From Hits to Physics: Event Reconstruction in High-Energy Physics Experiments

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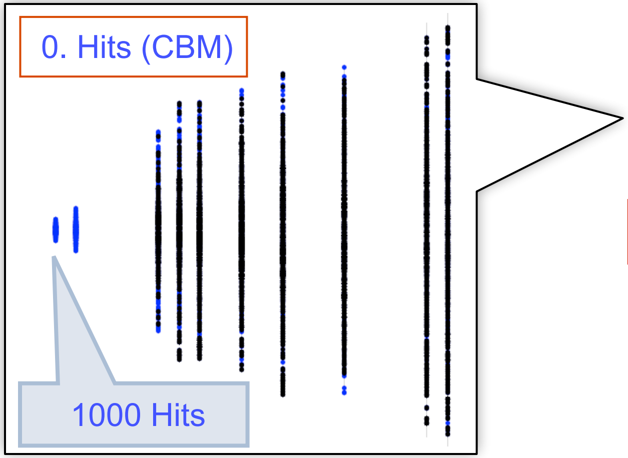
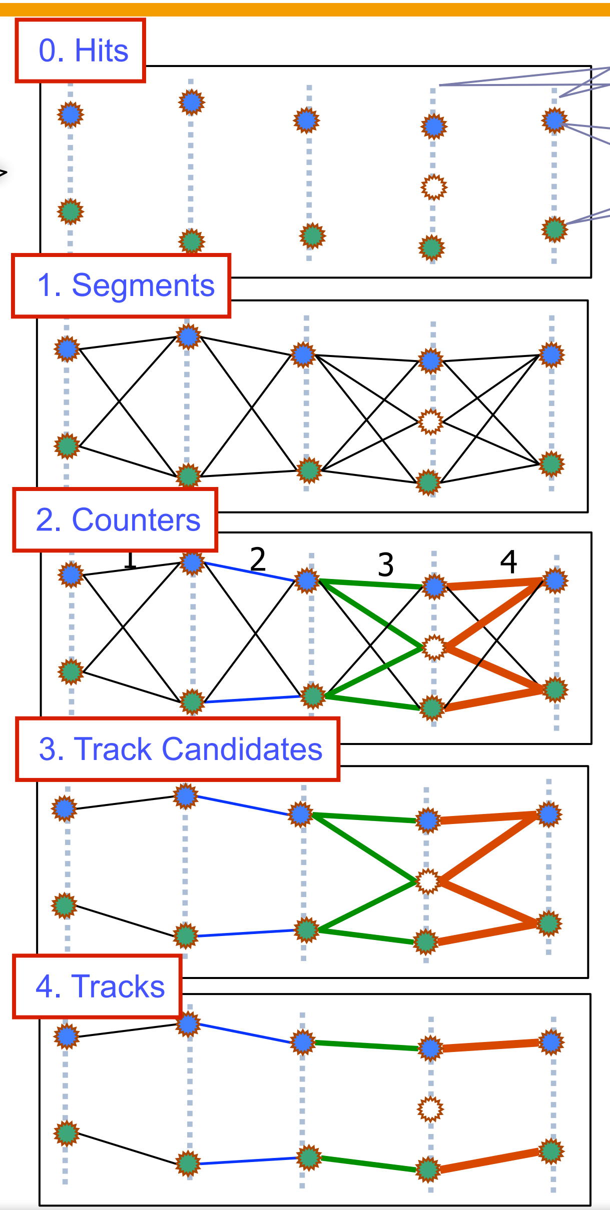
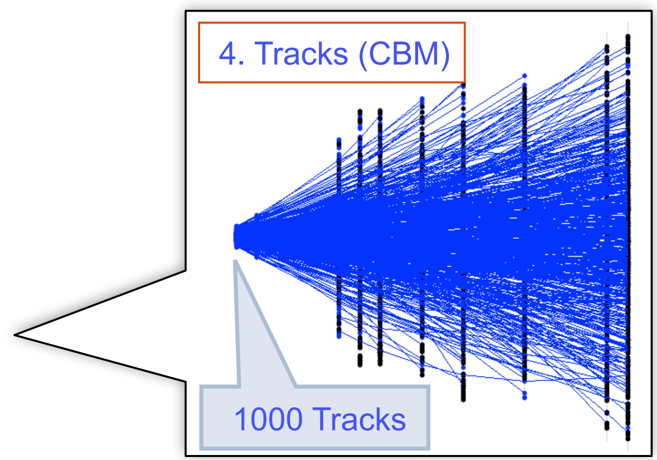
Goethe University Frankfurt am Main
FIAS Frankfurt Institute for Advanced Studies
GSI Helmholtz Center for Heavy Ion Research

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.



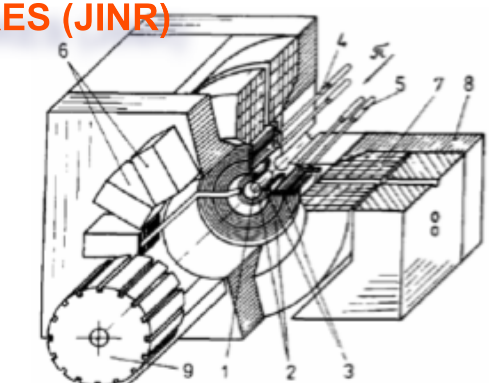
Cellular Automaton:
- local w.r.t. data
- intrinsically parallel
- extremely simple
- very fast

Perfect for many-core CPU/GPU !

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

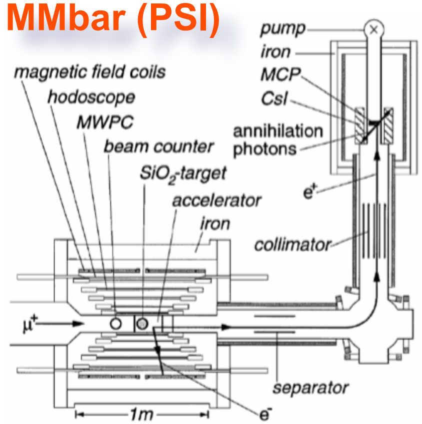
Our Application of CA in HEP Experiments

ARES (JINR)

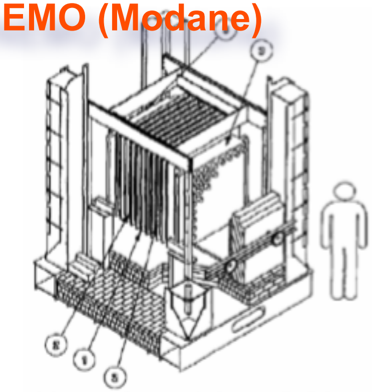


(1) target, (2) MWPC, (3) scintillation hodoscopes,
(4) lightguides, (5) photomultipliers, (6) electronics, (7)-(9) magnet.

MMbar (PSI)

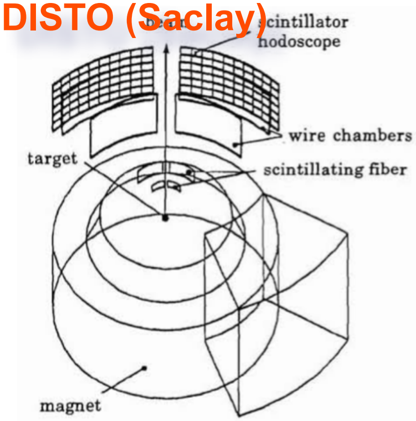


NEMO (Modane)

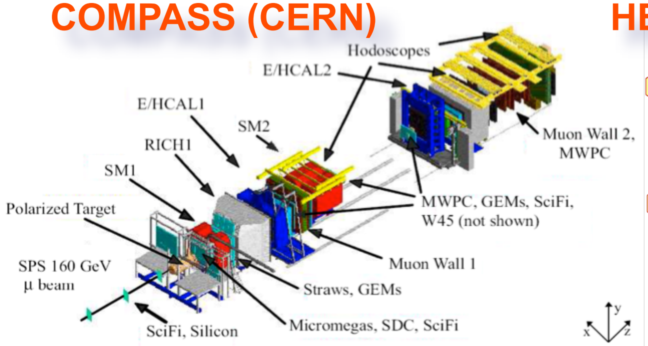


(1) central frame with the metallic foil,
(2) tracking device of 10 frames with 2x32 Geiger tubes each,
(3) scintillator walls of 5x5 counters.

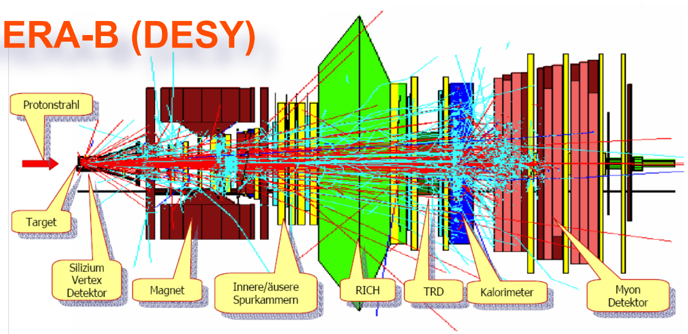
DISTO (Saclay)



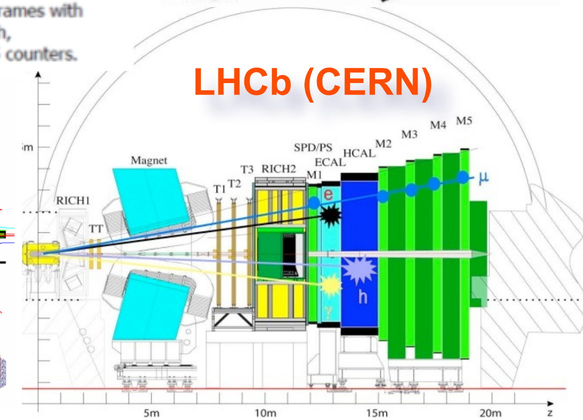
COMPASS (CERN)



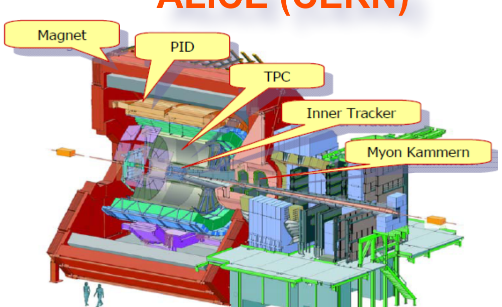
HERA-B (DESY)



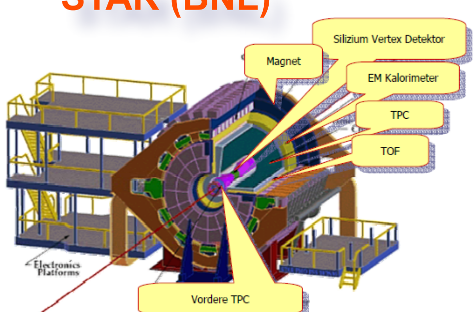
LHCb (CERN)



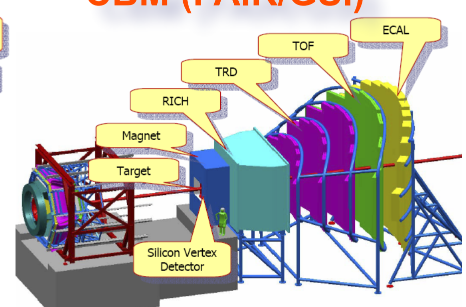
ALICE (CERN)



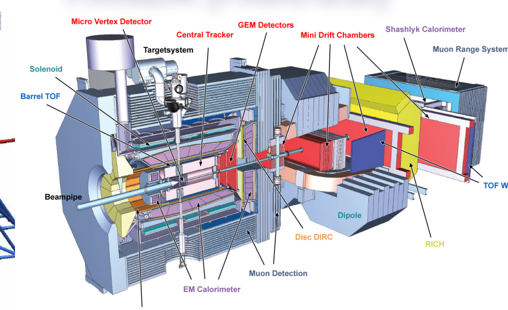
STAR (BNL)



CBM (FAIR/GSI)



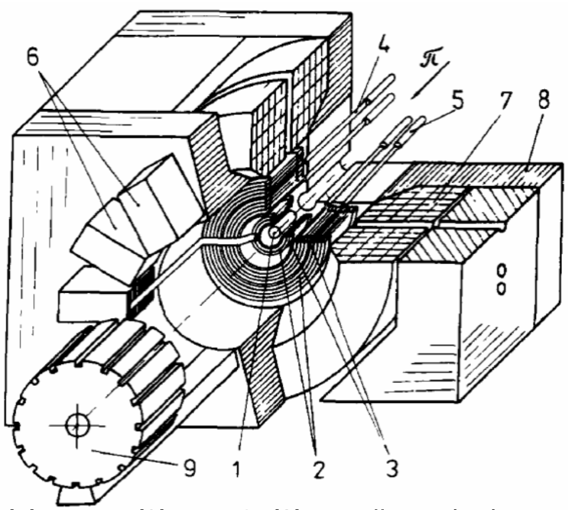
PANDA (FAIR/GSI)



CA Track Finder in ARES (JINR) and MMbar (PSI)

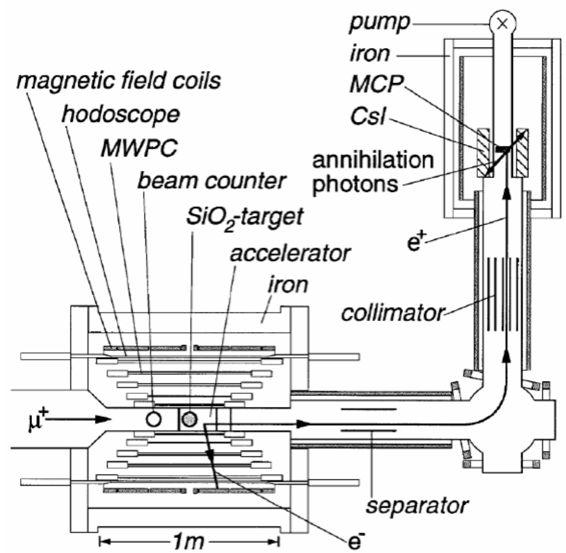
ARES

MMbar



Problems:
- Search for rare decays
- Detector inefficiency
- Electronics noise
- Slow PC

