moderating materials (low-Z), absolute efficiency, unknown configuration |
| Thermal neutron imaging | Presence of fissioning material, configuration of moderating materials, configuration of intervening material (thermal) | Position and orientation, moderating and absorbing materials in container |
| Fast neutron imaging | Presence and configuration of fissioning material, configuration of intervening material (low-Z) | Position and orientation, scattering materials in object and container |

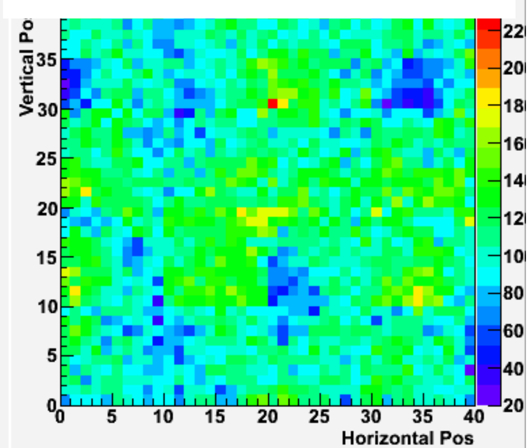
# Test Case: Neutron coded aperture imager

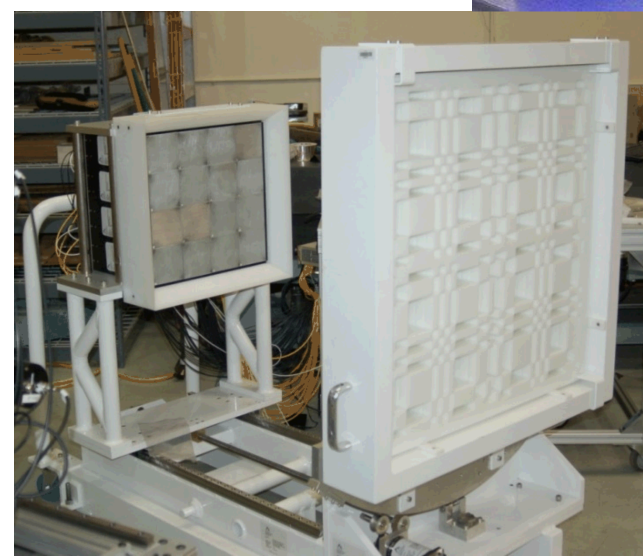
- ORNL/SNL fast neutron coded aperture imager developed for arms control treaty verification.
- Image plane consists of 16 organic scintillator pixelated block detectors
  - Each block consists of a 10x10 array of 1 cm. pixels.
  - PSD and pixel id accomplished by 4 photomultiplier tubes.
- Mask plane consists of 2.5 to 10 centimeters of HDPE.

**Reconstructed image**




**Raw counts**

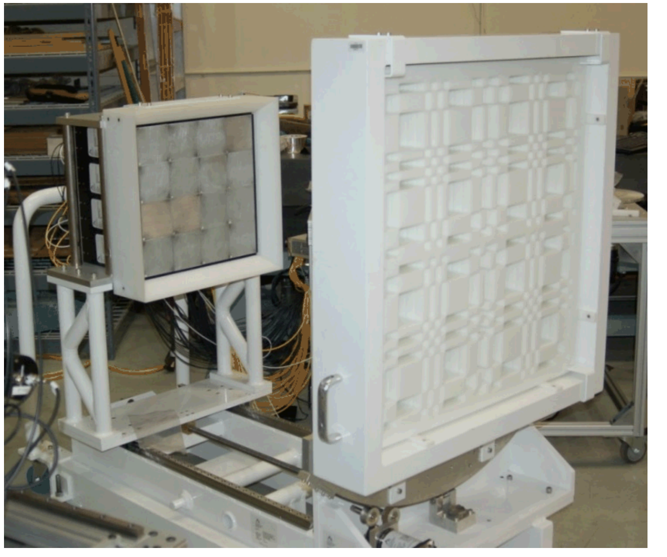


**Detector developed in collaboration with ORNL:** P. Hausladen, J. Newby, M. Blackston

# Example template matching process

- Take data
- Process data
- Reconstruct image
- Image registration vs template
- Pearson correlation vs template
- Compare PCC value to expected distribution
- Threshold $\Delta x/\sigma$, return pass or fail, confidence



Each step is an opportunity to introduce systematic variation!

