Fast Event Reconstruction

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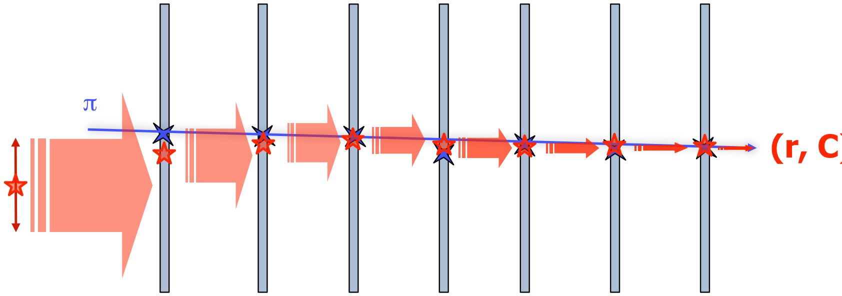
Stages of Event Reconstruction

1 Track Finder

- Conformal Mapping
- Hough Transformation
- Track Following + Kalman Filter
- Cellular Automaton + Kalman Filter

2 Track Fitter

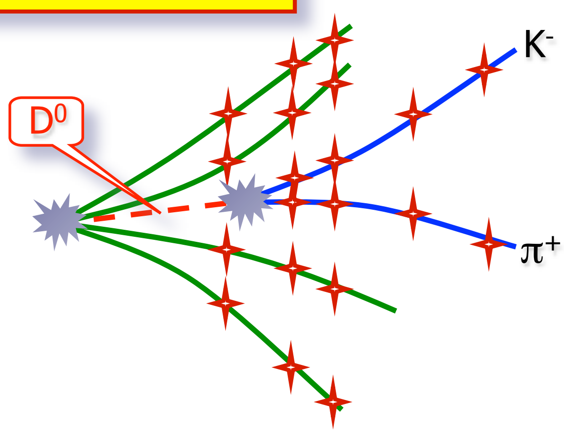


- Kalman Filter

3 Ring Finder (Particle ID)

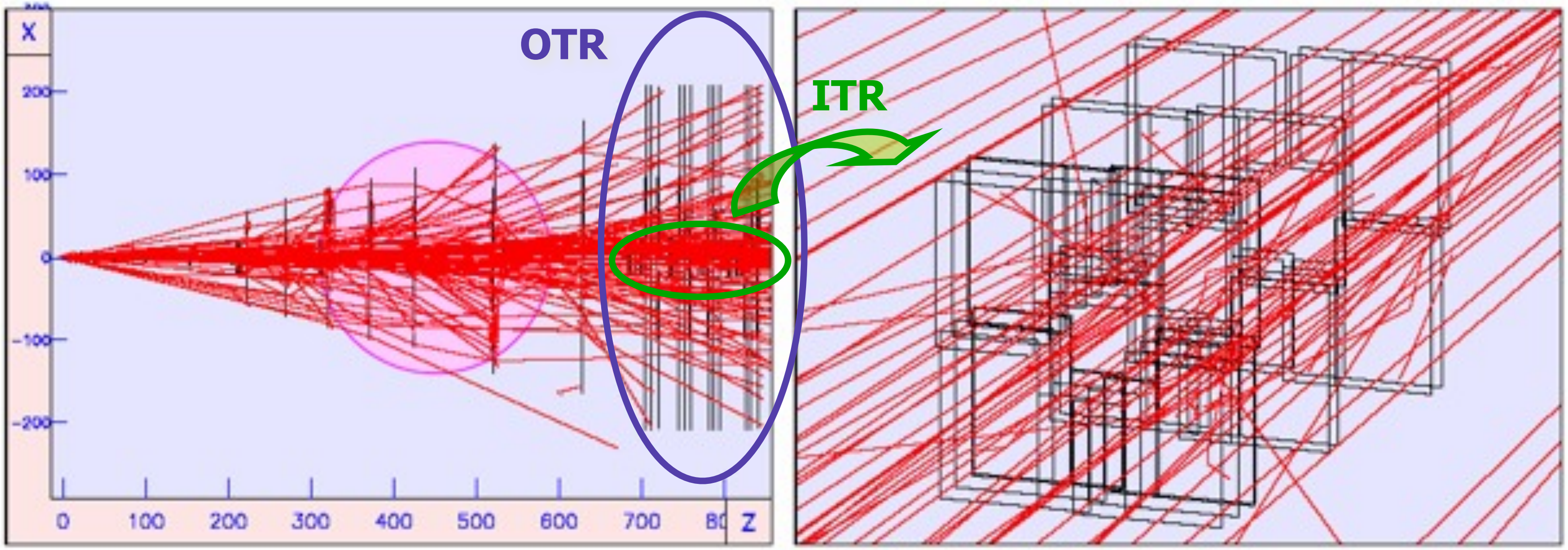
- Hough Transformation
- Elastic Neural Net

4 Short-Lived Particles Finder



- Kalman Filter

HERA-B: Track Finding in the Pattern Tracker



Extremely low resolution and efficiency
of the pattern tracker of HERA-B

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

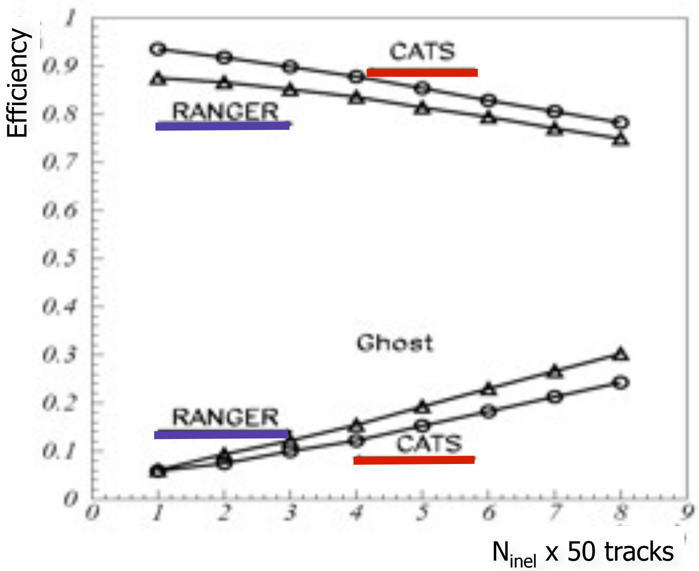
Hough Transformation → **TEMA** Uni-Ljubljana

Kalman Filter → **RANGER** DESY Zeuthen

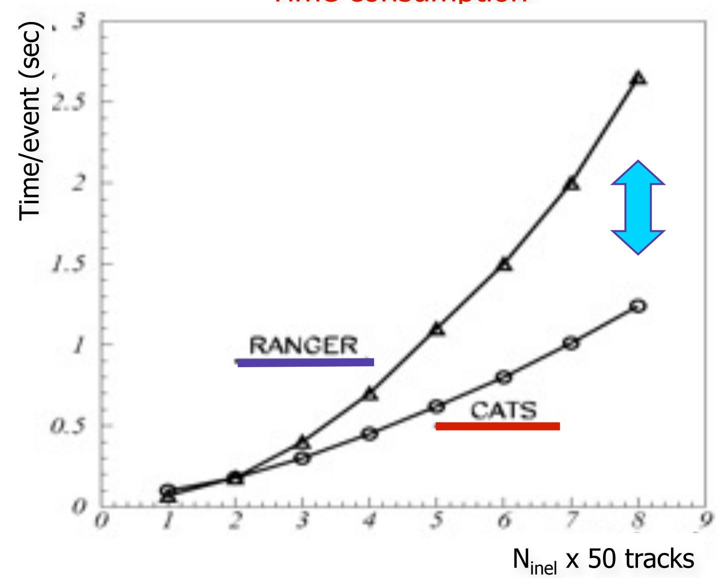
Cellular Automaton → **CATS** MPI Munich