Solution:
- Determine track direction from clusters



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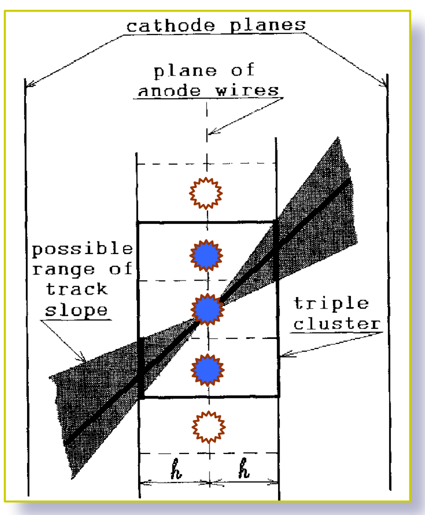
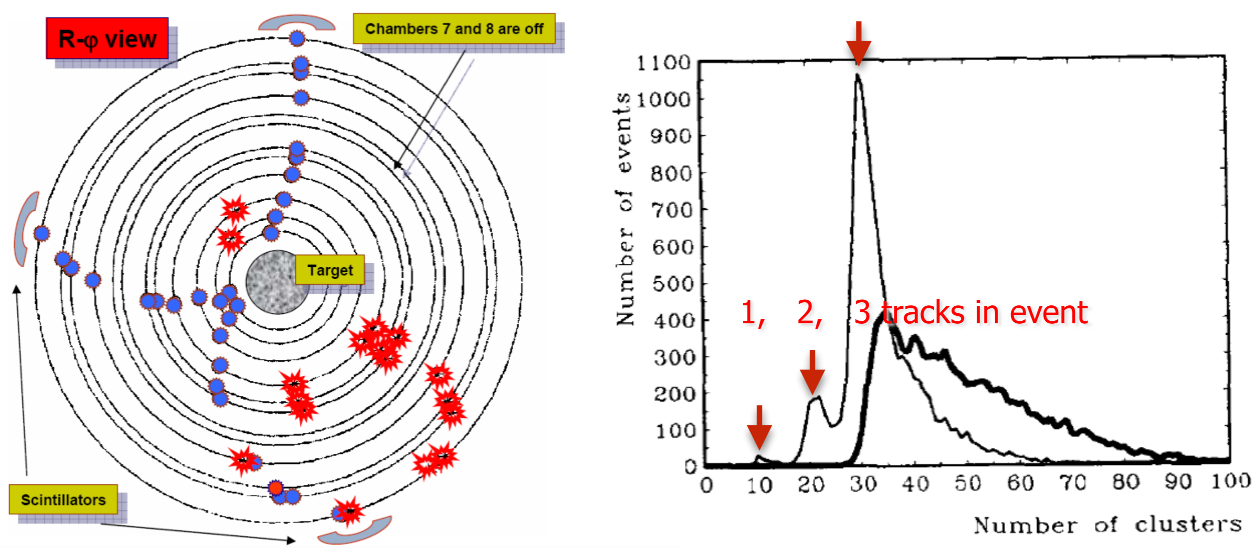
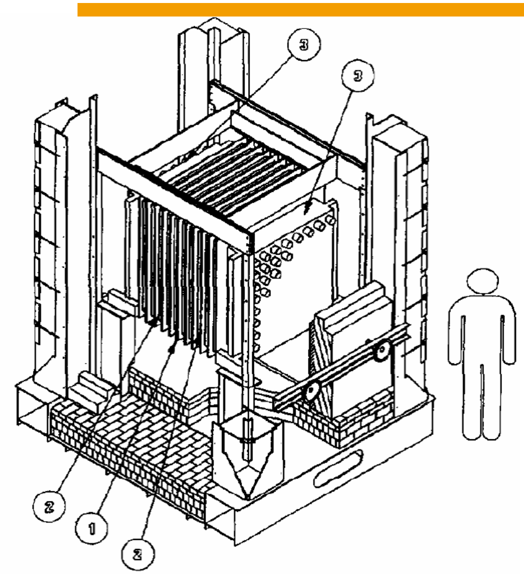




Estimation of the track direction from the cluster length

CA Track Finder in NEMO (Modane)



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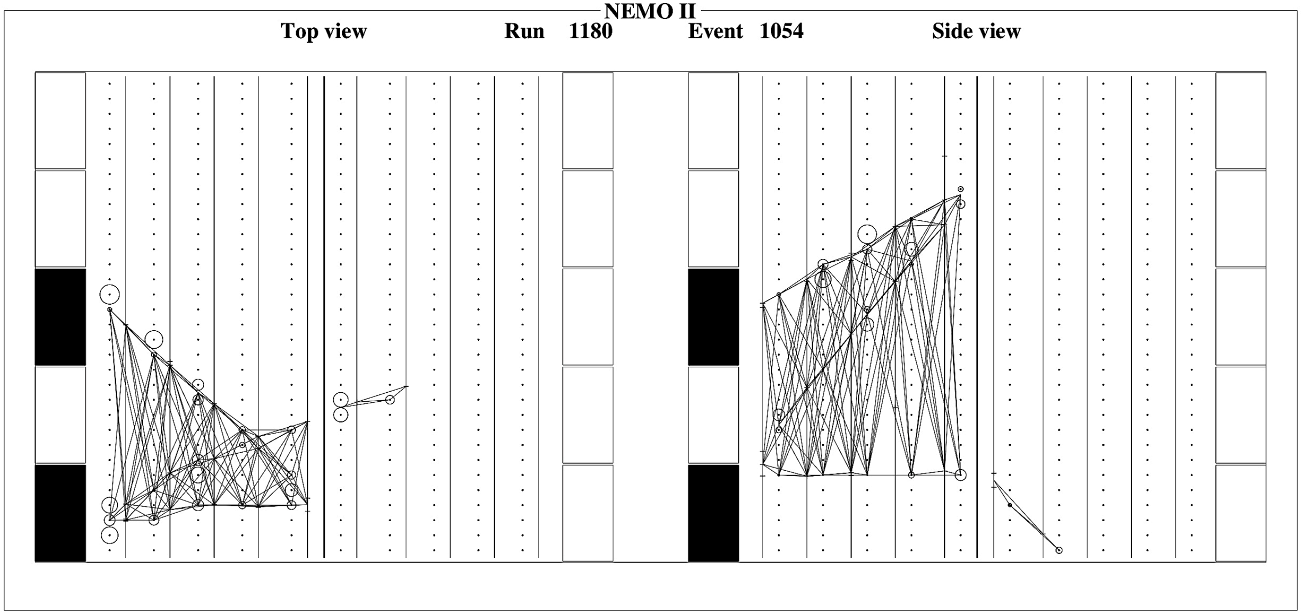
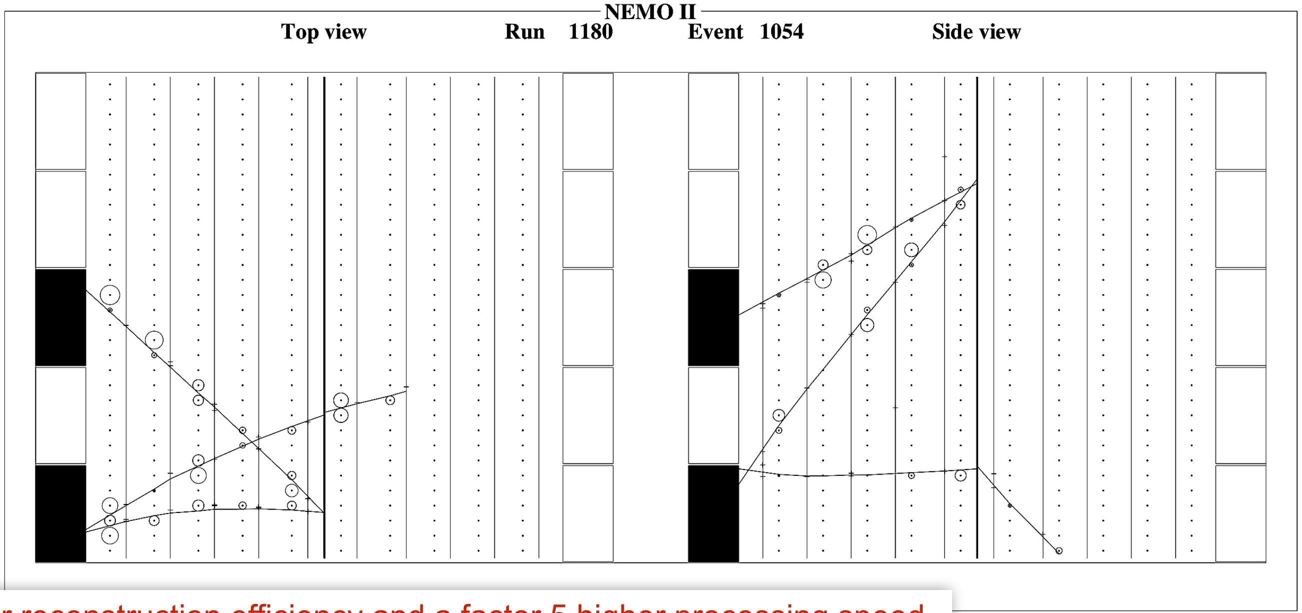




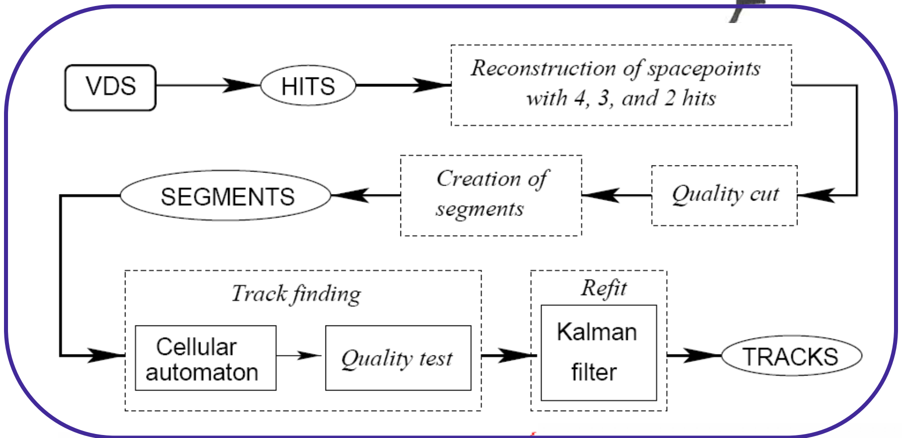
Problems:
- Neutrino experiment
- Very clean
- Cosmics
- Low momentum electrons
- Large multiple scattering on wires

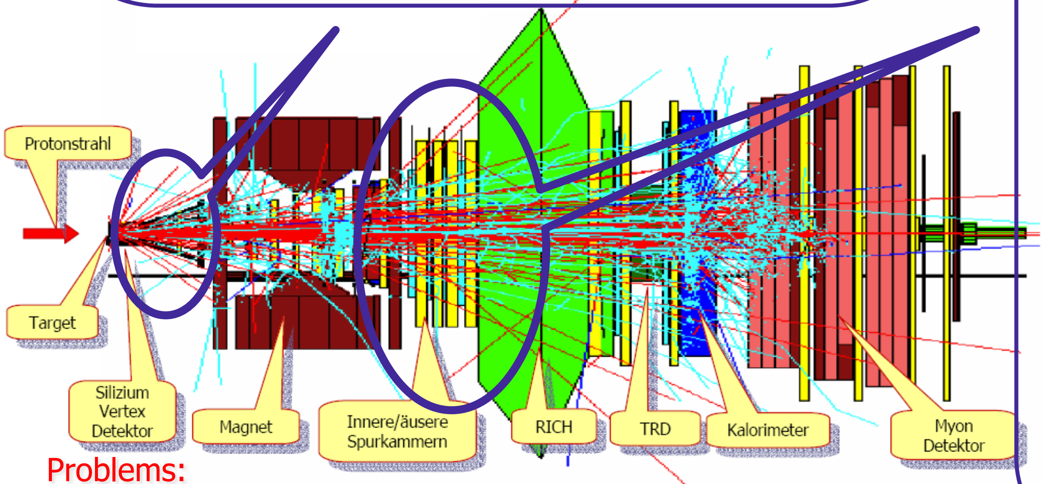
Solution:
- Define a smooth track model

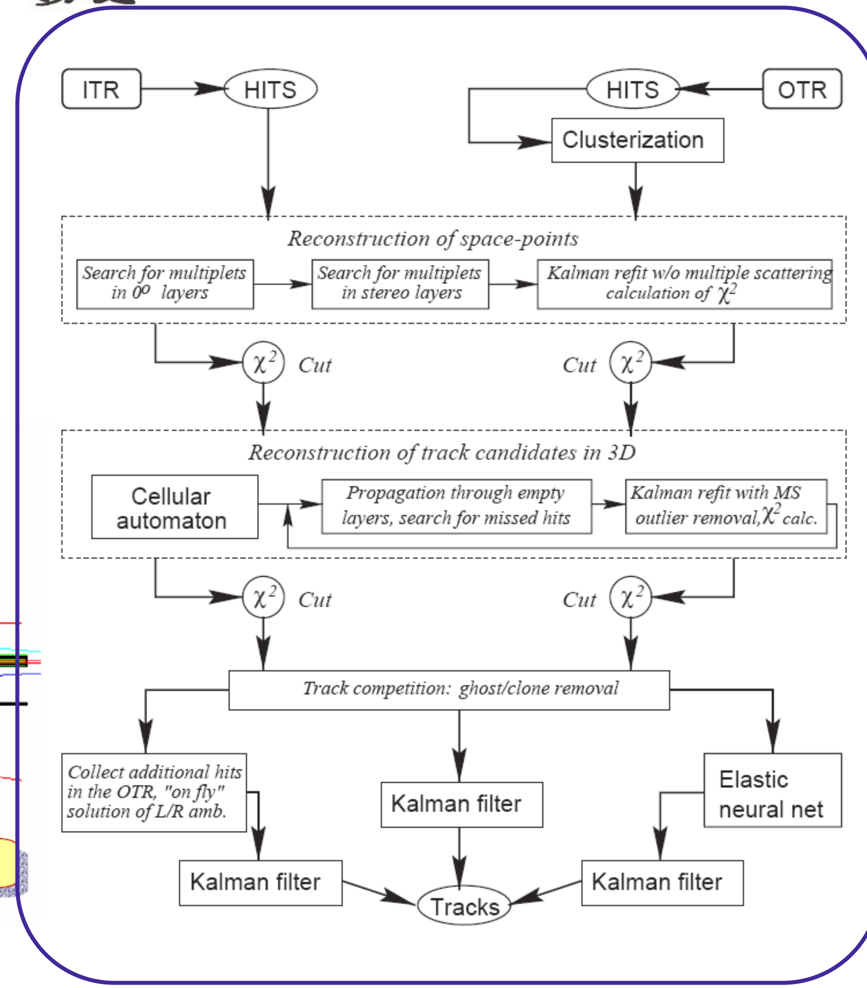
9% higher reconstruction efficiency and a factor 5 higher processing speed

CA Track Finder in HERA-B (DESY)

