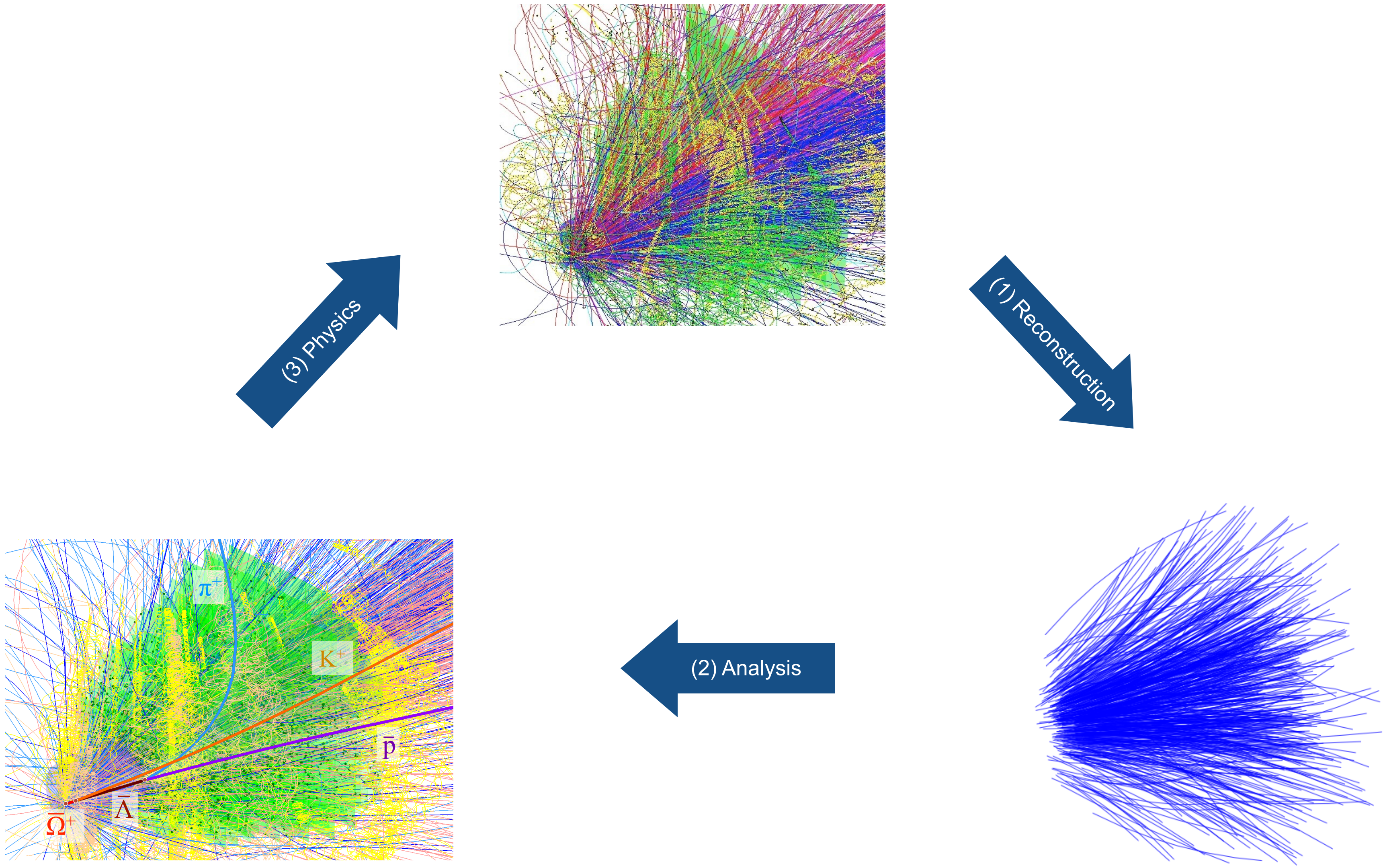
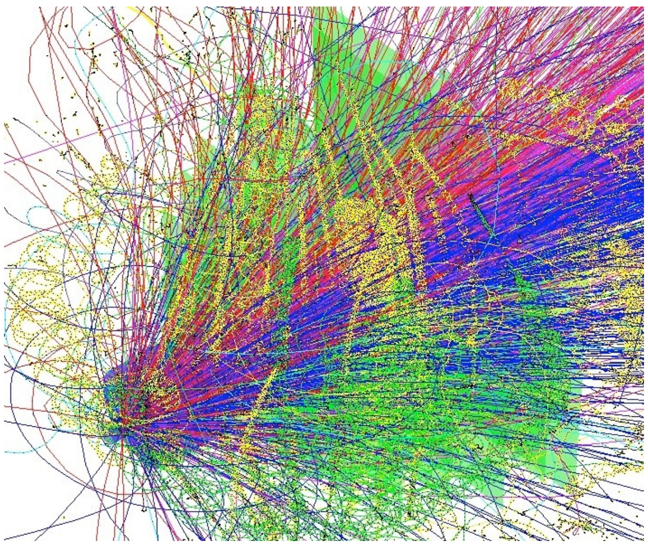
From particle trajectories to QGP with Artificial Neural Networks

Ivan Kisel

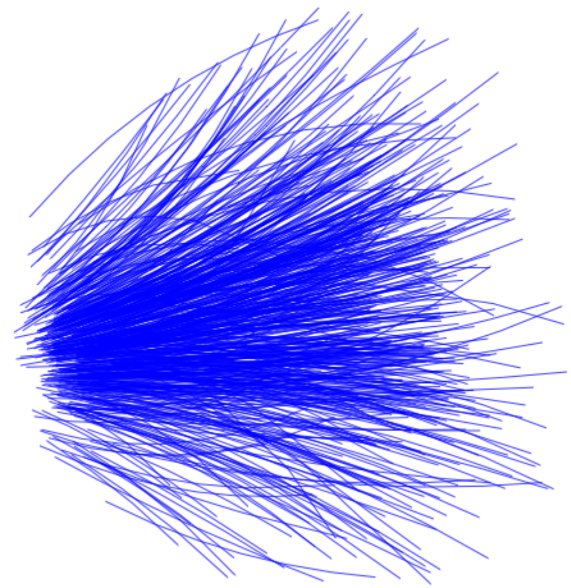
Outline


(1) Reconstruction
(2) Analysis
(3) Physics
π^+
K^+
$\bar{p}$
$\bar{\Lambda}$
$\bar{\Omega}^+$

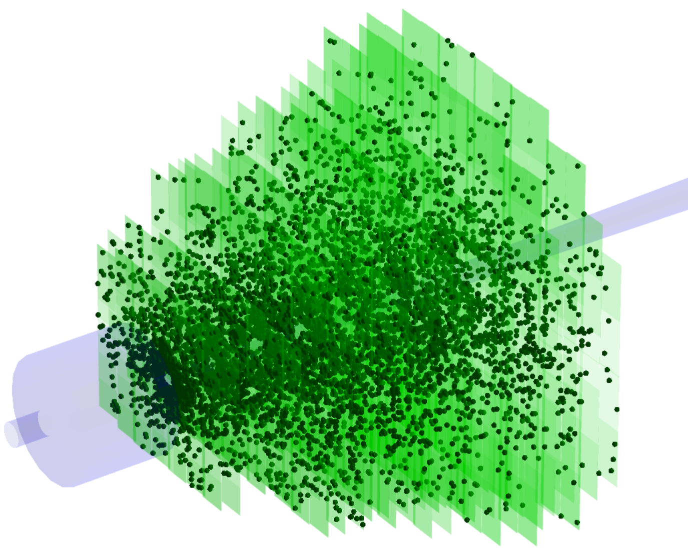
(1) Reconstruction



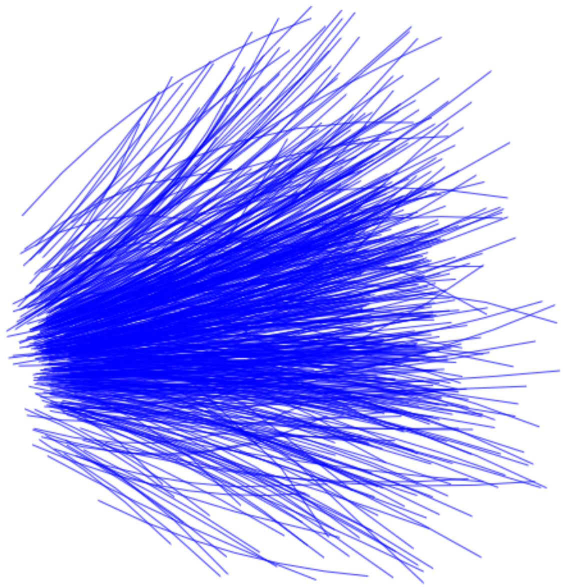
(1) Reconstruction



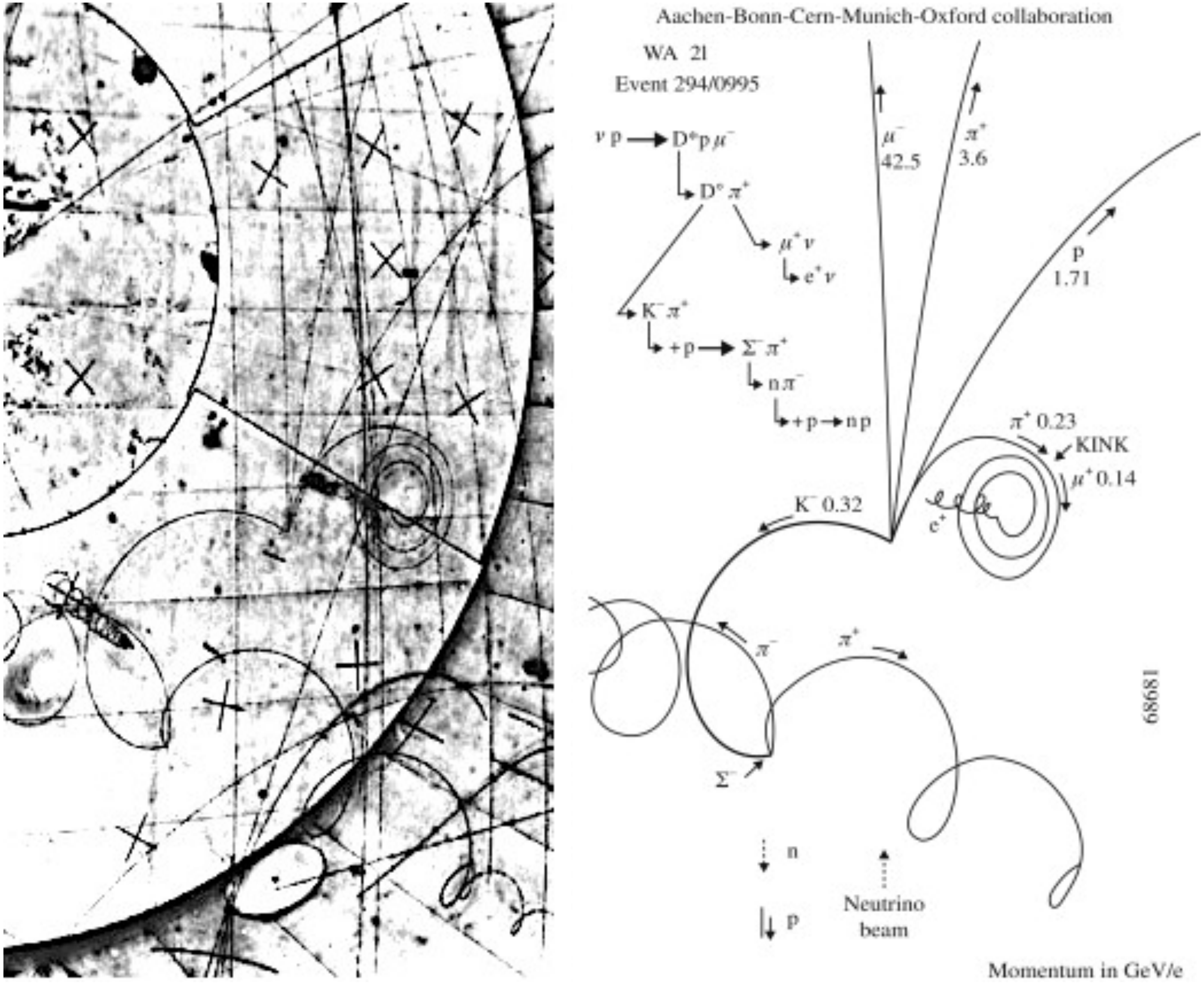
(1) Reconstruction



(1) Reconstruction



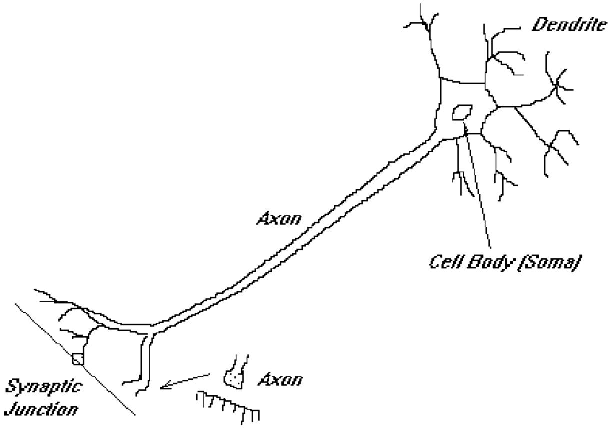
Reconstruction in Bubble Chambers



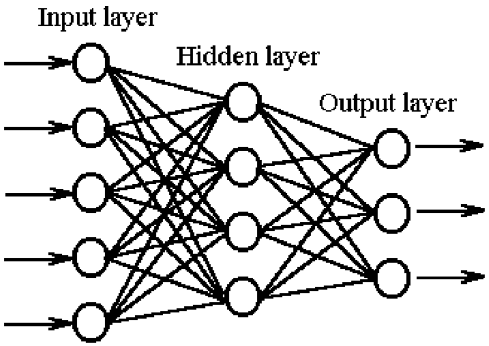
Typical particle tracks seen from a bubble chamber (left) and their interpretations (right). Courtesy of CERN.

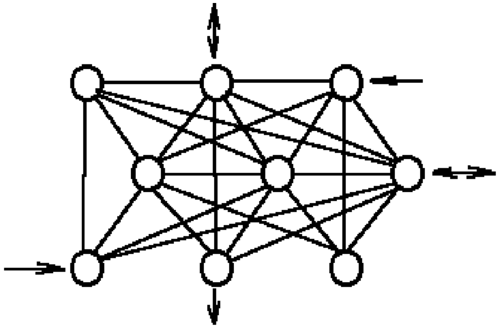
(Oversimplified) Artificial Neural Networks (ANNs)

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



Schematic structure of a neuron.



