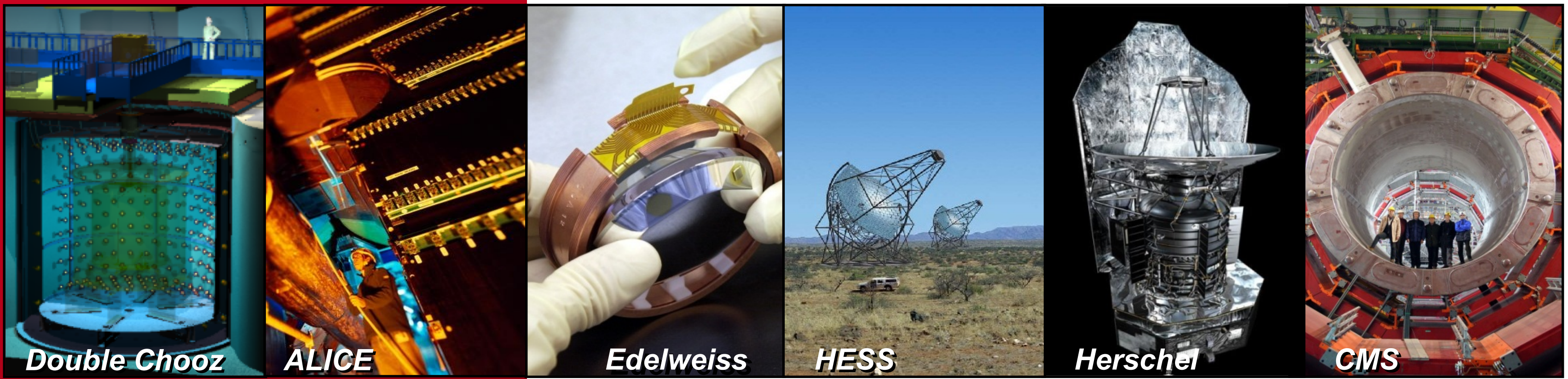
DE LA RECHERCHE À L'INDUSTRIE

Les applications du ML à l'IRFU



Déchiffrer les rayons de l'Univers

Valérie Gautard

25/09/2020

OUTLINE

- Overview of ML activities @ Irfu / IN2P3
  - ML algorithms and tools
  - Computing and hardware resources
  - Covered activities
  - Training and schools
  - Conclusion

ML SOFTWARE, TOOLS AND INTERFACES

Internal (HEP) tools

- ROOT framework for data storage and processing
- Multivariate Analysis: TMVA for mostly BDT and (deep) NN
- Specific for Neural Networks: NeuroBayes

External tools

- Data format: text, csv, images, HDF5, ...
- ML libraries: Keras+TensorFlow, Pytorch, scikit-learn (no DL), ...
- All kinds of popular algorithms: CNN, GAN, RNN, LSTM, AE, VAE ...

Interfaces and middleware

- PyMVA: Interface TMVA and Keras
- Several middleware file format conversion solutions:

PyROOT	Python extension module that allows the user to interact with ROOT data/classes. [69]
root_numpy	The interface between ROOT and NumPy supported by the Scikit-HEP community. [65]
root_pandas	The interface between ROOT and Pandas dataframes supported by the DIANA/HEP project. [70]
uproot	A high throughput I/O interface between ROOT and NumPy. [71]
c2numpy	Pure C-based code to convert ROOT data into Numpy arrays which can be used in C/C++ frameworks. [72]
root4j	The hep.io.root package contains a simple Java interface for reading ROOT files. This tool has been developed based on freehep-rootio. [73]
root2npy	The go-hep package contains a reading ROOT files. This tool has been developed based on freehep-rootio. [73]
root2hdf5	Converts ROOT files containing TTrees into HDF5 files containing HDF5 tables. [74]

Computing and Hardware Resources

ML computing @ IN2P3/Irfu

- Mostly **CPU**, sometimes **GPU**, and some attempts with **FPGA**
- **Local** resources: laptop, lab/university clusters
- **CCIN2P3** resources: lots of CPU, less GPU

Any other resources ?

- Tensor Processing Units (**TPU**)
- Vision Processing Units (**VPU**)
- Calculation on **cloud** from industry ?Amazon Web Services machines
- Google colab notebook with GPU support

...

Covered activities at Irfu/IN2P3

- Astrophysics
- Nuclear physics
- Accelerator / Detectors
- High energy physics
- Medical physics
- Ethics

Disclaimer
Just a brief outlook of all activities based on input that we received
And thanks a lot to all who provided for material and explanations !

ASTROPHYSICS

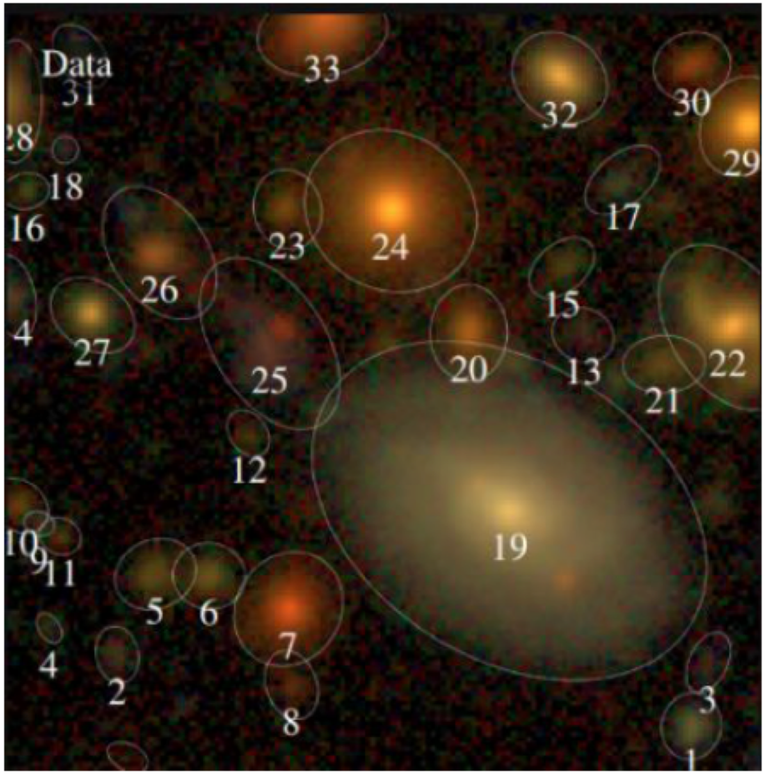
DEBLENDING

IDENTIFICATION OF RADIONUCLIDES

ASTROPHYSICS

- Cosmostat : http://www.cosmostat.org/communication
  - ASTRONOMICAL IMAGE PROCESSING
    - Weak And Strong Lensing
    - Dark matter maps
    - ERedshift
    - Deblending
  - ACTIVITIES IN PARTNERSHIP WITH NEUROSPIN: THE OBJECTS OF STUDY ARE NOT THE SAME BUT THE METHODS ARE THE SAME

THE DEBLENDING PROBLEM

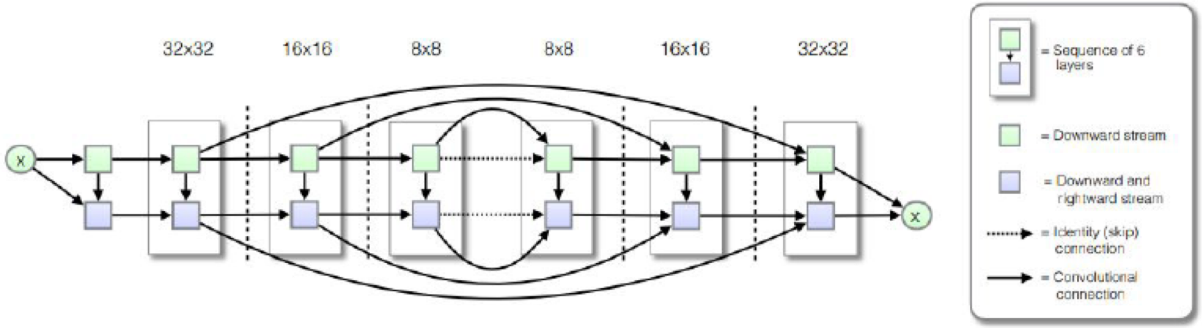


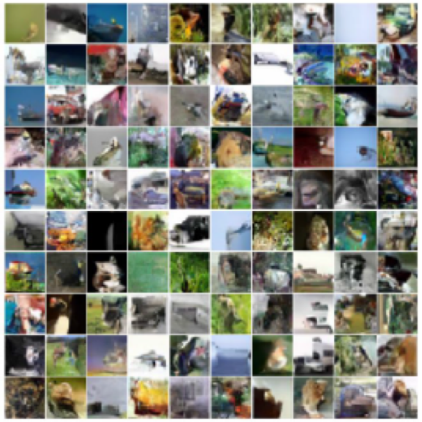
- Galaxies overlap on the sky, they are blended, they need to be de-blended in order to measure the properties of each galaxy individually
- Current deblenders struggle on complex images

Successful deblending

Deblending Failure

DEEP DEBLENDING WITH LEARNED SIGNAL PRIORS

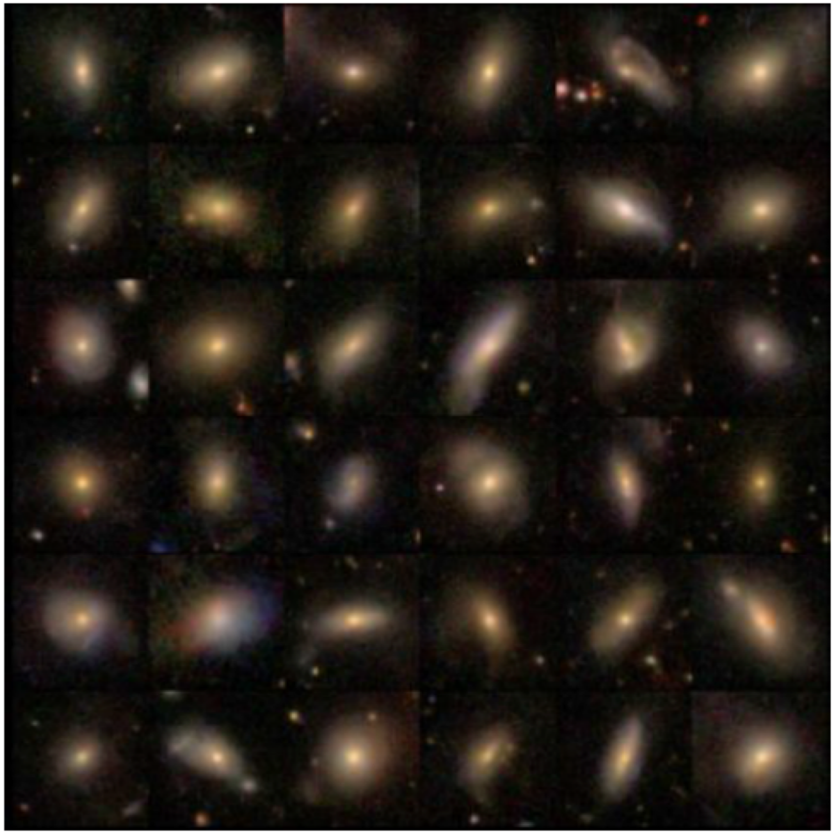


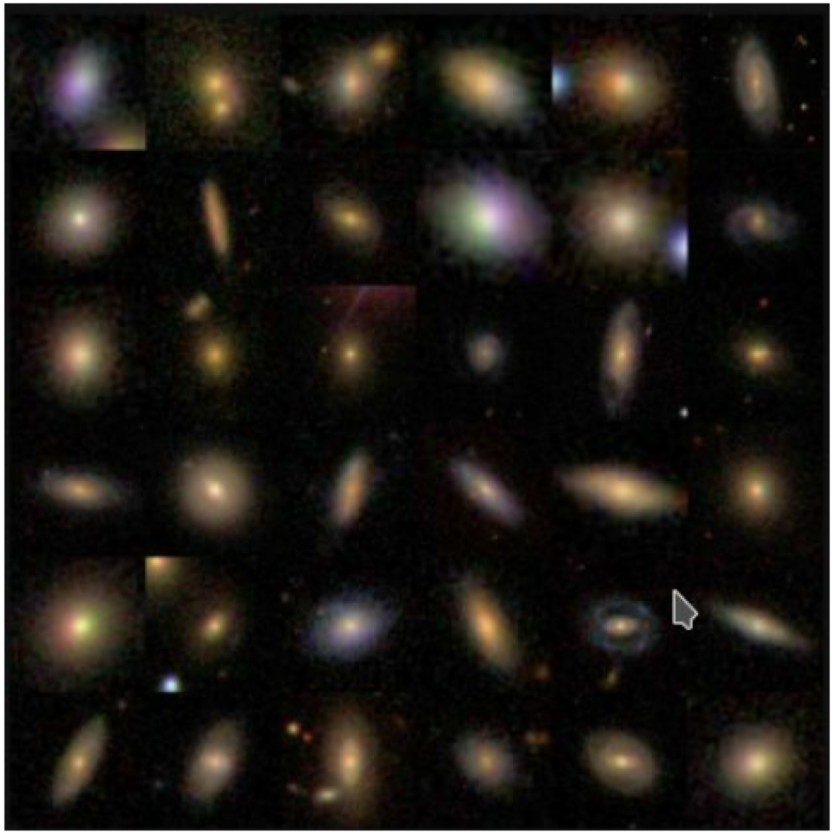


- The idea: learn what galaxies look like using a deep generative model, here a PixelCNN++ (Salimans, 2017)
- The model learns the probability p(x) of a given image x to belong to the training set

A VISUAL TEST

Which set of galaxies is real ?





