Updates on atmospheric neutrino analysis

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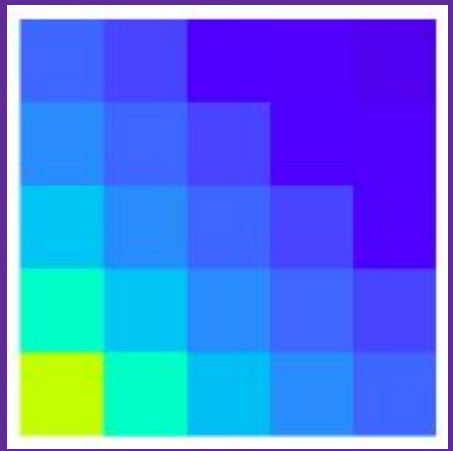
JUNO Europe-America Meeting, October 2022

Outline

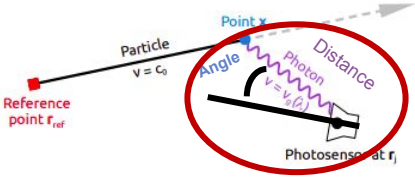
- Topological reconstruction
- OEC performance for HE events
- Towards next steps

Topological reconstruction for HE events

- Method aimed to reconstruct GeV particle tracks in LS.
- Main goal: reconstruction of atmospheric neutrinos

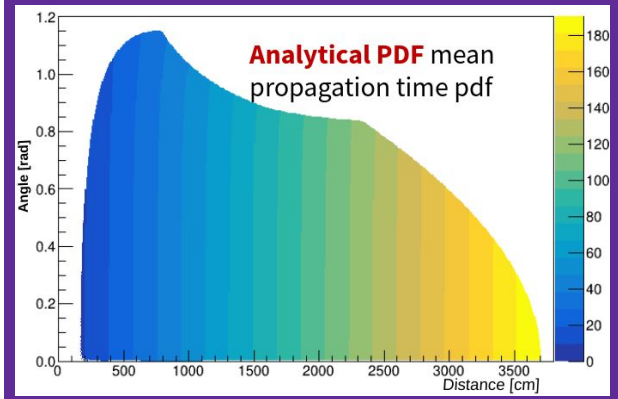


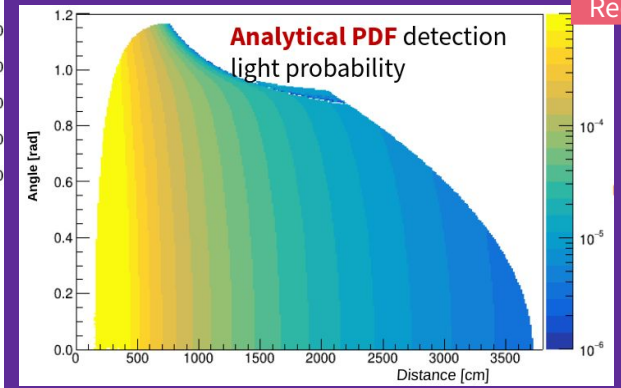
Topological reco in a nutshell



- **PDF:** topological method estimates two probability maps for each PMT:
  - Mean propagation time
  - Detection light probability
- **Reconstruction** of the light emission probability map in the detector through an iterative process
- **Reference point:** MC truth vertex (initial) smeared with 25 cm uncertainty + PMT time resolution

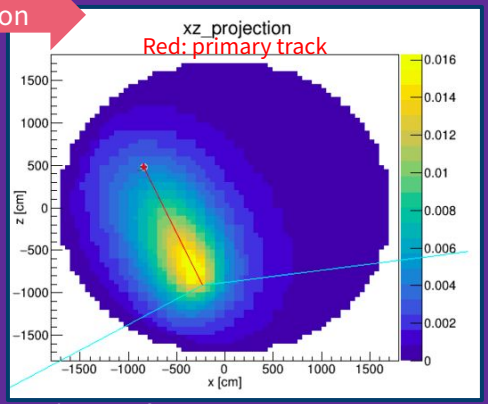
PDF





Reconstruction

After several iterations



Analytical PDFs use only direct light, where reflection has been removed (docDB-8302)
Calculation based on the scintillation average wavelength (436 nm)

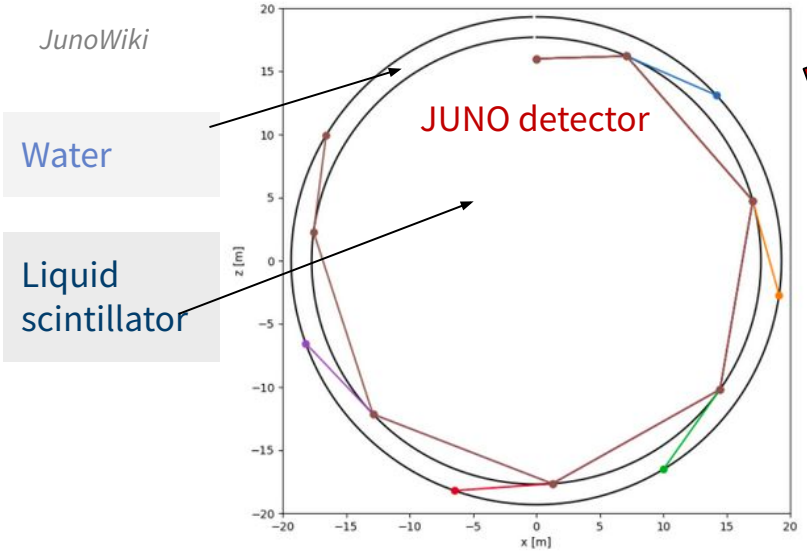
Data inputs: full hittime and charge < 200 ns [detsim level], atmospheric neutrinos with 3GeV

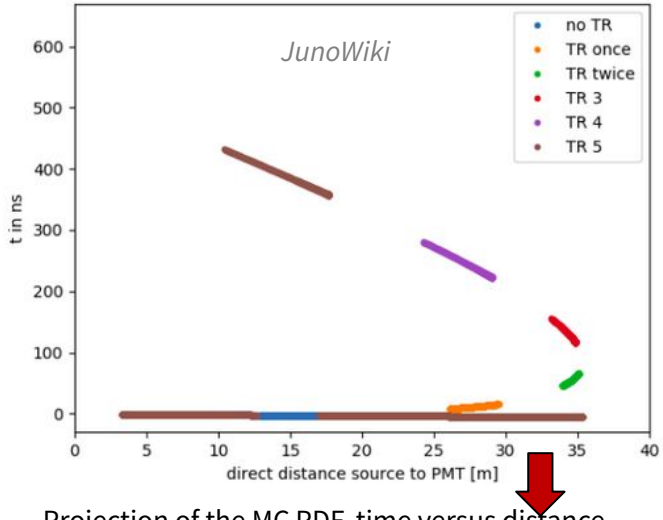
Topological reco in a nutshell

Steps for building the different PDFs and comparison:

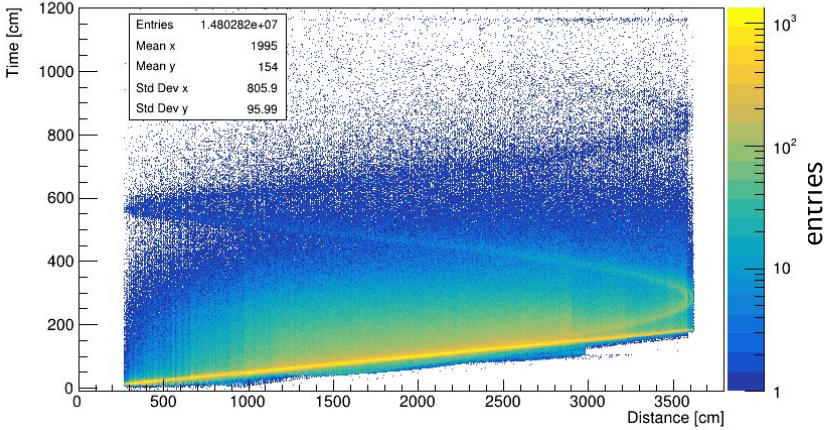
1. Software makes use of ONLY direct light info PDFs: analytical PDF removing reflection
2. Move to MC PDFs
3. Move from full hit time scintillation profile to first hit time

Total reflection effects



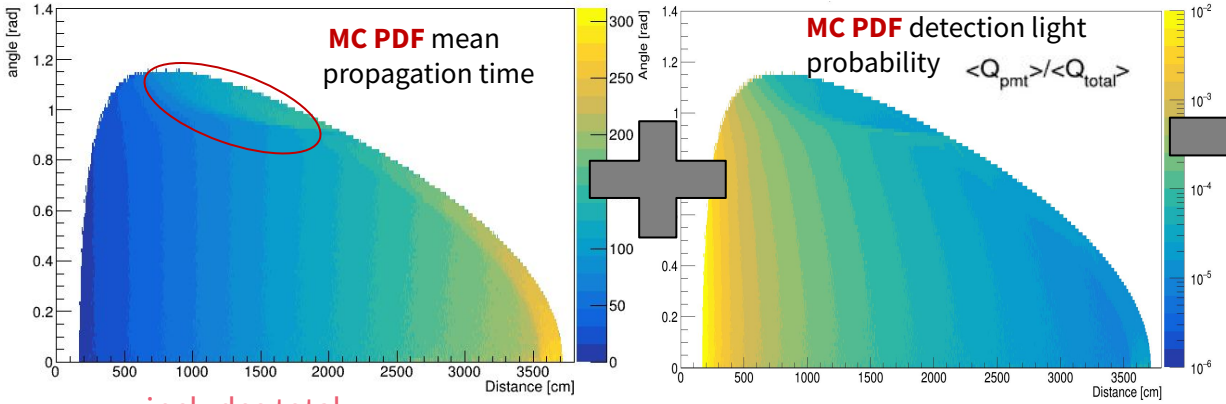


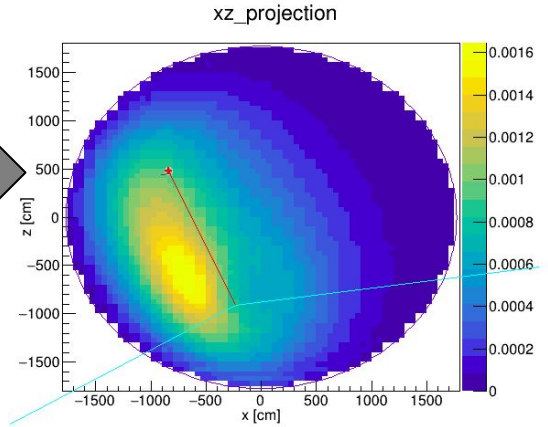
Projection of the MC PDF, time versus distance



- Mean propagation time of direct light is deviated by the reflection area

MC PDF performance with fiducial volume R< 17.2 m





includes total
reflection spots

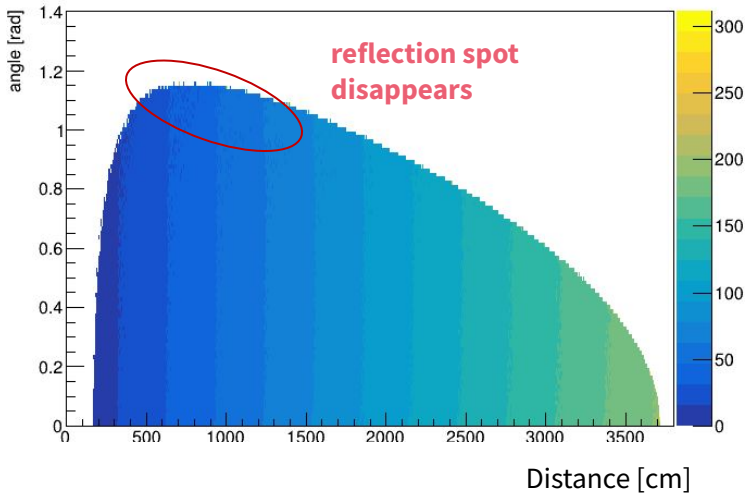
Atmospheric neutrino CC (3 GeV).
Reconstruction

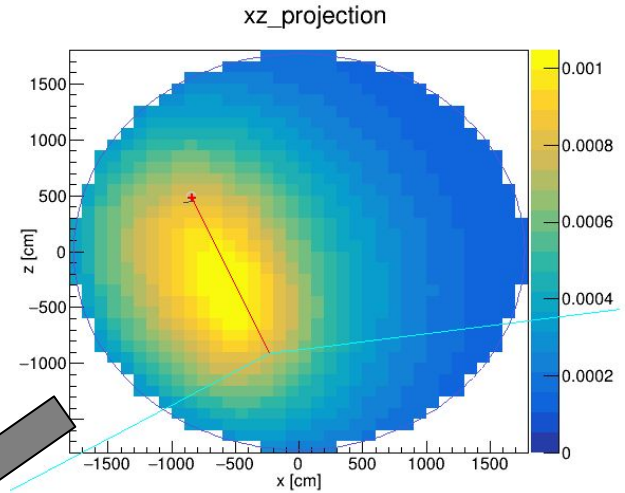
- **Generate 1 MeV electron uniformly generated inside the LS**
- **Full hit time scintillation profile and charge detected by all pmts [provided at detsim level]**
- **Total reflection area is not removed**

