Bayesian network-based 3D reconstruction for directional dark matter detection in CYGNO

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The prelude

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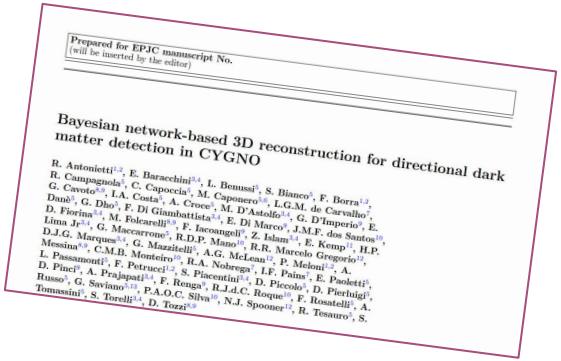
(+ Stefano/Giorgio)
22-04-2024

Today's meeting: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Bayesian network-based 3D reconstruction for directional dark matter detection in CYGNO

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Provide a brief presentation to the paper being submitted for internal review.

- Paper: *Bayesian network-based 3D reconstruction for directional dark matter detection in CYGNO*
- Scope: Explain how CYGNO can perform 3D reconstruction of tracks using *only* the PMT information, through a Bayesian Network-based algorithm (BAT–fit).

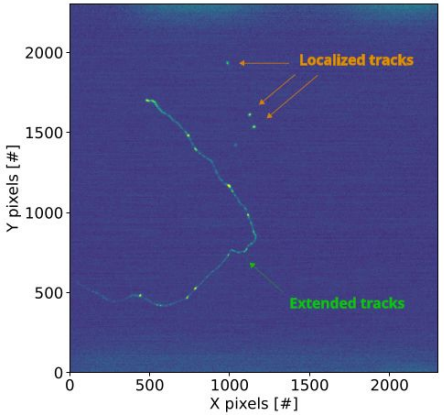
➔ *In this work, we present a **Bayesian Network-based algorithm** designed to **reconstruct** the events **using only PMT signals**, yielding a **full 3D description of the particle trajectories**.*

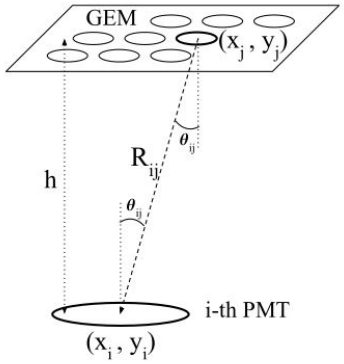
➔ *The algorithm models the light collection process probabilistically and **estimates spatial and intensity parameters** on the GEM plane, where light emission occurs. It is implemented within the **Bayesian Analysis Toolkit (BAT)** and uses **MCMC** sampling.*

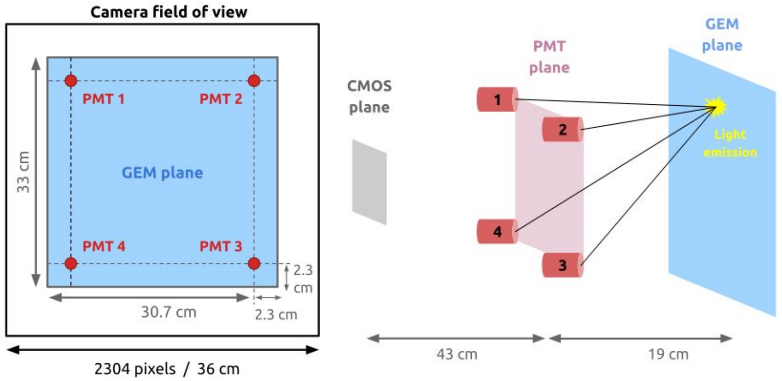
➔ *Validation using **data from the CYGNO LIME** prototype shows accurate **reconstruction of localized and extended tracks**. Results demonstrate that the Bayesian approach enables robust 3D description and, when combined with sCMOS data, further improves the precision of track reconstruction.*

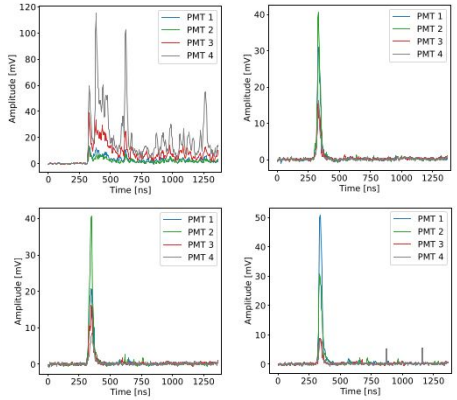
Paper organization:

- ➔ Introduction to LIME. Here, special care is given to what is:
  - A signal in LIME
  - What the PMTs see









$$\Phi = \frac{L \, dS \, dA \, \cos^2 \theta_i}{R_i^2}$$

$$L_i \propto \frac{L}{R_i^{\alpha}}, \text{ with } \alpha = 4$$

Paper organization:

- ➔ The BAT-fit. We explain how it works:
  - In sum, it takes the integrated charges of the PMTs for a given signal, and assuming the relation L ∝ R^{-4}, gets the (x,y,L) of the event in the GEM plane, as seen by the PMTs
  - More details here: https://agenda.infn.it/event/43261/contributions/243495/attachments/125545/185129/PMTs%20fit%20update.pdf

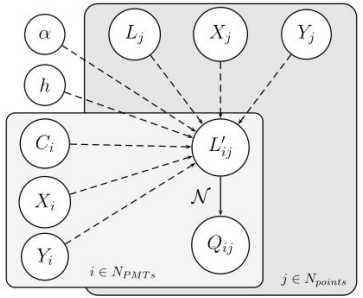


Fig. 5: Bayesian network adopted in the PMT reconstruction. The node Q_{ij} is the collected charge by i-th PMT for the j-th signal; L'_{ij} is the light reaching the PMT; L_j is the light produced at the GEM hole; X_j and Y_j are the position of the emitted light in the GEM plane; C_i are the proportionality factors relating light to charge; X_i and Y_i are the positions of the i-th PMT; h is the distance between the GEM plane and the PMT plane; and α is the power dependence of the light reaching the PMTs on the distance. A solid arrow between nodes represent probabilistic link between the two variables, while a dashed arrow between nodes represent a deterministic link between the two.

$$p(\theta|\{x\}) = \frac{p(\{x\}|\theta)\cdot\pi(\theta)}{p(\{x\})},$$

$$p(\{x\}|\theta) = \prod_{j=1}^{N}\prod_{i=1}^{4}\mathcal{N}(Q_{ij}|L'_{ij}(\theta)) = \prod_{j=1}^{N}\prod_{i=1}^{4}\frac{1}{\sqrt{2\pi}\sigma_{ij}}\exp\left[-\frac{(Q_{ij}-L'_{ij}(\theta))^2}{2\sigma_{ij}^2}\right], \quad (5)$$

With:

- $L'_{ji} = c_i \frac{L_j}{R_{ij}^{\alpha}}$
- $R_{ji} = \sqrt{x_{ji}^2 + y_{ji}^2 + z^2}$

Paper organization:

- ➔ For what can the BAT-fit be used for:
  - PMT calibration
  - Localized (spot-like) events
  - Extended tracks

Paper organization:

- **PMT calibration**
  - BAT is used to intercalibrate the PMTs.
  - We used events with fixed **L** and **known (x,y)**, to get the calibration constants $\mathbf{c_i}$
  - *NB:* In the future, this procedure should be performed sometimes, and the PMT voltages re-regulated accordingly.

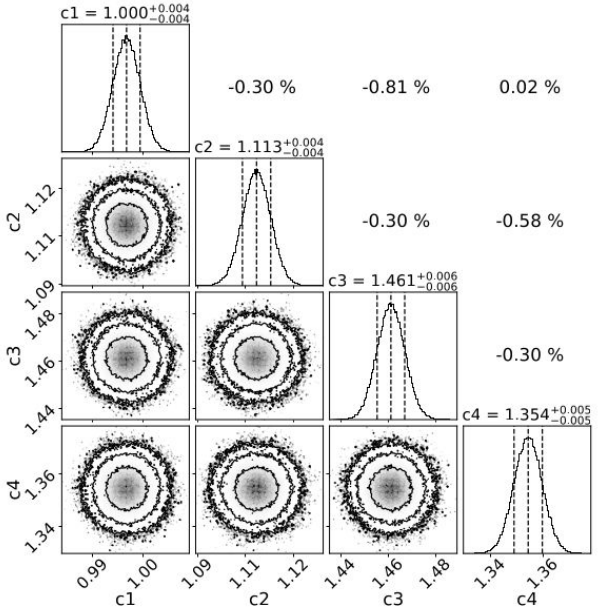
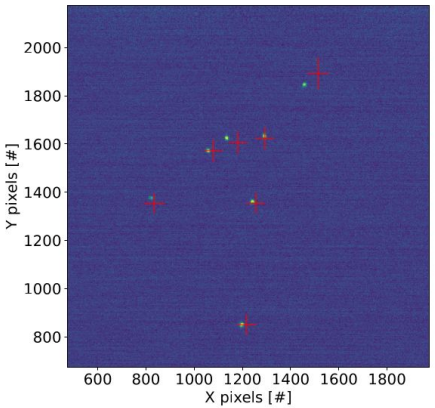
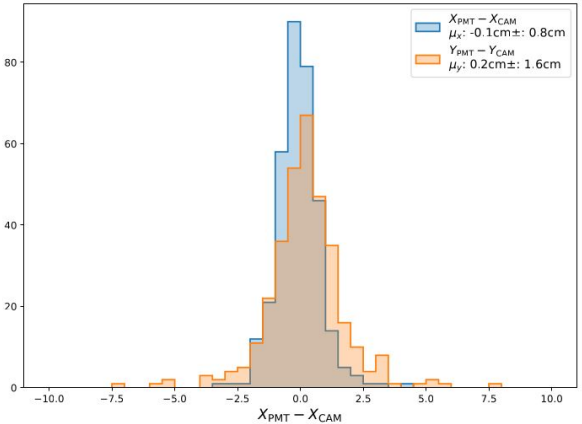