CATS = Cellular Automaton for Track Searching





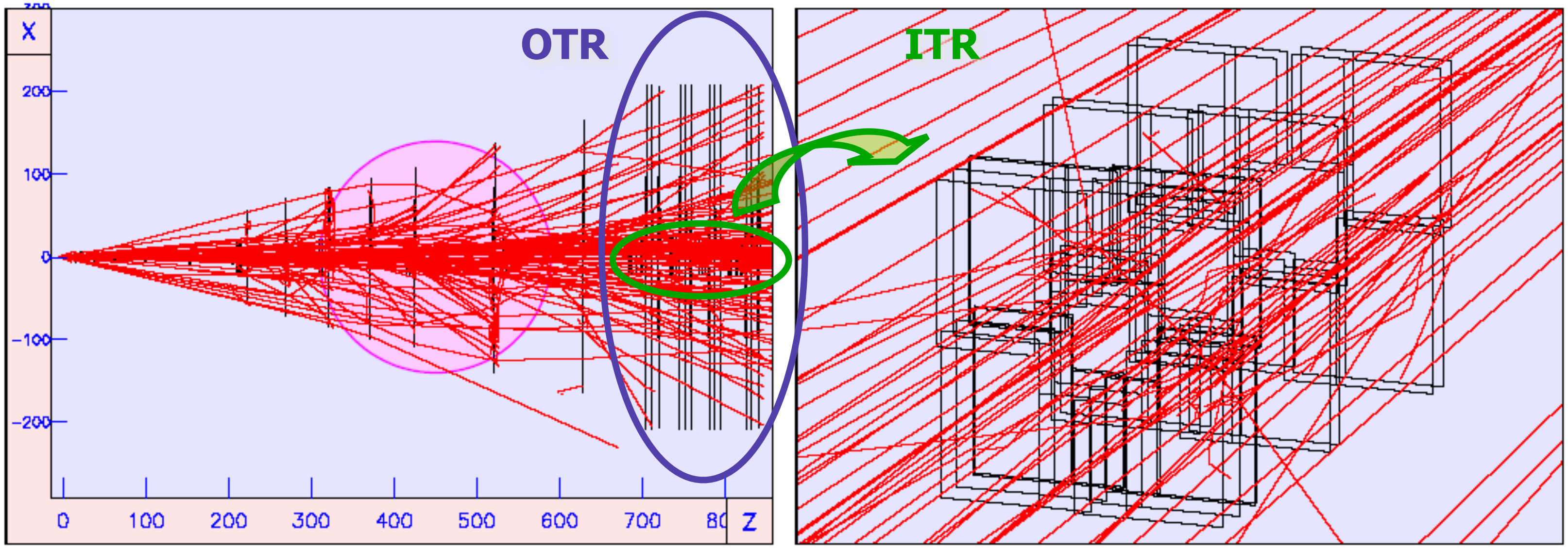


Problems:
- Complicated setup
- High track density
- Non-uniform magnetic field
- Single/Double-sided strip detectors (fakes)
- Honeycomb drift chambers (L/R ambiguity)
- Bad detector performance

Solution:
- From local to global reconstruction (CA approach)

Reliable reconstruction due to locality

HERA-B: Track Finding in the Pattern Tracker



Extremely low resolution and efficiency of the pattern tracker

Parameter	OTR	ITR
Hit resolution, μm	500	200
Hit efficiency, %	90	86

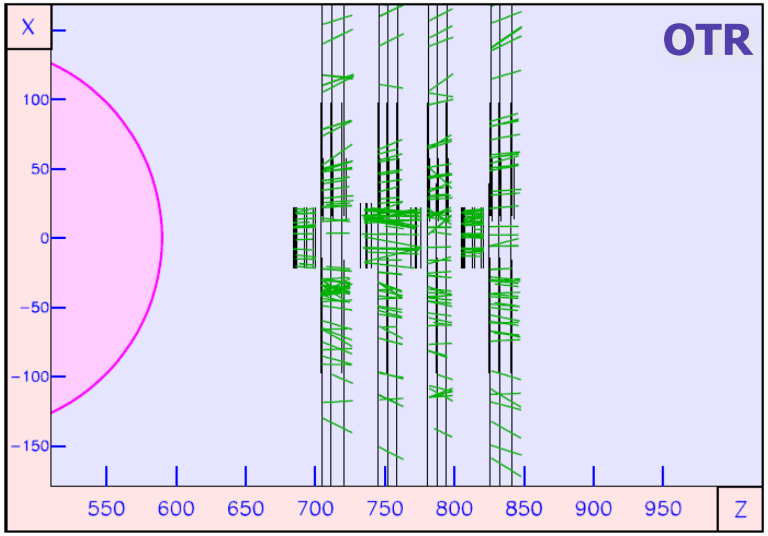
Hough Transformation → **TEMA** Uni-Ljubljana

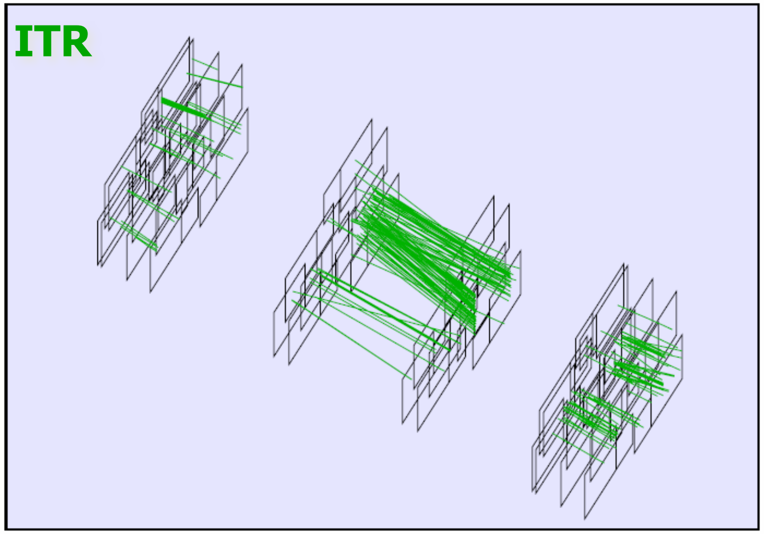
Track Following → **RANGER** DESY Zeuthen

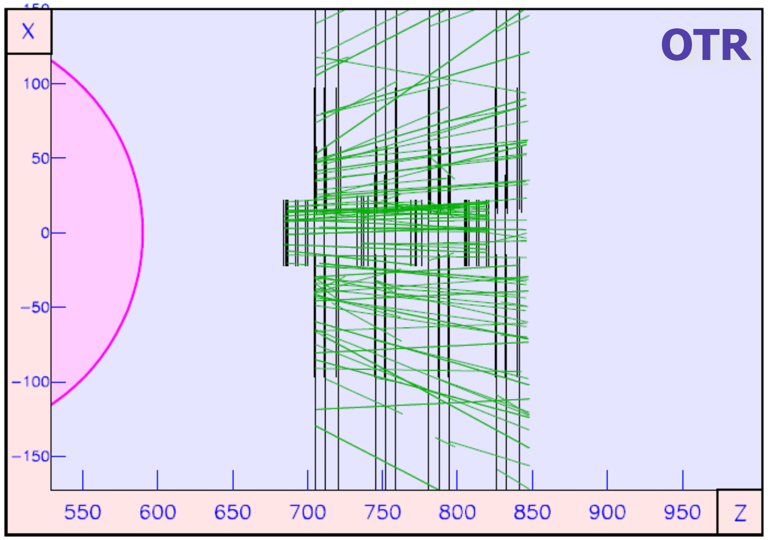
Cellular Automaton → **CATS** MPI Munich

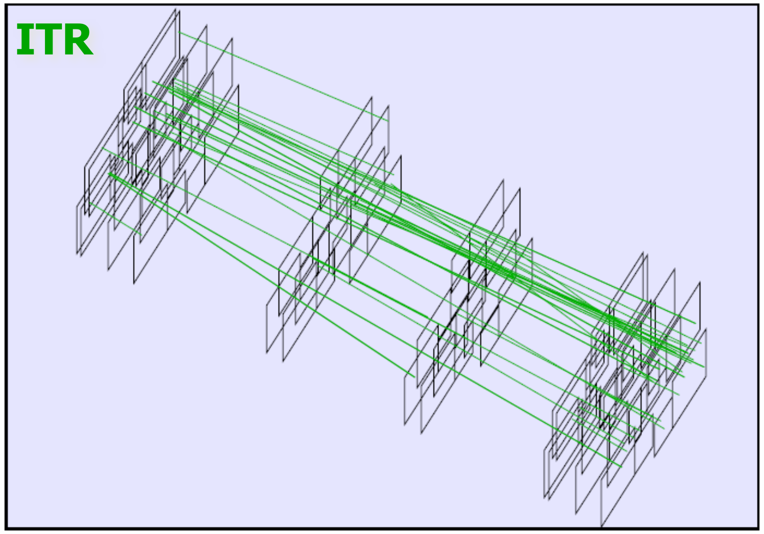
Competition between three different approaches developed by the independent groups

CA Track Finder in HERA-B (DESY)

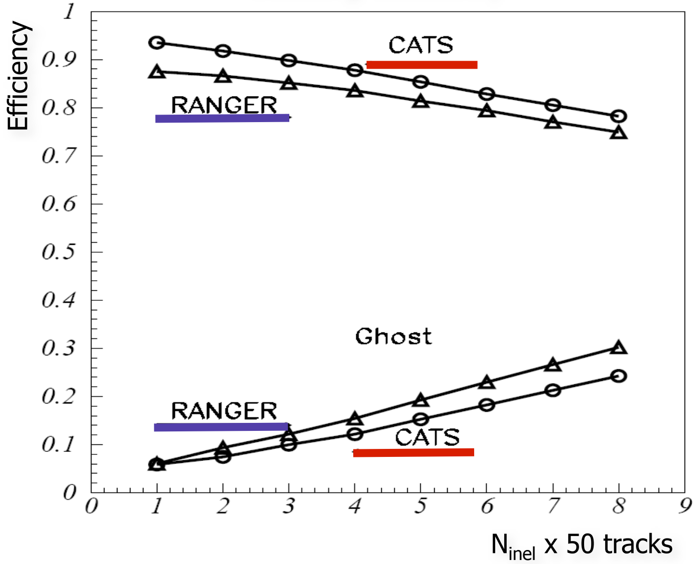


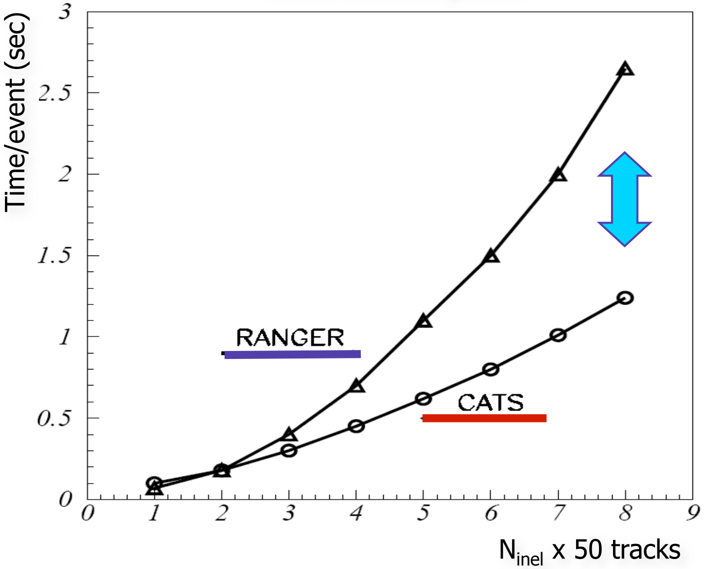






HERA-B Competition: CATS (CA), RANGER (TF), TEMA (HT)





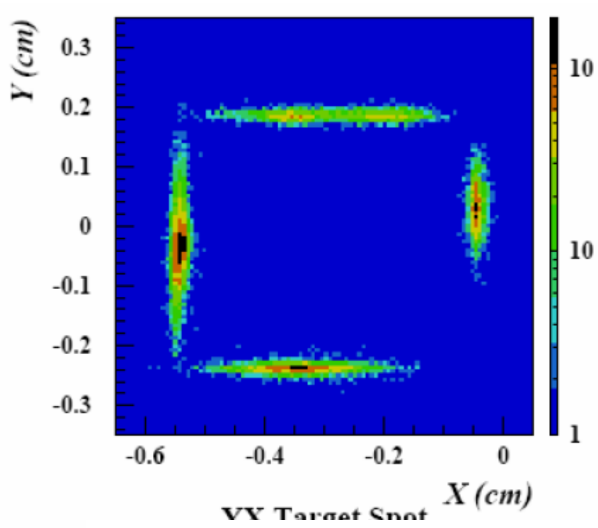
Tracking quality

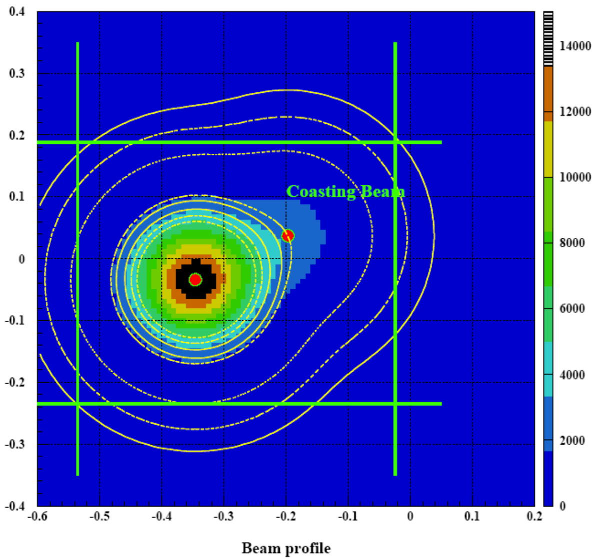
Resolutions, pulls P and mean length of reconstructed primary tracks.

