Methodology used in Borexino for the identification of cosmogenic long-time decay background

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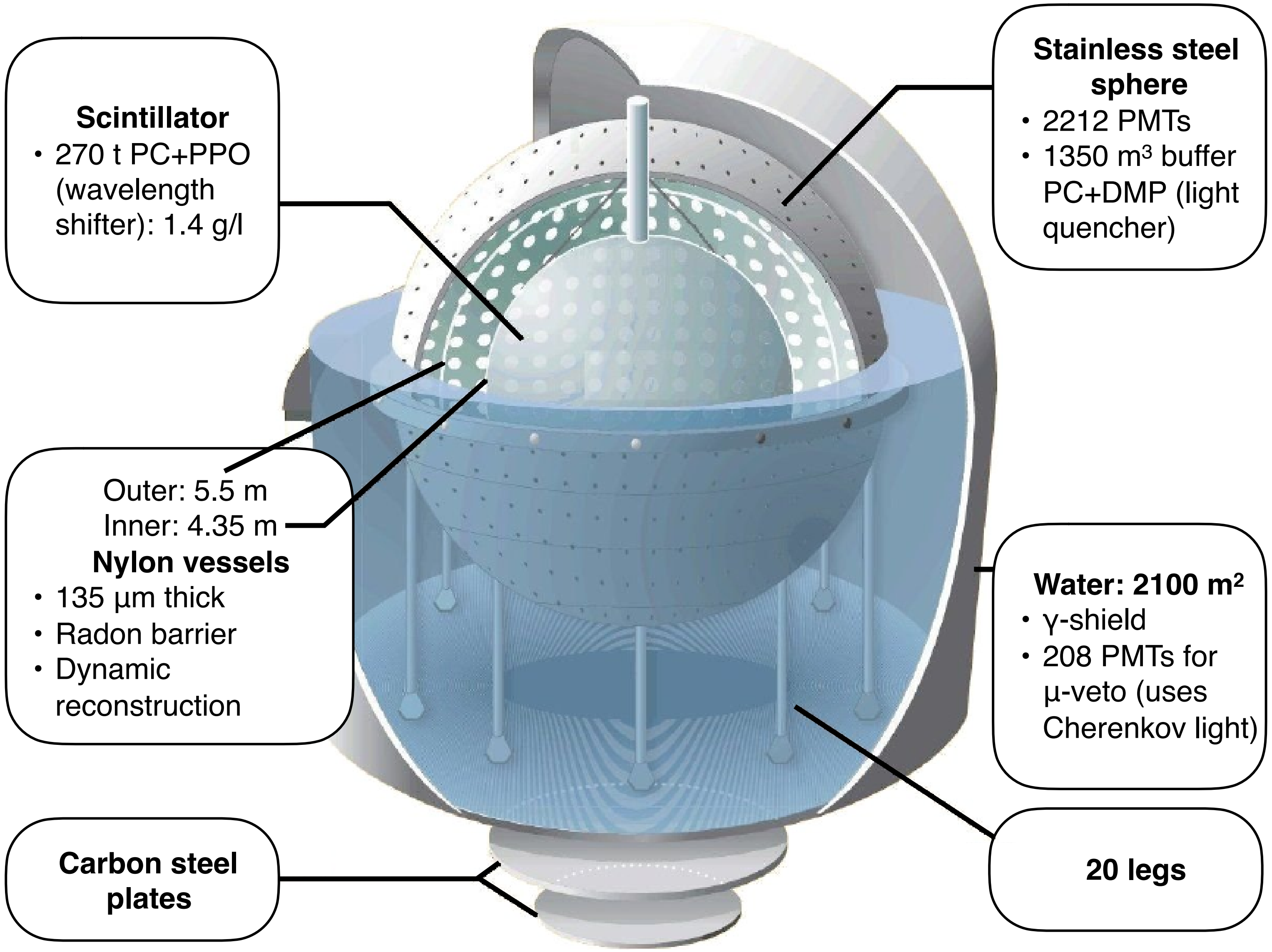
Low Radioactivity Techniques

2022

Workshop VIII

Borexino

Sited beneath Gran Sasso mountain (1400 m of rock shielding), Italy.



- 25% Coverage
- Light Yield (LY): 500 p.e./MeV

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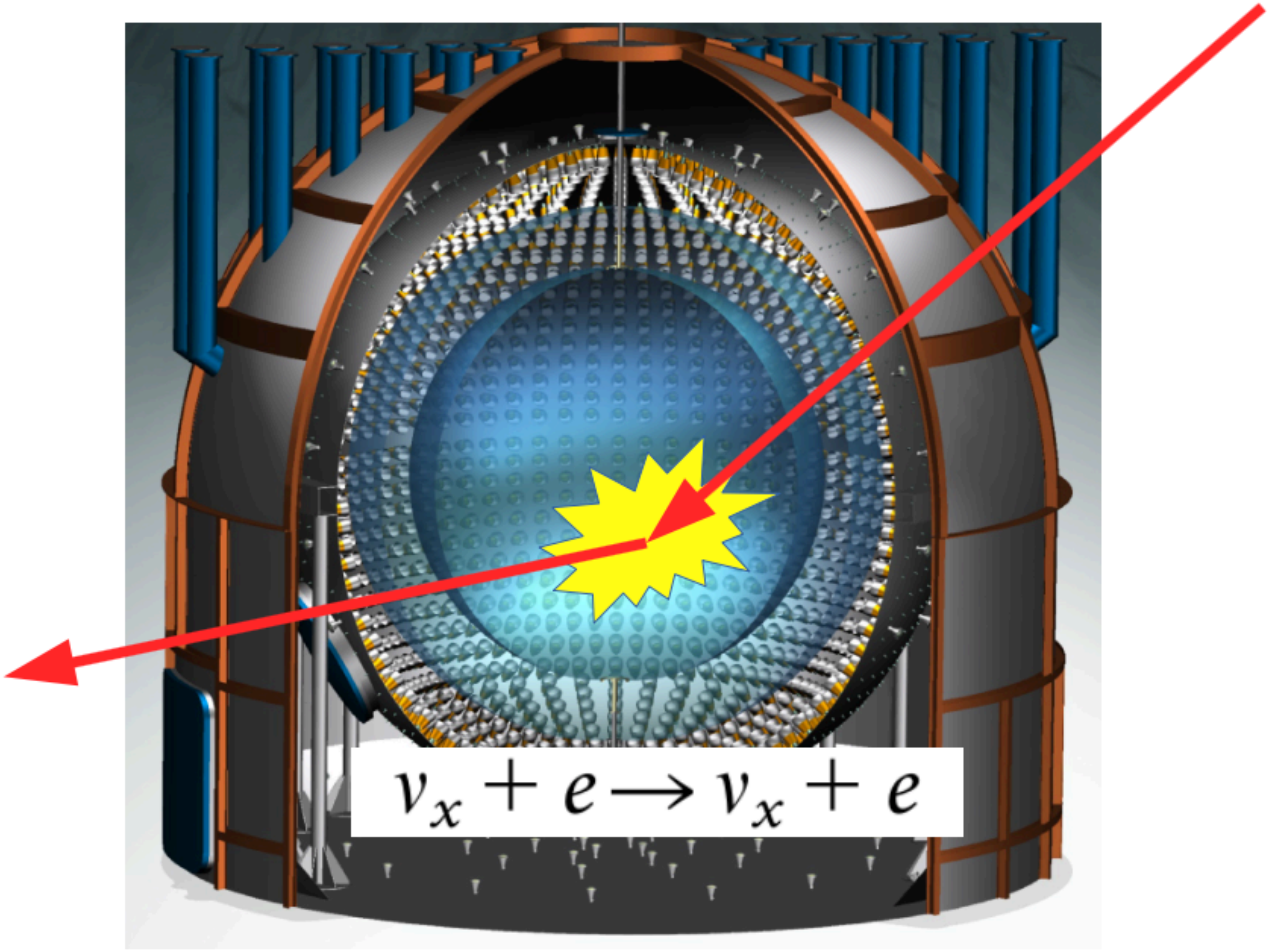

Borexino core is the most radio-clean spot on Earth with over 10 orders of magnitude below typical radioactivity levels

- 25% Coverage
- Light Yield (LY): 500 p.e./MeV
- Very low background
  - Nitrogen stripping
  - Distillation
  - Water extraction
- Continuous temperature and contamination monitoring

Signature for solar neutrinos: β-like spectrums (indistinguishable from the natural radioactivity (β^-/γ components)

Long-t decay cosmogenics

Cosmogenic background:

produced by the interaction of Cosmic Rays

Long-time decay:

much longer than the data acquisition speed

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Example: ^{11}C

- muon spallation kicks out a neutron from ^{12}C

$$\mu + ^{12}\mathrm{C} \rightarrow \mu + ^{11}\mathrm{C} + n$$

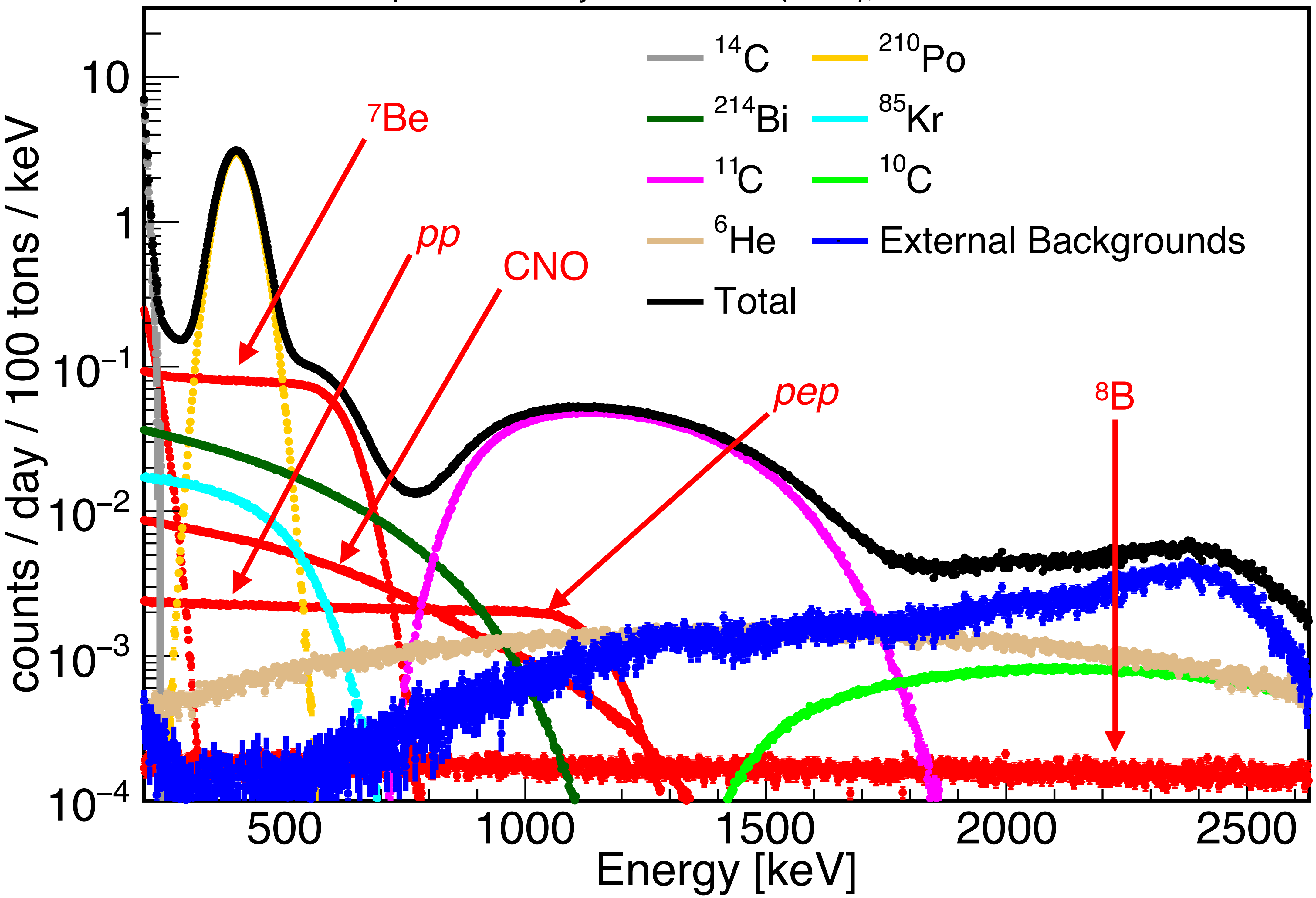
$$n + p \rightarrow D + \gamma_{2.2\mathrm{MeV}} \quad (250\ \mu\mathrm{s})$$