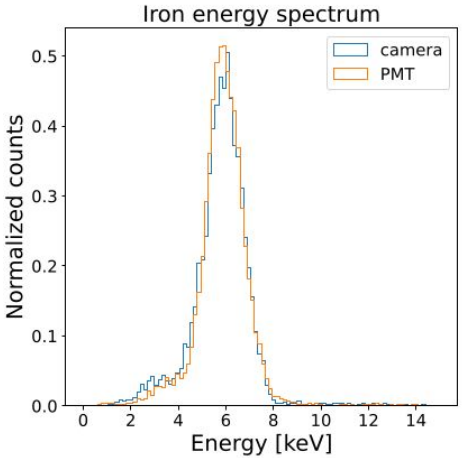
Fig. 6: Corner plot of the posterior distributions obtained from the calibration algorithm. The diagonal panels show the 1D histograms of each PMT calibration parameter C_i, while the off-diagonal panels display the scatter plots of the corresponding parameter pairs, along with their correlation. The labels in the diagonal histograms report the 16th, 50th, and 84th percentiles of each distribution.

Paper organization:

- **Localized (spot-like) events**
  - We show the ability to accuracy of getting the (x,y) positions of Fe spot-like events through the BAT-fit.
  - This is done by comparing these positions with the CMOS ones, for a dataset of clear matching (1 cluster and 1 trigger).
  - We also show the ***energy*** results, which are particularly interesting.

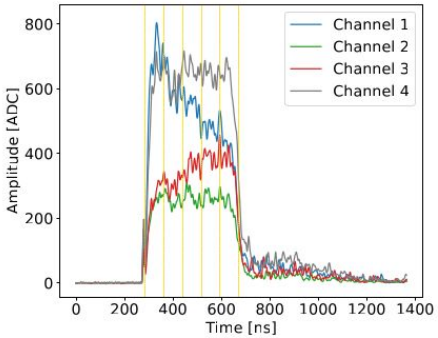


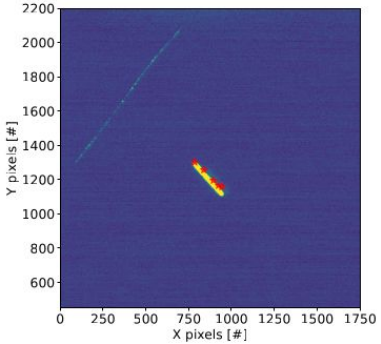


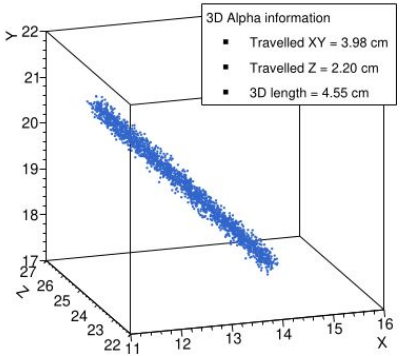


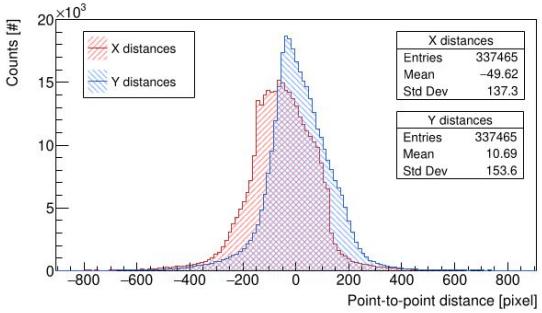
Paper organization:

- **Extended tracks (*possibly the most interesting case*)**
  - We *explain* how it can be done for high energy ERs (MIP-like)
  - We *show* how it is done with alphas (*ignoring the direction/sense part*)
    - In sum, we slice the waveform in spot-like interactions, and fit each individually.
    - We reconstruct the track in 3D using also the CMOS (since it's more accurate), and show the "efficiency" of the algorithm (which, in reality, was not fully optimized for this purpose).

