COMCHA Computing challenges

From Rare Events to Cosmic Correlations: Computational Developments at CAPA

CAPA's COMCHA Group: Jorge Alda, Swadheen Bharat, José Manuel Carmona, Iván Coarasa, Theopisti Dafni, Javier Galindo, ***Héctor Gómez***, María Martínez, Alejandro Mir, Siannah Peñaranda, María Luisa Sarsa. Carmen Seoane

CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Outline

1.- CAPA

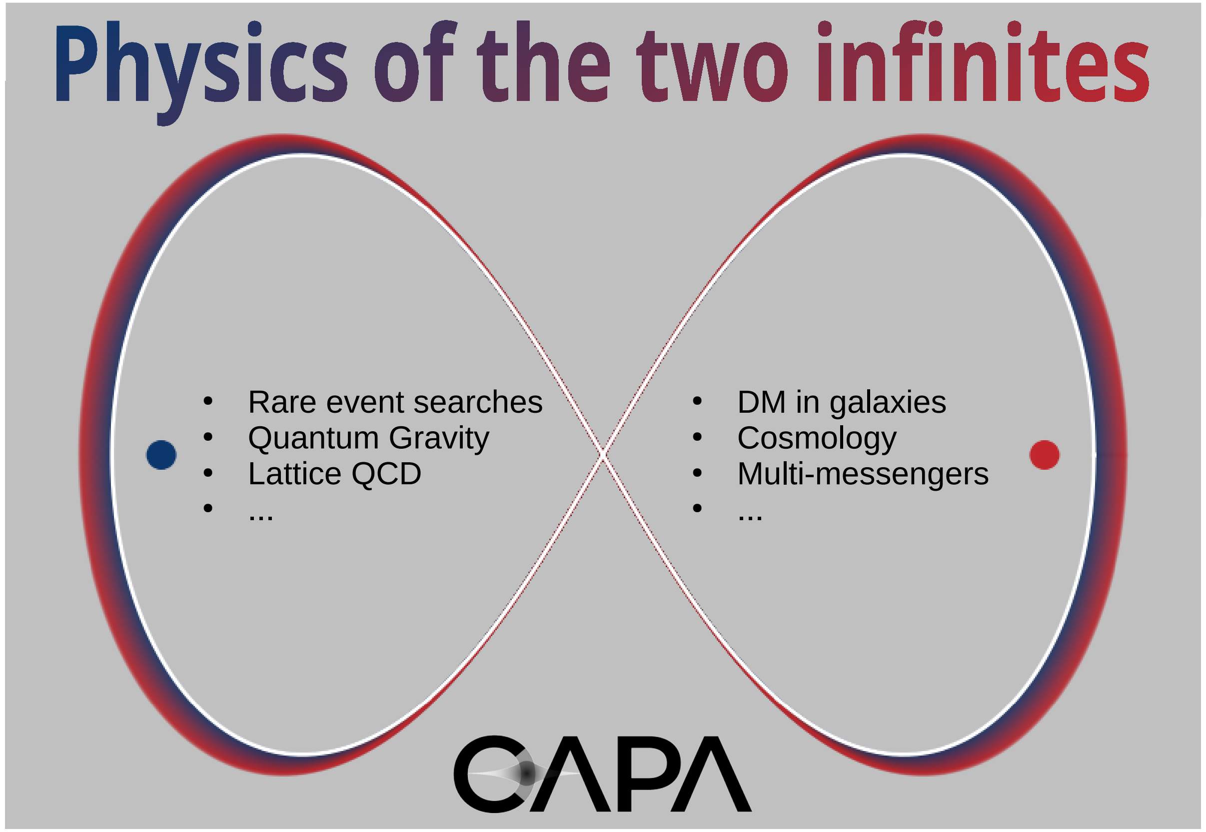
2.- COMCHA – related activities

- Rare events searches particularities
- From low to high level analysis
- Other activities

3.- Prospects

- Created in 2019, the Center for Astroparticles and High Energy Physics (CAPA) has been recently appointed as Research Institute of the University of Zaragoza

