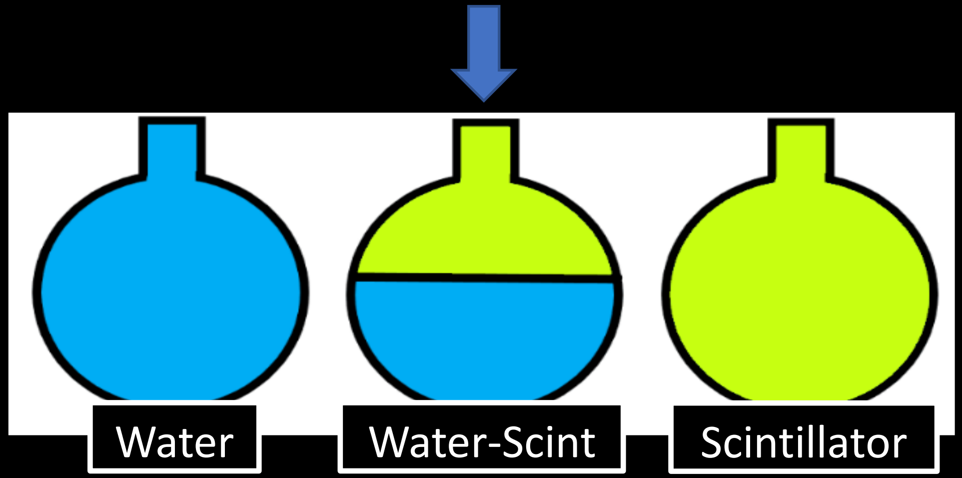
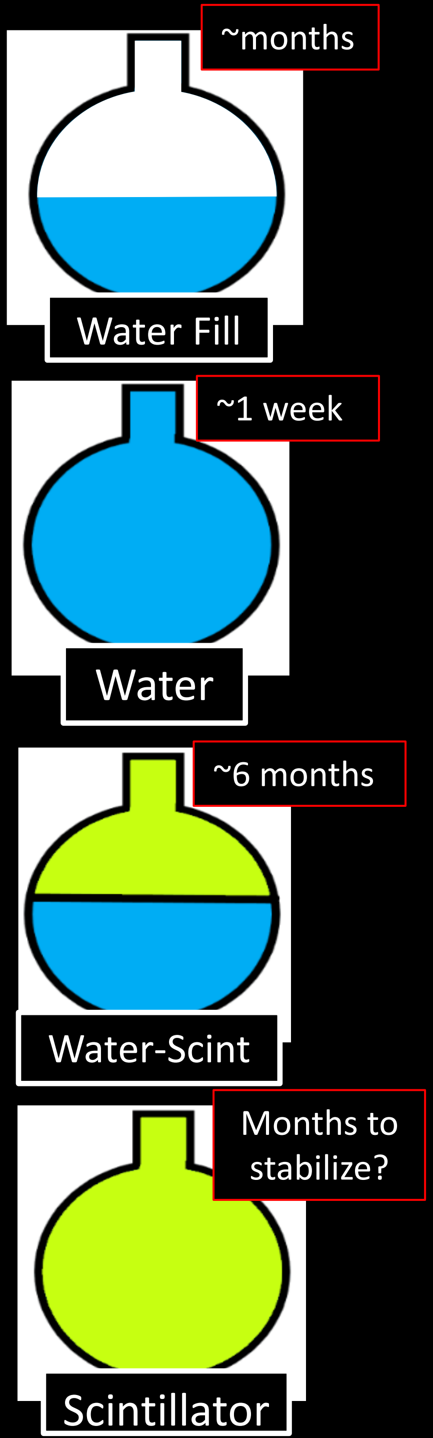
Physics in the Water and Filling Periods



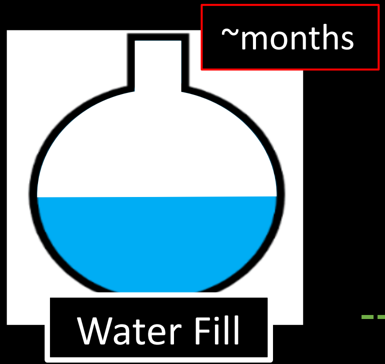
Baona Wu, Shishen Xian, Yuxin Xian, Akira Takenaka and Iwan Morton-Blake
on behalf of the SJTU/TDLI JUNO Group

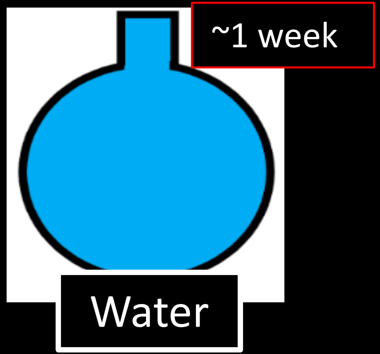


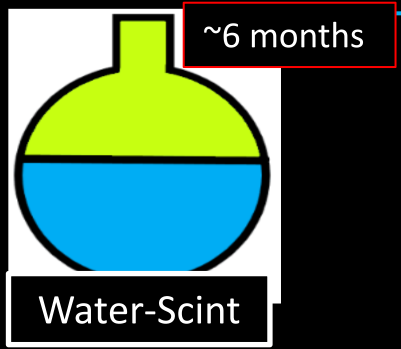
There will be extended time with a detector taking data.

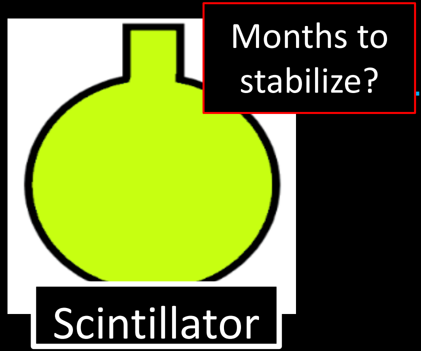
Commissioning will take close to a year (assuming no interruptions)

What do we want to do with these data?





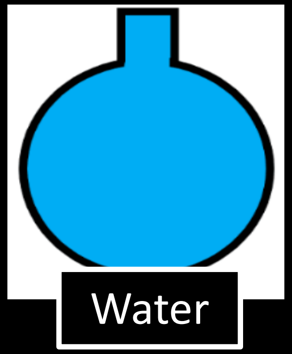




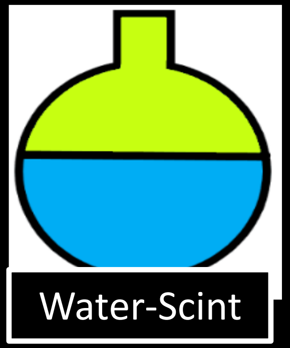
Physics in each phase	Needs / Tasks
Water Filling - Any Physics?	→ Calibrate Large PMTs → Measure PMT DN rates, Dark noise trigger rates
Full water - Measure IBDs in Water - Measure basic radioactivity	→ Position + Direction Reconstruction → Muon Tag + Recon + Veto → Trigger Threshold Efficiency: → Deploy AmC → PMT timing calib → Dark noise trigger measurement → Calibrate Water optics → Data quality/cleaning
Filling LS - Measure IBDs in LS - IBD backgrounds - Measure U/Th conc : BiPo212/214 (in early 50/100t)	→ Position + Energy recon + PSD → BiPo 212(Th)/214(U) tagging → Background singles spectrum and rates → Muon Tag + Recon + Veto → Calibration: Deploy sources + Naturally occurring radioactivity → Start LS optics calibration? → Data quality/cleaning
Early Full Fill - JUNO physics analyses start	→ Individual background measurements → Precise calibration across energies → Finely tuned reconstruction → Systematics

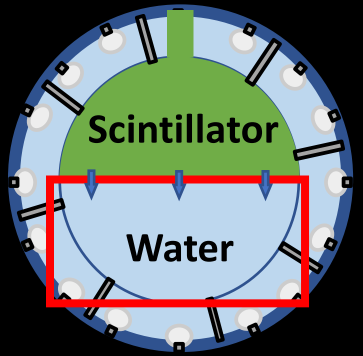
Contents

1) IBDs in water
- Progress
- Important needs/next



2) IBDs and Backgrounds during filling
- outline on physics + Backgrounds
- Needs/ahead





Interest in IBD Detection in Water

"Colloquium: Neutrino Detectors as Tools for Nuclear Security" arxiv:1908.07113

Some example experiments:

-**THEIA** – Type: *Water-based LS* arxiv:1911.03501.

-Reactor, geonu, IBDs from CCSN

-~ 20 IBDs per kT-year (@ SURF)

-**Super Kamiokande** – Type: *H_2O-Gd* arxiv:2006.01155

-Reactor, Supernova IBDs

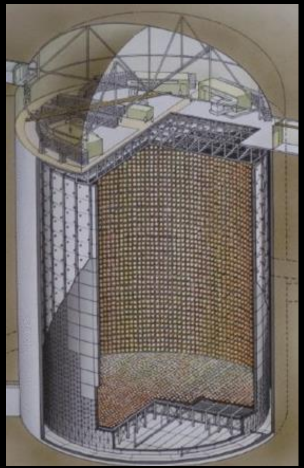
-**SNO+** – Type: *Pure H_2O phase*

- 3 Reactors ~240/350km baseline
- Measured 3-4 IBDs vs ~1 BG events in 190 days

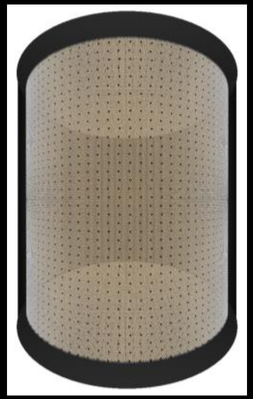
PRL 130, 091801 (2023)

Current "best" (and only) in pure water

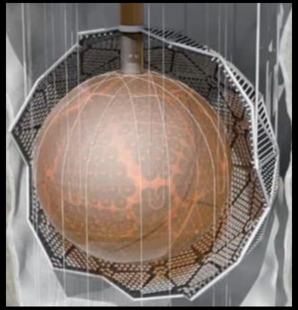
Super-K (50kT)

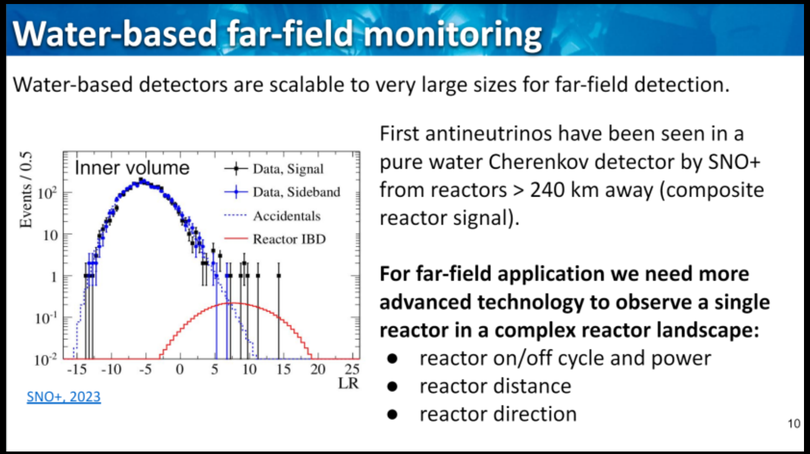


THEIA (25-100kT)



SNO+ (1kT)

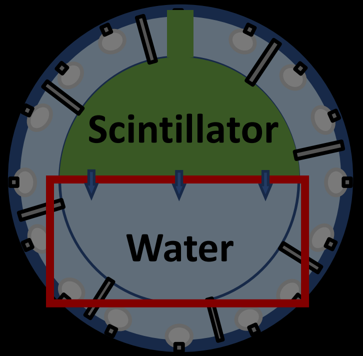




"Reactor Antineutrinos and Non-Proliferation"
Liz Kneale

Neutrino 2024

Interest in IBD Detection in Water



"Colloquium: N

Some example e 0kT)

-**THEIA** – Type:

-Reactor, geo

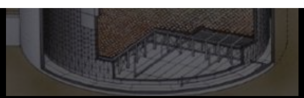
-~ 20 IBDs p

-**Super Kamioka**

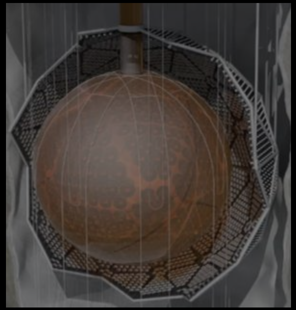
-Reactor, Supernova IBDs

For JUNO:

- How many IBDs can we see in ~10 days pure water?
- How many in ~6 months filling?
- Can we measure θ_{12}?
- Great test of detector, PMTs, trigger etc.



SNO+ (1kT)



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PRL 130, 091801 (2023)

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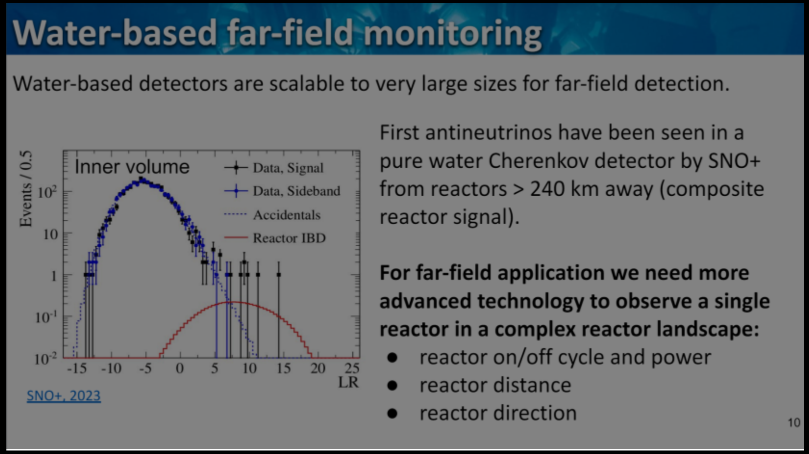
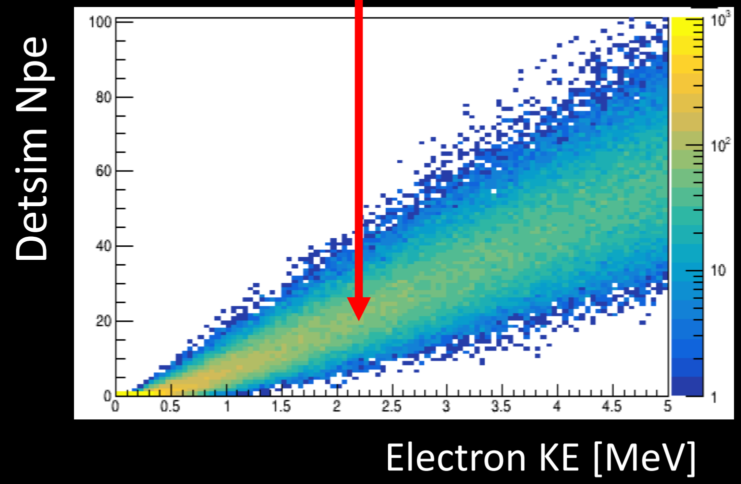
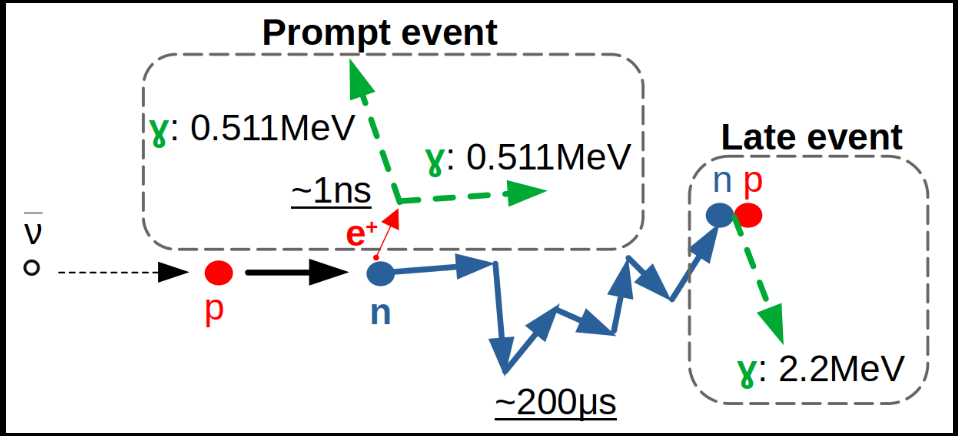


Big Challenges in Water

Neutron capture energy





Low Cherenkov Light Yield

- Only 10-30 npe from 2.2MeV neutron capture

High dark noise rates in JUNO PMTs

- DN rates ~30kHz * 17,612 PMTs → ~400 DN hits per 1000ns window!

Primary issues:

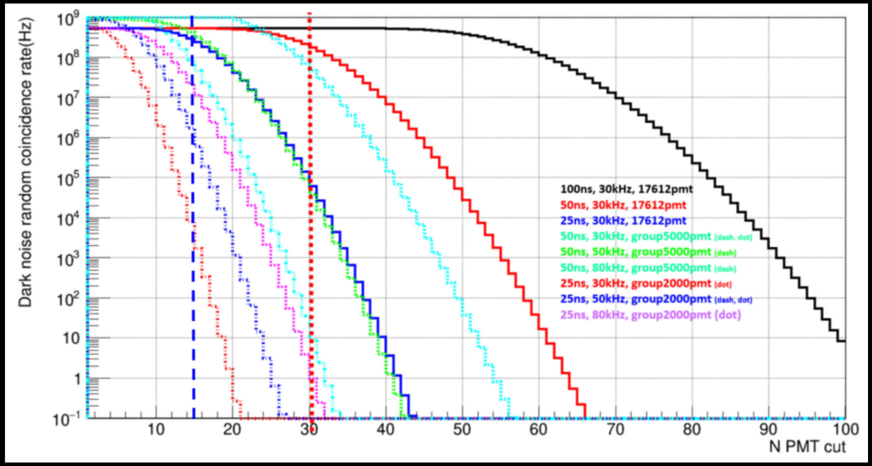
- Low signal efficiency → Triggering on positron and the neutron is **difficult**
- Poor position + energy reconstruction
- **High** DN rates → Additional **significant** background (dark noise triggers mimic neutrons)

Lowering the trigger threshold

Have had attempts with simple trigger methods in pure water:

→ E.g. #PMT hits per small time window

- Simulation studies in DocDB #10257
- Similar attempts made with 32ns window,
  - 2.2MeV gamma efficiency in water in AV
  - Trigger rate due to DN



Threshold	DN trigger rate	Gamma trigger eff(Inside Acrylic Vessel)
27	29,966±847Hz	10.51±0.23%
28	14,502±369Hz	7.65±0.20%
29	6,790±152Hz	5.31±0.16%
30	2,839±67Hz	3.79±0.14%

Shishen

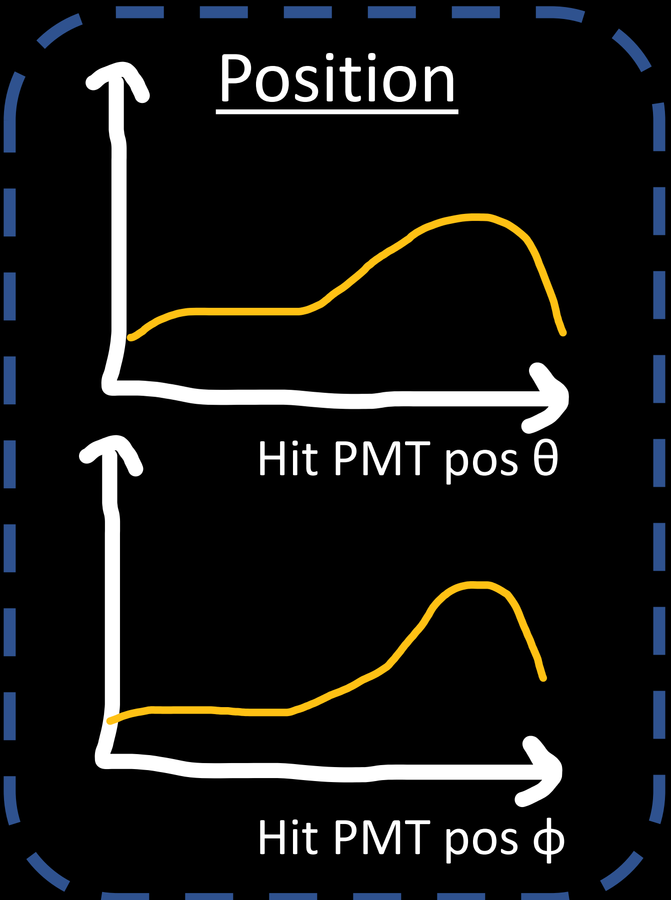
If #PMTs > X in 32ns → Trigger!

