Advanced Neural Network Applications in Heavy-Ion Physics:

From Track Search to Quark-Gluon Plasma Analysis

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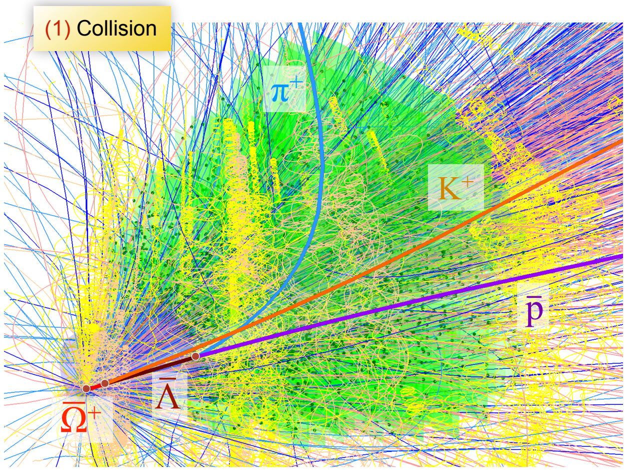
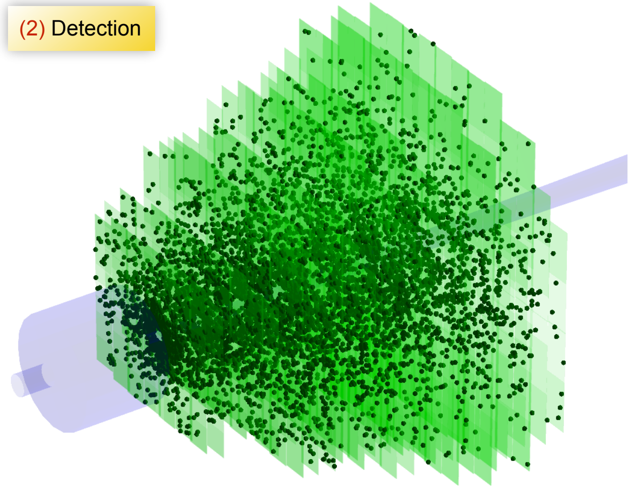
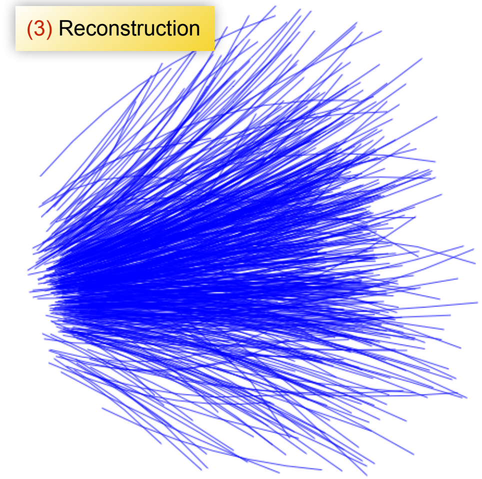
FLES: First Level Event Selection in CBM





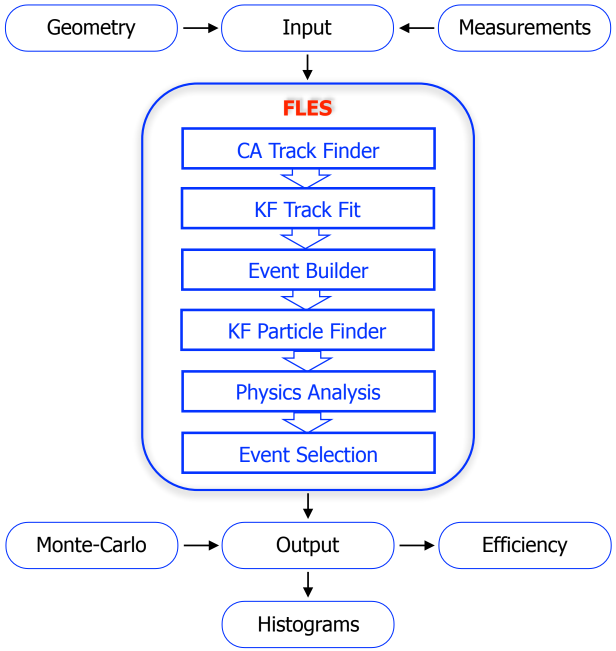


- Future fixed-target heavy-ion experiment at FAIR
- Explore the phase diagram at high net-baryon densities
- 10^7 Au+Au collisions/sec
- ~ 1000 charged particles/collision
- Non-homogeneous magnetic field
- Double-sided strip detectors
- 4D reconstruction of time slices.

The full event reconstruction will be done on-line at the First-Level Event Selection (FLES) and off-line using the same FLES reconstruction package.

- Cellular Automaton (CA) Track Finder
- Kalman Filter (KF) Track Fitter
- KF short-lived Particle Finder

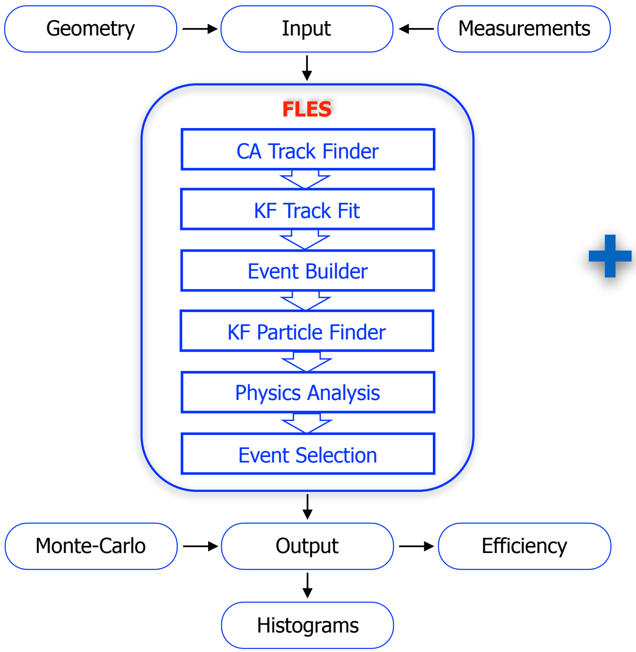
All reconstruction algorithms are vectorized and parallelized.



ANN4FLES : Artificial Neural Networks for FLES

Analytical and data based solutions

- **Analytical approach:** Uses well-defined physical models and mathematical methods to reconstruct particle trajectories, energies, and interactions in high-energy physics experiments.
- **Data-driven approach:** Uses large data sets and machine learning techniques, especially artificial neural networks (ANNs), to identify patterns and optimize reconstruction and analysis algorithms without explicit model assumptions.



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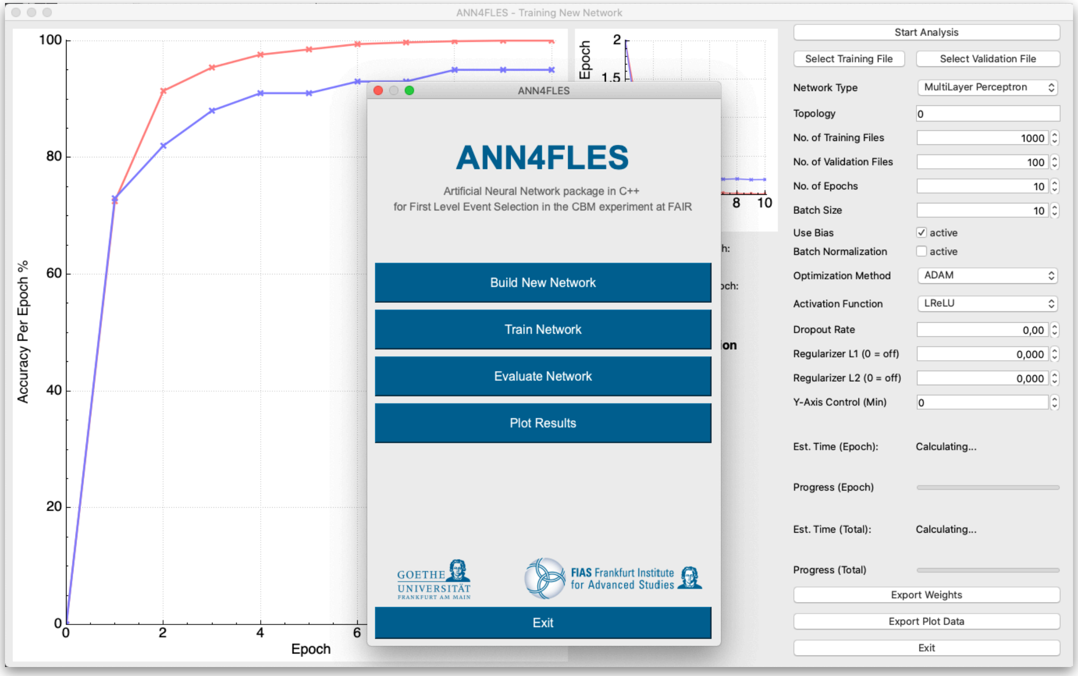
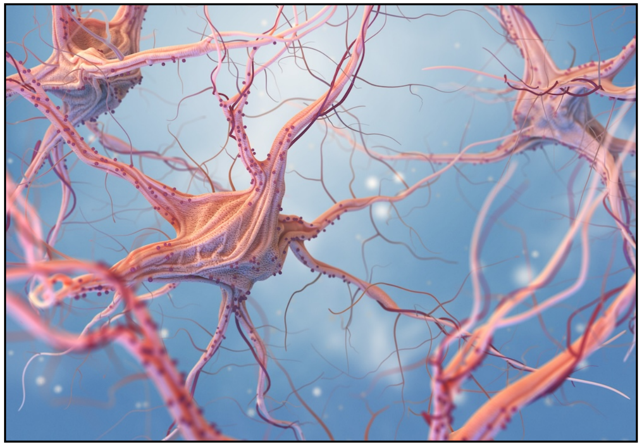


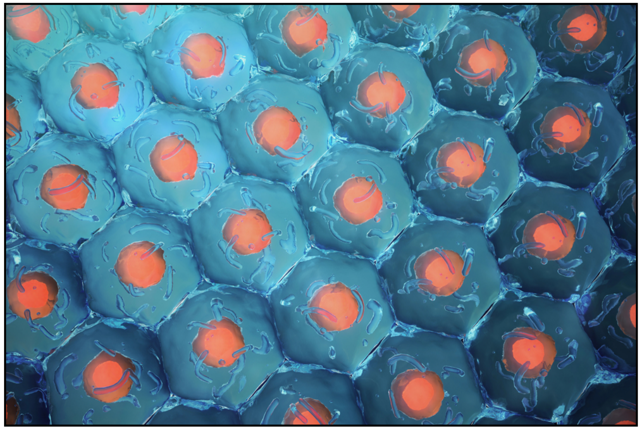
- ANN4FLES is a fast **C++ package** designed for use of Artificial Neural Networks (ANN) in the CBM experiment.
- The package includes a Graphical User Interface (GUI) for network selection and hyperparameter adjustment.
- **Implemented networks** in ANN4FLES include: Multilayer Perceptron (MLP), Convolutional Neural Network (CNN), Recurrent Neural Networks (RNN), Graph Neural Networks (GNN), Bayesian Neural Network (BNN), ...
- Extensive **testing** on datasets like **MNIST**, **CIFAR**, **Cora**, etc., has been **performed** and **compared** with PyTorch.

Schematic structure of a system of neurons.