- Multidisciplinary research fields:
    - High energy physics
    - Nuclear and particle physics
    - Astrophysics
    - Cosmology
    - Astroparticles
    - Theoretical physics
    - Associated technological developments



- CAPA joined COMCHA network last summer

- Some particularities for the implementation of Machine Learning tools (w.r.t. HEP, for example):

Limited and unbalanced datasets	*Signal events far fewer than background / noise events*	**Training difficulty and/or bias**
Low visibility of the signal	*Low probability of signal process*	**Potential miss-classifications**
Non-standard background distributions	*Non-standard statistical distributions*	**Difficulty to design ML models**
Dependence on high-precision simulations	*Simulations depends on theoretical models and parameters*	**Uncertainties during training**
Simulation to data mismatch	*Unknown background sources, detector response, ...*	**Generalization problems**
Low statistics	*Low overall counting rate*	**ML models extremely sensitive to small systematic variations**

- Data and Analysis Flow

Low Level

- Signal processing
- Deconvolution
- Noise filtering
- ...

Intermediate Level

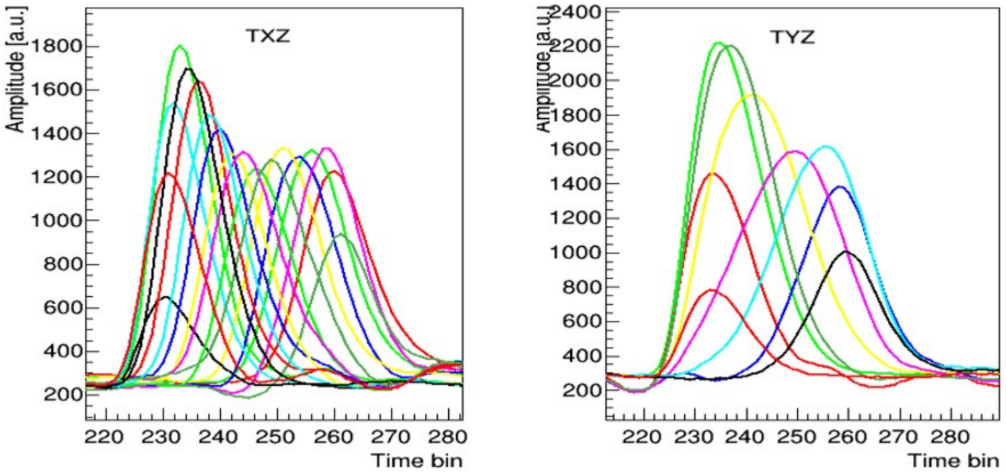
- Observable extraction:
  - Energy
  - Topology
  - PID

High Level

- Event classification
- Signal to noise discrimination
- Physics Analysis

H. Gómez et al

- Same family of readout chips for the lecture of highly pixelated MPGDs detectors
  - AGET → AFTER → DREAM → STAGE (CEA / Irfu)
    - “Well – known” transfer function
  - Axion Physics (***IAXO***), Dark Matter Searches (***TREX-DM***), Muography, …