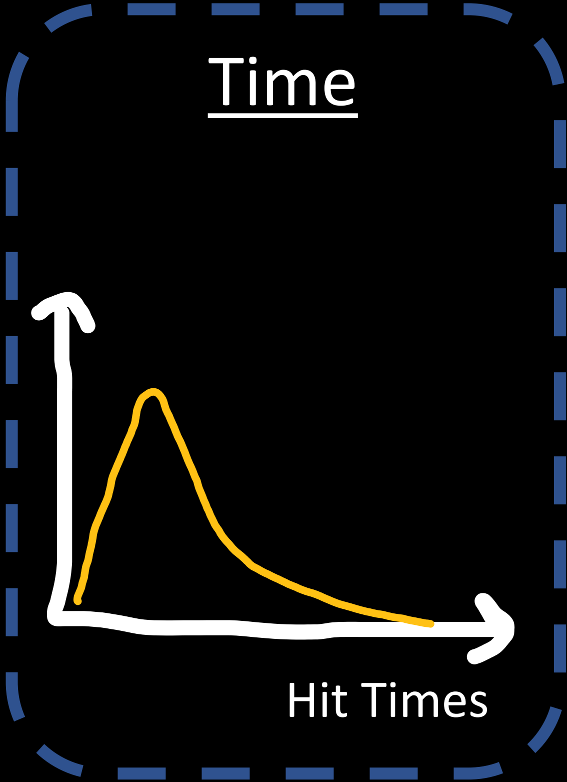
Still,
Efficiency too low &
DN rates too high!

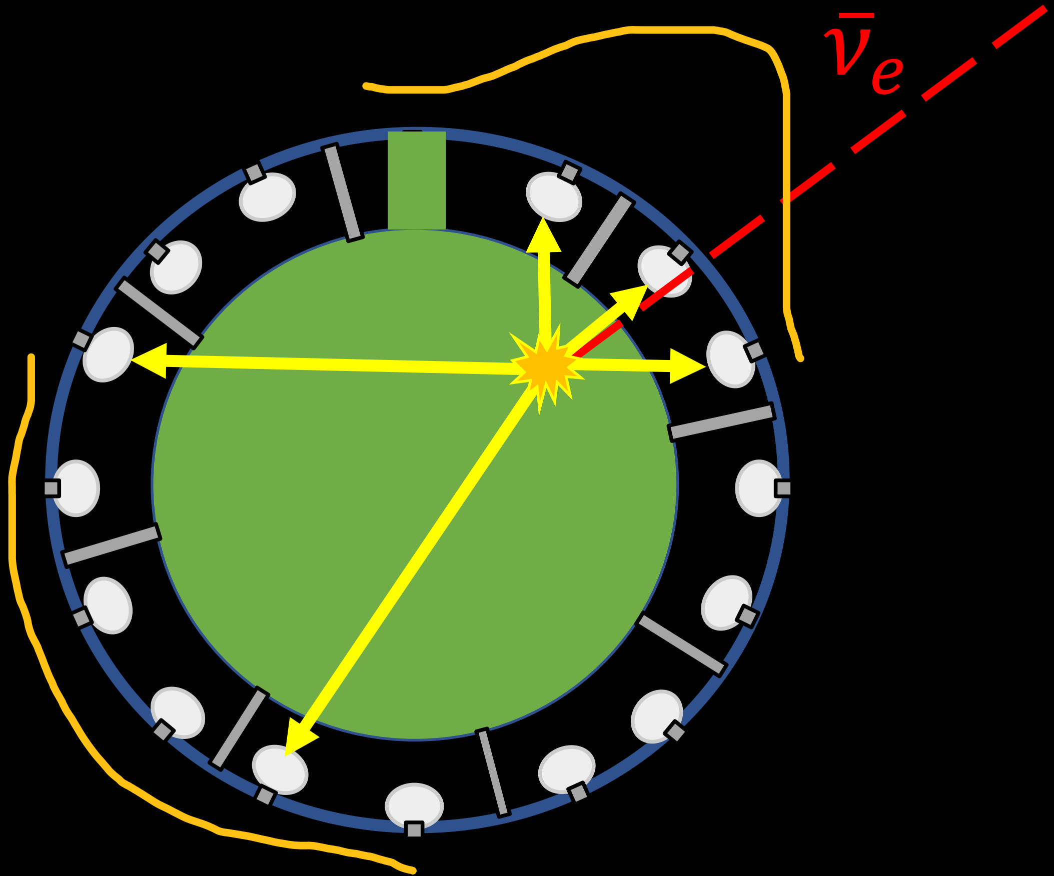
The Multi-Messenger Trigger

The Multi-Messenger trigger is designed to reach ~20keV energies in LS

FPGA-run likelihood algorithm used to measure clustering in PMT space and time







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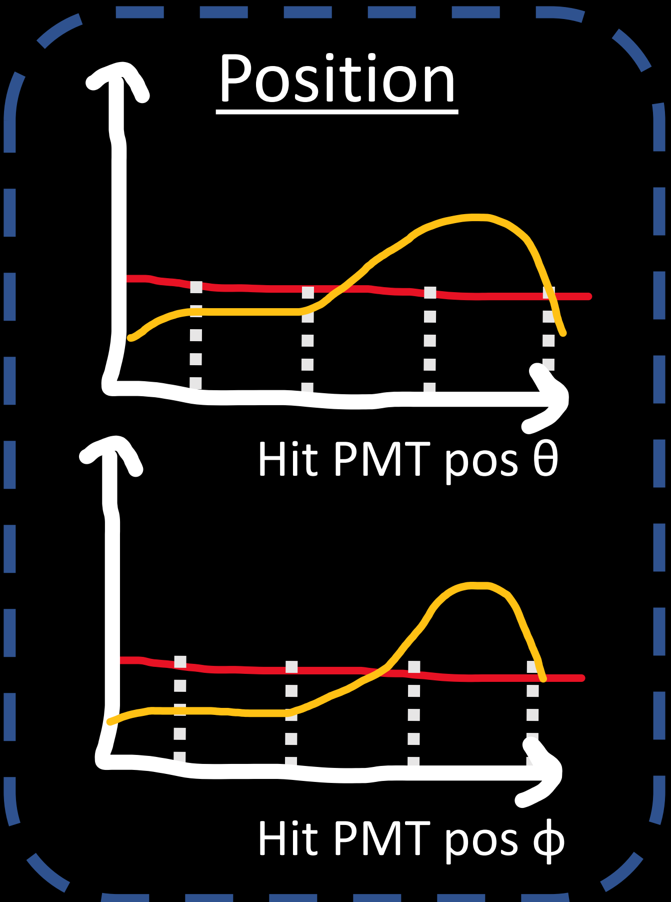
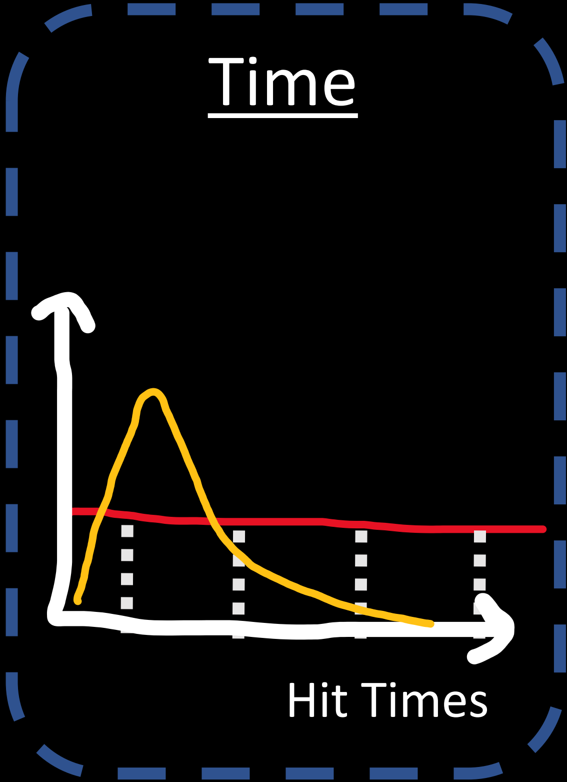
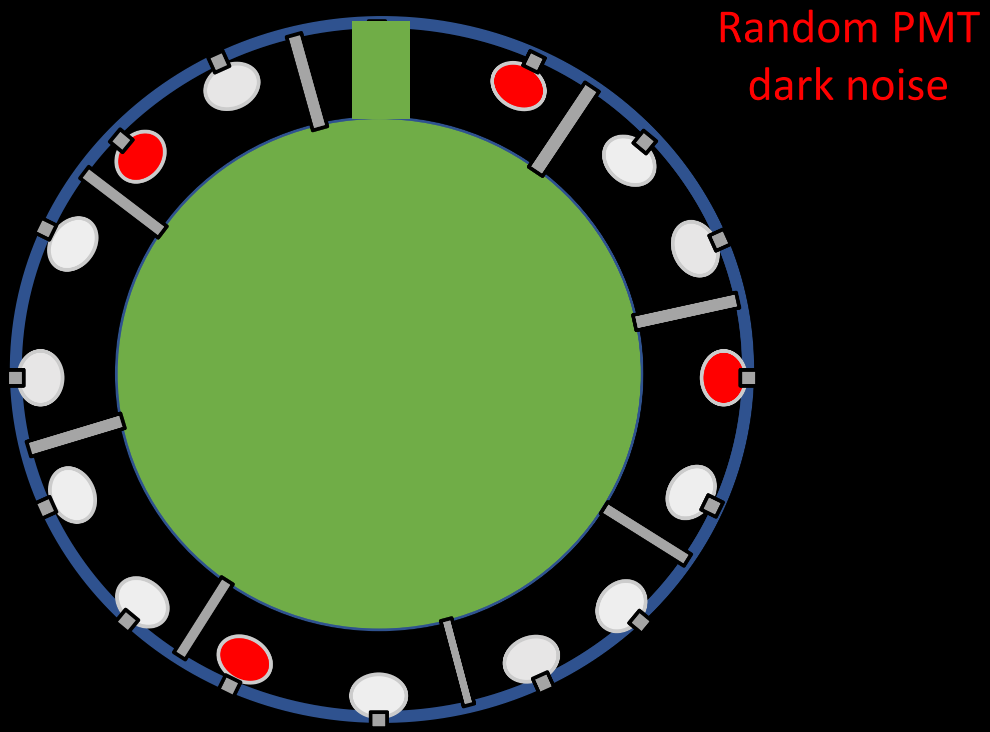




4x4x4 binning



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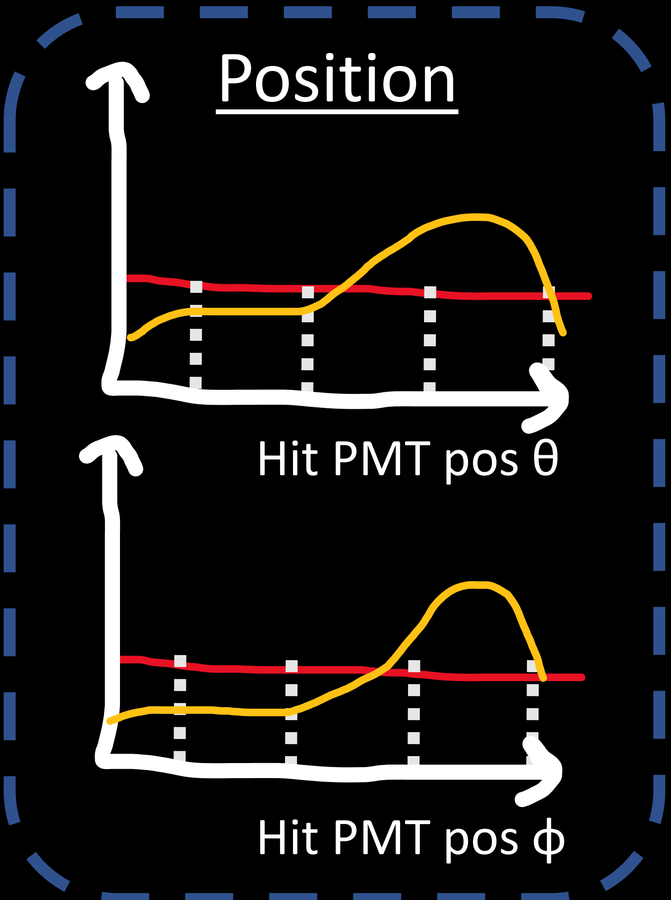

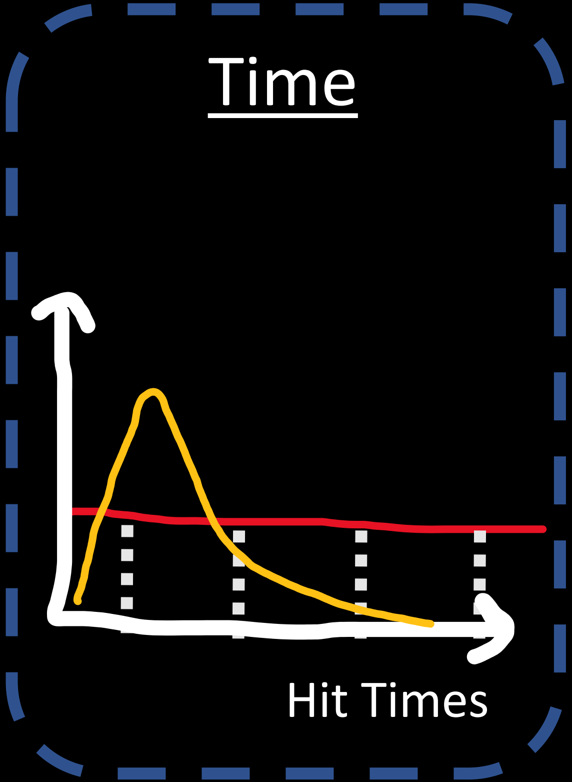

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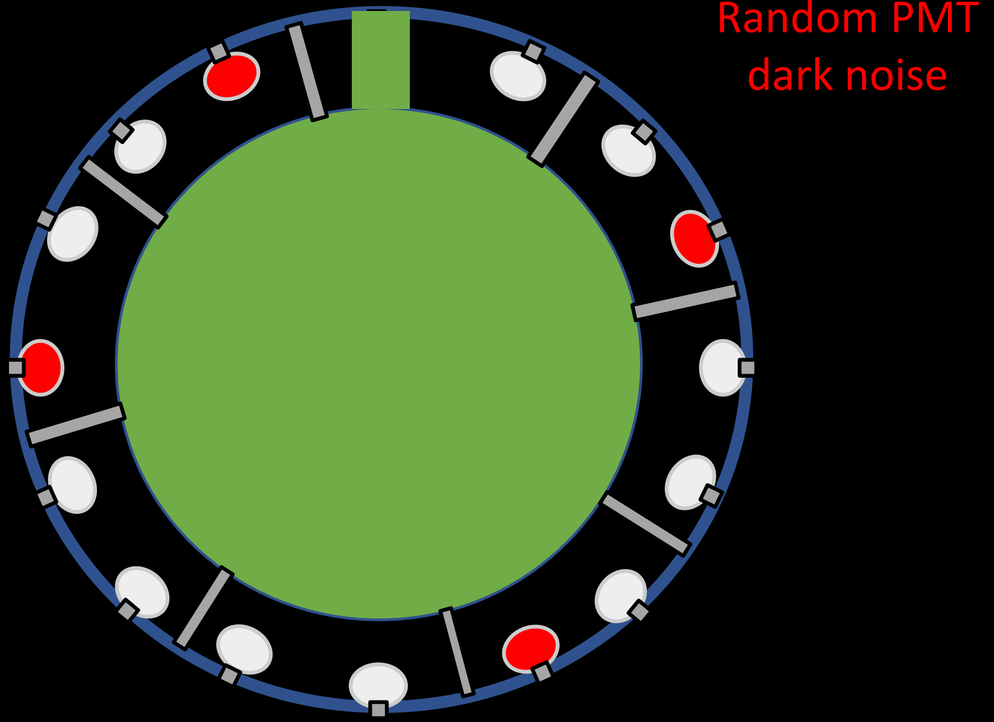

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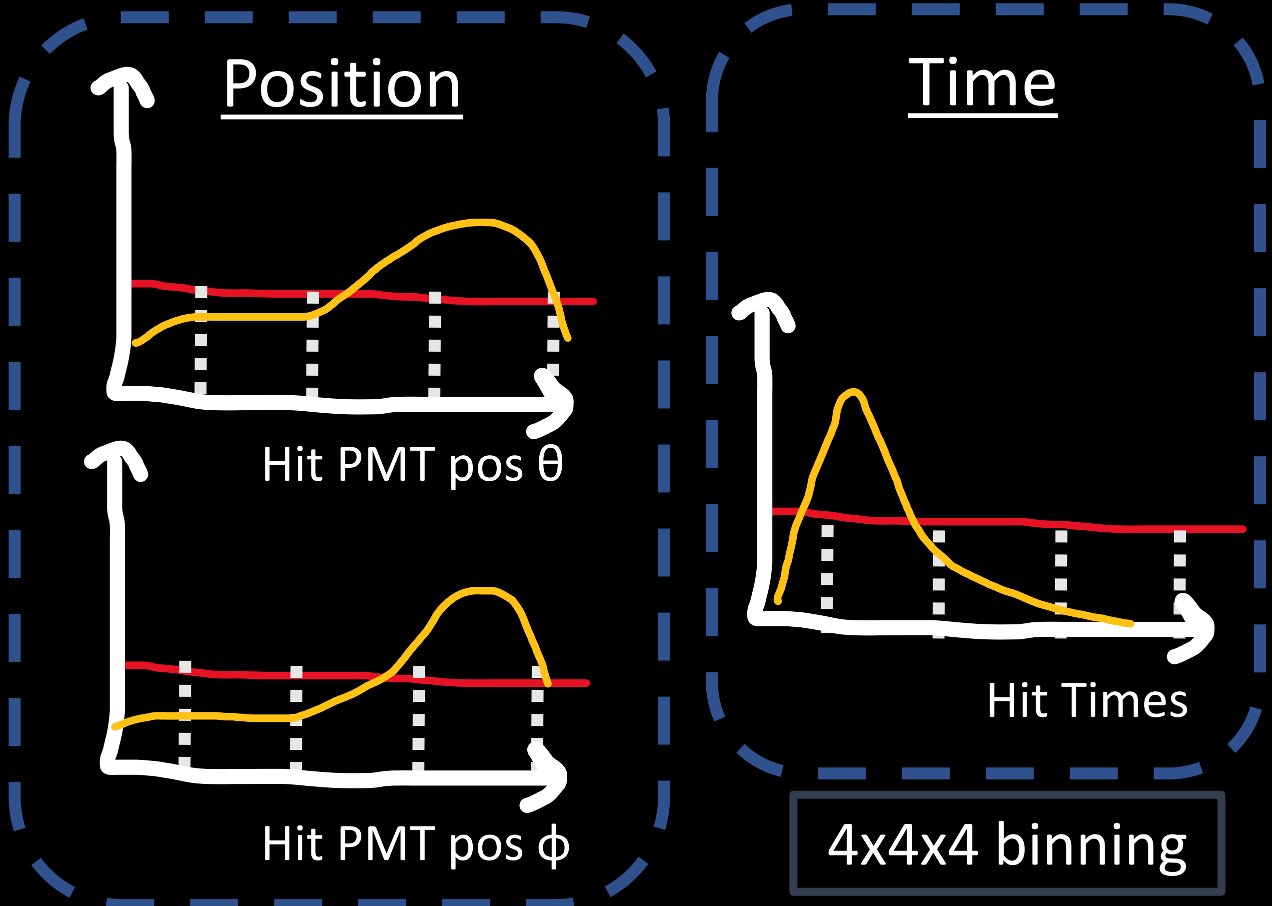

