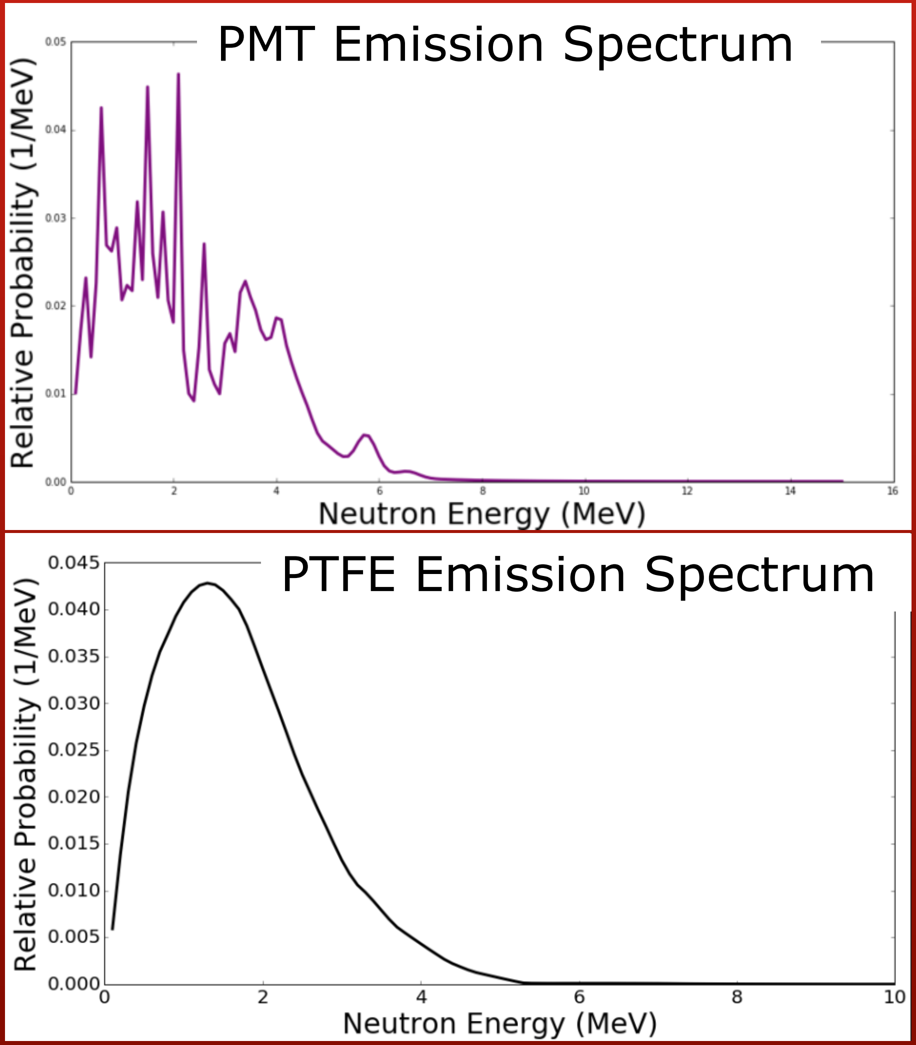
A Simulation of Neutron backgrounds in Run4

Shaun Alsum

Backgrounds Considered

- PMTs
  - Neutrons from (alpha, n) from U238 chain alphas
  - Neutrons from (alpha, n) from Th232 chain alphas
  - Neutrons from U235 fission
- PTFE
  - Neutrons from (alpha, n) from Po210 (U238 late) chain alphas

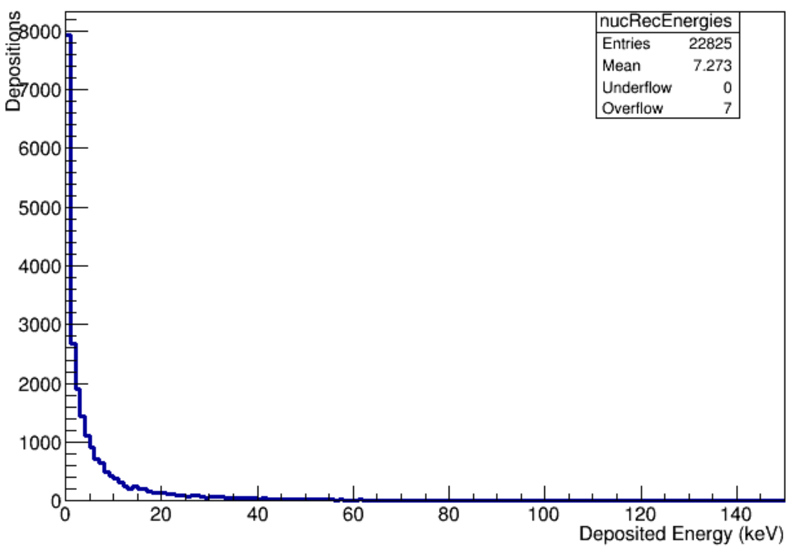
Neutron Emission Energy Spectra



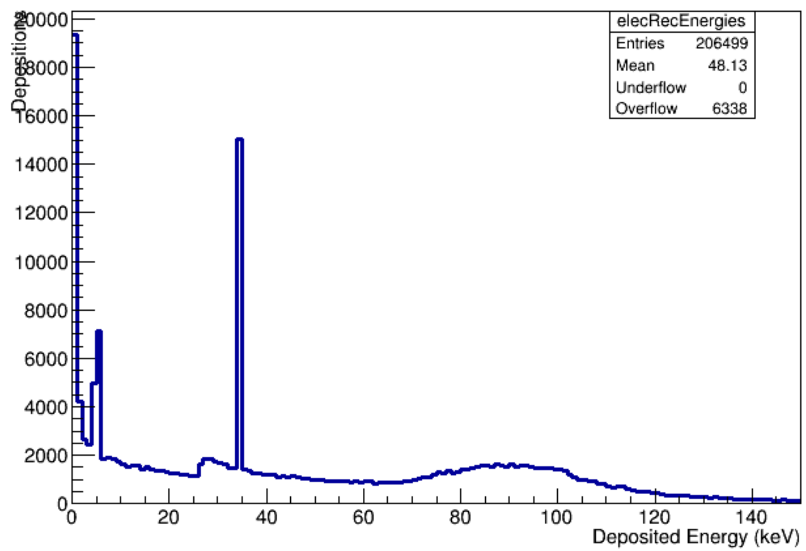
The Simulation

- Used LUXSim to simulate energy depositions
- Classified depositions as ER (γ, e^-, e^+) or NR (n, heavy particles)

Spectrum of nuclear recoils

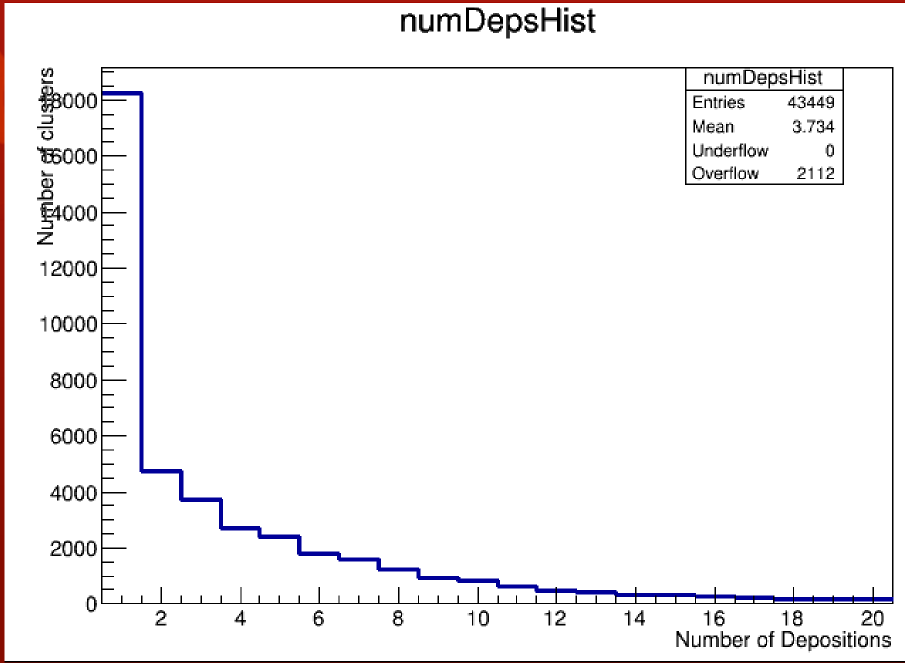


Spectrum of electron recoils



Clustering Energy Depositions

- Depositions are clustered if they are within:
  - a horizontal distance of 0.5 cm to another deposition, and
  - a vertical distance of 1 cm to another deposition.
- Cluster positions are determined by:
  - Average in horizontal plane weighted by expected S2-signal
  - uppermost event in the vertical direction.

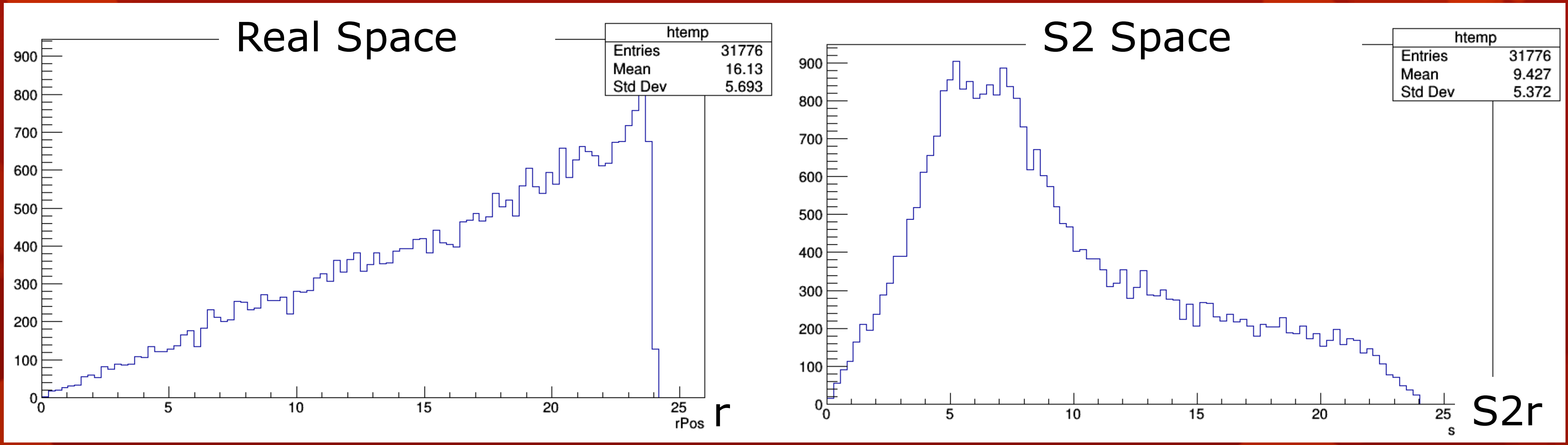


Number of depositions that make up each cluster.

