Towards the atmospheric mass splitting Δm^2_{31} in JUNO

Vanessa Cerrone, on behalf of the Padova analysis group

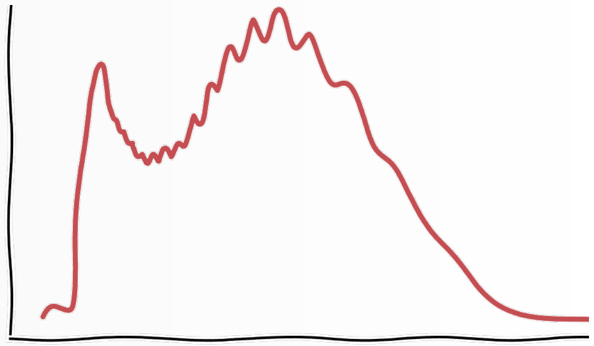
29/03/2022 -- JUNO Italia meeting, Roma Tre Università e INFN

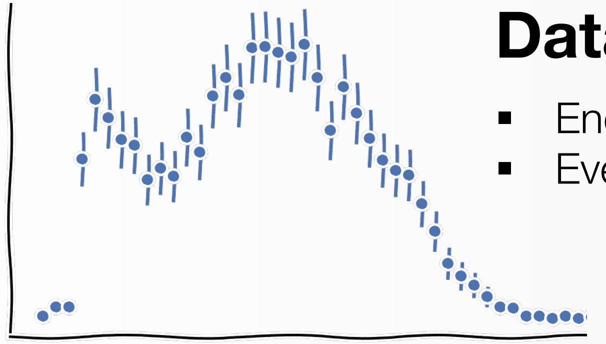
ORSA

(Oscillated Reactor Spectrum Analysis)

Model

- Reactor model
- Backgrounds model
- Covariances
- SNIPER
- Detector response



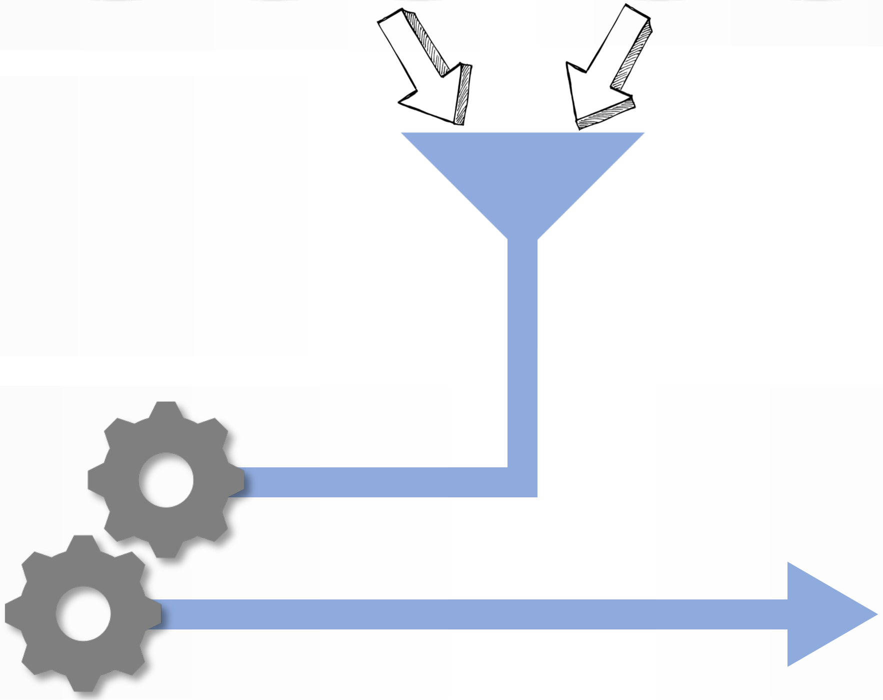


Data processing

- Energy reconstruction
- Event selection

Cost function

- χ^2 (Pearson, Neyman, combined)
- Likelihood (binned, extended)



Fitter

- Minuit
- Markov Chains MC
- Nested sampling

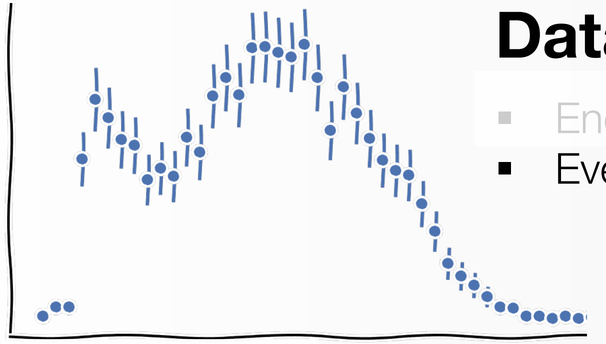
Results

- Best fit values
- Posteriors
- Correlations
- Model selection

ORSA (Oscillated Reactor Spectrum Analysis)

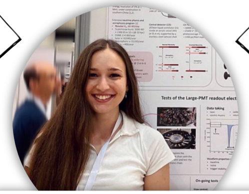
Model

- Reactor model
- Backgrounds model
- Covariances
- SNIPER
- Detector response



Data processing

- Energy reconstruction
- Event selection



Vanessa C.

Cost function

- χ^2 (Pearson, Neyman, combined)
- Likelihood (binned, extended)

Fitter

- Minuit
- Markov Chains MC
- Nested sampling

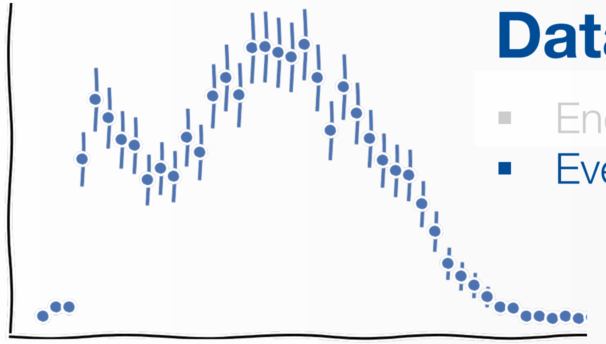
Results

- Best fit values
- Posteriors
- Correlations
- Model selection

ORSA (Oscillated Reactor Spectrum Analysis)

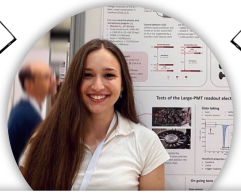
Model

- Reactor model
- Backgrounds model
- Covariances
- SNIPER
- Detector response



Data processing

- Energy reconstruction
- Event selection



Vanessa C.

Cost function

- χ^2 (Pearson, Neyman, combined)
- Likelihood (binned, extended)

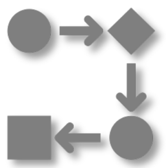
Fitter

- Minuit
- Markov Chains MC
- Nested sampling

Results

- Best fit values
- Posteriors
- Correlations
- Model selection

Analysis workflow



MC simulations (SNiPER)

↓

Reactor IBDs,
^{9}Li/^{8}He,
Accidentals,
Geo-neutrinos

*DocDB 9177- 9405

Analysis workflow

MC simulations (SNiPER)

Reactor IBDs, ^{9}Li/^{8}He, Accidentals, Geo-neutrinos

ORSA **Selection***

Selection efficiency

Rate

Analysis workflow

*DocDB 9177- 9405

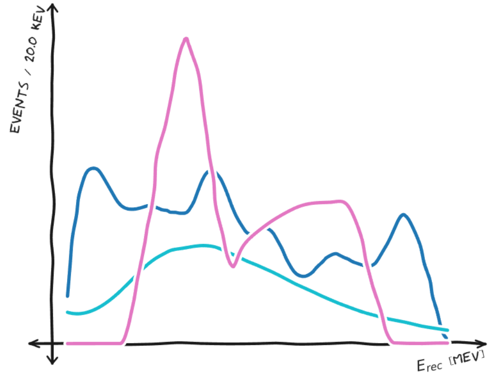
MC simulations (SNiPER)

Reactor IBDs,
$^{9}Li/^{8}He$,
Accidentals,
Geo-neutrinos

ORSA **Selection***

Selection efficiency

Rate



MC-driven PDFs production

Shape

*DocDB 9177- 9405

Analysis workflow

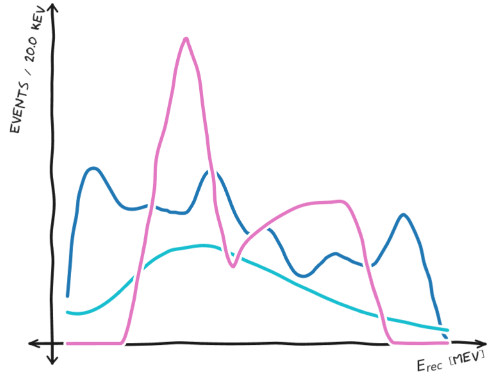
MC simulations (SNiPER)

Reactor IBDs,
$^{9}Li/^{8}He$,
Accidentals,
Geo-neutrinos

ORSA **Selection***

Selection efficiency

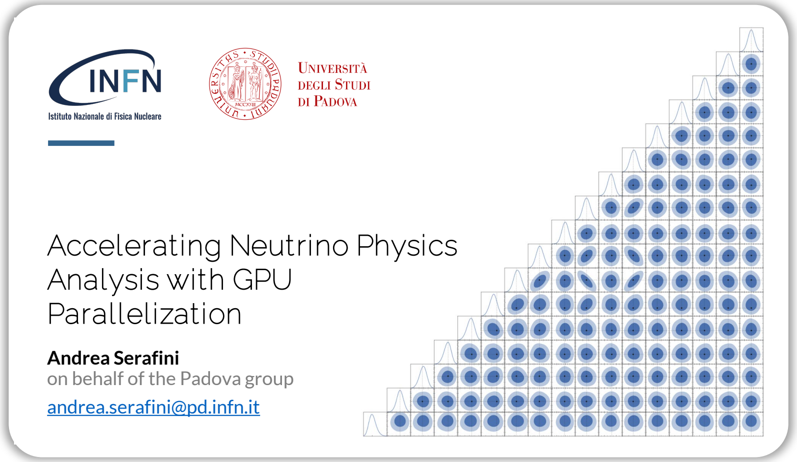
Rate



MC-driven PDFs production

Shape

Fitter



Analysis workflow

*DocDB 9177- 9405

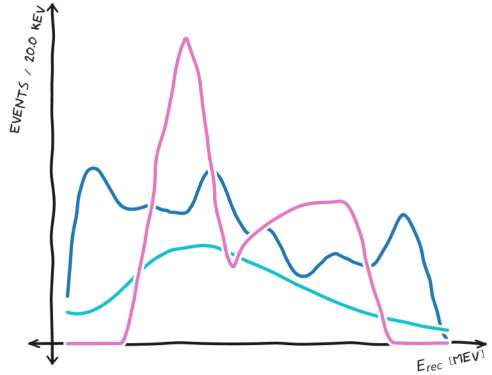
MC simulations (SNiPER)

Reactor IBDs,
$^{9}Li/^{8}He$,
Accidentals,
Geo-neutrinos

ORSA **Selection***

Selection efficiency

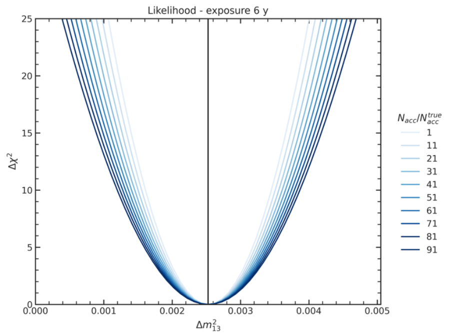
Rate



MC-driven PDFs production

Shape

Fitter



Sensitivity on Δm^2_{31}

*corrected for light yield following DocDB 8296

IBD dataset and pre-selection

Production configuration:

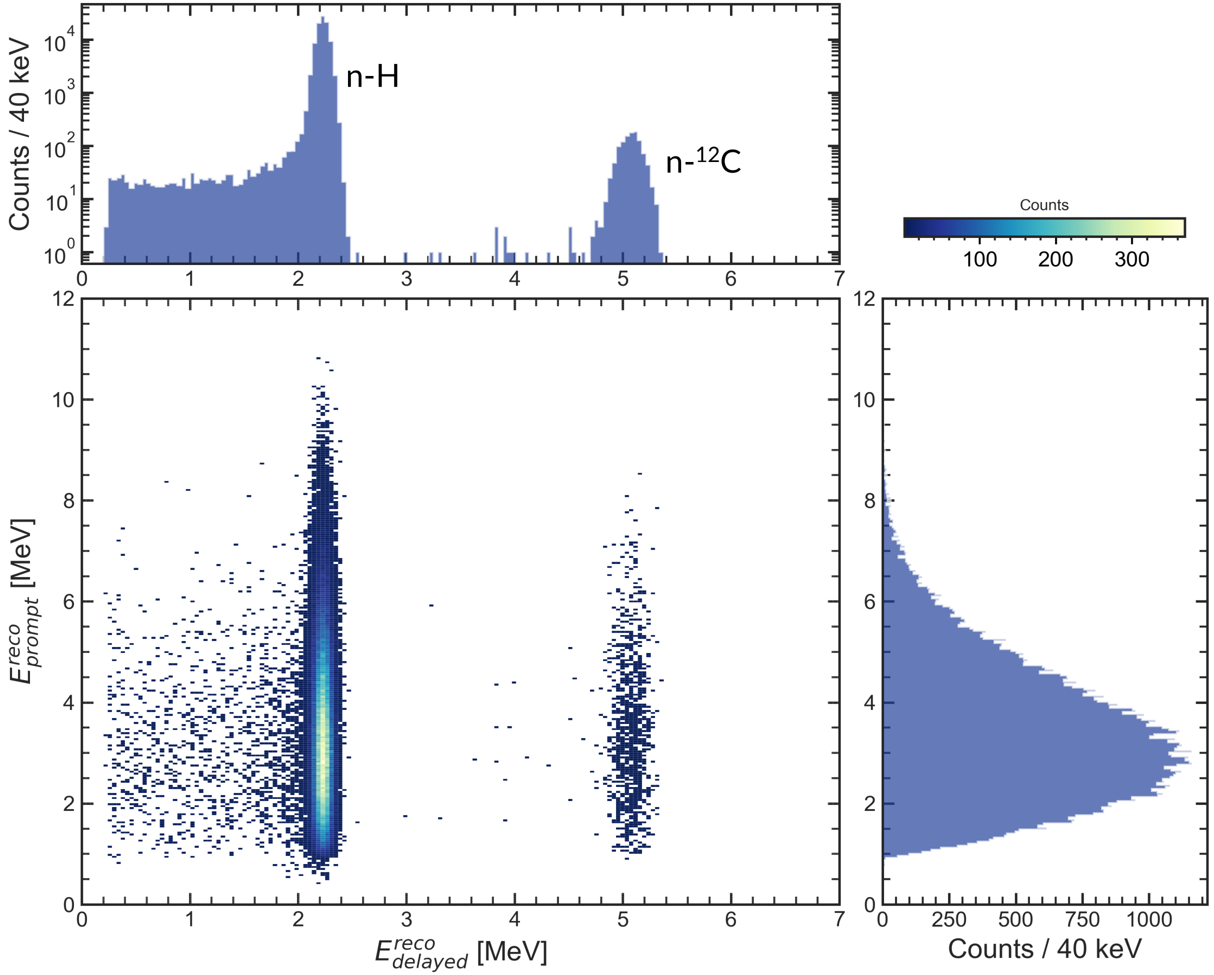
- Offline software version: J22.1.0-rc4
- Reconstruction algorithm: OMILRec*
- Unoscillated IBD events: ~96k

ORSA *selection configuration:**

- Spatial selection cut: Δr < 3 m
- Temporal selection cut: Δt < 2 ms
- Energy cuts: None
- FV cut: No

*DocDB 9177-9405

Energy distribution



[1] Chin. Phys. C 46, 123001 (2022)

IBD: selection efficiency

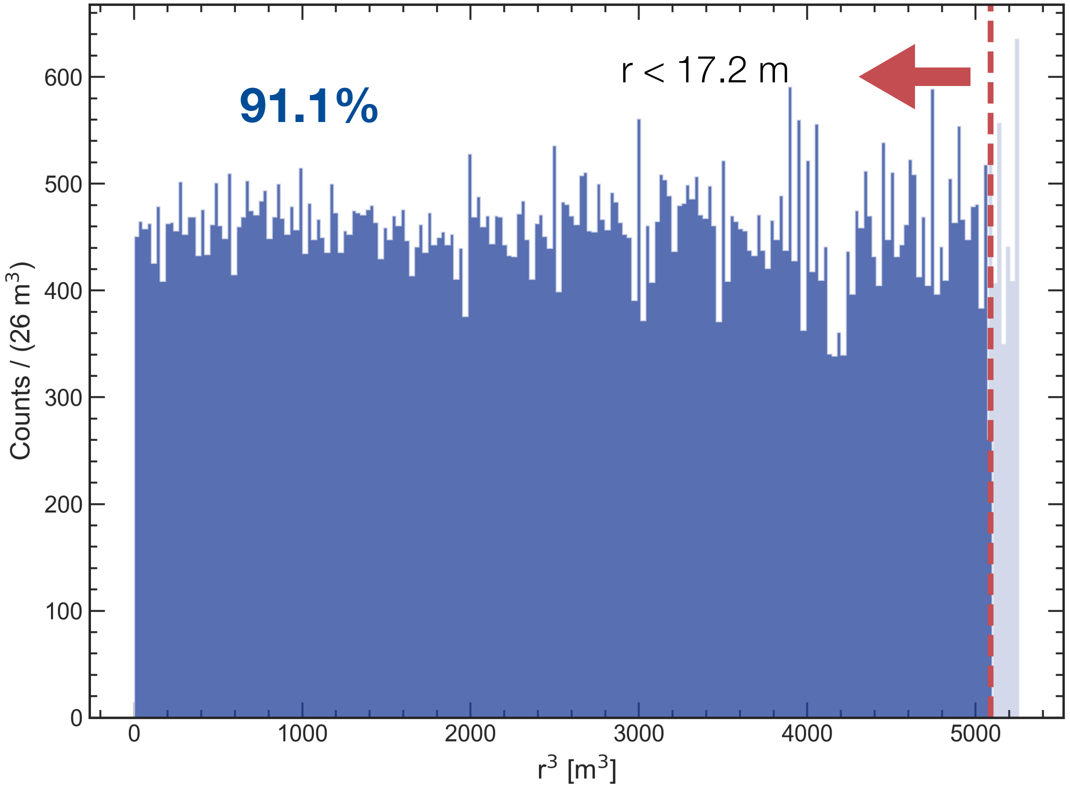
Efficiency	Evts/day
100%	57.4 [1]

[1] Chin. Phys. C 46, 123001 (2022)

IBD: selection efficiency

Efficiency	Evts/day
100%	57.4 [1]