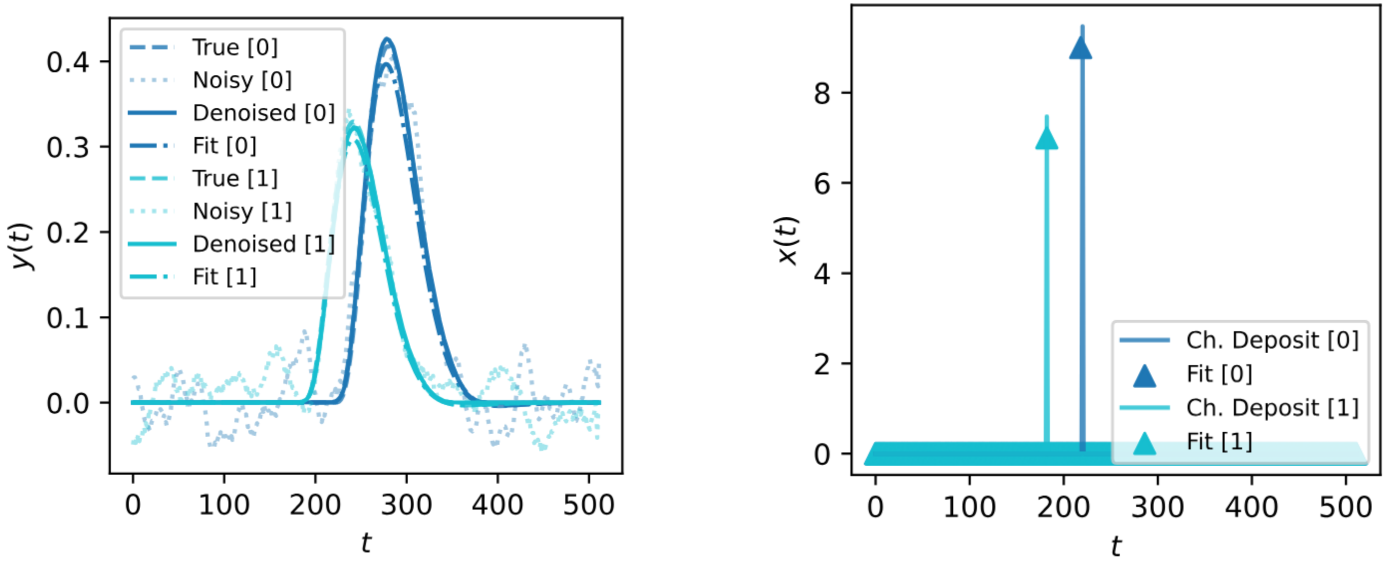


Real μM event

H. Gómez et al

- Same family of readout chips for the lecture of highly pixelated MPGDs detectors
  - AGET → AFTER → DREAM → STAGE (CEA / Irfu)
    - "Well – known" transfer function
  - Axion Physics (***IAXO***), Dark Matter Searches (***TREX-DM***), Muography, …

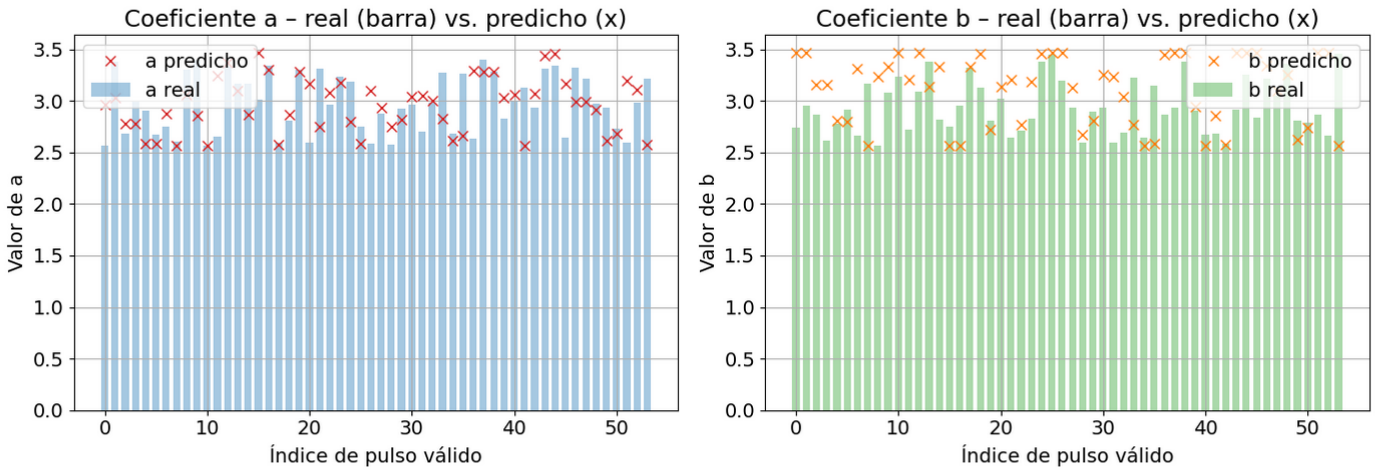
1.- Perfect transfer function → Noise management: ***Convolutional Autoencoders***



