Recent developments in tracking and vertexing methods

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Vertex 2015

Santa Fe, June 4, 2015

Outline

1. Developments for LHC Run 2
   - ATLAS
   - CMS
   - LHCB
2. Real-time Tracking
   - ATLAS
   - CMS
   - CBM
   - LHCb
3. Other developments
   - CMS @ HL-LHC
   - Belle II
   - Fuzzy c-regression
4. Summary and outlook

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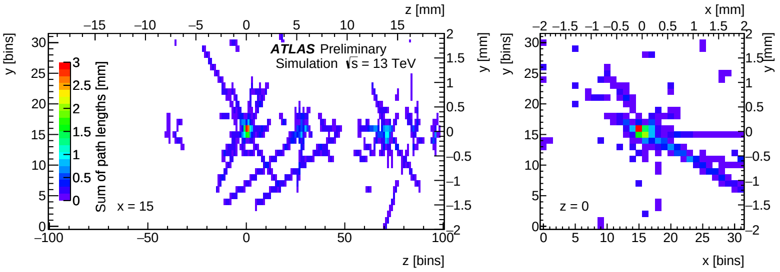
Developments for LHC Run 2: ATLAS Tracking

➽ See talk by Gabriel Facini!

Imaging algorithm for vertex reconstruction

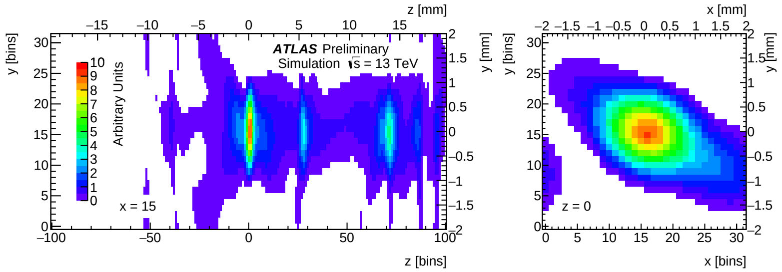
- Define **3D histogram** in box $4 \times 4 \times 400$ mm around the origin
- Helical track trajectories are linearised and **back-projected** into the histogram using a voxel raytracing algorithm
- Histogram content in each traversed bin is **incremented by the path length** of the linearised track in the bin
- Example:



ATL-PHYS-PUB-2015-008

Developments for LHC Run 2: ATLAS Vertexing

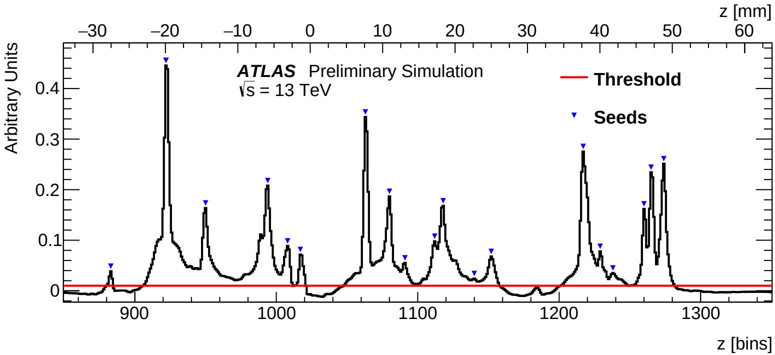
- The back-projected track image is **transformed into frequency space by** a discrete Fourier transform
- The frequency space histogram is multiplied by two **filters: acceptance and smoothing**
- The filtered frequency space image is **back-transformed to position space**
- Result:



ATL-PHYS-PUB-2015-008

Developments for LHC Run 2: ATLAS Vertexing

- The resulting image is passed to a separate **clustering algorithm** where all seeds are identified from peaks in the image
- Projection to the *z*-axis:



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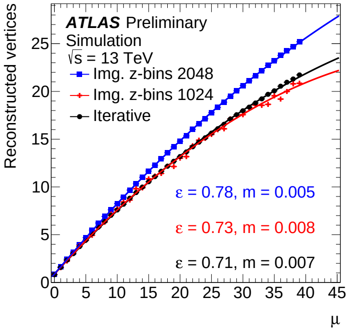
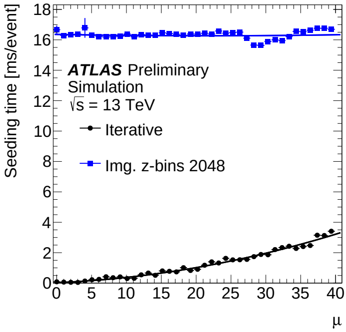
Developments for LHC Run 2: ATLAS Vertexing

- Comparison to iterative reconstruction with the **adaptive vertex finder**
- Min bias events, μ is number of in-time pile-up





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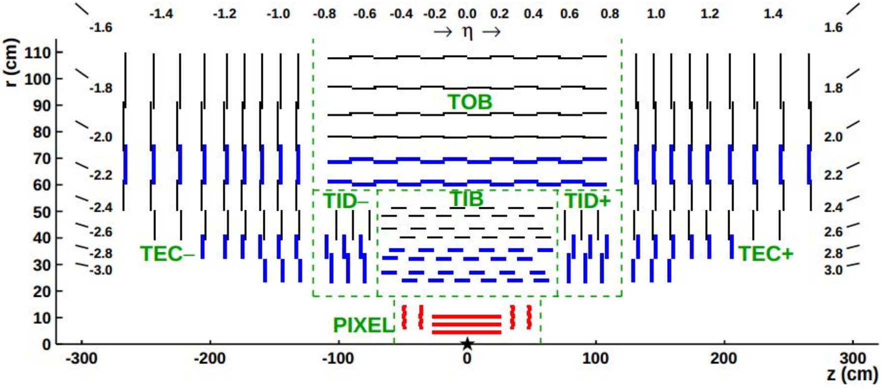
Developments for LHC Run 2: CMS Tracking