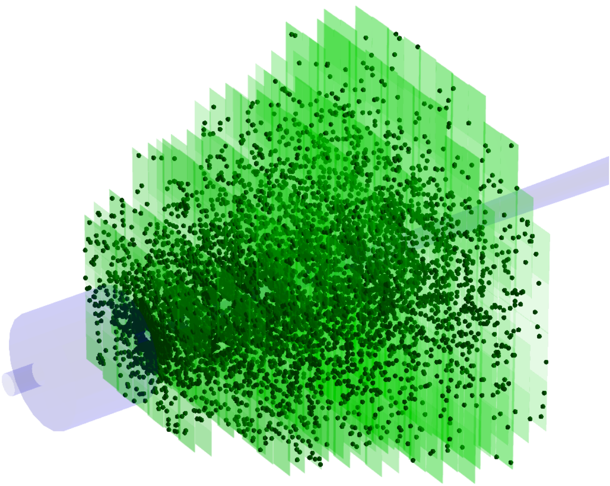
- Elementary units
- Global communication
- Parallel work
- Reliable system
- Pattern recognition

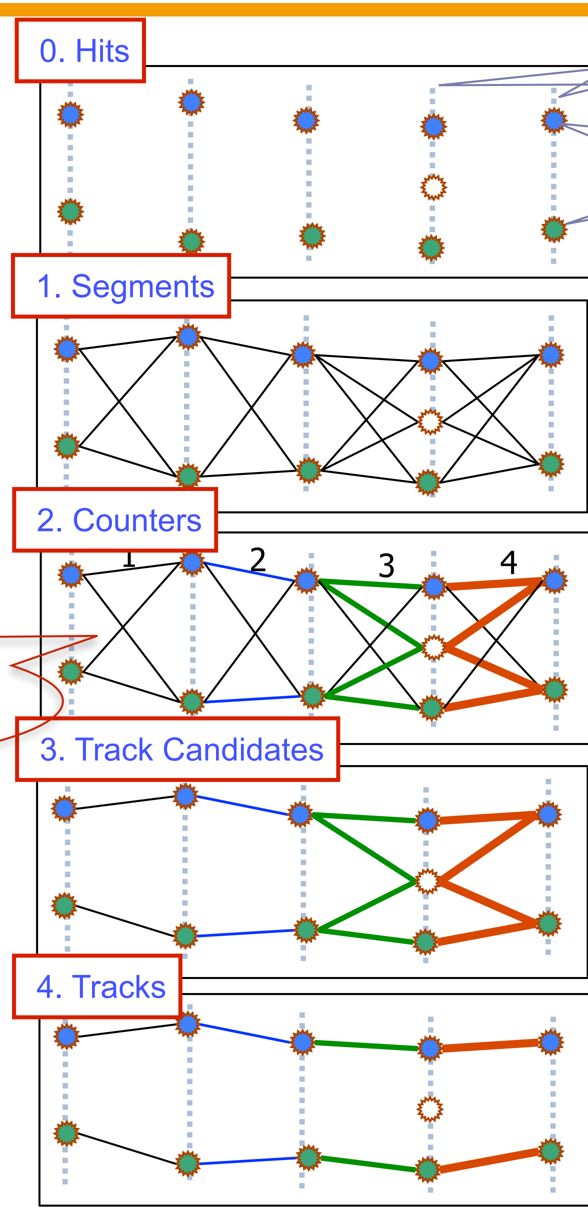
Schematic structure of a system of cells.



- Elementary units
- Local communication
- Parallel work
- Reliable system
- Pattern recognition

Cellular Automaton (CA) Track Finder



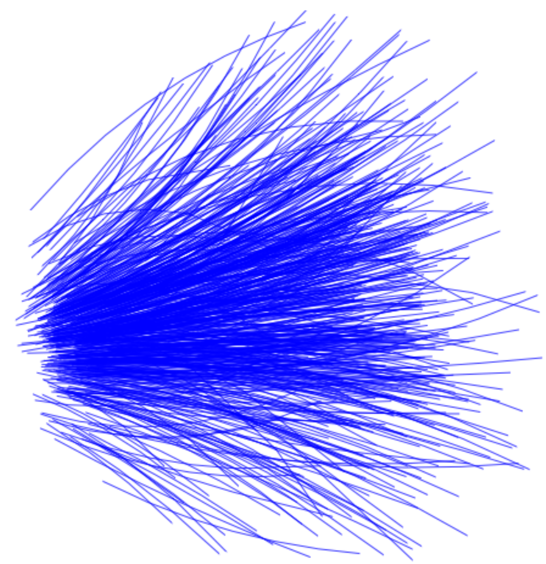


Cellular Automaton:
1. Build short track segments.
2. Connect according to the track model, estimate a possible position on a track.
3. Tree structures appear, collect segments into track candidates.
4. Select the best track candidates.

Local Graph Neural Network

Cellular Automaton:
- visually simple
- intrinsically parallel
- local w.r.t. data
- memory optimized
- staged algorithm

Well-suited for many-core CPU/GPU



Useful for complicated event topologies with heavy combinatorics

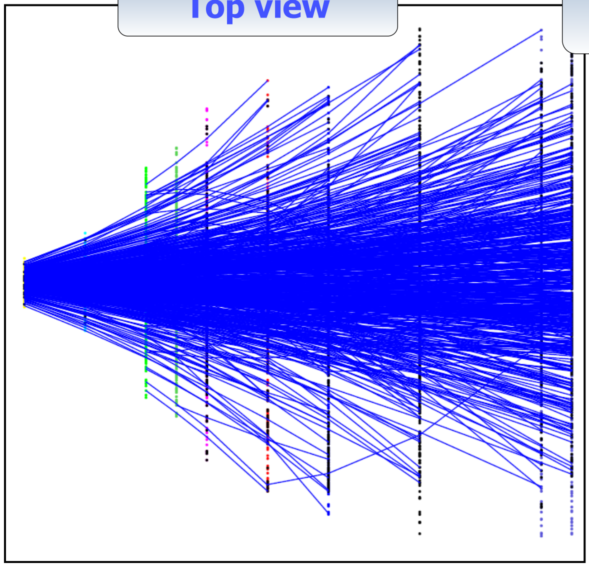
Cellular Automaton (CA) Track Finder

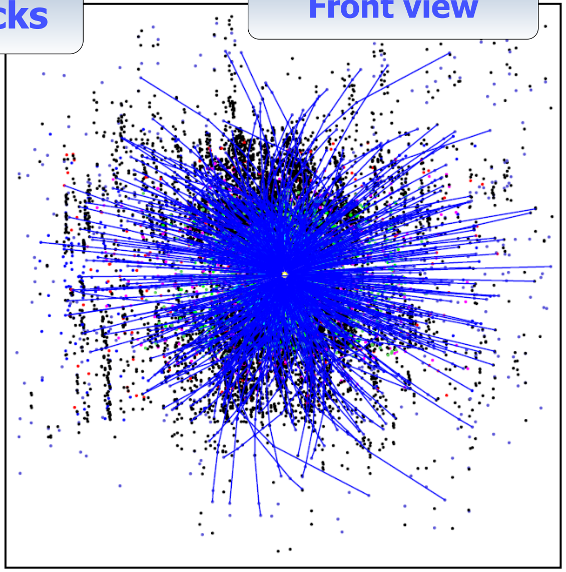
I. Kulakov

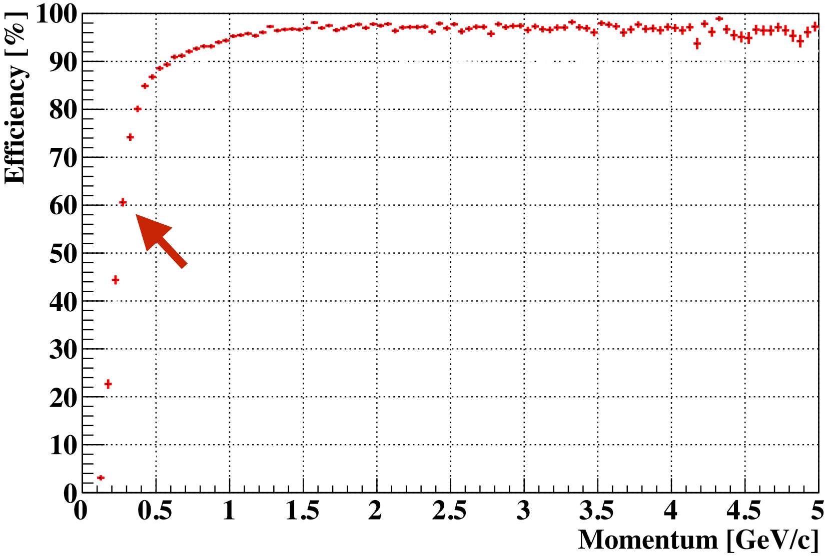
Top view

770 Tracks

Front view





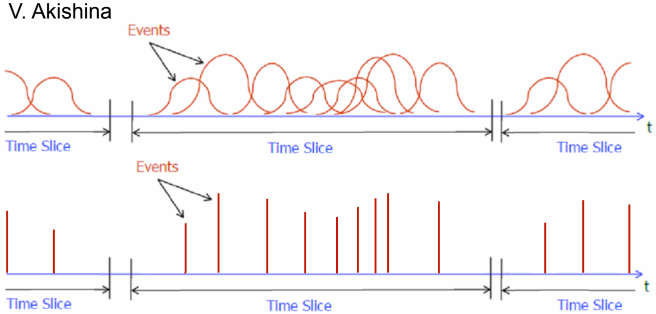


Track category	Eff, %
All tracks	90.9
Primary high-*p*	97.5
Primary low-*p*	92.6
Secondary high-*p*	91.1
Secondary low-*p*	63.8
Clone level	0.4
Ghost level	5.9
MC tracks found	134
Time, ms/ev	10

Fast and efficient track finder

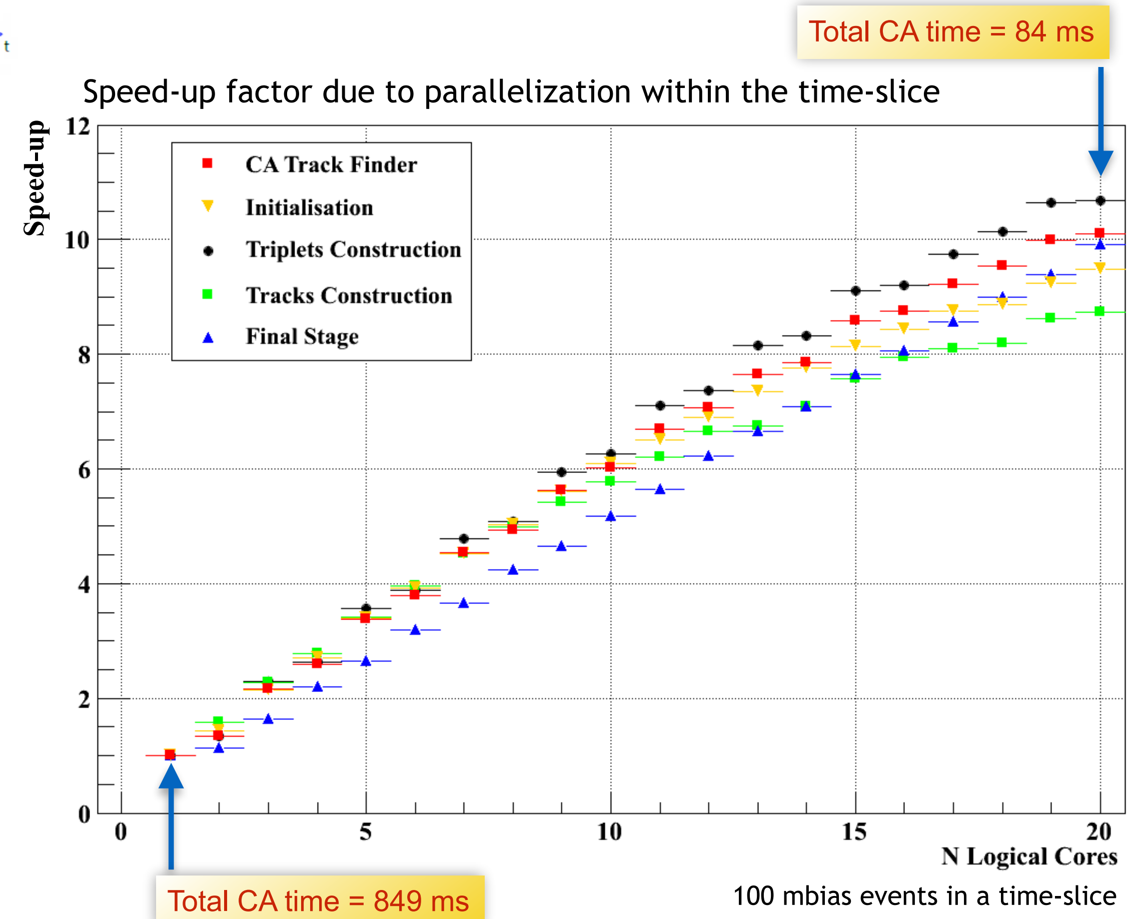
Time-based (4D) Track Reconstruction

V. Akishina



- The beam in the CBM will have no bunch structure, but continuous.
- Measurements in this case will be 4D (x, y, z, t).
- Significant overlapping of events in the detector system.
- Reconstruction of time slices rather than events is needed.