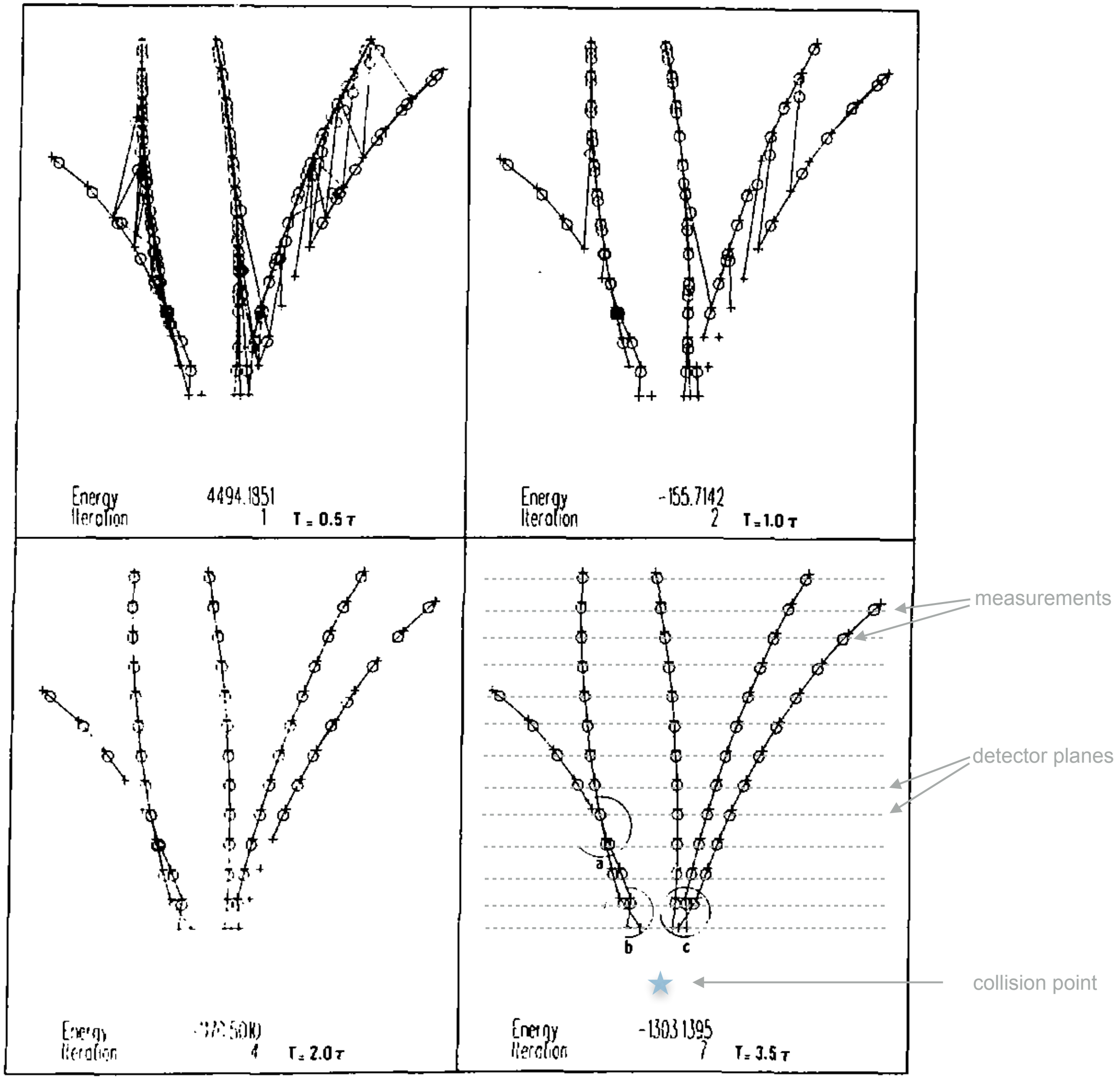


Two models of neural networks: the perceptron model and the recurrent model.

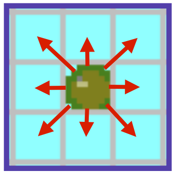
ANN for Reconstruction of Trajectories

Bruce Denby, Neural Networks and Cellular Automata in Experimental High Energy Physics, 1987

- Energy function
- Global interaction
- Local minima
- Very slow



Cellular Automaton - Game "Life"



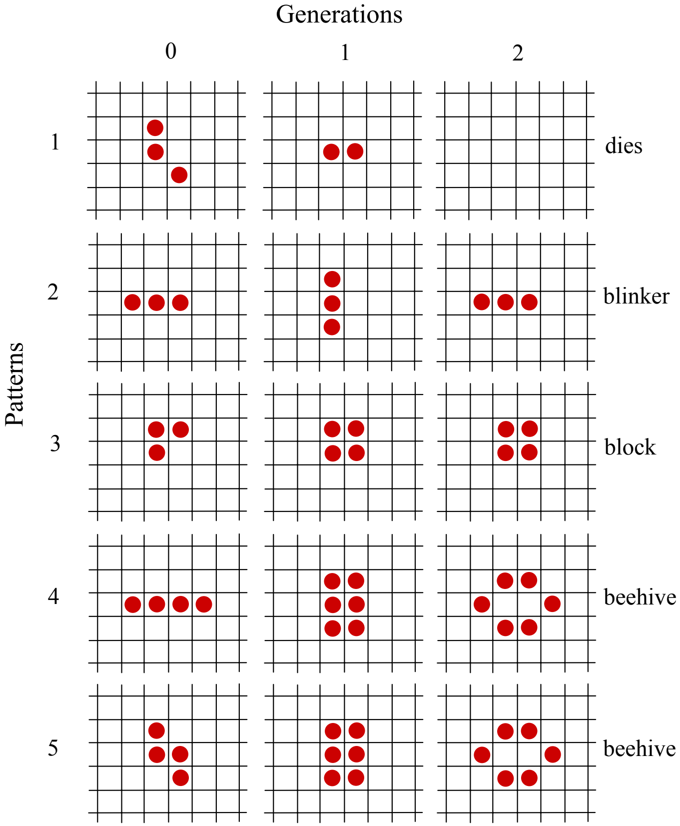
Each **cell** has 8 neighboring cells, 4 adjacent orthogonally, 4 adjacent diagonally. The **rules** are:

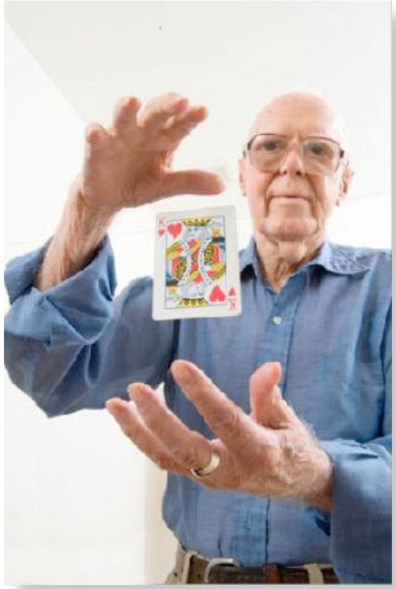
Survival: Every counter with 2 or 3 neighboring counters survives for the next generation.

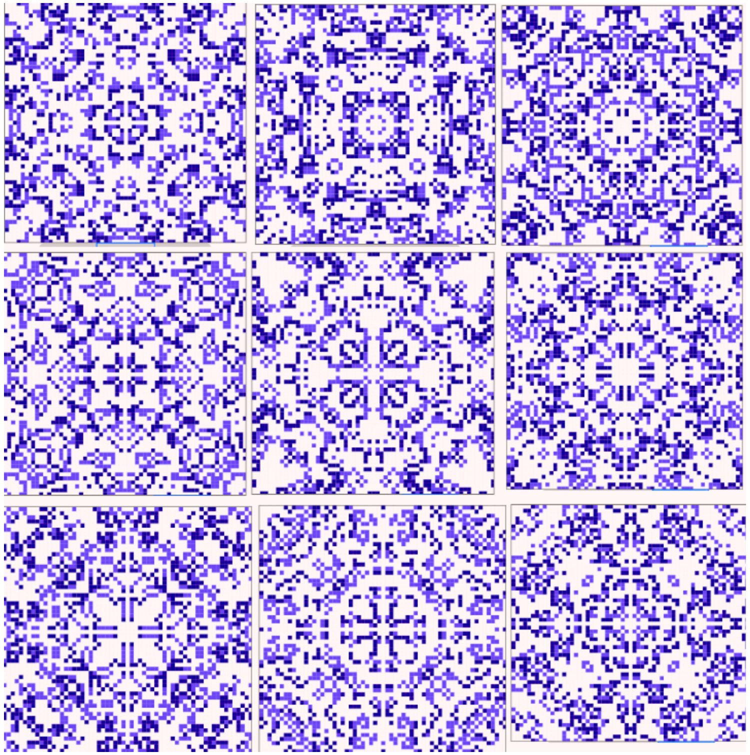
Death: Each counter with 4 or more neighbors dies from overpopulation, with 1 neighbor or none dies from isolation.

Birth: Each empty cell adjacent to exactly 3 neighbors is a birth cell.

It is important to understand that all births and deaths occur *simultaneously*.

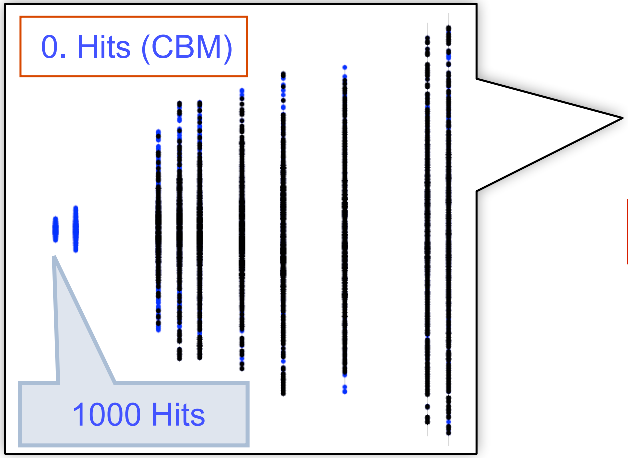


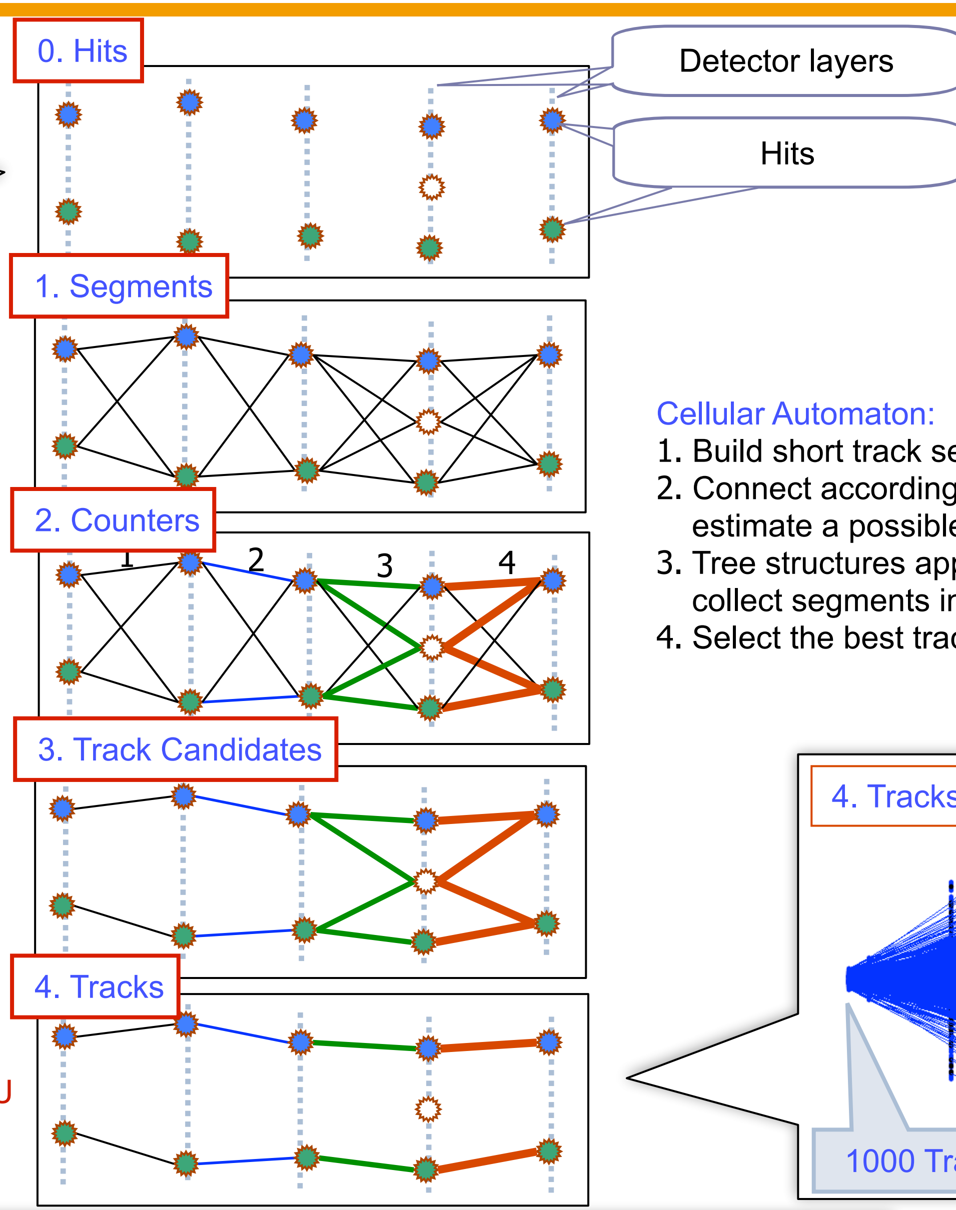




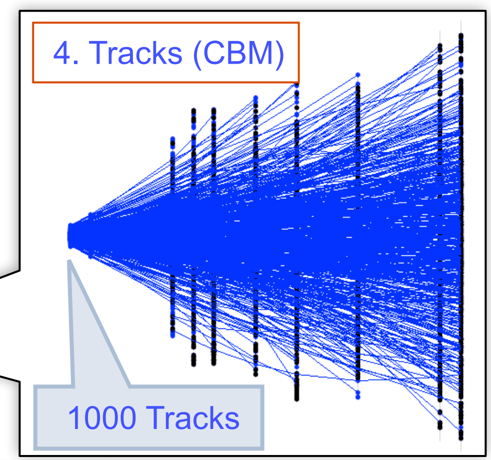
Martin Gardner, Mathematical games: The fantastic combinations of John Conway's new solitaire game „Life", Sci. Amer., 223 (1970) 120-123

CBM: 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.