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

Tracking efficiency



Time consumption



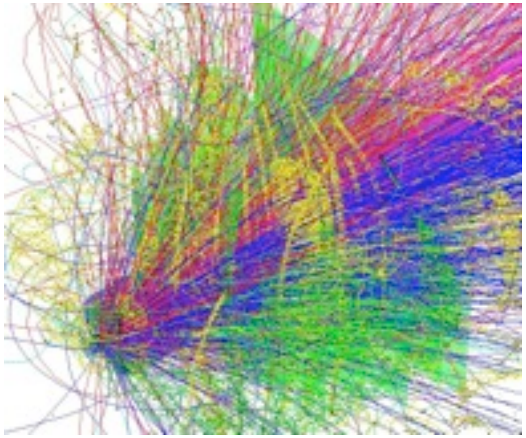
Tracking quality

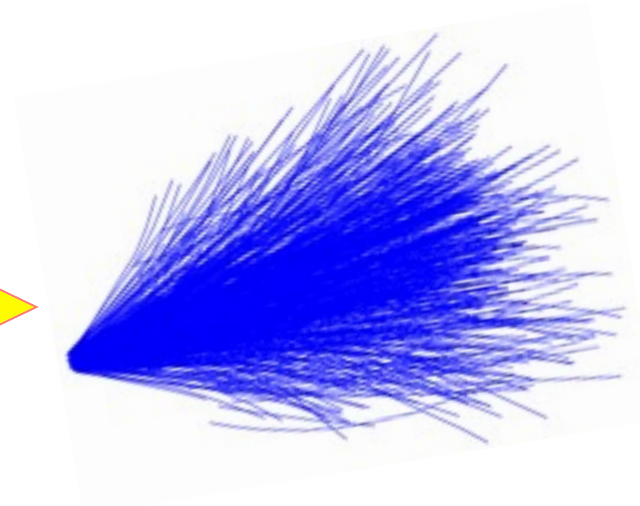
Resolutions, pulls P and mean length of reconstructed primary tracks.

	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

CBM STS Tracking Methods: 2005 vs. 2012

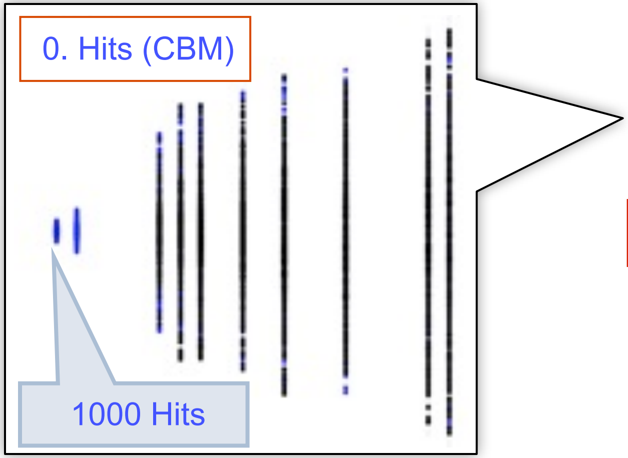


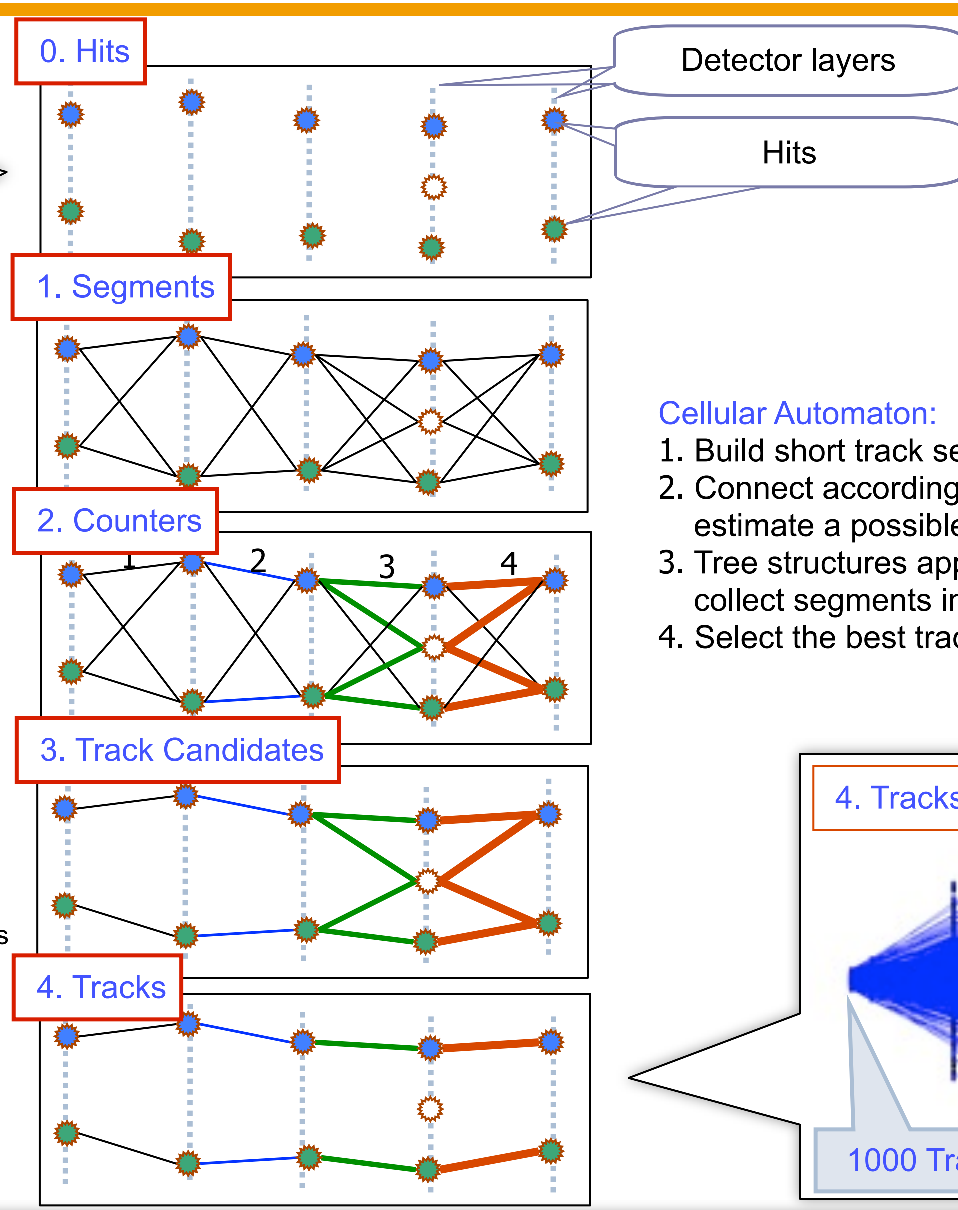


Developer	Tracking Method	2005	2012
LHEP JINR, Dubna	Conformal Mapping	✓	✗
ZITI, Mannheim	Hough Transformation	✓	✗
LIT JINR, Dubna	Track Following	✓	✗
Uni-Heidelberg, GSI	Cellular Automaton	✓	✓

CA is appropriate for complicated event topologies with large combinatorics

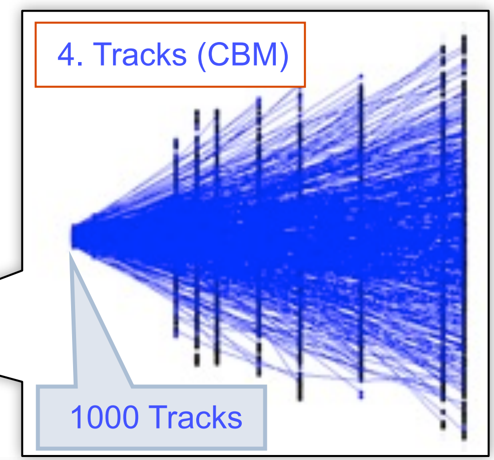
Cellular Automaton as Track Finder





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.



Features:

- Local relations -> simple calculations
- Local relations -> parallel algorithm
- Staged implementation: hits -> segments -> tracks
- Stepwise reduction of combinatorics
- Polynomial (2nd order?) combinatorics
- Track competition at the global level
- Includes the KF fitter for high track densities
- Detector inefficiency problem outside the combinatorics
- ...

