

Artificial Intelligence for background rejection in  
DEAP-3600  
XIII CPAN DAYS

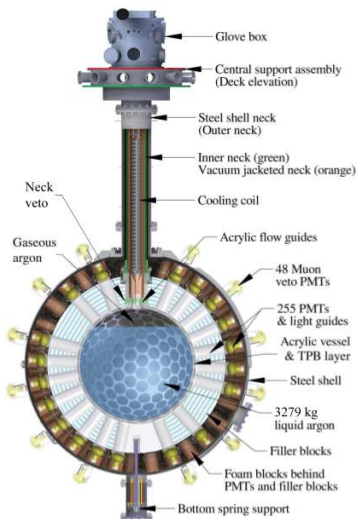
CIEMAT Dark Matter Group for the DEAP-3600 Collaboration

CIEMAT

Huelva, 21 March 2022

# DEAP-3600 detector

- Placed in SNOLAB under 2 km of rock ( $\approx 6000$  mwe of coverage).
- Spherical acrylic vessel with diameter of 170 cm. It is filled with 3279 kg Liquid Argon.
- Single phase detector with 255 PMTs covering the 75% of the sphere. Grouped in 35 rings from 5 to 10 PMTs.

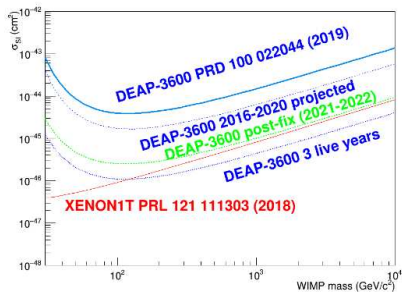


# DEAP-3600 analysis

- WIMP dark matter search with 2016-2020 dataset
  - Profile likelihood ratio analysis (open data strategy)
  - Blind analysis on full dataset
- Other searches
  - 5.5 MeV solar axions
  - ${}^8\text{B}$  neutrino absorption signal (inverse beta decay)
- ${}^{39}\text{Ar}$  Measurements
  - ${}^{39}\text{Ar}$  specific activity
  - ${}^{39}\text{Ar}$  half-life
  - ${}^{39}\text{Ar}$  decay spectrum and nuclear parameters
- Muon veto instrumentation and muon flux measurement
  - Muon flux annual modulation (or absence thereof)

# Status

- We are working in two fronts to recover the design sensitivity of the experiment, hardware upgrades and analysis refinement, which relies strongly on machine learning.



## World-leading sensitivity in argon

Published

Projected sensitivity second-fill

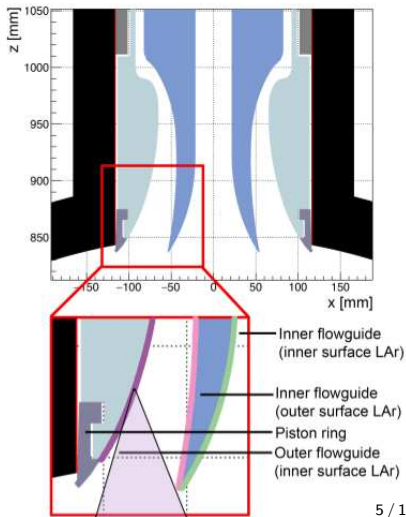
Projected sensitivity third-fill  
(now 2023-24)

“Design sensitivity”, no background

[M. Boulay, 2019]

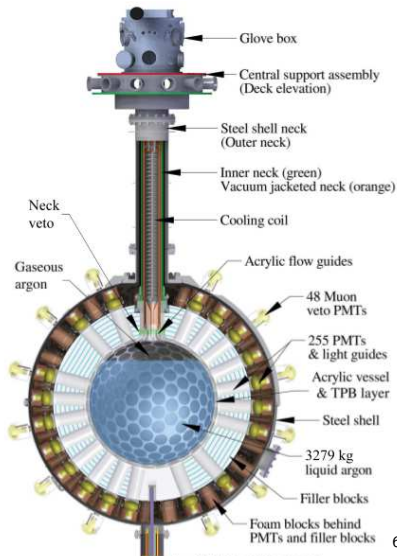
## Neck alpha events background

- The neck on top of the detector has two acrylic flow-guides.
- The surfaces are covered by a thin film of LAr due to condensation, where  $\alpha$  scintillation can happen.
- The light reaching the PMTs is a small fraction of a typical alpha event and its detection in the southern hemisphere is favored.