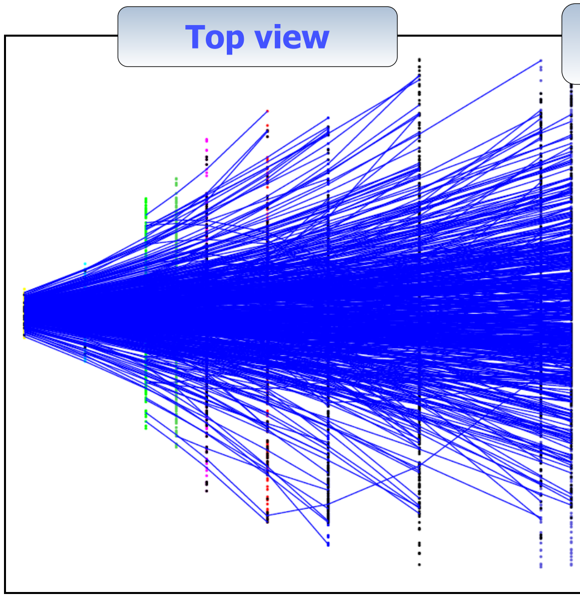


Cellular Automaton:
- local w.r.t. data
- intrinsically parallel
- extremely simple
- very fast

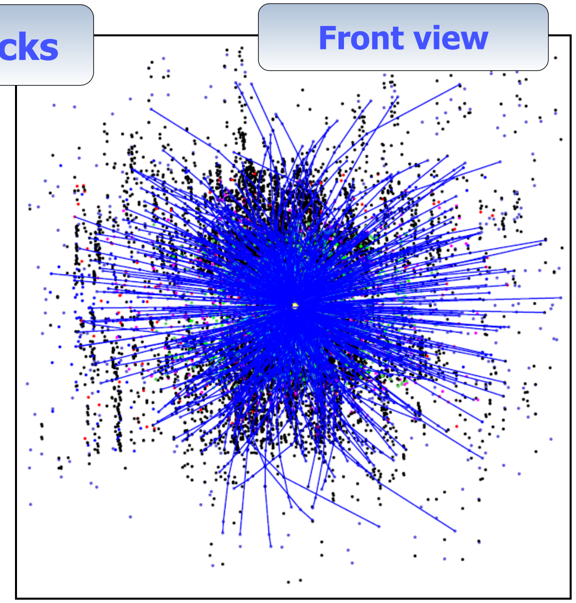
Deeply appropriate for many-core CPU/GPU

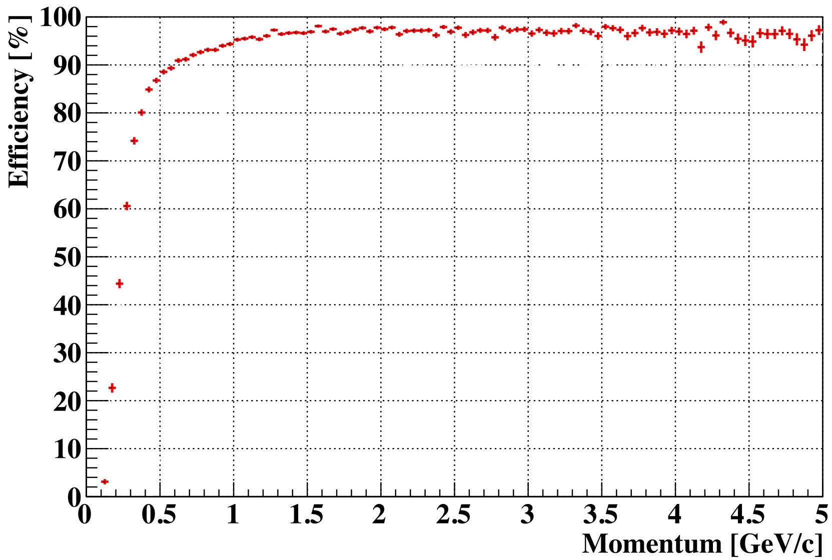
Useful for complicated event topologies with heavy combinatorics

CBM: Cellular Automaton (CA) Track Finder



770 Tracks



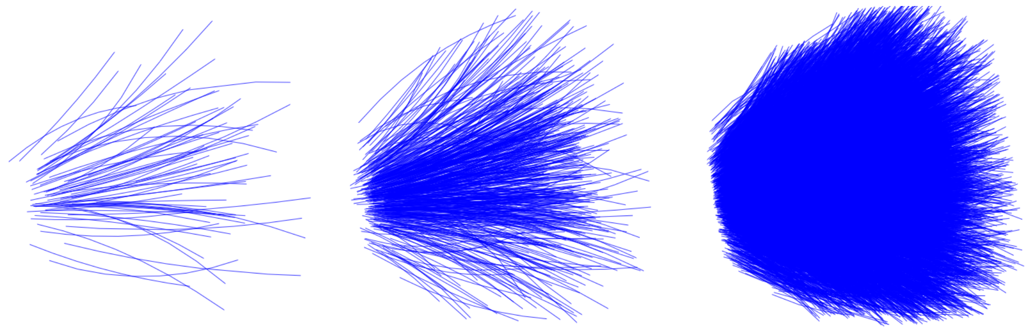


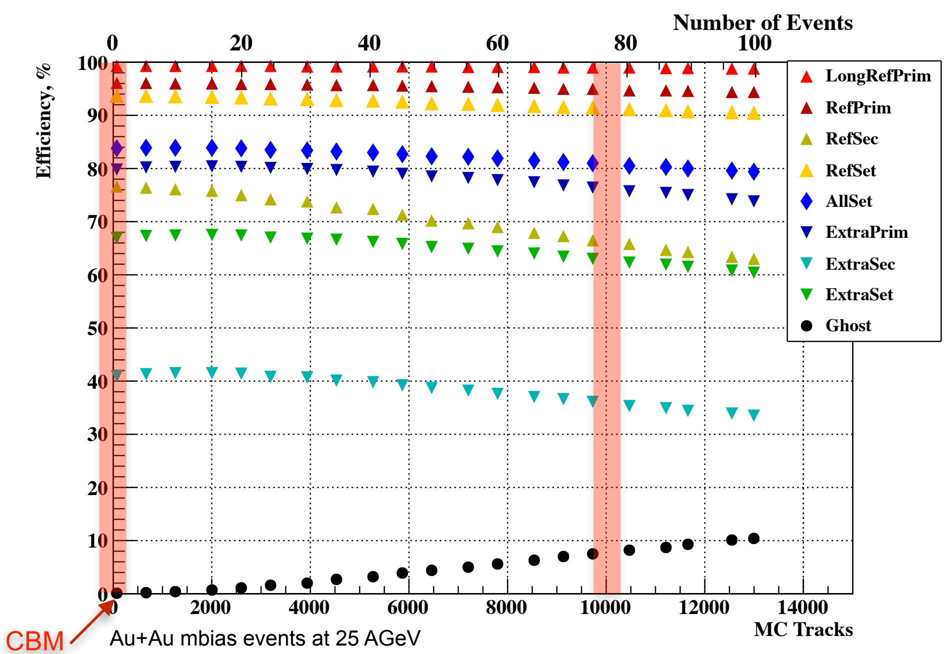
Track category	Eff, %
All tracks	90.9
Primary high-p	97.5
Primary low-p	92.6
Secondary high-p	91.1
Secondary low-p	63.8
Clone level	0.4
Ghost level	5.9
MC tracks found	134
Time, ms/ev	10

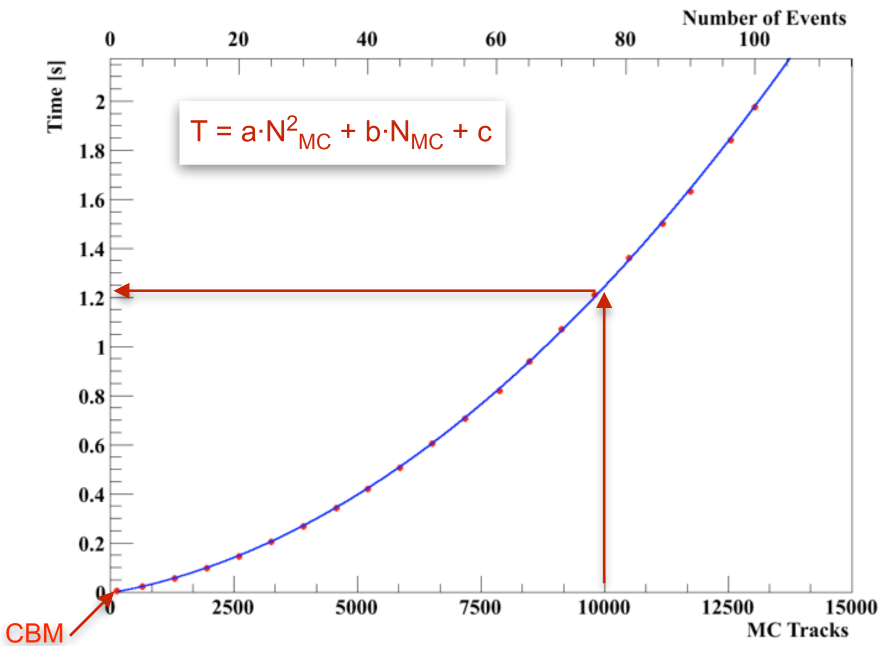
Fast and efficient track finder

CBM: CA Track Finder at High Track Multiplicity

A number of minimum bias events is gathered into a group (super-event), which is then treated by the CA track finder as a single event.



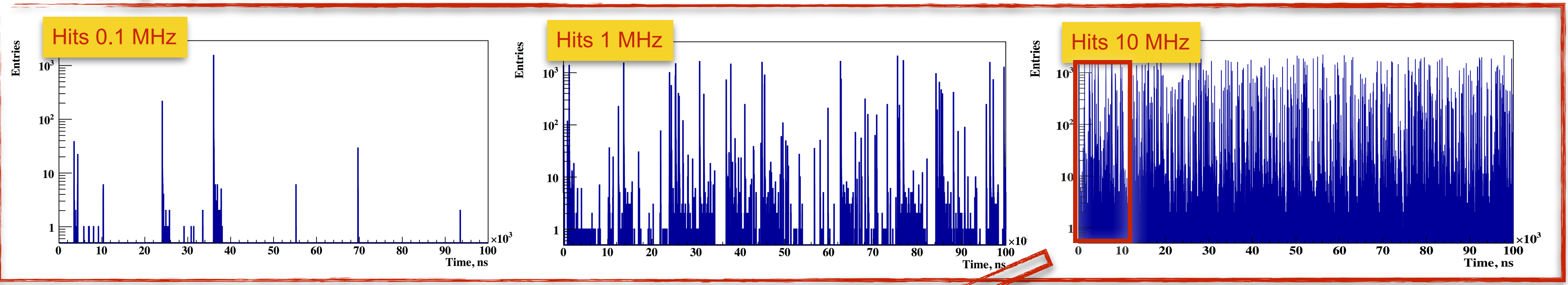




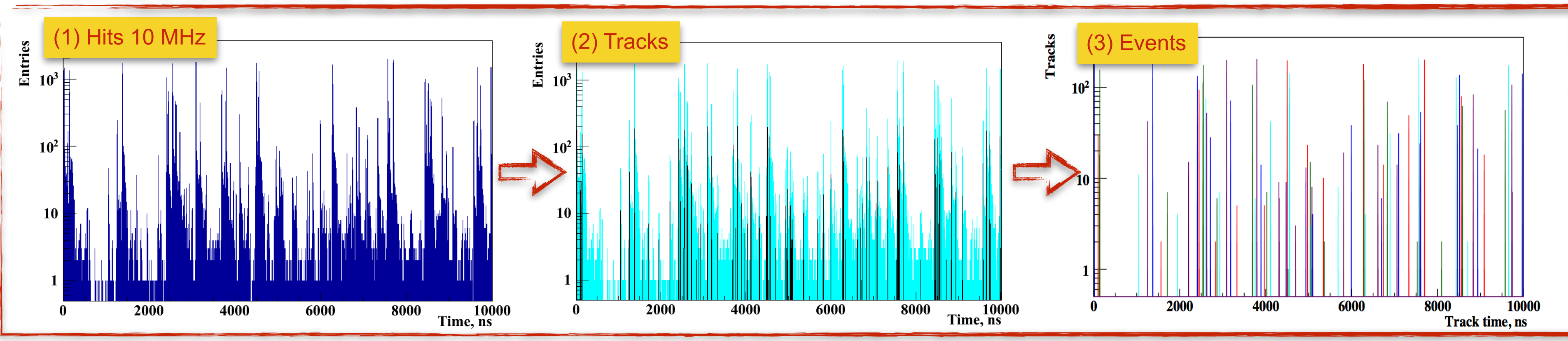
Reliable reconstruction efficiency and time as a second order polynomial w.r.t. to the track multiplicity

