Real-Time Event Reconstruction and Analysis in CBM and STAR Experiments

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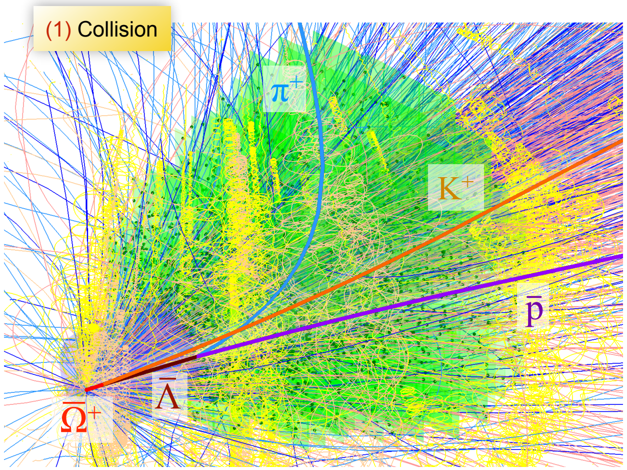
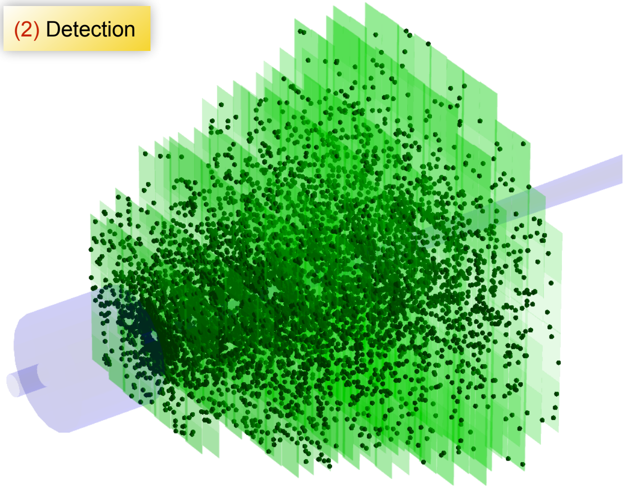
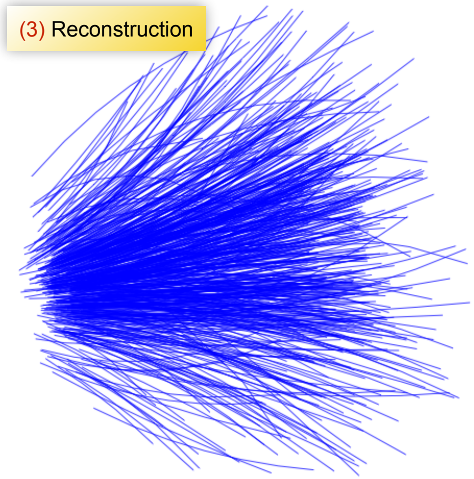
GSI Helmholtz Center for Heavy Ion Research

Reconstruction Challenge in CBM





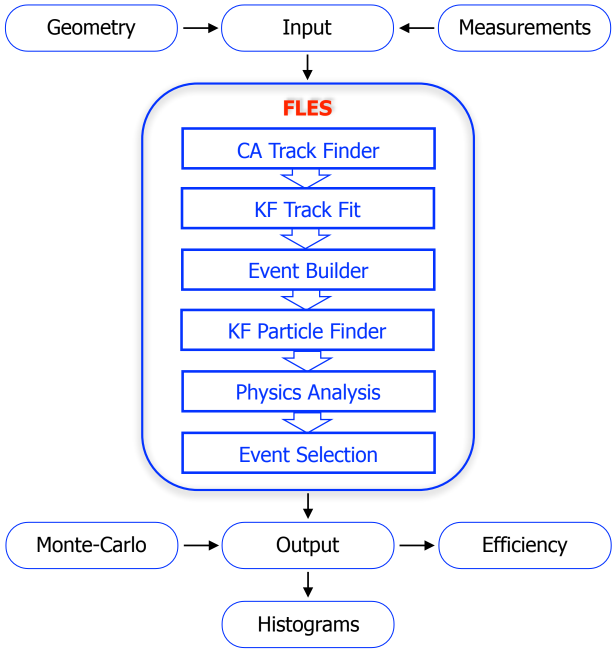


- Future fixed-target heavy-ion experiment at FAIR
- Explore the phase diagram at high net-baryon densities
- 10^7 Au+Au collisions/sec
- ~ 1000 charged particles/collision
- Non-homogeneous magnetic field
- Double-sided strip detectors
- 4D reconstruction of time slices.

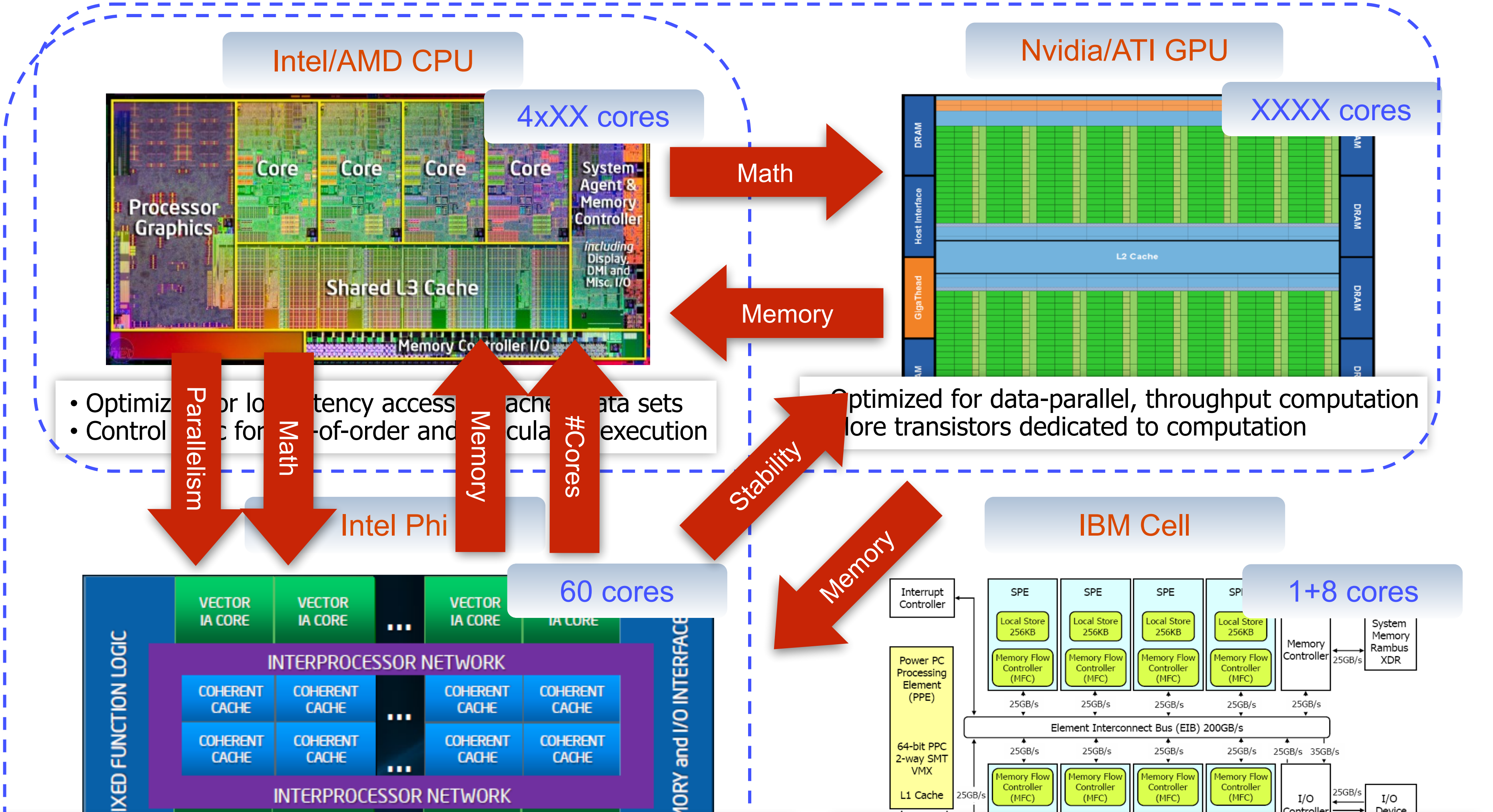
The full event reconstruction will be done on-line at the First-Level Event Selection (FLES) and off-line using the same FLES reconstruction package.

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

All reconstruction algorithms are vectorized and parallelized.



