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Single-Volume Scatter Camera: simulation results

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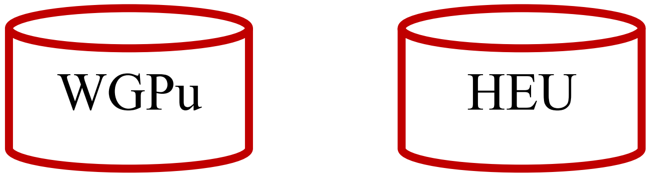
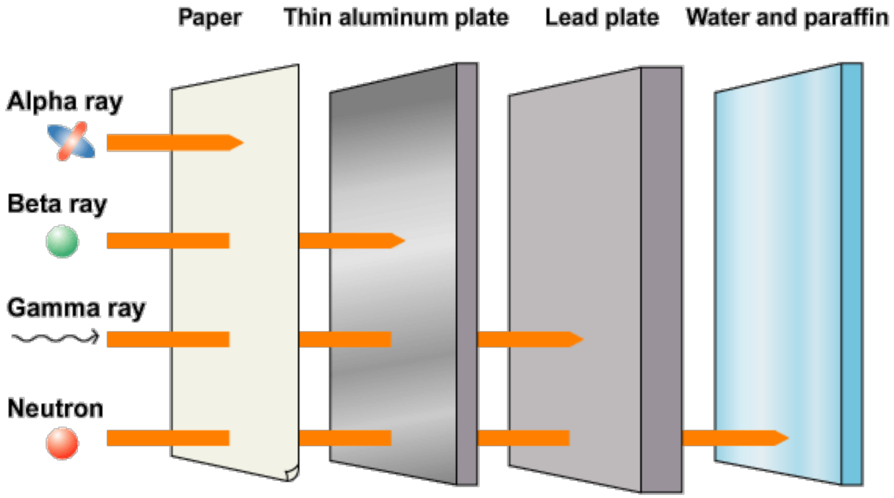
Outline

- **Motivation: why neutrons? Current approaches for neutron source imager.**
- **Advantages of a single volume neutron scatter camera.**
- **SVSC concept description and challenges.**
- **SVSC conceptual proof from simulation.**
- **Conclusions.**

Why neutron detection and imaging?

- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
- Only neutral particles penetrate shielding.
- Neutrons are more specific:
  - Lower natural backgrounds
  - Fewer benign neutron emitters





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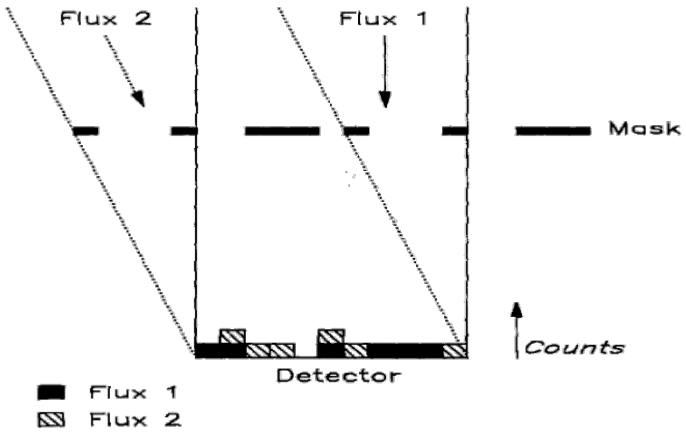
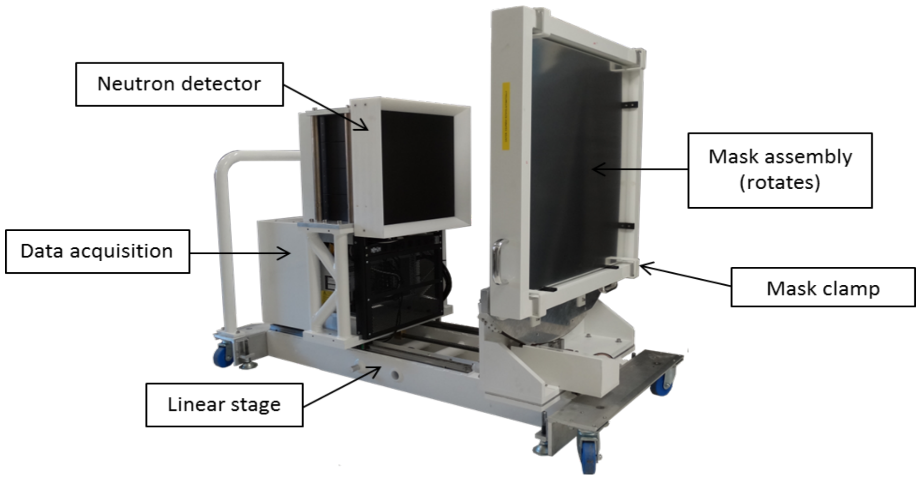
Neutron imagers:
- **Improve detection in low signal-to-background scenarios**
- **Allows source characterization: multiple or extended sources, spectral information**

