Recent results on a machine learning approach to event position reconstruction in the DEAP-3600 Dark Matter Search Experiment

Aidar Ilyasov on behalf of DEAP collaboration

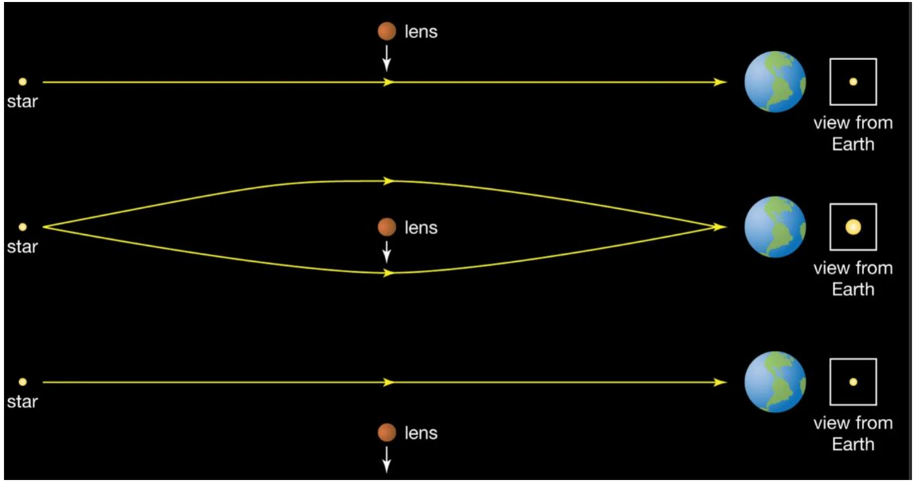
NRNU MEPhI
NRC Kurchatov Institute

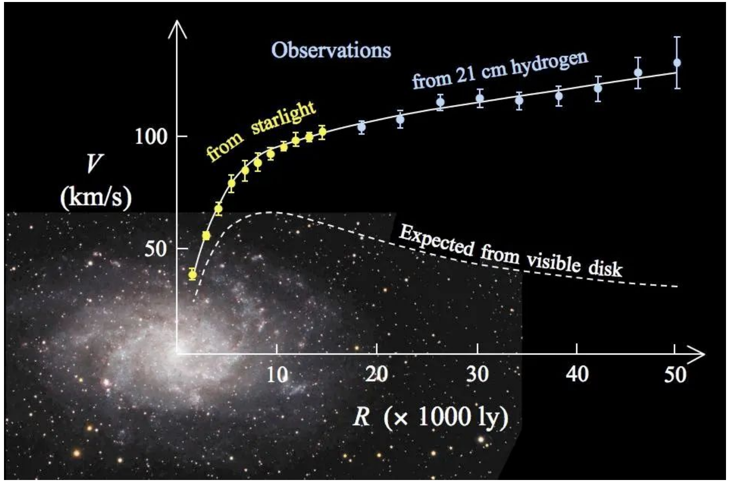
International Conference on Particle Physics and Cosmology (Rubakov conference)
October 02-07, 2023 Yerevan, Armenia

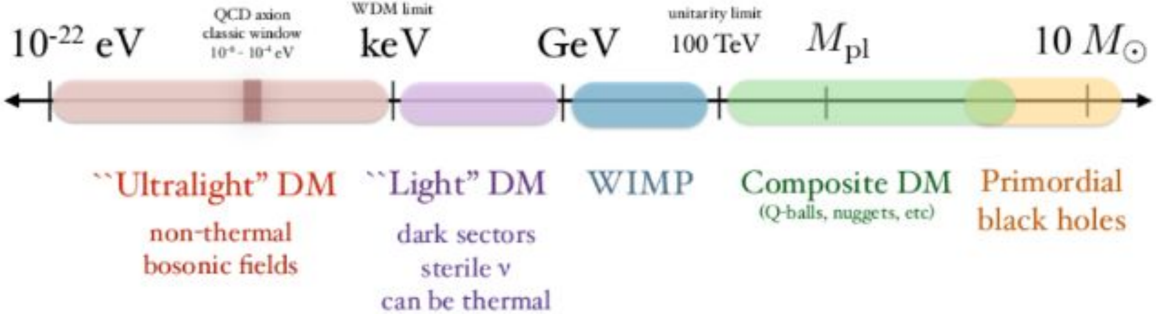
Overview of the Talk

- About dark matter
- DEAP-3600 experiment
- Machine learning overview
- ML application in DEAP-3600 experiment
- Conclusion