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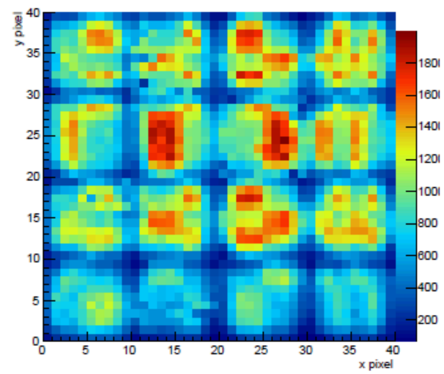
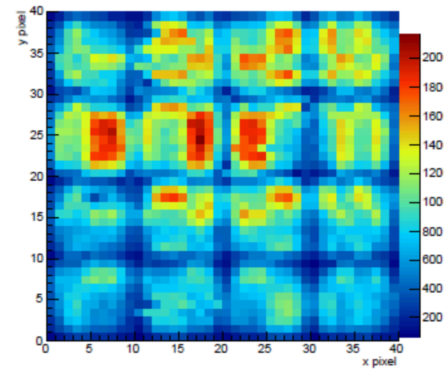
Apply calibrations, select neutrons, reconstruct pixel, etc…

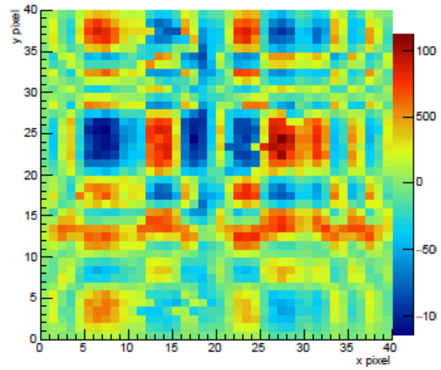
Mask data




Anti-mask data




Divide by “void” to correct for efficiency




Normalized & subtracted

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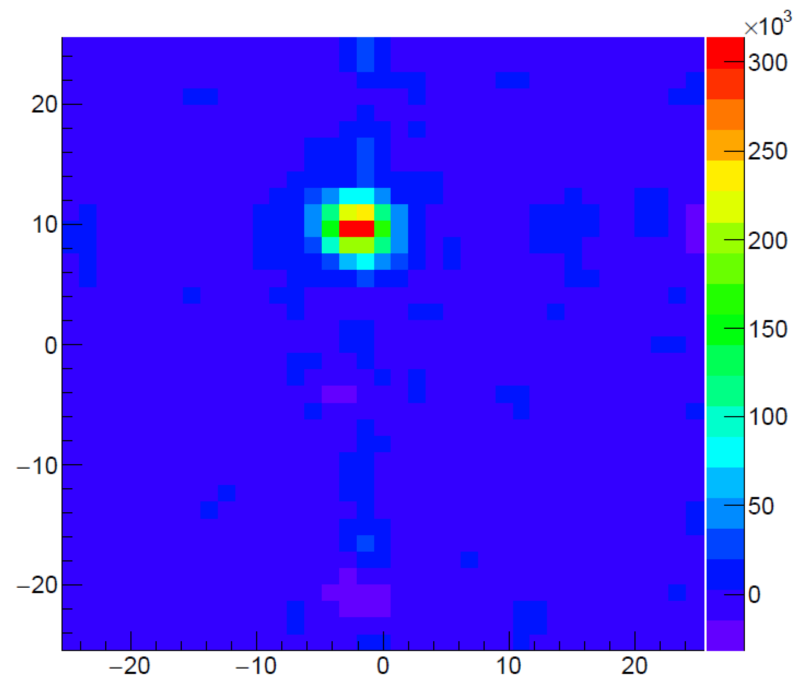
Uses knowledge of mask pattern to reconstruct source distribution:




This is the template!