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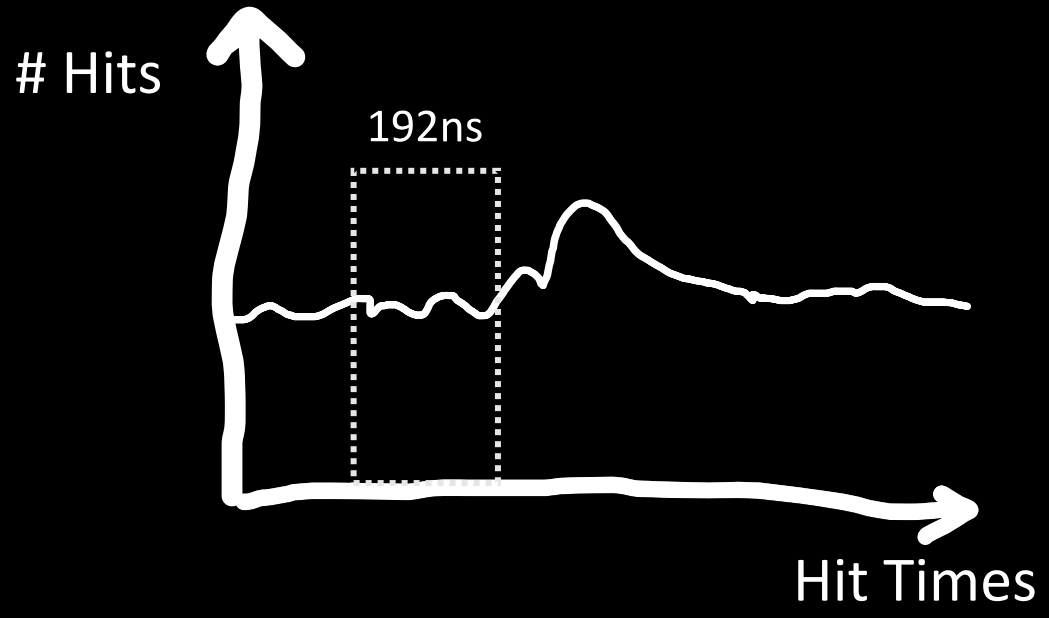

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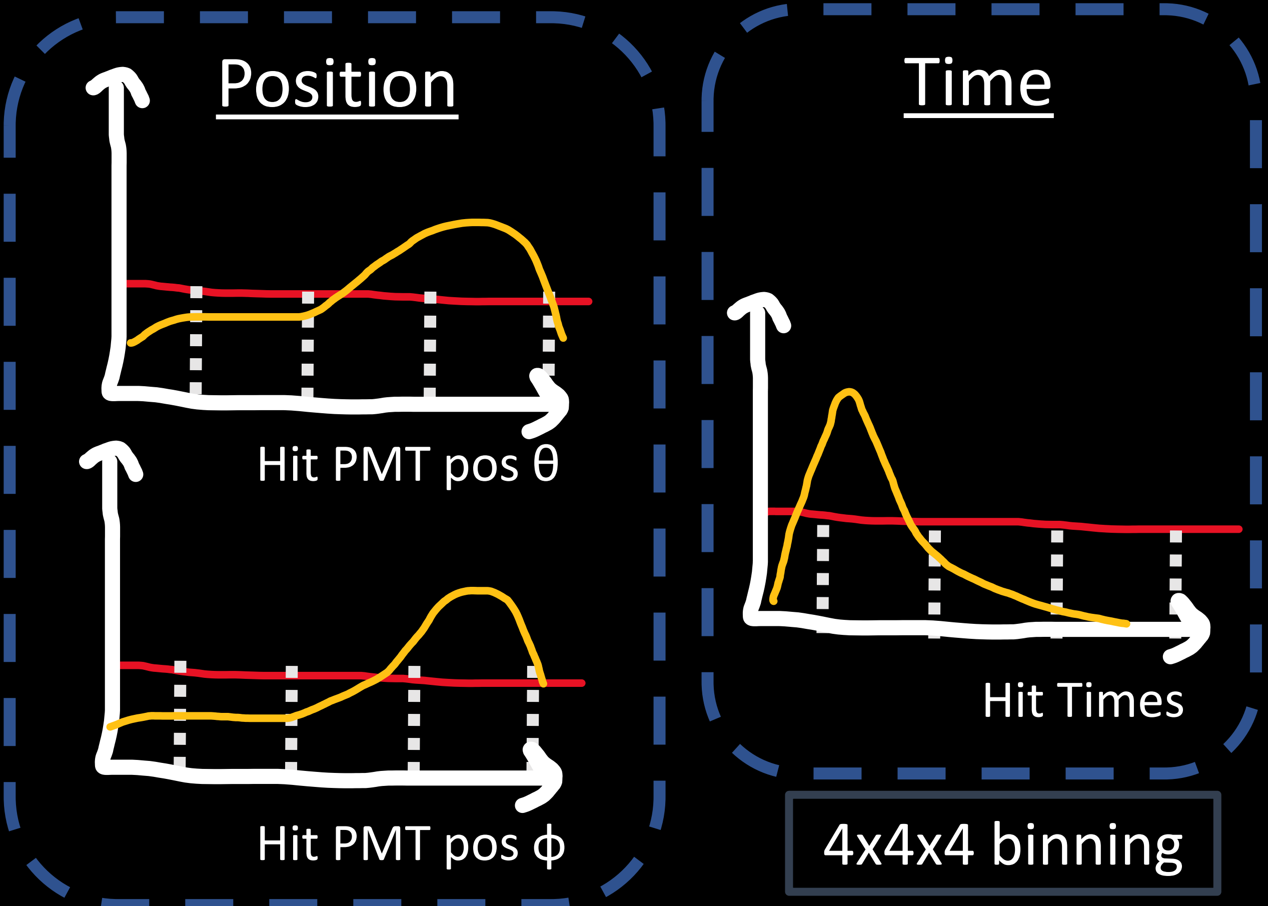

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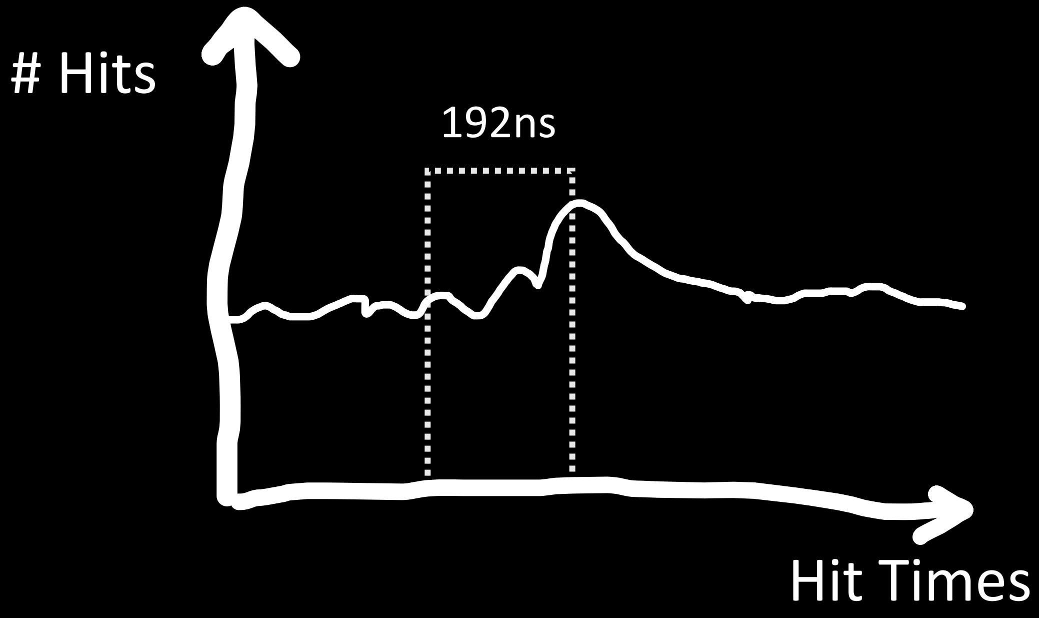

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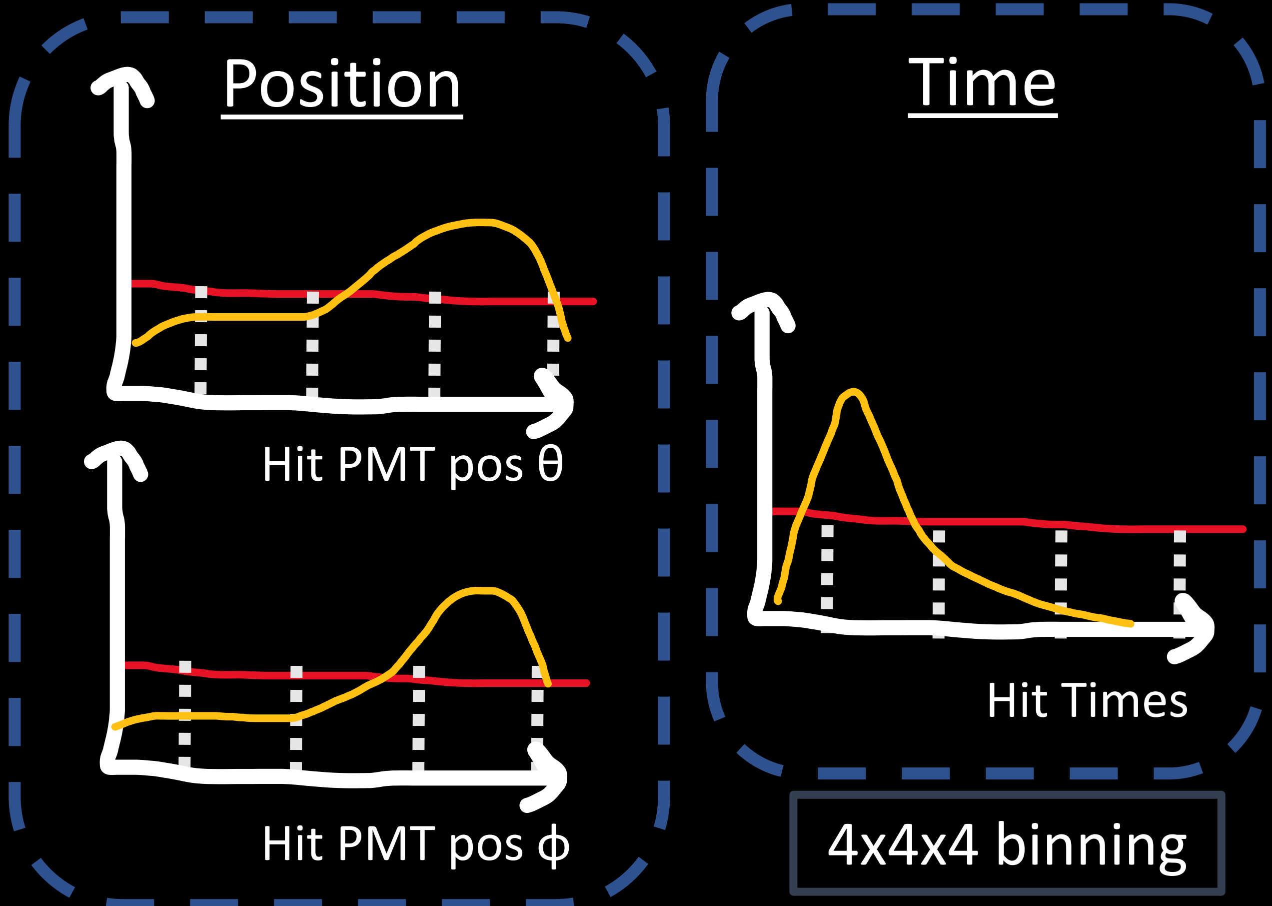

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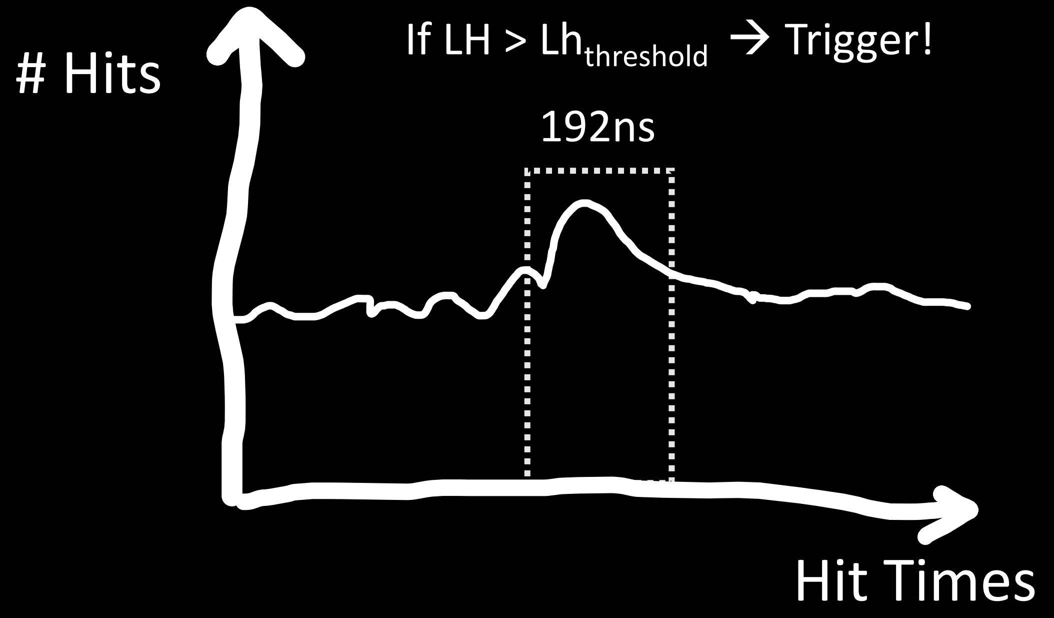
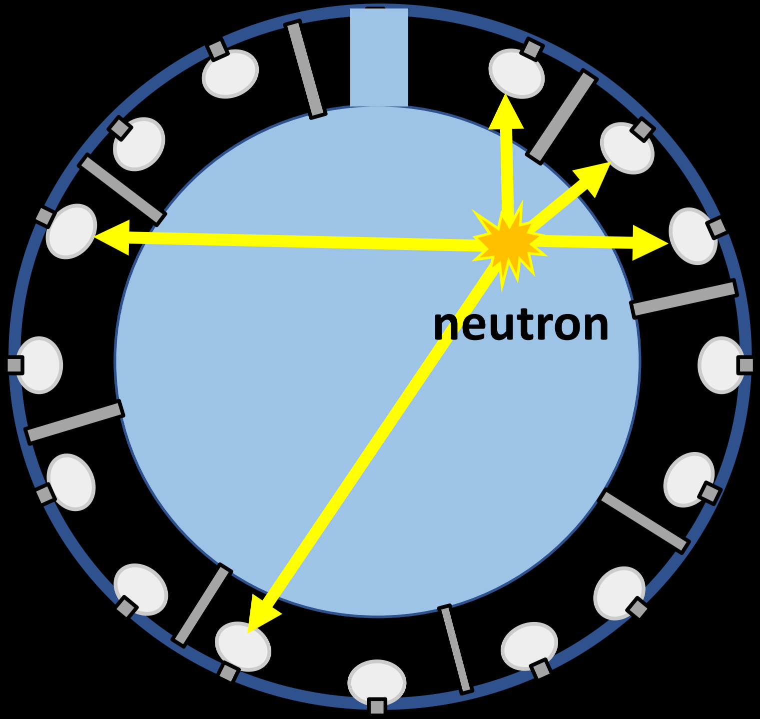


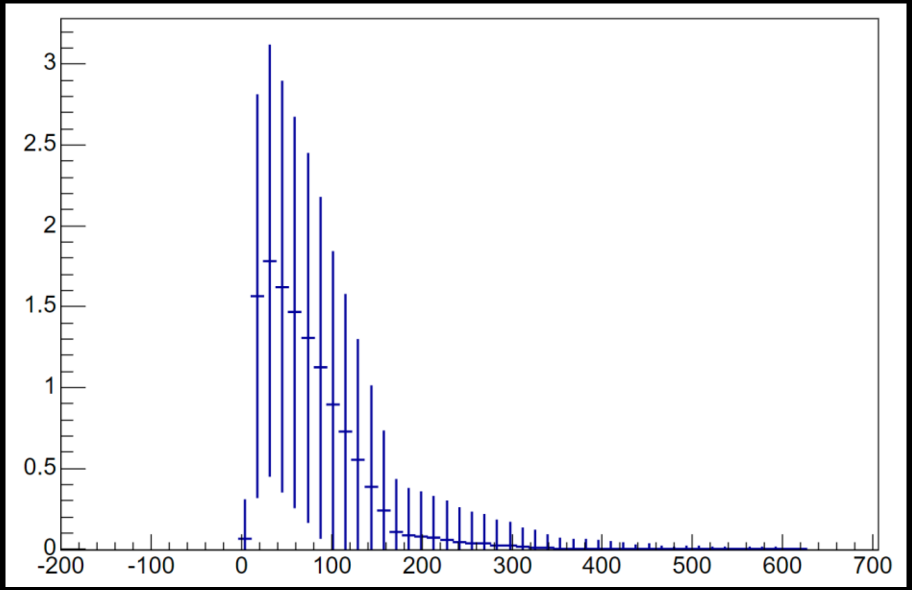
Lowering the trigger threshold further

Cherenkov light is less isotropic (PMTs more localised in space), faster emission

→ May need minor modification to use MM trigger in the water phase.



PMT hit times of 2.2MeV gammas distributed in water within the acrylic vessel



PMT hit times (detsim) [ns]

Majority of signal hits coming in ~100ns!
(Standard MM trigger is 196ns divided into 4 bins)

Lowering the trigger threshold further

Tested many configurations of the MM trigger algorithm, measuring

→2.2MeV gamma trigger efficiency

→Rate of triggers due to DN only

Baona, Shishen, Yuxin

MM trigger is limited by the LH calculation speed!