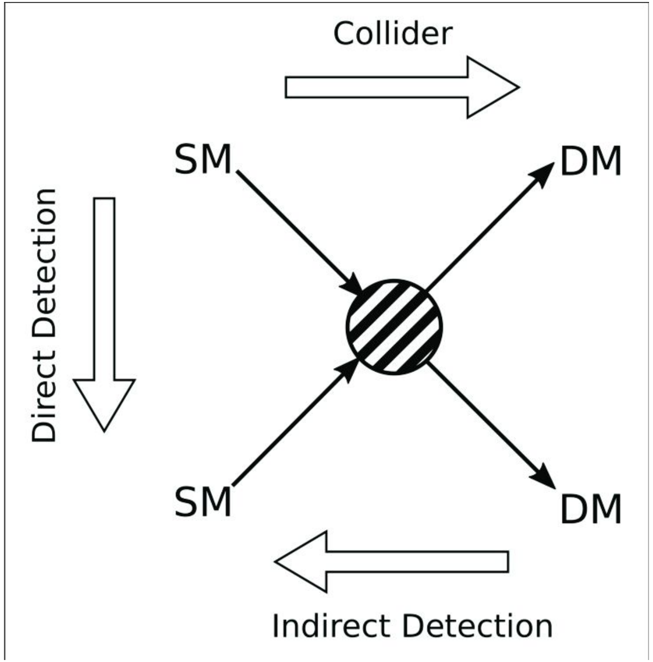
About dark matter

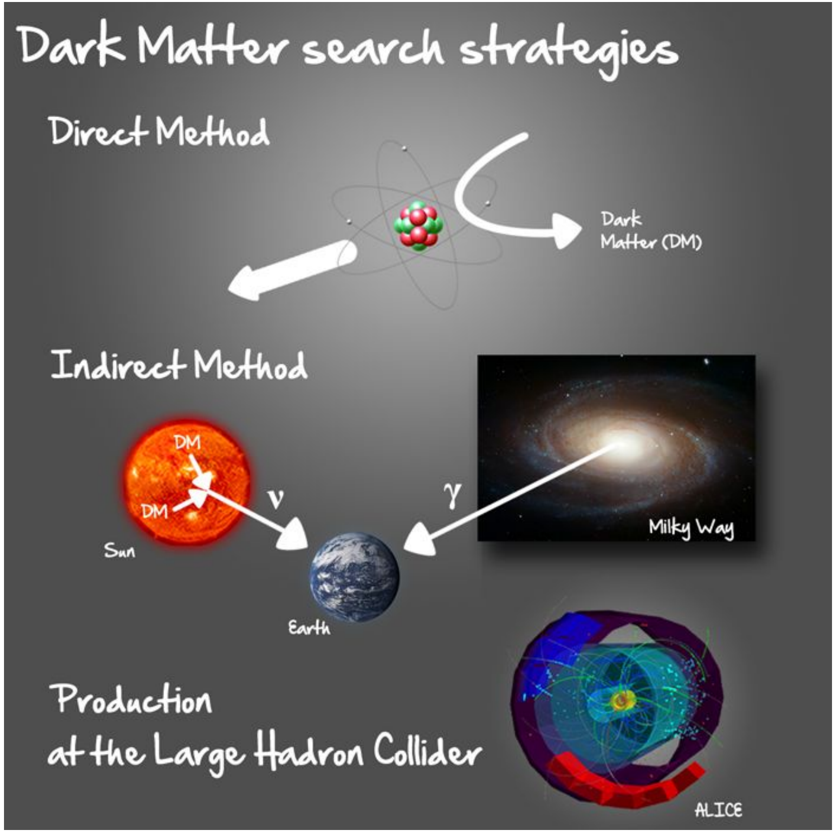






About dark matter





About dark matter

The collaboration

University of Alberta
UC Riverside
Carleton University
Gobierno de España, Ministerio de Ciencia, Innovación y Universidades
Ciemat
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
AstroCeNT
Laurentian University / Université Laurentienne
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
DEAP 3600
National Research Center "Kurchatov Institute"
Johannes Gutenberg Universität Mainz
JGU
Instituto de Física
Princeton University
SNOLAB
TRIUMF
Royal Holloway University of London
Technical University of Munich
TUM
University of Sussex
Queen's University
INFN Istituto Nazionale di Fisica Nucleare
Particle Physics Rutherford Appleton Laboratory

The detector

The DEAP Collaboration, Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNO hysical Review D 100.2 (2019)

Acrylic Vessel (AV)

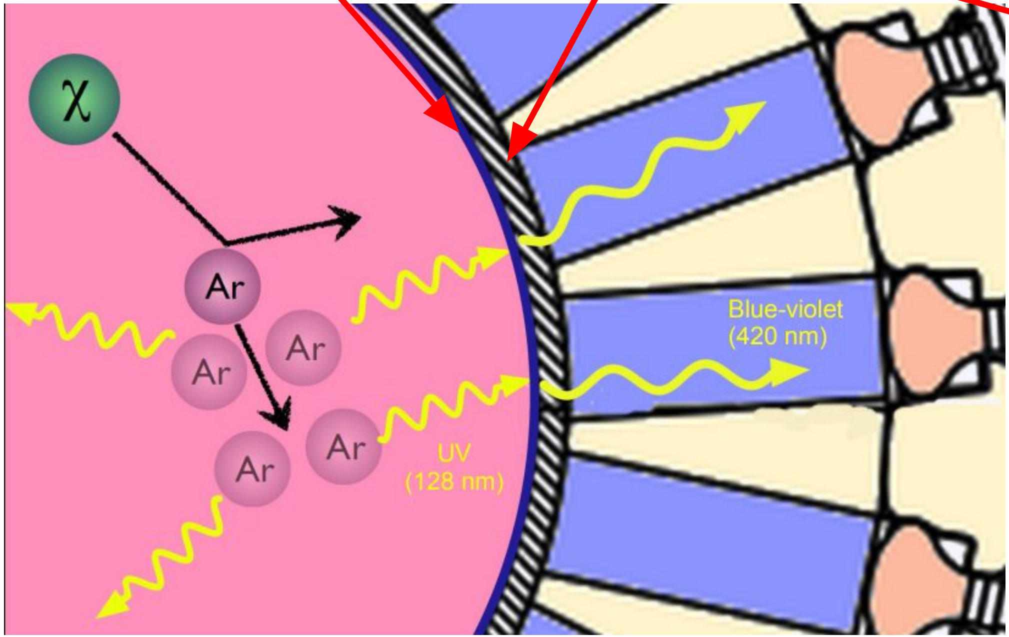
Wavelength Shifter (TPB)