CBM: 4D Event Building at 10 MHz

Hits at high input rates



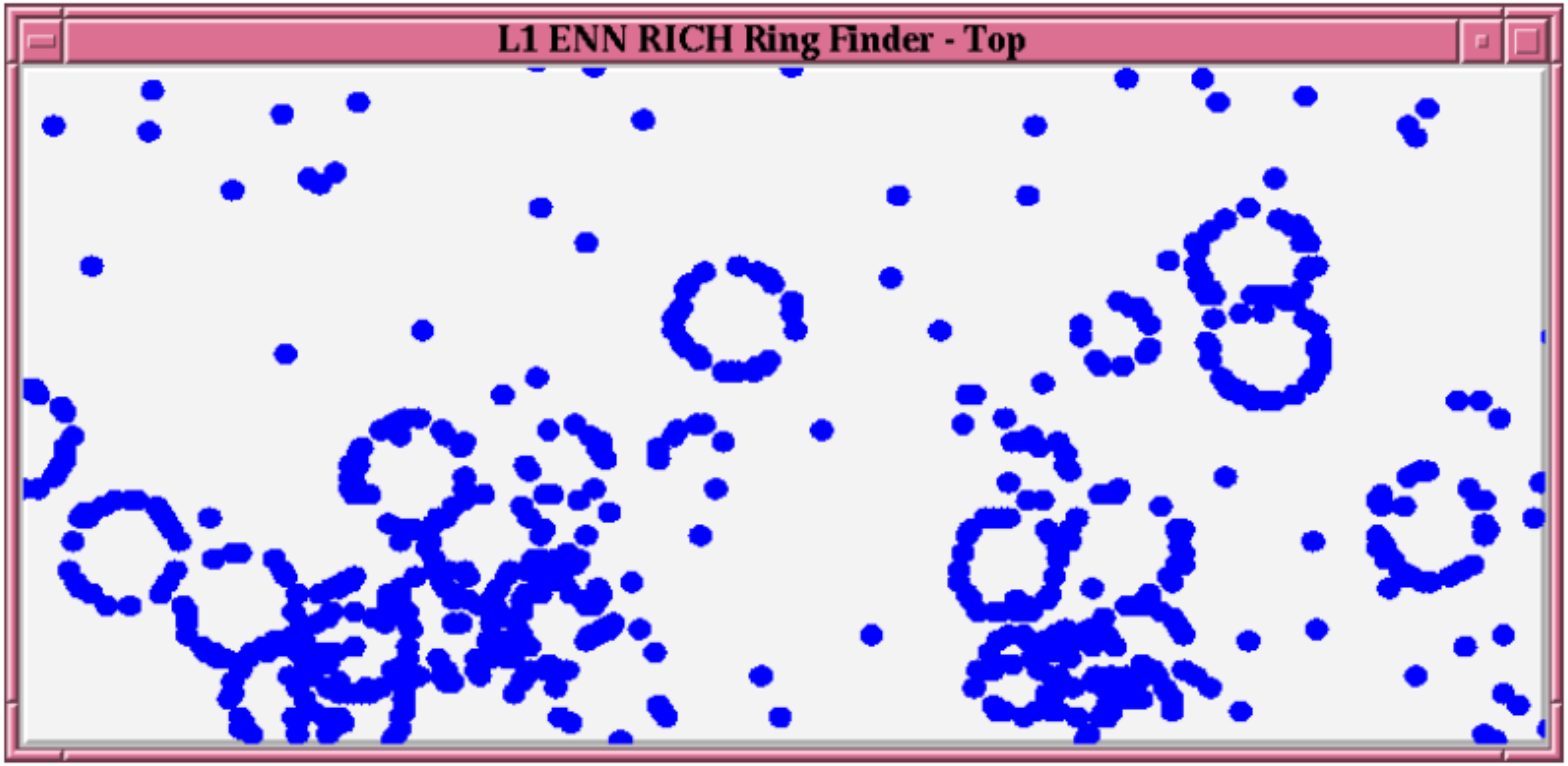
From hits to tracks to events



V. Akishina

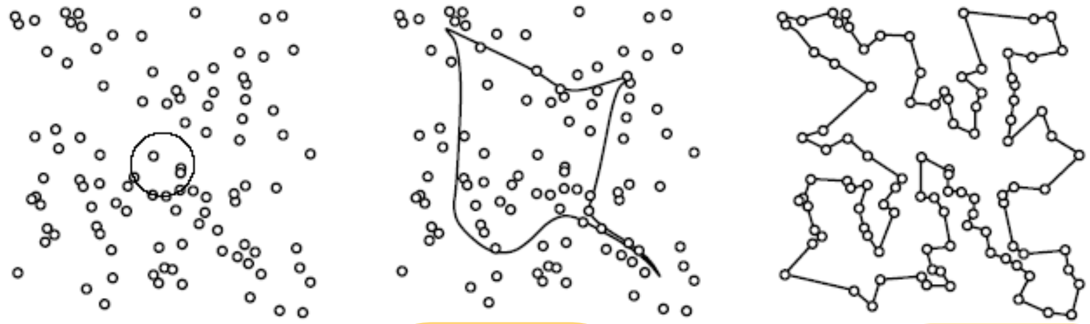
Reconstructed tracks clearly represent groups, which correspond to the original events

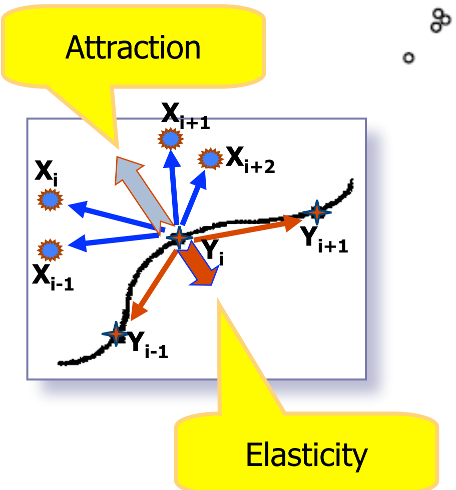
Ring-Imaging Cherenkov Detector (RICH)



Elastic Neural Net (EN) for TSP

R. Durbin and D. Willshaw, An analogue approach to the travelling salesman problem, Nature, 326 (1987) 689





Attraction

Elasticity

Simple

$$E(s_{ia},\vec{y}_a) = \sum_{ia} s_{ia}\cdot|\vec{x}_i-\vec{y}_a|^2 + \gamma\cdot\sum_{a} |\vec{y}_a-\vec{y}_{a+1}|^2$$

$$\Delta\vec{y}_a = \eta\left[2\sum_{i} v_{ia}\cdot(\vec{x}_i-\vec{y}_a)+\gamma\cdot(\vec{y}_{a+1}-2\vec{y}_a+\vec{y}_{a-1})\right]$$

Discrete EN

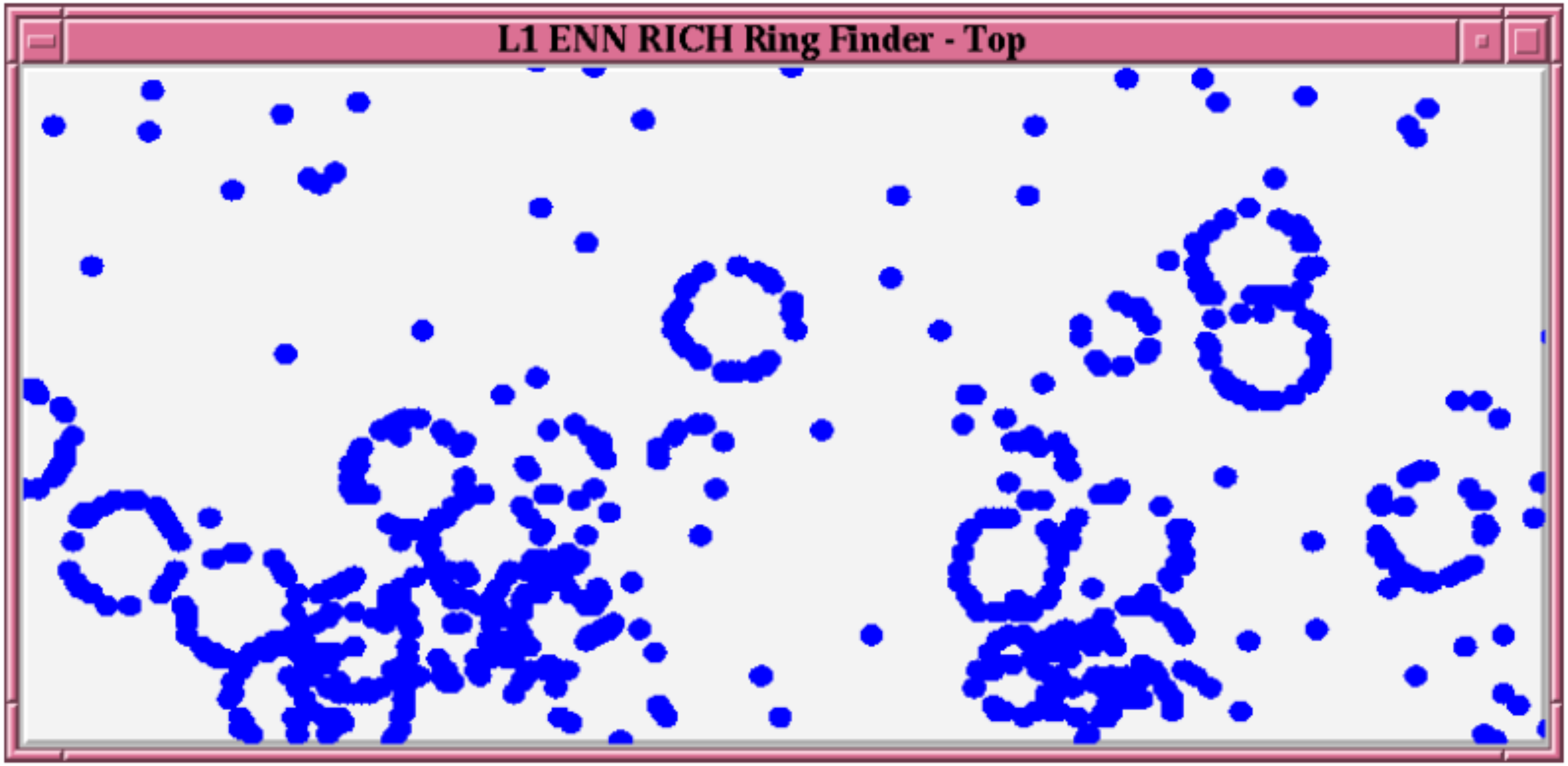
File name	Number of cities	Extra path (%)	Time, ms	Time per city, μs
berlin52	52	0.00	0.98	19
st70	70	4.27	1.27	18
kroA100	100	3.03	1.46	15
lin105	105	0.78	1.84	18
ch130	130	5.59	2.56	20
tsp225	225	5.34	4.36	19
pcb442	442	8.37	12.35	28
pr1002	1002	6.12	24.94	25
pr2392	2392	8.42	58.53	24