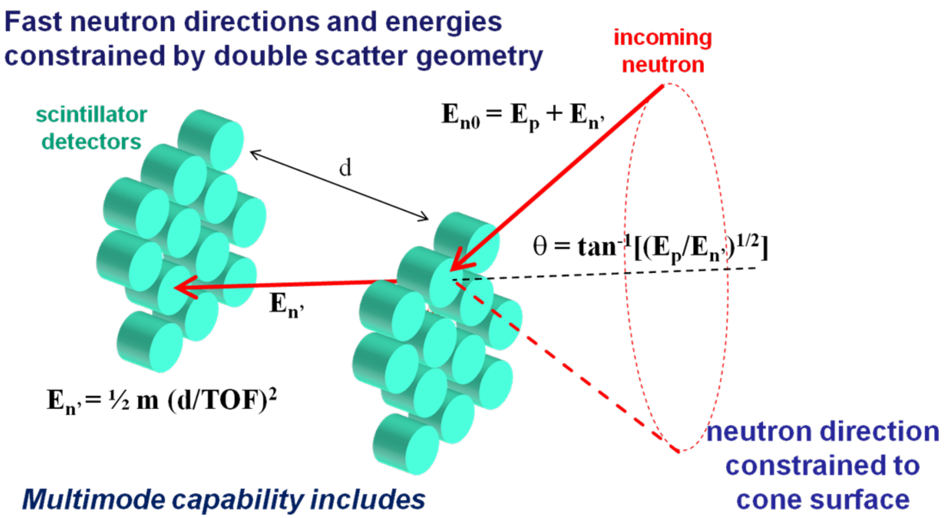
Neutron camera approaches

Coded aperture





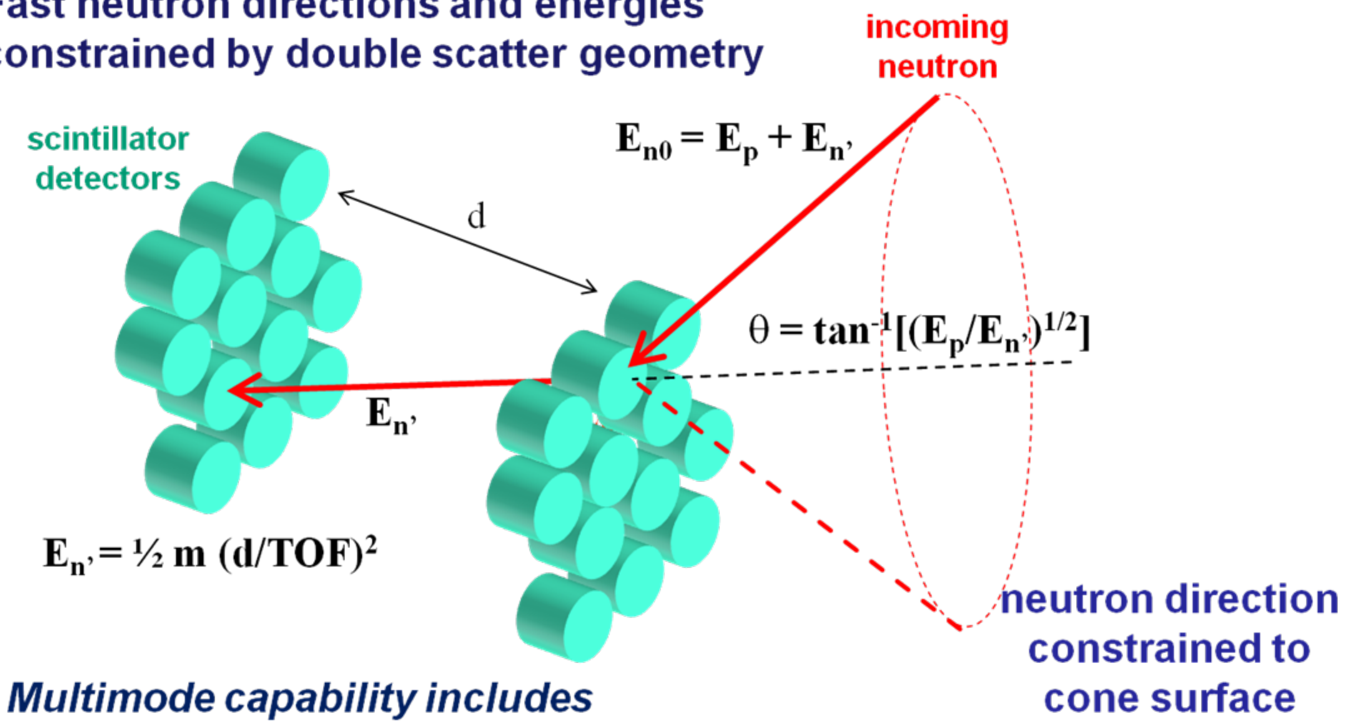
Double Scatter



Multimode capability includes
- ***Neutron energy spectrum.***
- ***Compton imaging.***

Cell-Based Neutron Scatter Camera (NSC)

Fast neutron directions and energies constrained by double scatter geometry



Multimode capability includes

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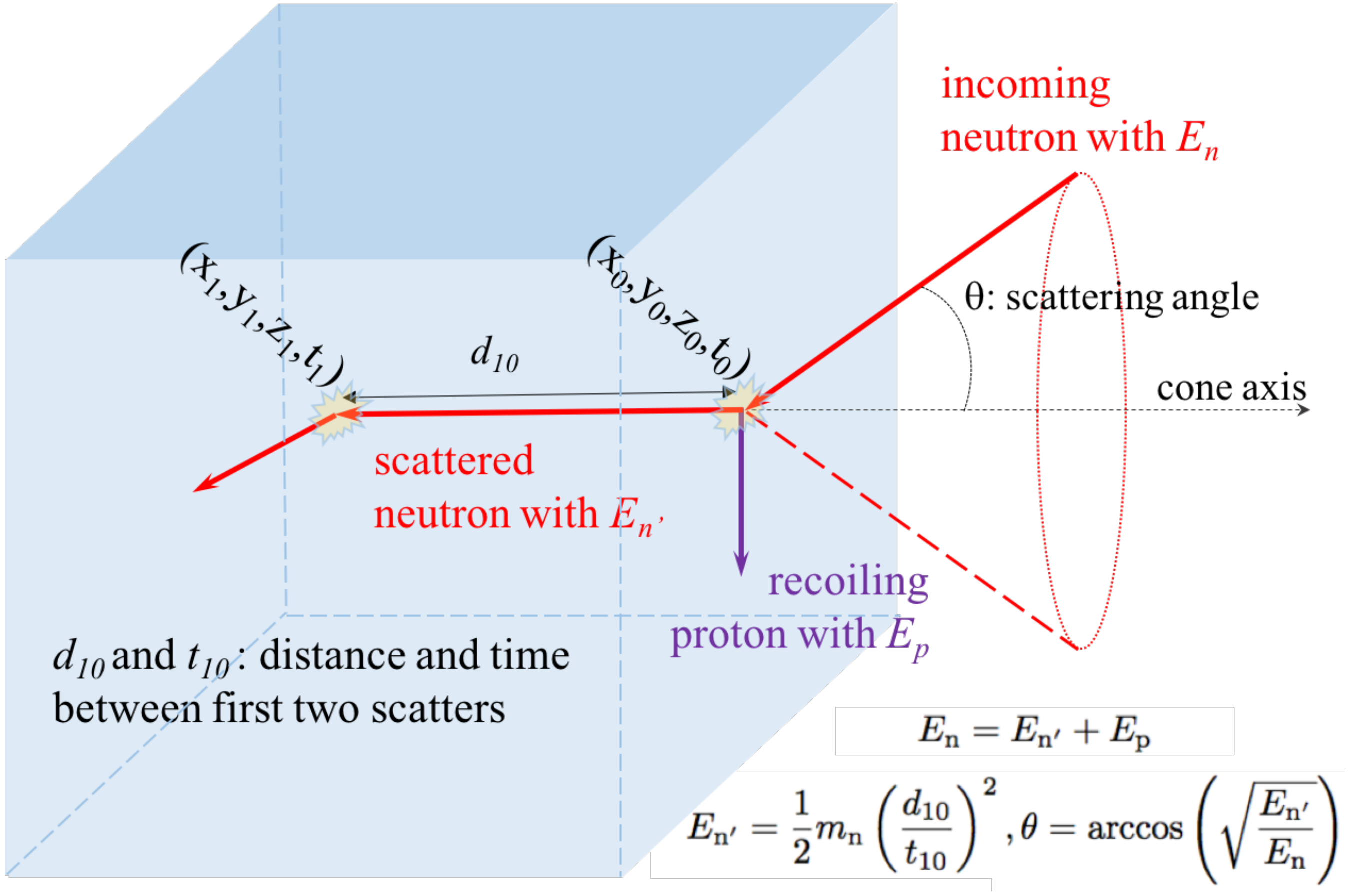
Single Volume Scatter Camera (SVSC)



$$E_n = E_{n'} + E_p$$

$$E_{n'} = \frac{1}{2} m_n \left(\frac{d_{10}}{t_{10}}\right)^2, \theta = \arccos\left(\sqrt{\frac{E_{n'}}{E_n}}\right)$$