$$^{11}\mathrm{C} \rightarrow ^{11}\mathrm{B} + e^{+} + \nu_e \quad \mathbf{(29.4\ min)}$$

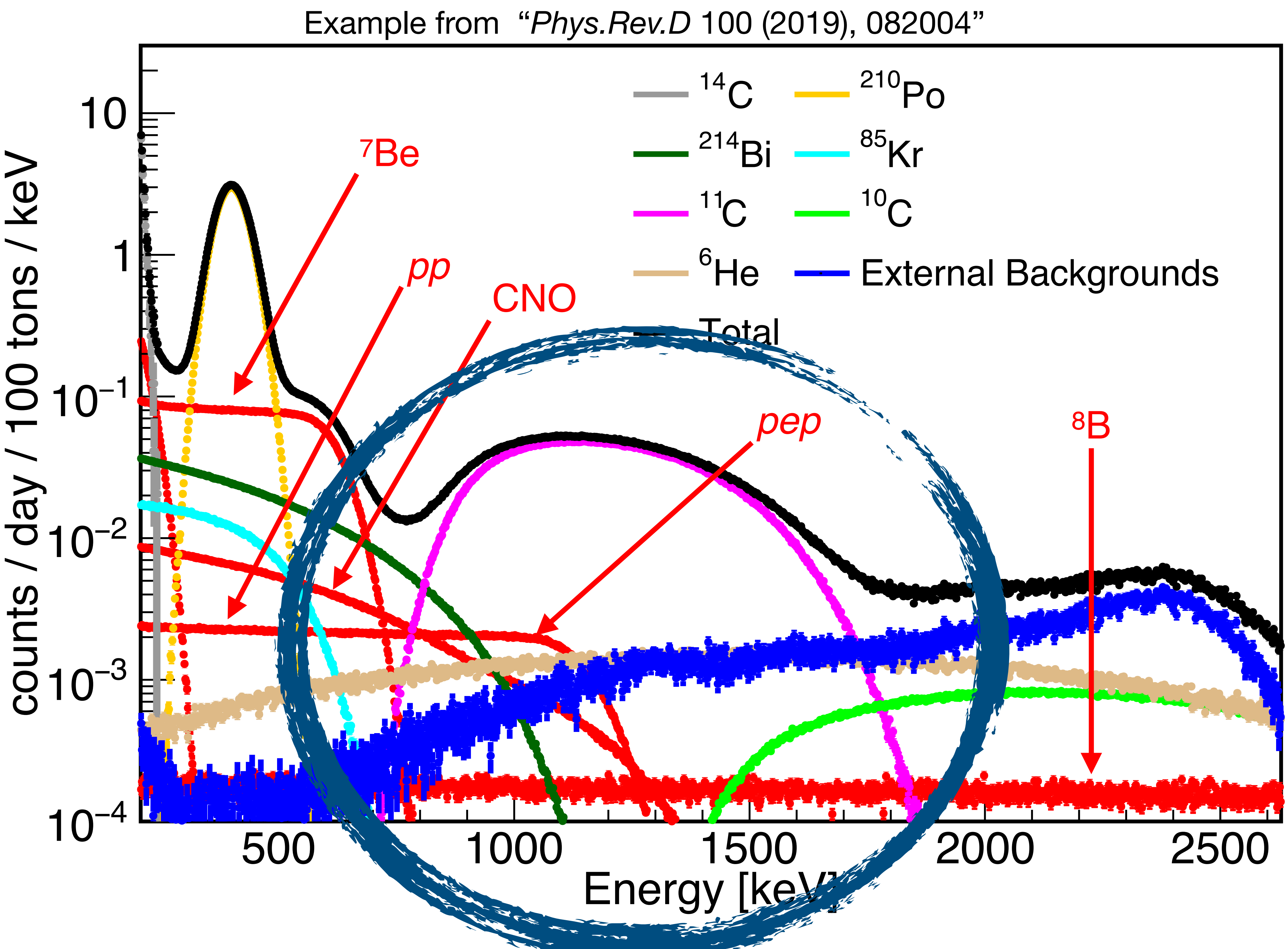
  - **hard to directly detect due to the long average β^+ decay time**
- ^{11}C decays β^+, $Q = 1.98$ MeV
- Physics not well understood: no simulations are possible

^{11}C

Example from "*Phys.Rev.D* 100 (2019), 082004"



^{11}C



Example from "Phys.Rev.D 100 (2019), 082004"
counts / day / 100 tons / keV
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
500
1000
1500
2000
2500
Energy [keV]
^{14}C
^{210}Po
^{214}Bi
^{85}Kr
^{11}C
^{10}C
^{6}He
External Backgrounds
Total
^{7}Be
pp
CNO
pep
^{8}B

^{11}C

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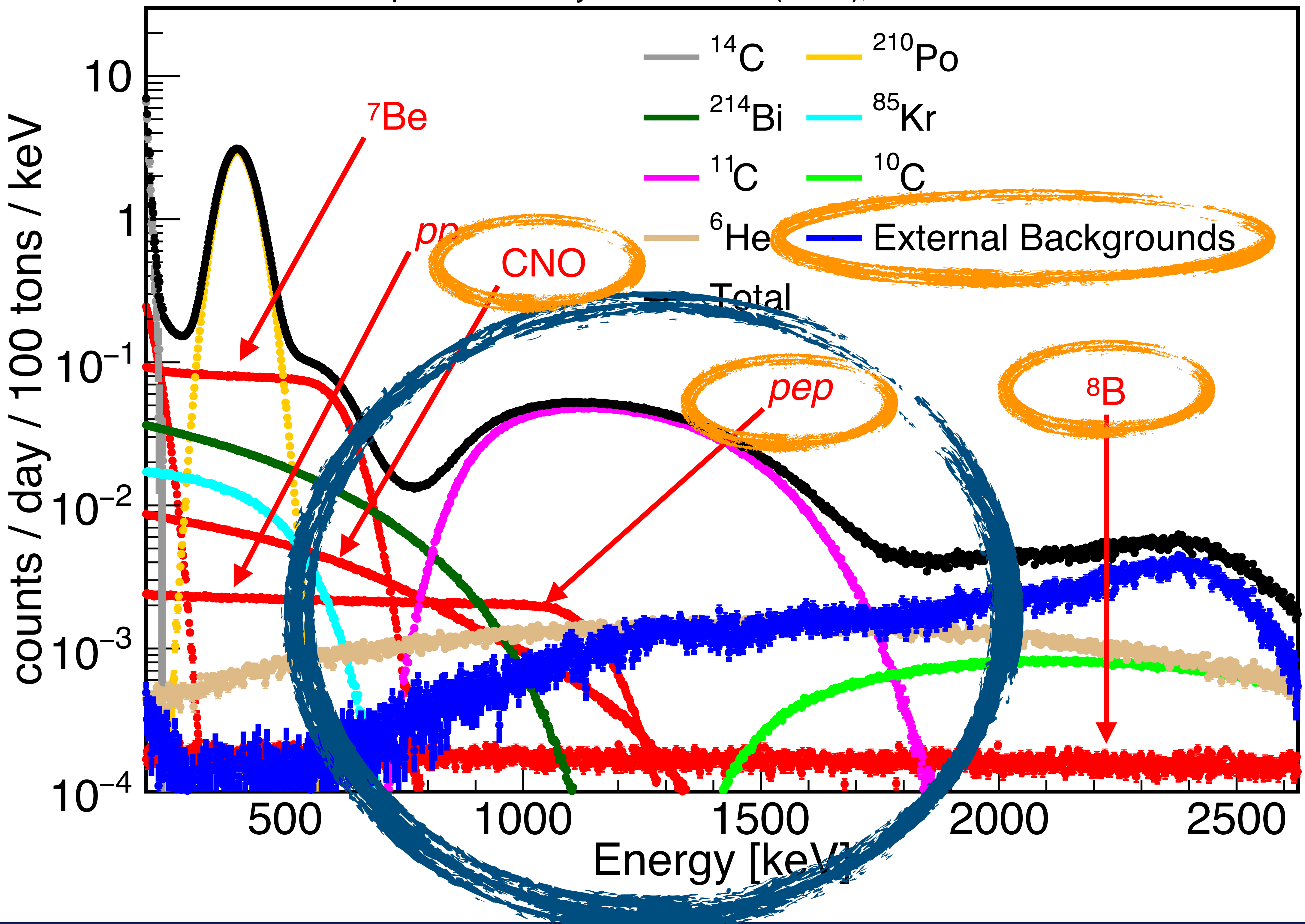
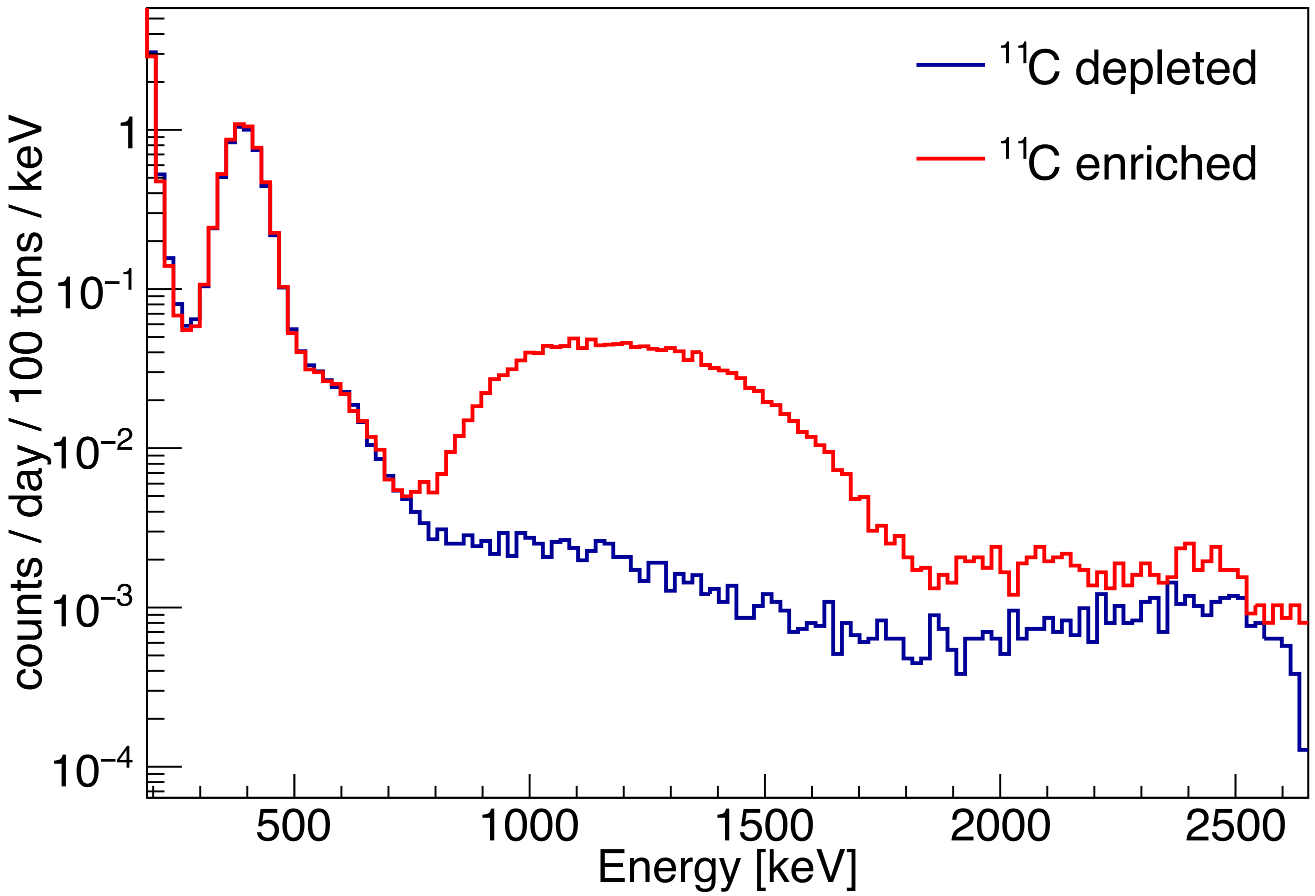


