Machine learning in nuclear and particle physics

Christophe Rappold

IEM – CSIC
GSI Helmholtz Centre for Heavy Ion Research – Darmstadt, Germany

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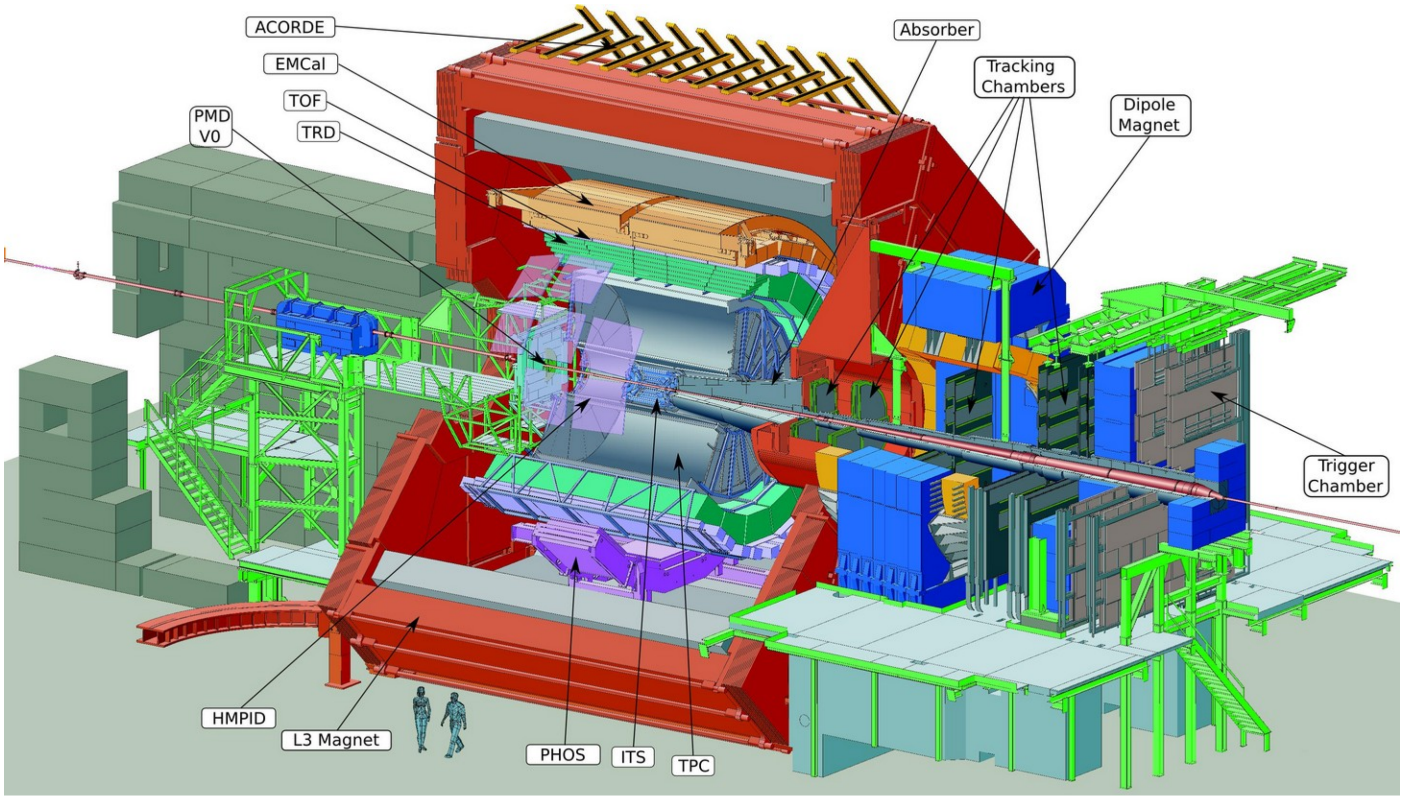
Outlook

- ML : particle identification
- GNN : particle tracking
- CNN : alpha decay in emulsion
- GAN : simulate emulsion reaction
- Mask R-CNN : hypernuclei finding in emulsion

ML for Particle Identification

Particle identification : Random Forest

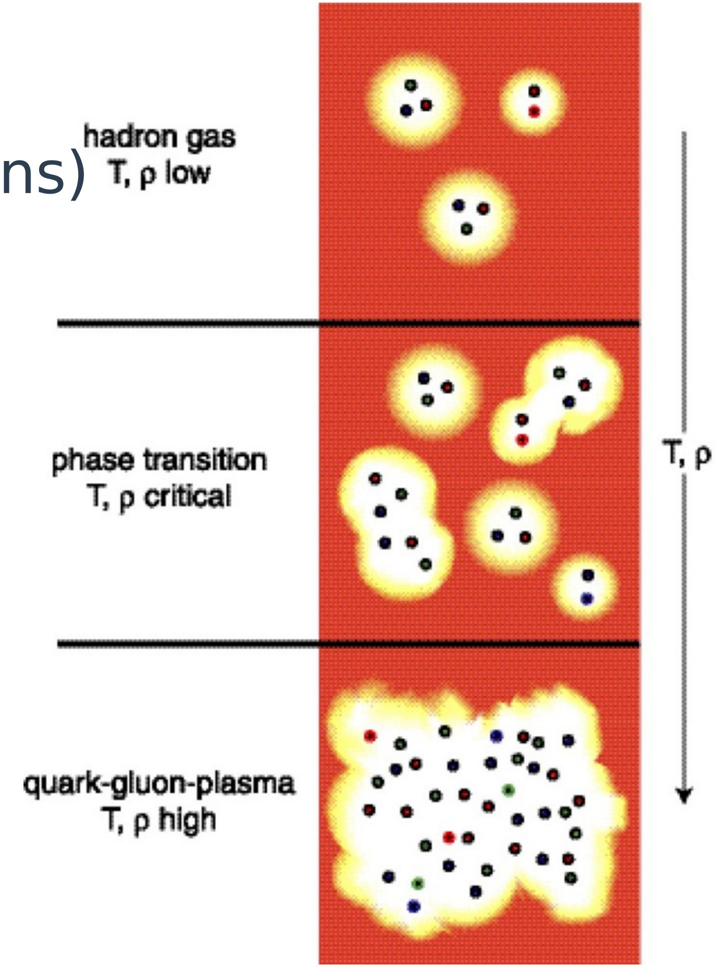
- **ALICE experiment :**
  - PID with TPC and TOF



Particle identification : Random Forest

QGP : Quark Gluon Plasma

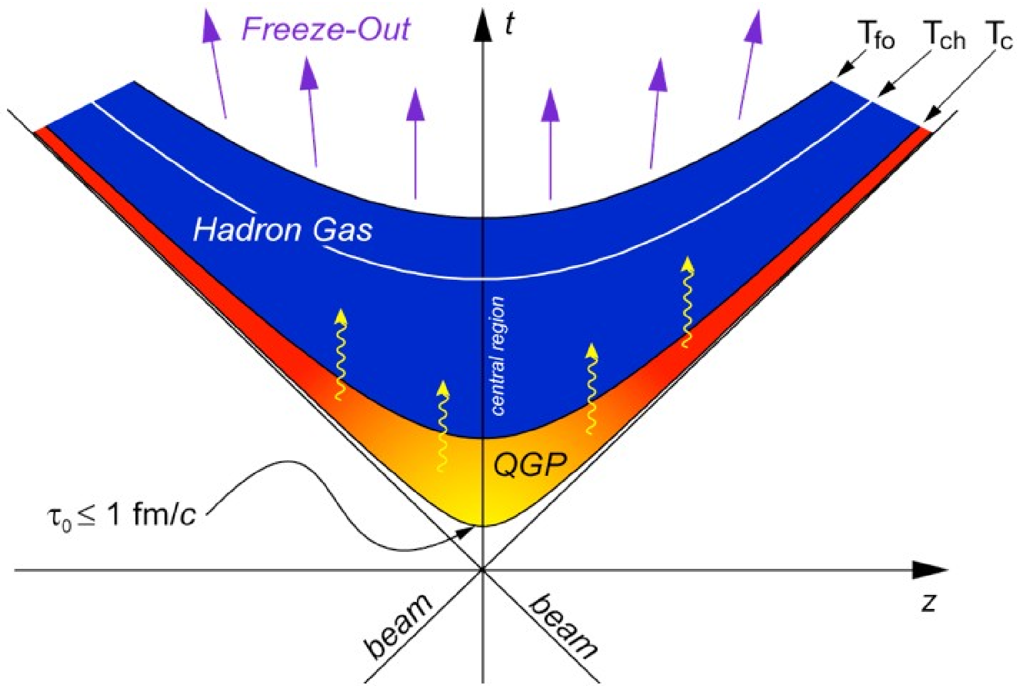
- Hadron: described QCD (quarks & gluons)
- When heated or compressed
  - → Overlap each others
- Quark and gluons move around in relatively large volume
- Phase transition between QGP and hadron gaz.



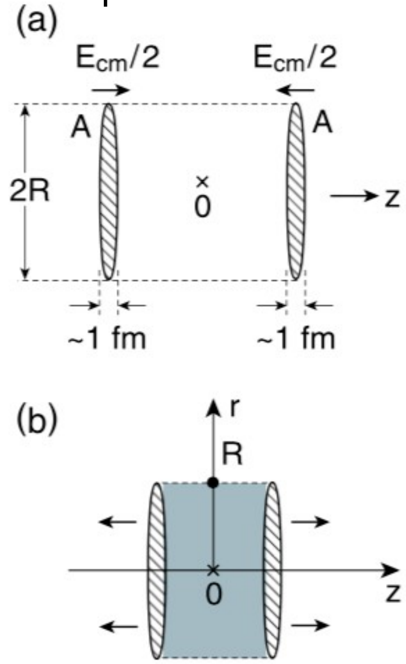
Particle identification : Random Forest

- **Features of the collisions at ALICE :**

$$^{208}Pb + ^{208}Pb \; \sqrt{s_{NN}} = 2.76 \; TeV$$
$$p + p \; \sqrt{s_{NN}} = 7 \; TeV$$
$$p + ^{208}Pb \; \sqrt{s_{NN}} = 5.02 \; TeV$$

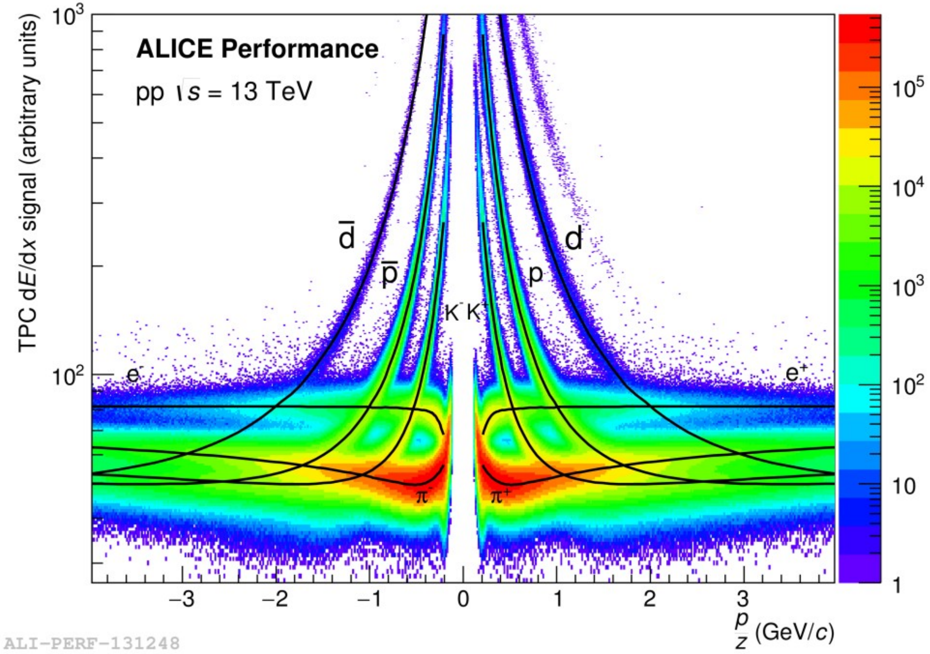


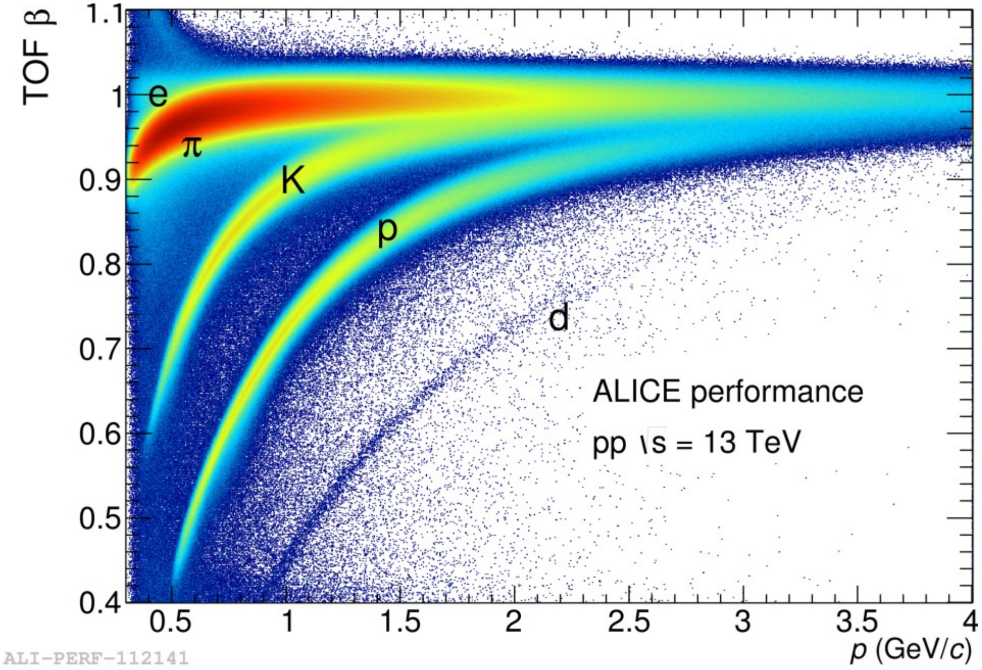
Bjorken representation



Particle identification : Random Forest

- **ALICE experiment :**
  - PID with TPC and TOF



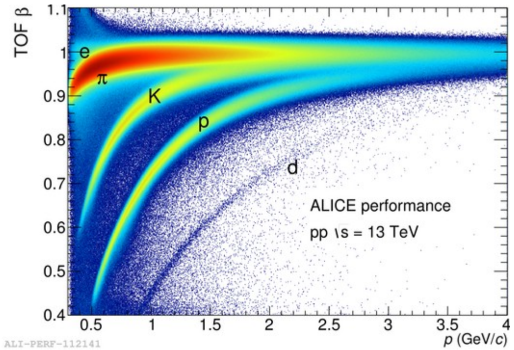


Particle identification : Random Forest

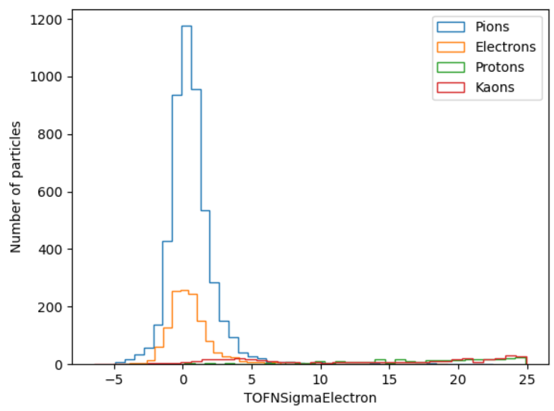
- **Models of dE/dx vs p/q & β vs p/q**

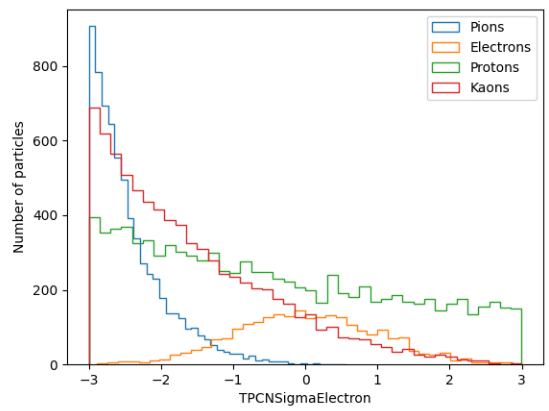
$$\langle -\frac{dE}{dx}\rangle = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2 m_e c^2 \beta^2 \gamma^2 Wmax}{I^2}\right)-\beta^2-\frac{\delta(\beta\gamma)}{2}\right]$$