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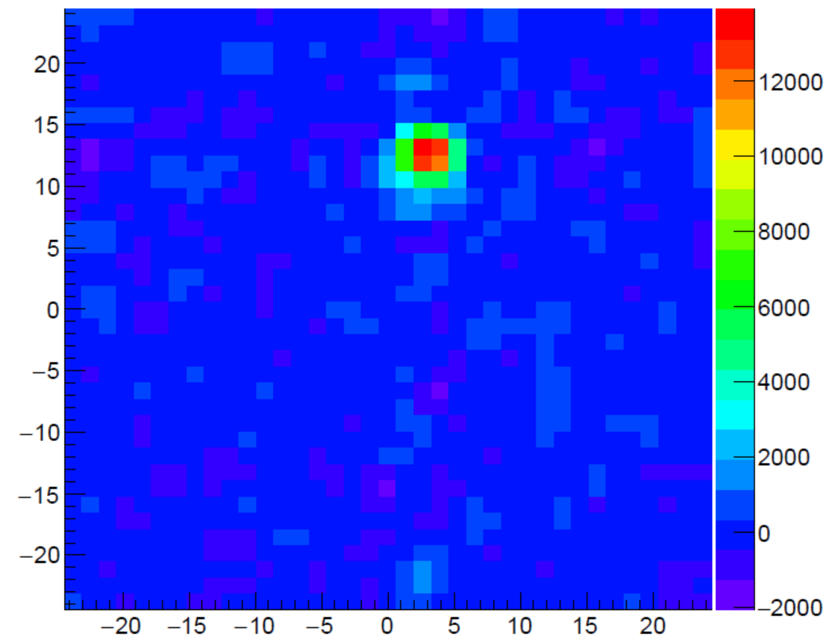
Repeat these steps for the confirmation measurement:




This is the confirmation measurement!

- Lower statistics
- Shift in location

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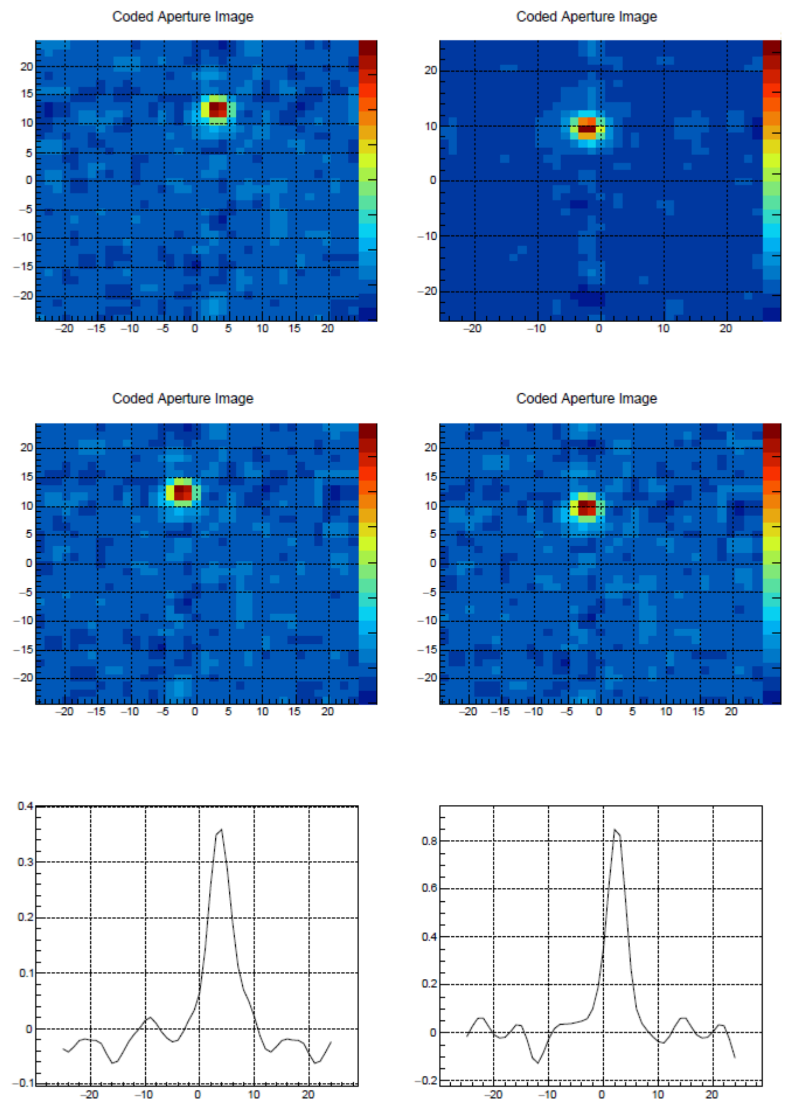