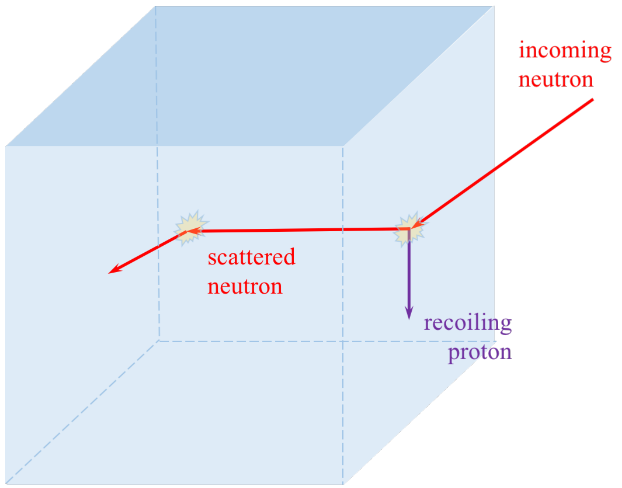
- **Both neutron scatters occur in the same active volume.**

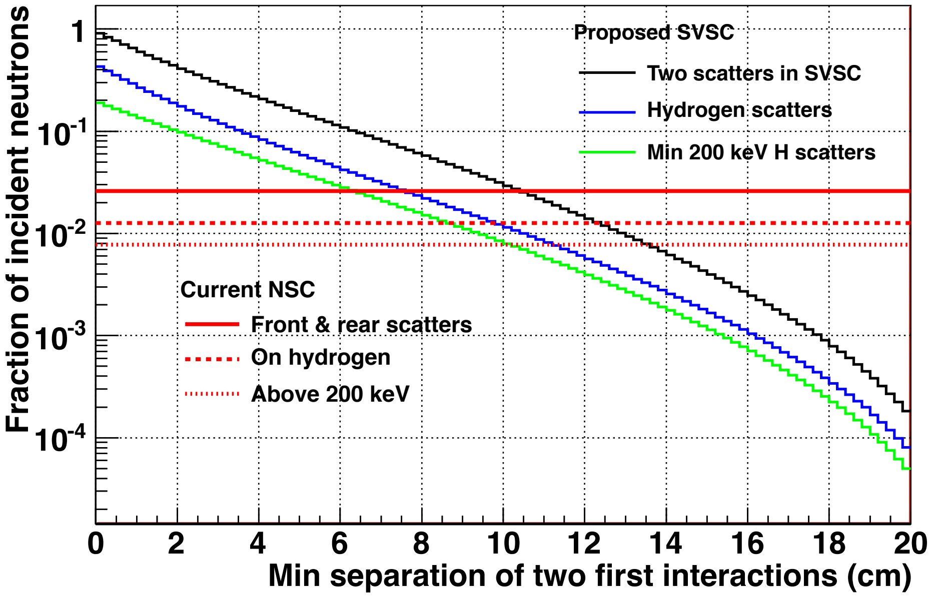
For fission neutrons En ~ 1MeV in organic scintillator:

- **the mean free path is ~ 3cm, and**
- **the average inter-scatter time is ~2 ns.**

SVSC advantages over Cell-Based NSC

- **Higher efficiency**
- **Detector footprint is more compact and lighter**
- **Allows more proximity to source for increase in rate by $1/r^2$**

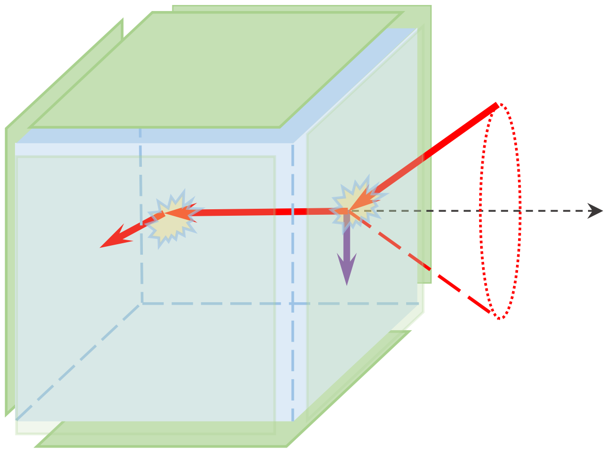


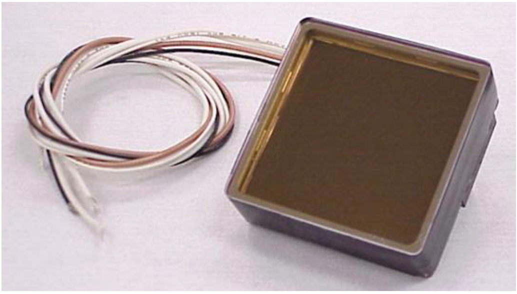


- A scatter camera built from a highly voxelated volume can recover more than an order of magnitude of efficiency if nearby interactions can be resolved.
- Resolving multiple interactions of a neutron separated by O(cm) and O(ns) is difficult!
- **Excellent spatial and temporal resolution of photodetectors based on micro-channel plates is the key enabling technology.**

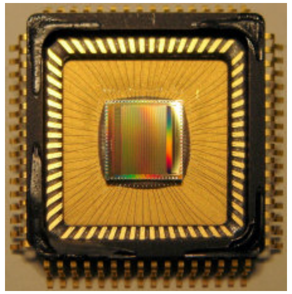
SVSC Concept: **fast hardware**

- Active material
  - Fast organic scintillator
  - O(ns) decay time (e.g. Ej232Q, t_{rise} = 0.11 ns, t_{decay} = 0.7ns)
- Photodetector
  - MCP-PMT, e.g. Planacon
  - Position resolution depends on anode structure (8x8)
  - 35 ps transit time spread
    - Equals 8 mm photon travel
- Electronic readout
  - Switched capacitor array
    - e.g. DRS4 (5 GS/s)
  - Long reset time
  - Scale to many channels





Photonis



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SVSC Concept: **3-stage data processing**

Digital Data processing:

Single-photon isolation per individual pixel

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Neutron double-scatter event reconstruction

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Image and Spectrum reconstruction

SVSC CONCEPT: 3-stage data processing

Digital Data processing:

Single-photon isolation per individual pixel

This talk — Neutron double-scatter event reconstruction

Image and Spectrum reconstruction

Direct reconstruction of the neutron interactions location and time using the arrival position and time at the scintillator surface of the isotopically-emitted photons.