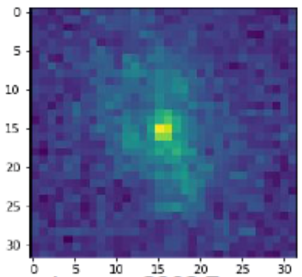
DEBLENDING AS AN OPTIMIZATION PROBLEM

- We are trying to find deblending solutions that fits the data the best, and as the same time the recovered galaxies should look realistic

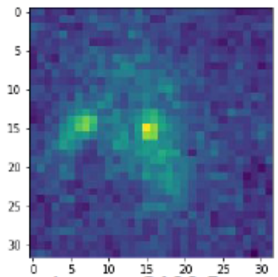
$$\arg\min \frac{1}{2} \parallel Y - \sum_k S_k \parallel_\Sigma^2 + \log p_\theta(S_1) + \log p_\theta(S_2)$$

where S1 and S2 are the individual blend components, Y is the observed image, and p is the learned probability of being a galaxy

- Illustration of probabilities for blended and isolated galaxies: The probability is higher for the isolated galaxie

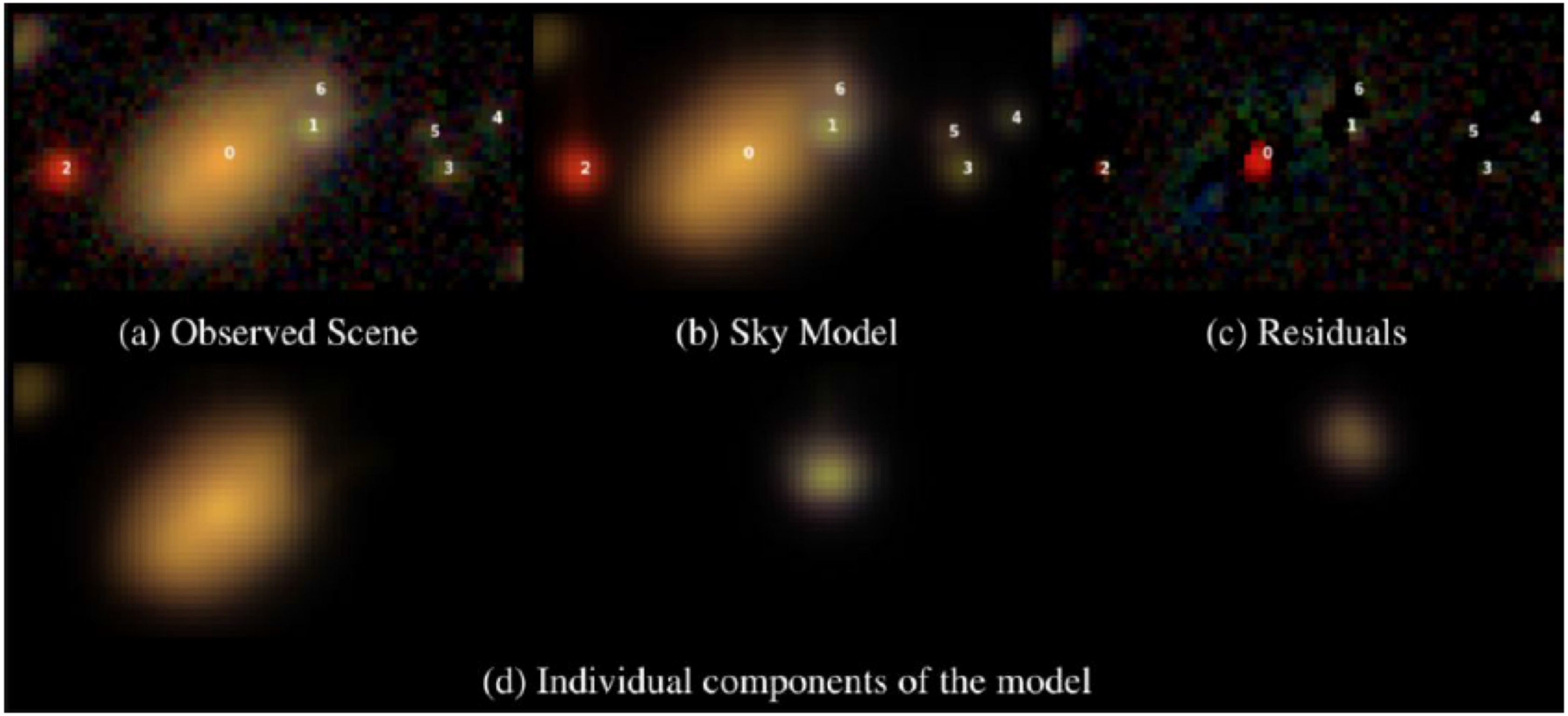


Log p = 3293.7



Log p = 3100.5

Example of deblending solutions

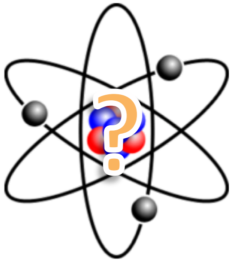


CONTEXT

Nuclear safety monitoring:
- Decomissionning and dismantling
- Post-accidental scenes

Nuclear security: radiation portal monitor

Characterization of radiological scenes

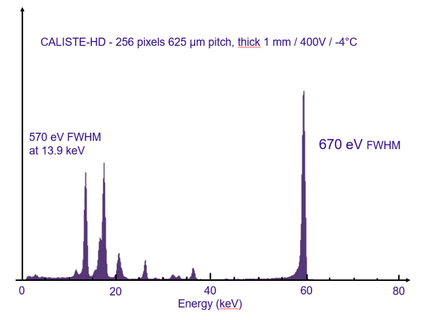


Fukushima accident

→ **Identification of the radionuclides in the scene**

→ **Proportion of each identified radionuclide**

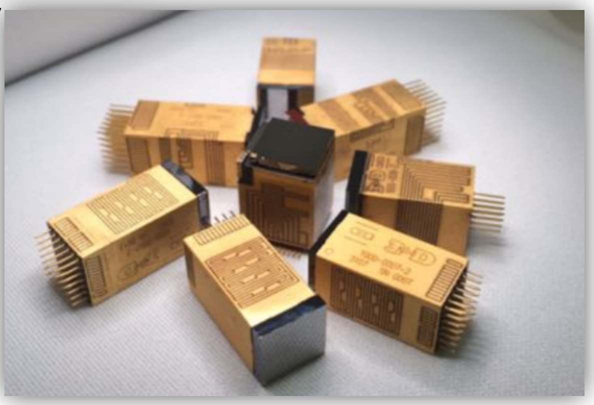
CALISTE DETECTOR



CdTe semi-conductor crystal

Miniature pixelated spectro-imager

Works at **nearly room temperature**: high performance at -15°C
Low power consumption: 200 mW



First developments for **astrophysical** application
→ STIX: Spectrometer Telescope Imaging X-rays
Observation of Bremstrahlung from accelerated electrons near the Sun

Different versions of Caliste: Caliste-SO, Caliste-HD, Caliste-O…

From space applications to **industrial** applications:
→ Medical application: breast tumor cells detection
→ **Nuclear safety application**

PROBLEM : SPECTRAL IDENTIFICATION

Input : Calibrated event list

Select	FRAME 1I	MULTIPLICITY 1B	MULT 1B	TIME 1D	PIXEL 1B	X 1I	Y 1I	TYPE 1I	ENERGY 1D
All Invert	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	0	1	0	0.000000000000E+000	128	0	8	1	9.794309200000E+001
2	1	1	0	3.062956094742E+000	145	1	9	1	9.333808000000E+001
3	2	1	0	3.107777595520E+000	126	14	7	1	5.661259000000E+001
4	3	1	0	3.311278343201E+000	176	0	11	1	1.204386400000E+002
5	4	1	0	4.261723756790E+000	117	5	7	1	5.908343000000E+001
6	5	1	0	4.685714244843E+000	155	11	9	1	3.126330300000E+001
7	6	1	0	7.426927089691E+000	134	6	8	1	2.661225810000E+002
8	7	2	0	7.764491081238E+000	242	2	15	255	1.749924320000E+002
9	8	2	1	7.764491081238E+000	243	3	15	255	2.266542400000E+001
10	9	1	0	8.099779129028E+000	226	2	14	1	2.673193900000E+001
11	10	2	0	8.122672319412E+000	119	7	7	255	3.066022800000E+001
12	11	2	1	8.122672319412E+000	135	7	8	255	1.780166800000E+001
13	12	1	0	8.208755016327E+000	252	12	15	1	4.416408700000E+001
14	13	1	0	8.331153392792E+000	254	14	15	1	7.991901300000E+001
15	14	1	0	8.772984504700E+000	47	15	2	1	1.588442560000E+002
16	15	1	0	9.839590549469E+000	59	11	3	1	2.487148740000E+002
17	16	1	0	9.900824785233E+000	191	15	11	1	2.493642300000E+001
18	17	1	0	1.208127880096E+001	239	15	14	1	6.909980000000E+001
19	18	1	0	1.288081645966E+001	10	10	0	1	2.669001630000E+002
20	19	1	0	1.323039579391E+001	97	1	6	1	1.040922665000E+003
21	20	1	0	1.323042392731E+001	97	1	6	1	5.778931210000E+002
22	21	1	0	1.323045206070E+001	97	1	6	1	1.885572170000E+002
23	22	1	0	1.470239663124E+001	120	8	7	1	1.665020800000E+001
24	23	1	0	1.472033309937E+001	77	13	4	1	7.437592800000E+001
25	24	1	0	1.529405093193E+001	52	4	3	1	8.464667200000E+001
26	25	1	0	1.603019905090E+001	217	9	13	1	5.825263600000E+001
27	26	1	0	1.623439192772E+001	169	9	10	1	3.984854400000E+001
28	27	1	0	1.637744331360E+001	202	10	12	1	5.378394600000E+001
29	28	1	0	1.652689838409E+001	48	0	3	1	3.205725600000E+001

Outputs

Which **radioelements**? → Classification

In which **proportions**? → Regression

With **uncertainties**?

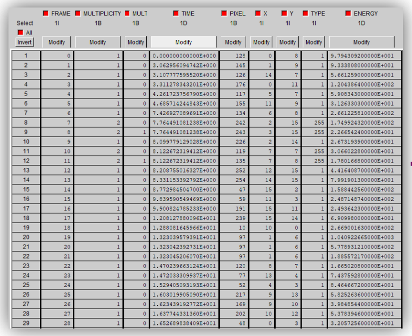
Some constraints:

- **Real-time** computation
- Identification for **low-statistics** of photon
- Independent on **operational conditions** (temperature, high-voltage… → impact on calibration)
- Not sensitive to environmental conditions (presence of absorbing materials or diffusing materials)

DATA TRANSFORMATION

Input

Calibrated event list

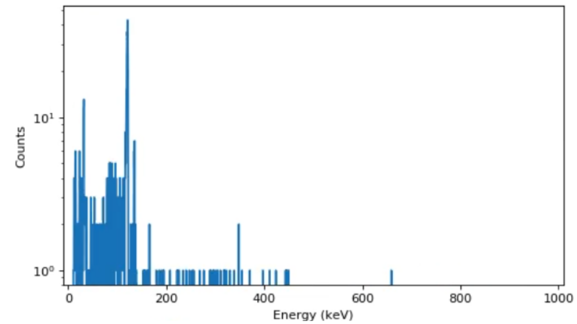


Histogram of measured energies
Classical way for these studies

Choices:
binning, range, single events, sum spectrum of all pixels

Vector of counts → Spectrum

0	25	100	50	12	….	4	0	0	0



Normalization

Log-normalization, max = 1

Input of ML algorithm

Convolutional Neural Network

Output of ML algorithm

Output

List of sources: ^{137}Cs, ^{57}Co

Proportions of the detected photons: ^{137}Cs: 30%, ^{57}Co: 70%

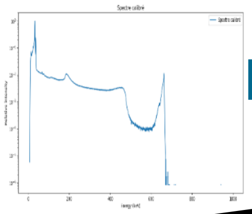
Mathematical representation

^{241}Am	^{133}Ba	^{57}Co	^{137}Cs	^{152}Eu	^{22}Na
0	0	1	1	0	0
0	0	0,7	0,3	0	0

CONVOLUTIONNAL NEURAL NETWORK

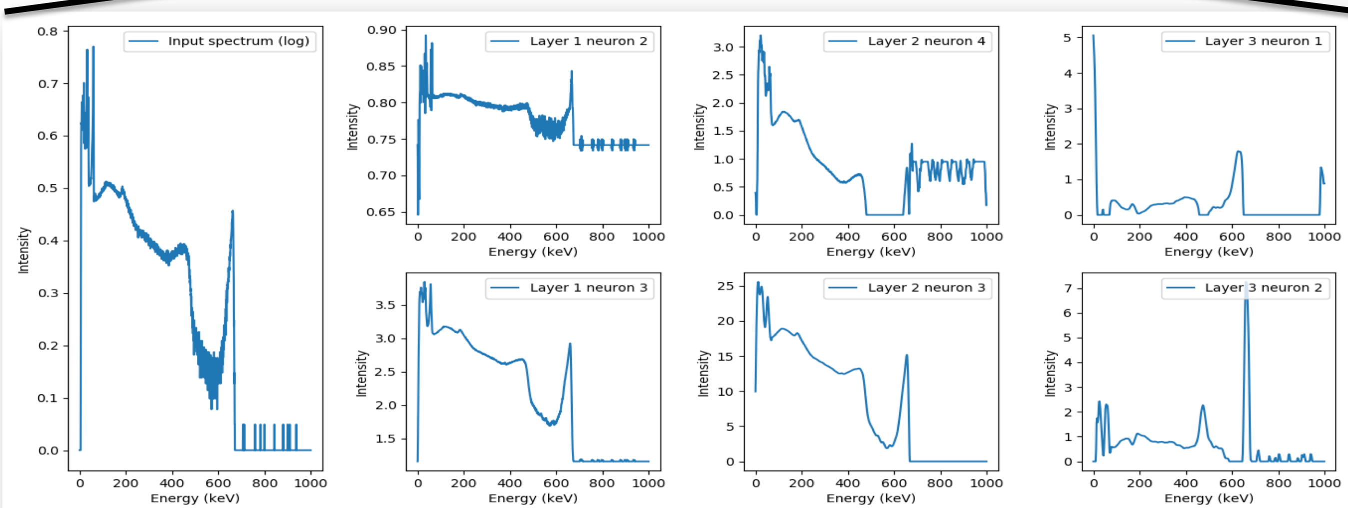
One identification network for each radio-element:

Input Spectrum



Neural network

Normalization → Convolution part: Characteristics extraction → Perceptron Identification → Cs137!



