Experimental techniques in high-energy nuclear and particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

LECTURE 6b.

Tracking at LHC

Prof. Rino Castaldi
INFN-Pisa
rino.castaldi@pi.infn.it

Tracking: an increasing challenge

- Tracking at LHC is a very complex procedure due to the high track density. It needs specific implementation adapted to the detector type and geometry

- Precise and efficient detector modules are required to measure where the particle crossed the module

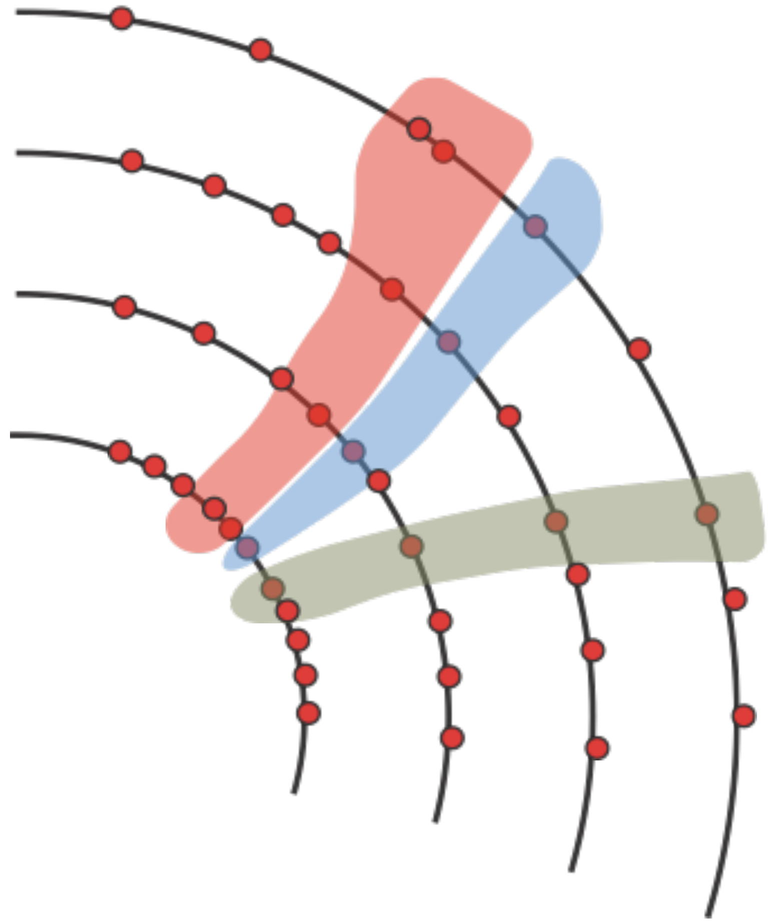
- Fast and radiation hard detectors and electronics are needed

- Track reconstruction requires specific software implementation:
  - track finding (pattern recognition)
  - estimation of track parameters (fitting)

- Precise alignment of detector modules is a prerequisite for efficient tracking

Pattern Recognition

▪The **main** goal of the pattern recognition is to **associate hits to tracks** (particle trajectories). It should be efficient (use of all hits) and robust (no noise or hits from other tracks)



Two approaches:
Global and **Local** pattern recognition

▪**Global methods:**
Template matching, neural network techniques, Hough space transform, …..
(Simultaneous consideration of all hits)

▪**Local methods (also called track following):**

Combinatorial Kalman filter updates the information (track parameters and error matrix) of candidates tracks along the track finding process and gives a precise prediction of the next point to be found. It is a progressive methods (boundary pattern recognition/track fitting vanished). Track fit became part of the track finding approach.

Track fitting

Process to estimate the kinematical parameters, such as position (or impact parameter), direction of flight and momentum of a particle starting from the measured hits which have been correctly identified in the pattern recognition step.

- ✓ **Multiple scattering effects and energy loss are taken into account in the track fitting procedure**
- ✓ **In general the fitting methods assume Gaussian errors**

Two approaches:

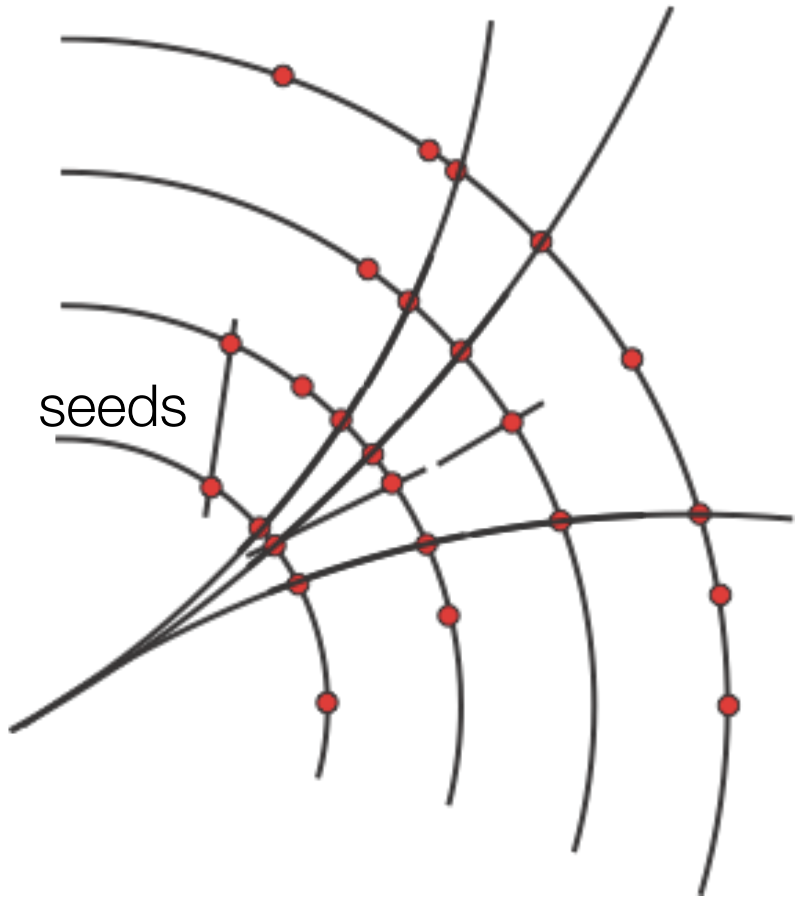
- ❑ **Least squares estimation**: requires the global availability of all measurements at fitting time
- ❑ The **Kalman filter technique**: proceeds progressively from one measurement to the next, improving the knowledge of the trajectory with each new measurement (**boundary pattern recognition/track fitting vanishes)**

Track finding / track fitting:
the combinatorial Kalman filter

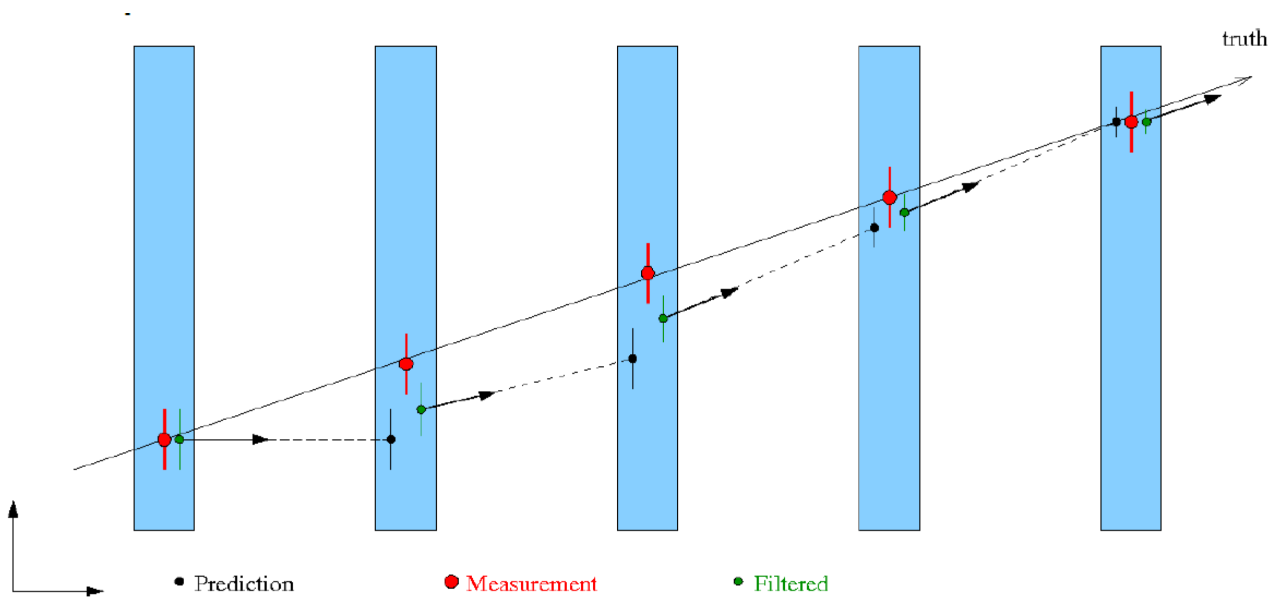
Progressive method: track fitting works simultaneously with track finding.

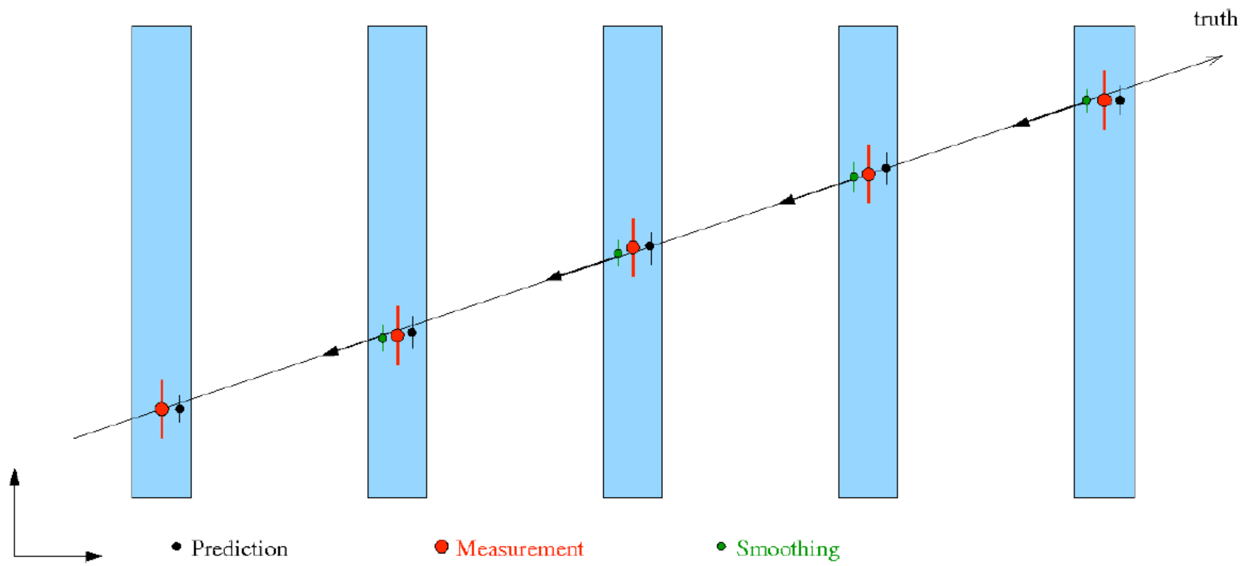
The Kalman Filter consists of a succession of alternating *prediction and filter steps:*

- ✓ As one example, in CMS track reconstruction is initiated by a *seeding* in the innermost tracker layers: both pixel and silicon strip hits.
- ✓ The system equation propagates the track state in one surface to the next.
- ✓ Accuracy on the track state estimate increases after each new measurement is added



Filtering and Smoothing





Is the Kalman Filter the last word?

- The Kalman filter is an optimal estimator of track parameters in case of
  - Unbiased measurements with Gaussian errors
  - Gaussian process noise (multiple scattering etc.)
  - No outliers (hits that don't belong to the track)

- Reaches its limits when underlying statistics are far from Gaussian. This problem is enhanced in electron fitting with plenty of material.

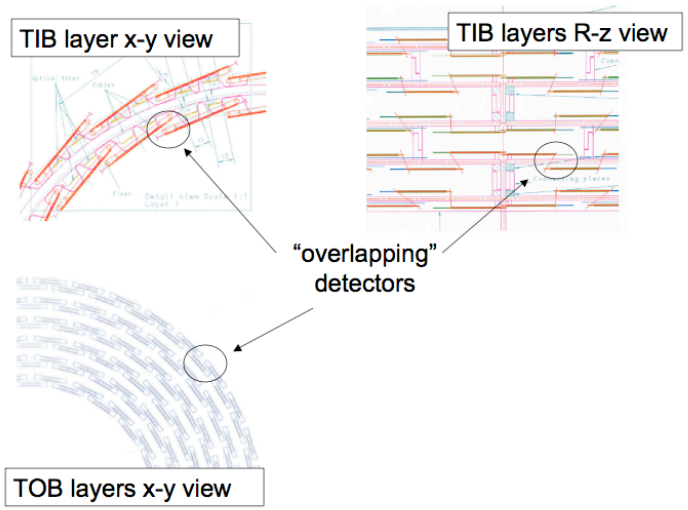
  Dense environment will also be a challenge for LHC reconstruction at full luminosity

- Non-Gaussian generalisations based on adaptive algorithms exist and are used:
  - Gaussian Sum Filter (GSF) Non-gaussian noise (energy loss) can degrade the fit seriously
  - Deterministic Annealing Filter (DAF) Ambiguous situation require more advanced treatment
  -
  -

Tracking

Each experiment needs specific software implementation adapted to the detector type and geometry to improve tracking efficiency.