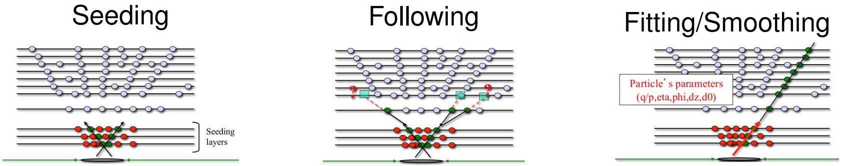


The CMS Tracker

Developments for LHC Run 2: CMS Tracking

Iterative combinatorial track finding

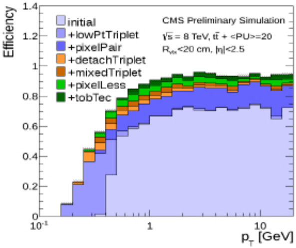
- In each iteration:
  - **Seed generation**: initial track segment with 2 or 3 hits
  - **Track following**: pick up compatible hits and branch
  - **Track fitting**: estimate track parameters
  - **Track selection**: drop bad track candidates
- After each iteration, hits belonging to high quality tracks are removed

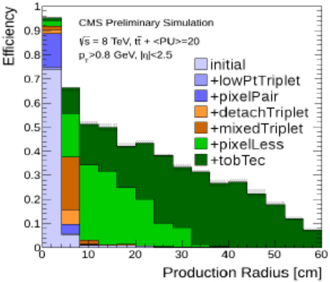


E. Brondolin, Connecting The Dots 2015

Developments for LHC Run 2: CMS Tracking

N	Step Name	Seeding	Target Track
0	Initial	pixel triplets	prompt, high p_T
1	LowPtTriplet	pixel triplets	prompt, low p_T
2	PixelPair	pixel pairs	high p_T recovery
3	DetachTriplet	pixel triplets	displaced--
4	MixedTriplet	pixel+strip triplets	displaced-
5	PixelLess	inner strip pairs	displaced+
6	TobTec	outer strip pairs	displaced++





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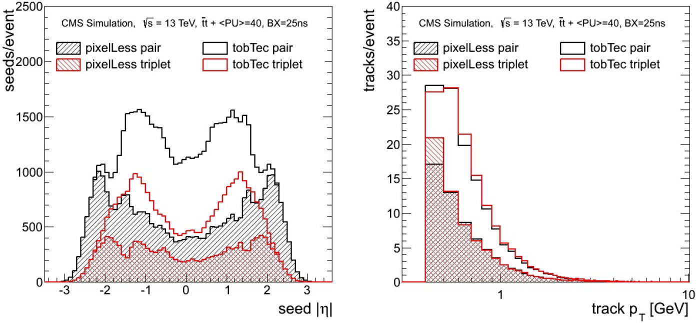
Developments for LHC Run 2: CMS Tracking

New seeding algorithm

- For **triplet**-based seeding from **strips**
- Straight-line fit of 3 points in *r*–*z* plane, tighter beam constraint, tighter quality selection
- Half of the seeds are rejected, efficiency not affected



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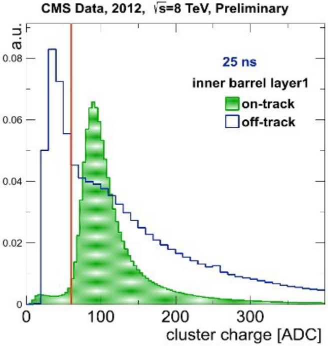
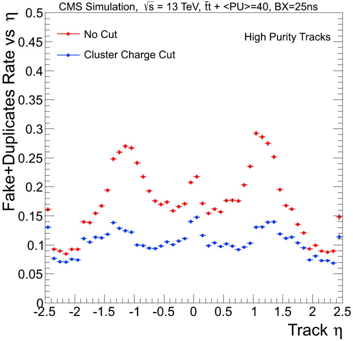
Developments for LHC Run 2: CMS Tracking

Cluster charge cut

- Larger occupancy resulted in doubling the time and the fake rate
- **Cluster charge cut** accounts for sensor thickness, p_T and crossing angle
- Timing and fake rate are back to normal





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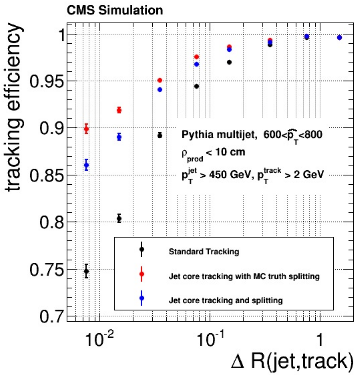
Developments for LHC Run 2: CMS Tracking

New iteration for high p_T jets

- **Iterative cluster splitting in the pixels**
- *k*-means clustering, taking into account the total cluster charge
- Improved efficiency at small ΔR



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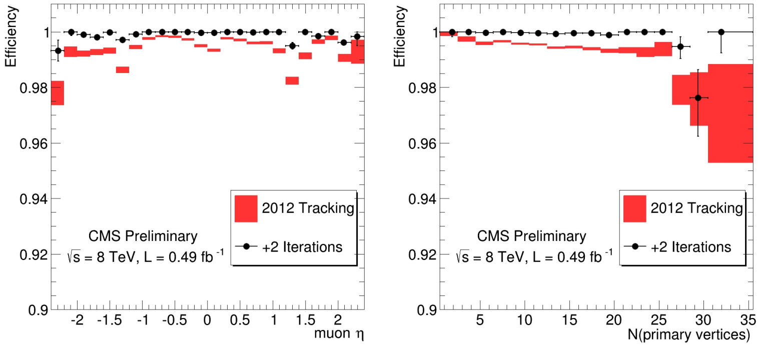
Developments for LHC Run 2: CMS Tracking

Two new iterations for muons

- Inward: muon system $\rightarrow$ tracker
- Outward: tracker $\rightarrow$ muon system, with looser cuts



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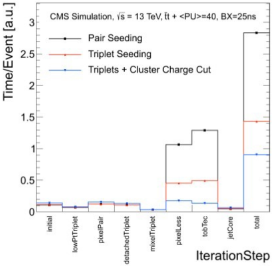
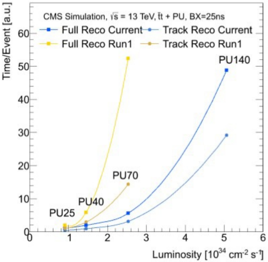
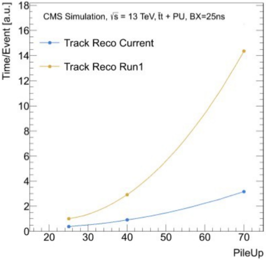
Developments for LHC Run 2: CMS Tracking