Probability multiples over all observed photons

Extended ML for accurate energy uncertainty

Probability to observe a photon is summed over all interactions

$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_j(\vec{x_i})$$

$$P_j(\vec{x_i}) = \frac{\cos\phi_{ij}}{4\pi d_{ij}^2}\cdot e^{\frac{-d_{ij}}{\lambda}}\cdot f(t_i - t_j - d_{ij}/c_p)$$

Solid angle

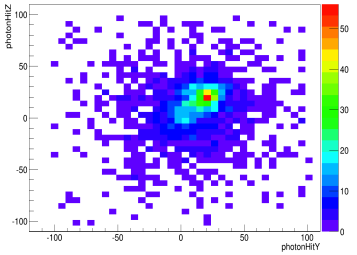
Optical attenuation

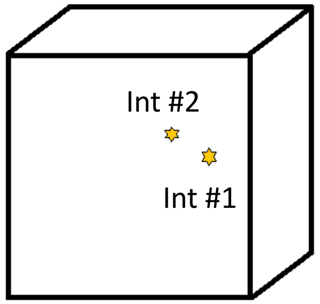
Pulse shape

Event reconstruction via likelihood maximization.

- MINUIT: SIMPLEX, MIGRAD

Input:
list of photon arrival positions and times





Output: (x,y,z,t,E) for each interaction

Will the “Event Reconstruction” work?

Let’s assume

- the hardware works
- raw signals can be parsed to list of photon arrival positions and times

Even then, is there enough information in the photon data to reconstruct the neutron interactions, and ultimately a neutron image?

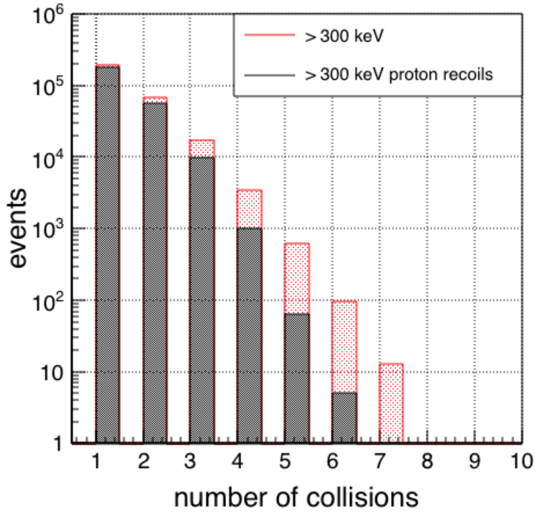
Geant4 Simulation Model

<u>SV(SC) detector</u>:
- **10x10x10 cm^3 of Ej232Q plastic scintillator;**
- **6 faces with by 1 mm–thick acrylic light-guide,**
- **and coupled to 1 mm–thick photodetector (PD);**
- **enveloped in a polyethylene cover.**

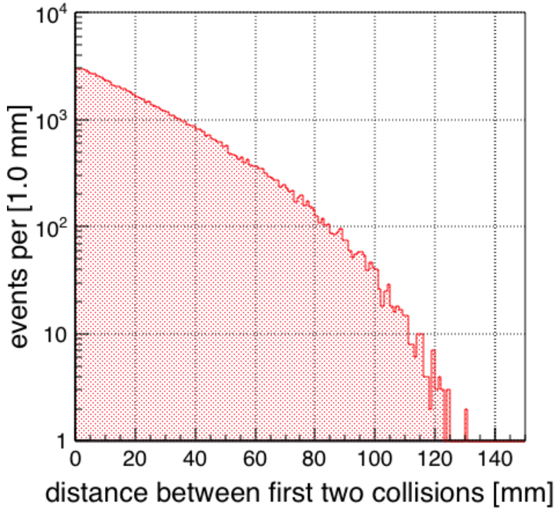
<u>Source</u>: isotropic ^{252}Cf at 1 m distance.

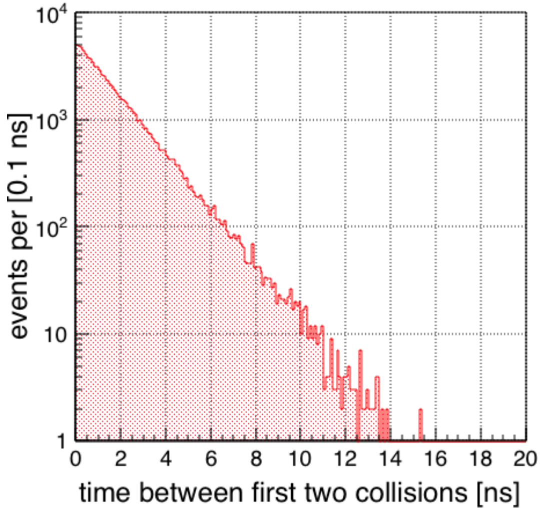
Attribute	Value
SC cube size	100 mm
SC Efficiency	2900 ph/MeVee
SC pulse rise time	0.11 ns
SC pulse decay time	0.7 ns
SC absorption length	80 mm
SC refraction index	1.58
LG refraction index	[acrylic]
PD quantum efficiency	0.25
PD absorption length	10^{-3} mm
PD refraction index	1.57
PD time spread	0.1 ns
PD pixel size	5.9 mm

~13% neutron-pair geometrical efficiently



- Neutron undergoes many elastic collisions within the scintillator
- Most neutron collisions deposit less than the 300 keV (~40 keVee light output)
- Most of the collisions above 300 keV produce proton recoils





- **Distance between the first two collisions averages ~2 cm.**
- **Time between the first two collisions averages ~ 1.7 ns.**

It is always easier in simulation land…

Simulation assumptions	Realistic detector
perfectly polished optical interfaces and nearly matching indexes of refraction	imperfect optical coupling and rougher surfaces
complete photocathode coverage	e.g., scintillator edges and corners not covered
no background; only neutron emission from ^{252}Cf	real data will have background and gammas