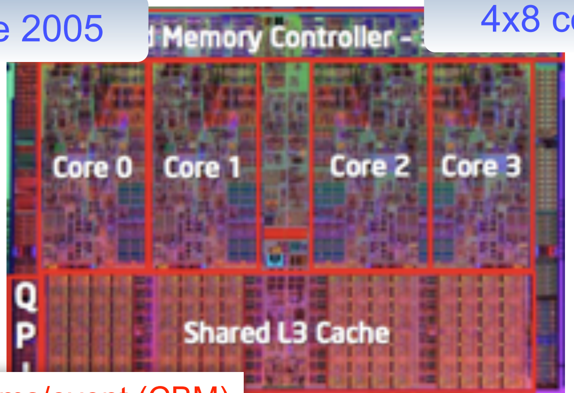
Useful for complicated event topologies with large combinatorics and for parallel hardware

Many-Core CPU/GPU Architectures: Our Experience

Intel/AMD CPU

Since 2005

4x8 cores



6.5 ms/event (CBM)

ATI/NVIDIA GPU

Since 2008

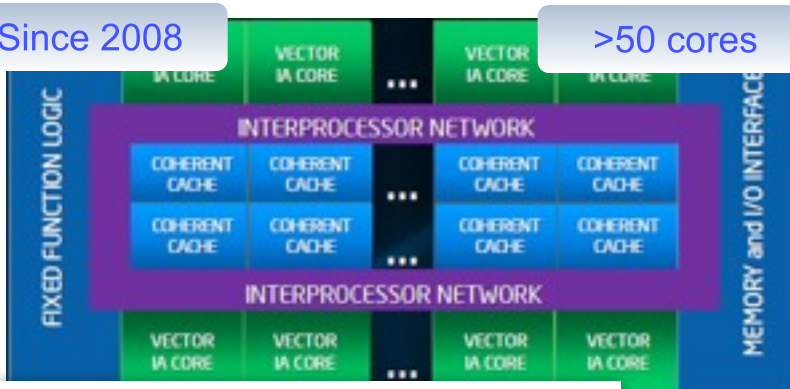
512 cores

63% of the maximal GPU utilization (ALICE)

Intel MIC

Since 2008

>50 cores

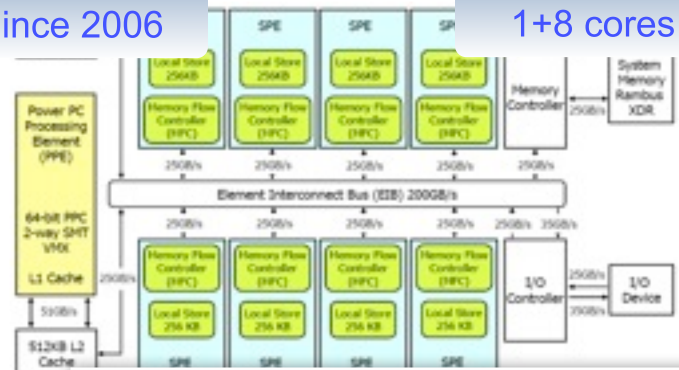


Cooperation with Intel (CBM/ALICE/STAR)

IBM Cell

Since 2006

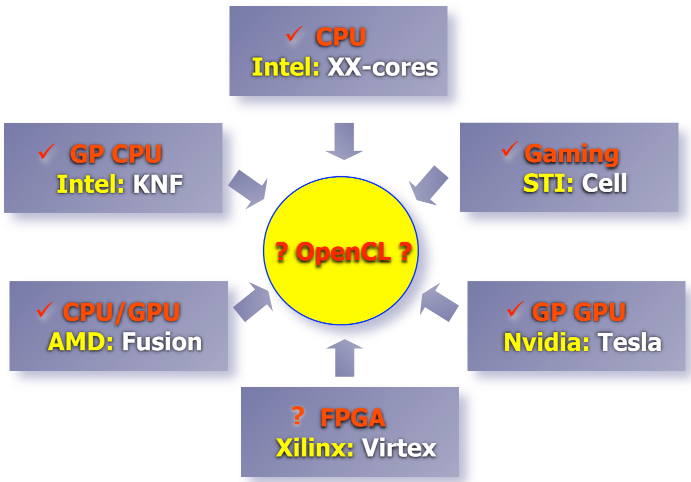
1+8 cores



70% of the maximal Cell performance (CBM)