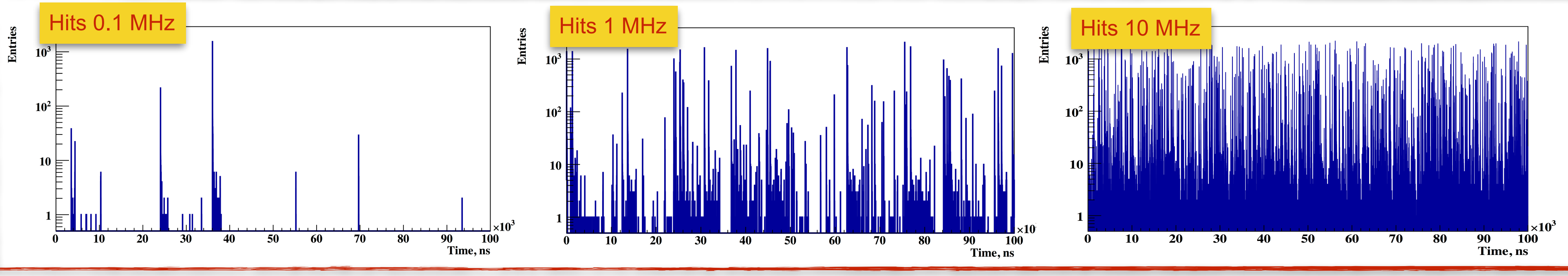
Efficiency, %	3D	4D
All tracks	83.8	83.0
Primary high-p	96.1	92.8
Primary low-p	79.8	83.1
Secondary high-p	76.6	73.2
Secondary low-p	40.9	36.8
Clone level	0.4	1.7
Ghost level	0.1	0.3
Time/event/core, ms	8.2	8.5



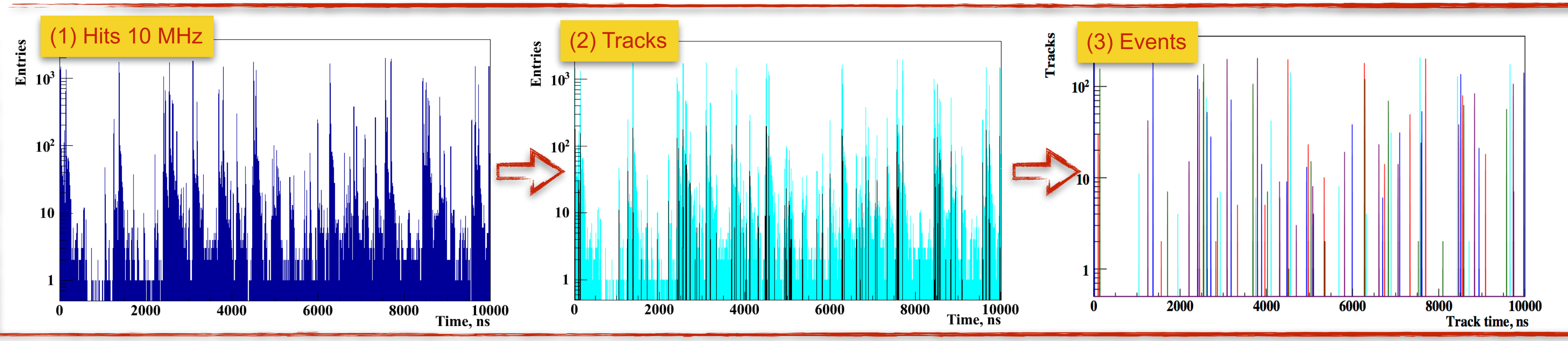
3D reconstruction time 8.2 ms/event is recovered in 4D case

V. Akishina

Hits at high input rates

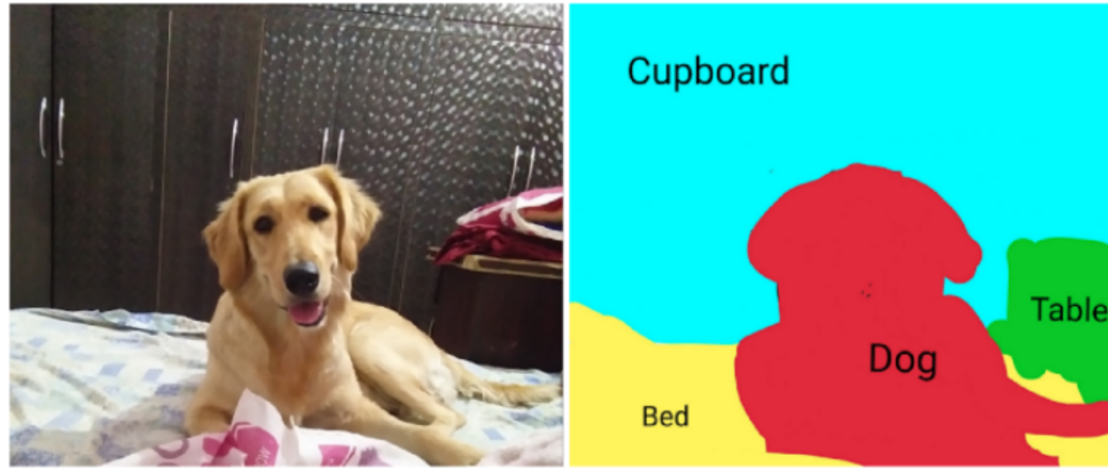


From hits to tracks to events



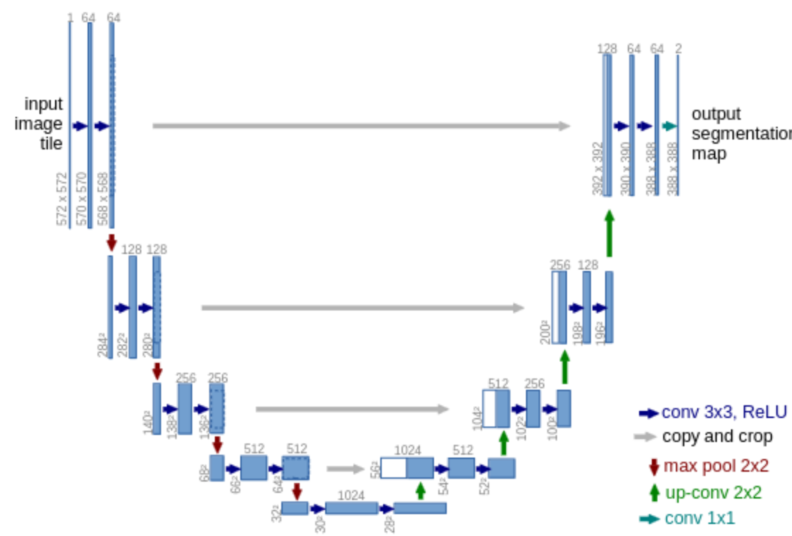
Reconstructed tracks clearly represent groups, which correspond to the original events

U-Net Segmentation ANN Model



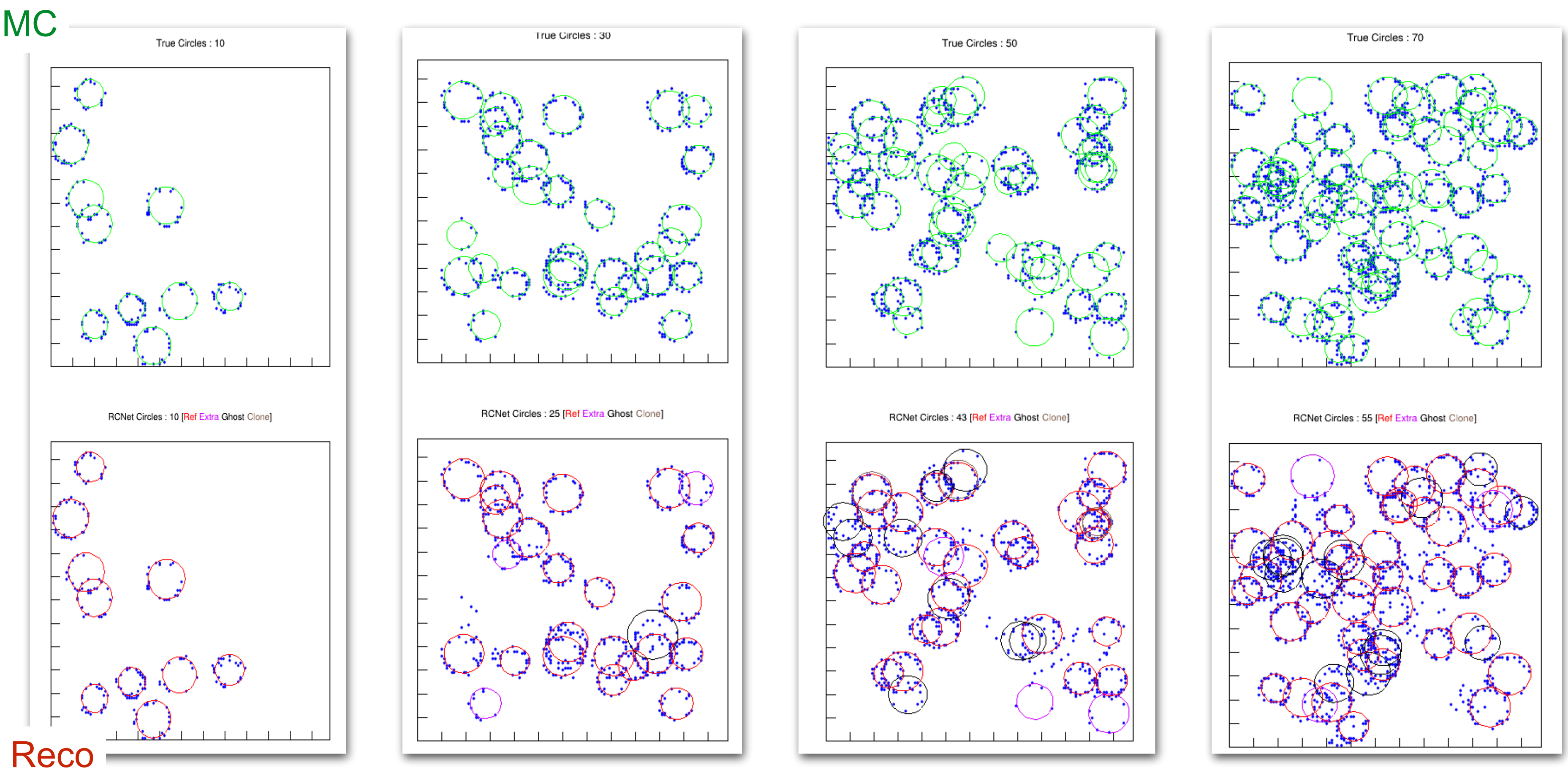
- Unlike image classification task, assign a class to each pixel of the image.
- A segmentation model returns much more detailed information about the image.

- U-shaped semantic segmentation which has a contracting path and an expansive path.
- During the contraction, the feature information is increased while spatial information is decreased.
- On the other hand, every step of expansive path feature map size by a factor of 2.
- Then the reduced feature map is concatenated with the corresponding cropped feature map from the contracting path.



U-Net architecture (https://arxiv.org/pdf/1505.04597.pdf)

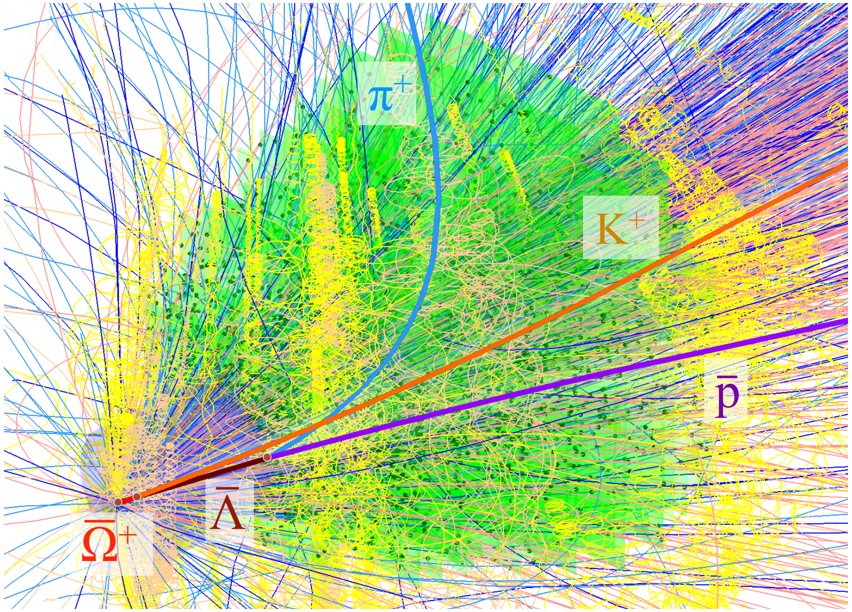
Ring Center Net for Ring Finding in High Density Regions



10 Rings *30 Rings* *50 Rings* *70 Rings*

RCNet is capable to find rings in high density regions

KF Particle - Reconstruction of short-lived Particles



Simulated AuAu collision at 25 AGeV

$$\bar{\Omega}^+ \leftarrow \bar{\Lambda}\, K^+$$
$$\quad\quad \hookrightarrow \bar{p}\, \pi^+$$

```
KFParticle Lambda(P, Pi);                 // construct anti Lambda
Lambda.SetMassConstraint(1.1157);         // improve momentum and mass
KFParticle Omega(K, Lambda);              // construct anti Omega
PV -= (P; Pi; K);                         // clean the primary vertex
PV += Omega;                              // add Omega to the primary vertex
Omega.SetProductionVertex(PV);            // Omega is fully fitted
(K; Lambda).SetProductionVertex(Omega);   // K, Lambda are fully fitted
(P; Pi).SetProductionVertex(Lambda);      // p, pi are fully fitted
```

$$\mathbf{r} = \{\, x, y, z, p_x, p_y, p_z, E \,\}$$

State vector

$$\mathbf{C} = \langle \mathbf{r}\mathbf{r}^T \rangle = \begin{bmatrix} \sigma_x^2 & C_{xy} & C_{xz} & C_{xp_x} & C_{xp_y} & C_{xp_z} & C_{xE} \\ C_{xy} & \sigma_y^2 & C_{yz} & C_{yp_x} & C_{yp_y} & C_{yp_z} & C_{yE} \\ C_{xz} & C_{yz} & \sigma_z^2 & C_{zp_x} & C_{zp_y} & C_{zp_z} & C_{zE} \\ C_{xp_x} & C_{yp_x} & C_{zp_x} & \sigma_{p_x}^2 & C_{p_xp_y} & C_{p_xp_z} & C_{p_xE} \\ C_{xp_y} & C_{yp_y} & C_{zp_y} & C_{p_xp_y} & \sigma_{p_y}^2 & C_{p_yp_z} & C_{p_yE} \\ C_{xp_z} & C_{yp_z} & C_{zp_z} & C_{p_xp_z} & C_{p_yp_z} & \sigma_{p_z}^2 & C_{p_yE} \\ C_{xE} & C_{yE} & C_{zE} & C_{p_xE} & C_{p_yE} & C_{p_zE} & \sigma_E^2 \end{bmatrix}$$