Left-most bin is 1, and has the most, but comprises less than ¼ of all depositions.

Detector Response

- Run libNEST twice on each cluster.
  - Once to determine the response due to NRs in cluster
  - Once for ER response
- Sum the S1c due to ER and NR, do the same for S2c.
- Map the clusters from real space to S2 space



Cuts

- Cluster Cuts
  - Cut clusters that will not be seen by the detector
    - Outside the TPC (i.e., in the skin)
  - Cut clusters whose S2 would not be classified correctly by the detector
    - S2 < 60
    - *Keep* the S1 and add it to a total tally for the event
- Event Cuts
  - Standard golden event cuts outlined on Run4 frozen page
  - Cut events above NR band mean (for later easy comparison to multiple scatters)

Expected Neutron Events

From all of run04…

- .16 from PMTs
- .016 from PTFE

```
Time bin 1: 46.766 live days.  17.67 PMT emitted neutrons
single scatter ratio: 0.00141287

Time bin 1: 46.766 live days.  1.22 PTFE emitted neutrons
single scatter ratio: 0.00208515


Time bin 2: 46.731 live days.  17.66 PMT emitted neutrons
single scatter ratio: 0.00135149

Time bin 2: 46.731 live days.  1.22 PTFE emitted neutrons
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Time bin 3: 91.552 live days.  34.59 PMT emitted neutrons
single scatter ratio: 0.0011604

Time bin 3: 91.552 live days.  2.38 PTFE emitted neutrons
single scatter ratio: 0.00177327


Time bin 4: 146.923 live days.  55.51 PMT emitted neutrons
single scatter ratio: 0.00123663

Time bin 4: 146.923 live days.  3.82 PTFE emitted neutrons
single scatter ratio: 0.00187525
pdsf6 $
```

Bonus Rounds

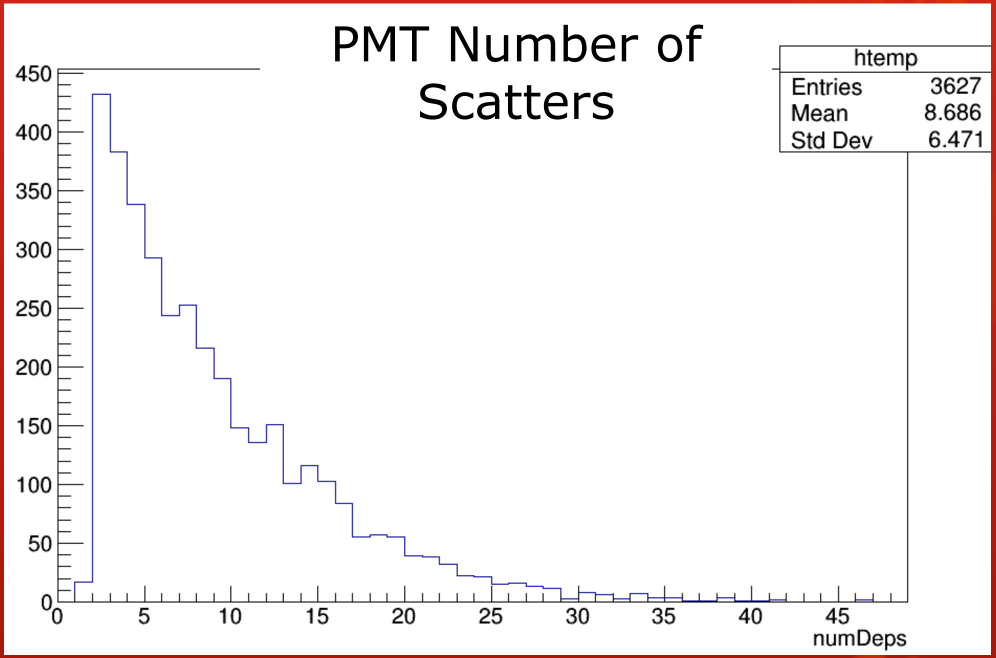
- Comparison to Multiple Scatters
- Background PDF generation

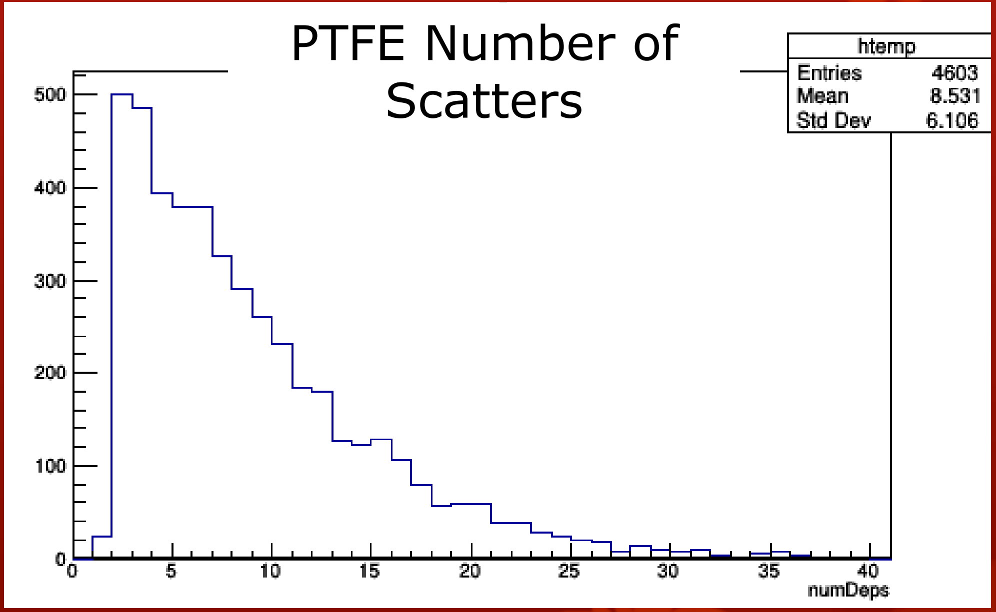
Cuts for Multiple Scatters

- **Goal**: Determine whether the MS is ER or NR.
- **Problem**: can’t do a traditional S2/S1 cut in the traditional style
  - S1s possibly merged, or the pairing of s1 to s2 is unknown.
- **Solution**: predict S1 for each event based on S2 *as if it were a NR* using the NR band mean. Sum all S1s and compare to the sum of expected S1s. Cut if measured S1 is lower.
  - Equivalent to cutting above NR band mean
  - Possibly not equivalent in ER p-value due to differences in combined standard deviations

Result of Cuts

- Ratio of total MS to cut SS
  - 430/17 (Double Scatter/SS)
- **Recall**: SS and MS were treated differently in cuts.





PDF Dimensionality

- In principle, PDF is 5-dimensional. Hard to integrate.
- See which dimensions are correlated
- Build PDF as direct product of uncorrelated lower-dimensional PDFs
- Could likely faithfully construct PDF as
  - (s2R, drift) ⊗ (s2Phi) ⊗ (s1c, s2c)

	S2R	S2Phi	drift	S1c	S2c
S2R	TRUE	FALSE	TRUE	FALSE	FALSE
S2Phi	FALSE	TRUE	FALSE	FALSE	FALSE
drift	TRUE	FALSE	TRUE	FALSE	FALSE
S1c	FALSE	FALSE	FALSE	TRUE	TRUE
S2c	FALSE	FALSE	FALSE	TRUE	TRUE

A Table displaying "true" for any pair of dimensions between which there is a correlation coefficient of 0.1 or higher. Seems to hold for all time bins.

Backup

Strategy

- Simulate neutron energy depositions
- Cluster depositions
- Use libNEST to get S1c, S2c
- Find and implement necessary cuts
- Determine dimensionality of PDF needed and create it
- Find rates of things that can be compared to neutron background rate (i.e. NR double-scatters) and compare to data

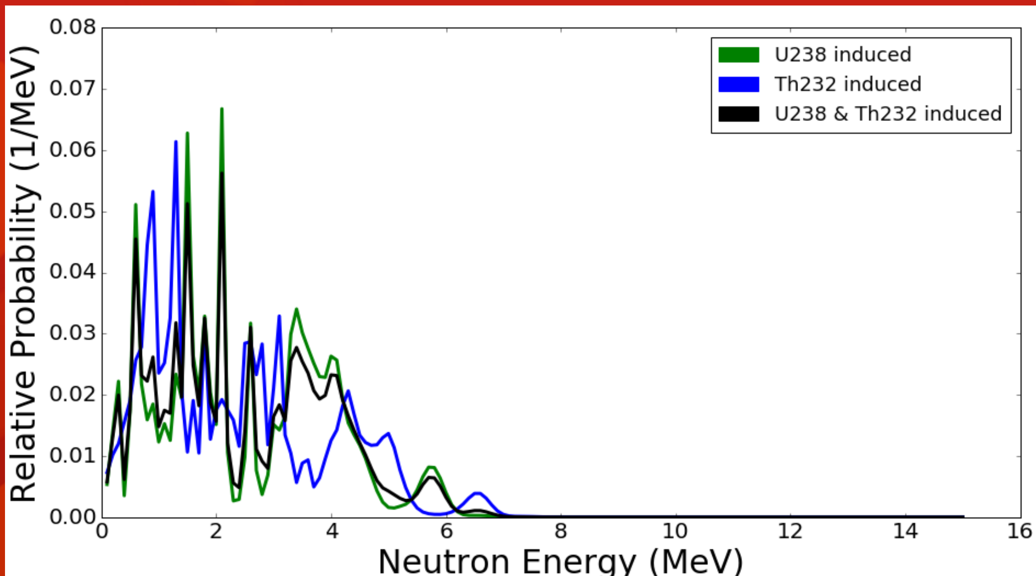
Simulating the Neutrons

Considered Backgrounds

Following Dave Malling's Thesis

- PMTs
  - Neutrons from (alpha, n) from U238 chain alphas
  - Neutrons from (alpha, n) from Th232 chain alphas
  - Neutrons from U235 fission
- PTFE
  - Neutrons from (alpha, n) from Po210 (U238 late) chain alphas

