Event Reconstruction on Many-Core Computer Architectures

(CBM Experiment at FAIR)

XIIth Quark Confinement and the Hadron Spectrum

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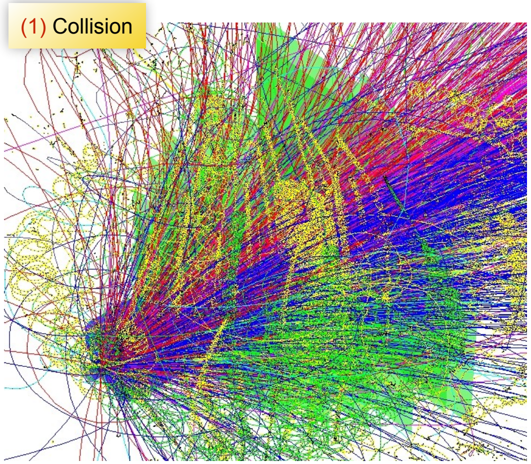
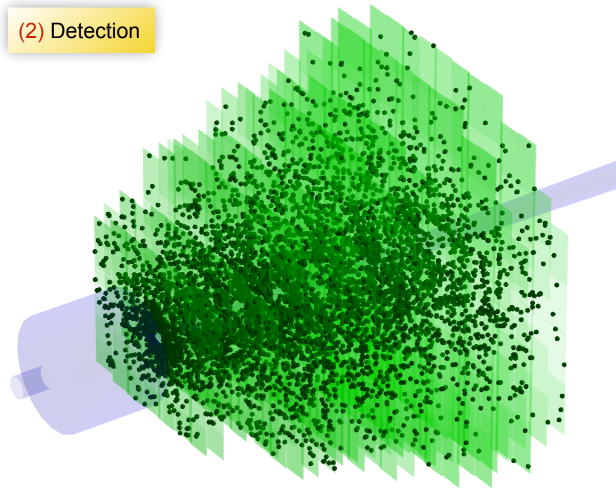
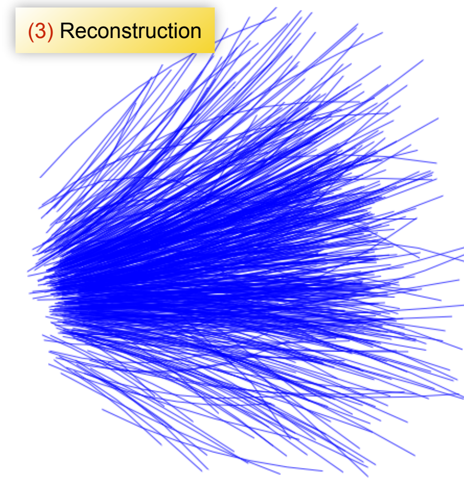
Goethe-University Frankfurt am Main
FIAS Frankfurt Institute for Advanced Studies
GSI Helmholtz Center for Heavy Ion Research

Reconstruction Challenge in CBM at FAIR/GSI





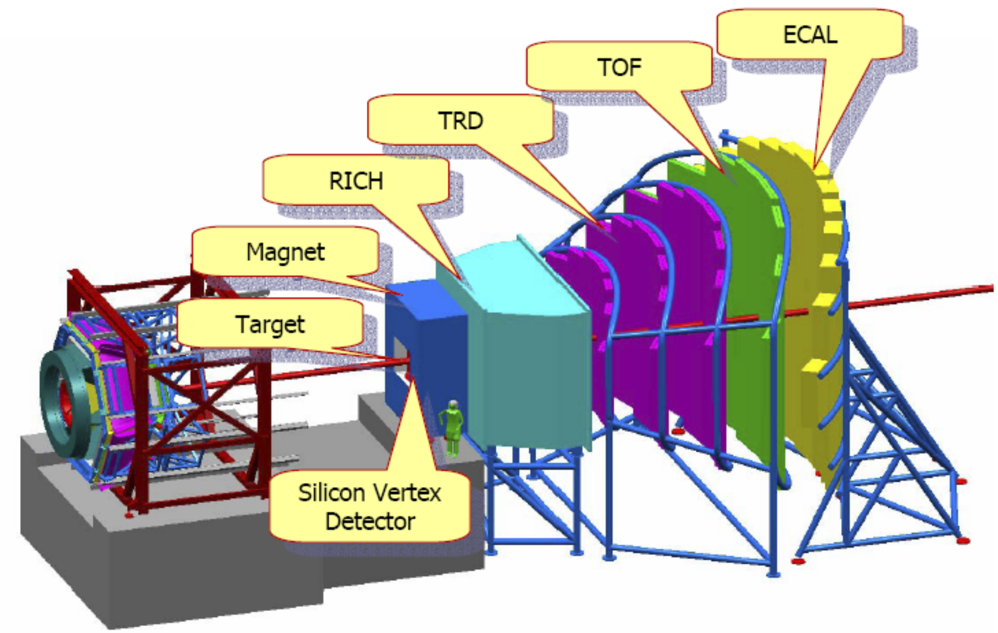


- Future fixed-target heavy-ion experiment
- 10^7 Au+Au collisions/sec
- ~ 1000 charged particles/collision
- Non-homogeneous magnetic field
- Double-sided strip detectors (85% fake space-points)

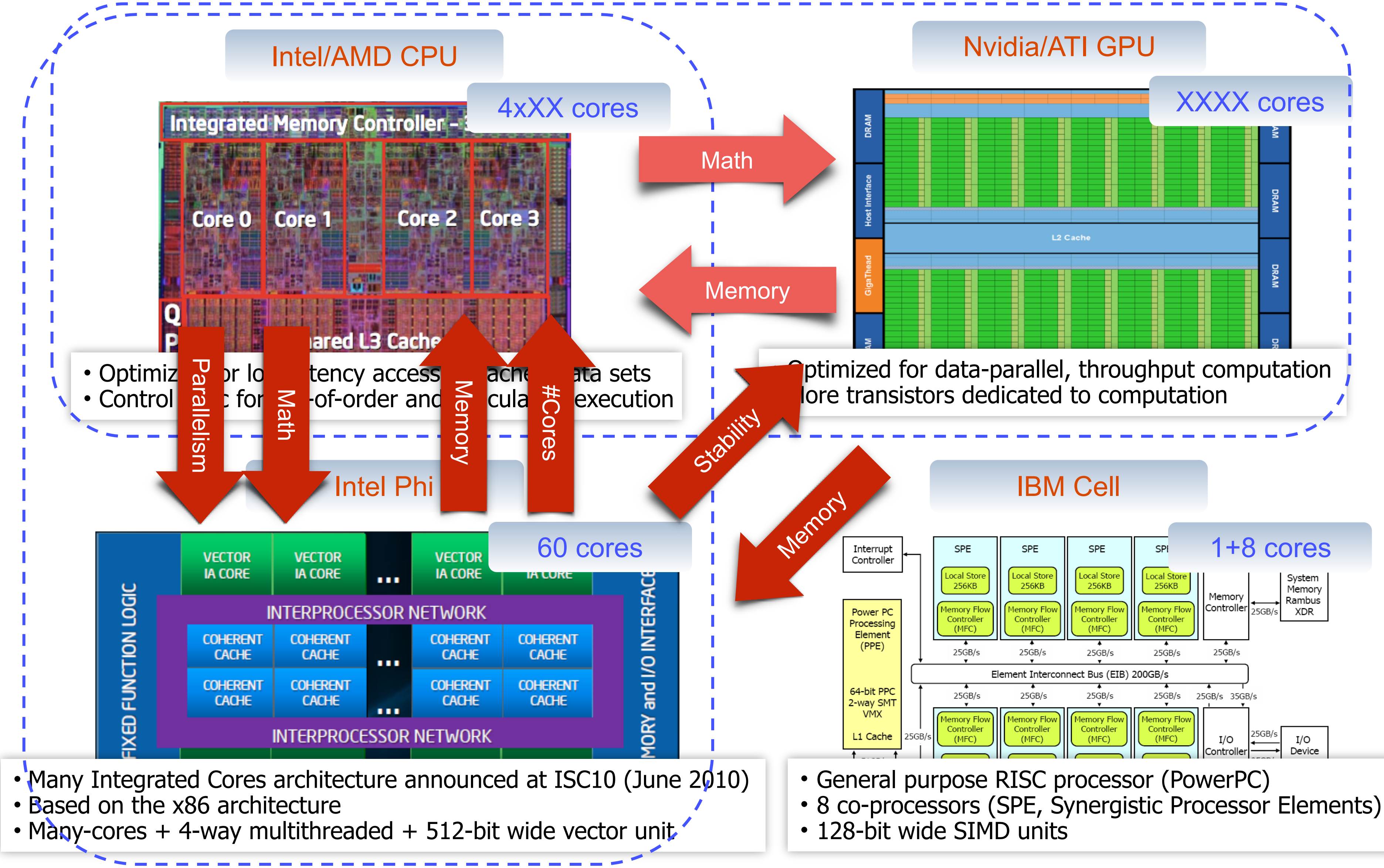
Full event reconstruction will be done on-line at the First-Level Event Selection (FLES) and off-line using the same FLES reconstruction package.

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

All reconstruction algorithms are vectorized and parallelized.