$$\beta=\frac{1}{\sqrt{m^2/p^2+1}}$$



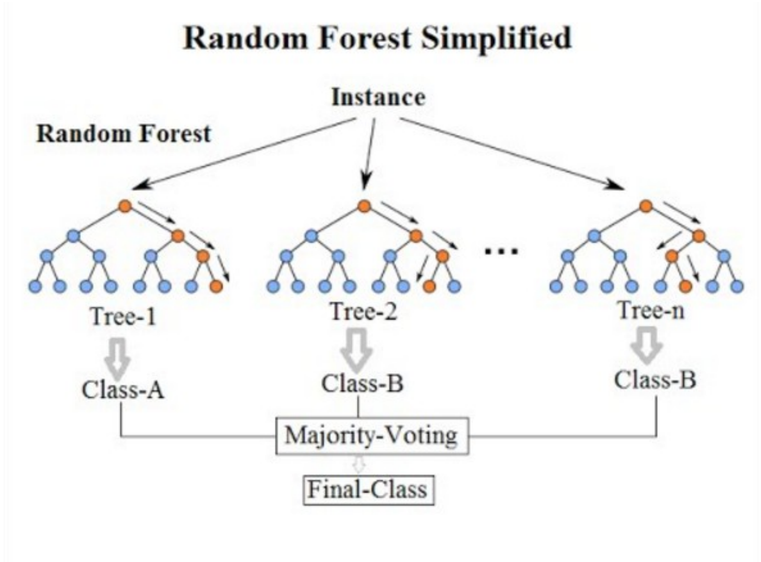
- **Considered features:**
  - $TOF\ N\ \sigma=\frac{TOF^{measured}-\langle TOF^{particle}\rangle}{\sigma_{TOF}}$ $\quad dE/dx\ N\ \sigma=\frac{dE/dx^{measured}-\langle dE/dx^{particle}\rangle}{\sigma_{dE/dx}}$
  - Multiplicities in detectors
  - DCA to primary vertex





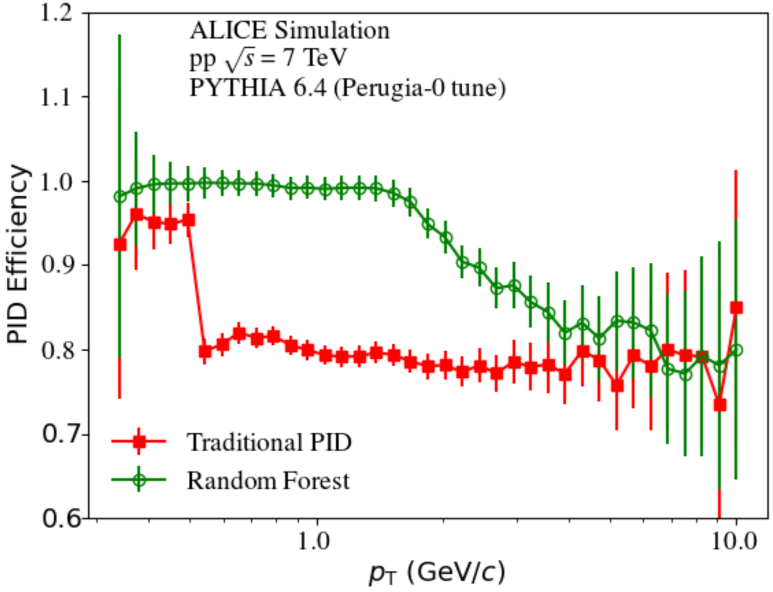
Particle identification : Random Forest

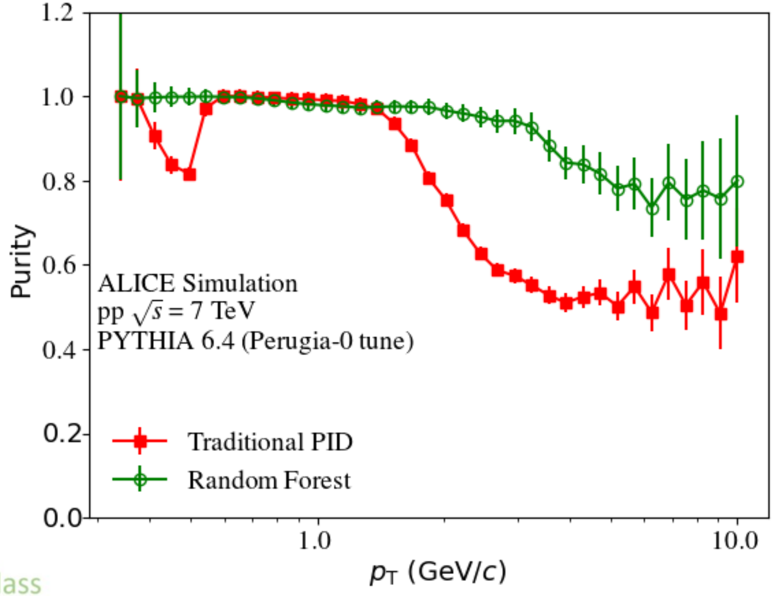
- **Random Forest :**
  - Create Decision Trees :
    - Each decision tree → optimized on a random subset of features & *only* access to a random set of the training data
    - increases diversity in the forest → more robust prediction
  - Final classification → vote



- **Results:**

Kaon class





Efficiency = TP / P

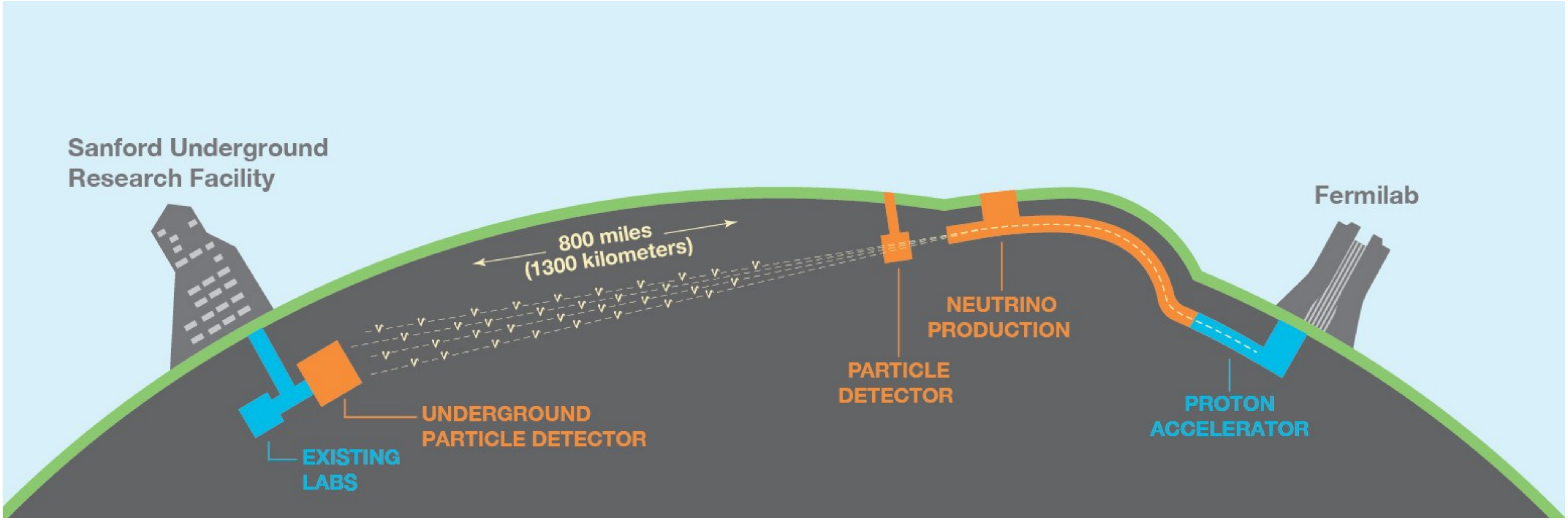
Purity = TP / (TP+FP)

DL in Particle Tracking

Particle tracking : Graph Neural Network

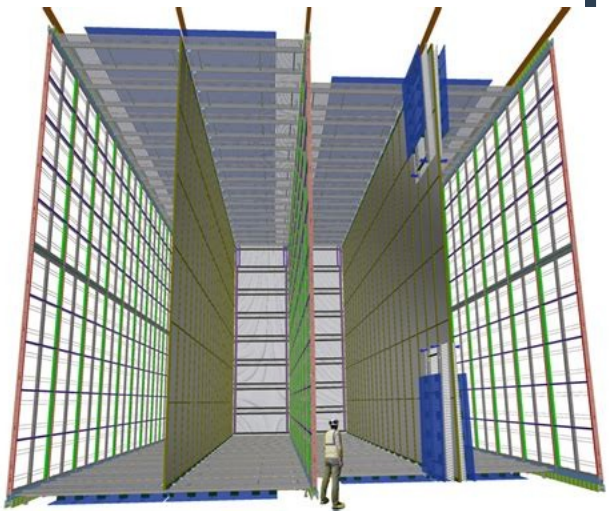
In accelerator-based neutrino oscillation experiments at Fermilab:

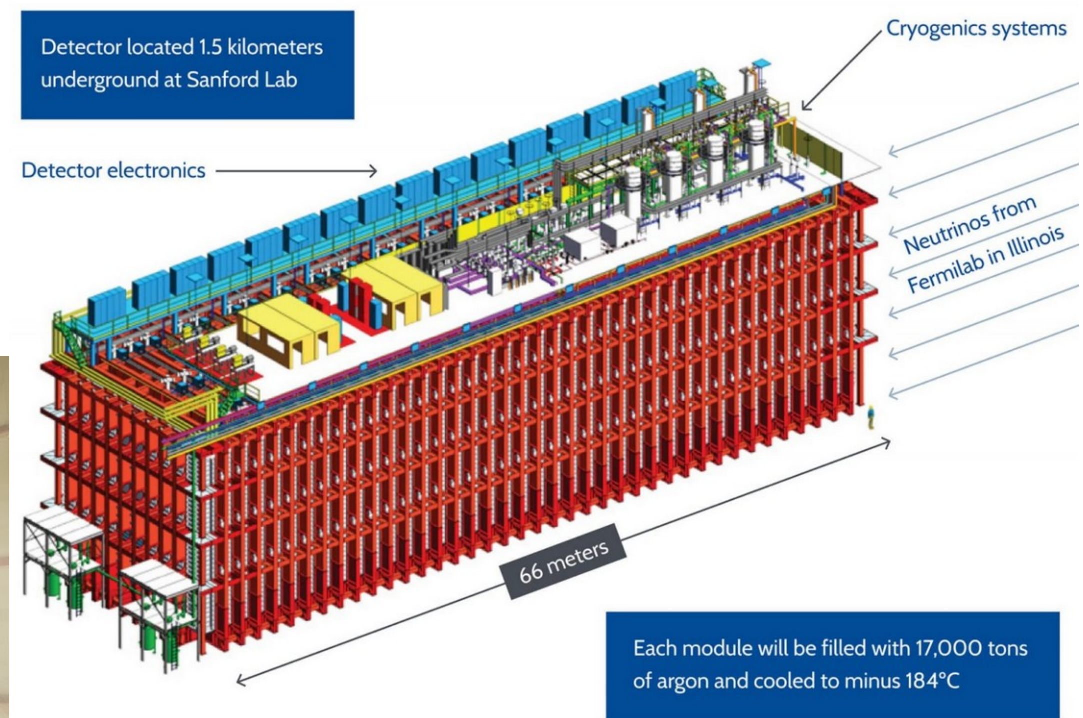
Proton beam (120 GeV) → π^+ beam (10GeV) : $\pi^+ \rightarrow \mu^+ + \nu_\mu$



