Applying Machine Learning for ββ-decay Identification

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Work in progress

In collaboration with
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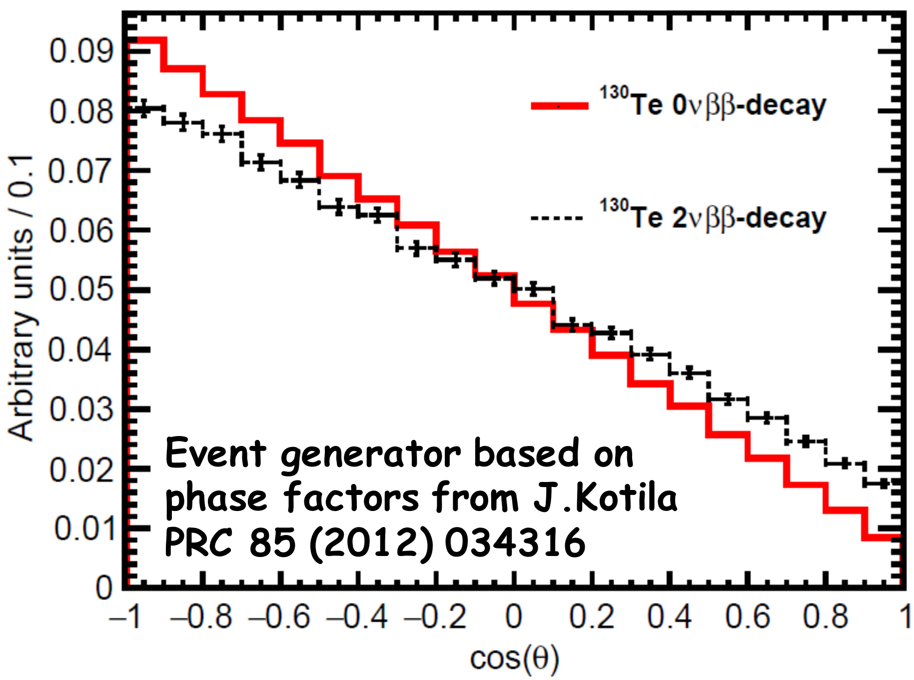
Outline

- Brief reminder on previous work: the Spherical Harmonics Analysis
- Current status of applying machine learning techniques to $0\nu\beta\beta$-decay identification

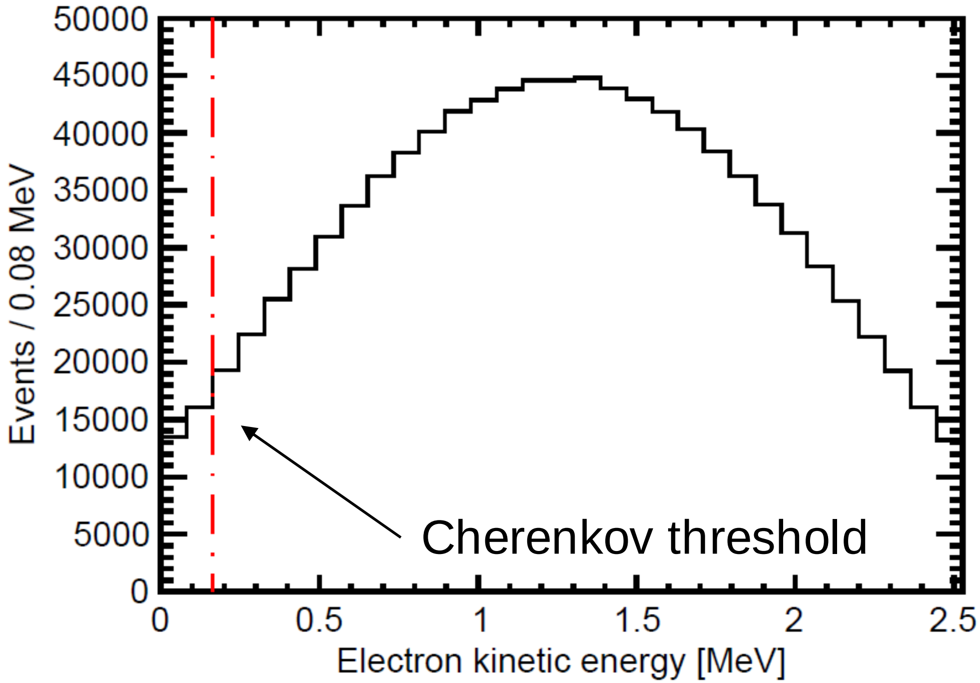
In this talk I focus specifically on $0\nu\beta\beta$-decay THEIA physics case

Double-Beta Decay Kinematics

Angle (cosΘ) between two electrons



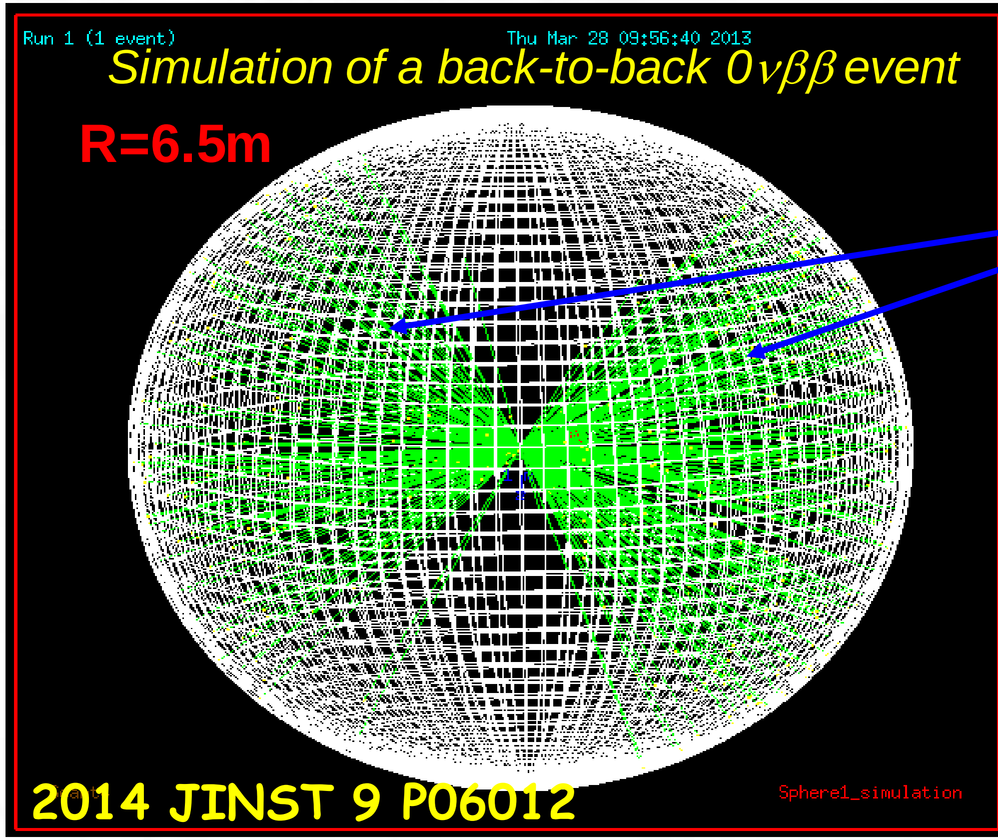
Kinetic energy of each electron



- Lots of "back-to-back" (large angle) events
- Most of electrons are above Cherenkov threshold

Can We See This?

Is it possible to use Cherenkov light for $0\nu\beta\beta$-decay reconstruction in a liquid scintillator detector?



Cherenkov Light

This question was formulated in: JINST 7 (2012) P07010; PRD87 (2013) 071301

Quantitative feasibility studies: JINST 9 (2014) 06012; arXiv:1409.5864; NIMA 849 (2017) 102

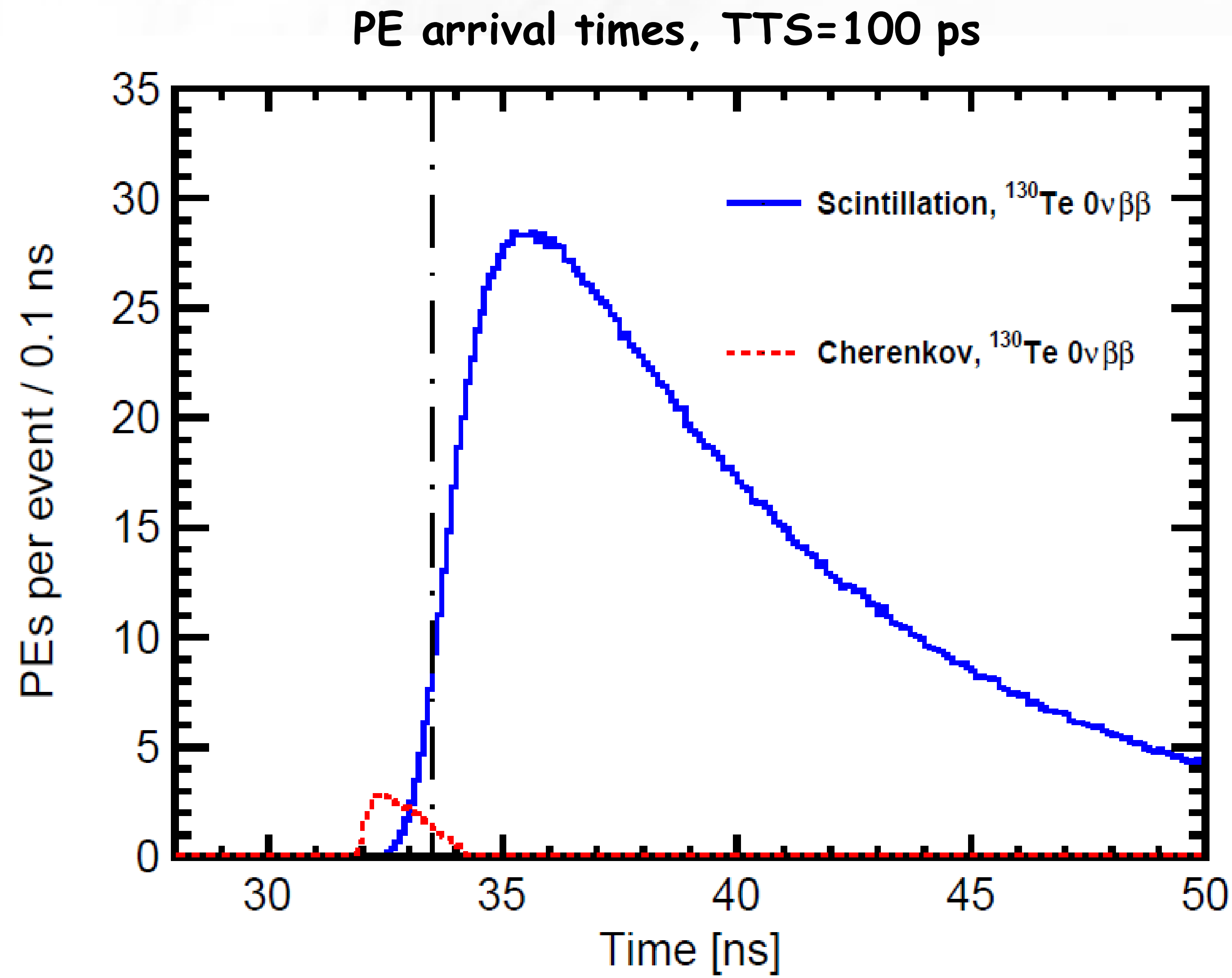
Work on experimental demonstration: NIMA 830 (2016) 303; PRC95 (2017) 055801; Eur.Phys.J. C77 (2017) no.12, 811

[In chronological order, comments on omissions and latest publications are welcome]

Yes, we can use Cherenkov light in $0\nu\beta\beta$-decay events, but this requires

- fast photo-detectors (red sensitive photo-cathode helps) [see JINST 9 (2014) 06012]
- slow scintillators [see NIMA 849 (2017) 102]