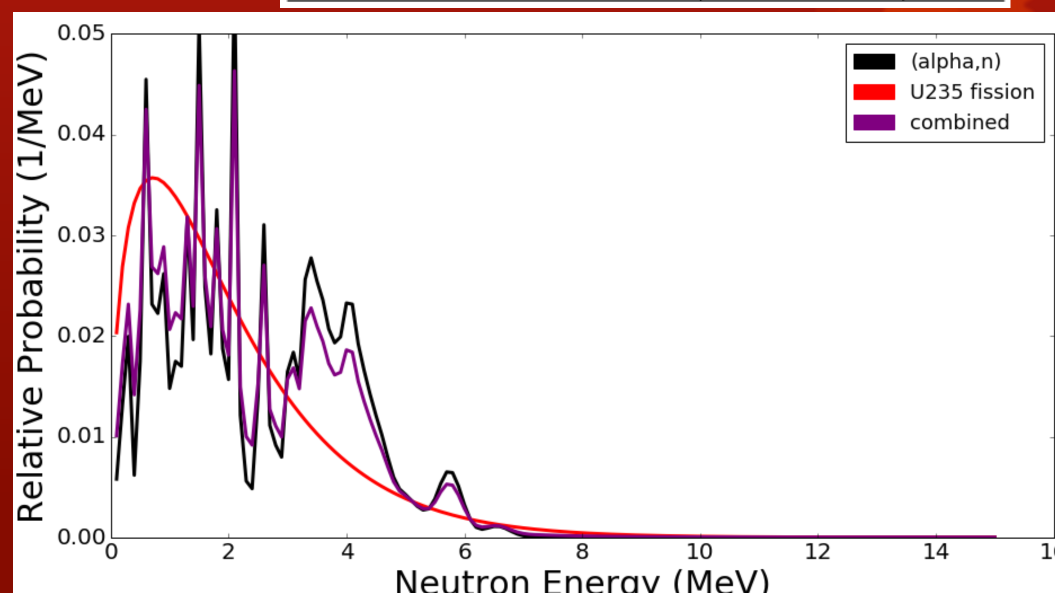
Background Energy Spectra - PMTs



(alpha, n) from neutronyield.usd.edu
With the following c

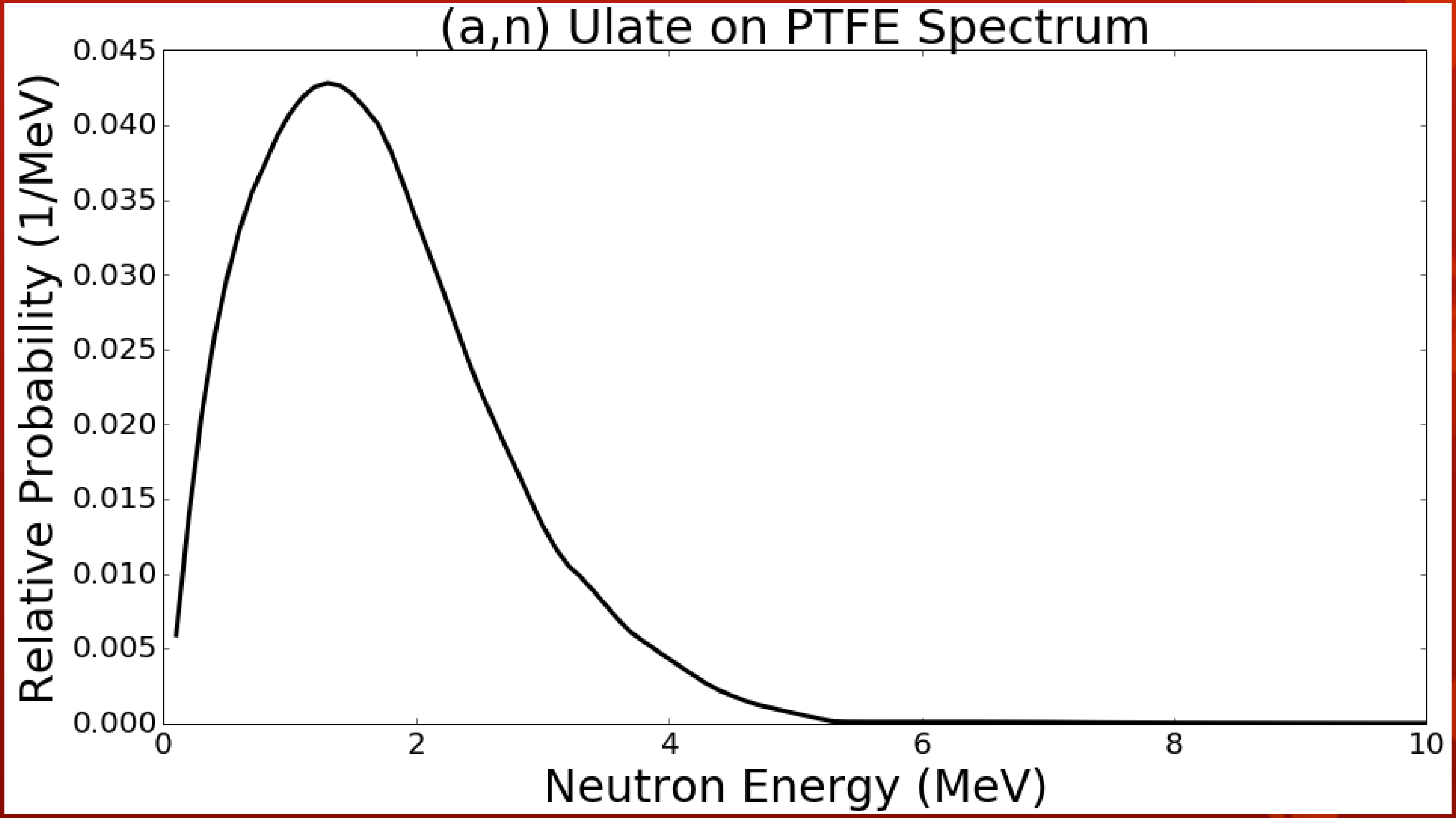
Compound	Mass [g]	(α,n) Yield [n/mBq/yr]		(α,n) Neutron Rate [n/PMT/yr]		
		^{238}U	^{232}Th	^{238}U	^{232}Th	Total
B2O3	4	1.17	0.950	2.67E-01	6.13E-02	3.28E-01
Al2O3	15	0.219	0.271	1.86E-01	6.55E-02	2.52E-01
Fe	63	0.0134	0.0426	4.78E-02	4.33E-02	9.11E-02
SiO2	26	0.0272	0.0303	4.02E-02	1.27E-02	5.29E-02
Na2O	1.3	0.329	0.322	2.43E-02	6.76E-03	3.10E-02
Co	13.6	0.0148	0.0524	1.14E-02	1.15E-02	2.29E-02
Li2O	0.22	0.764	0.554	9.54E-03	1.97E-03	1.15E-02
Cr	1.8	0.0502	0.187	5.13E-03	5.42E-03	1.06E-02
Al	0.26	0.402	0.502	5.93E-03	2.11E-03	8.04E-03
Mn	0.4	0.0378	0.100	8.59E-04	6.48E-04	1.51E-03
Ni	41	2.01×10^{-4}	1.45×10^{-3}	4.68E-04	9.62E-04	1.43E-03
Si	0.21	0.0449	0.0522	5.35E-04	1.77E-04	7.12E-04
BaO	0.44	1.22×10^{-3}	1.17×10^{-3}	3.06E-05	8.28E-06	3.88E-05
C	0.008	0.0306	0.0278	1.39E-05	3.59E-06	1.75E-05
S	0.0051	5.01×10^{-3}	7.63×10^{-3}	1.45E-06	6.28E-07	2.08E-06
Zr	0.042	5.34×10^{-6}	9.10×10^{-5}	1.27E-08	6.17E-08	7.44E-08
P	0.0068	5.16×10^{-8}	5.26×10^{-7}	1.99E-11	5.78E-11	7.77E-11
			Sum ((α,n) only)	**0.60**	**0.21**	**0.81**
			Sum ((α,n) + fission)	**0.93**	**0.21**	**1.15**

U238 fission from a parameterization I found in a lecture online… https://indico.cern.ch/event/145296/contributions/1381141/attachments/136909/194258/lecture24.pdf



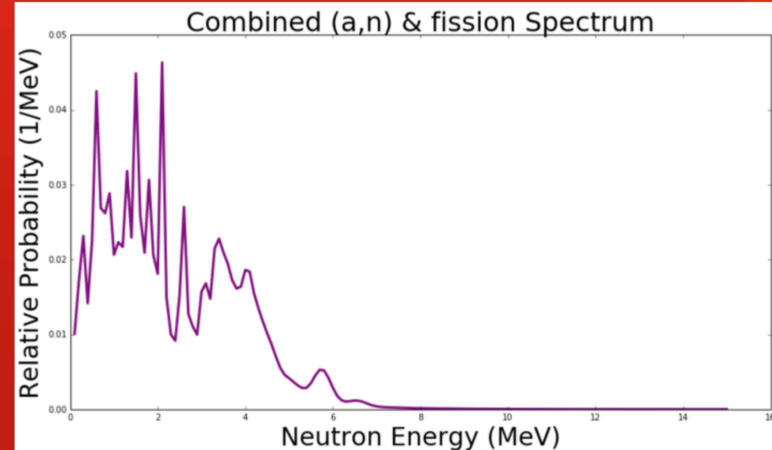
Background Energy Spectra - PTFE

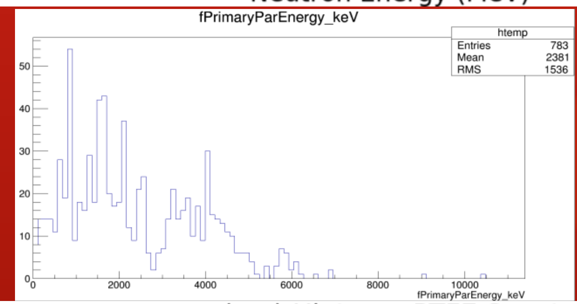
From Paolo…

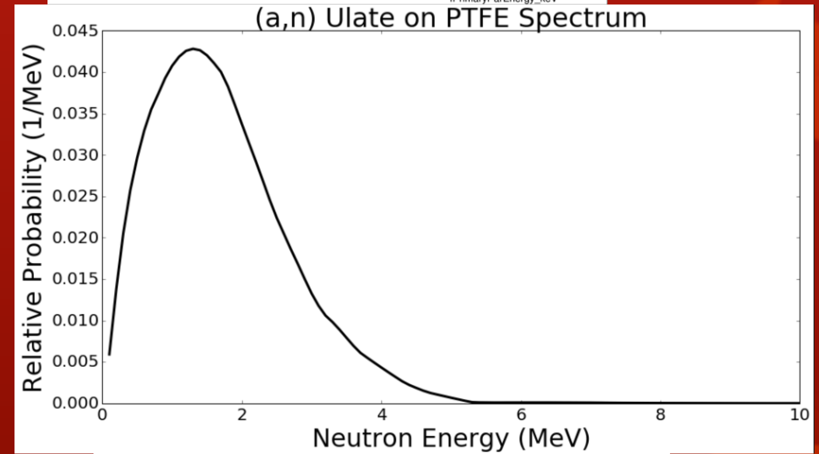


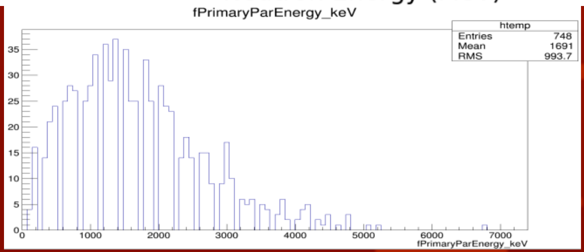
/hat was actually mulated?