(Standard MM running on FPGA takes ~60ns per calculation)

Simple hits/window method:
~10kHz DN → ~7 % efficiency

Standard MM
4x4x4 bins, 192ns window:
~10kHz DN → ~10% efficiency

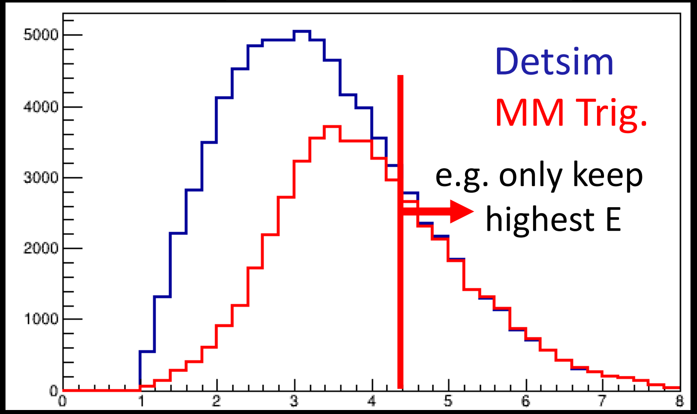
Optimized MM
4x4x1 80ns window:
~10kHz DN → 16% efficiency

Improved the neutron efficiency, can we decrease the DN rate with the trigger?

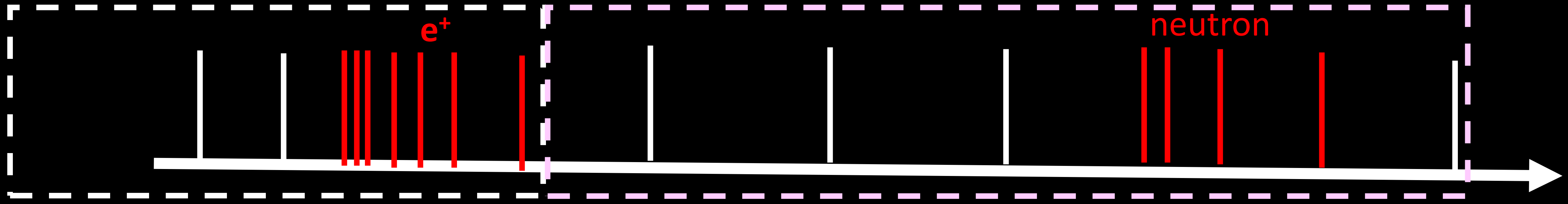
Lowering the trigger threshold further (x2)

- Idea from Akira: coincident triggering
  - If willing to sacrifice some signal:
    - Trigger on higher energy e^+, then can have **2** trigger thresholds.
  - E.g. high trigger threshold for e+, if triggered, apply a lower threshold for ~1ms (i.e. the neutron capture time window)
  - This *should* be achievable on the MM trigger built-in CPU system (needs testing in next lights-off tests)

e^+ from reactors



True Water Deposited Energy [MeV]



What trigger thresholds do we choose?

- Optimising the two threshold values, we must balance:
  - IBD signal efficiency
  - False IBD pair rate due to DN triggers

The Plan

- ➢ MM trigger only uses low-level PMT info to remove Dark noise triggers
- ➢ Safer to accept more dark noise triggers → Save the most potential signal events
- ➢ Following triggering, try to separate them offline using full PMT T,Q info

NEED:
→ Offline strong DN reduction using PMT T,Q info (e.g. run on OEC?)
→ What event rates can DAQ/OEC handle?

What trigger thresholds do we choose?

- Optimising the two threshold values, we must balance:
  - IBD signal efficiency
  - False IBD pair rate due to DN triggers

For demonstration purposes:

We don't have good offline DN removal currently

What if we just chose a severe trigger threshold on the MM trigger.

Assuming an e^+ LH cut of 60, and a neutron LH cut of 53:

Signal trigger Rate = (IBD Rate in full AV)(e^+ efficiency)*(neutron efficiency)*

(60/day)*(28.1%)*(2.2%) = **~0.4 IBDs per day within 17.7m**

False IBD pair rate from DN = (Trig Rate @ Lh_{high})(Trig Rate @ Lh_{low})*(delT)*

(2.5e-3Hz)*(1.21Hz)*(1ms)*(1day) = ~**0.26 false IBDs per day**

Severe MM trigger cuts:
i.e. in 10days
~4 signal events ~3 BG events
~on par with SNO+ 190 day result!
(Likely big improvement with DN reduction + reconstruction)

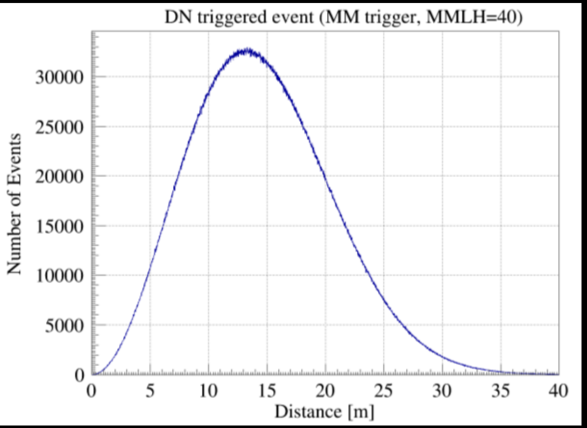
Reconstruction in water (in progress)

- Good progress in water position reconstruction work by Baona DocDB #
  - Resolution improved from ~10m → ~2.5m (for 2.2MeV gammas)
- Apply ΔR cut between e^+ and neutron
  - Random DN pairs expected further apart
- E.g. a ΔR < 9m reduces DN BG by ~80%

Severe MM trigger cut, 10 days:

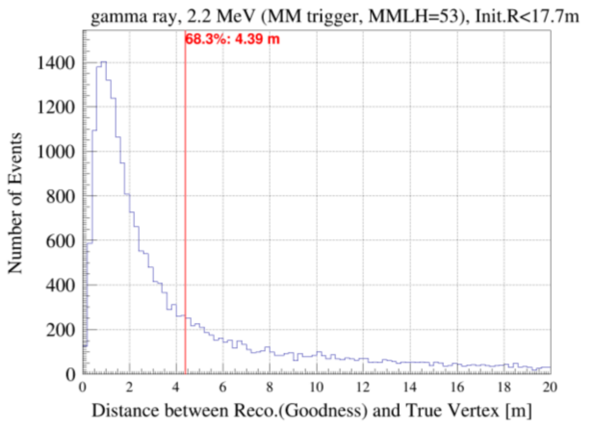
4 IBDs, 3 BGs → 4 IBDs, <1 BGs

NEED:
→ Faster water reconstruction
→ Improved resolution will increase signal efficiency and reduce BGs

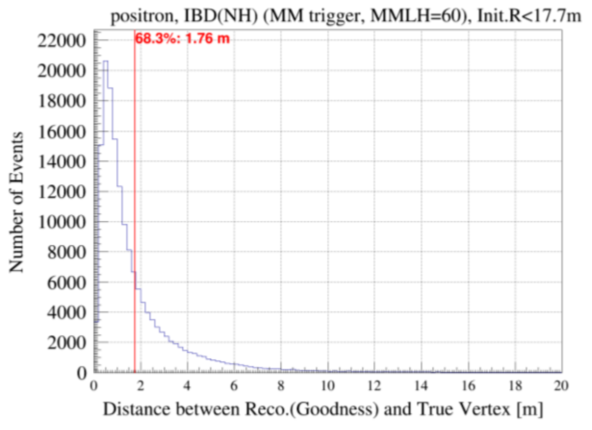


Reconstructed distance between random DN pairs

Neutron capture position resolution (<17.7m)



Reactor e^+ position resolution (<17.7m)

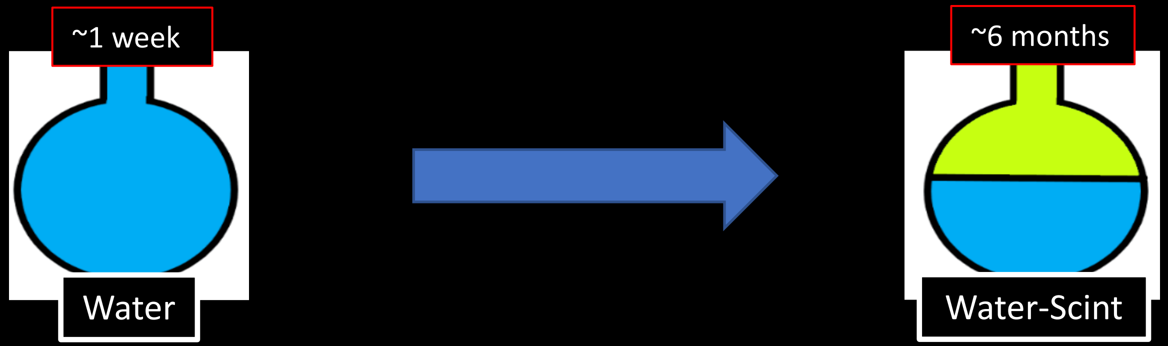


Onwards/Needs

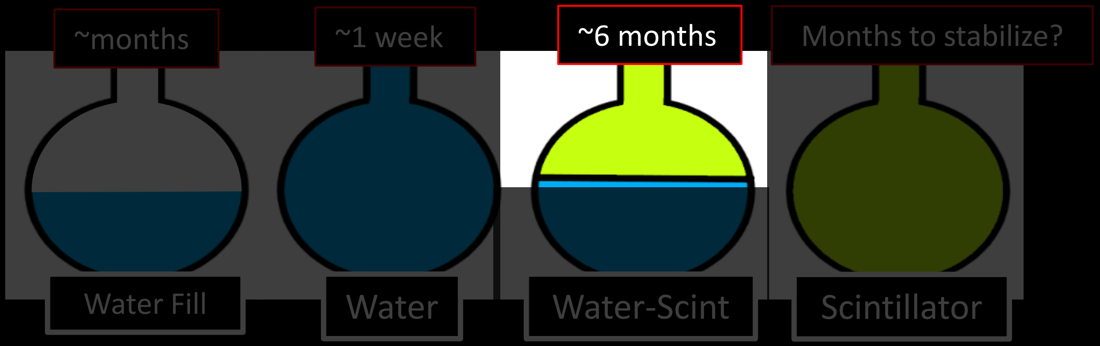
Seemingly (with work) a nice result is possible, however there are some **vital** needs moving forward:

- **Offline DN trigger removal** – need much stronger methods, must retain more signal efficiency
  - Plan to start one of our new students on an ML method
- **Radioactivity** – Water BGs possible can be 10x higher than LS
- **External water events** + associated higher BGs – **e.g. PMT glass!**
- **Impact of LS** – moving LS-H2O interface, extra low energy backgrounds from LS?
- **Muon recon + vetoing** – e.g. Akira+Yankai WP muon recon during filling veto strategies.
- **Exact calibration strategy** – what uncertainty levels can we reach in trigger efficiency.
- **Reconstruction** (water and LS-mixed) always need improvement - will improve signal + reduce all BGs
- **Electronics** - what event rates can we realistically handle? (MM, DAQ, OEC)
- Hardware testing on MM trigger – stress tests + coincidence triggering

Water → Liquid Scintillator



IBDs in LS during filling



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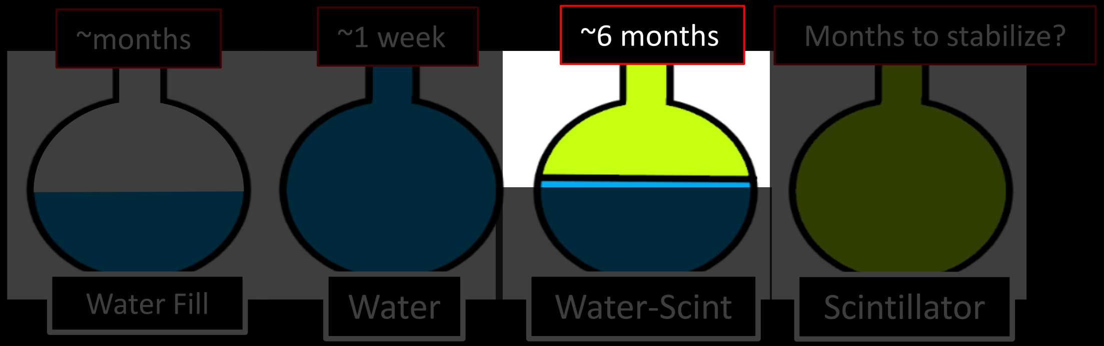
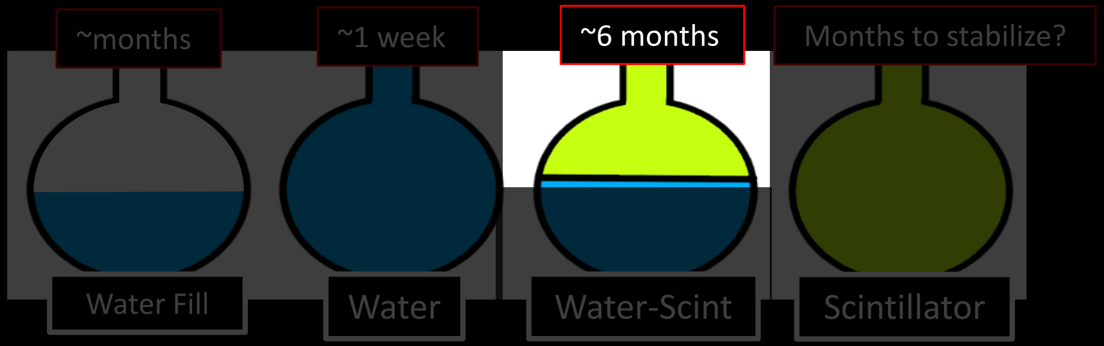


Hope to measure IBDs in the ~6months of filling (equiv. to ~3 months of full fill)

- Can we make “good” oscillation parameter measurements?
- Great stress test of detector, IBD extraction, BG determinations and calibration

IBDs in LS during filling



Contents:

1) Basic reconstruction during LS filling
2) Basic calibration with BiPo214
3) Application to IBDs during LS filling

Reconstruction in LS during Filling

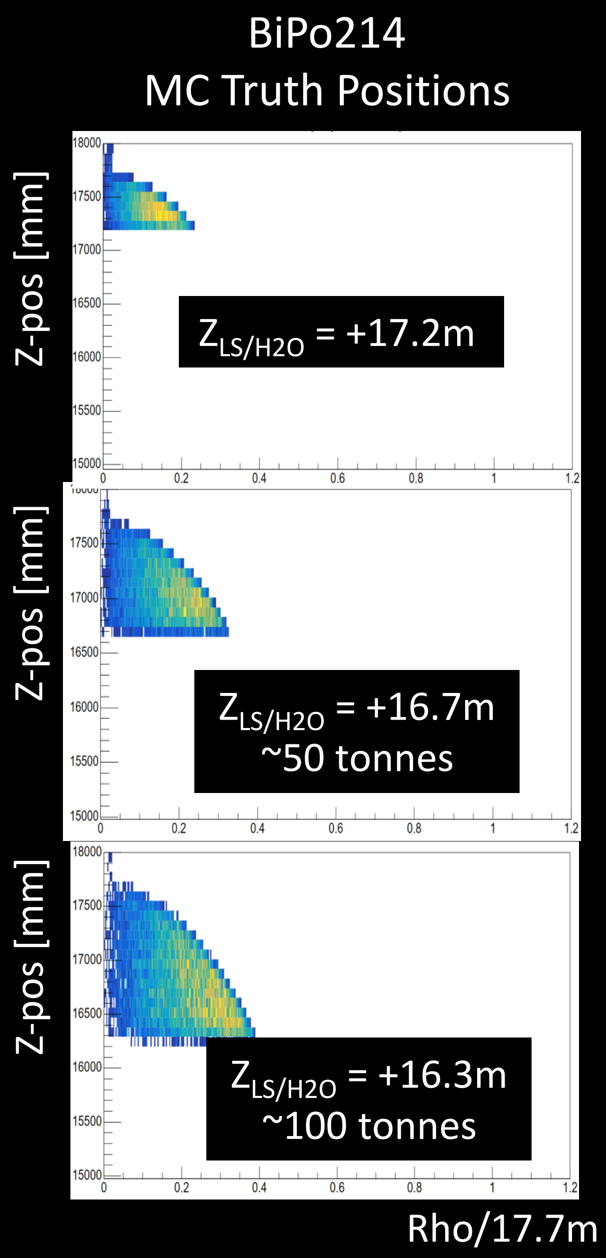
Reconstruction in LS during Fill

During fill, hope to

- ➢ Measure various backgrounds
- ➢ Tag IBD events

Issue: slowly moving LS-H2O interface height

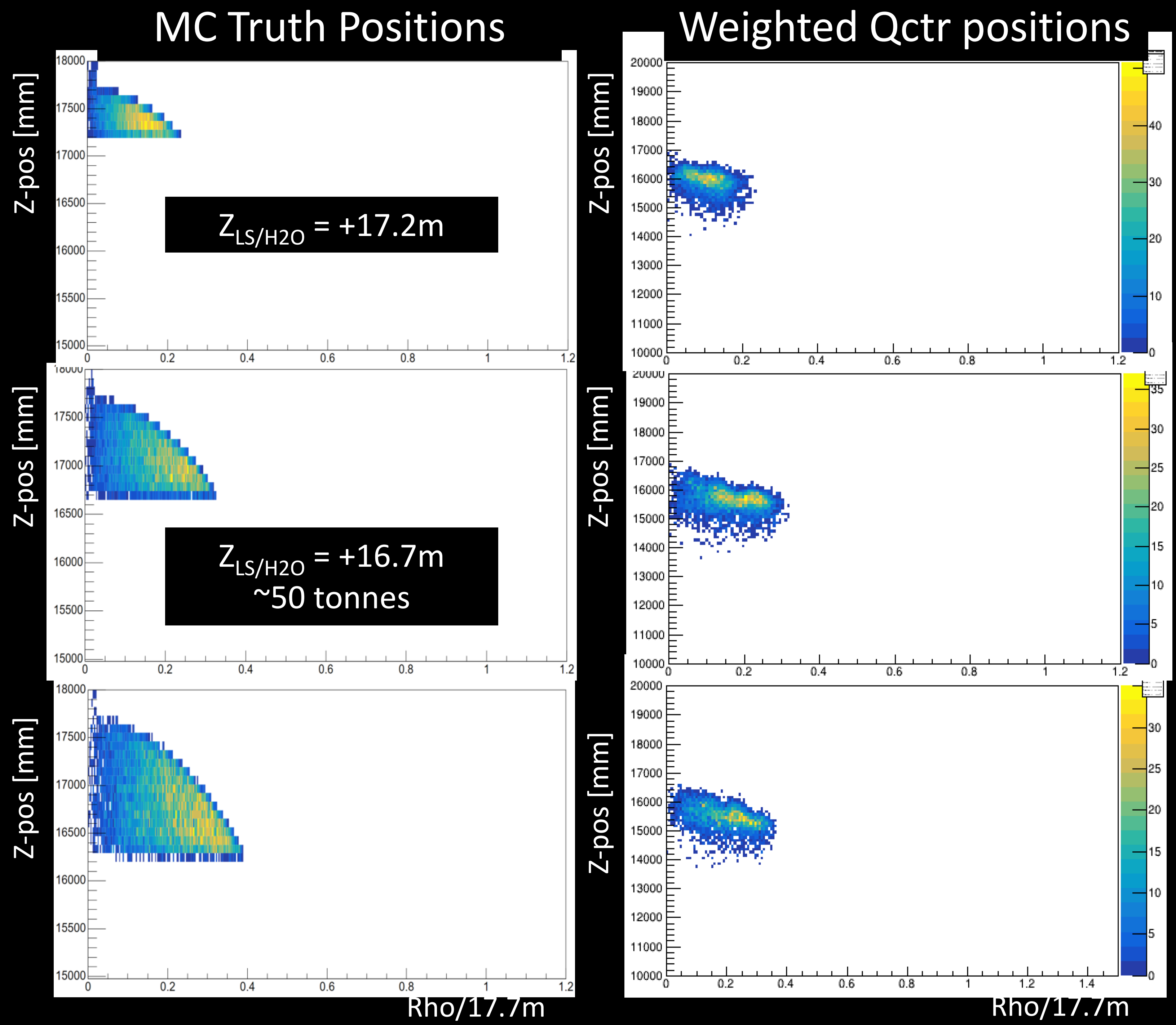
- Most full fill reconstruction algorithms cannot be used directly during the filling phase