Cherenkov Light Comes First

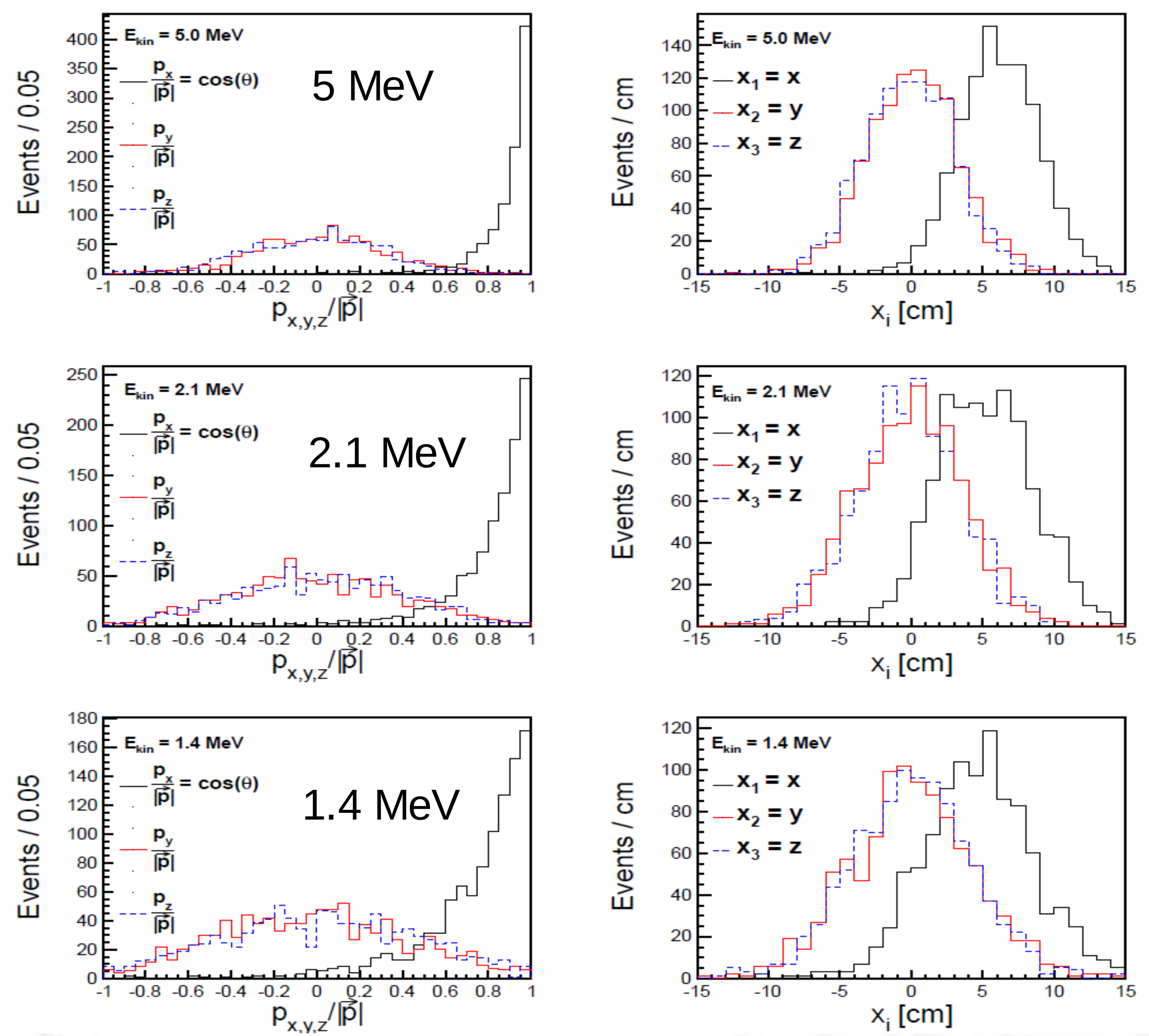


- Scintillation emission is slower
- Longer wavelengths travel faster
- Cherenkov light arrives earlier

370 nm → 0.191 m/ns
600 nm → 0.203 m/ns
~2 ns difference over 6.5m distance

Using Directionality of Early Light

Directionality   Vertex



Simulation:
- single electrons along X-axis at the center of 6.5m sphere
- KamLAND scintillator

Reconstruction:
- WCSim adapted for low energy

2014 JINST 9 P06012

First directionality feasibility study using che/sci separation in the energy range relevant for 0νββ-decay

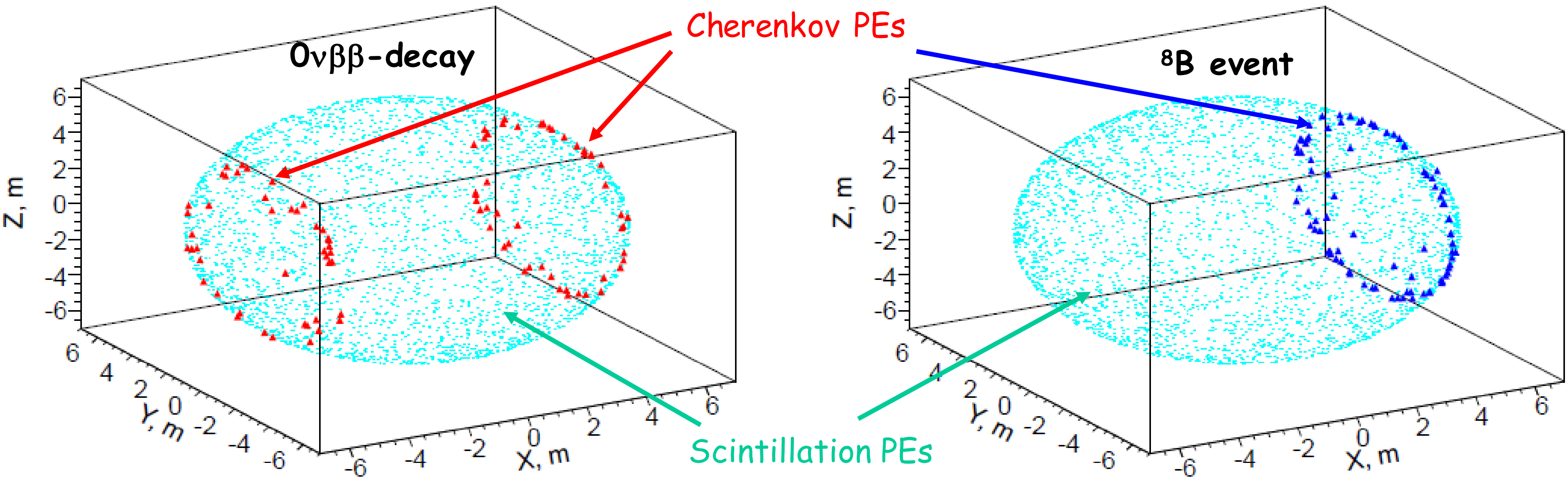
Directionality "survives" some detector effects

Vertex resolution is promising

Directionality is a handle on ^{8}B events

Directionality or Topology?

Idealized event displays: no multiple scattering of electrons, all PEs, QE=30%

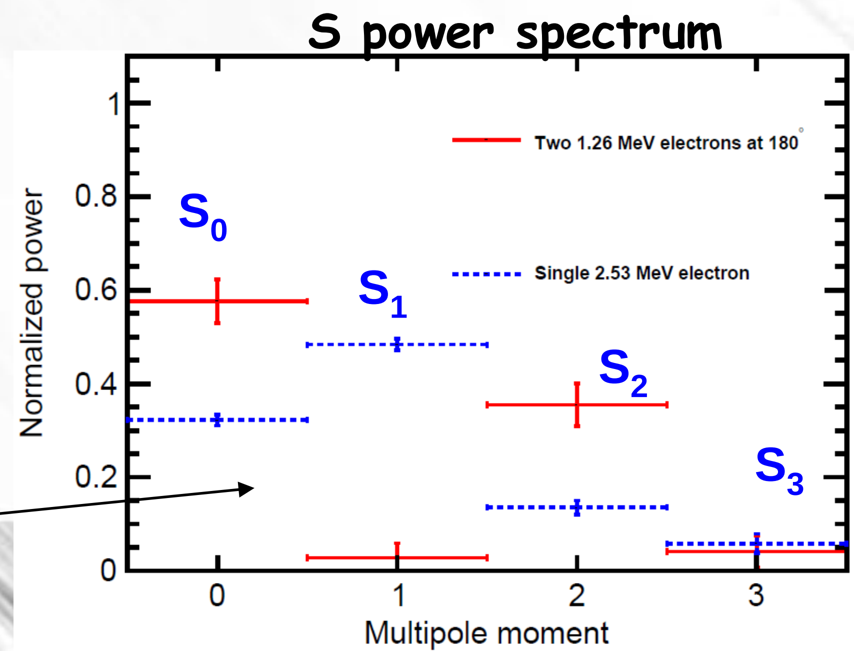


Spherical harmonics analysis

$$f(\theta,\varphi)=\sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta,\varphi).$$