Data inputs: full hittime scintillation profile and charge < 200 ns [detected by all pmt]
Red line: primary track , red cross: reference point, blue line: neutrinos

Moving to first hittime (FHT) PDFs

- Using FHT will by its own reduce reflection effects
- MC pdf: use electron events generated inside the LS with energy = 1, 20, 50 and 100 MeV.
- Mean propagation time: selecting the lowest time detected by each pmt





Data: Full hittime and charge < 200 ns,
2 iterations (using time pdf + charge pdfs)

Shift between truth and reco is corrected with first hittime PDF due to lower impact of reflection

Using the first hittime (FHT) data

Motivation:

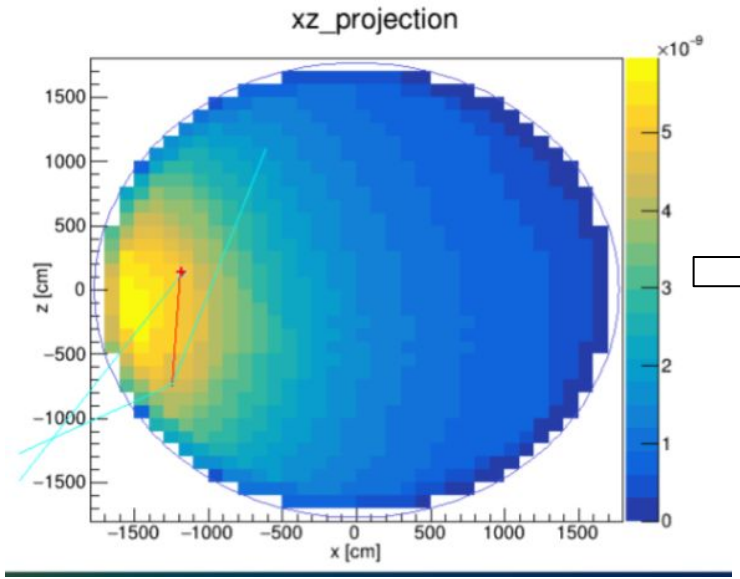
- ➢ Atmospheric neutrinos produce millions of hits per event -> will not be fully stored
- ➢ Reduce event reconstruction time (not all hits will be evaluated by the pmts)

Data: First hittime and total charge detected by each pmt < 200 ns, [MC level]
2 iterations (using charge + time pdfs)

Performance of first hit PDFs on first hittime data

Reconstruction performance

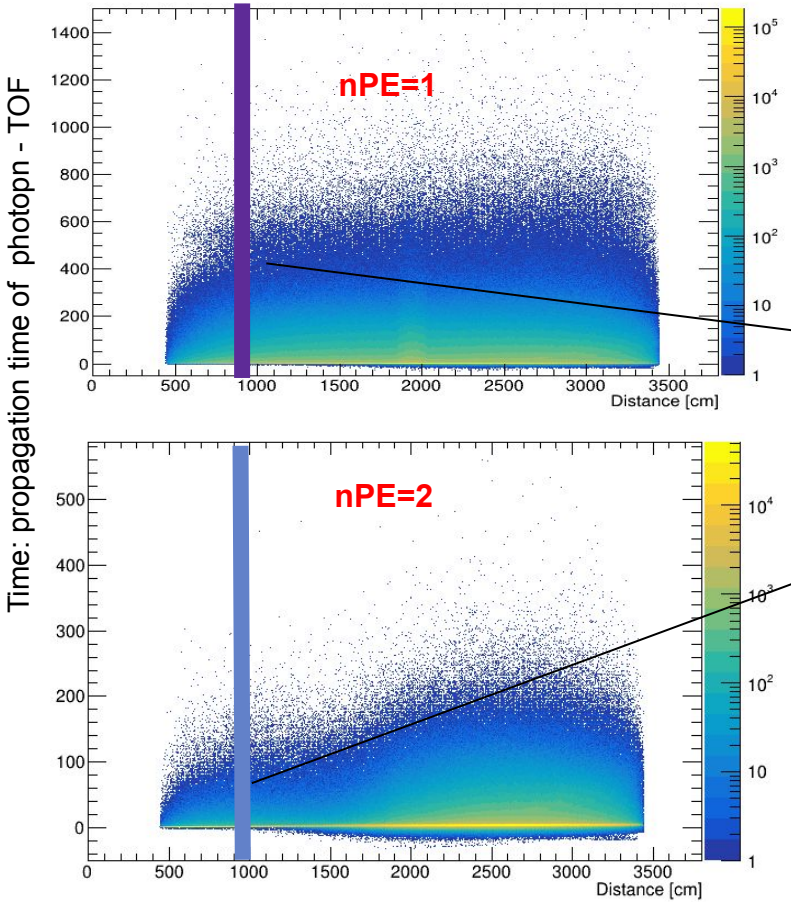
Atmospheric neutrino CC (3 GeV).
Reconstruction



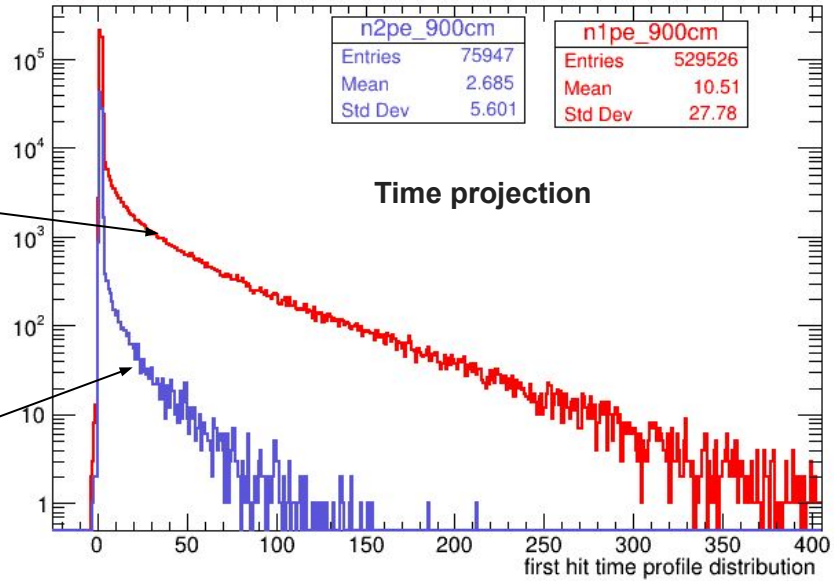
For the 1st hit time input: Total npe in a readout window < 200ns will be associated to the lowest time detected by each pmt = first hit time
2 iterations (using charge + time pdfs)

- Charge dependent correction of the first hit time is required
- Correction depends on the number of PE detected + distance between [source-pmt]