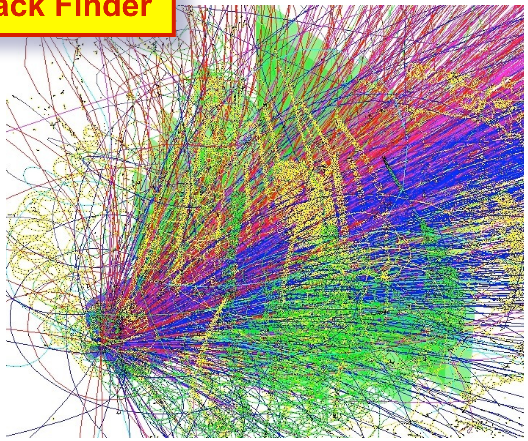
Many-Core CPU/GPU Architectures



Future systems are heterogeneous, but using the same code

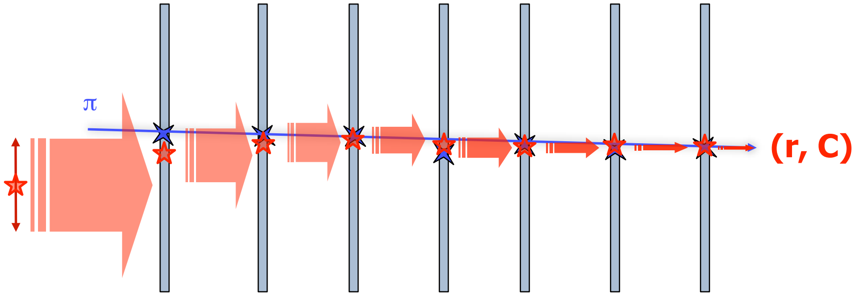
Stages of Event Reconstruction

1 Track Finder



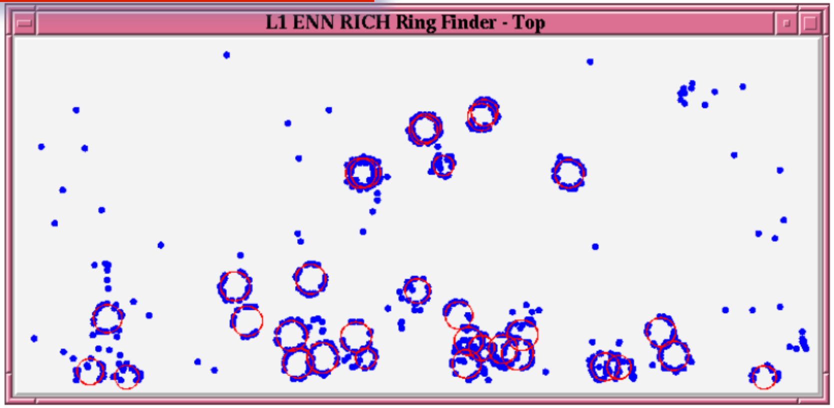
- Cellular Automaton
- Track Following

2 Track Fitter



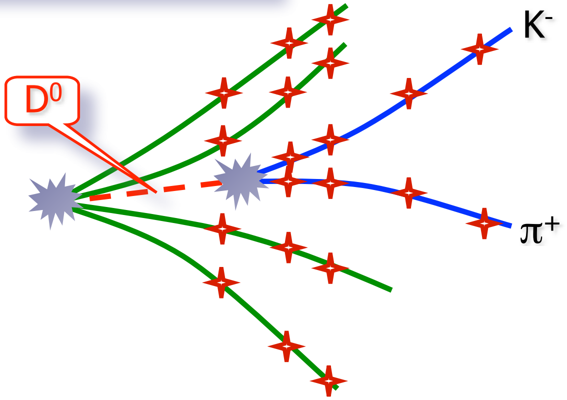
- Kalman Filter

3 Ring Finder (Particle ID)



- Hough Transformation
- Elastic Neural Net

4 Short-Lived Particles Finder



- Kalman Filter

Kalman Filter (KF) Track Fit Library

Kalman Filter Methods

Kalman Filter Tools:
- KF Track Fitter
- KF Track Smoother
- Deterministic Annealing Filter

Kalman Filter Approaches:
- Conventional DP KF
- Conventional SP KF
- Square-Root SP KF
- UD-Filter SP
- Gaussian Sum Filter

Track Propagation:
- Runge-Kutta
- Analytic Formula

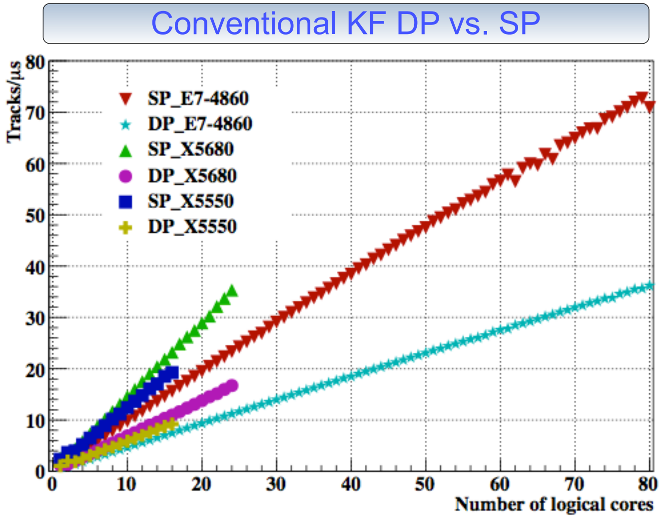
Implementations

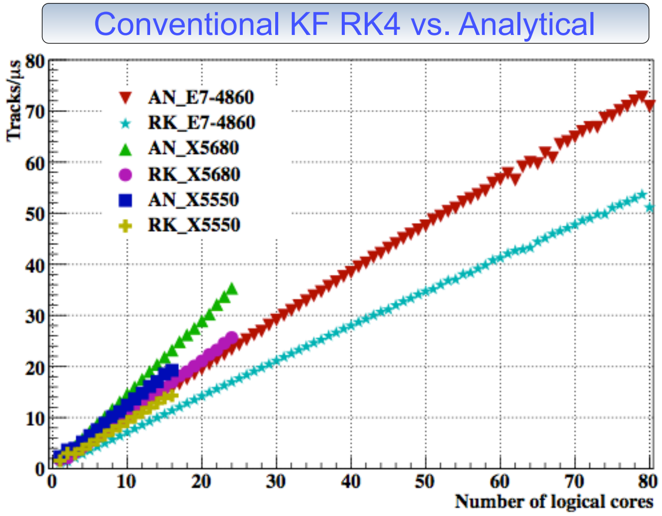
Vectorization (SIMD):
- Header Files
- Vc Vector Classes
- ArBB Array Building Blocks
- OpenCL

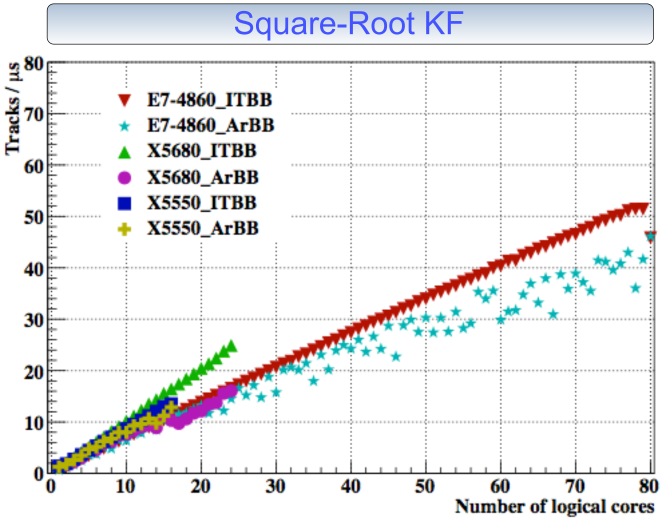
Parallelization (many-cores):
- Open MP
- ITBB
- ArBB
- OpenCL

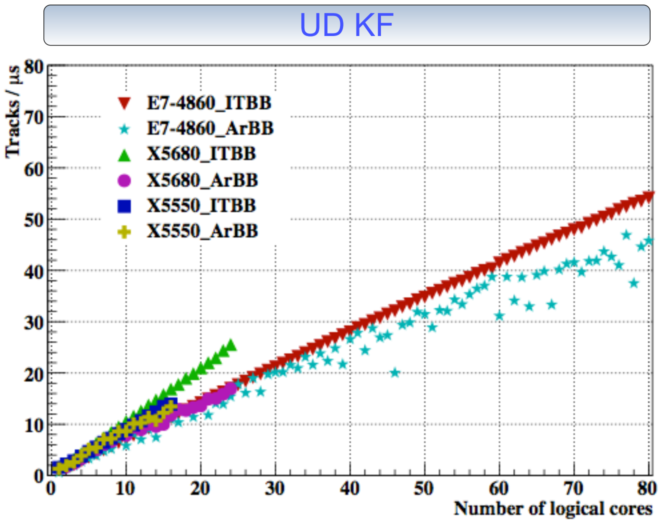
Precision:
- single precision SP
- double precision DP