Every cloud has a silver lining

The neutrino fluxes to fit are many: need constraints!

Finding ^{11}C candidates can be a benchmark for creating a dataset separator: one ^{11}C-**enriched** and one ^{11}C-**depleted**



Strategy: simultaneously fit of the two subsets allowing only the ^{11}C rate to be different

How to catch ^{11}Cs

We need to define a time and space “veto” region:

evens in “veto” ⇒ enriched dataset; else ⇒ depleted

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⇓

Three-Fold Coincidence (TFC)

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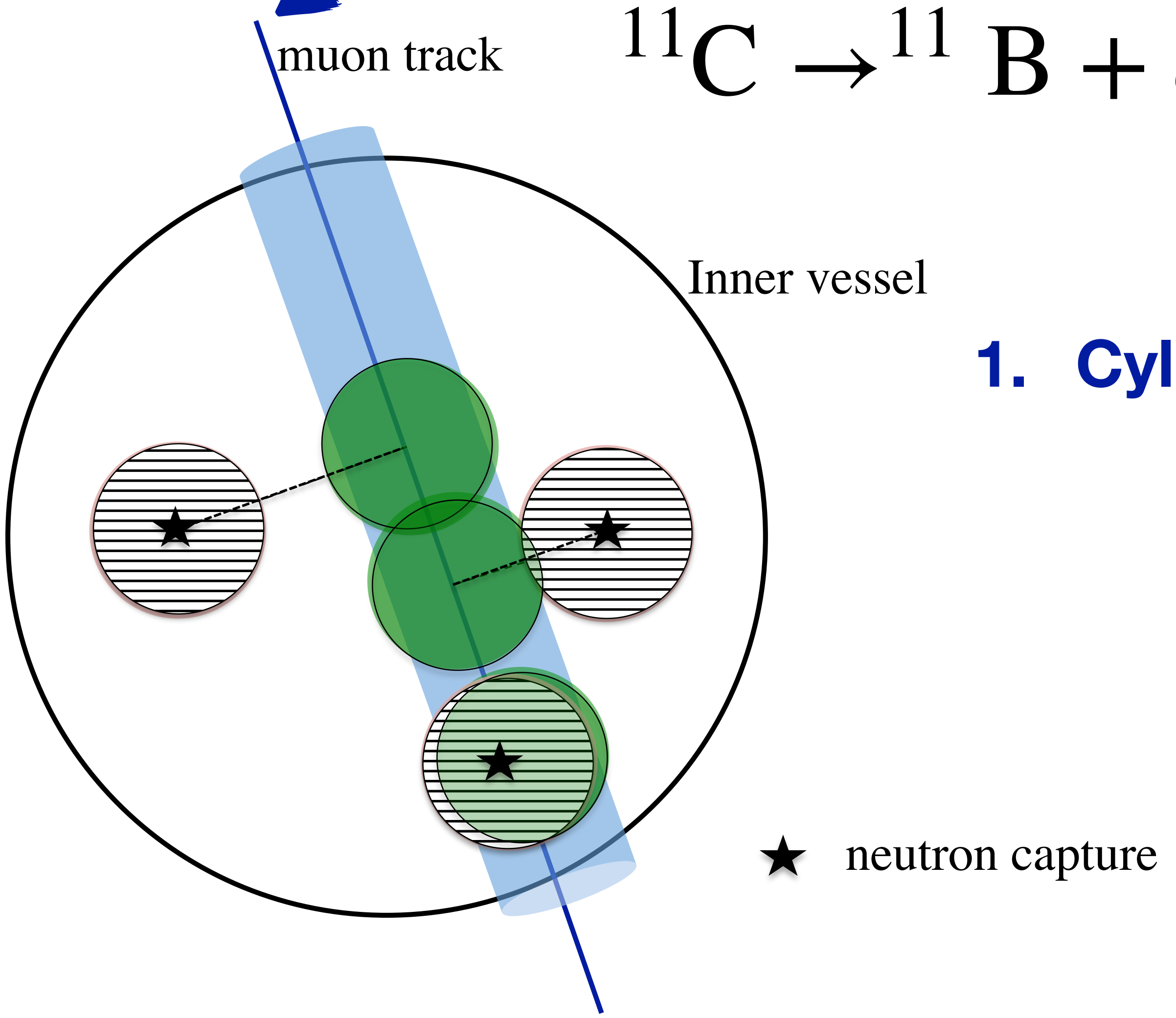

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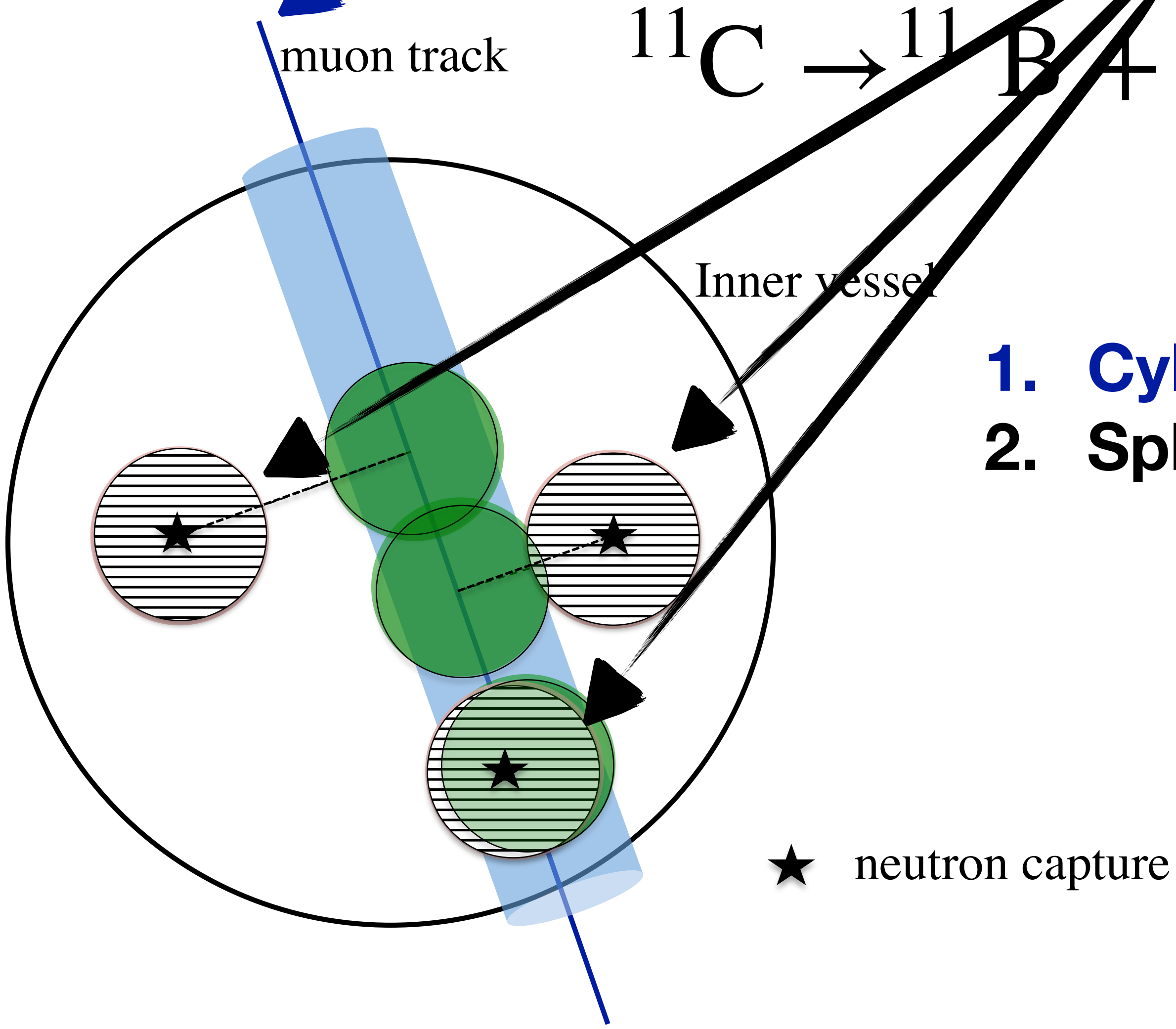