Reconstruction assumptions	Realistic detector
each photon positions and time individually resolved	overlapping single photo-electron waveforms
Include the effect of the MCP-PMT finite timing and spatial resolution: • Gaussian smear the photon arrival time with σ_t = 0.1 ns • Gaussian smear the photon arrival coordinates with σ_X = .	resolutions not strictly Gaussian and not constant with position; photo-e^- scattering from MCP can occur in ~10% of detections
Constrain N >= 2 (number of neutron scatters depositing > 300 keV) and assume N is known. *But use all emitted photons.*	guess N from photons' arrival time and spatial profile
In minimization algorithm, set initial guess close to the known simulation interaction location, time and number of emitted photons	…as above…

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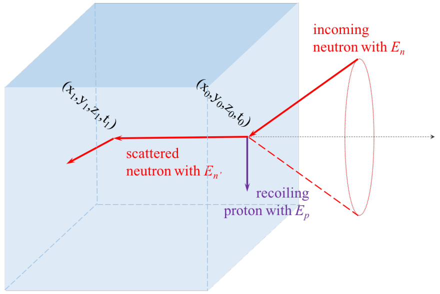
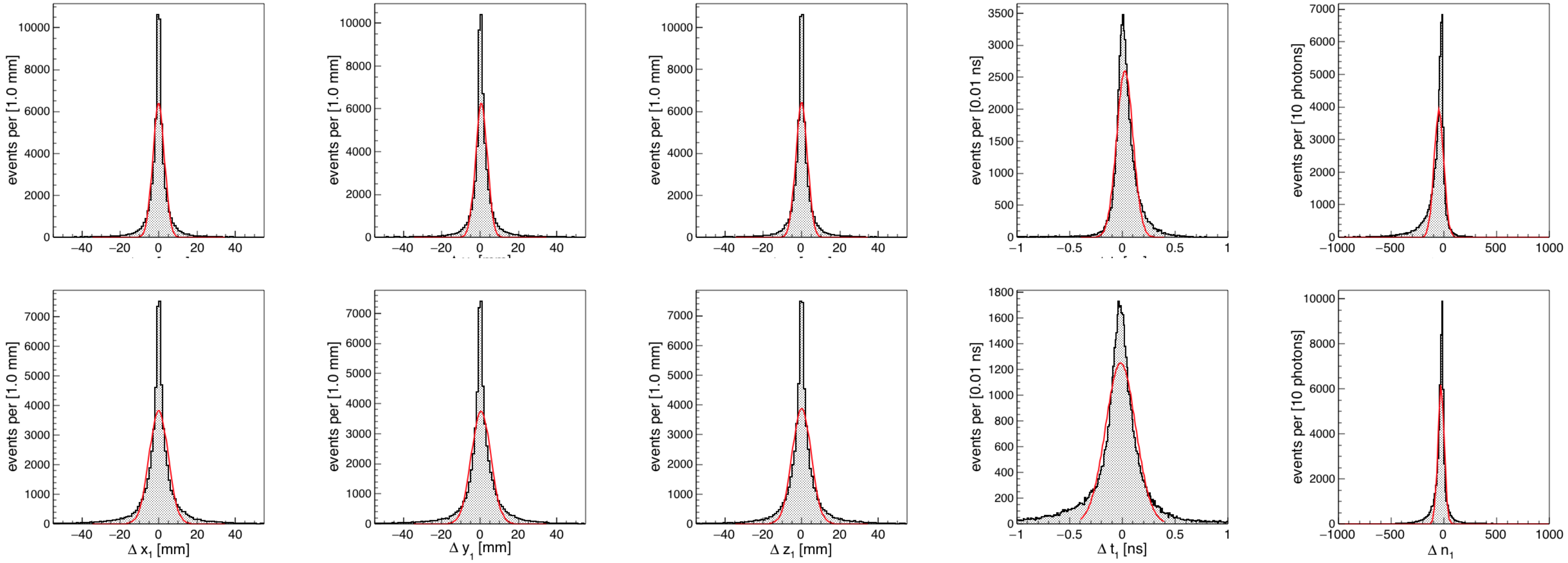
Event Reconstruction: scatters reconstruction

To evaluate the Event Reconstruction algorithm: let's plot the histograms of the difference between the reconstructed quantities and their simulation "true" values: $\Delta A = A_{recon} - A_{true}$

Δ-histograms for the **directly reconstructed quantities**: the locations, times and detected number of photons of the first and the second above-threshold proton recoils, (Δx_0, Δy_0, Δz_0, Δt_0, Δn_0) and (Δx_1, Δy_1, Δz_1, Δt_1, Δn_1)



	σ
Δx_0	3.02 mm
Δy_0	3.05 mm
Δz_0	3.02 mm
Δt_0	0.08 ns
Δn_0	45 photons

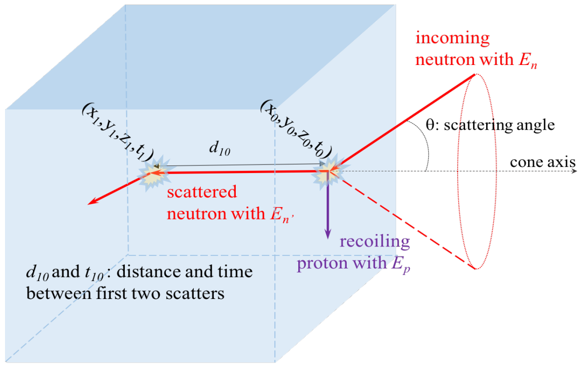


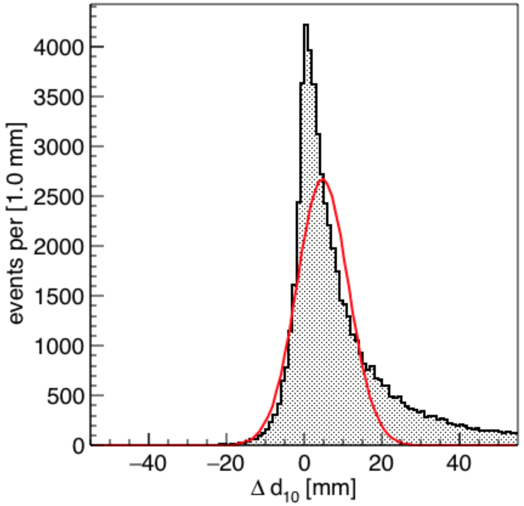
	σ
Δx_1	4.94 mm
Δy_1	5.08 mm
Δz_1	4.95 mm
Δt_1	0.14 ns
Δn_1	30 photons

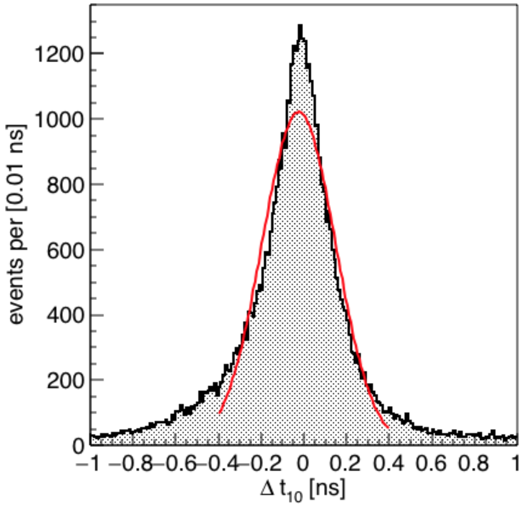
The reconstruction of the second interaction is generally less accurate.