Comp. Phys. Comm. 178 (2008) 374-383





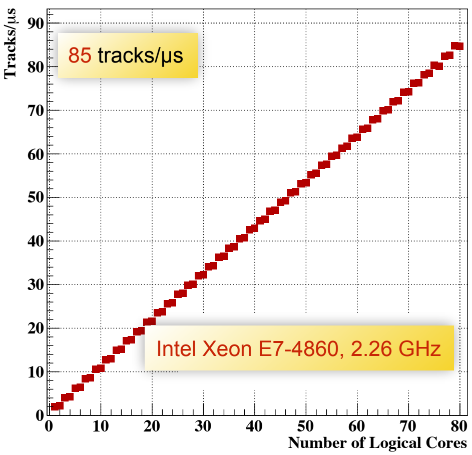


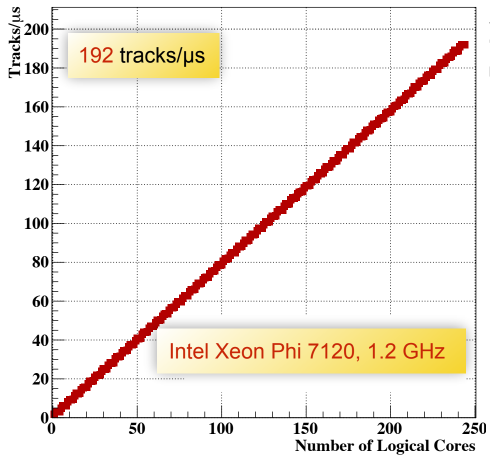


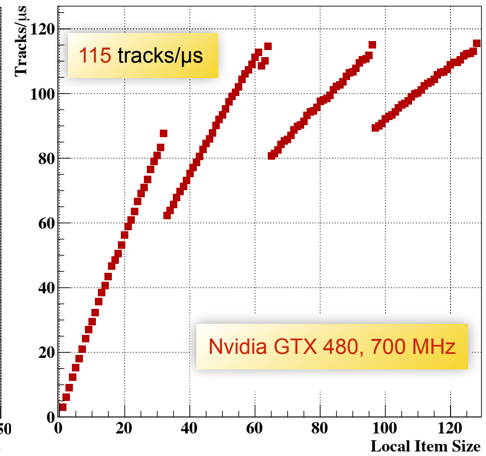
Strong many-core scalability of the Kalman filter library

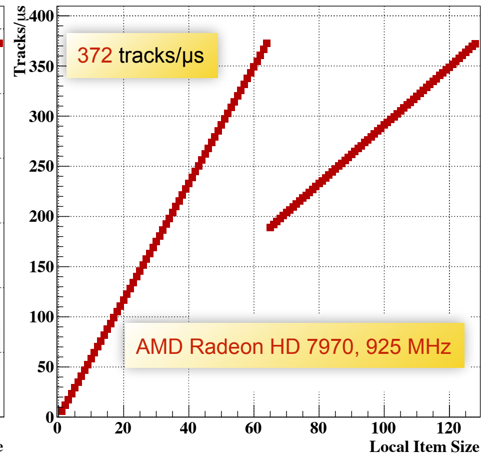
with I. Kulakov, H. Pabst* and M. Zyzak (*Intel)

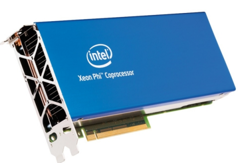
Kalman Filter (KF) Track Fit Library







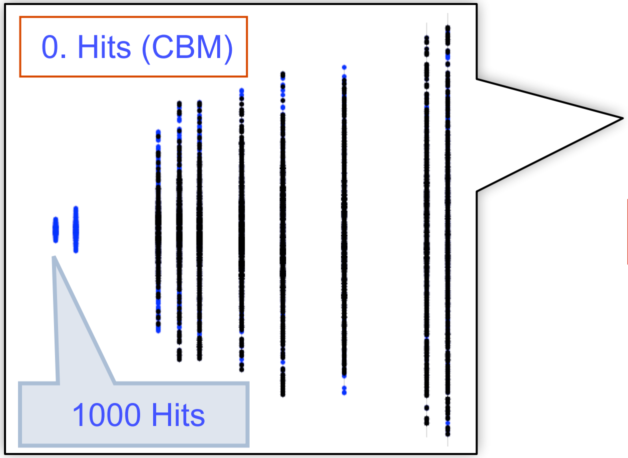


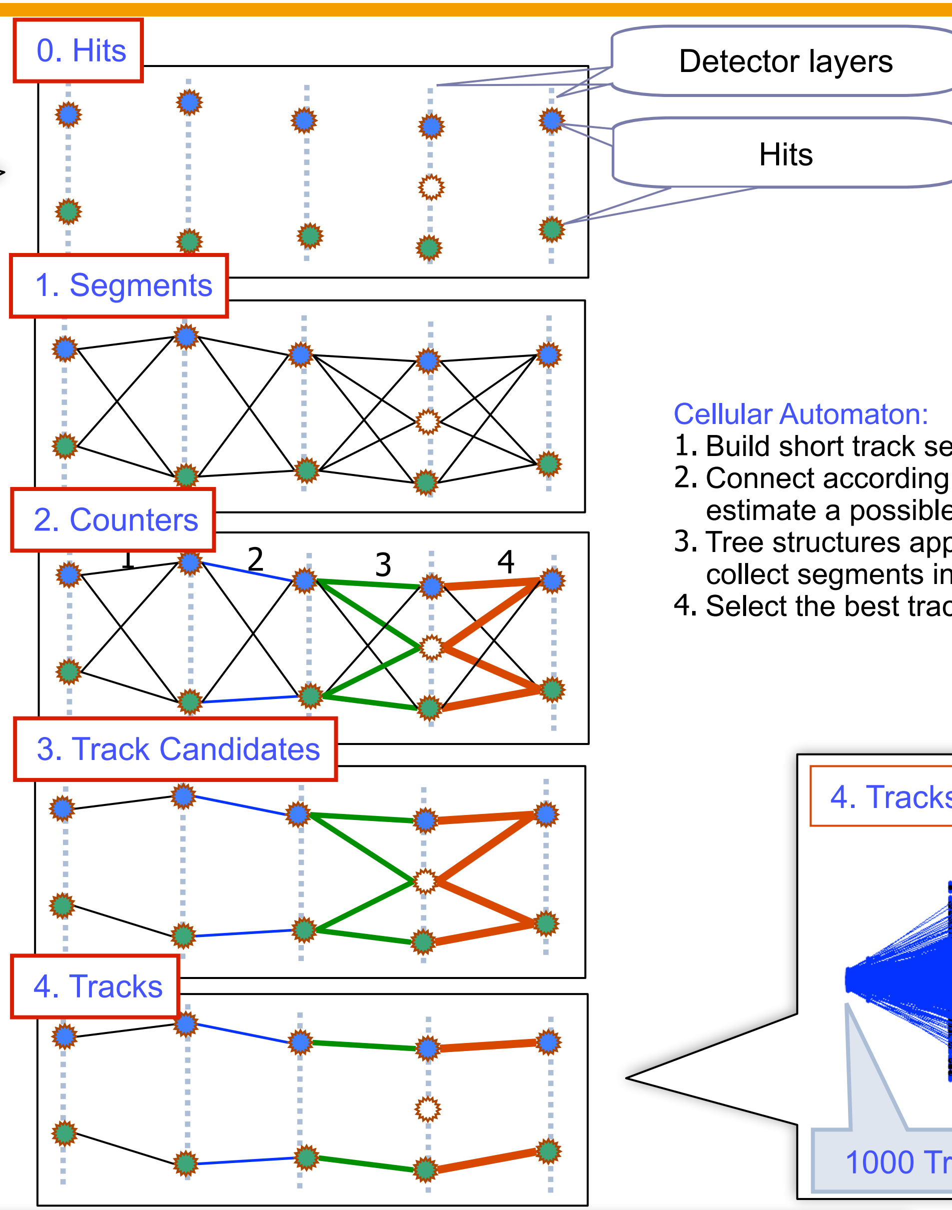


- Scalability with respect to the number of logical cores in a CPU is one of the most important parameters of the algorithm.
- The scalability on the Intel Xeon Phi coprocessor is similar to the CPU, but running four threads per core instead of two.
- In case of the graphic cards the set of tasks is divided into working groups of size *local item size* and distributed among compute units (or streaming multiprocessors) and the load of each compute unit is of the particular importance.

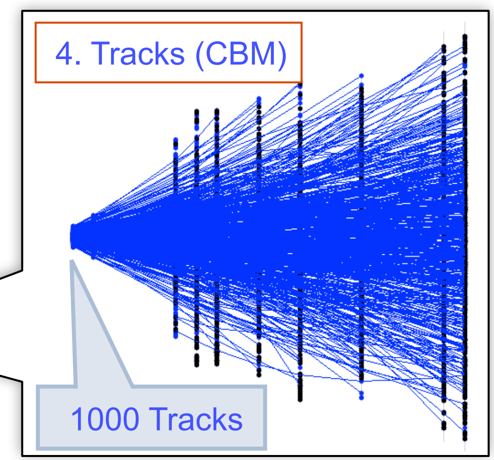
Full portability of the Kalman filter library

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.