(*) Pentium IV/2.4 GHz

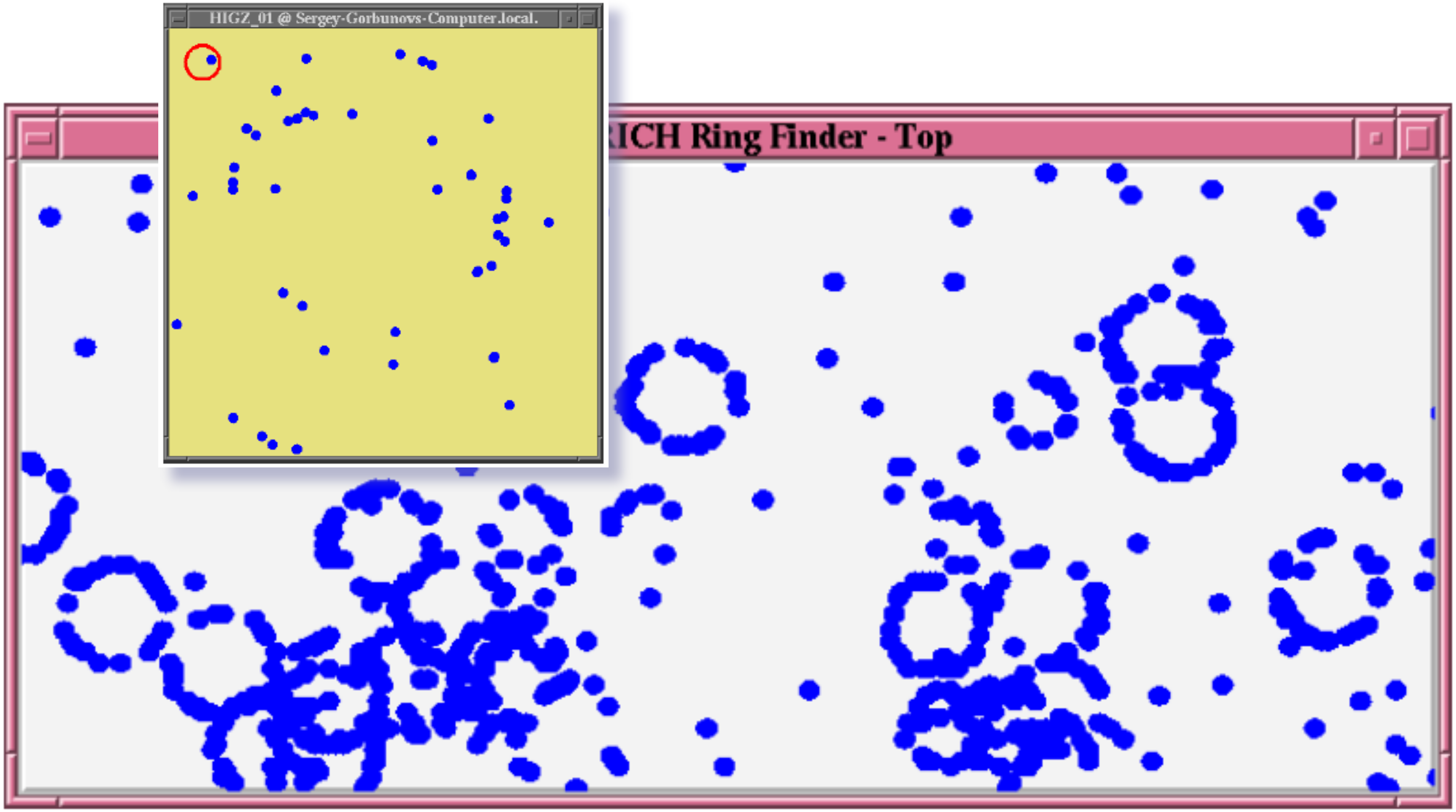
Fast

S. Gorbunov and I. Kisel, Elastic net for standalone RICH ring finding, CBM-SOFT-note-2005-002

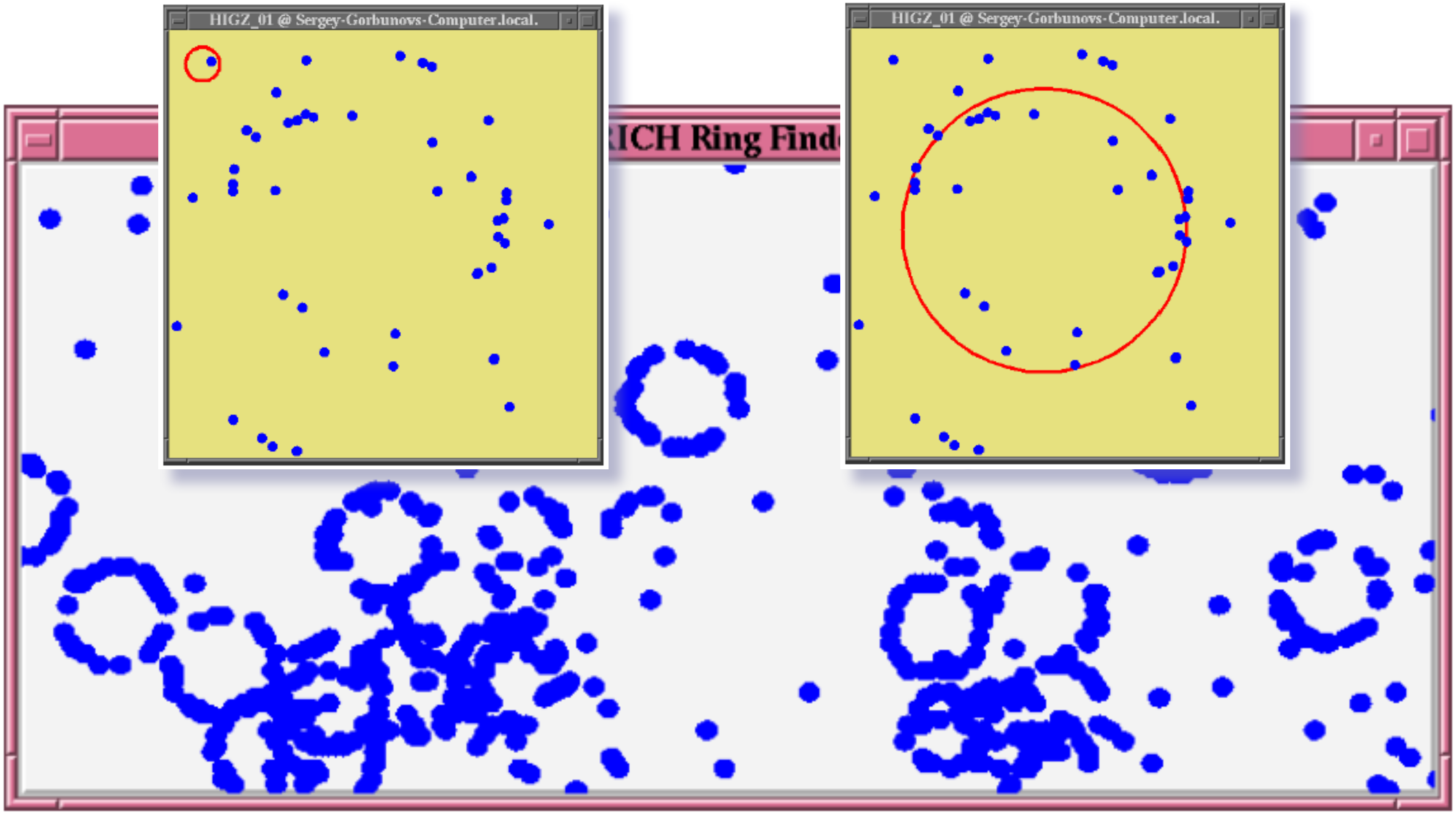
Elastic Neural Net (EN) for RICH



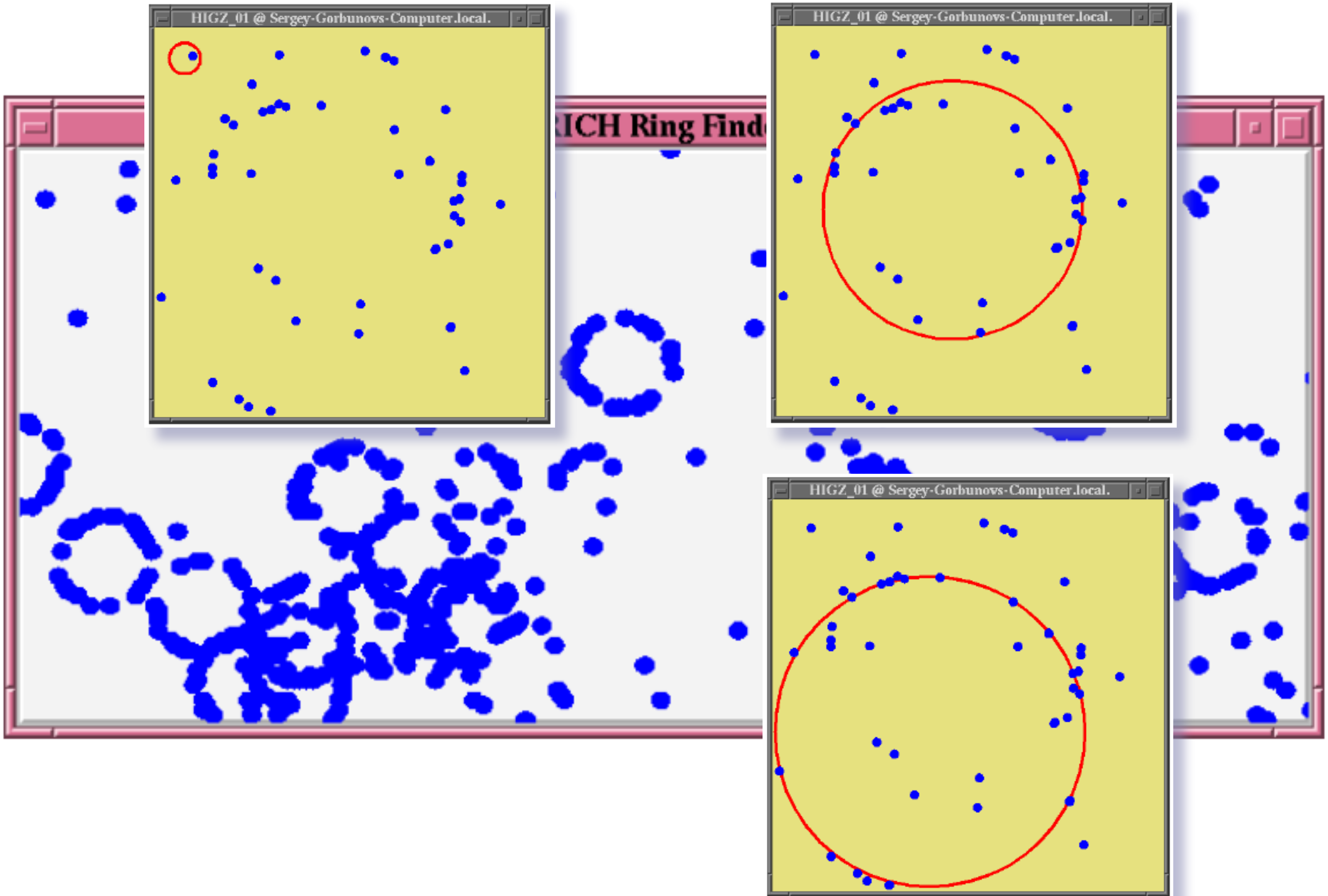
Elastic Neural Net (EN) for RICH



Elastic Neural Net (EN) for RICH



Elastic Neural Net (EN) for RICH



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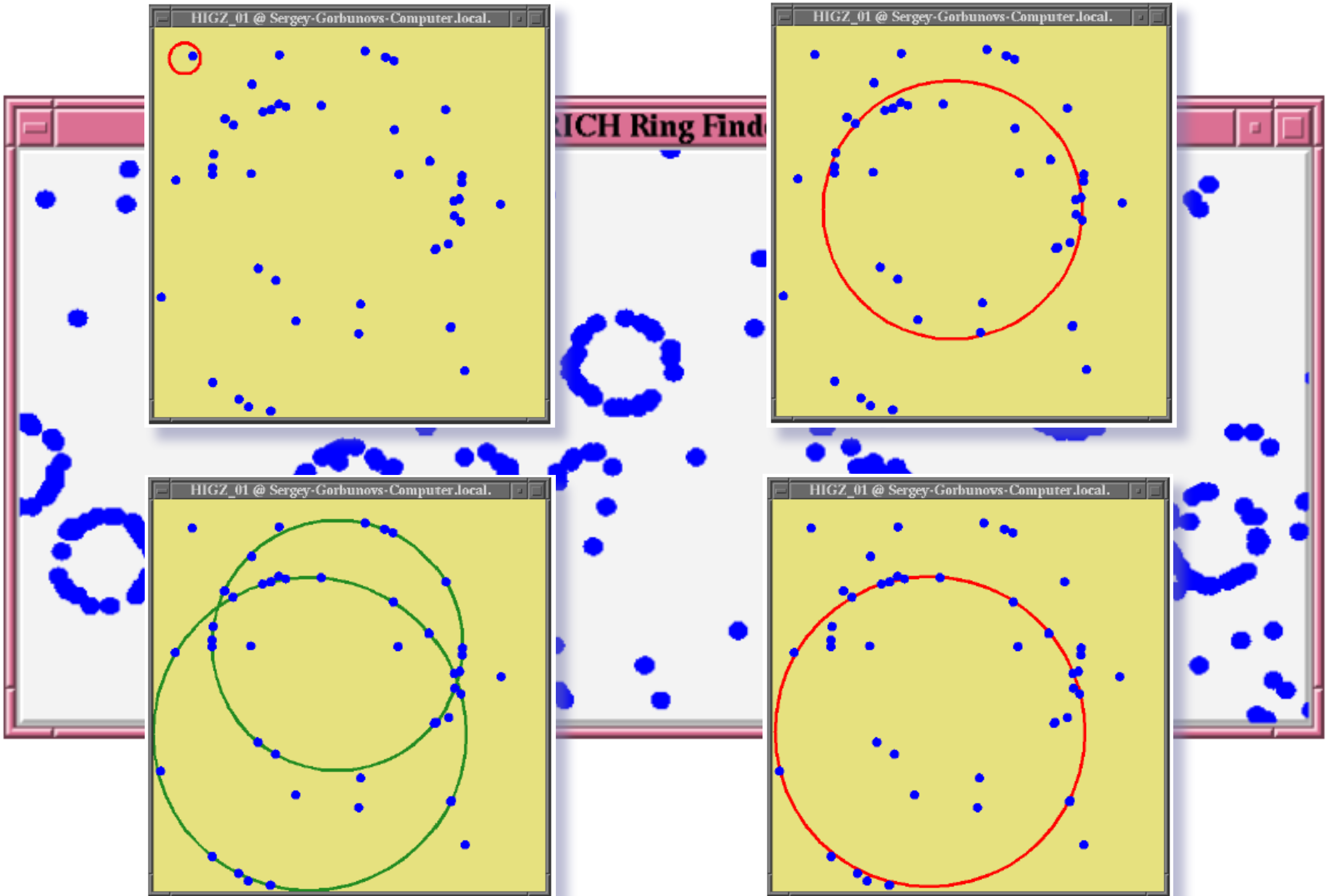
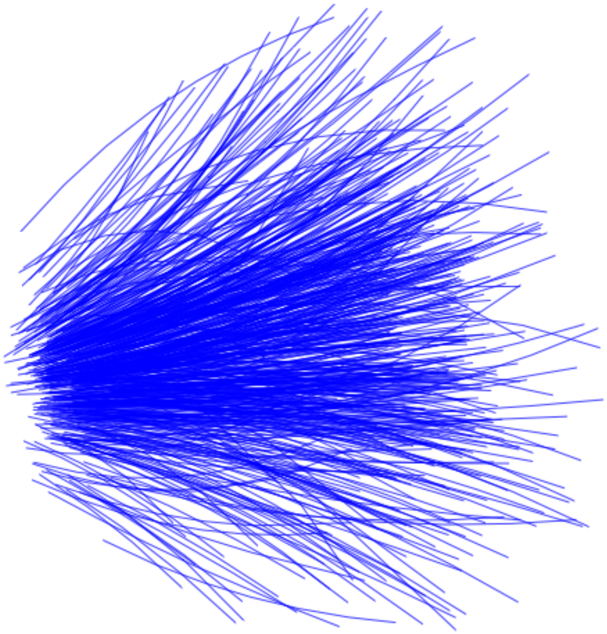
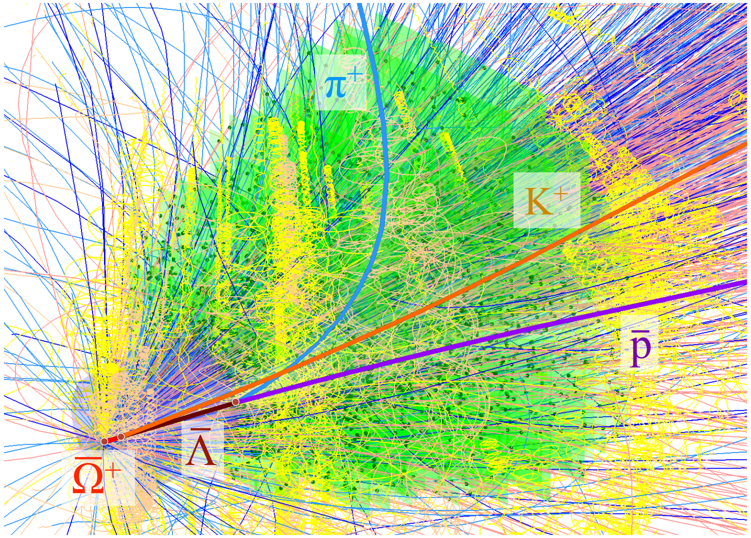