1. Fiducial volume (FV) cut r < 17.2 m

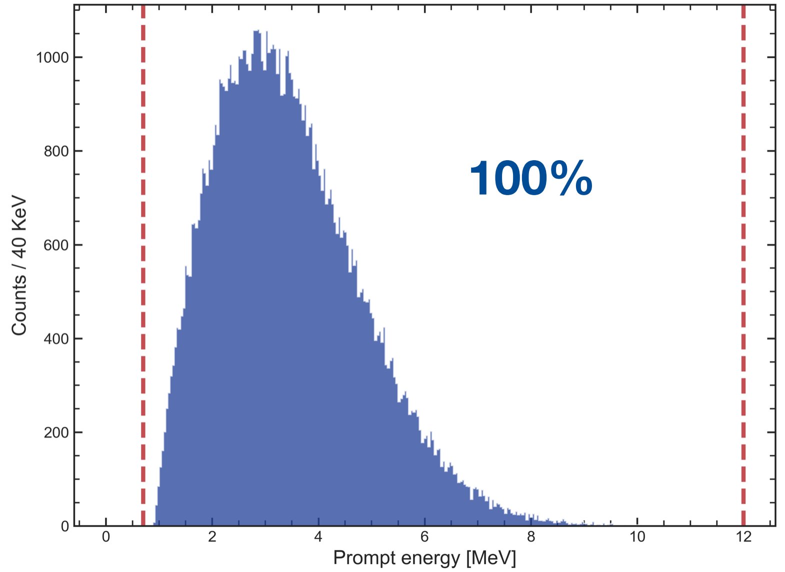


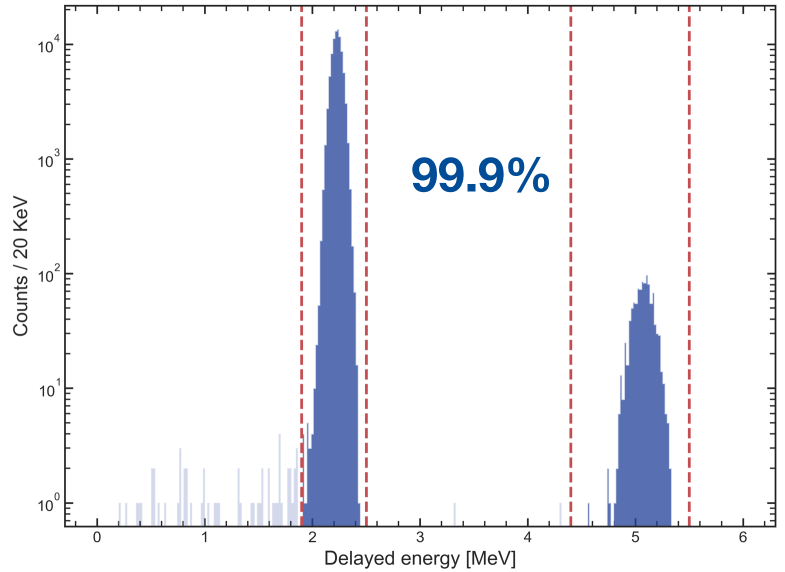
[1] Chin. Phys. C 46, 123001 (2022)

IBD: selection efficiency

	Efficiency	Evts/day
	100%	57.4 [1]
1. Fiducial volume (FV) cut r < 17.2 m	**91.1%**	**52.3**

2. Energy cut
   - Prompt energy $E_p \in (0.7, 12)$ MeV
   - Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV



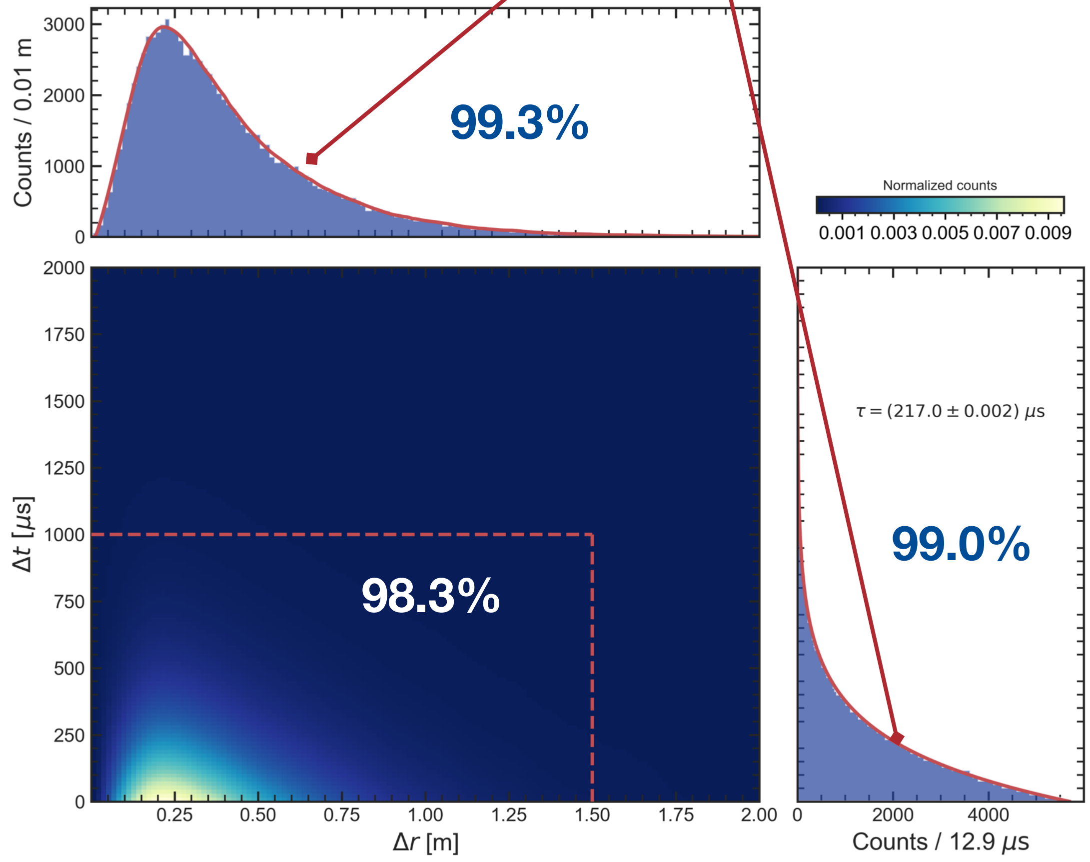


[1] Chin. Phys. C 46, 123001 (2022)

IBD: selection efficiency

	Efficiency	Evts/day
	100%	57.4 [1]
1. Fiducial volume (FV) cut r < 17.2 m	**91.1%**	**52.3**
2. Energy cut		
• Prompt energy $E_p \in (0.7, 12)$ MeV	**100%**	**52.3**
• Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**52.26**
3. Time/vertex cut		
• $\Delta t < 1$ ms $\quad \Delta r < 1.5$ m		

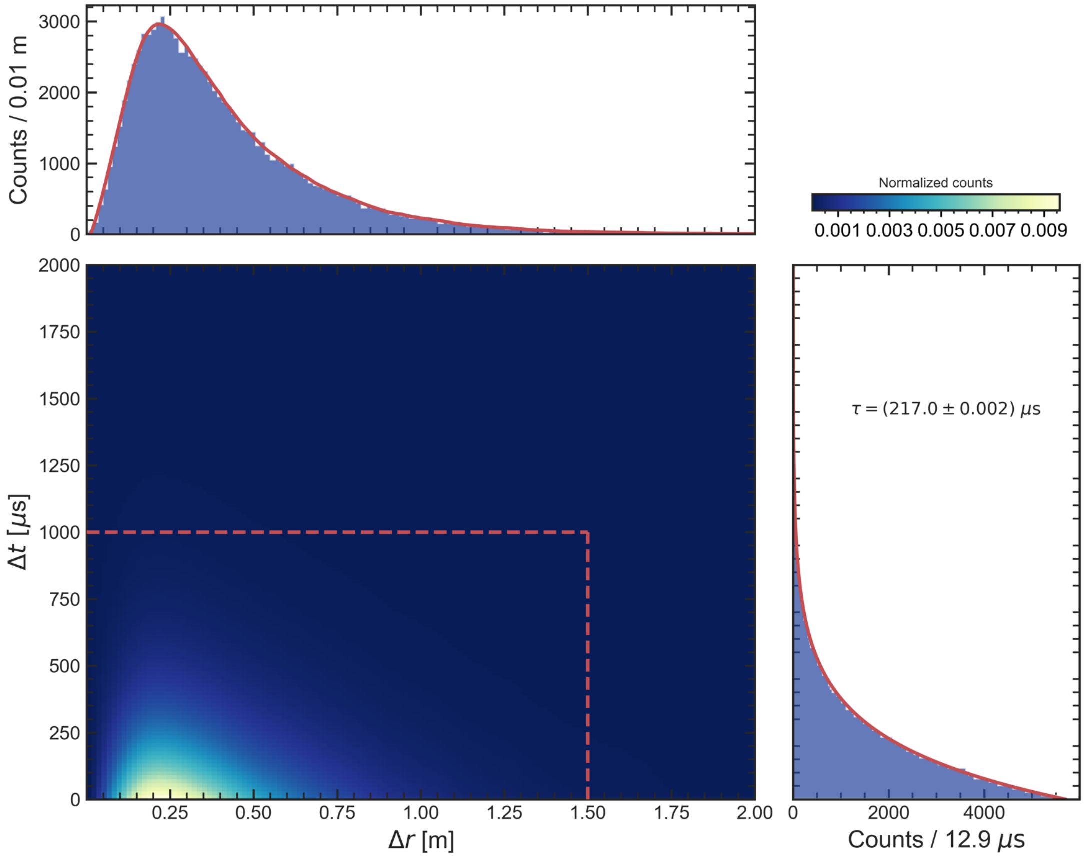
Semi-analytical approach



[1] Chin. Phys. C 46, 123001 (2022)

IBD: selection efficiency

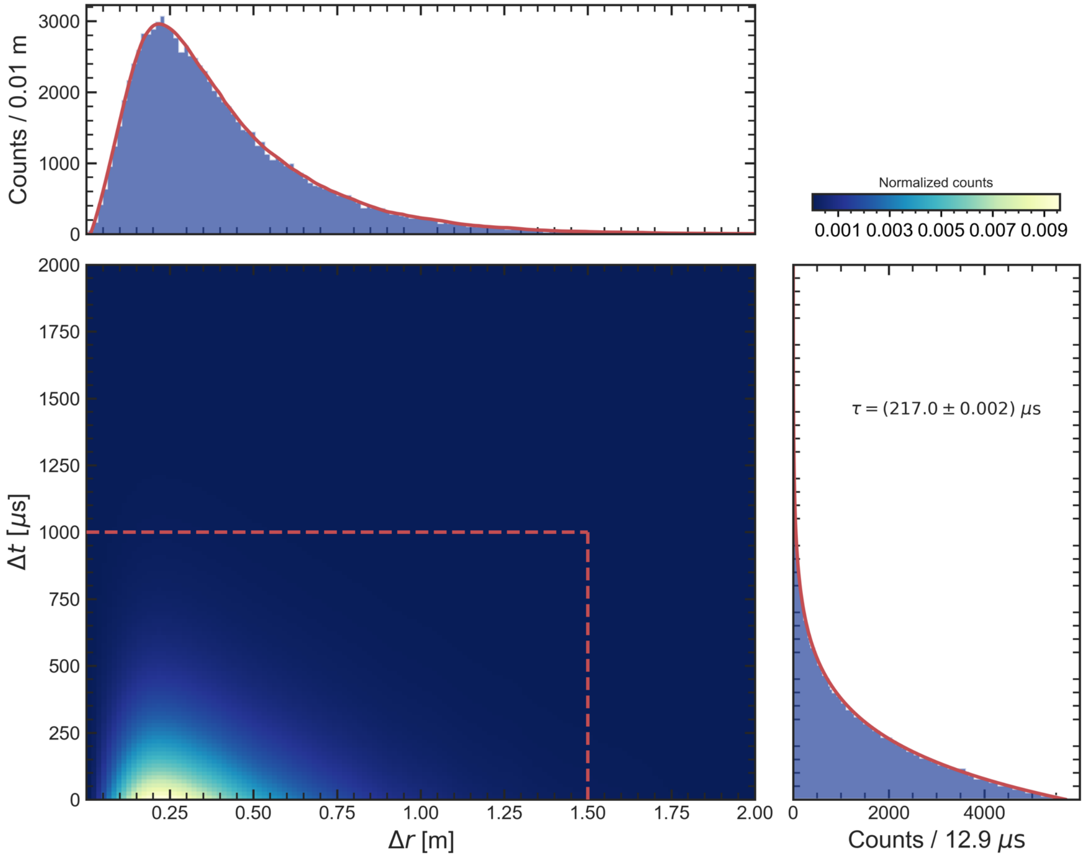
		Efficiency	Evts/day
		100%	57.4 [1]
1. Fiducial volume (FV) cut r < 17.2 m		**91.1%**	**52.3**
2. Energy cut			
• Prompt energy	$E_p \in (0.7, 12)$ MeV	**100%**	**52.3**
• Delayed energy	$E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**52.26**
3. Time/vertex cut			
• $\Delta t < 1$ ms	$\Delta r < 1.5$ m	**98.3%**	**51.4**



[1] Chin. Phys. C 46, 123001 (2022)

IBD: selection efficiency

		Efficiency	Evts/day
		100%	57.4 [1]
1. Fiducial volume (FV) cut r < 17.2 m		**91.1%**	**52.3**
2. Energy cut			
• Prompt energy	$E_p \in (0.7, 12)$ MeV	**100%**	**52.3**
• Delayed energy	$E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**52.26**
3. Time/vertex cut			
• $\Delta t < 1$ ms	$\Delta r < 1.5$ m	**98.3%**	**51.4**
4. Muon veto (temporal + spatial) [1]		**91.6%**	**47.1**
Combined efficiency		**82%**	**47.1**



*DocDB 5837

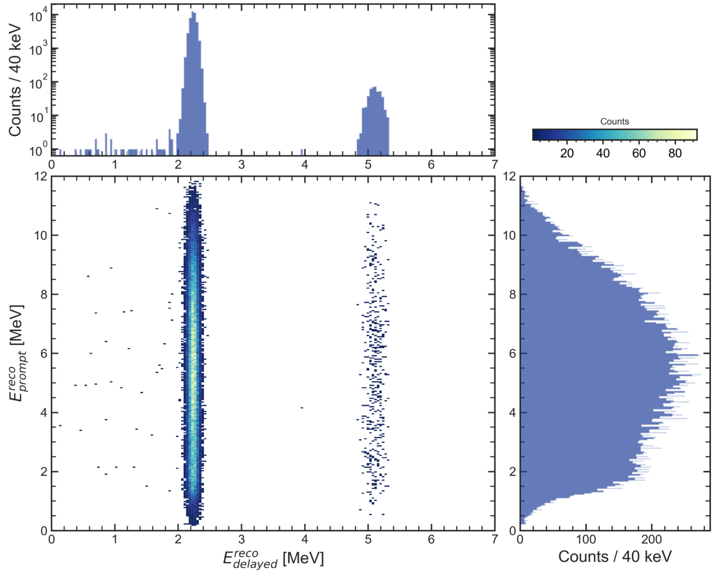
^{9}Li/ ^{8}He cosmogenic background

- Energetic cosmic muons interacting with ^{12}C in the LS can produce radioactive isotopes

- ^{9}Li and ^{8}He are the major correlated cosmogenic background source
  - They can decay emitting a β^- and a neutron mimicking a reactor IBD signal

- Total background level after new muon veto strategy: 0.9 cpd*
  - Apply IBD selection cuts to residual contribution

^{9}Li energy distribution (after FV cut)



Isotope	Branching ratio**	Expected yield [2][3]	Rate after muon veto*
^{9}Li	51 %	127.1 cpd	0.81 cpd
^{8}He	16.1 %	40.4 cpd	0.09 cpd

**in a neutron-unstable excited state

[2] Physical Review C 81.2 (2010): 025807.
[3] Journal of Cosmology and Astroparticle Physics 2013.08 (2013): 049.

[4] After muon veto - DocDB 5837

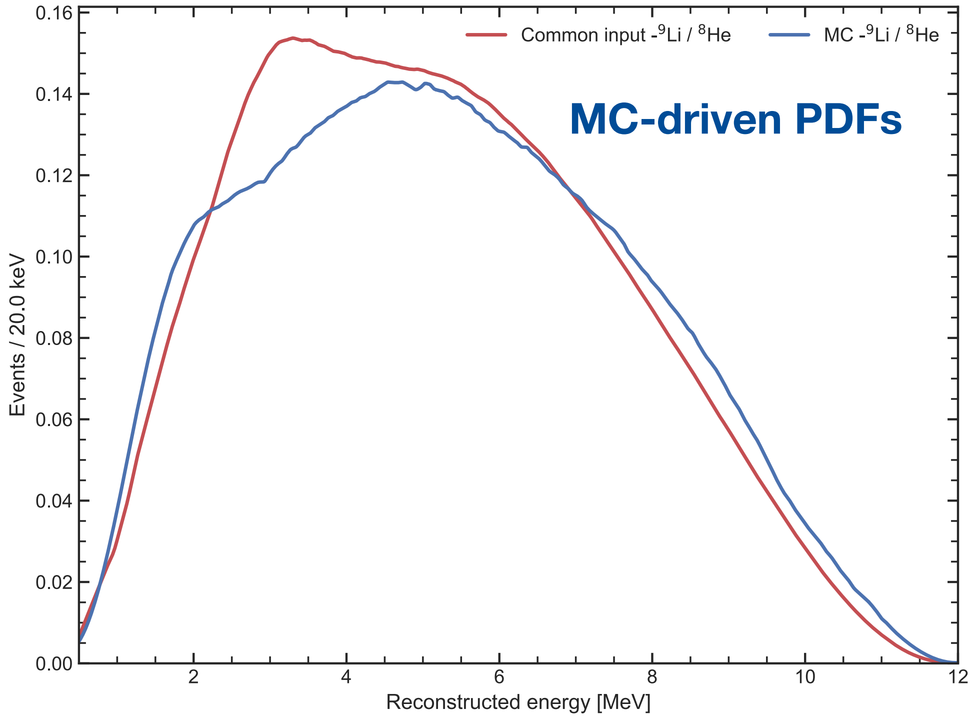
^{9}Li/ ^{8}He: selection efficiency

	^{9}Li		^{8}He	
	Efficiency	Evts/day	Efficiency	Evts/day
	100%	0.81 [4]	100%	0.09 [4]
1. Fiducial volume (FV) cut r < 17.2 m	**91.2%**	**0.75**	**91.4%**	**0.082**
2. Energy cut				
• Prompt energy $E_p \in (0.7, 12)$ MeV	**99.6%**	**0.74**	**99.8%**	**0.082**
• Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**0.74**	**99.9%**	**0.082**
3. Time/vertex cut				
• $\Delta t < 1$ ms $\Delta r < 1.5$ m	**98.4%**	**0.72**	**98.3%**	**0.08**
Combined efficiency	**89%**	**0.72**	**90%**	**0.08**

^{9}Li/ ^{8}He shape and rate

- ^{9}Li rate after IBD selection cuts: 0.72 cpd
- ^{8}He rate after IBD selection cuts: 0.08 cpd

Total residual rate **0.8 cpd**



Geo-neutrinos background

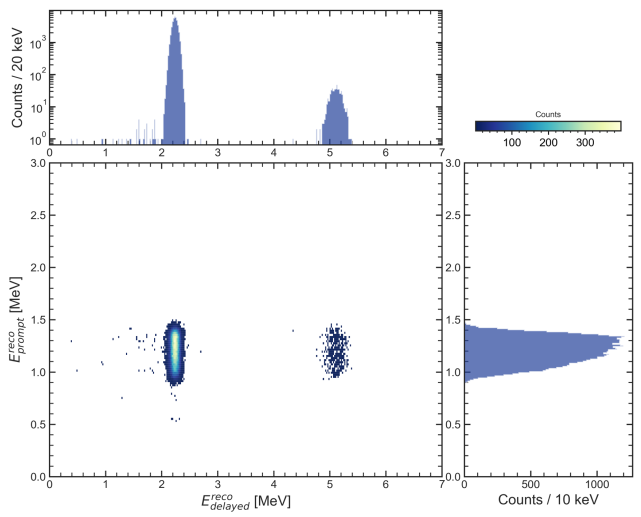
- Geo-neutrinos are produced by radioactive decay chains of Uranium and Thorium inside the Earth

- Detected geo-neutrinos are $\bar{\nu}_e$ originating from β^- decay branches of ^{238}U and ^{232}Th
  - They can be detected through IBD → same signature as the reactor antineutrinos.