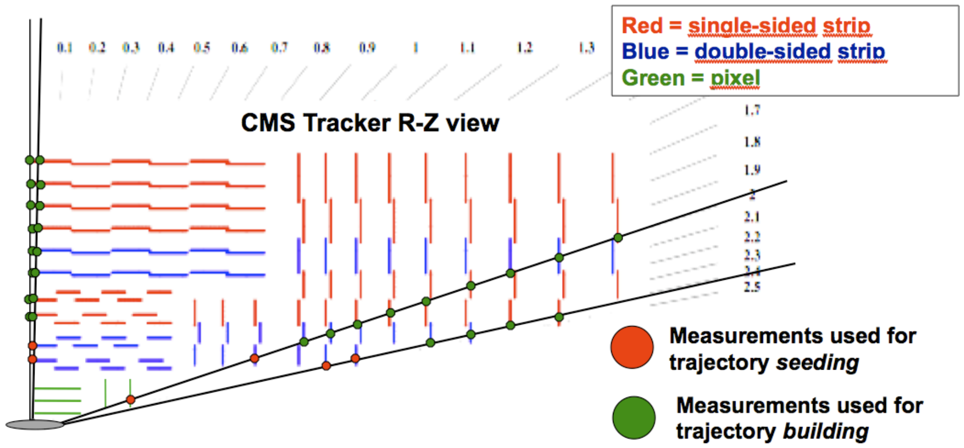
A couple of examples from CMS:



Overlapping modules in the same layer

Implementation obstacles:

- Because of the different design, each of the 6 Tracker sub-detectors involves different types of “overlaps”.
- Sorting of hits along the trajectory is not trivial.
- Track parameters are “updated” on each layer with the information provided by a track segment (instead of a point).



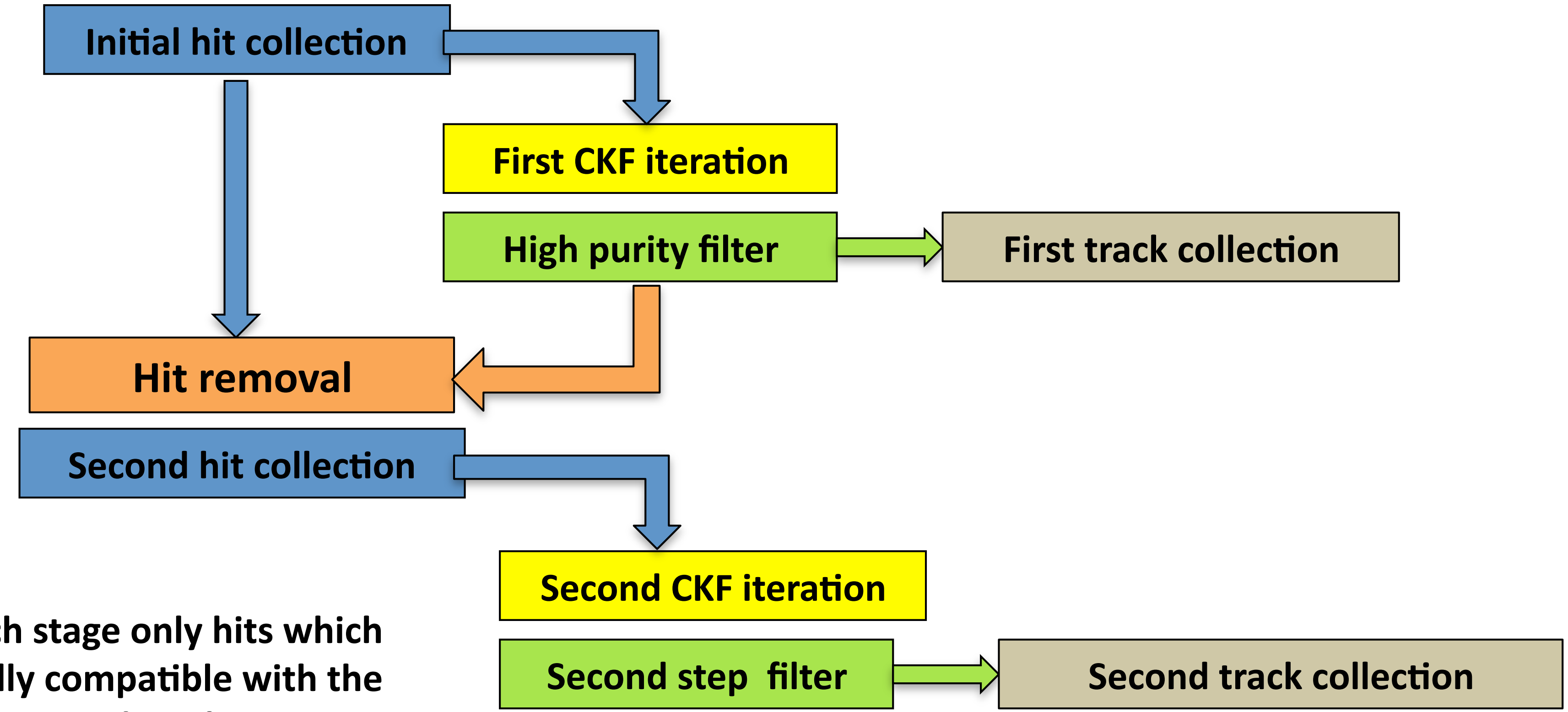
Inefficiency due to pixel-based seeding

Compared to the pixel-only seeder, the new implementation had to cope with:

- position measurements with uncertainties spanning more than order of magnitude.
- sensors with 4 different topologies arranged on 4 different types of “layers”.
- material budget in between Tracker sub-detectors had to be optimally parameterized.

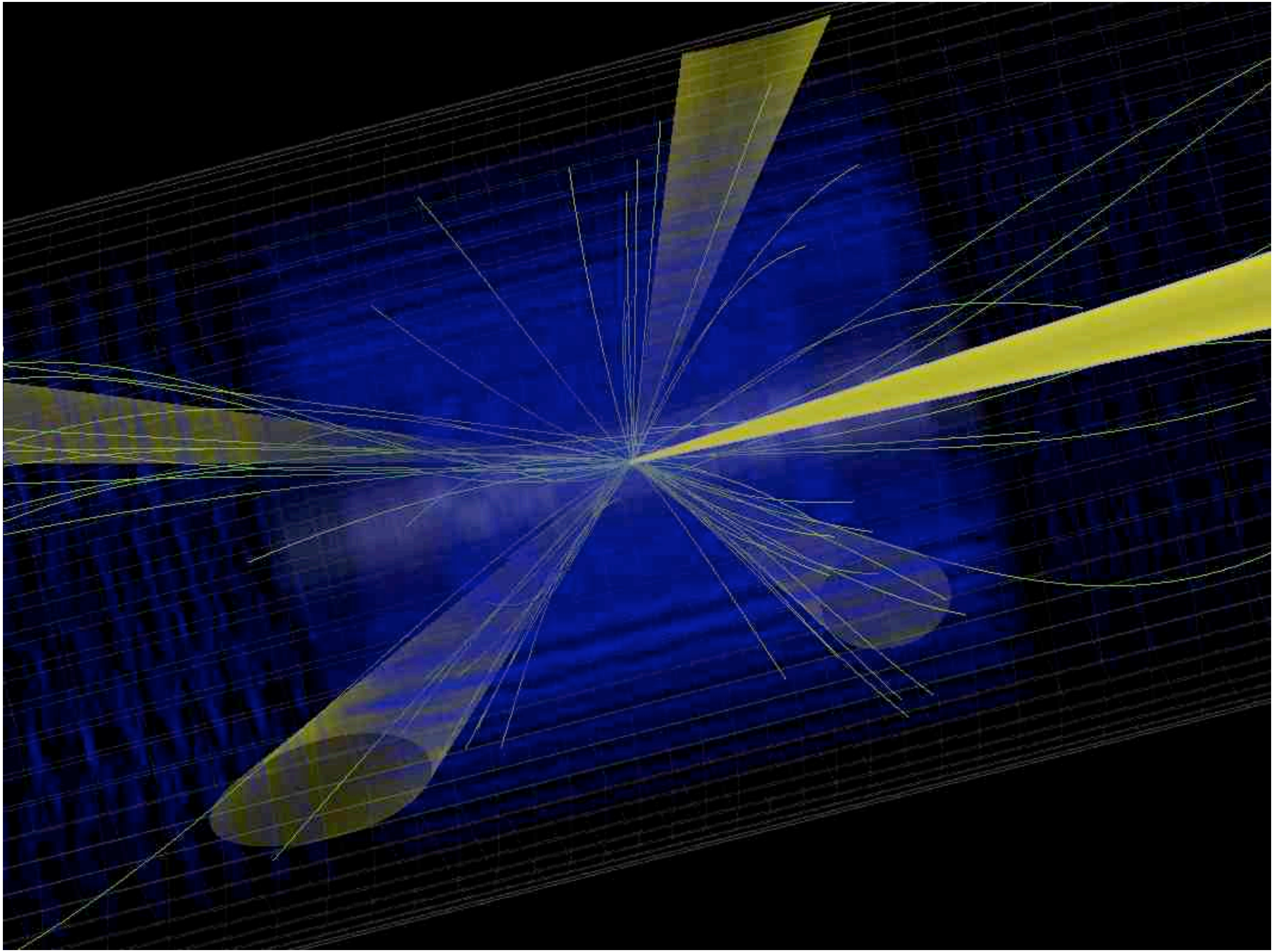
Iterative tracking

An *iterative procedure* performs the track reconstruction in stages, **running different times the CKF reconstruction**



At each stage only hits which are fully compatible with the reconstructed tracks are removed.

(higher fake rate level)



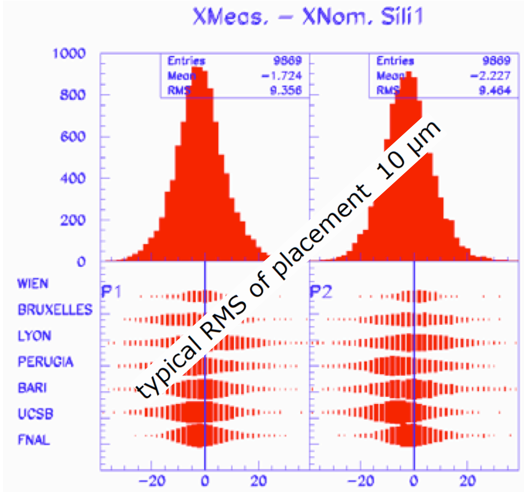
Tracking: an increasing challenge

- Tracking at LHC is a very complex procedure due to the high track density. It needs specific implementation adapted to the detector type and geometry
- Precise and efficient detector modules are required to measure where the particle crossed the module
- Fast and radiation hard detectors and electronics are needed
- Track reconstruction requires specific software implementation:
  - track finding (pattern recognition)
  - estimation of track parameters (fitting)
- Precise alignment of detector modules is a prerequisite for efficient tracking

Alignment

- Precise alignment of detector modules is a prerequisite for efficient tracking.
- must be well monitored during the construction process from single module assembly to final operation of the full tracking system

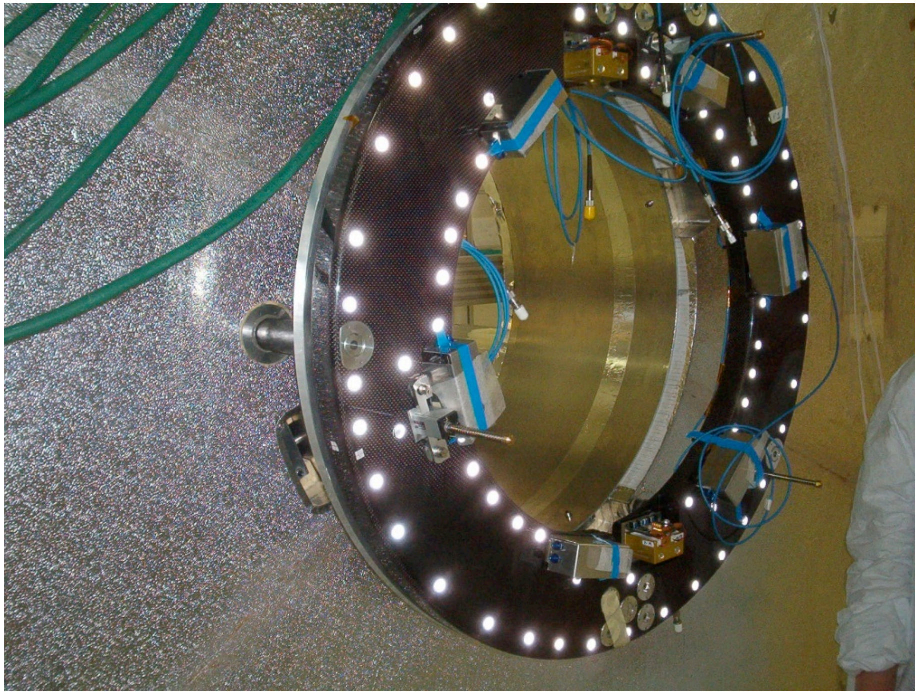
automated module assembly



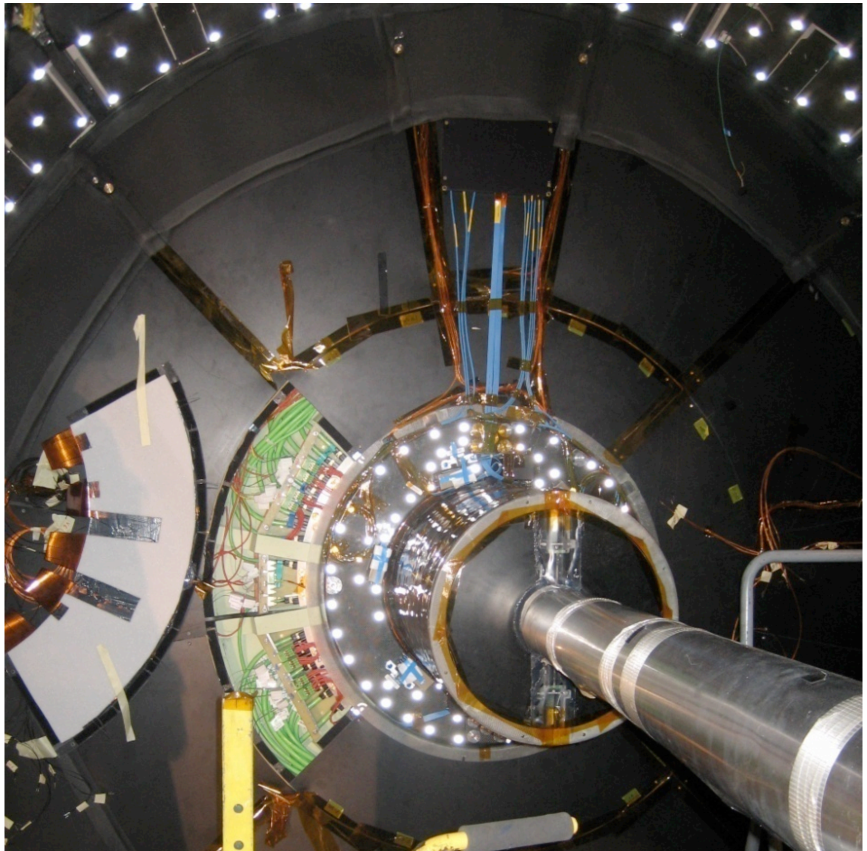
precise tooling and quality control measurements