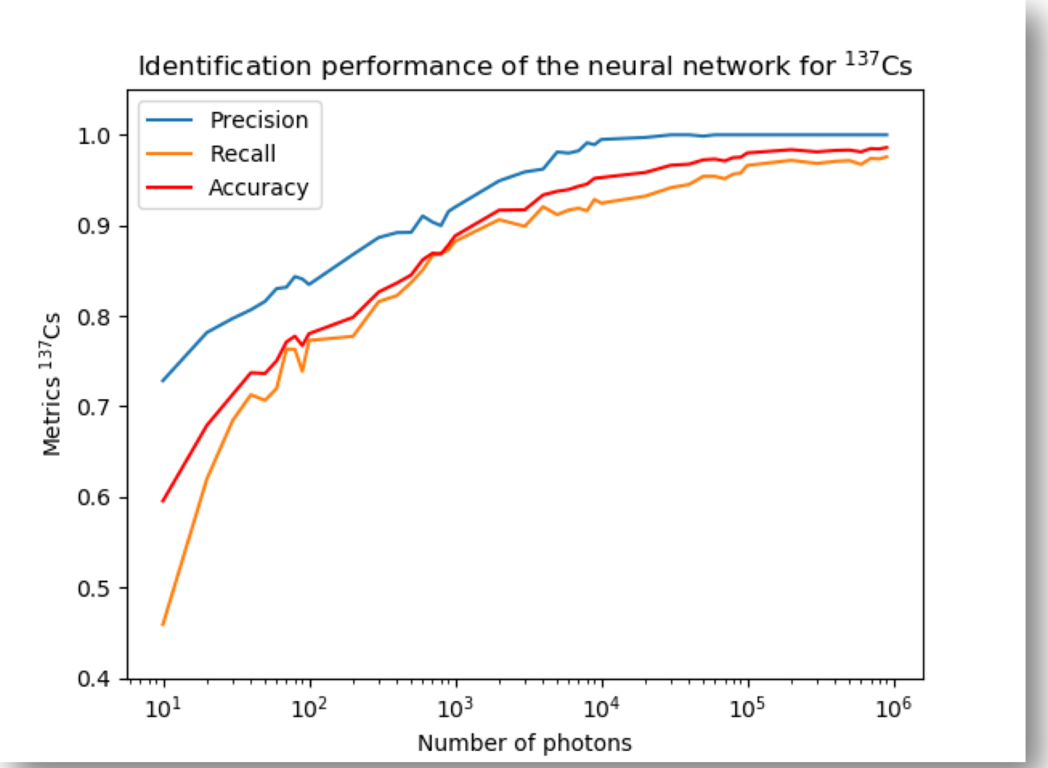
Performance

Precision: False positive influence
Recall: False negative influence
Accuracy: Right identification rate

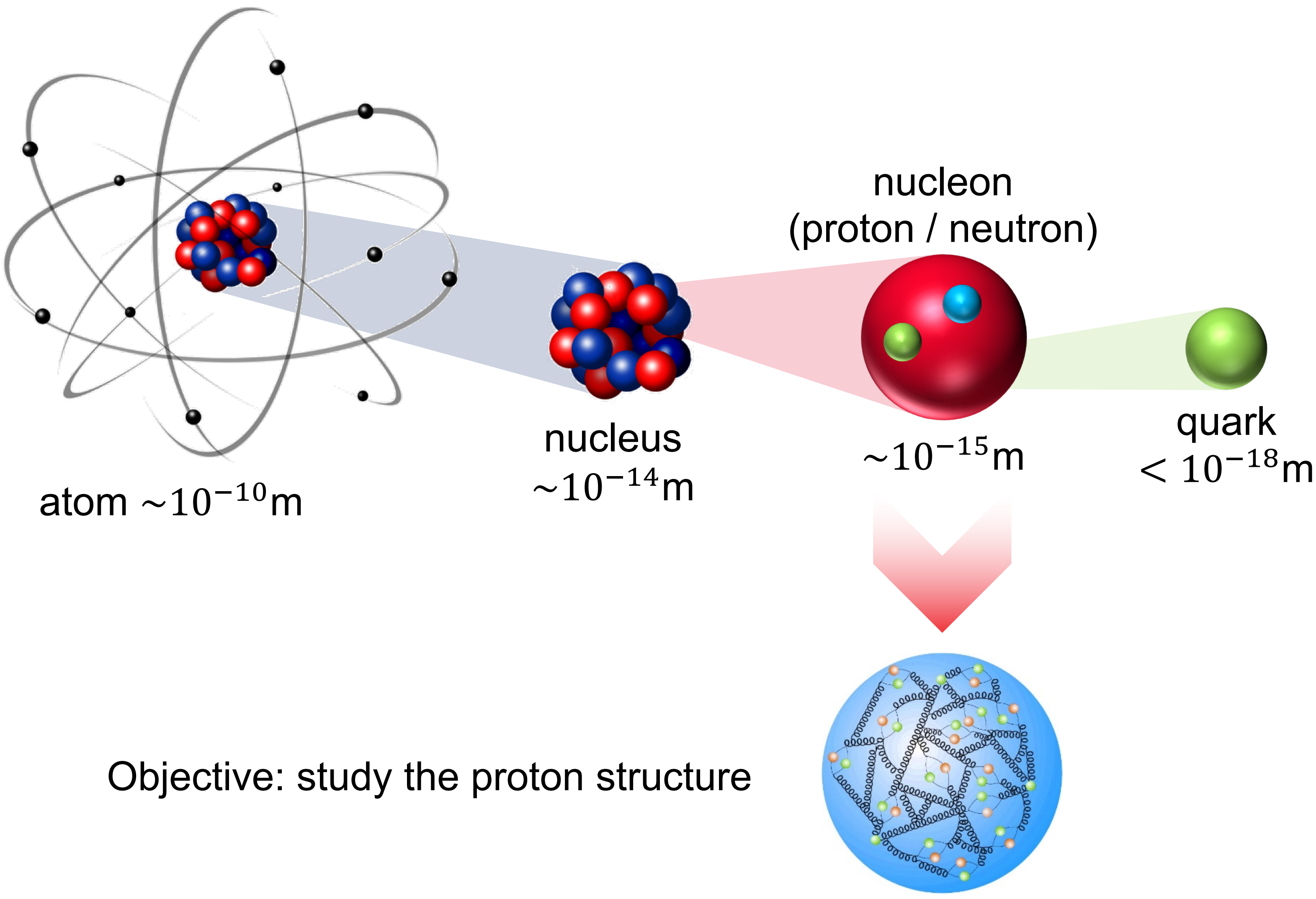
Accuracy:
- > 80 % with more than 200 photons
- > 90 % with at least 1000 photons
- > 95 % with at least some thousands of photons

- Similar performance for other radionuclides: ^{241}Am, ^{133}Ba, ^{57}Co, ^{152}Eu, ^{22}Na

Test on real data of mixtures with **random decalibration**



PHYSIQUE NUCLÉAIRE

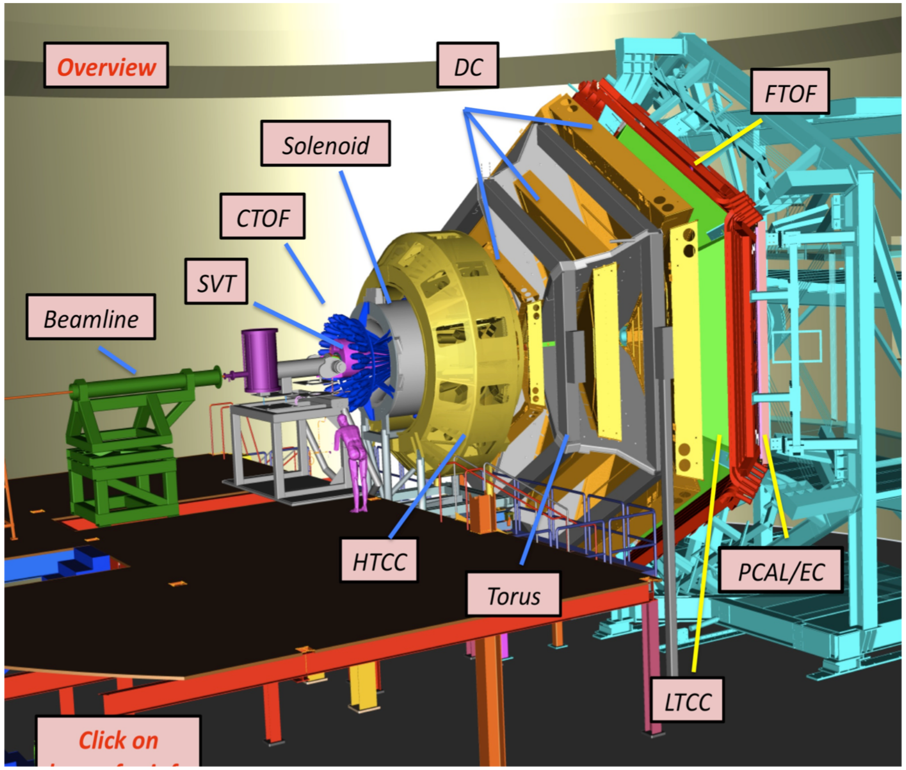


Objective: study the proton structure

JEFFERSON LAB: 10.6 GEV ELECTRON BEAM

CLAS12 DATA TAKING SINCE 2018: HYDROGEN TARGET

EVENT CLASSIFICATION TASK: ISOLATE DVCS EVENTS ($ep \rightarrow ep\Gamma$)