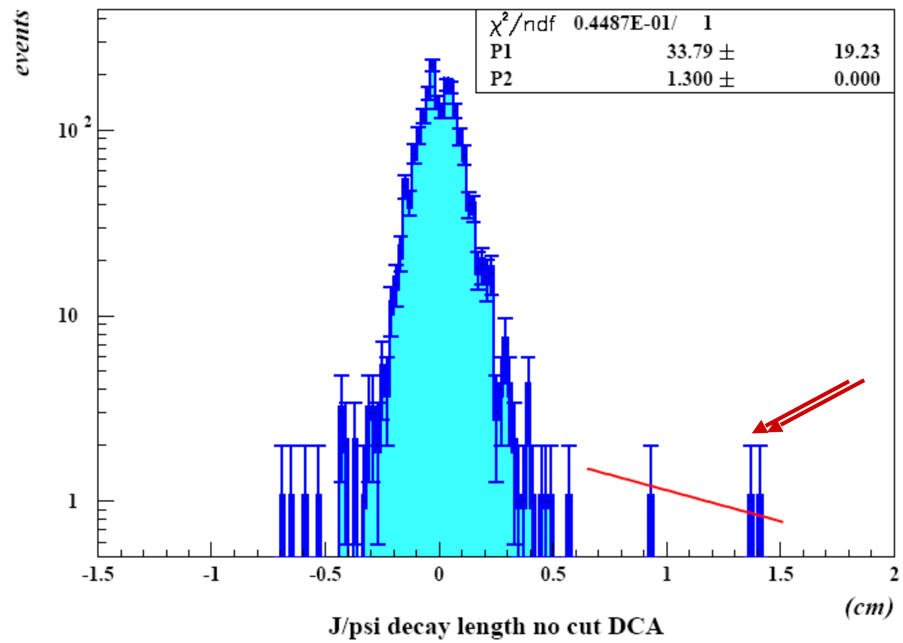
	CATS		RANGER		TEMA	
Resolutions	OTR	ITR	OTR	ITR	OTR	ITR
x, μm	246	93	322	91	291	98
y, mm	3.7	1.4	5.0	1.4	4.1	1.4
t_x, mrad	0.62	0.24	0.71	0.24	0.76	0.26
t_y, mrad	4.73	1.79	6.96	1.79	5.39	1.87
Pulls						
$P(x)$	1.59	1.11	1.37	1.10	1.45	1.06
$P(y)$	1.52	0.98	1.25	1.11	1.81	1.16
$P(t_x)$	1.16	0.93	1.25	0.89	1.18	1.15
$P(t_y)$	1.53	0.99	1.39	1.15	1.92	1.23
Hits/track	31	23	26	21	31	21

CATS outperforms other alternative packages (SUSi, HOLMES, L2Sili, OSCAR; RANGER, TEMA) in efficiency, accuracy and speed

Coasting Beam and the First J/psi Decays found in HERA-B

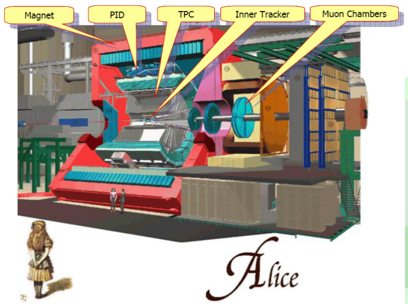


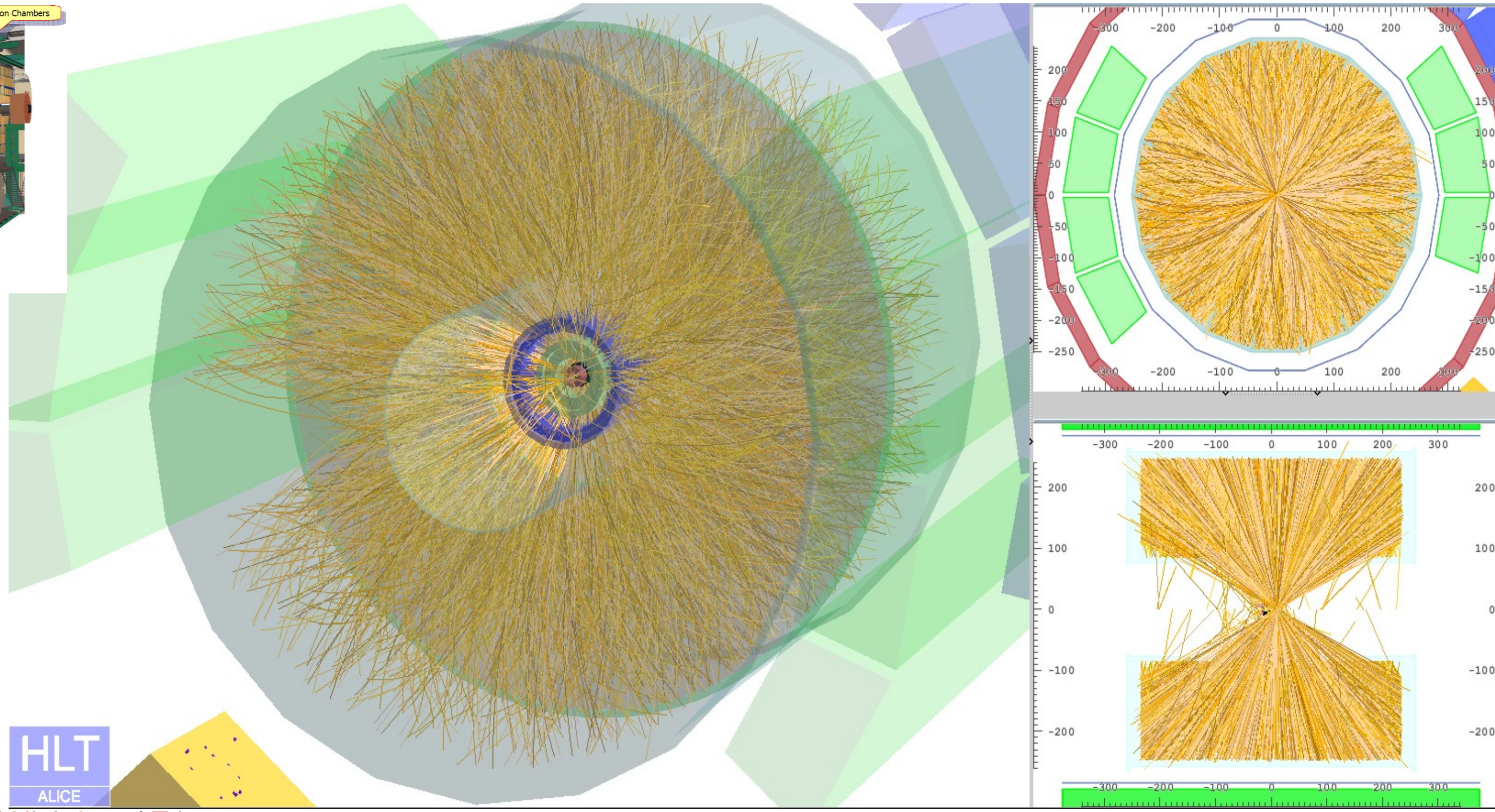




Provided detailed analysis of data and the first J/ψs found in HERA-B

CA Track Finder in ALICE (CERN)





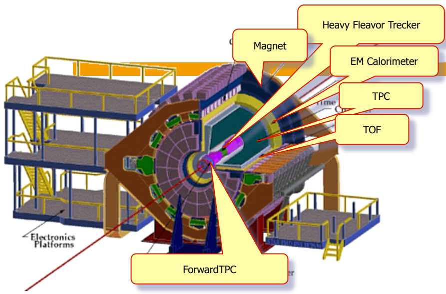
ALICE High-Level Trigger:
Event reconstructed with the Cellular Automaton GPU track finder in the first heavy-ion run of the LHC.

Problems:
- ~ 10000 charged particles/collision
- High track density
- Huge number of measurements (TPC)

Solution:
- Parallel processing:
  - vectorization,
  - multi-threading,
  - multi-core systems (CPU/GPU)

First HI collisions reconstructed with CA on GPU

CA Track Finder in STAR (BNL)



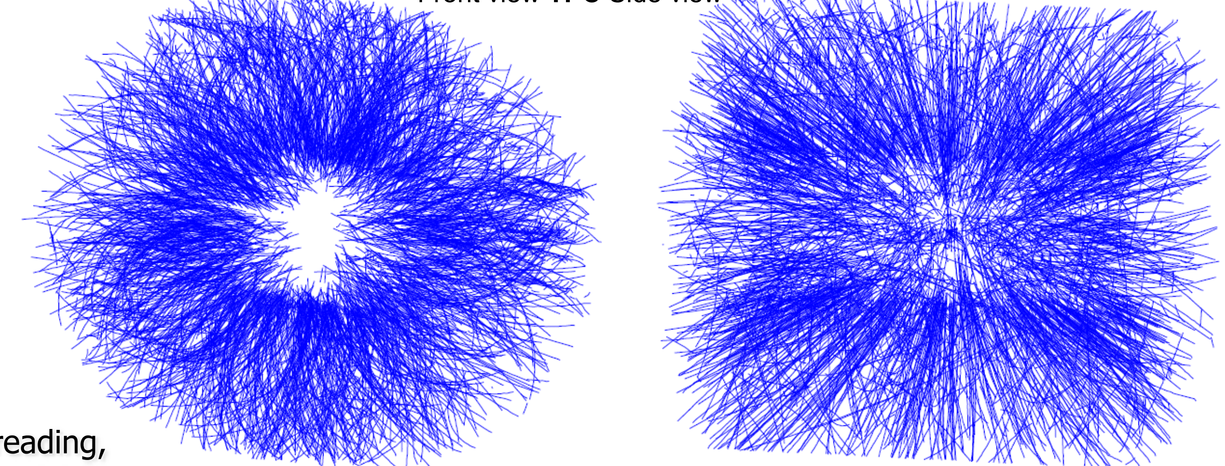
Problems:

- > 1000 charged particles/collision
- High track density
- Large number of measurements (TPC)

Solution:

- Parallel processing:
  - vectorization, multi-threading,
  - multi-core systems (CPU/Phi)

Front view **TPC** Side view



Au+Au event with 1446 reconstructed tracks in TPC

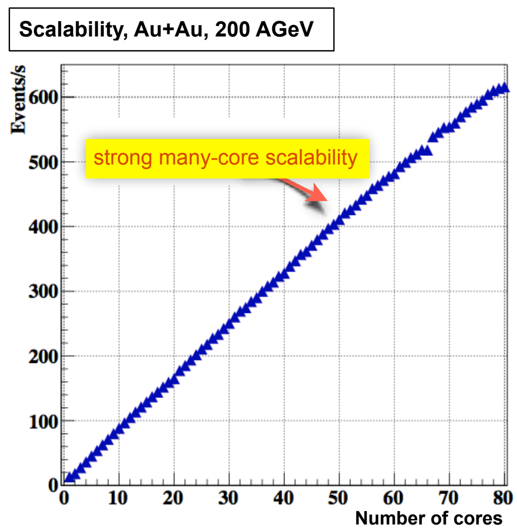
Online TPC CA: simulated Au+Au data, 200 GeV

Efficiency and ratio, %

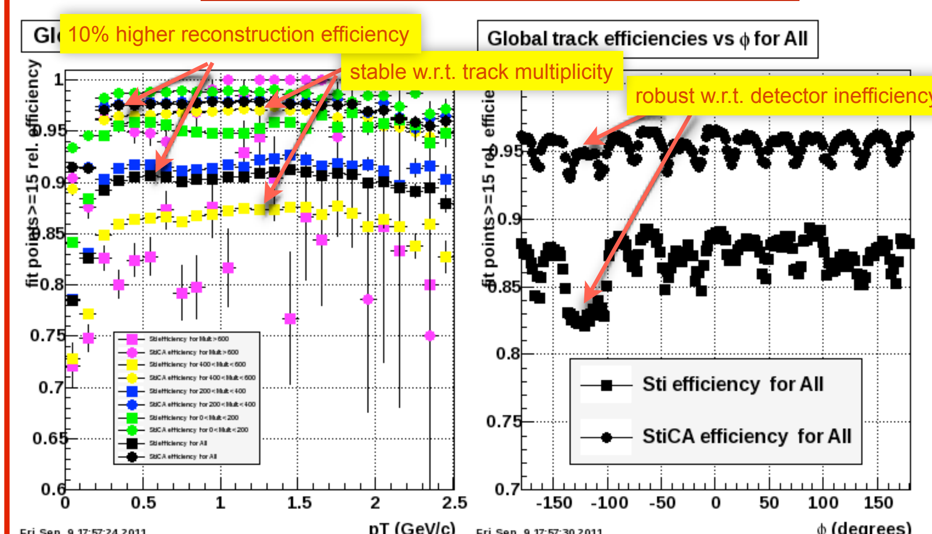
since 2013 runs online in HLT

Ref Set	96.6
All Set	88.6
Clone	10.6
Ghost	12.6
Tracks/ev	659
Time/ev, ms	47

All set: $p \geq 0.05$ GeV/c
Reference set: $p \geq 1$ GeV/c
Ghost: purity < 90%

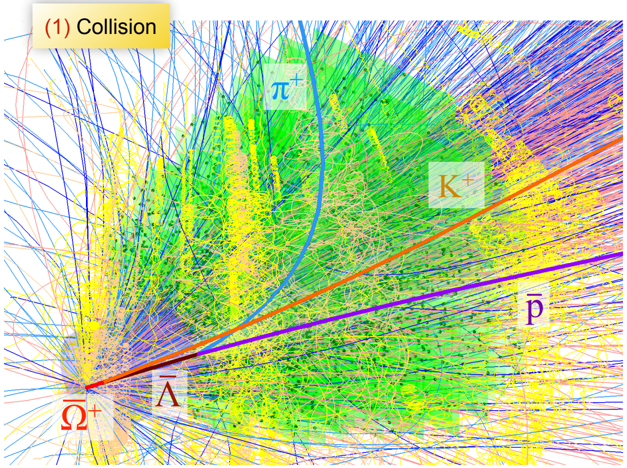


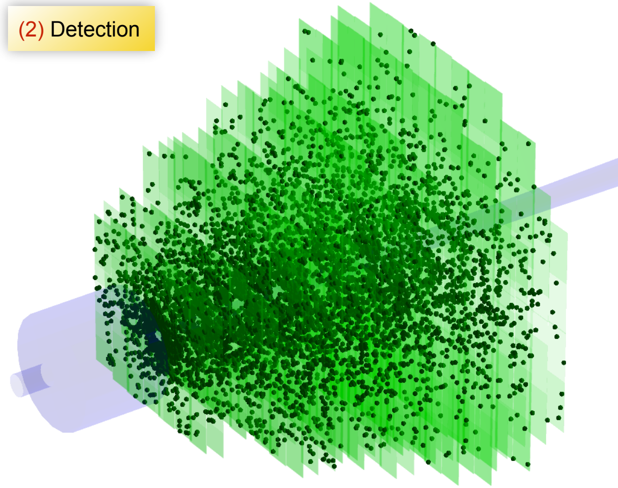
Offline TPC Sti+CA: real Au+Au data, 200 GeV, Year 2010

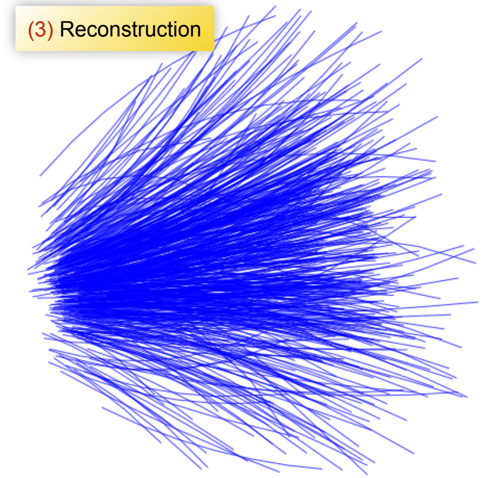


Since August **2016** the Sti+CA track finder is the **standard STAR track finder** for offline data production, providing **25%** more **D^0** and **20%** more **W**