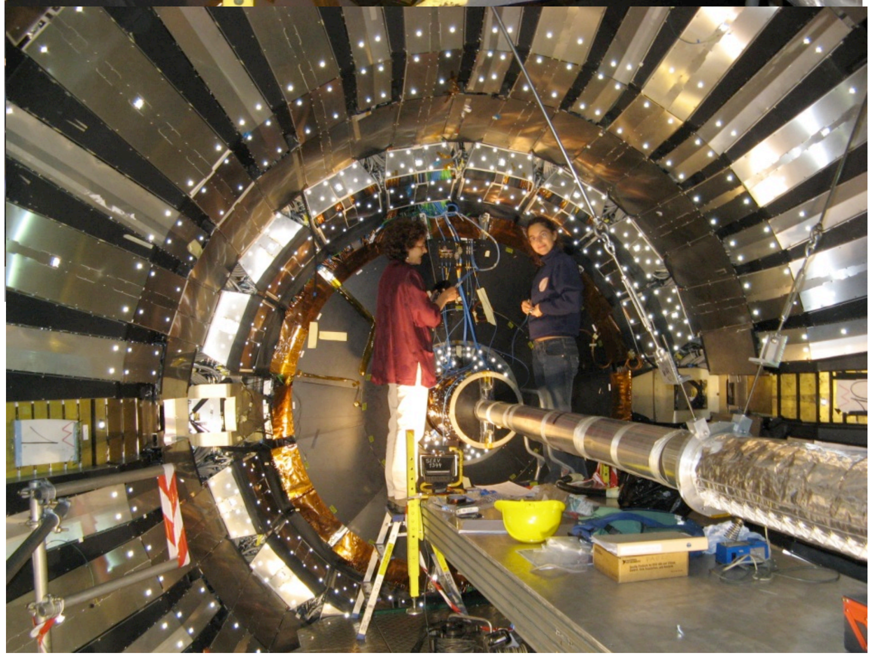
Survey and optical measurements

CMS Alignment rings



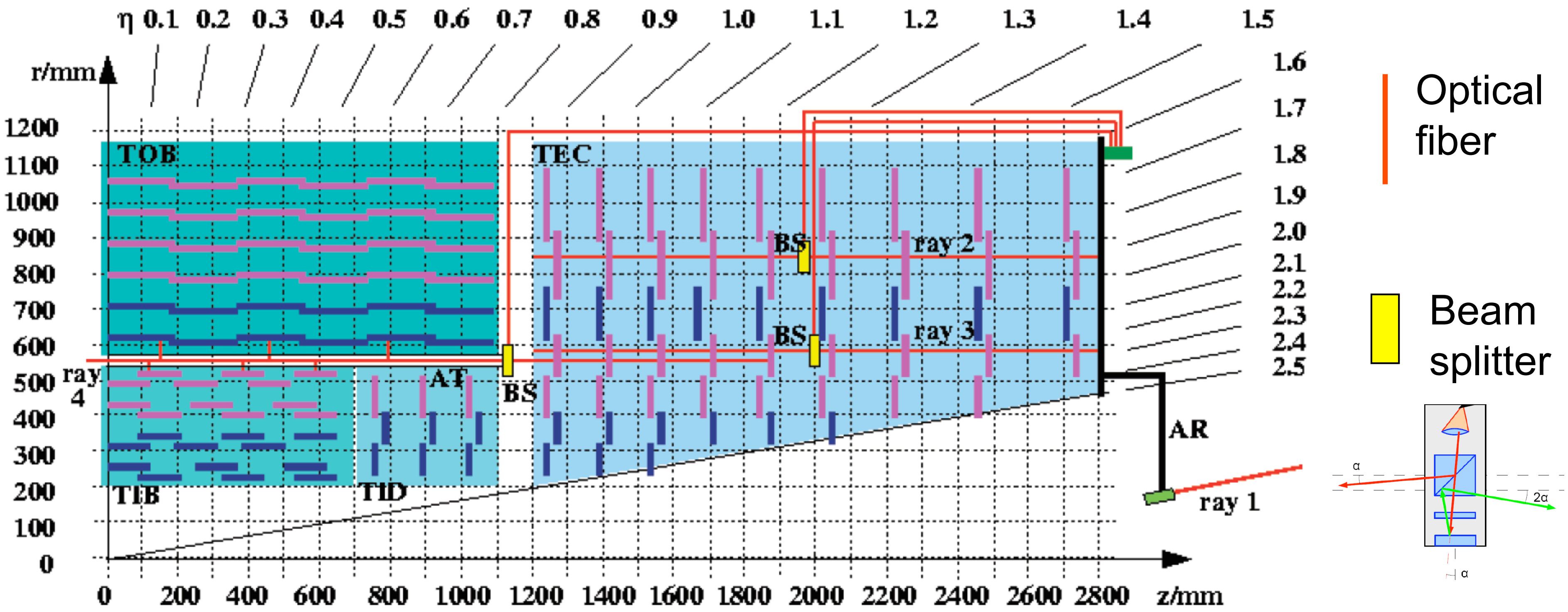
Installed in Endcap Tracker
end plates (precise mechanical mounts)





Optical alignment / monitoring

CMS Si Tracker: Laser Alignment System

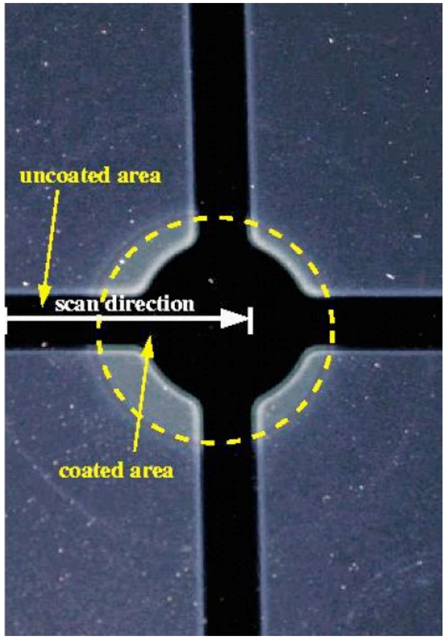


2 x 8 beams for internal alignment of each Endcap
8 beams to align subdetectors (Inner/Outer Barrel and Endcaps)

- LAS operates globally on tracker substructures: TIB, TOB and TEC discs. It does not attempt to determine the position of individual modules
- Laser measurements can be performed during physics data-taking
- Relative position monitoring of global tracker structures with a precision of ~100 μm (needed to start track reconstruction)

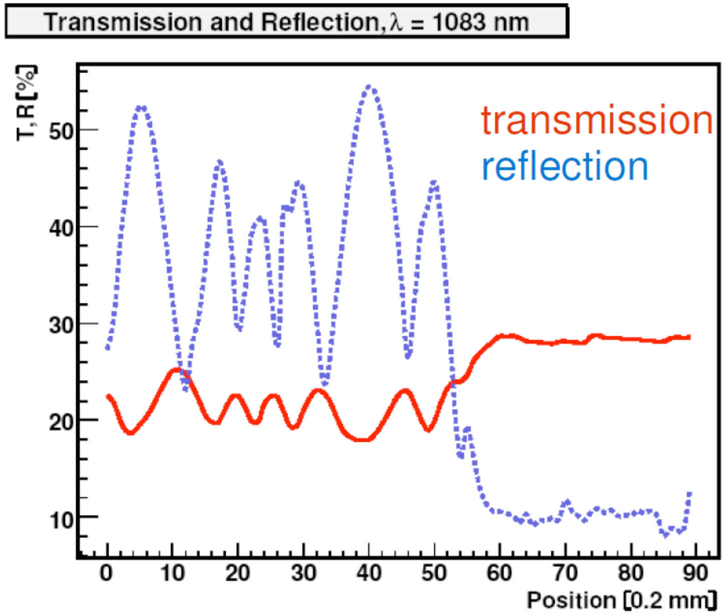
CMS Silicon Tracker

Silicon is semitransparent to infrared light (laser pulses λ ~1080 nm)



Sensor treatment:

- Silicon sensors polished on both sides
- ~ 10 μm hole in backplane metallization
- Antireflective coating on backside: improves transmission and reduces multiple reflections, interference, and distortions of the beam profiles
  No antireflective coating on strips due to effects on interstrip capacitance

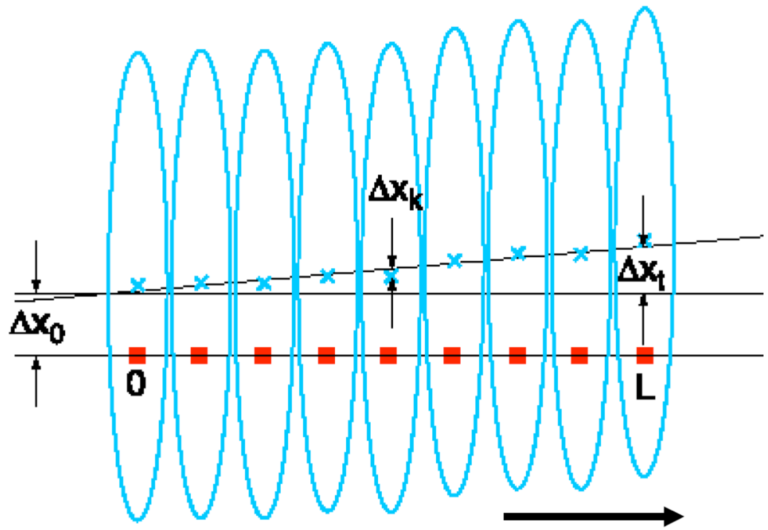


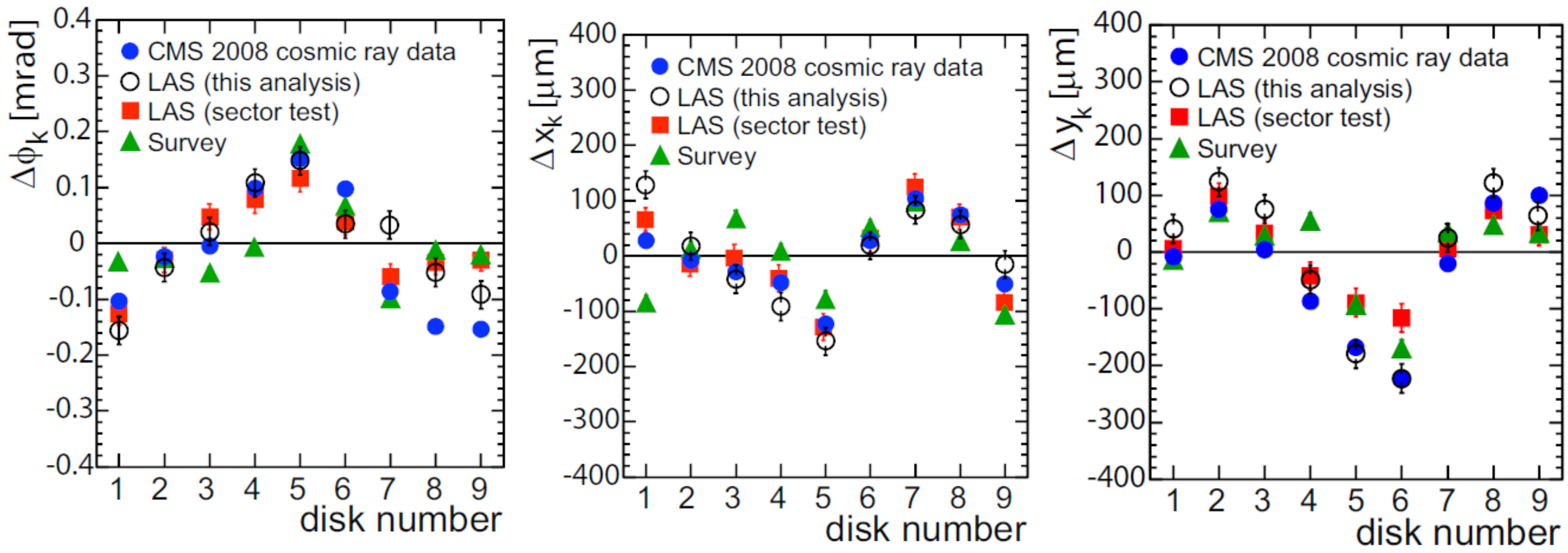
Laser intensity adjusted for each layer to obtain an optimal signal-over-noise ratio. Accumulate several "laser events"