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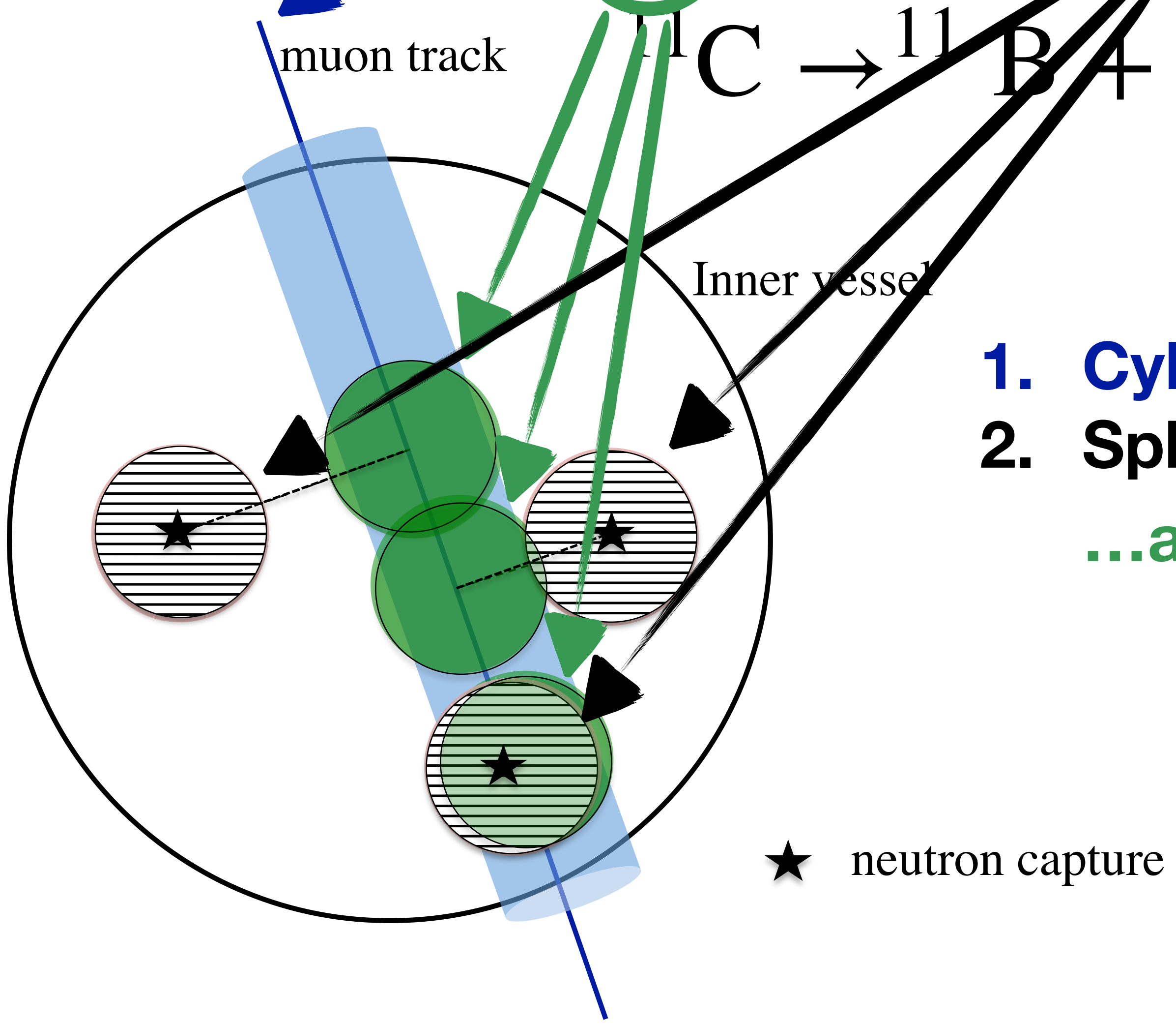

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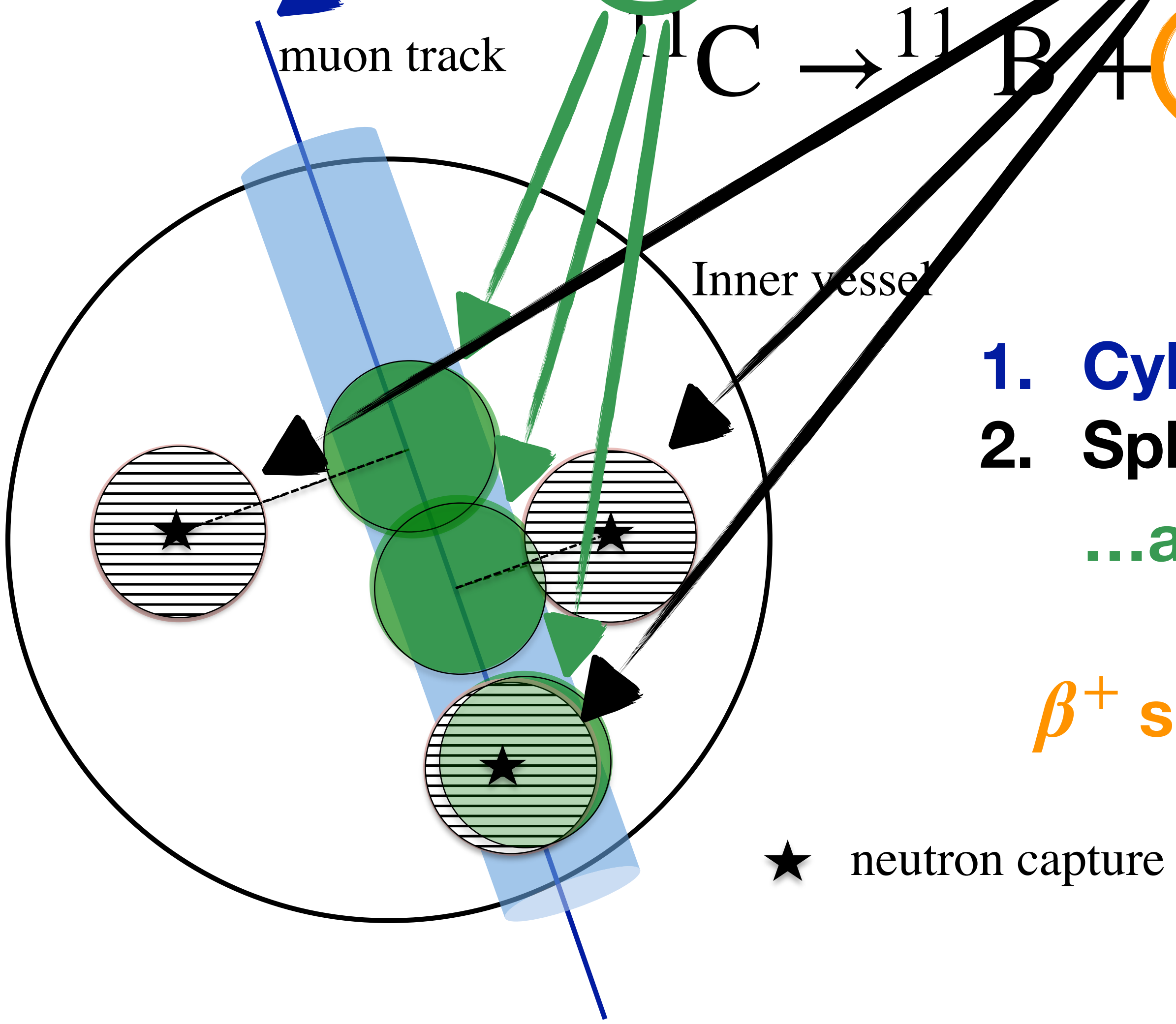

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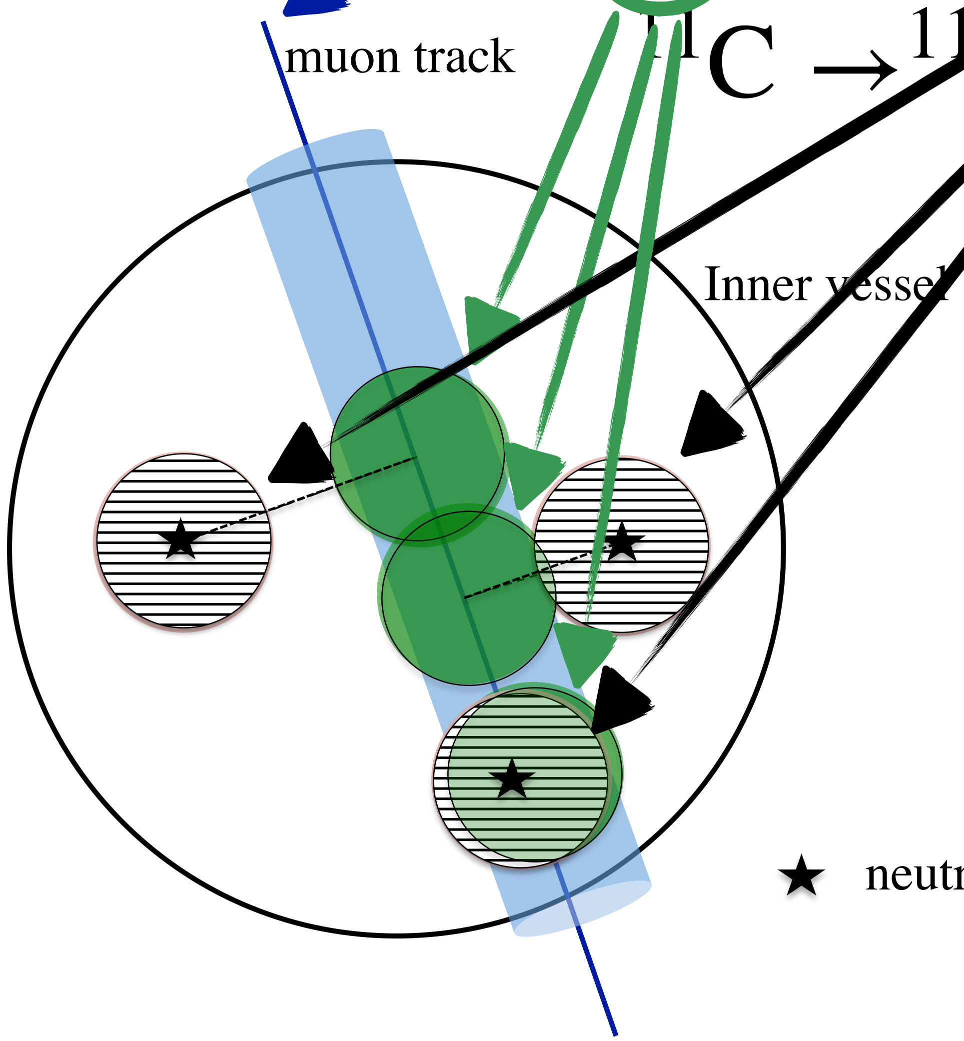