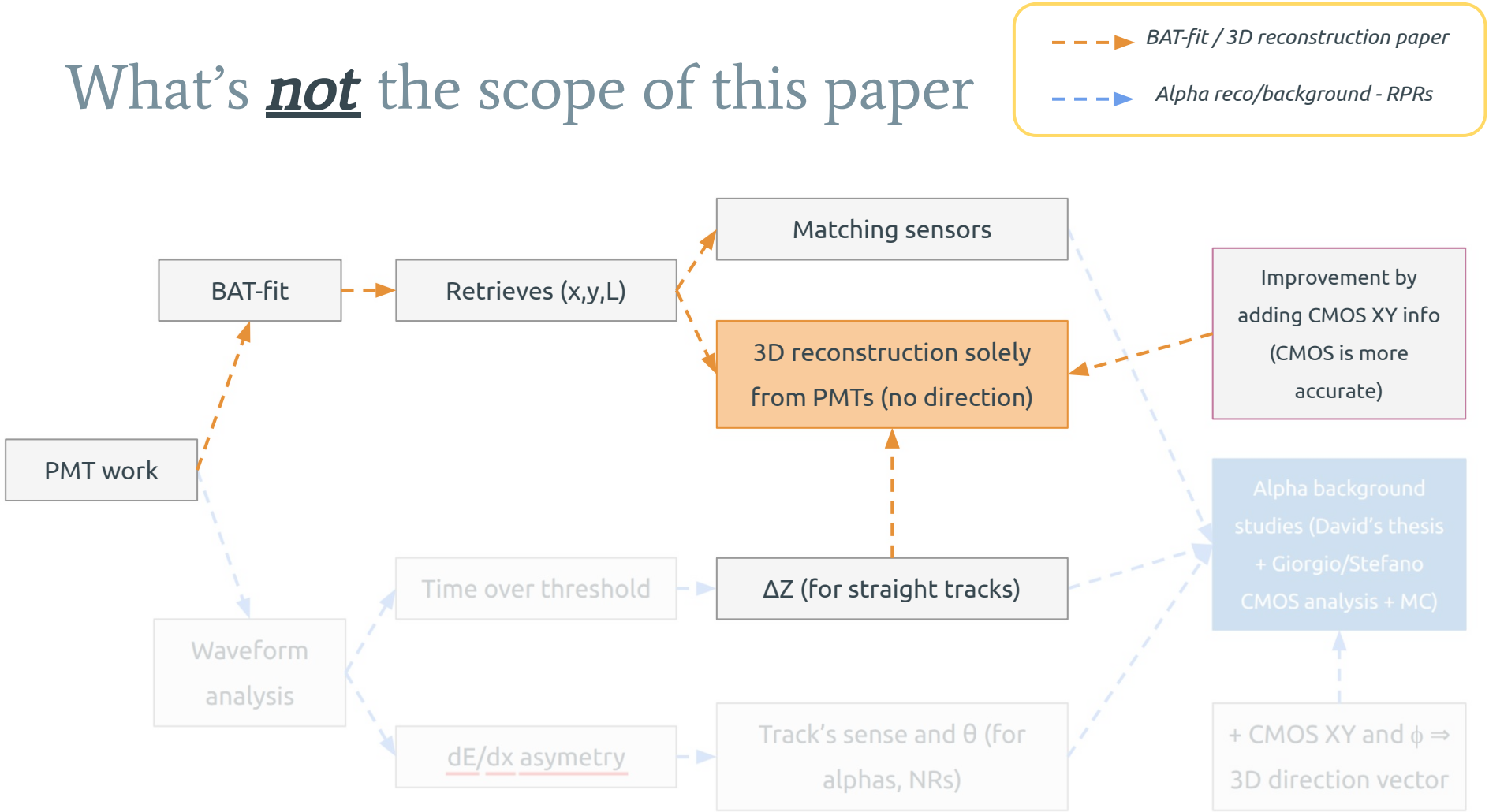








What's ***not*** the scope of this paper



Conclusions and details:

- This paper has 10 pages and 12 figures.
- This paper is a short and concise description of the BAT-fit that can serve as a reference point for future CYGNO paper on track reconstruction.
    - We decide to include only the BAT part also to keep it concise and readable.
    - We mention that: "*Ongoing developments aim to extract not only the track geometry but also its direction and sense, a key requirement for identifying WIMP-induced nuclear recoils. These techniques are currently being applied to the study of alpha-induced backgrounds in LIME, including Radon progeny recoils, and will be detailed in a forthcoming publication.*"
- Possible weak points:
    - The short discussion for longer tracks. This topic should appear again in the follow-up paper.
    - The reasoning behind $L \propto R^{-4}$ ⇒ We actually have some plots to back it up, if needed
- Possible journal: EPJ C (?)

- For review, do you prefer a pdf or overleaf version?

Thanks

... questions?