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- Process data
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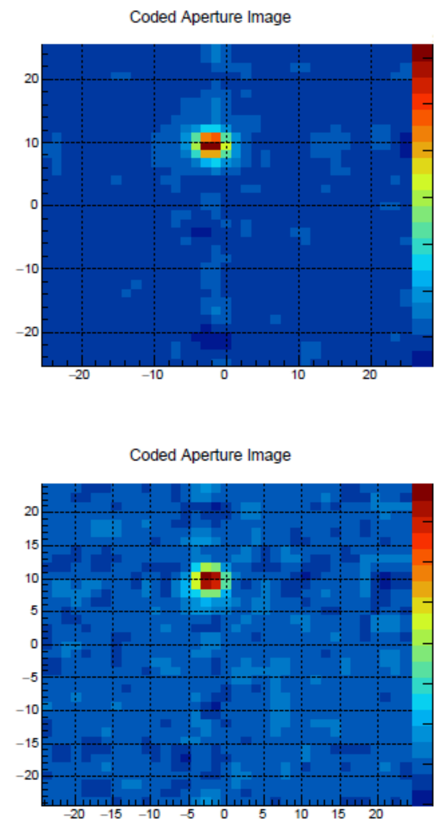



PCC = 0.849

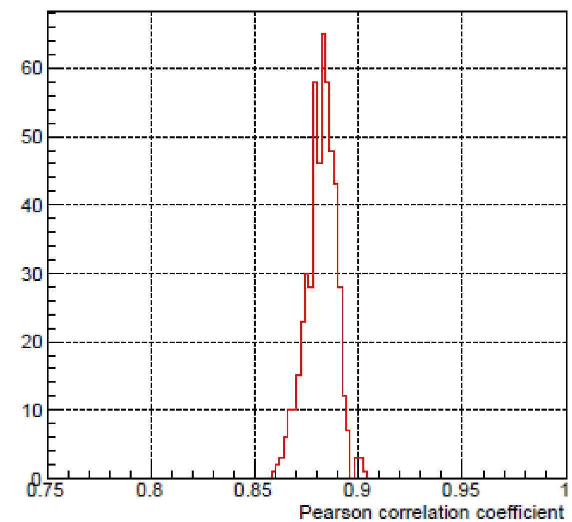
Um… so what?

# Example template matching process

500 times

- Sample ~~Take~~ data
- Process data
- Reconstruct image
- Image registration vs template
- Pearson correlation vs template
- Compare PCC value to expected distribution
- Threshold $\Delta x/\sigma$, return pass or fail, confidence

- Sample low-stats data many times from the template.
- Process through whole chain.




Expected PCC distribution accounting for statistical fluctuations only.

# Example template matching process

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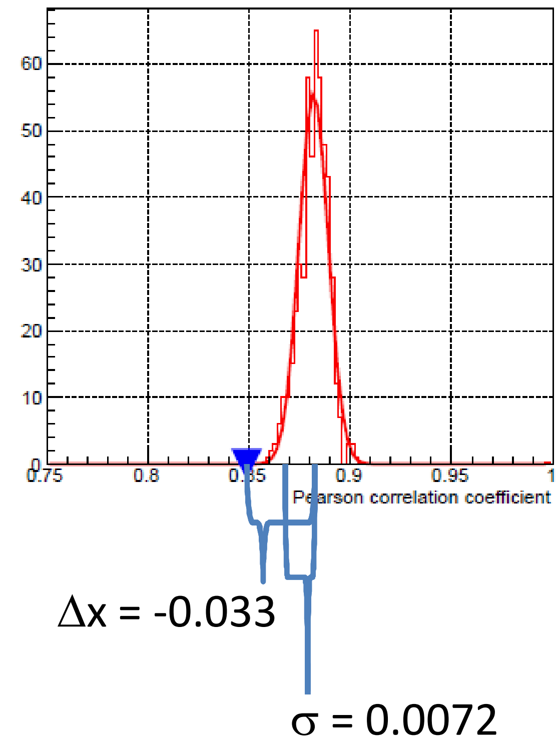