Covariance matrix

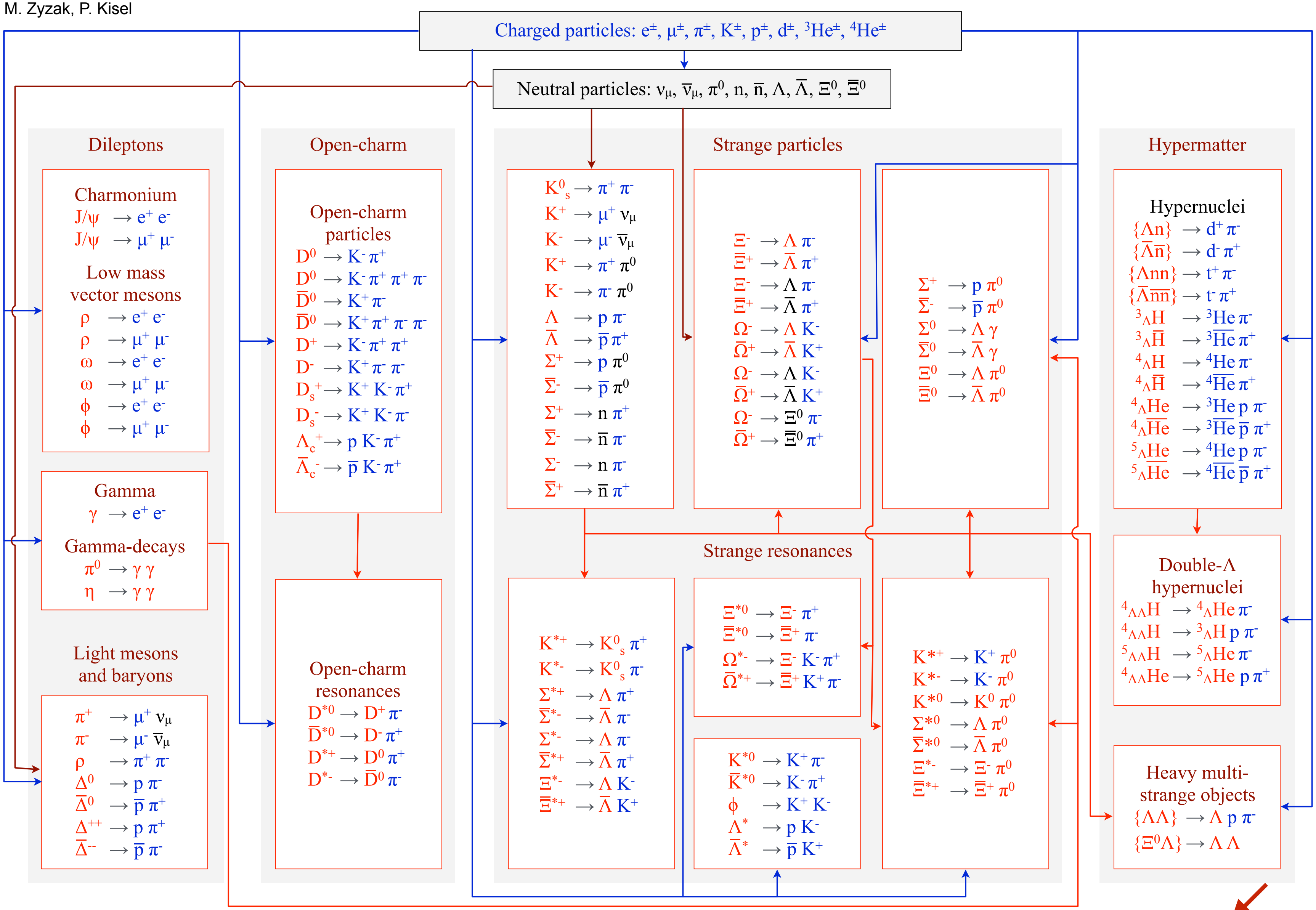
Features:

- KF Particle class describes particles by the state vector and the covariance matrix.
- Covariance matrix contains essential information about tracking and detector performance.
- The method for mathematically correct usage of covariance matrices is provided by the KF Particle package based on the Kalman filter (KF).
- Heavy mathematics of KF requires fast and vectorised algorithms.
- Mother and daughter particles are treated in the same way.
- The natural and simple interface allows two reconstruct easily complicated decay chains.
- The package is geometrically independent and can be adapted to different experiments (CBM, ALICE, STAR).