★ neutron capture

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…and their projection onto μ-track

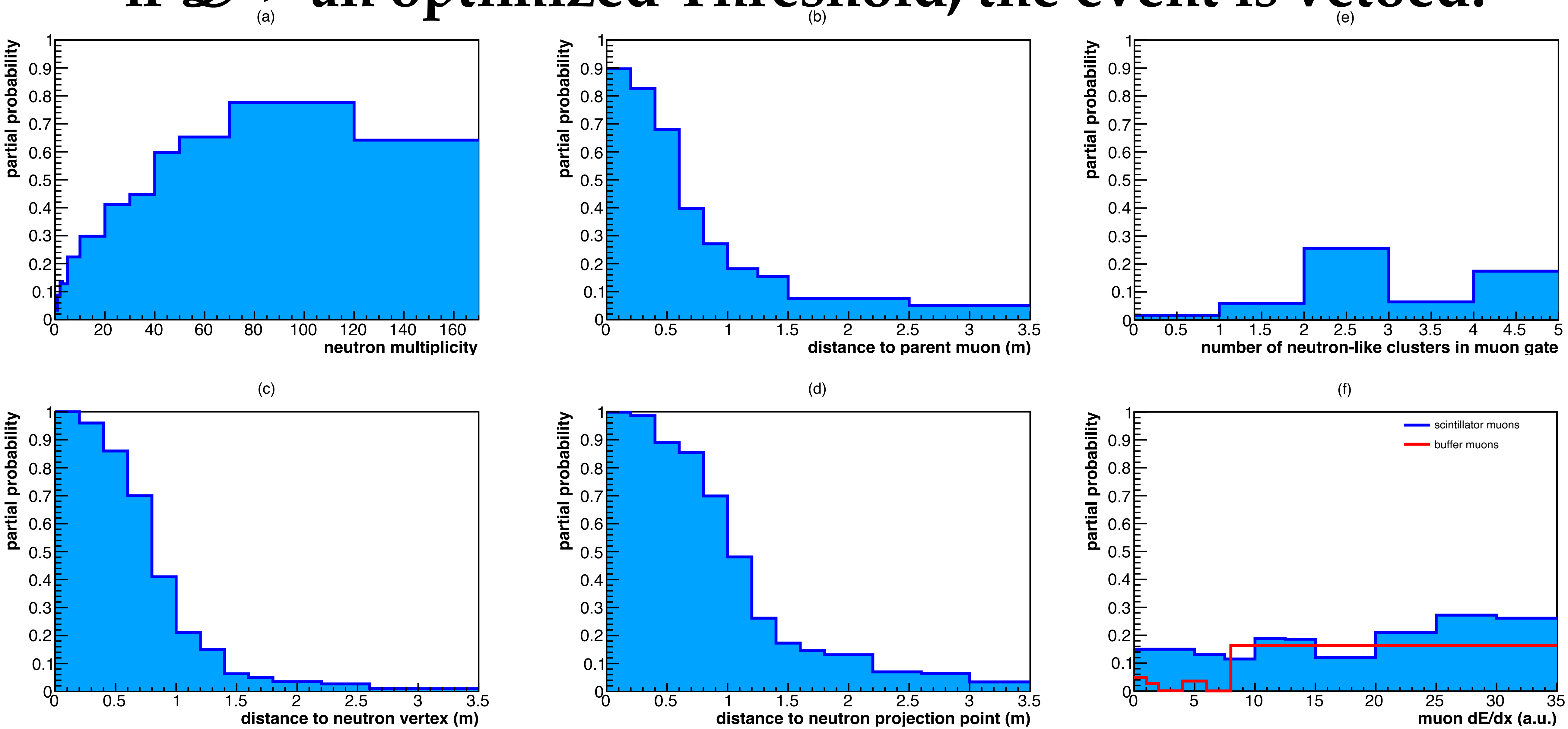
β^{+} signature is the event tested against the veto

…blinded periods (board saturated, in-between runs) are considered time vetoed: **F**ull **V**olume **V**eto (**FVV**)

TFC with a Likelihood

How much is the likelihood $\mathscr{L}$ of e^+ to be in coincidence with μ and n?

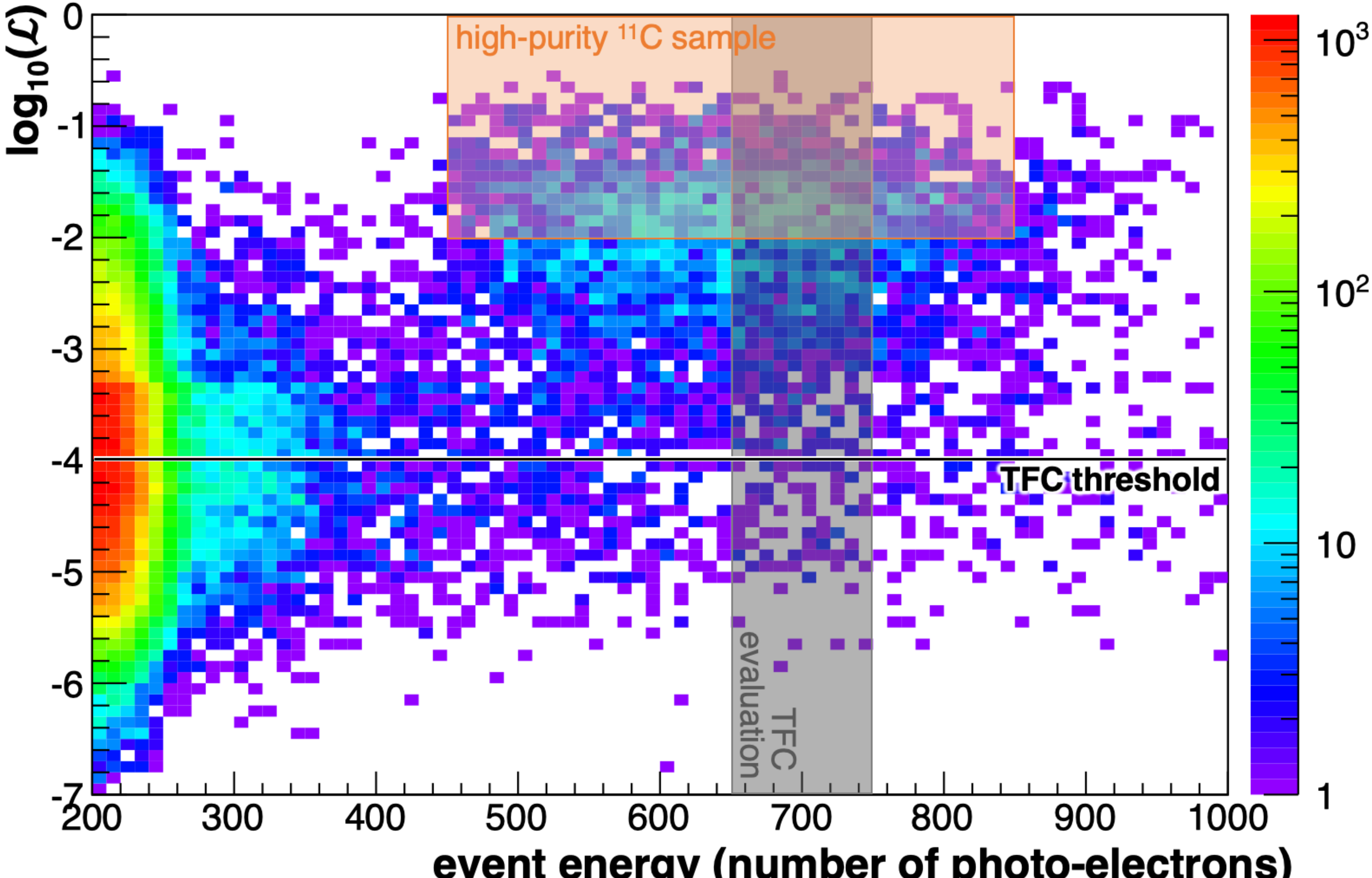
if $\mathscr{L}$ > an optimized Threshold, the event is vetoed!



Different weighted combinations of (a)–(f) give 4 likelihoods: only the maximum is considered for the LH

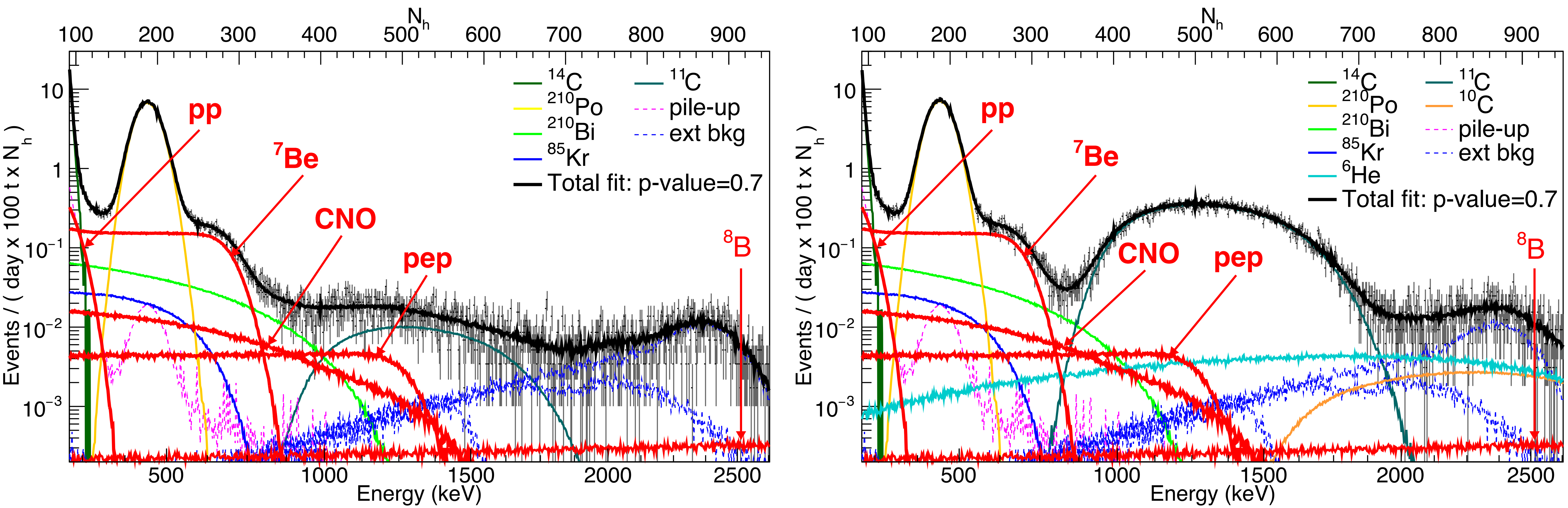
See "*Eur.Phys.J.C* 81 (2021) 12, 1075" for details on both **HC** and **LH** approaches