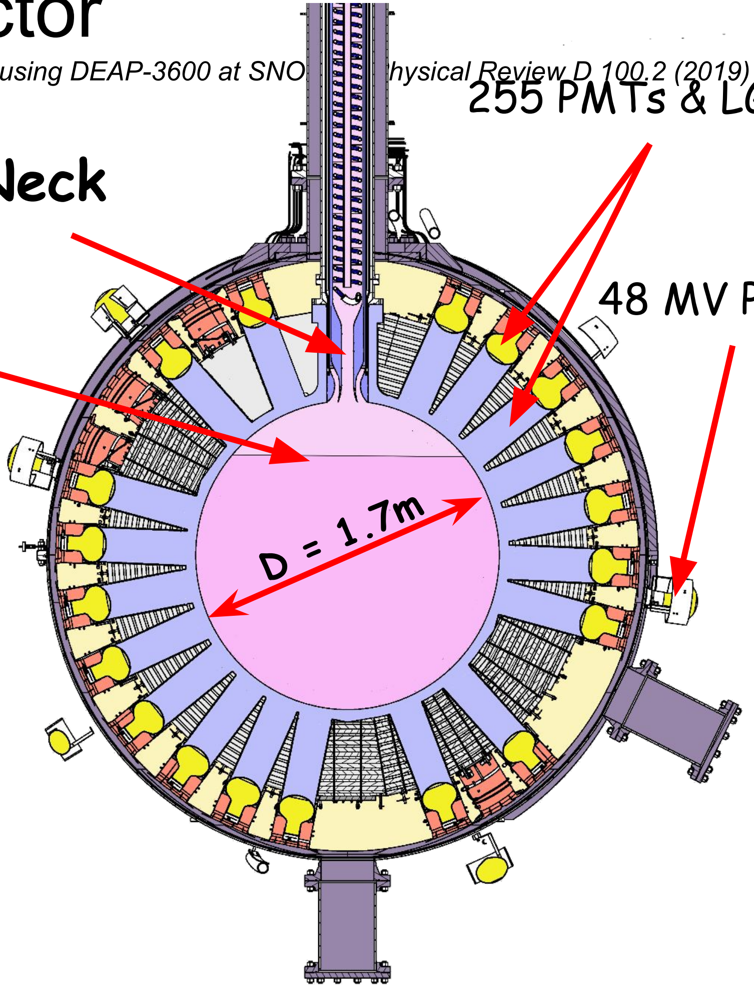
Neck

Fill level

255 PMTs & LGs

48 MV PMTs



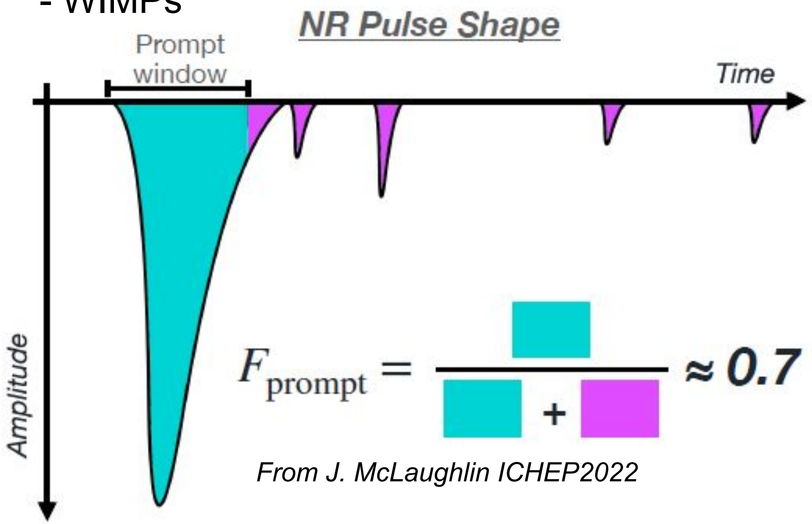


Pulse Shape Discrimination

The DEAP Collaboration, Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB, Physical Review D 100.2 (2019)

Nuclear Recoils

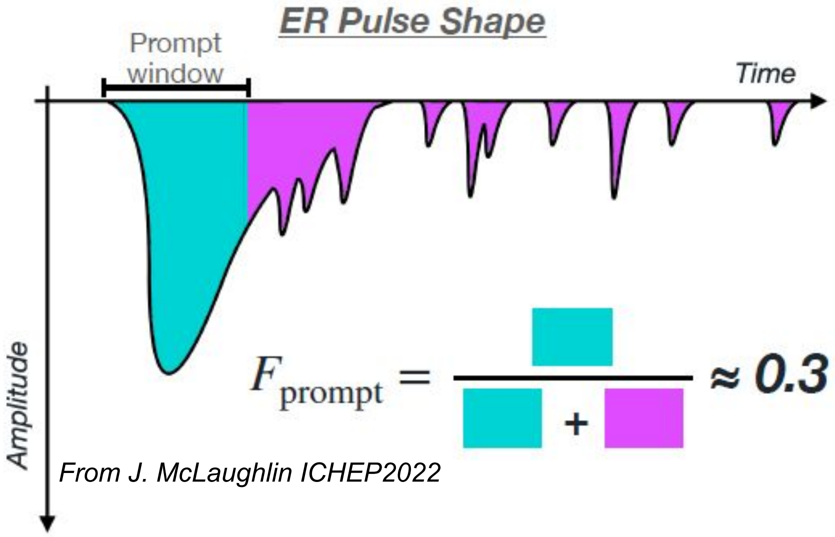
- Scattering directly with argon nuclei;
- Excimers mostly populate the singlet state, relax quickly. Induced by:
    - Neutrons
    - Alphas
    - WIMPs



From J. McLaughlin ICHEP2022

Electronic Recoils

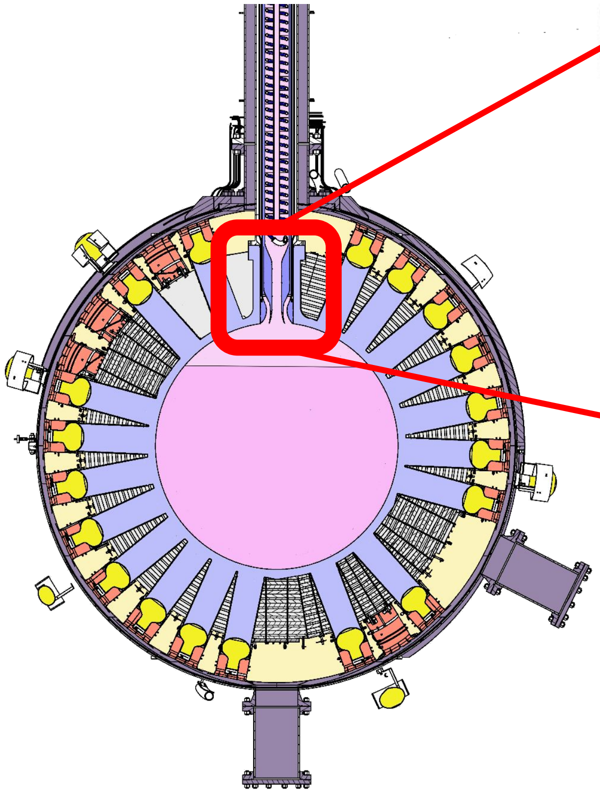
- Scattering with argon atomic electrons, ionizing argon;
- excimers tend to populate triplet state, relax slowly. Induced by:
    - Betas (especially 39Ar at ~3 kHz)
    - Gammas