Future systems are heterogeneous

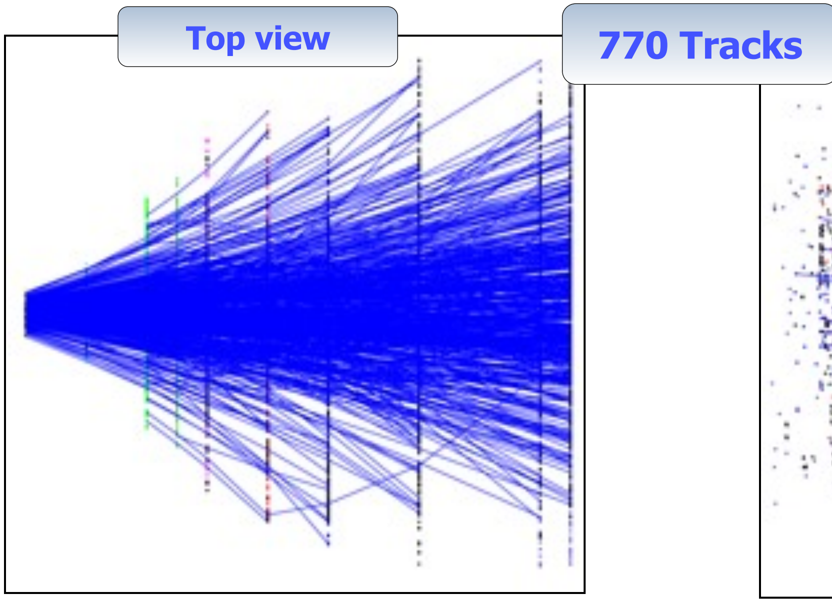
CPU/GPU Programming Frameworks

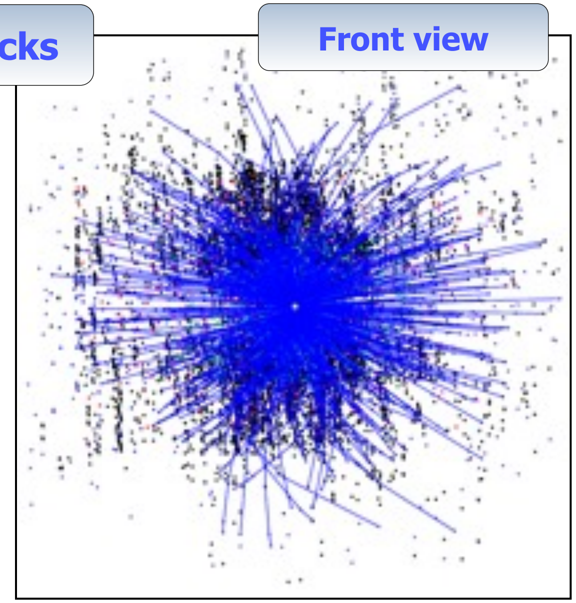


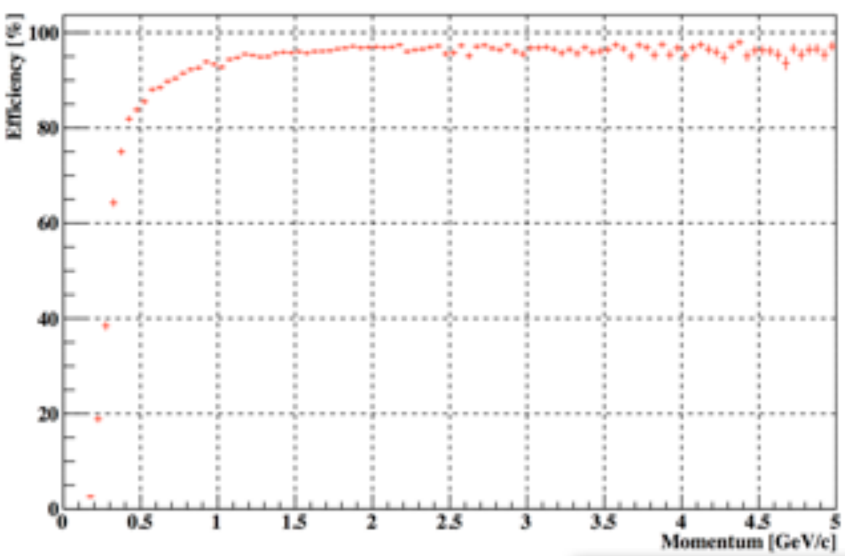
- Intel Ct (C for throughput), ArBB (Array Building Blocks)
  - Extension to the C language
  - Intel CPU/GPU specific
  - SIMD exploitation for automatic parallelism
- NVIDIA CUDA (Compute Unified Device Architecture)
  - Defines hardware platform
  - Generic programming
  - Extension to the C language
  - Explicit memory management
  - Programming on thread level
- OpenCL (Open Computing Language)
  - Open standard for generic programming
  - Extension to the C language
  - Supposed to work on any hardware
  - Usage of specific hardware capabilities by extensions
- Vector classes (Vc)
  - Overload of C operators with SIMD/SIMT instructions
  - Uniform approach to all CPU/GPU families
  - Uni-Frankfurt/FIAS/GSI

Choice of CPU/GPU/Programming is a practical question

CBM CA Track Finder: Efficiency





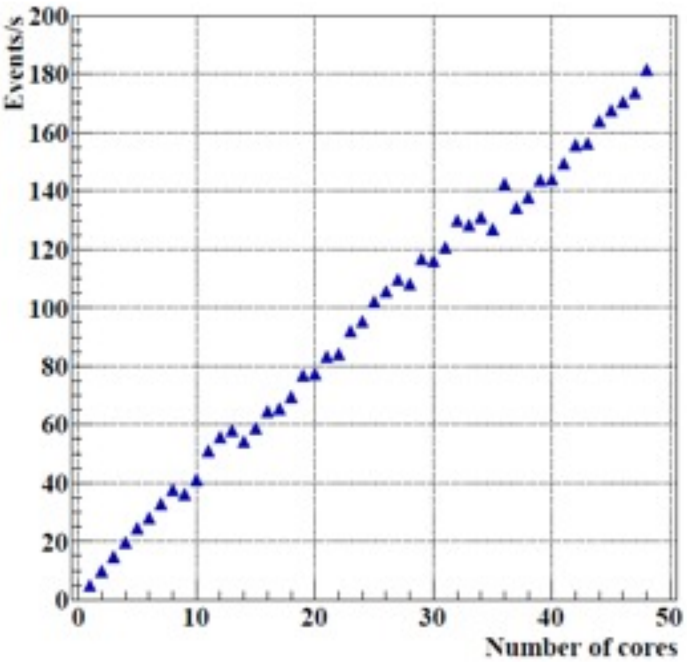


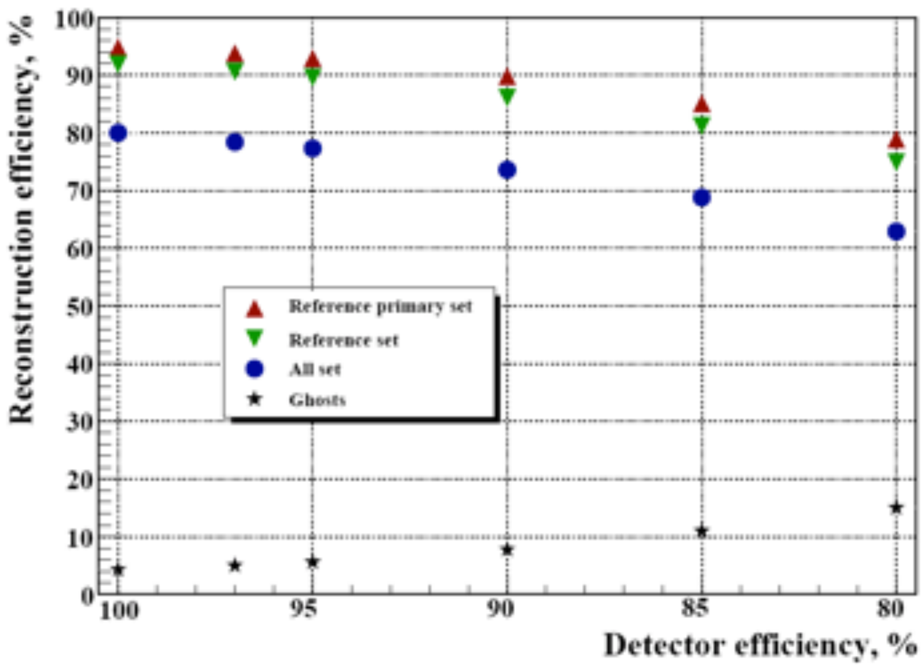
	Efficiency, %	
	mbias	central
Primary high-p tracks	97.1	96.2
Primary low-p tracks	90.4	90.7
Secondary high-p tracks	81.2	81.4
Secondary low-p tracks	51.1	50.6
All tracks	88.5	88.3
Clone level	0.2	0.2
Ghost level	0.7	1.5
Reconstructed tracks/event	120	591
Time/event/core	8.2 ms	57 ms

Efficient and stable event reconstruction

CBM CA Track Finder: Scalability and Reliability

Central Au-Au collisions





- AMD 6164EH
- 12 cores per CPU, 1.7 GHz
- Openlab CERN

Strong many-core scalability and stable down to 80% detector efficiency (both on central events)

CBM Kalman Filter 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

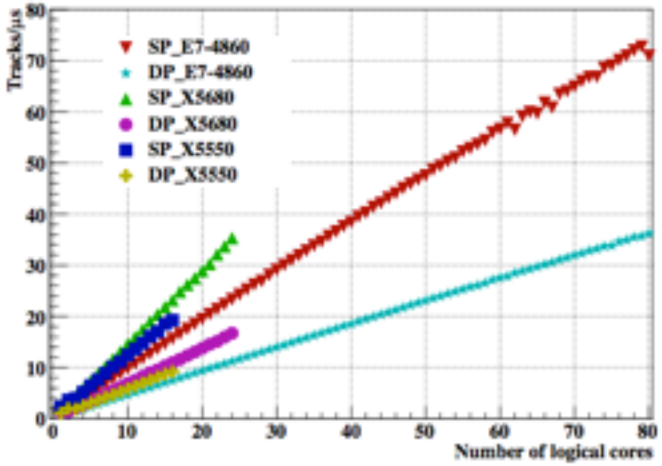
Implementations

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

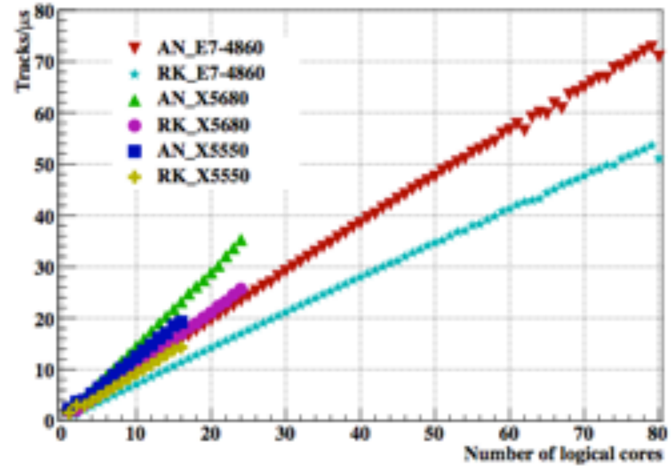
Parallelization (many-cores):
- Open MP
- ITBB
- ArBB
- OpenCL