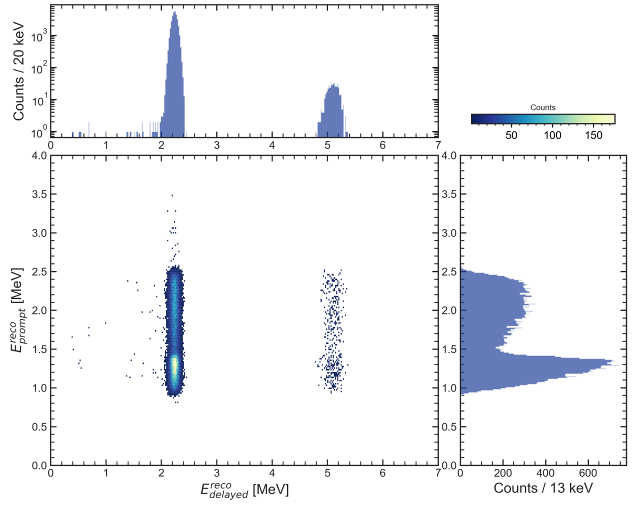
Isotope	Contribution [1]	Expected yield
^{238}U	77 %	1.155 cpd
^{232}Th	23 %	0.345 cpd

[1] Chin. Phys. C 46, 123001 (2022)

^{232}Th geo-ν energy distribution (after FV cut)



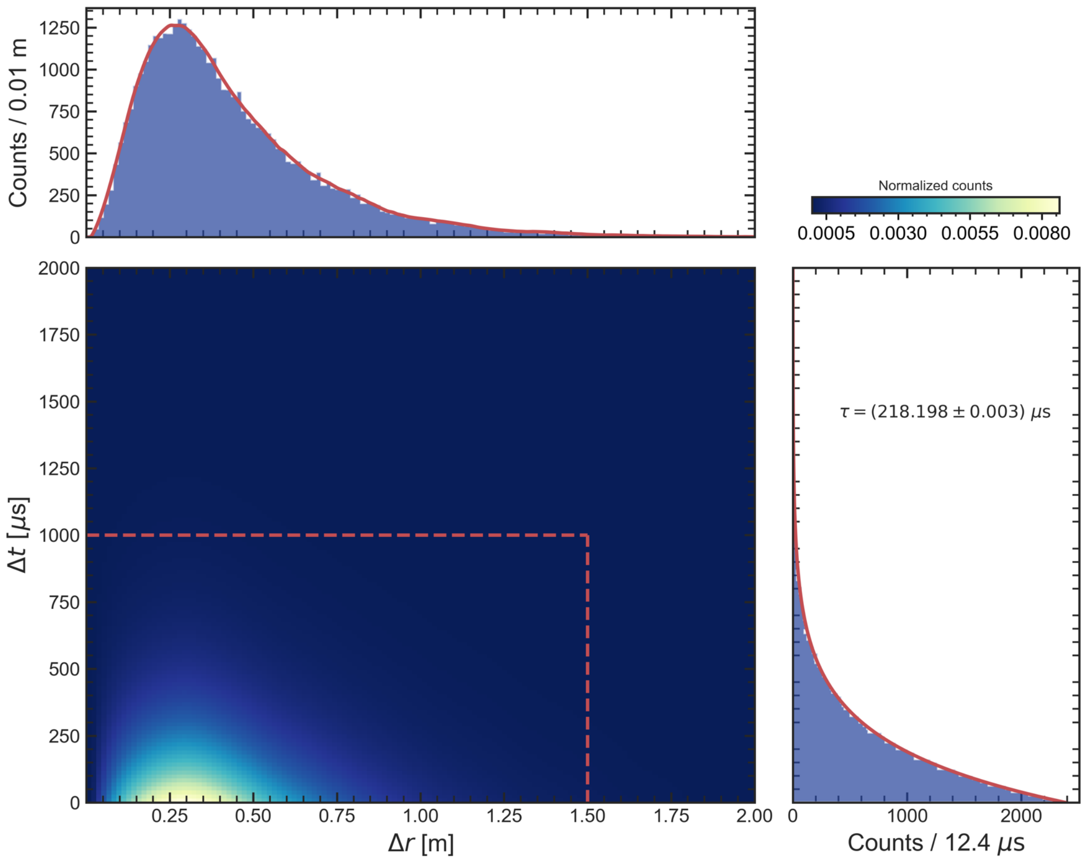
^{238}U geo-ν energy distribution (after FV cut)



^{232}Th geo-ν: selection efficiency

[1] Chin. Phys. C 46, 123001 (2022)

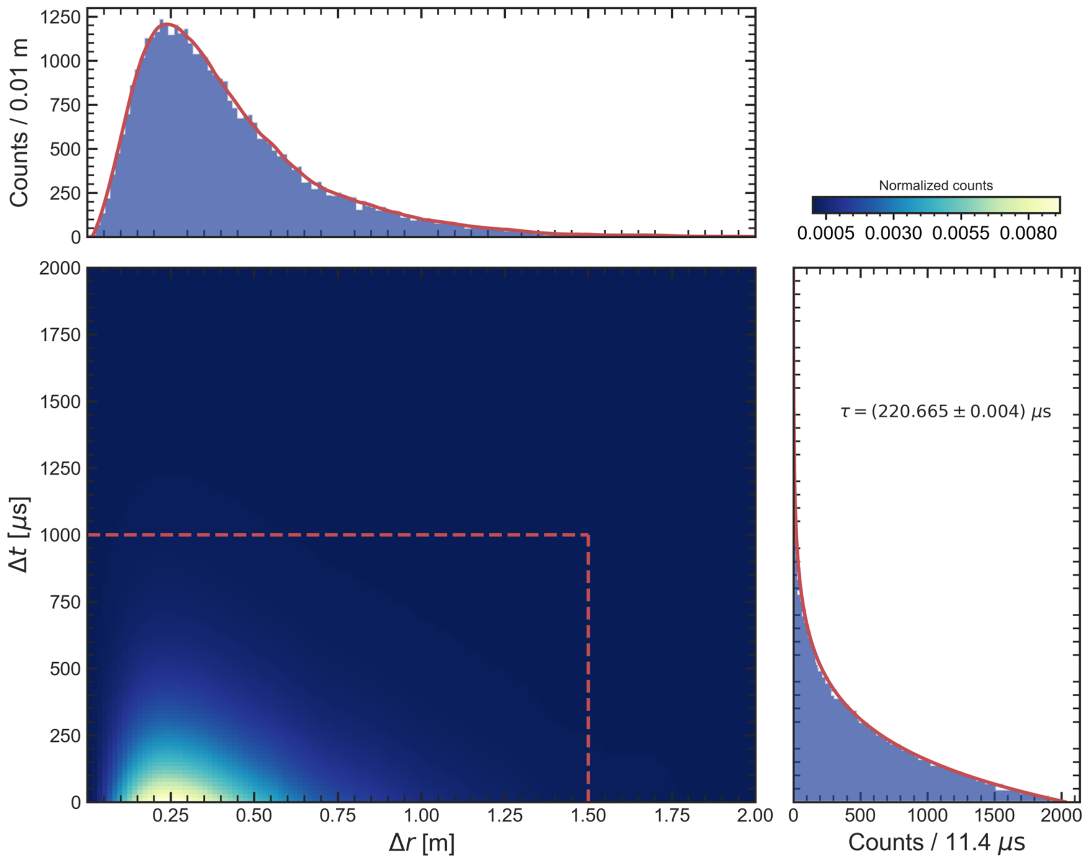
		Efficiency	Evts/day
		100%	0.345
1. Fiducial volume (FV) cut r < 17.2 m		**91.2%**	**0.31**
2. Energy cut			
• Prompt energy	$E_p \in (0.7, 12)$ MeV	**99.99%**	**0.31**
• Delayed energy	$E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.89%**	**0.31**
3. Time/vertex cut			
• $\Delta t < 1$ ms	$\Delta r < 1.5$ m	**98.3%**	**0.30**
4. Muon veto (temporal + spatial) [1]		**91.6%**	**0.28**
Combined efficiency		**82%**	**0.28**



[1] Chin. Phys. C 46, 123001 (2022)

^{238}U geo-ν: selection efficiency

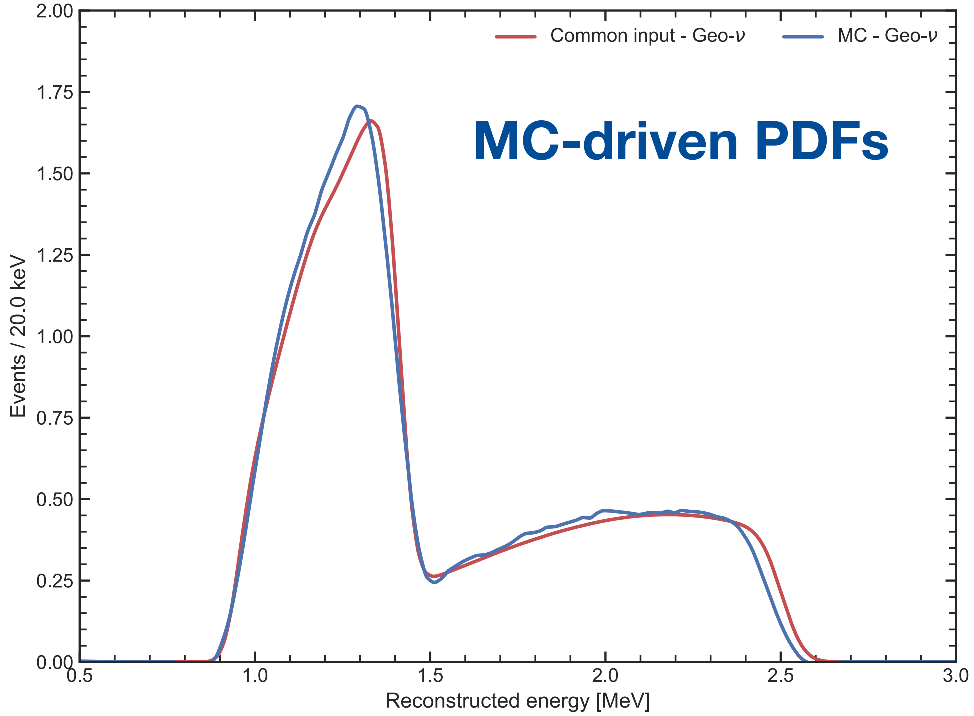
	Efficiency	Evts/day
	100%	1.155
1. Fiducial volume (FV) cut r < 17.2 m	**91.0%**	**1.05**
2. Energy cut		
• Prompt energy $E_p \in (0.7, 12)$ MeV	**100%**	**1.05**
• Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**1.05**
3. Time/vertex cut		
• $\Delta t < 1$ ms $\Delta r < 1.5$ m	**98.2%**	**1.03**
4. Muon veto (temporal + spatial) [1]	**91.6%**	**0.94**
Combined efficiency	**82%**	**0.94**

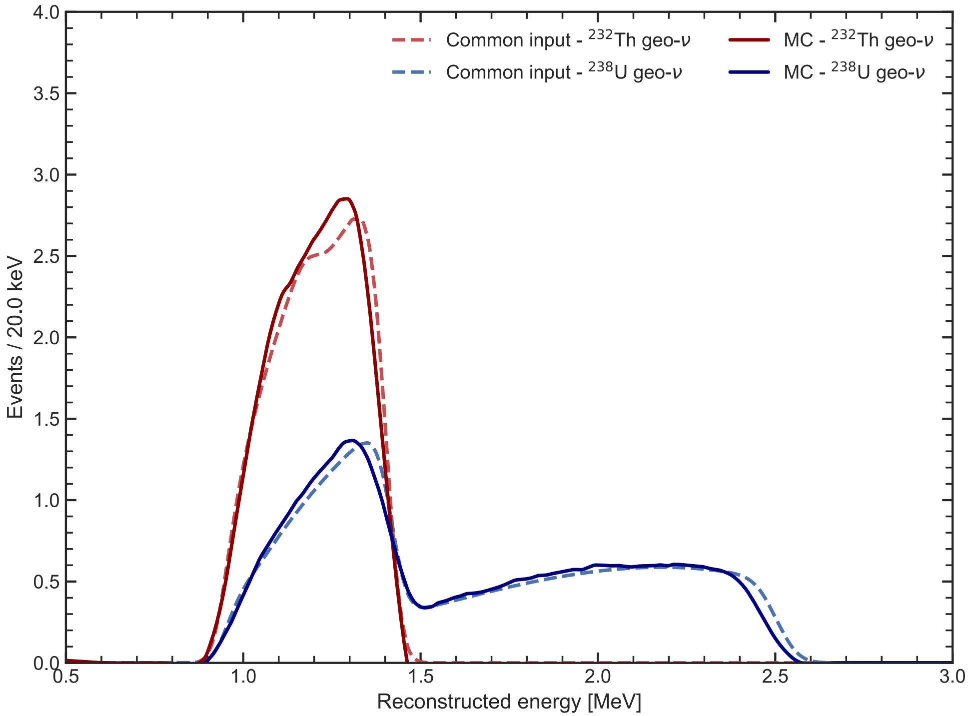


Geo-ν shape and rate

- ^{232}Th geo-ν rate after IBD selection cuts: 0.28 cpd
- ^{238}U geo-ν rate after IBD selection cuts: 0.94 cpd

→ **Total residual rate** **1.22 cpd**





Radioactivity dataset

*DocDB 9405 - 9614

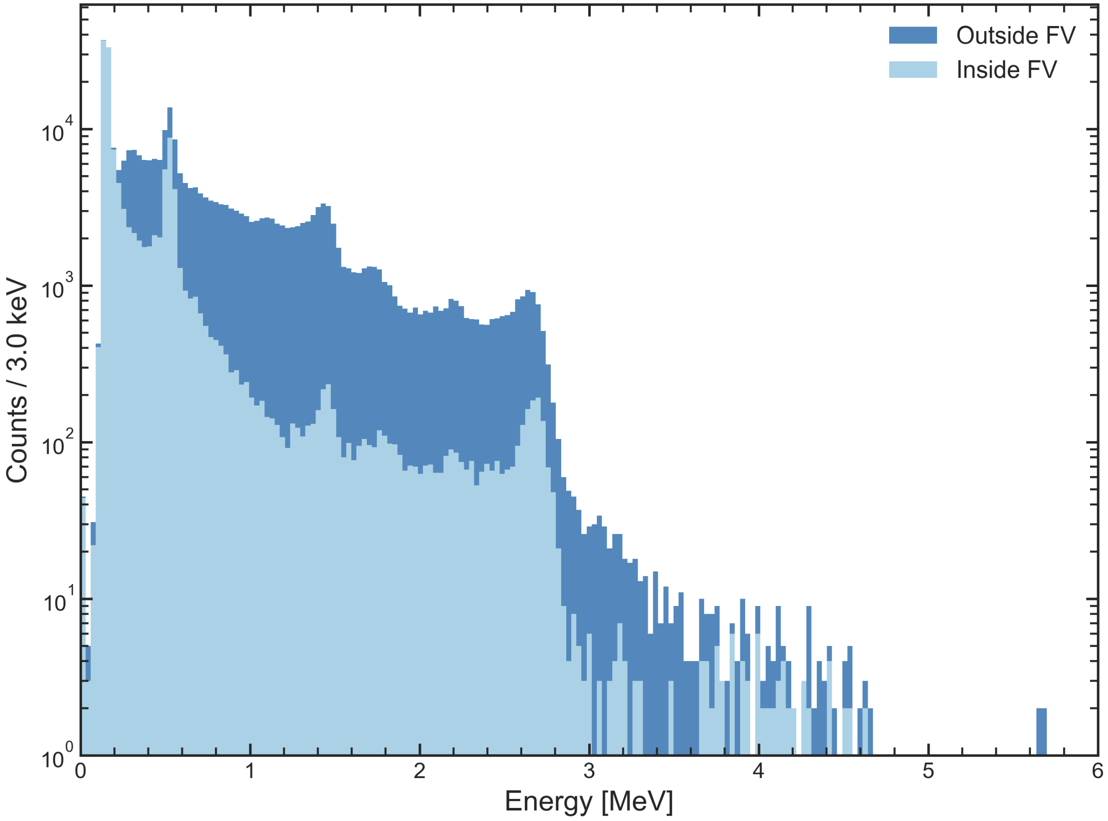
- Study based on Reco EDM variables
- Detsim samples from Mock Data challenge
  (/eos/juno/dirac/juno/production/radioactivity/centos7_amd64_gcc830/Pre-Release/J22.1.0-rc0/scratch/)

IBD anti-selection to tag uncorrelated events*
Correlated pairs (e.g., Bi-Po) are discarded from the start

ORSA selection configuration:

- Spatial selection cut: $\Delta r < 3$ m
- Temporal selection cut: $\Delta t < 2$ ms
- Energy cuts: None
- FV cut No