Distance - time pdfs for nPE =1,2 reaching out the PMT



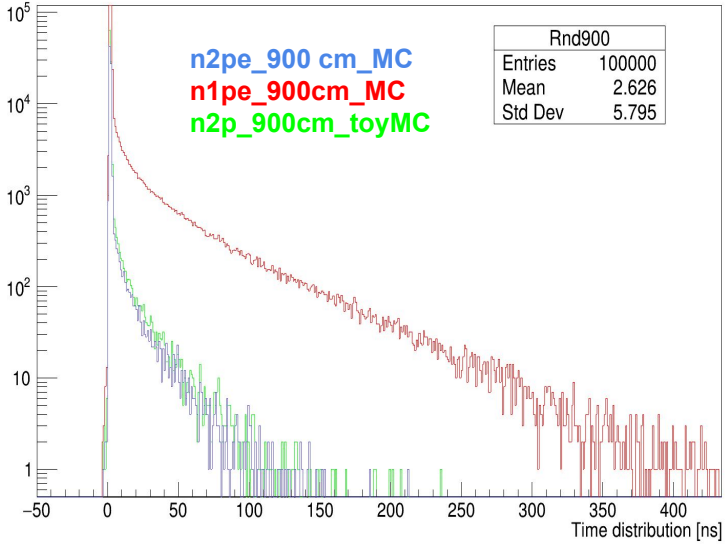
Projection of the first hit time profile distribution at same distance for different npe



The time profile distribution getting sharper when nPE increase.

Apply a toy MC to build PDFs for nPE > 1

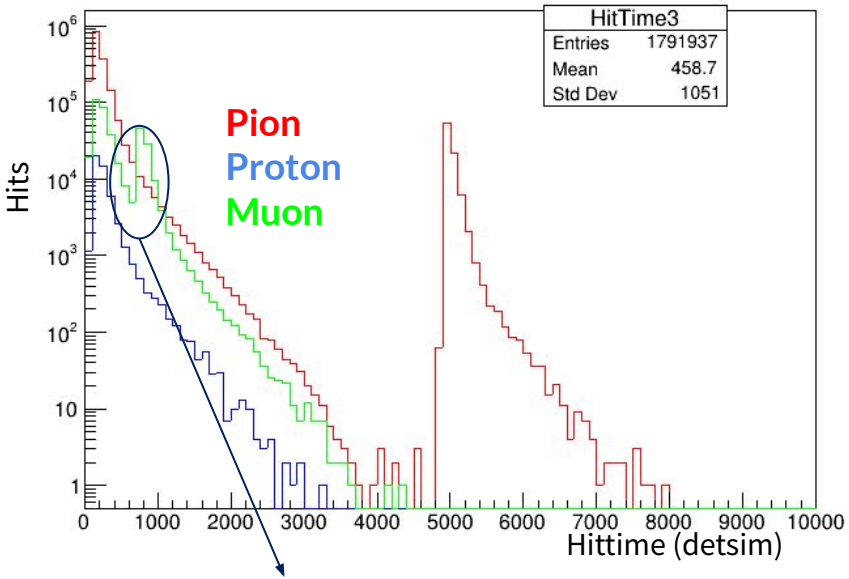
- 1 MeV electrons lack of statistics for high npe and larger distances
- Going to 100 MeV electrons does not help → more uncertainty in the detected charge
- Do a toy MC to increase statistics and reproduce the tail
  (From the time profile distribution of npe =1 -> Generate a random distribution for npe =2)



WORK IN PROGRESS
trying to find the best way to normalize the pdf

NOTE on the event selection and reco performance

muon neutrino (CC, DIS, E > 2GeV)



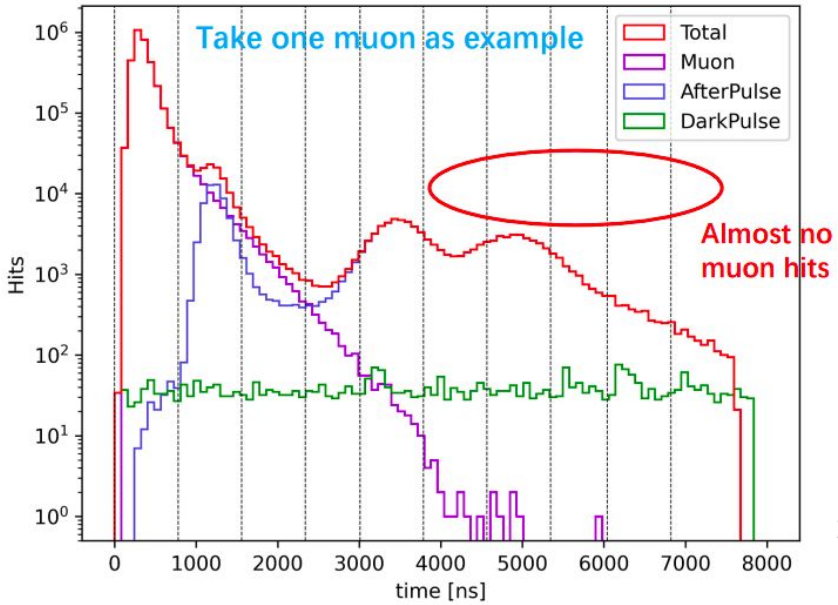
Muon -> Michel electron
Pion-> muon, positron, gamma, muon anti/neutrino
Proton -> gamma

- Different signatures expected for different atmospheric neutrino interaction channels
  - This will impact the performance at different levels (selection, reconstruction)
  - PID work is needed (see talk by Rosmarie)
- The atmospheric neutrino pdf will help to define what information we would like to save in OEC

OEC performance for high-energy events

HE events: a reminder note to start

HE events (muons or atmospheric neutrinos) will trigger O(10) readouts, including correlated particles (michel e- / spallation n) and afterpulses after large charge deposited (most of them) -> We need to filter out the data