- All components of PMTs, but all neutrons originating in the PMT window.
- All PTFE is the source (specifically, anything with PTFE in the name in LUXSim…)
- Discrete energies normalized to approximate the correct spectrum.







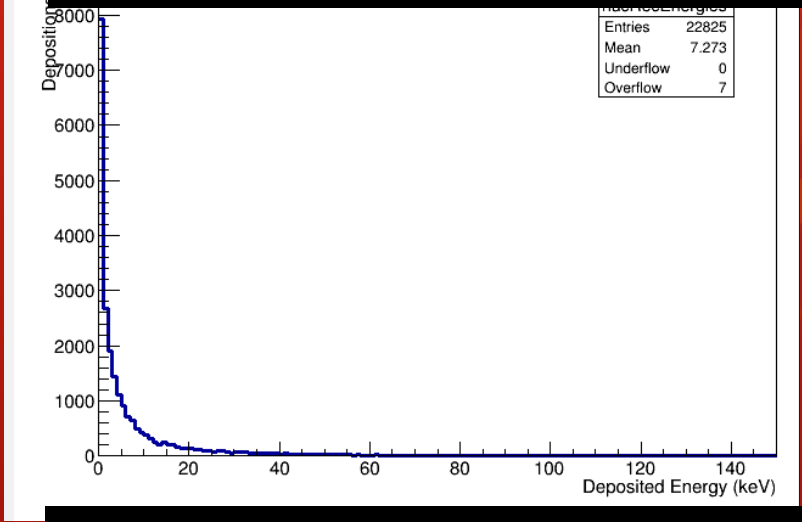


Clustering the Output

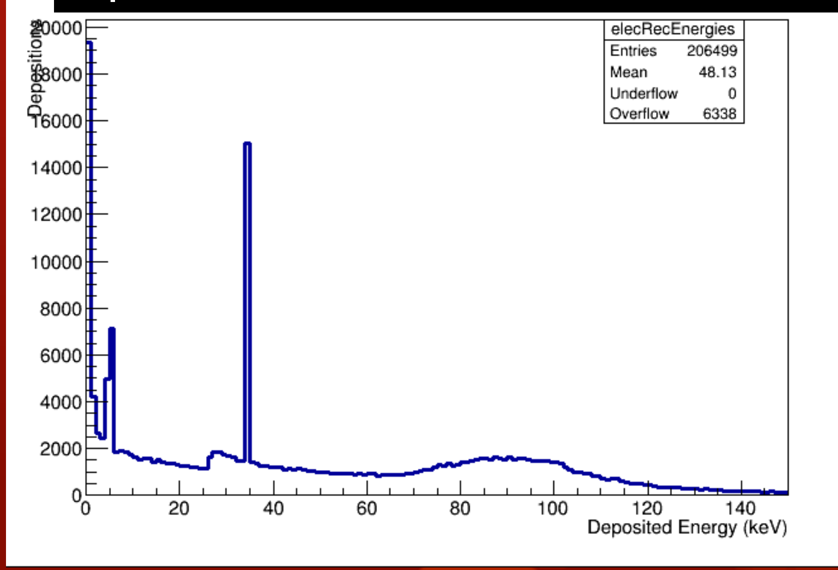
Splitting up ER and NR

- Include both heavy particle (atom sized) as well as neutron depositions as NR.
  - This INCLUDES kinetic energy gained by heavy particles which gain their energy via decay after neutron capture.
- Call interactions from gammas, electrons, and positrons ER.
- Doing this, get the following spectra

Spectrum of all nuclear recoils



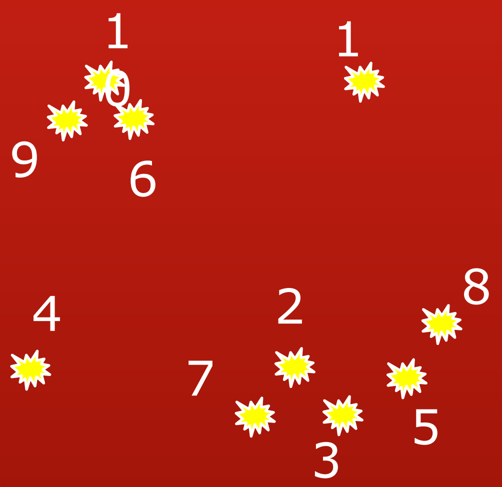
Spectrum of all electron recoils



The Clustering algorithm

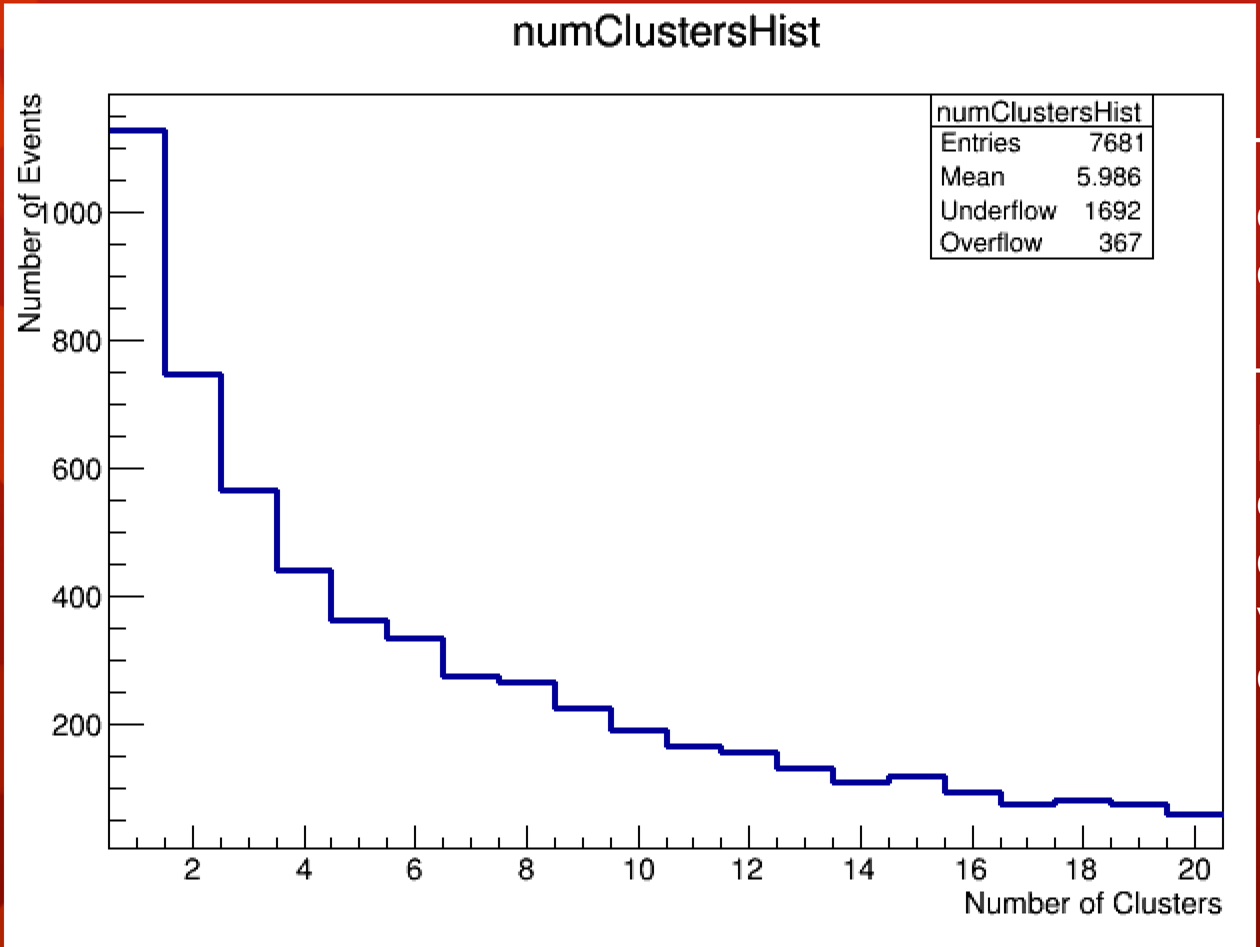
- Cluster into cylinders (right now Δxy < 0.5 cm, Δz < 1 cm)
- Pick a deposition,
  - add it to a cluster,
  - check around it for any others.
    - If found, add that one.
    - check around *that one* for any others
      - and add them continue on in this fashion.
      - Once no more are found, step back up to the last and keep searching.
- Once all in a cluster are found, start with another point (not in the cluster)
- Illustration on next slide.

Clustering Algorithm illustration



1. Creates new cluster containing dep 1 (cluster 1)
2. No more neighbors. Marks dep 1 as clustered and moves on to a new point.
3. Creates new cluster containing dep 2 (cluster 2)
4. Looks around dep 2 for neighbors, finds dep 3, adds dep 3 to cluster 2
5. Looks around dep 3 for neighbors, finds dep 5, adds dep 5 to cluster 2
6. Looks around dep 5 for neighbors, finds dep 8, adds dep 8 to cluster 2
7. No more neighbors, resumes search around dep 5.
8. No more neighbors, resumes search around dep 3, finds dep 7, adds dep 7 to cluster 2.
9. No more neighbors. Marks deps 2, 3, 5, 8, and 7 as clustered and moves on.
10. Creates new cluster containing dep 4 (cluster 3)

How many clusters are in each event, then?