Reduction of time consumption

- Optimization of the code and the iteration logic
- Factor 2 at PU=20, factor 3 at PU=30, factor 4 at PU=70







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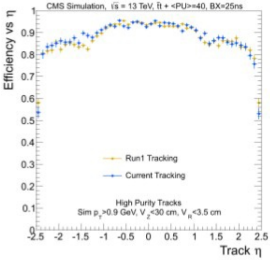
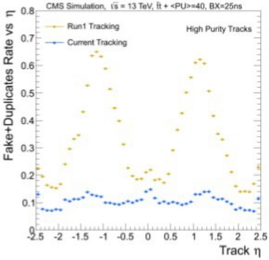
Developments for LHC Run 2: CMS Tracking

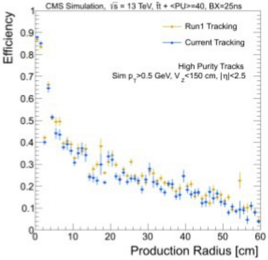
Expected performance for Run 2



high p_T prompt tracks



all tracks



low p_T displaced tracks

- Efficiency for prompt tracks is similar
- Fake rate is reduced by a factor of up to 6
- Efficiency for displaced tracks is slightly lower

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Developments for LHC Run 2: LHCB Tracking

➽ See talk by Stefano Gallorini!

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Real-time Tracking: ATLAS Fast Tracker

➡ See talk by Guido Volpi!

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Real-time Tracking: CMS Track Trigger

➽ See talk by Marco De Mattia!

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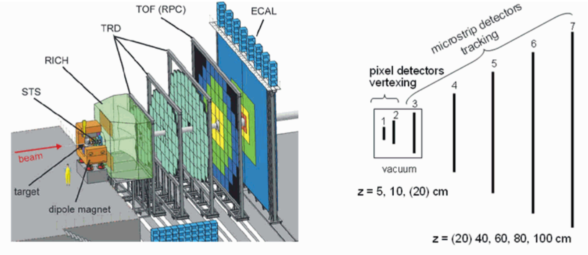
Real-time Tracking: CBM Tracking

CBM experiment

- Future fixed-target heavy-ion experiment at FAIR
- 10^7 Au+Au collisions/sec
- $\sim$1000 charged particles/collision
- Non-homogeneous magnetic field
- Double-sided strip detectors $\rightarrow$ 85% fake space-points!

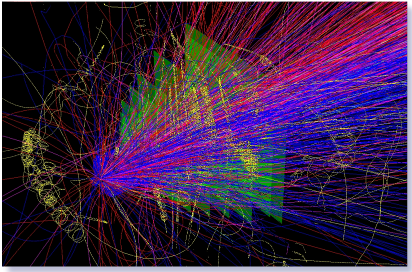


http://www-alt.gsi.de/documents/DOC-2006-Nov-46-1.pdf

Real-time Tracking: CBM Tracking

Event reconstruction

- **Full reconstruction online and offline**
- **Cellular Automaton** track finder
- Kalman filter track fitter
- Short-lived-particle finder
- All reconstruction algorithms are **vectorized** and **parallelized**

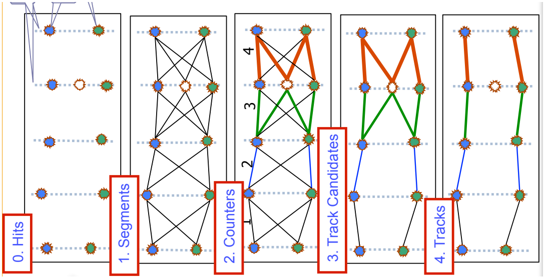


V. Akishina and I. Kisel, CHEP2015

Real-time Tracking: CBM Tracking

CA track finder

- Intrinsically parallel, simple, very fast
- Build short track segments
- Connect according to the track model
- Tree structures appear, collect segments into track candidates
- Select the best track candidates

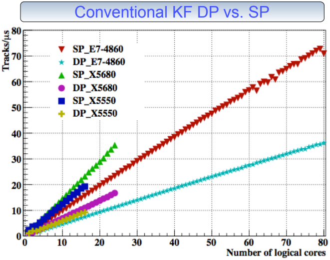


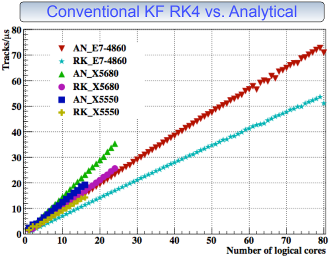
V. Akishina and I. Kisel, CHEP2015

Real-time Tracking: CBM Tracking

KF track fit library

- Tools: filter, smoother, deterministic annealing filter
- Variants: single precision, double precision, square-root filter, UD factorization filter
- Propagator: Runge-Kutta, analytic formulas
- Excellent many-core scalability!





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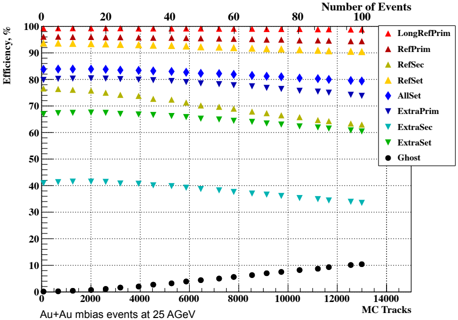
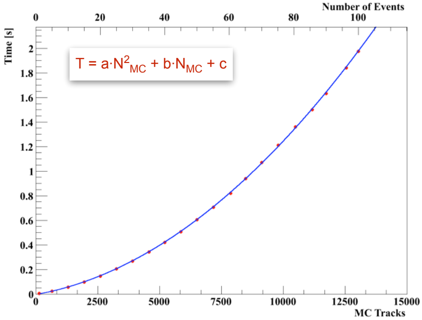
Real-time Tracking: CBM Tracking