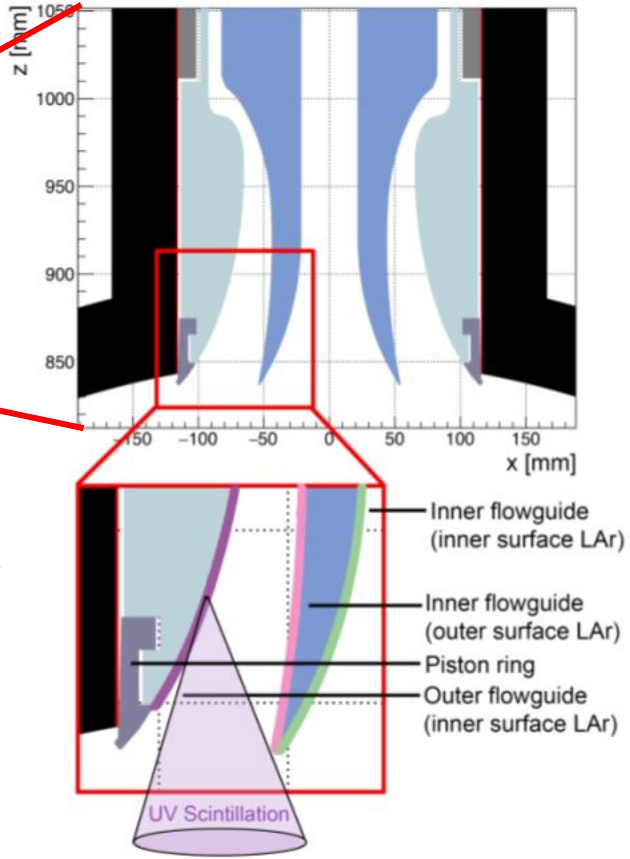


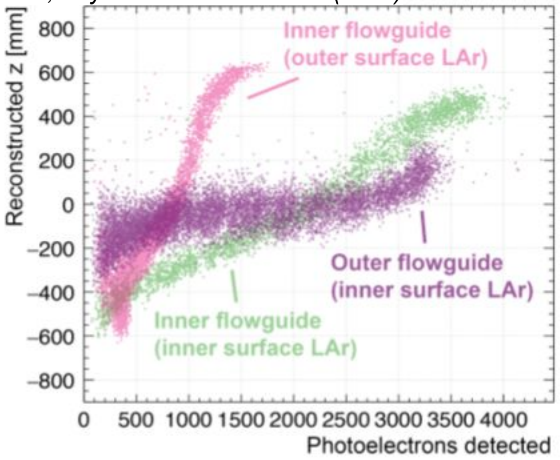
From J. McLaughlin ICHEP2022

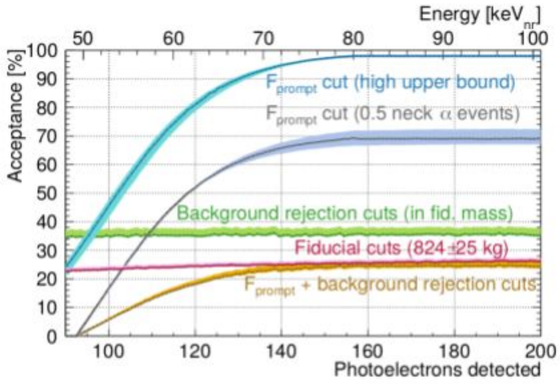
The neck

The DEAP Collaboration, Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB, Physical Review D 100.2 (2019)







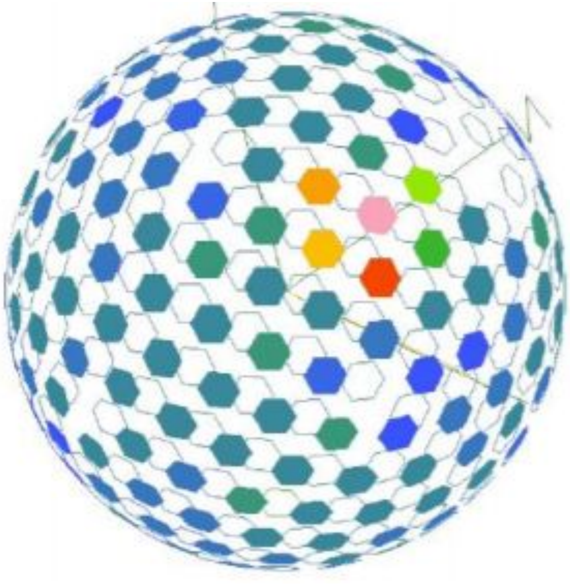


$$N_{bkg}^{ROI} = N_{ER}^{ROI} + N_{Cher}^{ROI} + N_{n,rdg}^{ROI} + N_{n,csg}^{ROI} + N_{\alpha,AV}^{ROI} + N_{\alpha,neck}^{ROI}$$

Position reconstruction

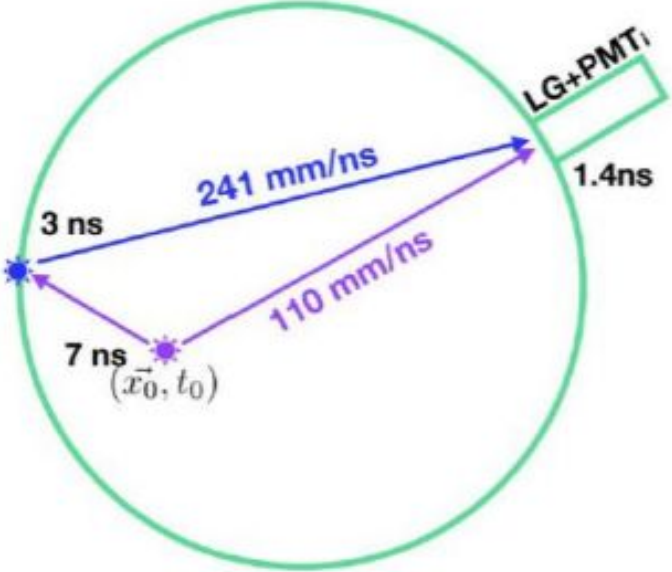
The DEAP Collaboration, Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB, Physical Review D 100.2 (2019)

MBLikelihood - MBL



compares the **observed distribution of PE** in each PMT with the predicted distribution given a hypothesised event vertex