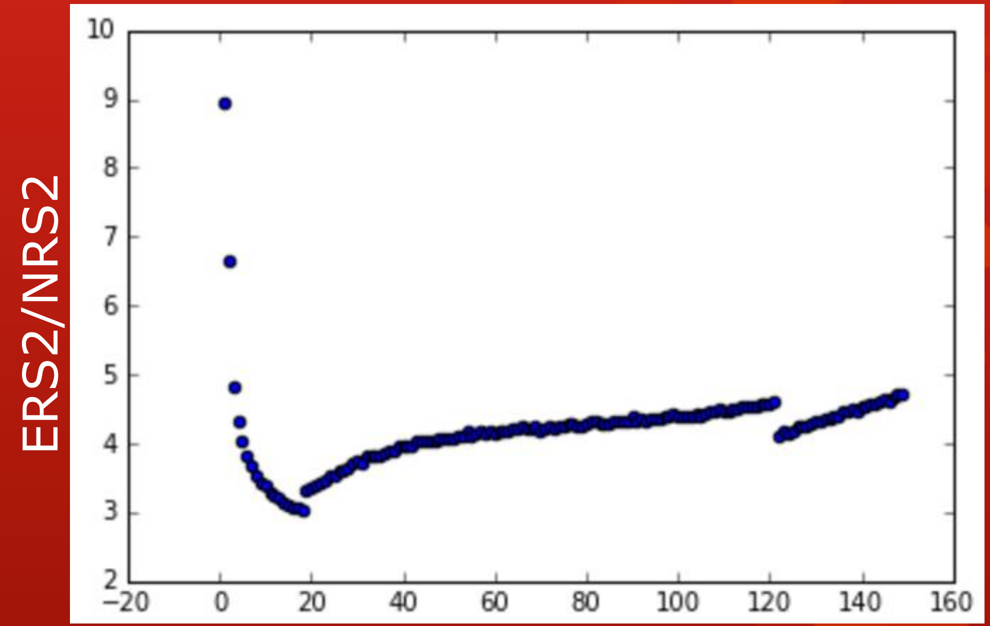


The number of clusters in each event.

The number that have enough energy to be detected has not yet been determined…

What about the cluster's position and energy?

- Where should the cluster be?
  - The xy cluster position is determined by an expected-S2 weighted average in x and y
  - The z cluster position is determined to be at the location of the uppermost deposition in the cluster



- What is the cluster's energy?
  - Energy from NR are summed into an NR total energy.
  - Energy from ER are summed into an ER total energy.

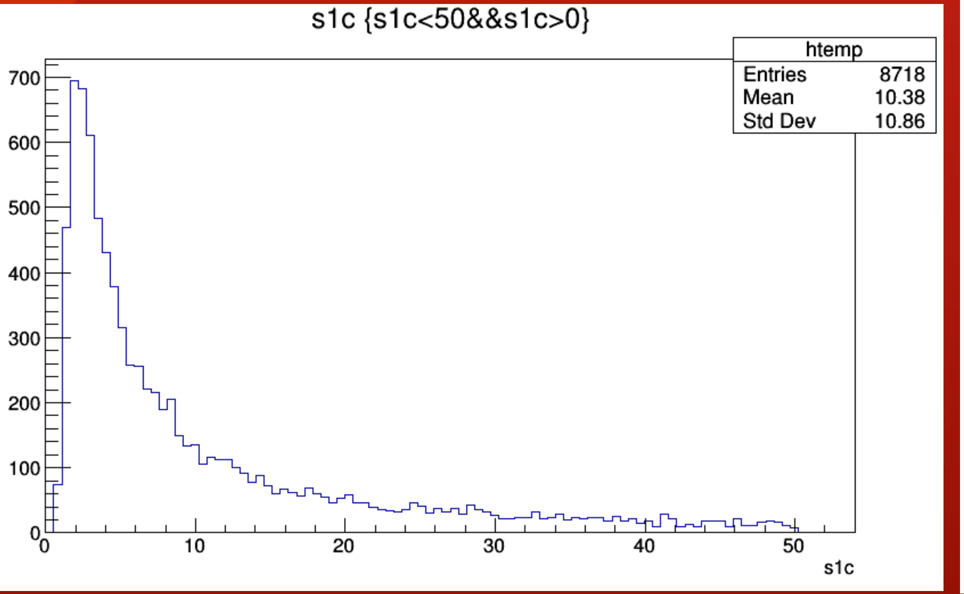
    This is because in the end what we want to simulate is the total S1 and S2 from the cluster, so the energy deposited via different methods needs to be distinguished.

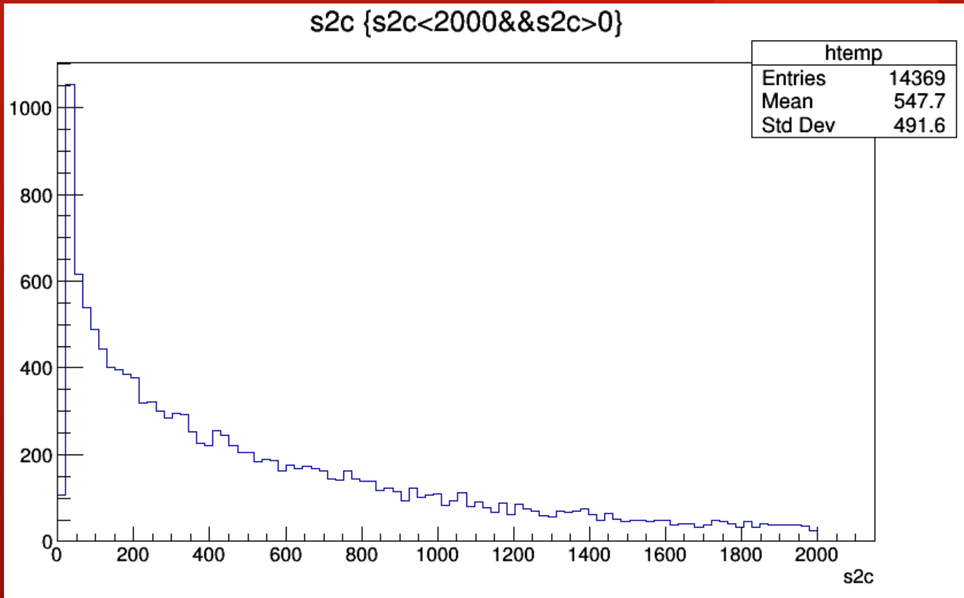
Get the S1 and S2 from libNEST

libNEST

- Run libNEST twice for each cluster.
  - Once with the NR energy in NR mode
  - Once with ER energy in ER mode
- Sum the S1c and S2c from the two runs
- Save file with x, y, z, r, phi, drift, s1c, s2c
- Currently just using run04 tb4 g1 and g2 etc, but run03 fields (Lucie's maps not yet implemented)
  - Both for Qy/Ly and for translation from z to drift