Particle tracking : Graph Neural Network

- **The DUNE experiment: Liquid Argon TPC**

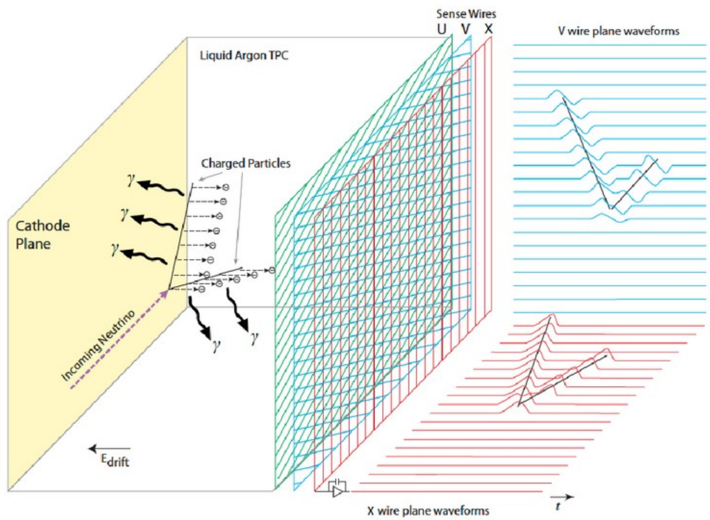


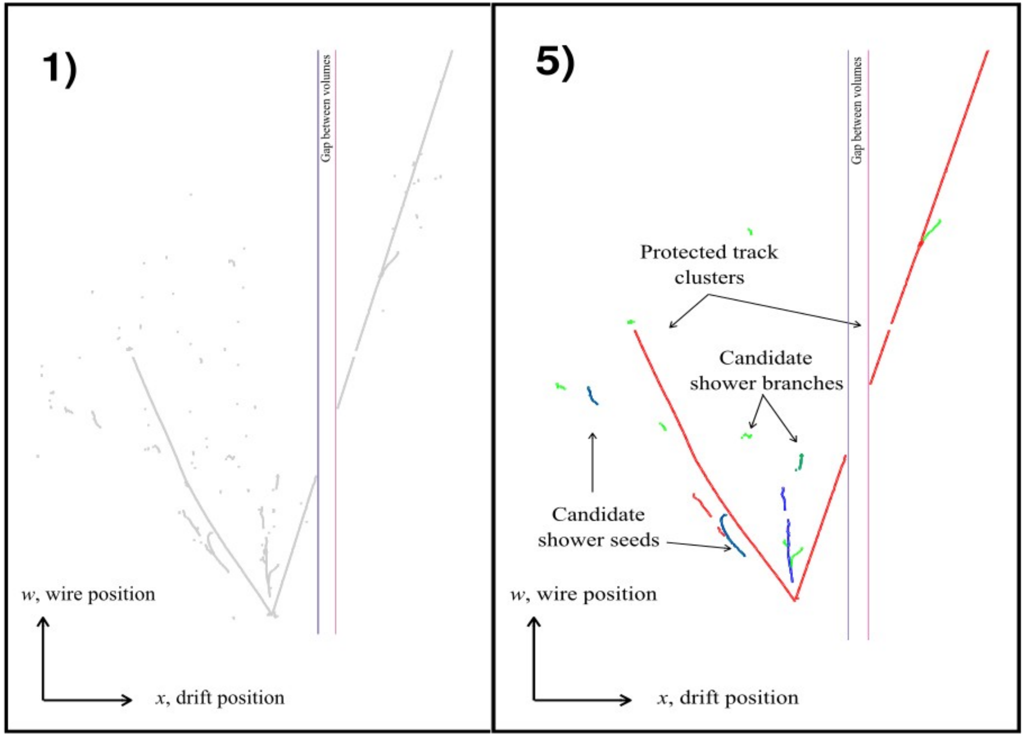


Particle tracking : Graph Neural Network

- **Type interaction :**
  - Neutrino oscillation $\nu_\mu / \bar{\nu}_\mu \rightarrow \nu_e / \bar{\nu}_e$ Interact in LArTPC
  - Electromagnetic shower :

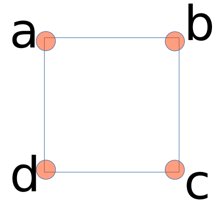
    $\gamma \rightarrow e^- e^+ \rightarrow \gamma\gamma \rightarrow \ldots$
  - Tracks (p,π,μ)



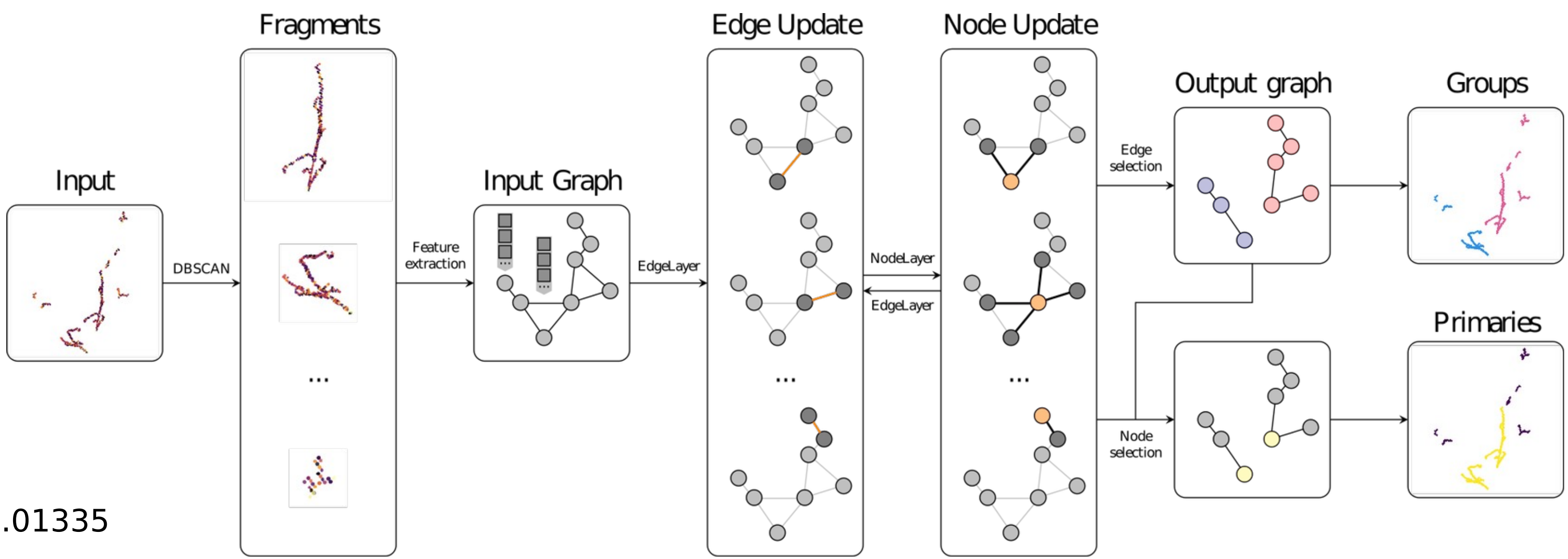


Particle tracking : Graph Neural Network

- **Graph neural network:**
  - CNN + network embedding.
    - CNN → receptive field in local spatial features
    - Networks & graph → generalize to arbitrary object
  - CNN : conv filter → locality / Graph : adjacency matrix → object relationships



$$\begin{array}{c|cccc} & a & b & c & d \\ \hline a & 0 & 1 & 0 & 0 \\ b & 0 & 0 & 1 & 0 \\ c & 0 & 0 & 0 & 1 \\ d & 1 & 0 & 0 & 0 \end{array}$$

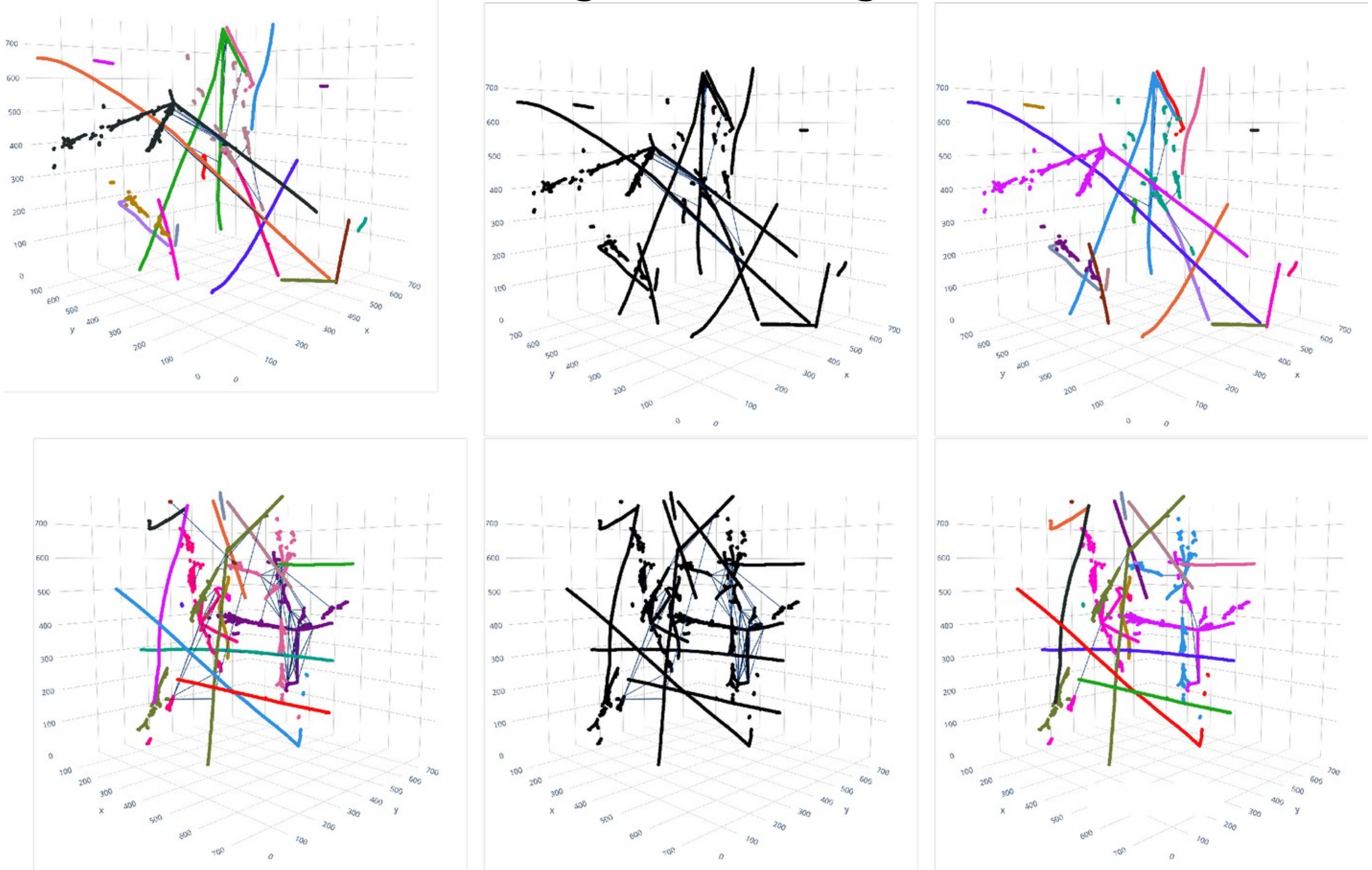


arXiv:2007.01335

Particle tracking : GNN

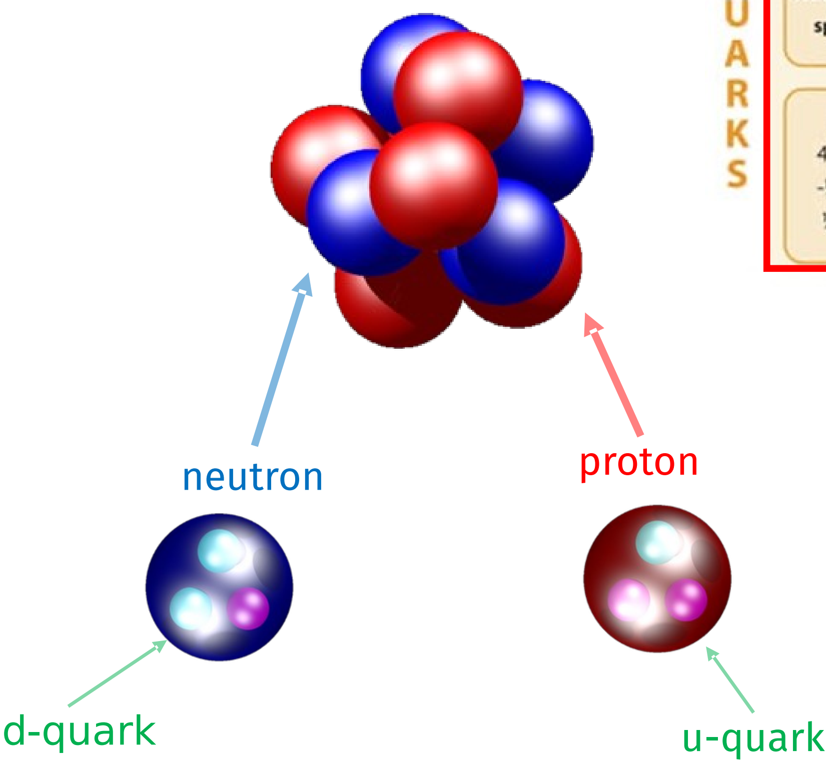
- **Achieved efficiency and purity : > 99% !**

True event | Edge clustering | Classification & edge selection



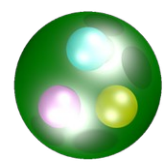
Particle tracking : GNN

- **Hypernuclear study:**



Hyperon	Quarks	$I(J^P)$	Mass (MeV)
Λ	uds	$0(1/2^+)$	1115
Σ^+	uus	$1(1/2^+)$	1189
Σ^0	uds	$1(1/2^+)$	1193
Σ^-	dds	$1(1/2^+)$	1197
Ξ^0	uss	$1/2(1/2^+)$	1315
Ξ^-	dss	$1/2(1/2^+)$	1321
Ω^-	sss	$0(3/2^+)$	1672

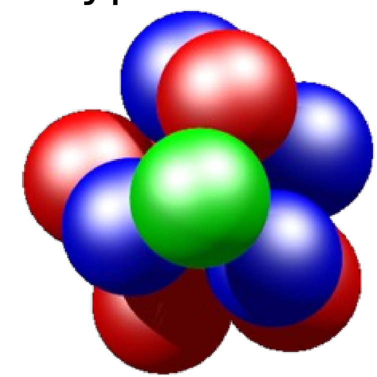
hyperon (Λ)



Lifetime~ 10^{-10} ps

s-quark : distinguishable from u- and d-quark

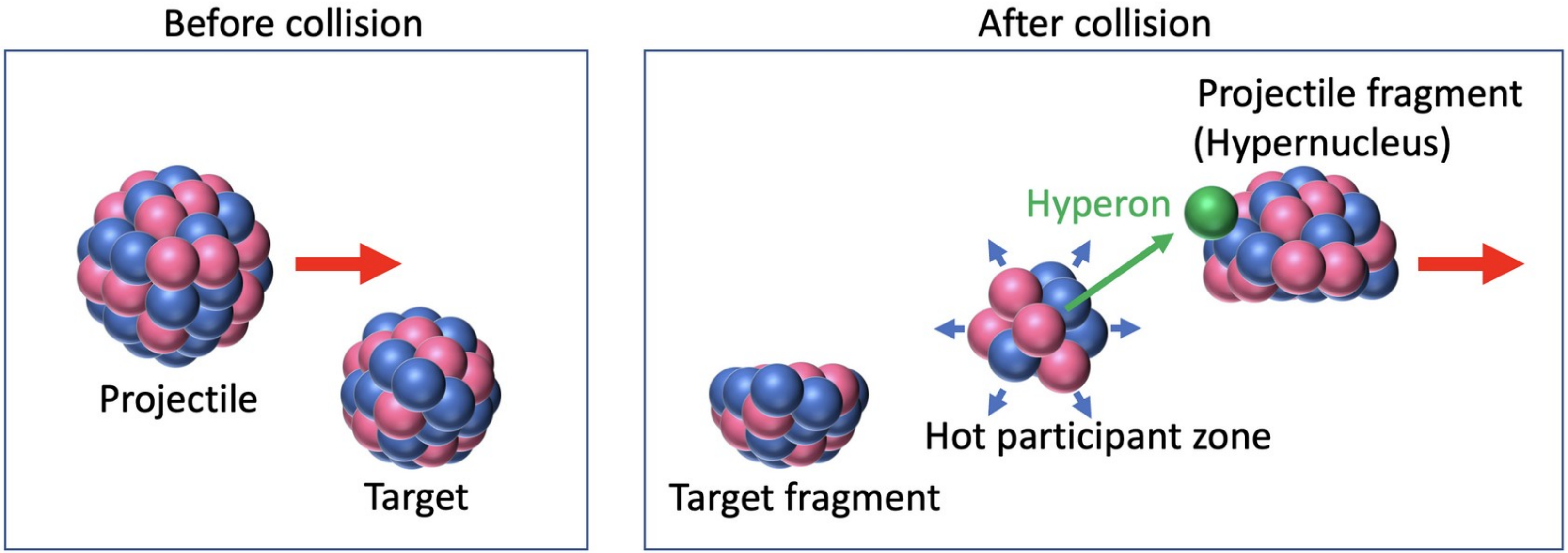
Hypernucleus



Micro-lab for study Baryon interactions

Particle tracking : GNN

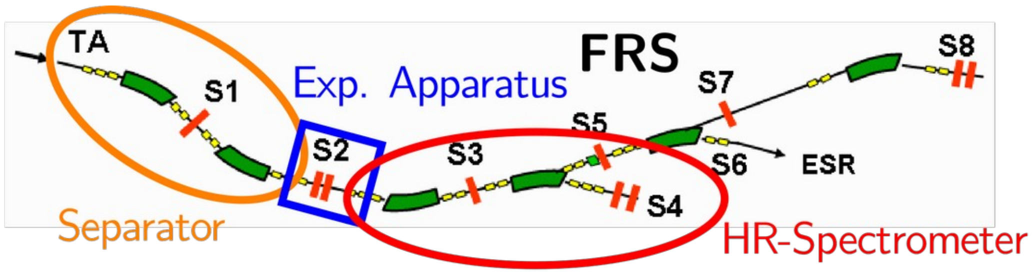
- **Hypernuclear production in heavy ion collisions:**
  - NN → ΛKN E_{th} ~ 1.6 GeV : Beam > E_{th} : available at GSI (2 *A*GeV)