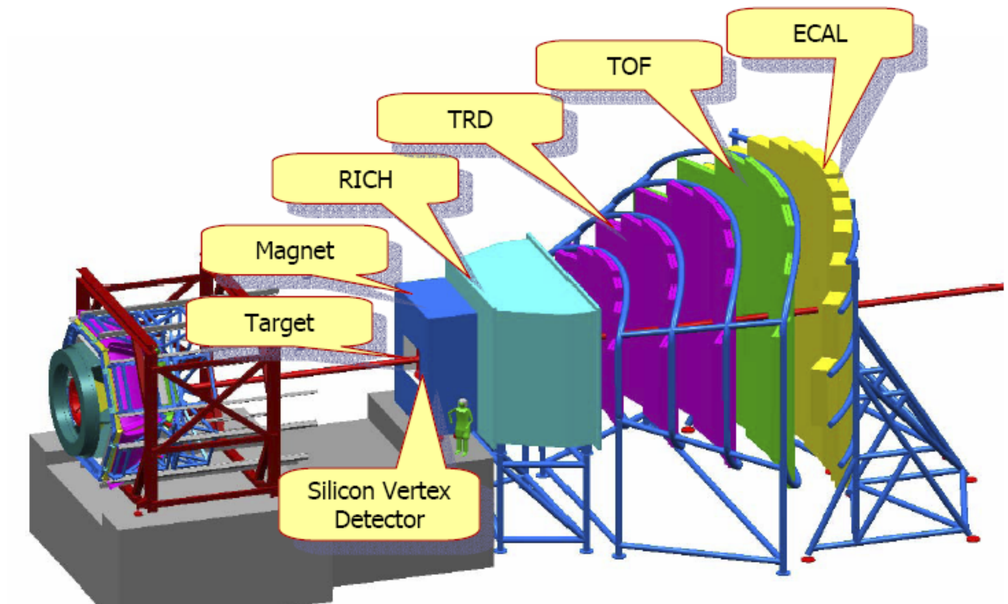
Reconstruction Challenge in CBM (FAIR)





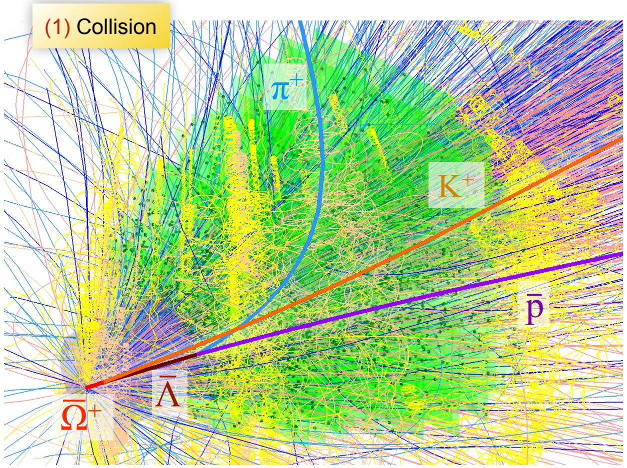


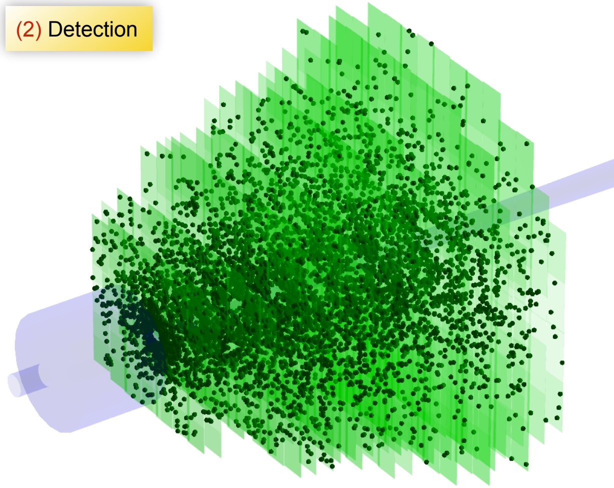
- Future fixed-target heavy-ion experiment at FAIR
- Explore the phase diagram at high net-baryon densities
- 10^7 Au+Au collisions/sec
- ~ 1000 charged particles/collision
- Non-homogeneous magnetic field
- Double-sided strip detectors
- 4D reconstruction of time slices.

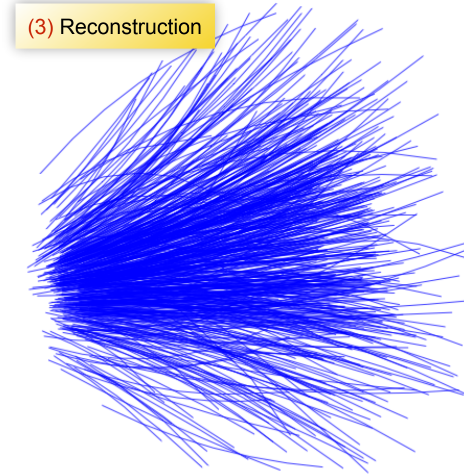


A simplified CBM detector setup

Reconstruction Challenge in CBM (FAIR)



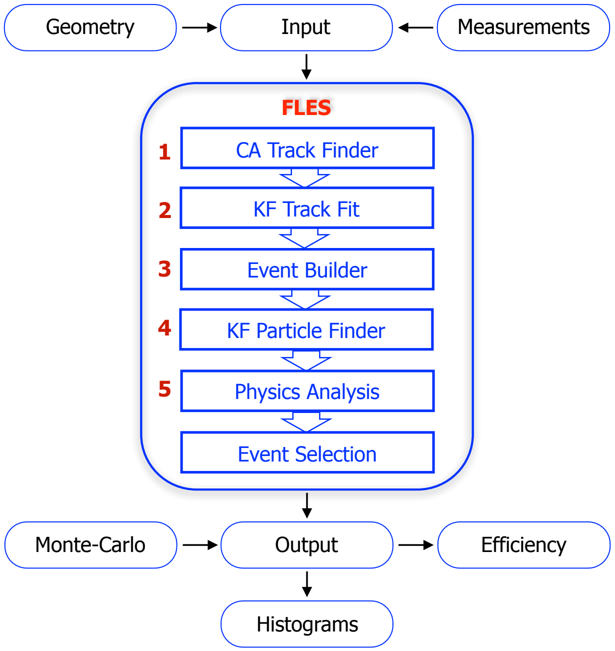




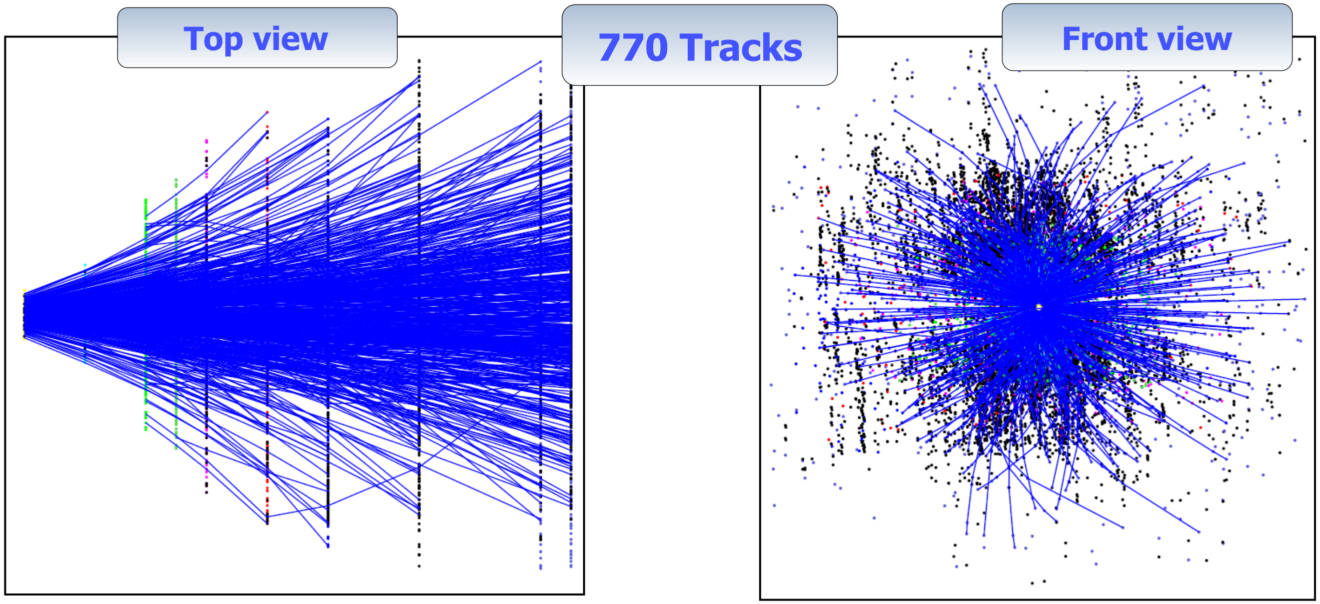
The full event reconstruction will be done on-line at the First-Level Event Selection (FLES) and off-line using the same FLES reconstruction package.

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

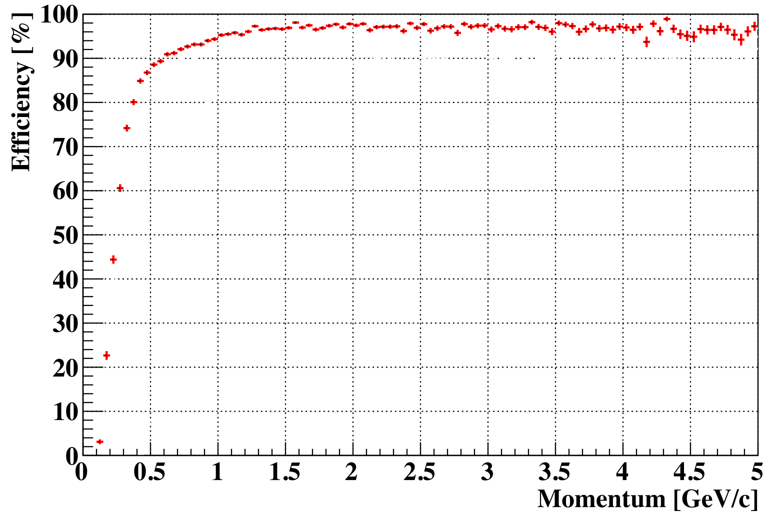
All reconstruction algorithms are vectorized and parallelized.



CA Track Finder in CBM



Developer	Tracking Method	<2005	>2005
LHEP JINR	Conformal Mapping	✓	✗
LIT JINR	Track Following	✓	✗
ZITI Mannheim	Hough Transform	✓	✗
FIAS	Cellular Automaton	✓	✓

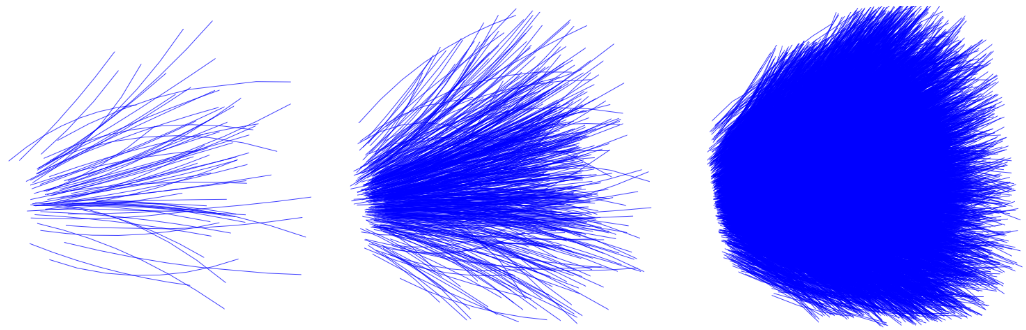


Track category	Eff, %
All tracks	90.9
Primary high-p	97.5
Primary low-p	92.6
Secondary high-p	91.1
Secondary low-p	63.8
Clone level	0.4
Ghost level	5.9
MC tracks found	134
Time, ms/ev	10

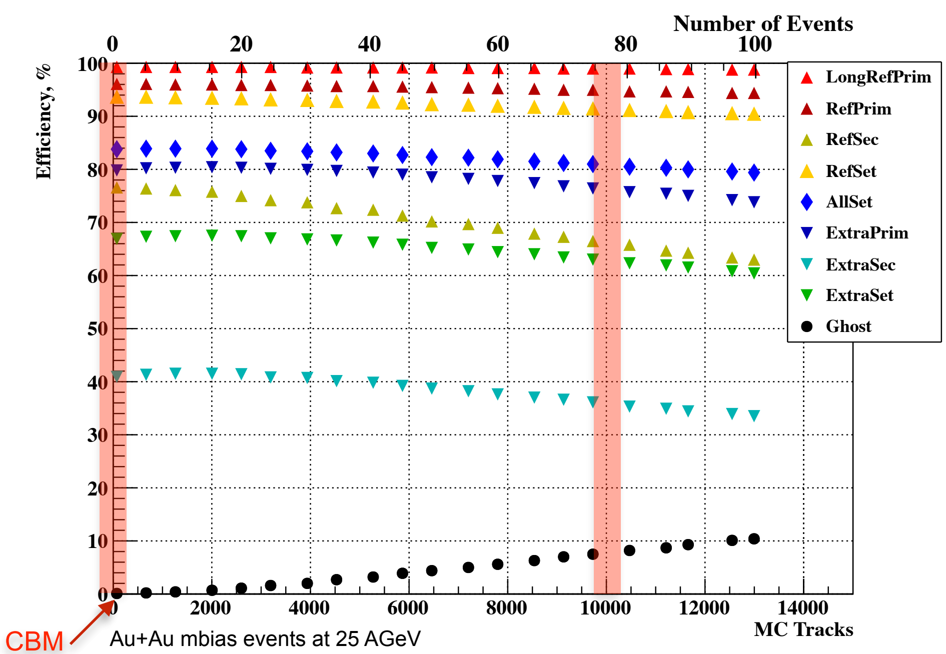
Fast and efficient track finder

CA Track Finder at High Track Multiplicities in CBM

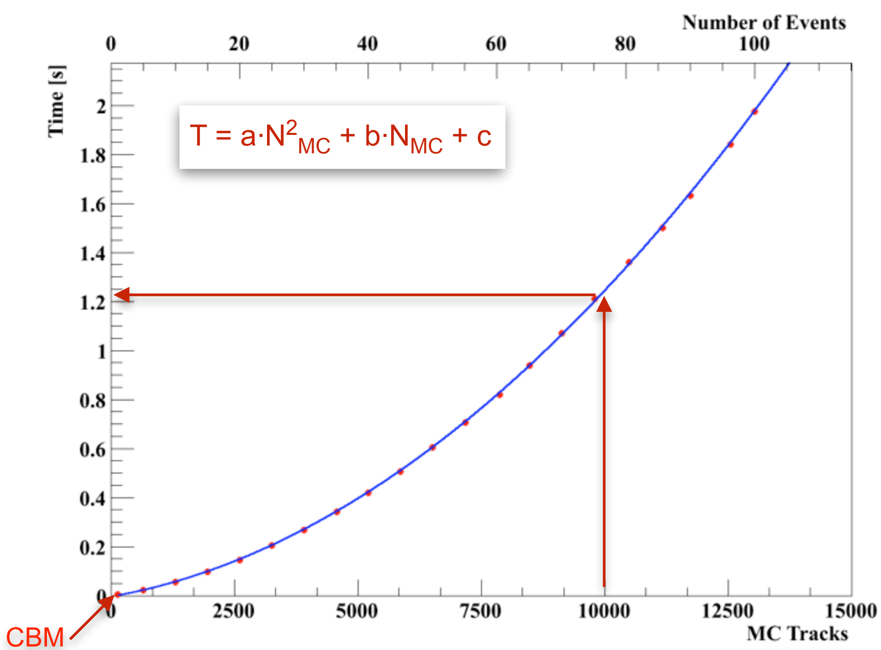
A number of minimum bias events is gathered into a group (super-event), which is then treated by the CA track finder as a single event.