Feature construction

Motivation: these models do not build a sufficiently complex internal representation of the data

p_x^e φ^τ

θ^γ

p_T^{lep}

$\longrightarrow$

$p_z^e + p_z^p + p_z^{\gamma_1}$

$\cos(\theta^{lep} - \theta^\tau)$

$angle(p^{\gamma_1}, p^{\gamma_1} + p^{\gamma_2})$

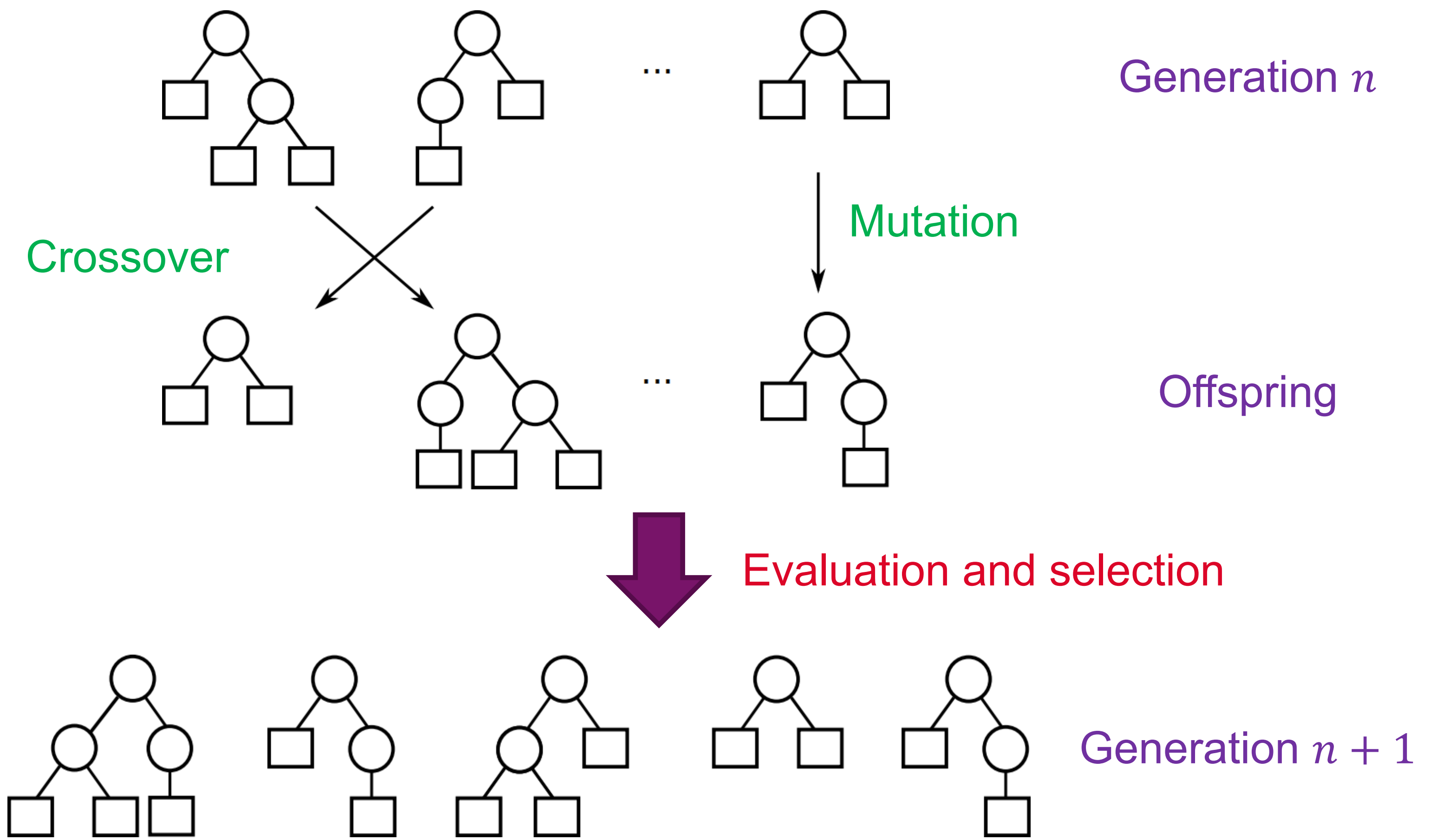
$\cos(\varphi^{lep} - \varphi^\tau)$

Base variables

Discriminative and intelligible features

In machine learning: feature engineering, feature construction

Feature construction



Feature construction: Practical use in MML Algorithms

Cherrier, N., Defurne, M., Poli, J. P., & Sabatié, F. (2019). Embedded Constrained Feature Construction for High-Energy Physics Data Classification. In *Workshop on Machine Learning for the Physical Sciences, NeurIPS* 2019.

p_x^e φ^τ θ^γ

Constrained Genetic Programming

$p_z^e + p_z^p + p_z^{\gamma_1}$

$\cos(\theta^{lep} - \theta^\tau)$

$angle(p^{\gamma_1}, p^{\gamma_1} + p^{\gamma_2})$

$\cos(\varphi^{lep} - \varphi^\tau)$

Features in the dataset

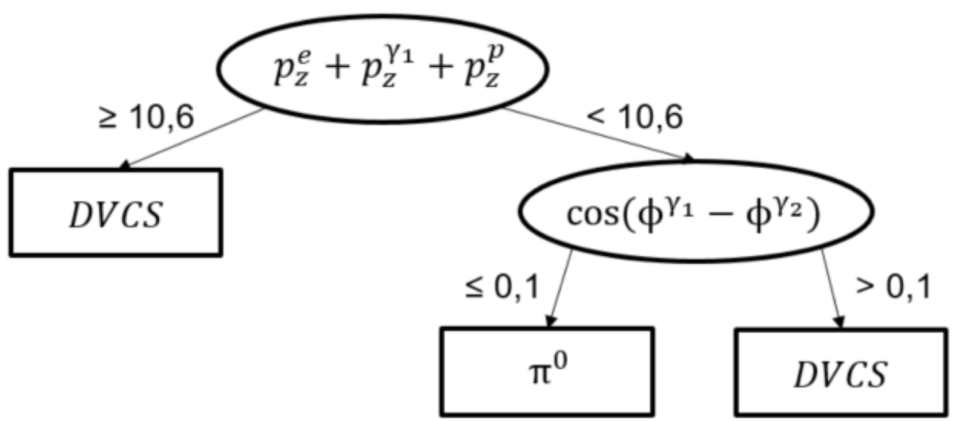
Discriminative and intelligible features

embedded into tree node induction

Fitness: tree splitting criterion (information gain, Gini index, ...)

✓ Faster construction

("filter" methods are faster to evaluate than training a whole ML model)

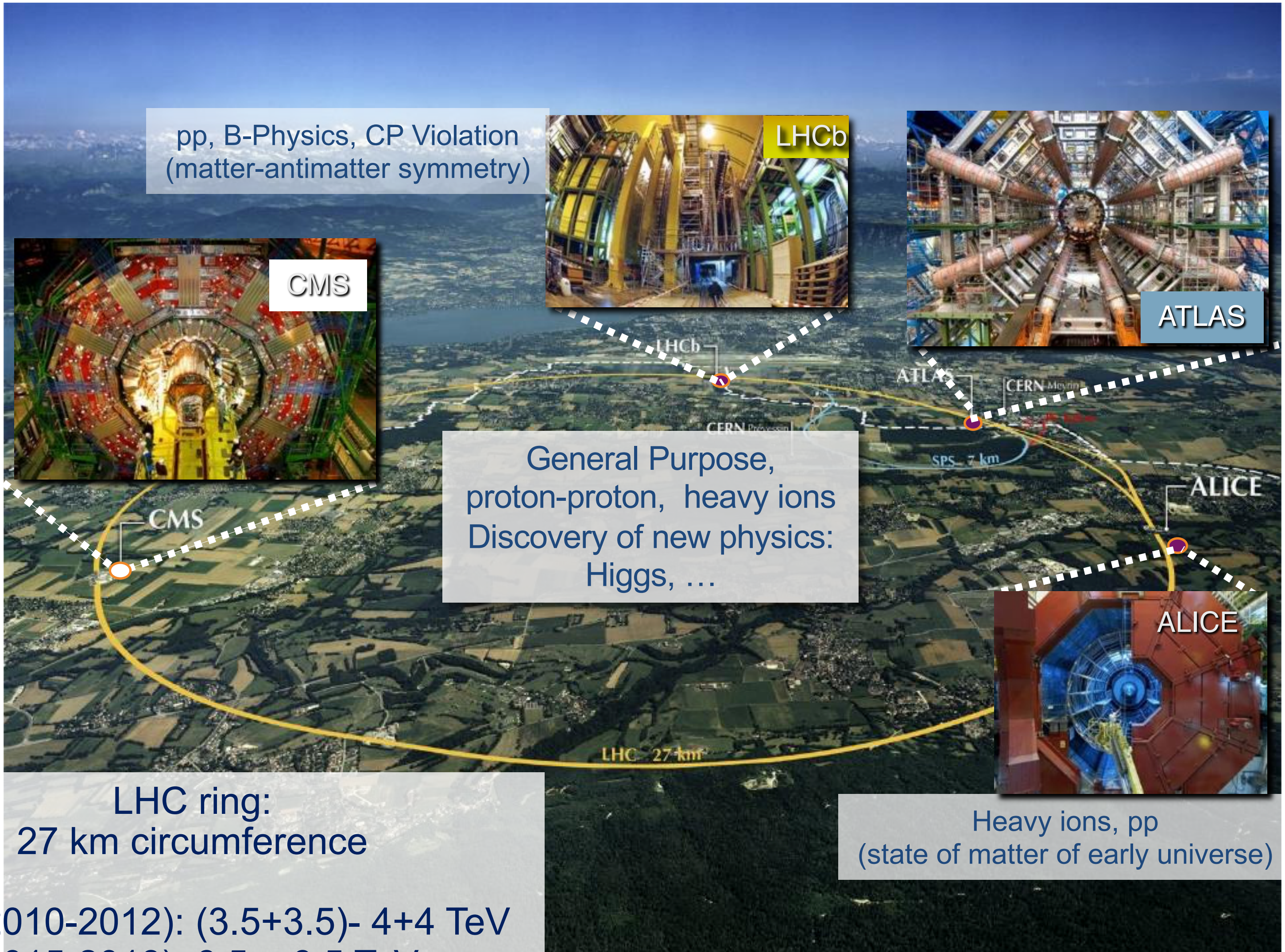


ACCELERATOR

DESIGNING SUPERCONDUCTING MAGNET

MODELLING DYNAMIC APERTURE

LHC

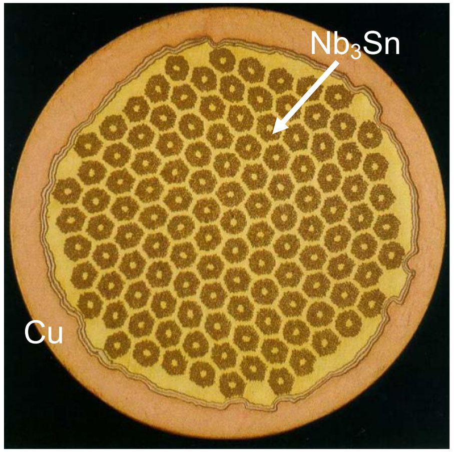


Run 1 (2010-2012): (3.5+3.5)- 4+4 TeV
Run 2 (2015-2018): 6.5 + 6.5 TeV

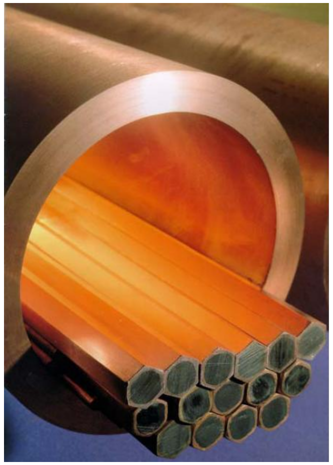
Challenges in Designing Superconducting Magnets

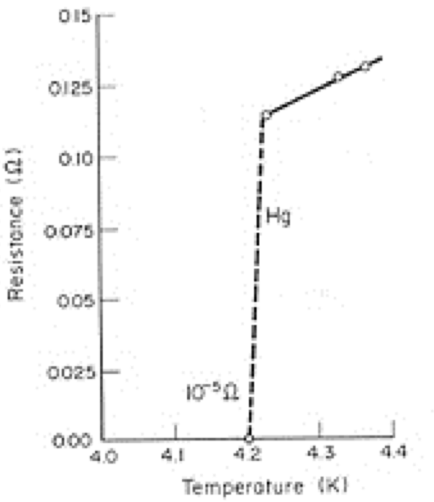
Why superconductivity?

Superconductive materials show zero electric resistance
→ they can transport a lot of current without heating

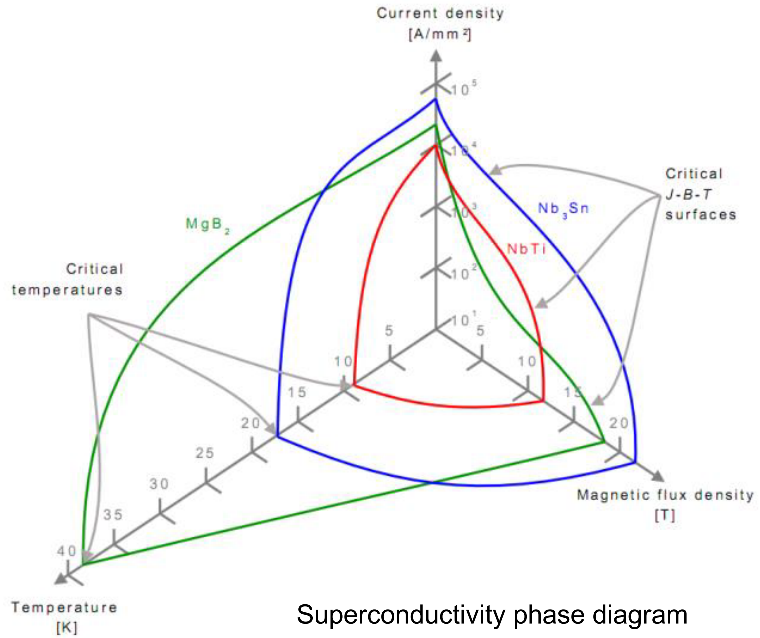


Nb_3Sn bronze-process wire [1]





Hg resistivity



Superconductivity phase diagram

The superconducting state is limited by

- $\vec{B}$ magnetic field
- $\vec{J}$ current density inside the material
- T temperature

CHALLENGES IN DESIGNING SUPERCONDUCTING MAGNETS

Which challenges?