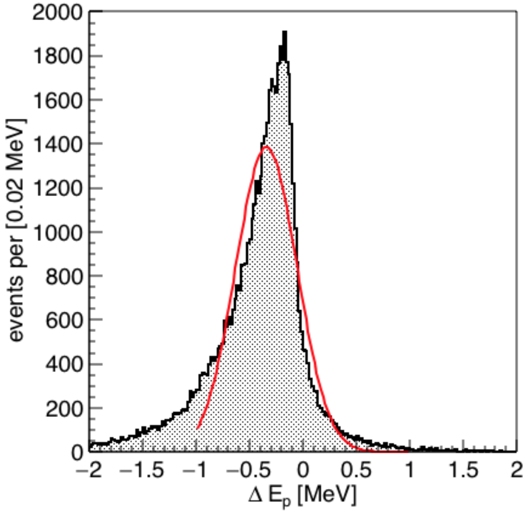
Event Reconstruction: kinematic quantities

Δ-histograms of **derived quantities**: distance d_{10} and time t_{10} between the first and the second proton recoils and energy Ep deposited by the first recoiling proton, Δd_{10}, Δt_{10}, ΔE_{p}.









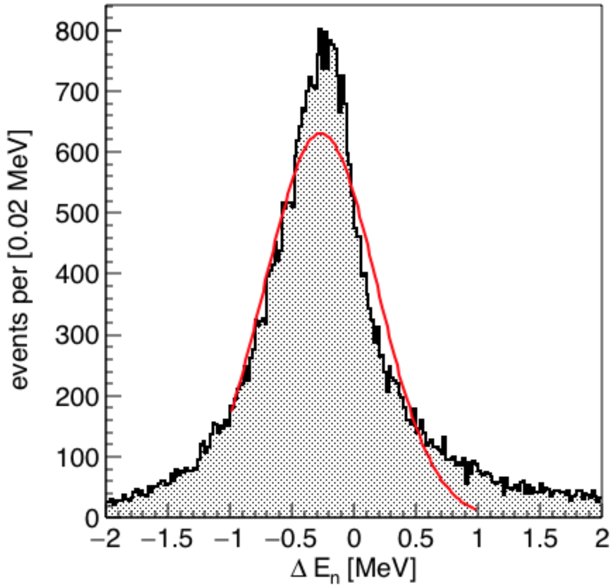
	σ
Δd_{10}	6.65 mm
Δt_{10}	0.17 ns
ΔE_p	0.29 MeV

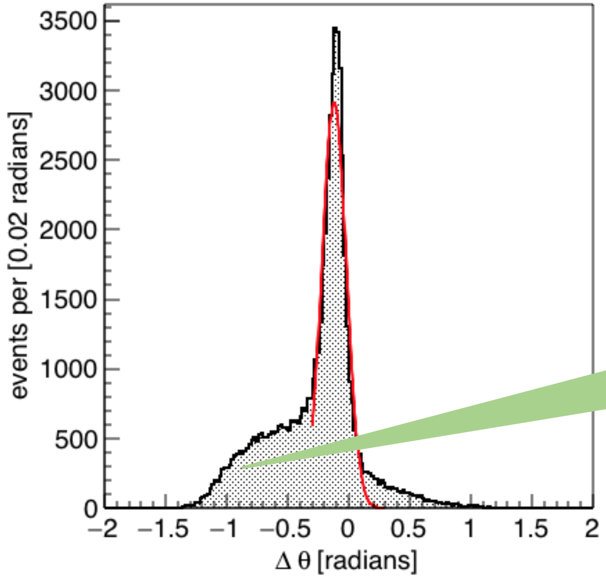
- d_{10} and t_{10} are not independent variables but instead are correlated by the reconstruction algorithm.
- The asymmetric non-Gaussian tails of the Δd_{10} and Δt_{10} histograms reveal correlations in the misreconstruccion of the individual scatters (x,y,z,t,n).

Event Reconstruction: source quantities

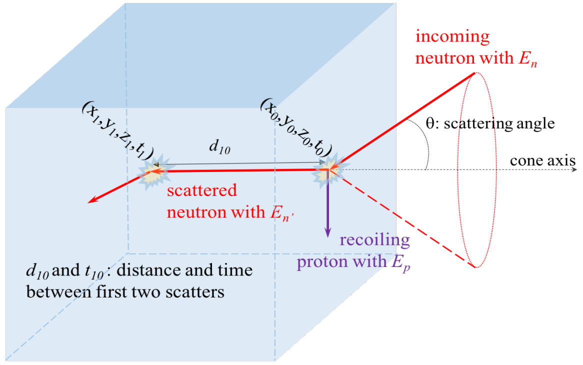
Δ-histograms of **source quantities**:
incident neutron energy E_n,
scattering cone angle θ

	σ
ΔE_n	0.45 MeV
$\Delta\theta$	0.1 rad





Hump for negative $\Delta\theta$, representing reconstructed scattering angles smaller than the simulated angles



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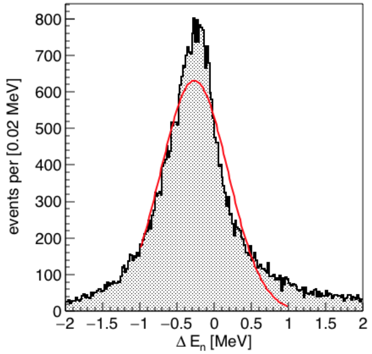

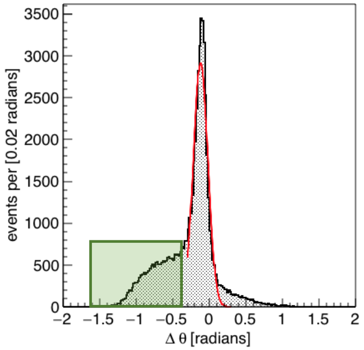

	σ
ΔE_n	0.45 MeV
$\Delta\theta$	0.1 rad

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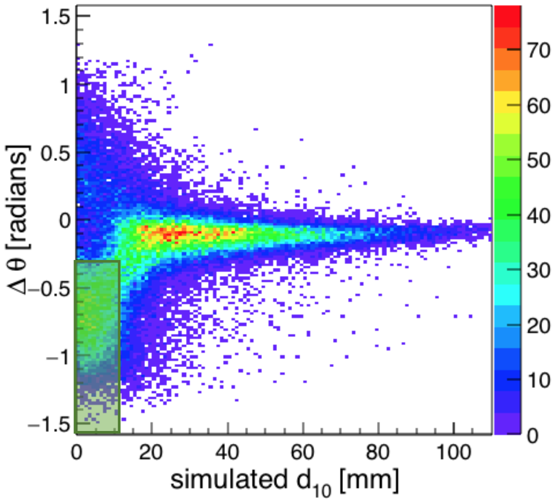