1 mbias event, $\langle N_{reco} \rangle = 109$ 5 mbias events, $\langle N_{reco} \rangle = 572$ 100 mbias events, $\langle N_{reco} \rangle = 10340$

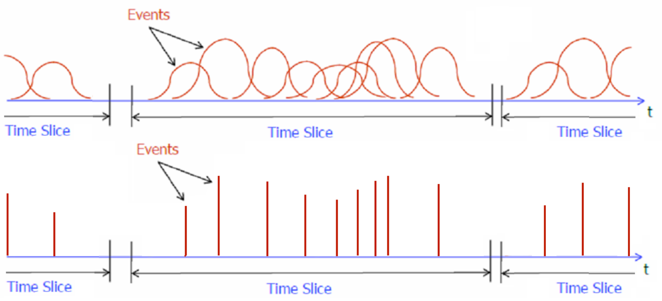


Au+Au mbias events at 25 AGeV



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

Time-based 4D CA Track Finder in CBM

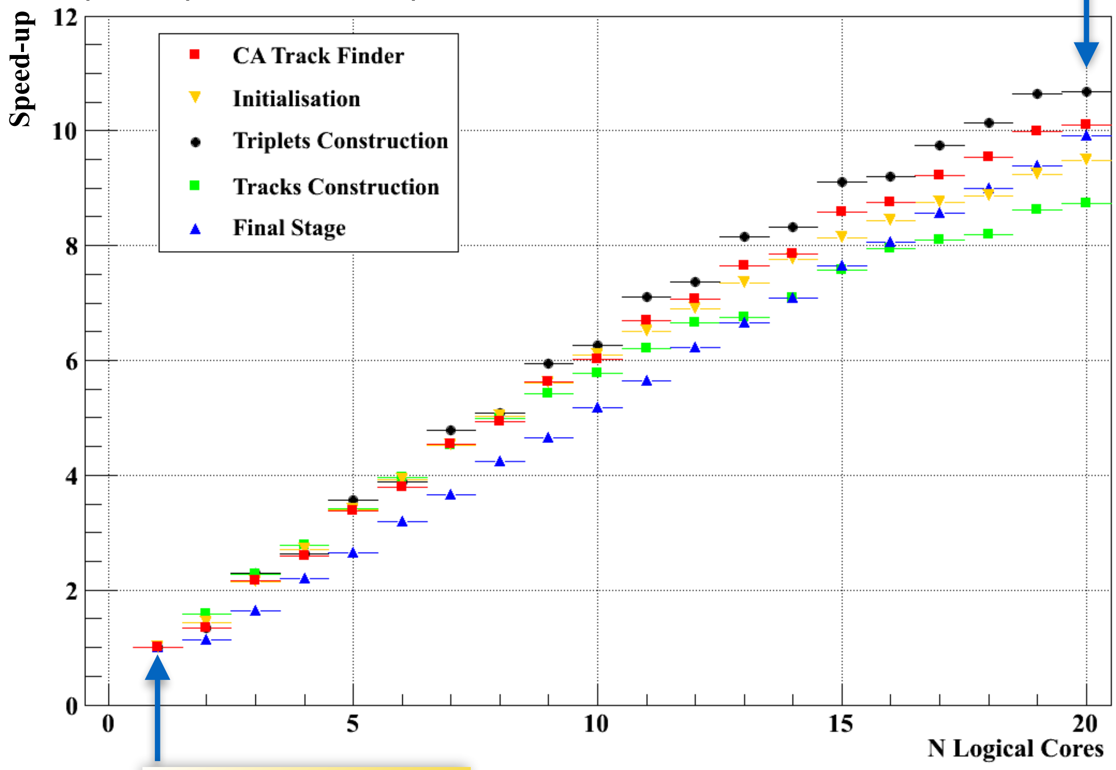


- The beam in the CBM will have no bunch structure, but continuous.
- Measurements in this case will be 4D (x, y, z, t).
- Significant overlapping of events in the detector system.
- Reconstruction of time slices rather than events is needed.

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

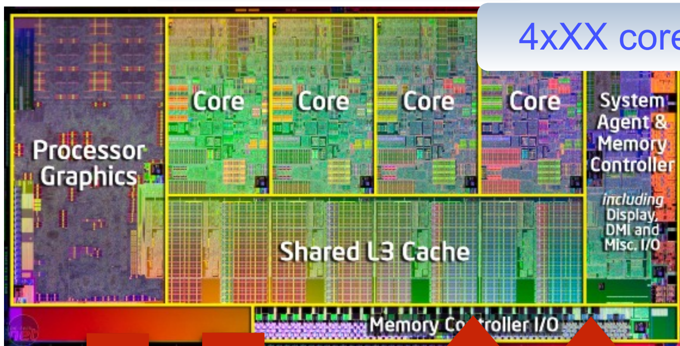
100 mbias events in a time-slice

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

Many-Core CPU/GPU Architectures

Intel/AMD CPU

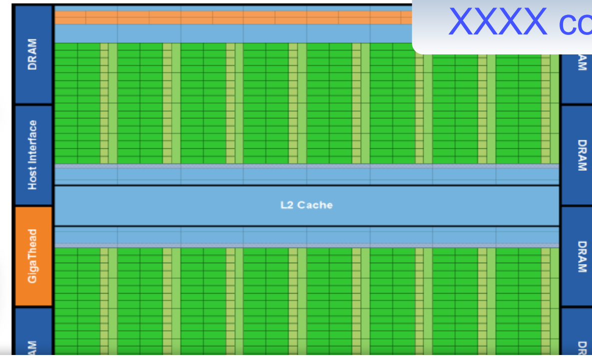
4xXX cores



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

Nvidia/ATI GPU

XXXX cores



- Optimized for data-parallel, throughput computation
- More transistors dedicated to computation

Math

Memory

Parallelism

Math

Memory

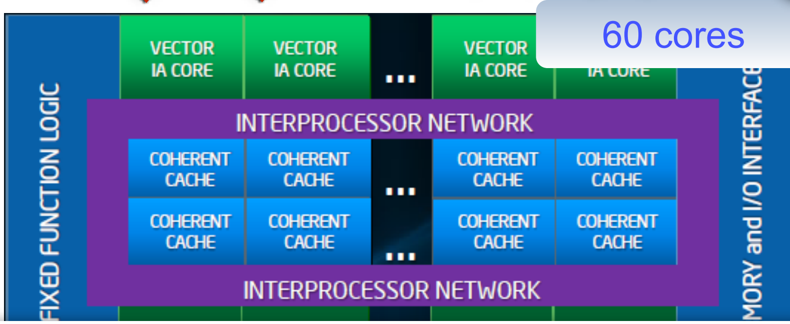
#Cores

Stability

Memory

Intel Phi

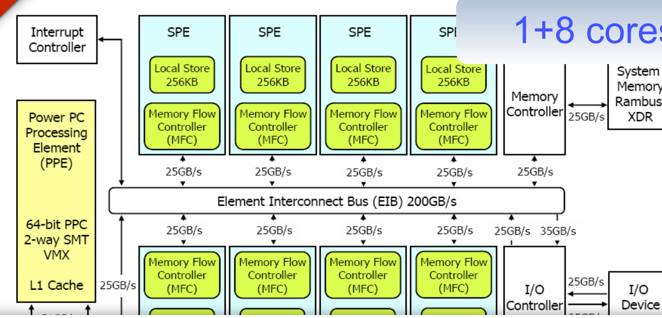
60 cores



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

IBM Cell

1+8 cores

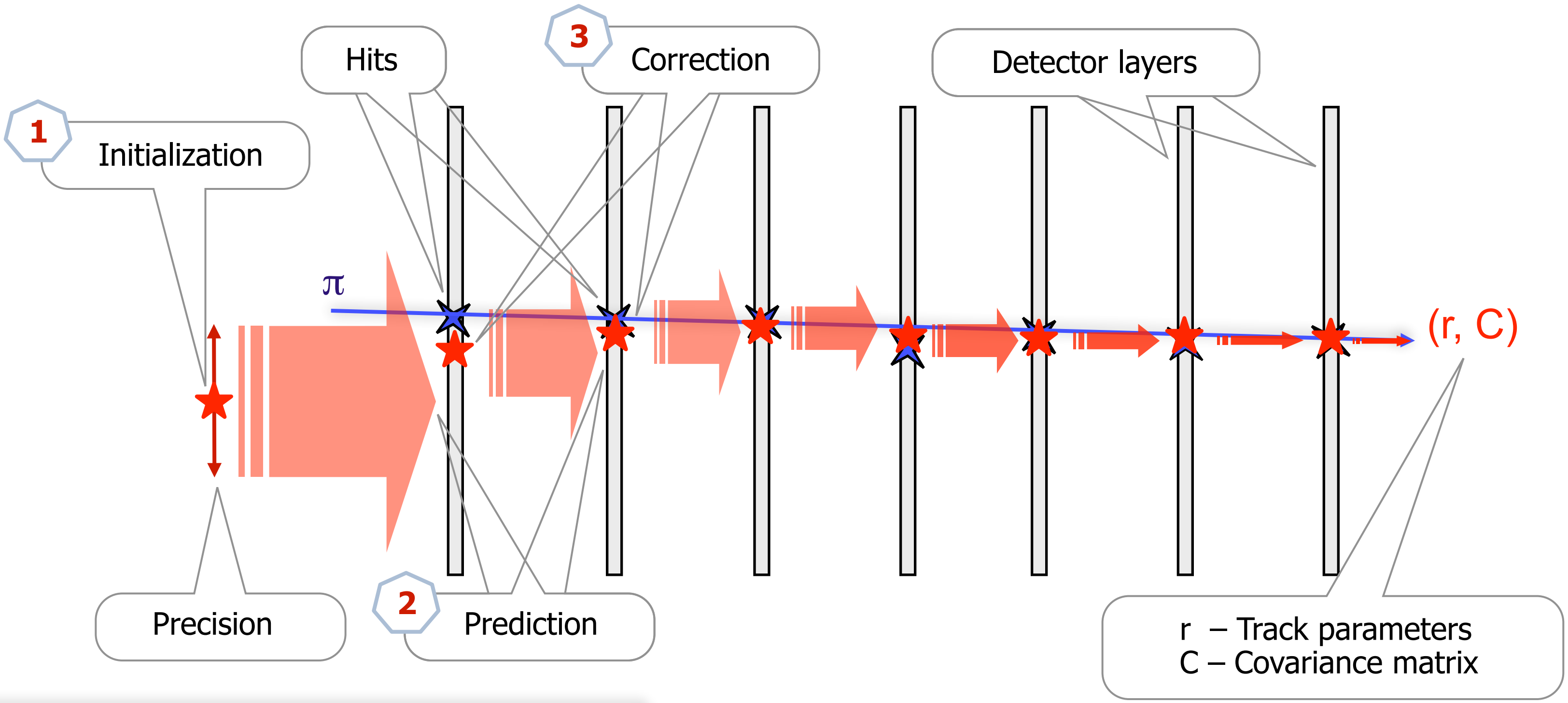


- General purpose RISC processor (PowerPC)
- 8 co-processors (SPE, Synergistic Processor Elements)
- 128-bit wide SIMD units

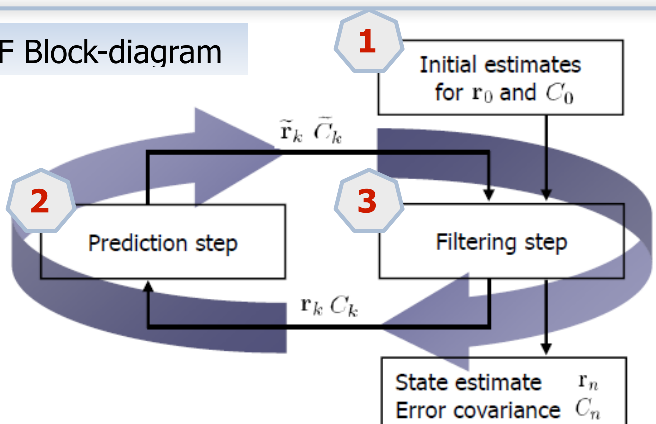
Future systems are heterogeneous. Fundamental redesign of traditional approaches to data processing is necessary

Kalman Filter (KF) Track Fit

Estimation of the track parameters at one or more hits along the track – Kalman Filter (KF)



KF Block-diagram



KF as a recursive least squares method

State vector

Position, direction and momentum

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

Kalman Filter:

1. Start with an arbitrary initialization.
2. Add one hit after another.
3. Improve the state vector.
4. Get the optimal parameters after the last hit.