The S1 and S2 plots

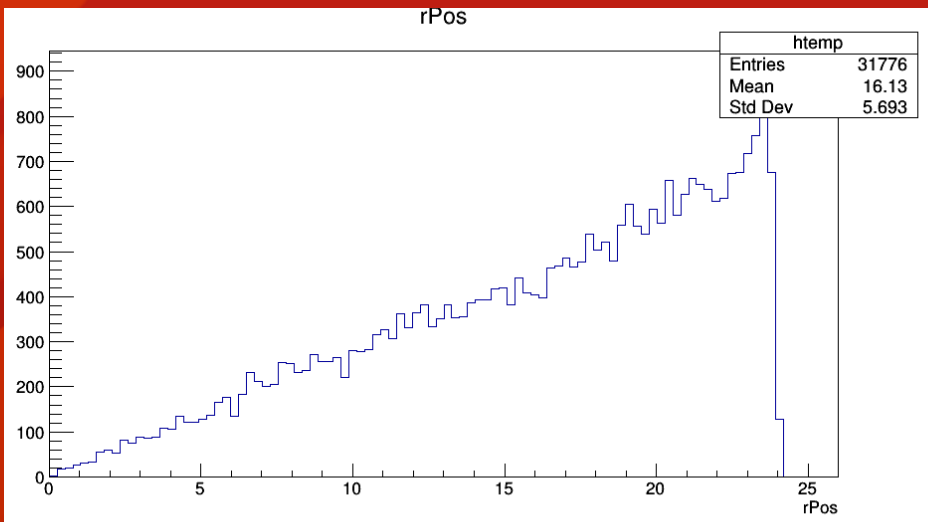


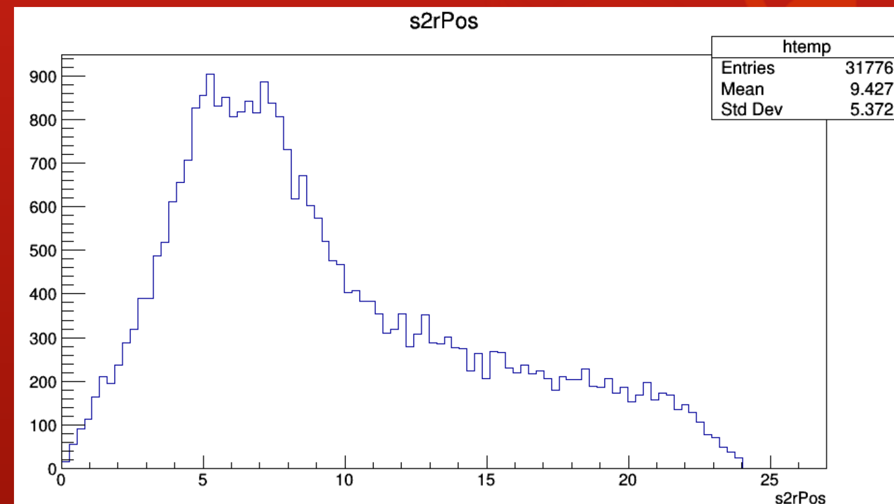


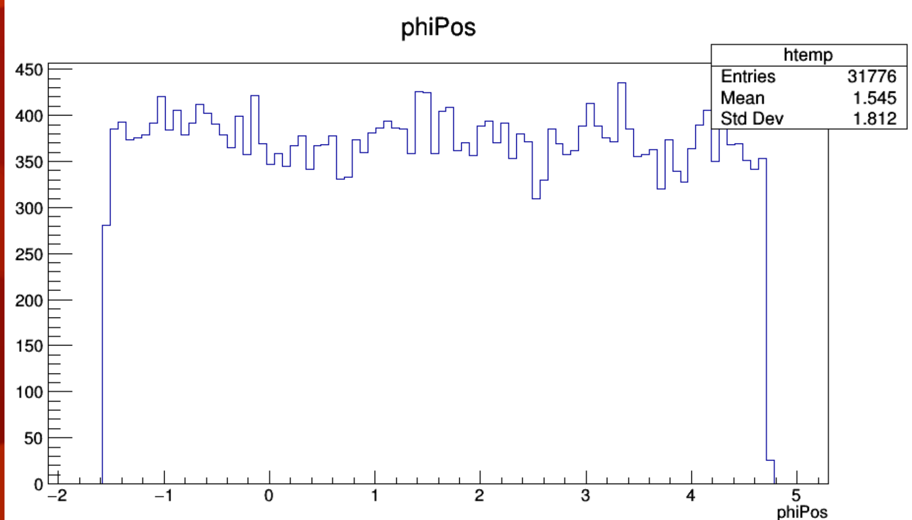
Positions mapped to S2-space

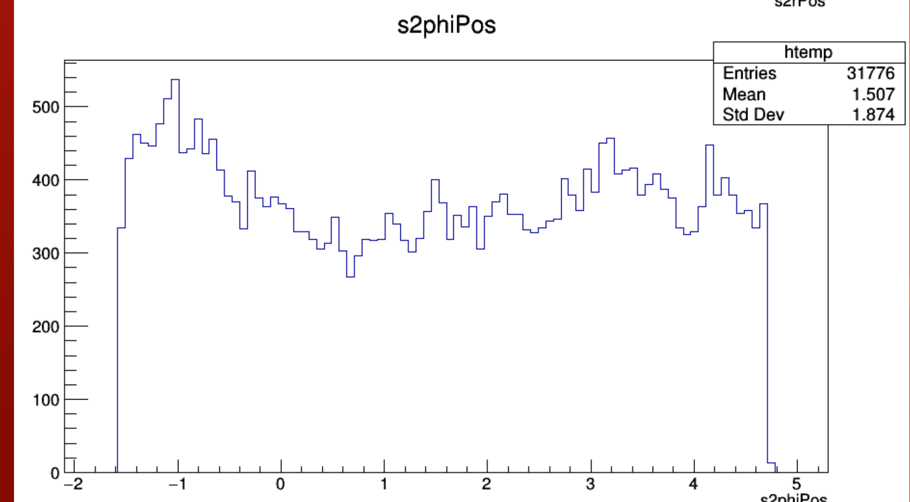
(x,y,z) ->(s2x, s2y, drift)

- S2-Space



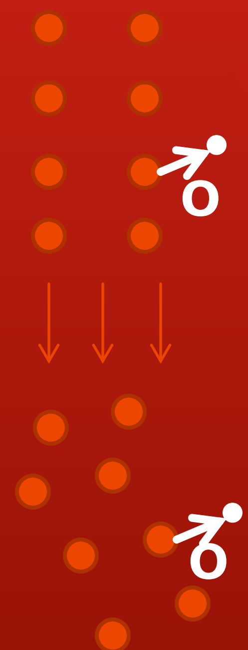


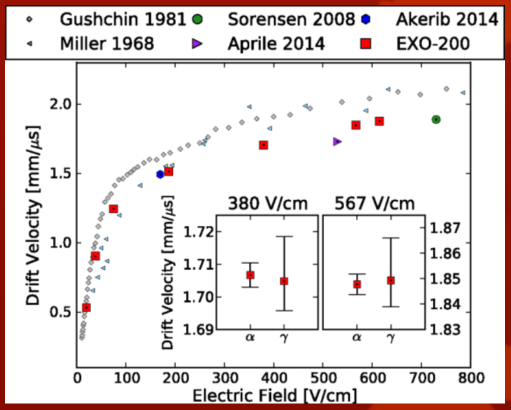




Implementation

- Find offset of nearest point, maintain offset from mapped point
- Need to know drift speed vs. electric field to translate z-offset to drift offset.
  - Very nice Exo data (inc LUX)
  - Fit to the form of b*log(c*x)+d/x works nearly perfectly.





Results after cuts

Expected Neutron Events

From all of run04…

- .16 from PMTs
- .016 from PTFE

```
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single scatter ratio: 0.00141287

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pdsf6 $
```

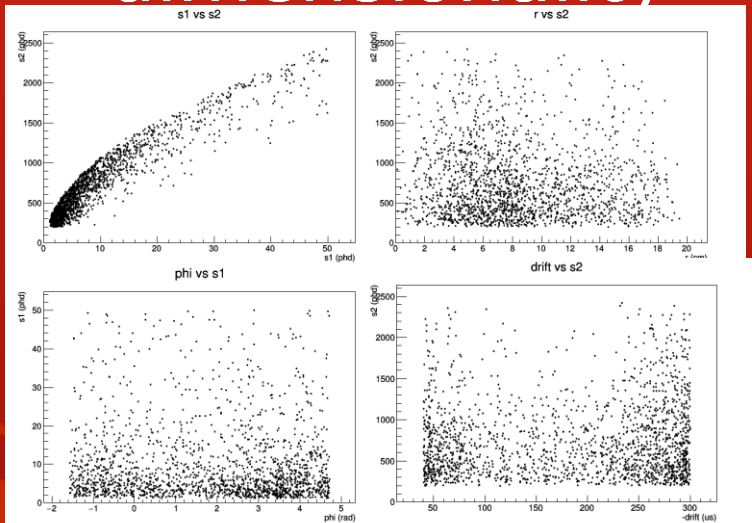
PDF Creation

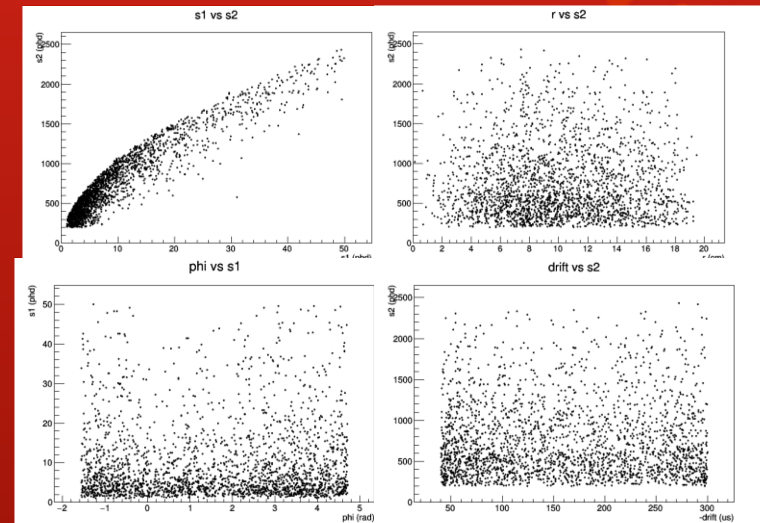
Plots to determine PDF dimensionality

PMT

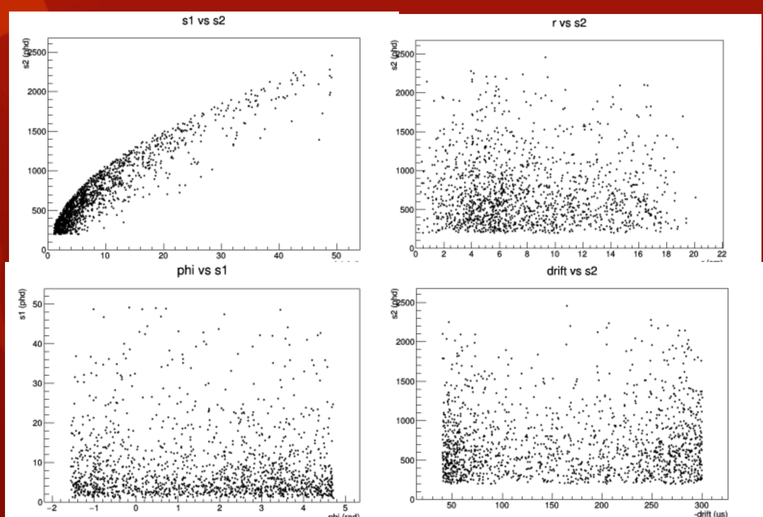
PTFE

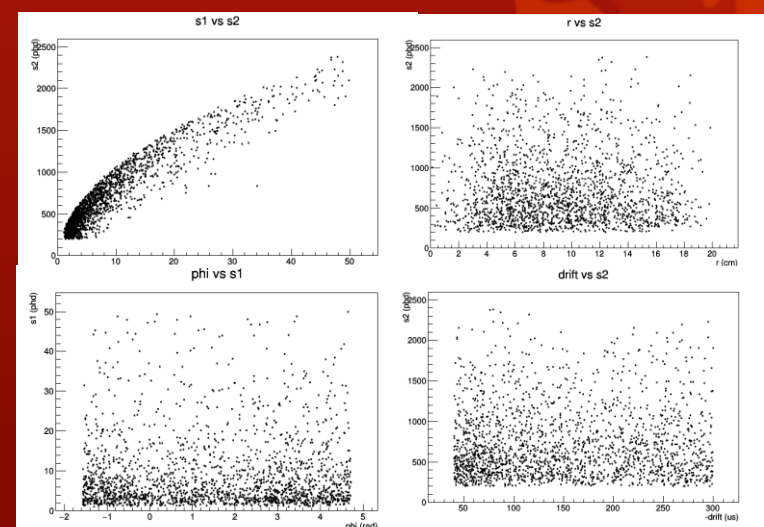
tb1





tb4





Correlation Matrices

Order is (s2R, s2Phi, drift, s1c, s2c)

tb 1

PMT

1	0.038348	-0.71189	-0.09228	-0.07449
0.038348	1	0.024852	-0.03186	-0.03008
-0.71189	0.024852	1	0.087557	0.073527
-0.09228	-0.03186	0.087557	1	0.936193
-0.07449	-0.03008	0.073527	0.936193	1