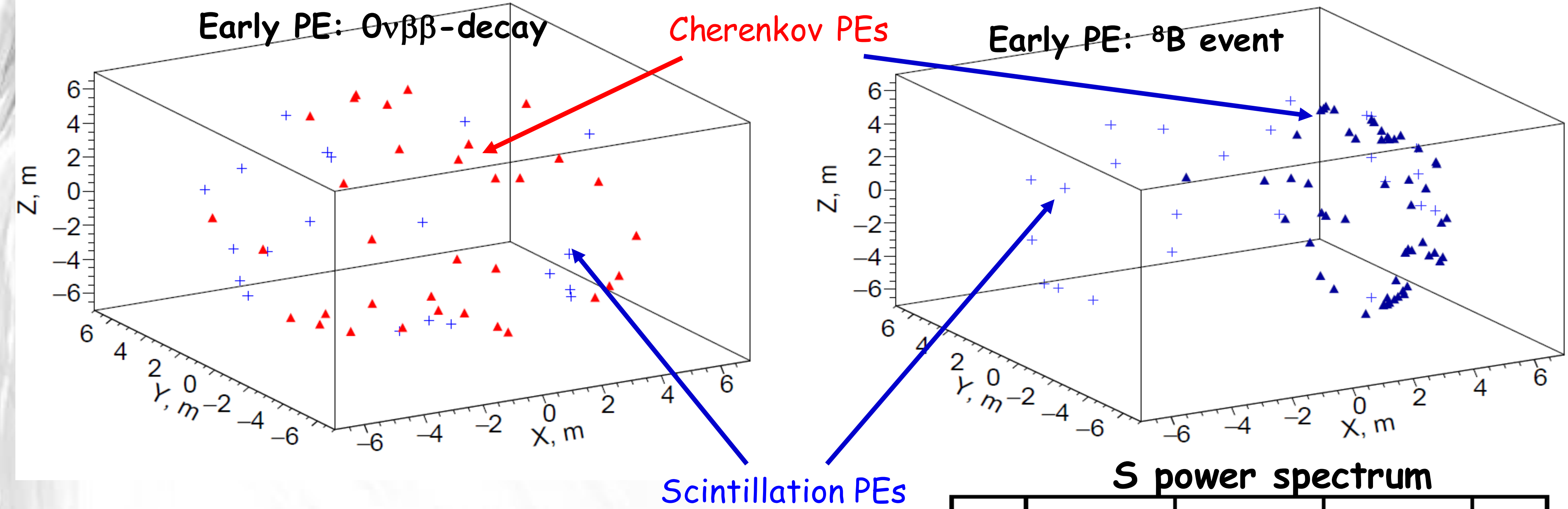
Rotation invariant power spectrum

$$S_{ff}(\ell)=\sum_{m=-\ell}^{\ell}|f_{\ell m}|^2$$



Early Light Topology

"Realistic" event displays: early PEs only, KamLAND PMTs QE: Che~12%, Sci~23%

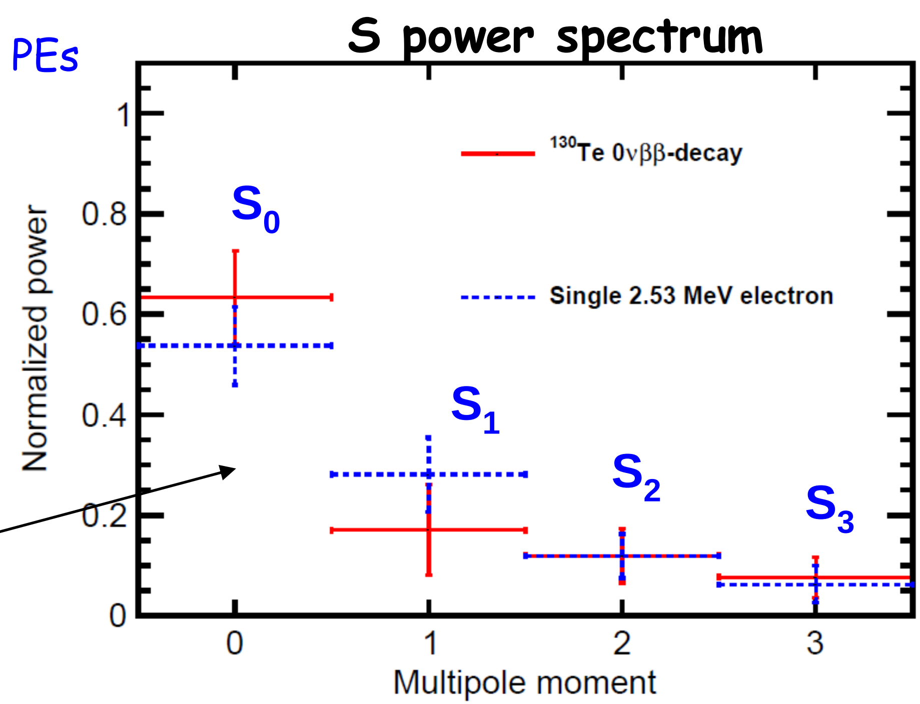


Spherical harmonics analysis

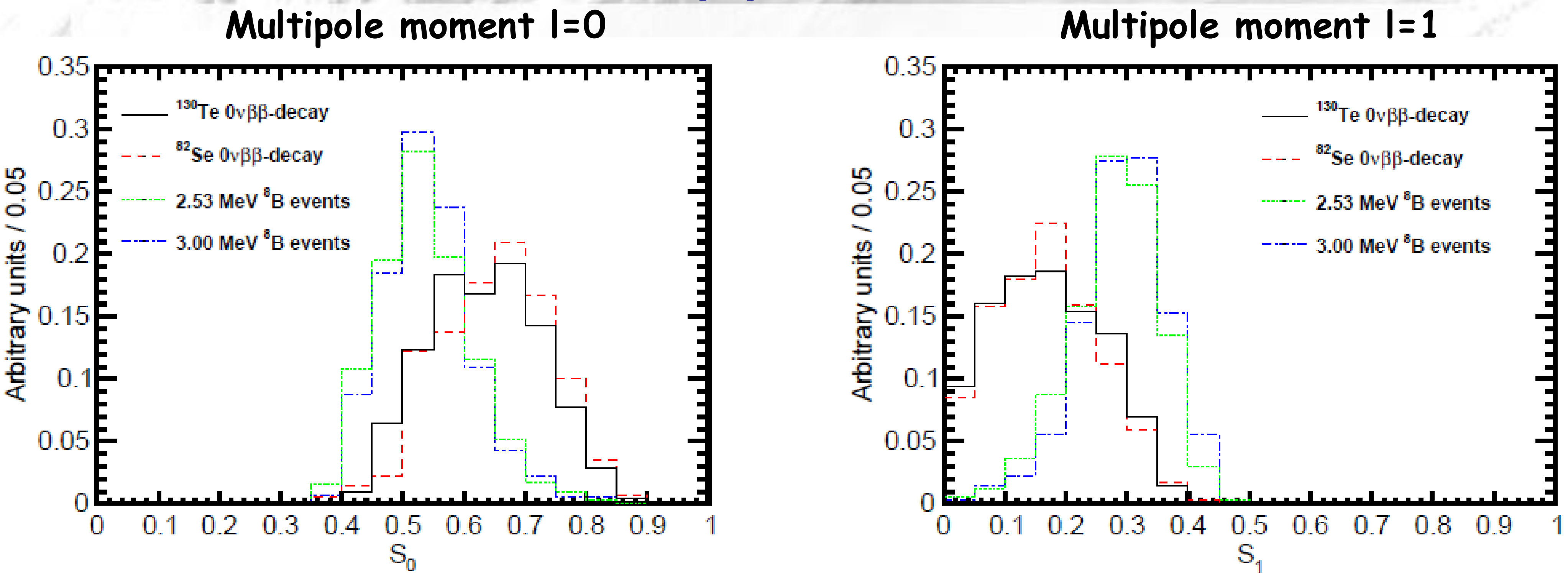
$$f(\theta,\varphi)=\sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} f_{\ell m}Y_{\ell m}(\theta,\varphi).$$

Rotation invariant power spectrum

$$S_{ff}(\ell)=\sum_{m=-\ell}^{\ell}|f_{\ell m}|^2$$



$0\nu\beta\beta$ vs ^{8}B



Simulation details:

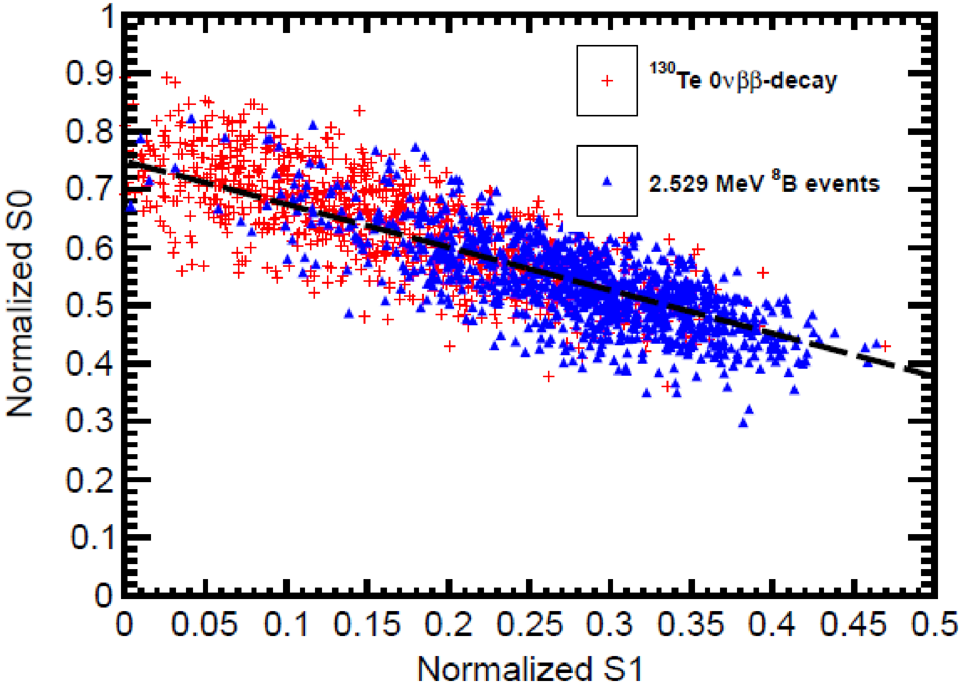
- 6.5m radius detector
- Scintillator model from KamLAND simulation (1 ns rise time)
- TTS=100 ps, 100% area coverage, QE(che) ~12, QE(sci) ~23%
- Central events only

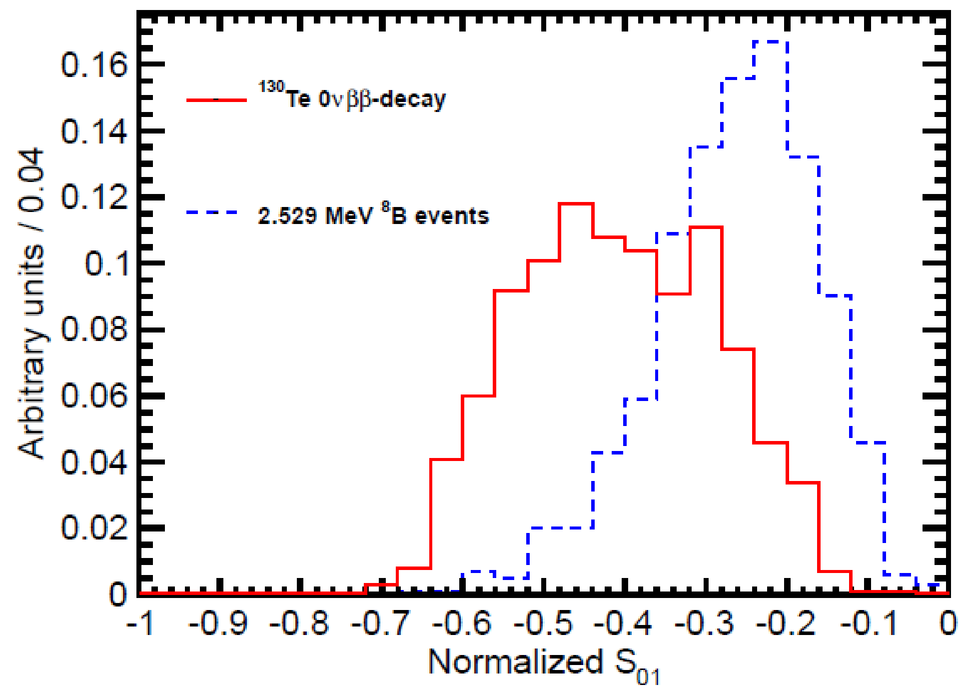
Key parameters determining separation of $0\nu\beta\beta$-decay from ^{8}B:

- Scintillator properties (narrow spectrum, slow rise time)
- Photo-detector properties (fast, large-area, high QE, red-sensitive)

Single-Variable Discriminant S_{01}

Linear combination of S_0 and S_1





Current implementation of the spherical harmonics analysis requires vertex reconstruction

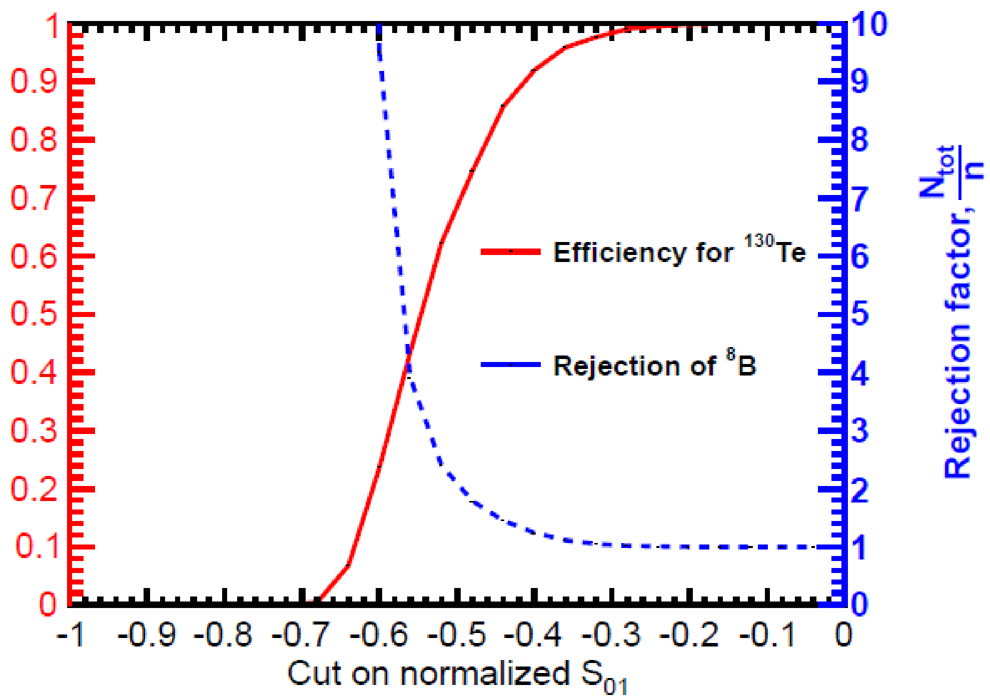
This limits applicability to multi-vertex events such as ^{10}C and gammas