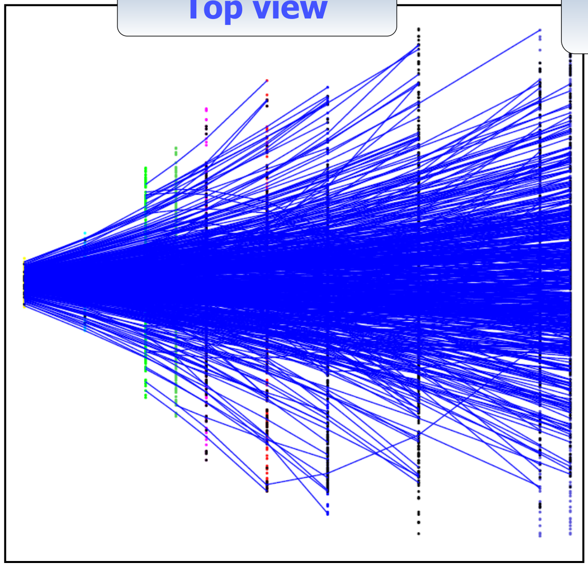


Cellular Automaton:
- local w.r.t. data
- intrinsically parallel
- extremely simple
- very fast

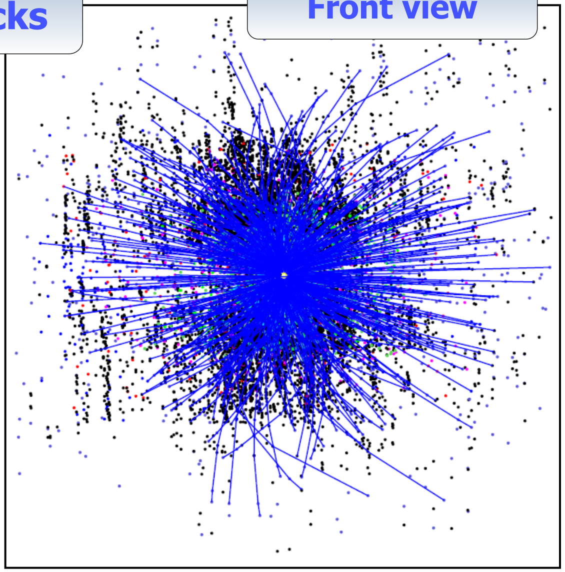
Perfect for many-core CPU/GPU !

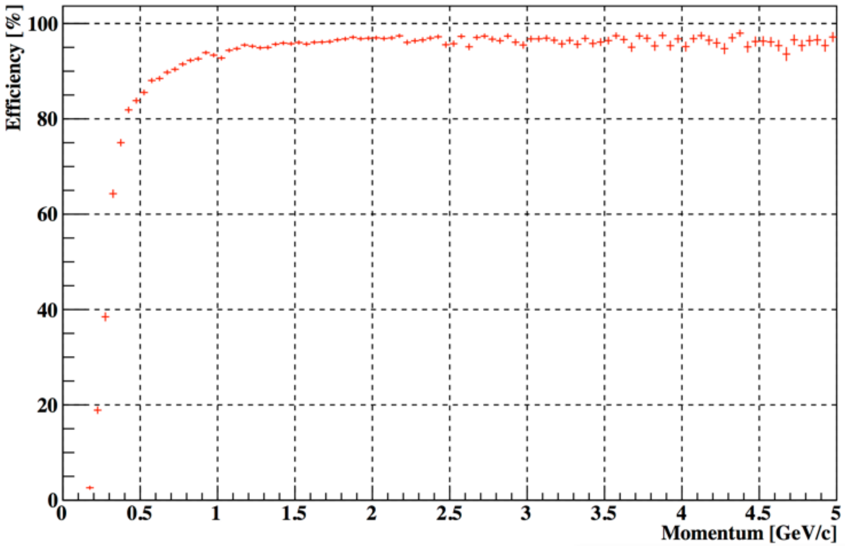
Useful for complicated event topologies with large combinatorics and for parallel hardware

CA Track Finder: Efficiency



770 Tracks



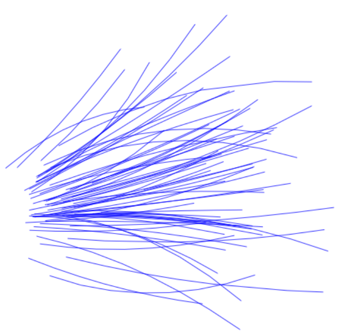


	Efficiency, % mbias	Efficiency, % central
Primary high-p tracks	97.1	96.2
Primary low-p tracks	90.4	90.7
Secondary high-p tracks	81.2	81.4
Secondary low-p tracks	51.1	50.6
All tracks	88.5	88.3
Clone level	0.2	0.2
Ghost level	0.7	1.5
Reconstructed tracks/event	120	591
Time/event/core	8.2 ms	57 ms

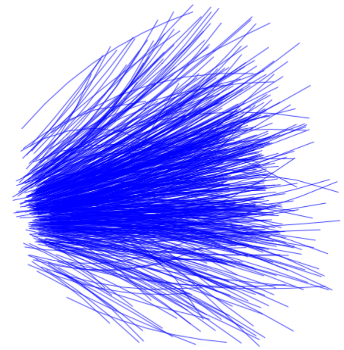
Efficient and clean event reconstruction

CA Track Finder at High Track Multiplicity

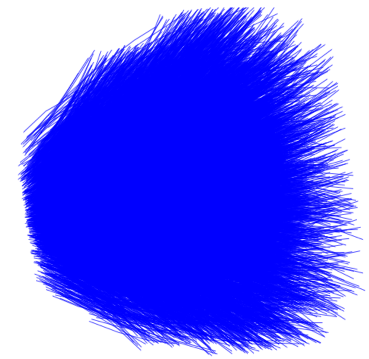
A number of minimum bias events is gathered into a group (super-event), which is then treated by the CA track finder as a single event