Precision:
- single
- double

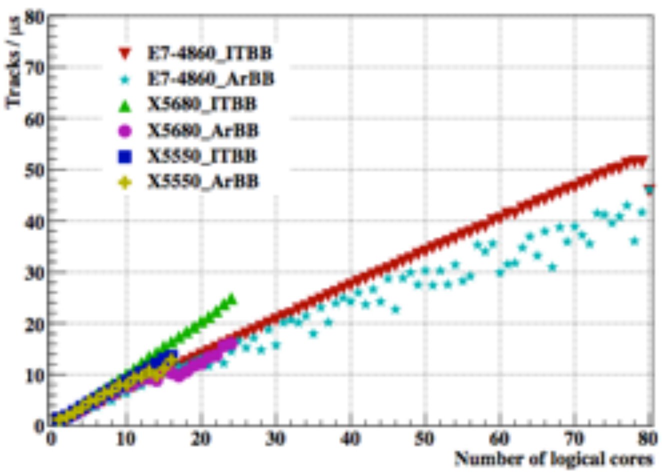
Conventional KF DP vs. SP



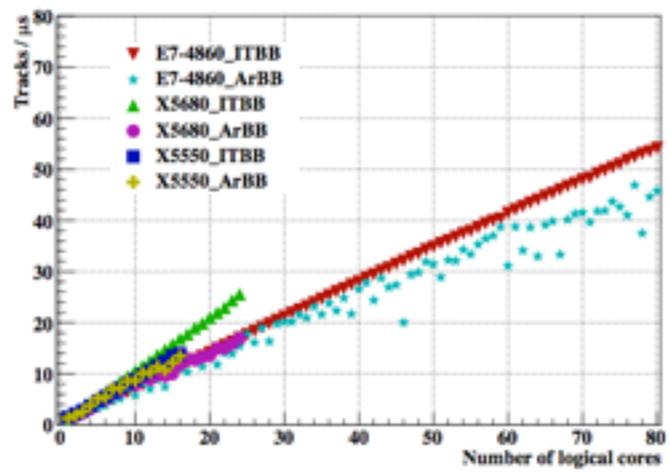
Conventional KF RK4 vs. Analytical



Square-Root KF

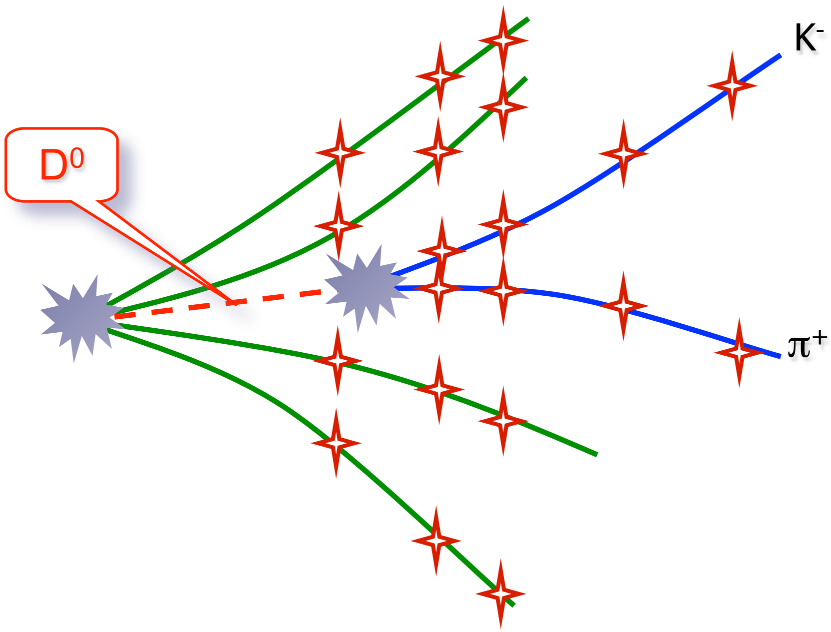


UD KF



Strong many-core scalability of the Kalman filter library

KFParticle: Reconstruction of Vertices and Decayed Particles



State vector

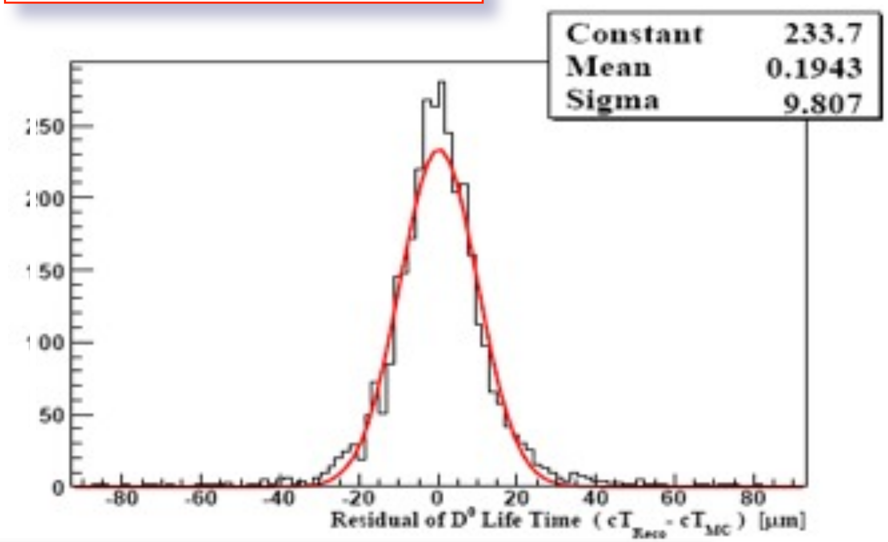
Position, direction, momentum and energy

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

- Mother and daughter particles have the same state vector and are treated in the same way
- Geometry independent
- Kalman filter based

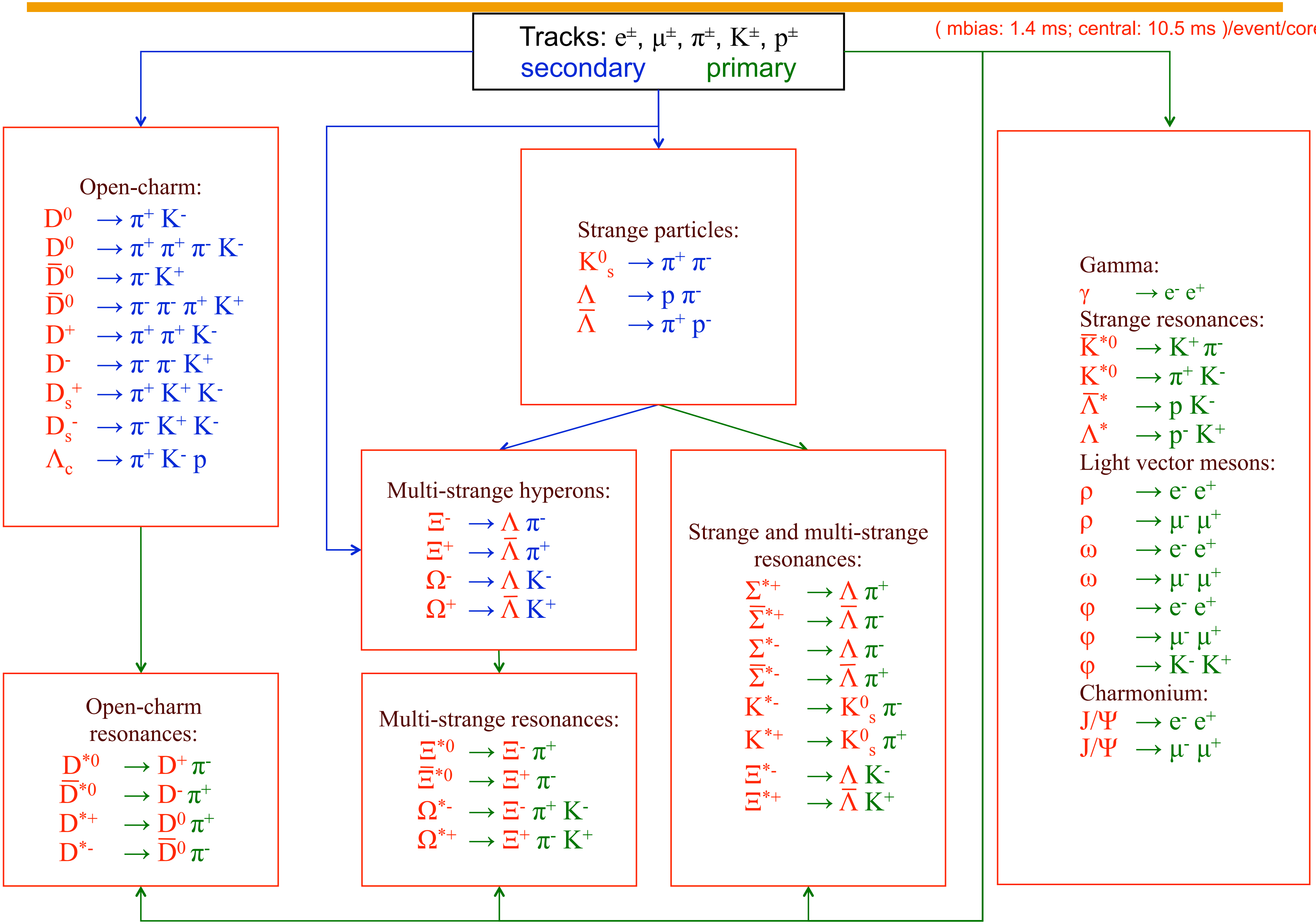
$x, y, z, p_x, p_y, p_z, E, m, L, c\tau$

```
AliKFVertex PrimVtx( ESDPrimVtx );  // Set primary vertex
                                    // Set daughters
AliKFParticle K( ESDp1, -321 ), pi( ESDp2, 211 );

AliKFParticle  D0( K, pi );         // Construct mother
PrimVtx += D0;                      // Improve the primary vertex

D0.SetProductionVertex( PrimVtx );  // D0 is fully fitted
K.SetProductionVertex( D0 );        // K is fully fitted
pi.SetProductionVertex( D0 );       // pi is fully fitted
```