XinHuang, JUNO-doc-8851-v2

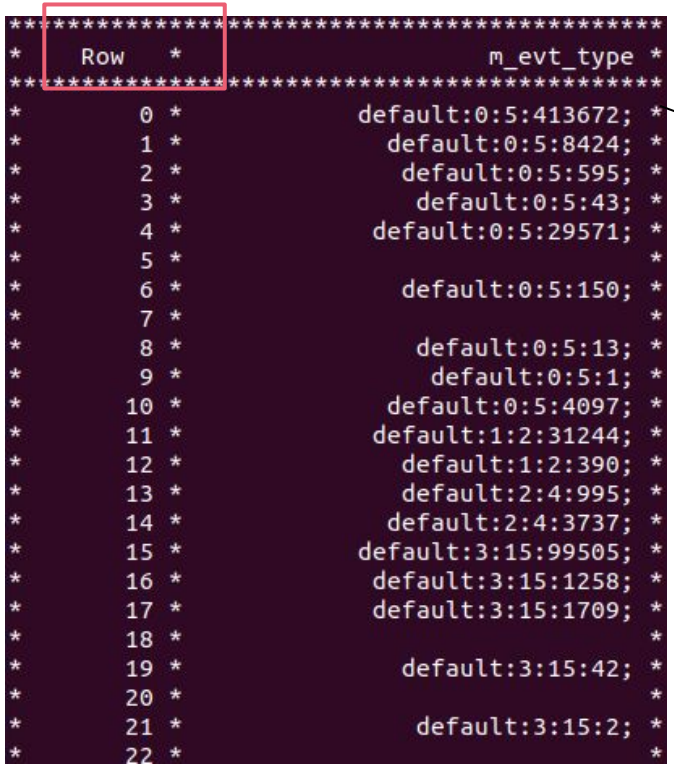
OEC classification for HE events in a nutshell

- OEC main focus is give fast answer to the question: should we keep the waveform?
- Goal: classify atmospheric neutrinos (fully contained event vs partially contained), distinguish them from cosmic muons, and remove non-wanted secondary triggers
- Muon will always cross the detector -> rely on water pool information to do the selection

OEC event processing

- OEC puts together CD and WP triggers, mixed -> not taken into account before
- OEC ID from SimHeader in output file needs to be used to keep track of the true ID
- If eventindex is used when looping over OEC events -> miss-alignment appears
    - This is what was happening for previous results (docDB-8940), not correct

OEC event processing: WP / CD association



Row	m_evt_type
0	default:0:5:413672;
1	default:0:5:8424;
2	default:0:5:595;
3	default:0:5:43;
4	default:0:5:29571;
5	
6	default:0:5:150;
7	
8	default:0:5:13;
9	default:0:5:1;
10	default:0:5:4097;
11	default:1:2:31244;
12	default:1:2:390;
13	default:2:4:995;
14	default:2:4:3737;
15	default:3:15:99505;
16	default:3:15:1258;
17	default:3:15:1709;
18	
19	default:3:15:42;
20	
21	default:3:15:2;
22	

OEC ID#

OEC tag → **Unphysical events are tagged as CDMuon and WPMuon,**

CDMuon

WPMuon
CDMuon
WPMuon

CDMuon

WPMuon
CDMuon

default:0:5:413672

- default: signal type
- 0: event ID in detsim
- 5: track ID (primary+ secondaries)
- 413672: nhits saved in Event keeper

Using this information is the only way to associate oec with MC truth information

OEC classification for HE events in a nutshell

- Current criteria: E>20 MeV by OEC
- OEC energy: rough reco using the center of charge (QctrRecAlg) to infer energy and vertex (approx linear Q fit corrected by non-uniformities)
- OEC tags: in json input 32bits value (0x20101000) → i_tags in ouput: int (537923584)

Updates in rc4:

- We temporary do not tag (i.e. save waveform) of events within 7μs from a HE tag: avoid the impact of afterpulses -> Impact of this “veto” should be carefully evaluated
- Correlated tags (i.e. michel electrons and spallation neutrons), see issue #9:
  - For now, only searched when muon vetoed (by TT or WP), not for CD events
  - Now include a space coincidence (200 cm), not only time coincidence

OEC performance for HE event tagging

Results for 1000 atmospheric neutrino events processed: (all readouts, 20 MeV cut)

- Total number of OEC HE tags: 1335
- Number of readout events wrongly tagged as muons in OEC:
  100% afterpulse (no true hits): 0 / physics dominated: 439 (~33% contamination)

- Number of atmo neutrinos that are not tagged by OEC >20MeV: 102 → ~10% loss
- Number of atmo neutrinos correctly tagged by OEC >20MeV: 896 → ~90% eff
- Atmo neutrinos not even triggered in elecsim: 2

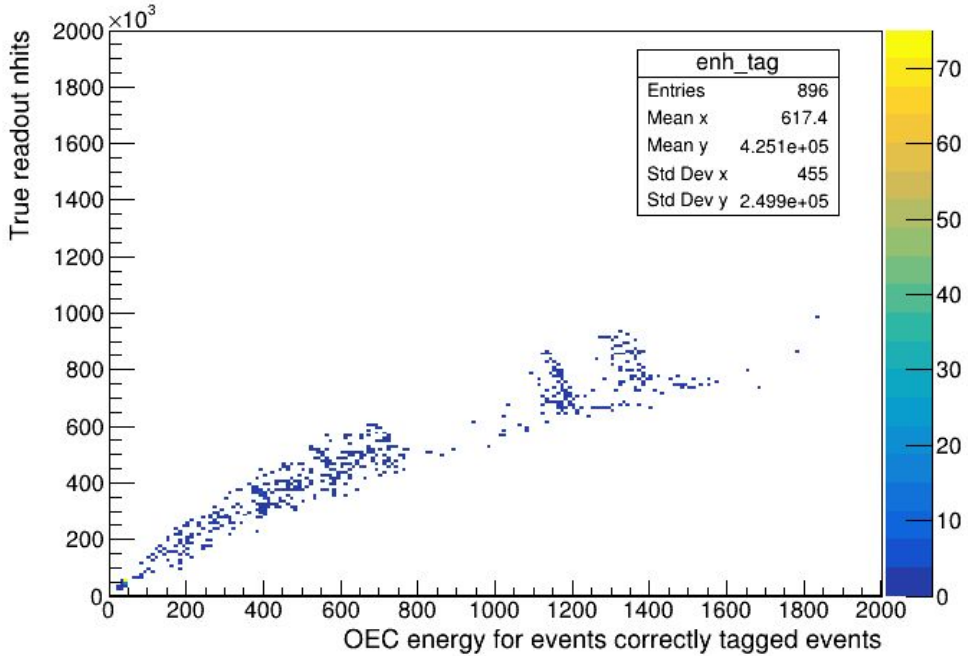
Good: 90% efficiency against 10% loss // Bad: ~33% contamination (wrongly selected)

NOTE: 100% afterpulse events are tagged as WP -> OEC WP tag helps removing them

OEC performance for HE event tagging

How well the Ereco algorithm in OEC is doing?