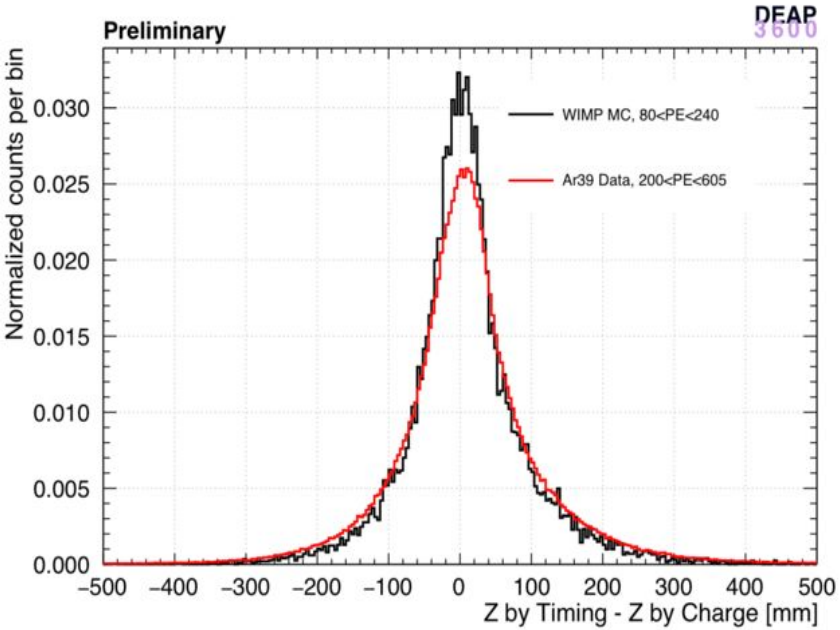
TimeFit2 - TF

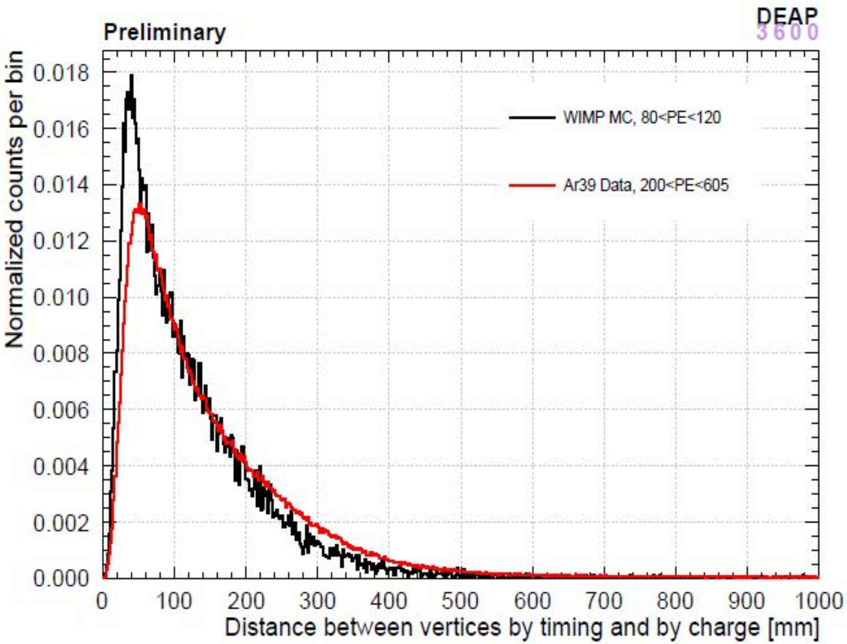


Determines the reconstructed event vertex by finding the hypothesised value $\vec{x}$ that **maximises a likelihood function**

Position reconstruction

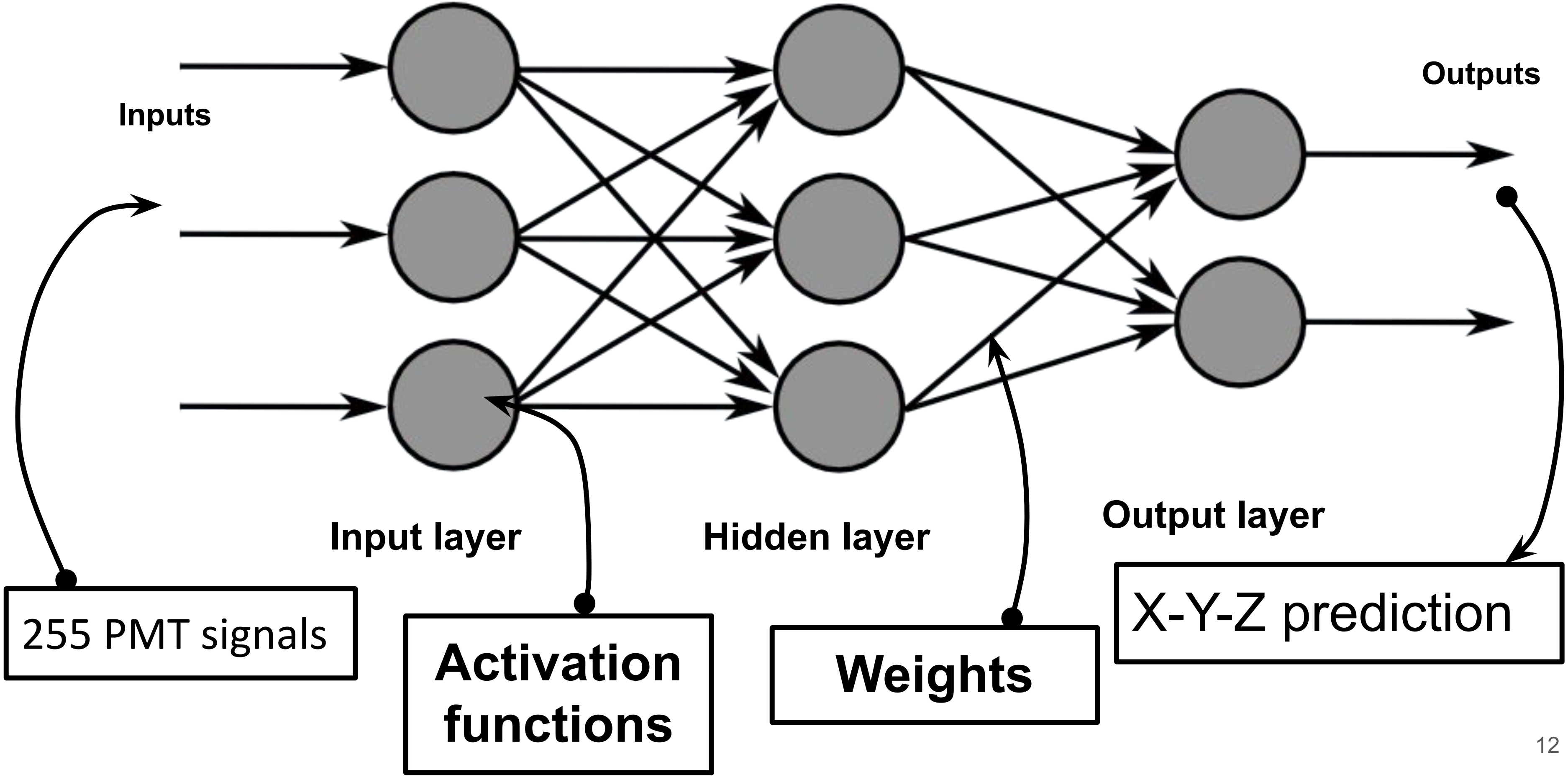
The DEAP Collaboration, Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB, Physical Review D 100.2 (2019)





- Both algorithms work well in the LAr area of the detector, but for events in the neck region, they do not match in their results and cannot accurately determine the event position
- To solve this, it was decided to **use machine learning techniques to determine the position** of the event in the entire detector volume, **including the neck area**

Fully-connected neural network



Working process

- **Creating a dataset** - using the Geant4, ROOT and RAT* packages for modeling;
- **Algorithm development** - using machine learning (several algorithms have been tested);
- **Application of the algorithm** - on events obtained from Geant4 simulations;
- **Creating three different algorithms** - for better understanding of operation and easier control;
- **Algorithm tuning** - analyzing the physics of events, adjusting the neural network structure to the complexity of the problem;
- **Analyzing the results** - creating comparative plots on two regions of detector operation (LAr and neck);
- **Algorithm implementation** - performance verification, calibrations.