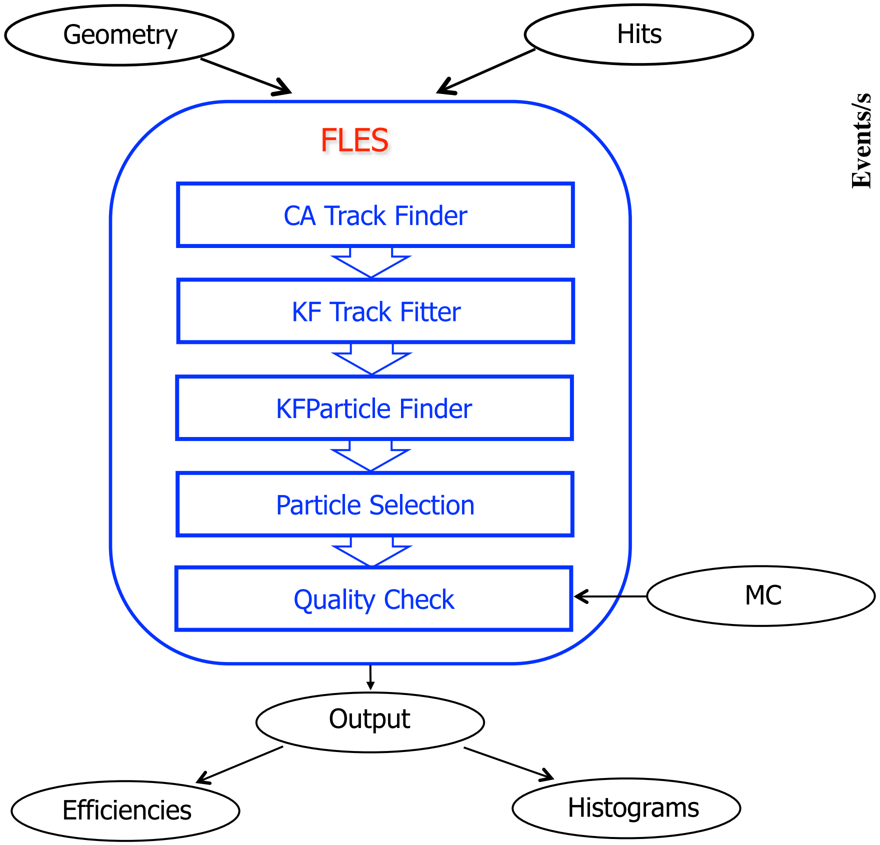


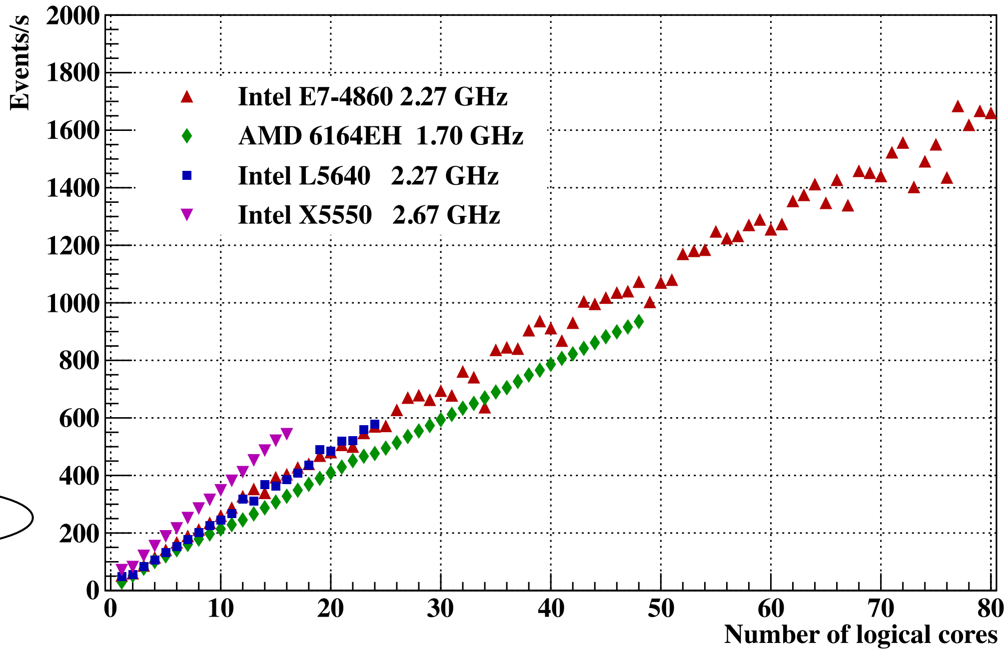
KFParticle provides uncomplicated approach to physics analysis (used in CBM, ALICE and STAR)

KFParticle Finder for Physics Analysis and Selection



CBM Standalone First Level Event Selection (FLES) Package





Given n threads each filled with 1000 events, run them on specified n cores, thread/core.

The first version of the FLES package is vectorized, parallelized, portable and scalable

Parallelization in the CBM Event Reconstruction

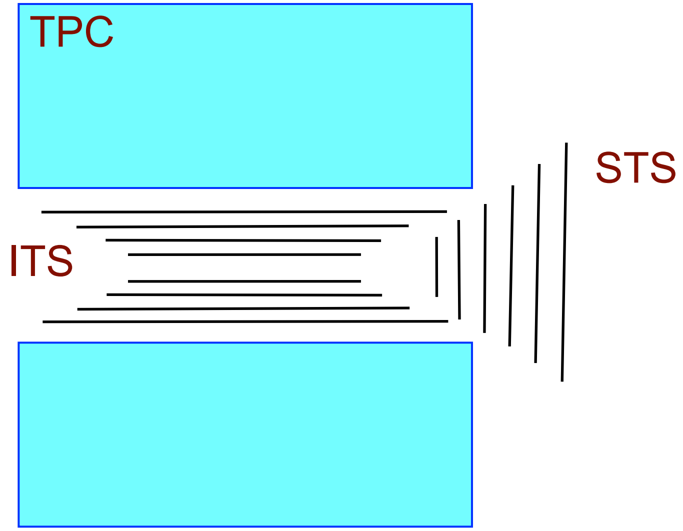
Algorithm	Vector SIMD	MultiThreading	CUDA	OpenCL CPU/GPU
Hit Producers				
STS KF Track Fit	✓	✓	✓	✓/✓
STS CA Track Finder	✓	✓		
MuCh Track Finder	✓	✓	✓	
TRD Track Finder	✓	✓	✓	
RICH Ring Finder	✓	✓		(✓/✓)
Vertexing (KFParticle)	✓	✓		
Off-line Physics Analysis	✓			
FLES Analysis and Selection	✓	✓		

Parallelization becomes a standard in the CBM experiment

HEP Experiments: Common Tracking Algorithms

Activities:
1. Experiments: CBM, ALICE, STAR;
2. Sub-detectors:
    - TPC (ALICE, STAR),
    - Barrel ITS ALICE, HFT STAR,
    - Forward STS CBM, FGT STAR,
3. Parallelization: CPU/GPU, SIMD/Threads, Languages.