➔ Linearity is not really kept, but does the good job for classification



OEC performance for HE event tagging

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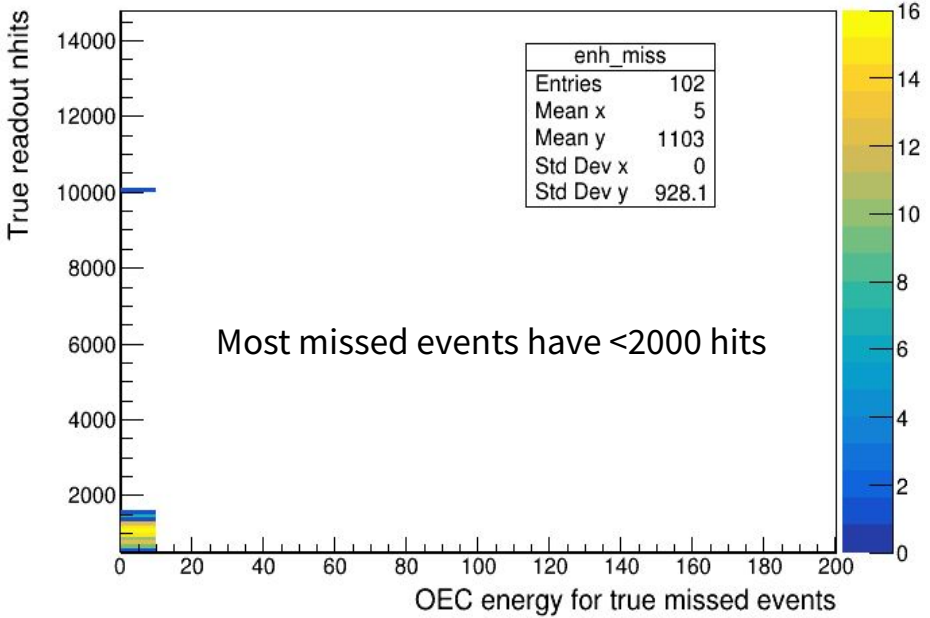
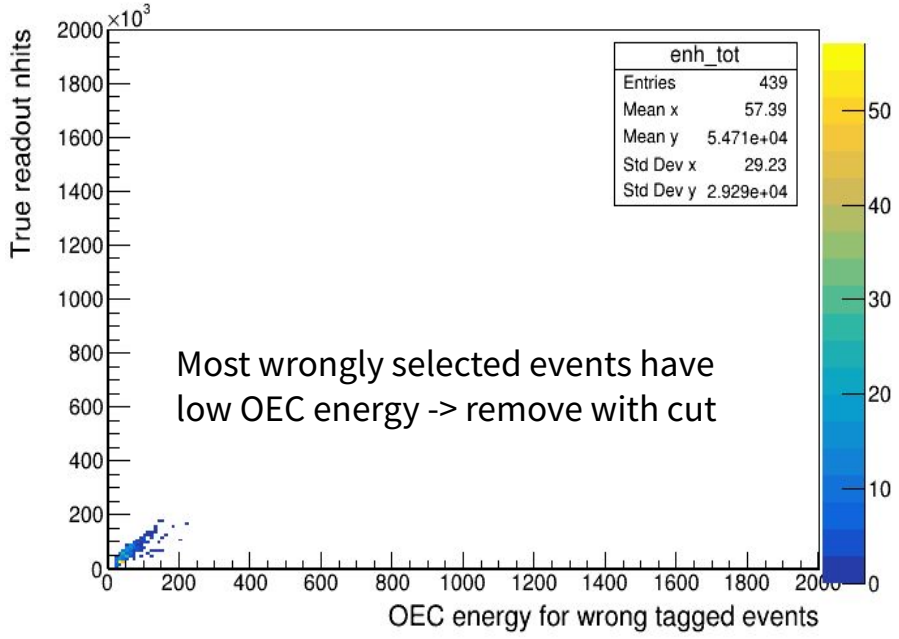




OEC performance for HE event tagging

Results for 1000 atmospheric neutrino events processed: (all readouts, 200 MeV cut)

- Total number of OEC HE tags: ~750
- Number of readout events wrongly tagged as muons in OEC:
  100% afterpulse (no true hits): 0 / physics dominated: 2 (<1% contamination)

- Number of atmo neutrinos that are not tagged by OEC >20MeV: 254 → ~25% loss
- Number of atmo neutrinos correctly tagged by OEC >20MeV: 744 → ~75% eff
- Atmo neutrinos not even triggered in elecsim: 2

Increasing energy cut:

- Reduces efficiency from 90% to 75%, but do we remove only low E events?
- Reduces contamination to <1% level from >30%
- Loss increases from 10% to 25%, but loss before were mostly events with <200 hits

-> Find an optimal compromise

Why not every HE event was triggered?

```
root [4] pgst->Show(9)
======> EVENT:9
 iev             = 9
 neu             = 12
 tgt             = 1000060120
 qel             = 1
 res             = 0
 dis             = 0
 coh             = 0
 dfr             = 0
 imd             = 0
 nuel            = 0
 cc              = 0
 nc              = 1
 Ev              = 1.76579
 pxv             = -0.613036
 pyv             = -0.253417
 pzv             = -1.63646
 fspl            = 12
 El              = 1.44217
 pxl             = -0.311319
 pyl             = -0.74258
 pzl             = -1.19646
 pl              = 1.44217
 cthl            = 0.917697
 nf              = 1
 pdgf            = 2112
 Ef              = 1.21837
```

Neutrino and primary lepton have E>1GeV (generator level)

But is NC, so primary lepton is invisible… and hadron energy might go outside CD, but detsim does not keep WP info…

Low edep and npe at detsim level

```
root [3] evt->Show(9)
======> EVENT:9
 evtID           = 9
 edep            = 0.382999
 edepX           = -17322.2
 edepY           = -1000.7
 edepZ           = 1524.23
 nPhotons        = 120
 totalPE         = 134
 LpmtPE          = 129
 SpmtPE          = 5
 NNVTPE          = 99
 HamaPE          = 30
 CDPE            = 134
 WPPE            = 0
```

small fraction (1 per 1000) might not be triggered…

OEC performance: what about WP tagging?

Notes

- ➔ WP triggers will be useful to tag FC atmospheric neutrinos against muons
- ➔ Afterpulses will also trigger WP tags in large part
- ➔ The highest energy atmospheric neutrinos will end up triggering a WP tag

“Issues”

- ➔ Timing between different sub-detectors are not ordered to find correlations (issue #28)
- ➔ This is also causing overlapping between readouts (issue #18)
- ➔ It is not possible to know which same event triggered both sub-detectors (issue #29)