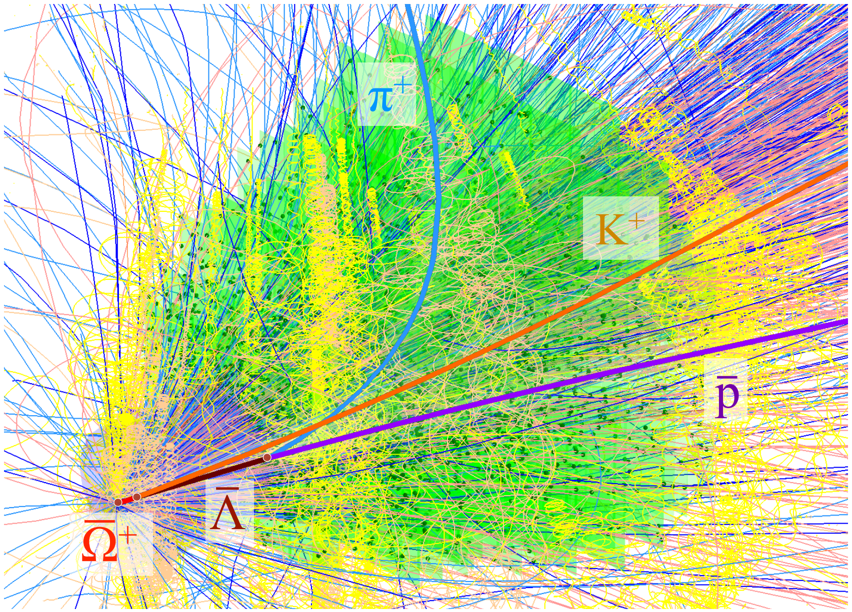
(2) Analysis



(2) Analysis



CBM: KF Particle - Reconstruction of short-lived Particles



Simulated AuAu collision at 25 AGeV

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

```
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

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

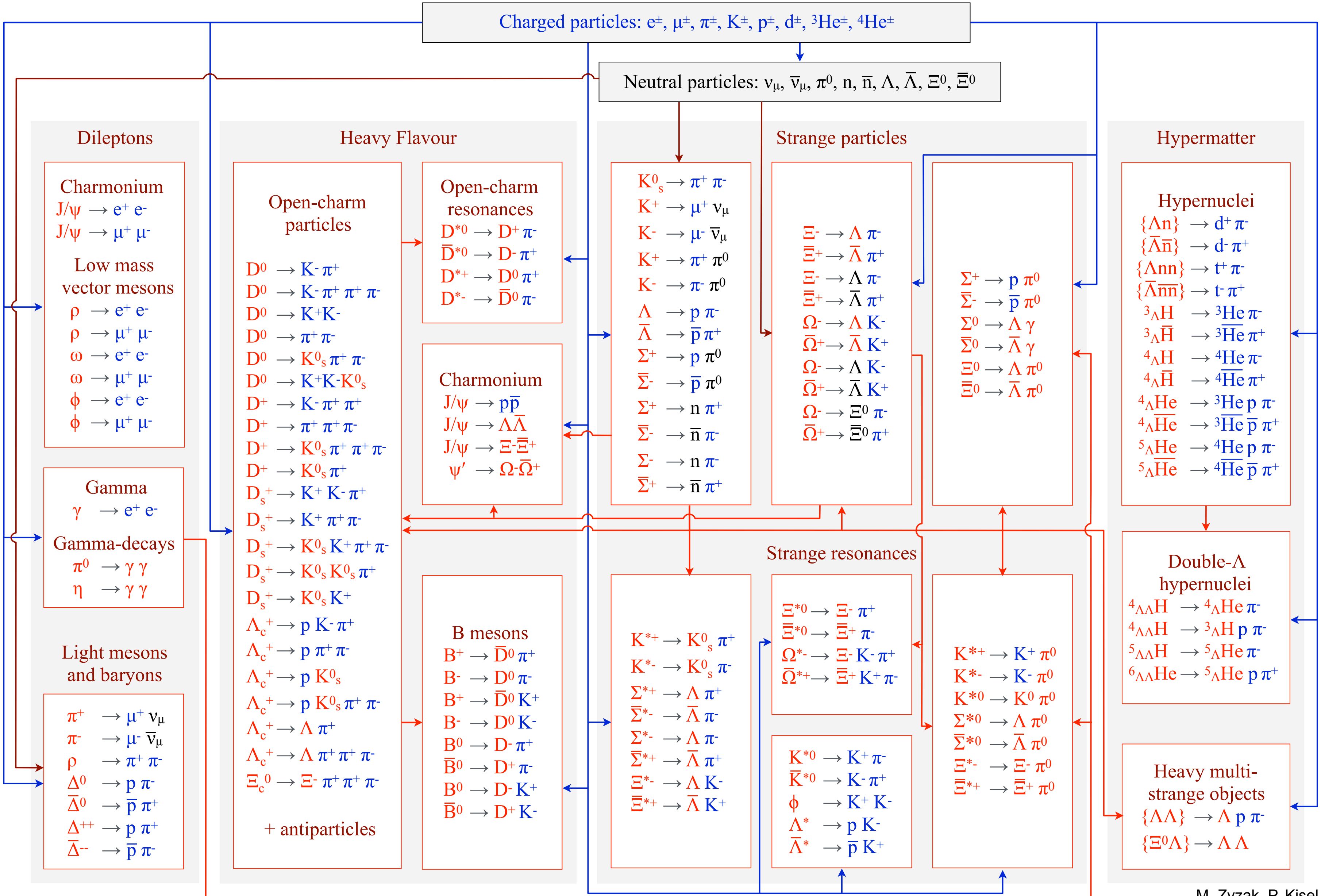
Covariance matrix

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).

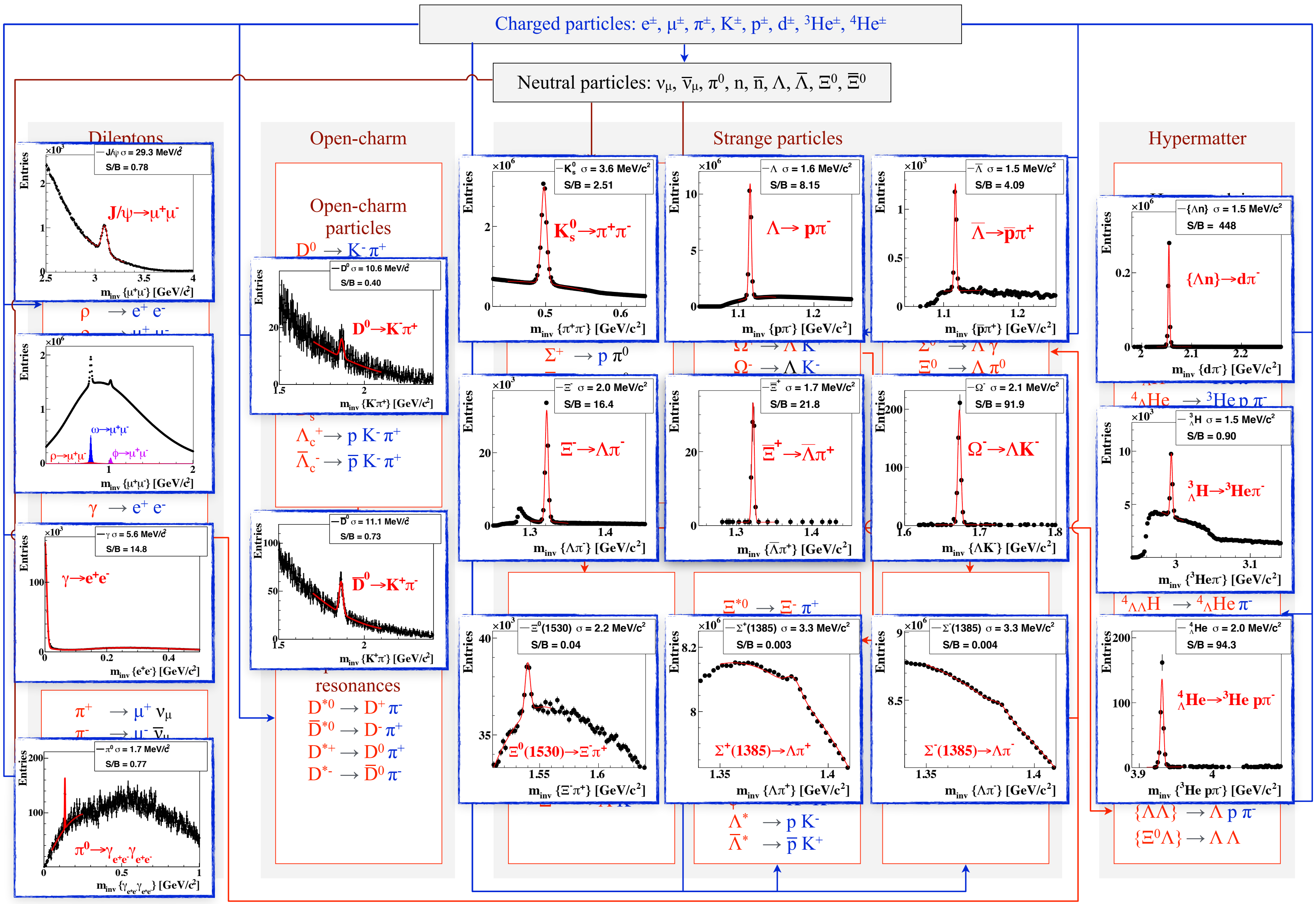
KF Particle provides a simple and very efficient approach to physics analysis

CBM: KF Particle Finder for short-lived Particles



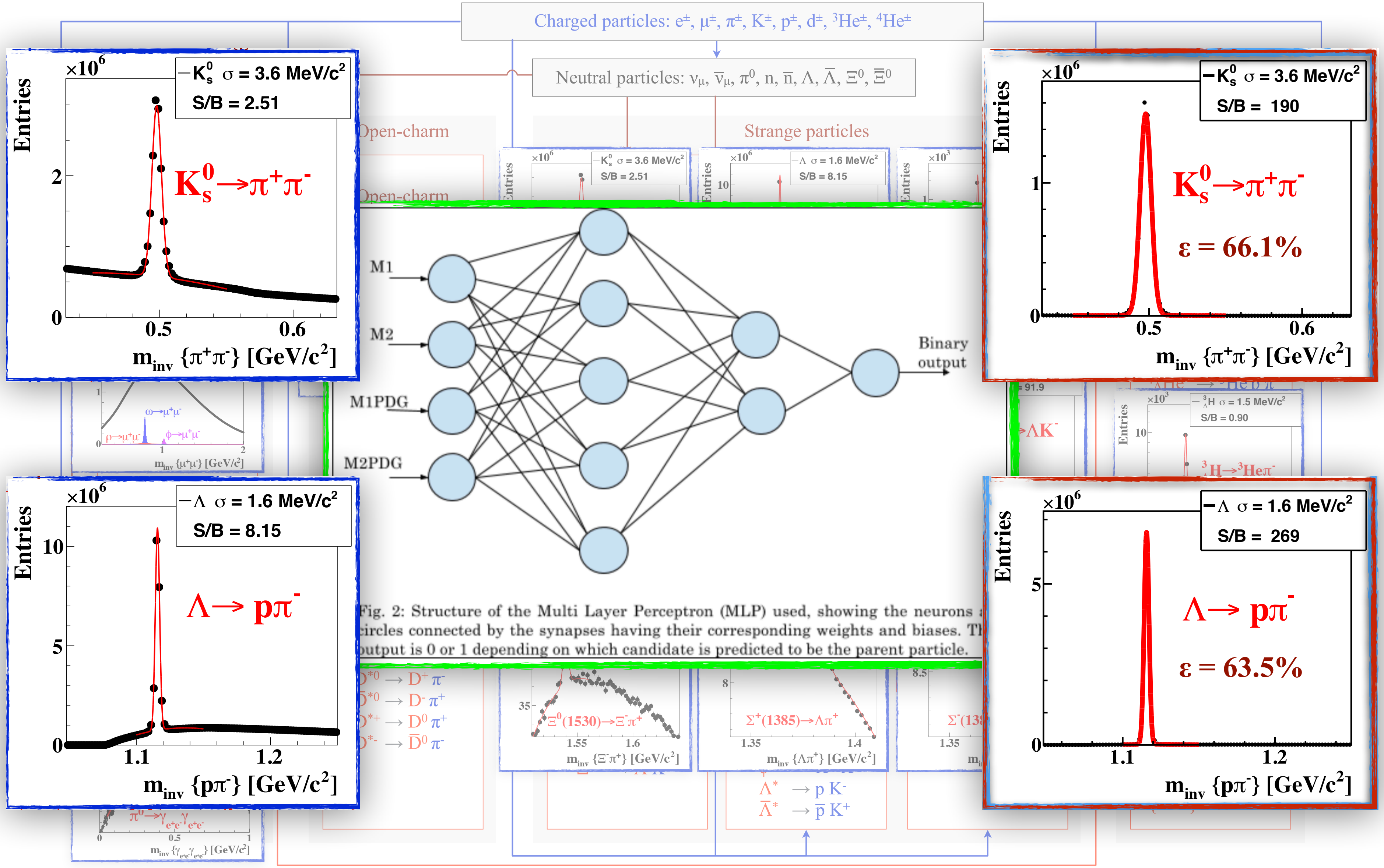
M. Zyzak, P. Kisel

CBM: KF Particle Finder for short-lived Particles



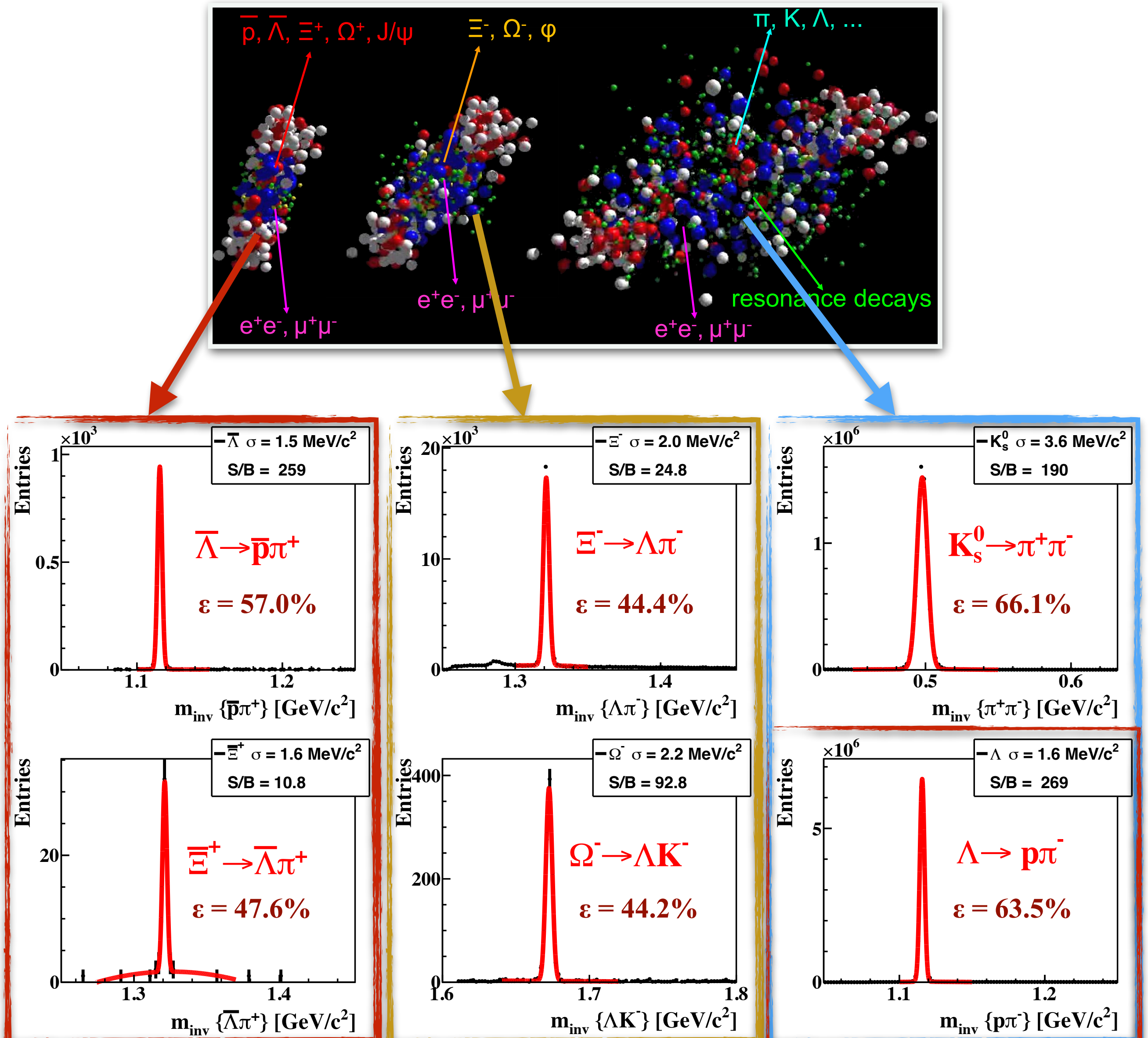
1.4 ms/event/core

ANN for Identification of short-lived Particles



A. Banerjee, I. Kisel and M. Zyzak, Int. Mod. Phys. A, Vol. 35, No. 33, 2043003 (2020)

CBM: Very Clean Probes of Collision Stages

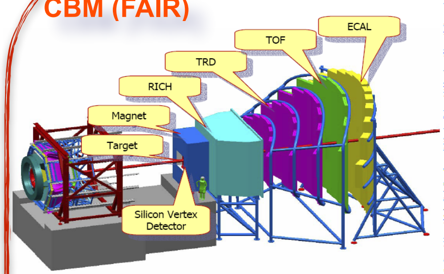


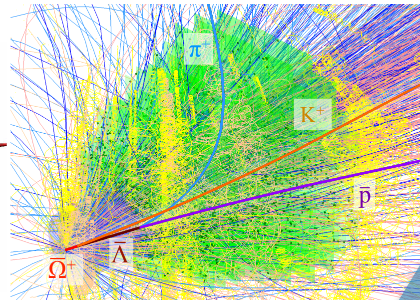
AuAu, 10 AGeV, 3.5M central UrQMD events, **MC PID**

CBM → STAR: Reconstruction and Analysis Software

Within the FAIR Phase-0 program the CBM KF Particle Finder has been adapted to STAR and applied to Au+Au collisions recorded during 2014, 2016 and BES-I.

CBM (FAIR)



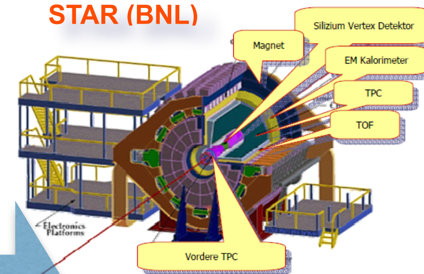


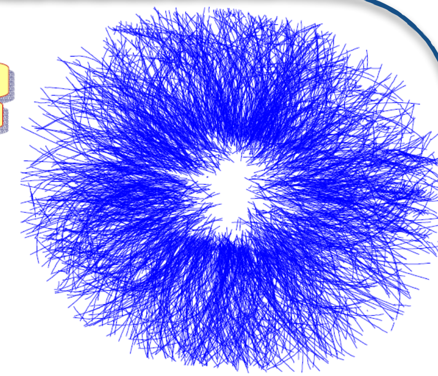
$\bar{\Omega}^+ \rightarrow \bar{\Lambda}\, K^+$

$\hookrightarrow \bar{p}\, \pi^+$

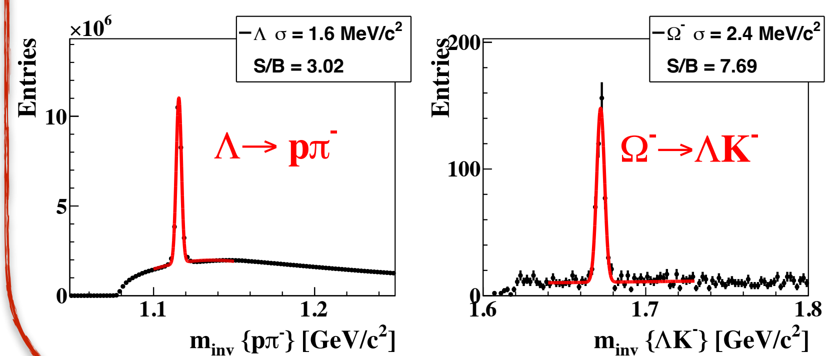
FAIR Phase-0

STAR (BNL)

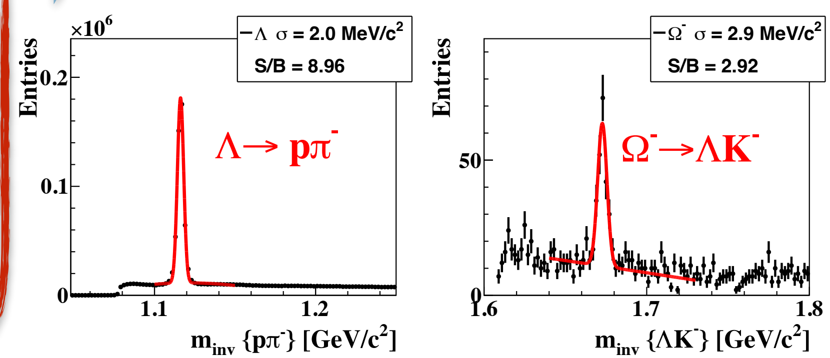




CBM, simulated data, 5M central Au+Au, 10 AGeV, PHSD



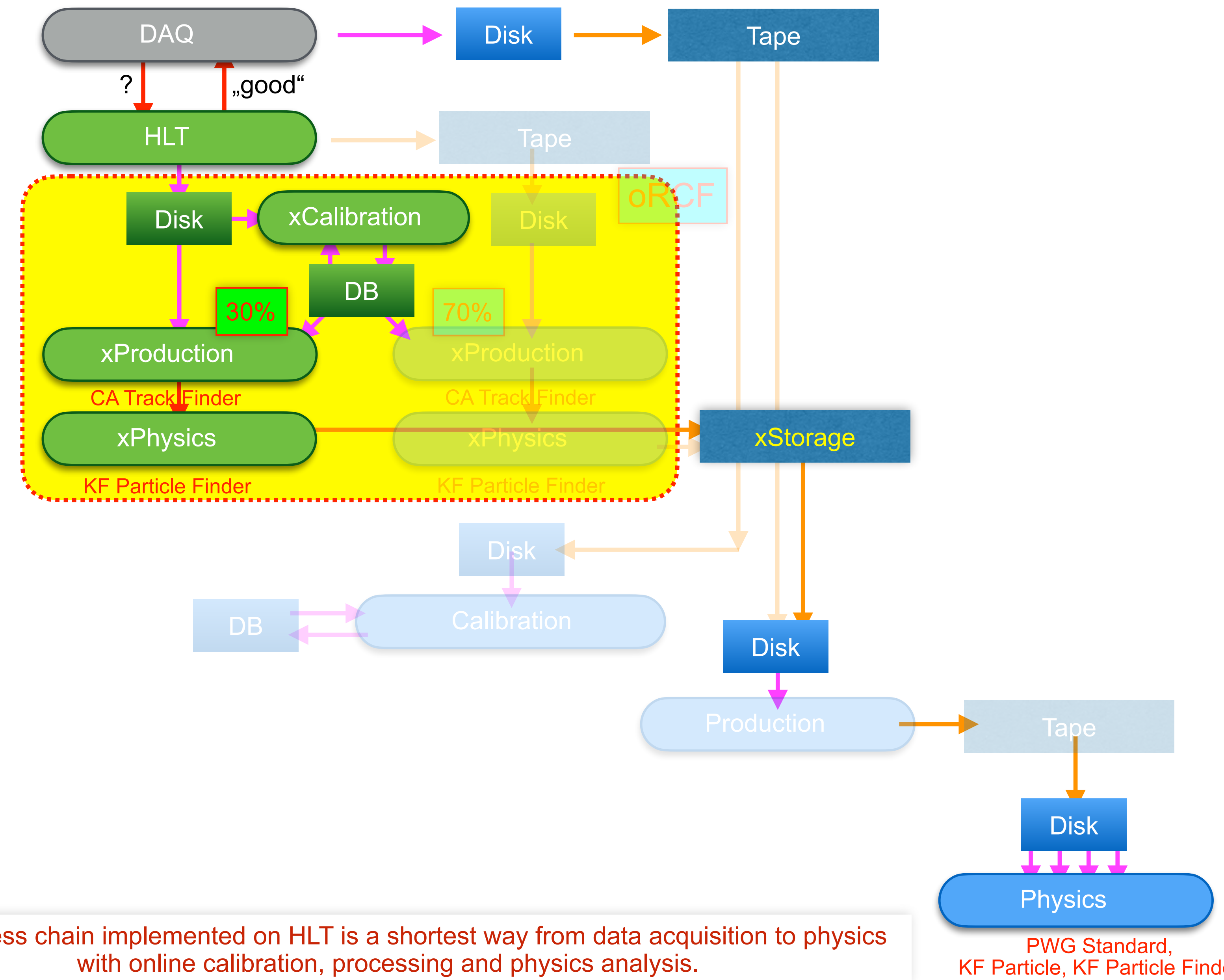
STAR, real data, 1.3M mbias Au+Au, 200 AGeV, Run 2016