Setup:

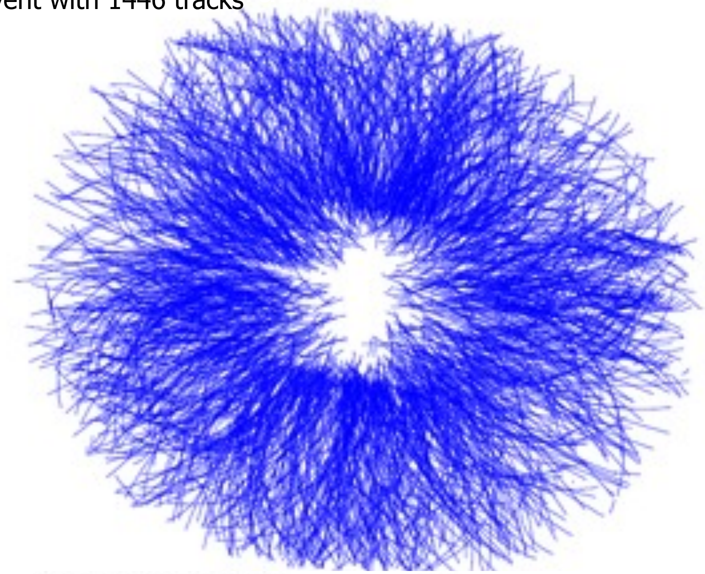


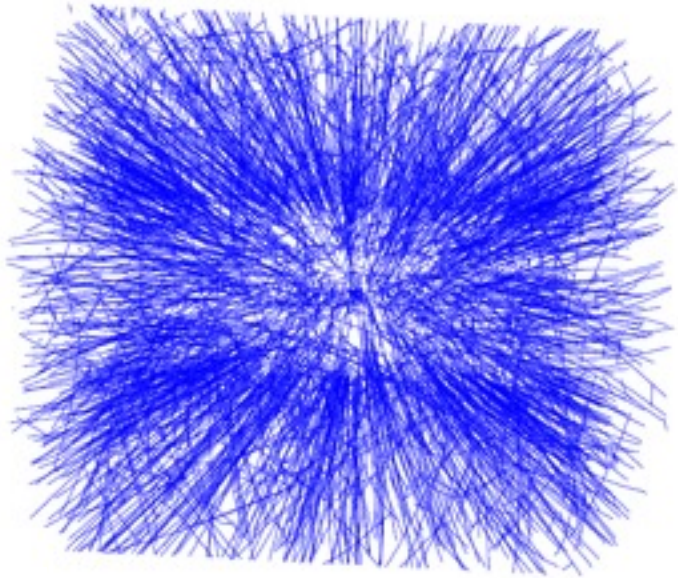
Stages:
1. Common ITS+STS tracking;
2. Common ITS+TPC tracking;
3. Common TPC+ITS+STS tracking.

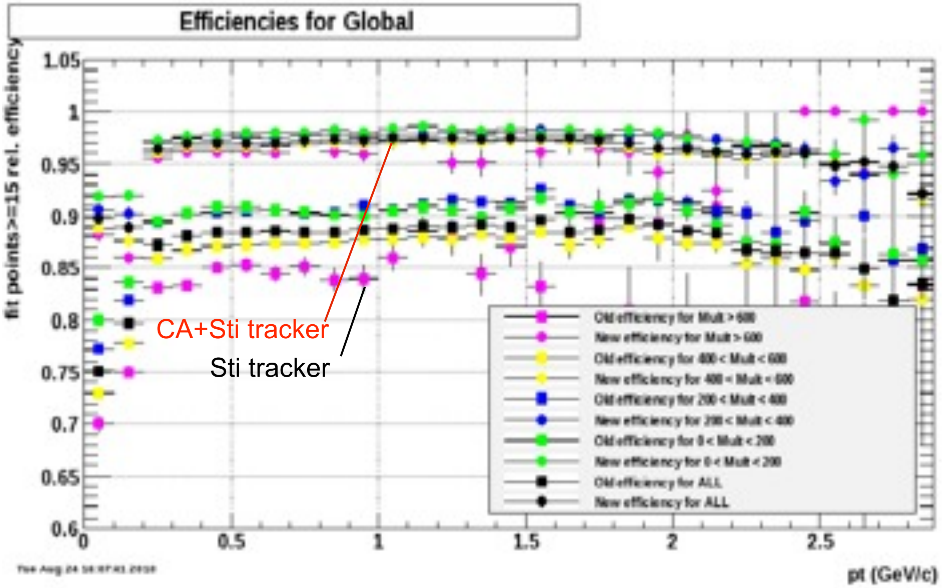
Develop a common TPC+ITS+STS tracking algorithm