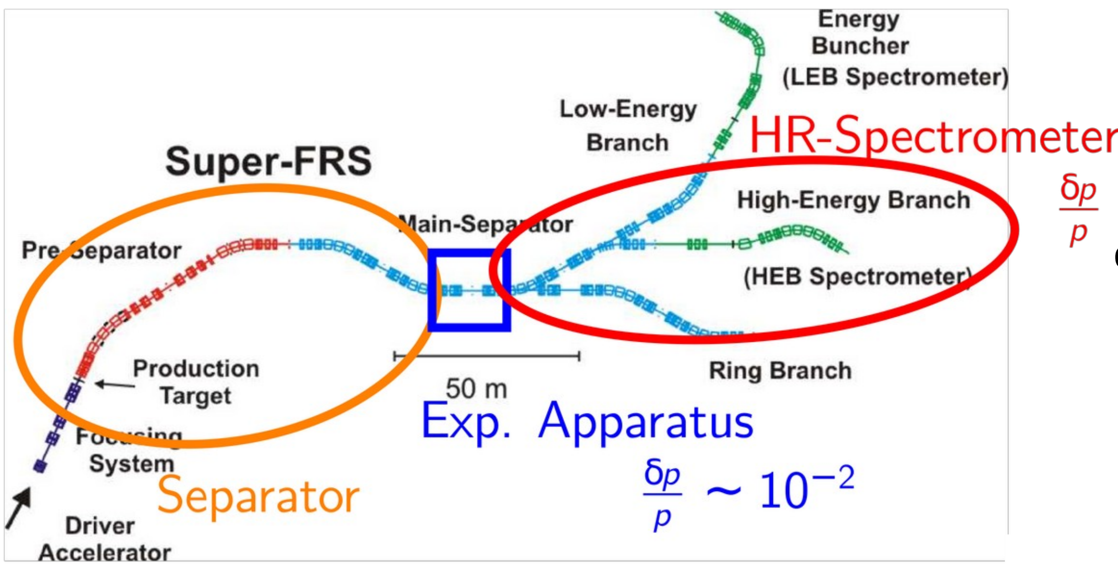


  - Coalescence of Λ in spectator fragment
    - same velocity than projectile: Lorentz Boosted
    - study Hypernuclei in flight

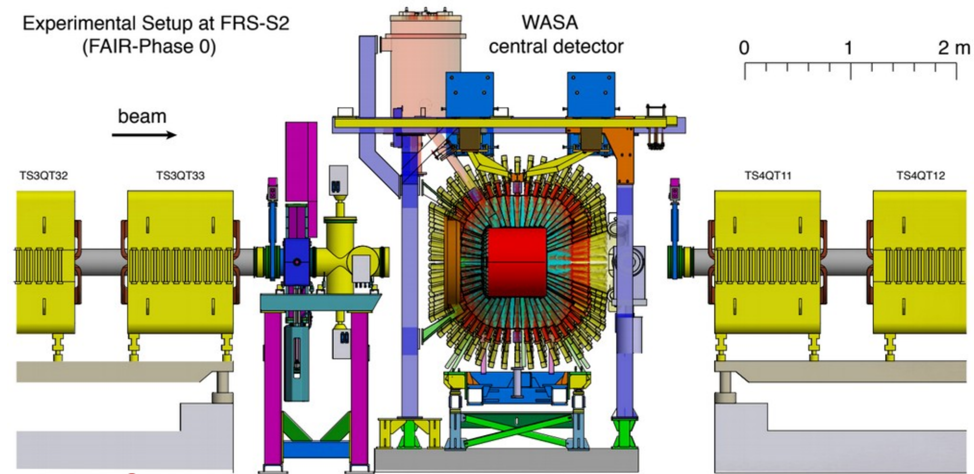
Particle tracking : GNN

- **Hypernuclear study our WASA-FRS experiment:**





$\frac{\delta p}{p} \sim 10^{-3}$



$$^{6}Li(@2GeV/u) + {}^{12}C \rightarrow {}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H, nn\Lambda + K^{+}$$
$$Fragments + Hadrons$$

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$
$$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$
$$nn\Lambda \rightarrow n + d + \pi^{-}$$

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Particle tracking : GNN

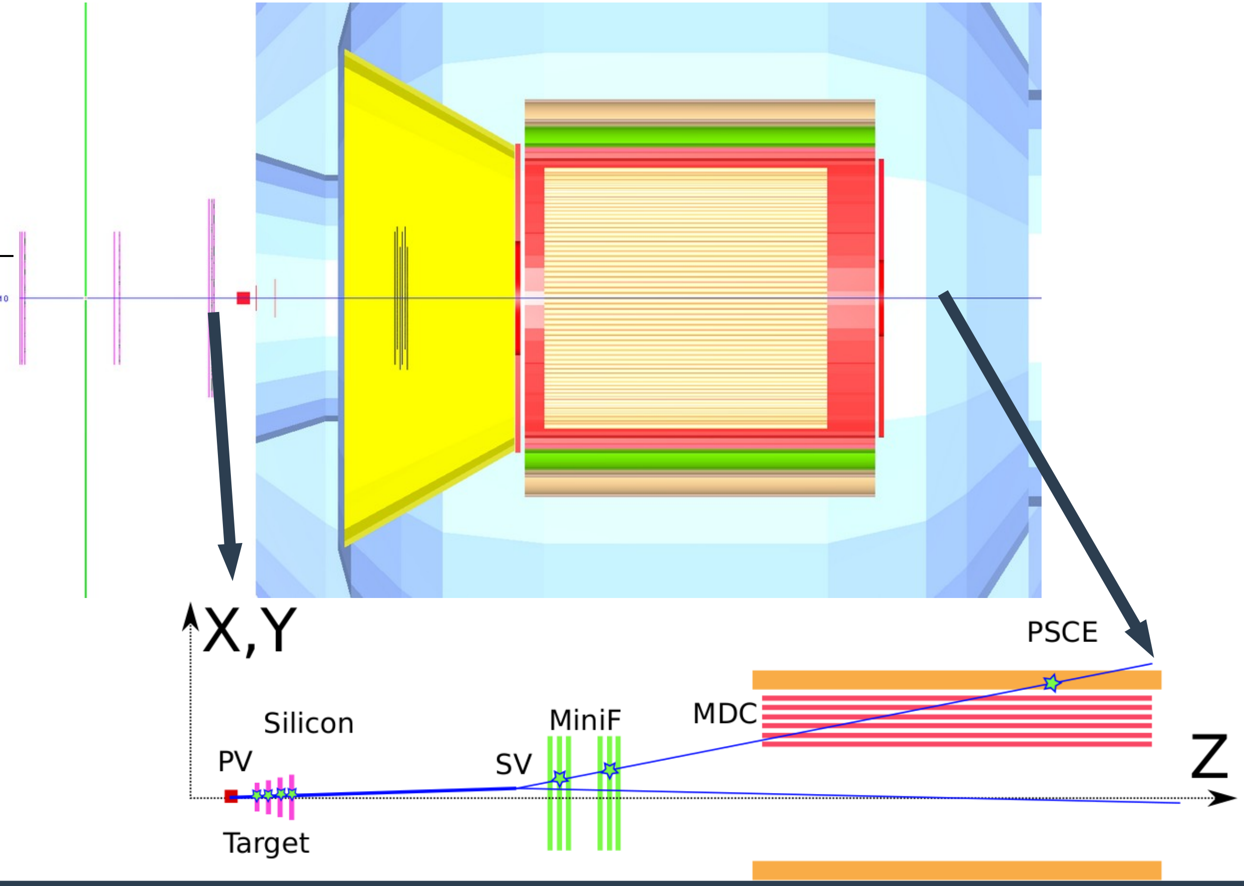
- **Hypernuclear study in our WASA-FRS experiment:**

$$ {}^{6}Li(@2\,GeV/u) + {}^{12}C \rightarrow {}^{3}_{\Lambda}H, {}^{4}_{\Lambda}H, nn\Lambda + K^{+} + Fragments + Hadrons $$

$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} $$

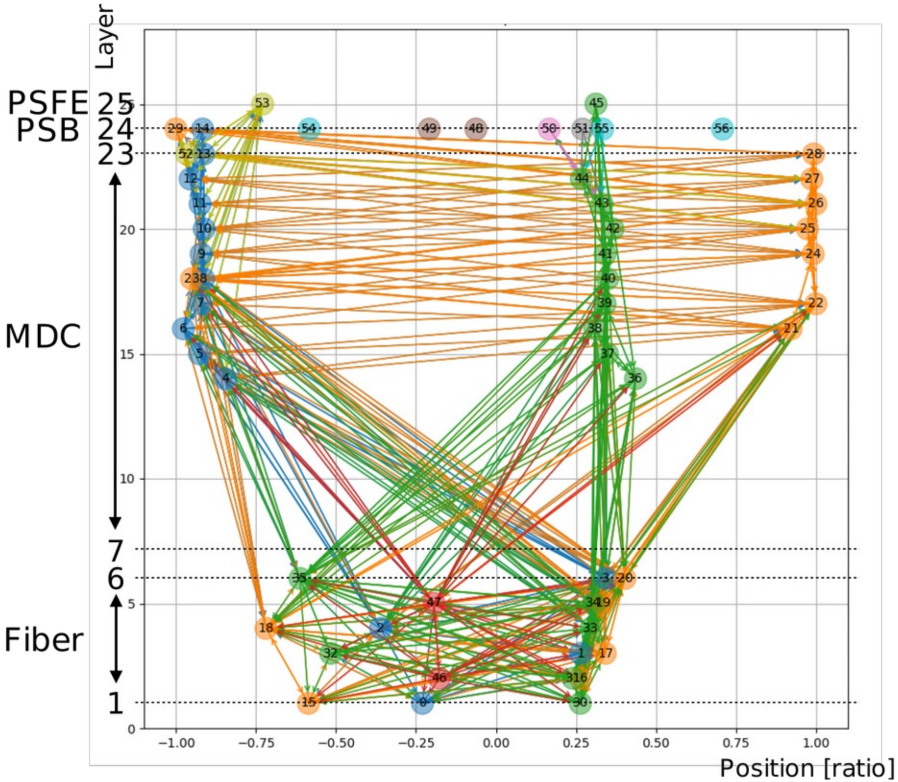
$$ {}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-} $$

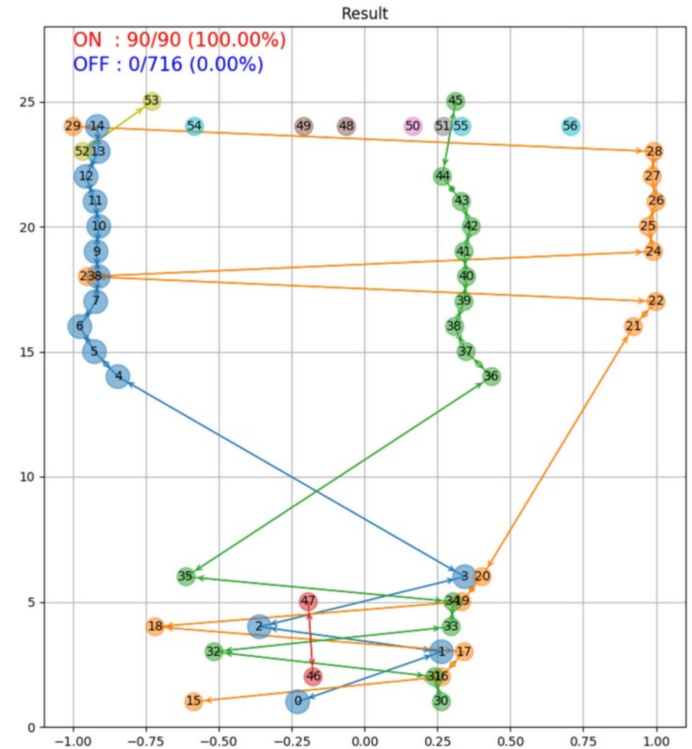
$$ nn\Lambda \rightarrow n + d + \pi^{-} $$