Uncorrelated coincidences energy spectrum



*DocDB 9405 - 9614

Radioactivity dataset

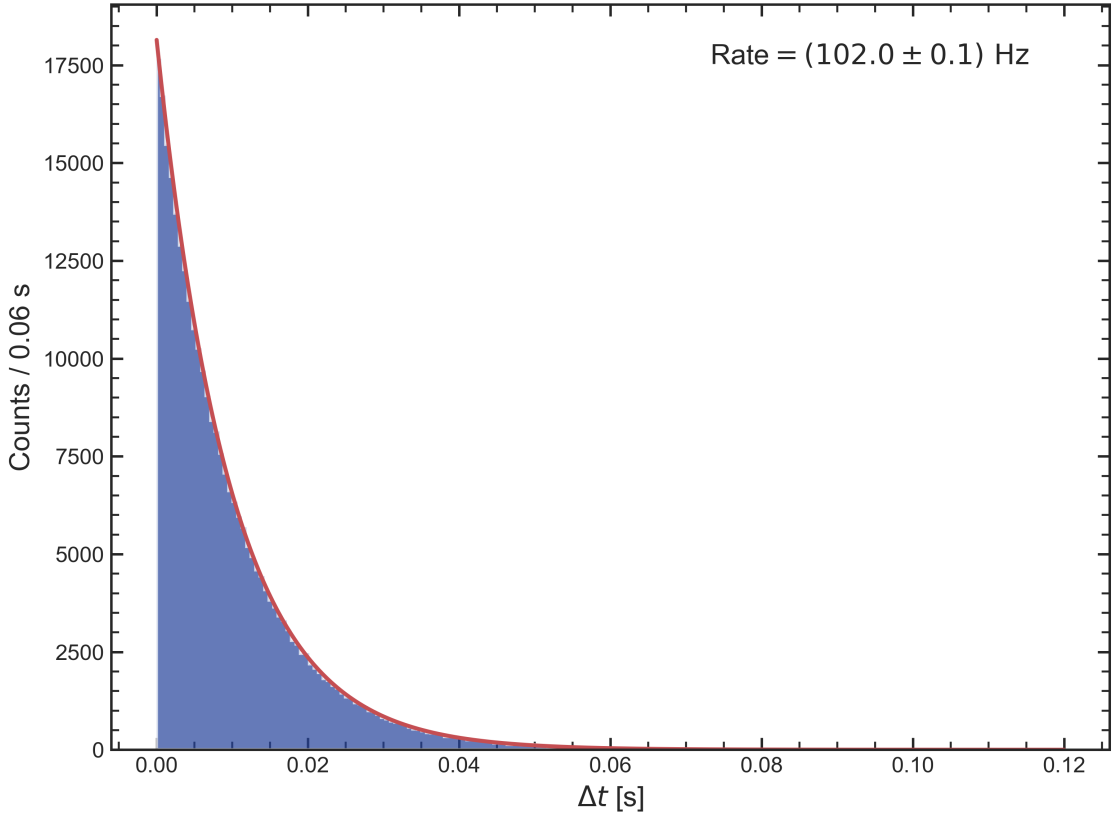
- Study based on Reco EDM variables
- Detsim samples from Mock Data challenge
  (/eos/juno/dirac/juno/production/radioactivity/centos7_amd64_gcc830/Pre-Release/J22.1.0-rc0/scratch/)

IBD anti-selection to tag uncorrelated events*
Correlated pairs (e.g., Bi-Po) are discarded from the start

ORSA selection configuration:

- Spatial selection cut: $\Delta r < 3$ m
- Temporal selection cut: $\Delta t < 2$ ms
- Energy cuts: None
- FV cut No

Rate of radioactivity from MC sample (102.0 ± 0.1 Hz) ≈ 8.8 x 10^6 evts/day



Accidental background: different approach

[5] DocDB 9474

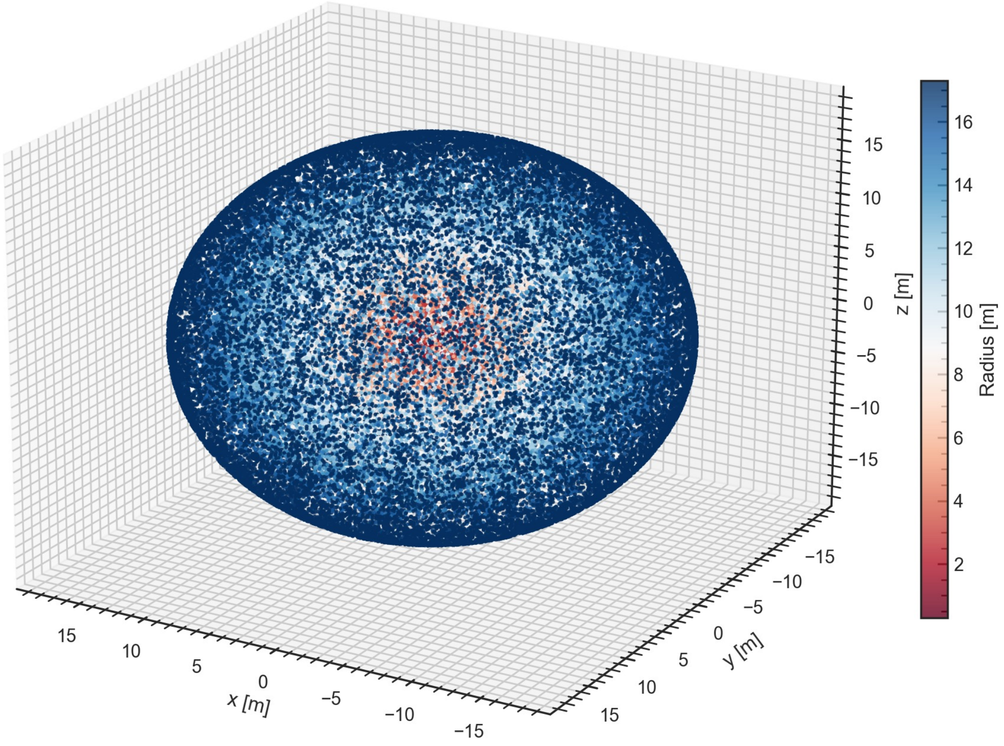
- Selection efficiency terms cannot be computed independently for radiogenic background
  - IBD-like approach is an approximation and leads to a biased accidentals rate
  - **Vertex** and **energy** selection efficiencies cannot be calculated individually and then combined

- Analytical approach (similar to [5])
  - Accounts for energy-radius correlation
  - Radioactive background **rate** is computed from the MC sample **data**

- **Rate of accidentals:** $R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$

Accidentals: **efficiency factor**

- Preliminary energy cut: E > 0.7 MeV
- Construct all possible Δr combinations among N events N_{comb} = N(N-1) satisfying IBD cuts:
  - Fiducial volume (FV) cut r < 17.2 m
  - Energy cut
    - Prompt energy $E_p \in (0.7, 12)$ MeV
    - Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV
  - Vertex cut $\Delta r < 1.5$ m
- Calculate efficiency factor $\varepsilon = \frac{N_{sel}}{N_{comb}}$

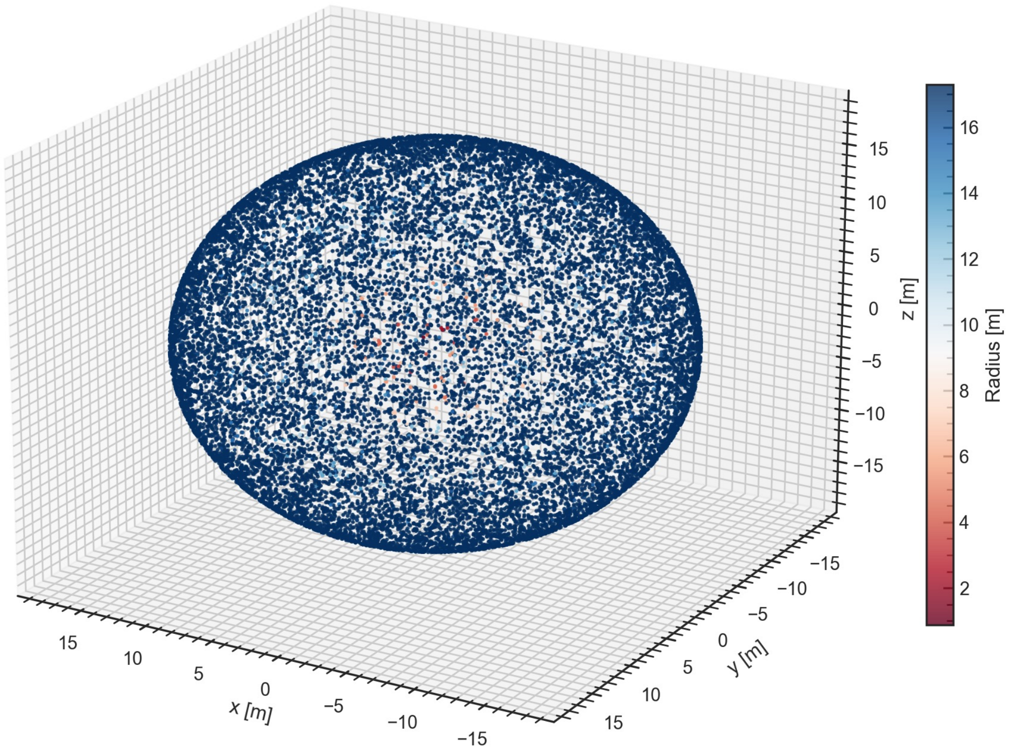


50k events displayed

Accidentals: **efficiency factor**

- Preliminary energy cut: E > 0.7 MeV
- Construct all possible Δr combinations among N events N_{comb} = N(N-1) satisfying IBD cuts:
  - Fiducial volume (FV) cut r < 17.2 m
  - Energy cut
    - Prompt energy $E_p \in (0.7, 12)$ MeV
    - Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV
  - Vertex cut $\Delta r < 1.5$ m
- Calculate efficiency factor $\varepsilon = \frac{N_{sel}}{N_{comb}}$

E > 0.7 MeV



50k events displayed

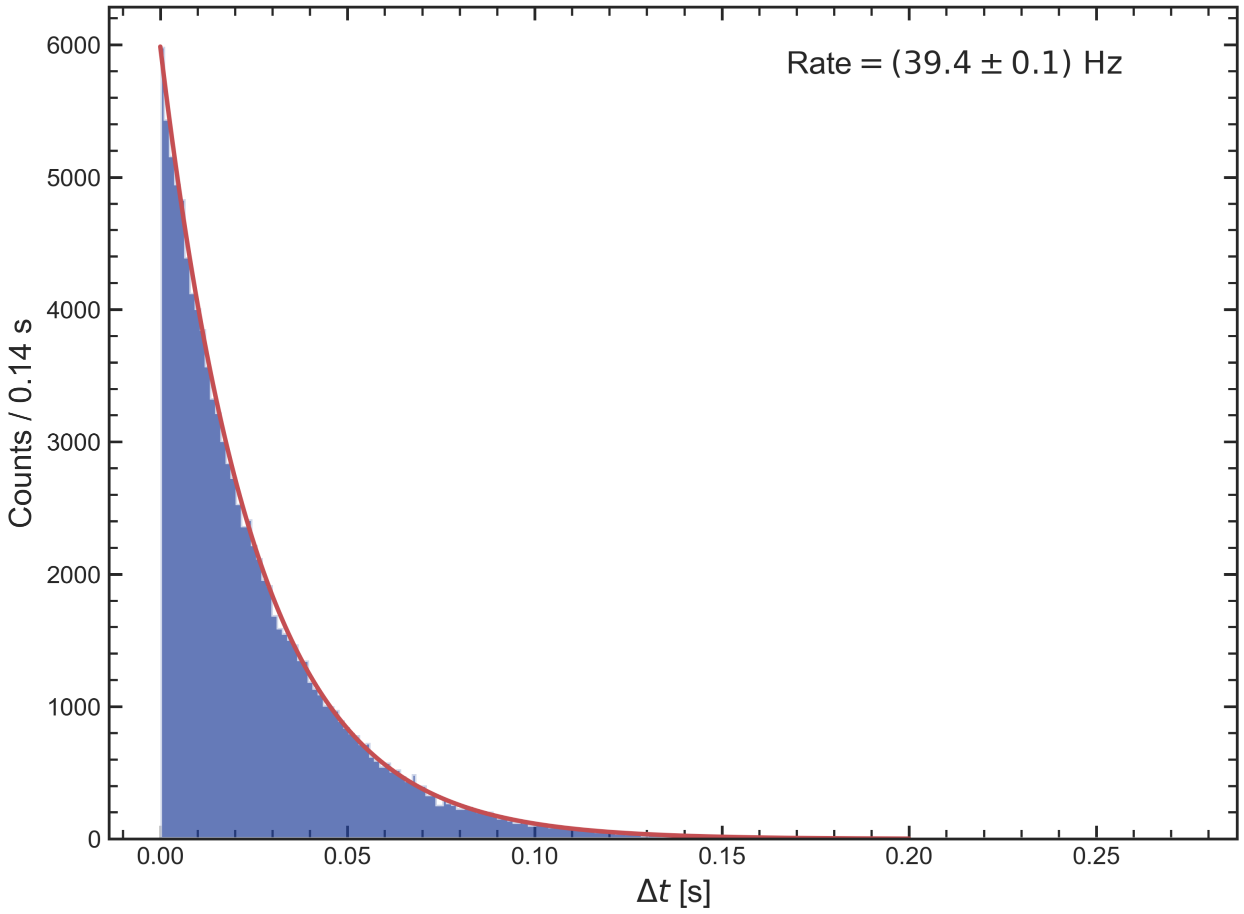
Accidentals rate calculation

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $$\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.41 \pm 0.01) \times 10^{-6}$$

Accidentals: **background rate**

- Radioactivity background rate is obtained directly from the dataset
- Consider only events with E > 0.7 MeV
- Calculate **time difference between consecutive events**
- Uncorrelated events $\rightarrow R_p = R_d$



Accidentals rate calculation

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.41 \pm 0.01) \times 10^{-6}$

2. $R_p = R_d = (39.4 \pm 0.1)\ \mathrm{Hz}$

Accidentals rate calculation

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.41 \pm 0.01) \times 10^{-6}$

2. $R_p = R_d = (39.4 \pm 0.1)\ \mathrm{Hz}$

3. $\Delta t = 1\ \mathrm{ms}$

Accidentals rate calculation

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.41 \pm 0.01) \times 10^{-6}$
2. $R_p = R_d = (39.4 \pm 0.1)\ \mathrm{Hz}$
3. $\Delta t = 1\ \mathrm{ms}$
4. $R_{acc} = (0.189 \pm 0.002)\ \mathrm{evts/day}$

With muon veto: $R_{acc} = (0.172 \pm 0.002)\ \mathrm{evts/day}$

[1] Chin. Phys. C 46, 123001 (2022)

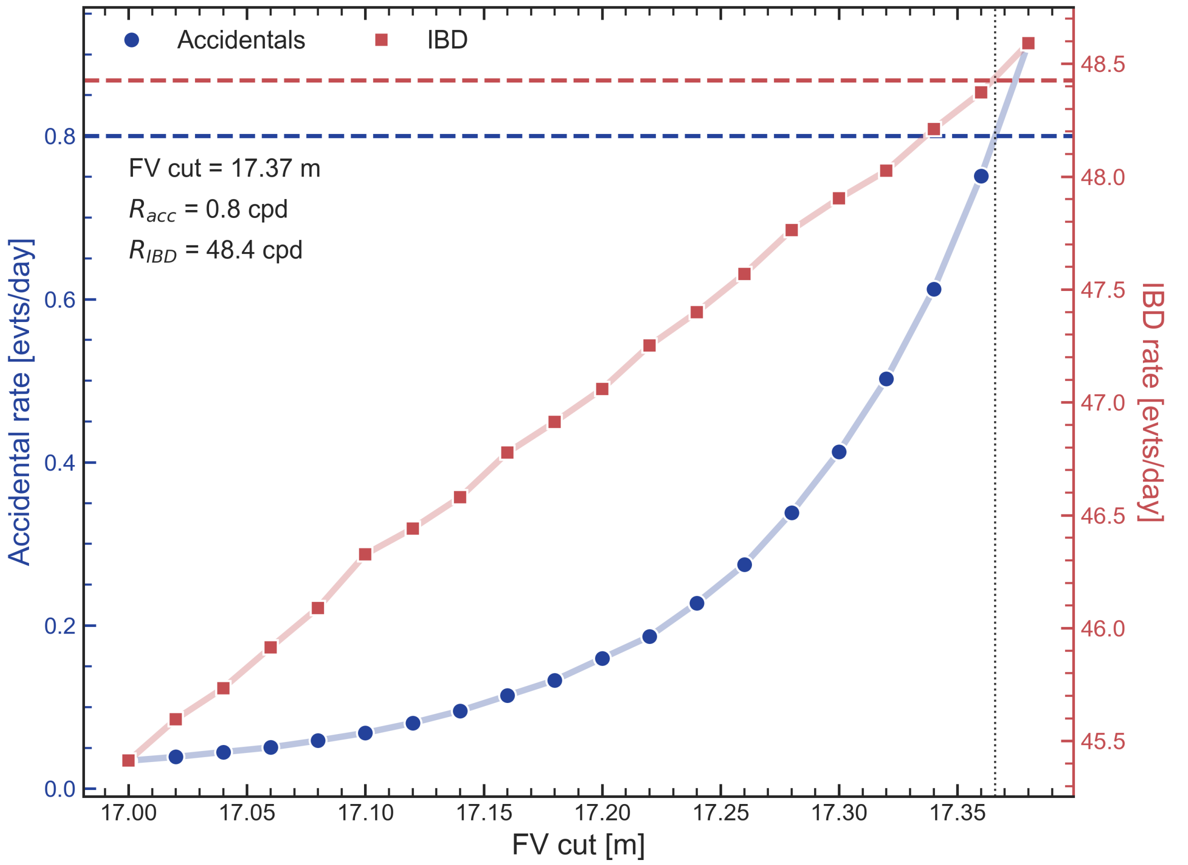
Signal and background rates

	Event type	Rate from SNiPER MC [events/day]	Rate from common input [events/day]
From MC	**IBD candidate**	47.1	47.1
	^{9}Li/ ^{8}He	0.8	0.8
	Geo-ν	1.22	1.2
	Accidentals	**0.17**	**0.8**
From [1]	**World reactors**	1.0	1.0
	Atmospheric ν	0.16	0.16
	Fast neutrons	0.1	0.1
	^{13}C(α,n)^{16}O	0.05	0.05

Accidentals rate

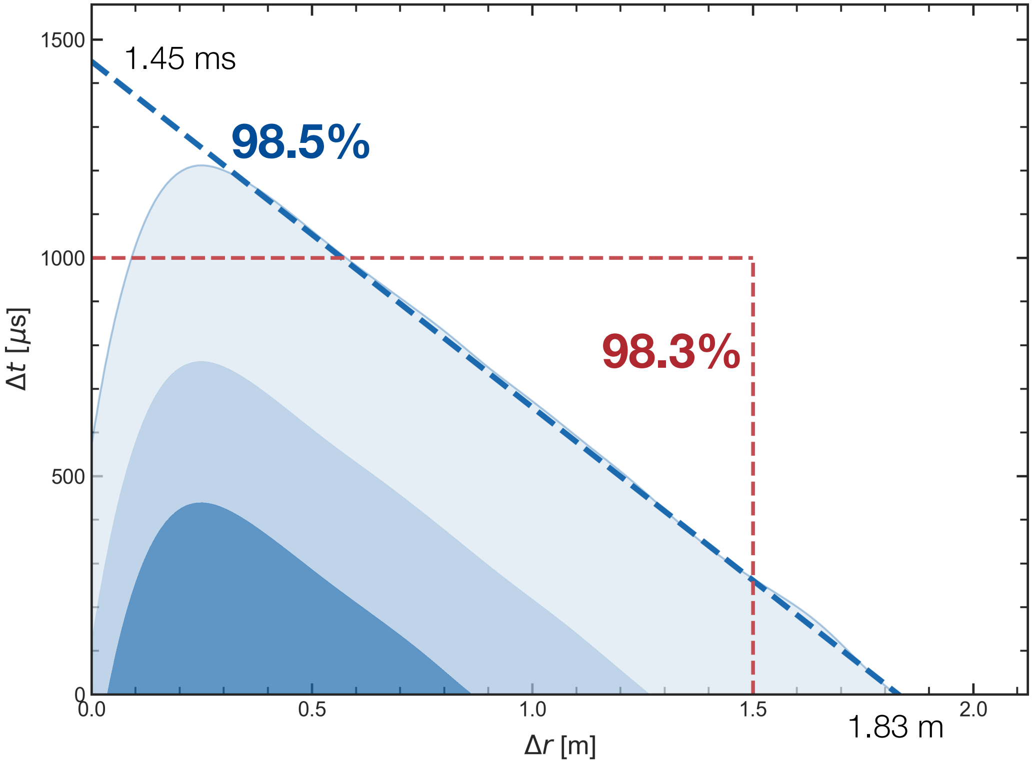
*for a room temperature density of 0.86g/mL
arXiv:2107.03669v2

- According to this calculation 0.8 evts/day correspond to a FV of ≈ **17.37 m**
- With FV cut at 17.37 m, IBD rate increases from 47.1 to 48.4 evts/day
- Volume is increased by ≈ 2.7 %
- FV gain corresponds to ≈ 535 ton of liquid scintillator* (1.9 x Borexino active mass!)