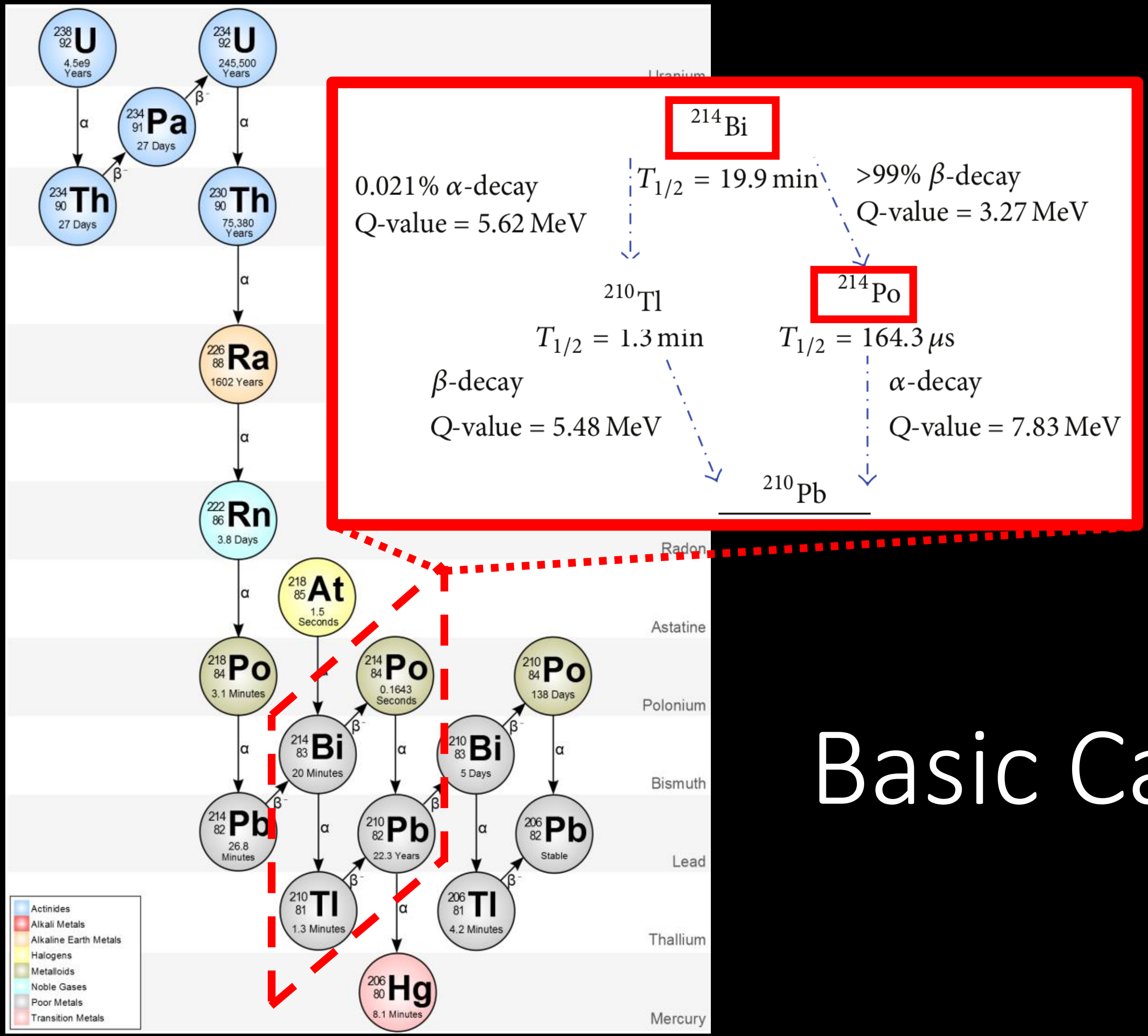
Recon in early Fill

Simple time-weighted charge centre position fitter used in this study (DocDB #10210)

Tagging BiPo214 pairs during LS filling using IMB QCtr method



- True pos != Recon pos
- But, closer to real distribution around the detector
- Reduced clustering of events



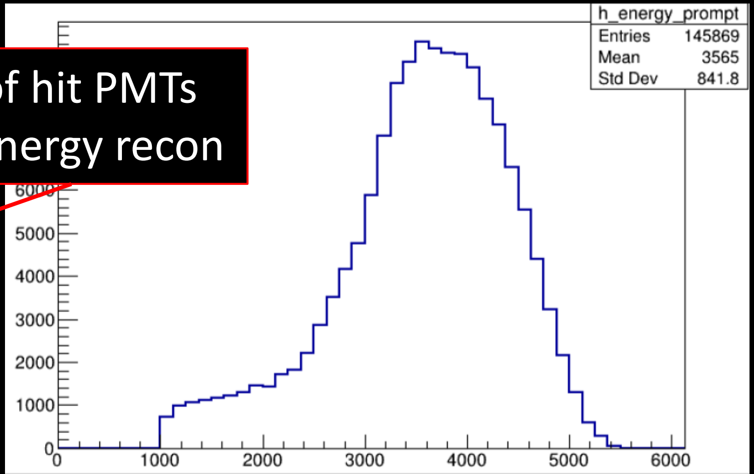
Basic Calibration during Filling with BiPo214

BiPo214 Tagging with Simple Reconstruction

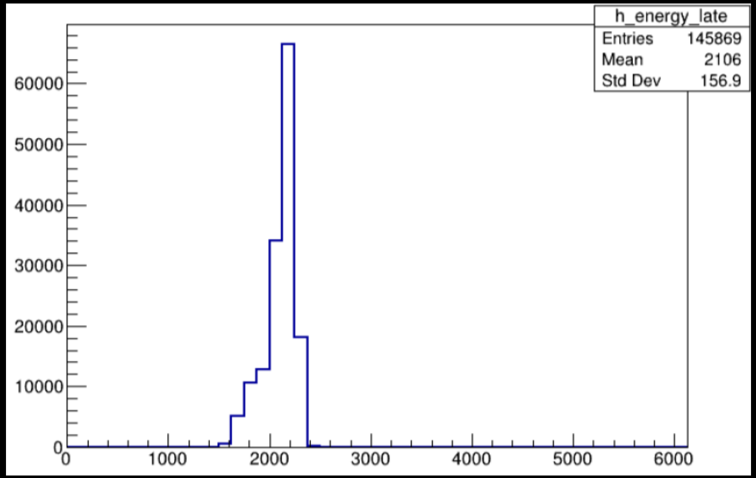
<u>Example BiPo214 cuts</u>

Prompt	Late
No radius cut	
E > 1000 PMT hits	1500 < E < 2500 hits
Δr < 2 m	
1200ns < Δt < 2ms	

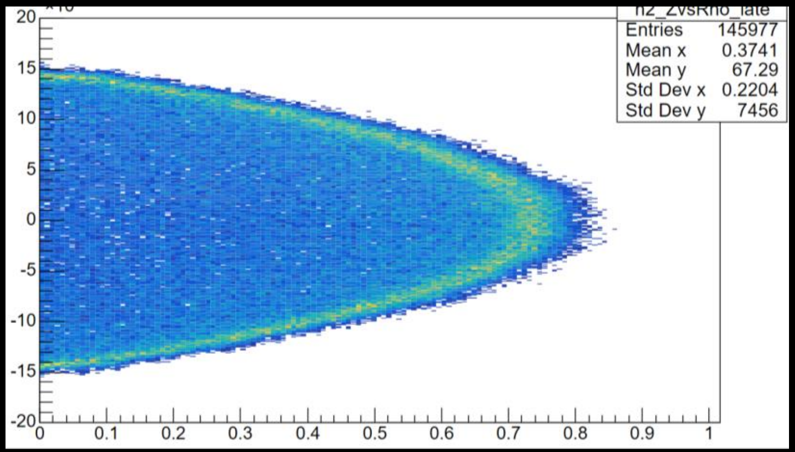
\# of hit PMTs as energy recon



Prompt (Bi214) nhits

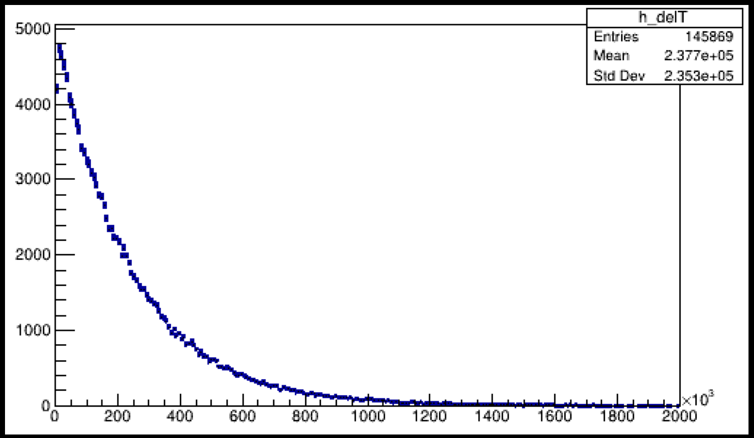


Late (Po214) nhits

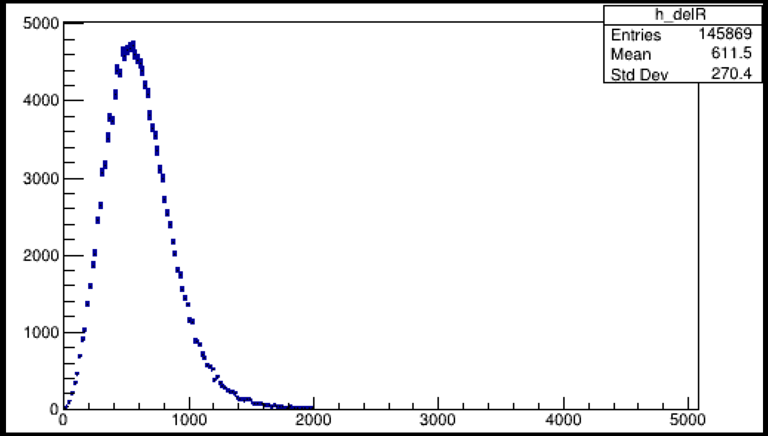


QCtr z [mm]

$x^2 + y^2 / 17.7^2$ (QCtr)



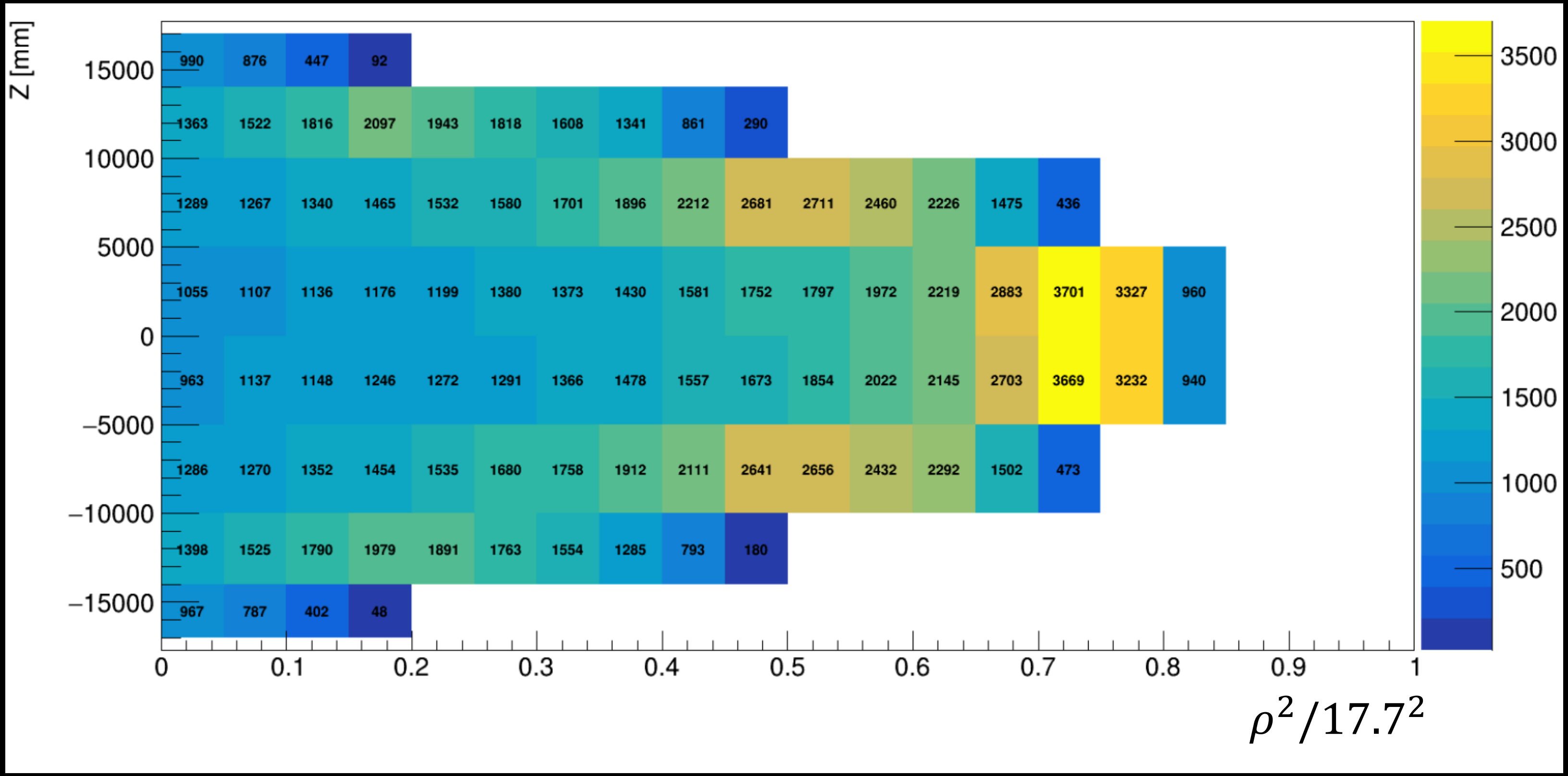
delT [ns]



delR (QCtr) [mm]

Basic Calibration during Fill

Number of tagged BiPo214 in each bin over ~1week

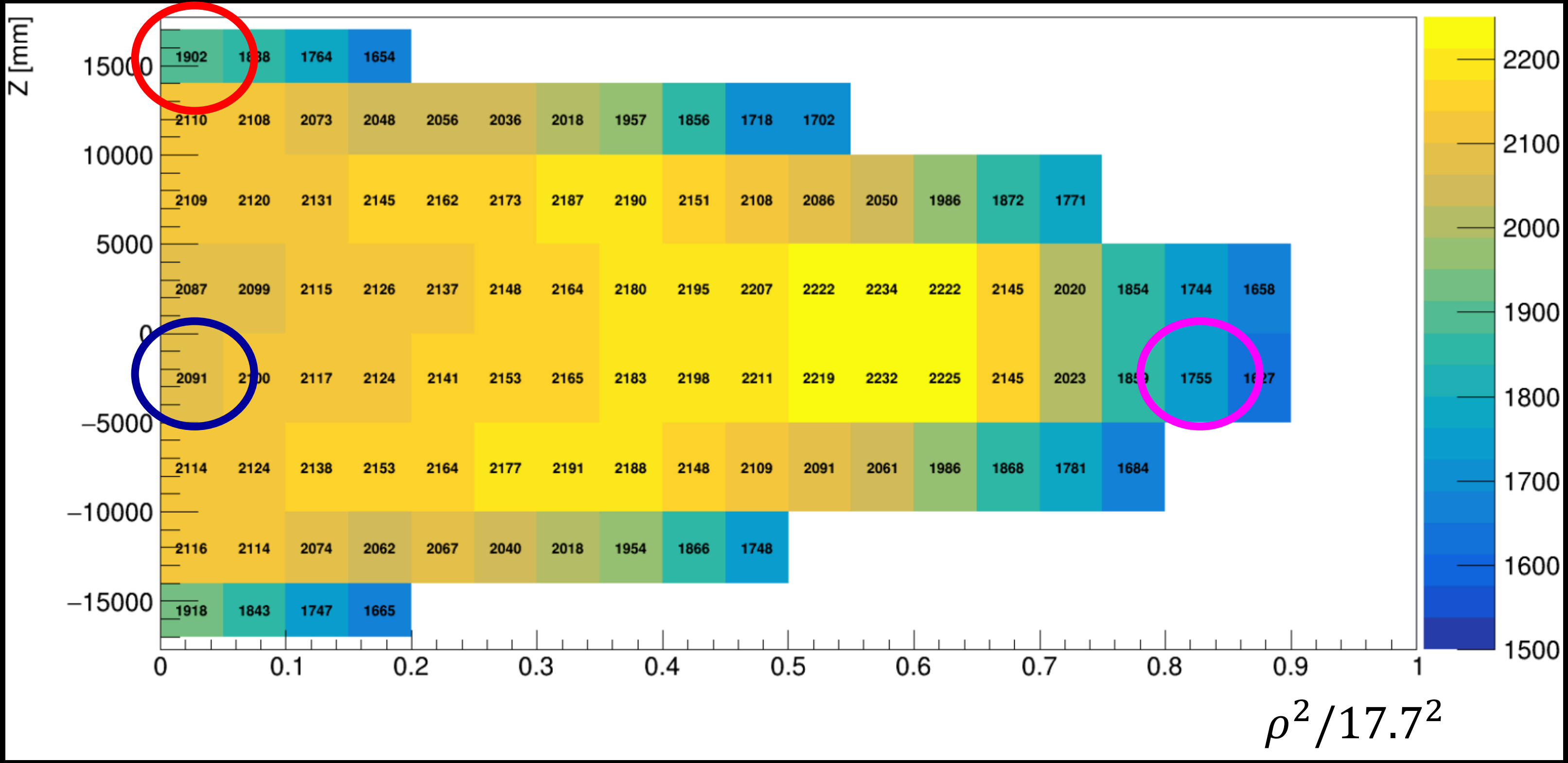


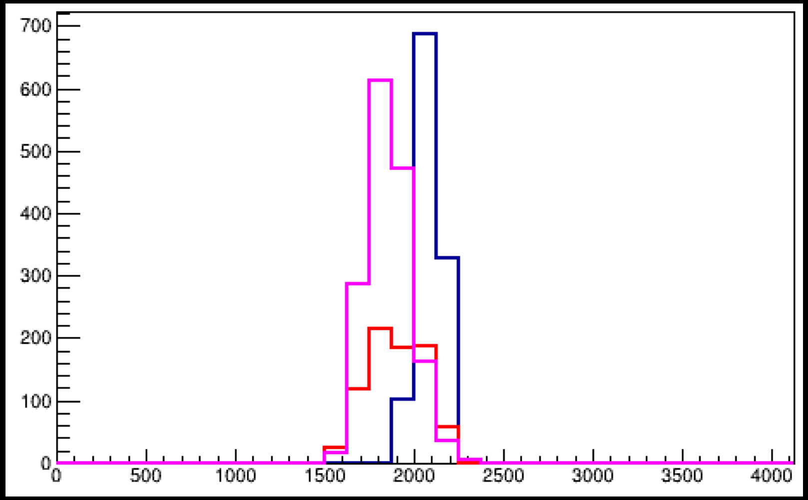
Assuming 10^{-15} gU/gLS, Likely will have much more due to Rn ingress during fill