Particle tracking : GNN

- **Study of Hypernuclei in our WASA-FRS experiment:**



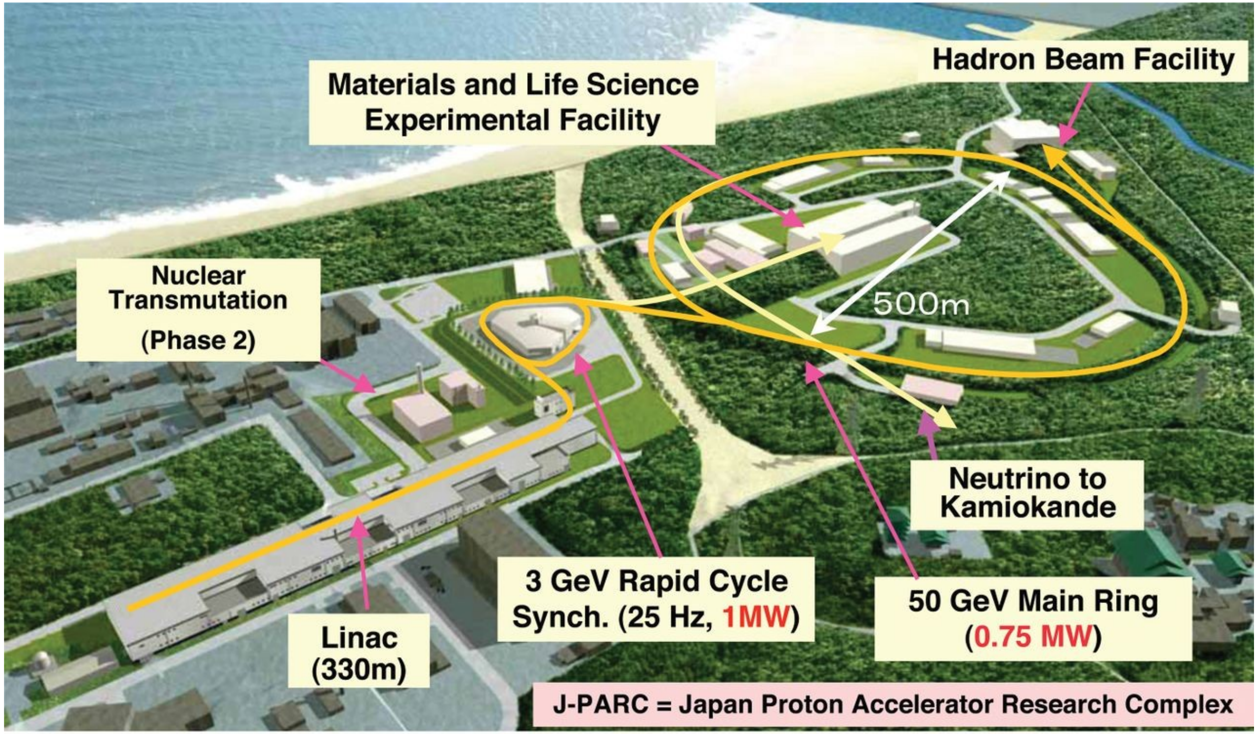


π– (perfect)	π– (valid)	Other (perfect)	Other (valid)
98.09 %	99.92 %	97.05 %	99.07 %

DL in emulsion analysis

Finding hypernuclei in emulsion : MaskCNN

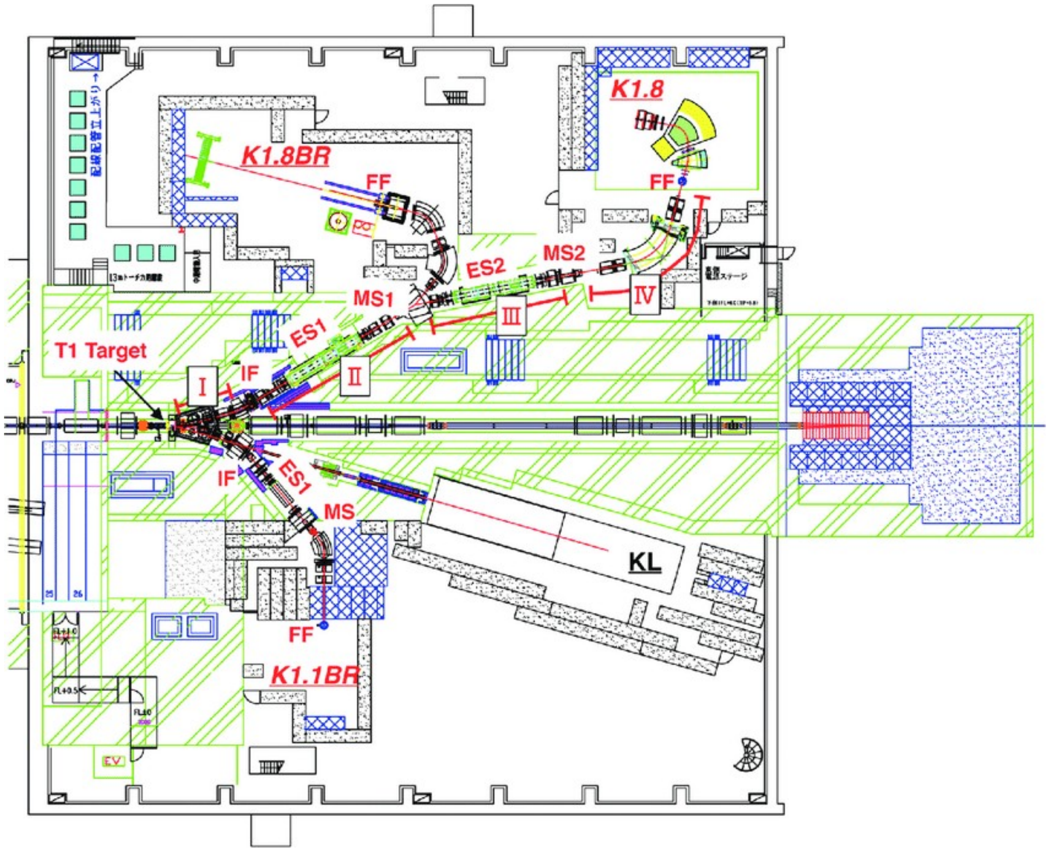
- **J-PARC E07 experiment :**
  - J-PARC : Japan Proton Accelerator Research Complex

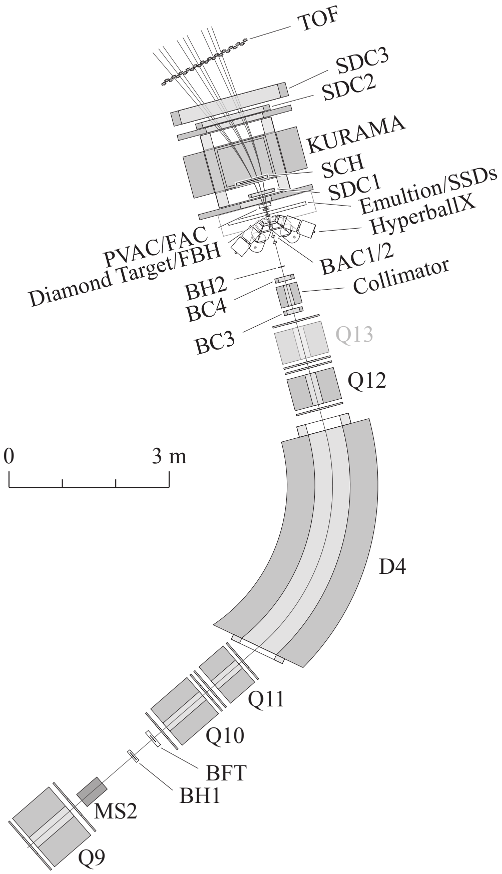


Joint Project between KEK and JAEA

Finding hypernuclei in emulsion : MaskCNN

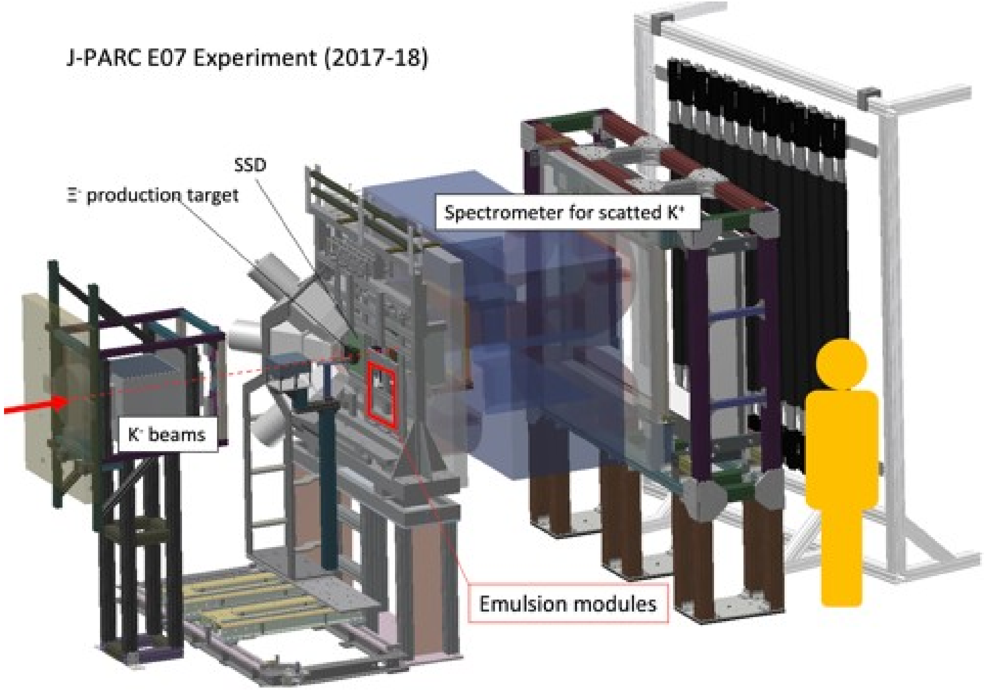
- **J-PARC E07 experiment : at K1.8 beam line**



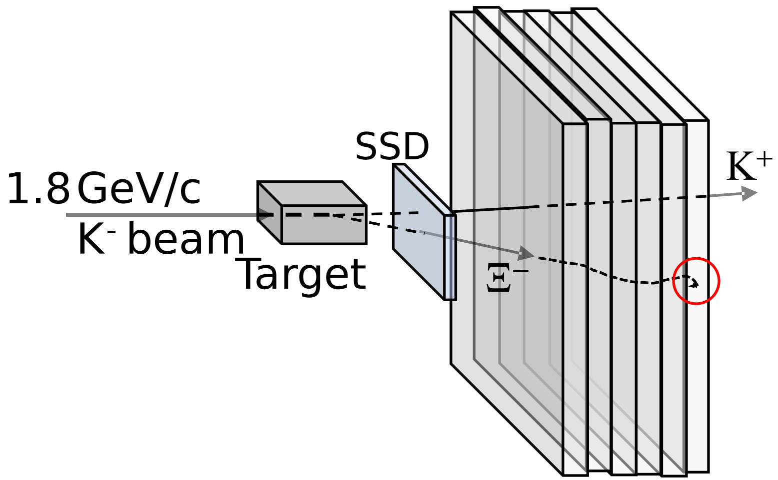


Finding hypernuclei in emulsion : MaskCNN

- **J-PARC E07 experiment**
  - Study of double-strangeness hypernuclei
  - **Hybrid methods** : Triggered detectors + nuclear emulsions

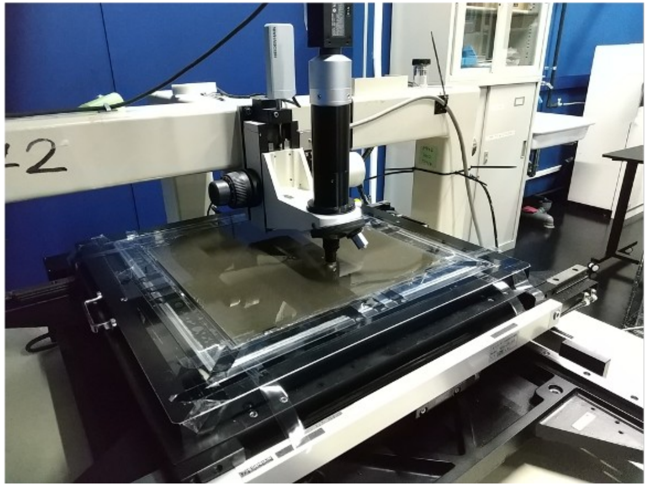


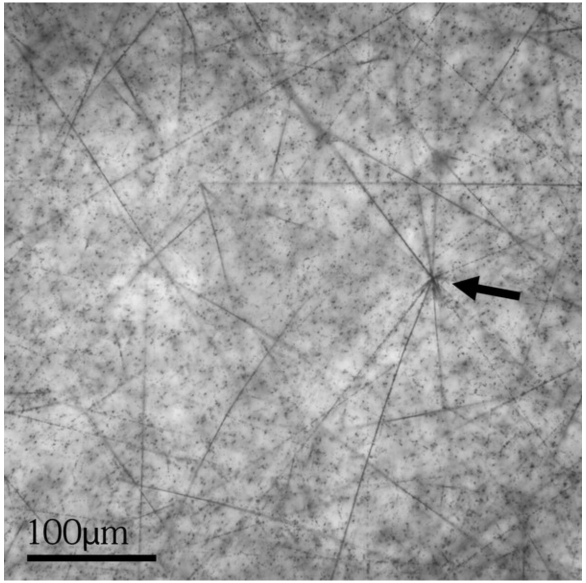
Triggers by the observation of (K-, K+) reactions



Finding hypernuclei in emulsion : MaskCNN

- **Scanning methods :**



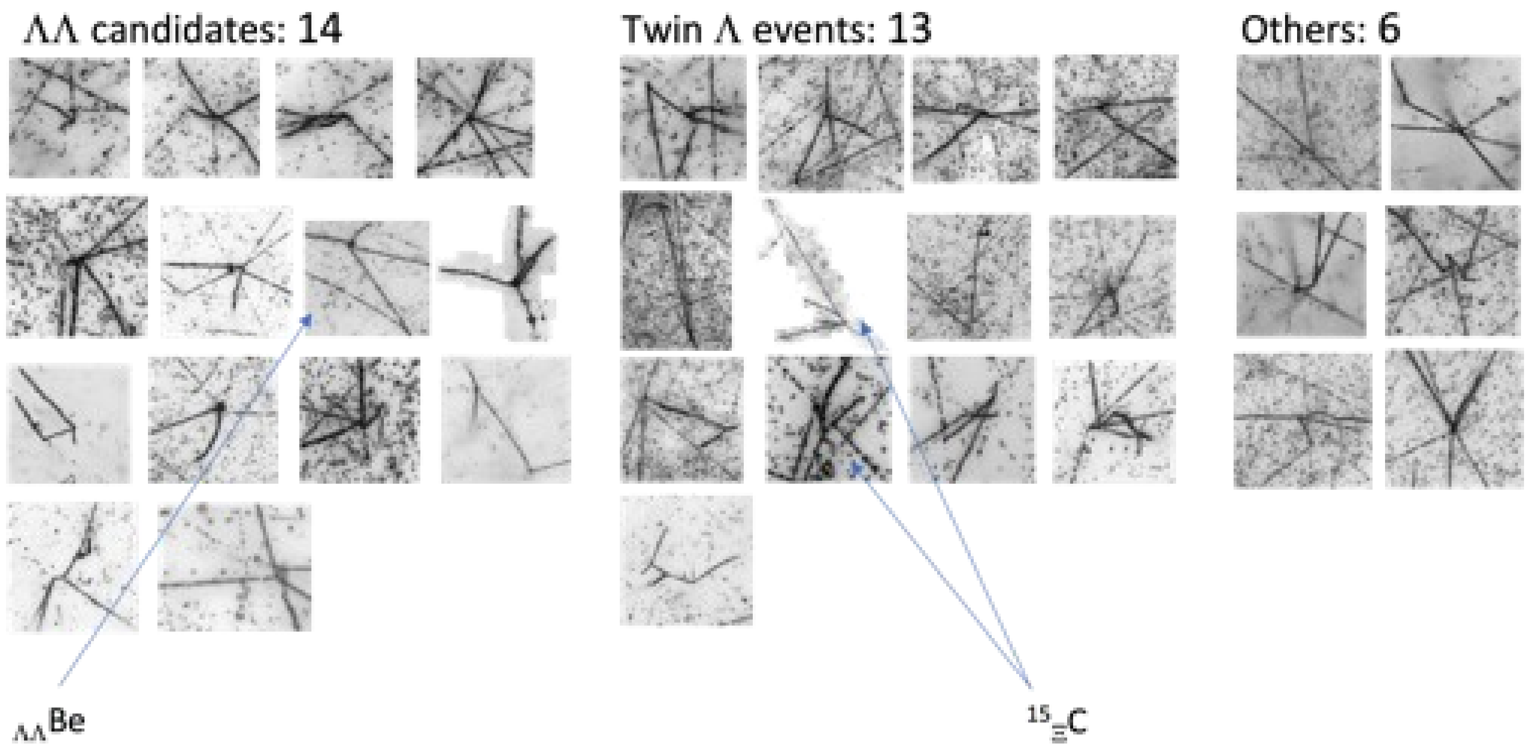


Finding hypernuclei in emulsion : MaskCNN

- **Current outcome of E07:**
  - Triggered events : Ξ^- identified and tracked by detectors + outgoing K+ → estimation of the position of stopped Ξ^- in emulsion
  - Visual inspections by an optical microscope → around the estimated stop position
  - Small portion of emulsion plates analyzed → to much human workload !