Track finding efficiency

- Gather minimum bias events into a single event



Au+Au mbias events at 25 AGeV

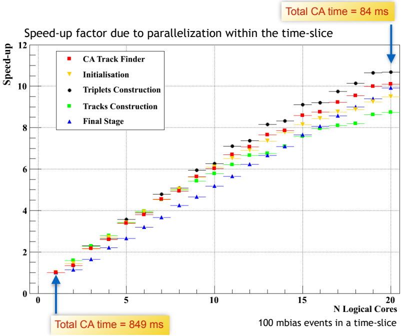


V. Akishina and I. Kisel, CHEP2015

Real-time Tracking: CBM Tracking

Time-based track reconstruction

- Beam in CBM is continuous
- Measurements will be 4D: x, y, z, t
- Significant overlapping of events in the detector
- Reconstruction of **time slices** instead of events



V. Akishina and I. Kisel, CHEP2015

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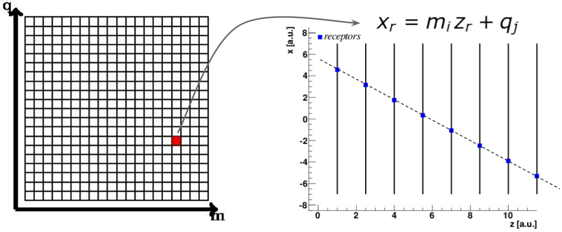
Real-time Tracking: LHCb

Plans for HL upgrade

- Specialized tracking processor with 40 MHz throughput
- Based on concept of **Artificial Retina**

Principles of Artificial Retina

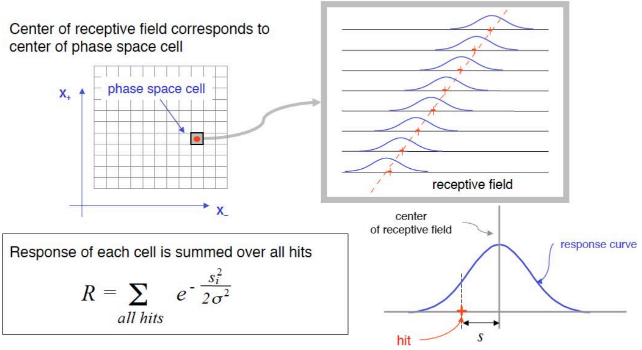
- The parameter space of the tracks is discretized into **cells**
- Each cell corresponds to an ideal track intersecting the detector layers in the centers of its **receptive fields**



A. Abba et al., JINST 10 C03018

Real-time Tracking: LHCb

- For a real track, the **distance** between the actual hits and the centers of the receptive fields is computed
- The **response** or **excitation** of a cell is a function of these distances, summed over all receptors and hits



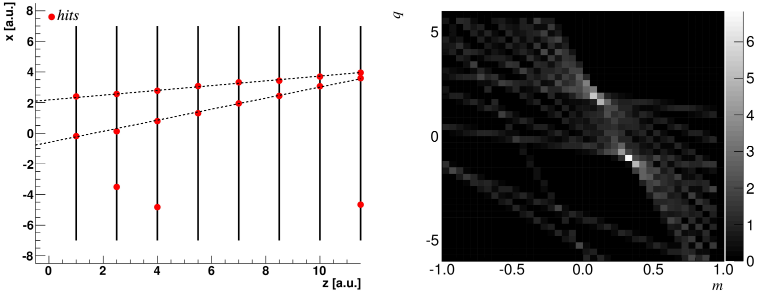
Response of each cell is summed over all hits

$$R = \sum_{\text{all hits}} e^{-\frac{s_i^2}{2\sigma^2}}$$

A. Abba et al., LHCb-PUB-2014-026

Real-time Tracking: LHCb

- Tracks are identified by **local maxima of response** in the array of cells
- Similar to Hough transform in 2D

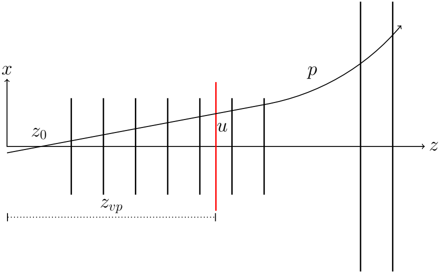


A. Abba et al., JINST 10 C03018

Real-time Tracking: LHCb

Artificial Retina for VELO/UT

- Consider virtual plane at $z = z_{vp}$
- Track is defined by transverse coordinates u, v
- 2D artificial retina with 2$\times$22500 cells
- Implementation in FPGA

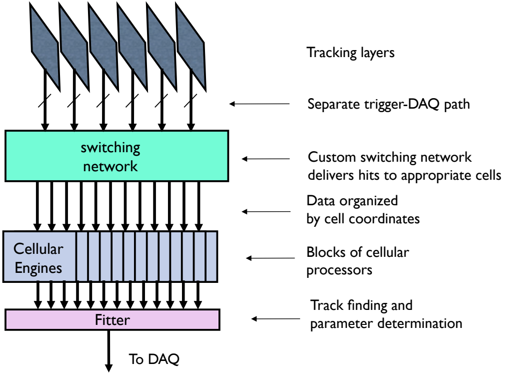


A. Abba et al., LHCb-PUB-2014-026

Real-time Tracking: LHCb

Architecture

- Overview of the architecture of the track processing unit (TPU)

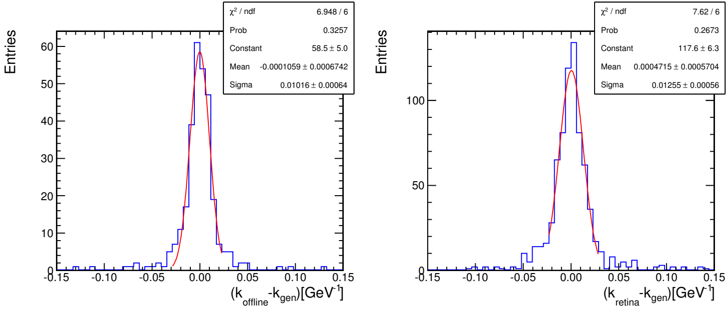


A. Abba et al., LHCb-PUB-2014-026

Real-time Tracking: LHCb

Simulation, timing and resolution

- Design has been validated by a ModelSim simulation
- TPU can keep up with an input frequency of 40 MHz at the occupancy predicted for 2020
- Curvature resolution about 25% worse as offline