Outlook: optimization of selection cuts

- Optimization of selection cuts to further increase signal to noise ratio
  - Cut following (Δr, Δt) equiprobability curves



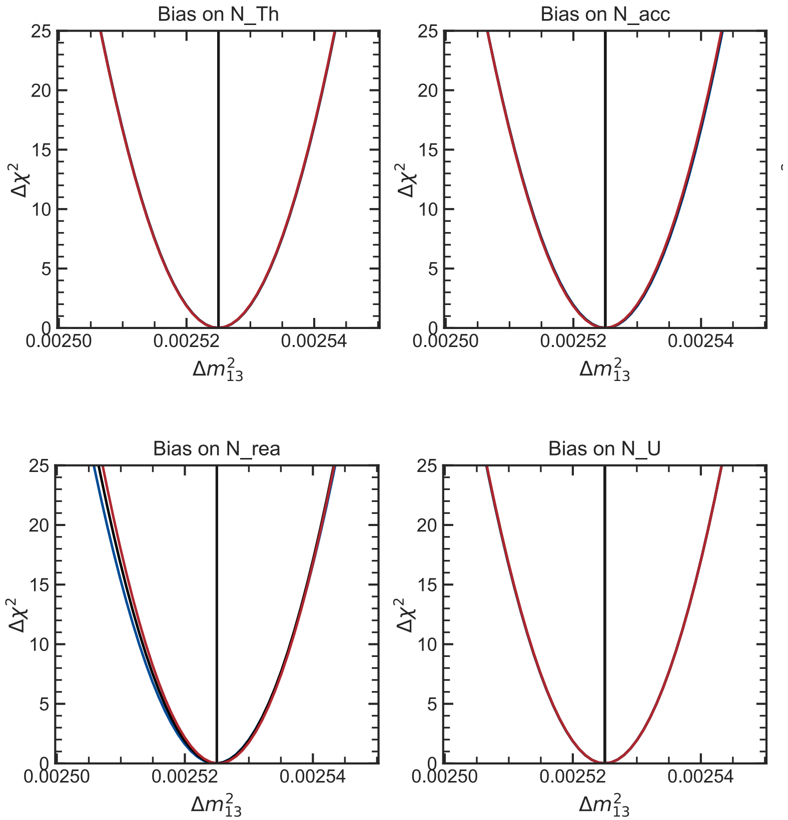
	Standard cut	Optimized cut
IBD	47.1 cpd	47.1 cpd
Accidentals	0.172 cpd	≈ 0.13 cpd*

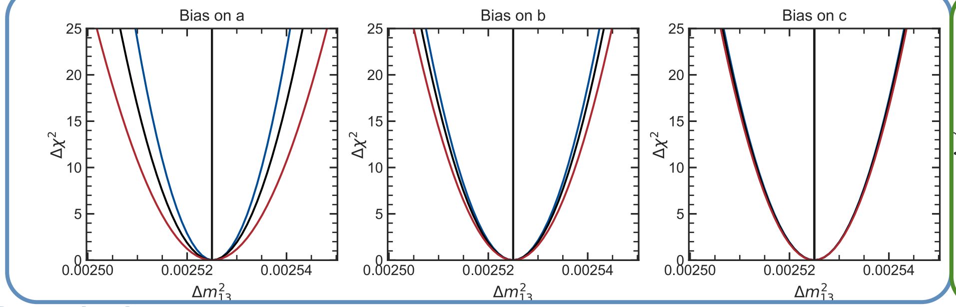
*scaled with analytical method

Future outlook: sensitivity to Δm^2_{31}

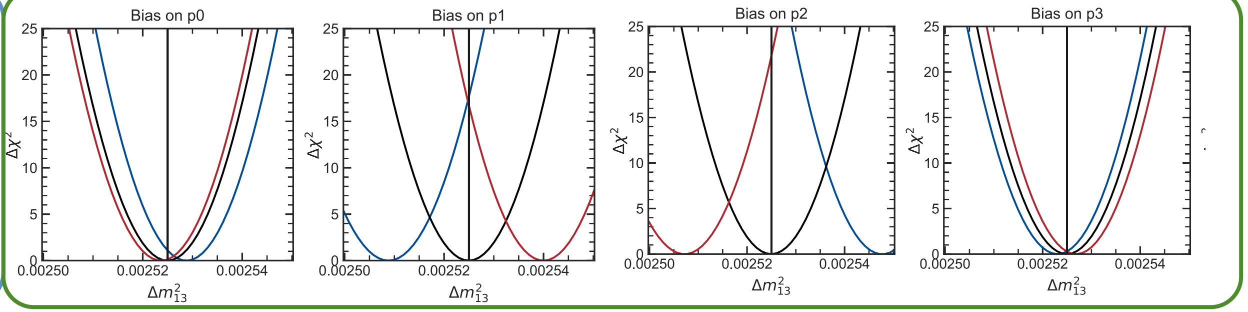
- Optimization of selection cuts for this specific physics channel

- Sensitivity to Δm^2_{31}:
  - Non-linearity and resolution parameters highly affect the estimation of Δm^2_{31}
  - No significant dependence on background rates
  - Possibility to enlarge FV to increase signal rate





Resolution



Non-linearity

Summary

- SNiPER MC simulations of spectral components used to extrapolate **rate** and **shape**
  - Residual rate after IBD selection cuts is obtained for reactor IBD signal and for some major background components (geo-neutrinos, $^{9}Li/^{8}He$, accidentals)

- IBD, geo-neutrinos, $^{9}Li/^{8}He$ rates are found to be comparable with common inputs

- **Accidental coincidences rate** of ≈ **0.17 cpd** lower than previous calculation (0.8 cpd)
  - Critical input parameter for NMO analysis
  - Needs further discussion and crosschecks

- Possibility to enlarge fiducial volume + optimized cuts: better signal to noise ratio

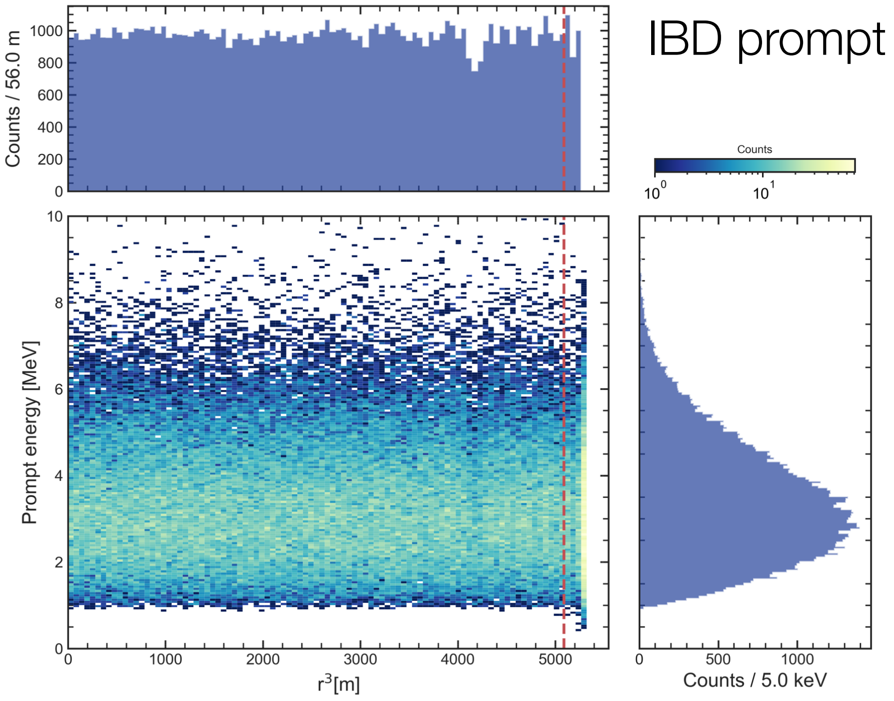
Thank you

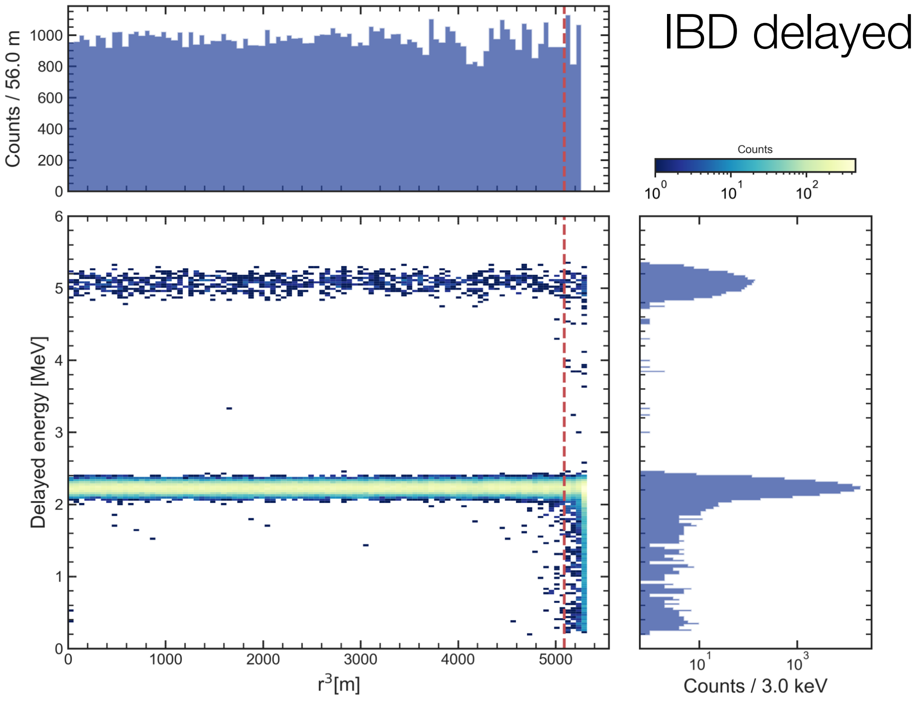
Backup

IBD distributions

- Treating selection variables as uncorrelated (IBD-like approach) works if:
  - Events are uniformly distributed inside LS → Δr distribution does not depend on FV cut
  - Energy distribution is independent of radius → After FV cut energy distribution is uniform

Ok for IBD ✓

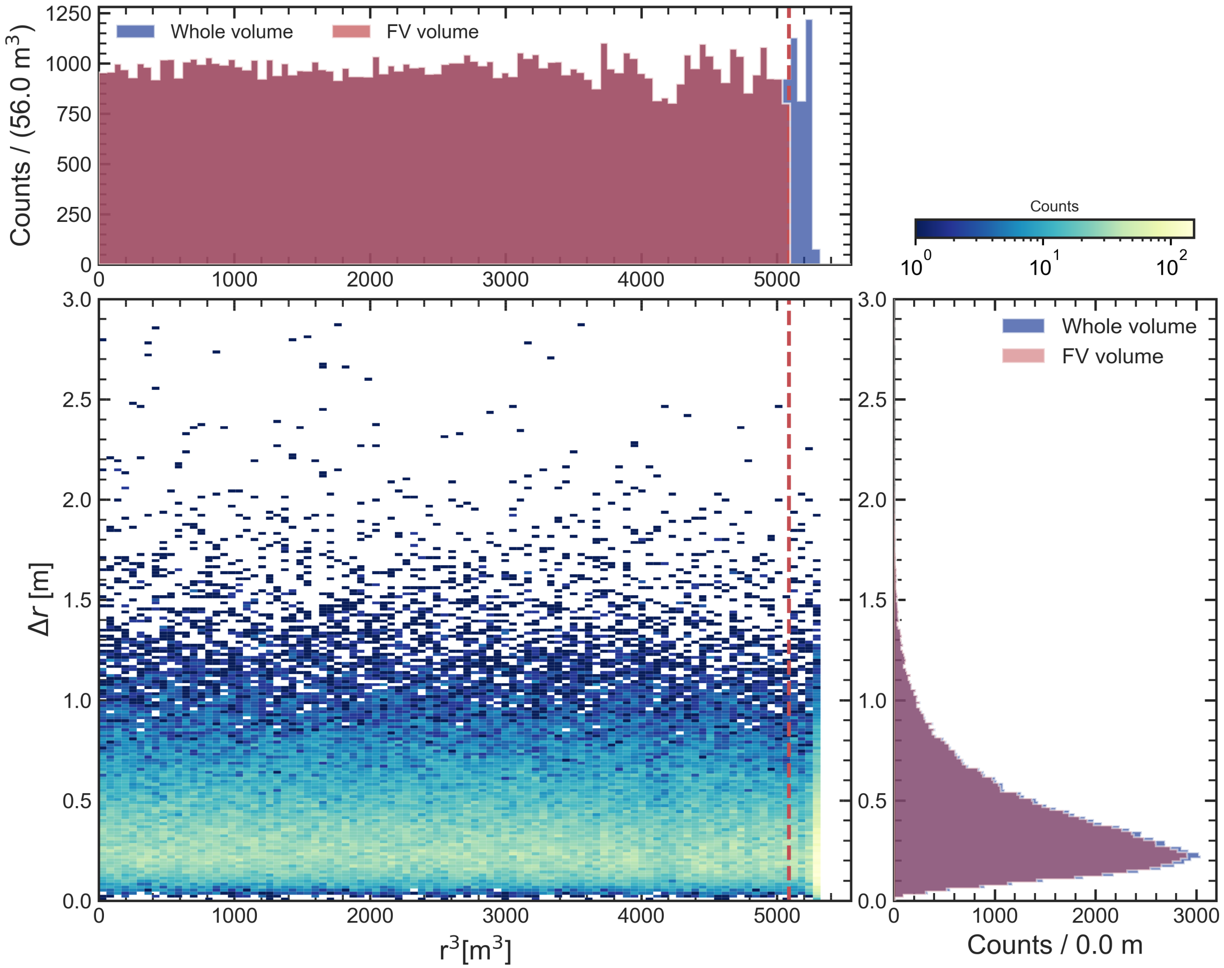




IBD: radial distribution

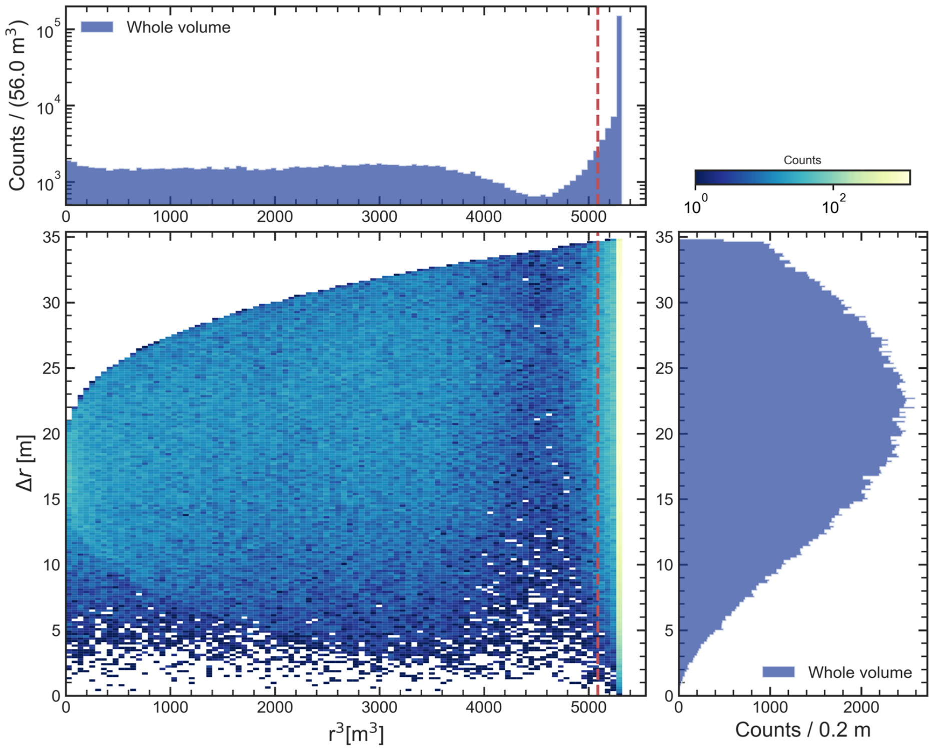
- Events are uniformly distributed inside LS → Δr distribution does not depend on FV cut