- **Field quality**
  $\Delta B/B \sim 10^{-4}$ for particle accelerators
  $\Delta B/B \sim 10^{-8}$ for MRI

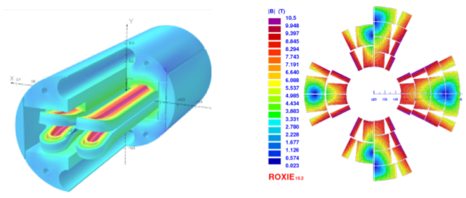
- **Mechanics**
  Stress can reach 300 MPa on the conductor

- **Cryogenics**
  Must cool down tons of materials

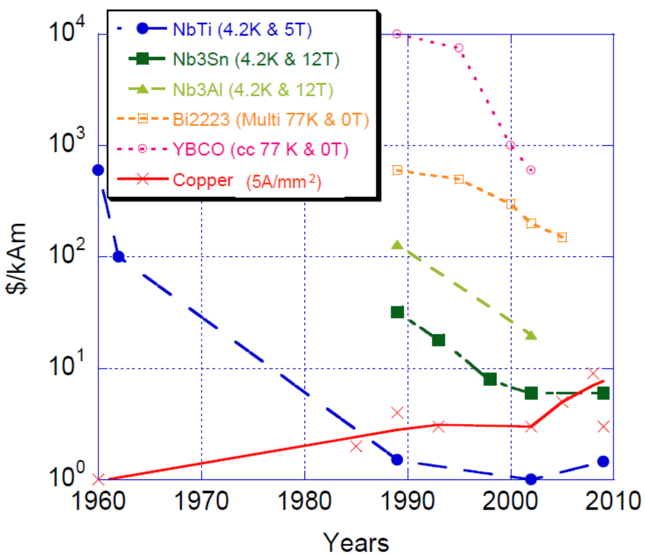
- **Protection**
  Transition to the normal state means 1000s A in ~mm² wires (normal Cu wire carries some A)

- **Cost**
  Superconductors can cost up to 1000$/kAm

FCC Dipole & Quadrupole



US$ 150/kg ↔ ~1 $/kAm



P. Fazilleau – Ecole des accelerateurs 2016

WHY USING AI METHODS?

Field Quality

Depends on:

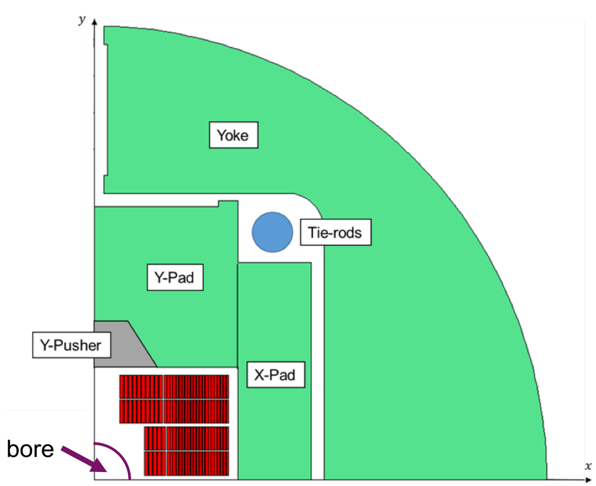
- Position of the coils → linear contribution to B
- Position of the ferromagnetic materials → non linear contribution to B

Cost

Depends on:

- The volume of conductor needed
- The quantity of superconducting material needed in the cable to stand the magnetic field peak

Not possible to write down an analytical function



Problem is :
Given a certain B according to specs,

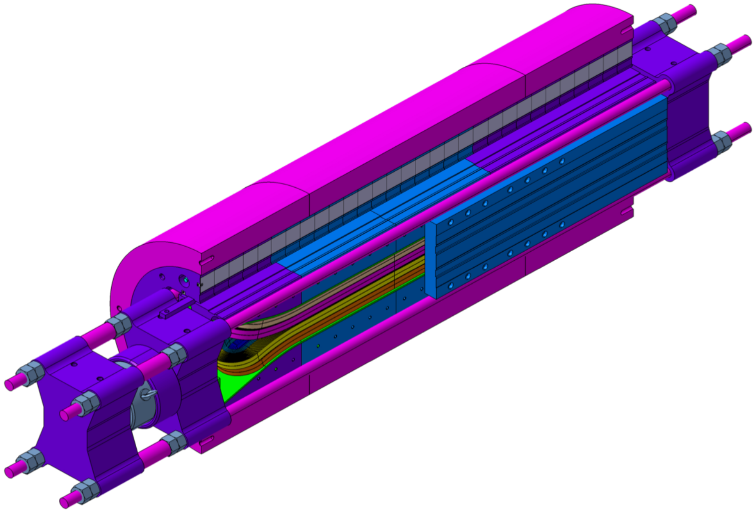
Field Quality
Minimization of the ratio $\Delta B/B$ in the bore region

Cost
Minimization of the ratio $\Delta B/B$ on the conductors

Examples of Genetic Algorithms Applications

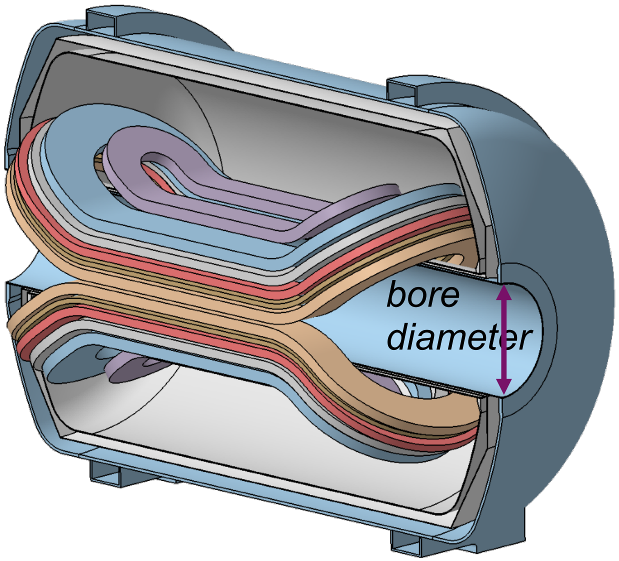
Field Quality

F2D2
The 16 T graded Nb_3Sn flared ends dipole to prove the feasibility of the Future Circular Collider at CERN.



Cost

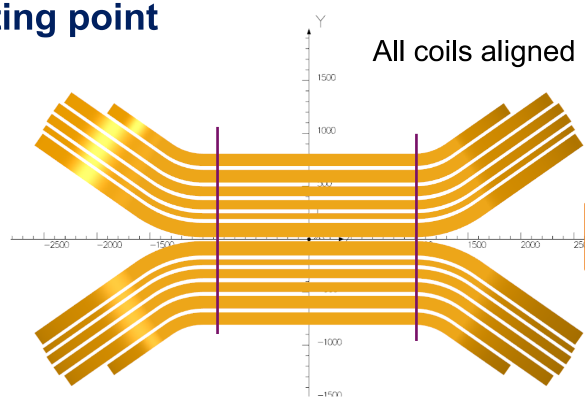
MADMAX
The 9 T NbTi, 1.3 m of useful diameter dipole (the biggest in the world) to find axions-like particles.



Results on MADMAX Version 9.0

Starting point

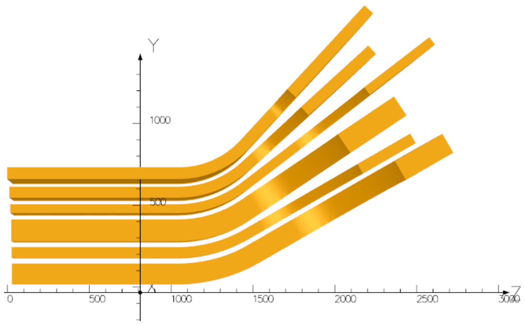
All coils aligned



7980 k€

Intermediate solution

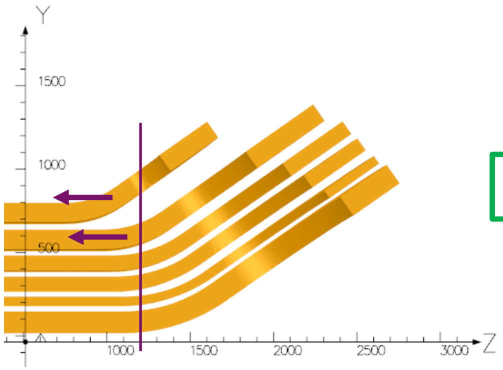
GA study varying many parameters



2816 k€

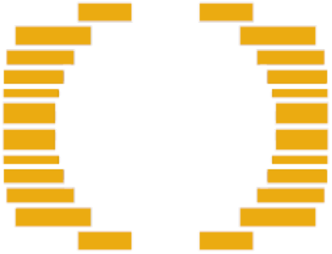
but not feasible for assembly

Final solution

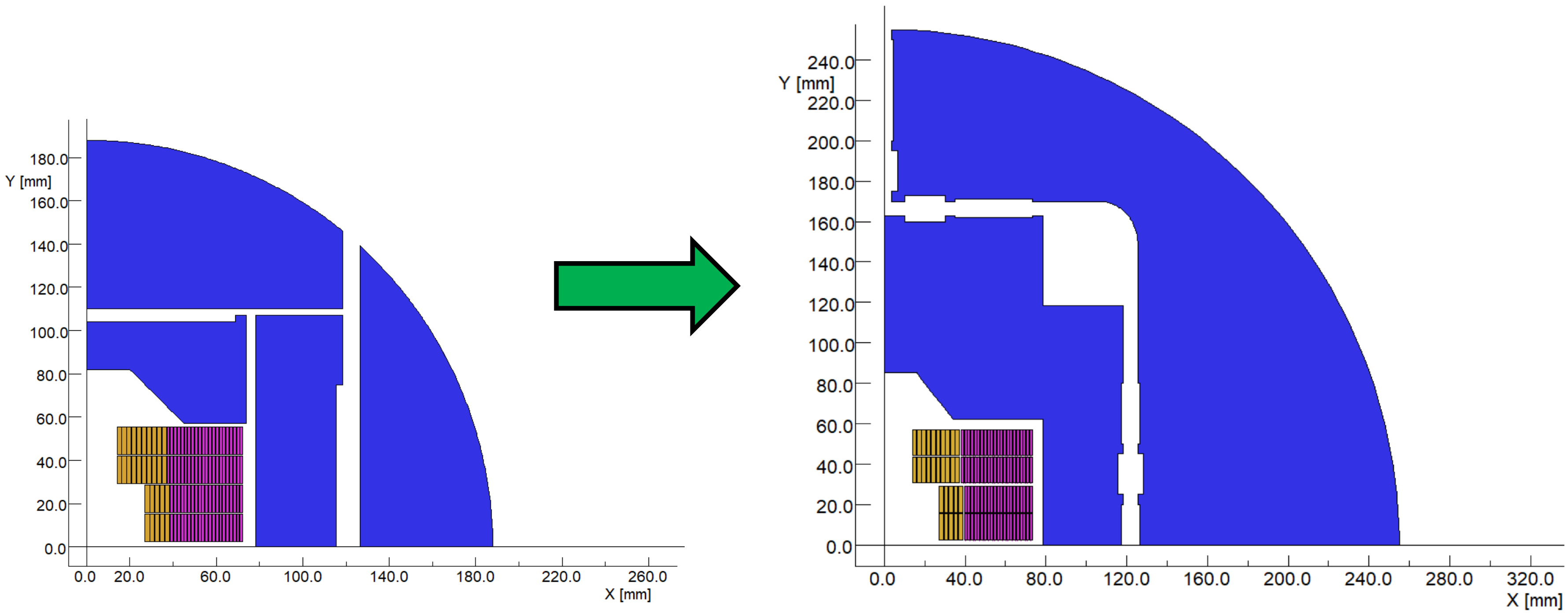


3088 k€

GA + parametric study
to understand the sensitivity of parameters



F2D2 – From Beginning to Final Design



Modelling Dynamic Aperture (DA) of future circular particle accelerators

- Focus on the long-term DA

DA

What's a → region of stable motion of a particle in an accelerator

What's DA used for →
- used to define tolerances on field quality
- used to define non-linear corrections schemes in the design phase of the accelerator

- Different possibilities to define DA:

DA

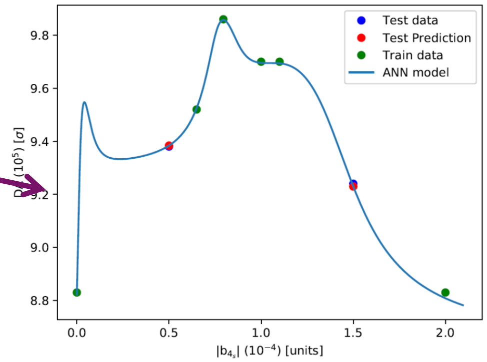
Define DA → **Particle amplitude**: DA is the amplitude corresponding to particle losses after the 10^n revolutions in the accelerator

Define DA → **Trajectory**: DA is the divergence of nearby trajectories in the phase space to define the limit between chaotic and non-chaotic motion