Basic Calibration during Fill

<u>Detector non-uniformity:</u>

Po214 Number of PMT hits vs position





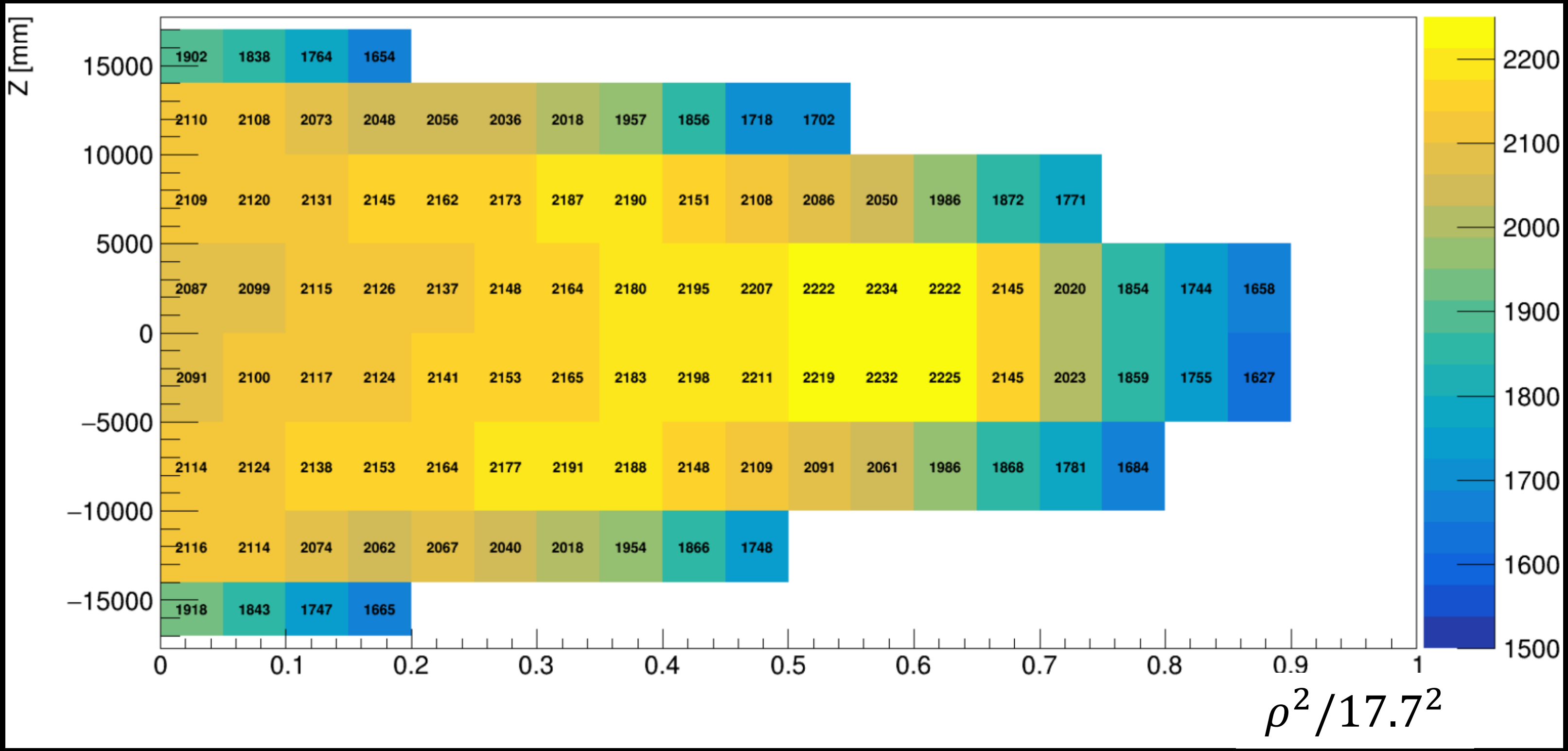
Po Number of PMT hits
(Measure of light collection)

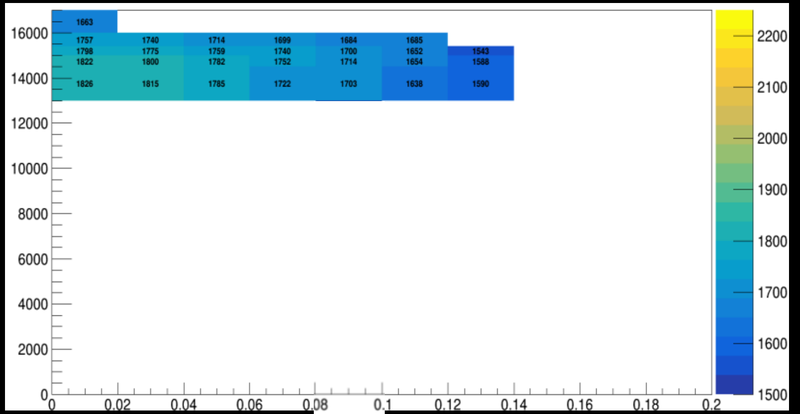
Can use tagged BiPo214 events to map out light collection around the detector

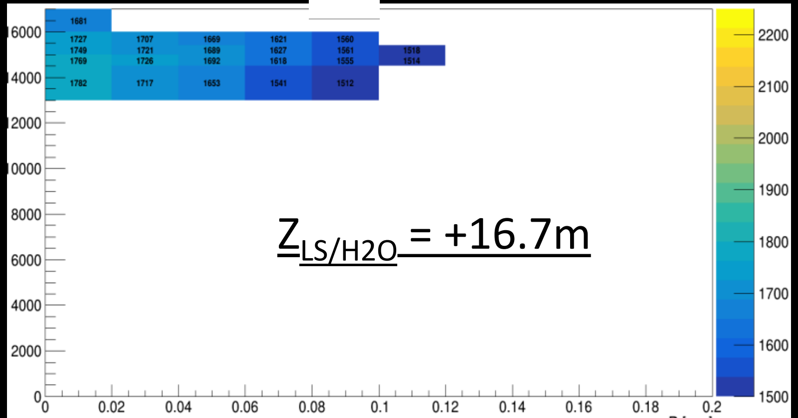
Basic Calibration during Fill

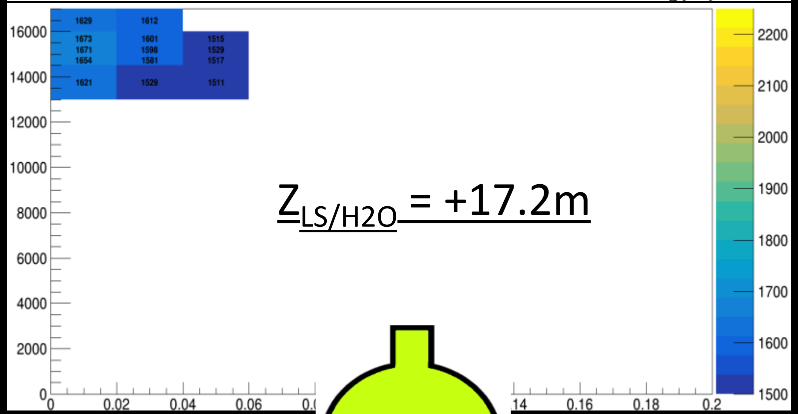
Detector non-uniformity:

Po214 Number of PMT hits vs position









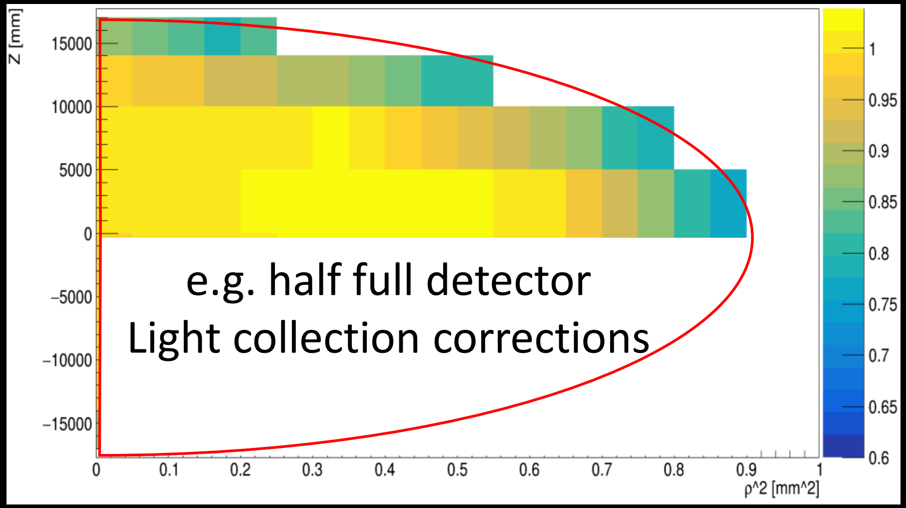
Average light yield seems to depend on interface level

Basic Calibration during Fill

- Produce ~weekly updates of detector conditions:
  - Use BiPo214 + neutron followers
    - Light collection vs pos
    - Position resolution vs pos
    - Time residual shapes?
- E.g. Analyser uses the light collection around the detector in the Xth week of 2025

  → Energy reconstruction ~ Apply nhit corrections vs reconstructed position

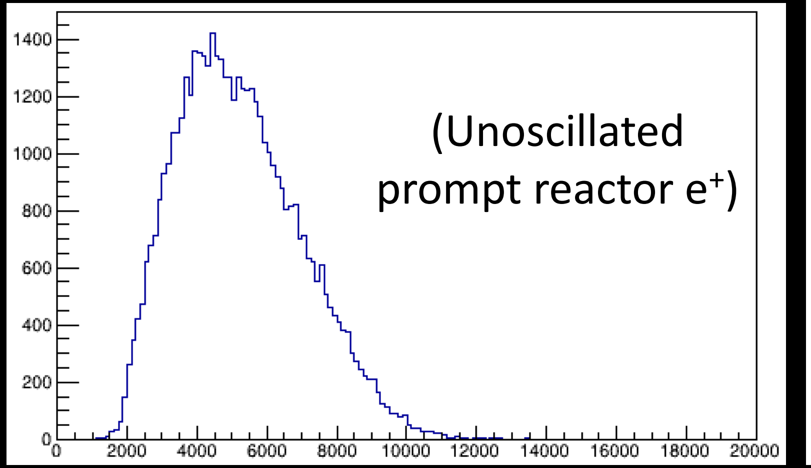
Po214 light collection
(relative to centre) vs QCtr position



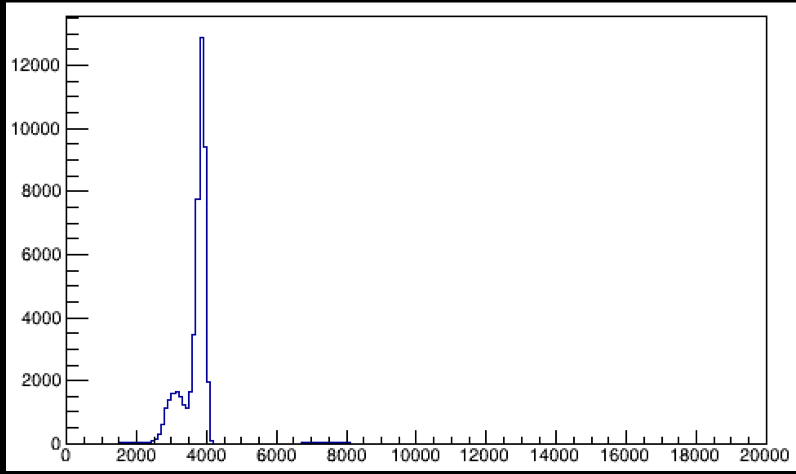
NEED:
→ P.e. separation, uncertainties understood
→ Improved, simple position reconstruction

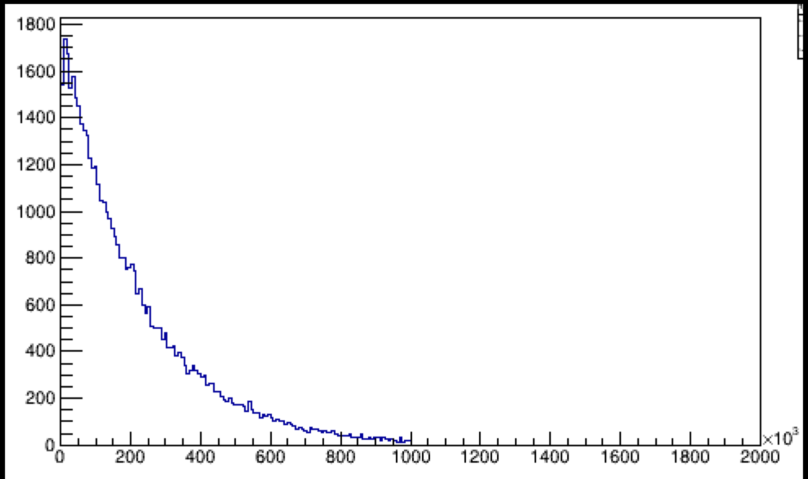
Applying Simple Calibration to Reactor IBDs

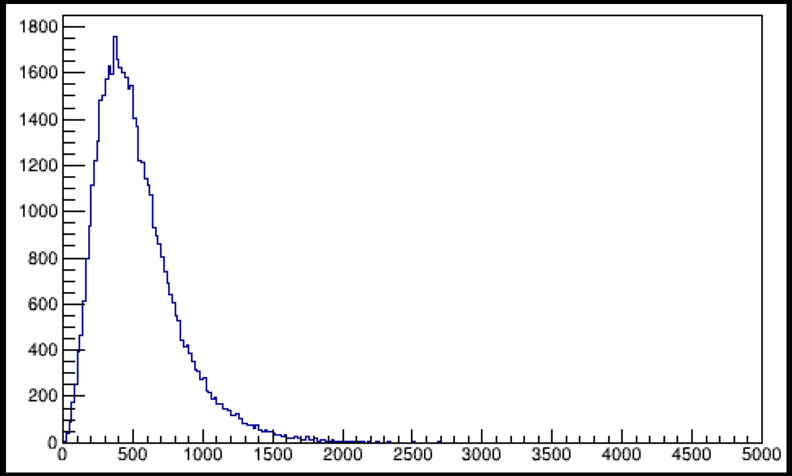
Tagging IBDs with Simple Reconstruction



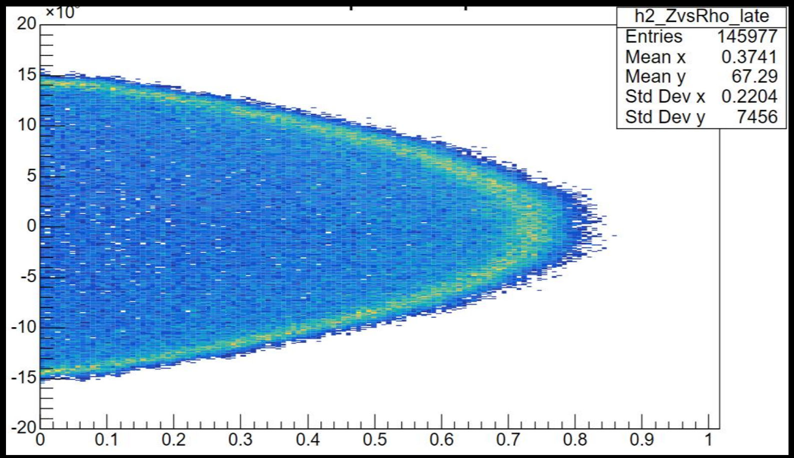
Prompt (e+) npe


Late (neutron) npe


delT [ns]


delR QCtr [mm]

QCtr z [mm]



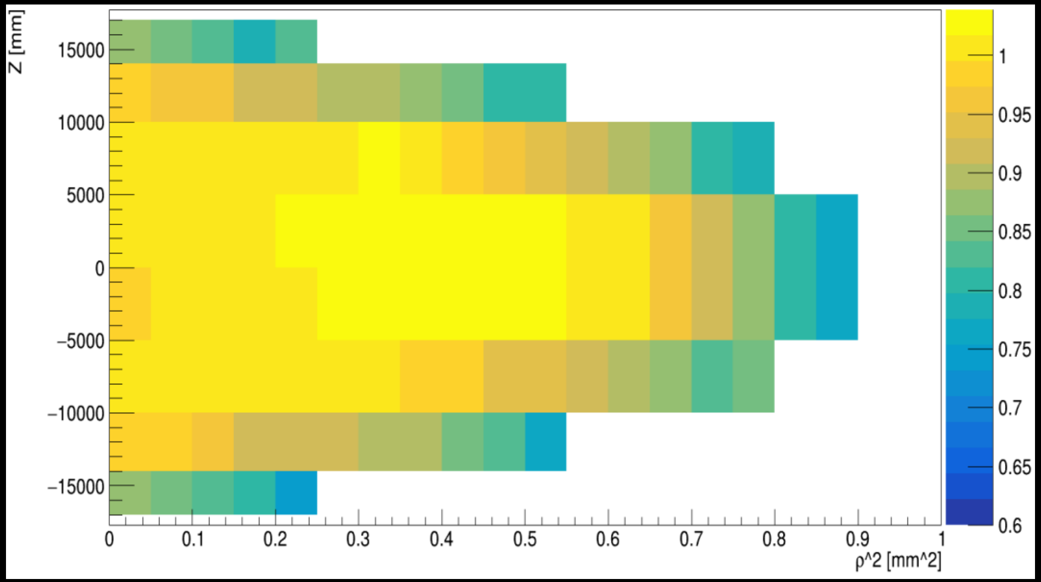
QCtr $(x^2 + y^2) / 17.7^2$

Simple calibration example

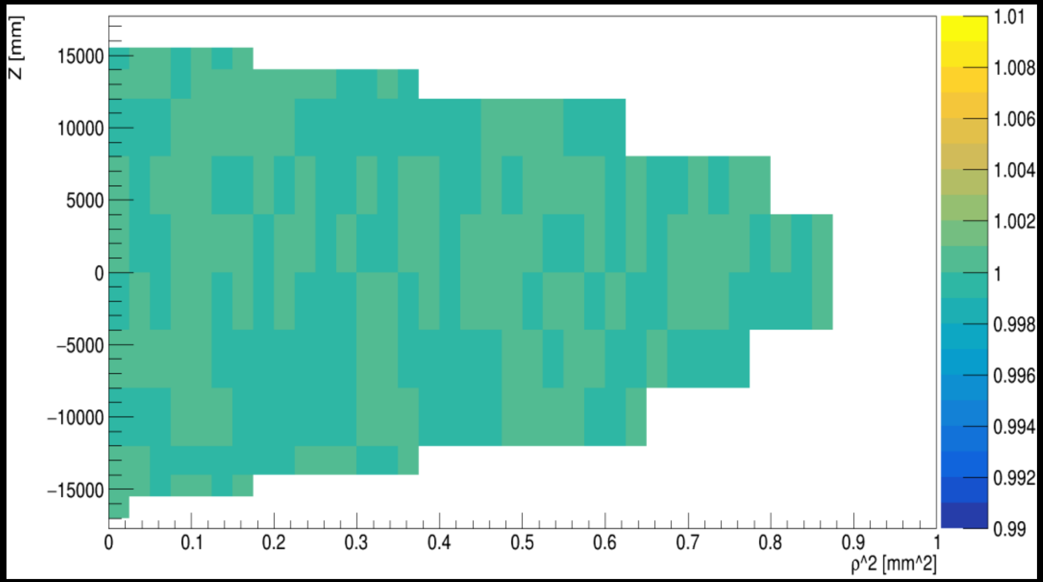
- Use tagged BiPo214 to correct #PMT hits vs position