CMS Tracker Endcap Alignment

Separate collective movements from individual disc movements

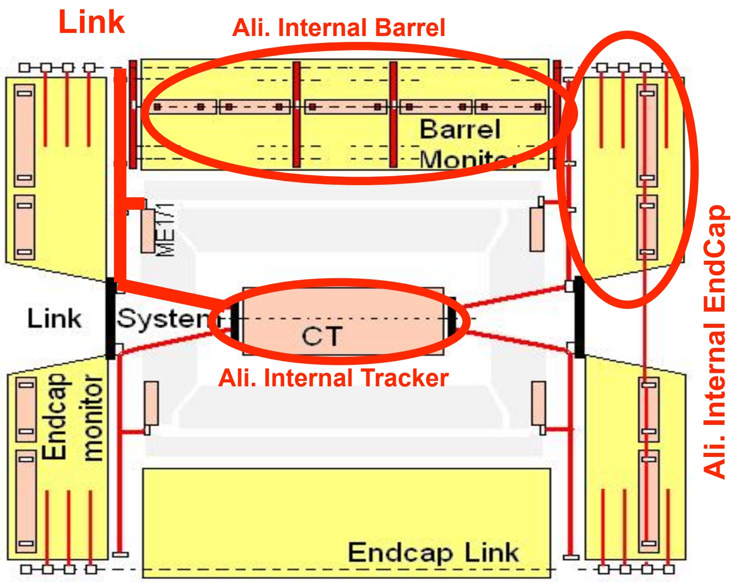
Overall TEC movement Δx_0
Overall TEC skew Δx_t

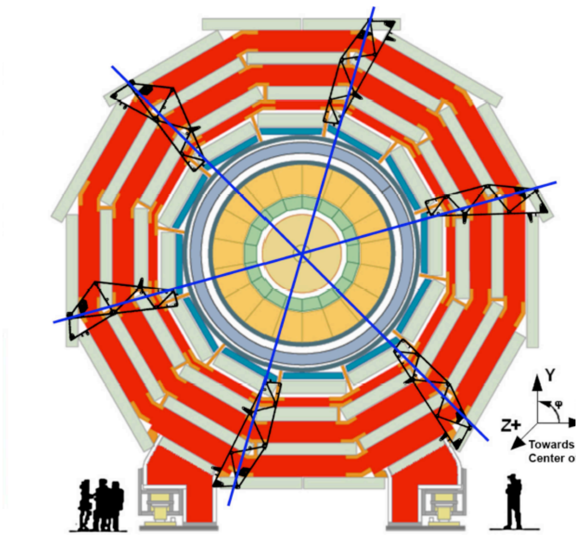


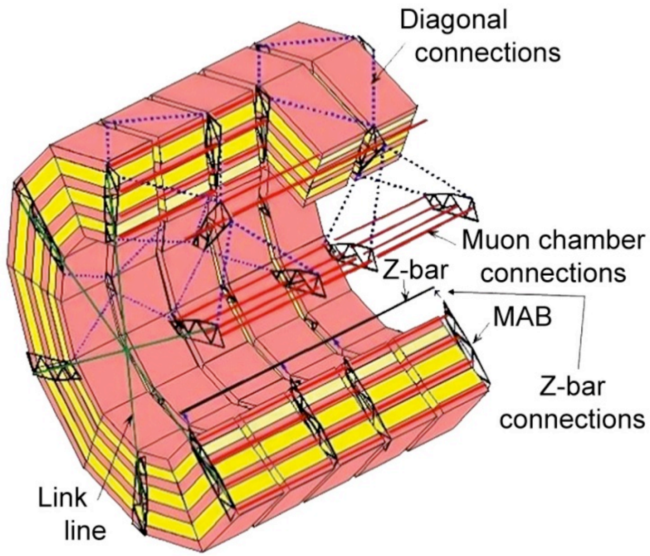


CMS Alignment System

Tracker internal alignment and monitoring the muon chambers relative positions (barrel and endcap) with respect to the tracker.

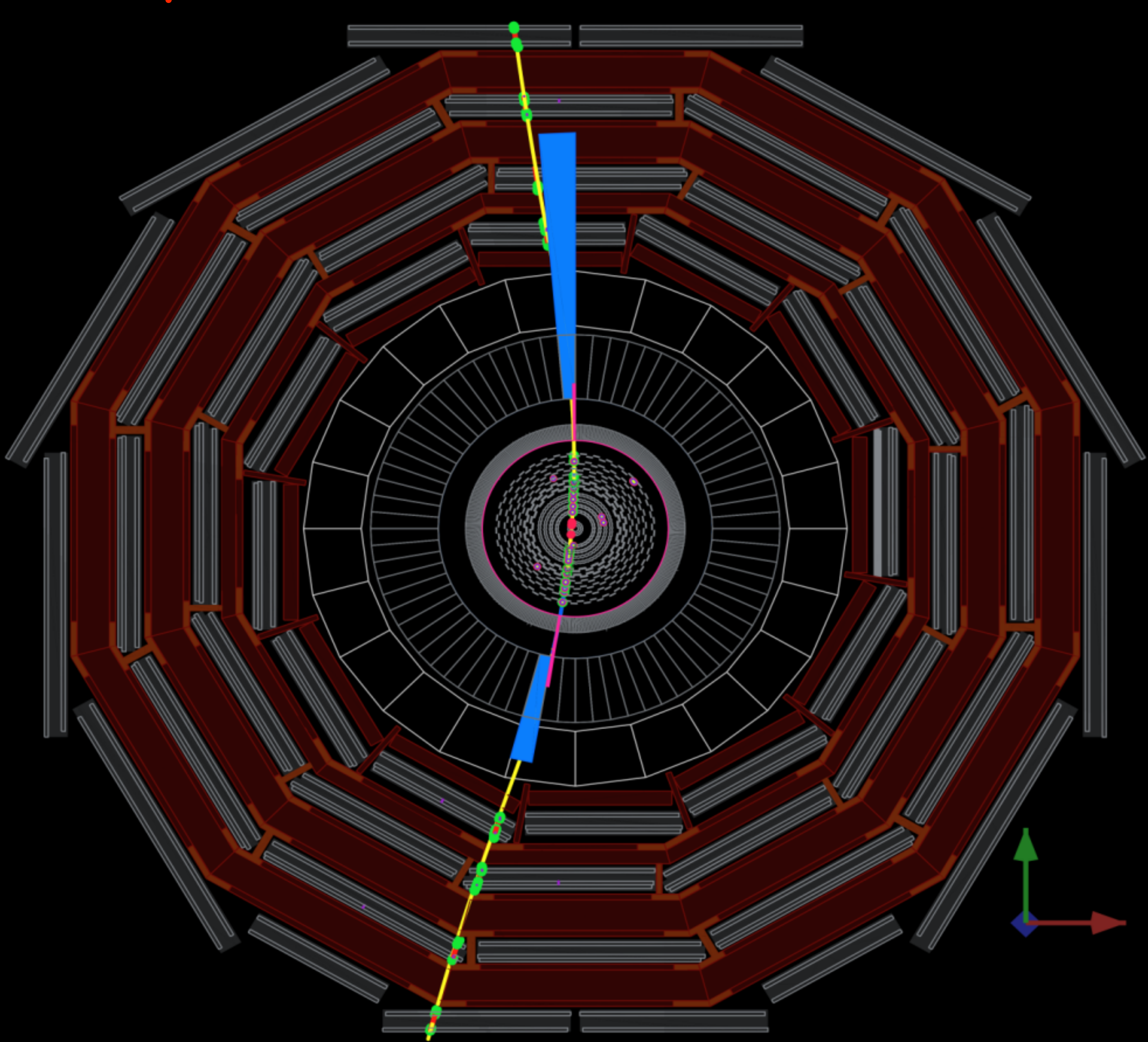




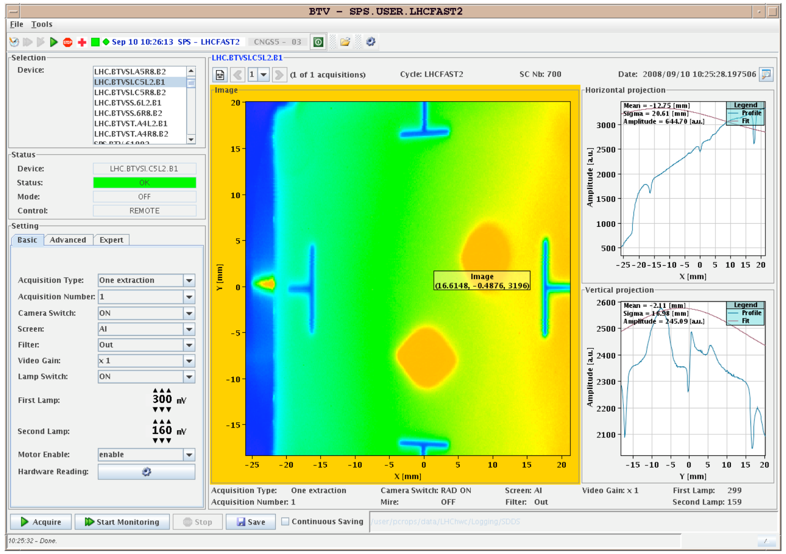


Muon align components:
Light sources: 10000 LEDs + 150 lasers.
~900 Photosensors + ~ 600 analog sensors (position, tilt sensors)
Temperature, humidity and Magnetic probes
→ ~ 30000 parameters in the geometrical reco.

After installation in 2008 precise alignments were done by all experiments with millions of cosmic muons

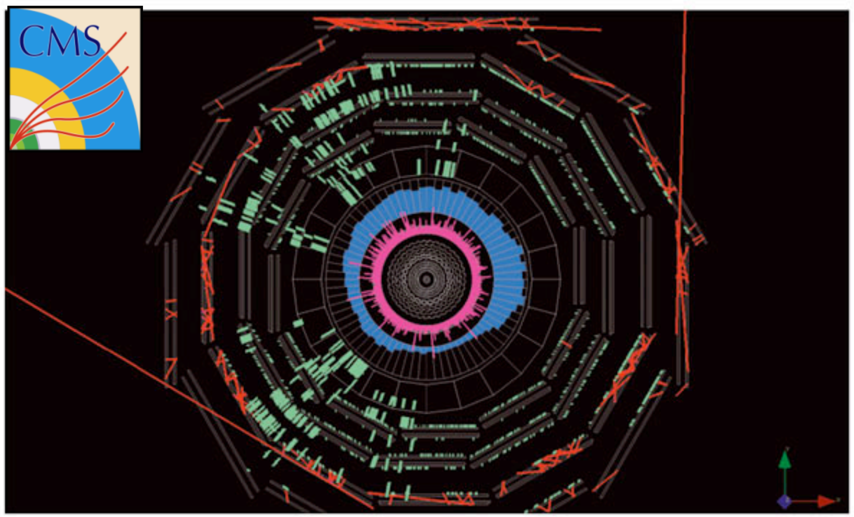


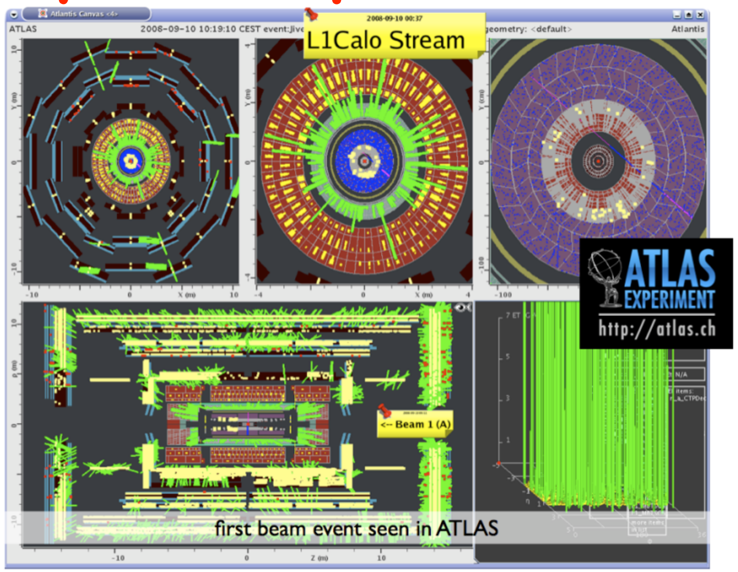
10 September 2008:



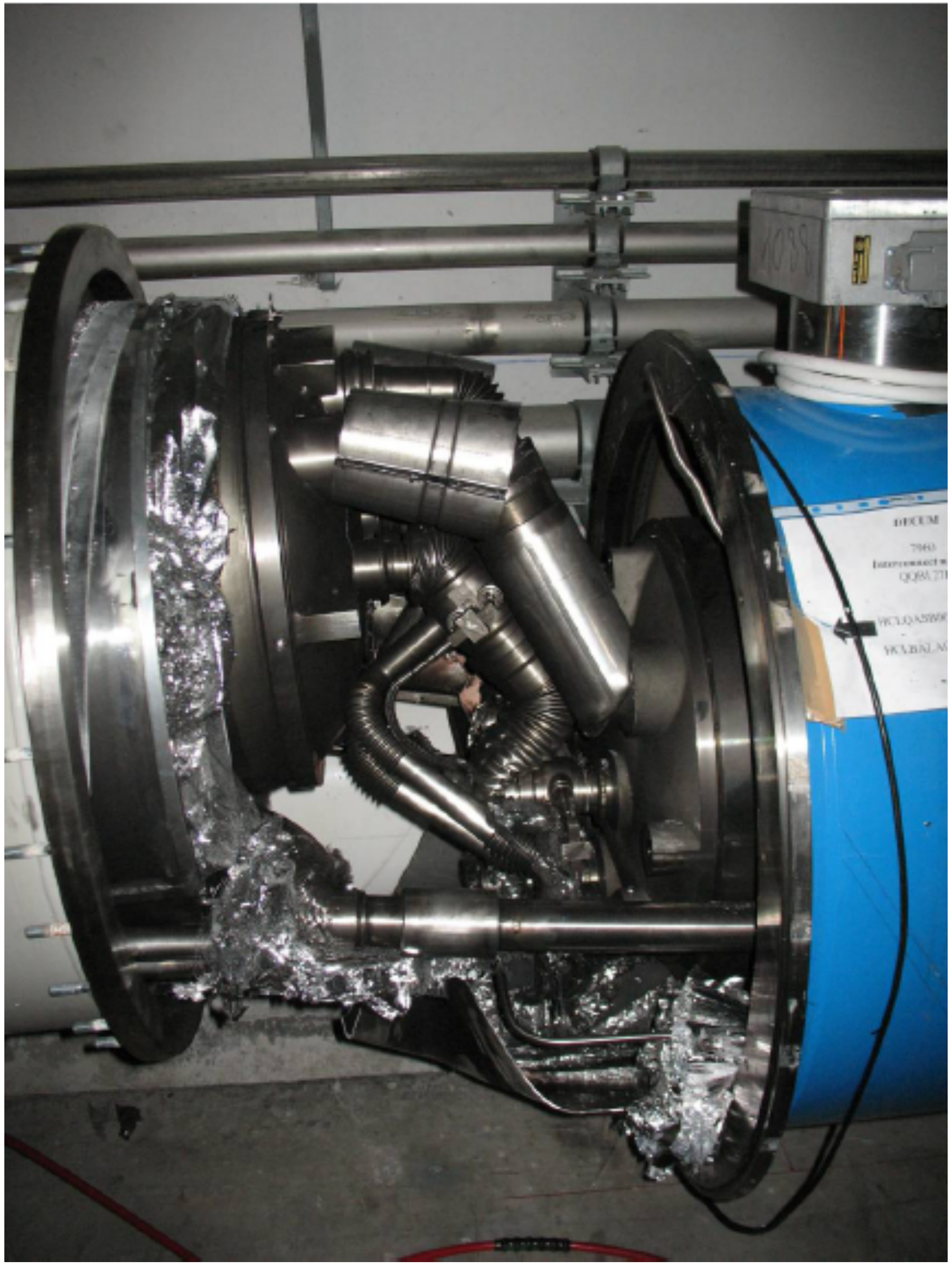
The first LHC beam !

First splash events seen by the experiments

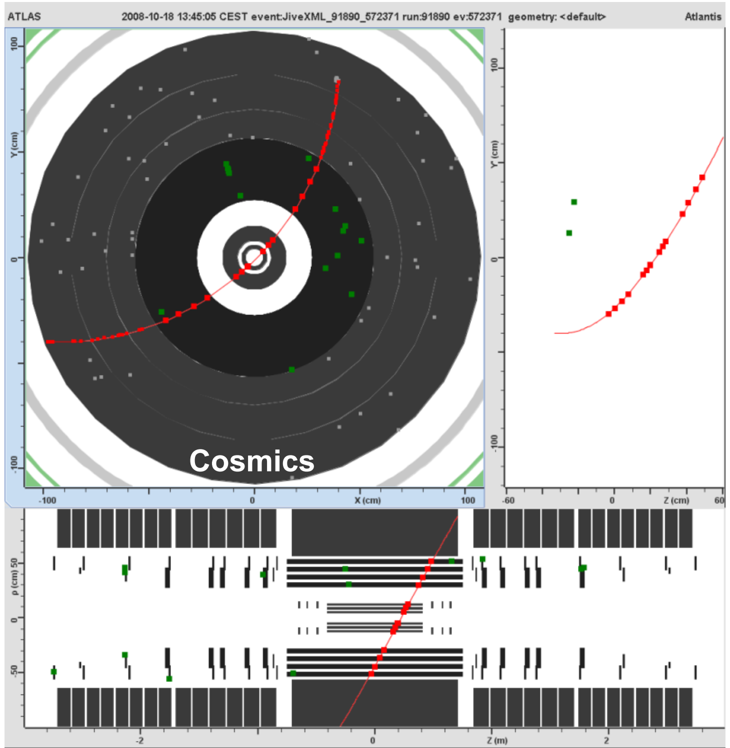




19 September 2008 ….

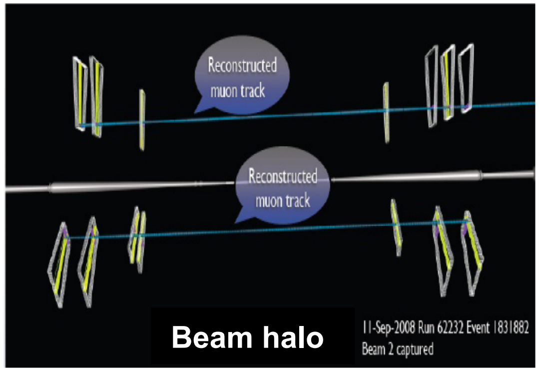


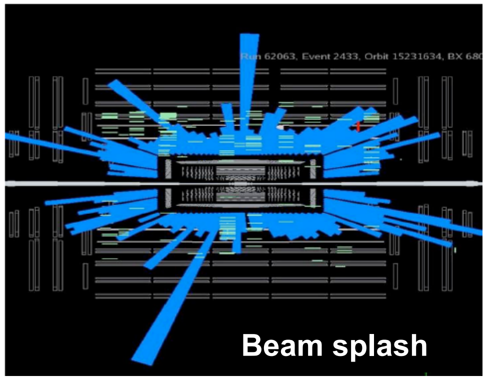
Another full year (2008+2009) for commissioning with Cosmics



- ✓ **Alignements**
- ✓ **Calibrations**
- ✓ **Timing**
- ✓ **Studies of magnetic field**

+

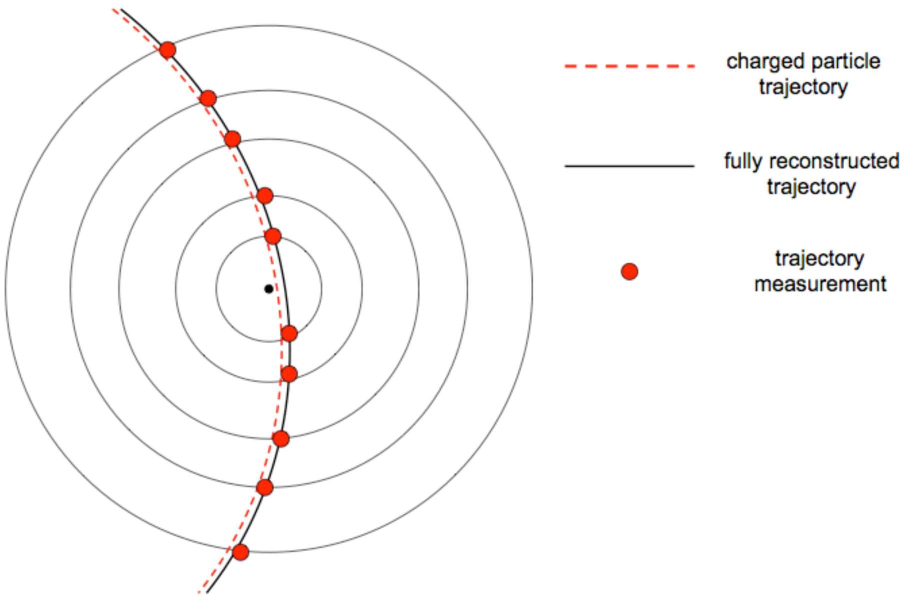


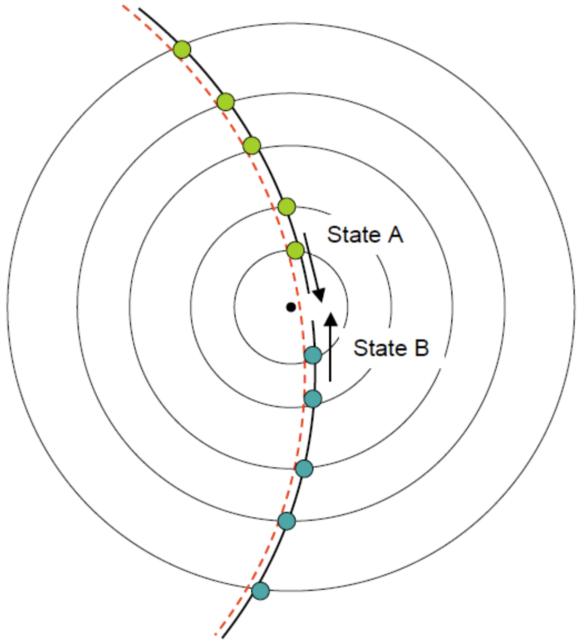


Reconstruction of Cosmic ray data

Cosmic rays data have been very useful to align the tracking detectors before the LHC start-up.

Data with magnet on can also be used to evaluate the resolution of the momentum measurement.

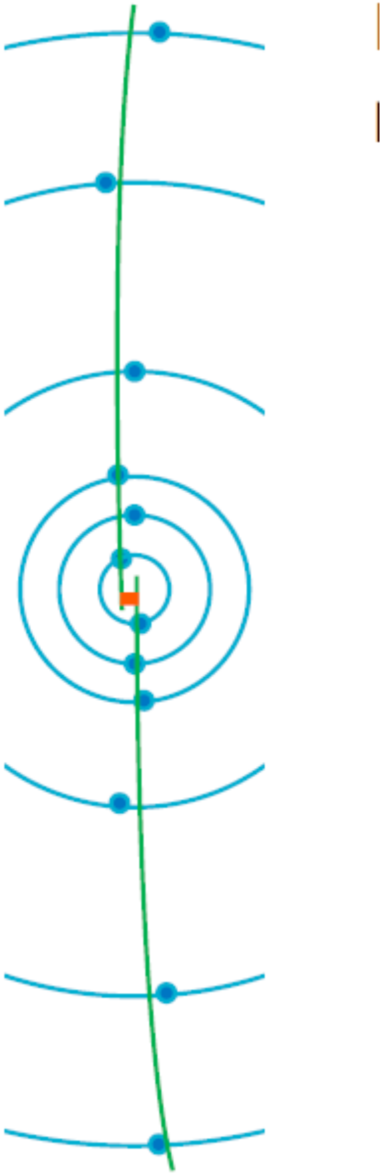


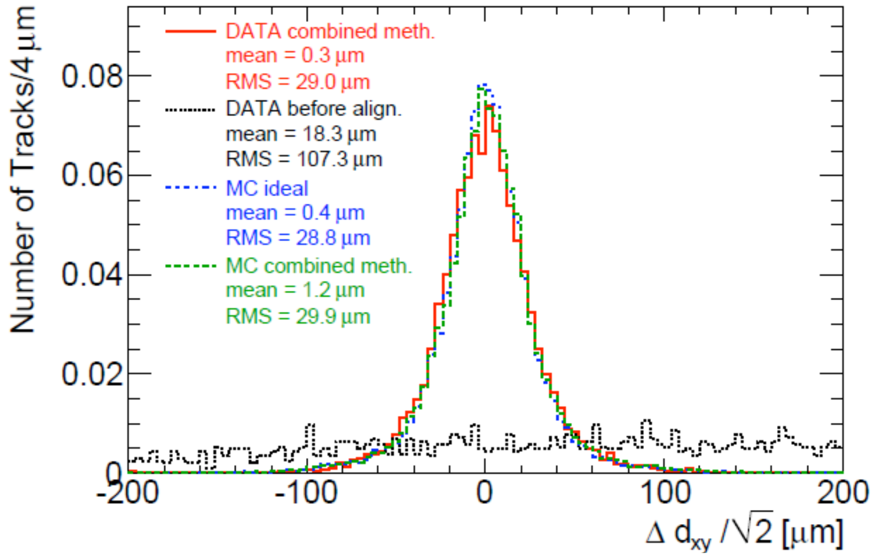


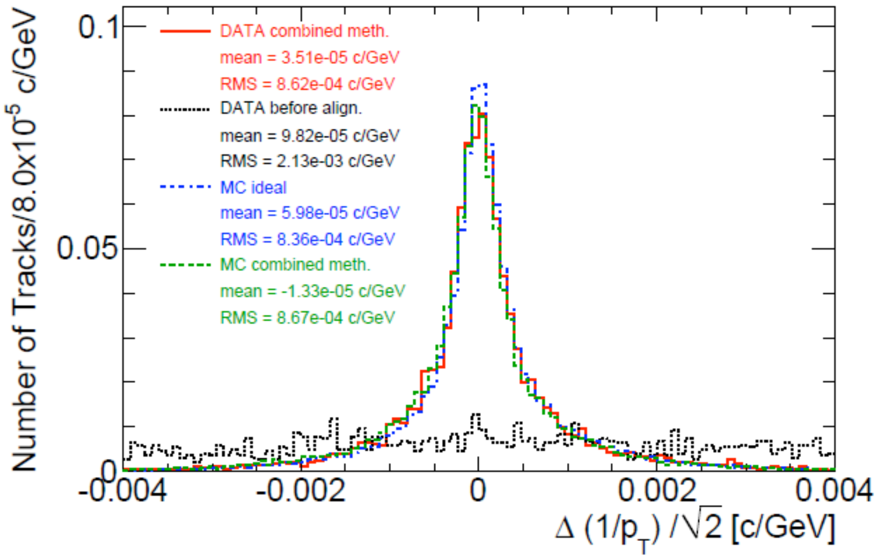
Cosmic rays have the special feature of crossing the Tracker volume on both hemispheres: The same particle is *reconstructed twice.*

The distribution of the difference of the momenta of the 2 tracks is an estimation of the resolution of the momentum measurement itself.