A. Abba et al., LHCb-PUB-2014-026

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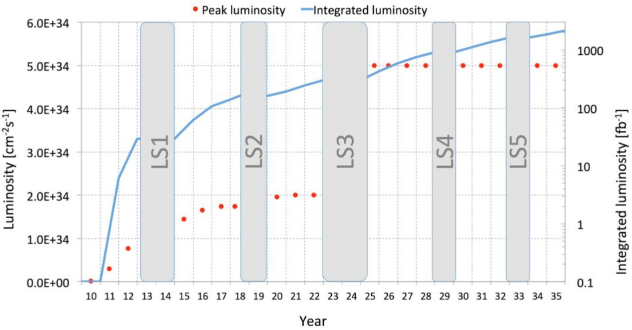
Other developments: CMS @ HL-LHC tracking

New tracker for High-Luminosity LHC

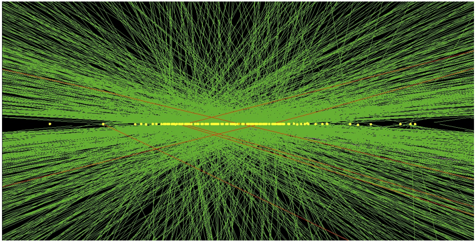
- Main challenges are **radiation** and **pile-up** caused by the high luminosity
- Radiation challenge will be addressed by the detector designers
- Pile-up challenge requires a **track trigger** complementing the muon and calorimeter information

See talk by Marco De Mattia!

Other developments: CMS @ HL-LHC tracking

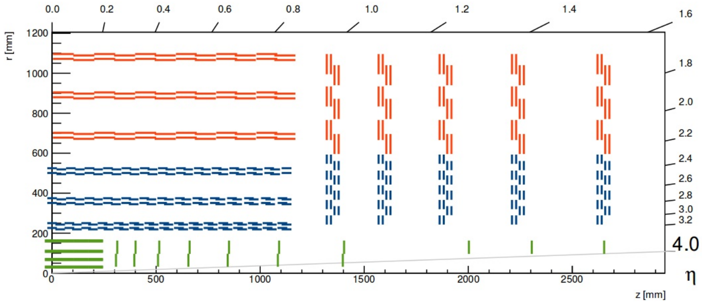


Simulated Event at PU=140 (102 Vertices)



Other developments: CMS @ HL-LHC tracking

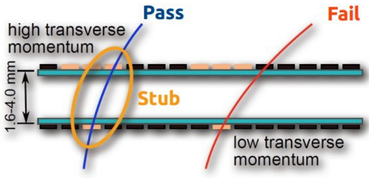
Layout of the CMS tracker for HL-LHC



- Pixels: 4 barrel layers and 10 forward/backward disks
- Pixel-strip (PS) modules: 3 barrel layers and 5 forward/backward disks
- Strip-strip (2S) modules: 3 barrel layers and 5 forward/backward disks

Other developments: CMS @ HL-LHC tracking

Stacked sensors for triggering



- Want to exploit the stacked geometry for full offline reconstruction
- Reconstruct **Vector hits** from position measurements
- PS modules: 2 precise coordinates, 1 precise direction
- 2S modules: 1 precise coordinate, 1 precise direction
- Precision depends on stack separation
- Rough estimate of curvature possible

Other developments: CMS @ HL-LHC tracking

Track finding with vector hits

- Preliminary study for WIT 2012, simplified simulation
- Have begun to set up a full simulation
- Will explore several algorithms:
  - Convergent Hough transform
  - Cellular Automaton
  - Artificial Retina
  - Combinatorial Kalman filter
  - . . .

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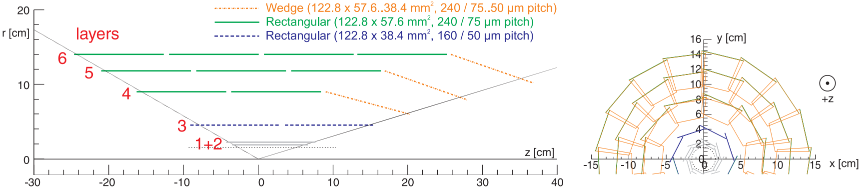
Other developments: Belle II track finding

VXD — Vertex Detector

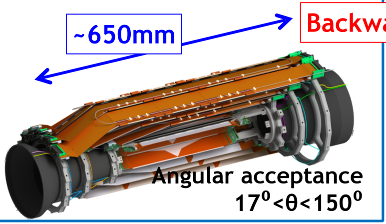
- VXD consists of two parts
- **SVD** (Silicon Vertex Detector) with 4 layers of double-sided Si strip sensors
- **PXD** (Pixel Detector) with two layers of DEPFET pixel sensors



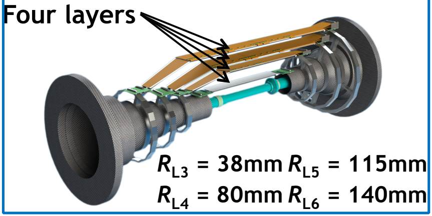
Other developments: Belle II track finding

SVD structure

SVD cut model



Layer structure



Other developments: Belle II track finding

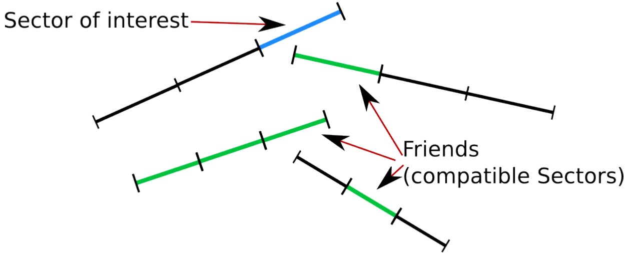
SVD stand-alone track finding

- Want to find low p_{T} tracks
- Needed for data reduction in the PXD, has to run in HLT
- Only 4 layers, little internal redundancy $\rightarrow$ **prior information** required
- Combinatorics reduced by precomputed **sector map**
- Several sector maps for different momentum ranges allowed

Other developments: Belle II track finding

Sector map

- Sensors are sub-divided into sectors
- Each sector knows its **friend** sectors
- Sectors are friends if a track from the vertex can pass through both of them
- Hits are sorted into sectors