Po214 Mean n.p.e. (relative to centre) vs position

Before Correction



After Correction

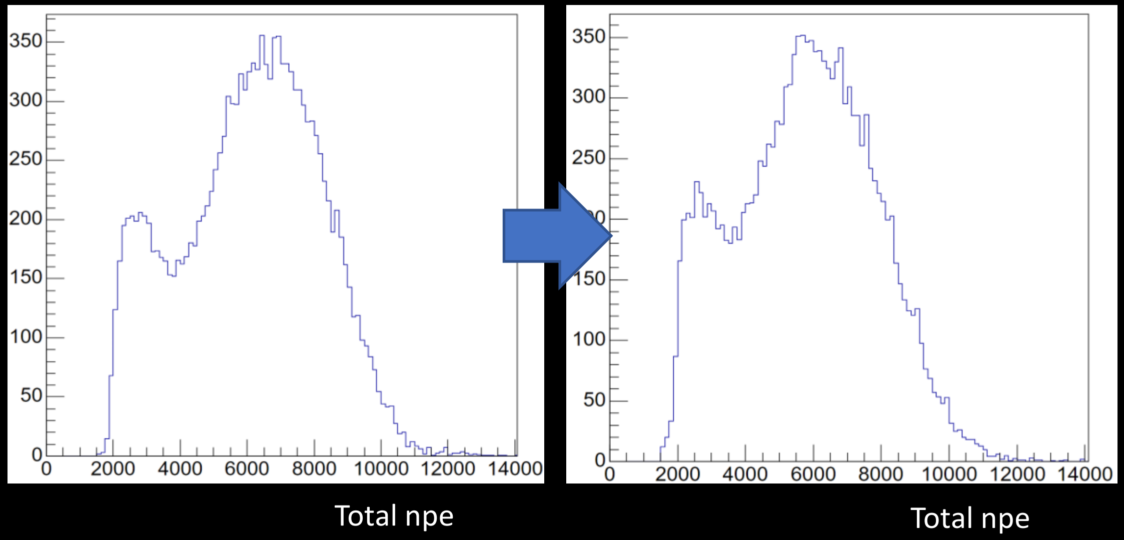


Simple calibration example

- Use tagged BiPo214 to correct #PMT hits vs position
- Apply corrections to tagged IBD events

Can afford a narrower neutron cut → reduced backgrounds

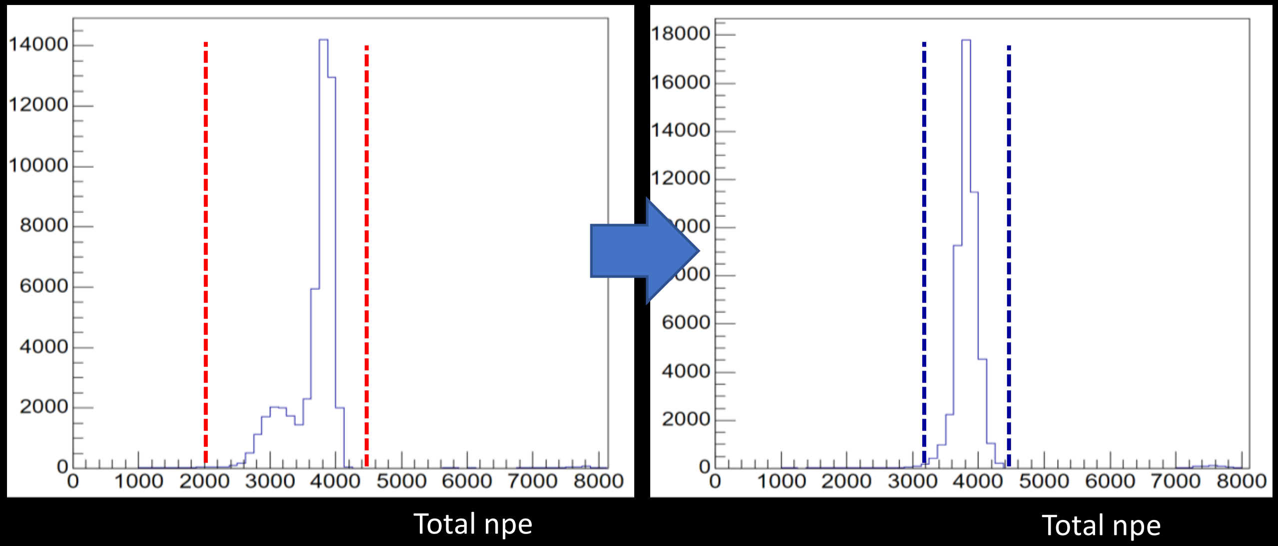
IBD – Prompt e$^+$ (oscillated)



Before Correction

After Correction

IBD – Late neutron



Before Correction

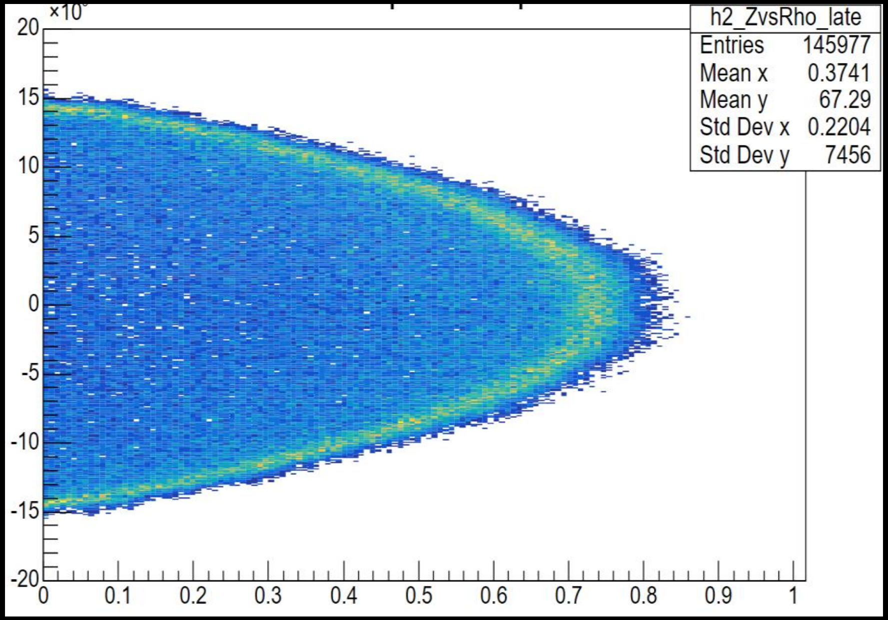
After Correction

IBDs in LS → Simple Example Case #1

Case 1:

→ Don't trust position recon accuracy for a FV cut, use it for delR only

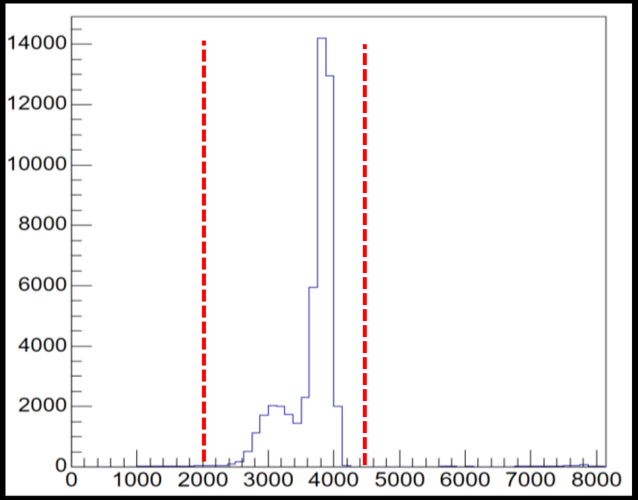
→ Don't use non-uniformity corrections



Example IBD cuts

Prompt	Late
R_{Qctr} < --	
E > 1500 PMT hits	**2000 < E < 4500 hits**
Δr < 1.5 m	
1200ns < Δt < 1ms	

No energy correction



Cut signal efficiency: ~95%
BG: Accidentals = 22 /day
(no muon veto)

IBDs in LS → Simple Example Case #2

Case 2:

→ Don't trust position recon accuracy for a FV cut, use it for delR only

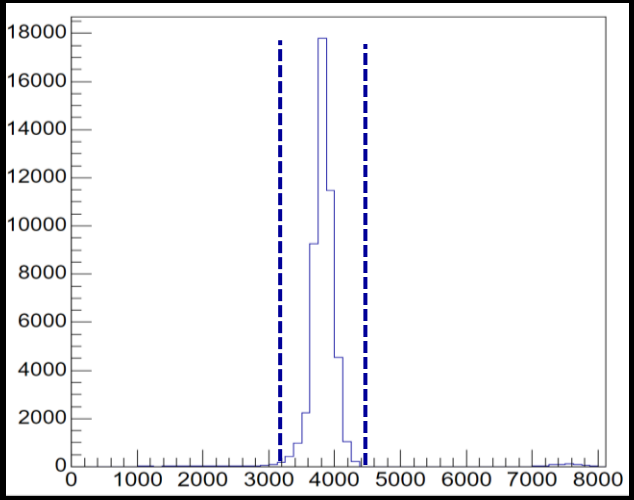
→ Apply non-uniformity corrections (BiPo214)

Example IBD cuts

Prompt	Late
R_{Qctr} < --	
E > 1500 PMT hits	**3300 < E < 4300 hits**
Δr < 1.5 m	
1200ns < Δt < 1ms	

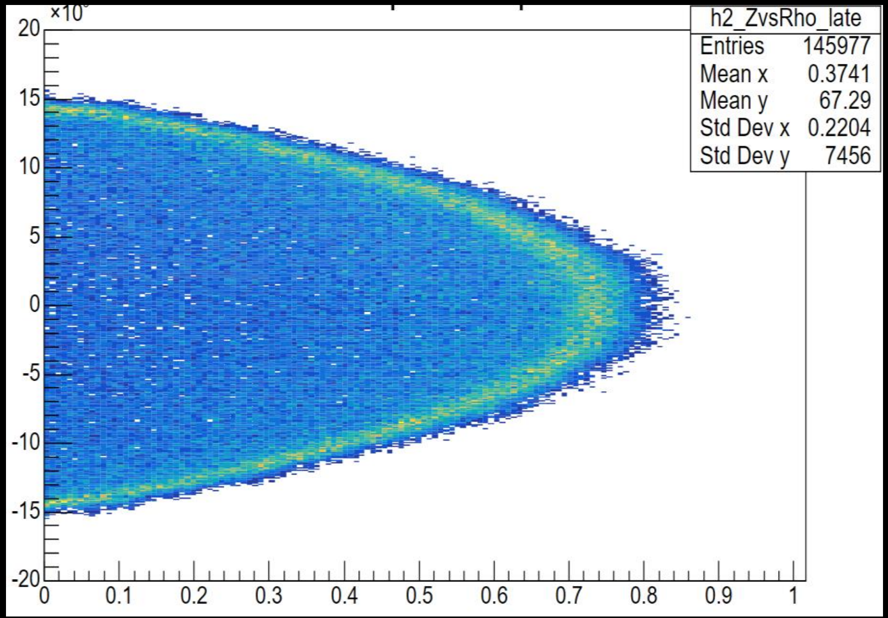
Cut signal efficiency: ~95%
BG: Accidentals = 16.7 /day
(no muon veto)

Applying energy correction



Total npe

QCtr z [mm]



QCtr $(x^2 + y^2) / 17.7^2$

IBDs in LS → Simple Example Case #3

Case 3:

→ Apply a FV cut
(NEED: calibration sources near the AV)

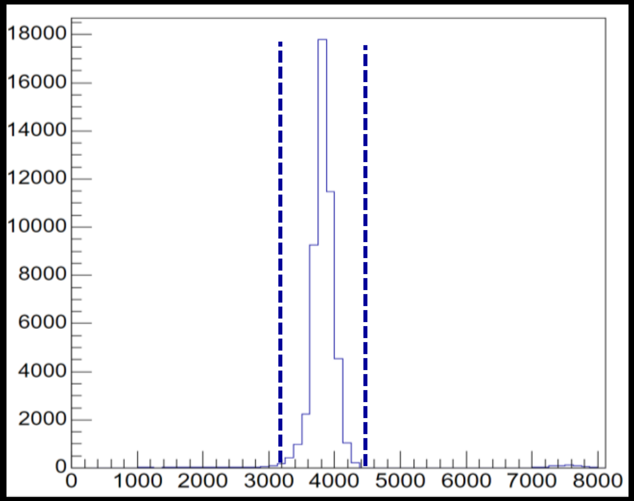
→ Apply non-uniformity corrections (BiPo214)

Example IBD cuts

Prompt	Late
R_{Qctr} < 15.7m	
E > 1500 PMT hits	**3300 < E < 4300 hits**
Δr < 1.5 m	
1200ns < Δt < 1ms	

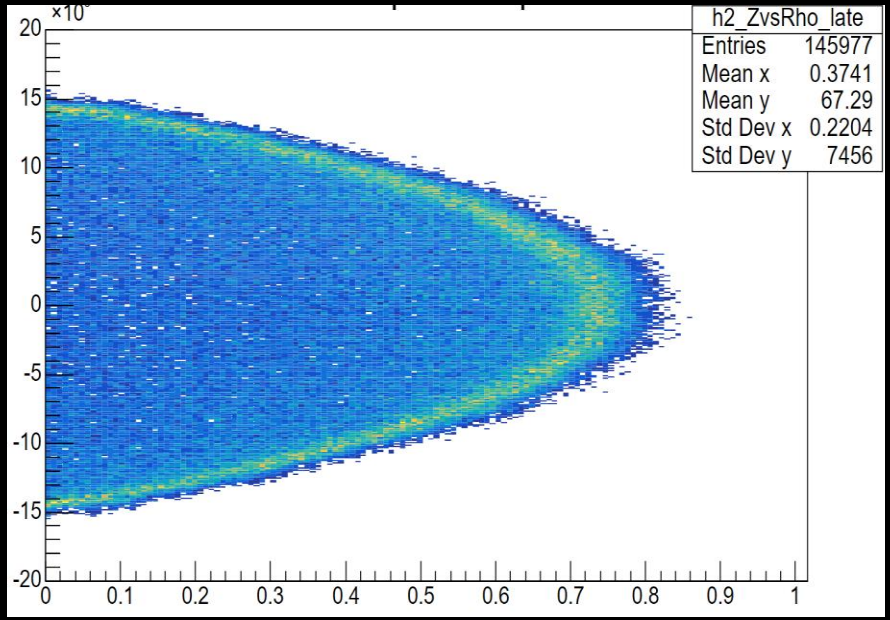
Cut signal efficiency: ~77%
BG: Accidentals = ~ 0.5 /day
(no muon veto)

Applying energy correction



Total npe

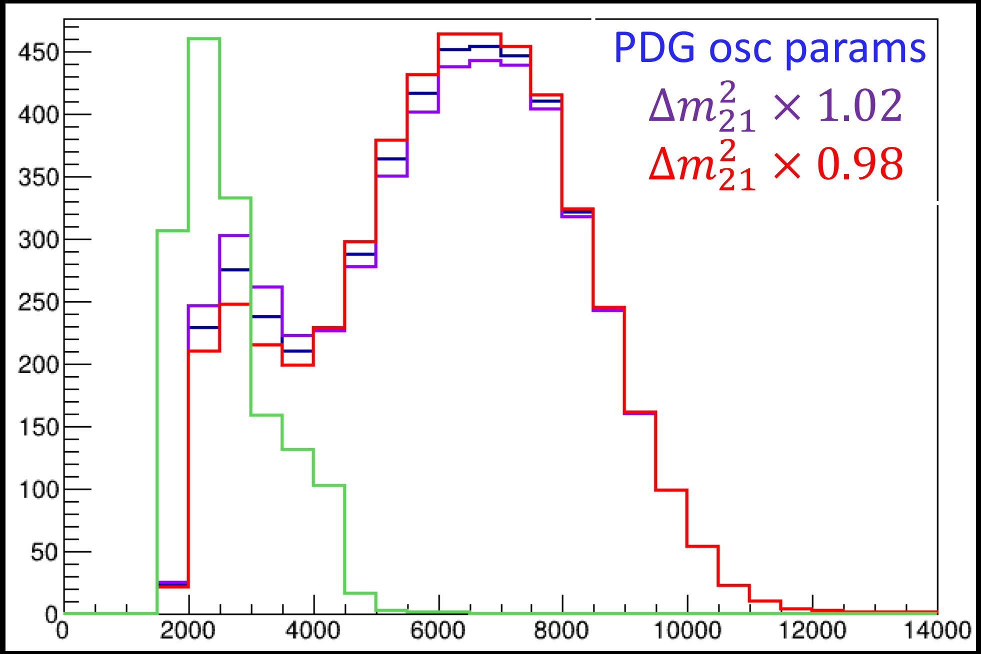
QCtr z [mm]



QCtr $(x^2 + y^2) / 17.7^2$

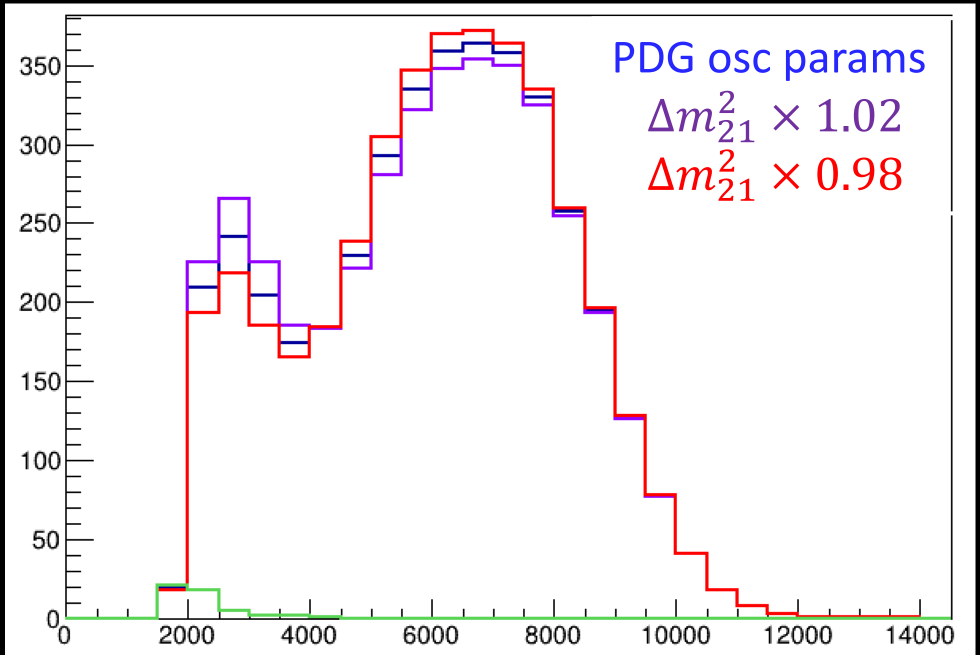
Oscillation parameter extraction

- No FV cut (high accidentals, lower uncert)
- Non uniformity correction applied



Total npe (~energy)