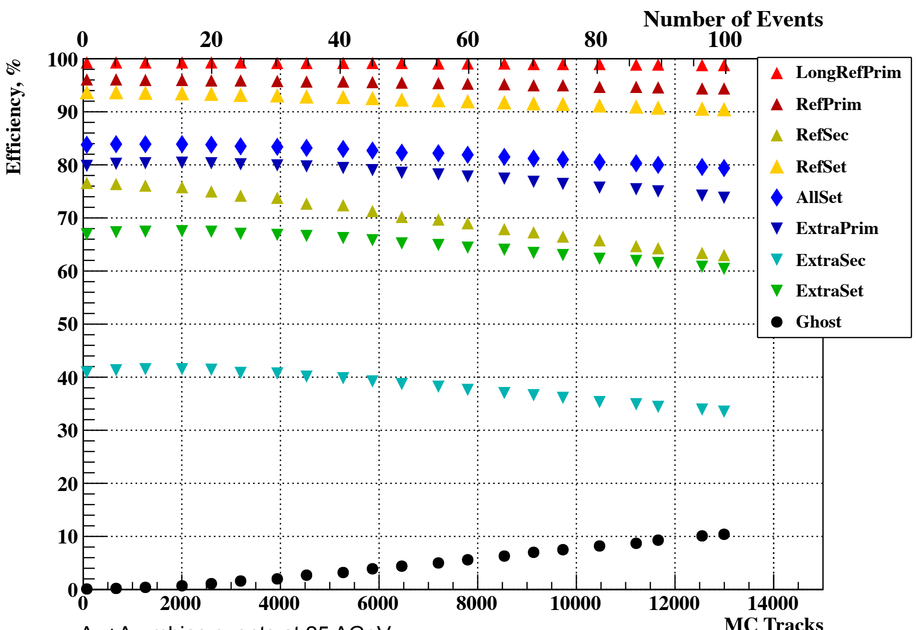
1 mbias event, $<N_{reco}>$ = 109



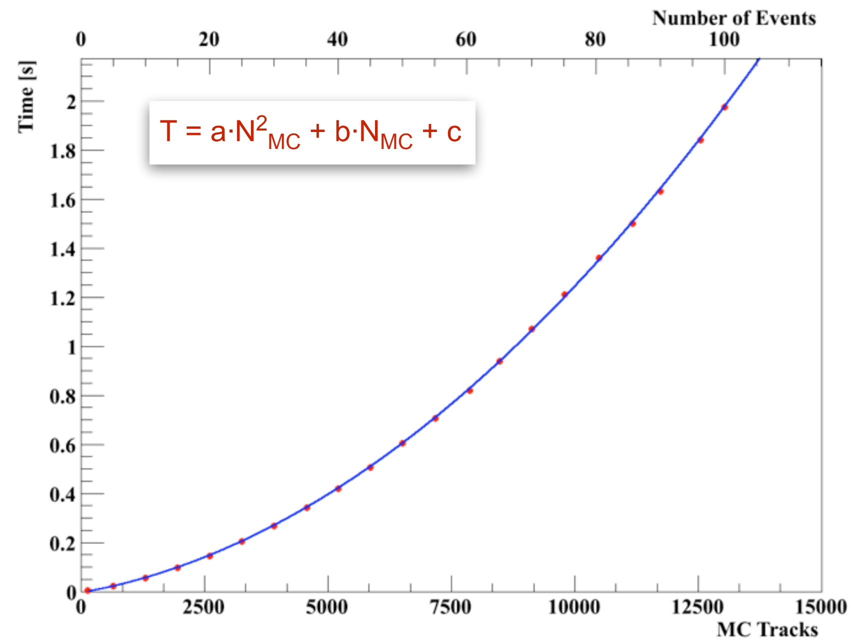
5 mbias events, $<N_{reco}>$ = 572



100 mbias events, $<N_{reco}>$ = 10340

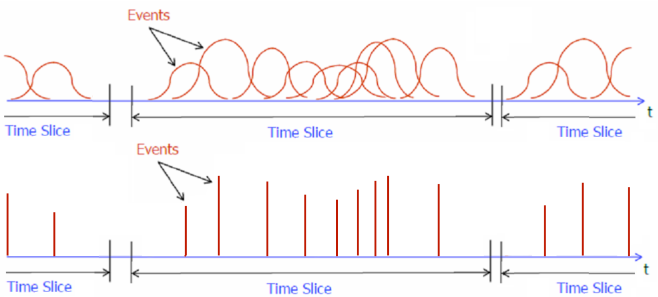


Au+Au mbias events at 25 AGeV



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

Time-based (4D) Track Reconstruction with CA Track Finder

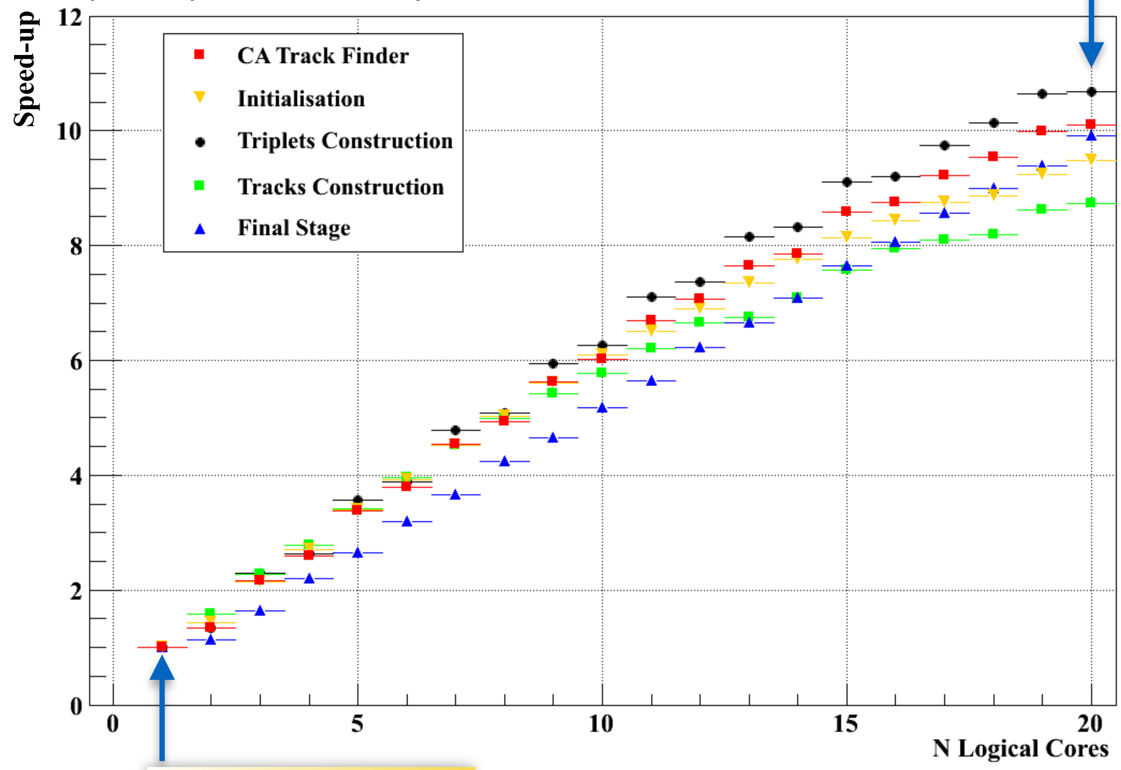


- The beam in the CBM will have no bunch structure, but continuous.
- Measurements in this case will be 4D (x, y, z, t).
- Significant overlapping of events in the detector system.
- Reconstruction of time slices rather than events is needed.

Stage of the algorithm	% of total execution time
Initialisation	8
Triplets construction	64
Tracks construction	15
Final cleaning	13

Total CA time = 84 ms

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



Total CA time = 849 ms

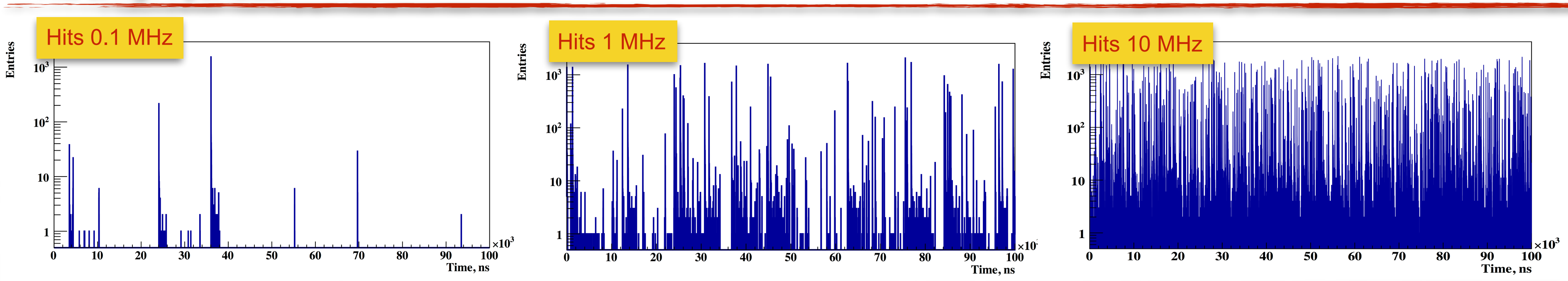
100 mbias events in a time-slice

Efficiency, %	3D	3+1 D	4D
All tracks	83.8	80.4	83.0
Primary high-p	96.1	94.3	92.8
Primary low-p	79.8	76.2	83.1
Secondary high-p	76.6	65.1	73.2
Secondary low-p	40.9	34.9	36.8
Clone level	0.4	2.5	1.7
Ghost level	0.1	8.2	0.3
Time/event/core, ms	8.2	31.5	8.5

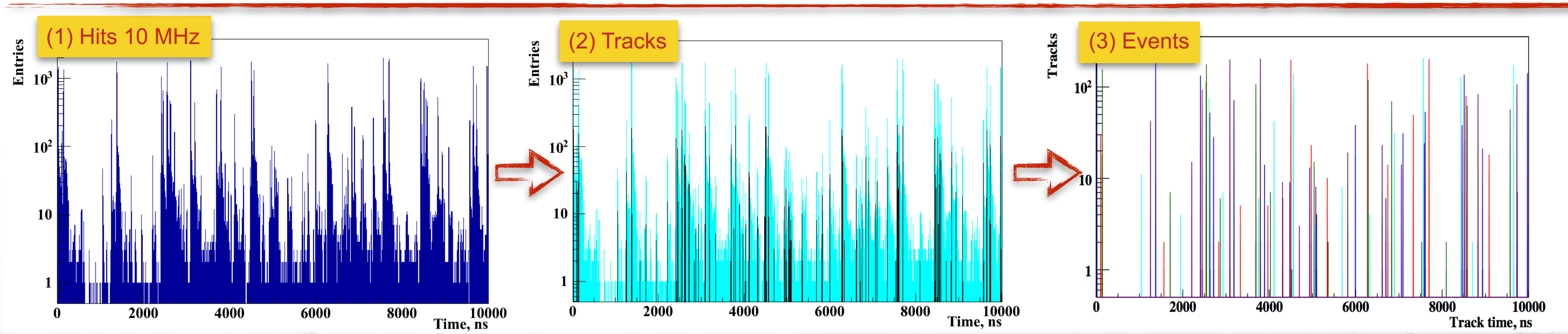
4D event building is scalable with the speed-up factor of 10.1; 3D reconstruction time 8.2 ms/event is recovered in 4D case

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
83% of single events, no splitted events, further analysis with TOF information at the vertexing stage

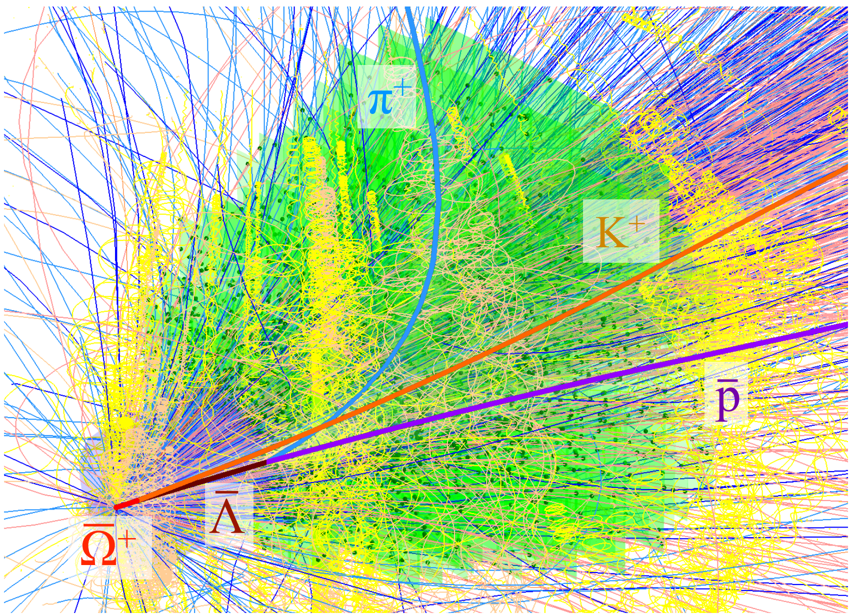
KF Particle: Reconstruction of Decayed Particles