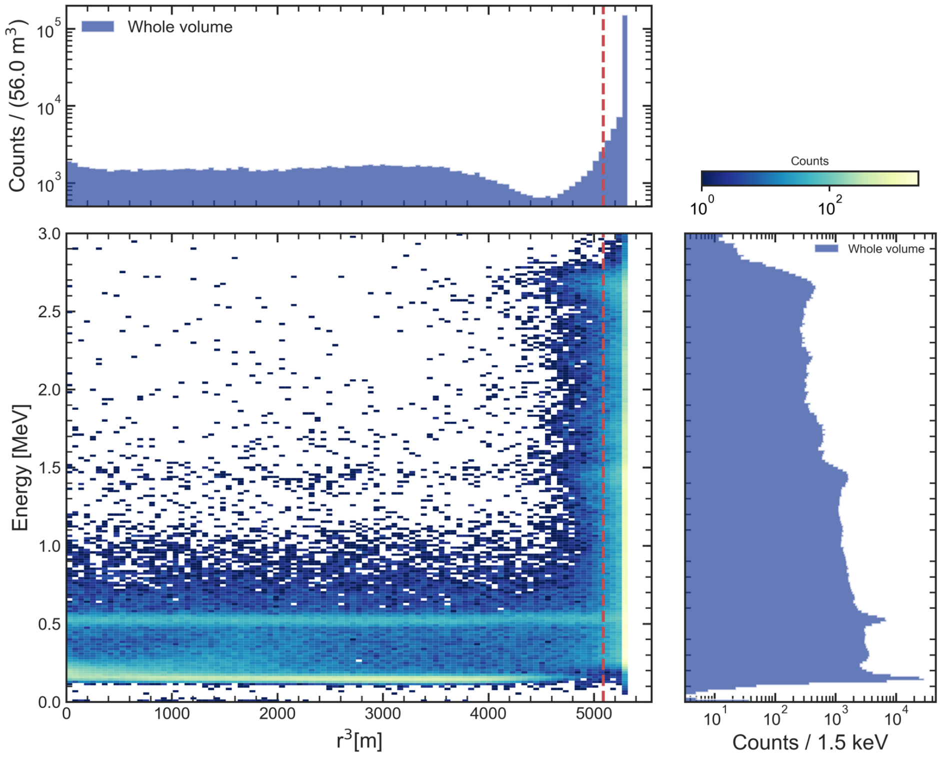
- This plot is for delayed event



Accidental background distributions

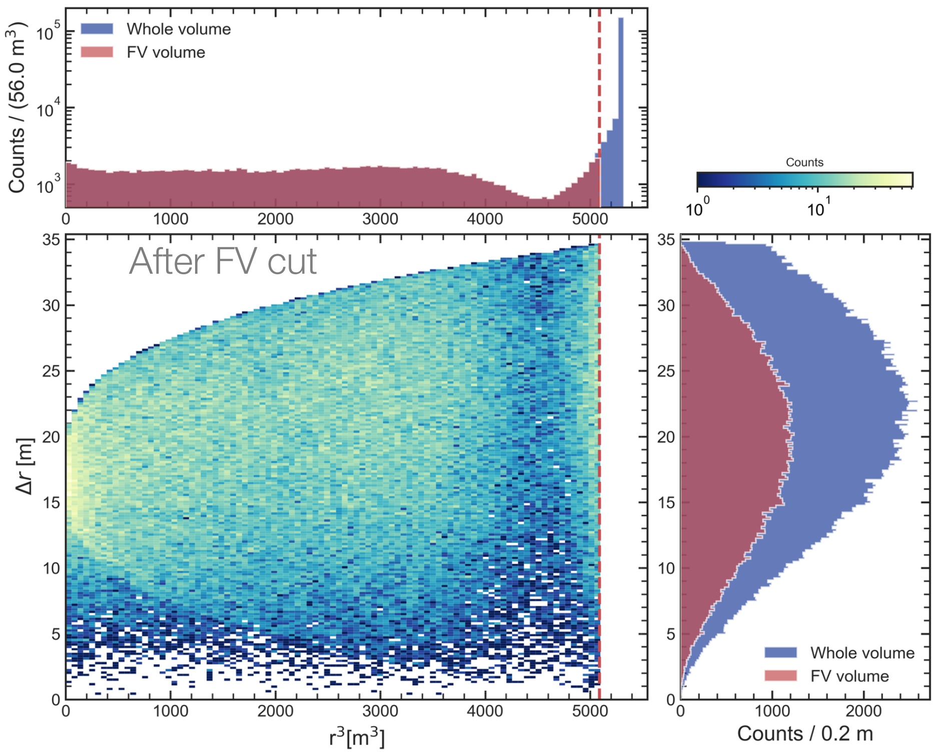
- Are events uniformly distributed inside the detector? Is Δr distribution depending on FV cut?
- Is energy distribution independent of radius and uniform after FV cut?





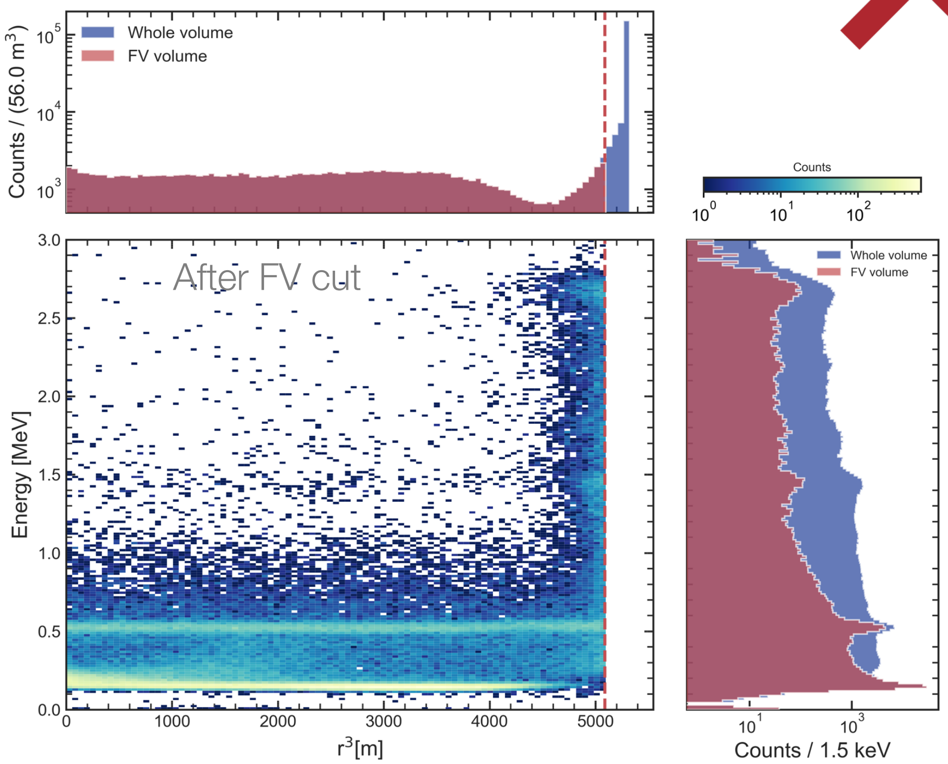
Accidental background distributions

- Are events uniformly distributed inside the detector? Is Δr distribution depending on FV cut?



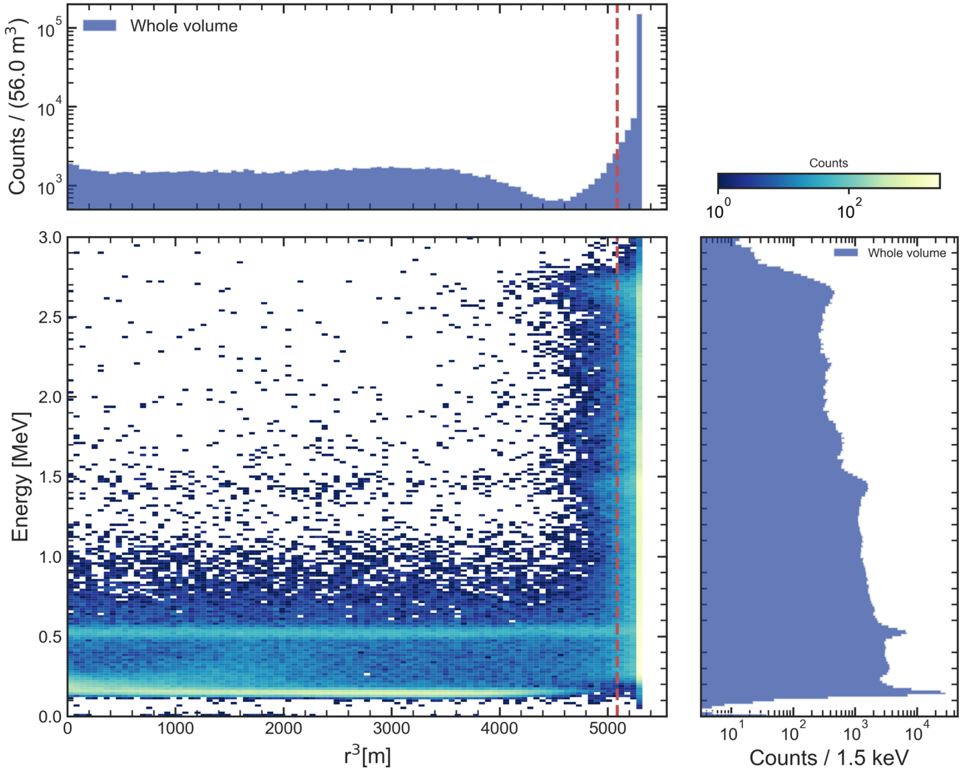
- Is energy distribution independent of radius and uniform after FV cut?

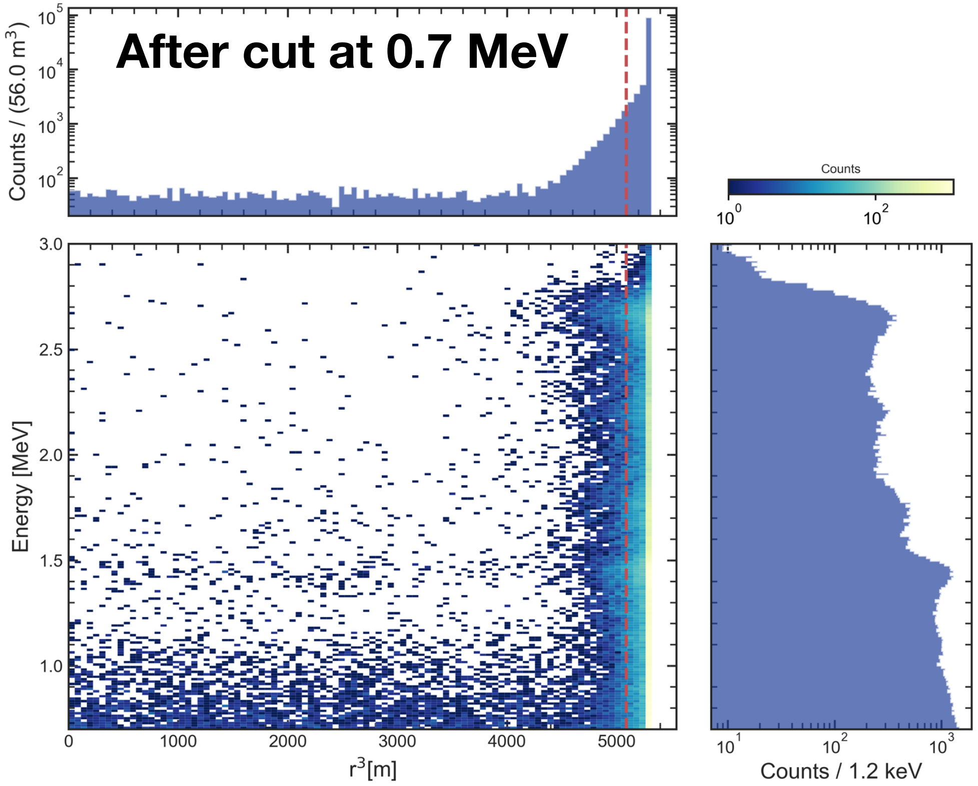
Not ok



Accidentals: energy distribution

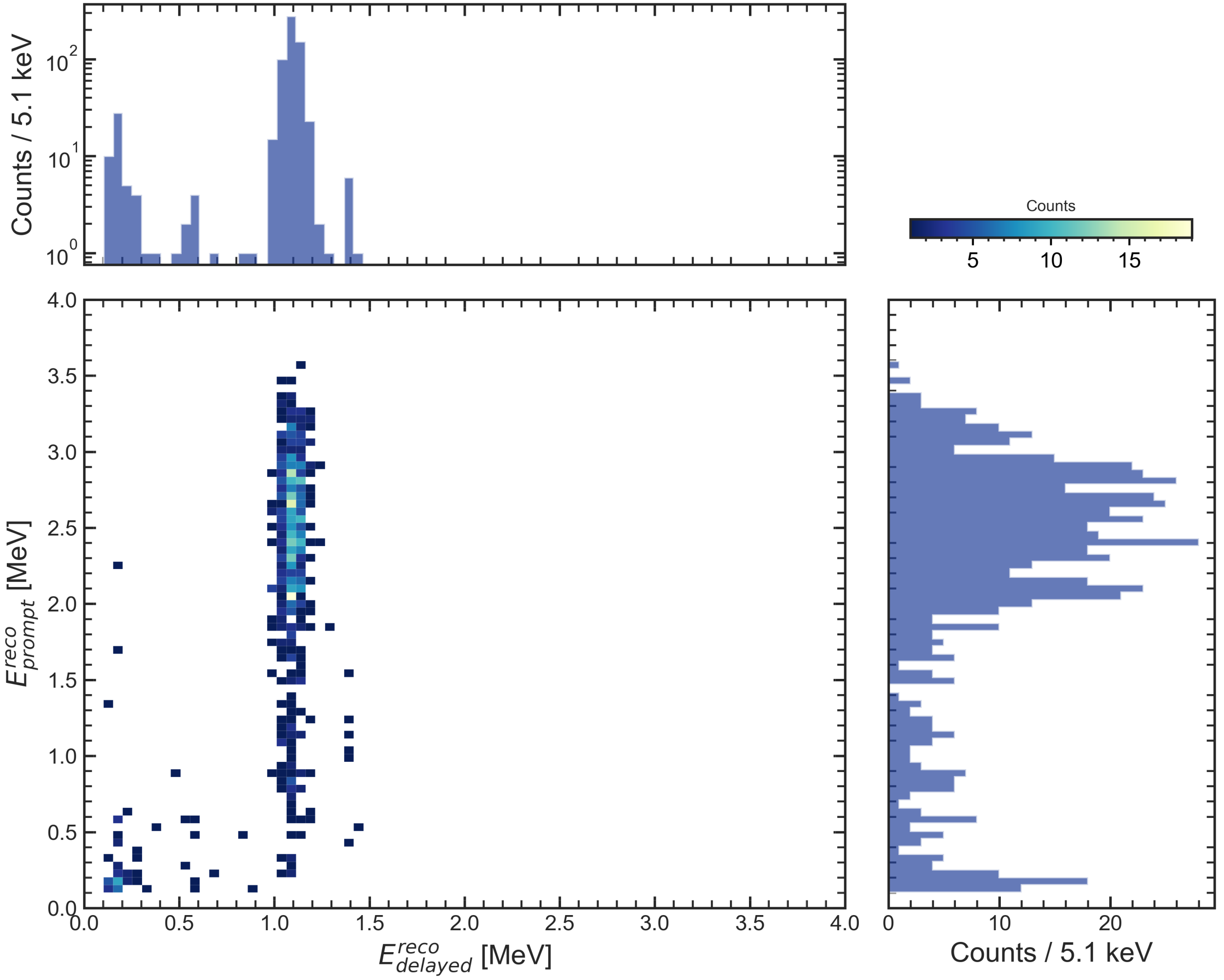
- Most events inside LS are due to ^{14}C (β spectrum end point at ≈ 156 KeV)
- Note: still no access to MC truth of secondary particles





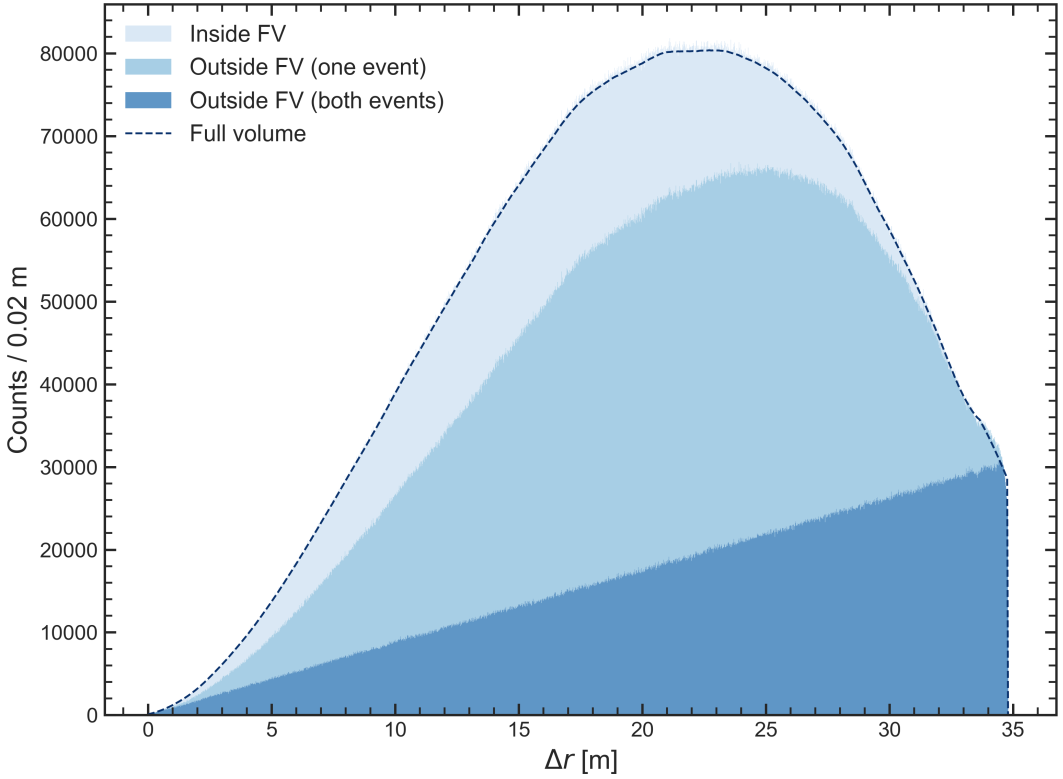
Radioactivity correlations

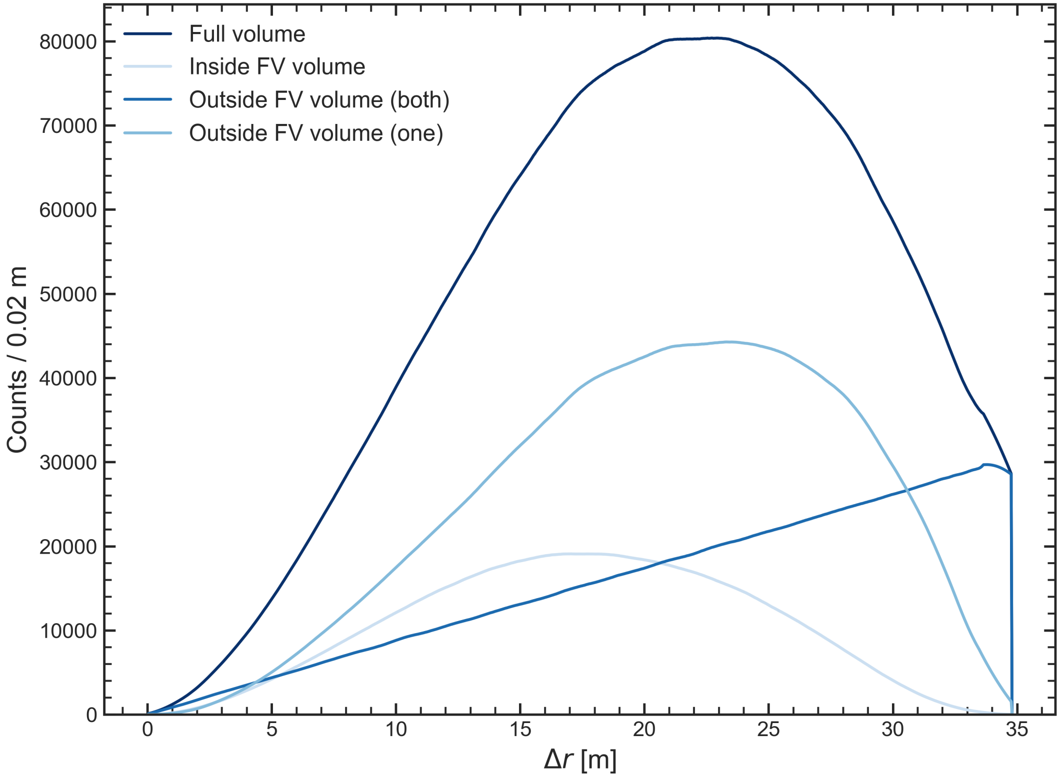
- Correlated pairs are identified thanks to selection algorithm