KF Particle provides a simple and very efficient approach to physics analysis

KF Particle Finder for Online Analysis and Selection

M. Zyzak, P. Kisel

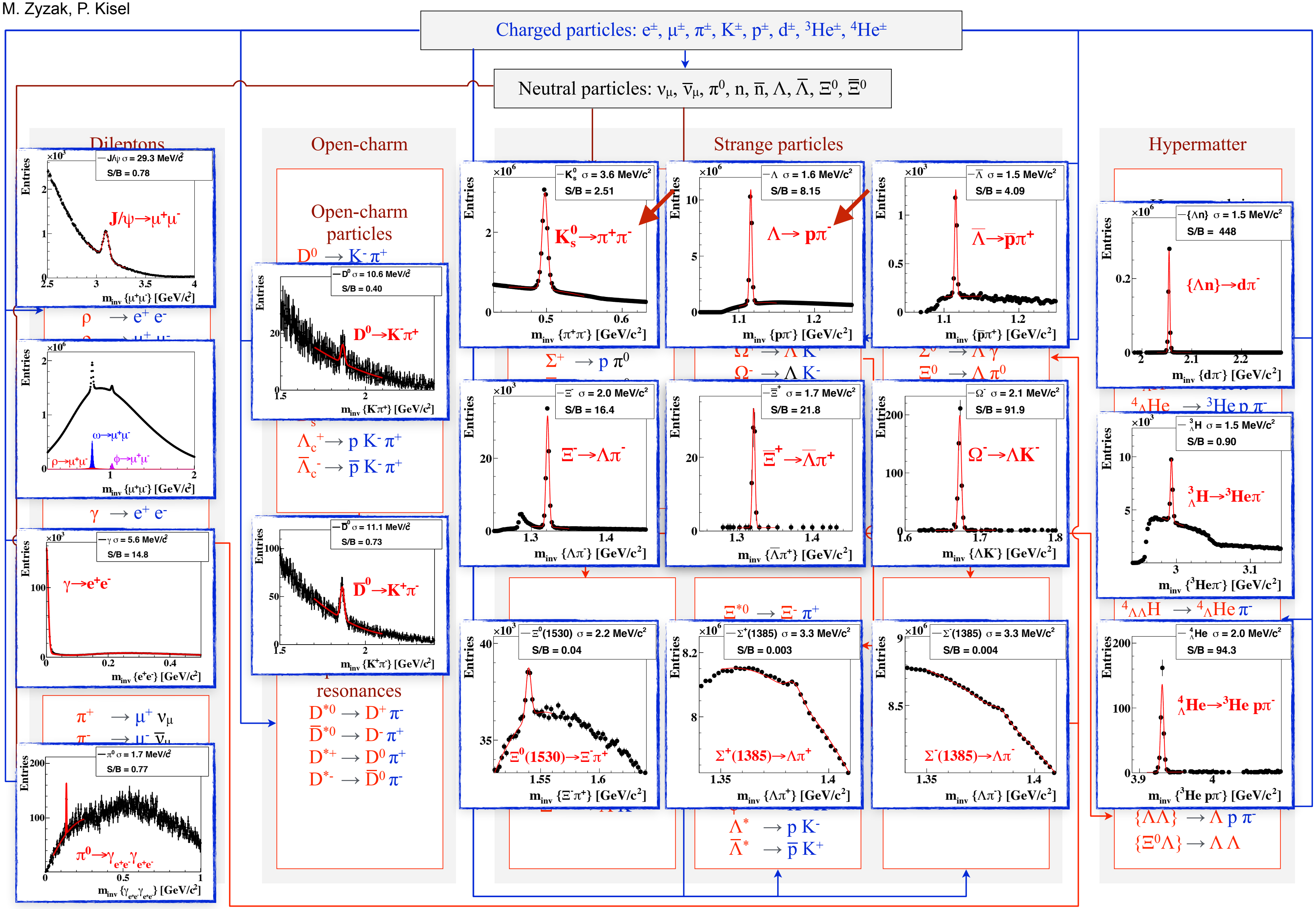


1.4 ms/event/core

Online search for short-lived particles

KF Particle Finder for Online Analysis and Selection

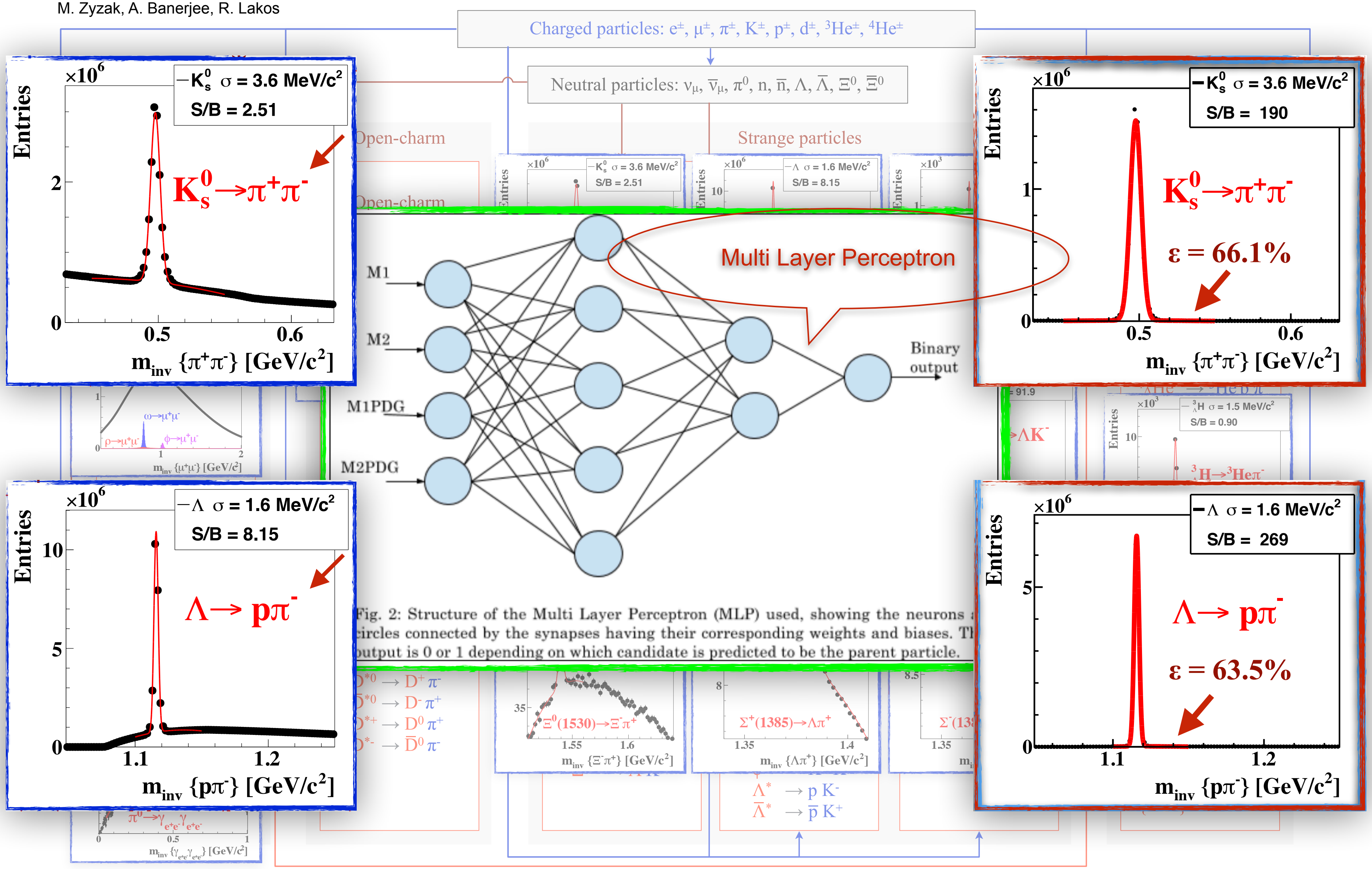
M. Zyzak, P. Kisel



Online search for short-lived particles

ANN based Particle Competition in the KF Particle Finder

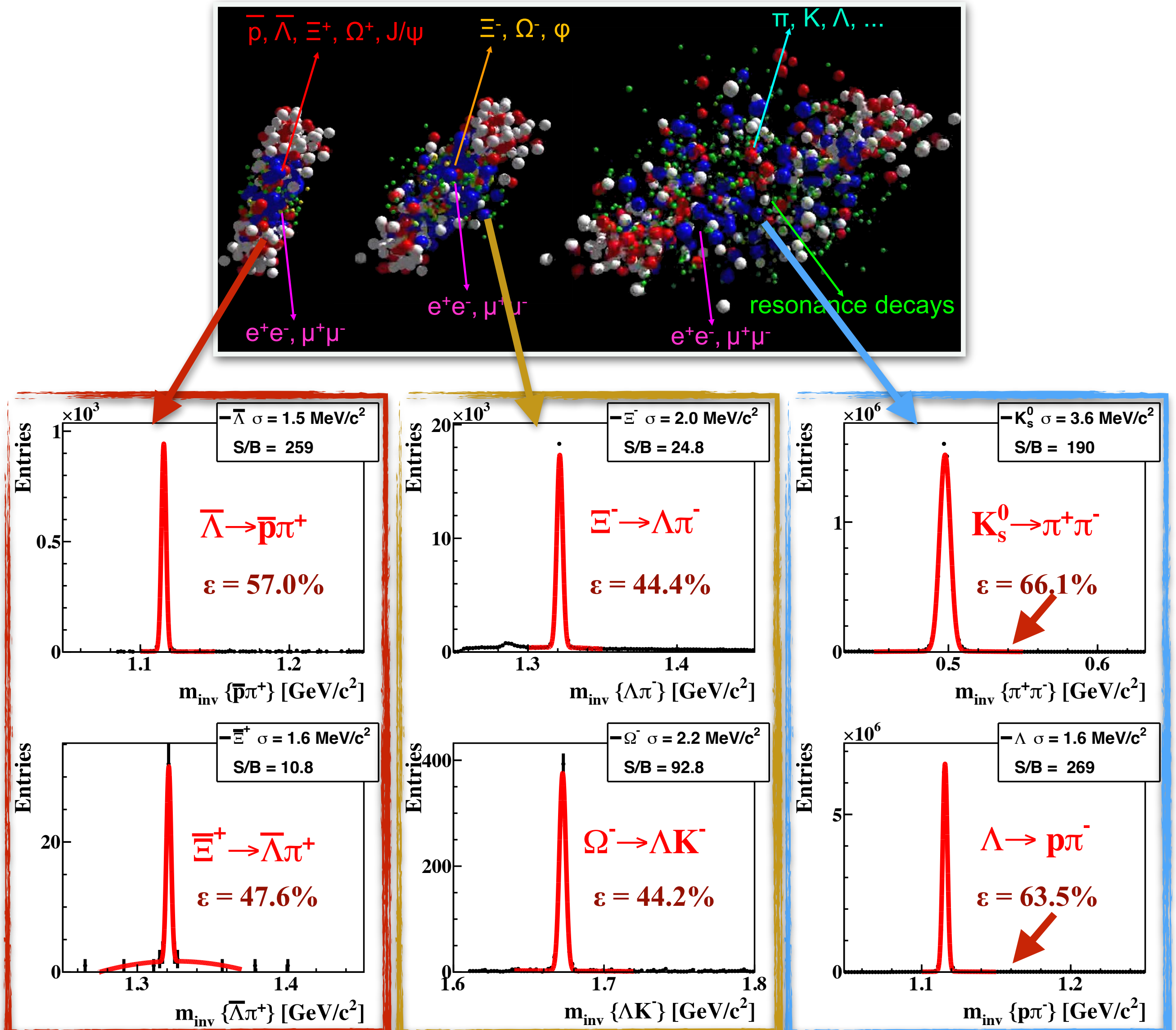
M. Zyzak, A. Banerjee, R. Lakos



A Multilayer Perceptron is used to solve the particle competition task in the KF Particle Finder

Clean Probes of Collision Stages

M. Zyzak



AuAu, 10 AGeV, 3.5M central UrQMD events, MC PID

Study of the properties of colliding matter is possible

Online physics analysis = online extraction of medium properties in heavy-ion collisions

Direct approach

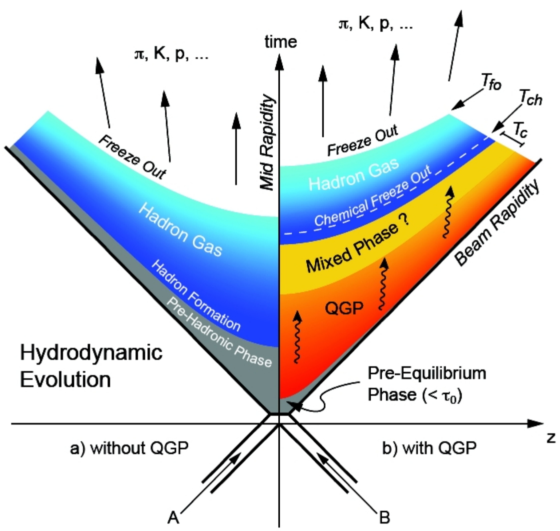
Theoretical model (T, μ,V, σ,...) ⇄ $\omega_p \frac{dN}{dp^3}$ (observable)

Inverse approach

Motivation:

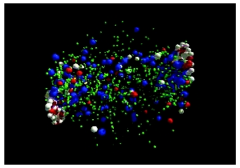
- Determination of physical properties of QCD matter created in HIC (temperature, flow, phase transitions, …)

Stages of a collision

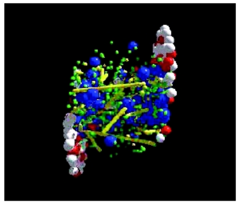


Chemical freeze-out (Tch) inelastic collisions cease
Kinetic freeze-out (Tfo < Tch) elastic collisions cease

Models for different stages

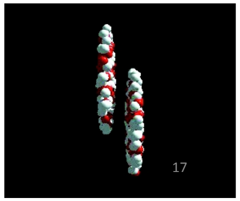


Final momentum spectrum (Blast-Wave, Tsallis, …)



Statistical-thermal models for chemical freeze-out (ideal hadron gas, Van der Waals hadron gas, Hagedorn states, …)

Relativistic hydrodynamics (ideal, viscous; (0+1)D, (1+1)D, (3+1)D, …)

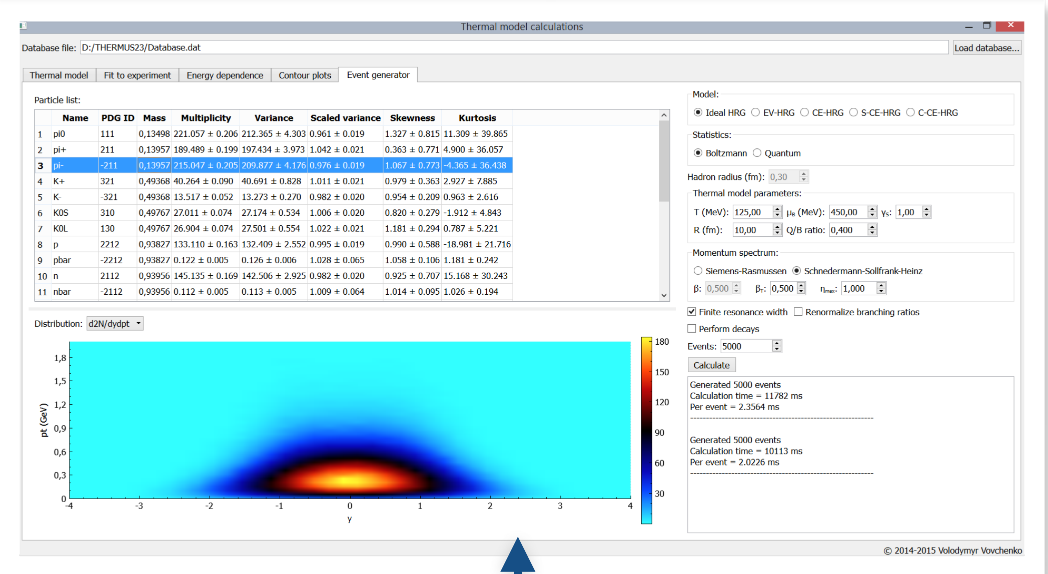


Initial stage (Glauber, CGC, …)

How to extract the parameters of theoretical models?

Online Physics Analysis (macroscopic)

V. Vovchenko

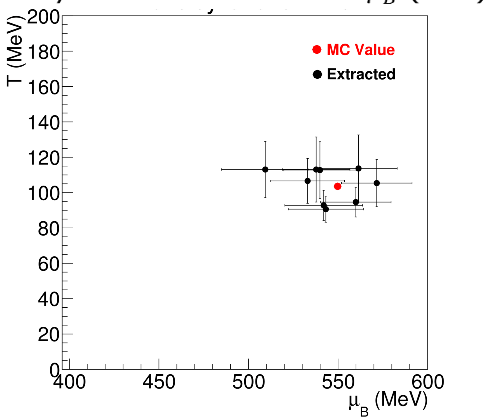


Direct approach

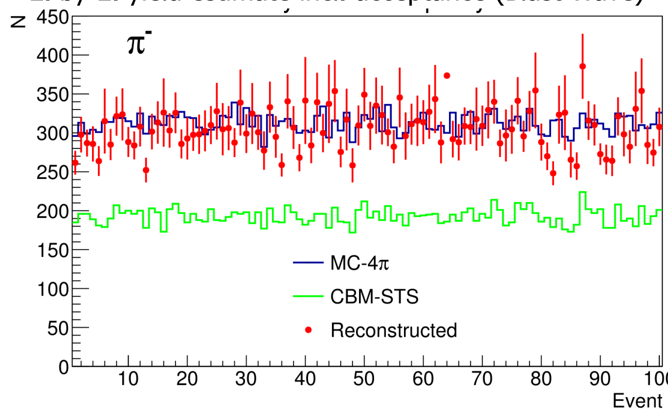
Theoretical model (T, μ,V, σ,...) ⇄ $\omega_p \frac{dN}{dp^3}$ (observable)

Inverse approach

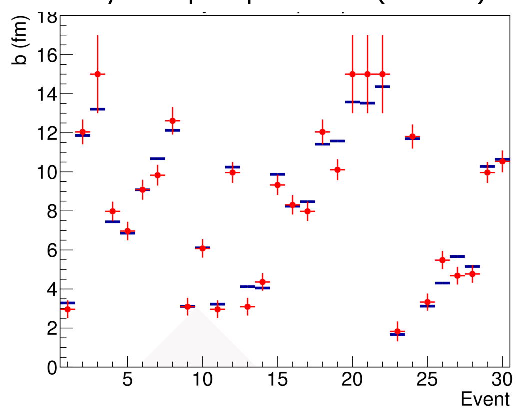
E.-by-E. extraction of T and μ_B (HRG)



E.-by-E. yield estimate incl. acceptance (Blast-Wave)



E.-by-E. impact parameter (Glauber)



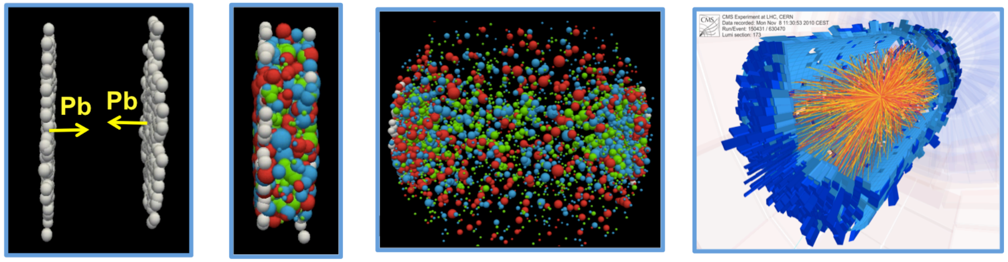
Extraction of the parameters of macroscopic theoretical models is feasible

Online Physics Analysis (microscopic)