PTFE

1	-0.01823	-0.71251	0.00669	0.01652
-0.01823	1	0.062657	0.034068	0.035132
-0.71251	0.062657	1	0.024891	0.012057
0.00669	0.034068	0.024891	1	0.938586
0.01652	0.035132	0.012057	0.938586	1

tb 2

PMT

1	-0.01782	-0.73014	-0.05713	-0.0524
-0.01782	1	0.087523	-0.01438	-0.01623
-0.73014	0.087523	1	0.051623	0.04339
-0.05713	-0.01438	0.051623	1	0.926534
-0.0524	-0.01623	0.04339	0.926534	1

PTFE

1	-0.04057	-0.72231	0.000252	0.013491
-0.04057	1	0.086113	0.045914	0.038045
-0.72231	0.086113	1	0.069078	0.049003
0.000252	0.045914	0.069078	1	0.931879
0.013491	0.038045	0.049003	0.931879	1

tb 3

PMT

1	0.015255	-0.76422	-0.07692	-0.0592
0.015255	1	0.048662	-0.03268	-0.02901
-0.76422	0.048662	1	0.066563	0.04441
-0.07692	-0.03268	0.066563	1	0.934456
-0.0592	-0.02901	0.04441	0.934455	1

PTFE

1	-0.09264	-0.73922	0.01368	0.020828
-0.09264	1	0.059898	0.010869	-0.0008
-0.73922	0.059898	1	-0.00754	-0.01837
0.01368	0.010869	-0.00754	1	0.936692
0.020828	-0.0008	-0.01837	0.936692	1

tb 4

PMT

1	-0.04515	-0.76227	-0.02367	-0.02062
-0.04515	1	0.073236	-0.05028	-0.06333
-0.76227	0.073236	1	0.058368	0.044627
-0.02367	-0.05028	0.058368	1	0.928679
-0.02062	-0.06333	0.044627	0.928679	1

PTFE

1	-0.03953	-0.76952	-0.01774	-0.00056
-0.03953	1	0.028558	0.010215	0.007231
-0.76952	0.028558	1	0.041957	0.017651
-0.01774	0.010215	0.041957	1	0.93395
-0.00056	0.007231	0.017651	0.93395	1

Consequences

- Each (I think) have the structure below if 0.1 is chosen as a threshold
- Could li nfully cor DF as

  (s2R, drift) ⊗ (s2 s1c, s2c)

TRUE	FALSE	TRUE	FALSE	FALSE
FALSE	TRUE	FALSE	FALSE	FALSE
TRUE	FALSE	TRUE	FALSE	FALSE
FALSE	FALSE	FALSE	TRUE	TRUE
FALSE	FALSE	FALSE	TRUE	TRUE

Backup

/run/initialize

set how frequently the sims will update it's progress, i.e. every n events

/LUXSim/io/updateFrequency 100

choose a directory to which to save the output

/LUXSim/io/outputDir .

The Macros

PMT Made

choose name of output files

/LUXSim/io/outputName PMT_an_

geometry?

/LUXSim/detector/select 1_0Detector

no grids (faster and not doing optics or activity from them)

/LUXSim/detector/gridWires off

no cryostand

/LUXSim/detector/cryoStand off

I need to do this as well

/LUXSim/detector/update

record energy deposits in the volume "LiquidXenon" (i.e., in the active xenon)

/LUXSim/detector/recordLevel LiquidXenon 2

place source

/LUXSim/source/set PMT_Window SingleParticle_neutron 0.0100862457815 Bq/kg 0.1 MeV

/LUXSim/source/set PMT_Window SingleParticle_neutron 0.0172169043921 Bq/kg 0.2 MeV

/LUXSim/source/set PMT_Window SingleParticle_neutron 0.0231564684468 Bq/kg 0.3 MeV

/LUXSim/source/set PMT_Window SingleParticle_neutron 0.0141594862236 Bq/kg 0.4 MeV

/LUXSim/source/set PMT_Window SingleParticle_neutron 0.0225755162408 Bq/kg 0.5 MeV

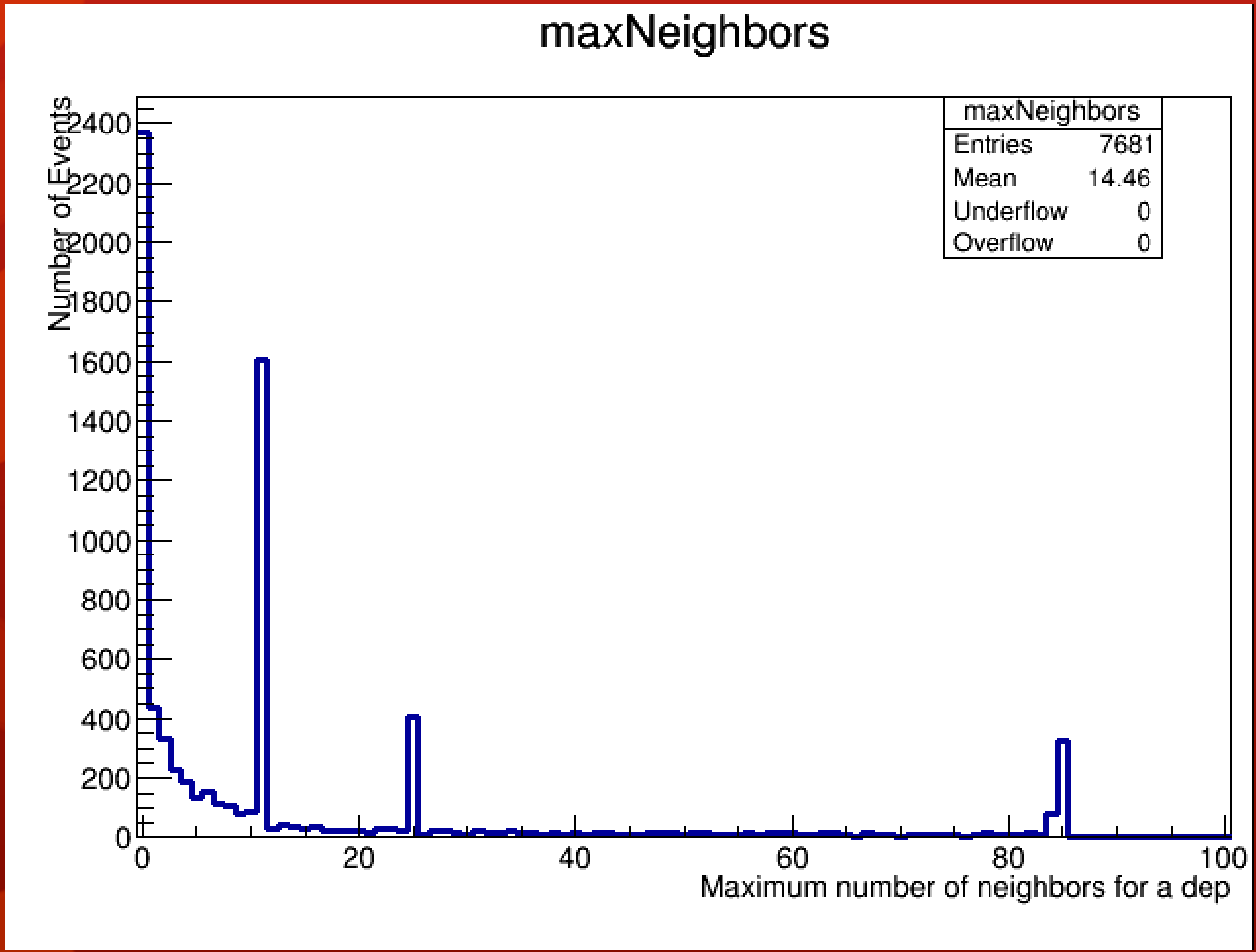
/LUXSim/source/set PMT_Window SingleParticle_neutron 0.0425102014676 Bq/kg 0.6 MeV

(more of the same, a LOT more)

PTFE is the exact same, but with PTFE in place of PMT_Window and different numbers.

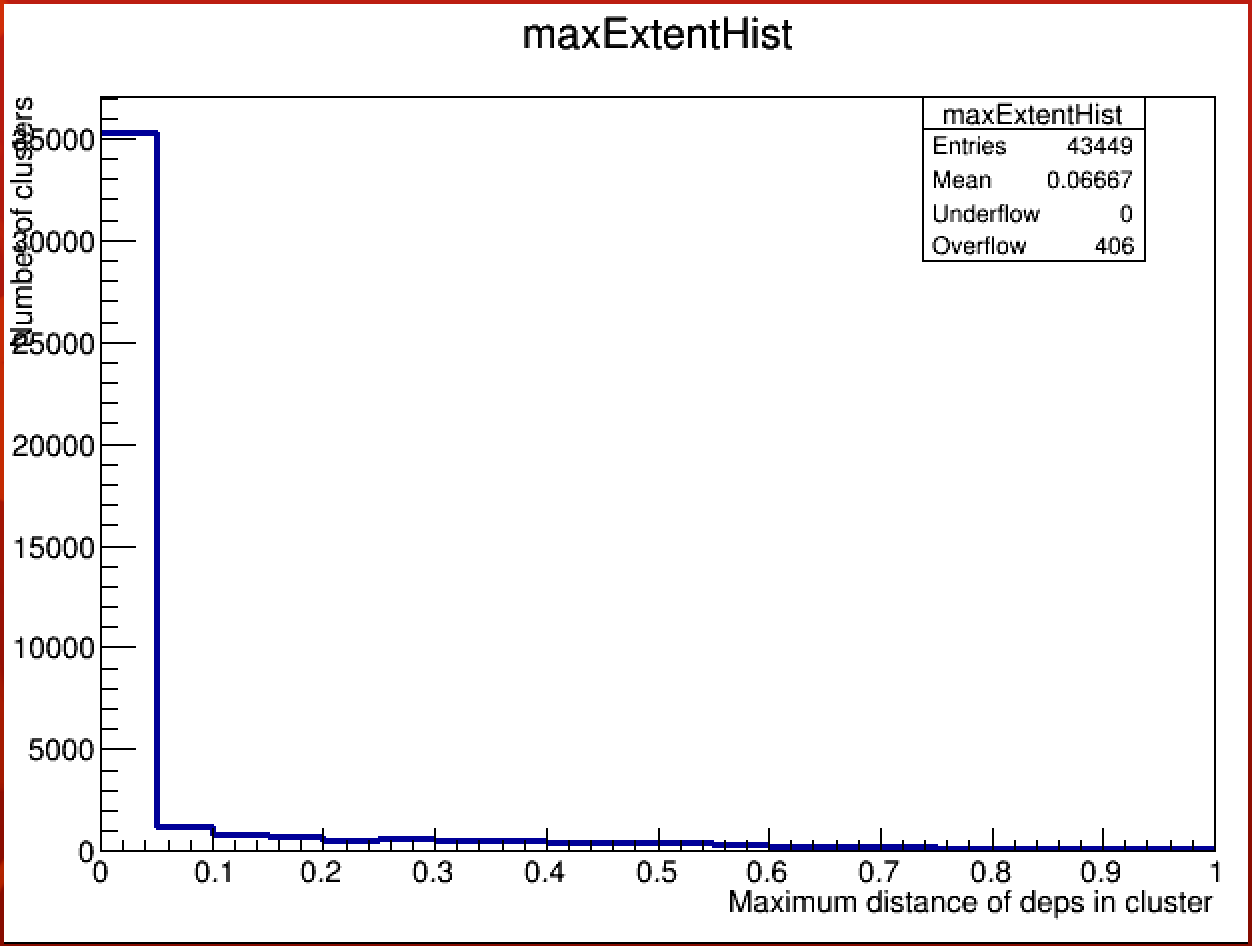
Do I somehow have to account for many, or can I cut it off at a few?