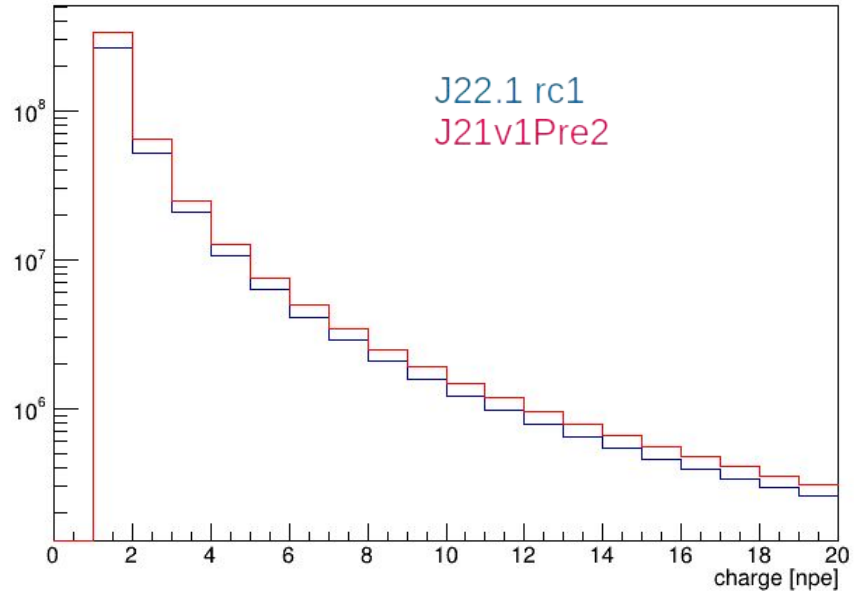
OEC: next steps

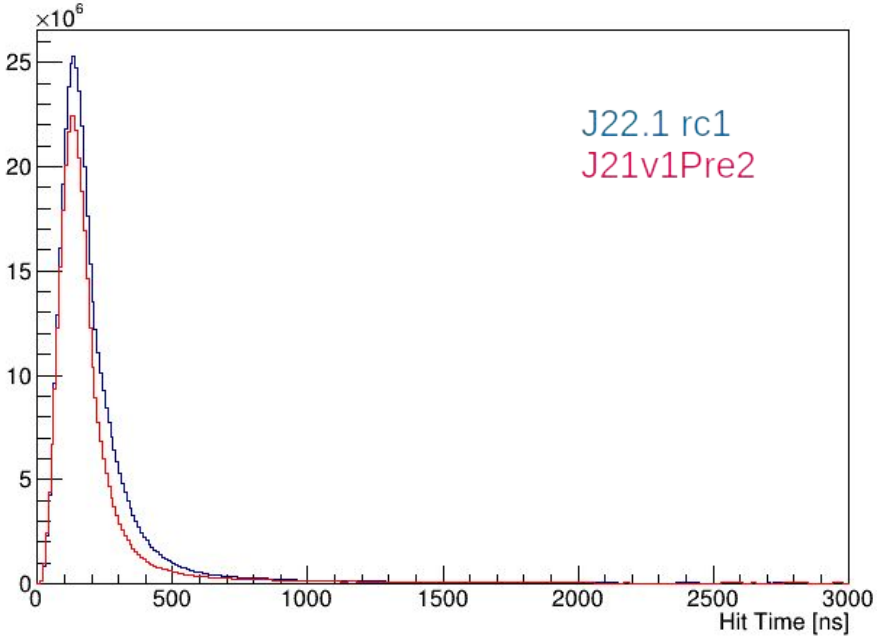
- Find a good condition for atmo neutrino VS muons tagging (PC/FC)→ Mariam and Marta
- Find a good condition for afterpulse tagging → Feifei and Marta
- Checks on correlated events tagging
- Check further E and vertex OEC QctrRecAlg performance for GeV events
- Checks on cascade and WP conditions

Towards next steps

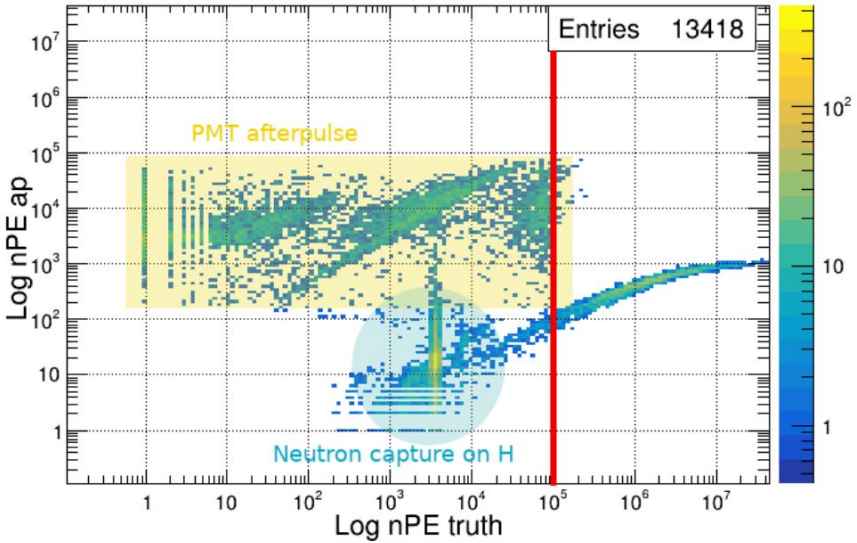
Significant differences between offline versions

Large differences at detsim level from J21 and J22:
→ more spread hit time distribution and less charge detected
→ THIS WILL WORSEN OUR RECO PERFORMANCE
→ We need to understand the reason





Event selection



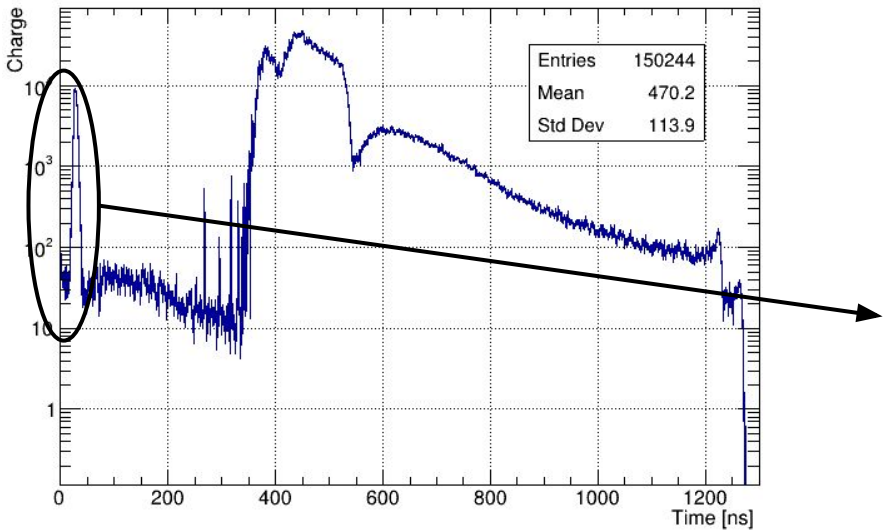
*** none of the ongoing analysis have a data based event selection, use MC truth