Likelihood VS Threshold



Is TFC working?

depleted **enriched**



Example from “*Phys.Rev.D* 100 (2019), 082004”

All components are identical except ^{11}C (+ ^{10}C and ^{6}He)

It is not expected a 100% separation efficiency; hence, some residual ^{11}C is expected in **depleted**

Performances

- **Exposure fraction**: fraction of toyMC events falling in the ^{11}C depleted sample (not vetoed)

$$\varepsilon_{\text{depleted}}$$

- **Tagging efficiency**: tagged events in ^{11}C region normalized by the sample fraction (by using Exposure fraction).

$$e_{\text{tagged}} = 1 - \frac{^{11}\text{C}_{\text{untagged}}}{^{11}\text{C}_{\text{total}}} \cdot \frac{1}{\varepsilon_{\text{depleted}}}$$

	Borexino data periods:	2012-2016 Phase-II	2016-2020 Phase-III
Hard Cut	Tagging efficiency (e_{tagged})	90.2%	90.7%
	Exposure fraction ($\varepsilon_{\text{depleted}}$)	63.3%	63.6%
Likelihood	Tagging efficiency (e_{tagged})	89.8%	90.1%
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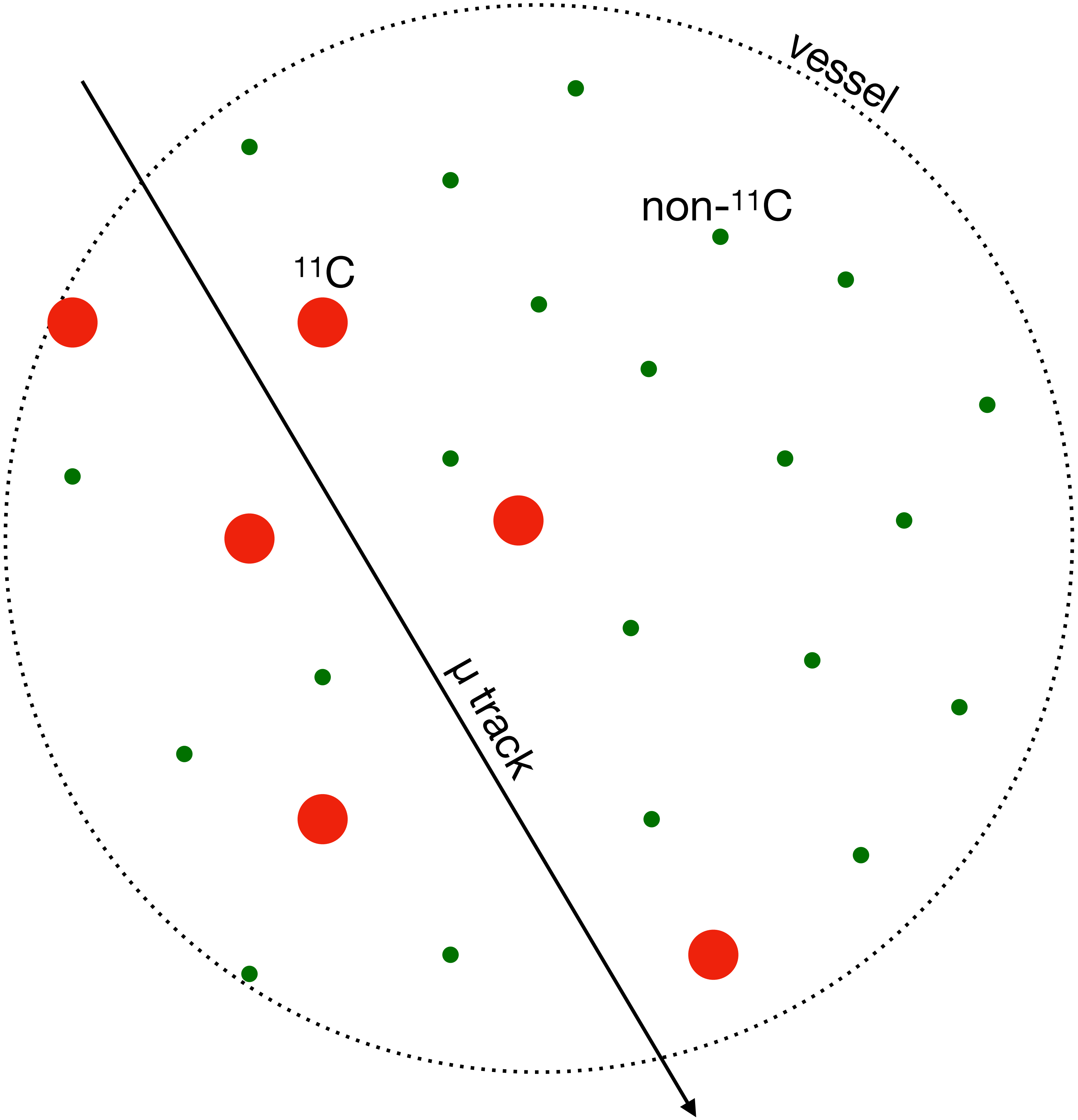
Can we leave out the FVV?



Along the μ-tracks, multiple ^{11}C are generated by spallation Can we use these "^{11}C bursts" to recover some exposure?

What we know of ^{11}C

- Charge spectrum: $400 \leq E(\text{p.e.}) \leq 1000$
- Decay time: $\tau = 1.8e9\ \mu s = 0.5$ h

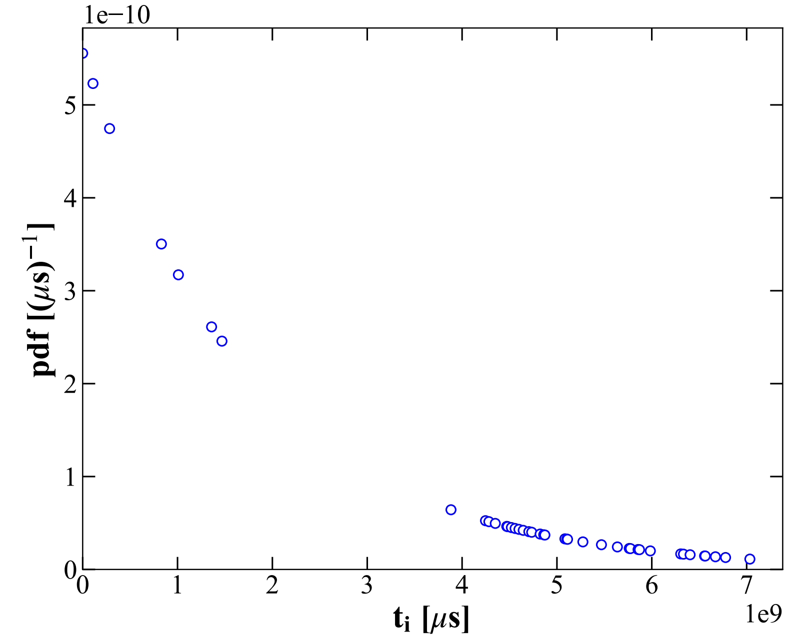
Idea: correlations along tracks

- in time: $\sim P_{\text{decay}}(t, \tau)$
- in space: unknown pdf
- …full of non-correlated event

Burst Identification (BI) steps

1. Time correlation

1. Select events in ^{11}C E region in a 2 hours window (non muon/neutron, $800 \leq E[keV] < 2000$)
2. Assign to each event a weight given by the decay p.d.f
3. Check for time correlation: good distribution, sum of weight > of a **threshold** (parameter)



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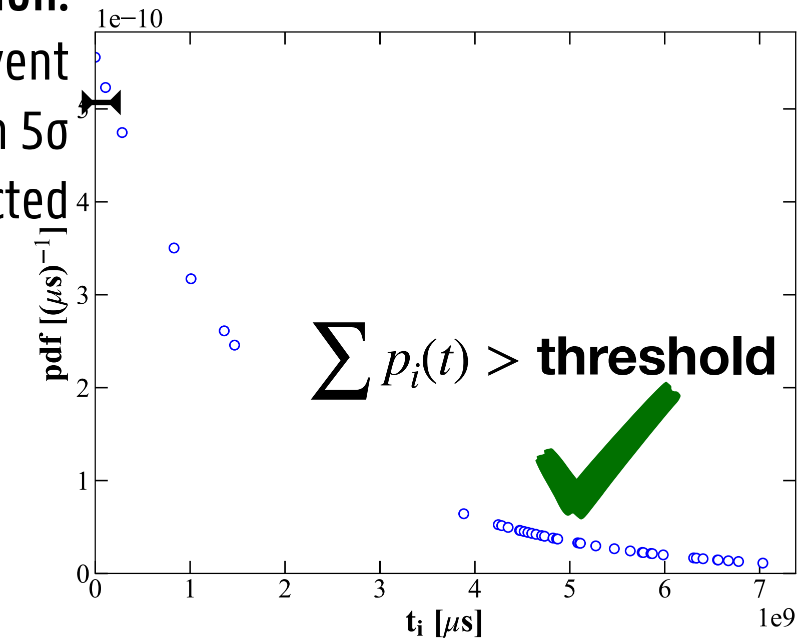
good distribution:
Distance initial-first event not larger than 5σ of the expected