Finding hypernuclei in emulsion : MaskCNN

- **Current outcome of E07:**



H. Ekawa et al., Prog. Theor. Exp. Phys. 2019, 021D02

Finding hypernuclei in emulsion : MaskCNN

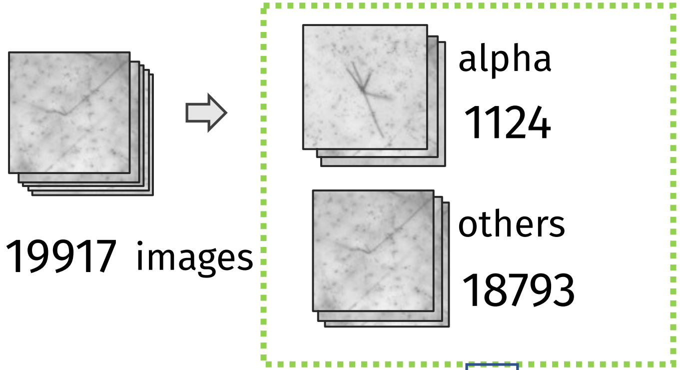
- **Still in those 1300 emulsion plates :**
  - K- beam interacted directly with the nuclei of the emulsions
    → produce hypernuclei (single & double)
  - It was proposed to search for hypertriton ($^{3}_{\Lambda}H$)
  - But : no additional information → need to scan everything !
    → 1.4 billion images / emulsion : 110 TB x 1300 → 140 PB
    → 560 years to analyze this
  - Background :
    - Beam tracks & Nuclear fragmentation : 10000 & 1000 / mm^2
- **Use of machine learning to find those events !**

  → To be done in 3 years

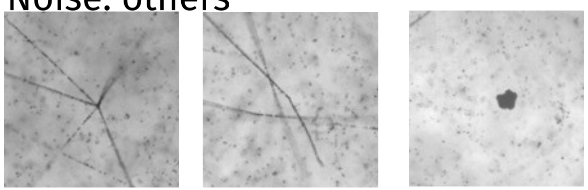
Finding hypernuclei in emulsion : MaskCNN

- **alpha decay events (calibration) : CNN**

Training data (real images)



Noise: others

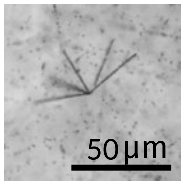


Other interaction

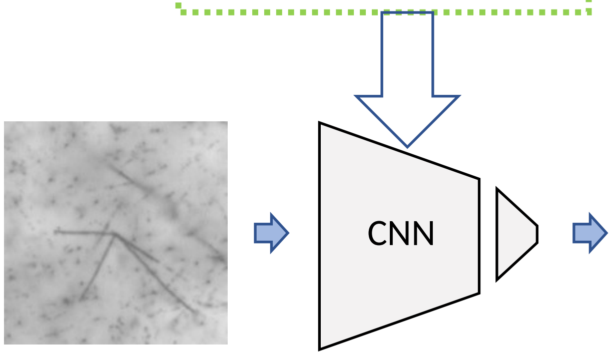
Cross

Dust

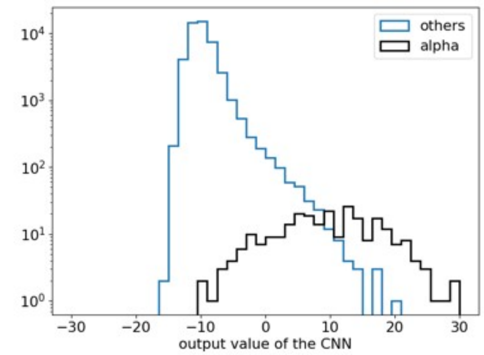
Target



α decay



300x300 pixels



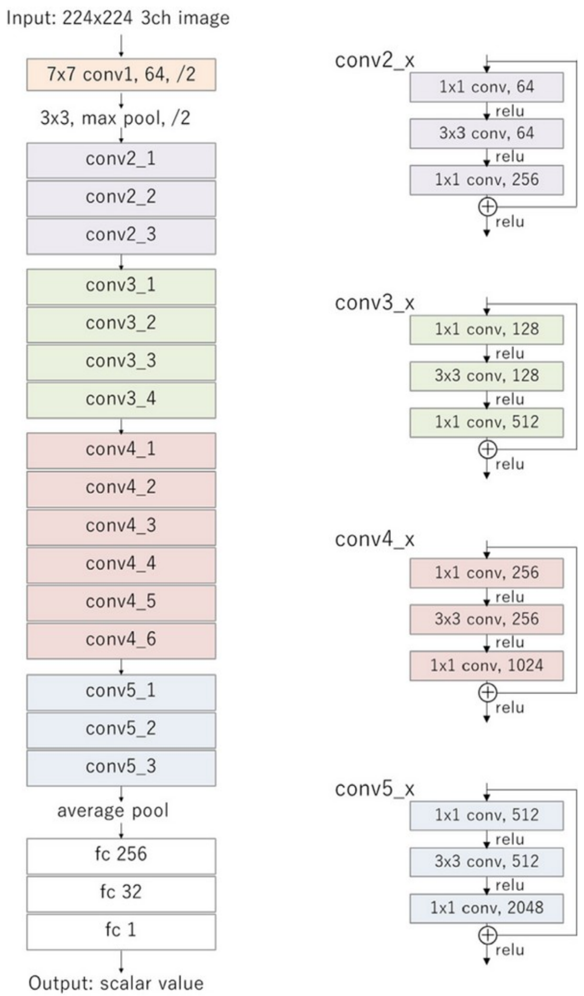
Purity improved by 7 times

J. Yoshida, et al., NIM A, 989 (2021) 164930

Finding hypernuclei in emulsion : MaskCNN

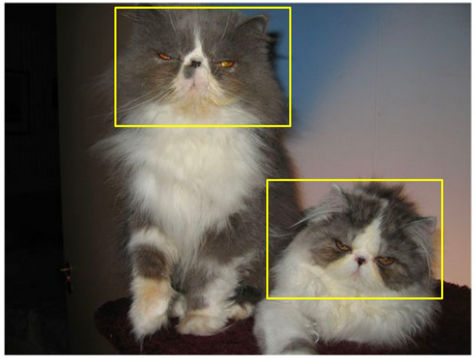
- **Alpha decay events:**
  - Spontaneous decay chain of long-lived radioisotopes such as uranium and thorium in the emulsion
  - calibration for density / space homogeneous
- **Convolutional Neural Network**
  - ResNet-50

- **Let have a small digression for some explanations**



Finding hypernuclei in emulsion : MaskCNN

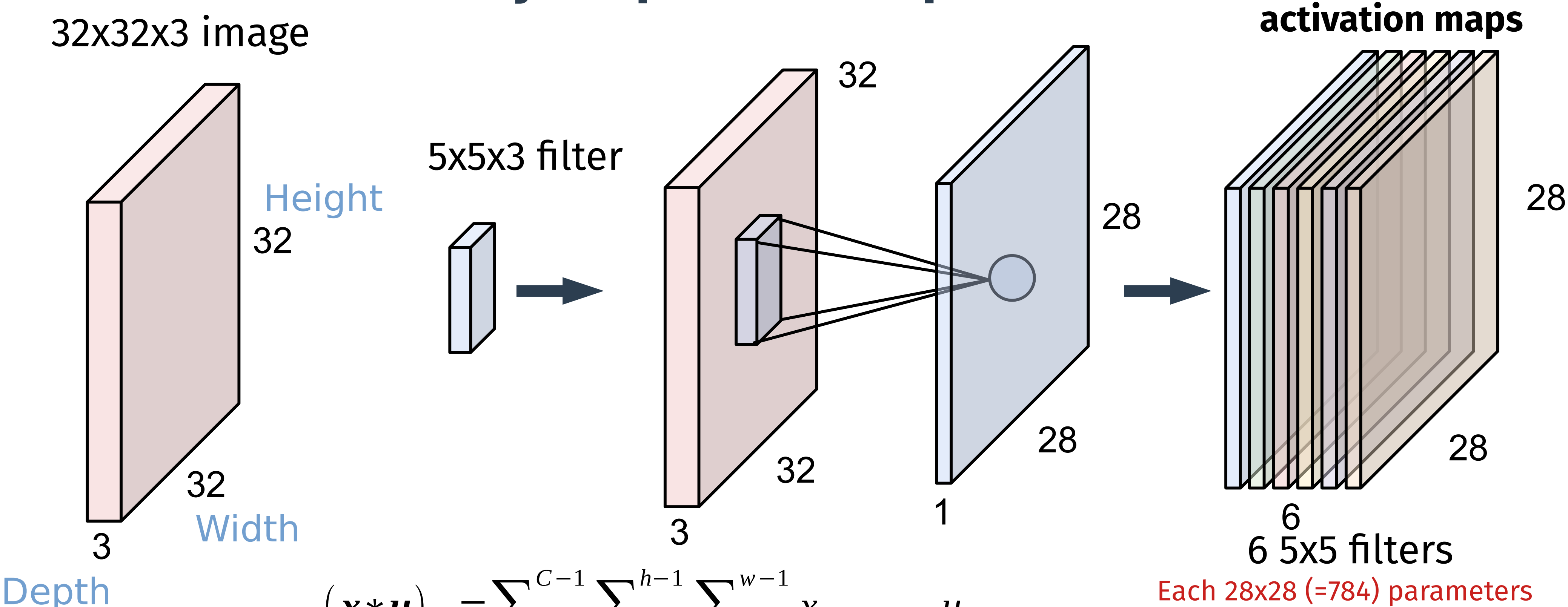
- **What is a CNN :**
  - When the structure of data includes "invariance to translation", a representation meaningful at a certain location can / should be used everywhere



  - Covolutional layers build on this idea, that the same "local" transformation is applied everywhere and preserves the signal structure
  - 1D Discrete Convolution: $x \in \mathbb{R}^M, u \in \mathbb{R}^n, \forall i \in [0 \dots M-n+1] : (x * u)_i = \sum_{j=0}^{n-1} x_{i+j} u_j$
    - u is called Convolutional kernel of width k
    - Scan across data and multiply by kernel elements

Finding hypernuclei in emulsion : MaskCNN

- **Convolution Layer: preserve spatial structure**



$$(\boldsymbol{x}*\boldsymbol{u})_{i,j}=\sum_{c=0}^{C-1}\sum_{n=0}^{h-1}\sum_{m=0}^{w-1}x_{c,n+i,m+j}u_{c,n,m}$$

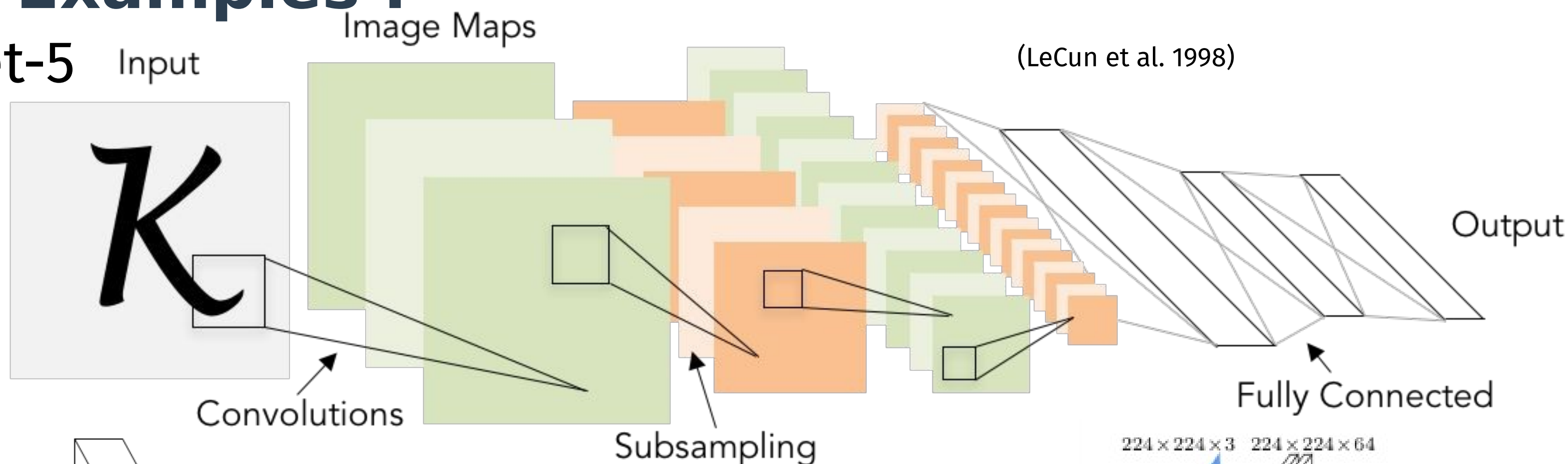
$$i\times j\in(H-h+1)\times(W-w+1)$$

Each 28x28 (=784) parameters
Fully Connected Layer :
32x32x3 x size Hidden (784) → 2.4M