- We use MC info: we know which readouts belong to a same event, and which is th 1st
- We need to find a way to identify the fist event readout in real data
- We need to evaluate the efficiency of this cut: i.e. how many bg muons, secondary and AP readouts will remain

Moving to a realistic scenario: calib data J22

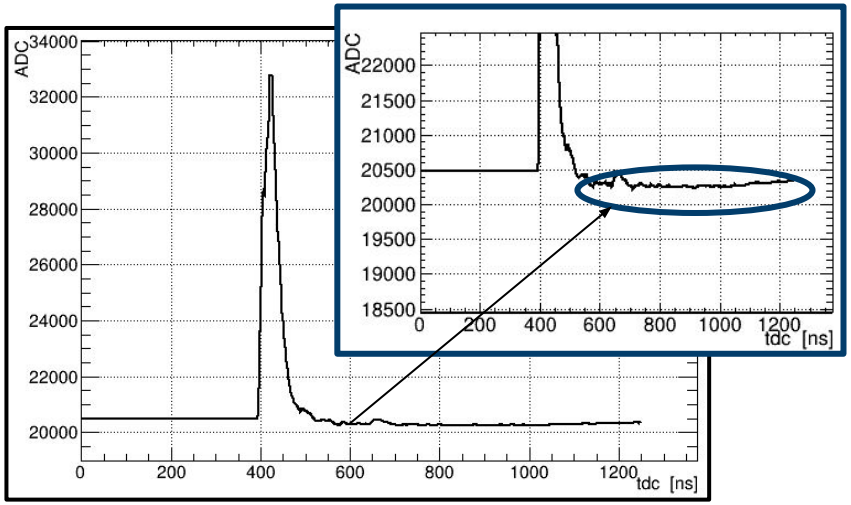
Example of an atmospheric muon neutrino CC: E=3.02 GeV

Calib - (Q,t) pair DocDB #8868 -> Ongoing work



Strange distribution, at calib level.
Unphysical peak at zero
Difficult to define the first hit time!

Waveform simulation performance, pmtID #9280



Failed to recover after the peak,signal below the baseline is the reason of the peak at ZERO

Backup

Online event classification: WP and CD association

- **For event generated in CD, simulated at elecsim, waterpool will trigger dark noise events or physical events partially deposited their energy inside WP :**

Event Keeper: CD

Row	Instance	eventid.e	nevents.n	tags	filenames	entries	nhits
0	0	0	1	default	/storage/	0	413672
1	0	1	1	default	/storage/	0	8424
2	0	2	1	default	/storage/	0	595
3	0	3	1	default	/storage/	0	43
4	0	4	1	default	/storage/	0	29571
5	0	5	1	default	/storage/	0	150
6	0	6	1	default	/storage/	0	13
7	0	7	1	default	/storage/	0	1
8	0	8	1	default	/storage/	0	4097
9	0	9	1	default	/storage/	1	31244
10	0	10	1	default	/storage/	1	390
11	0	11	1	default	/storage/	2	995
12	0	12	1	default	/storage/	2	3737
13	0	13	1	default	/storage/	3	99505
14	0	14	1	default	/storage/	3	1709
15	0	15	1	default	/storage/	3	42
16	0	16	1	default	/storage/	3	2
17	0	17	0				
18	0	18	1	default	/storage/	3	3343

Elecsim ID#

Detsim ID#
nhits exracted
from detsim

Event Keeper: WP

```
root [4] WPeventindex->Scan()
```

Row	Instance	eventid.e	nevents.n	tags	filenames	entries	nhits
0	0	0	0				
1	0	1	0				
2	0	2	1	default	/storage/	3	1258
3	0	3	0				
4	0	4	0				
5	0	5	0				
6	0	6	0				
7	0	7	0				
8	0	8	0				
9	0	9	0				
10	0	10	0				
11	0	11	0				
12	0	12	0				
13	0	13	0				
14	0	14	0				
15	0	15	0				
16	0	16	0				
17	0	17	0				
18	0	18	0				
19	0	19	0				
20	0	20	0				
21	0	21	0				
22	0	22	0				

```
(long long) 23
```

Elecsim ID#

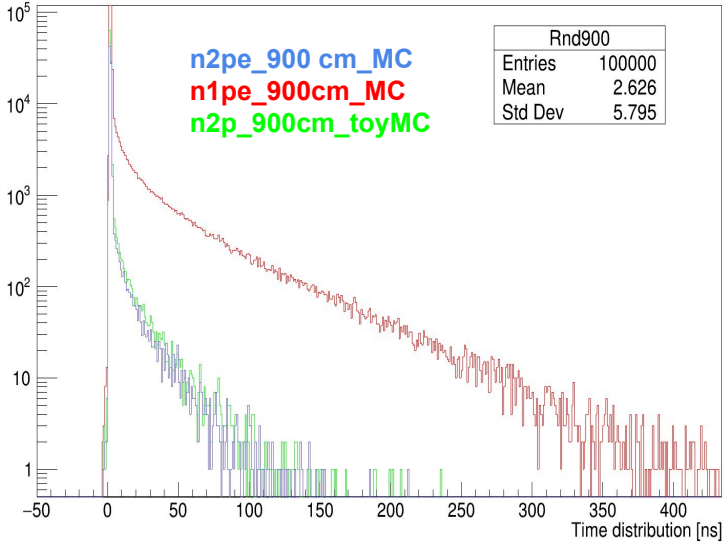
Detsim ID#

Dark
noise
events

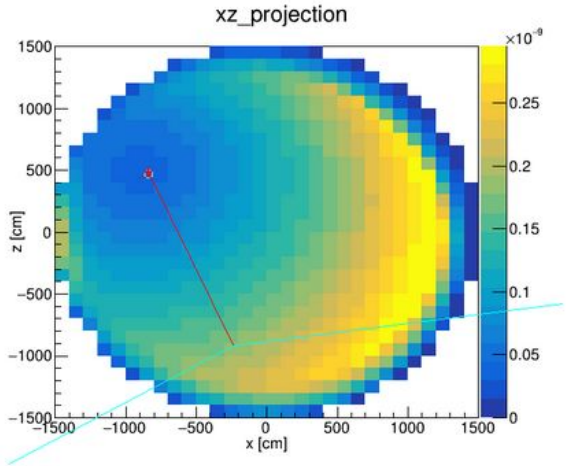
- **OEC will evaluate all events in WP and CD in random order depends on the trigger time -> alignement is very important but it's not trivial**

Apply a toy MC to build PDFs for nPE > 1

- 1 MeV electrons lack of statistics for high npe and larger distances
- Going to 100 MeV electrons does not help → more uncertainty in the detected charge
- Do a toy MC to increase statistics and reproduce the tail (From the time profile distribution of npe =1 -> Generate a random distribution for npe =2)



Reconstruction



Under investigation