Simulate DA: From 1 day to one week or more…

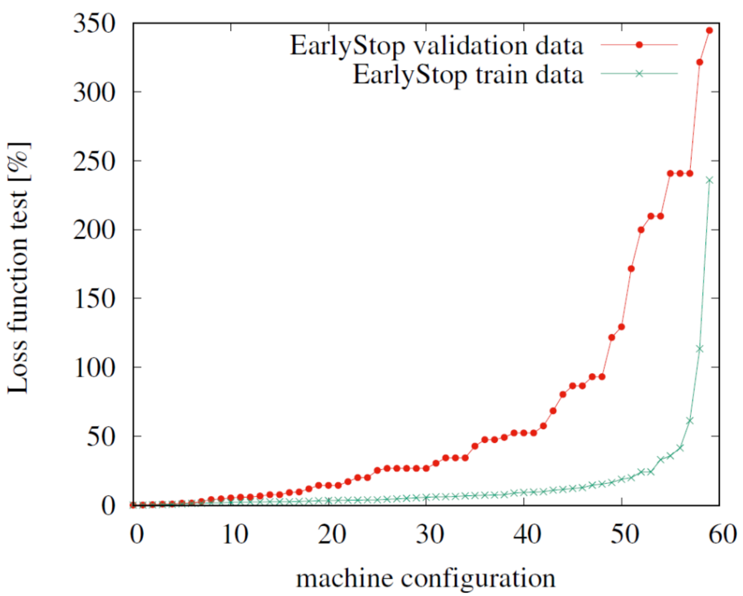
Tuning ANN to interpolate DA values

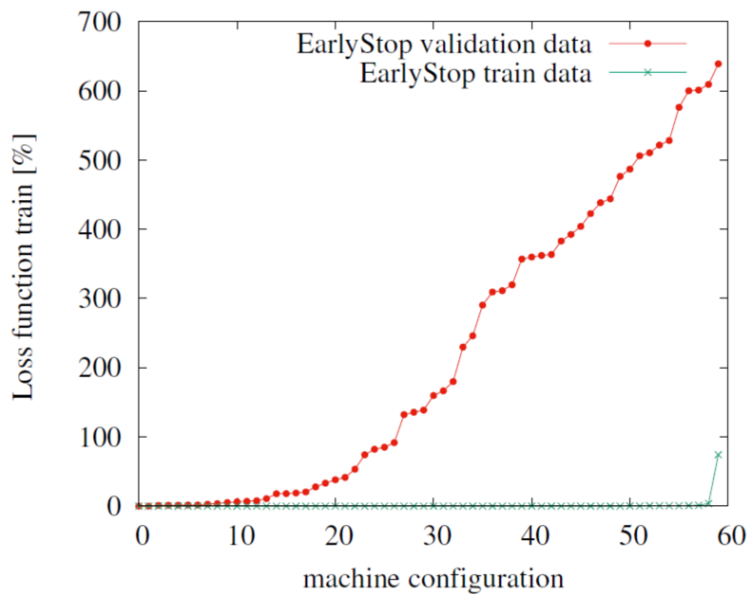
Minimum DA over 60 machine configurations as a function of octupole errors in the ring



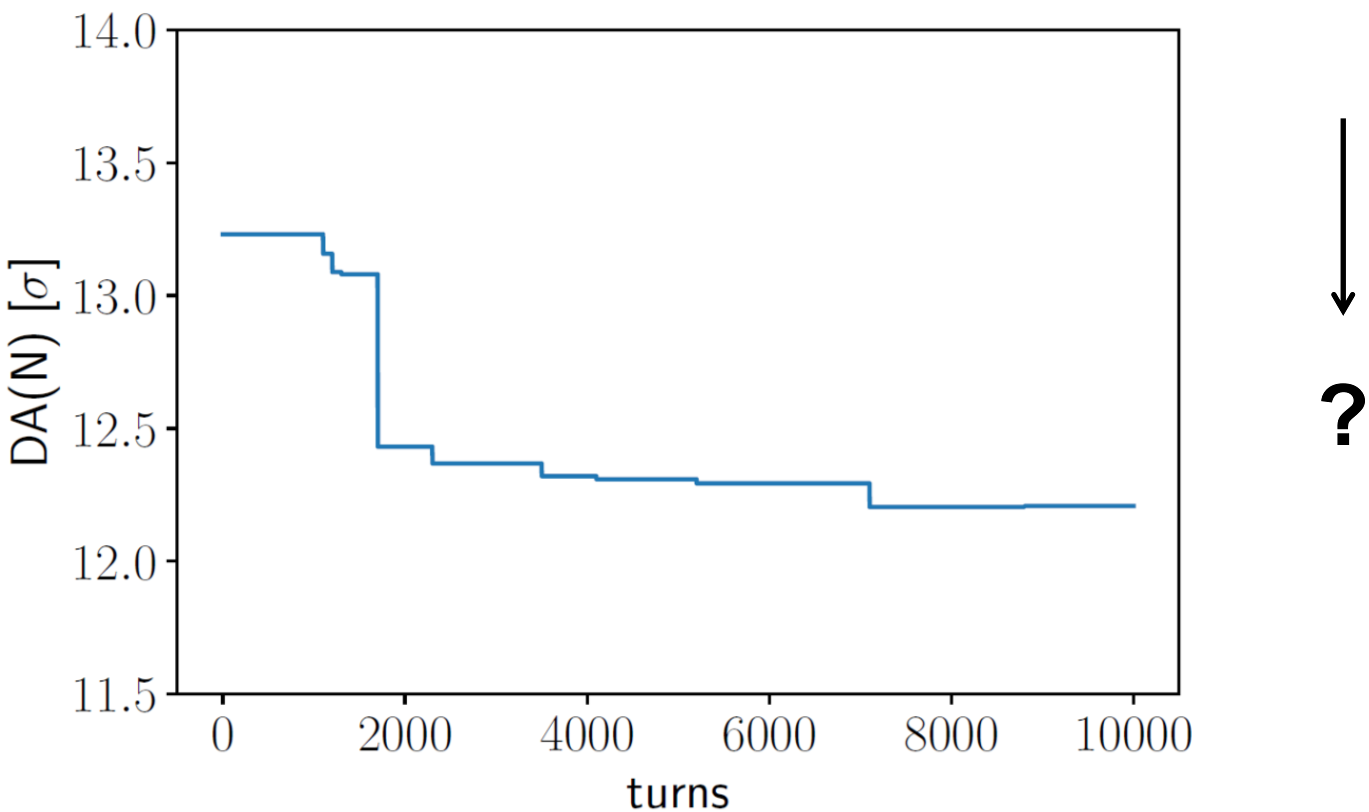
Same ANN on each machine configuration

- Performance are not the same for each machine configuratio
- Early stop on test data not good as EarlyStop on train
- Still some overfitting remains
- Loss function values depends also on seed of Keras-Tensorflow initializations





- Predict DA values at 10^5 turns knowing its values up to 10^4 turns, i.e. number (N) of revolutions in the machine



DETECTORS

ATLAS NSW

CLEARMIND

RAINFROG: PROCESS AUTOMATION ON THE ATLAS/NSW FACILITY

Context

Fabrication & test of detector elements in the CICLAD clean room facility at Saclay

NSW Micromegas detectors are scanned for planarity on 2 instrumented gantry granite tables

Planarity scans occur at various stages of construction and for final QC acceptance

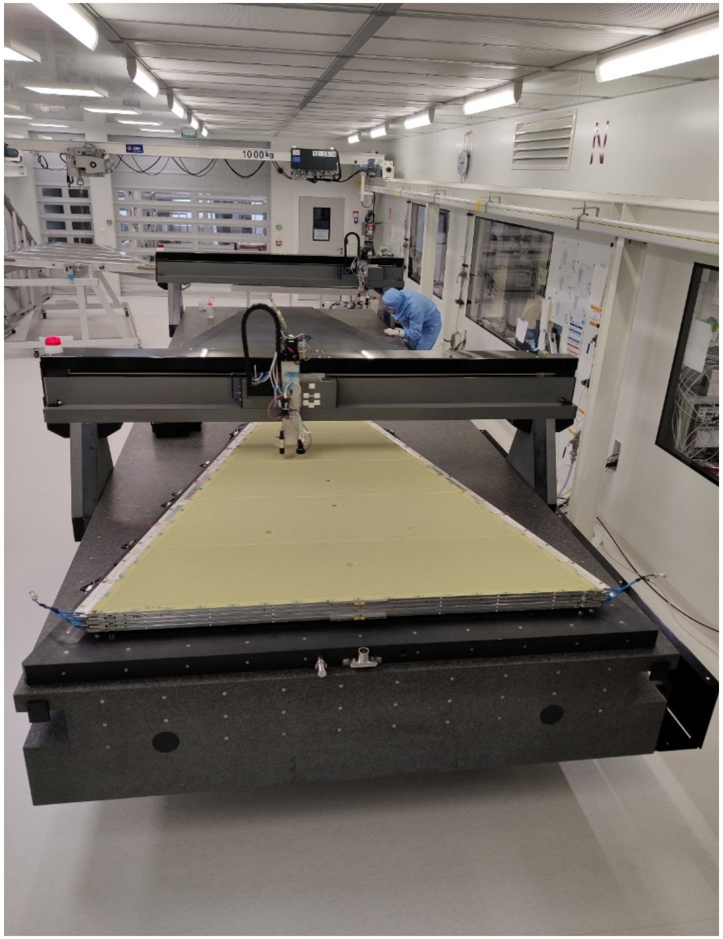
A large variety of scans requiring different settings, a total of 31 distinct configurations

Problem

Can we automatically find the active configuration, just by looking at the current part with a camera?

Algorithmic image processing would be very complicated.

Can we handle this by machine learning?



A completed module being scanned for planarity with a contactless optical sensor

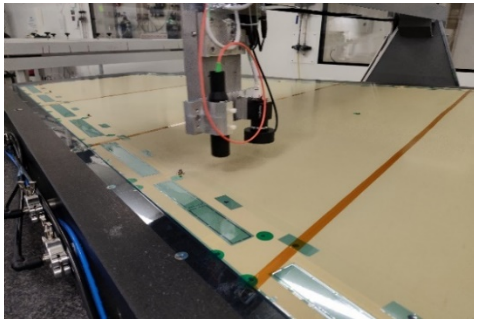
Look and Guess

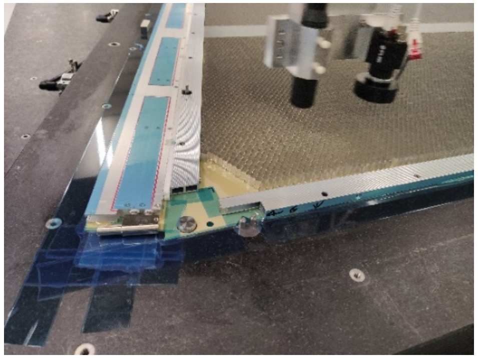
What needs to be discovered

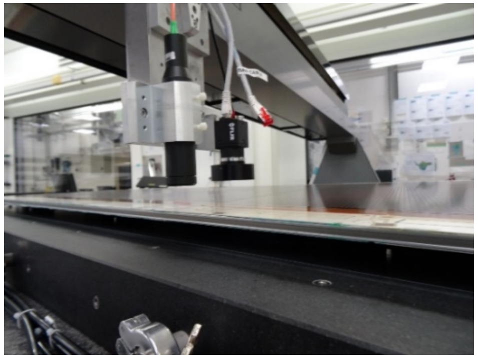
- The type and subtype of the object: drift panel *front/central/back*, readout panel *eta/stereo*, module
- The nature of the surface *pcb/honeycomb/resist/copper*
- Which side of the part is exposed for measurement *A/B*
- The height at which the part is exposed

A non standard image classification problem

- A total of 20 categories in 5 families
- Will pick the highest score in each family
- Categories are non exclusive, showing inclusion and intersection across families







A variety of configurations of parts, sides, surfaces, heights

IMAGE COLLECTION STRATEGY

Take photos at 6 strategic locations

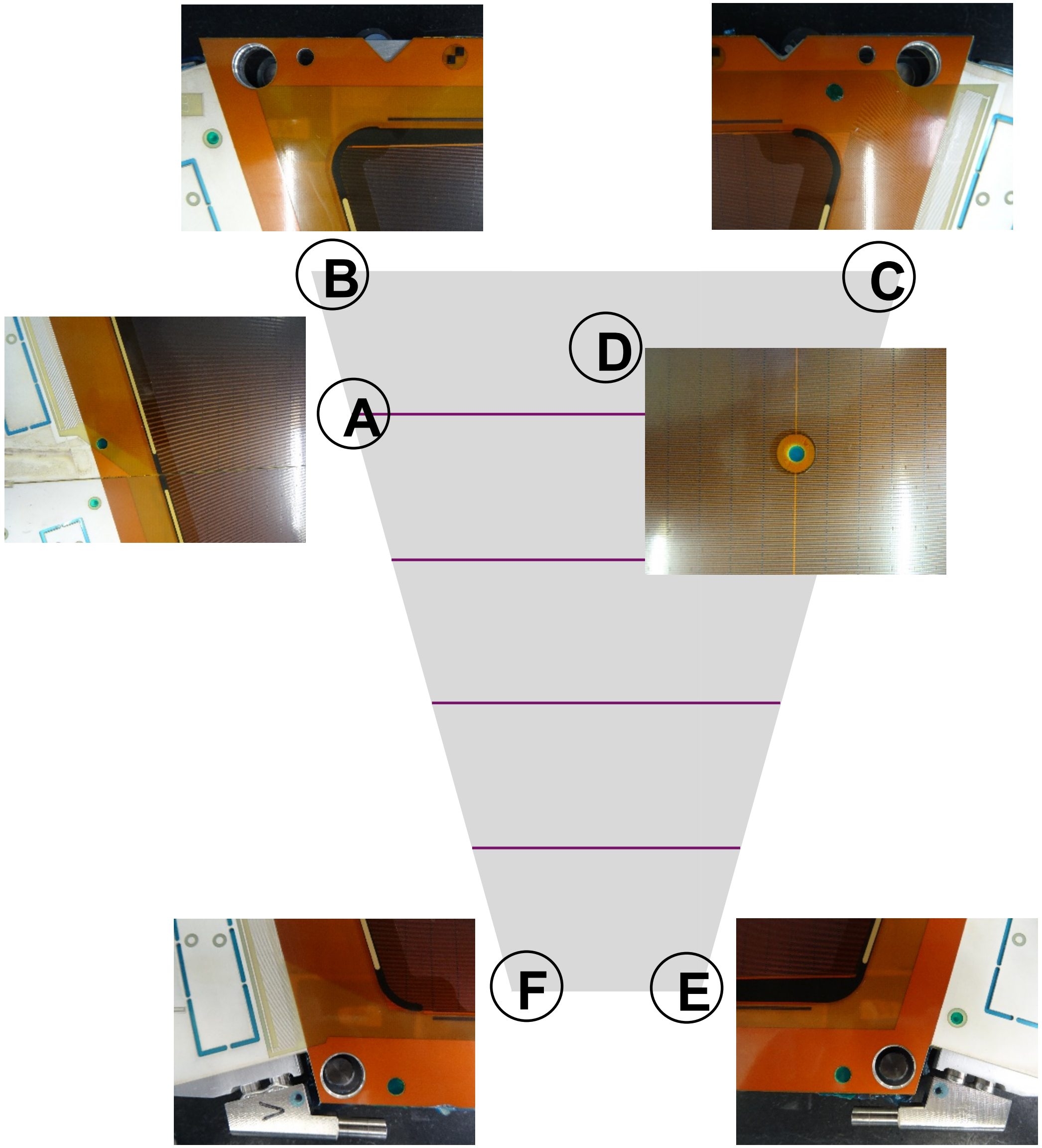
A	Pcb frontier & edge
B, C, E, F	Corners
D	Interconnect