A. Belousov, R. Lakos, A. Mithran, O. Tyagi

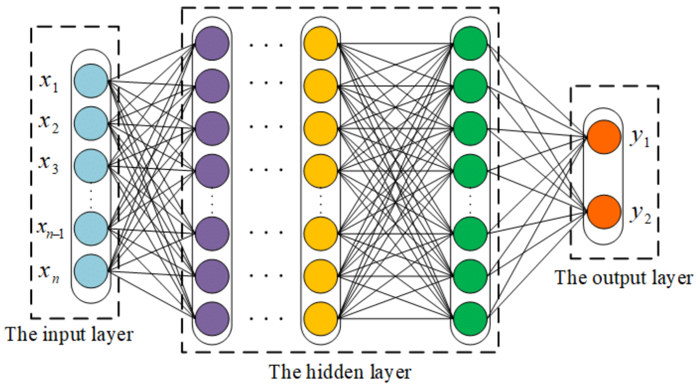
time

Pre-reaction | **QGP** | **Hadronization** | **Detection**



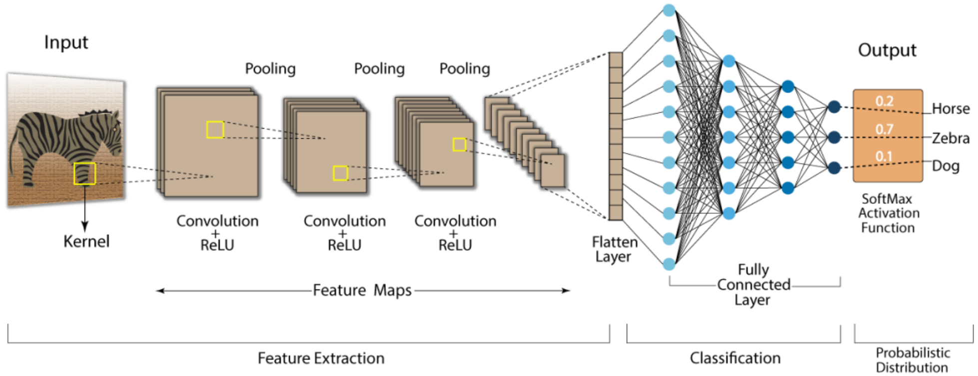
- A **QGP** can be formed by compressing a large amount of energy into a small volume.
- Direct observation of QGP is not possible.
- Rely on the produced particles as probes.
- Classify events with QGP based on the reconstructed particles to prove **feasibility of using ANNs**.

Fully-Connected Neural Network (FCNN)



https://www.researchgate.net/publication/342092474_Diagnosis_of_Blade_Icing_Using_Multiple_Intelligent_Algorithms

Convolutional Neural Network (CNN)



https://developersbreach.com/convolution-neural-network-deep-learning/

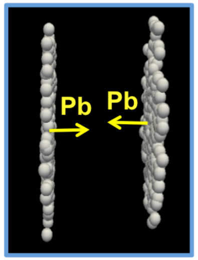
Use of Artificial Neural Networks for selection of events with QGP

Online Physics Analysis (microscopic)

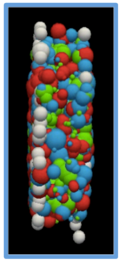
A. Belousov, R. Lakos, A. Mithran, O. Tyagi

time

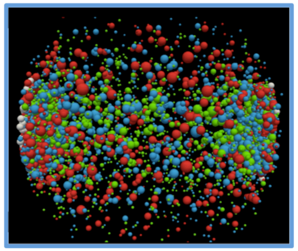
Pre-reaction



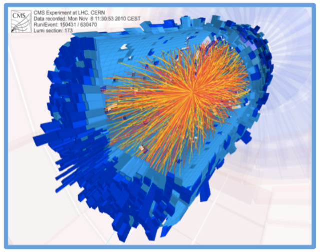
QGP



Hadronization



Detection



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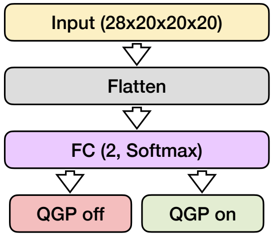
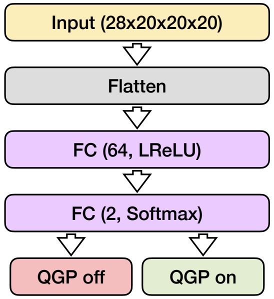
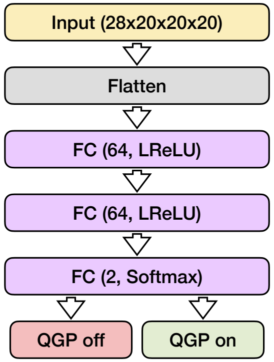
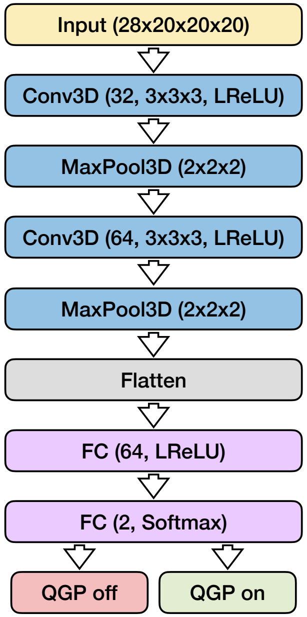
Fully-Connected Neural Networks (FCNN)





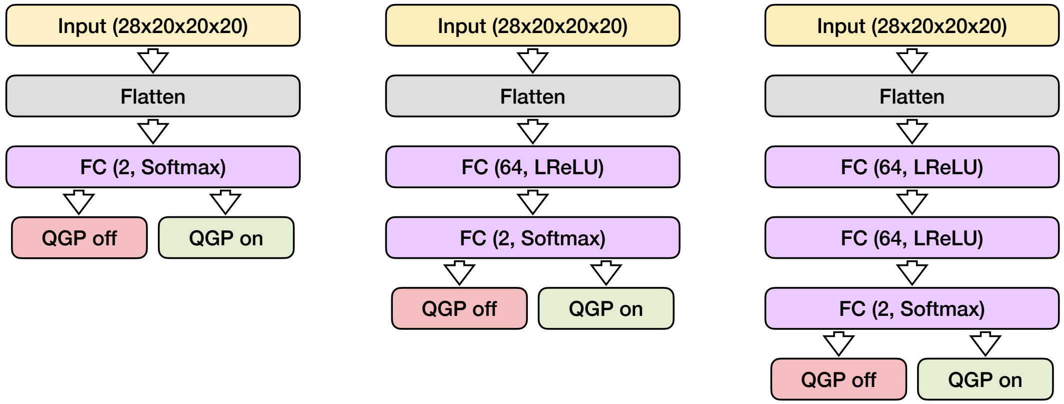


Convolutional Neural Network (CNN)

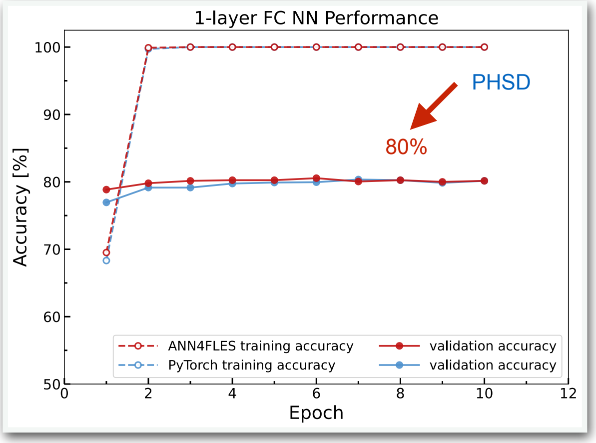


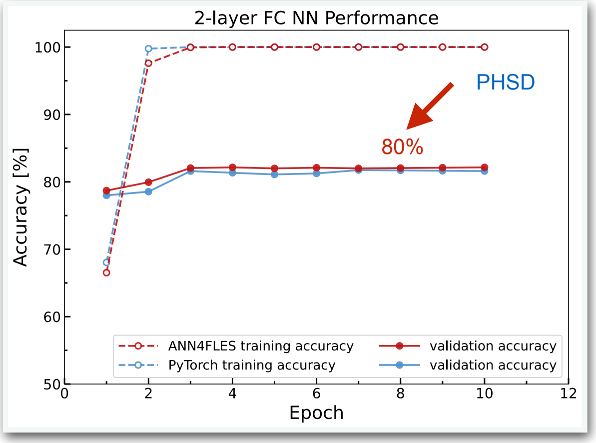
Use of Artificial Neural Networks for selection of events with QGP

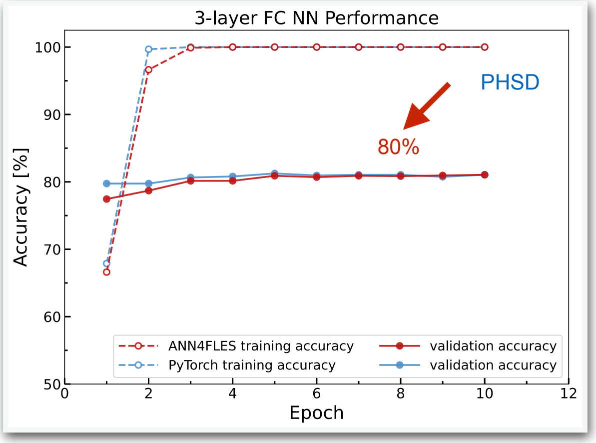
A. Belousov, R. Lakos



Structure of **one-**, **two-** and **three-layer** Fully-Connected Neural Networks used for QGP detection



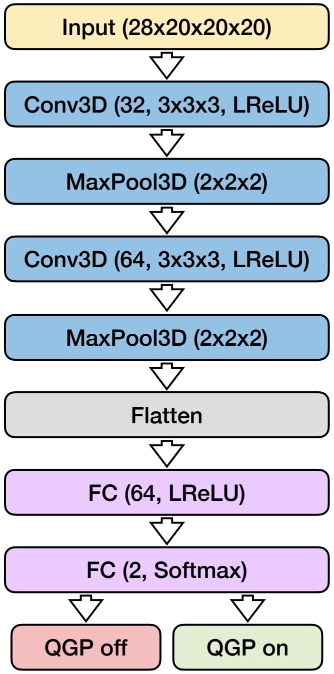


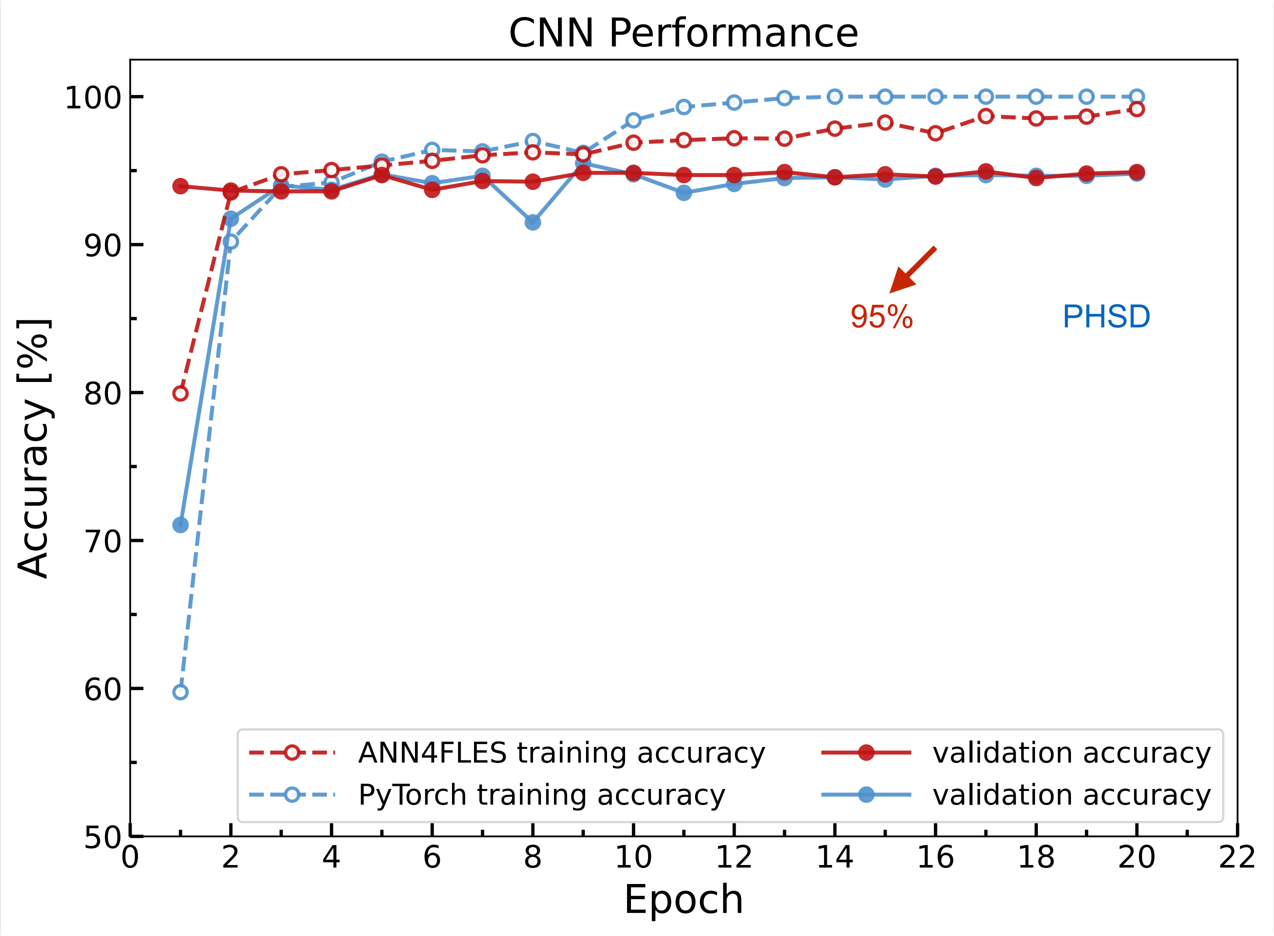


Training and validation accuracy for the **FCNN** networks

A Fully-Connected Neural Network (**FCNN**) based **QGP Trigger** is **not feasible**