Accidentals: Δr distribution ($\approx 10^8$ combinations)

- Δr distribution for accidentals
- $f(r) = A \cdot \frac{3}{R^3}\left(r'^2 - \frac{3r'^3}{4R} + \frac{r'^5}{16R^3}\right)$ [6] where $r' = a + r \cdot b$





Accidentals rate calculation (prompt energy cut at 0.8 MeV)

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.30 \pm 0.01) \times 10^{-6}$
2. $R_p = R_d = (39.4 \pm 0.1)\ \mathrm{Hz}$
3. $\Delta t = 1\ \mathrm{ms}$
4. $R_{acc} = (0.175 \pm 0.002)\ \mathrm{evts/day}$

Accidentals rate calculation (including correlated pairs)

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.57 \pm 0.01) \times 10^{-6}$

2. $R_p = R_d = (40.6 \pm 0.3)\ \mathrm{Hz}$

3. $\Delta t = 1\ \mathrm{ms}$

4. $R_{acc} = (0.224 \pm 0.004)\ \mathrm{evts/day}$

Accidentals rate calculation (with correlated pairs + E_{prompt} > 0.8 MeV)

$$R_{acc} = R_d \cdot R_p \cdot \Delta t \cdot \varepsilon$$

1. $\varepsilon = \frac{N_{sel}}{N_{comb}} = (1.45 \pm 0.01) \times 10^{-6}$
2. $R_p = R_d = 58.9 \text{ Hz}$ from radiopurity paper [7]
3. $\Delta t = 1 \text{ ms}$
4. $R_{acc} = (0.435 \pm 0.003) \text{ evts/day}$

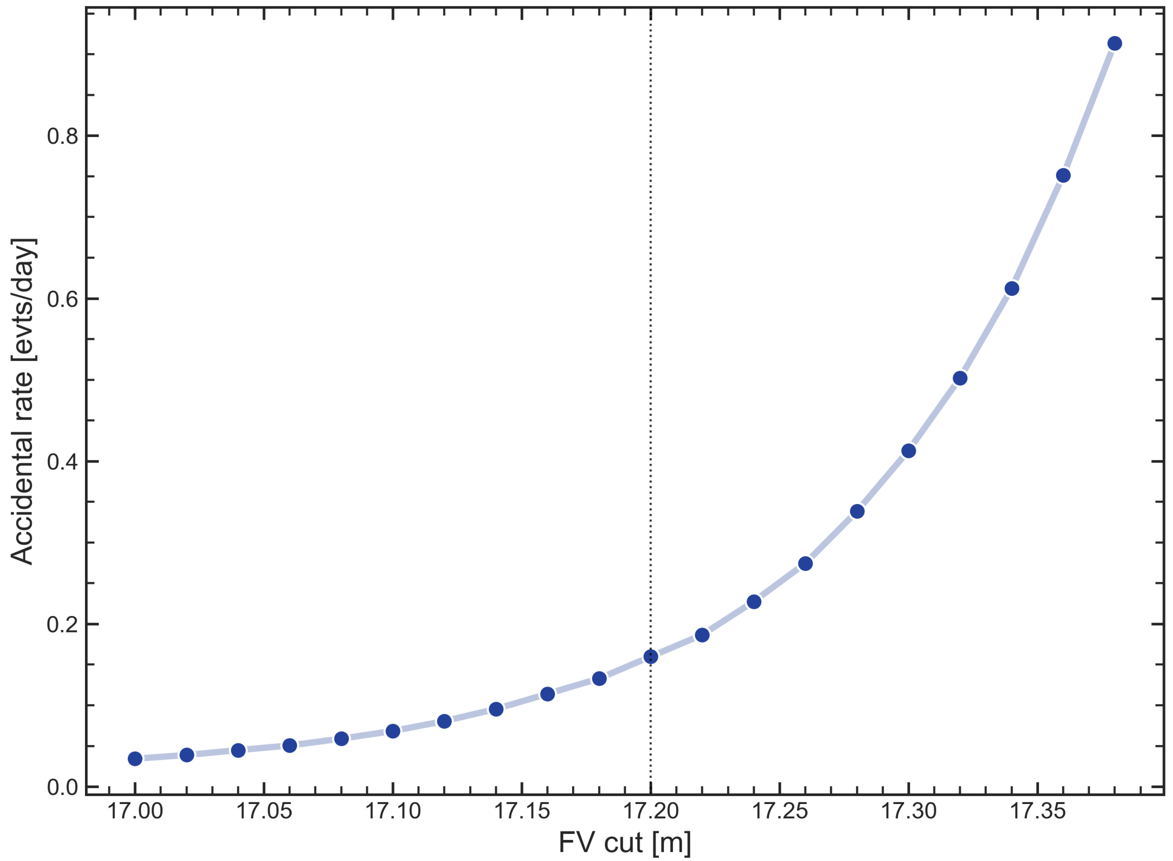
[7] arXiv:2107.03669v2

Accidentals rate

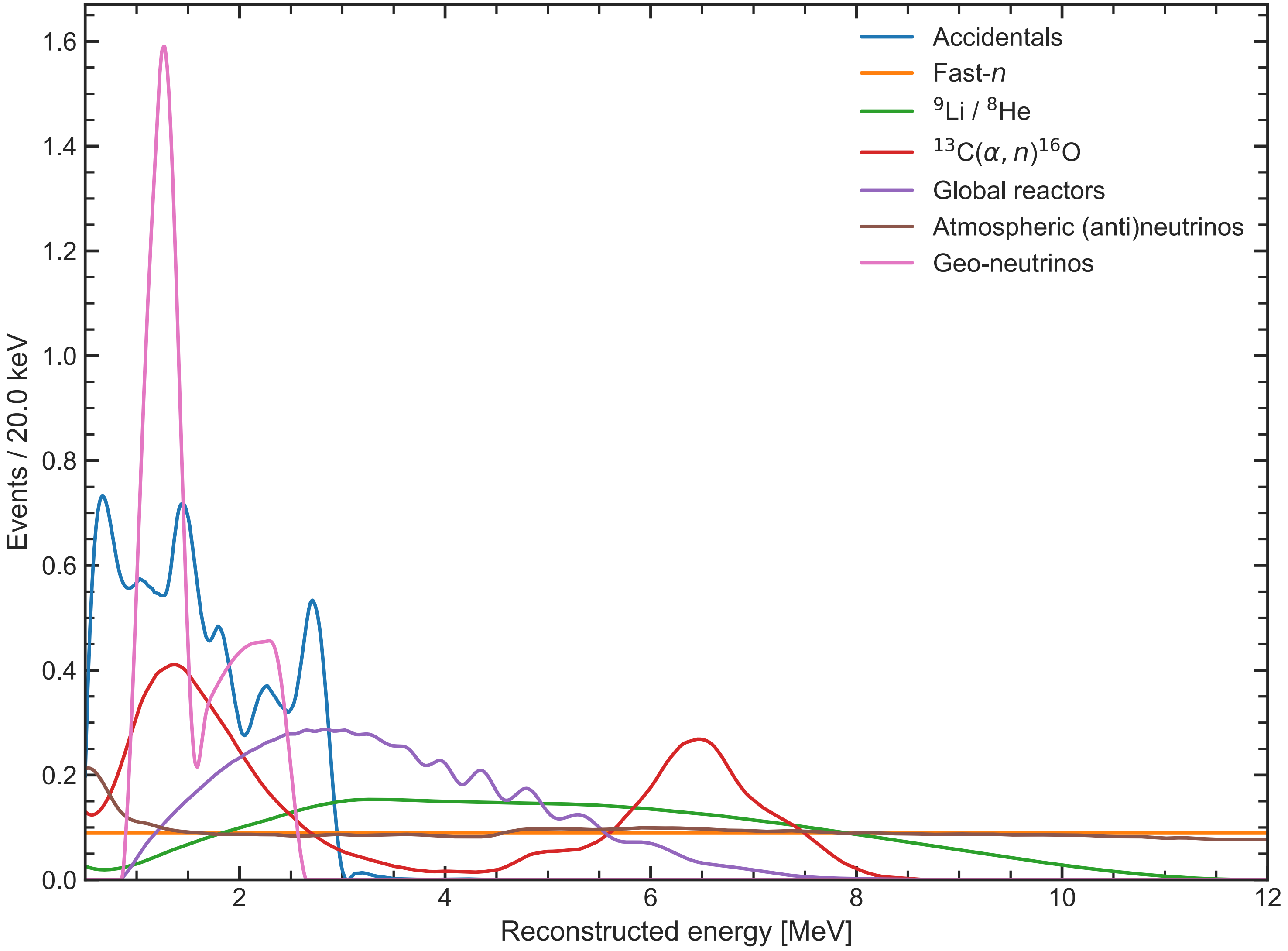
*for a room temperature density of 0.86g/mL
arXiv:2107.03669v2

- According to this calculation 0.8 evts/day correspond to a FV of ≈ **17.37 m**
- With FV cut at 17.37 m, IBD rate increases from 47.1 to 48.4 evts/day

- Volume is increased by ≈ 2.7 %
- FV gain corresponds to ≈ 535 ton of liquid scintillator* (1.9 x Borexino active mass!)

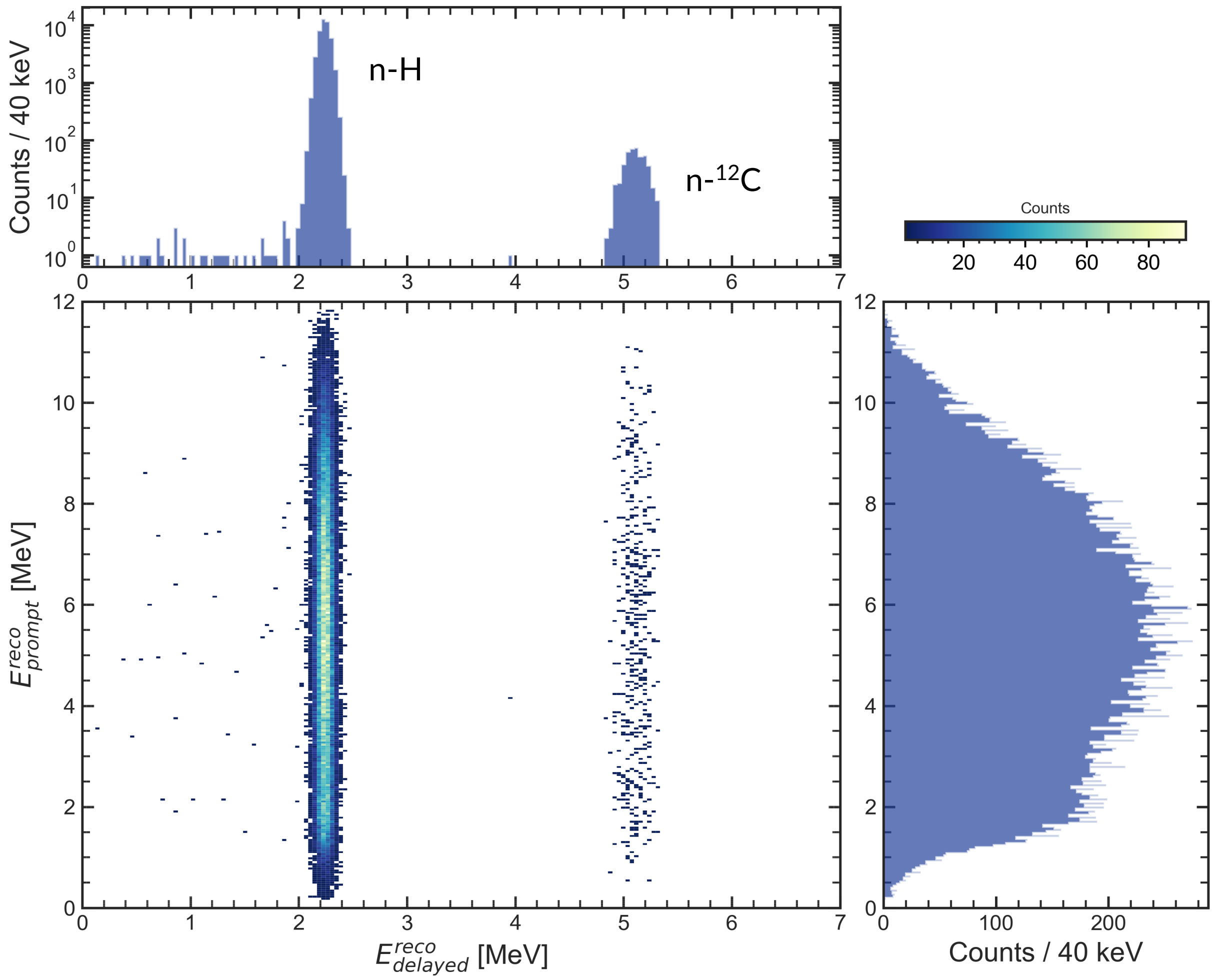


Background spectra (CI)

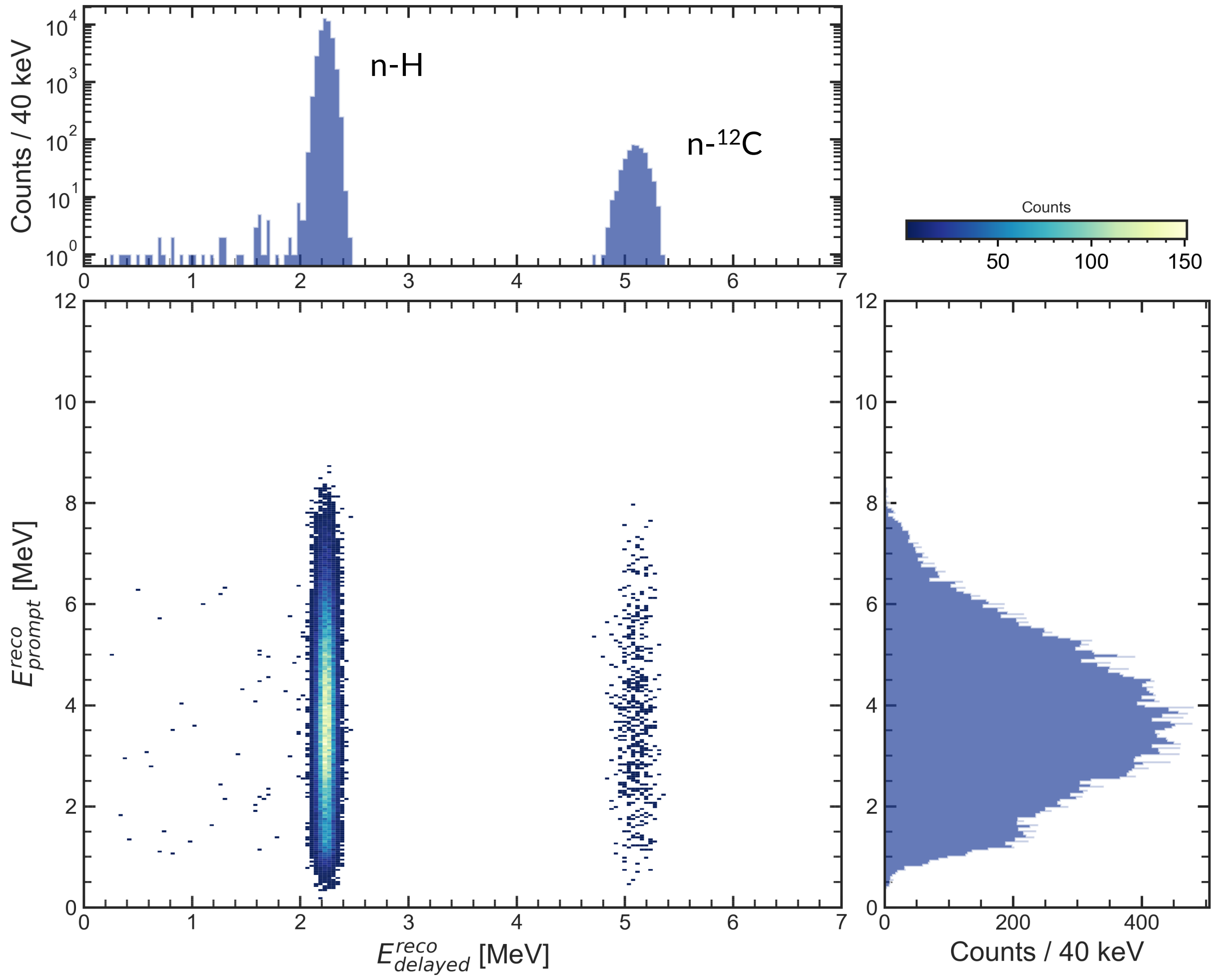


^{9}Li/ ^{8}He energy distributions

^{9}Li energy distribution (after FV cut)