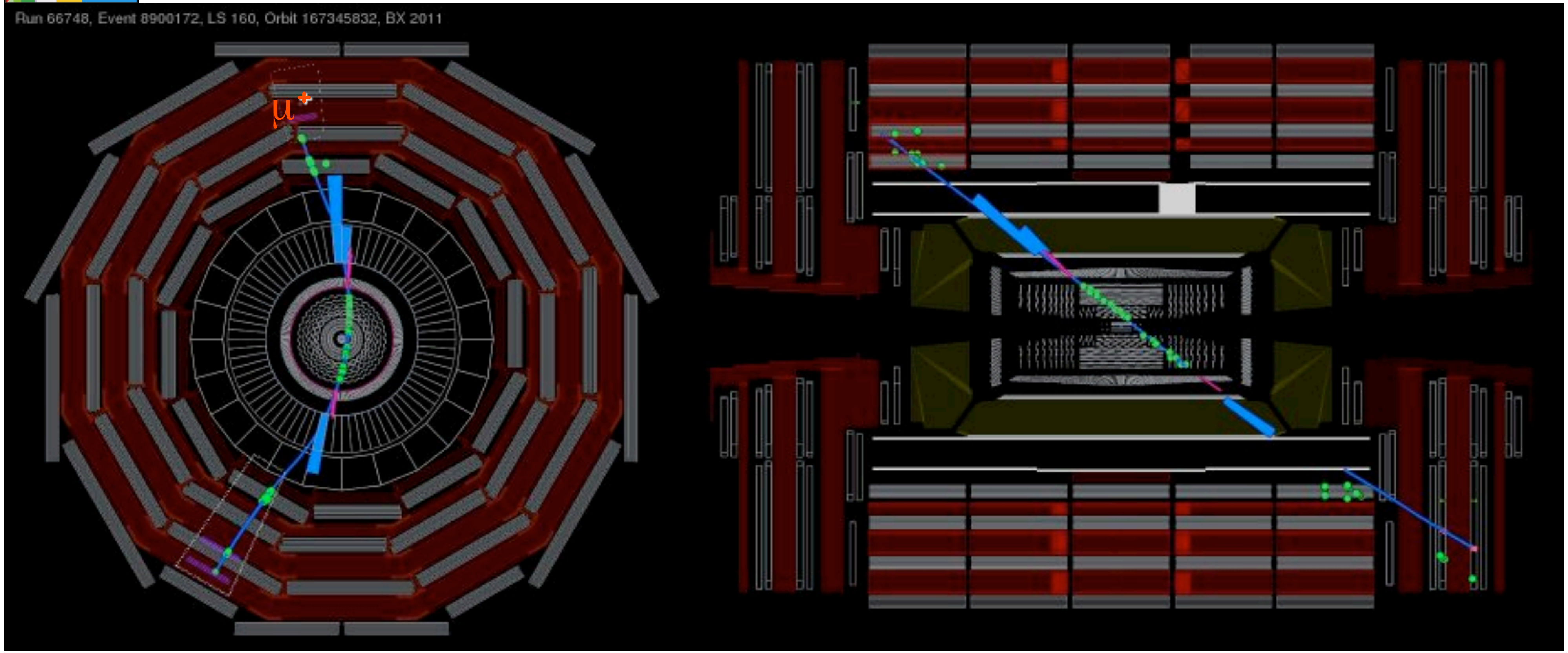
Results with Cosmics (CMS as example)

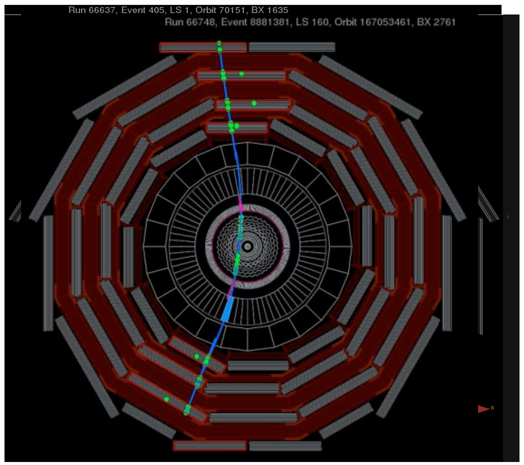


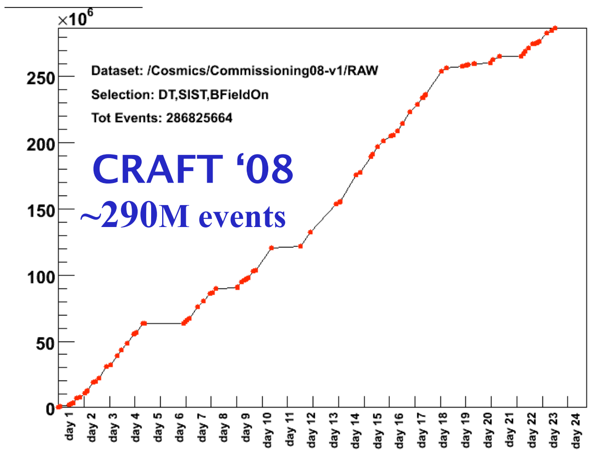


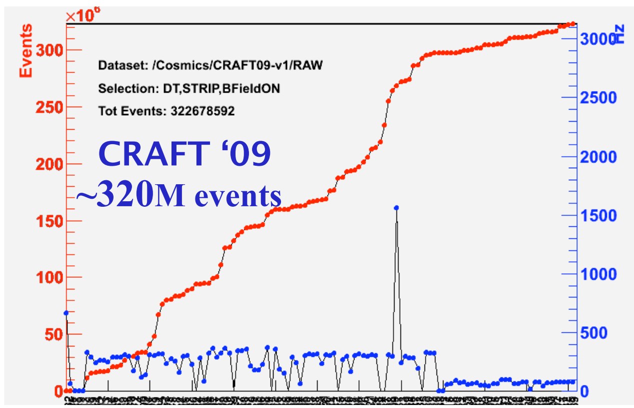


CMS: Cosmic Runs At Four Tesla



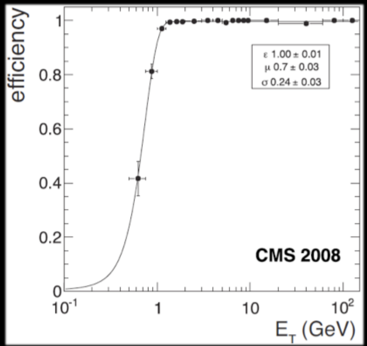


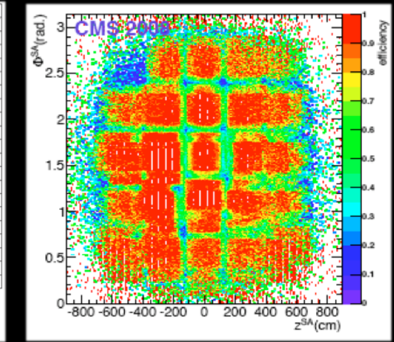


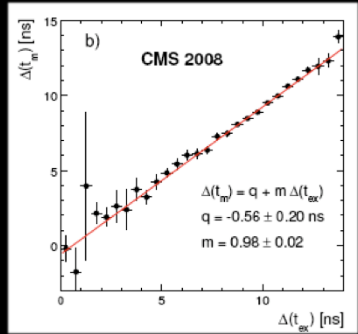


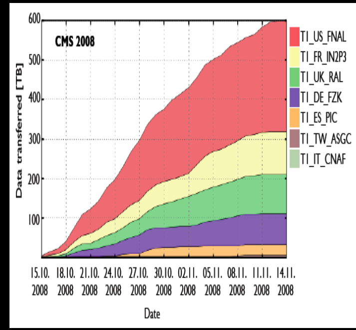
23 “CRAFT” Papers Published in JINST

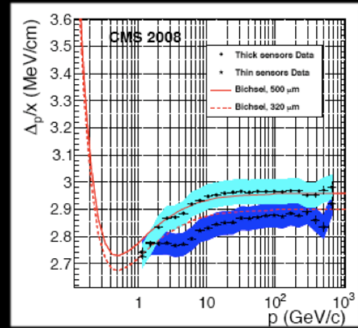
http://iopscience.iop.org/1748-0221/focus/extra.proc6