State vector

Position, direction, momentum and energy

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

Central AuAu event at 25 AGeV simulated with UrQMD



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

Concept:

- Mother and daughter particles have the same state vector and are treated in the same way
- Reconstruction of decay chains
- Kalman filter 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

KFParticle provides uncomplicated approach to physics analysis (used in CBM, ALICE and STAR)

KF Particle Finder Algorithm

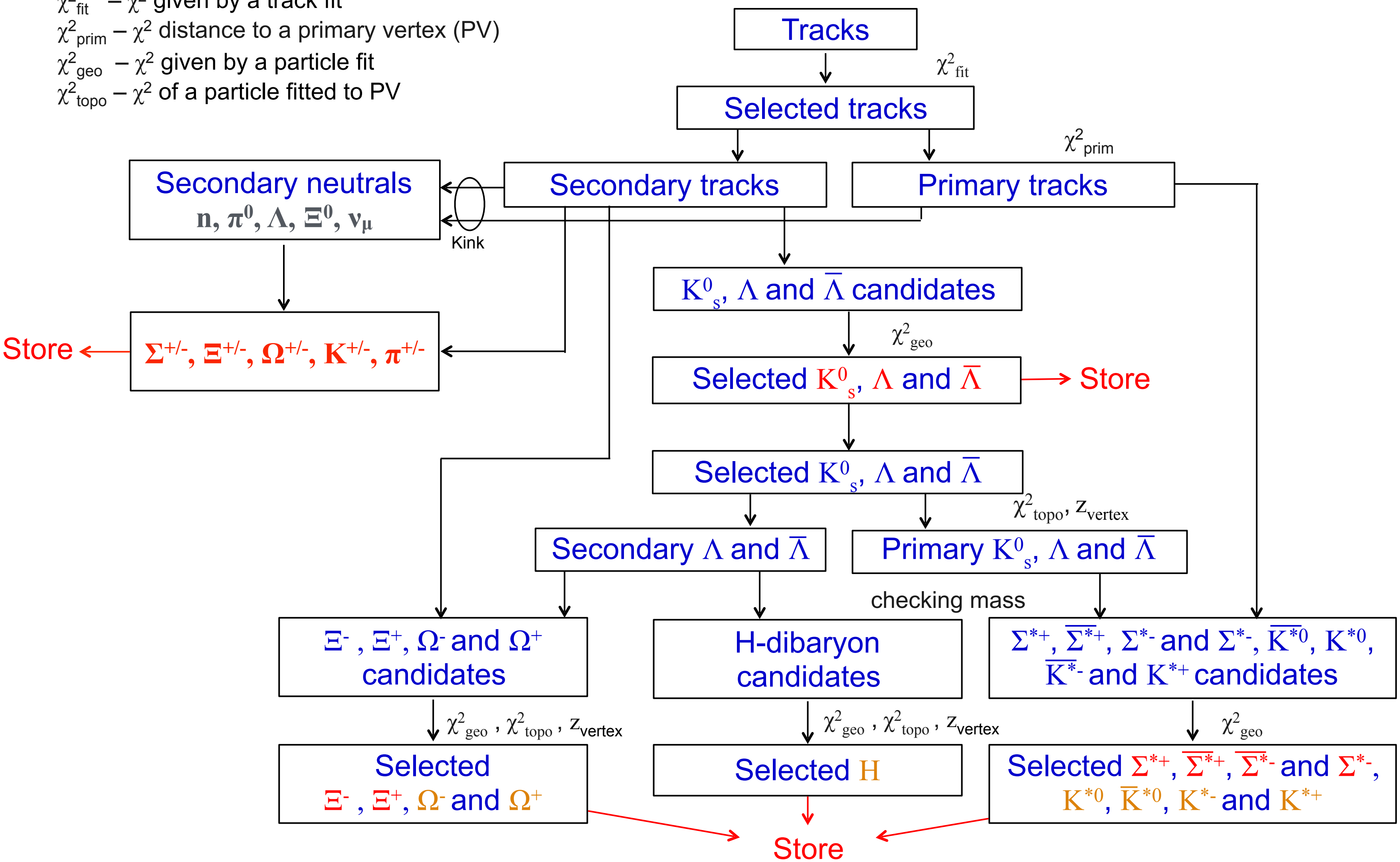
Selection criteria:

χ^2_{fit} – χ^2 given by a track fit

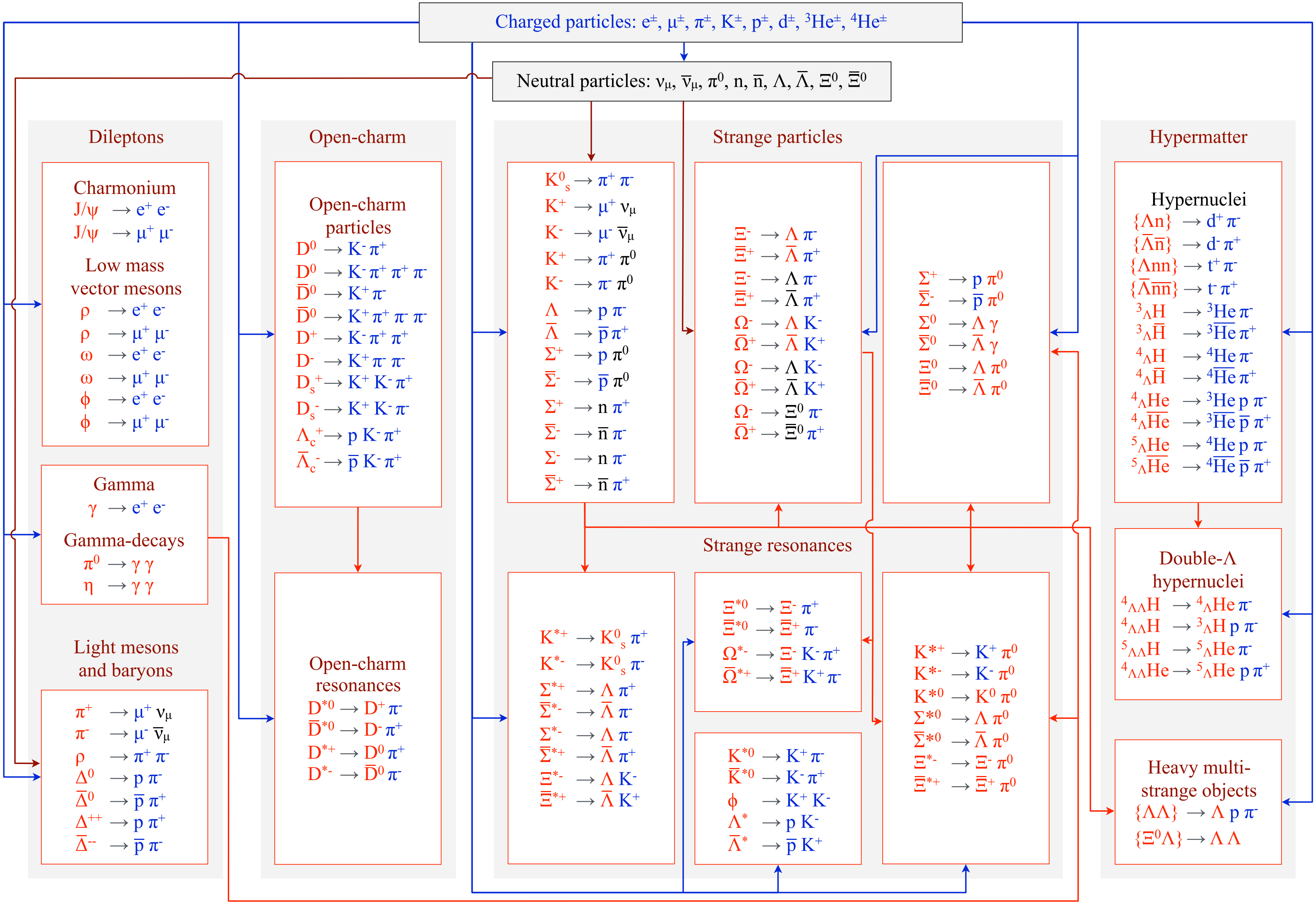
χ^2_{prim} – χ^2 distance to a primary vertex (PV)