## Neck alpha events background

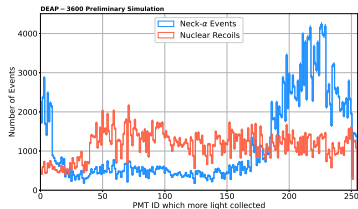
- Potential paths in that direction: small fraction is reflected in the interface. Also a high proportion arrives in the PMTs of the southern hemisphere.
- Approaches based on machine learning are exploited to remove neck events.
- Goal: improving the Acceptance for Background Rejection of 99.9%.



# Acceptance Evolution

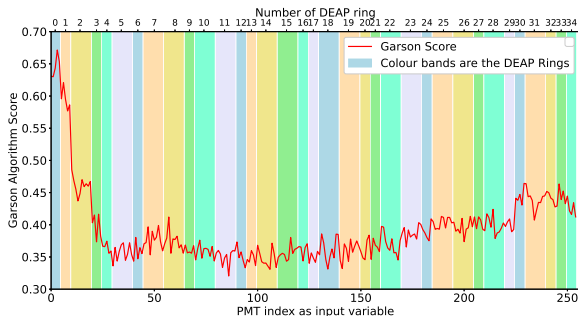
## Rejection 99.9%

- 2019 MLP: D256D32 (100k events per label)  $A = 41.5$ ,
- 2020 MLP: (300k events per label)  $A = 44.7$
- 2020 Inception (300k)  $A = 57.9$
- 2021 MLP: D100 (300k)  $A = 51.5$



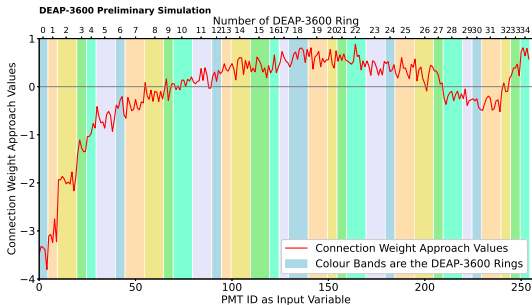
# Global XAI: Garson Algorithm

- Addressing the explainability of models is important for understanding the decision-making process, informing the transformation of the independent variables in the outputs. **eXplainable Artificial Intelligence (XAI)**.
- Global XAI interprets the weights of the MLP to evaluate the importance of the independent variables.



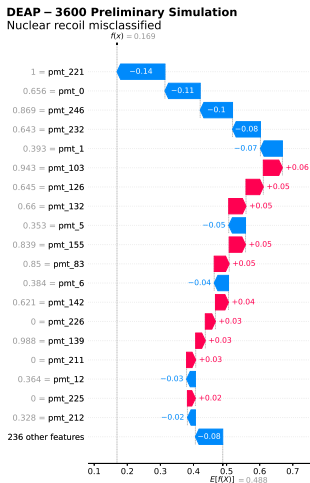


# Global XAI: Olden Algorithm



# SHapley Additive exPlanations (SHAP)

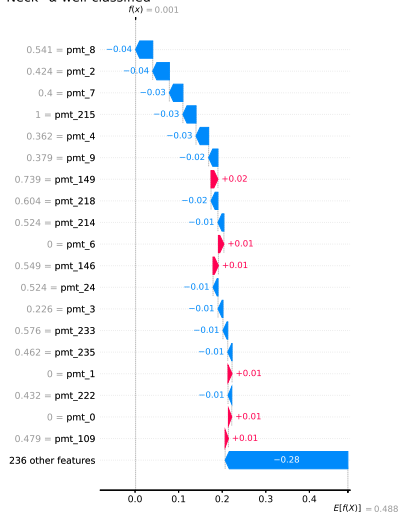
- Local XAI since it explains a single example prediction. **New knowledge vector.**
- Agnostic algorithm to retrieve interpretability for all ML models.
- SHAP calculates individual explanations for each event.