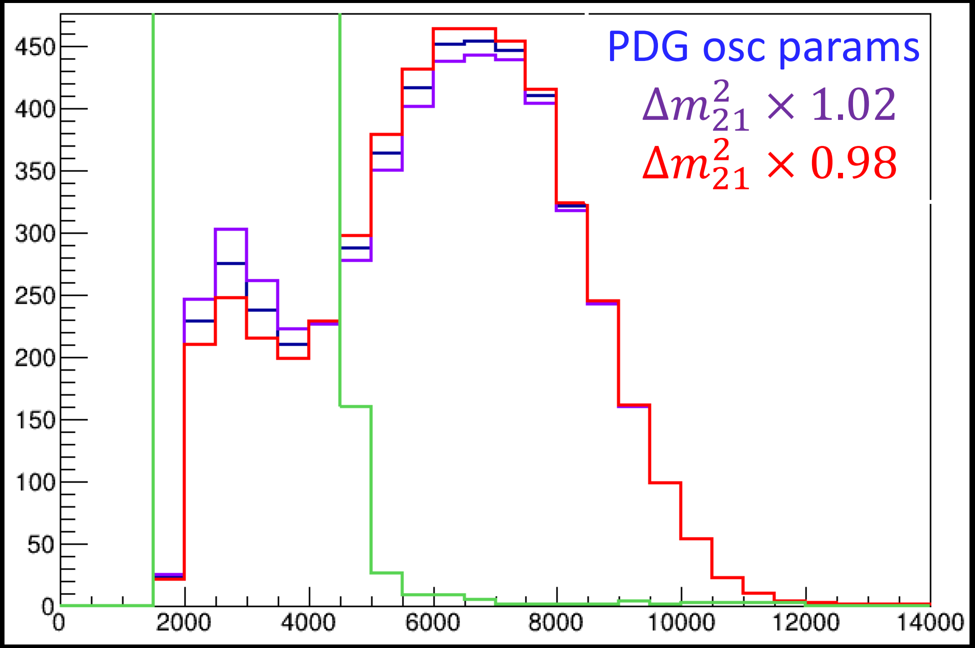
- FV cut of 15.7m (lower accidentals, needs calibration near edge for uncertainty)
- Non uniformity correction applied



Total npe (~energy)

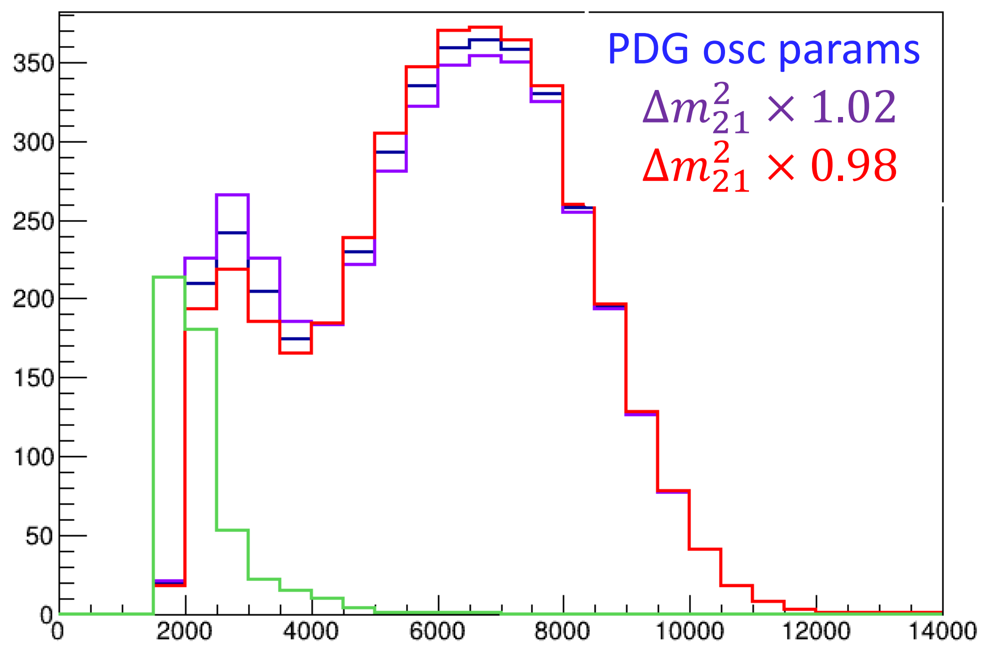
Oscillation parameter extraction

- No FV cut (high accidentals, lower uncert)
- Non uniformity correction applied



Total npe (~energy)

- FV cut of 15.7m (lower accidentals, needs calibration near edge for uncertainty)
- Non uniformity correction applied



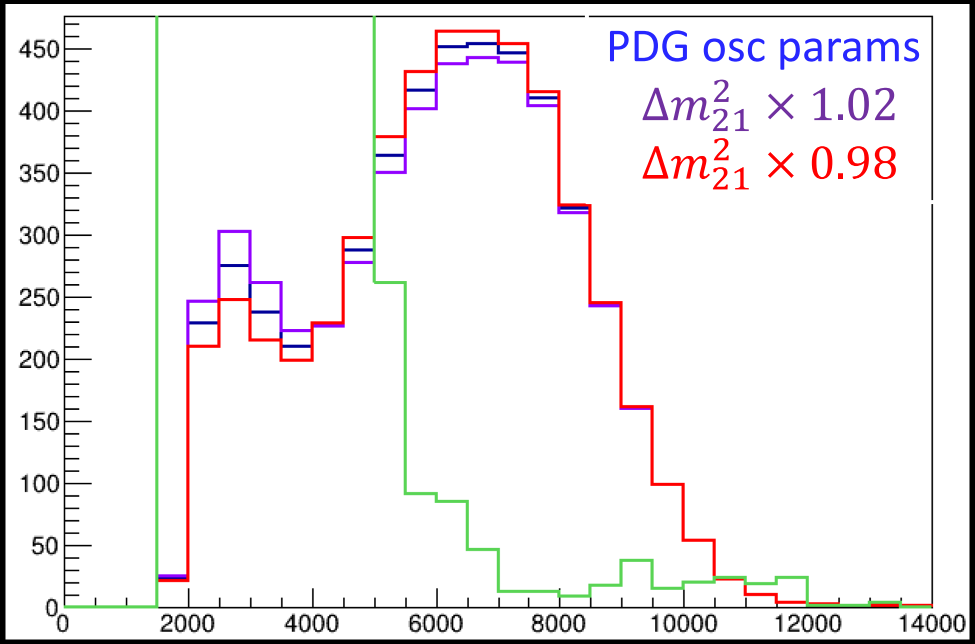
Total npe (~energy)

e.g.
x10 Acc

(Although external backgrounds should be well known!)

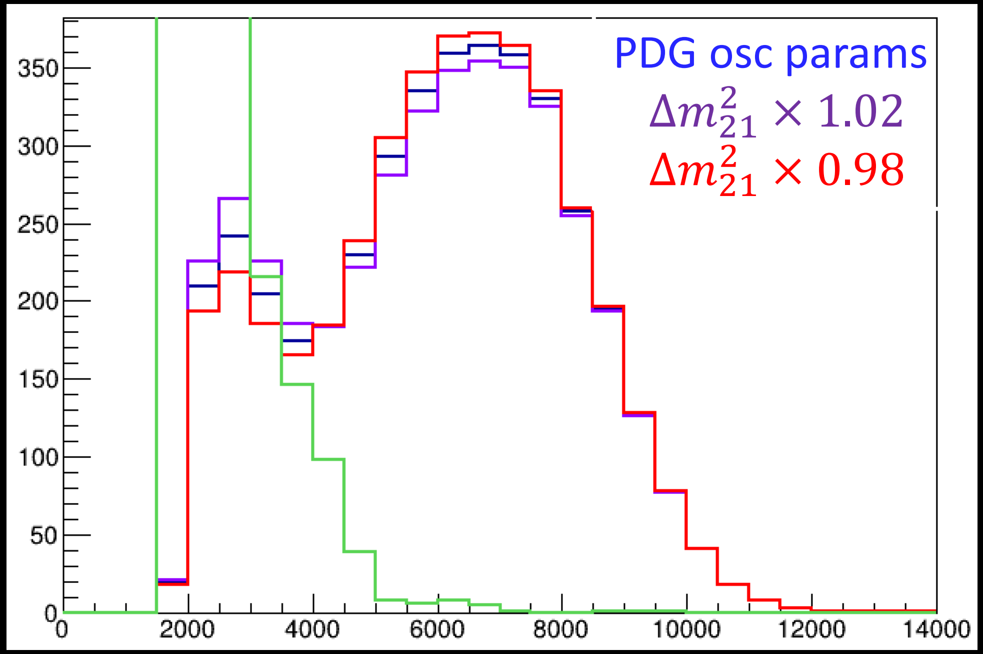
Oscillation parameter extraction

- No FV cut (high accidentals, lower uncert)
- Non uniformity correction applied



Total npe (~energy)

- FV cut of 15.7m (lower accidentals, needs calibration near edge for uncertainty)
- Non uniformity correction applied



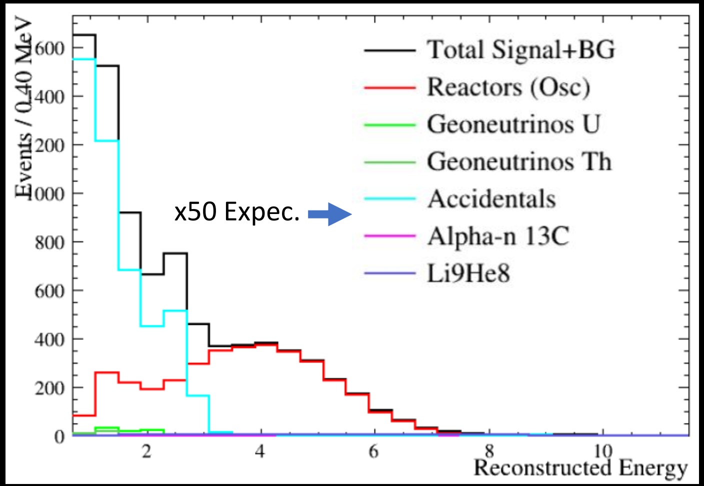
Total npe (~energy)

e.g.
x100 Acc

(Although external backgrounds should be well known!)

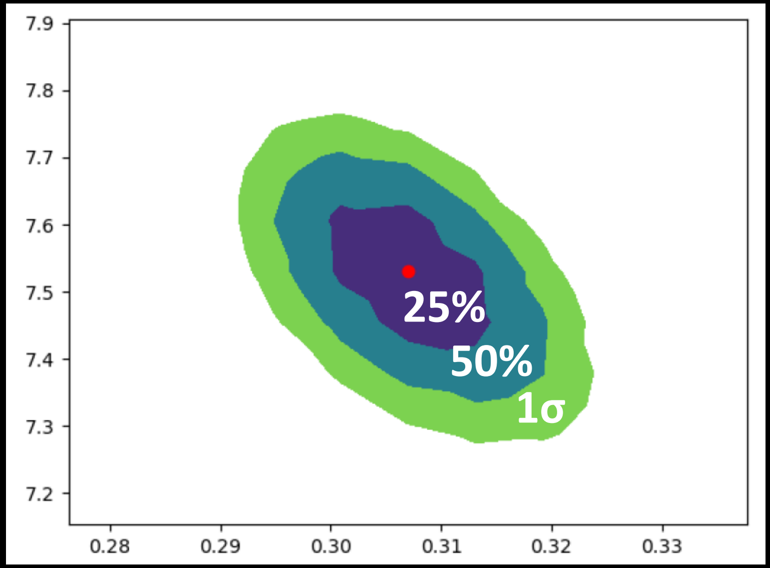
(Previous sensitivity study from DocDB #11328)

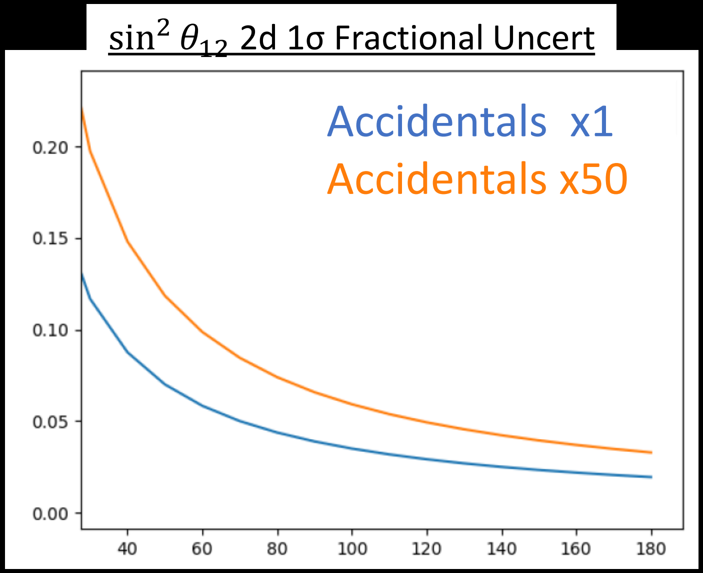
Sensitivity to Δm^2_{21} and $\sin^2\theta_{12}$



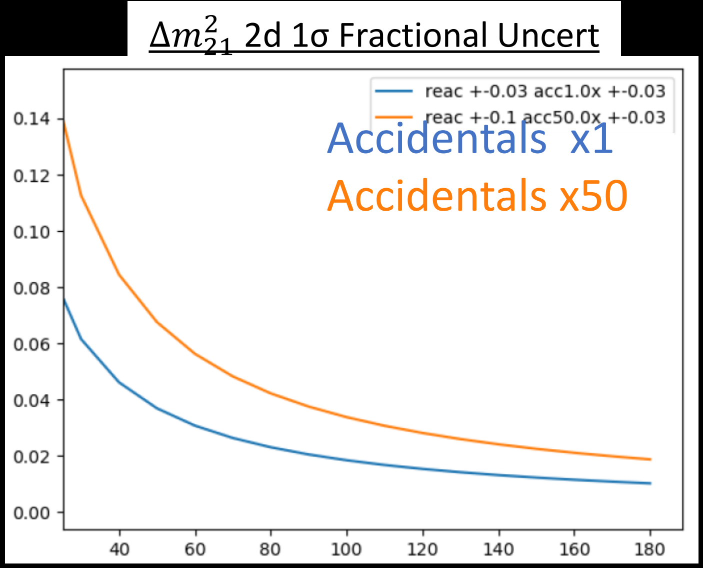
Profile likelihood

(assuming pdg values of Δm^2_{32} and θ_{13})





Days into fill



Days into fill

Current global PDG:

Global Oscillation Parameters 2021	
Δm^2_{21}	$7.53^{+0.18}_{-0.18}\times10^{-5}\mathrm{eV}^2$
$\sin^2(\theta_{12})$	$0.307^{+0.013}_{-0.013}$

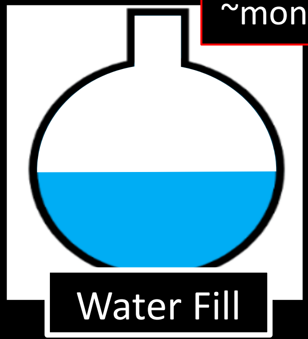
IBDs in LS during Mixed Phase Conclusion

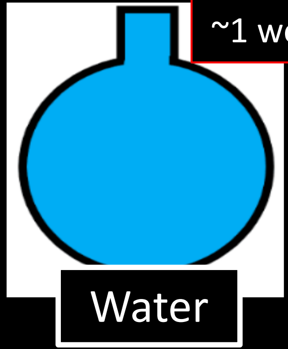
Water:

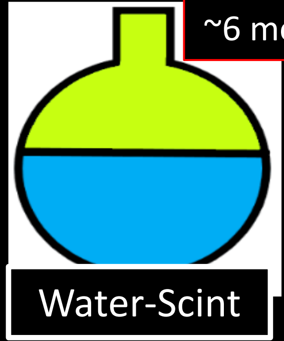
- IBD measurement in water looks feasible, could be world-leading in ~1 week and would be an impressive demonstration of detector understanding.

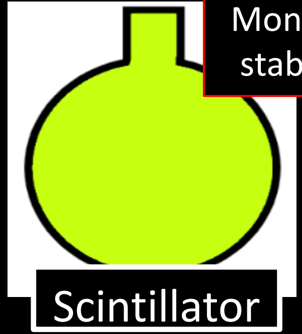
Liquid Scintillator:

- Even with simple reconstruction, can run a respectable neutrino oscillation measurement campaign.
- Not aiming for ground-breaking measurements is still a fantastic test of all the tools needed in future analyses.









- Plan in place
- Needs work, people assigned
- Urgent

Physics in each phase

Water Filling

- Any Physics?

Full water

- Measure IBDs in Water
- Measure basic radioactivity

Filling LS

- Measure IBDs in LS
  - IBD backgrounds
- Measure U/Th conc : BiPo212/214 (in early 50/100t)

Early Full Fill

- JUNO physics analyses start

Needs / Tasks

Water Filling

→ Calibrate Large PMTs
→ Measure PMT DN rates, Dark noise trigger rates

Full water

→ Position + Direction Reconstruction
→ Muon Tag + Recon + Veto
→ Trigger Threshold Efficiency:
  → Deploy AmC
→ PMT timing calib
→ Dark noise trigger measurement
→ Calibrate Water optics
→ Data quality/cleaning

Filling LS

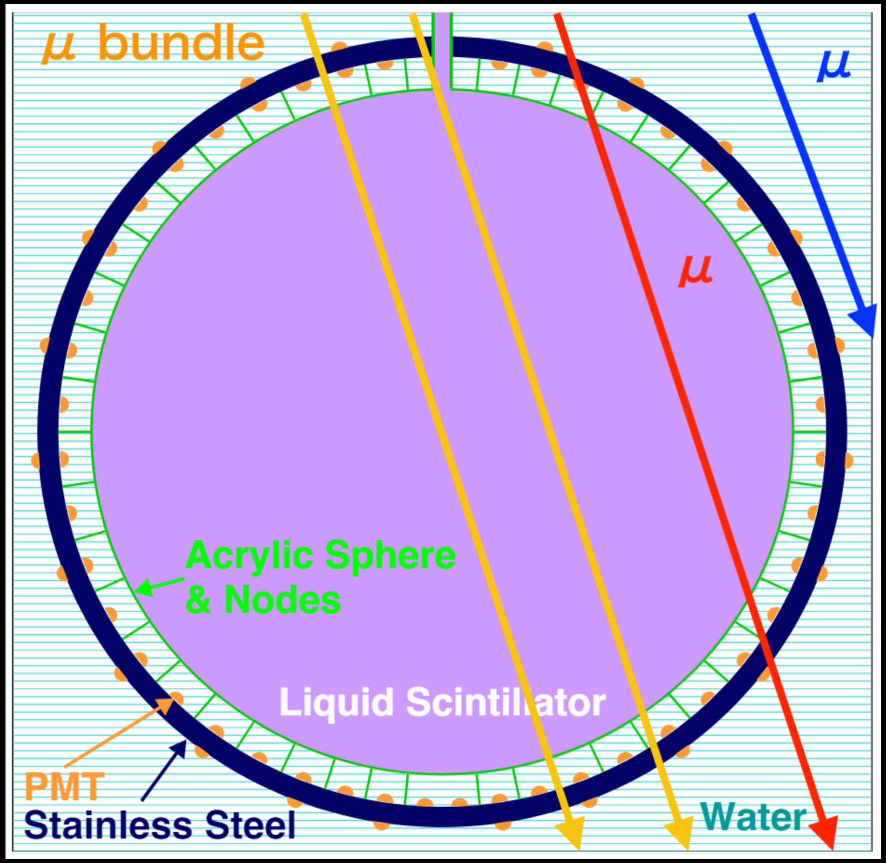
→ Position + Energy recon + PSD
→ BiPo 212(Th)/214(U) tagging
→ Background singles spectrum and rates
→ Muon Tag + Recon + Veto
→ Calibration: Deploy sources + Naturally occurring radioactivity
→ Start LS optics calibration?
→ Data quality/cleaning

Backup

Muon tagging, reconstruction + vetoing

Muon tagging + reconstruction using WP PMTs

- Muon tagging, reconstruction and vetoing is a need for almost all analyses (and isn't fully mature in full fill).
- Akira→Yankai has developed framework that uses WP PMTs only for muon ID and reconstruction → can smoothly use throughout LS/Water filling!
- Uses charge density-finding algorithms to reconstruct direction, but also muon types and multiplicity. DocDB11744



Muon tagging + reconstruction using WP PMTs

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