STAR TPC CA Track Finder

Au-Au event with 1446 tracks





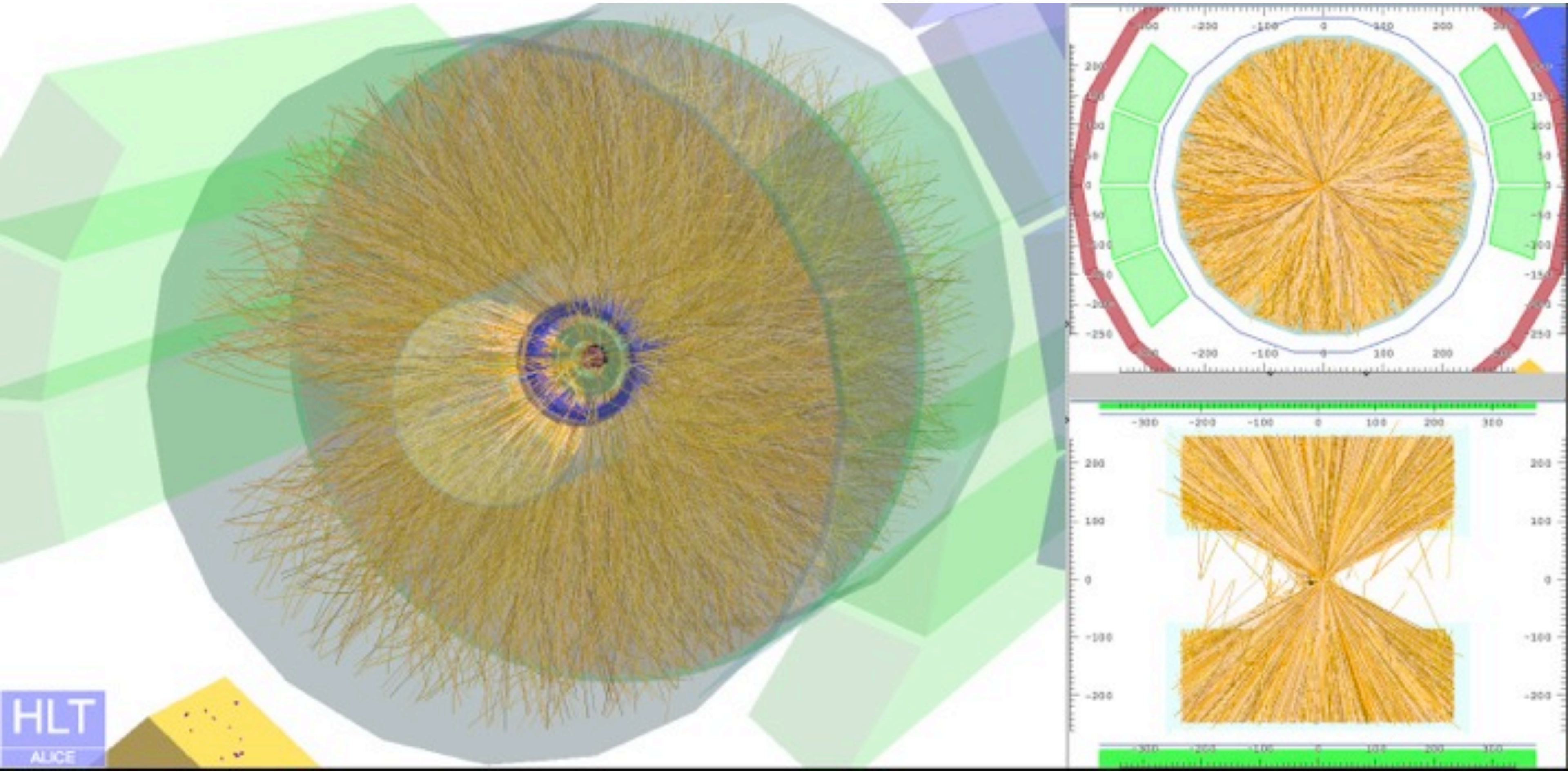


Efficiency and ratio, %	
Ref Set	96.6
All Set	88.6
Clone	10.6
Ghost	12.6
Tracks/ev	659
Time/ev, ms	47

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

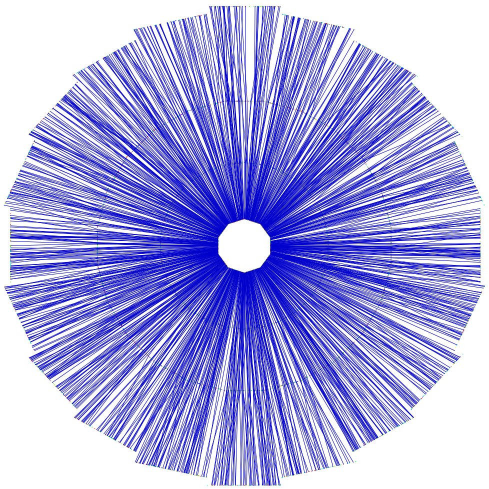
The CA track finder is more stable w.r.t. track multiplicity and is ~10 times faster than the TF based Sti track finder.

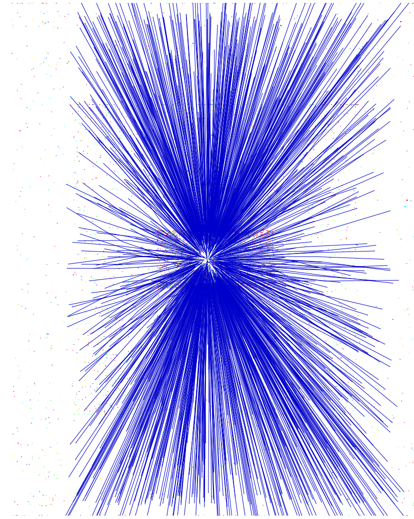
ALICE HLT: Event of the First Run with the GPU CA Tracker

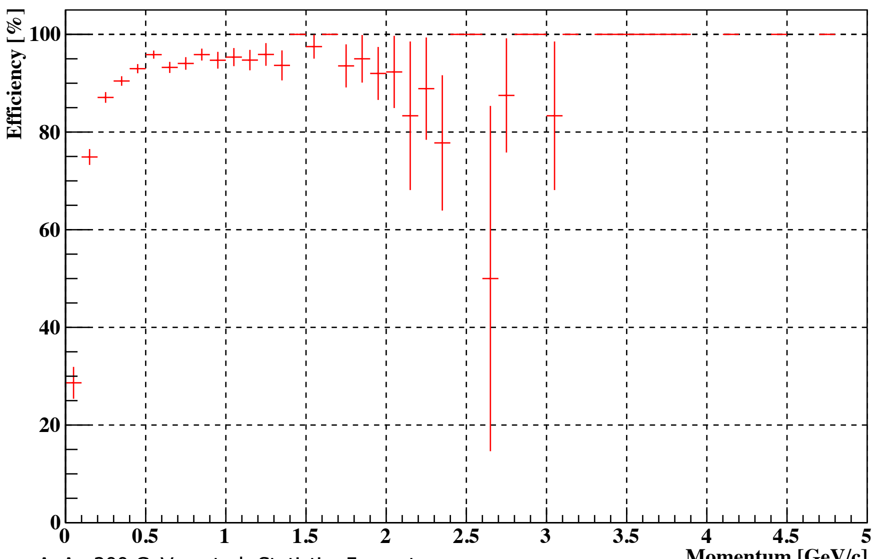


ALICE HLT Group

STAR HFT CA Track Finder







AuAu 200 GeV central; Statistic: 5 events
1 core of Intel Core i7, 2 GHz, 4 MB L3 cache, 8 GB RAM

Efficiency and ratio, %	
High-mom. primary	95.3
Low-mom. primary	91.0
High-mom. secondary	72.0
Low-mom. secondary	50.2
All tracks	88.4
Clone	0.0
Ghost	5.2
Tracks/ev	1055
Time/ev, s	1.72

Reconstructable track:
4 consecutive MC points

All set:	p ≥ 0.05 GeV/c
Fast set:	p ≥ 1 GeV/c
Ghost:	purity < 70%

A common ITS ALICE / HFT STAR + STS CBM / FGT STAR CA track finder is under development

Consolidate Efforts: Common Reconstruction Package

Uni-Frankfurt/FIAS:
Vector classes
CPU/GPU implementation

GSI:
Algorithms development
Many-core optimization

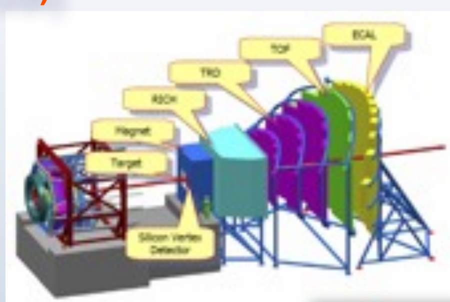
OpenLab (CERN):
Many-core optimization
Benchmarking

HEPHY (Vienna)/Uni-Gjovik:
Kalman Filter track fit
Kalman Filter vertex fit

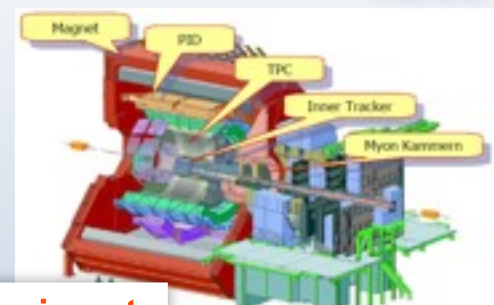
Common Reconstruction Package

Intel:
ArBB/OpenCL implementation
Benchmarking

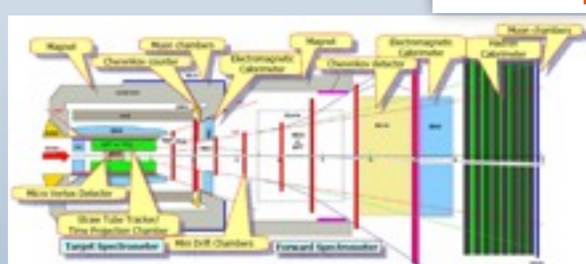
CBM (FAIR/GSI)



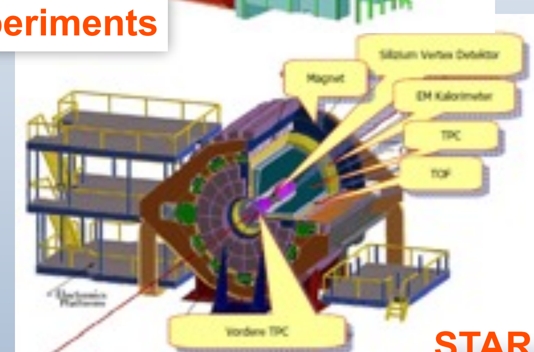
ALICE (CERN)



Host Experiments



PANDA (FAIR/GSI)



STAR (BNL)