0νββ vs ^8B

For details see NIM A849 (2017) 102

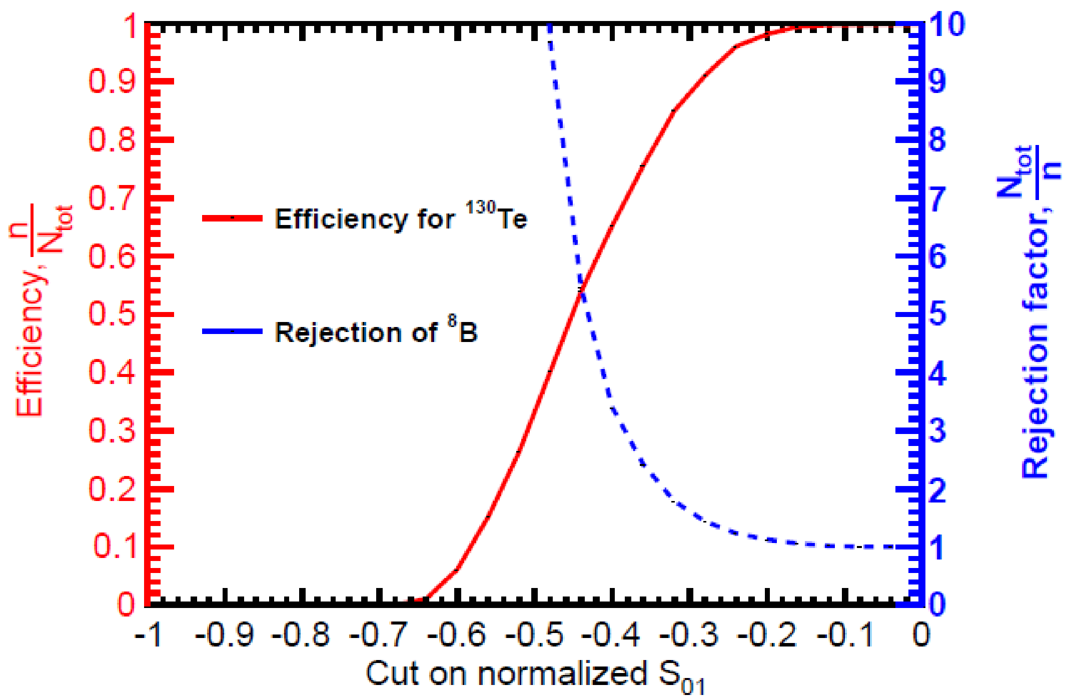
First quantitative demonstration of benefits of slow scintillators for 0νββ-decay event topology reconstruction

Vertex res **5cm**, events within **R<3m**
Scintillation rise time **1 ns**



Background rejection factor = 2
@ 70% signal efficiency

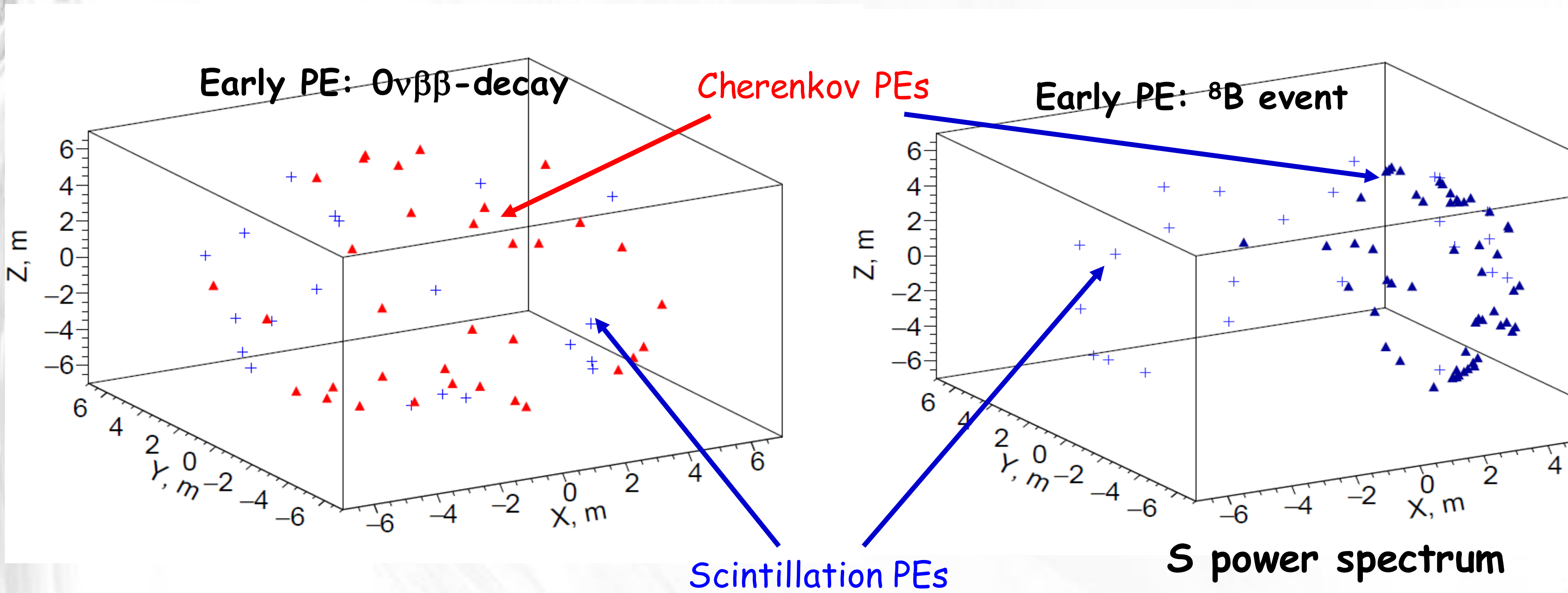
Vertex res **5cm**, events within **R<3m**
Scintillation rise time **5 ns**



Background rejection factor = 3
@ 70% signal efficiency

Can We Use Machine Learning ?

In the early light, the difference between one-track and two-track events often can be seen by eye
Computer should be able to learn to see the difference



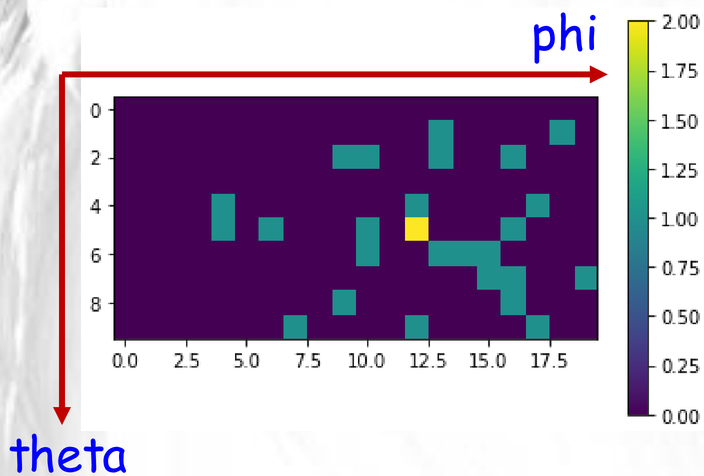
There are plenty of tools to try
A 2D Convolutional Neural Network seems to be a natural choice to start

- Feed "photos" of theta-phi plane into a convolutional neural network
- Bin the photos in time and treat those timing bins as color channels

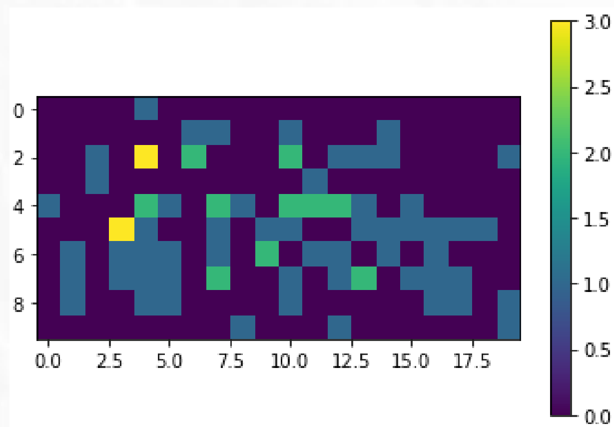
"Photos" of $0\nu\beta\beta$ and ^{8}B Events