- ✓ Since 2016 the Cellular Automaton (CA) Track Finder is the default STAR track finder for data production. Use of CA provides 25% more D^0 and 20% more W by reprocessing 2013 pp 510 GeV data sample.
- ✓ The KF Particle Finder provides a factor 2 more signal particles than the standard approach in STAR. The integration of the KF Particle Finder into the official STAR repository for use in physics analysis is currently in progress.

Used for the real-time express physics analysis during the BES-II runs (2018-2021)

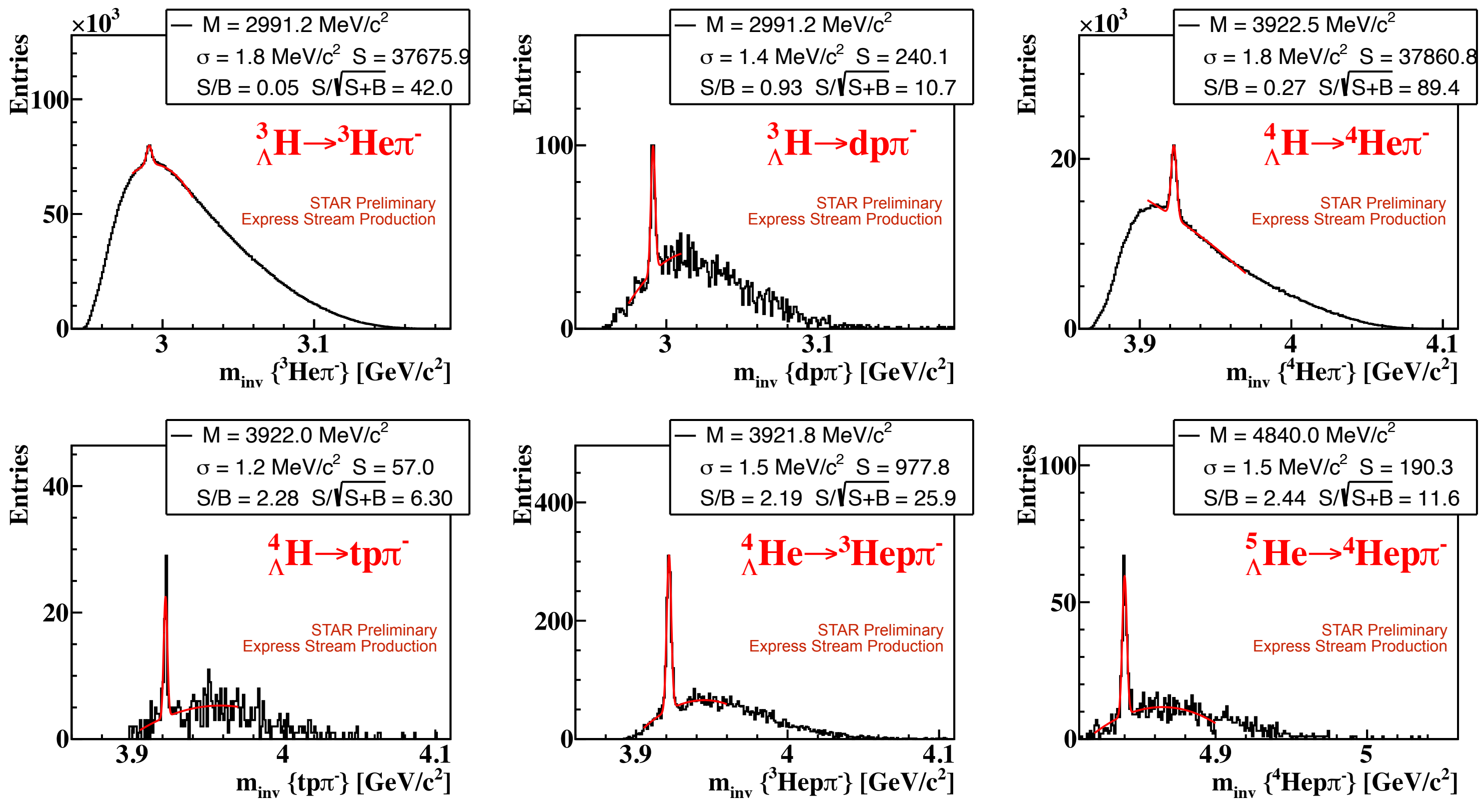
STAR BES-II: Express Production Data Stream



The express chain implemented on HLT is a shortest way from data acquisition to physics with online calibration, processing and physics analysis.

STAR BES-II: Hypernuclei

2018, 2019, 2020, 2021x FXT and 2021x collider at 7.7 GeV



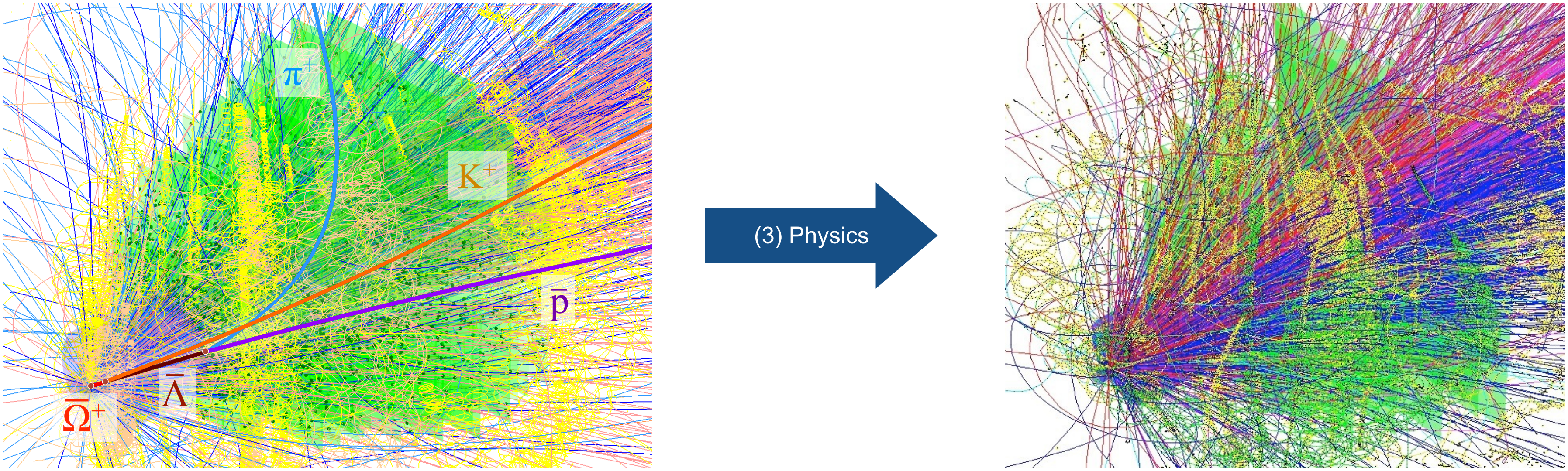
I. Kisel (for the STAR Collaboration), EPJ Web of Conferences 271, 08001 (2022)

- With the same procedure all FXT data from 2018, 2019 and 2020 were analyzed.
- In all (standard and express) production data $^{5}_{\Lambda}$**He** is visible with significance **11.6 σ**.

FIAS, GSI, BNL

The collected statistics is enough to measure yields, lifetimes and spectra of these hypernuclei

(3) Physics



CBM: Online Physics Analysis?

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

Direct approach

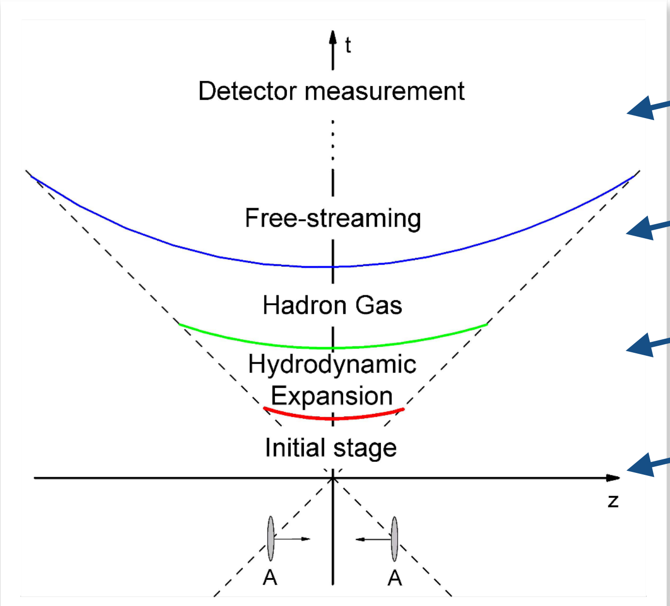
Theoretical model (T, μ,V, σ,...) ⇄ $\omega_p \frac{dN}{dp^3}$ (observable)

Inverse approach

Motivation:

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

Stages of collision



Models for different stages

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

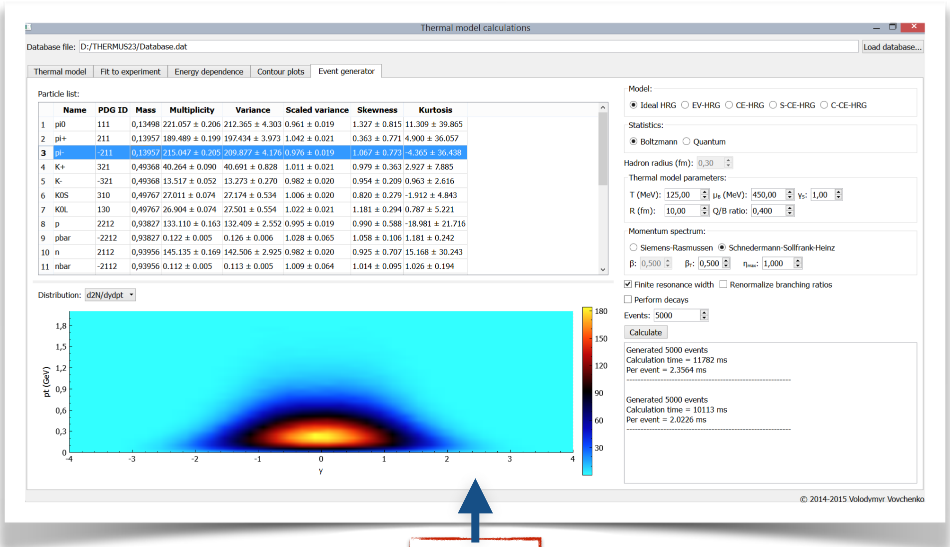
Statistical-thermal models for chemical freeze-out