$\Delta x/\sigma$ = -4.6

# Example template matching process

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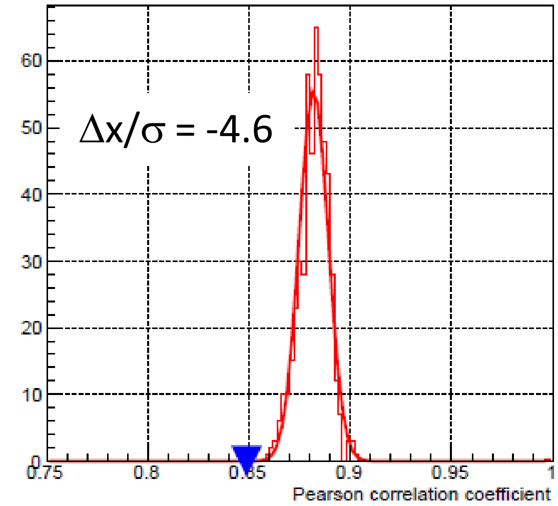
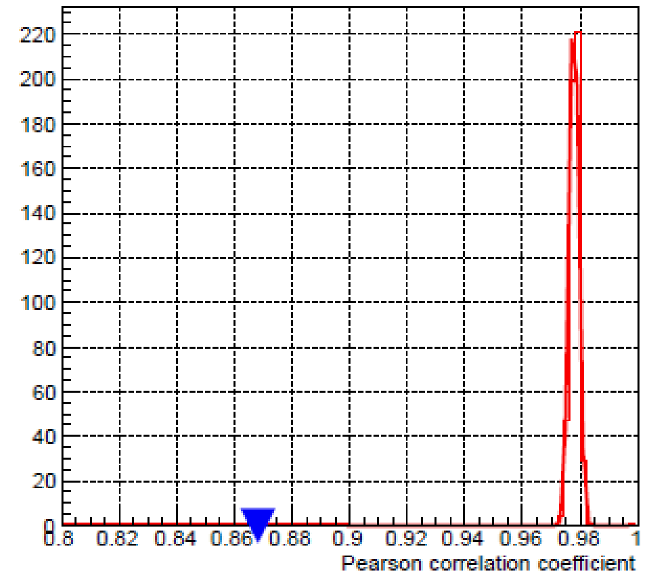



- Uh-oh! Why are they different?
- We only accounted for statistical fluctuations, not real-life differences between measurements.
- Add a fudge factor:
  - Anything less than $10\sigma$ away passes.
  - $1-(\mathrm{Erf}((|\Delta x/\sigma|-10)/3)+1)/2 \gtrsim 0.5$

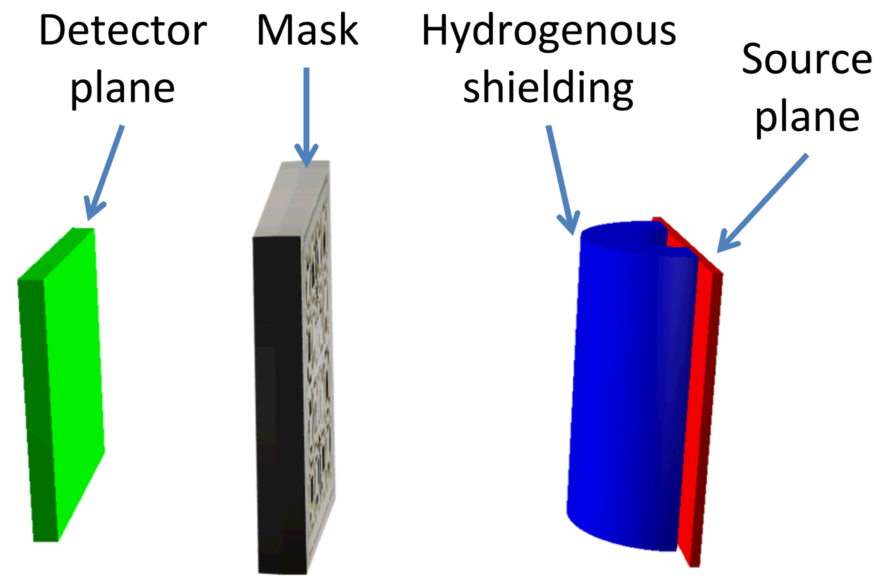
# Second test object

- ~22x stronger Cf-252 source!
- Statistical spread of PCC distribution shrinks
- But systematic effects don't get better
- Our multiplicative fudge factor no longer covers…
- → False negative!