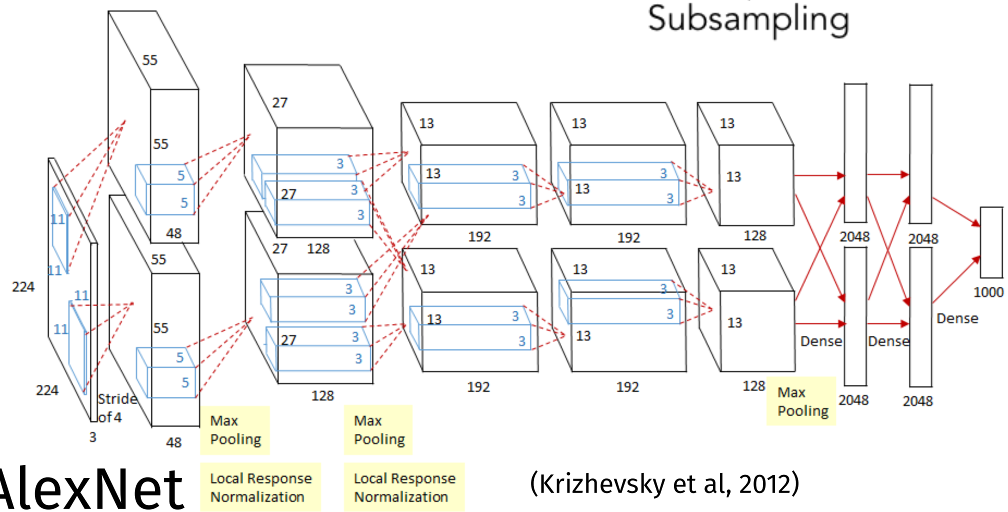
Finding hypernuclei in emulsion : MaskCNN

- **Examples :**

LeNet-5



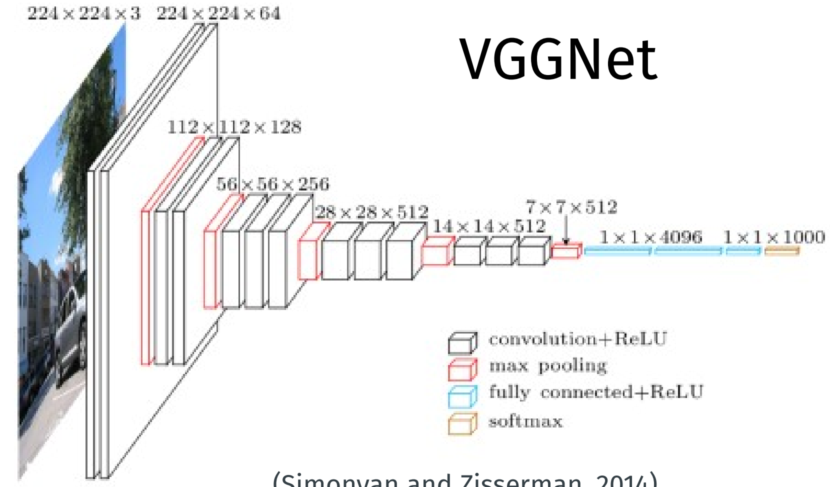
(LeCun et al. 1998)



AlexNet

(Krizhevsky et al, 2012)

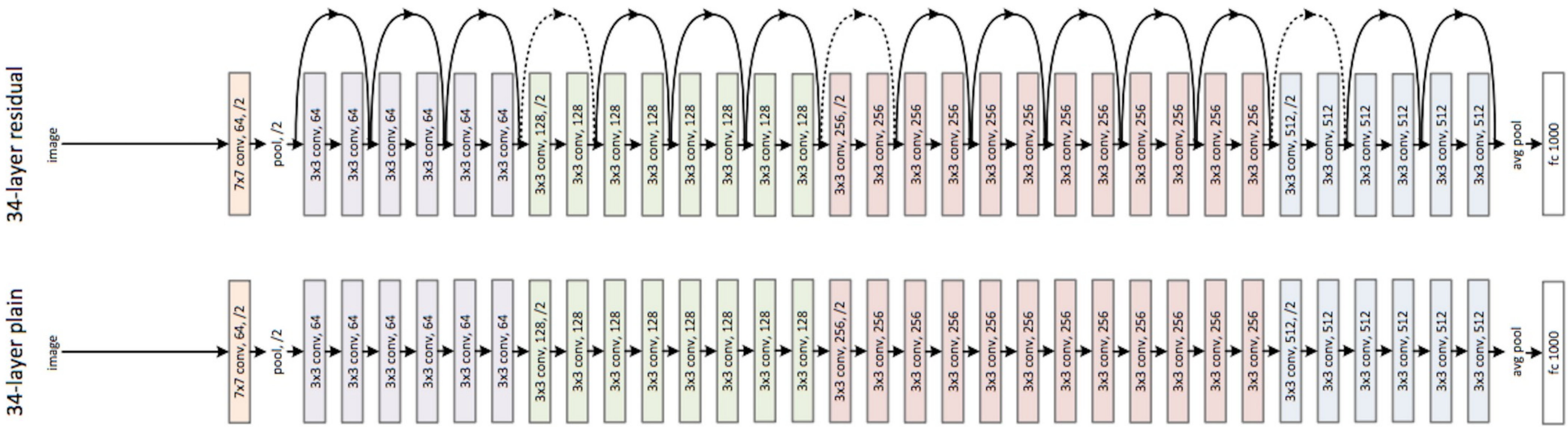
VGGNet



(Simonyan and Zisserman, 2014)

Finding hypernuclei in emulsion : MaskCNN

- **Back to ResNet:**
  - 34 layers :



  - Classics : ResNet – 18, -34, -50, 101, 152 (layers)

Params :25M

Params :60M

Finding hypernuclei in emulsion : MaskCNN

- **CNN classifier : Alpha decay detection**

	Precision	Recall	# of candidates
Conventional method	0.081 +- 0.006	0.788 +- 0.056	2489
CNN classifier	0.547 +- 0.025	0.788	366 +- 18

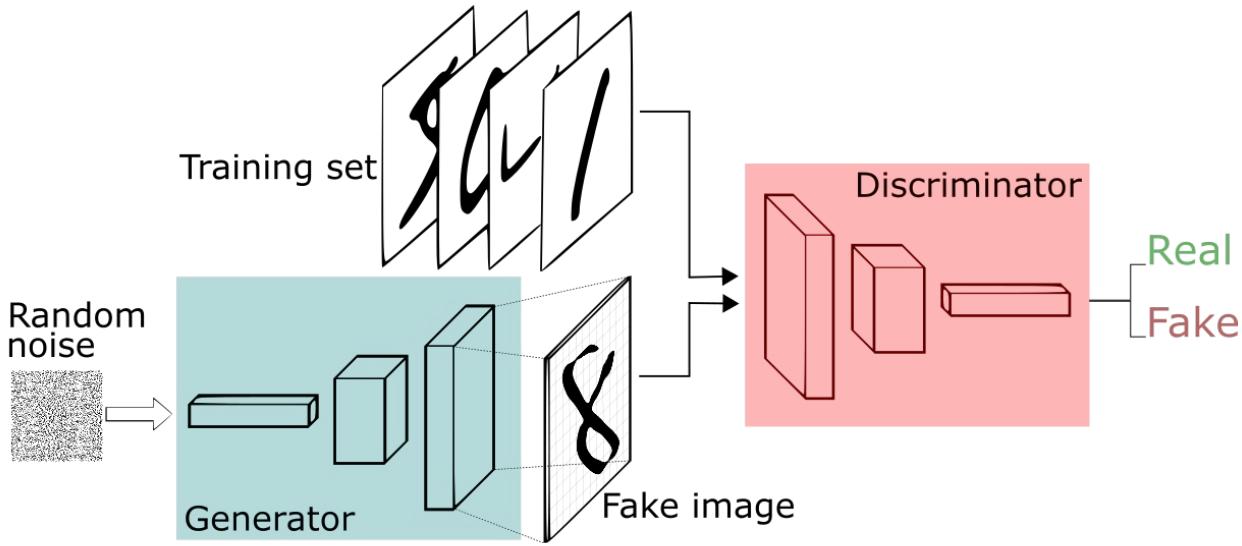
- **Precision = TP / TP + FP** **Recall = TP / TP + FN**

model's ability to detect Positive samples

- **7 times more precision !**
- **Conventional :**
  - 2489 out of 46948 events, including 201 true alpha decay
- **CNN classifier:**
  - 350 alpha-decay candidates,including 201 true alpha-decay

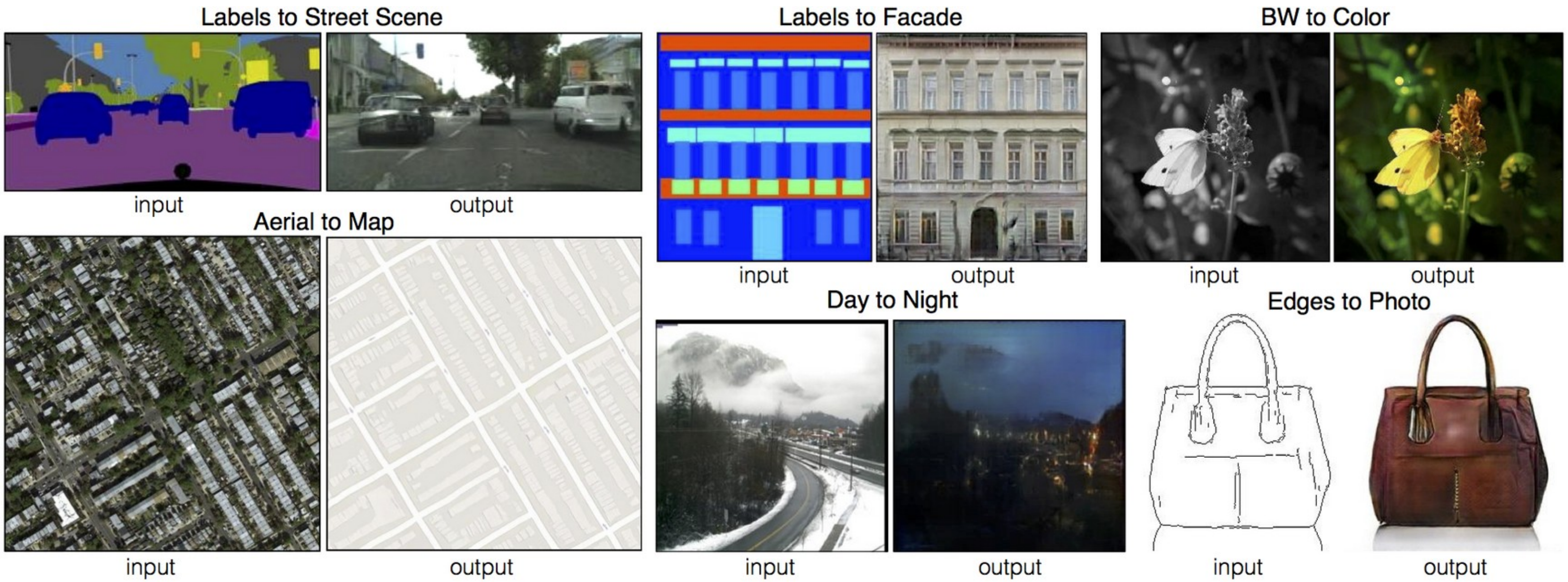
Finding hypernuclei in emulsion : MaskCNN

- **Finding hypertriton :**
  - Needs of training data ! But none has been found
    → generating event from simulations !
  - Problem : how to simulate nuclear emulsion ?!
- **GAN : Generative adversarial networks**



Finding hypernuclei in emulsion : MaskCNN

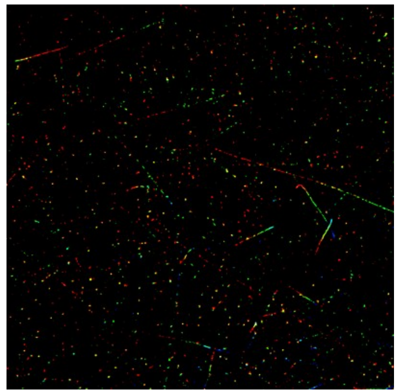
- **Simulated hypertriton : GAN + Geant4**
  - pix2pix (Image-to-Image Translation with Conditional Adversarial Nets)



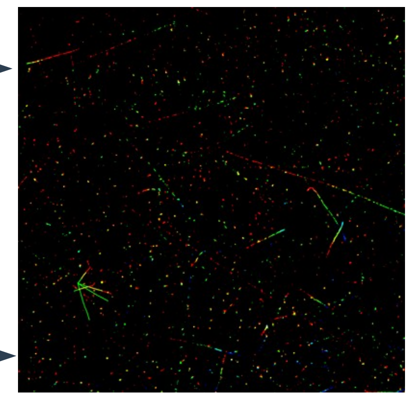
Finding hypernuclei in emulsion : MaskCNN

- **Simulated emulsion :**

Background (real)
→ from emulsion plate



Mix



Synthesized images

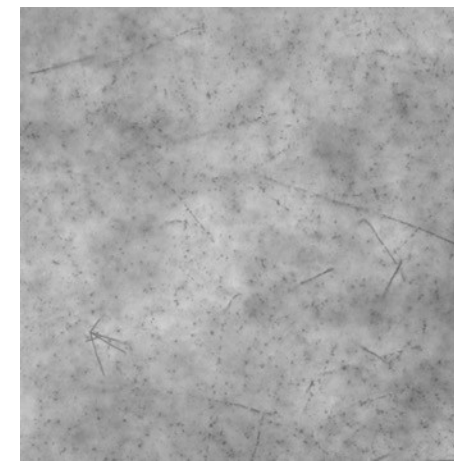


Image
Converter
pix2pix

Events (Geant4)
→ simulation of
weak decay

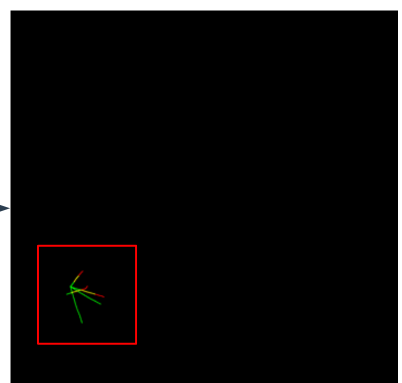
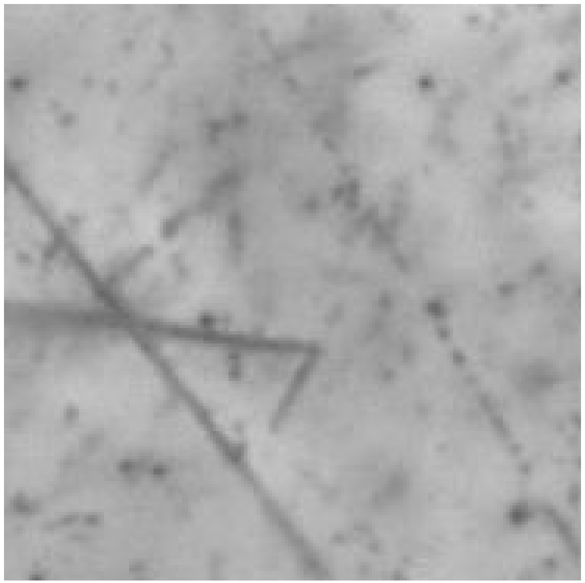