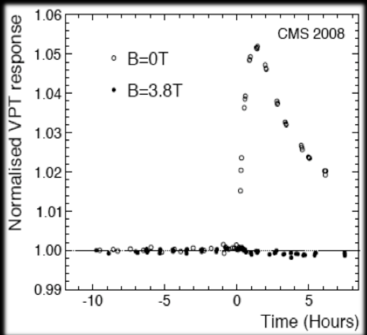


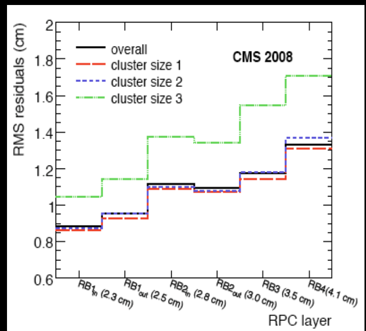


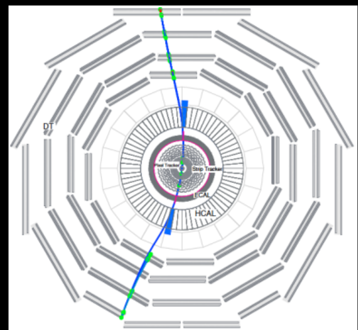


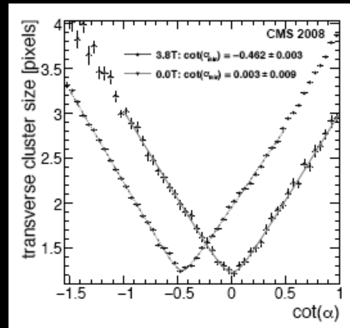


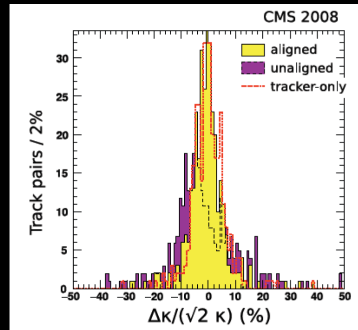


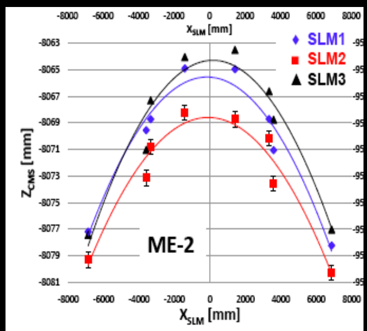


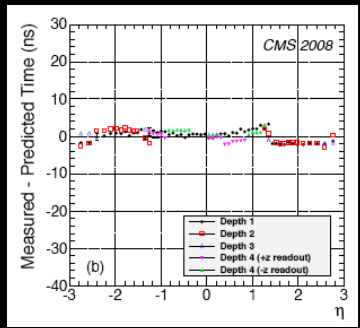


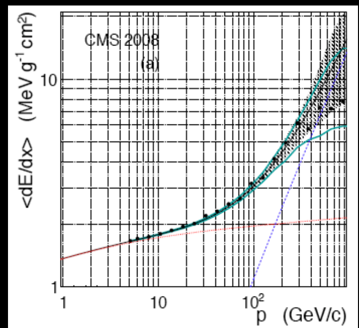


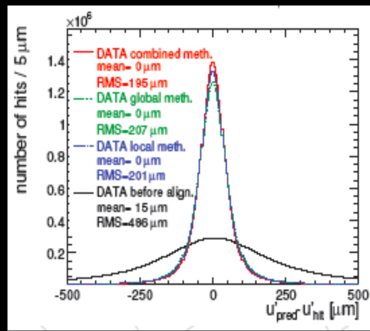


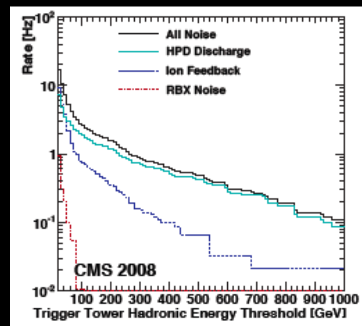


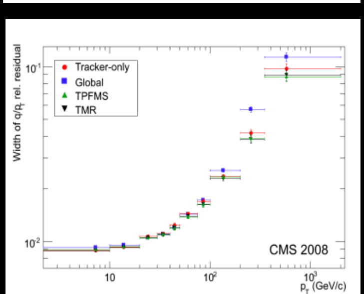


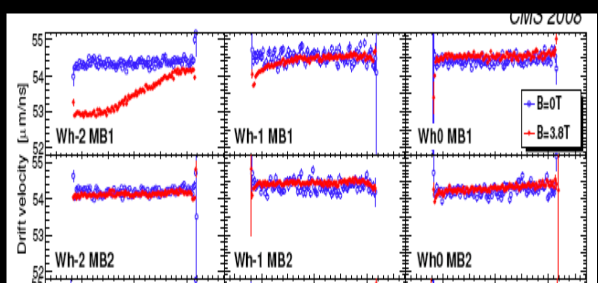


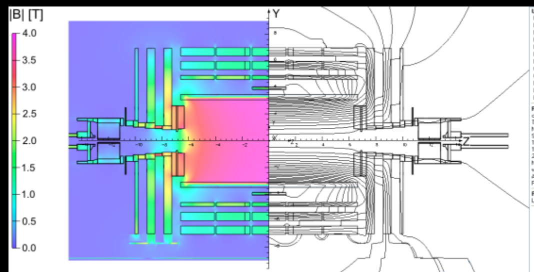


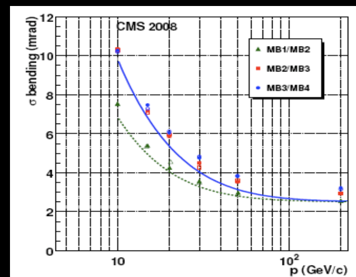






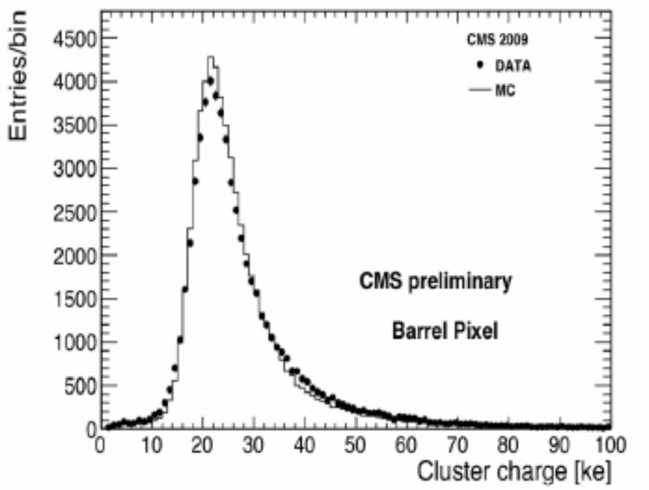


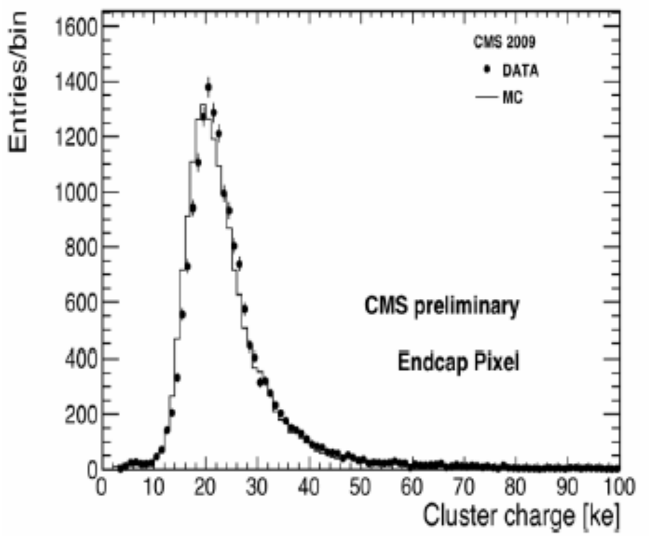




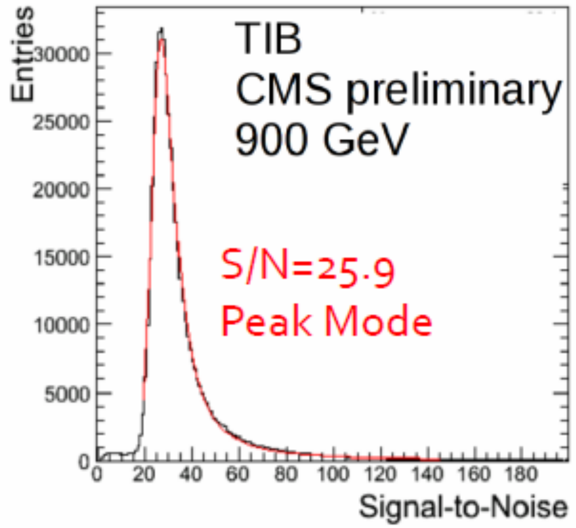
CMS: Tracker Performance at √s = 900 GeV

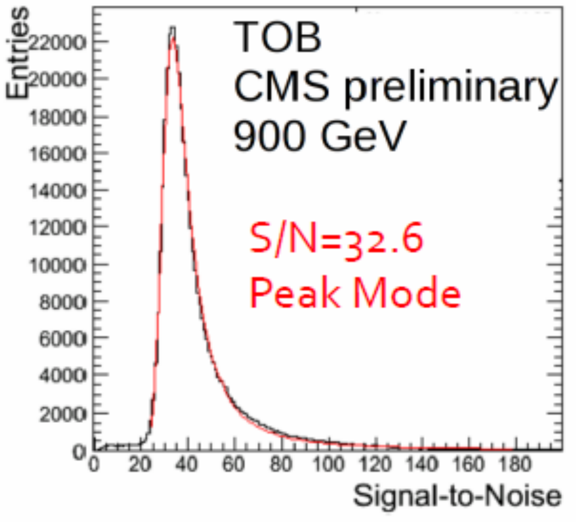
Pixel: Charge Distribution



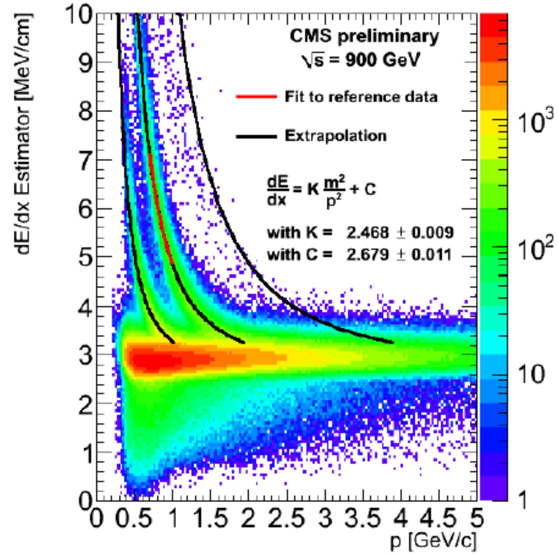


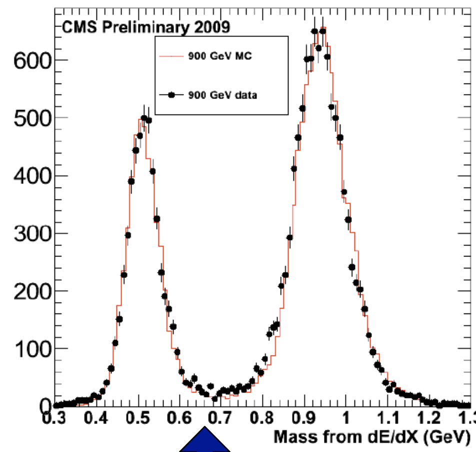
Si-Strip: Charge Distribution





dE/dx

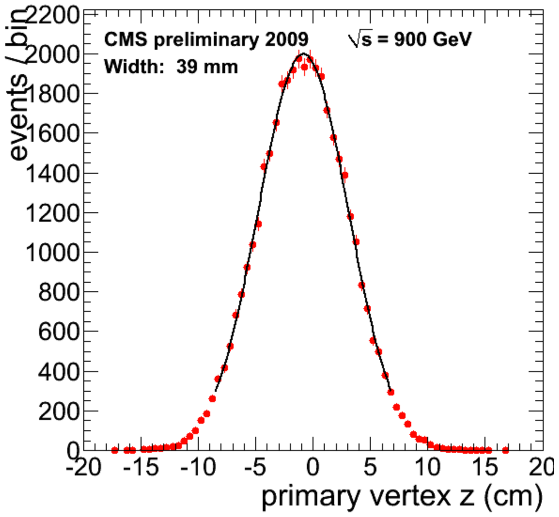




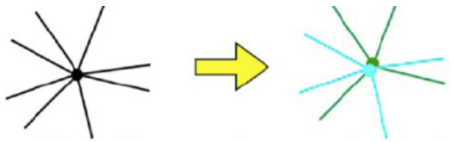
p < 2 GeV
dE/dX > 4.15 MeV/cm

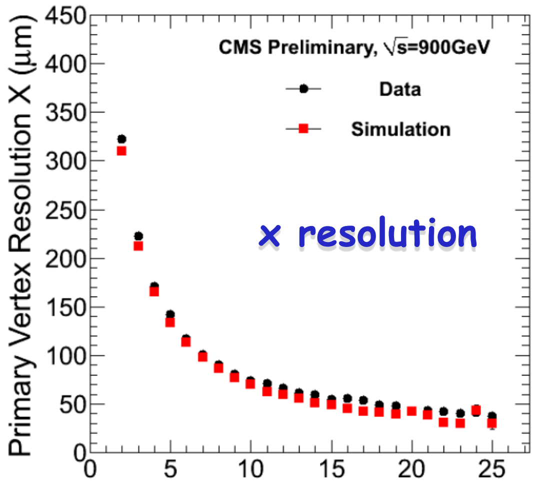
CMS: Tracker Performance at √s = 900 GeV

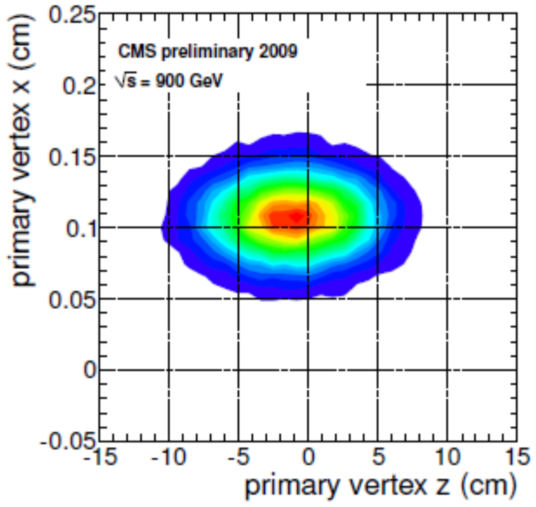
Primary Vertex

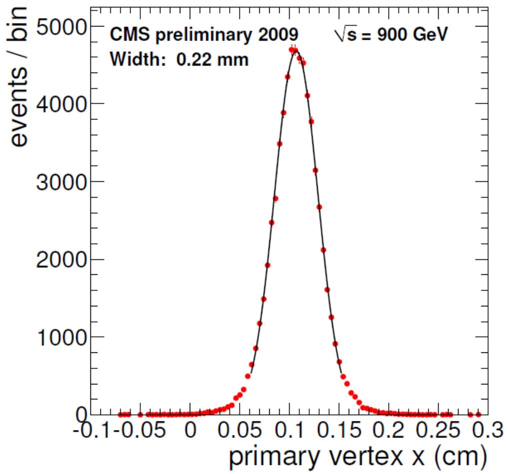


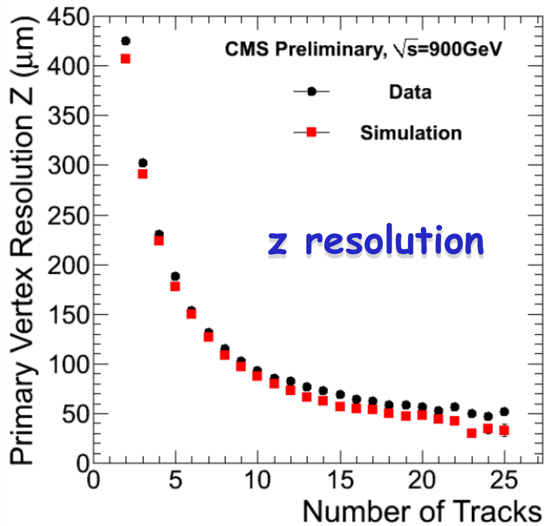
Primary vertex resolution obtained splitting tracks and comparing fits











MORE

SLIDES

Track reconstruction:

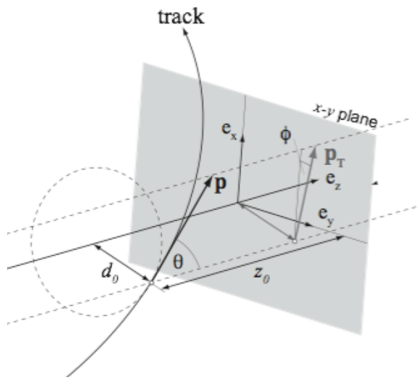
- Track finding, or "pattern recognition":
  the attribution of hits to tracks

- Track fitting, or the determination of
  the track parameters from a given set of hits

Track model and parameters

The **track model** depends on:

- Detector geometry
- Measurement type (2D, 3D)
- Straight tracks or **Helix** (depending on magnetic field)



Forward geometry

Assuming the *z* coordinate points down the spectrometer axis and *x*, *y* are the transverse coordinates:

Cylindrical geometry

In a homogenous axial solenoid field with the *z* coordinate oriented along the detector axis: helix parameters

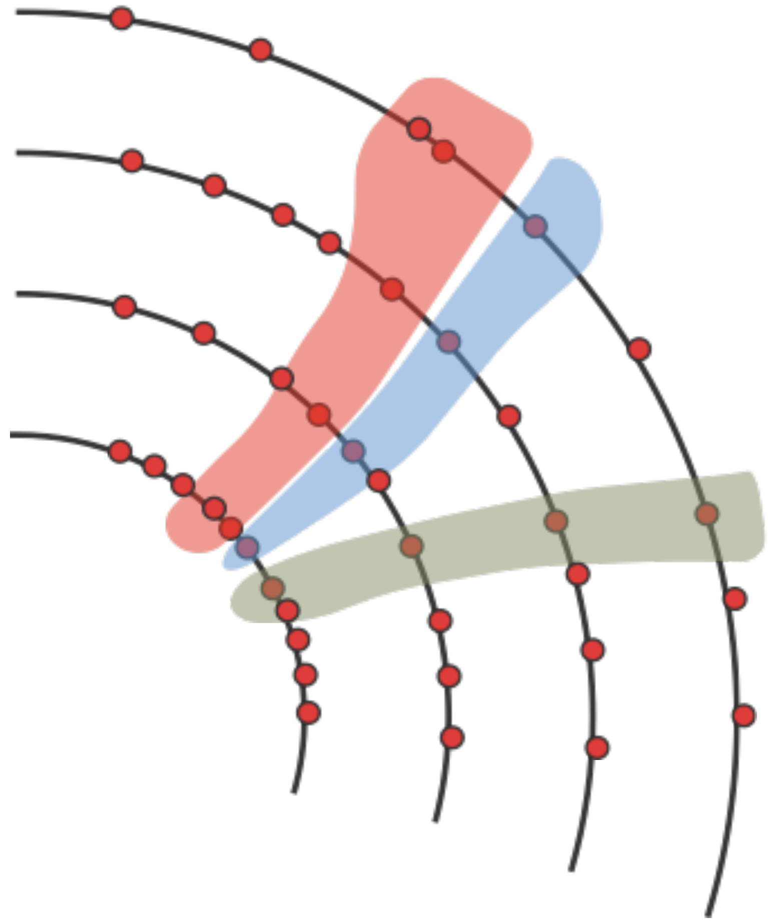
Track State Parametrization:

A track state can be represented as a point in 5D linear space (usually 2 positions, 2 angles and a curvature) and 5x5 symmetric error matrix.