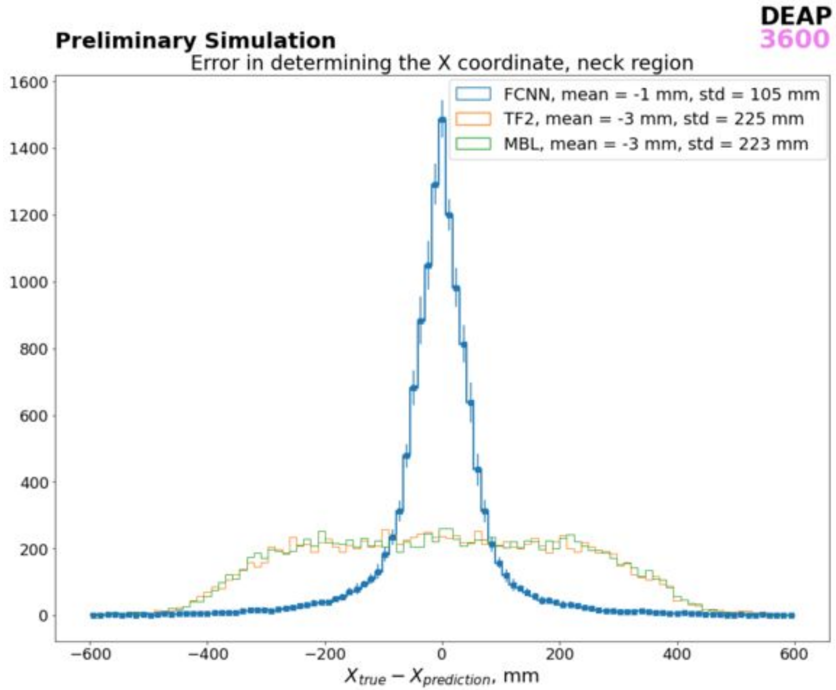
* Bolton T. et. al. RAT (Is an Analysis Tool) User's Guide. 2018. Available online: https://rat.readthedocs.io/

First result

Collaboration D. Machine Learning Approach for Event Position Reconstruction in the DEAP-3600 Dark Matter Search Experiment //MDPI Physics. – 2023. – T. 5. – №. 2. – C. 483-491.

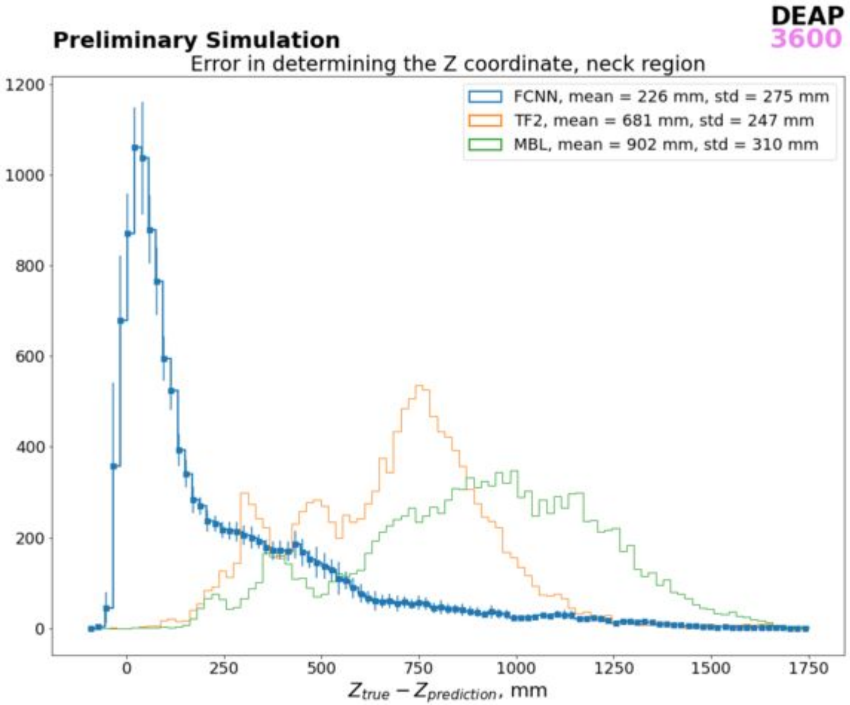
X and Y coordinate reconstruction, **neck**

$$\frac{255}{\text{sigmoid}} \rightarrow \frac{255}{\text{sigmoid}} \rightarrow \frac{255}{\text{sigmoid}} \rightarrow \frac{16}{\text{sigmoid}} \rightarrow \frac{1}{\text{linear}}$$



Z coordinate reconstruction, **neck**

$$\frac{255}{\text{softmax}} \rightarrow \frac{512}{\text{tanh}} \rightarrow \frac{512}{\text{tanh}} \rightarrow \frac{1}{\text{linear}}$$