Must account for many.



Number of depositions within 0.5 cm of the deposition with the most in any given event.

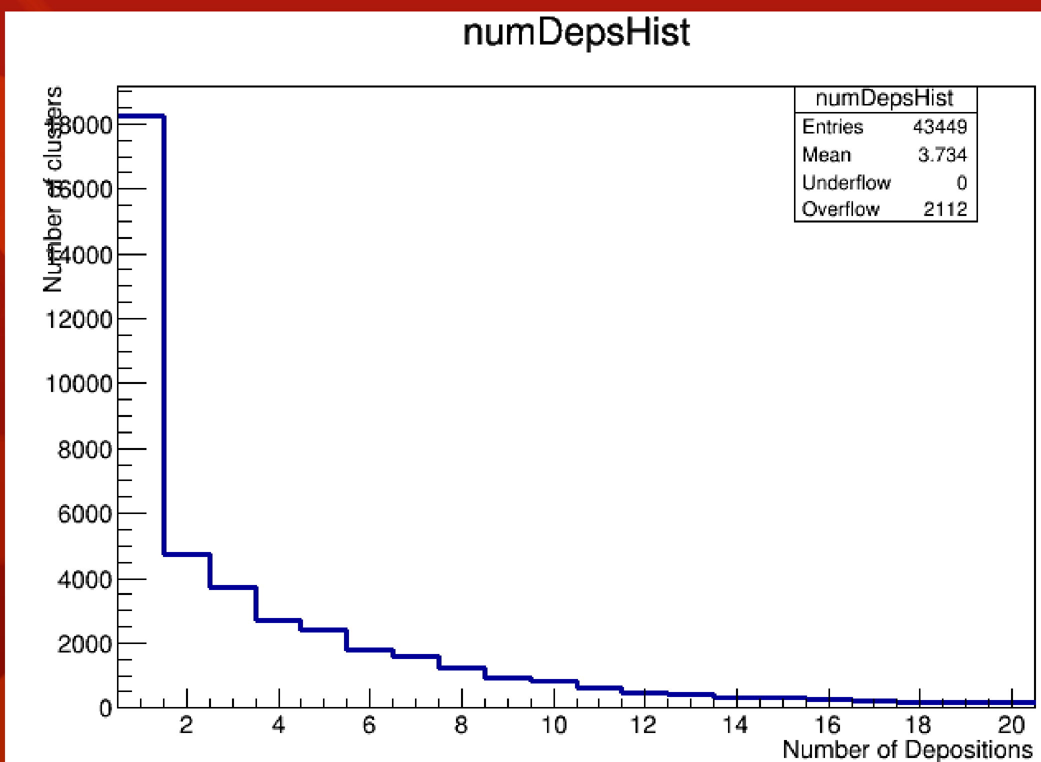
This can create a cluster out of chains, is this a problem?



Distance (in cm) between the two most distant depositions in each cluster.

The vast majority are still very compact.

Then was this level of clustering sophistication really necessary?



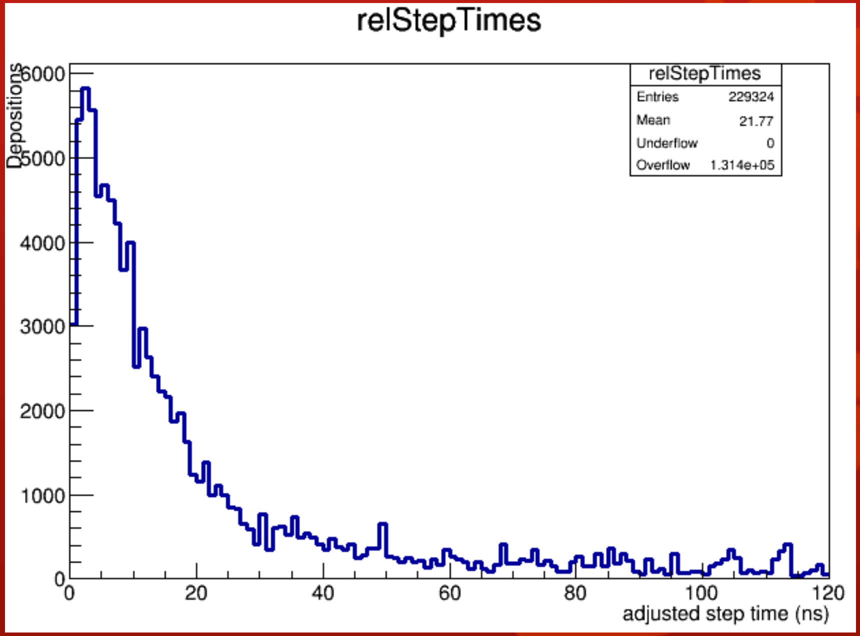
clude arbitrarily many
easy to accomplish with

Number of depositions that make up each cluster.

Left-most bin is 1, and has the most, but comprises less than ¼ of all the depositions.

Time Cut

- Make sure I'm not contaminating my data with depositions that occur long after the initial deposits.
  - i.e. if a neutron takes a long time to capture or the capture product decays after a long time
- A cut of 500us accepts 99.994% of depositions
- Currently using a cut of 400us
- Implemented *before* clustering



Deposition Cuts

- Cut depositions that will not be seen by the detector
  - Outside the TPC (i.e., in the skin)
- Cut depositions whose S2 would not be classified correctly by the detector
  - S2 < 60
  - *Keep* the S1 and add it to a total tally for the event

Event Cuts

- Treat Multiple Scatters and Single Scatters differently.
- Multiple scatter defined as an event which contains 2 or more depositions *after* the previous deposition cuts.
  - Does *NOT* need to pass any fiducial cuts

Multiple Scatter Cuts

- Determine whether the MS is ER or NR.
- Problem: can’t do a traditional S2/S1 cut in the traditional style
  - S1s possibly merged, or the pairing of s1 to s2 is unknown.
- Solution: predict S1 for each event based on S2 *as if it were a NR* using the NR band mean. Sum all S1s and compare to the sum of expected S1s. Cut if measured S1 is lower.
  - Equivalent to cutting above NR band mean
  - Possibly not equivalent in ER p-value due to differences in combined standard deviations

Single Scatters

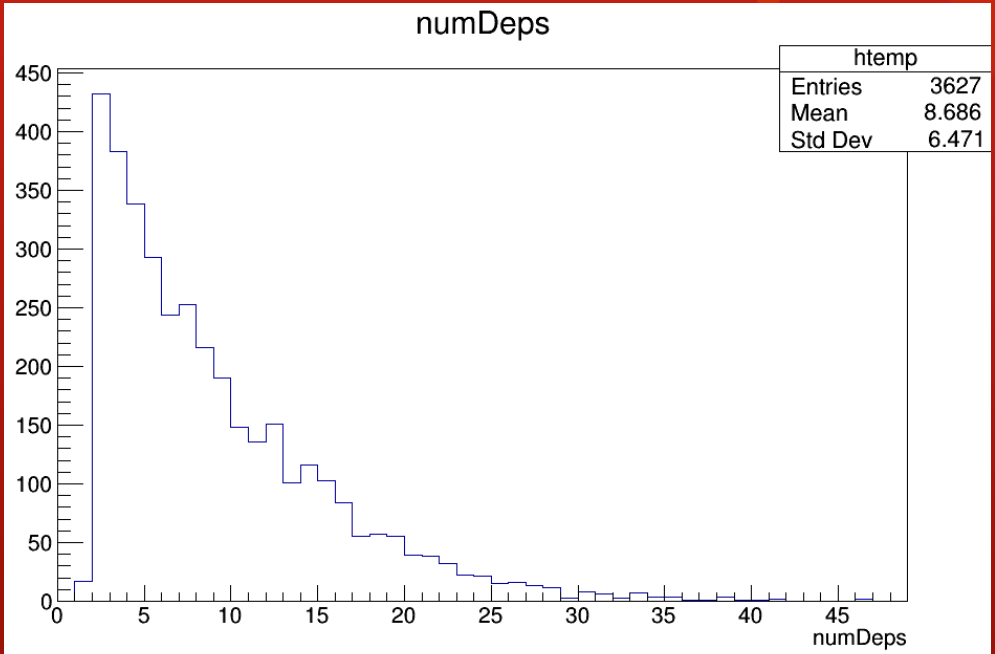
- Use the standard Run04 cuts detailed on the frozen page http://teacher.pas.rochester.edu:8080/wiki/bin/view/Lux/Run4_frozen_page
  - Fiducial cut
  - S1 cut
  - S2 cut
  - ER_mean + 3 sigma
  - NR_mean – 7 sigma
- Also cut events above NR band mean (it occurs to me that this is only necessary for finding the overall normalization, if that)

Correct Fiducial cut Implemented

- $r(\text{event}) < r_{wall}(\varphi_{event},\text{drift}_{event}) - 3\text{cm}$
- Impact of this change still pending
- This, of course, depends on time bin so have to run sims dedicated to each. In progress.

Result of Cuts: PMTs

- Main result is ratio of total MS to cut SS
  - 430/17   Double Scatter/SS)
- Ratio of total simulated to WIMP-like events: 0.0017
  - Taking the guess of 138 n/yr from PMTs this amounts to 0.23 WIMP-foolers/yr. Or 0.21 in our 332 live-day run strictly from PMTs.



Recall: SS and MS were treated differently in cuts.

Results of Cuts: PTFE

- Ratio of total simulated to WIMP-like events: .0019
- From Dave Malling's thesis "9.5 n/yr from PTFE" which means in 332 live days ~.016 WIMP-like.