Other developments: Belle II track finding

Segment finding

- **Segments** are pairs of hits in friend sectors
- Sector map decides whether segment is accepted (2-hit filter)

Tracklet finding

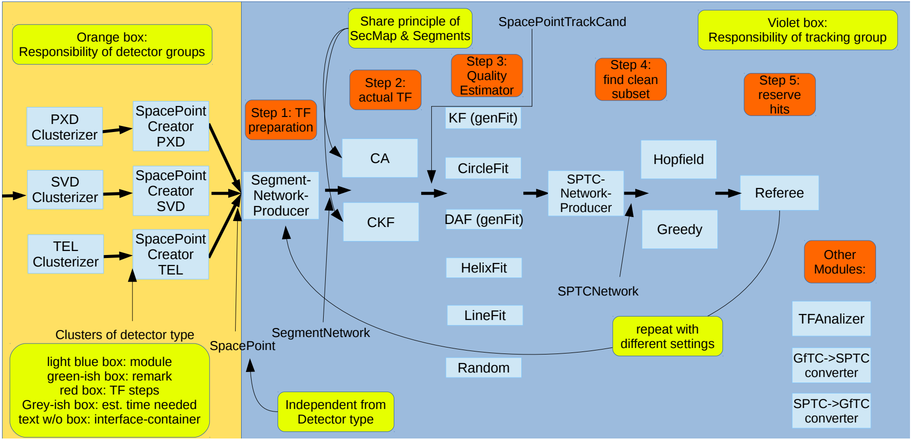
- **Tracklets** are pairs of segments sharing a hit
- Sector map decides whether tracklet is accepted (3-hit filter)
- Cut-based at the moment, will be supplemented by a NN

Track finding

- **Cellular Automaton** connects tracklets to **track candidates**
- **Quality estimation** by fast circle/helix fit or full KF track fit
- **Hopfield network** selects best non-overlapping set of track candidates
- Extrapolate to PXD and define **regions of interest**
- Alternatives are envisaged, e.g. **combinatorial Kalman Filter**, 4-hit filters

Other developments: Belle II track finding

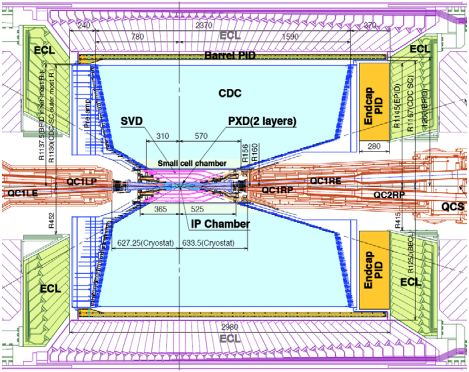
Overview of SVD track finding



Other developments: Belle II track finding

CDC — Central Drift Chamber

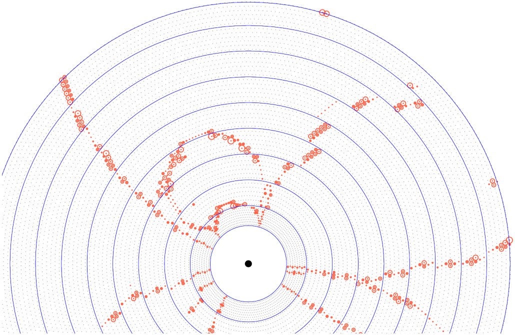
- 56 concentric layers in 9 super layers, alternating axial and stereo
- 14336 drift cells with sense wires in approximate hexagonal arrangement



Other developments: Belle II track finding

Algorithms

- Cellular Automaton
- Legendre transform

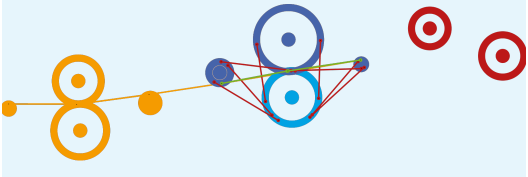


V. Trusov, Belle II Tracking Meeting Pisa 2014

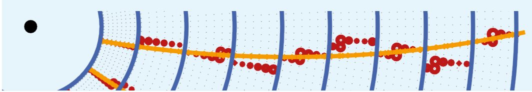
Other developments: Belle II track finding

Cellular Automaton

- Step 1: Build segments from individual hits in each super layer



- Step 2: Build tracks from segments

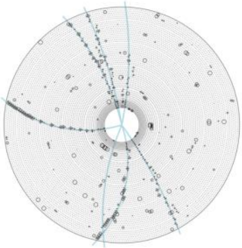


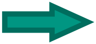
O. Frost, CHEP 2015

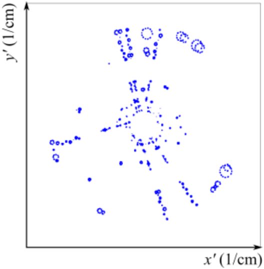
Other developments: Belle II track finding

Legendre transform

- Extension of Hough transform
- **Conformal mapping** transforms tracks to straight lines, drift circles remain circles



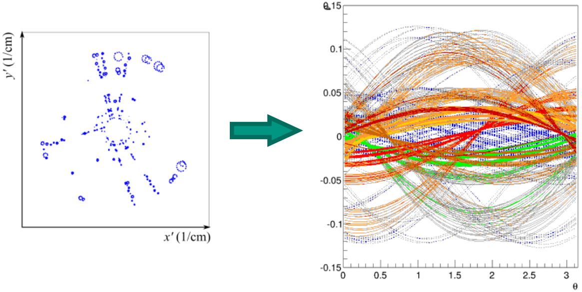




V. Trusov, Belle II Tracking Meeting Pisa 2014

Other developments: Belle II track finding

- Legendre transform: drift circles to **sine curves**
- An intersection of sinusoids in Legendre space corresponds to a **common tangent** to drift circles
- Legendre space is discretized, maxima found by **voting algorithm**
- Voting implemented by **QuadTree**