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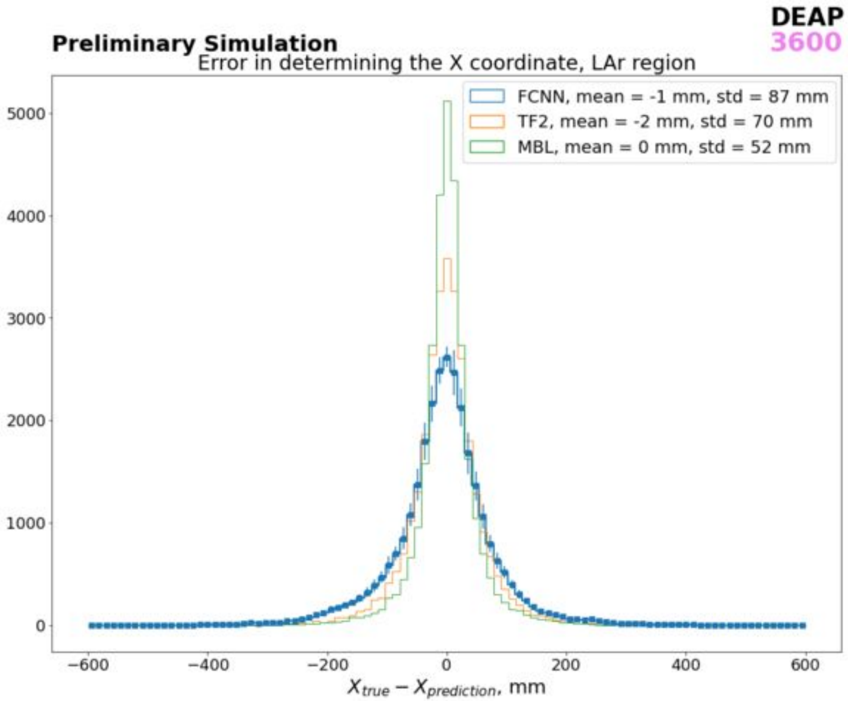

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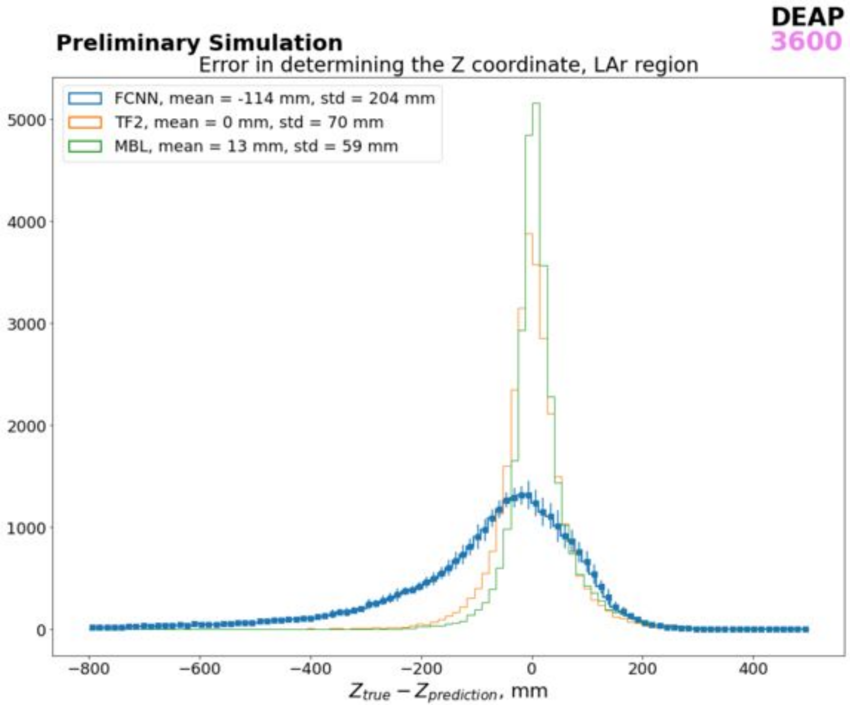
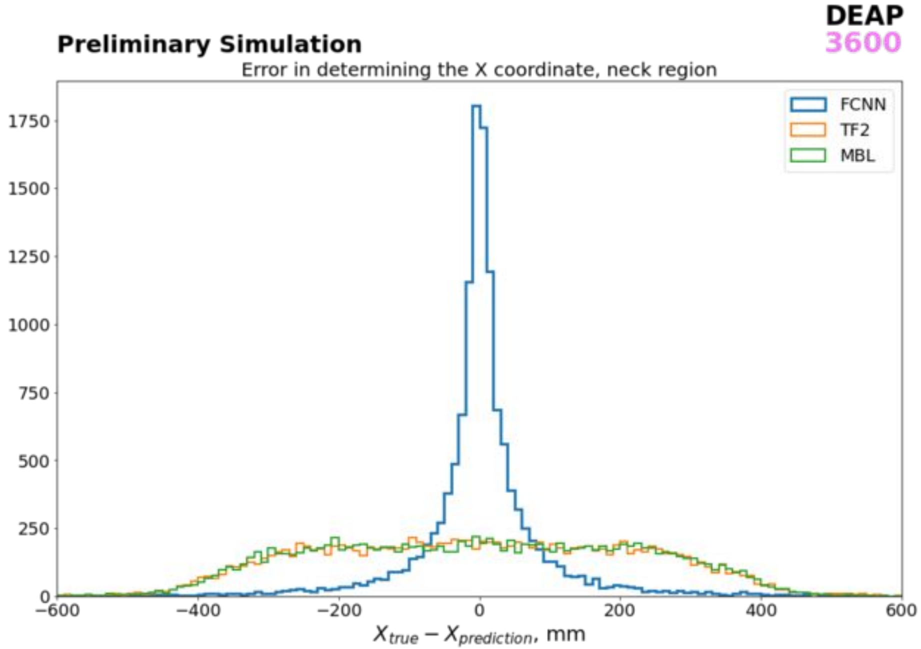


New result

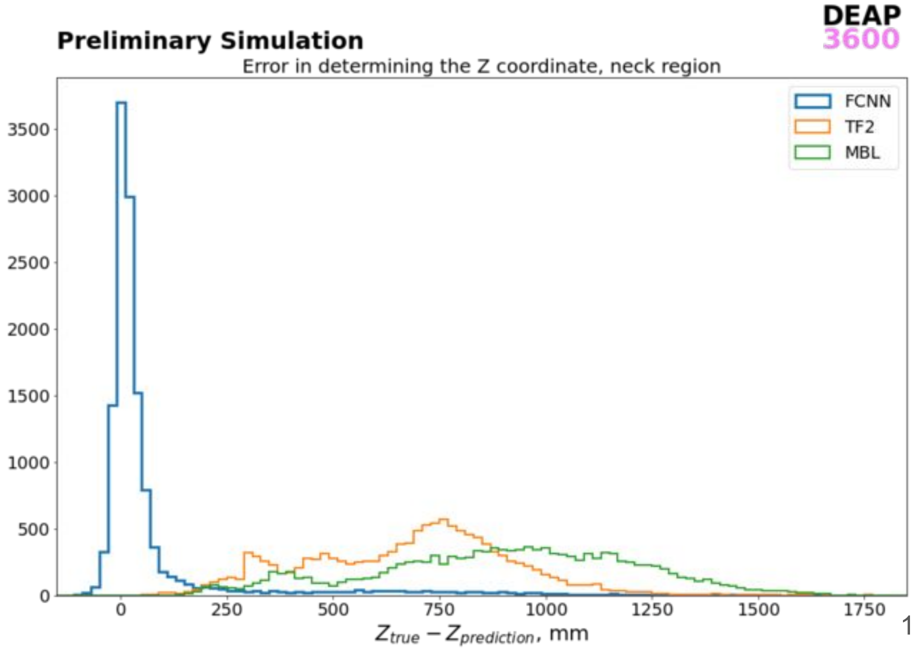
X and Y coordinate reconstruction, **neck**