Nowadays the Kalman Filter is used in almost all HEP experiments

KF Track Fit on Cell

Stage	Description	Time/track	Speedup
	Initial scalar version	12 ms	–
1	Approximation of the magnetic field	240 μs	50
2	Optimization of the algorithm	7.2 μs	35
3	Vectorization	1.6 μs	4.5
4	Porting to SPE	1.1 μs	1.5
5	Parallelization on 16 SPEs	0.1 μs	10
	Final simdized version	0.1 μs	120000

Intel (stages 1–3)

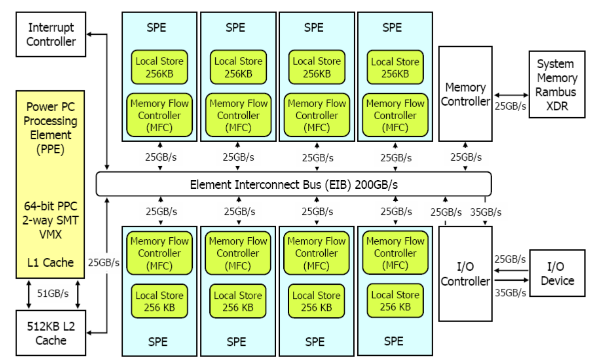
Cell (stages 4–5)

10000x faster on any PC

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

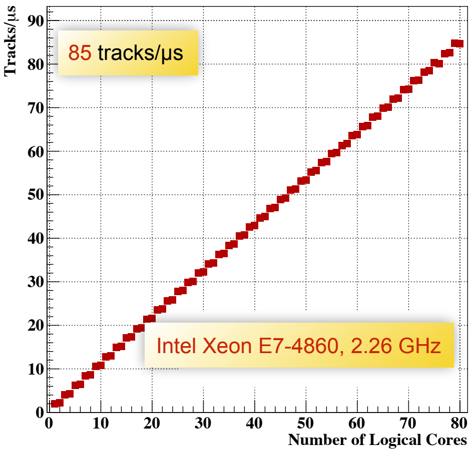
The KF speed was increased by 5 orders of magnitude

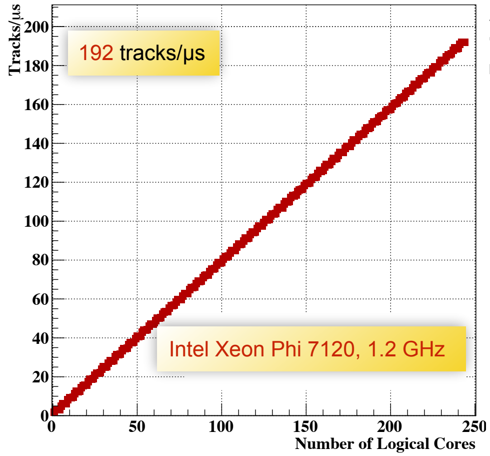
blade11bc4 @IBM, Böblingen:
2 Cell Broadband Engines, 256 kB LS, 2.4 GHz

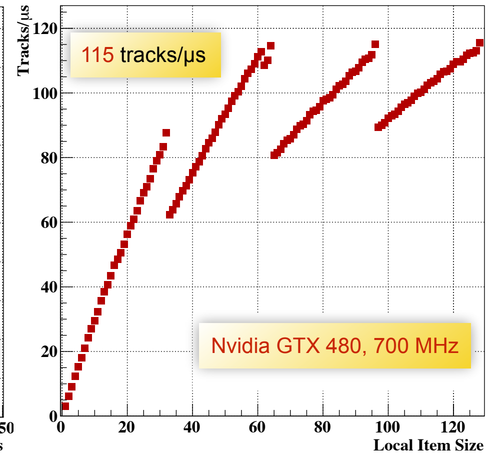


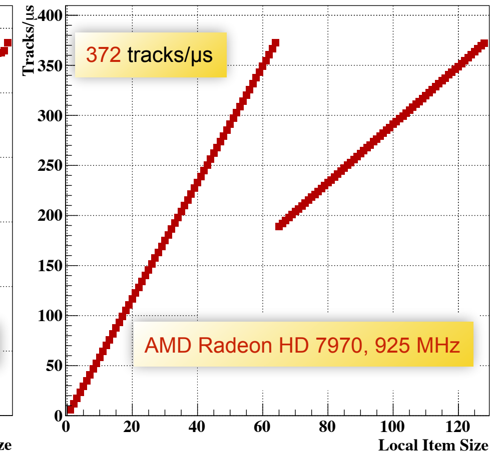
Motivated by, but not restricted to Cell !

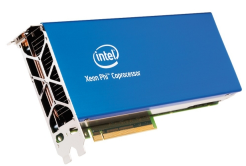
KF Track Fit on CPU, Phi, GPU

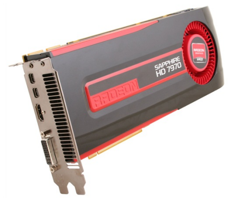








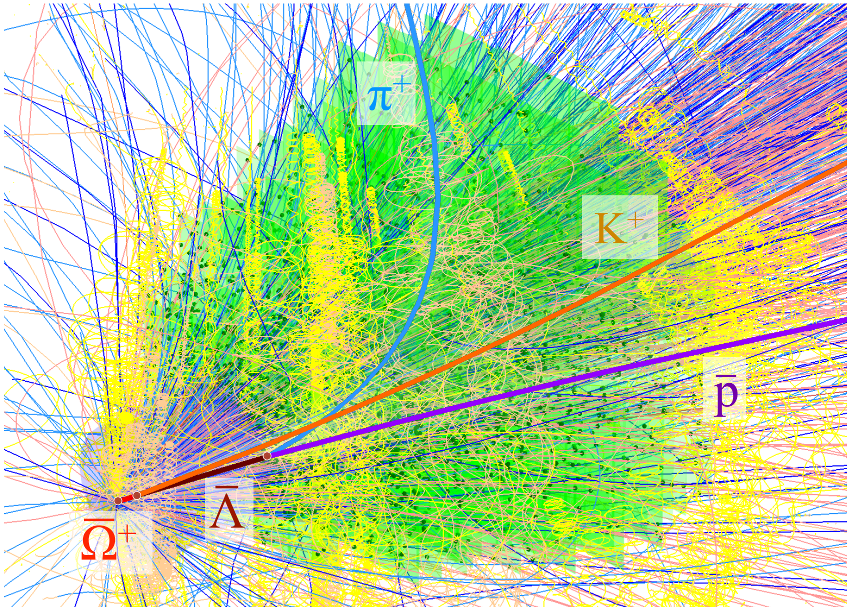




- Precise estimation of the parameters of particle trajectories is the core of the reconstruction procedure.
- The track fit performance on a single node: 2*CPU+2*GPU = 10^9 tracks/s = (100 tracks/event)* 10^7 events/s = 10^7 events/s.
- One computer is enough to estimate parameters of all particles produced at 10^7 interaction rate!

Fast, precise and portable Kalman filter track fit

KF Particle: Reconstruction short-lived Particles in CBM



Simulated AuAu collision at 25 AGeV

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

```
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
```

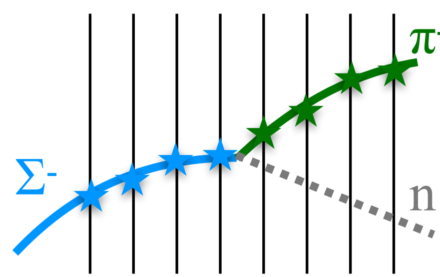
Concept:

- 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:

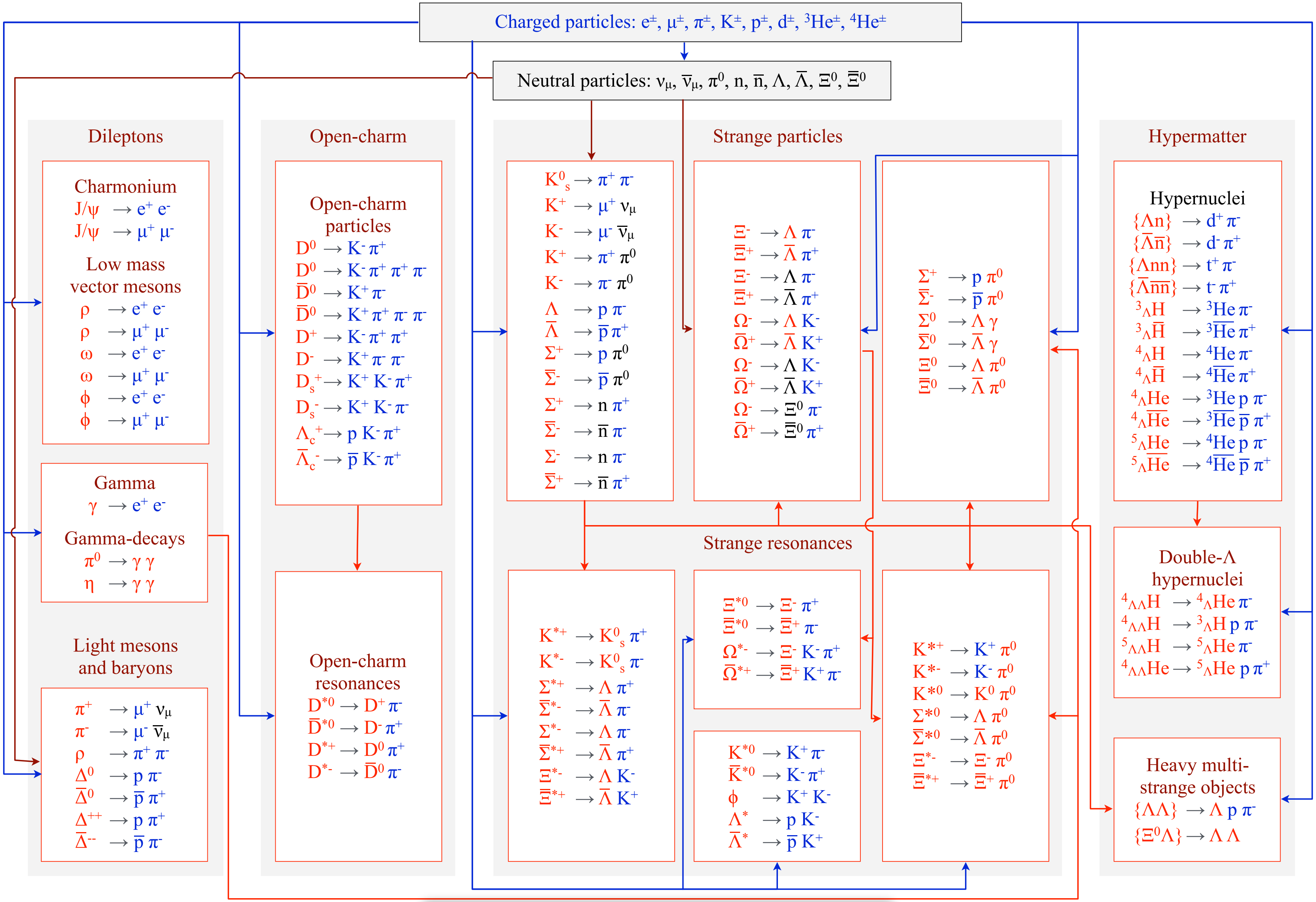
- Construction of short-lived particles
- Addition and subtraction of particles
- Transport
- Calculation of an angle between particles
- Calculation of distances and deviations
- Constraints on mass, production point and decay length
- KF Particle Finder

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



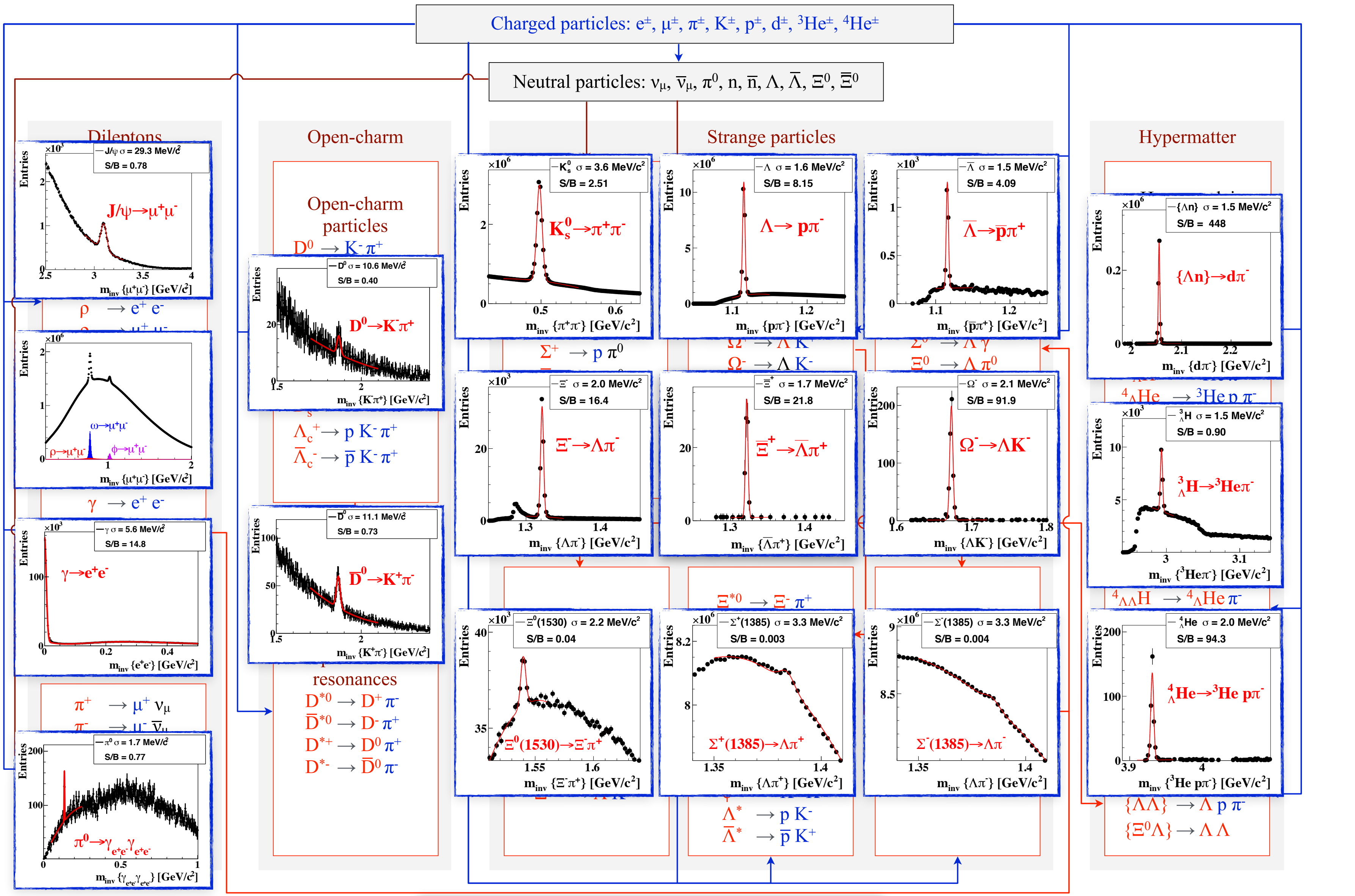
KF Particle provides a simple and direct approach to physics analysis (used in CBM, ALICE and STAR)