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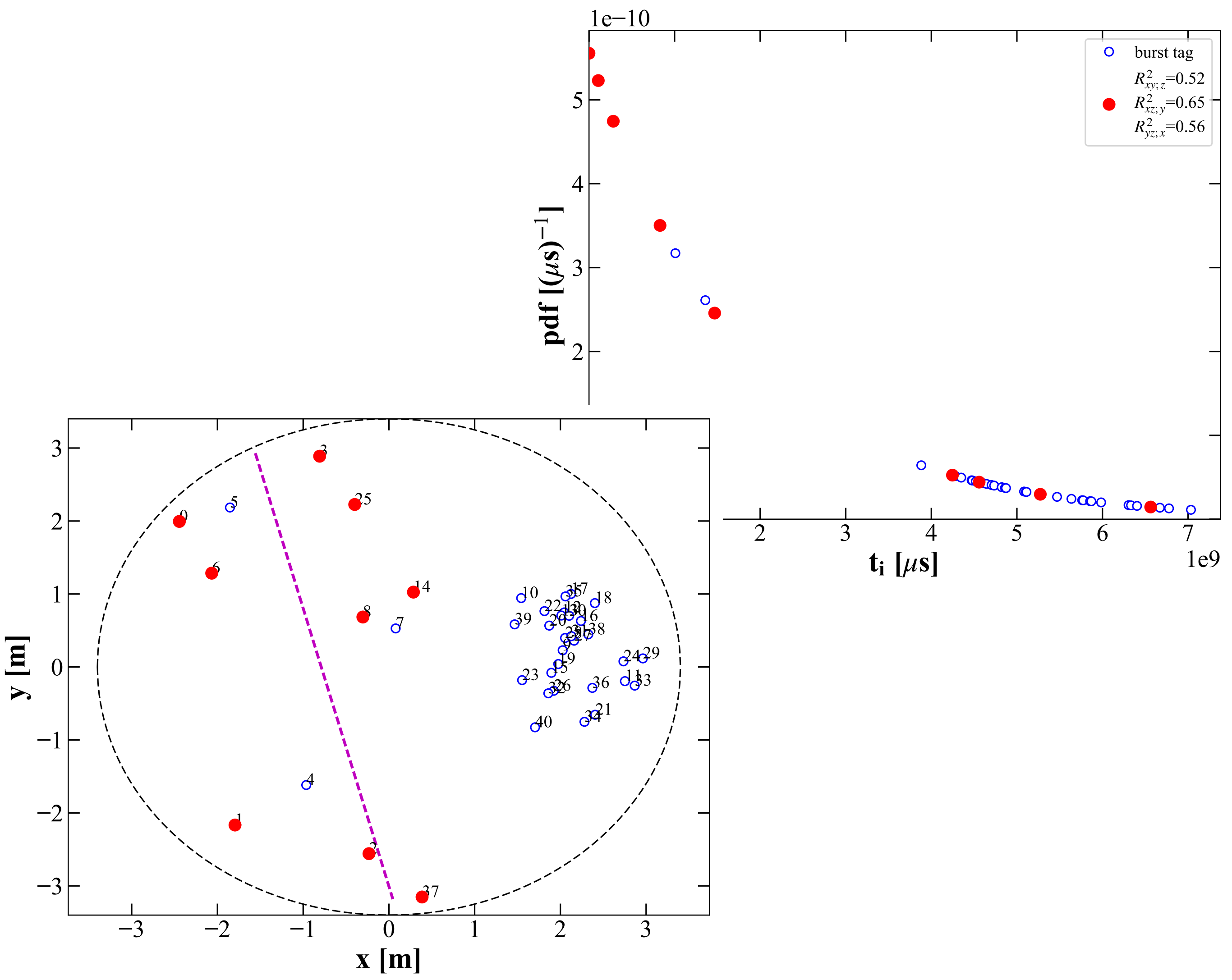
2. Space correlation

1. Starting from the first 4 events, test the change of the 3 squared correlation factors R^2 [backups!]
2. Change must not be larger than a **Tolerance** and R^2 cannot be smaller than **R2lim** (both parameters!)
3. Best correlation line (Theil-Sen lin.reg.): **R2line**



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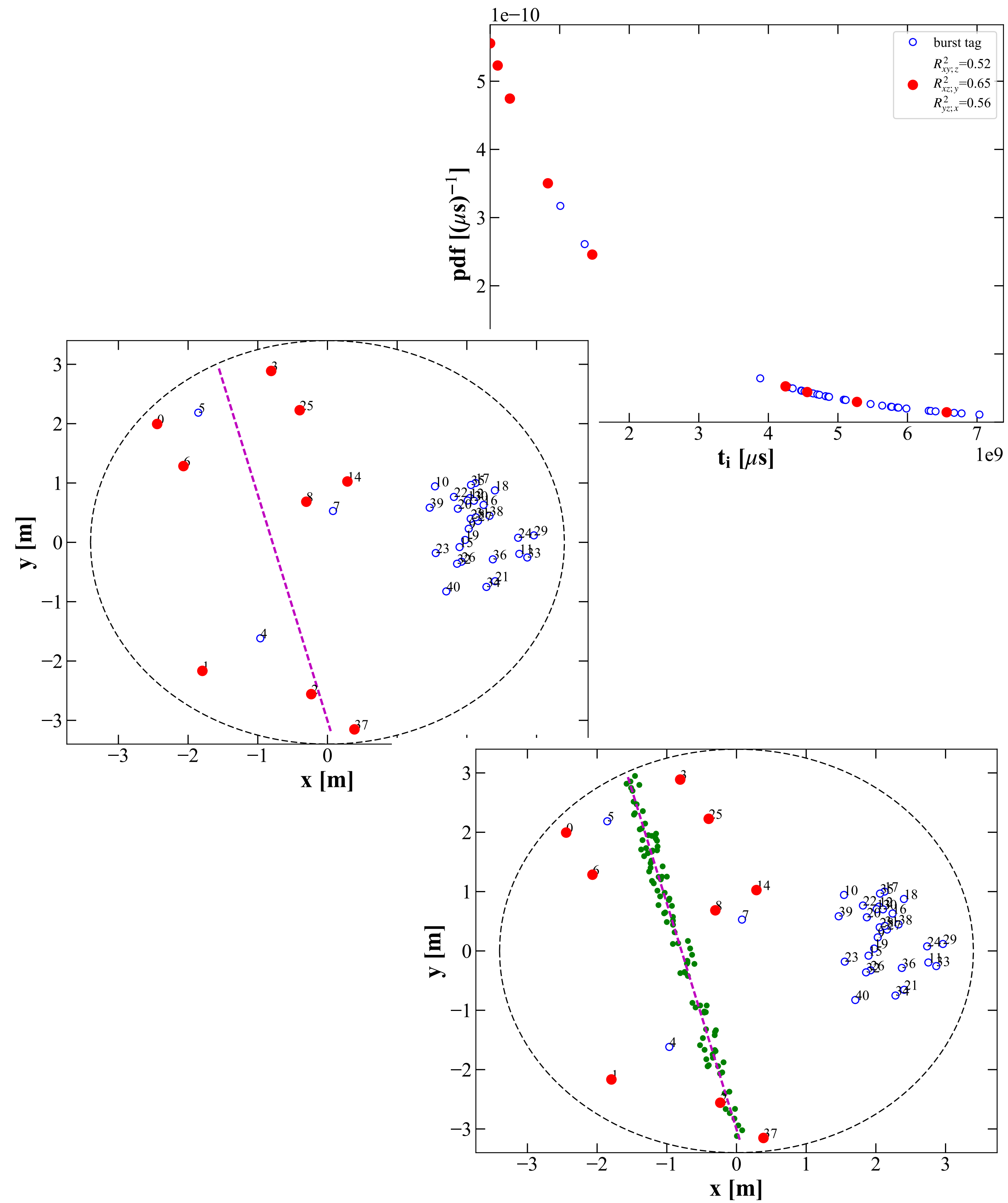
3. Tagging

1. To be unbiassed, ignore if an eventi is in ^{11}C E region!
2. Populate the line: starting from events closer to the line, check their correlation factors R^2



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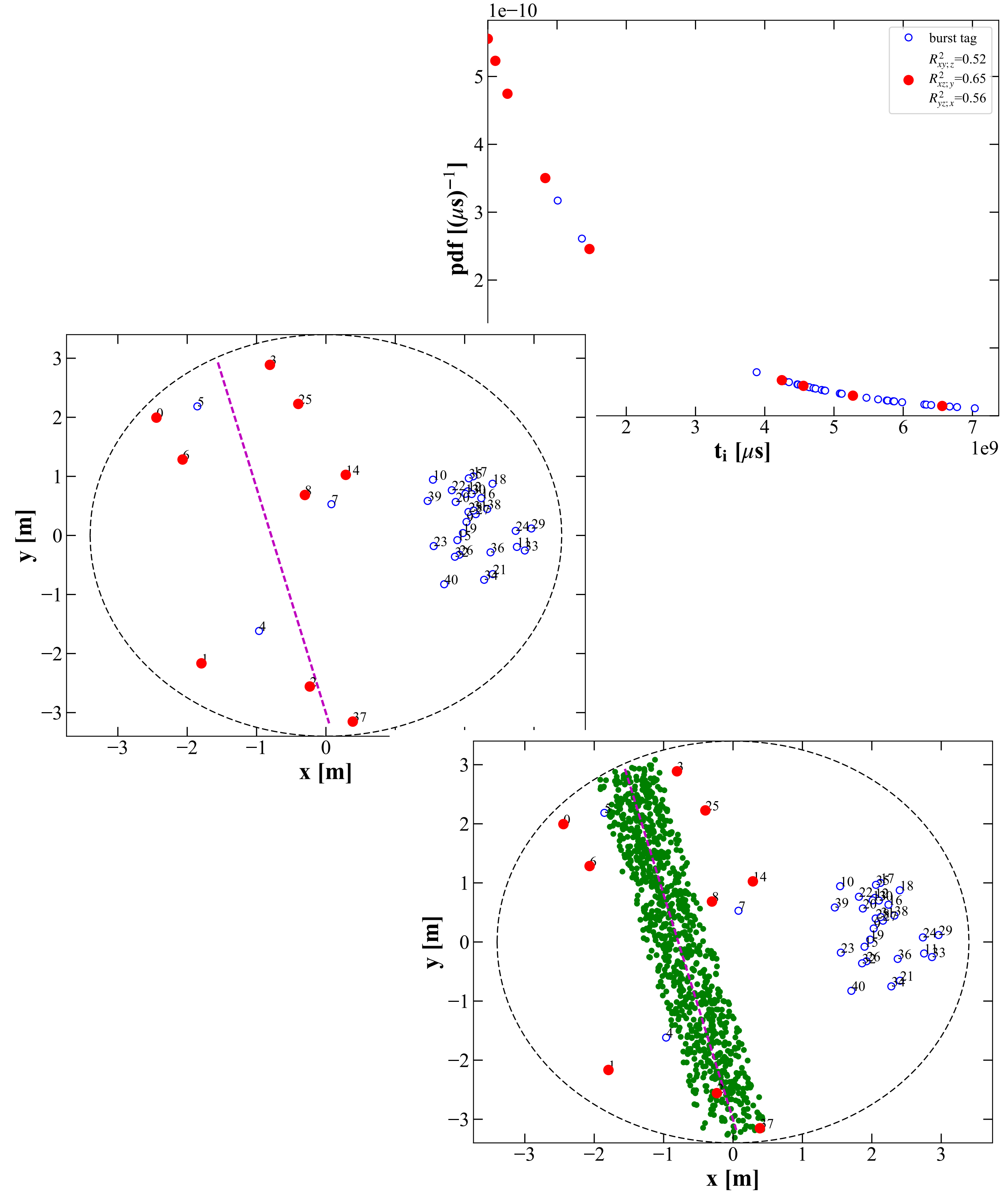