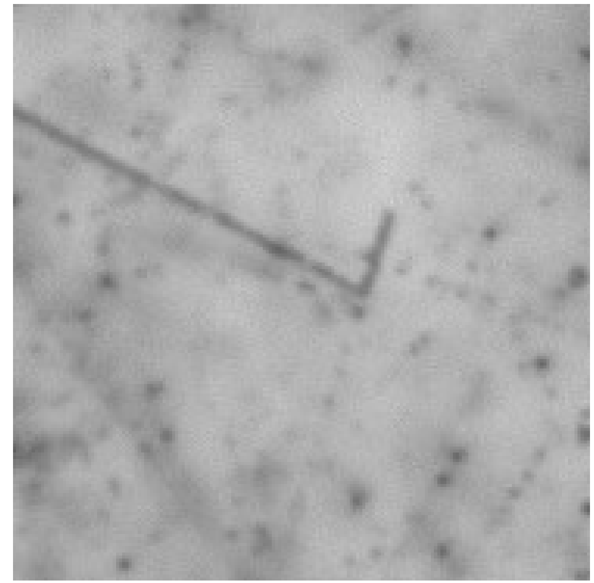
Image
Converter
pix2pix

Finding hypernuclei in emulsion : MaskCNN

- **Simulated event : hypertriton via GAN**



Simulated



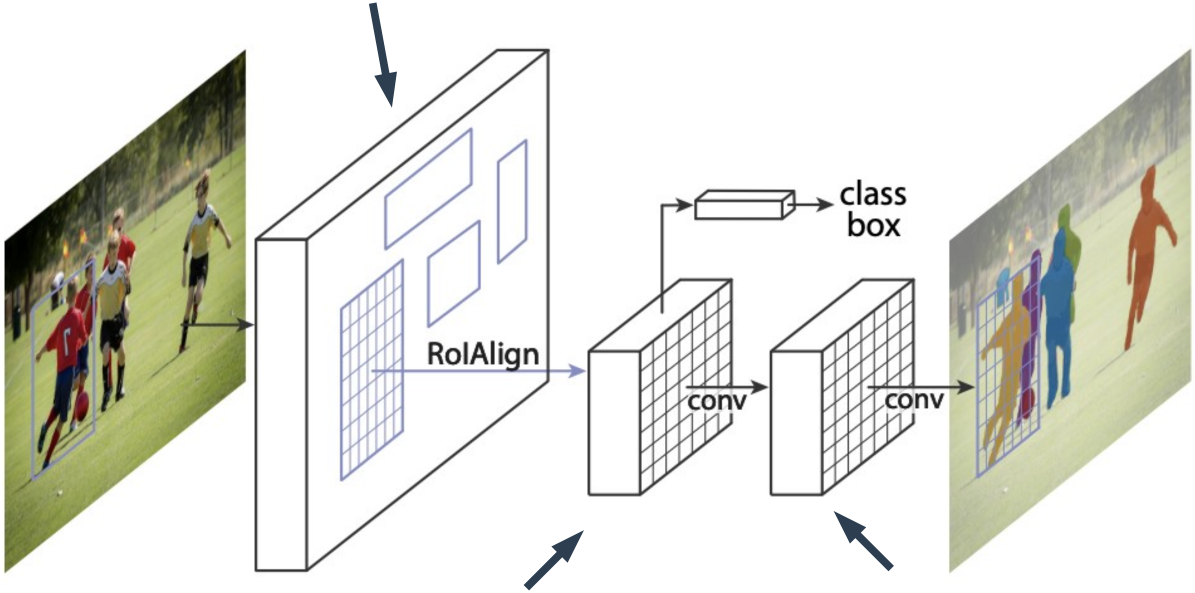
Real

- **hypertriton decay at rest :** $^{3}He + \pi^{-}$ back-to-back
- **Q-value fixed: length of pion 28 mm of $^{3}_{\Lambda}H$ vs 42 mm for $^{4}_{\Lambda}H$**

Finding hypernuclei in emulsion : MaskCNN

- **Search for hypertriton-like decay:**
  - **Mask R-CNN : Instance Segmentation**

Region Proposal Network



feature extraction Network

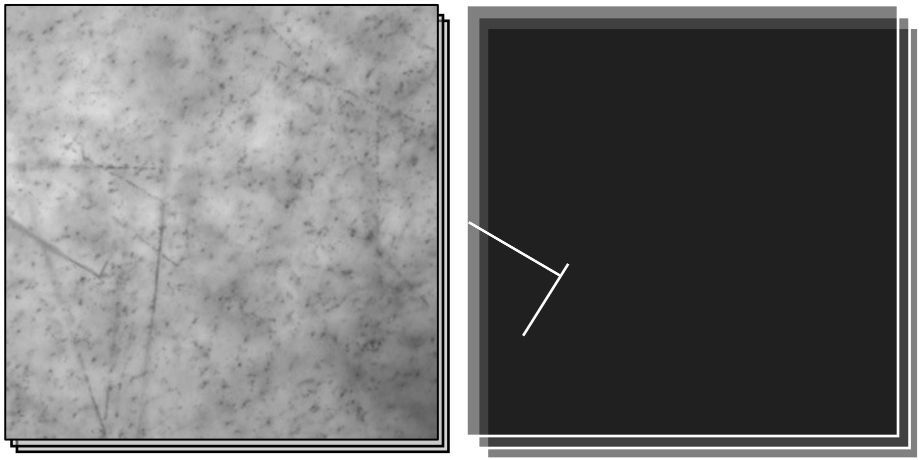
Network *head* for bounding-box recognition

Backbone architecture:
Networks inside
Ex: ResNet, ResNeXt,
Feature Pyramid Network

Finding hypernuclei in emulsion : MaskCNN

- **Search for hypertriton-like decay:**
  - Training on simulated and generated event
    - “Real” images of simulated emulsion
    - Masks of the instance segmentation of the decay

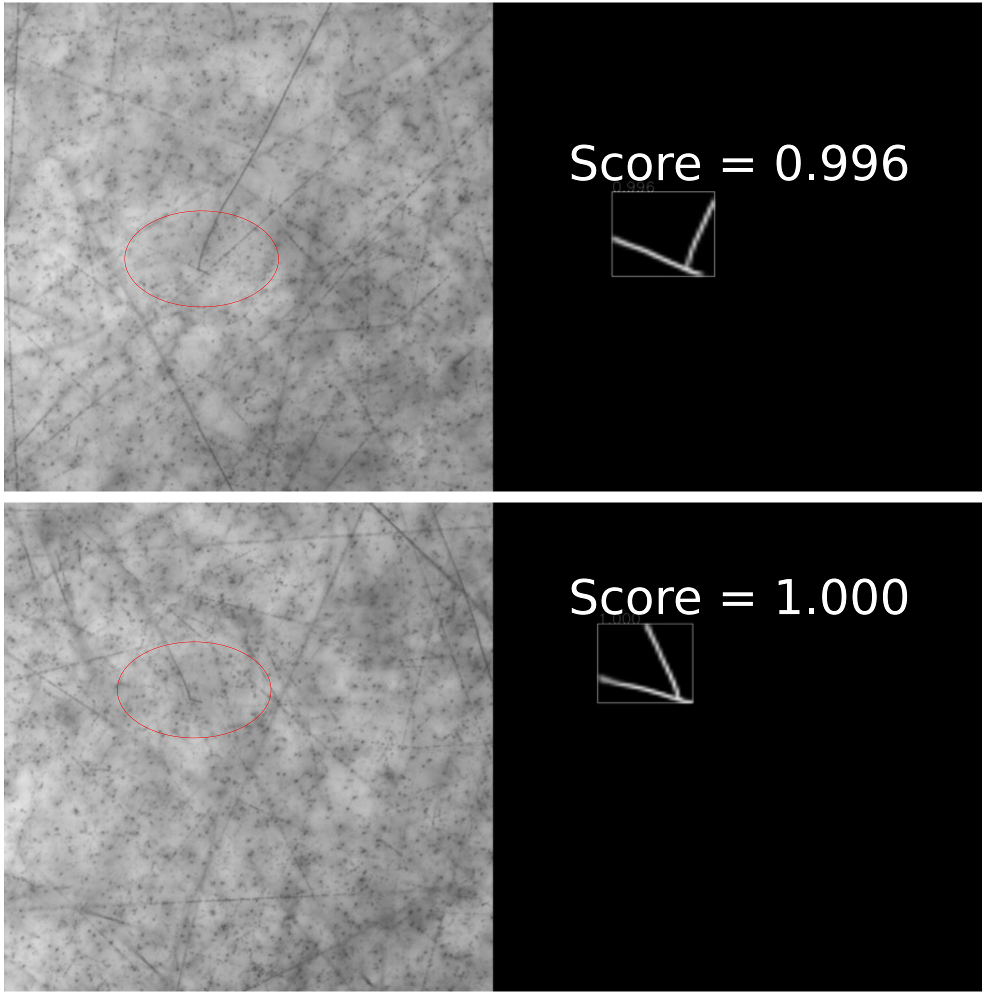
Simulation



Finding hypernuclei in emulsion : MaskCNN

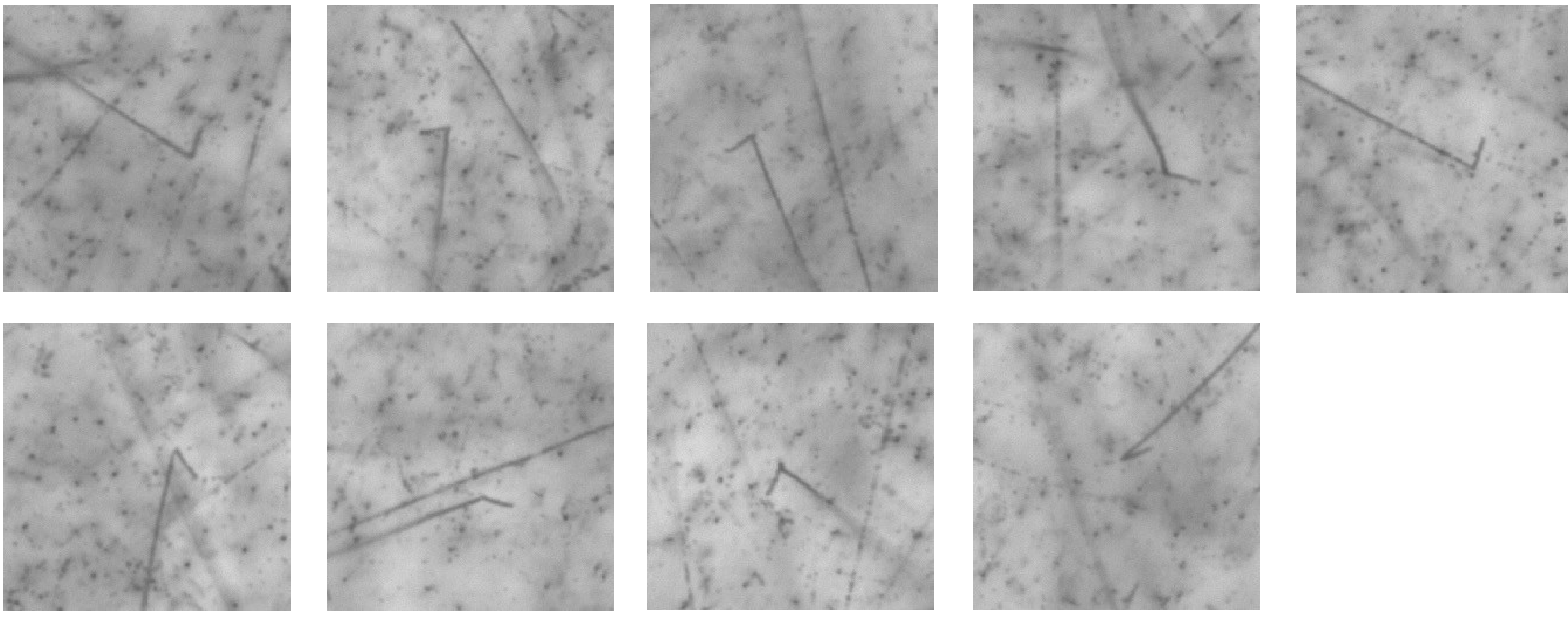
- **Search for hypertriton-like decay:**
  - Training on simulated and generated event → done
  - Analyze the real emulsion images

    → Give us the image and and mask – bounding box of what the algorithm found :



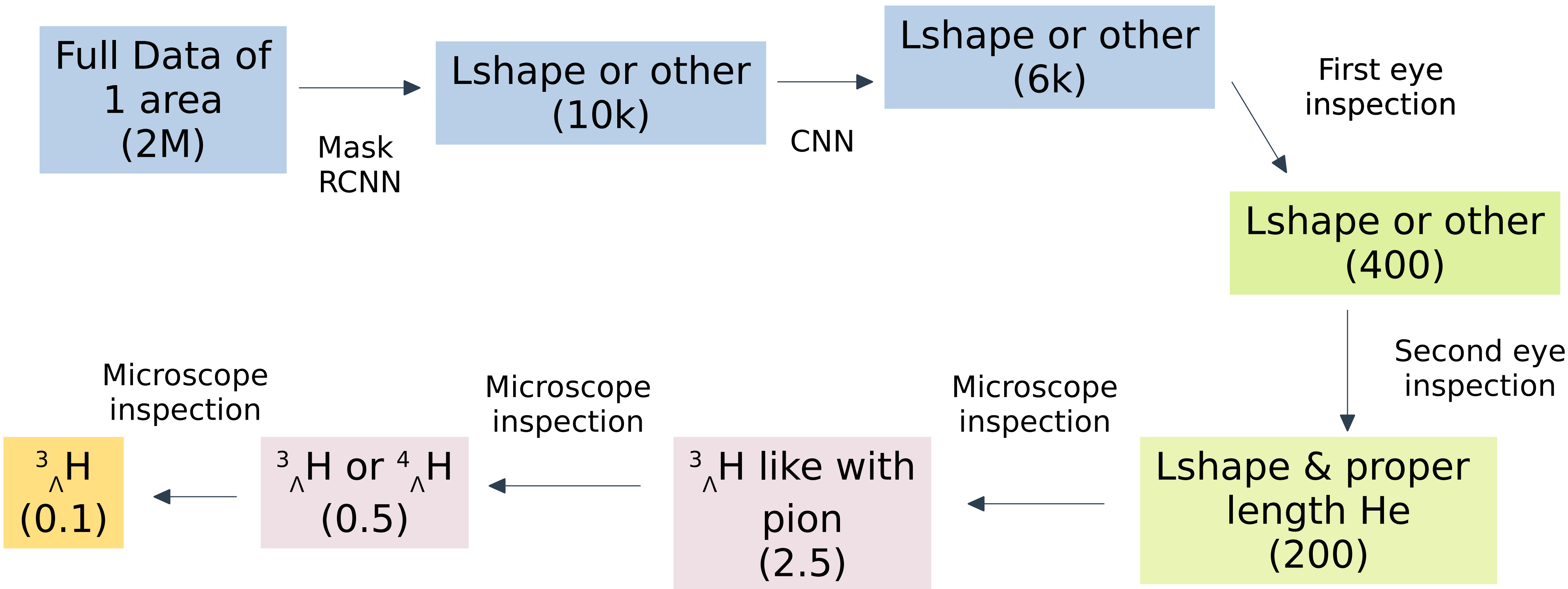
Finding hypernuclei in emulsion : MaskCNN

- **Search for hypertriton-like decay:**



10 µm

- **The Mask R-CNN is not perfect :**
  - Need people to cross check the dataset selected by the NN



Any questions ?