A. Belousov, A. Mithran





Training and **validation** accuracy for the **CNN**

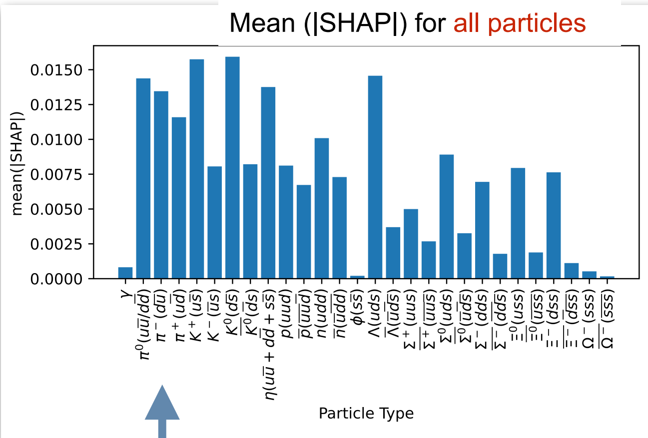
A Convolutional Neural Network (**CNN**) based **QGP Trigger** is **feasible**

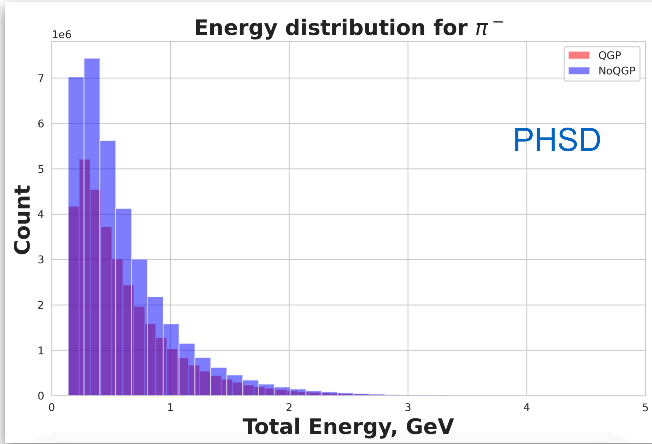
Interpretable ANN: Shapley Additive Explanations

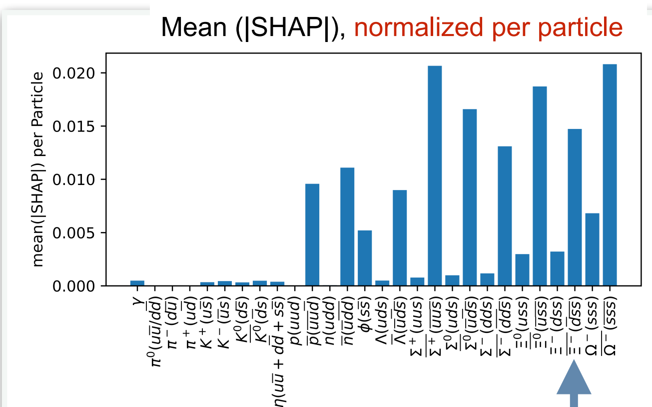
A. Belousov, O. Tyagi

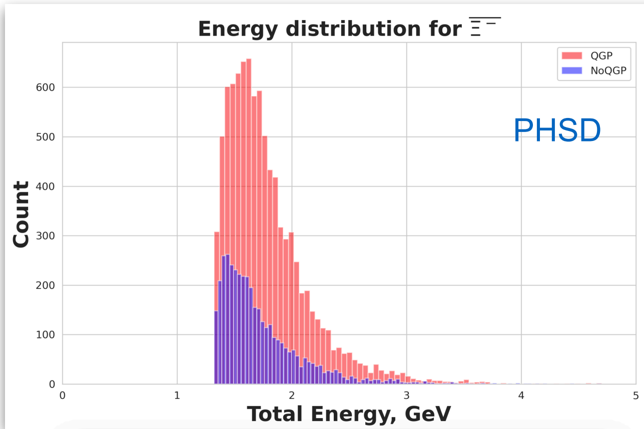
Method based on cooperative game theory used to increase transparency and interpretability of machine learning models.

For each feature, SHAP score is determined by evaluating the average contribution of adding the feature over all possible feature subsets defined without that feature.









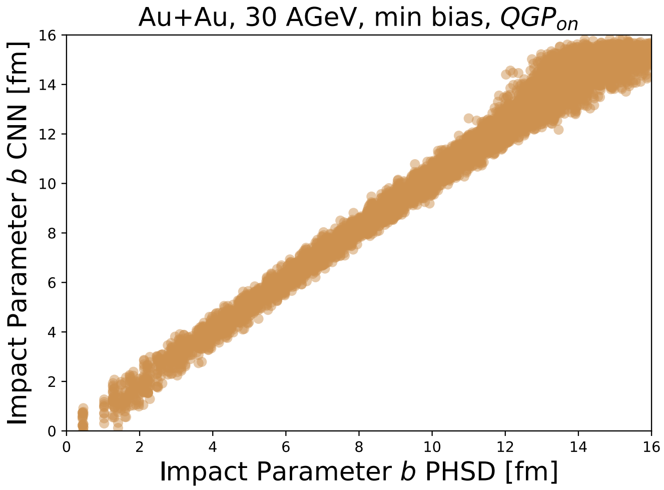
- Light particles are important for model prediction
- Anti-baryons are more important than baryons per particle

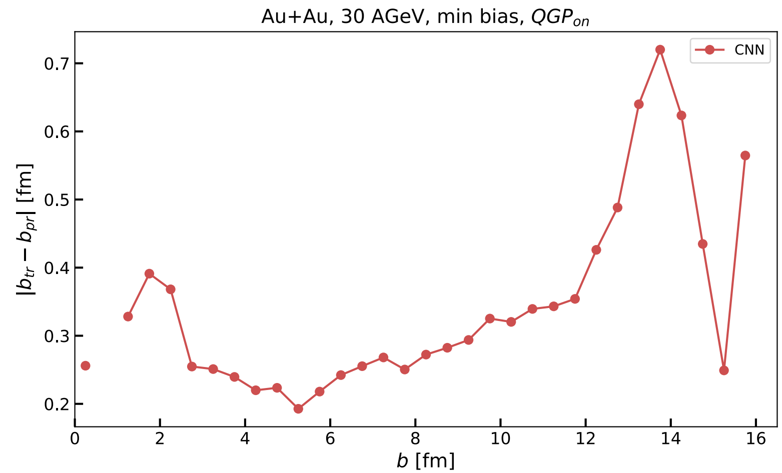
SHAP analysis shows that ANN has learned the correct features associated with **QGP** production.

PHSD: Trained and Validated

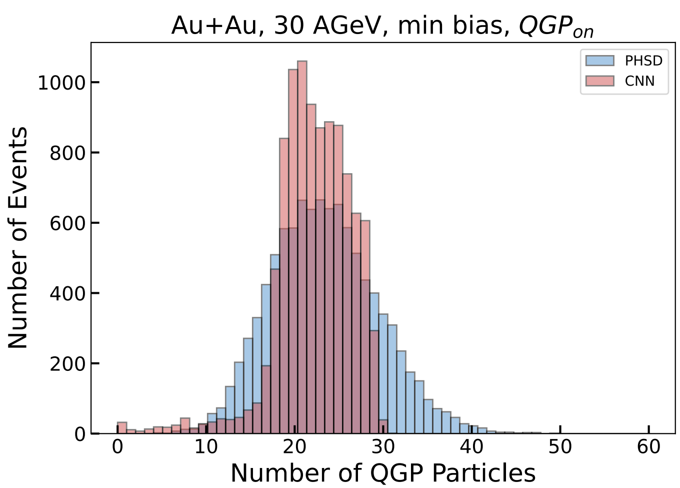
A. Belousov, E. Bratkovskaya, O. Soloveva

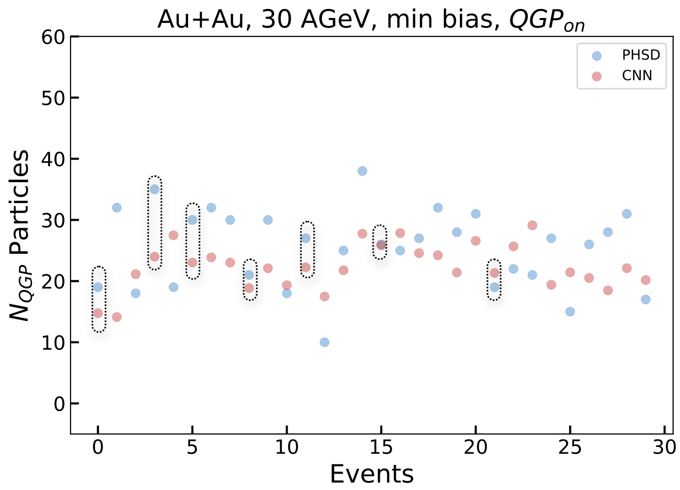
Impact Parameter





Number of QGP Particles



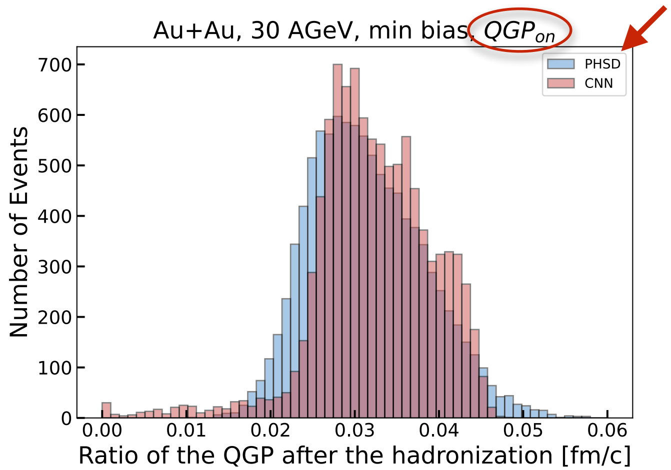


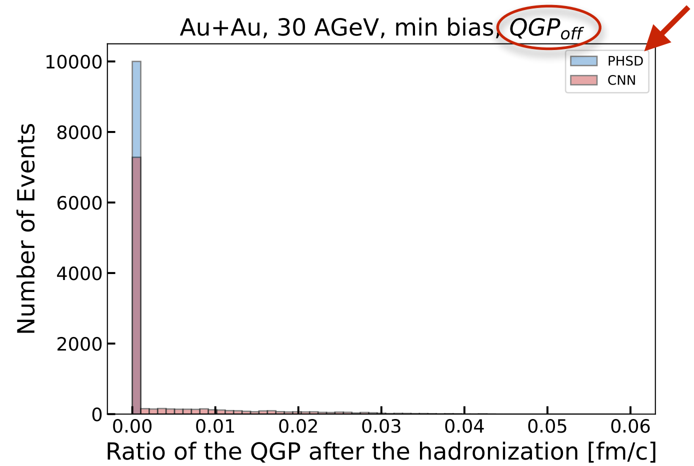
The basic characteristics of the collision are well reconstructed by ANN (according to the PHSD model)

PHSD Trained: Case1 and Case2 Data of UrQMD?