Many-Core CPU/GPU Architectures



- Optimiz… r lo… tency access… ache… ata sets
- Control… for… -of-order and… cula… execution

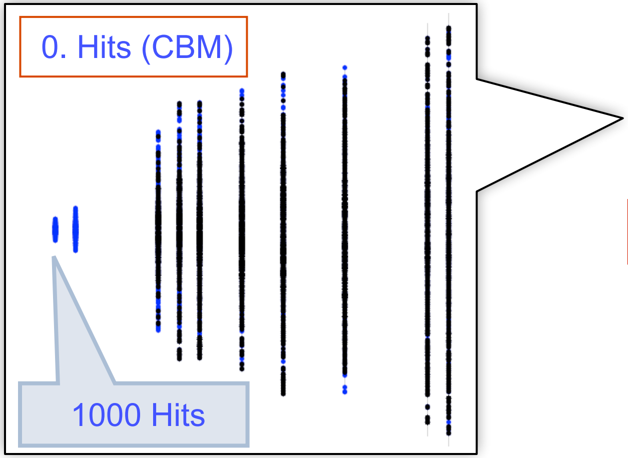
- …ptimized for data-parallel, throughput computation
- …lore transistors dedicated to computation

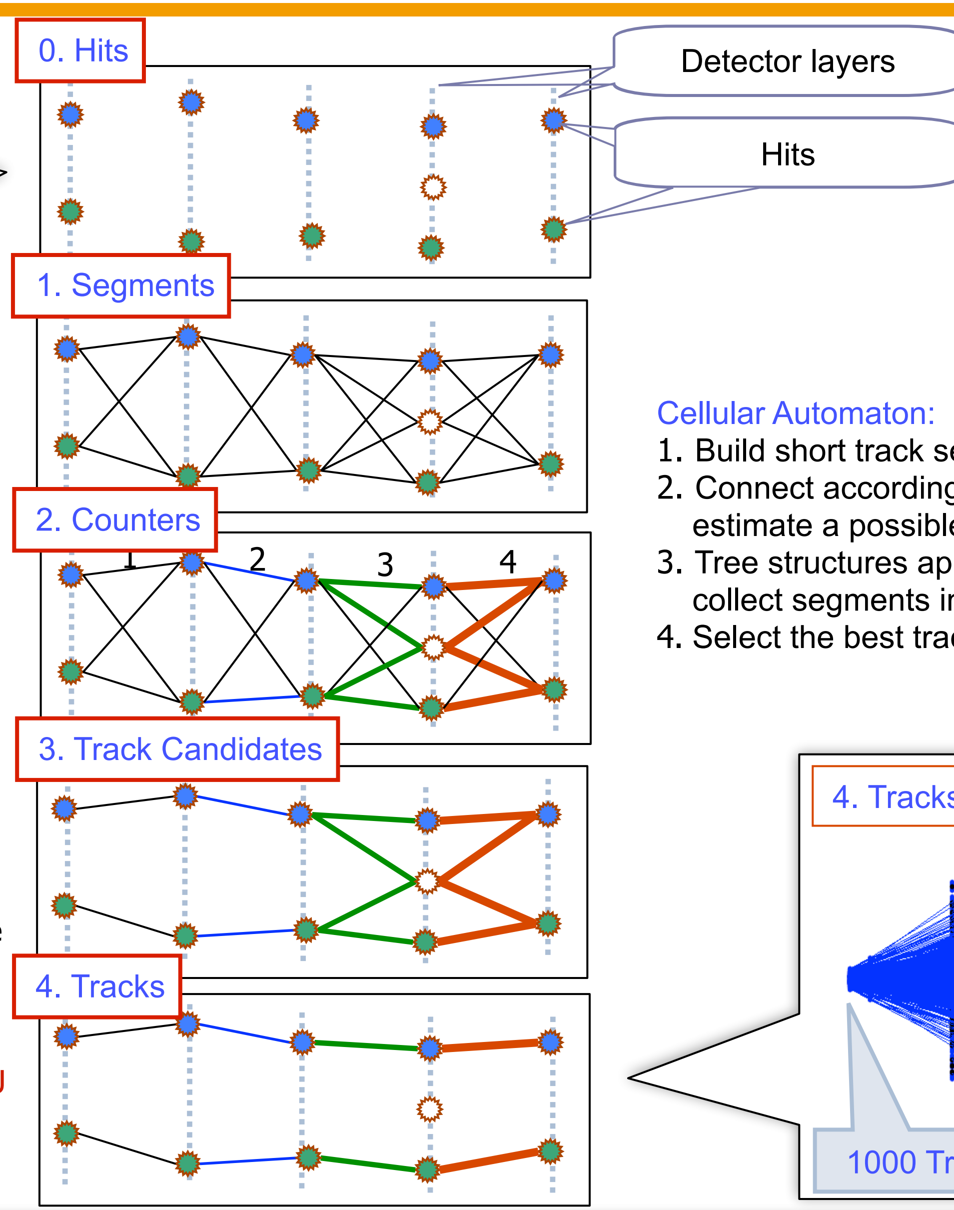
- Many Integrated Cores architecture announced at ISC10 (June 2010)
- Based on the x86 architecture
- Many-cores + 4-way multithreaded + 512-bit wide vector unit

- General purpose RISC processor (PowerPC)
- 8 co-processors (SPE, Synergistic Processor Elements)
- 128-bit wide SIMD units

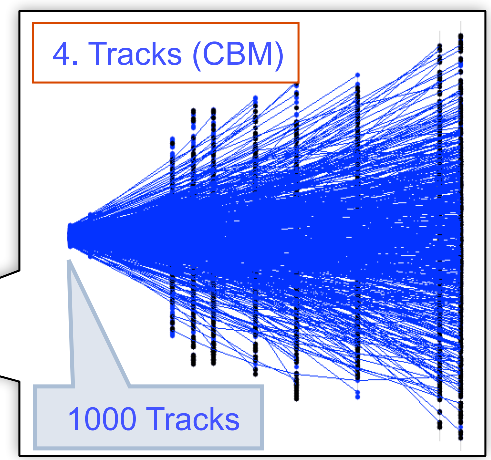
Future systems are heterogeneous. Fundamental redesign of traditional approaches to data processing is necessary

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.



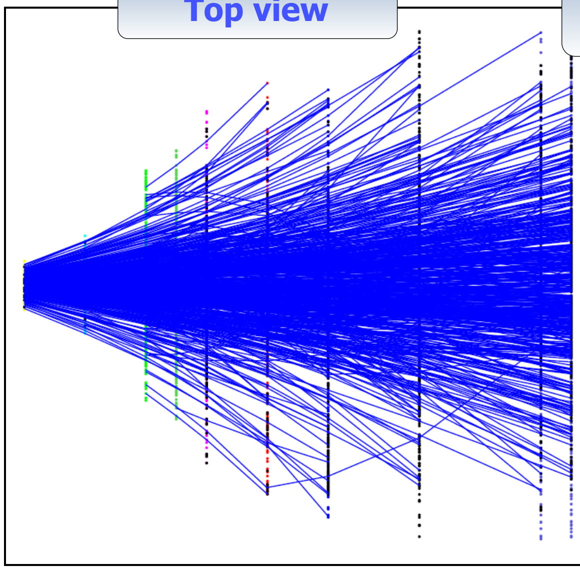
Cellular Automaton:

- extremely simple → relatively short code
- intrinsically parallel → many-core architecture
- local w.r.t. data. → memory optimal
- very fast → CPU/GPU optimal

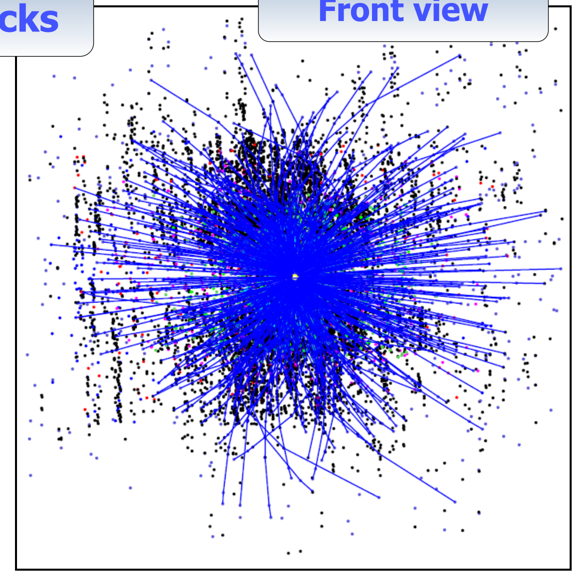
Deeply appropriate for many-core CPU/GPU

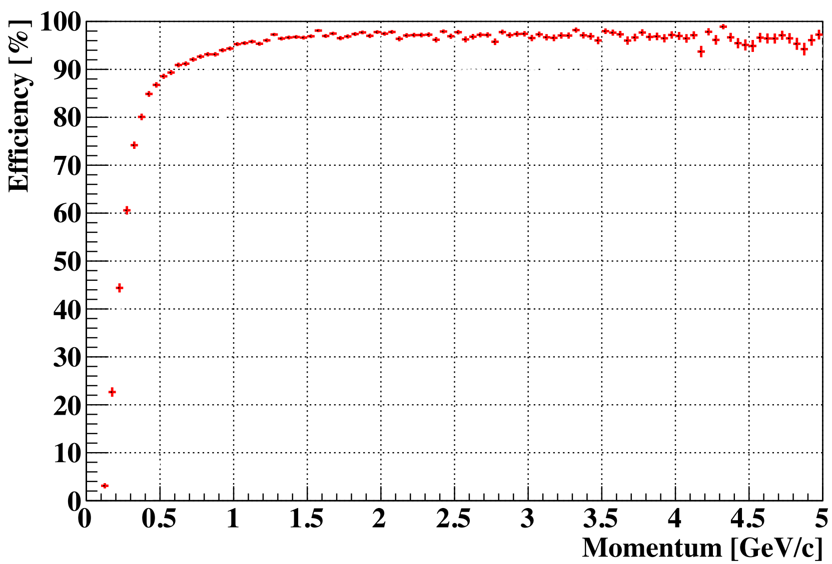
CA is now used at various stages of data reconstruction in many HEP and HI experiments

Cellular Automaton (CA) Track Finder



770 Tracks



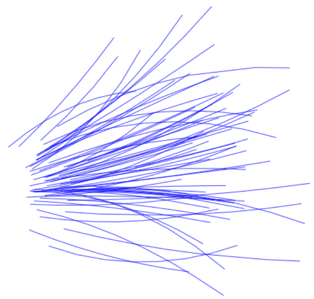


Track category	Eff, %
All tracks	90.9
Primary high-p	97.5
Primary low-p	92.6
Secondary high-p	91.1
Secondary low-p	63.8
Clone level	0.4
Ghost level	5.9
MC tracks found	134
Time, ms/ev	10

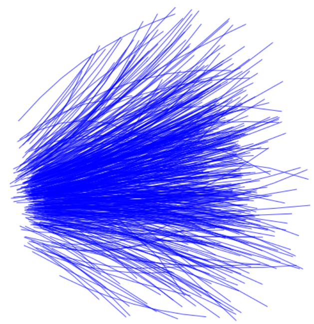
Fast and efficient track finder

CA Track Finder at High Track Multiplicity

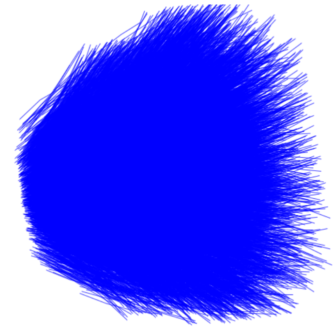
A number of minimum bias events is gathered into a group (super-event), which is then treated by the CA track finder as a single event.