KF Particle Finder for Physics Analysis and Selection



More than 100 decay channels online

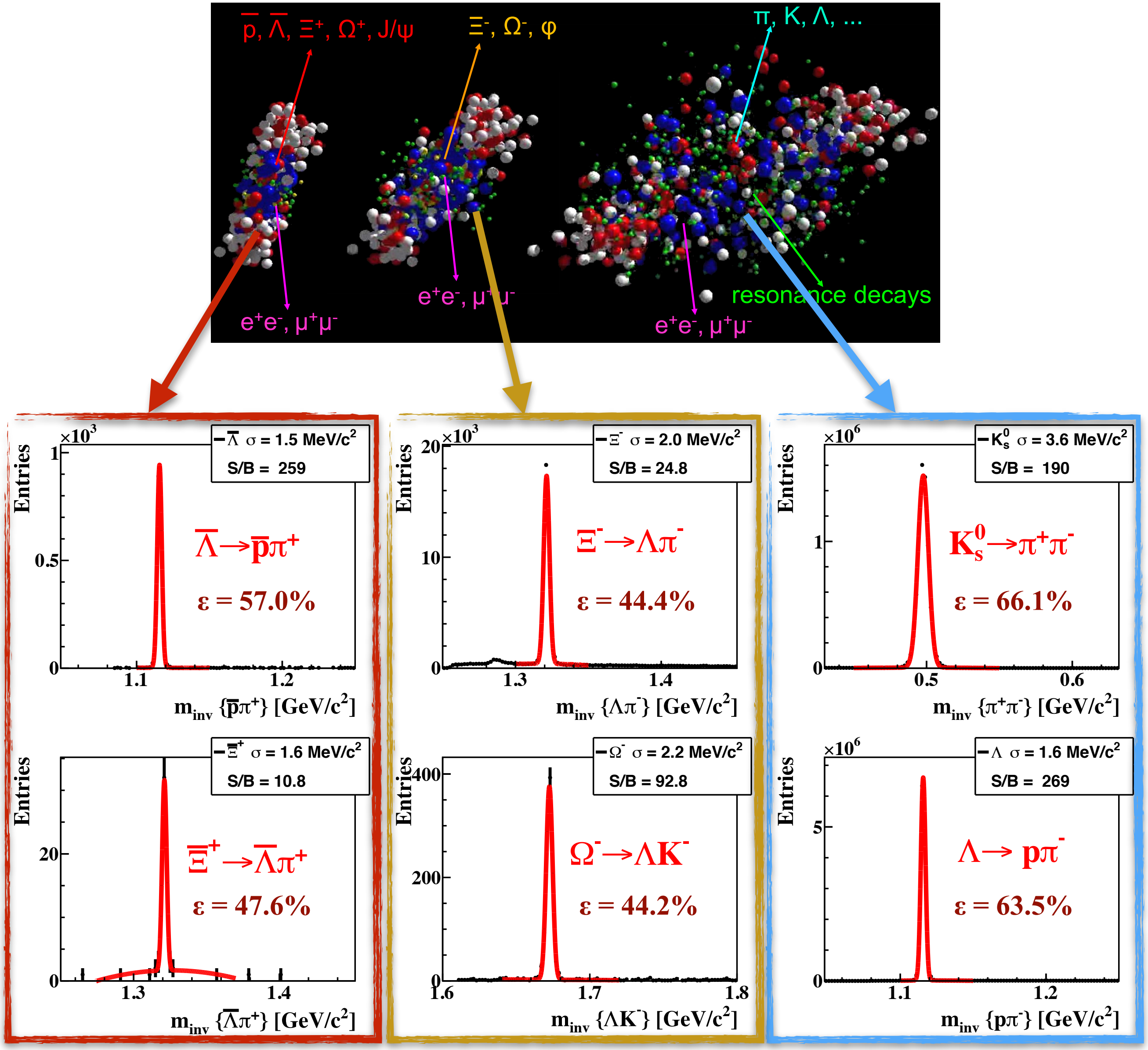
KF Particle Finder for Physics Analysis and Selection



More than 100 decay channels online

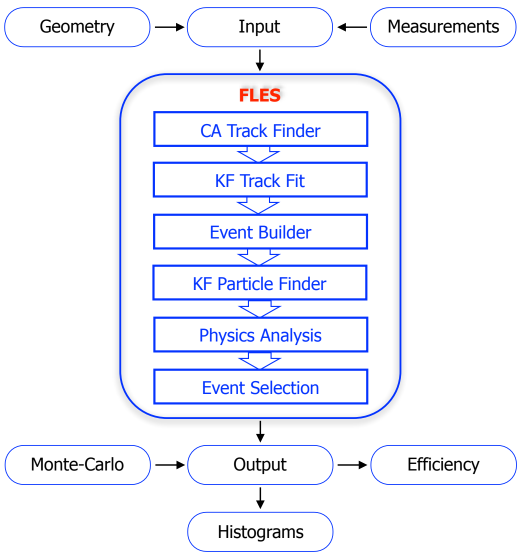
(mbias: 1.4 ms; central: 10.5 ms)/event/core

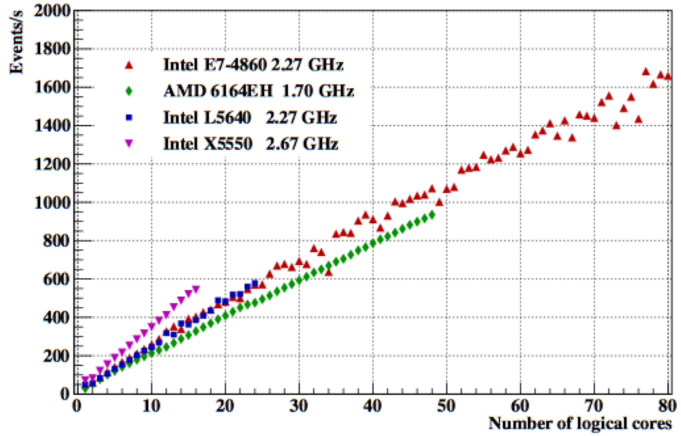
Clean Probes of Collision Stages

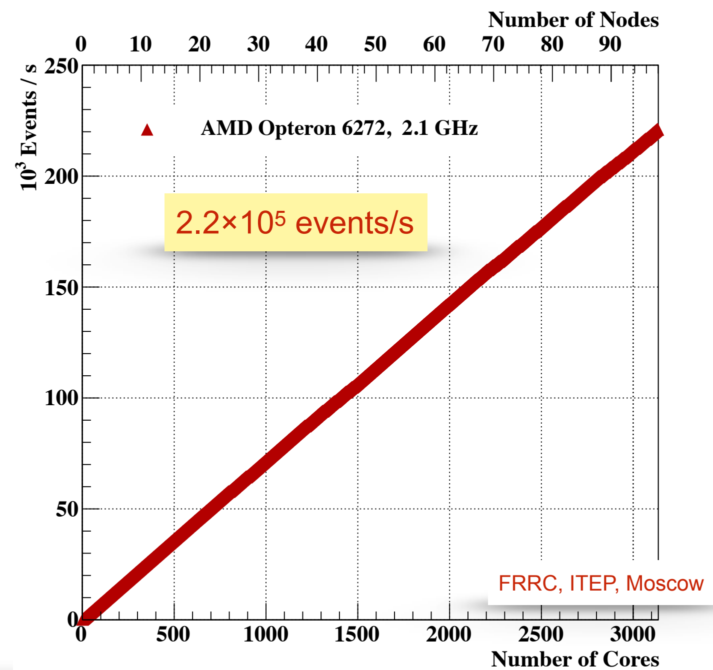


AuAu, 10 AGeV, 3.5M central UrQMD events, MC PID

Standalone First Level Event Selection (FLES) Package in CBM





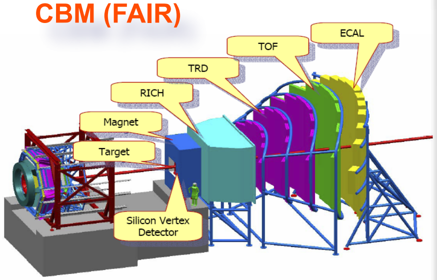


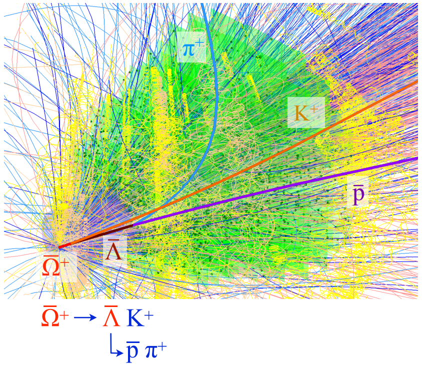
The FLES package is vectorized, parallelized, portable and scalable up to 3 200 CPU cores

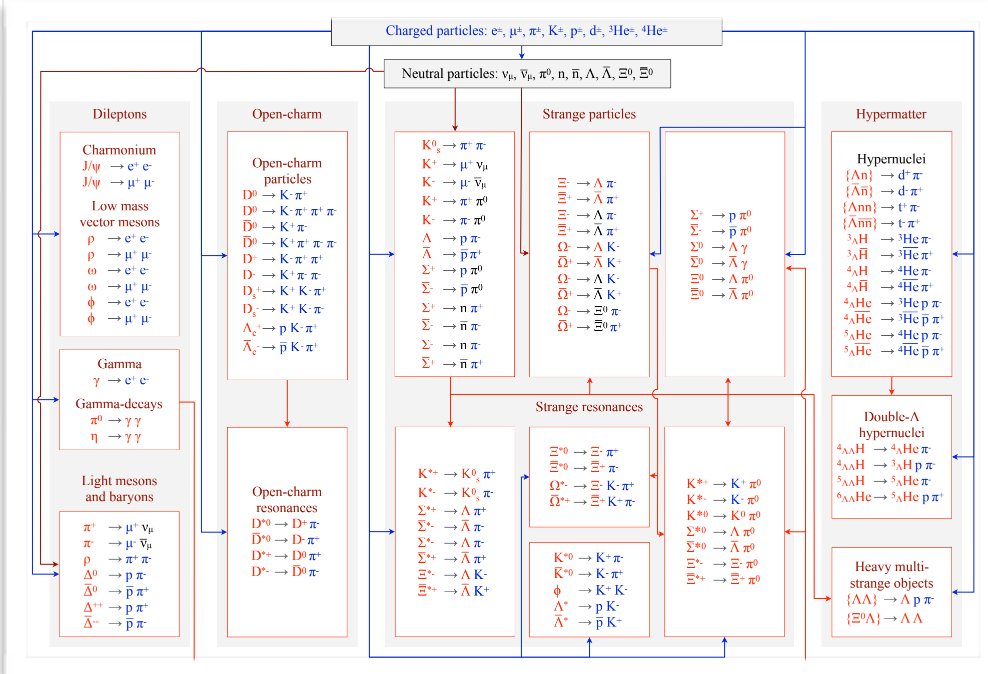
Search for short-lived Particles in CBM and STAR

Within the FAIR Phase-0 program the CBM KF Particle Finder has been adapted to STAR and applied to real data of 2016, 2014 and BES-I in order to investigate decays of strange ($K^{\pm}$, Λ, Ξ^-, Ω^-), open charm (D^0, D^+, D_s^+, Λ_c^+) and other particles with the KF Particle Finder.

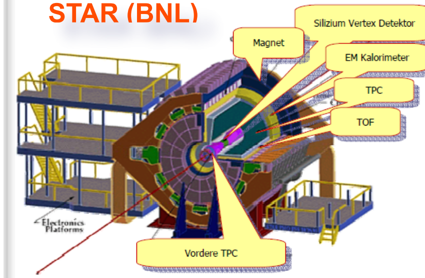
CBM (FAIR)

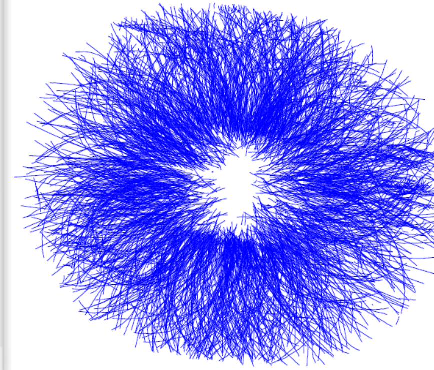




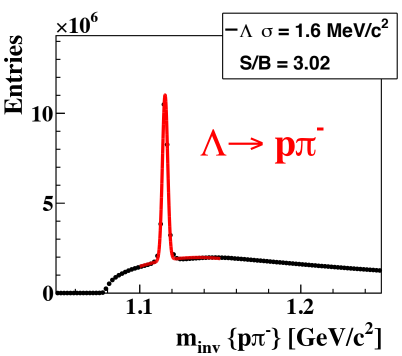


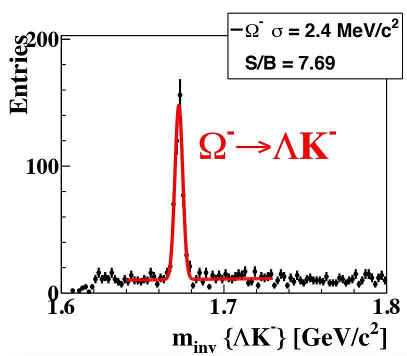
STAR (BNL)



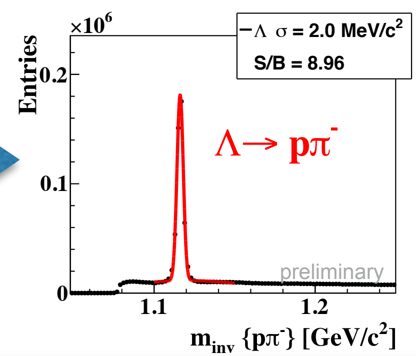


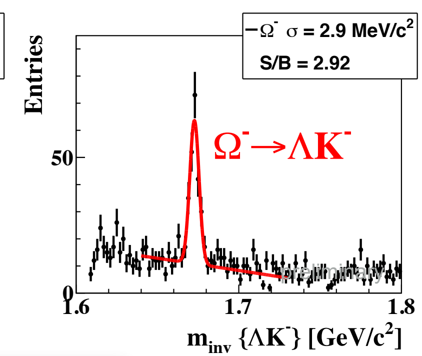
CBM, 5M central Au+Au, 10 AGeV, PHSD





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





Preparation for the real-time physics analysis during BES-II is in progress

Summary

- ✓ More than 25 years of experience in event reconstruction in HI and HEP experiments.
- ✓ Efficient and fast reconstruction of stable and long-lived particles with the CA Track Finder
- ✓ Precise and extremely fast estimation of particles parameters together with their covariance matrices with the KF Track Fitter
- ✓ Accurate and clean reconstruction of short-lived particles with the KF Particle package
- ✓ KF Particle Finder is a universal platform for short-lived particles reconstruction and physics analysis in on- and off-line modes
- ✓ Reconstruction is highly parallelized and vectorized for use on many-core CPU/Phi/GPU computer architectures
- ✓ Within FAIR Phase-0 develop a common CBM+STAR event reconstruction package based on the CBM FLES package