- Two-track event

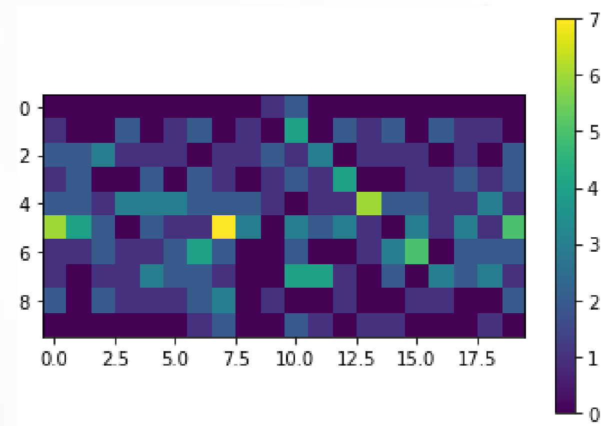
"color" channel ΔT_1



"color" channel ΔT_2

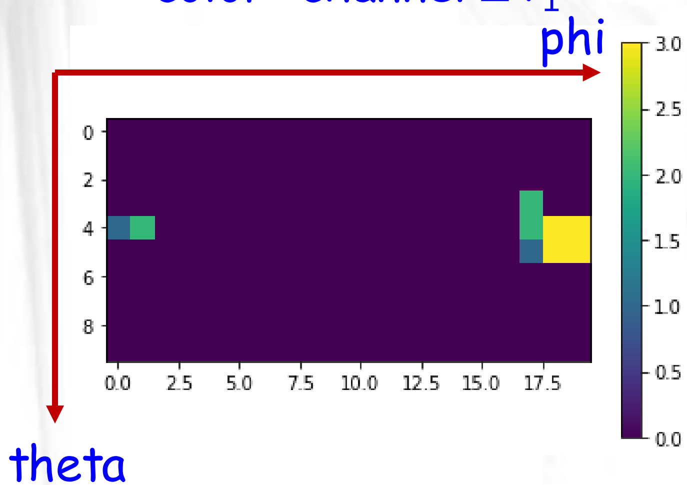


"color" channel ΔT_3

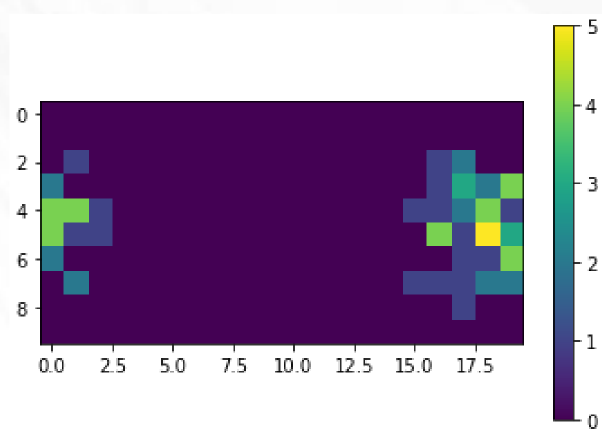


- One-track event

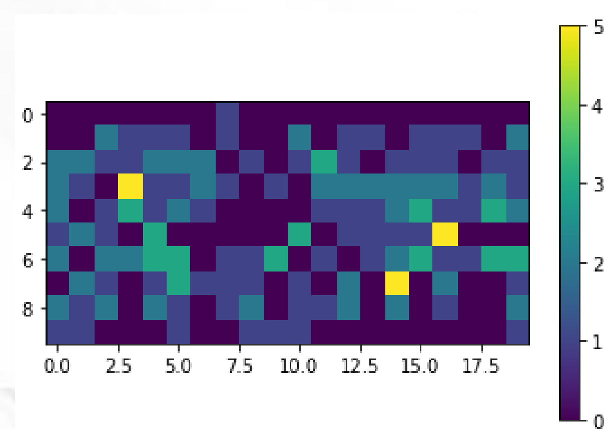
"color" channel ΔT_1



"color" channel ΔT_2



"color" channel ΔT_3

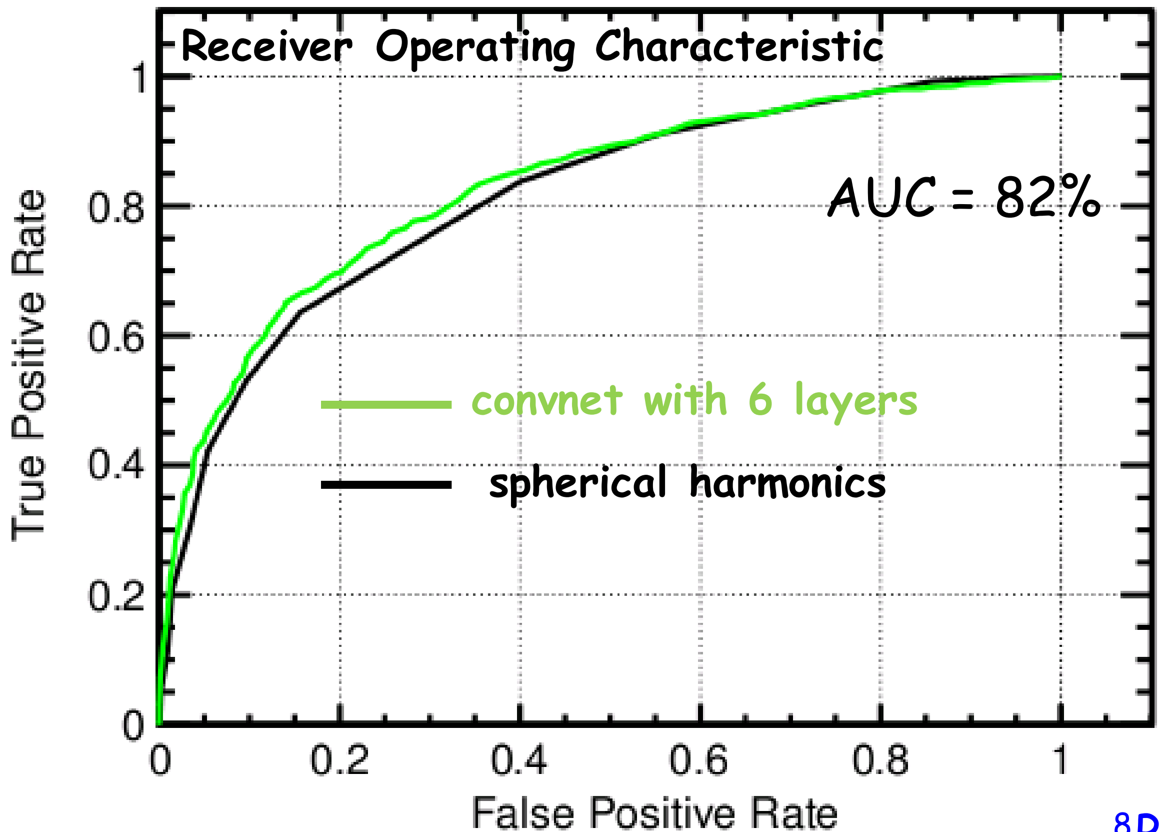


ConvNet vs Spherical Harmonics

$0\nu\beta\beta$-decay vs ^{8}B: central events only

Work in progress

ROC curve



$0\nu\beta\beta$-decay event labeled as such

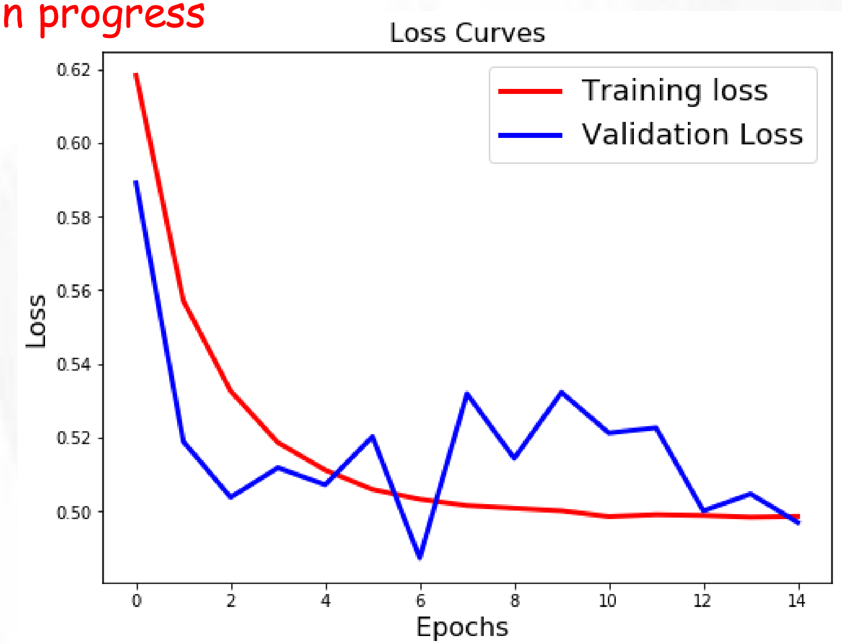
^{8}B event mislabeled as $0\nu\beta\beta$-decay

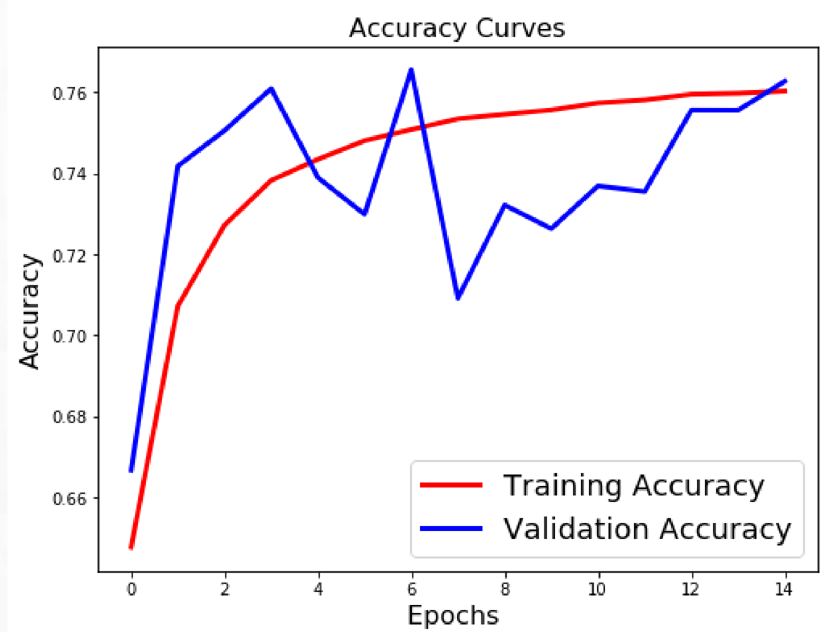
While currently there is only small improvement over spherical harmonics, ConvNet does not use any information about vertex -> important simplification in dealing with off-center events as well as with gammas, positrons, and ^{10}C backgrounds

ConvNet for 0νββ-decay vs γ

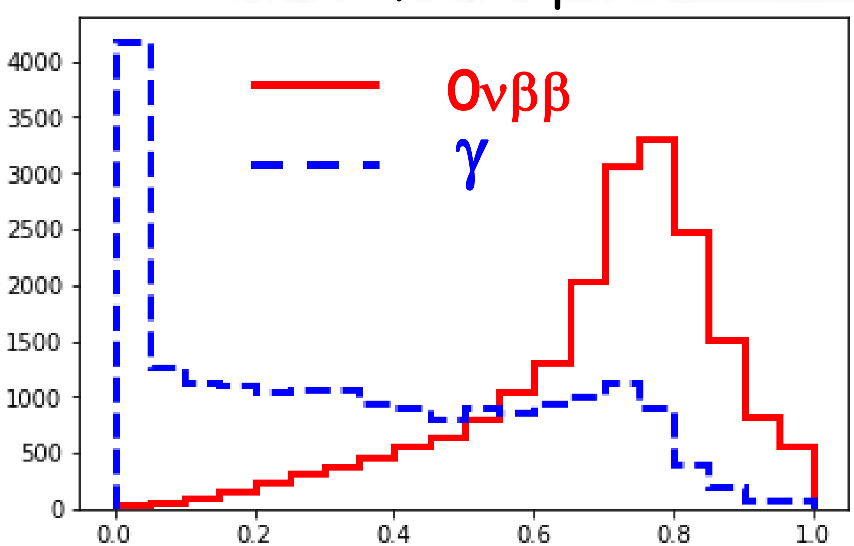
0νββ-decay vs γ: any events with R<3m

Work in progress

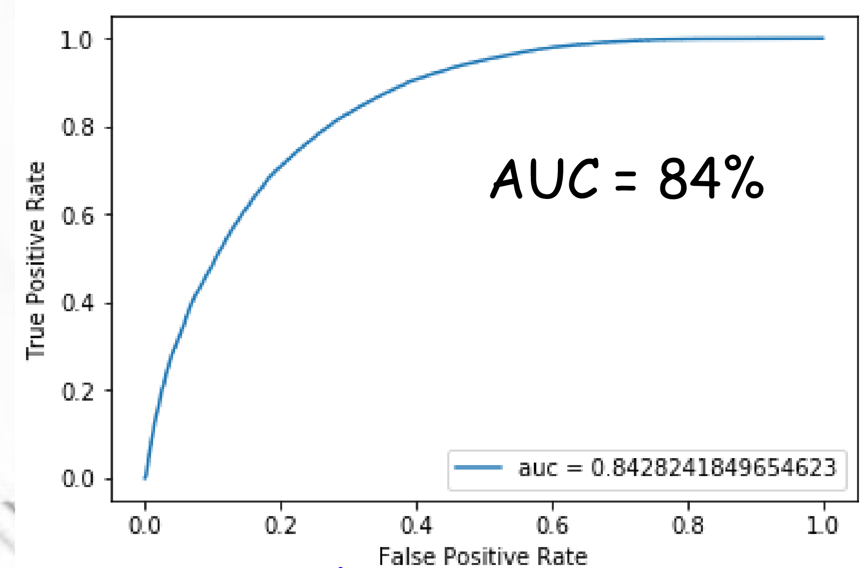




Classifier output



ROC curve



No explicit vertex reconstruction

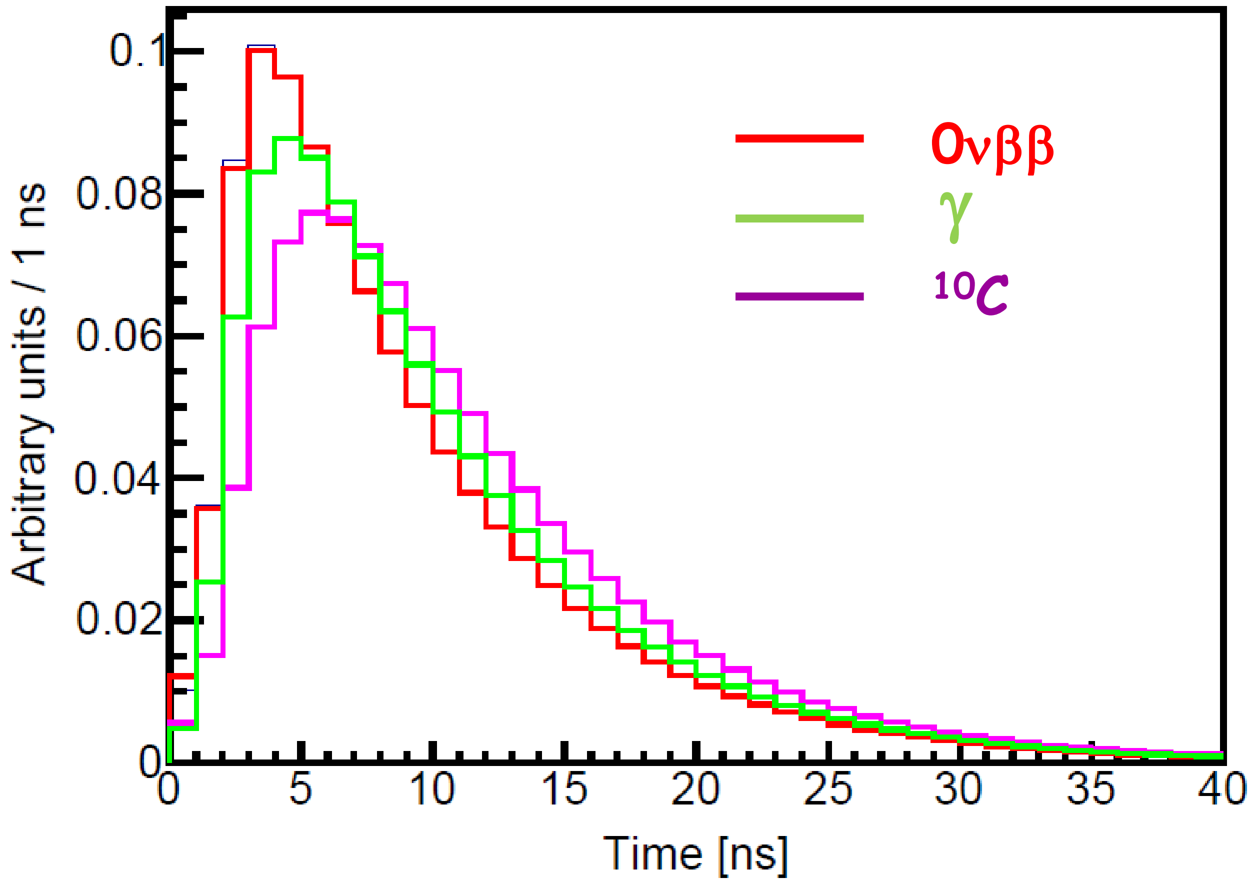
Why it works better on γ?