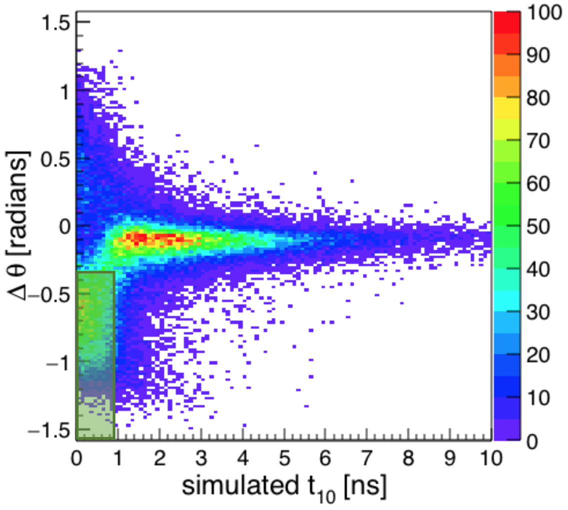

- These angular miss-reconstructions correspond to events where the first two interactions are closer than ~1.5 cm in distance and ~1ns in time.
- They correspond to positive tail in the Δd_{10} histogram (larger reconstructed d_{10}) and negative tail in the Δt_{10} histogram (smaller reconstructed t_{10})

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Photodetector finite time and spatial resolution

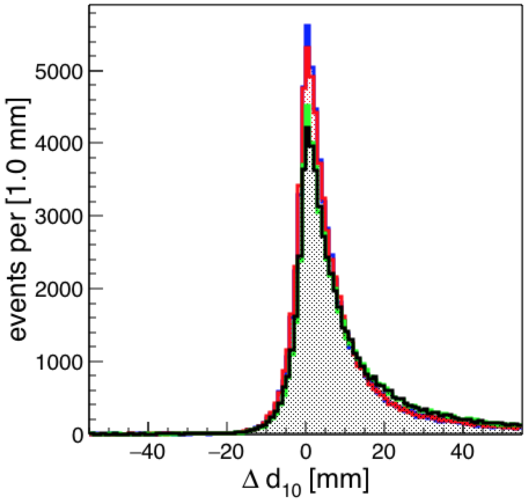
MCP-PMT finite timing and spatial resolution:

- Gaussian smear the photon arrival time with σ_t = 0.1 ns
- Gaussian smear the photon coordinates with σ_X = 1.7 mm.

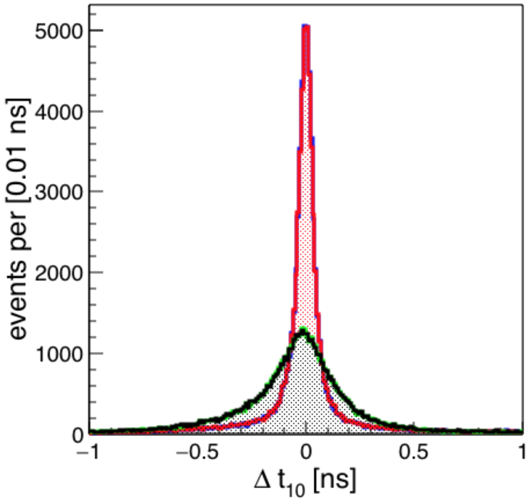
Histograms legend

- (black) the photon arrival time and coordinates (X,Y,Z) are smeared
- (green) only the photon time T is smeared
- (red) only the photon coordinates (X,Y,Z) is smeared
- (blue) exact photon time and coordinates