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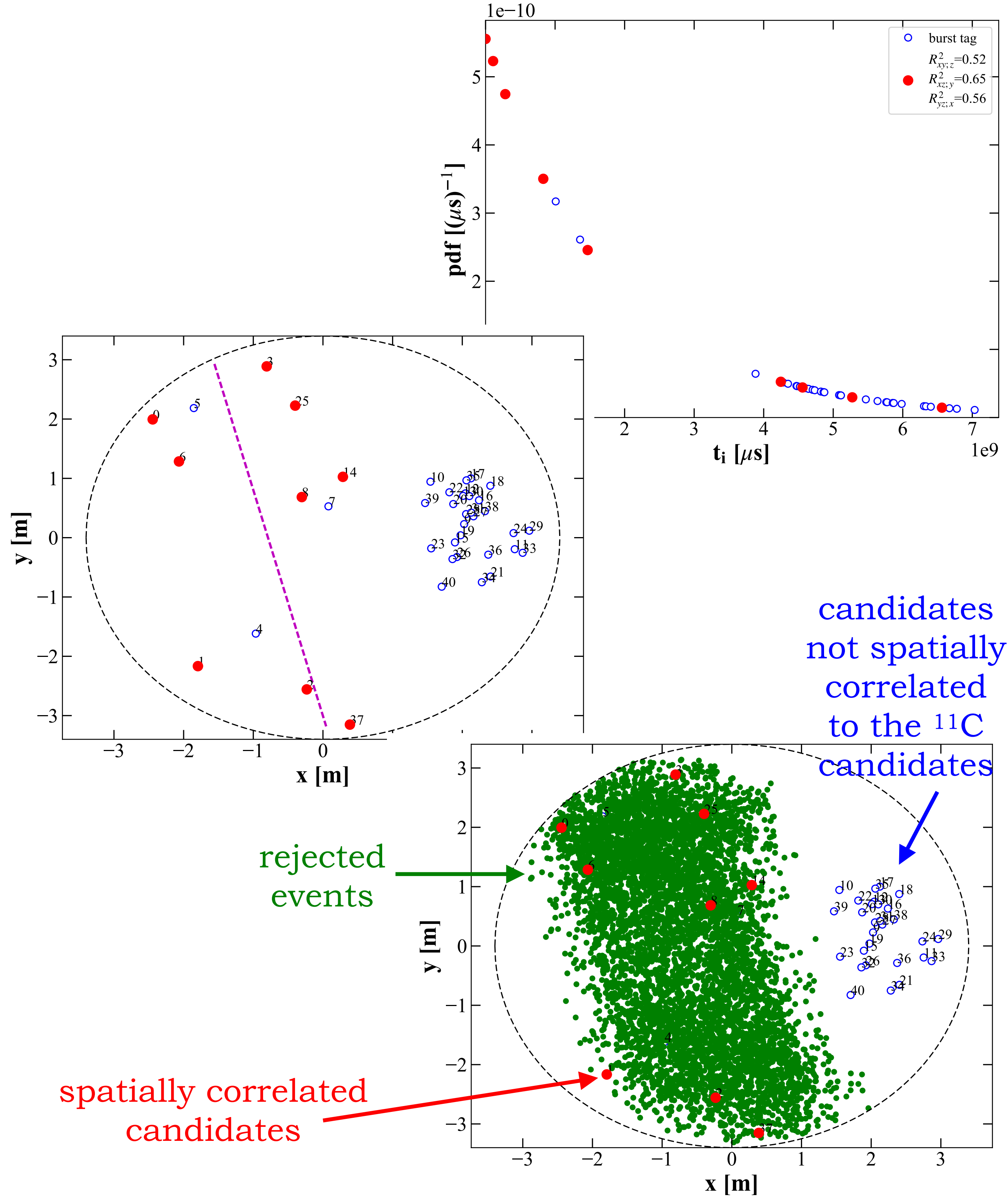
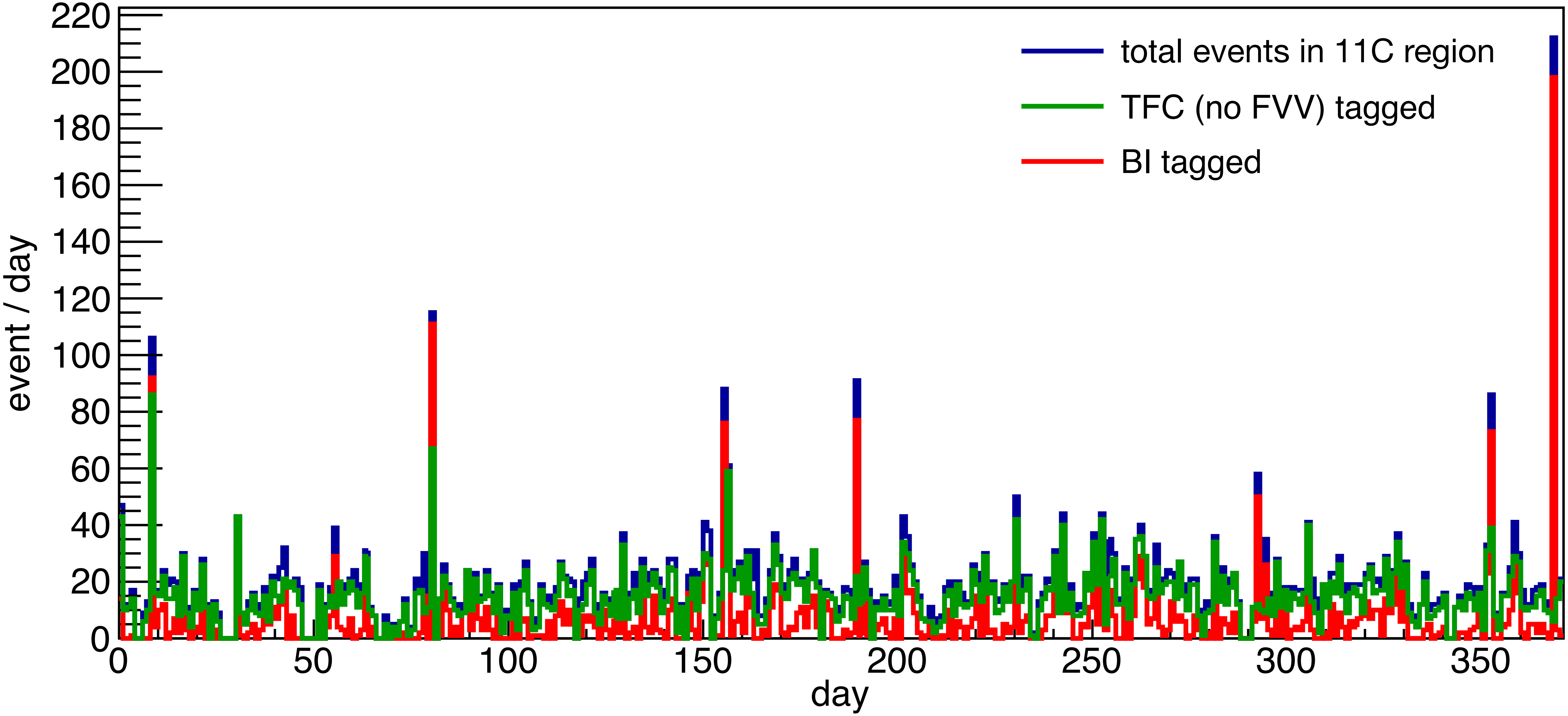
2. Populate the line: starting from events closer to the line, check their correlation factors R^2
3. Stop populating when the R^2 < **R2line**
4. **All events that populate the line are Tagged**



Is BI working?



The **BI** successfully identifies the region of higher ^{11}C multiplicity, especially when boards saturate.

TFC and **BI** are meant to be combined with an OR logic!

See "*Eur.Phys.J.C* 81 (2021) 12, 1075" for details

BI and TFC comparison

BI “minimal gain” configuration:

with the ~ same tagging power of the (HC-)TFC, what is the minimal gain in exposure rate?

HC-TFC		Phase-II	Phase-III
no FVV	Tagging efficiency (e_{tagged})	79.5%	77.6%
	Exposure fraction ($\varepsilon_{\text{depleted}}$)	70.8%	69.7%
no FVV + BI	Tagging efficiency (e_{tagged})	89.3%	90.4%
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with FVV (standard)	Tagging efficiency (e_{tagged})	90.2%	90.7%
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This is a borderline case!

The best configuration will be determined by the best trade-off between e_{tagged} and $\varepsilon_{\text{depleted}}$: how much fit performance we can gain?

Simulation ongoing…

Learning from Borexino…

Three-Fold Coincidence:

- Used NOT TO IDENTIFY (i.e., not remove) ^{11}C events, but to separate (i.e., treat) the dataset into one enriched and one depleted of ^{11}C
- Two approaches: Hard Cut (HC) used as official, Likelihood (LH) as cross-checker
- To be conservative, a Full Veto Volume (FVV) is applied: when boards saturate and the runs break, 2.5 hours of full volume vetoed are considered
- **Fundamental for the last years Borexino's results (*pp*, *pep*, CNO…)**

Burst identification:

- to be used TOGETHER (OR logic) with TFC
- instead of 2.5 hours of FVV, we catch at least the high multiplicity ^{11}C ("bursts")
- ONGOING simulations for e_{tagged} / $\varepsilon_{\text{depleted}}$ best trade-off

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THANK YOU!

BACKUPS

…some math for R²s

- $R^2_{ij;k} = (\rho^2_{ik} + \rho^2_{jk} - 2\rho_{ij}\rho_{ik}\rho_{jk})/(1 - \rho^2_{ij})$ [ρ is the Pearson's correlation]
- $\rho = \mathrm{cov}(\alpha, \beta)/\sqrt{\mathrm{Var}(\alpha) \cdot \mathrm{Var}(\beta)}$ [Pearson's correlation]
- Theil-Sen regression: median of all possibile lines

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no FVV	Tagging efficiency (e_{tagged})	79.5%	77.6%
	Exposure fraction ($\varepsilon_{\text{depleted}}$)	70.8%	69.7%
no FVV + BI	Tagging efficiency (e_{tagged})	89.3%	90.4%
	Exposure fraction ($\varepsilon_{\text{depleted}}$)	68.3%	66.7%
with FVV (standard)	Tagging efficiency (e_{tagged})	90.2%	90.7%
	Exposure fraction ($\varepsilon_{\text{depleted}}$)	63.3%	63.6%

BI "minimal background" configuration:

outside the ^{11}C energy region, $e_{\text{tagged}} \sim 0$. This configuration is optimized through a further reduction of this e_{tagged}

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BI and TFC comparison

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These are borderline cases!

The best configuration will be determined by the best trade-off between e_{tagged} and $\varepsilon_{\text{depleted}}$: how much fit performance we can gain?

Simulation ongoing…