$$\frac{255\ \text{(Input)}}{\text{relu}} \rightarrow \frac{255}{\text{relu}} \rightarrow \frac{255}{\text{relu}} \rightarrow \frac{16}{\text{relu}} \rightarrow \frac{1\ \text{(Output)}}{\text{linear}}$$



Z coordinate reconstruction, **neck**

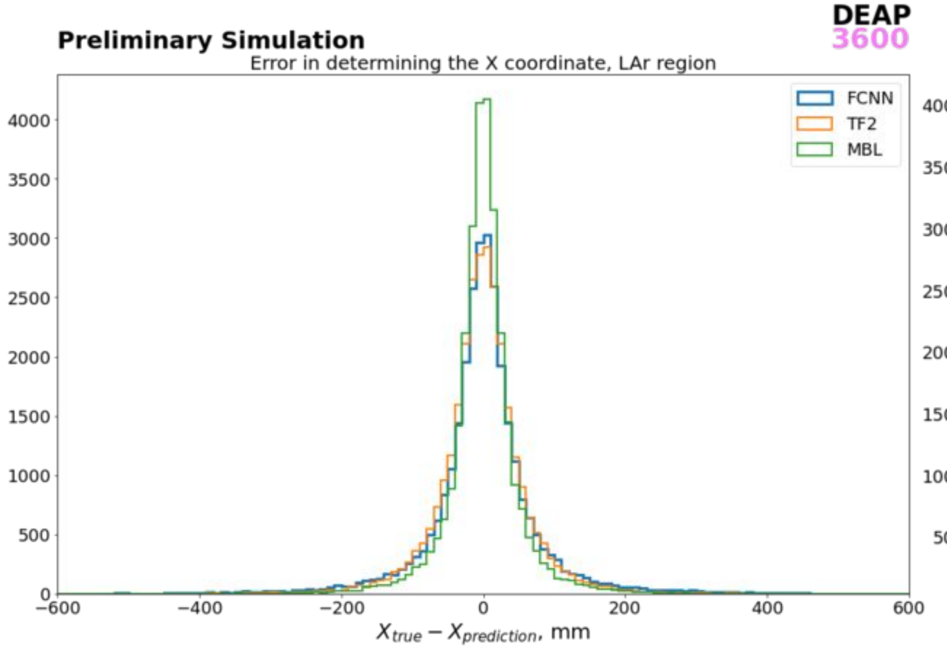
$$\frac{255\ \text{(Input)}}{\text{relu}} \rightarrow \frac{1024}{\text{relu}} \rightarrow \frac{1024}{\text{relu}} \rightarrow \frac{1024}{\text{relu}} \rightarrow \frac{1\ \text{(Output)}}{\text{linear}}$$



New result

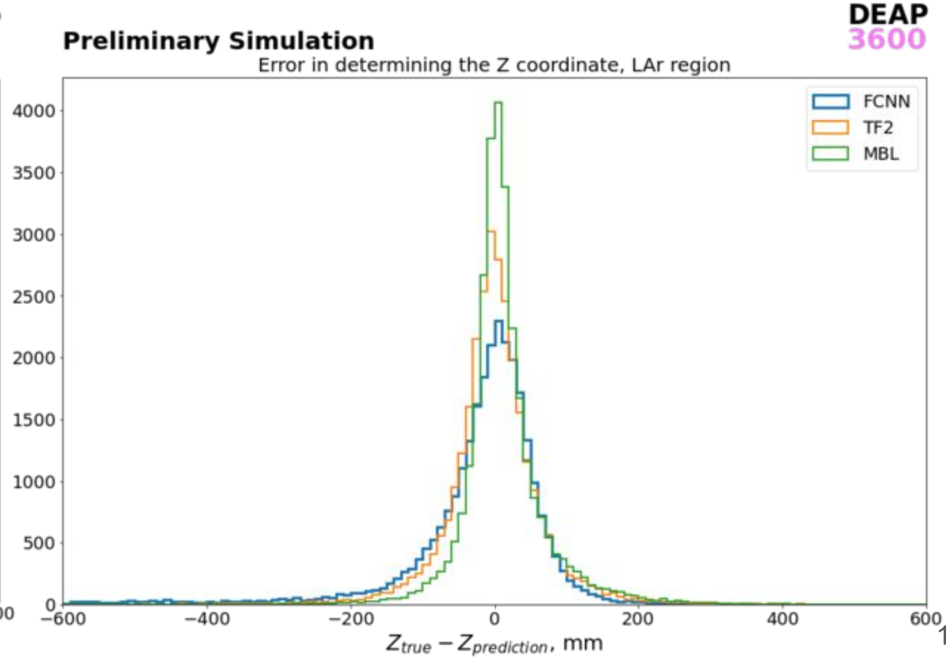
X and Y coordinate reconstruction, **LAr**

$$\frac{255\ \text{(Input)}}{\text{relu}} \rightarrow \frac{255}{\text{relu}} \rightarrow \frac{255}{\text{relu}} \rightarrow \frac{16}{\text{relu}} \rightarrow \frac{1\ \text{(Output)}}{\text{linear}}$$



Z coordinate reconstruction, **LAr**

$$\frac{255\ \text{(Input)}}{\text{relu}} \rightarrow \frac{1024}{\text{relu}} \rightarrow \frac{1024}{\text{relu}} \rightarrow \frac{1024}{\text{relu}} \rightarrow \frac{1\ \text{(Output)}}{\text{linear}}$$



Conclusion

- Most successful (for now) ML algorithm for this task is **FCNN**;
- **3 different models** for 3 coordinates (X, Y, Z) have been created and tested;
- **Different** neural network **structures** have been tested;
- A neural network structure was found that significantly **improves the previous result**;
- This algorithm performs **much better in the neck region** of the detector, while not being as inferior to existing algorithms in the bulk region.

Thank you for your attention!