Pattern Recognition

- The **main** goal of the pattern recognition is to **associate hits to tracks** (particle trajectories). It should be efficient (use of all hits) and robust (no noise or hits from other tracks)

Two approaches:
Global and **Local** pattern recognition



- **Global methods:**
  Template matching, neural network techniques, Hough space transform, …..
  (Simultaneous consideration of all hits: can be very inefficient in terms of speed)

- **Local methods (also called track following):**

Combinatorial Kalman filter updates the information (track parameters and error matrix) of candidates tracks along the track finding process and gives a precise prediction of the next point to be found. It is a progressive methods (boundary pattern recognition/track fitting vanished). Track fit became part of the track finding approach.

Track fitting

Process to estimate the kinematical parameters, such as position (or impact parameter), direction of flight and momentum of a particle starting from the measured hits which have been correctly identified in the pattern recognition step.

- ✓ **Multiple scattering effects and energy loss are taken into account in the track fitting procedure**
- ✓ **In general the fitting methods assume Gaussian errors**

Two approaches:

- ❑ **Least squares estimation**: requires the global availability of all measurements at fitting time

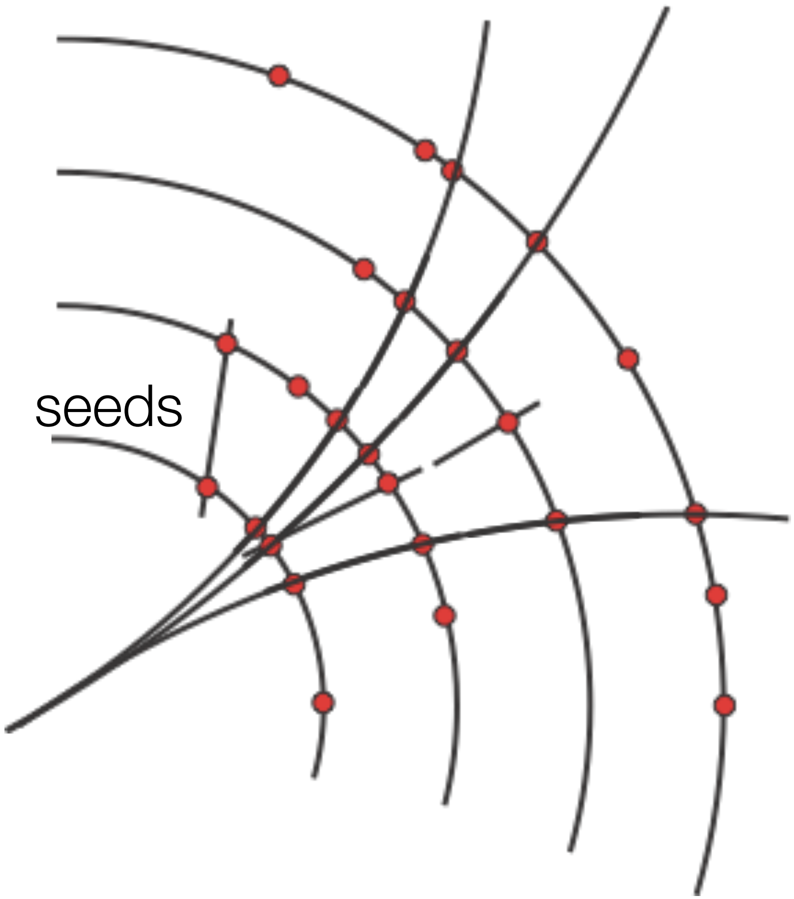
- ❑ The **Kalman filter technique**: proceeds progressively from one measurement to the next, improving the knowledge of the trajectory with each new measurement (**boundary pattern recognition/track fitting vanishes)**

Track finding / track fitting:
the combinatorial Kalman filter

Progressive method: track fitting works simultaneously with track finding.

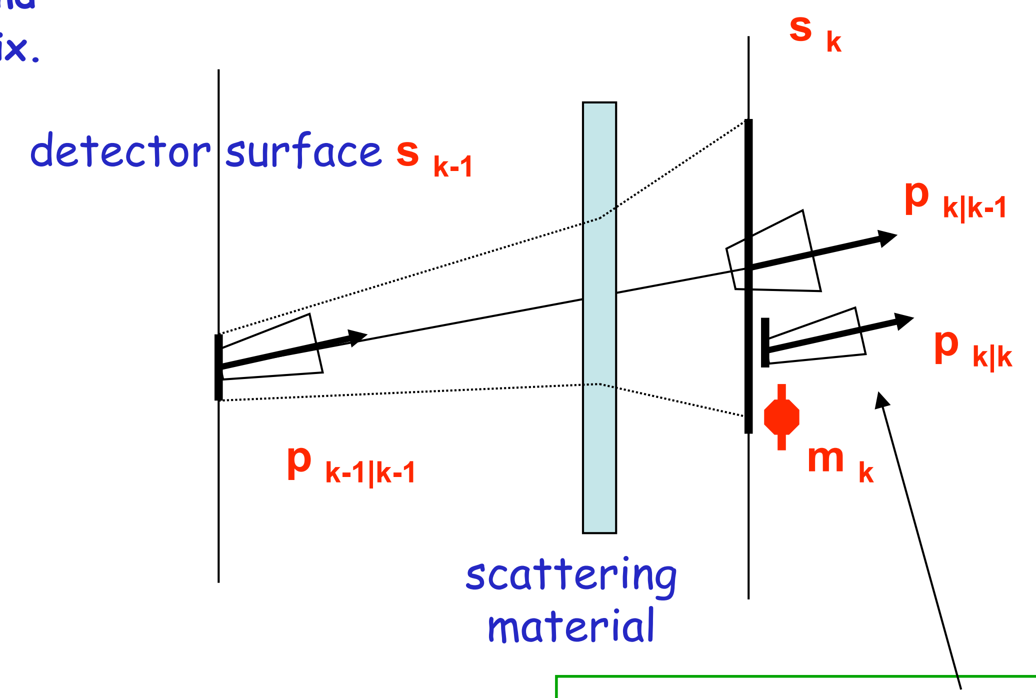
The Kalman Filter consists of a succession of alternating *prediction and filter steps:*

- ✓ As one example, in CMS track reconstruction is initiated by a *seeding* in the innermost tracker layers: both pixel and silicon strip hits.
- ✓ The system equation propagates the track state in one surface to the next.
- ✓ Accuracy on the track state estimate increases after each new measurement is added



Kalman filter formalism for track fitting

Consider a track state $p_{n|n}$ as known on a surface n and represented as a point in 5D linear space (usually 2 positions, 2 angles and a curvature) and 5x5 symmetric error matrix.



Extrapolation on surface k of the state known on surface k-1:

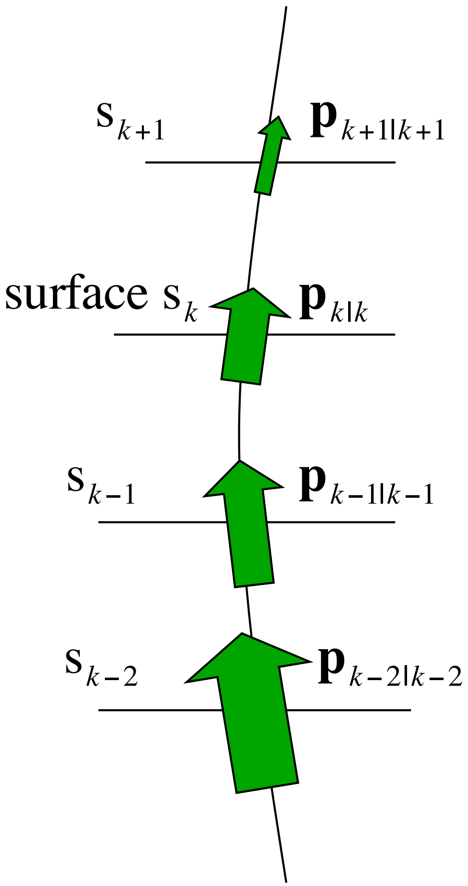
$$\mathbf{p}_{k|k-1} = \underbrace{\mathbf{F}_k}_{\text{Equations of motion}} \cdot \mathbf{p}_{k-1|k-1}$$

Covariance matrix of the extrapolated state:

$$\mathbf{C}_{k|k-1} \equiv \mathbf{C}(\mathbf{p}_{k|k-1}) = \underbrace{\mathbf{F}_k \cdot \mathbf{C}_{k-1|k-1} \cdot \mathbf{F}_k^{-1}}_{\text{propagation of errors}} + \underbrace{\mathbf{P}_k \cdot \mathbf{Q}_k \cdot \mathbf{P}_k^{-1}}_{\text{effect of material}}$$

$p_{k|k}$ is the result of the combination of the extrapolated state and the information provided by the measured hit position

Kalman filter formalism for track fitting



Accuracy on the track state estimate increases after each new measurement is added.

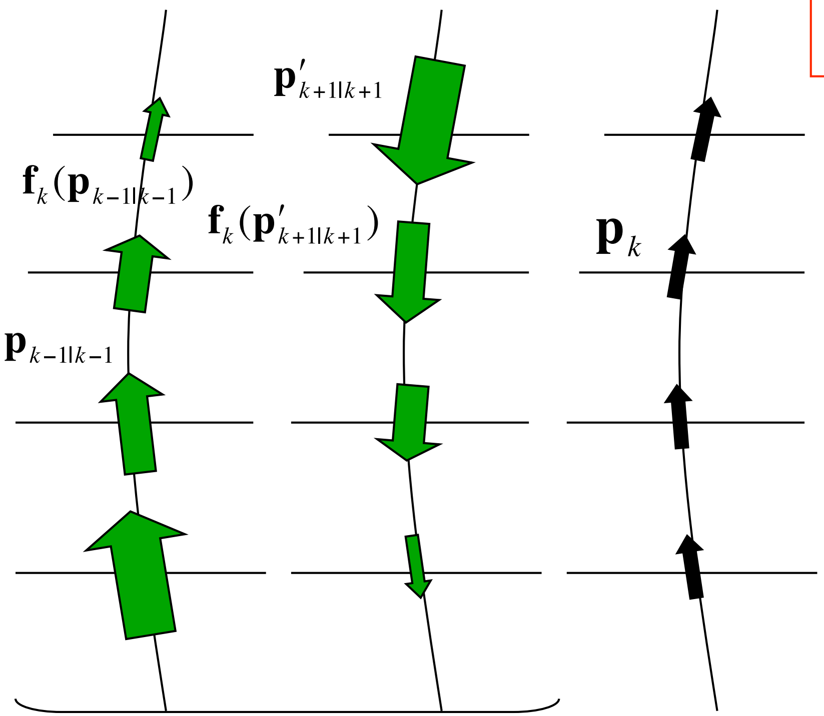
The last track state $p_{n|n}$ is determined with the best precision: it is the only one which **is estimated using the full information provided by the detector**, i.e. all the *n* measurements.

An increasing accuracy is adequate for trajectory building. Nevertheless is often desirable to have the best estimate of track's parameters on all the detector surface.

In particular **the track has to be know with the best precision at the point of max approach** to the primary vertex of interaction.

Kalman *smoothing* for track fitting

- At the end of the "forward in-out fit", the track parameters are known precisely at the exit of the tracker, but completely unknown at the origin
- We can perform a "backward out-in fit", using only the hits from the forward fit (no pattern recognition) to find the parameters at origin
  - But we lose them at the other end
- A procedure, called *smoothing*, allows to combine the forward and backward fits in such a way that the parameters are optimally known at every measurement



Both in-out filter and out-in one are run

$$\mathbf{p}_k = \mathbf{p}_{k|k} \oplus \mathbf{f}_k(\mathbf{p}'_{k+1|k+1})$$

A statistically correct *weighted mean:* **Kalman *smoother***

$\mathbf{p}_{k|k}$ **Contains information from measurements: 1,2,..,k**

$\mathbf{p}'_{k+1|k+1}$ **Contains information from measurements: n,n-1,…,k+1**

$\mathbf{p}_k$ **Contain the full information. All measurement from 1 to n are used.**

Filtering and Smoothing