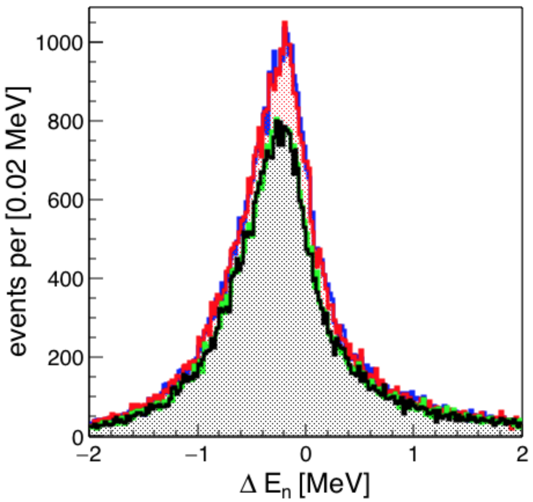
Δd_{10}



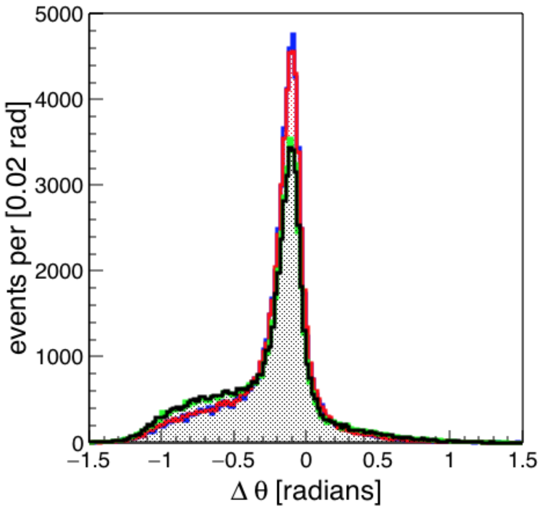
Δt_{10}



ΔE_n



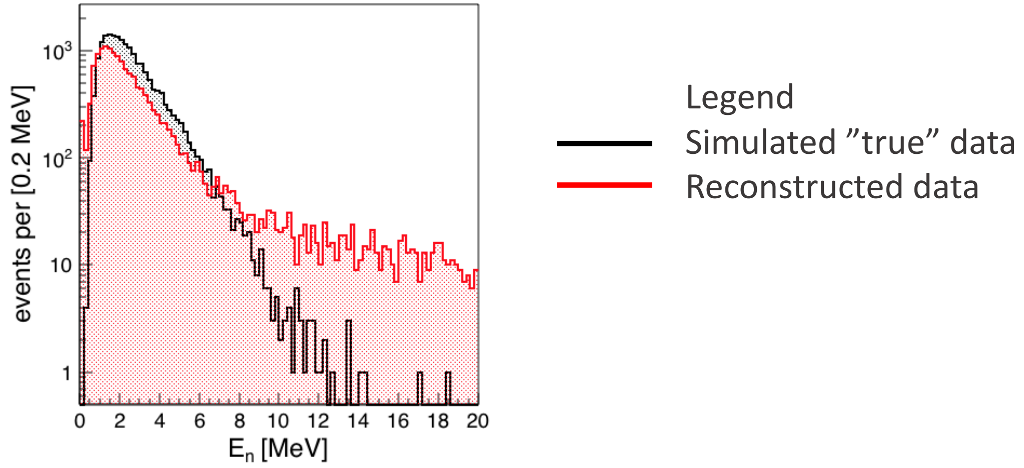
$\Delta\theta$



The smearing of photon detection time according to uncertainty values measured in current MCP-PMTs is the main contributor to the error in event reconstruction, causing also a significant decrease in reconstruction success rate by 20-30%.

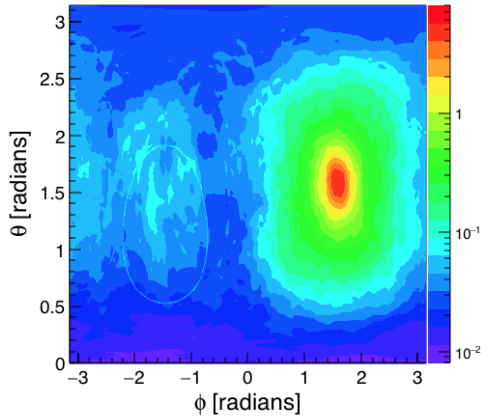
Spectrum and Image reconstruction

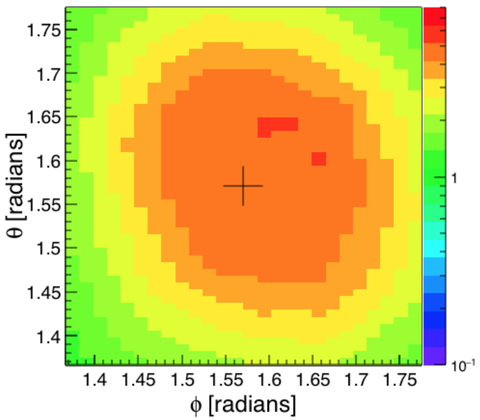
The energy spectrum obtained using the reconstructed interactions smears out around the maximum producing a tail at larger energies: the SVSC response is dominated by the uncertainties in time, distance and number of photons introduced by the reconstruction algorithm and the measurement process.



<u>Image generated with list-mode MLEM</u>: response map constructed on the flight by back-projecting the cone of each coincident event and assigning a 2D probability distribution (in terms of source θ and ϕ) around the cone projection according to the variances of θ and $\Delta\alpha$.

For a simulated 2.7 uCi Cf252 neutron source located at 1 meter, this image is equivalent to 29 minutes of measurement time, without background.





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Conclusions

- **Simulation results indicate expected significant improve of SVSC efficiency (> 10%) over cell-based NSC (~1%)**
- **Direct event reconstruction algorithm is working: reconstructing inter-collision distance to ~ 6 mm and inter-collision time to ~ 0.2 ns accuracy**
- **Event Reconstruction efficiency: 50% (within 10mm and 2 ns)**
- **Simulation results establish an upper limit to the realistic detector performance: but there is no indication of any major issue preventing success.**

Backup Slides

SVSC CONCEPT: **3-stage data processing**

Digital Data processing:

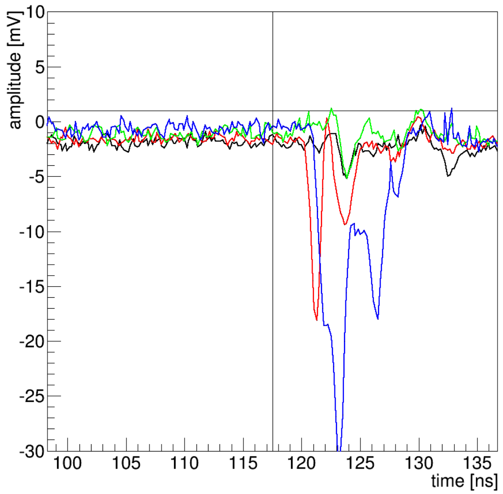
Single-photon isolation per individual pixel

Neutron double-scatter event reconstruction

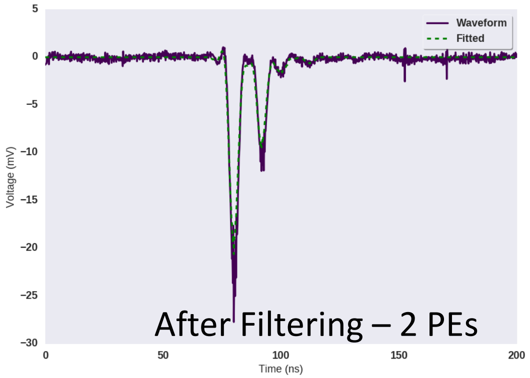
Image and Spectrum reconstruction

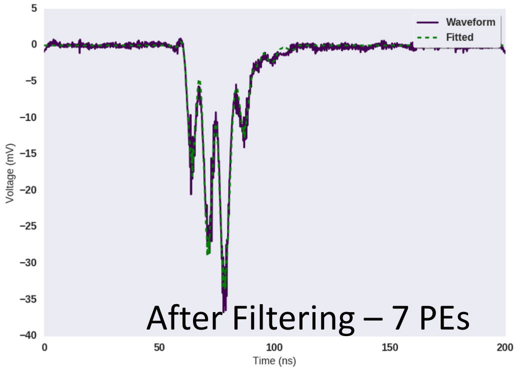
Reconstruction algorithm assumes it is handed a list of photon arrival positions and times.

- Need to resolve single photons at each photodetector pixel
- But might be limited by pixels timing resolution and gain variability.



Testing of a fitting procedure to extracts number of photons and their times of arrival.





Reconstruction efficiencies

Reconstruction success rate for events with 2, 3 and 4 above- threshold (E_p > 300 keV) neutron interactions, where the reconstructed locations and times of the first two neutron collisions are close to the simulated values by less than 10 mm and 2 ns, respectively.

	Smeared (X,Y,Z) Smeared T	Exact (X,Y,Z) Smeared T	Smeared (X,Y,Z) Exact T	Exact (X,Y,Z) Exact T
% of 2 scatters	52	51	67	67
% of 3 scatters	37	37	54	55
% of 4 scatters	26	27	48	48

5-minute equivalent image