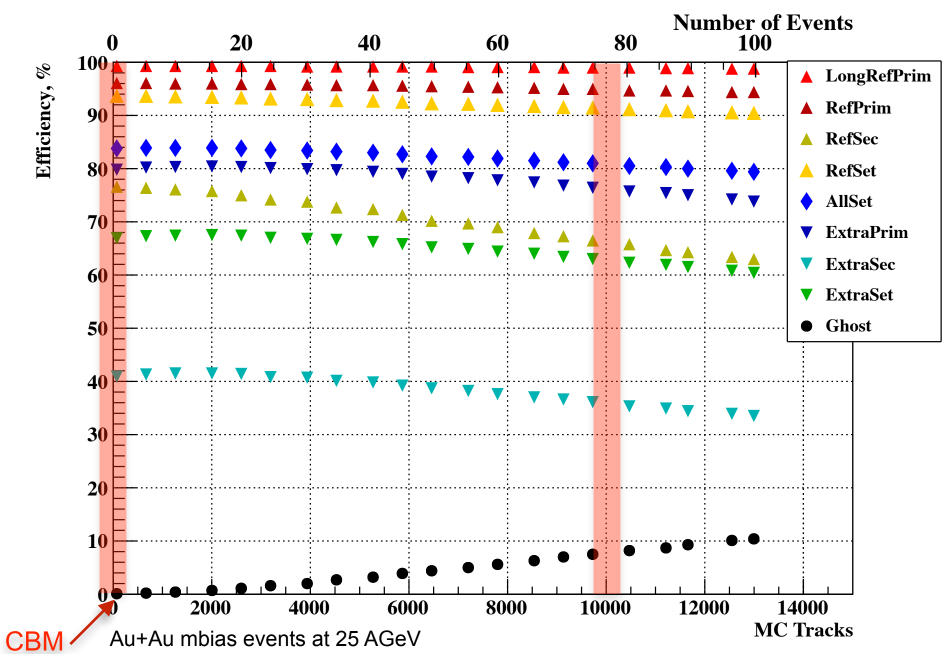
1 mbias event, $\langle N_{reco} \rangle$ = 109

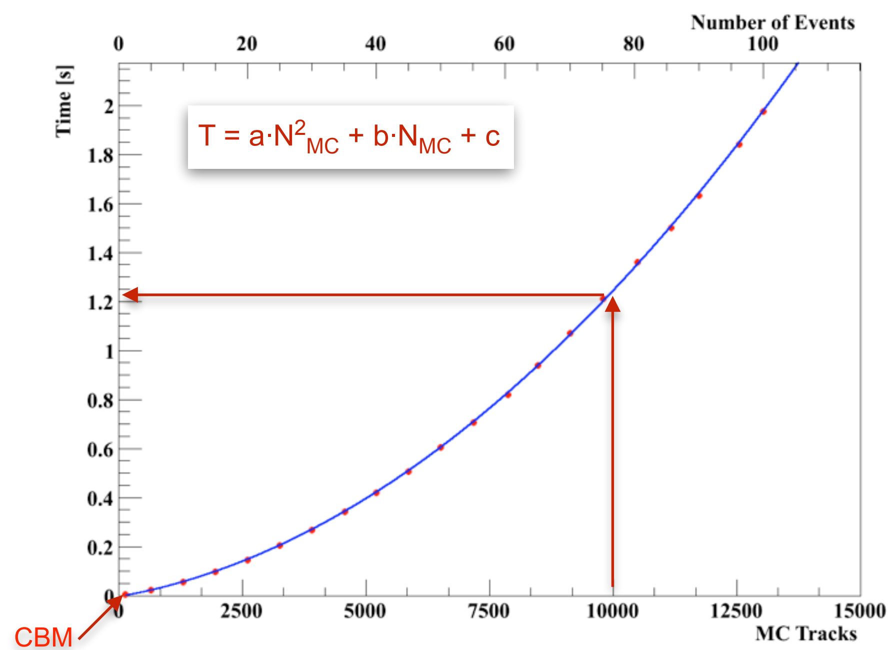


5 mbias events, $\langle N_{reco} \rangle$ = 572



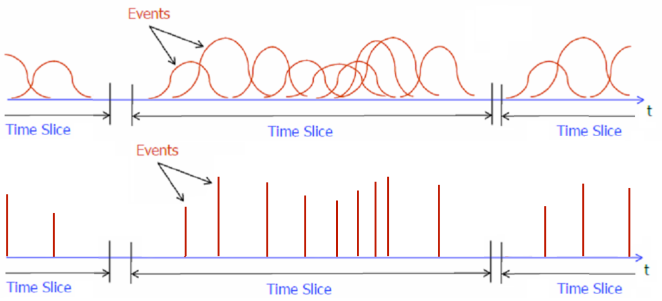
100 mbias events, $\langle N_{reco} \rangle$ = 10340





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

Time-based (4D) Track Reconstruction

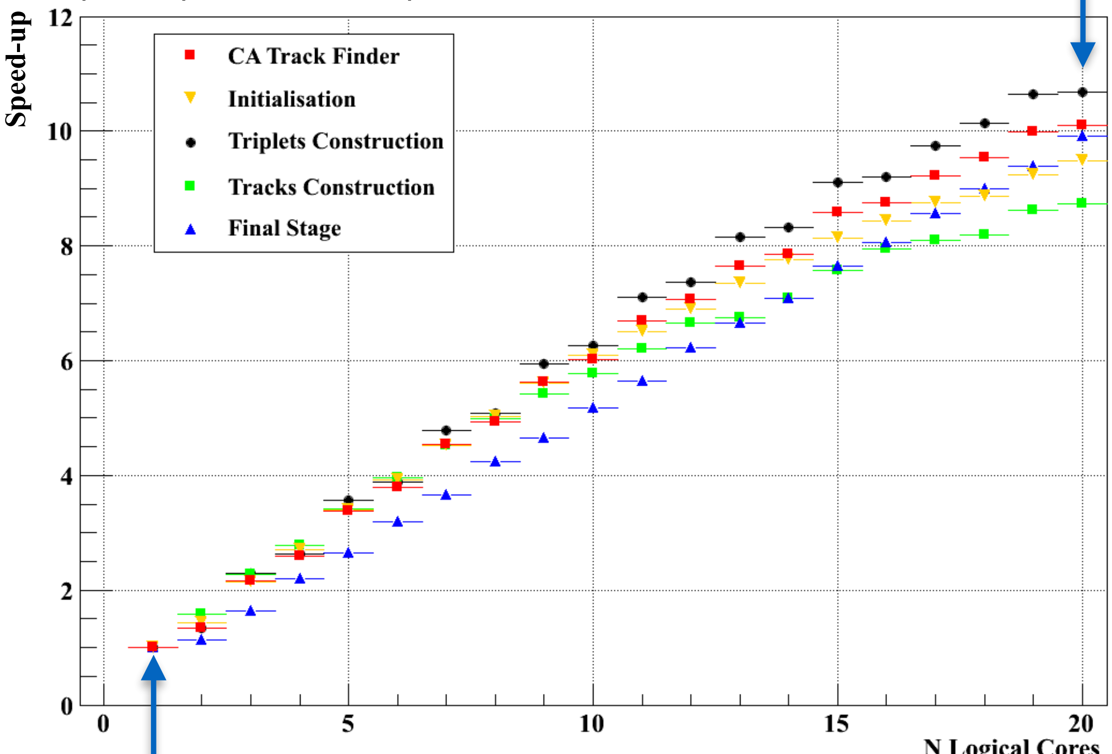


- The beam in the CBM will have no bunch structure, but continuous.
- Measurements in this case will be 4D (x, y, z, t).
- Significant overlapping of events in the detector system.
- Reconstruction of time slices rather than events is needed.