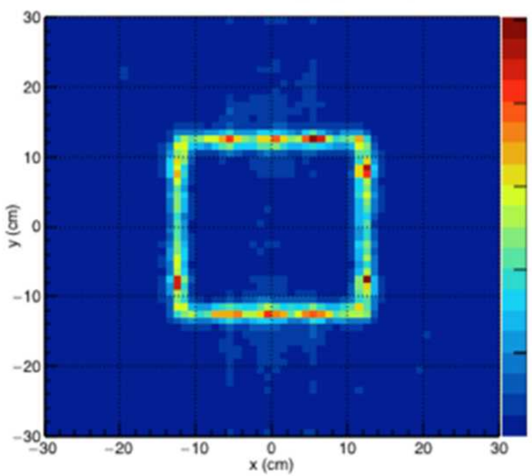



$\Delta x/\sigma = -71$

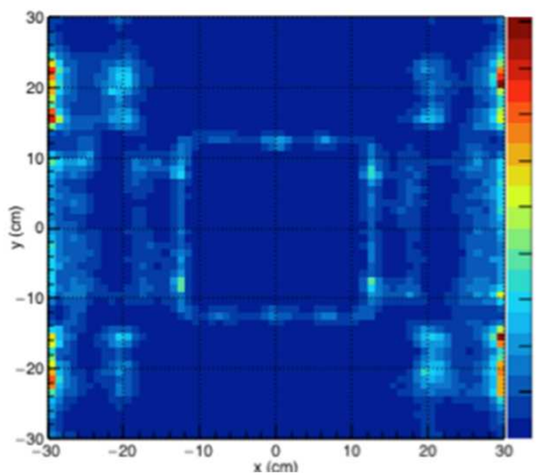
# Container effects: toy model



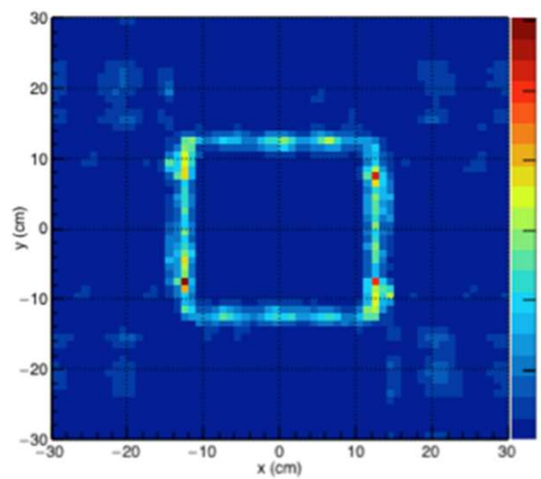

Reconstructed Image: unshielded square source




Reconstructed Image: shielded square source ***without*** accounting for the shielding




Reconstructed Image: shielded square source ***corrected*** for the shielding



# Takeaways

- Many ways to implement template matching.
- Real life is not simple. Nuisance parameters are deadly.
- Making techniques robust is key.

- Some nuisance parameters:
  - Object characteristics
    - Position
    - Orientation
    - Material (isotopics)
  - Environment
    - Background
    - Variability in container
    - Walls/floor, other scatterers
    - Nearby sources
  - Detector characteristics
    - Response drifts
    - Temperature effects, etc.

# Future directions

- It may not be exciting, but a nuisance parameter measurement campaign may be more important than an object measurement campaign.
- Some nuisance parameters:
  - Object characteristics
    - Position
    - Orientation
    - Material (isotopics)
  - Environment
    - Background
    - Variability in container
    - Walls/floor, other scatterers
    - Nearby sources
  - Detector characteristics
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# Backups

# Example template matching process

- Take data
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- Threshold $\Delta x/\sigma$, return pass or fail, confidence

- Pearson correlation is a measure of similarity between two datasets:

$$r = r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\ \sqrt{n\sum y_i^2 - (\sum y_i)^2}}.$$

- $x_i$ & $y_i$ are the binned template & test values
- Result r in [-1,1]
- PCC is invariant to scaling and shifting
  - No need to adjust for measurement time; S:B will still have an effect.

# Account for sub-pixel position shift

- Our image registration technique finds best shift in pixel units.
- Sub-pixel shifts change pixel values in a non-Poisson way.
- Implement sub-pixel shifts in the sampling of template data to build distribution
  - Significantly “improves” match by accurately accounting for that effect
  - Results in a correct confirmation