χ^2_{geo} – χ^2 given by a particle fit

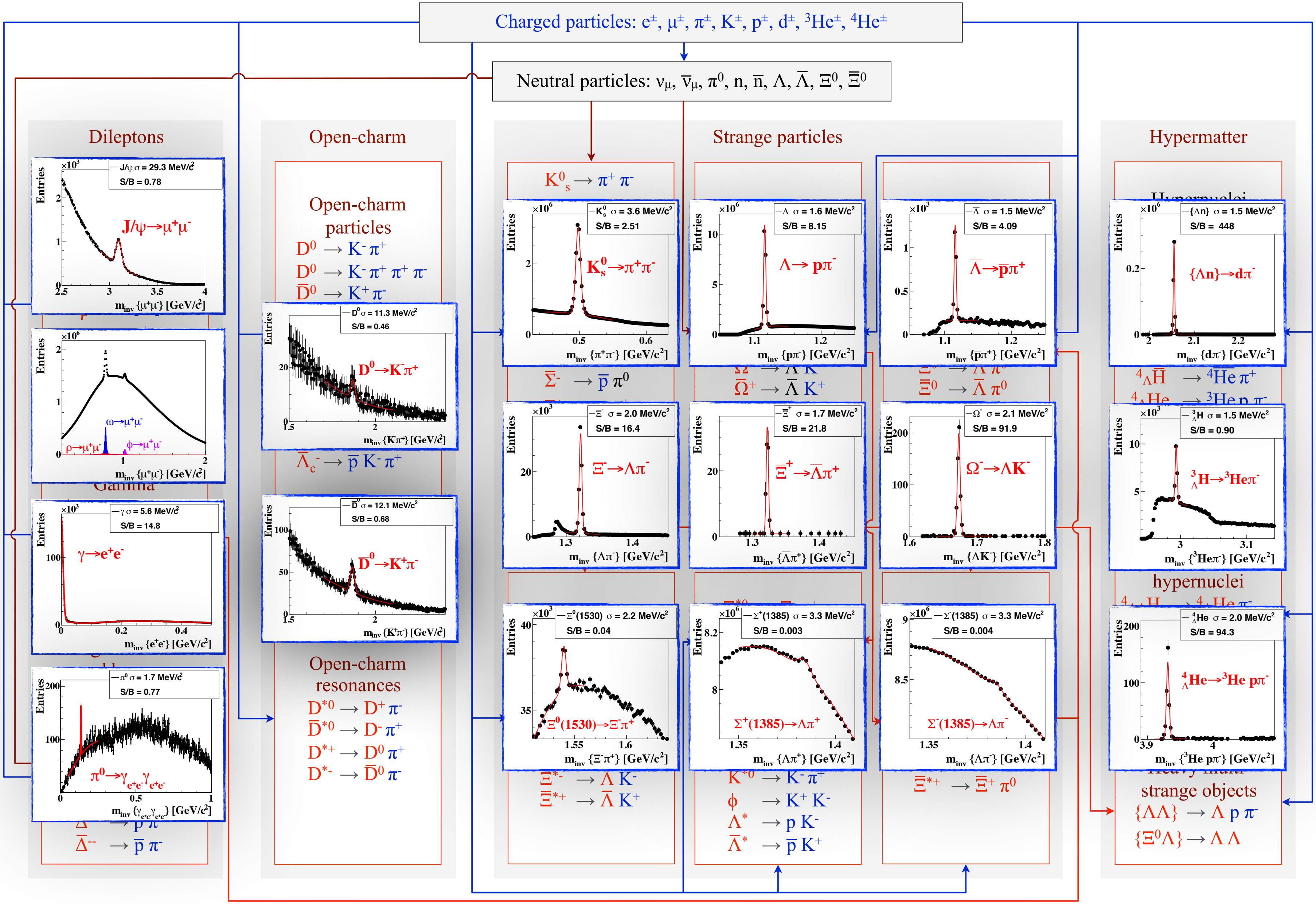
χ^2_{topo} – χ^2 of a particle fitted to PV



KF Particle Finder for Physics Analysis and Selection

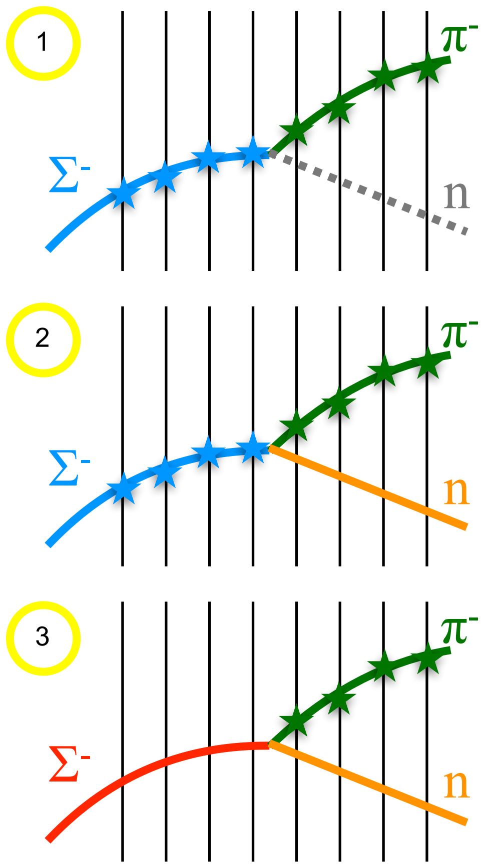


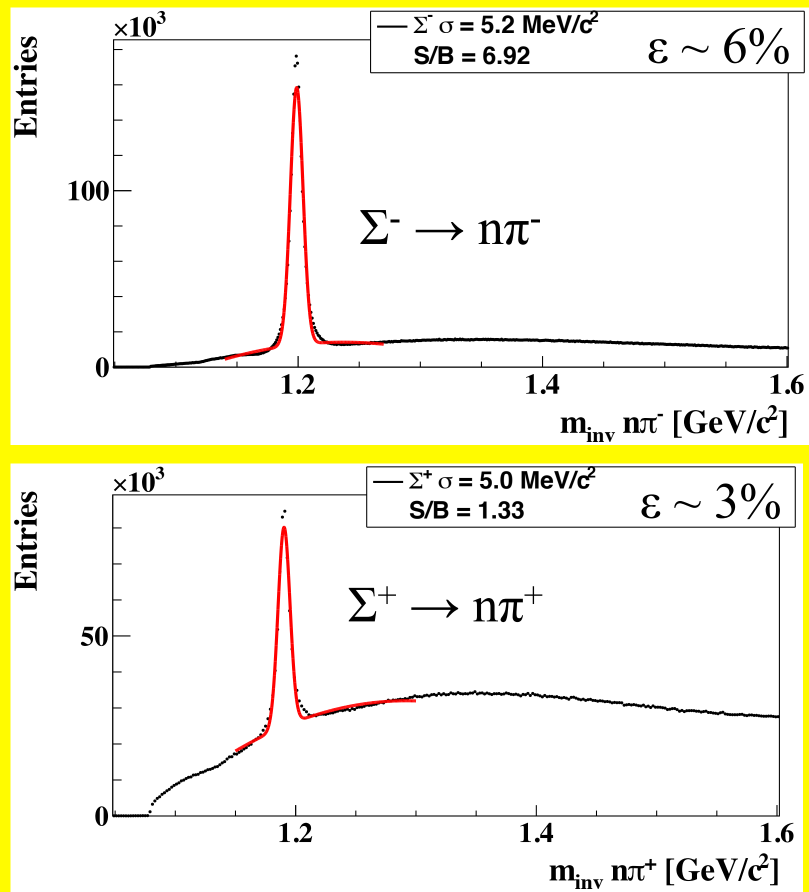
KF Particle Finder for Physics Analysis and Selection



Decays with Neutral Daughter

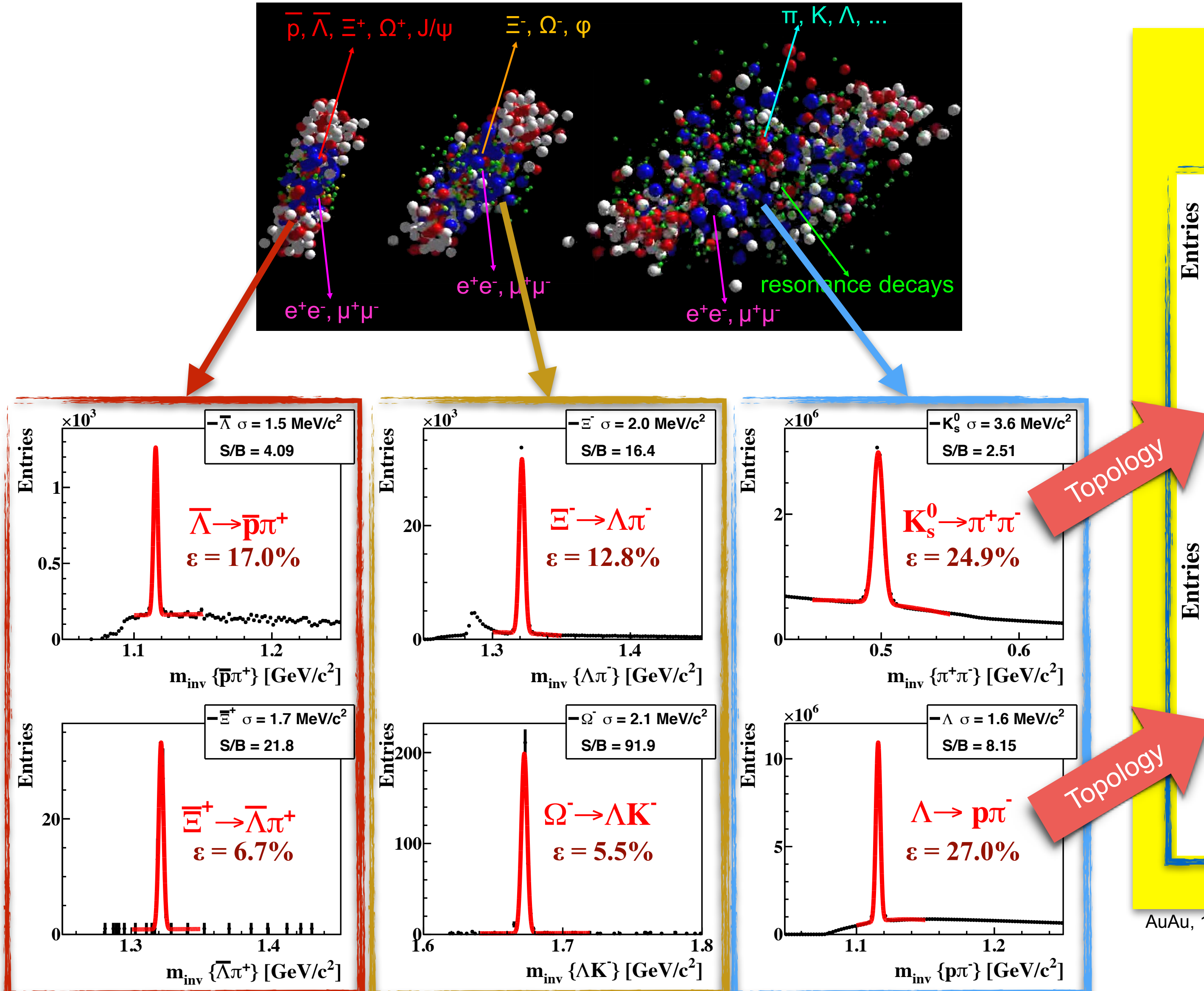
- Some particles (Σ^+ and Σ^-) have channels with at least one neutral daughter.
- A lifetime is sufficient to be registered by the tracking system: $c\tau$ = 2.4 cm for Σ^+ and $c\tau$ = 4.4 cm for Σ^-.
- Can not to be identified by the PID detectors.
- Identification is possible by the decay topology using the missing mass method:
  1. Find tracks of Σ and its charged daughter (kink);
  2. Reconstruct a neutral daughter from the mother and the charged daughter;
  3. Reconstruct Σ mass spectrum from the charged and obtained neutral daughters.