Work in progress

More differences in overall timing distributions

γ Compton scatters -> may have multiple vertices

PE arrival times relative to the very first PE



Also ~50% of e^+ from ^{10}C will form an ortho-positronium -> even longer delay

Next Steps

- Try current ConvNet on ^{10}C events
- Check correlation between spherical harmonics and ConvNet classifier outputs
    - Likely to be highly correlated given similar performance, but this needs to be checked
    - If there is independent information use ConvNet for vertexing and feed it into spherical harmonics, then add spherical harmonics to the ConvNet classifier
- Try more “color” channels
    - currently using 0.5 ns timing bins, smaller bins are computationally more challenging
- Try more sophisticated ML techniques
    - Consulting with experts in computer vision
- Apply to more realistic detector settings
    - SNO+ and/or KamLAND-Zen
    - THEIA detector parameter optimization (including mirrors)
- Are we using all information?
    - wavelength
    - polarization
    - photon angular information (the Distributed Imaging method: PRD **97** 052006)

Conclusions

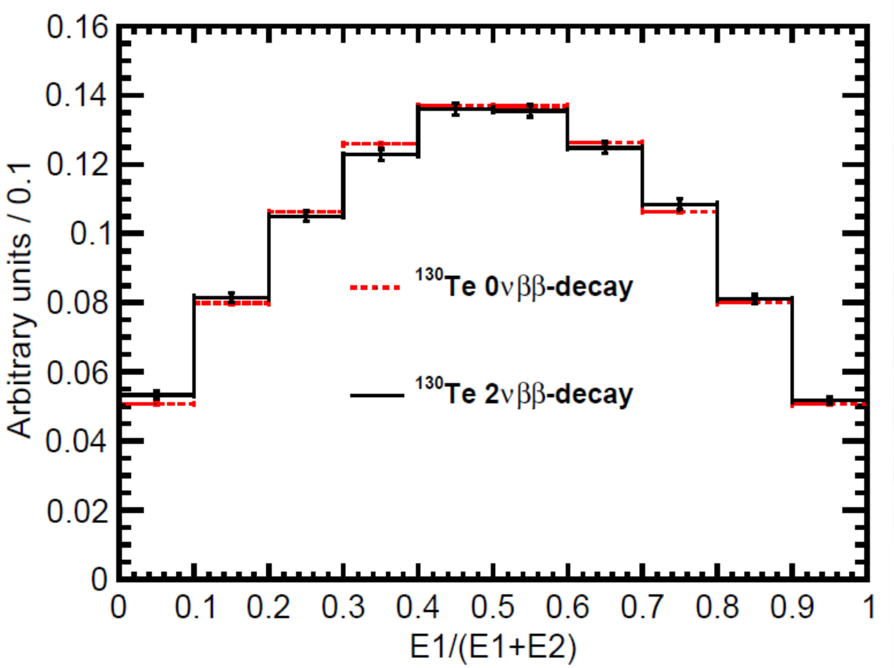
- A rather simple implementation of ML techniques looks promising
- Current performance on $0\nu\beta\beta$-decay vs ^{8}B is similar to spherical harmonics analysis
- Key advantage of ML methods is that they do not explicitly depend on vertex reconstruction

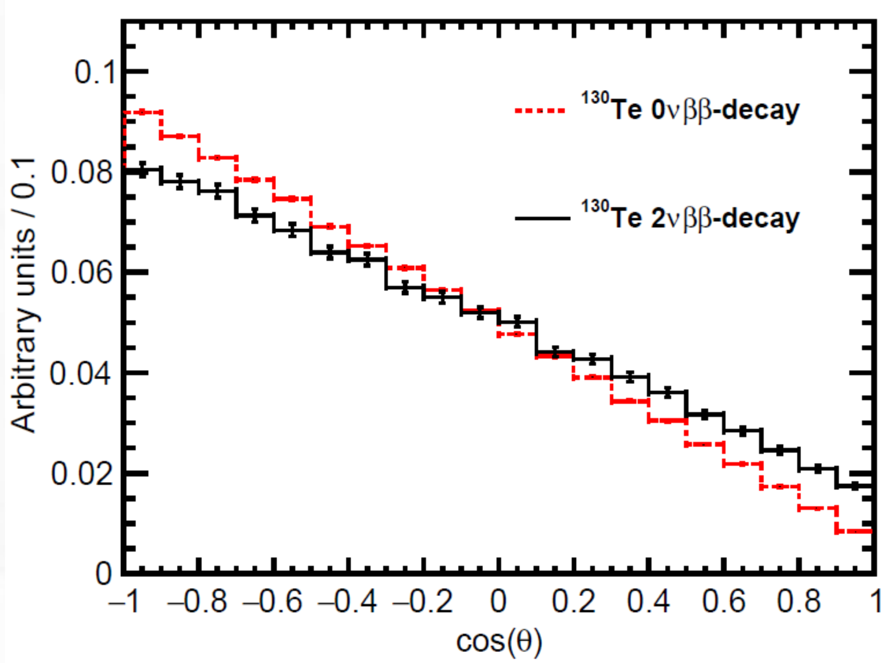
Back-up

$0\nu\beta\beta$ vs $2\nu\beta\beta$

Events within 5% of the end point

Event generator from L.Winslow based on phase factors from PRC 85, 034316 (2012) by J. Kotila and F. Iachello

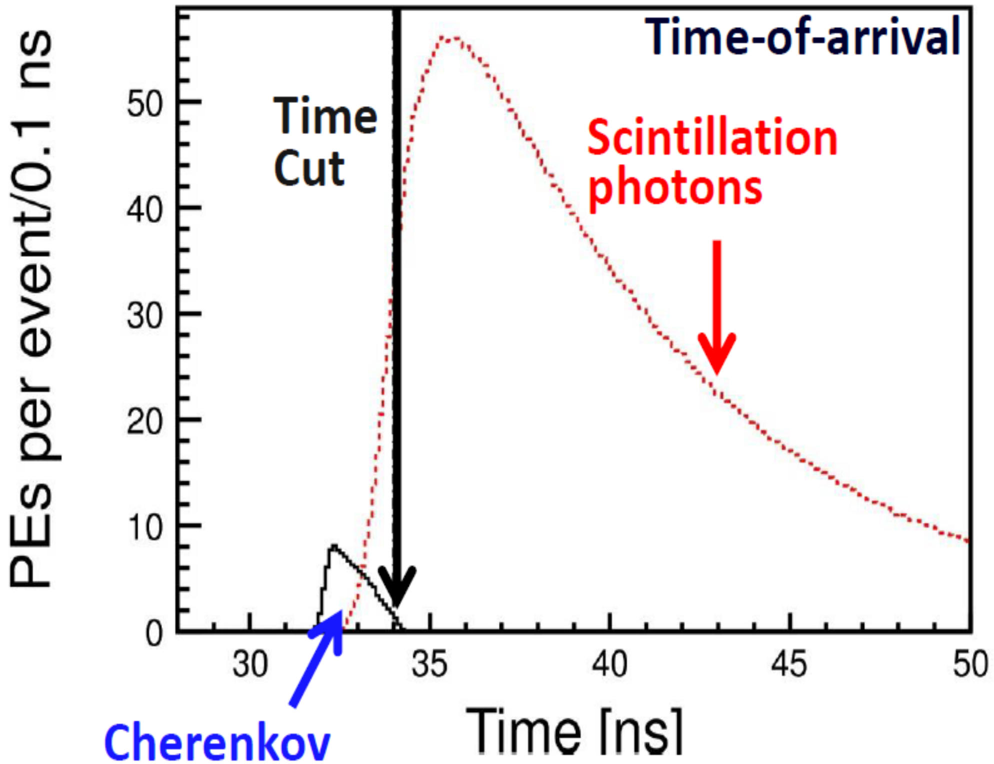




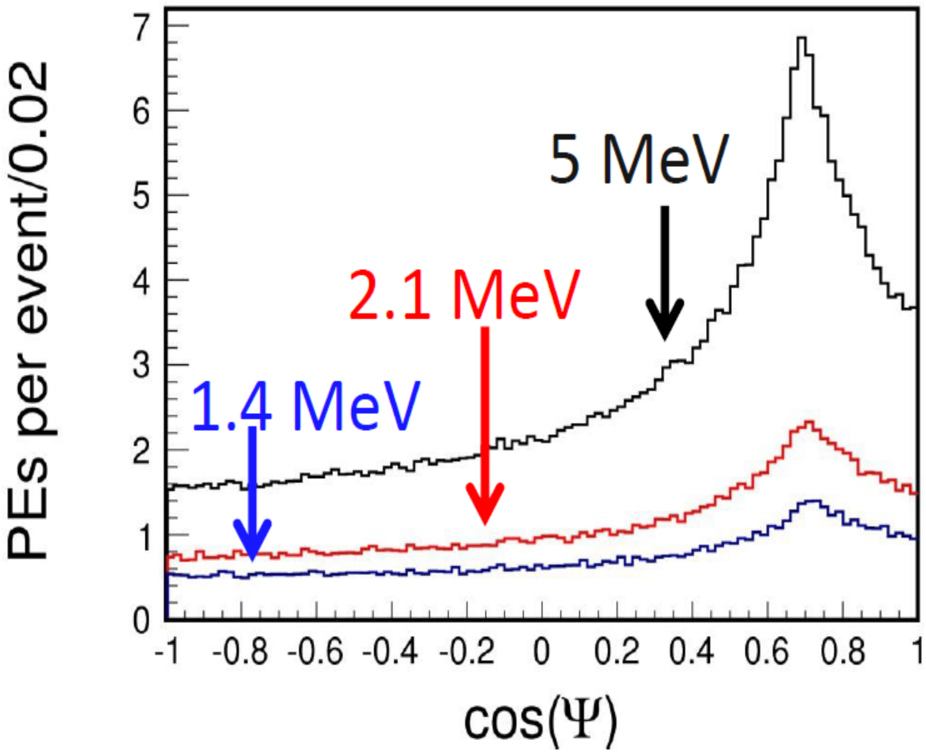
My e-mail exchange with Jenni Kotila:

"...The angular correlation is basically the a^(1)/a^(0), where a^(i) are defined in Eq. (24) for 2nbb and in Eq. (51) for 0nbb. In case of 0nbb only thing that matters are the electron wavefunctions but in case of 2nbb there are these additional factors that are a combination of ‹K_N› and ‹L_N›, that are defined in Eq. (23) and include the electron energies, the neutrino energies and the closure energy. So even with small neutrino energies, for example e_1=0.749Q, e_2=0.249Q, w_1=0.002Q, w_2=0 a factor of 0.4329 is obtained. Regarding the question about the situation for different isotopes, the closure energy entering the equations is different for each isotope and can be approximated by 1.12A^(1/2) MeV..."