(ideal hadron gas, Van der Waals hadron gas, Hagedorn states, ...)

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?

CBM: Online Physics Analysis (macroscopic)

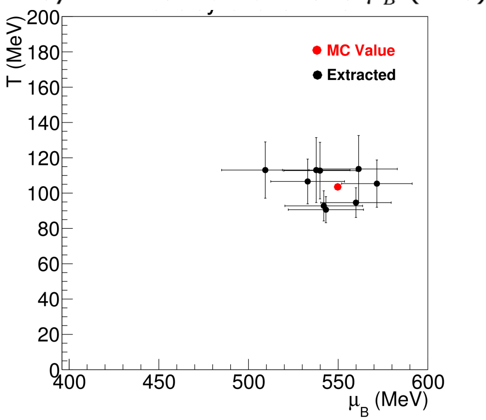


Direct approach

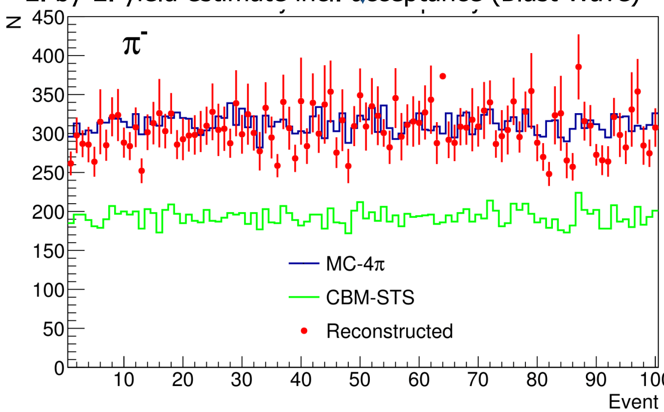
Theoretical model (T, μ,V, σ,...) $\rightleftarrows$ $\omega_p \frac{dN}{dp^3}$ (observable)

Inverse approach

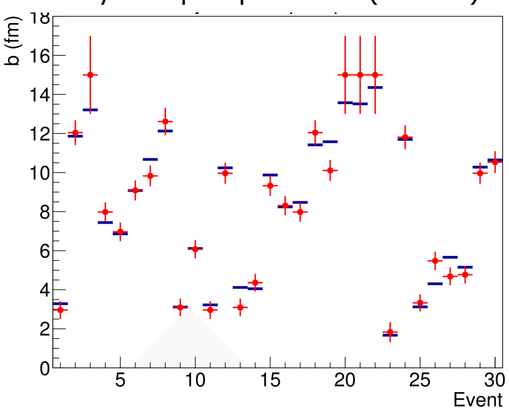
E.-by-E. extraction of T and μ_B (HRG)



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



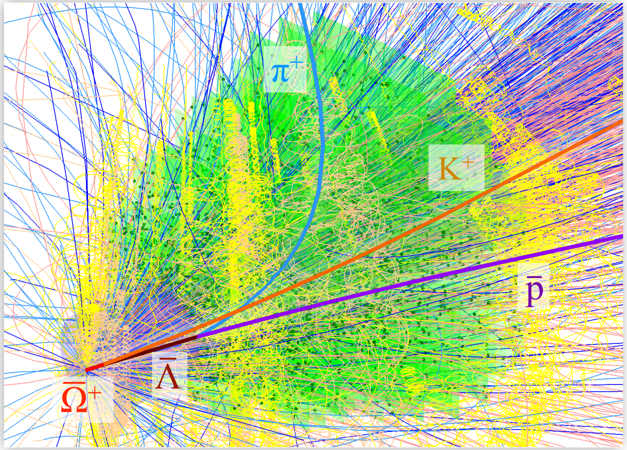
E.-by-E. impact parameter (Glauber)

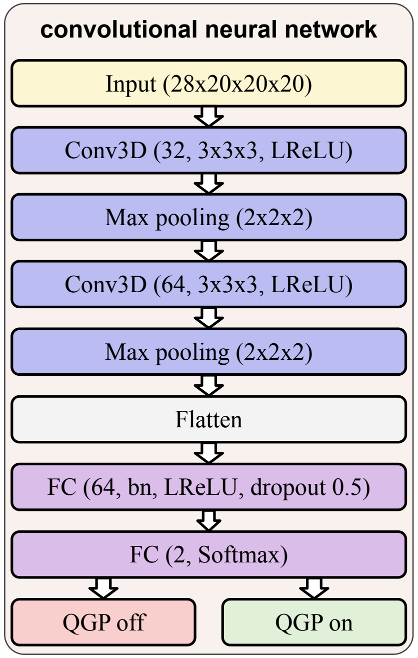


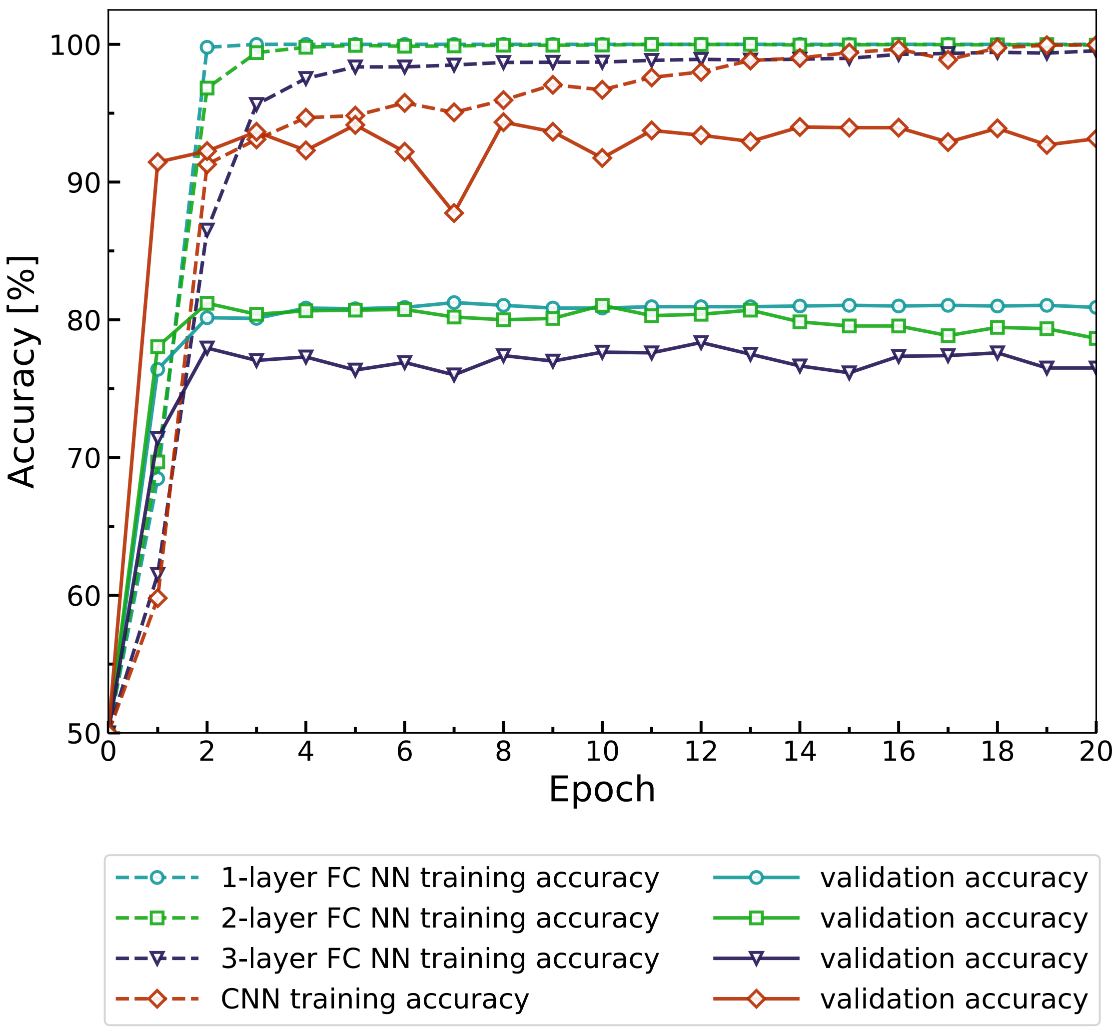
I. Kisel, V. Vovchenko

A package to extract the parameters of macroscopic theoretical models in CBM experiment is implemented

CBM: Online Physics Analysis (microscopic)



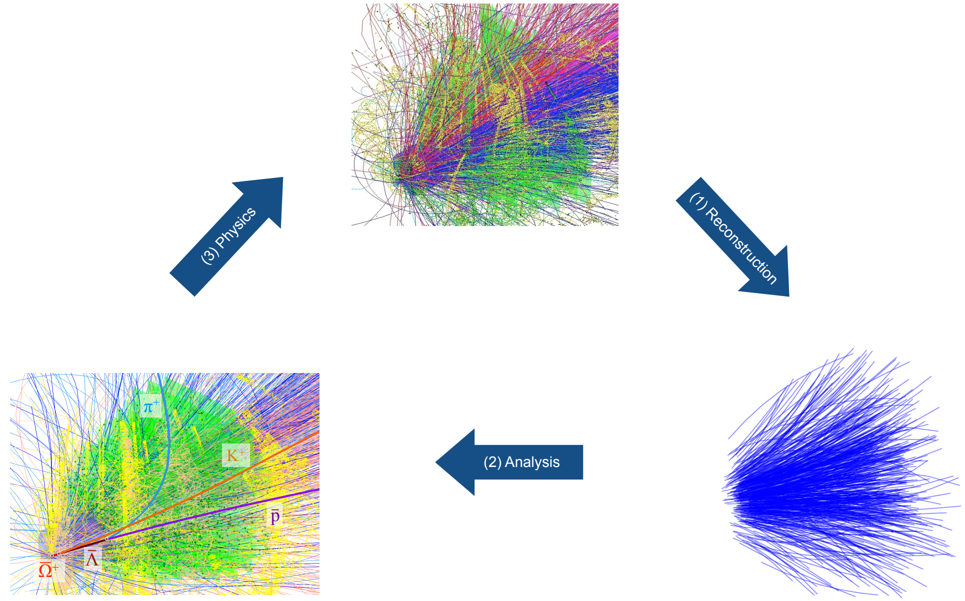




F. Sergeev, E. Bratkovskaya, I. Kisel and I. Vassiliev, Int. Mod. Phys. A, Vol. 35, No. 33, 2043002 (2020)

An ANN package to extract the parameters of microscopic theoretical models in CBM experiment is under development

Summary



- Our reconstruction and analysis algorithms have shown high efficiency and reliability on both simulated data of the CBM experiment and real data of the STAR experiment in online mode.
- Our Frankfurt group of 3 PhD students and 6 master and bachelor students, together with the group of Dr. Gligorov (LPNHE, Paris), is currently working on developing a package of neural network algorithms for the tasks of reconstruction and analysis of experimental data.
- With the artificial neural network approach, we expect to make further progress both quantitatively and qualitatively in investigating the properties of matter in heavy ion collisions.