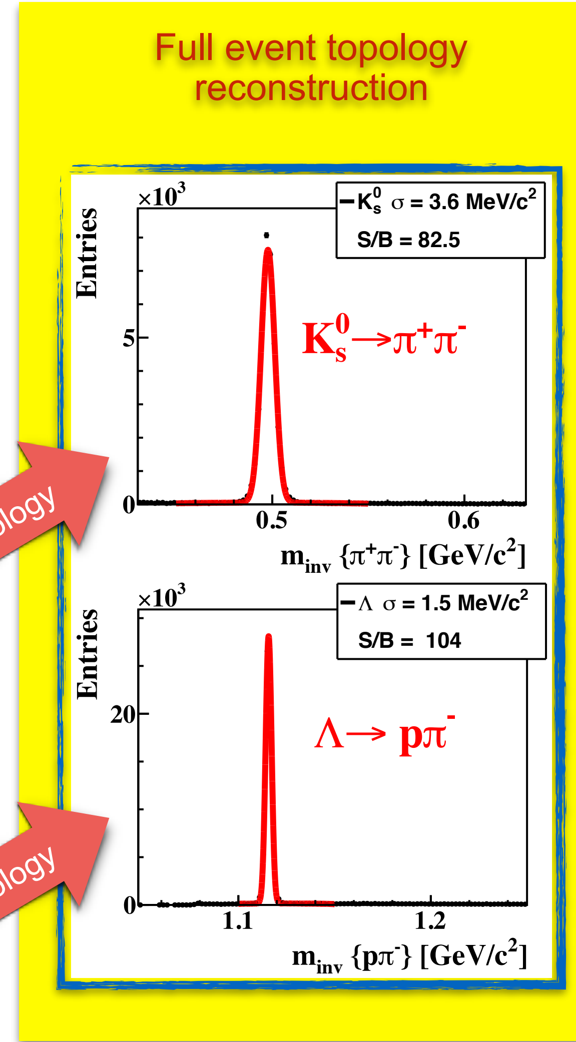


AuAu, 10 AGeV, 5M central UrQMD events, no PID

Clean Probes of Collision Stages



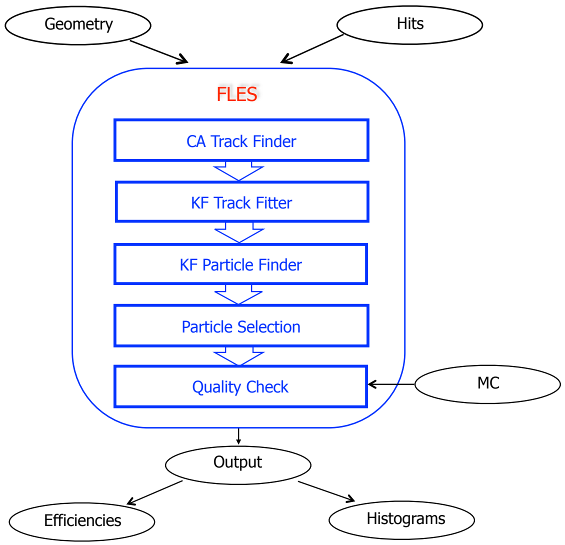
AuAu, 10 AGeV, 5M central UrQMD events, realistic PID

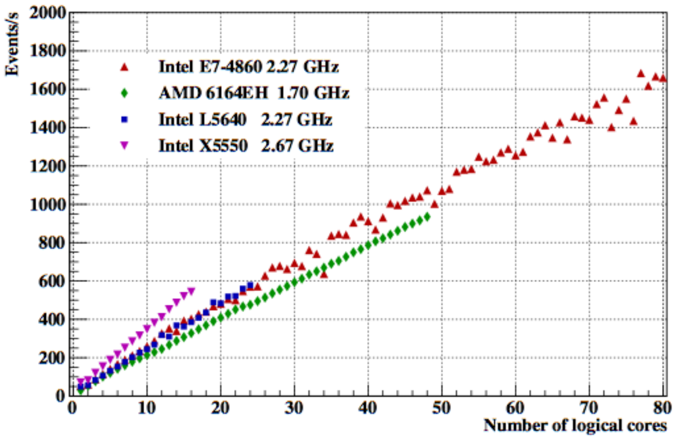


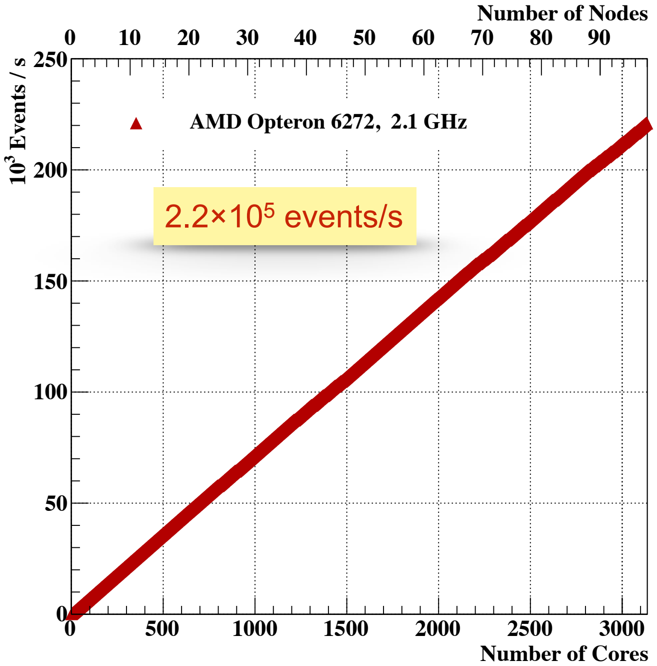
AuAu, 10 AGeV, 80K mbias UrQMD events, no PID

M. Zyzak

CBM Standalone First Level Event Selection (FLES) Package







The first version of the FLES package is vectorized, parallelized, portable and scalable up to 3 200 CPU cores

Parallelization in the CBM Event Reconstruction

CPU - Full reconstruction

CPU - Tracking

Algorithm	SIMD	ITBB, OpenMP	CUDA	OpenCL CPU/GPU	Phi	ArBB
Hit Producers						
STS KF Track Fit	✓	✓	✓	✓/✓	✓	✓
STS CA Track Finder	✓	✓				
MuCh Track Finder	✓	✓	✓			
TRD Track Finder	✓	✓	✓			
RICH Ring Finder	✓	✓		✓/✓		
KF Particle Finder	✓	✓		✓/✓	✓	
Off-line Physics Analysis	✓					
FLES Analysis and Selection	✓	✓				

All - Benchmark

GPU/Phi - Selection

Andrzej Nowak (OpenLab, CERN) by Hans von der Schmitt (ATLAS) at GPU Workshop, DESY, 15-16 April 2013

	SIMD	Instr. Level Parallelism	HW Threads	Cores	Sockets	Factor	Efficiency
MAX	4	4	1.35	8	4	691.2	100.0%
Typical	2.5	1.43	1.25	8	2	71.5	10.3%
HEP	1	0.80	1	6	2	9.6	1.4%
CBM@FAIR	4	3	1.3	8	4	499.2	72.2%

Parallelization becomes a standard in the CBM experiment

Summary

- The Kalman Filter track fit library is vectorized, parallelized and portable to CPU/Phi/GPU architectures.
- The Cellular Automaton track finder is vectorized and parallelized between CPU cores.
- The KF Particle Finder for reconstruction of short-lived particles is vectorized and portable to CPU/Phi architectures.
- Online physics analysis approaches are under investigation.

More details:
- V. Akishina, 4D event reconstruction in the CBM experiment, PhD Thesis, Uni-Frankfurt, 2016
- M. Zyzak, Online selection of short-lived particles on many-core computer architectures in the CBM experiment at FAIR, PhD Thesis, Uni-Frankfurt, 2016