^{8}He energy distribution (after FV cut)



^{9}Li dataset and pre-selection

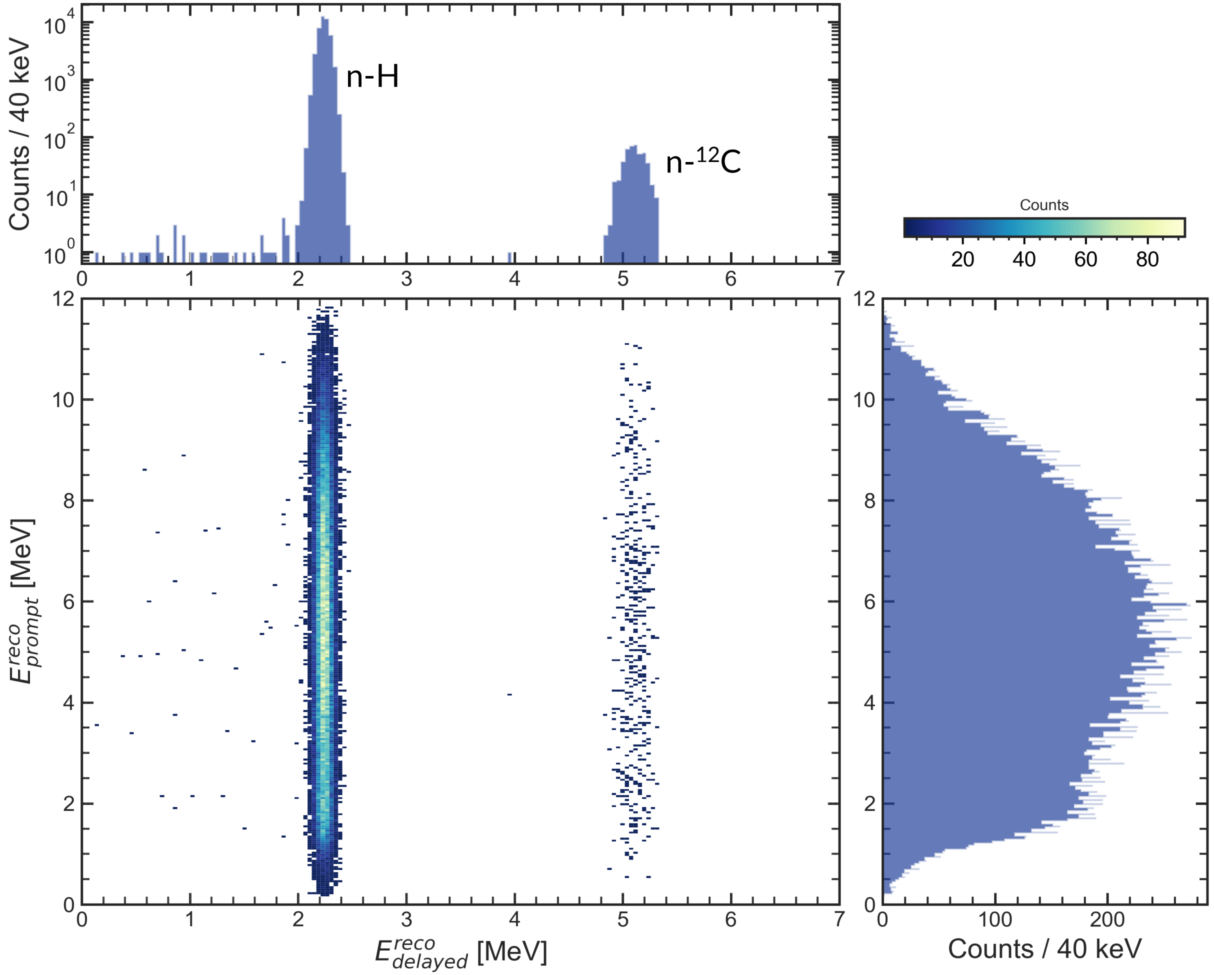
Production configuration:

- Offline software version: J22.1.0-rc4
- Reconstruction algorithm: OMILRec
- Number of events: ~50k

ORSA selection configuration:

- Spatial selection cut: Δr < 3 m
- Temporal selection cut: Δt < 2 ms
- Energy cuts: None
- FV cut: No

Energy distribution (after FV cut)



^{8}He dataset and pre-selection

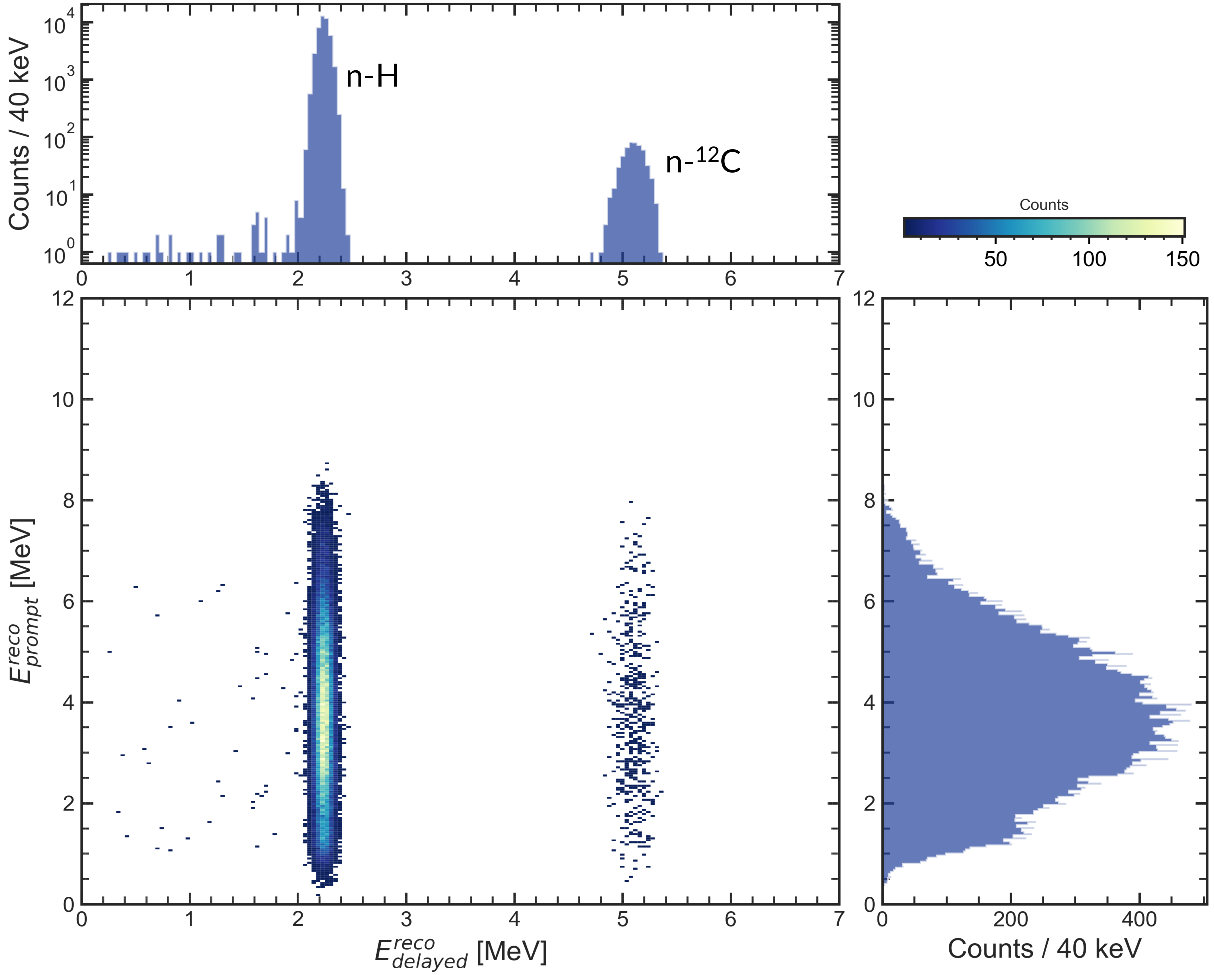
Production configuration:

- Offline software version: J22.1.0-rc4
- Reconstruction algorithm: OMILRec
- Number of events: ~50k

ORSA **selection configuration:**

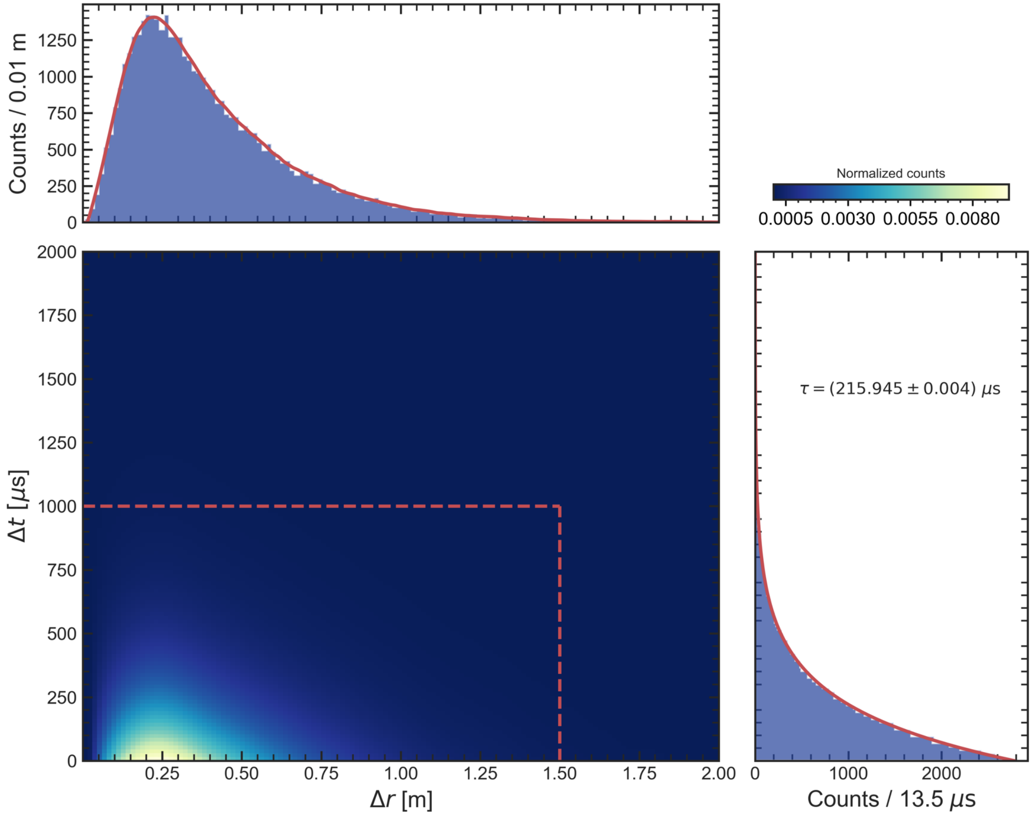
- Spatial selection cut: $\Delta r < 3$ m
- Temporal selection cut: $\Delta t < 2$ ms
- Energy cuts: None
- FV cut No

Energy distribution (after FV cut)



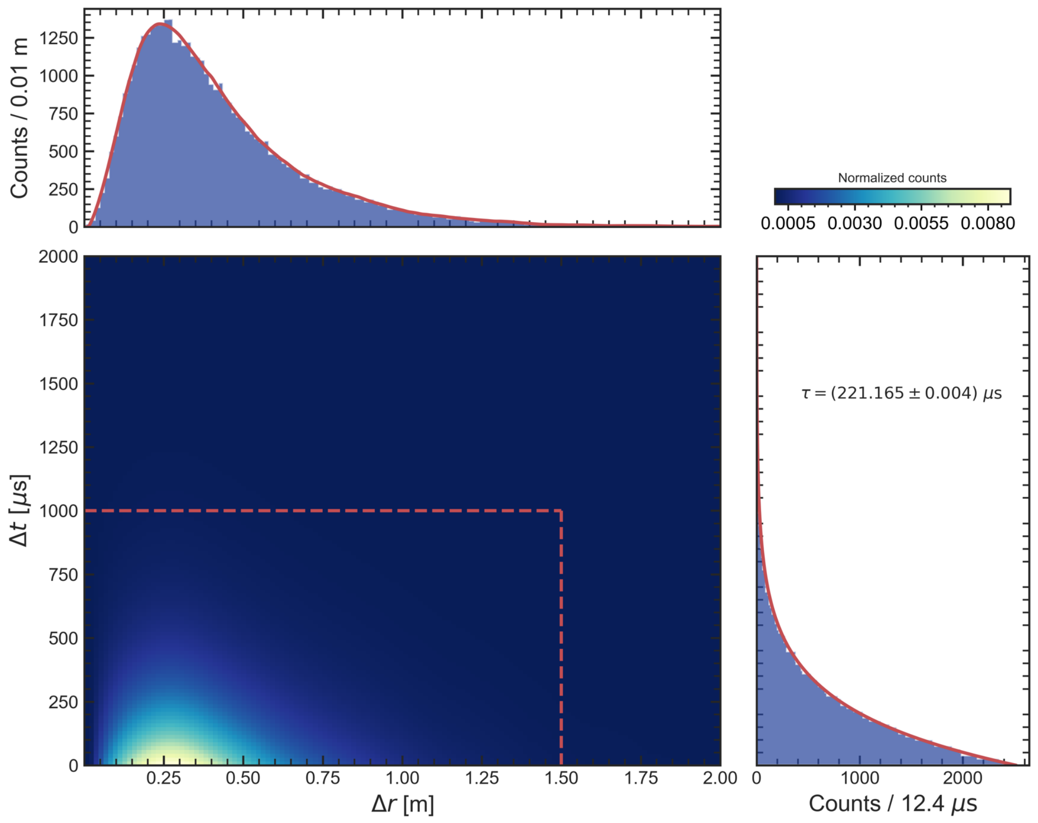
^{9}Li: selection efficiency

		Efficiency	Evts/day
		100%	0.81 [4]
1. Fiducial volume (FV) cut r < 17.2 m		**91.2%**	**0.75**
2. Energy cut			
• Prompt energy	$E_p \in (0.7, 12)$ MeV	**99.6%**	**0.74**
• Delayed energy	$E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**0.74**
3. Time/vertex cut			
• $\Delta t < 1$ ms	$\Delta r < 1.5$ m	**98.4%**	**0.72**
Combined efficiency		**89%**	**0.72**



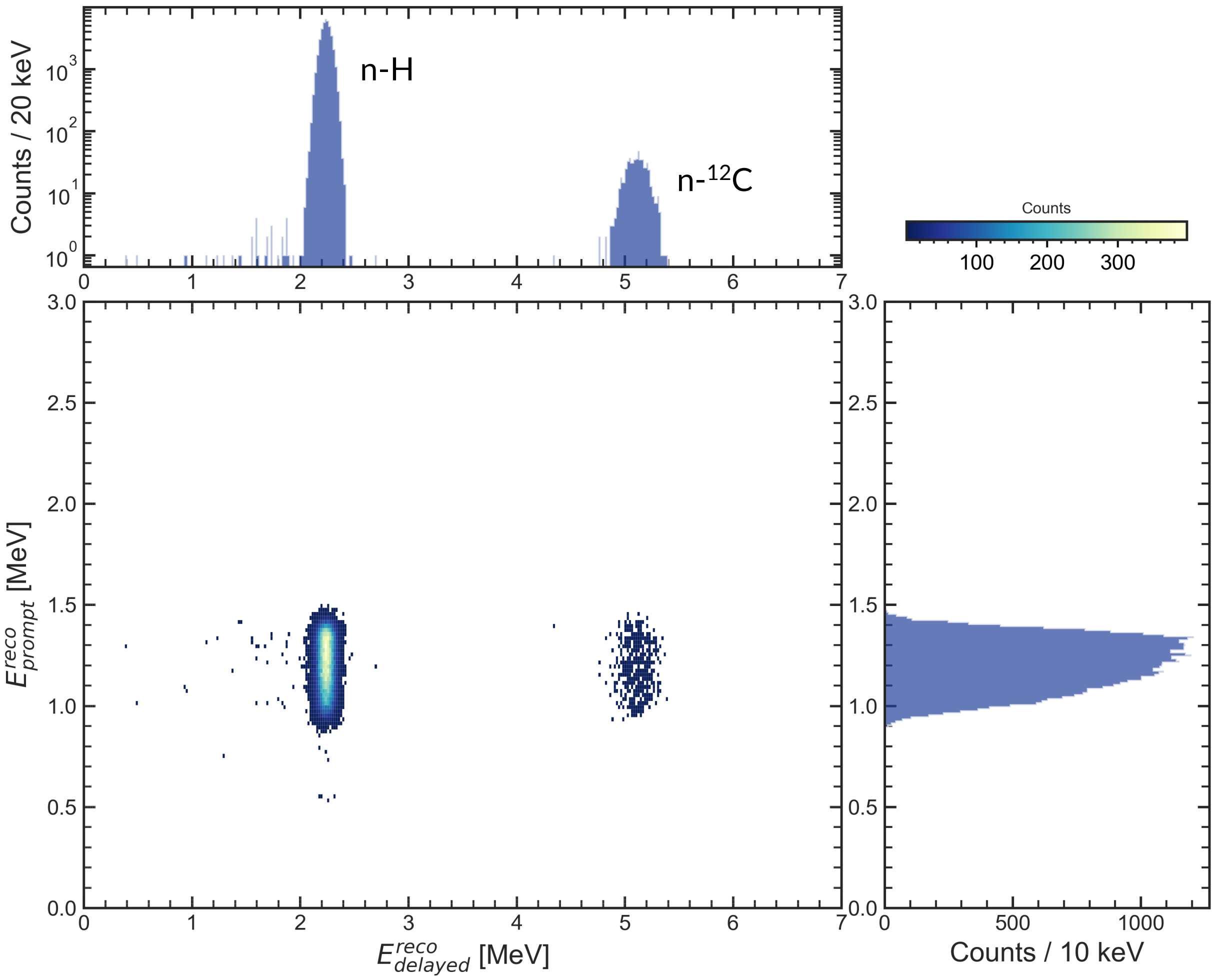
^{8}He: selection efficiency

	Efficiency	Evts/day
	100%	0.09 [4]
1. Fiducial volume (FV) cut r < 17.2 m	**91.4%**	**0.082**
2. Energy cut		
• Prompt energy $E_p \in (0.7, 12)$ MeV	**99.8%**	**0.082**
• Delayed energy $E_d \in (1.9, 2.5) \cup (4.4, 5.5)$ MeV	**99.9%**	**0.082**
3. Time/vertex cut		
• $\Delta t < 1$ ms $\Delta r < 1.5$ m	**98.3%**	**0.08**
Combined efficiency	**90%**	**0.08**



Geo-ν energy distributions

^{232}Th geo-ν energy distribution (after FV cut)



^{238}U geo-ν energy distribution (after FV cut)