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

Total CA time = 84 ms

Speed-up factor due to parallelization within the time-slice



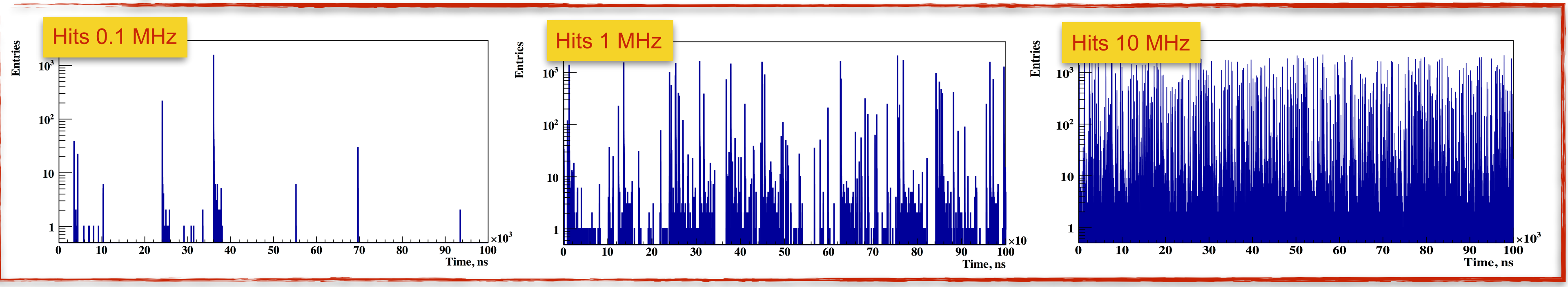
Total CA time = 849 ms

100 mbias events in a time-slice

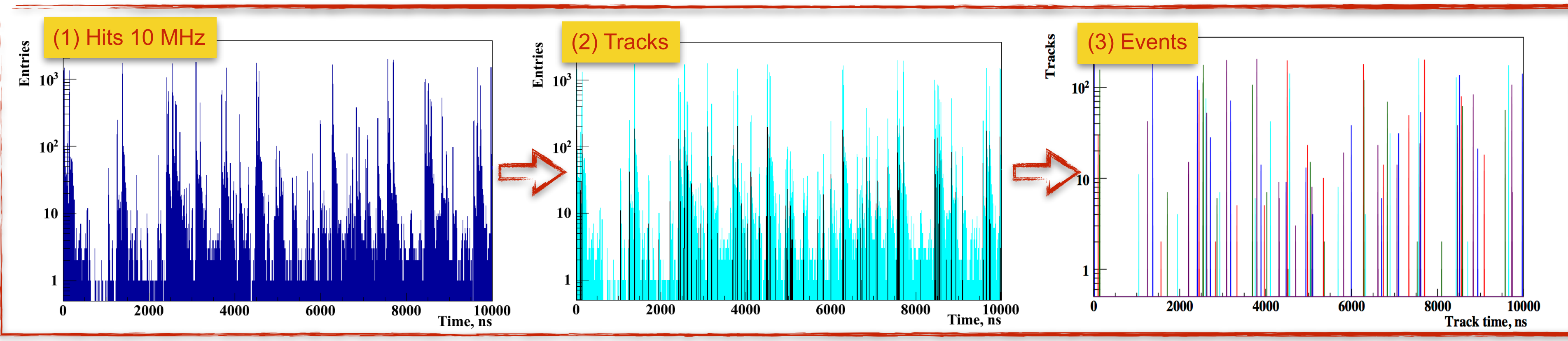
3D reconstruction time 8.2 ms/event is recovered in 4D case

4D Event Building at 10 MHz

Hits at high input rates

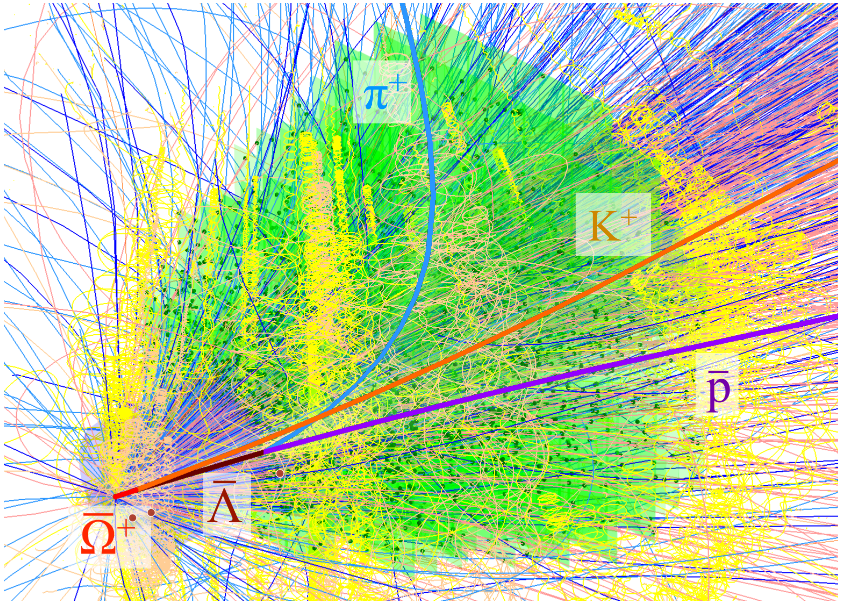


From hits to tracks to events



Reconstructed tracks clearly represent groups, which correspond to the original events:
85% of single events, no splitted events, further analysis with TOF information at the vertexing stage

KF Particle: Reconstruction short-lived Particles



Simulated AuAu collision at 25 AGeV

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

$\quad\quad\quad \llcorner \bar{p}\, \pi^+$

(r,C)

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

State vector

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

Covariance matrix

```
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
```

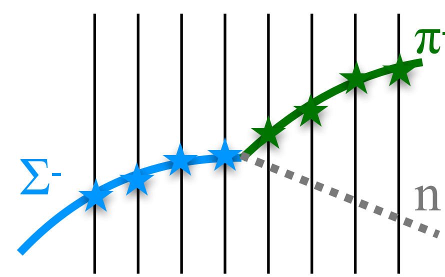
Concept:

- Mother and daughter particles have the same state vector and are treated in the same way
- Reconstruction of decay chains
- Kalman Filter (KF) based
- Geometry independent
- Vectorized
- Uncomplicated usage

Functionality:

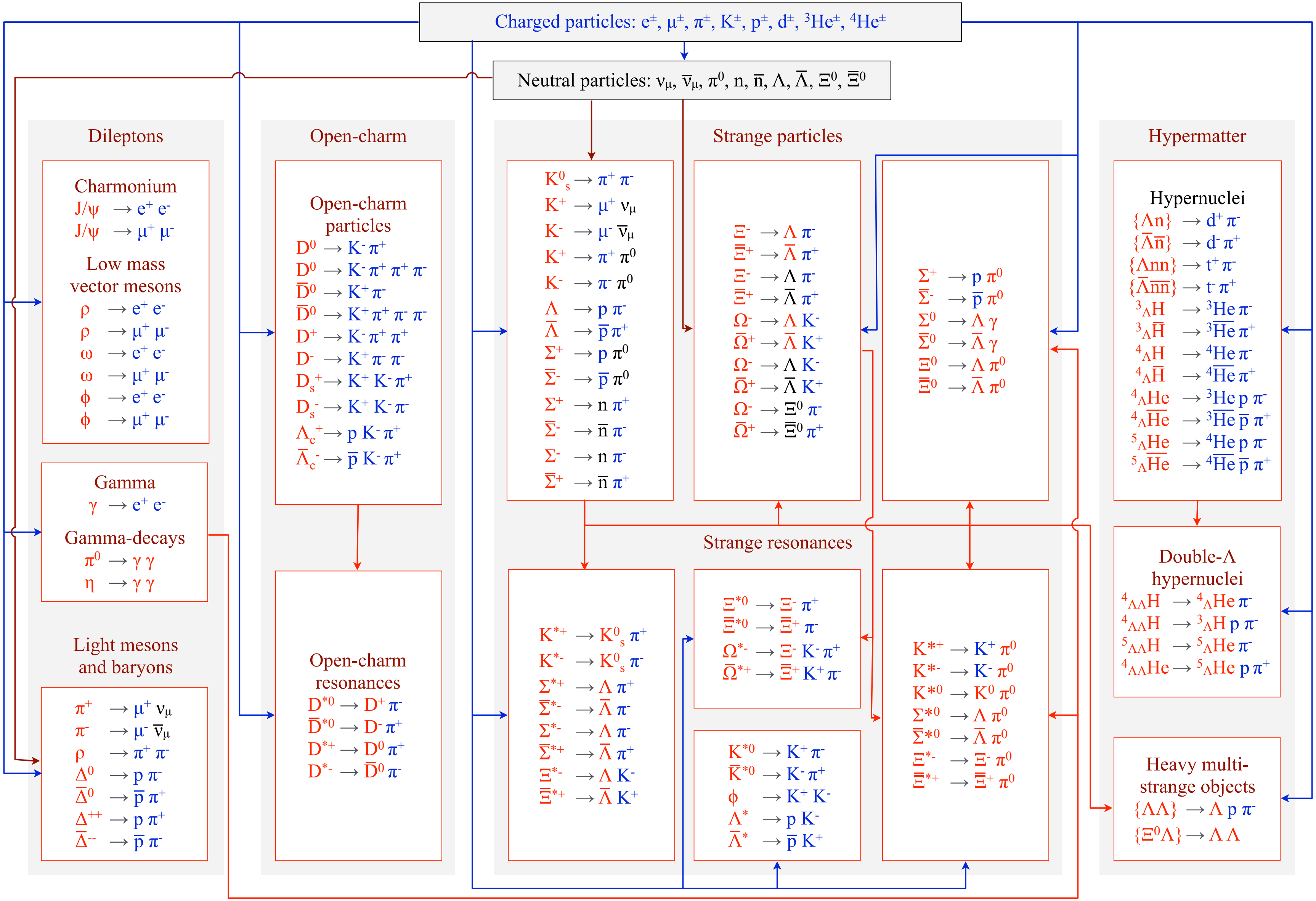
- Construction of short-lived particles
- Addition and subtraction of particles
- Transport
- Calculation of an angle between particles
- Calculation of distances and deviations
- Constraints on mass, production point and decay length
- KF Particle Finder

Reconstruction of decays with neutral daughter
by the missing mass method:



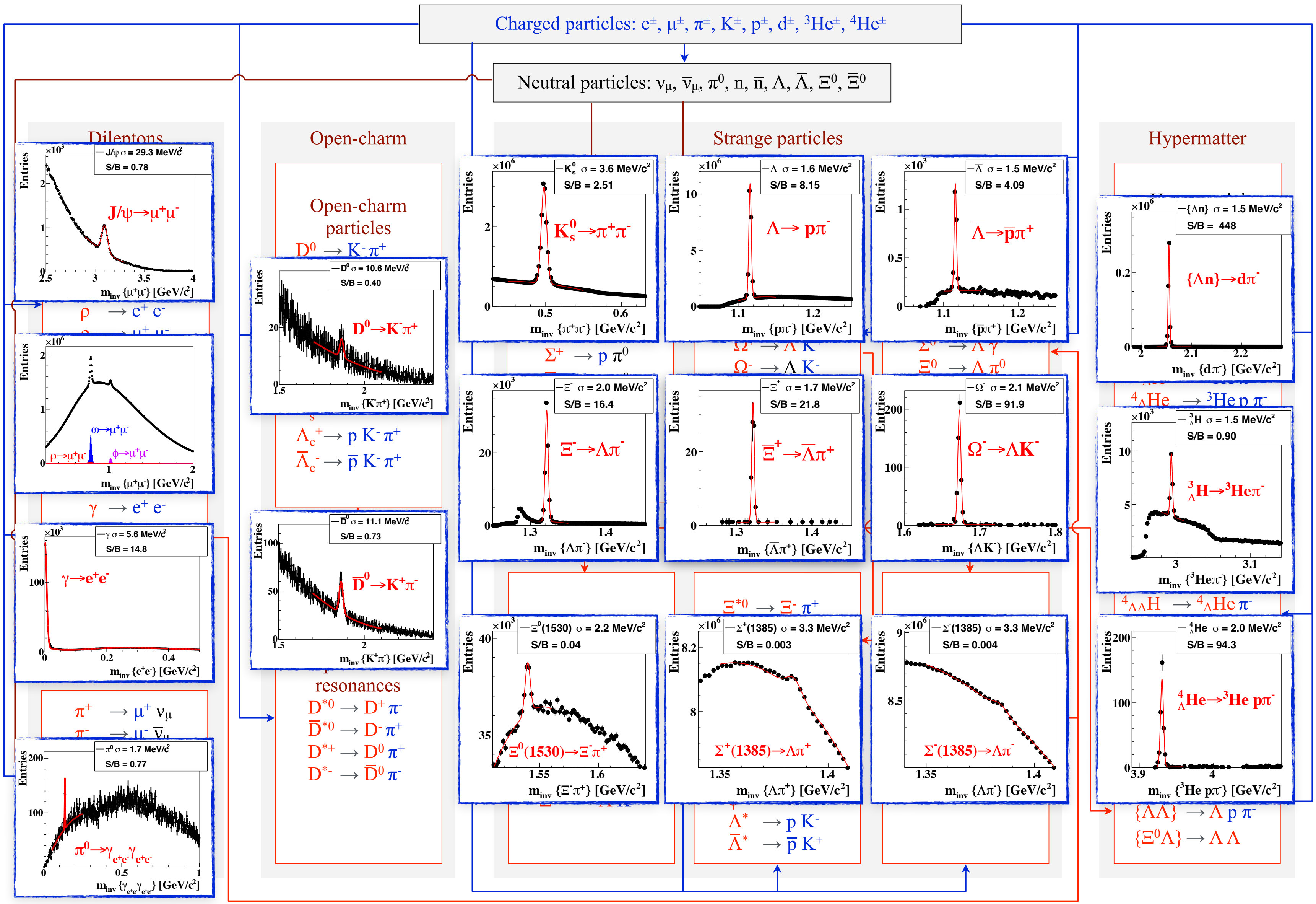
KF Particle provides a simple and direct approach to physics analysis (used in CBM, ALICE, STAR and sPHENIX)

KF Particle Finder for Physics Analysis and Selection

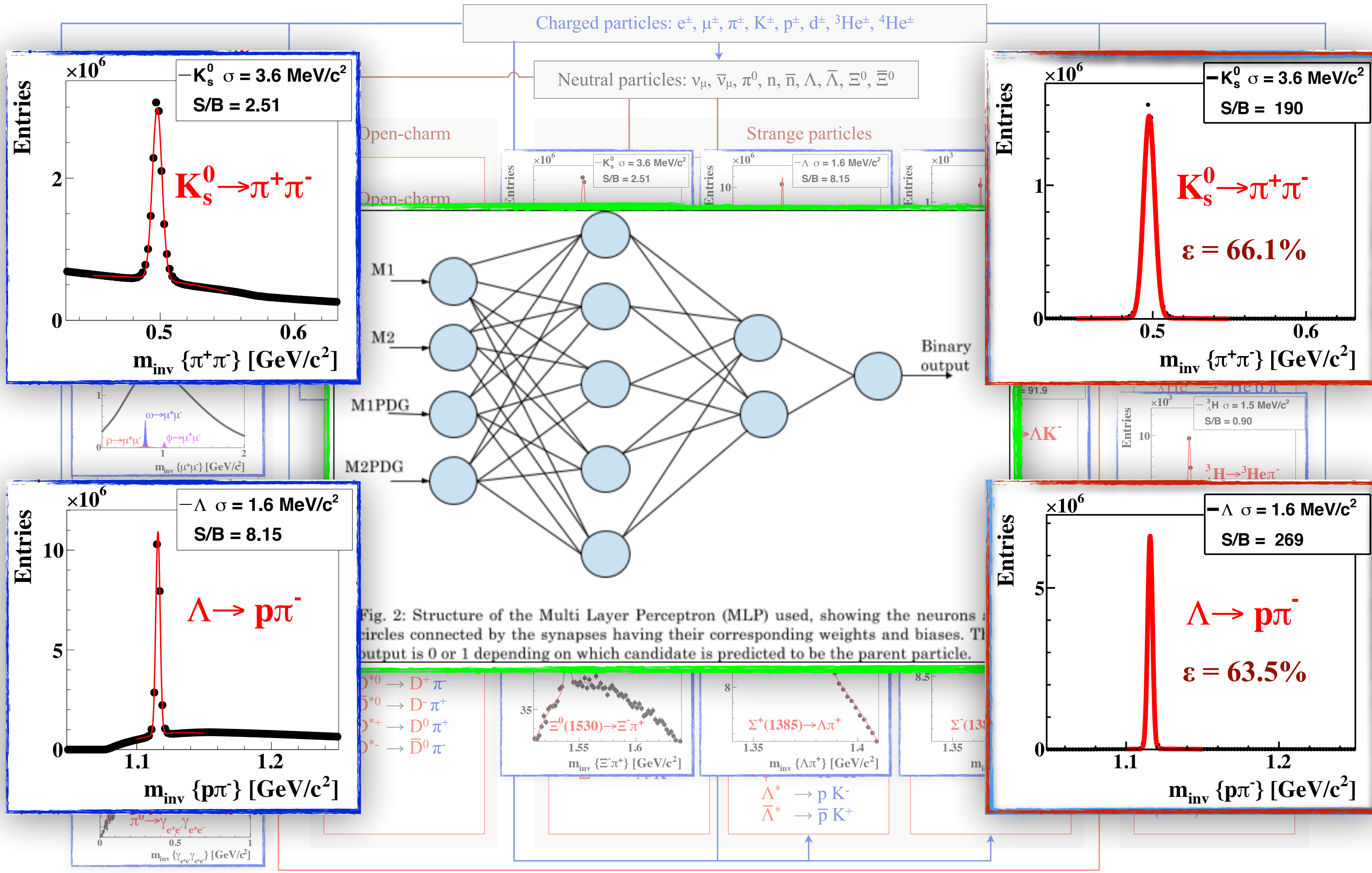


(mbias: 1.4 ms; central: 10.5 ms)/event/core

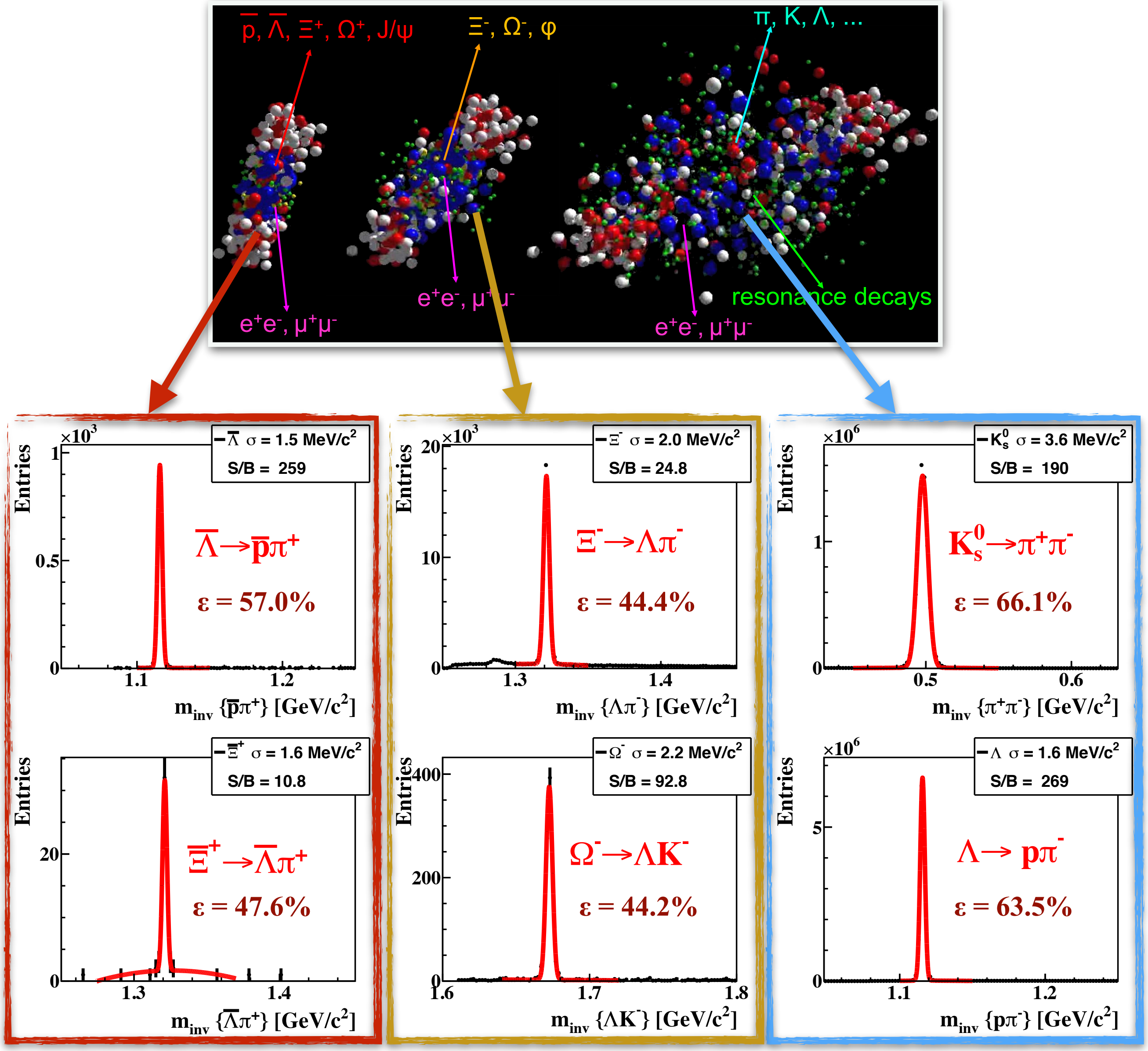
KF Particle Finder for Physics Analysis and Selection