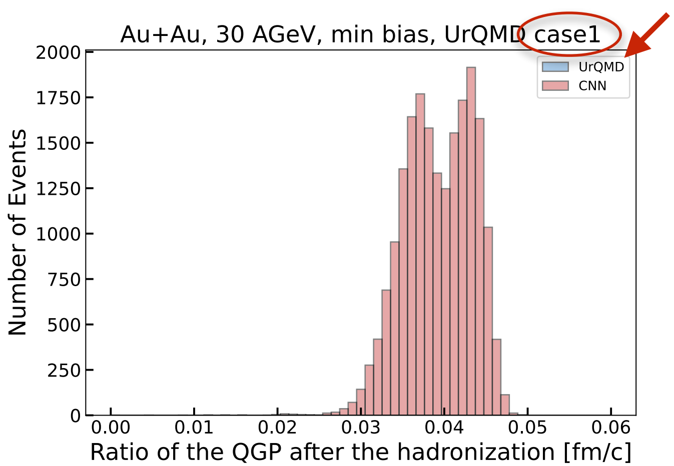
A. Belousov, E. Bratkovskaya, O. Soloveva, M. Bleicher, J. Steinheimer-Froschauer

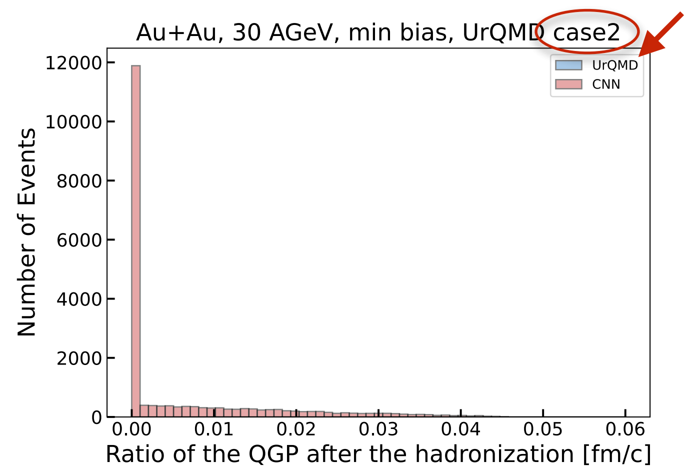
PHSD: Ratio of the QGP (≈ the QGP Volume)





UrQMD: Ratio of the QGP (≈ the QGP Volume)



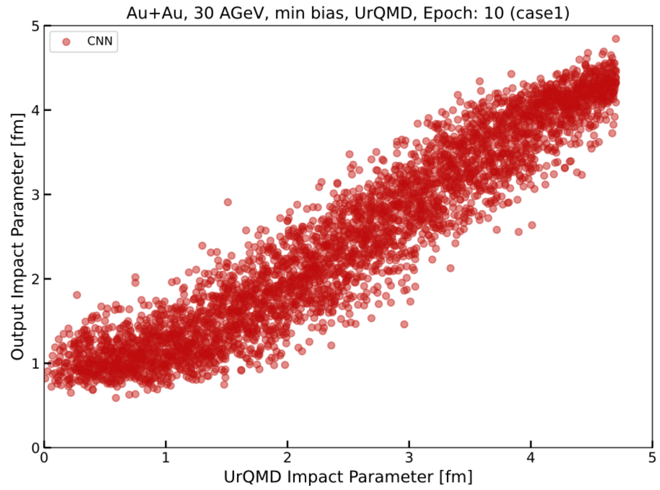


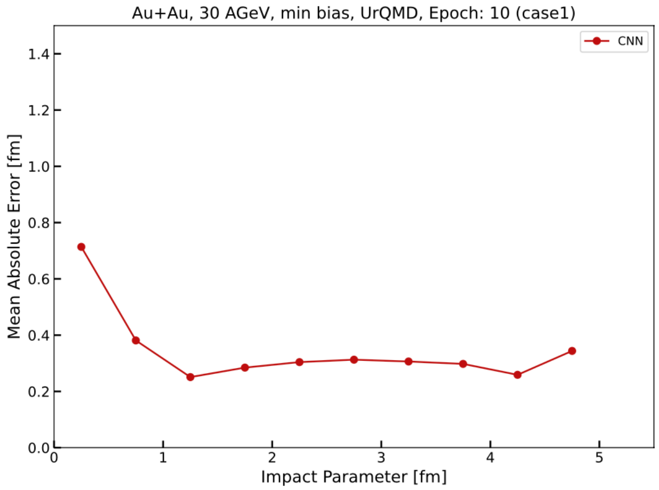
Since the ANN detects QGP collisions equally well, it is model independent in this case

UrQMD: Trained and Validated

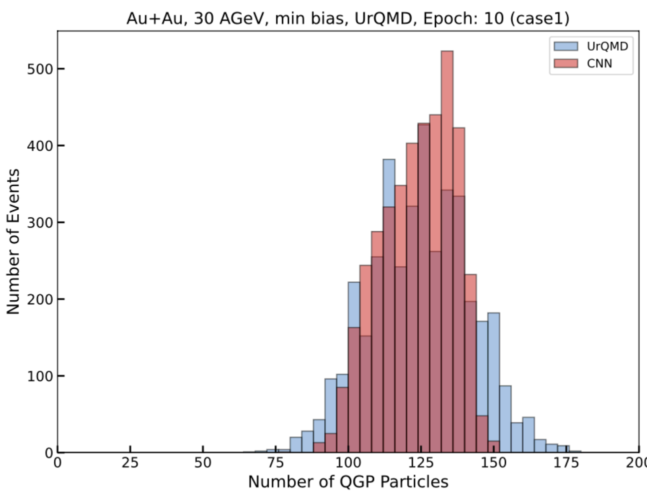
A. Belousov, M. Bleicher, J. Steinheimer-Froschauer

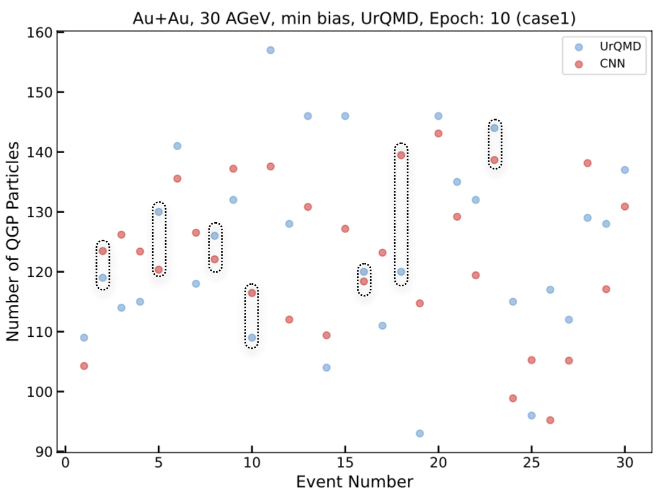
Impact Parameter





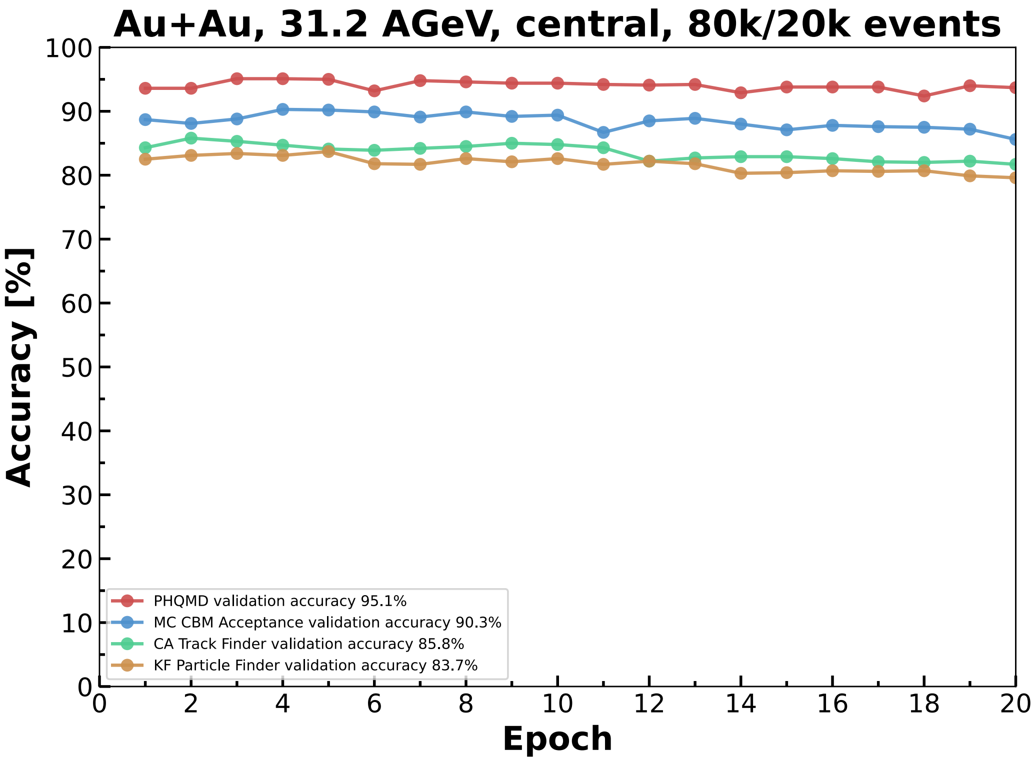
Number of QGP Particles





The basic characteristics of the collision are well reconstructed by ANN (according to the UrQMD model)

A. Belousov, P. Kisel



	Stage	Efficiency	Drop
1	CNN on PHSD	**95.1%**	
2	CBM Acceptance	**90.3%**	- 4.8%
3	CA Track Finder	**85.8%**	- 4.5%
4	KF Particle Finder	**83.7%**	- 2.1%

Online selection of collisions with QGP is possible in the CBM experiment with the efficiency of 83.7%.

Publications:

- Belousov, A.; Kisel, I.; Lakos, R. A Neural-Network-Based Competition between Short-Lived Particle Candidates in the CBM Experiment at FAIR. *Algorithms* **2023**, *16*, 383. https://doi.org/10.3390/a16080383
- Belousov, A.; Kisel, I.; Lakos, R.; Mithran, A. Neural-Network-Based Quark–Gluon Plasma Trigger for the CBM Experiment at FAIR. *Algorithms* **2023**, *16*, 344. https://doi.org/10.3390/a16070344

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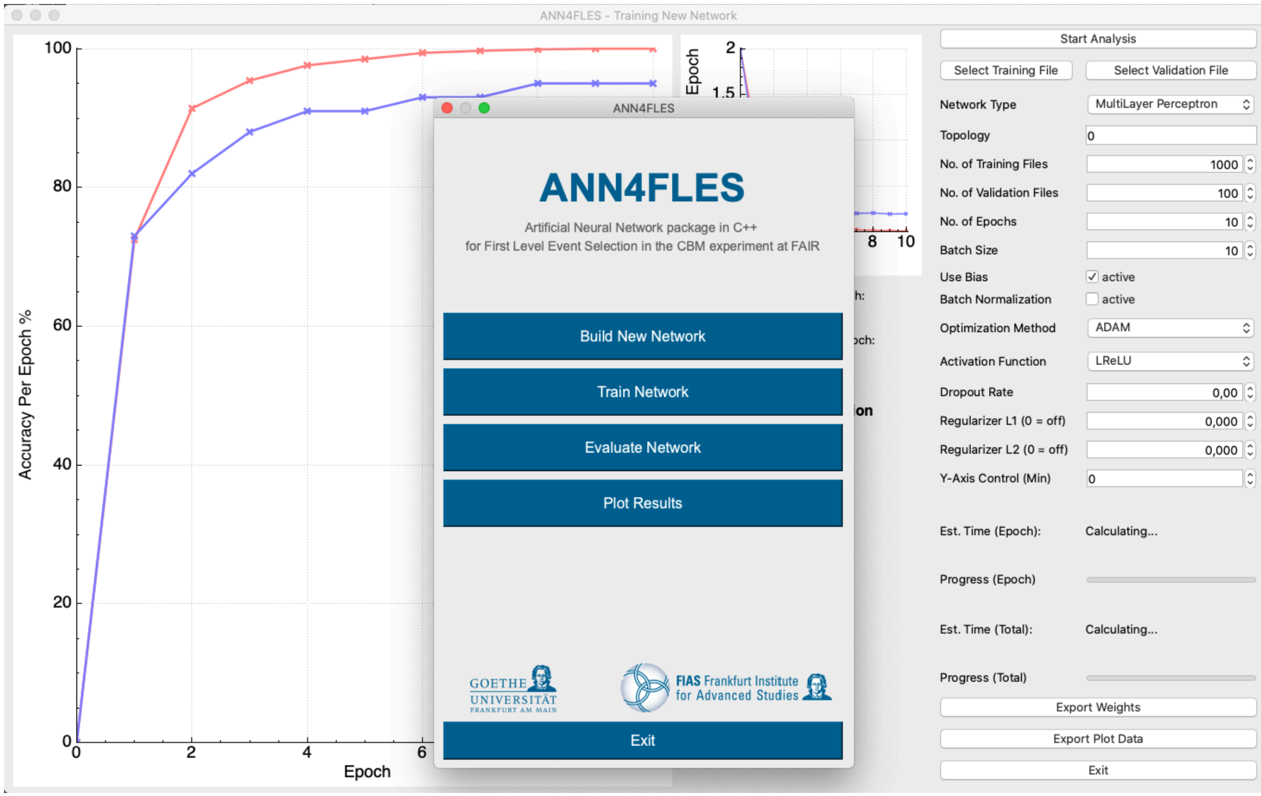
Summary



- A package of algorithms ANN4FLES based on Artificial Neural Networks for the CBM, ALICE and STAR experiments is under development.
- The package has already been successfully used for data reconstruction and analysis, and for the estimation of the properties of colliding matter.