H. Gómez et al

- Same family of readout chips for the lecture of highly pixelated MPGDs detectors
  - AGET → AFTER → DREAM → STAGE (CEA / Irfu)
    - “Well – known” transfer function
  - Axion Physics (***IAXO***), Dark Matter Searches (***TREX-DM***), Muography, …

2.- Variable transfer function → Fit management: ***Specialized Transformer Model***



- Preliminary results
  - For ~10 energy deposits
    - $\Delta t < 0.6$ Time bins
    - $\Delta A \sim 10$ ADC units

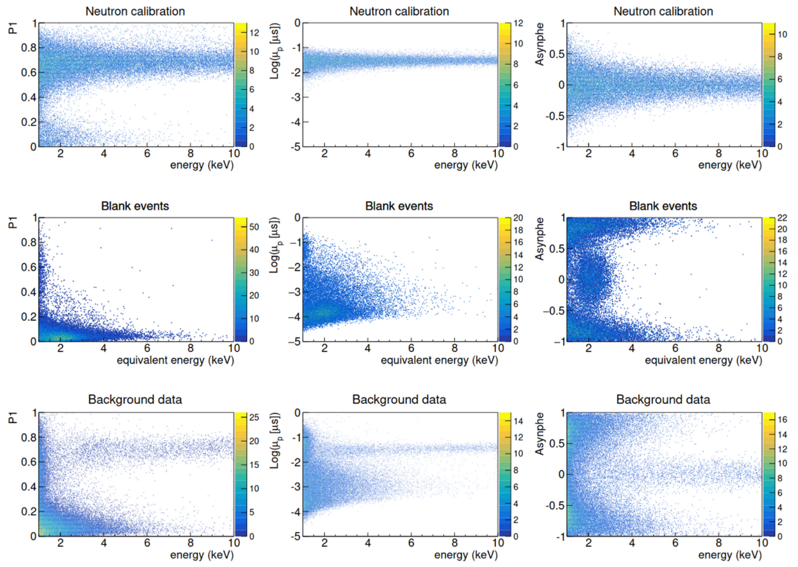
Event clasification: ANAIS experiment

S. Bharat, I. Coarasa, M. Martínez, M.L. Sarsa. C. Seoane

Boosted Decision Tree (BDT)	Event classification: Bulk scintillation vs Noise / Bkg	• 30% improvement in detection efficiency @ RoI • ~18% Bkg reduction @ RoI

- 15 discrimination parameters @ BDT (vs 4 parameters used in “classical” analysis)
- Neutron calibrations for signal – like events
- “Empty “ modules for Noise / Bkg events
- Sensitivity improvement

→ Faster comparison with DAMA / Libra results



(a) Slow charge, P_1 (b) Mean time, $Log(\mu_p[\mu s])$ (c) *Asynphe*

Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques.
JCAP11 (2022) 048
ANAIS–112 three years data: a sensitive model independent negative test of the DAMA/LIBRA dark matter signal.
Comm Phys (2024) 7:345

J. Alda, A. Mir, S. Peñaranda

- Machine Learning techniques for data analysis in Particle Physics and Flavour Phenomenology
- Implementation of methods such as:
  - Regression Trees
  - SHAP values (Shapely Additive exPlanation)
- Goals / Outcomes
  - Identification of complex correlations between experimental observables
  - Improvement on the precision of the Physical Parameters estimation
  - Interpretation of Predictive Models