Cleaning Decay Channels using Artificial Neural Network

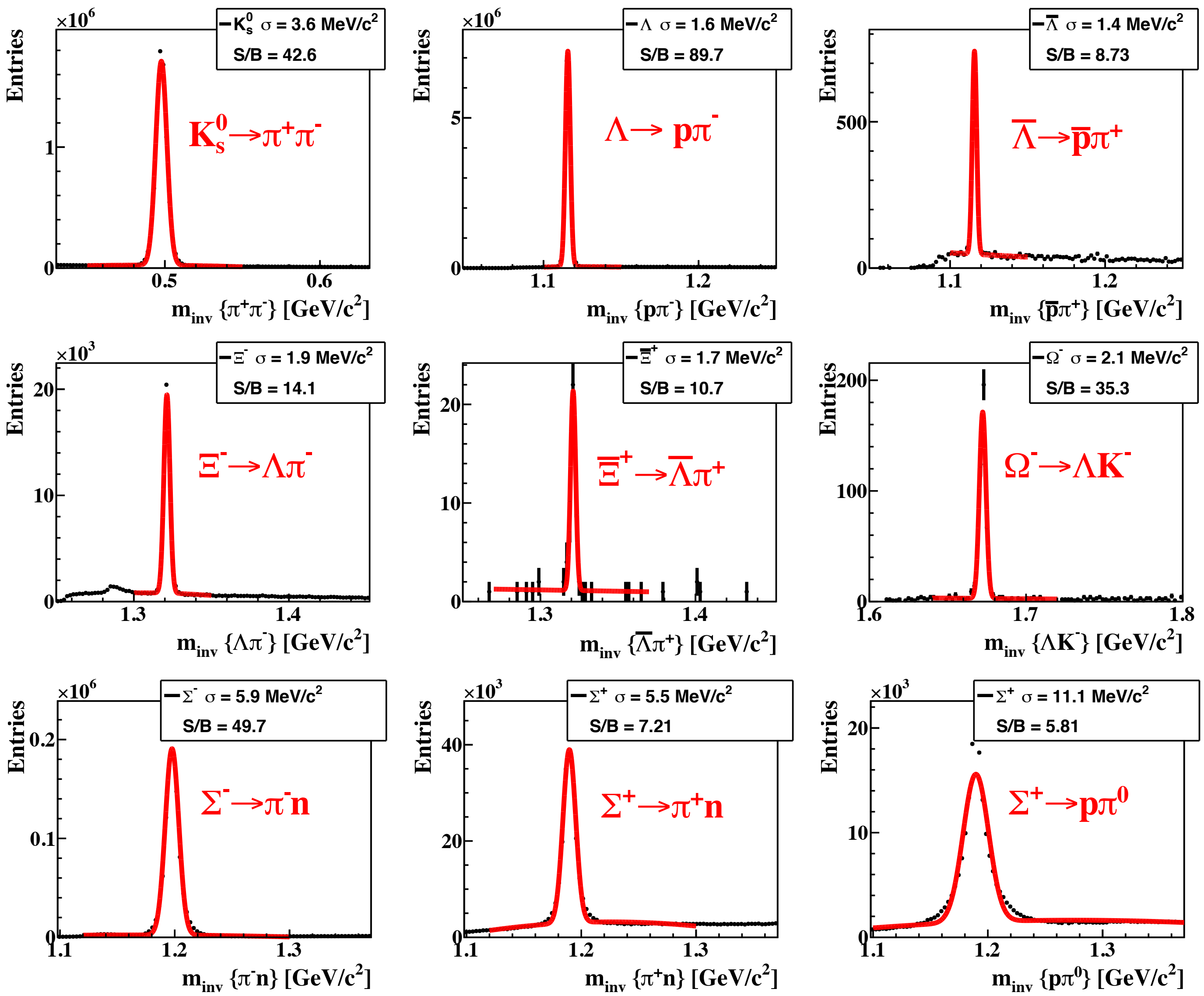


Clean Probes of Collision Stages



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

Clean Probes of Collision Stages

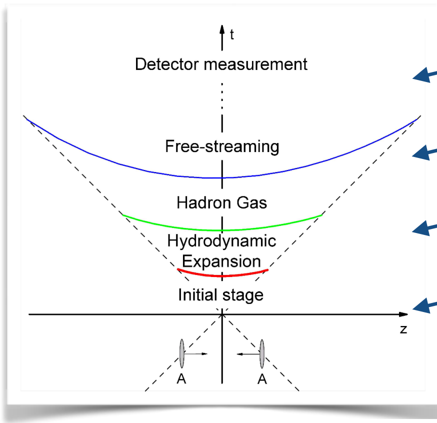


5M central AuAu UrQMD events at 10 AGeV with realistic PID

Macroscopic Inverse Approach in Real-Time Physics Analysis

Since the CBM experiment operating at a 10^7 interaction rate will be forced to select on average 1 event out of 10^3-10^4 collisions, only immediate comparison of the results of online analysis with the predictions of theoretical models can guarantee the proper operation of the entire experiment, including the performance of both the detector system and the alignment, reconstruction, analysis and selection algorithms to avoid incorrect selection of events resulting in a complete loss of the data collected during the entire period of running the accelerator

Stages of collision



Models for different stages

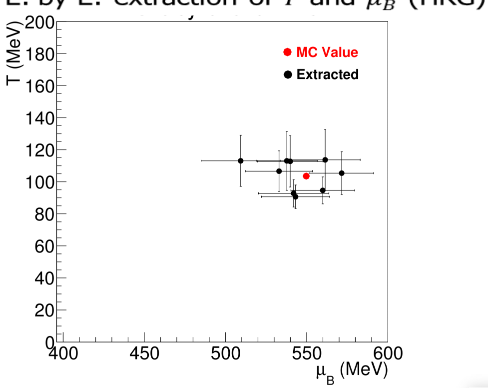
- Final momentum spectrum (Blast-Wave, Tsallis, ...)
- Statistical-thermal models for chemical freeze-out (ideal hadron gas, Van der Waals hadron gas, Hagedorn states, ...)
- Relativistic hydrodynamics (ideal, viscous; (0+1)D, (1+1)D, (3+1)D, ...)
- Initial stage (Glauber, CGC, ...)

Direct approach

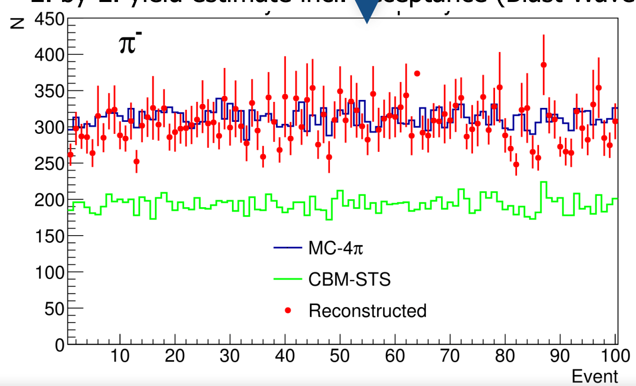
Theoretical model (T, μ,V, σ,...) ⇄ $\omega_p \frac{dN}{dp^3}$ (observable)

Inverse approach

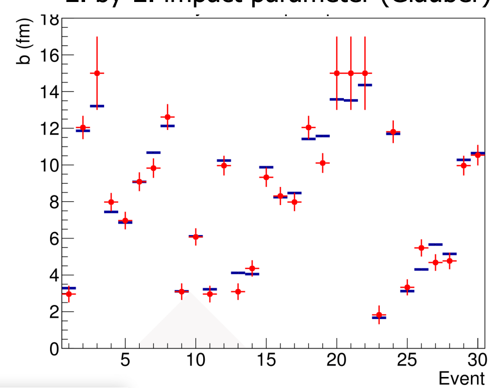
E.-by-E. extraction of T and μ_B (HRG)



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



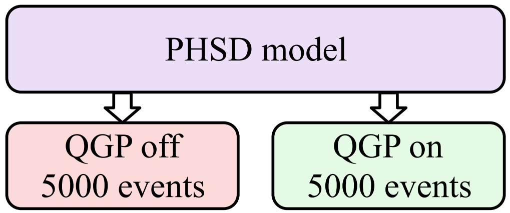
E.-by-E. impact parameter (Glauber)