Independantly infer for each photo

Fuse 6 scores for final decision

This example session

S23_BonPads	Stereo readout panel
	Side B
	Sitting on pads



WORKFLOW

Jan '20 → Feb '20 → Mar '20 → May '20 → Jun '20 → Now

- Local
- Tensorflow, Local or Google Colab
- Local
- TfLite inference, StilFlying

Select NN architecture
↓
Collect & prepare input data
↓
Train network
↓
Analyse
↓
Integrate on target
↓
Test
↓
Deploy

Tune hyperparameters (batch size, learning rate, etc.)

Class balance, data augmentation

Python / opencv numpy pandas seaborn

C++ / Qt opencv (Windows)

NN SELECTION, TRANSFER LEARNING & TRAINING

NN

(headless) MobileNetV2 feature extractor
- A Google development
- Aimed at « small » inference machines (mobile phones…)

Pretrained on ImageNet public dataset
- Publicly available repository
- **2.3 million trained parameters**

Fully connected classification head added *(2 layers)*
- Will produce our own category label scores
- **1.3 million trainable parameters**

Input	Operator	t	c	n	s
$224^2 \times 3$	conv2d	-	32	1	2
$112^2 \times 32$	bottleneck	1	16	1	1
$112^2 \times 16$	bottleneck	6	24	2	2
$56^2 \times 24$	bottleneck	6	32	3	2
$28^2 \times 32$	bottleneck	6	64	4	2
$14^2 \times 64$	bottleneck	6	96	3	1
$14^2 \times 96$	bottleneck	6	160	3	2
$7^2 \times 160$	bottleneck	6	320	1	1
$7^2 \times 320$	conv2d 1x1	-	1280	1	1
$7^2 \times 1280$	avgpool 7x7	-	-	1	-
$1 \times 1 \times 1280$	conv2d 1x1	-	k	-	

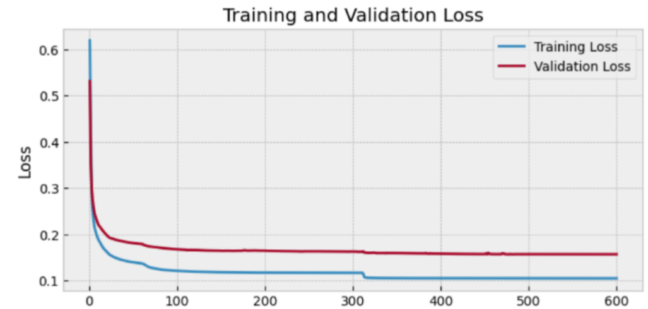
MobileNetV2 feature extractor architecture (21 layers)

Training

750 source images in 60 distinct sessions *Too few!*
- Hand taken Jan to Mar '20

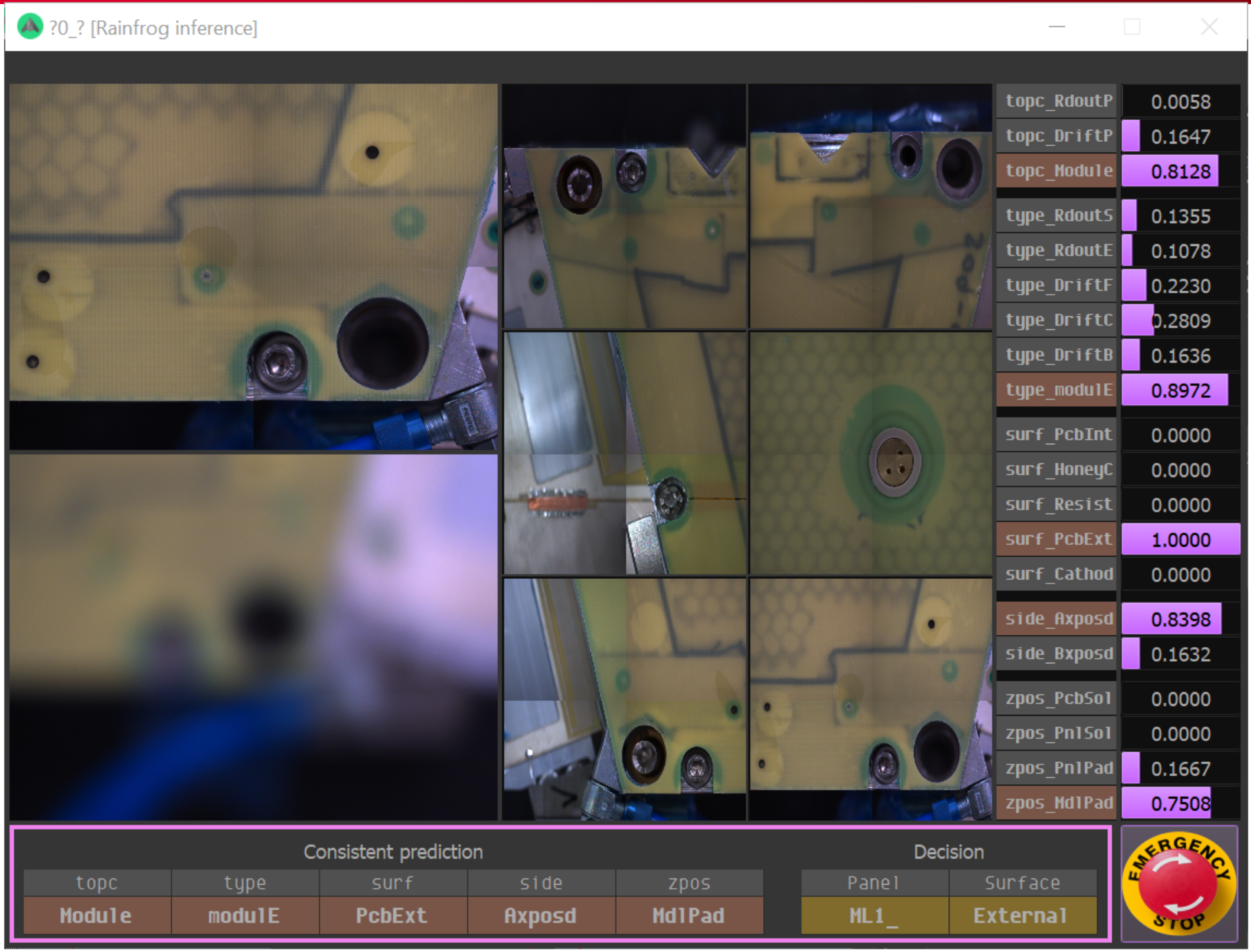
Dataset augmented to 7000+ images
- Improve category balance
- Shift, rotate, adj. brightness, saturate, smooth, crop and scale

Dedicated loss function needed
- Maximise soft-F1, harmonic mean of precision and recall
- … when handling false/true positive/negative category matches



Training and validation loss

FIELD TEST: A CORRECT INFERENCE, M22 MODULE

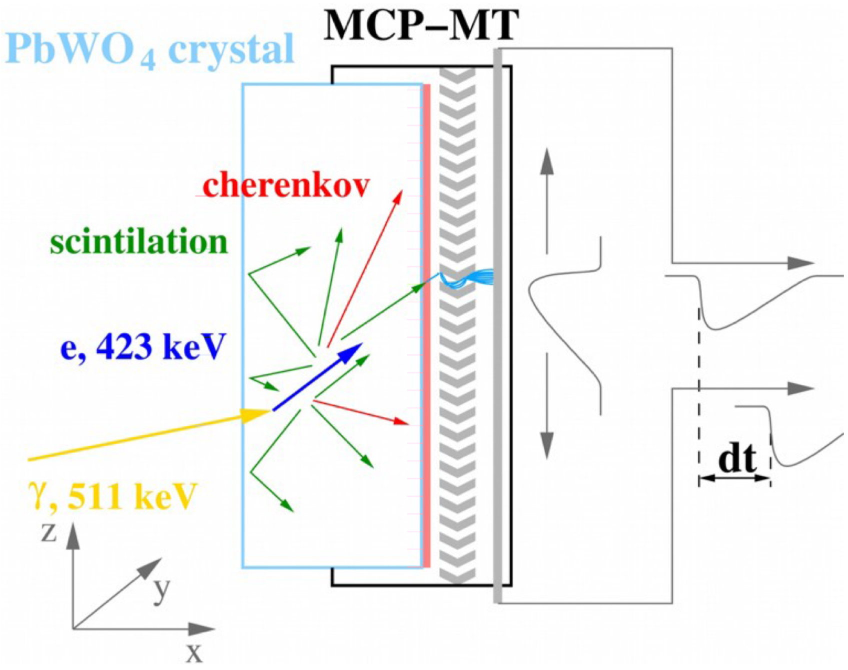


a γ-detector for PET

Spec. list :

- Accurate interaction positioning, 3D : Down to few mm3
- Accurate Timing: Few tens of ps (1s)
- Efficiency: Highest can be - 9 mm att. Length @ 511 keV

- Plug and Play: Once developed



Simulated Shallow Event

Geant 4 Simulation

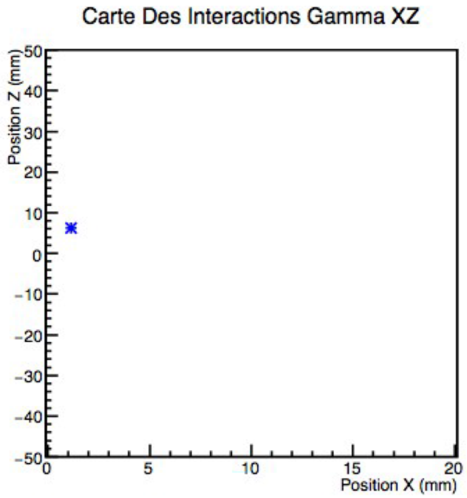
Using Multivariate analysis techniques from MC simulation :

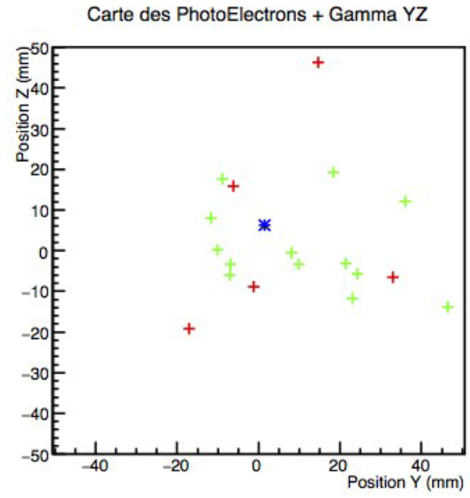
- Positioning accuracy of γ interaction : 4 mm3 ==> ? 1 mm3 ?
- Timing accuracy : few 10 ps (1s)