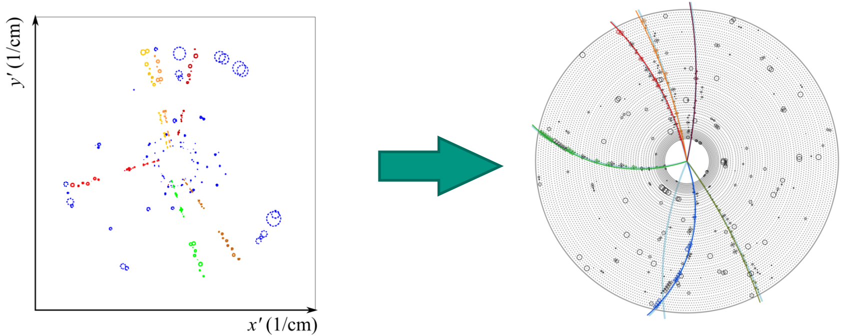


V. Trusov, Belle II Tracking Meeting Pisa 2014

Other developments: Belle II track finding

Example event

- Simulated event: $B^- \to D^0 (\to K^- \pi^+) \pi^-$ + beam background



V. Trusov, Belle II Tracking Meeting Pisa 2014

Other developments: Belle II Track merging and fit

Track merging

- Extrapolate tracks from CDC into VXD
- Extrapolate tracks from VXD into CDC

Final track fit

- Least-squares fit with **GENFIT** package
- Can be done for several mass hypotheses

GENFIT

- **Detector independent** fitting package, detector description is Geant4 geometry/material
- **Various propagators**: analytical, Runge-Kutta, others can be implemented by the users
- **Various methods**: Kalman filter, deterministic annealing filter, general broken lines fit
- **Very flexible**: accepts hits on plane sensors (pixels/strips), wires with drift circles, other geometries can be implemented by the users
- Easy to **interface with MillePede**

Outline

1 Developments for LHC Run 2

2 Real-time Tracking

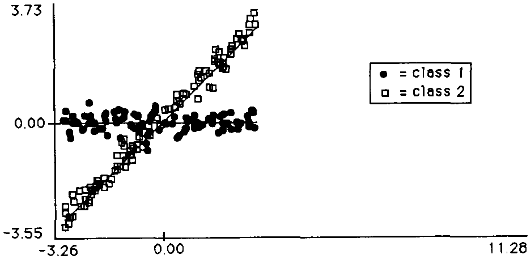
3 Other developments
- CMS @ HL-LHC
- Belle II
- Fuzzy c-regression

4 Summary and outlook

Other developments: Fuzzy c-regression

Basics

- Starting point is an unlabeled mixture of regression models
- Fuzzy c-regression (FCR) is a method for simultaneous fuzzy labeling and estimation of the regression models, see [?]
- Solution is obtained by an iterative procedure, similar to EM algorithm

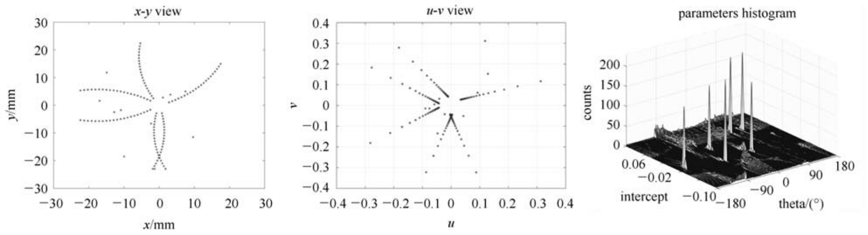


Niu Li-Bo, Chinese Physics C Vol. 39, No. 3 (2015)

Other developments: Fuzzy c-regression

Application to tracking

- Conformal transformation transforms circles to straight lines
- Initial number of tracks and initial values of angle and intercept from 2D Hough transform
- Run FCR on all hits in the *u*-*v* plane

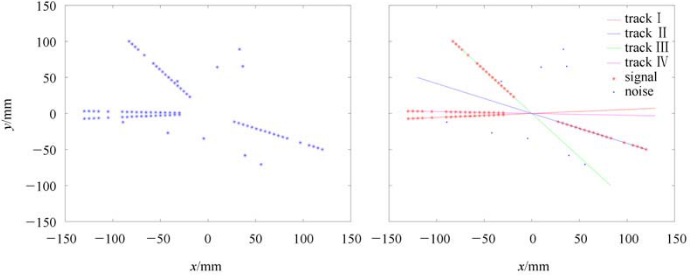


Niu Li-Bo, Chinese Physics C Vol. 39, No. 3 (2015)

Other developments: Fuzzy c-regression

Simulated example

- Prototype TPC for ILC
- 21 measurements between 30 mm and 130 mm
- Spatial resolution $\sigma = 100\,\mu m$
- Hit efficiency 90%
- Artificial noise added

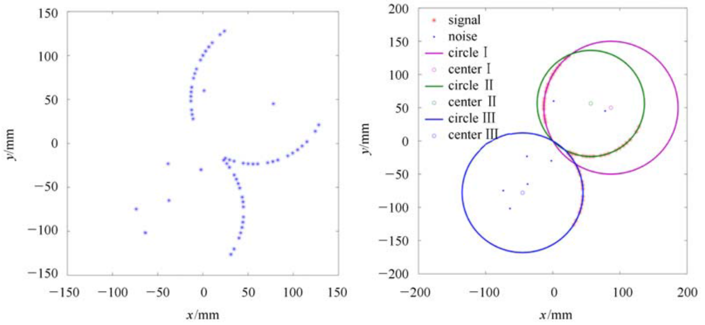


Niu Li-Bo, Chinese Physics C Vol. 39, No. 3 (2015)

Other developments: Fuzzy c-regression

Extension to circle finding

- A circle fit in the plane can be transformed to fitting a plane in 3D by projection to the Riemann sphere or a circular paraboloid
- FCR can be used to fit all planes/circles simultaneously



Niu Li-Bo, Chinese Physics C Vol. 39, No. 3 (2015)

Other developments: Fuzzy c-regression

How useful is it?