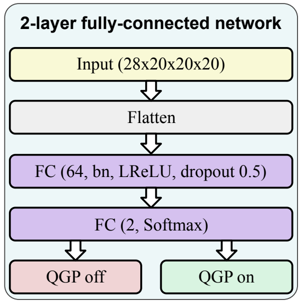


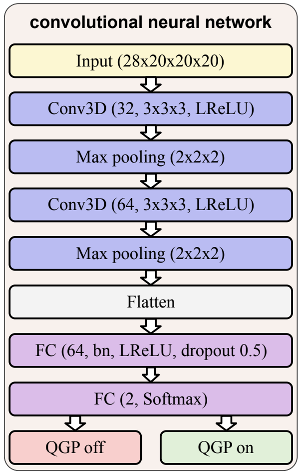
A package to estimate the medium parameters is implemented

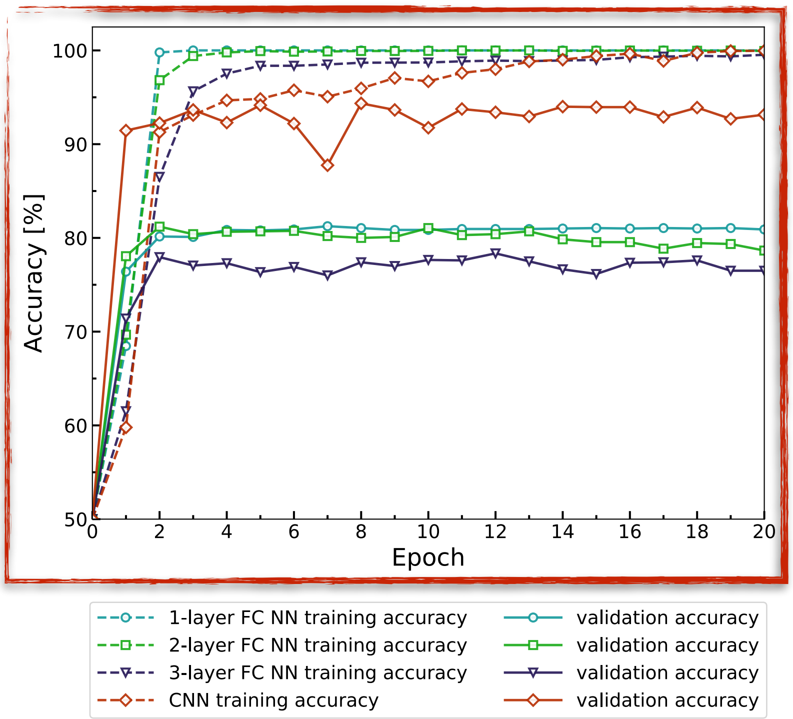
QM-2015, Kobe

Microscopic Inverse Approach using Artificial Neural Network







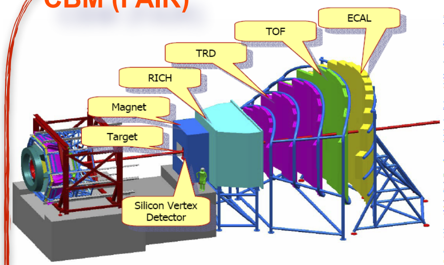


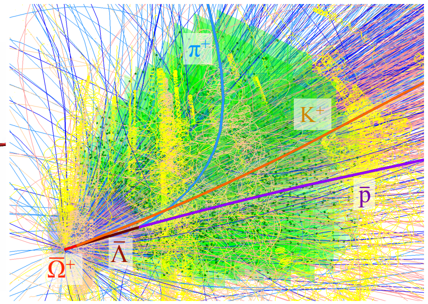
Architecture		Accuracy
FC NN	1-layer	~80%
	2-layer	~80%
	3-layer	~75%
CNN		**>90%**

Goal is to determine physical properties of QCD matter in real time

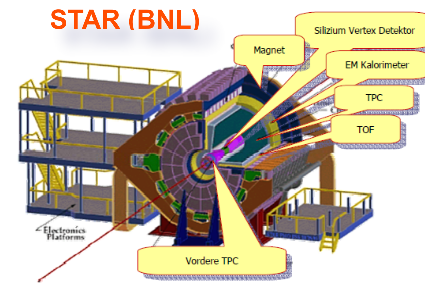
CBM → STAR: Reconstruction and Analysis Software

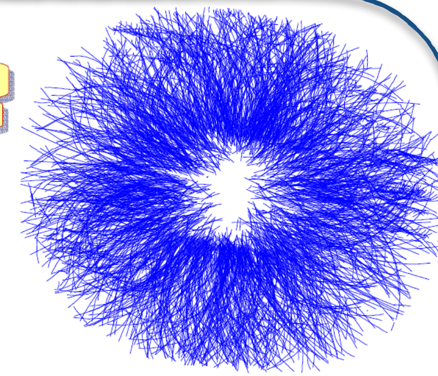
Within the FAIR Phase-0 program the CBM KF Particle Finder has been adapted to STAR and applied to real data of 2014, 2016 and BES-I.



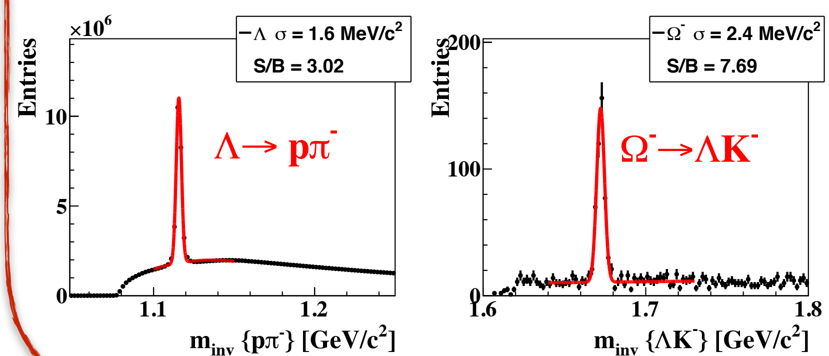


$\bar{\Omega}^+ \to \bar{\Lambda} K^+$
$\hookrightarrow \bar{p}\, \pi^+$

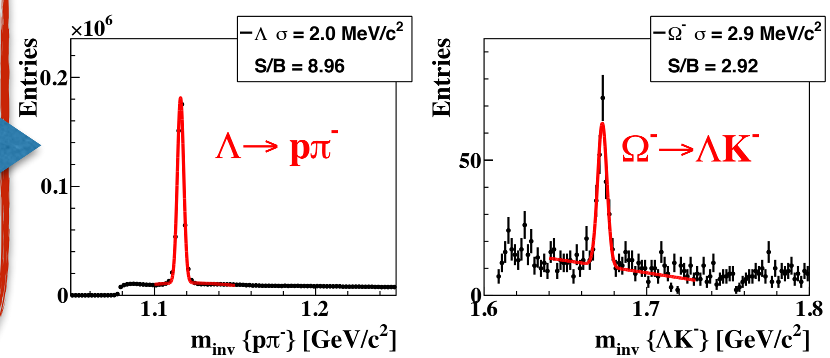




CBM, 5M central Au+Au, 10 AGeV, PHSD



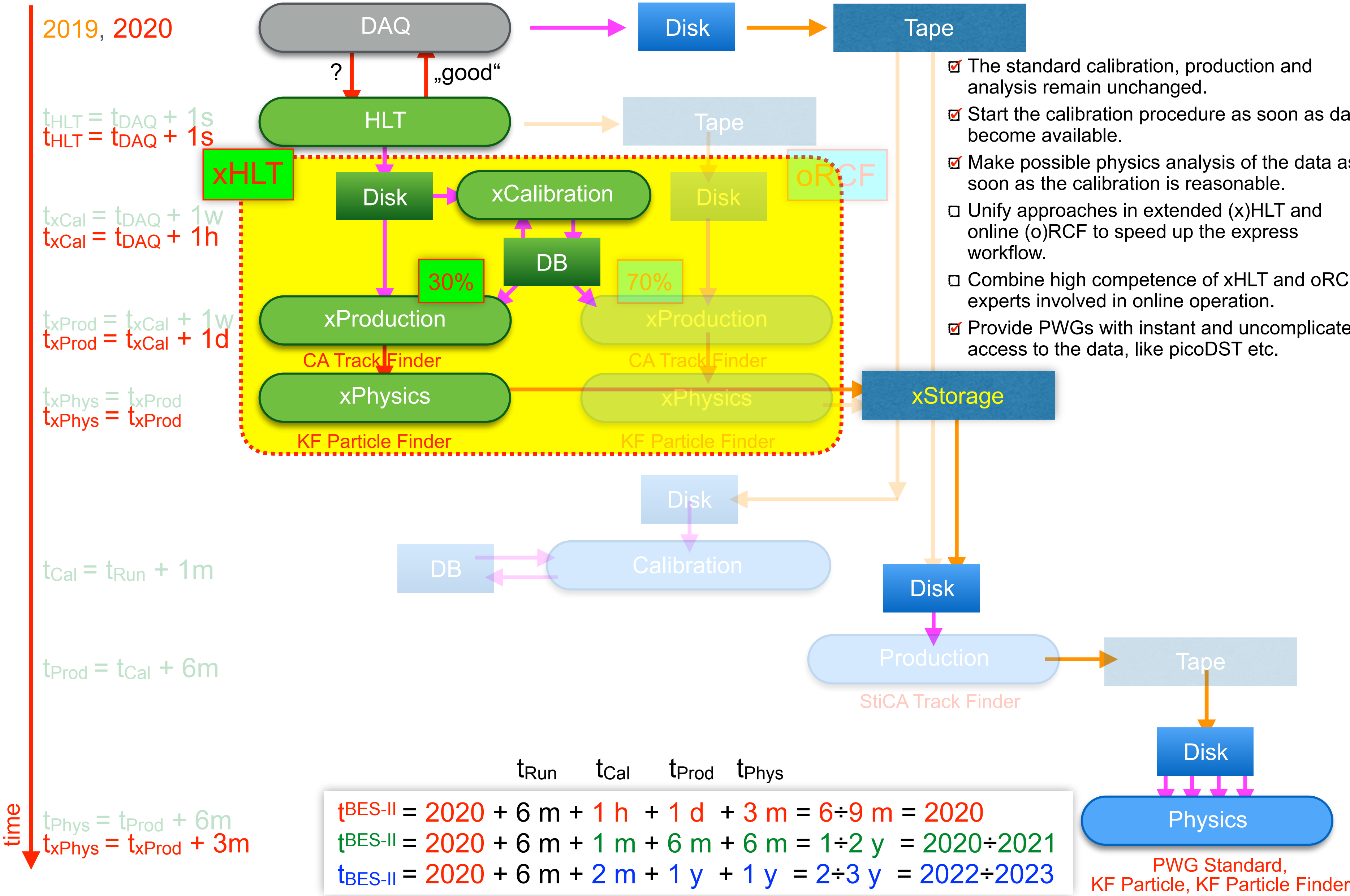
STAR, 1.3M mbias Au+Au, 200 AGeV, Run 2016



- ✓ Since 2013 (online) and 2016 (offline) the CA track finder is the standard STAR track finder for data production. Use of CA provides 25% more D^0 and 20% more W.
- ✓ 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.