After decorrelation from Depth of Interaction in crystal

Will be limited by MCP-PMT, single g TTS

- Energy resolution: ~ 15 -20 % (FWHM) @ 511 keV





Energie deposee: 511 keV

Nbre Interactions Gamma: 2

Nbre Photons Optiques: 152

Nbre Photo-Electron: 18

Nbre Photo-Electron Back: 19

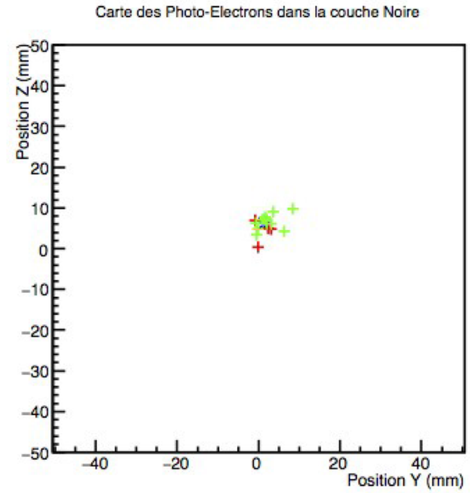
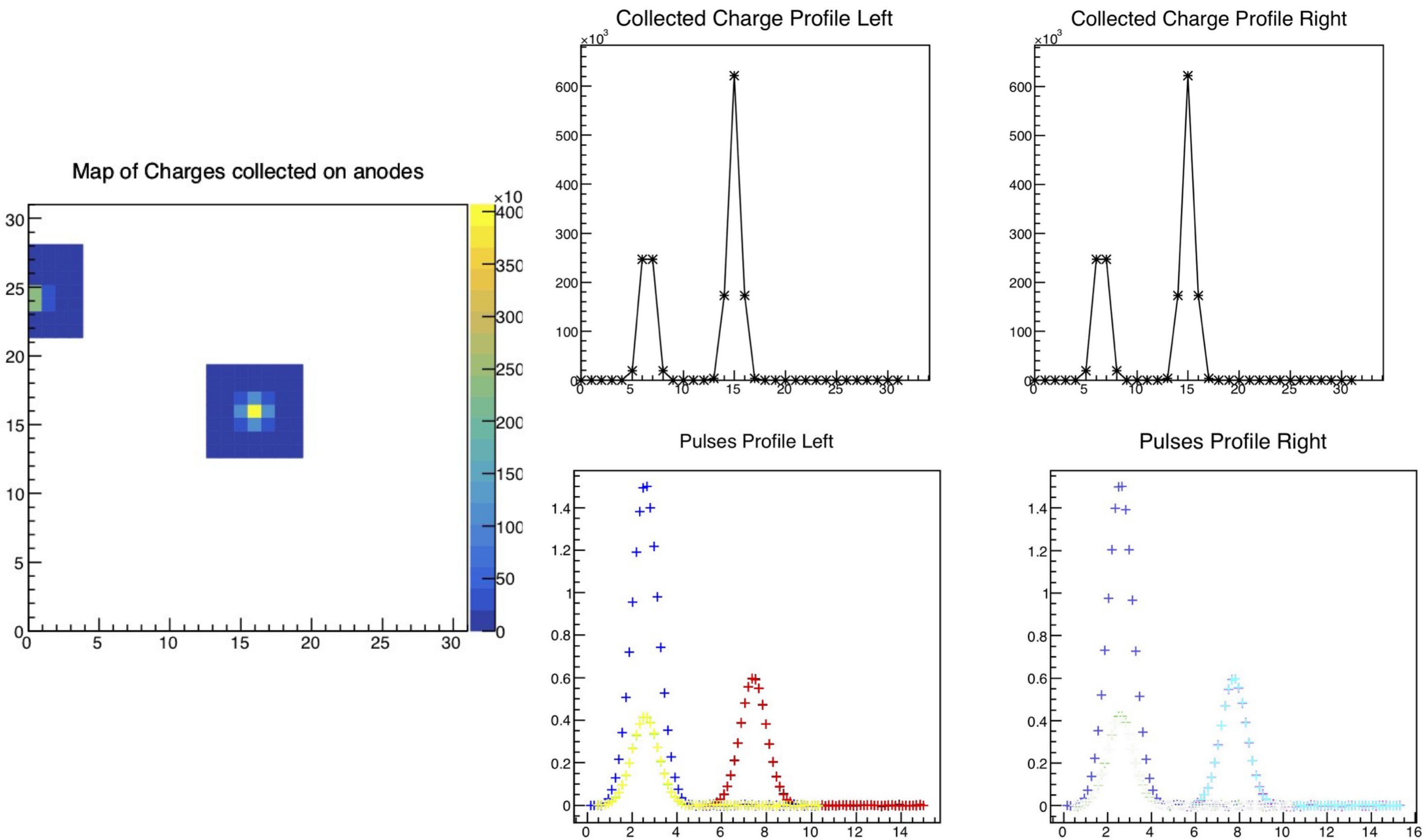
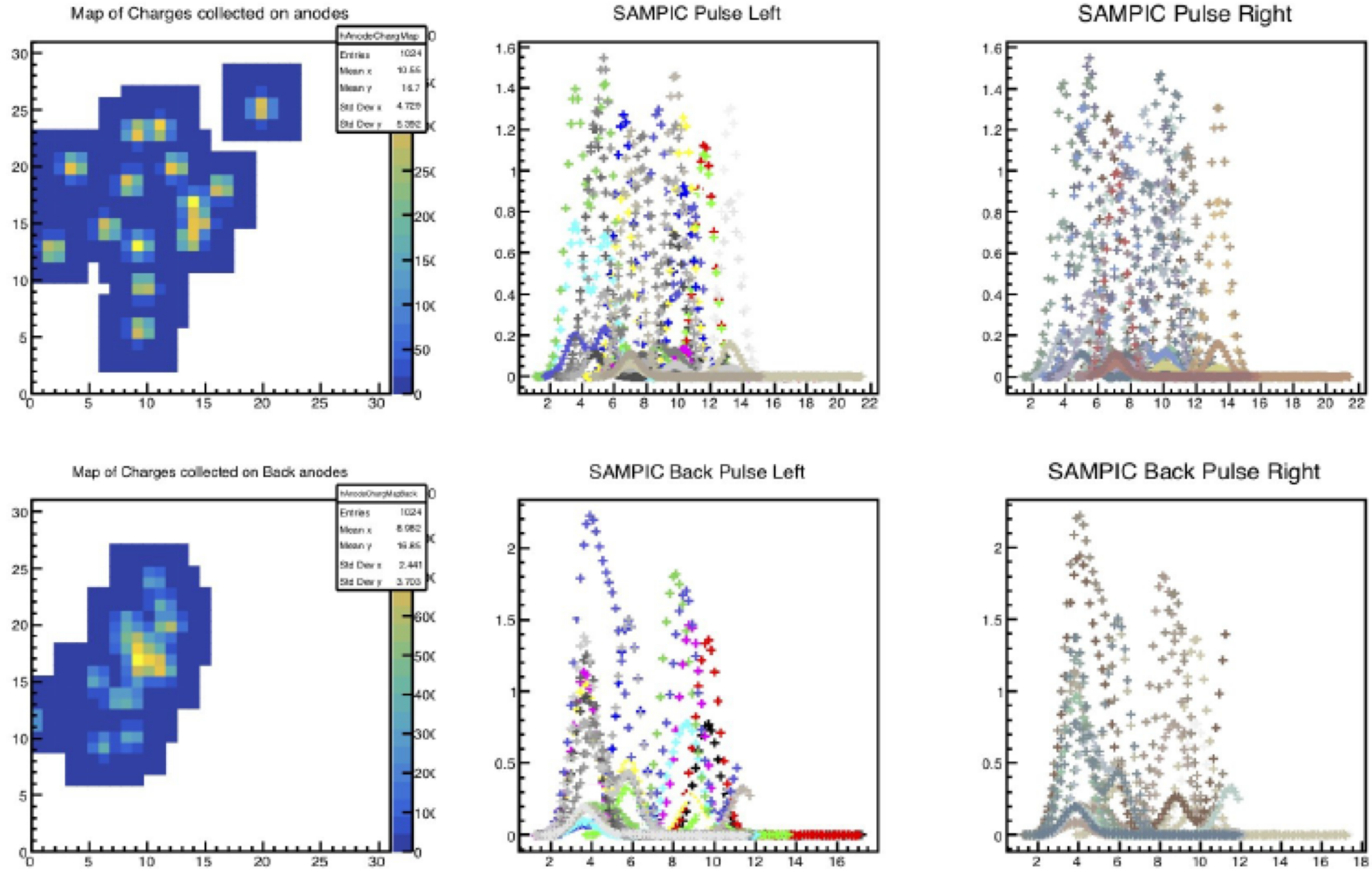


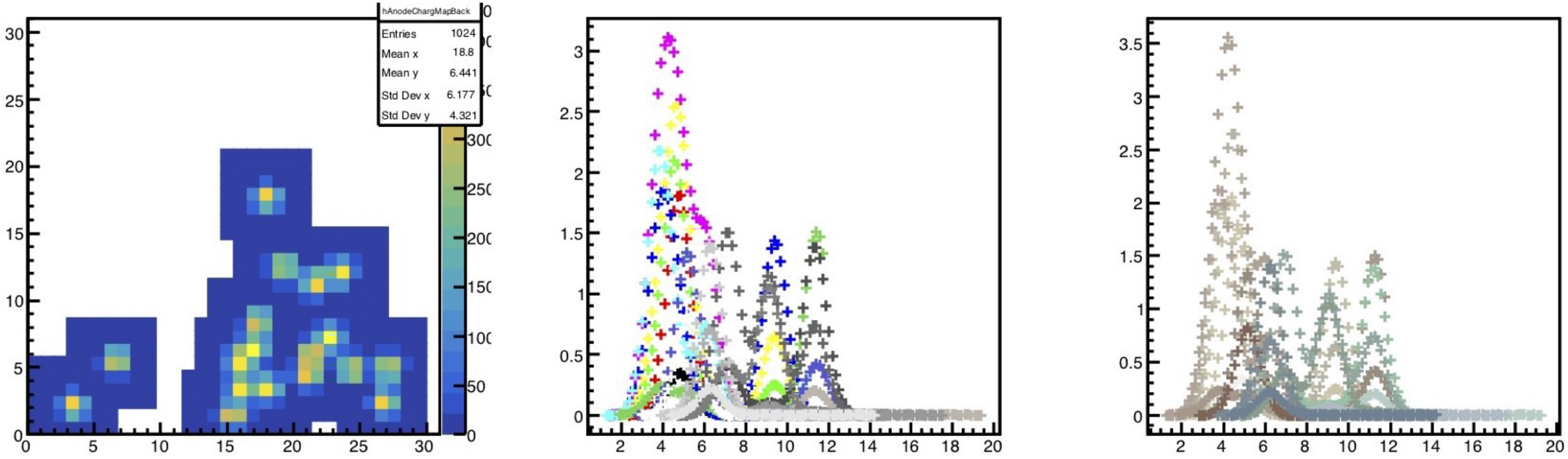
PHOTO-DETECTOR SIMULATION



Event Visualisation



EVENTS RECONSTRUCTION



- From an registered waveform list
  - Information is complex and intricated
- To Gamma interaction properties
  - 3D positionning in Crystal.
  - Time of interactions.
  - Gamma interaction multiplicity
    - weighted by a probability

EVENT RECONSTRUCTION

Using Geant4/Gate simulated data

Calibrated on lab measurements

Specific methods and algorithms

- Machine learning methods
- Convolutional neural networks adapted to the detector spatio-temporal data.
- May require online pre-processing
  - for signals dimension reduction

Validation of Algorithms on detector data

ÉTHIQUE

ÉTHIQUE

- Collège éthique
  - Enjeux moraux dans les processus de décisions automatiques
  - C. Gamrat, C. Castille, M. Duranton, V. Gautard, J.M. Martinez, F. Schindele, V. van Wassenhove

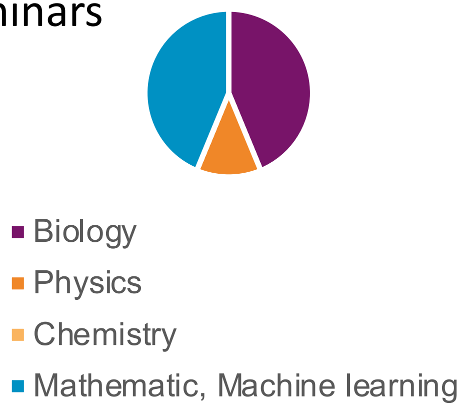
- Larsim
  - Ethique de l'IA
  - Participation a la commission CERNA (commission de réflexion sur l'Ethique de la Recherche en sciences et technologies du Numérique d'Allistene (Alliance des sciences et technologies du numérique)
  - Formation sur l'éthique de l'IA (INRIA, PSL et ENSTA)
  - Parution de livres : les robots et le mal, Alexei Grinbaum

To subscribe : mail at valerie.gautard@cea.fr

About 100 persons from

- LSCE, CNRGH, IRFU
- DES, DRT
- Paris-Sud university, etc.

- Roadmap:
  - Pedagogic presentation
  - Seminars



  - Research project
  - Training

- **Training**
  - For internship persons from LSCE and IRFU
  - Machine Learning technics for cahotics system

- **PhD thesis**
  - Artificial Intelligence for a gamma-detector for high resolution PET imaging
    (dir. V. Sharyy, IRFU)

- **Workshop**

- **Web site:**

https://indico.in2p3.fr/event/17858/page/1967-intheart

CONCLUSION

- Wide variety of applications at IRFU
- Difficulty in choosing a priori methods
- Quite targeted applications that give precise results

- Need for expertise before beginning on a project
- Interest in comparing experiences and thus having an active community (IntheArt forum)
- It would be interesting to also work on the methods themselves for example in the validation of results

- Users must be made aware of ethics from the start of a project

Thanks a lot to :

V. Calvelli - N. Cherrier – B. Dalena – G. Daniel – A. Grinbaum – F. Lanusse – M. Mur - D. Yvon

MERCI !

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