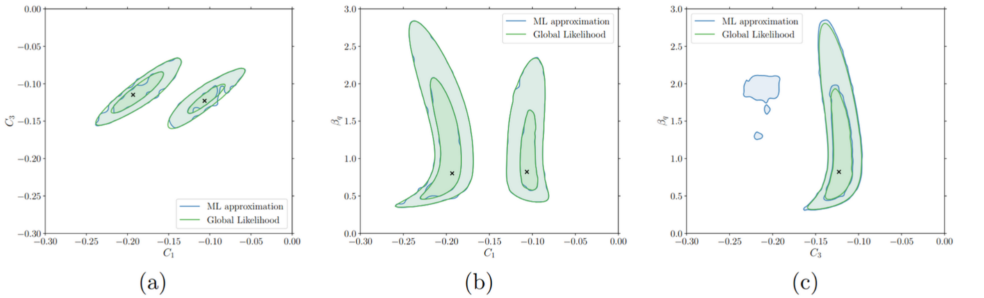


Figure 10: Comparison between the $1\,\sigma$ and $2\,\sigma$ likelihood contours obtained using the ML approximation (blue) and the actual contours (green) in (a) C_1 and C_3 plane, (b) C_1 and β^q plane and (c) C_3 and β^q plane.

A comparative analysis of results on B-anomalies using a machine learning algorithm.
e-Print: 2412.15830 [hep-ph]
Using Machine Learning techniques in phenomenological studies on flavour physics.
JHEP 07 (2022) 115
Exploring B-physics anomalies at colliders.
PoS EPS-HEP2021 (2022) 494

COMCHA – related activities

Software development

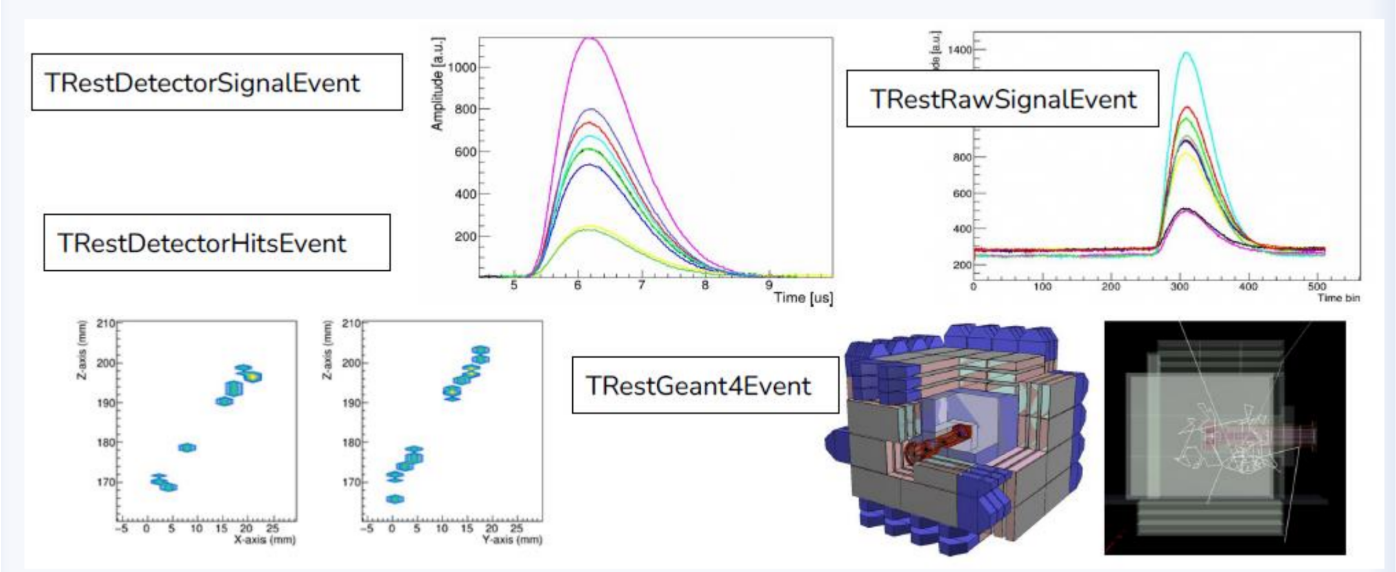
- Rare Event Searches Toolkit (https://rest-for-physics.github.io/)
    - A collaborative software effort that provides common tools for acquisition, simulation, and data analysis.
    - Initially developed for rare event searches with TPC → but not limited to this.
- Created in University of Zaragoza as an effort to unify experimental and analysis activities in a common environment.
    - First "established" version from ~2014-2015.
- Mainly written in C++ and it is fully integrated with ROOT I/O interface input information, via configuration (.rml) files.
- Composed by different modular libraries and packages.
- REST provides ready to use examples. This is especially useful for (undergraduate) students.