Directionality of Early Photons



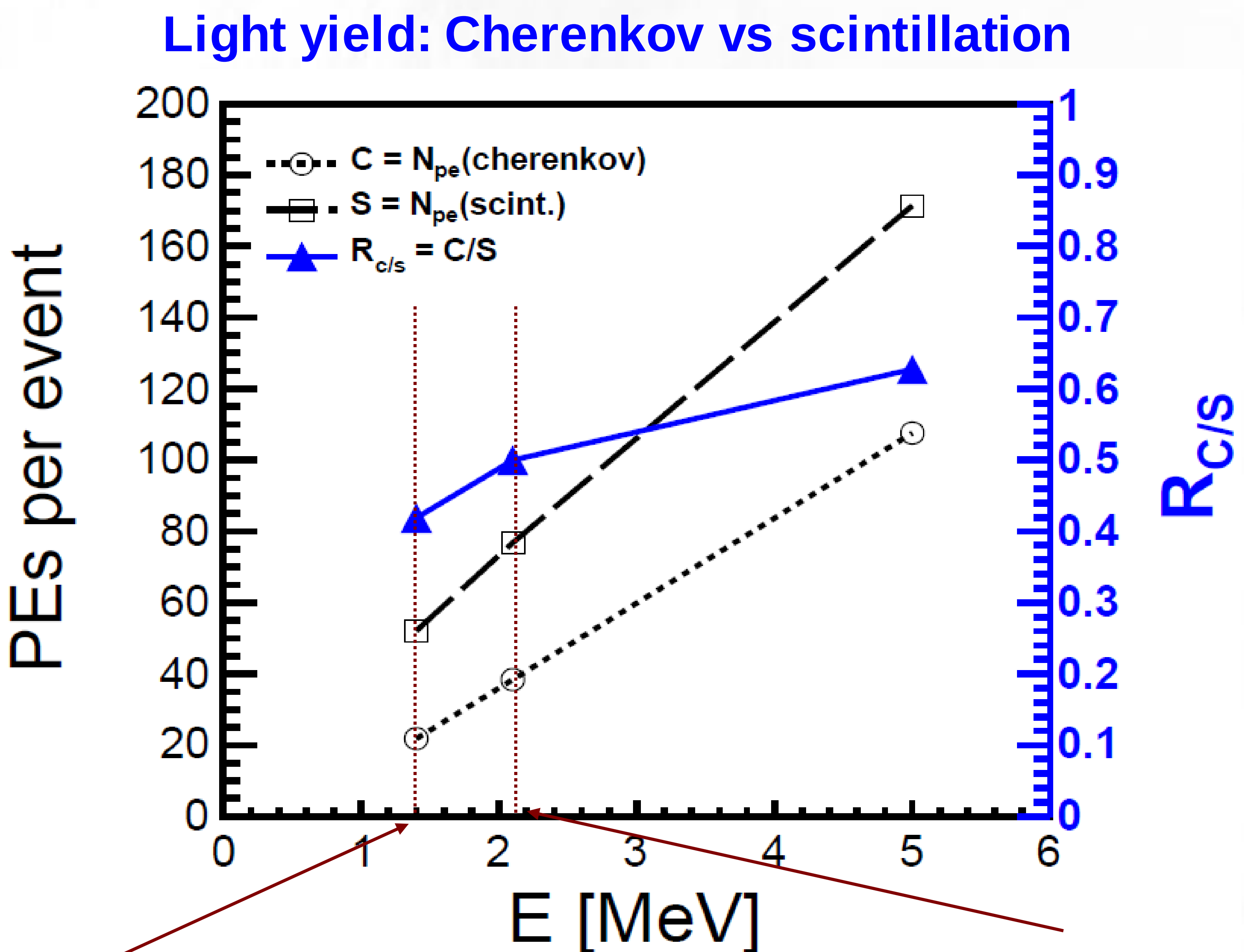
Cherenkov photons from center of 6.5m-radius sphere: TTS=100 psec



Cosine of angle between the photoelectron hit and the original electron direction after the 34 ns cut. Both Cherenkov and scintillation light are included. Note the peak at the Cherenkov angle.

C.Aberle, A.Elagin, H.Frisch,
M.Wetstein, L.Winslow
2014 JINST 9 P06012

What About Lower Energies?