# SHAP on well-classified examples

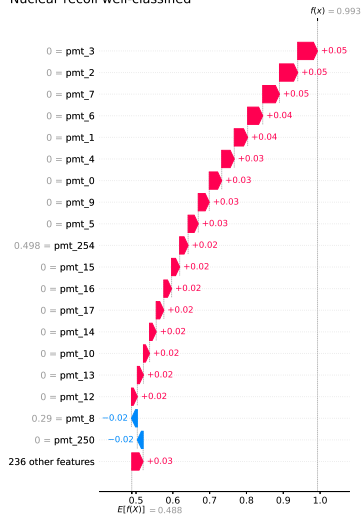
## DEAP – 3600 Preliminary Simulation

Neck- $\alpha$  well-classified



## DEAP – 3600 Preliminary Simulation

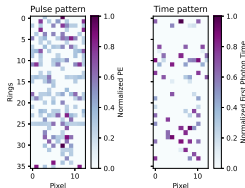
Nuclear recoil well-classified



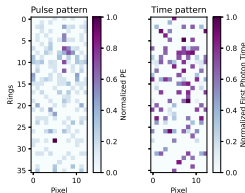
# Based on images (preliminary)

- Time and light pattern imaging. Using a 2D CNN.
- To make the images we apply an equirectangular transformation to the PMTs coordinates and generate a map.
- The first three columns on the left on the right side of the image are replicated.

**DEAP – 3600 Preliminary Simulation**  
Neck- $\alpha$



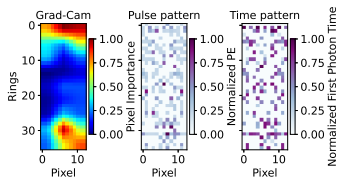
**DEAP – 3600 Preliminary Simulation**  
Nuclear recoil R = 650 mm



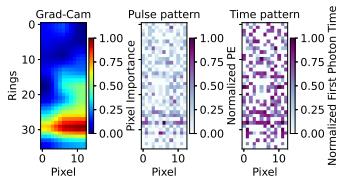
## Based on images (preliminary)

- Using the criterion of eliminating 99.9% of neck events, an acceptance of 80% is obtained.
- To apply Grad-Cam to these images and see how CNN makes its prediction on them.
- It is a highly geometric problem where the PMTs that are closer to the neck or at the bottom of the detector give relevant information for classification.

**DEAP – 3600 Preliminary Simulation**  
Neck -  $\alpha$



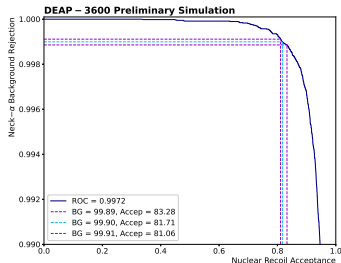
**DEAP – 3600 Preliminary Simulation**  
Nuclear Recoil R = 431 mm



## Based on images (preliminary)

- The main disadvantage of this method is the cost of storage: 100k events weighs about 1.1 Gb. Its applicability to datasets with millions of data can be a problem in terms of RAM and hard disk.
- To work with batches of data?
- The main advantage is the high efficiency in background discrimination.

- Preliminary results show an additional acceptance in the ballpark of 20% with respect to previous machine learning approaches.



Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

*Fostering a European approach to Artificial Intelligence (21.04.2021)*

The potential **benefits of AI** for our societies are manifold, from less pollution to fewer traffic deaths, from improved medical care and enhanced opportunities for persons with disabilities ...  
AI has demonstrated its potential by contributing to the fight against COVID-19 ...

At the same time,

... the use of AI also carries certain **risks**, such as potentially exposing people including children, to significant mistakes that may undermine fundamental rights and safety, as well as to our democratic processes ...

... **high-risk AI systems need** to respect a set of specifically designed requirements, which include the use of high-quality datasets, the establishment of appropriate documentation to enhance traceability, the sharing of adequate information with the user, the design and implementation of appropriate **human oversight measures**, and the achievement of the highest standards in terms of **robustness**, ...

## AI

- AI is ubiquitous in science, including Particle Physics.
- XAI methods are helpful to understanding how predictions are made.  
**Robust and interpretable predictions.**
- XAI is the place where scientists of different expertise areas meet.
- XAI as a vector of new knowledge.

## Dark Matter

- DEAP has the strongest limit for spin independent WIMP-nucleon interaction for non-Xe nucleus.
- Lots of analysis and searches on neutrino physics, axion searches and exotic dark matter candidates.
- The developments going on in DEAP are informing the design of DarkSide-20k and ARGO.