Preparing for the real-time express physics analysis during the BES-II runs (2019-2020)

BES-II: eXpress+Standard Data Production and Analysis

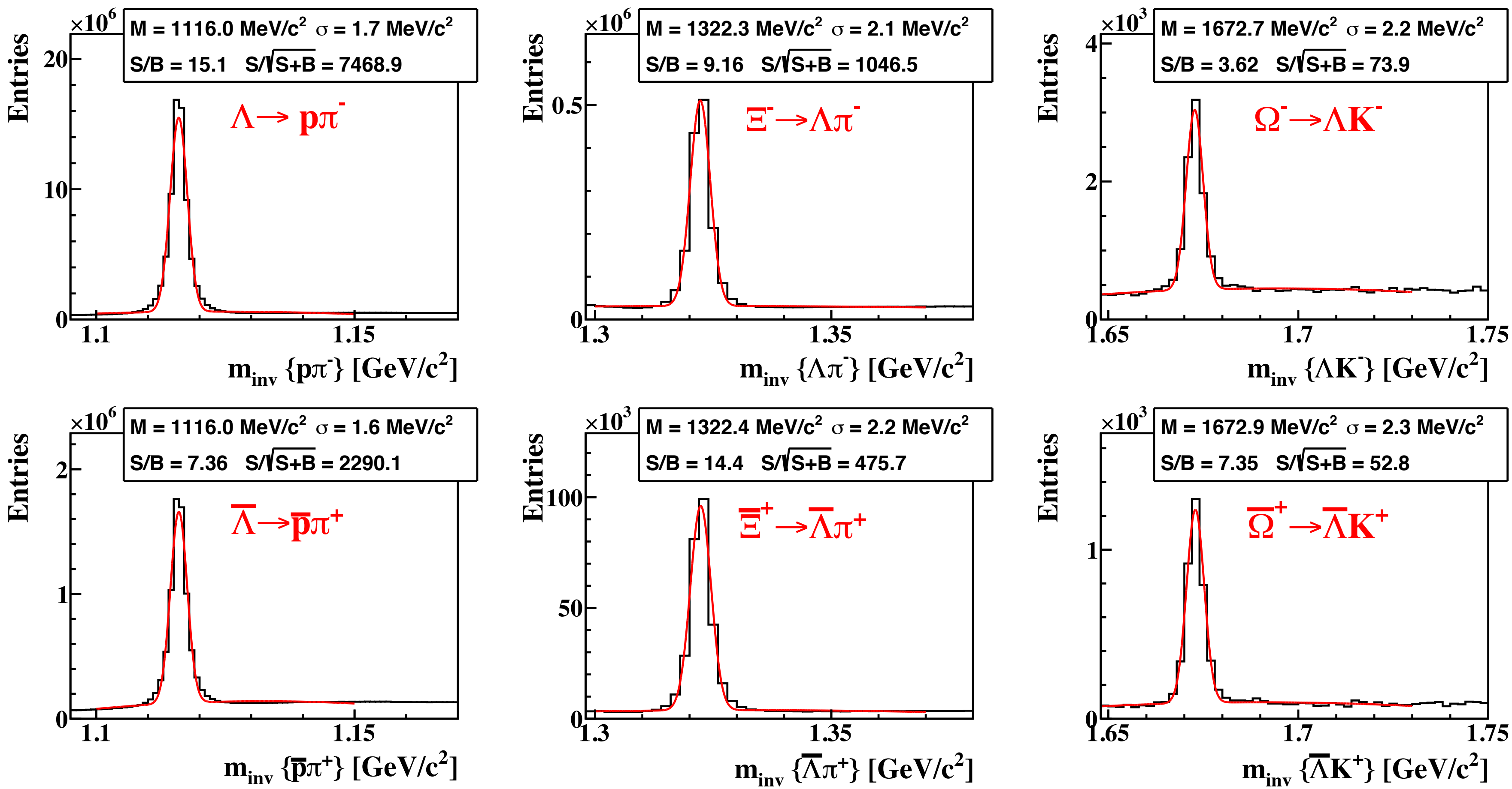


- ☑ The standard calibration, production and analysis remain unchanged.
- ☑ Start the calibration procedure as soon as data become available.
- ☑ Make possible physics analysis of the data as soon as the calibration is reasonable.
- ☐ Unify approaches in extended (x)HLT and online (o)RCF to speed up the express workflow.
- ☐ Combine high competence of xHLT and oRCF experts involved in online operation.
- ☑ Provide PWGs with instant and uncomplicated access to the data, like picoDST etc.

	t_{Run}		t_{Cal}		t_{Prod}		t_{Phys}			
$t^{BES\text{-}II}$ =	2020 + 6 m	+	1 h	+	1 d	+	3 m	= 6÷9 m	=	2020
$t^{BES\text{-}II}$ =	2020 + 6 m	+	1 m	+	6 m	+	6 m	= 1÷2 y	=	2020÷2021
$t_{BES\text{-}II}$ =	2020 + 6 m	+	2 m	+	1 y	+	1 y	= 2÷3 y	=	2022÷2023

BES-II: xHyperons

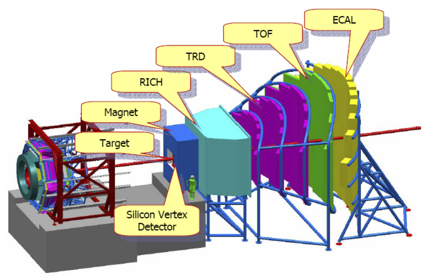
200M AuAu events at 14.5 GeV, 2019 BES-II express production



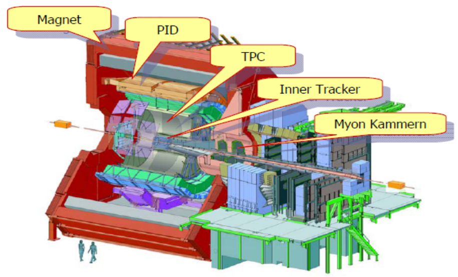
- With the express calibration and alignment we reconstruct hyperons with high significance and low level of background.
- Hyperons are clearly seen at all BES-II energies: 3, 3.2, 3.9, 7.7, 9.1, 14.5, 19.6, 27 GeV.
- High significance allows extraction of spectra.

Summary

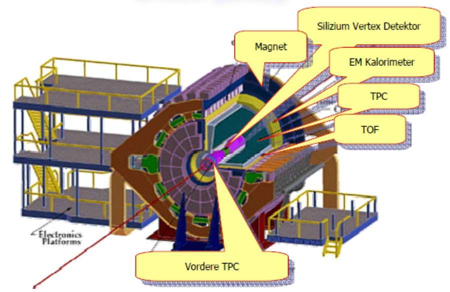
CBM (FAIR/GSI)



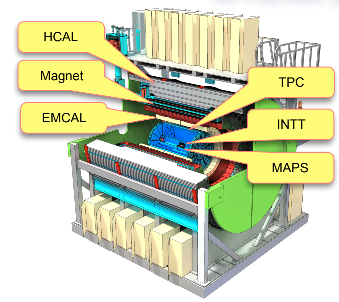
ALICE (CERN)



STAR (BNL)



sPHENIX (BNL)



- The CBM experiment with 10^7 input rate will require the full event reconstruction and physics analysis of the experimental data online. As the same HPC farm will be used for offline and online processing of experimental data, the main reconstruction and analysis algorithms will work both offline and online.
- Errors and insufficient accuracy in online data processing, physics analysis or selection of interesting collisions by the reconstruction algorithms will lead to complete loss of all experimental data, since only the incorrectly selected data will be stored in this case. Therefore only immediate comparison of the results of online analysis with the predictions of theoretical models using ANNs can guarantee the proper operation of the whole experiment.
- We have demonstrated, that the core algorithms of the FLES package, the Cellular Automaton for searching for particle trajectories (100 μs/core/track) and the Kalman Filter to estimate their parameters (0.5 μs/core/track), have a very high level of intrinsic parallelism for their fast and efficient implementation on many-core CPU/GPU architectures.
- The KF Particle Finder package with more than 150 decay channels implemented (100 μs/core/decay) is a common platform for offline physics analysis and for real-time express analysis at 10^7 interaction rate in CBM.
- Adaptation of the FLES algorithms within the CBM Phase-0 program to the STAR experiment with its excellent detector performance, high quality experimental data and a well established reconstruction chain is the first and successful step in preparing the FLES algorithms for reconstruction and analysis of CBM real data at Day-1.
- Use of the CA Track Finder and KF Particle Finder developed in the CBM experiment can be beneficial for other experiments as the experimental heavy ion physics becomes more and more challenging.