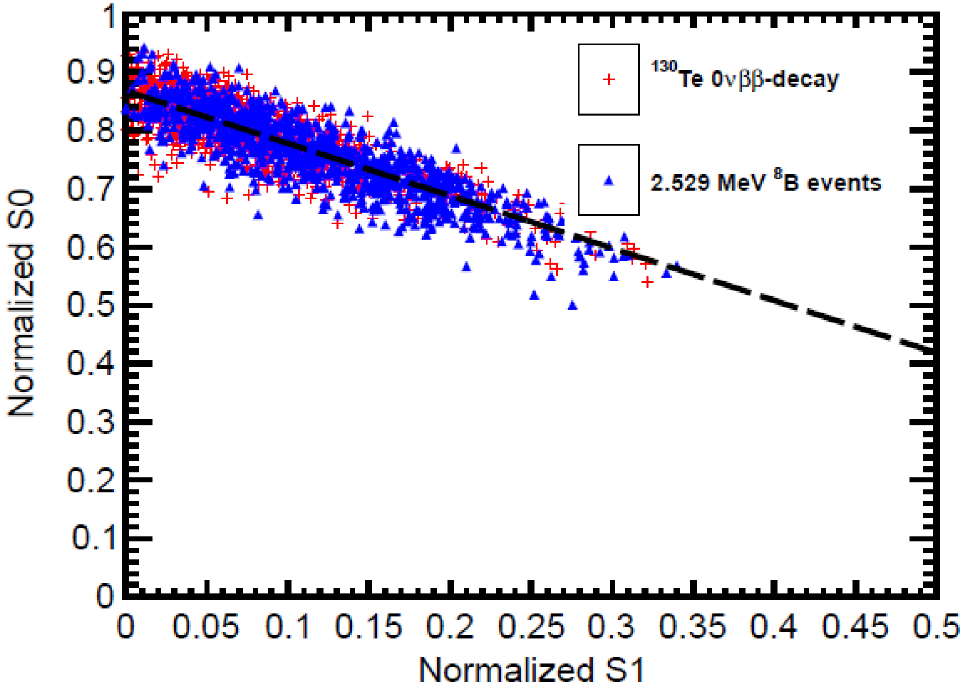


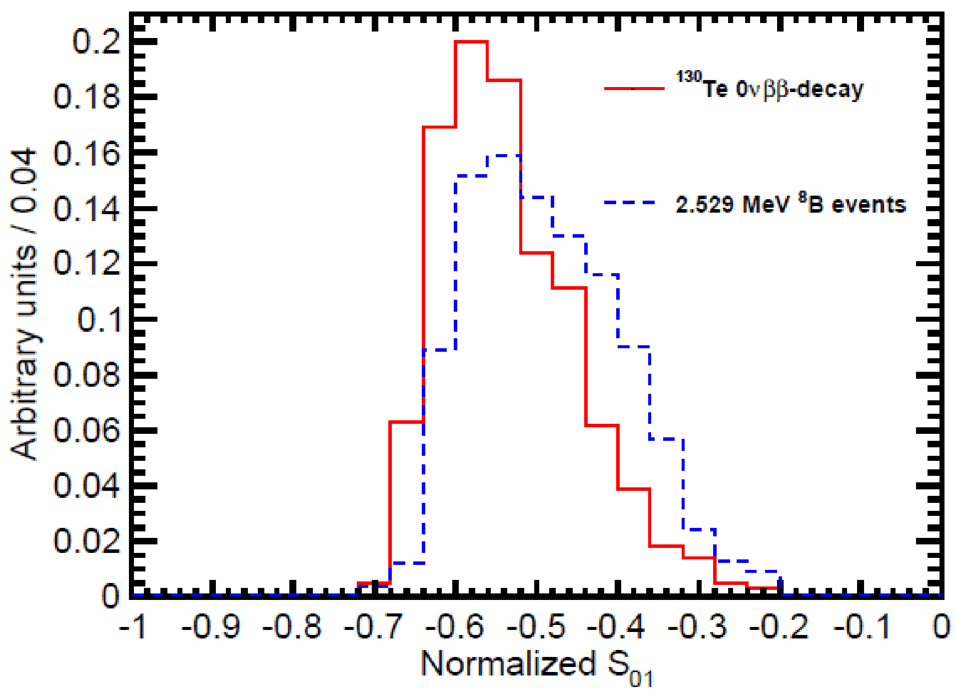
½ Q (^{116}Cd) =1.4 MeV

½ Q (^{48}Ca) =2.1 MeV

$0\nu\beta\beta$ vs ^8B

Vertex res **5cm**, events within **R<3m**
Sci rise time **1 ns**

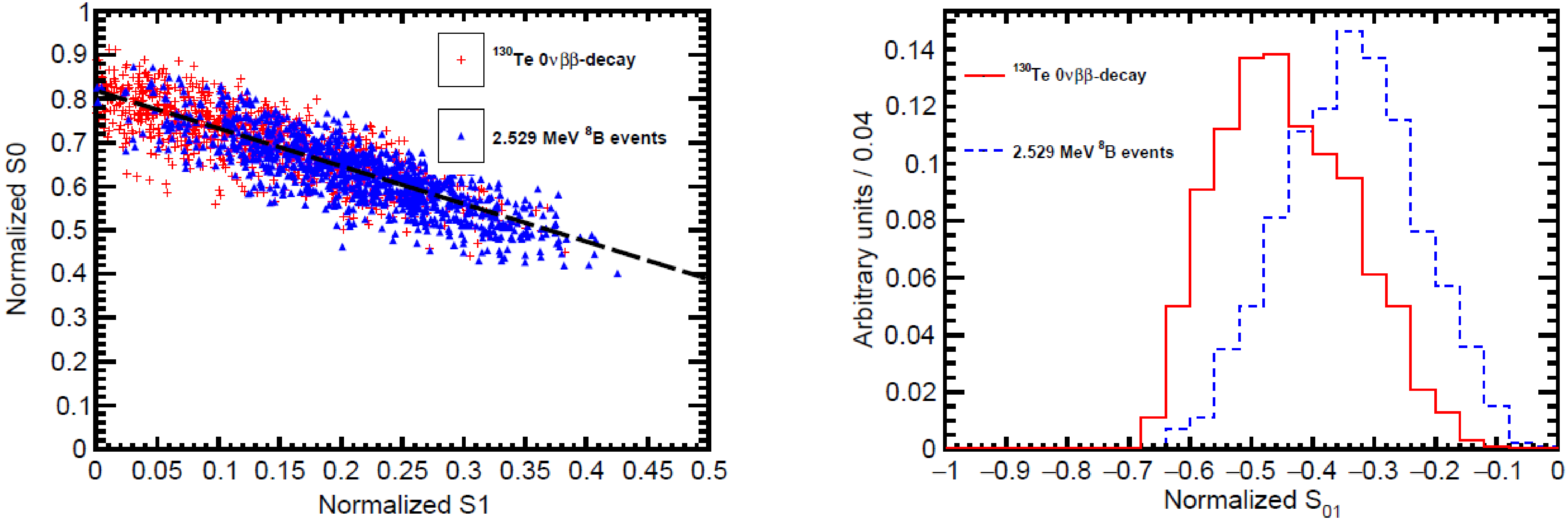




$I_{overlap} = 0.79$

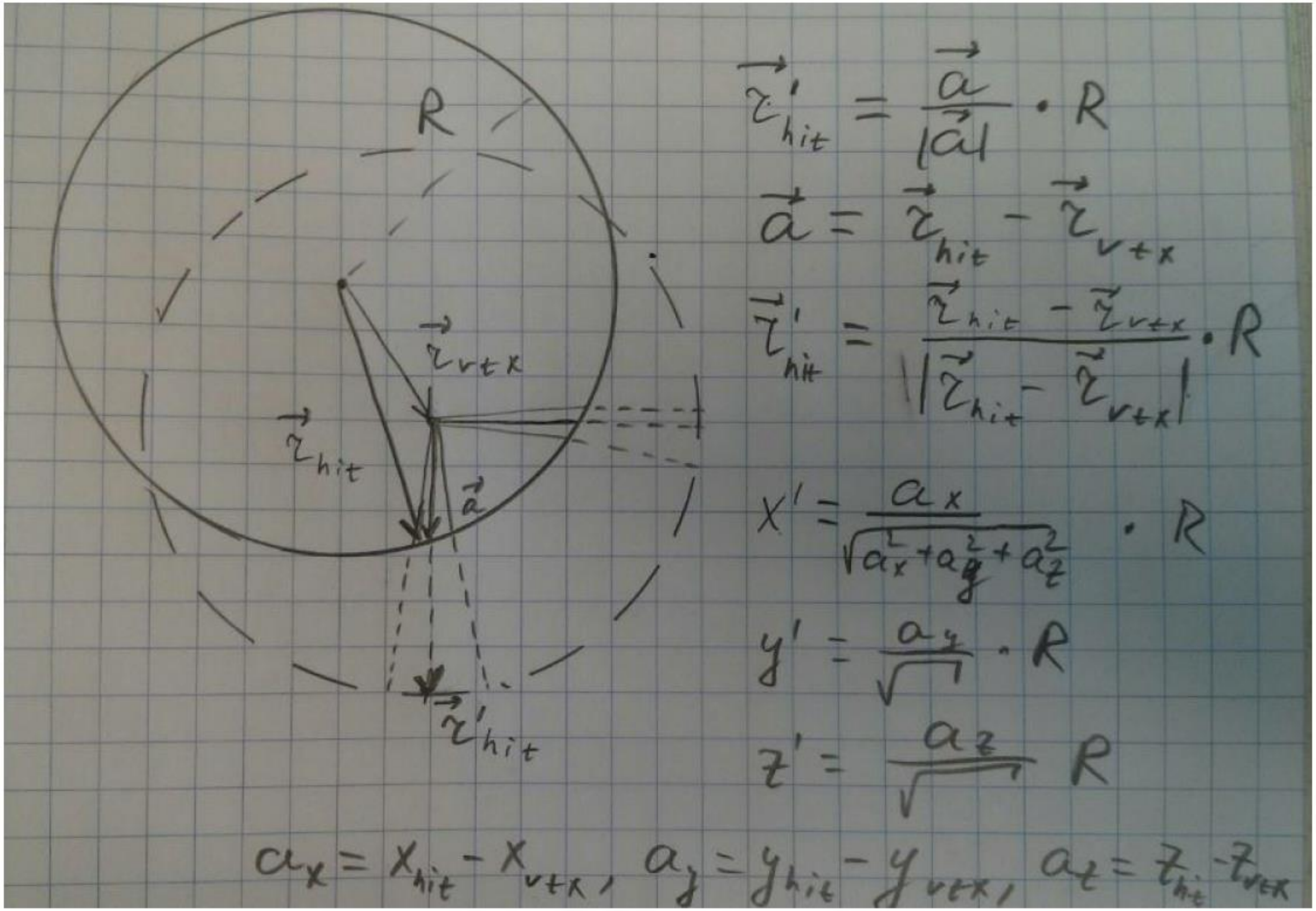
$0\nu\beta\beta$ vs ^{8}B

Vertex res **5cm**, events within **R<3m**
Sci rise time **5 ns**



$I_{overlap}$ = 0.64

Off-Center Events



0νββ-decay vs ^{10}C

two-track vs a "complicated" topology

^{10}C decay chain:

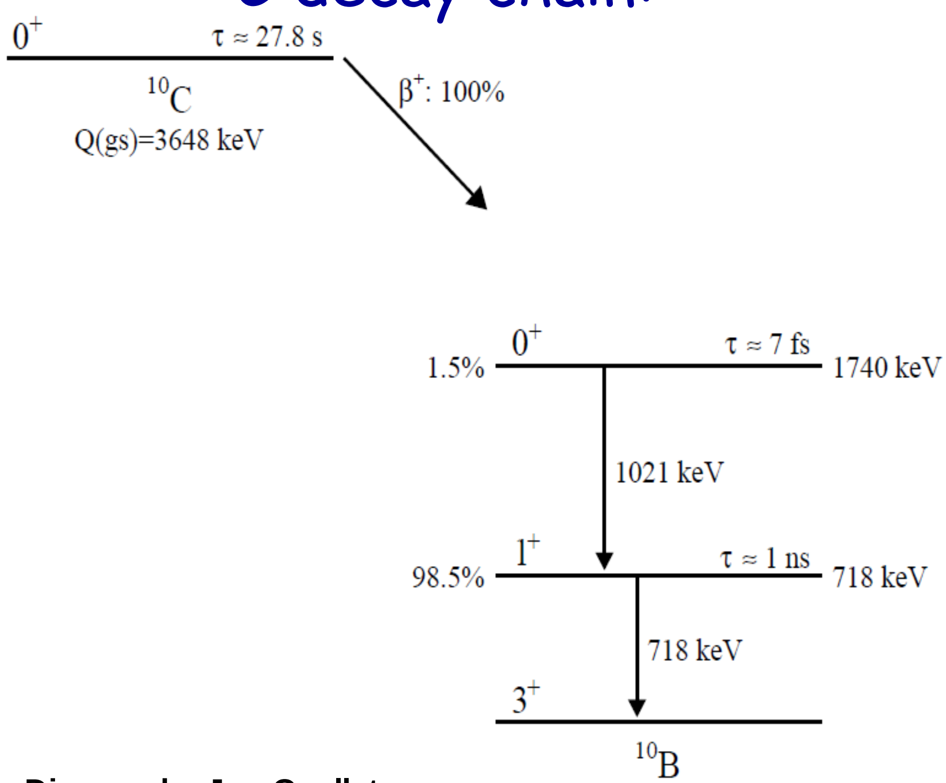
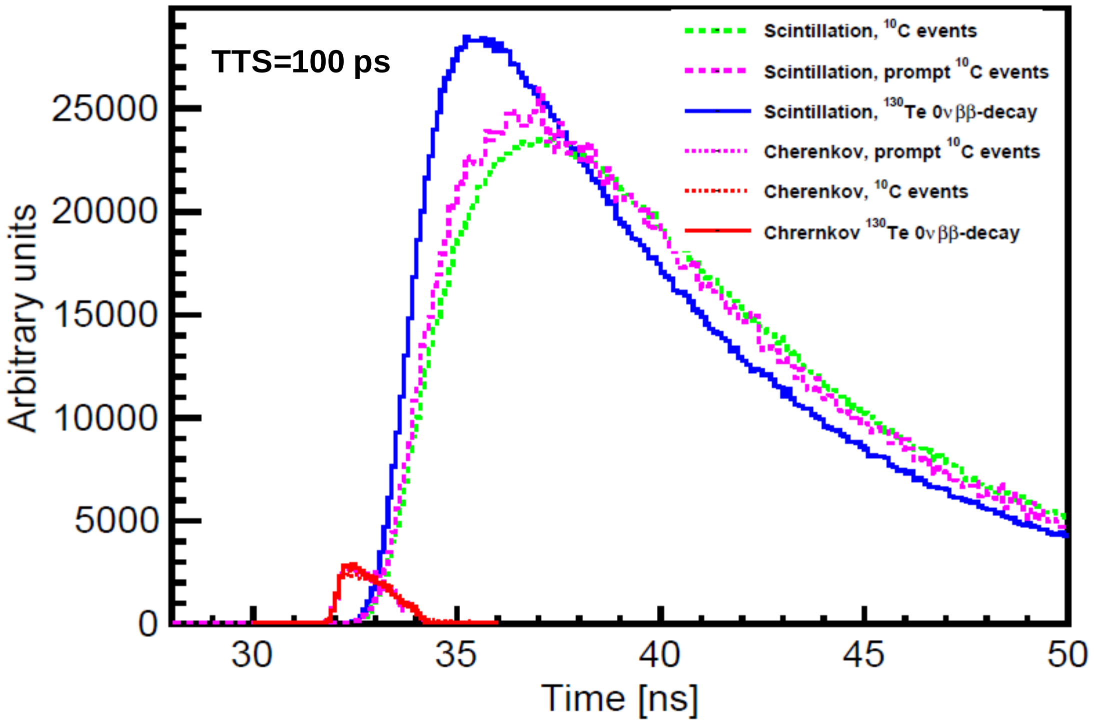


Diagram by Jon Ouellet

^{10}C vs 0νββ-decay: photons arrival time profile

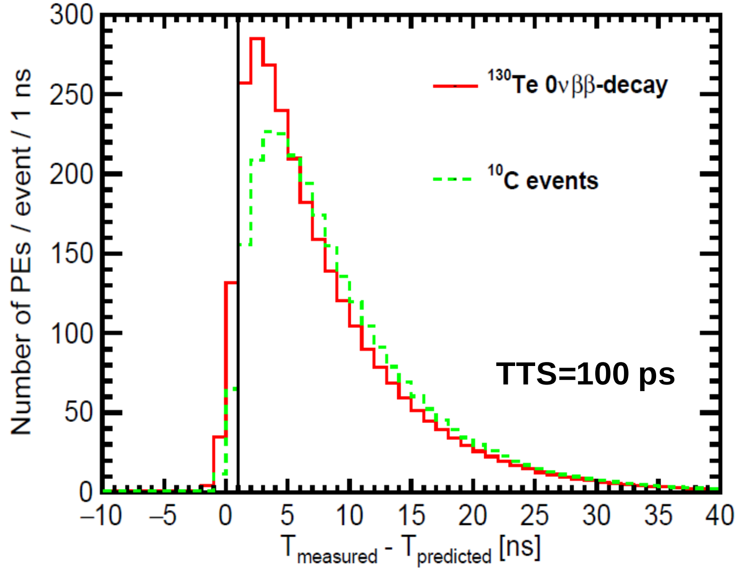


- ^{10}C final state consist of a positron and gamma (e+ also gives 2x0.511MeV gammas after loosing energy to scintillation)
- Positron has lower kinetic energy than 0νββ electrons
- Positron scintillates over shorter distance from primary vertex
- Gammas can travel far from the primary vertex

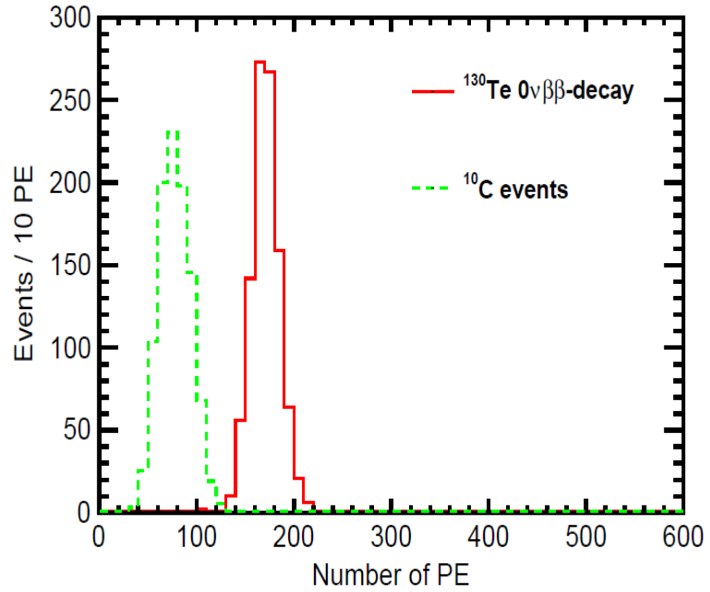
^{10}C background can be large at a shallow detector depth

0νββ-decay vs ^{10}C

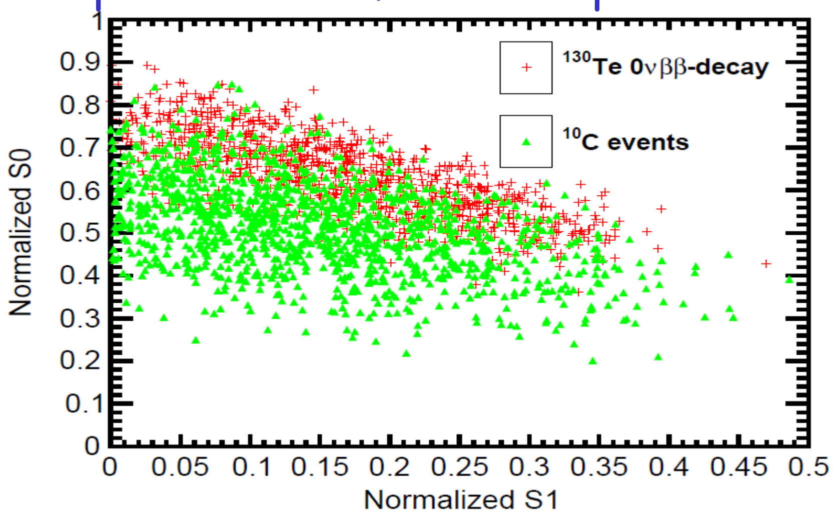
Time profile for events uniformly distributed within the fiducial volume, R<3m
Vertex resolution of 3cm is assumed



Photons count in early light sample



Spherical harmonics help here too



Disclaimer: there are other handles on ^{10}C that are already in use (e.g., muon tag, secondary vertices). Actual improvement in separation power may vary.