- Depends heavily on a good initialization of the regression models
- Remains to be seen whether useful for high track multiplicity

Outline

1 Developments for LHC Run 2

2 Real-time Tracking

3 Other developments

4 Summary and outlook

Summary and outlook

Improvements for Run2

- Basic approach of **iterative seeding** and **track following** still feasible
- Accumulation of “small” changes can have a **big impact**
- **Correct treatment of pixel clusters** essential for efficiency and resolution in narrow jets

Real-time tracking

- Requires **hardware beyond CPU**: GPU, Associative Memory, FPGA
- Code adapted to various types of hardware, **vectorized**, **parallelized**
- If correctly designed, bulk of code can still be **shared between on-line and off-line**

Summary and outlook

Vertex reconstruction

- **Iterative vertex finding** still feasible in Run 2
- **Imaging algorithm** possible alternative
- Plan to study application of **model-based clustering** to vertex finding
  - Uses Bayesian paradigm
  - Can use prior information on number of vertices
  - Can use prior information on vertex distribution

Other topics

- See talks at “**Connecting The Dots**" workshop in Berkeley, Feb. 2015:

  https://indico.physics.lbl.gov/indico/conferenceDisplay.py?confId=149

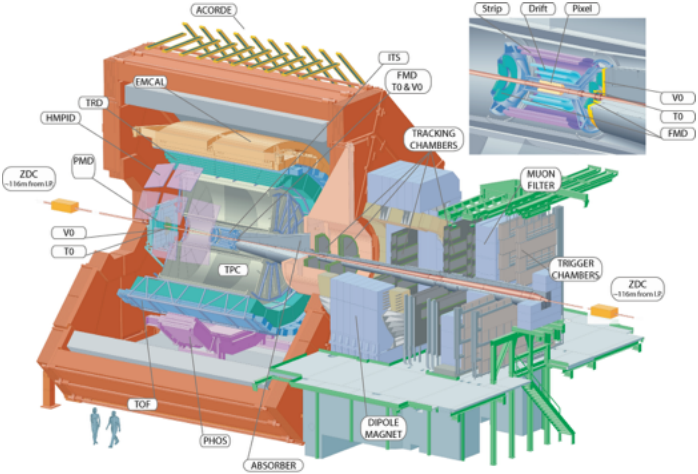
Summary and outlook

Thank you!

Bonus slides

Bonus slides: ALICE GPU Tracking

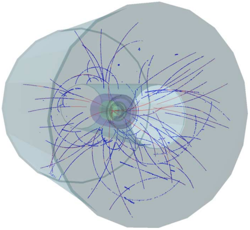
ALICE detector



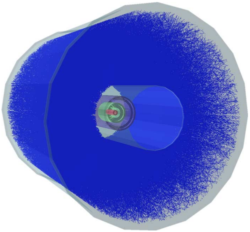
Bonus slides: ALICE GPU Tracking

ALICE TPC

- Formidable tracking problem



A pp event (real data)



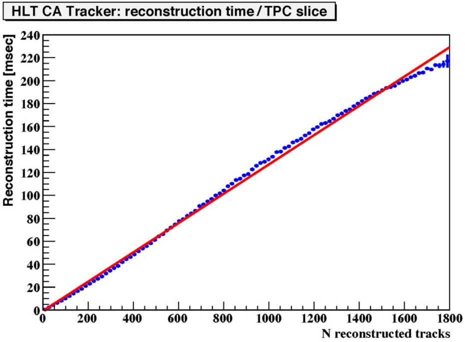
A heavy ion event (simulated)

S. Gorbunov et al., IEEE TNS 58 (2011)

Bonus slides: ALICE GPU Tracking

ALICE High-level trigger

- Full track reconstruction in HLT
- Based on Cellular Automaton approach
- Reconstruction time proportional to multiplicity

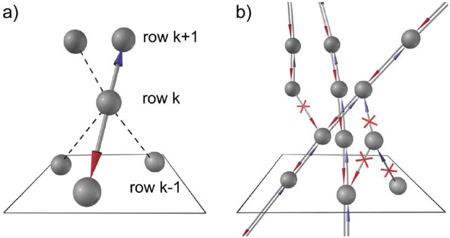


S. Gorbunov et al., IEEE TNS 58 (2011)

Bonus slides: ALICE GPU Tracking

Cellular automaton

- Combinatorial search for track candidates
- Unphysical hit combinations are eliminated at the local level
- Two steps
  a) **Neighbor finder**: For each hit in row *k*, search the best pair of adjacent hits; store the links of the three hits that form a straight line
  b) **Evolution step**: Reciprocal links are determined and saved, all the other links are removed



S. Gorbunov et al., IEEE TNS 58 (2011)

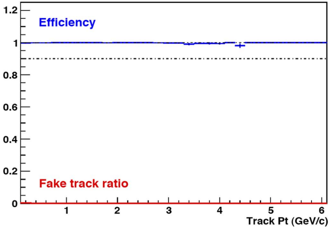
Bonus slides: ALICE GPU Tracking

Track finding and fitting

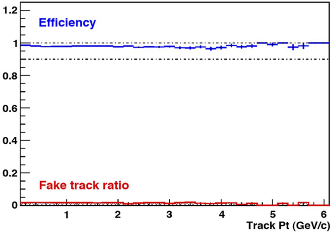
- Track finding: Track candidates are created by following the hit-to-hit links
- Track fit: The geometrical trajectories are fitted by a Kalman Filter, with a quality check
- Track extension: Track candidates are extended in order to collect hits close to the trajectory
- Track candidate selection: In case of overlaps select the longest track candidate
- Final quality check: Lower cut on number of hits and momentum

Bonus slides: ALICE GPU Tracking

➤ Efficiency and fake rate



pp collisions at 14 TeV

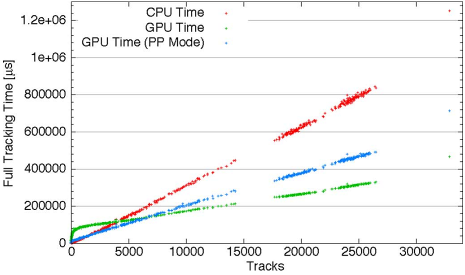


Central heavy ion collisions at 5 TeV

Bonus slides: ALICE GPU Tracking

Tracking on GPU hardware

- Code ported first to NVIDIA/CUDA, recently to AMD/OpenCL
- Only single precision calculations
- Numerically stable Kalman filter
- Dynamic scheduler, optimized memory layout



S. Gorbunov et al., IEEE TNS 58 (2011)