REST-for-Physics. Zenodo (2024) https://doi.org/10.5281/zenodo.11110607

- **Main project**
  - Framework

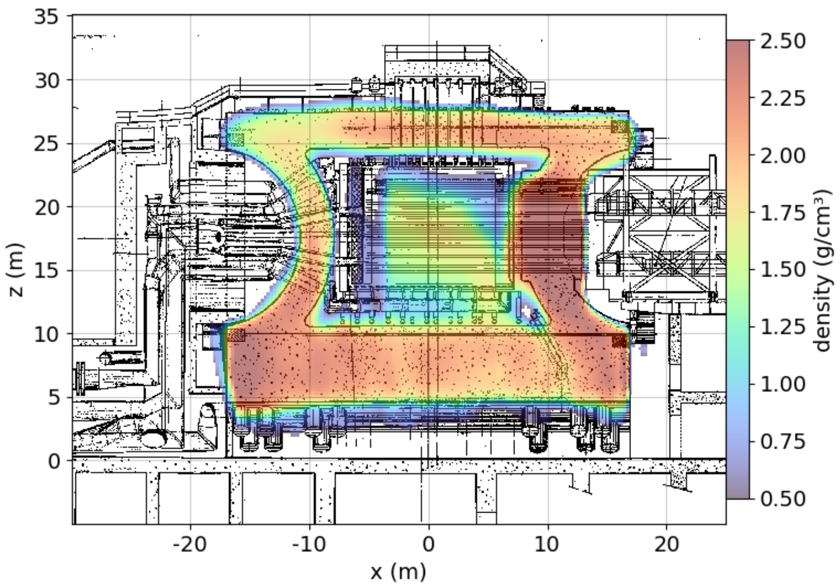
- **Libraries** for montecarlo and detector data processing
  - Rawlib / Geant4lib
  - Detectorlib / Tracklib
  - Basic-readouts / Connectorslib
  - Axionlib / Wimplib
  - ...

- **Packages** that exploit REST libraries
  - restG4
  - restROOT
  - restSQL
  - ...



REST-for-Physics. Zenodo (2024) https://doi.org/10.5281/zenodo.11110607

- Muography using Micromegas detectors
- Several application fields
  - Special interest on nuclear domain
    - Reactor surveillance: In operation or dismantling phases
      - First 3D Muography of a Nuclear reactor
        - Different ML techniques for data analysis
        - PRX Energy 4 (2025) 013002
    - Waste container characterization
      - Data Augmentation, Bayesian Inference, MLEM …
- Collaborative projects CAPA – CEA/Irfu ongoing



- **Prospects:**
  - Several CAPA groups / members considering to implement ML-based tools and other COMCHA related subjects:
    - Data correlation in **Astroparticle experiments** (IceCube, Km3NET)
    - Algorithms implementation in **FPGAs** (digital signal processing)
    - **Rare events searches** → Physics beyond SM
      - Pulse shape discrimination, tracking and topological analysis, event classification and background rejection
      - Different types of detectors: Scintillators, liquid and gaseous TPCs, quantum sensors, ...
    - Global fits and observable correlation studies in **flavor physics experiments**
    - Density and image reconstruction using **muon tomography**

COMCHA
Computing challenges

From Rare Events to Cosmic Correlations: Computational Developments at CAPA

CAPA's COMCHA Group: Jorge Alda, Swadheen Bharat, José Manuel Carmona, Iván Coarasa, Theopisti Dafni, Javier Galindo, ***Héctor Gómez***, María Martínez, Alejandro Mir, Siannah Peñaranda, María Luisa Sarsa. Carmen Seoane

Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

Acknowledgments:
The Spanish ***Agencia Estatal de Investigación (AEI)*** under grant PID2019-108122GB-C31 funded by MCIN/AEI/10.13039/501100011033.