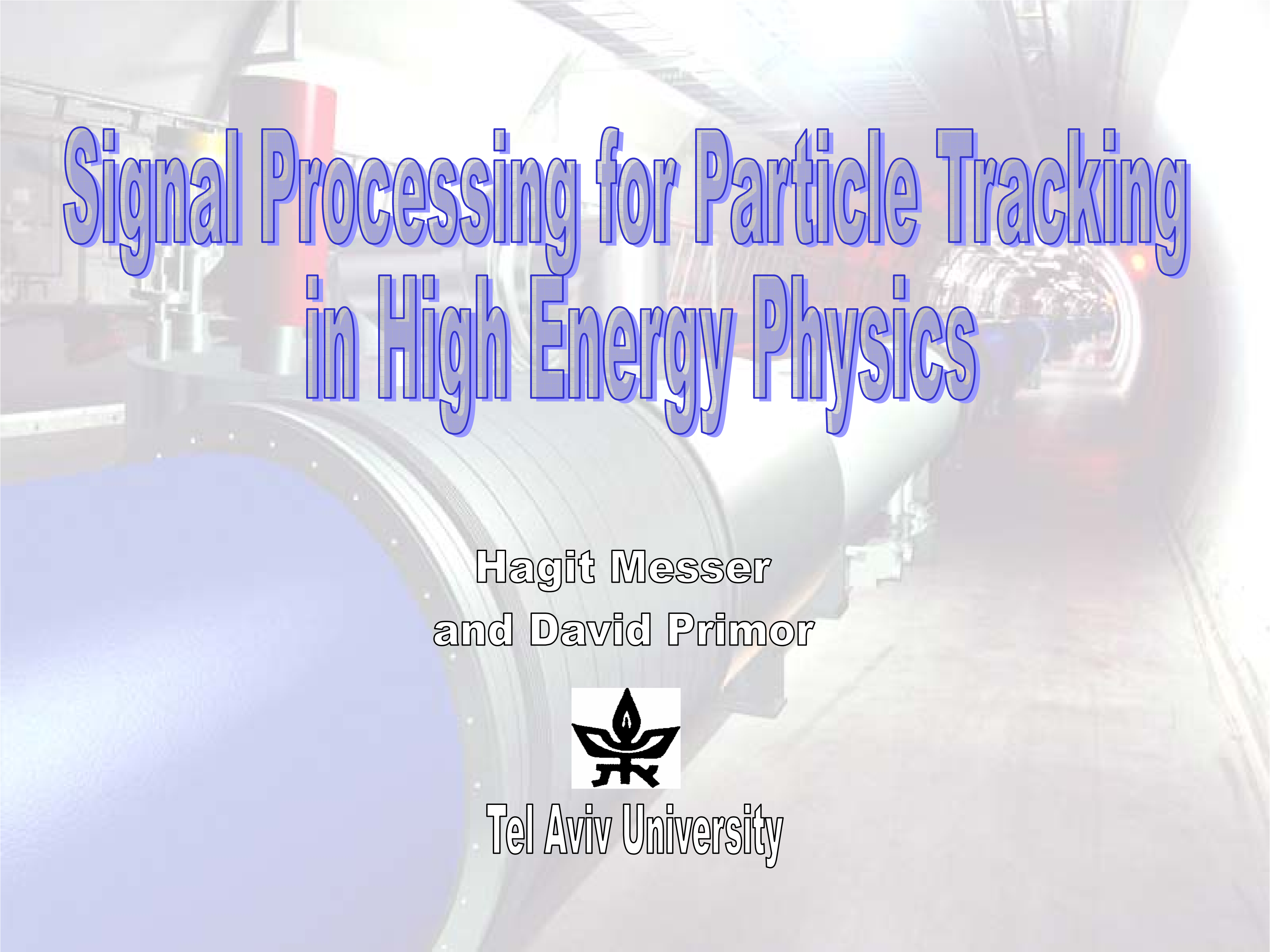
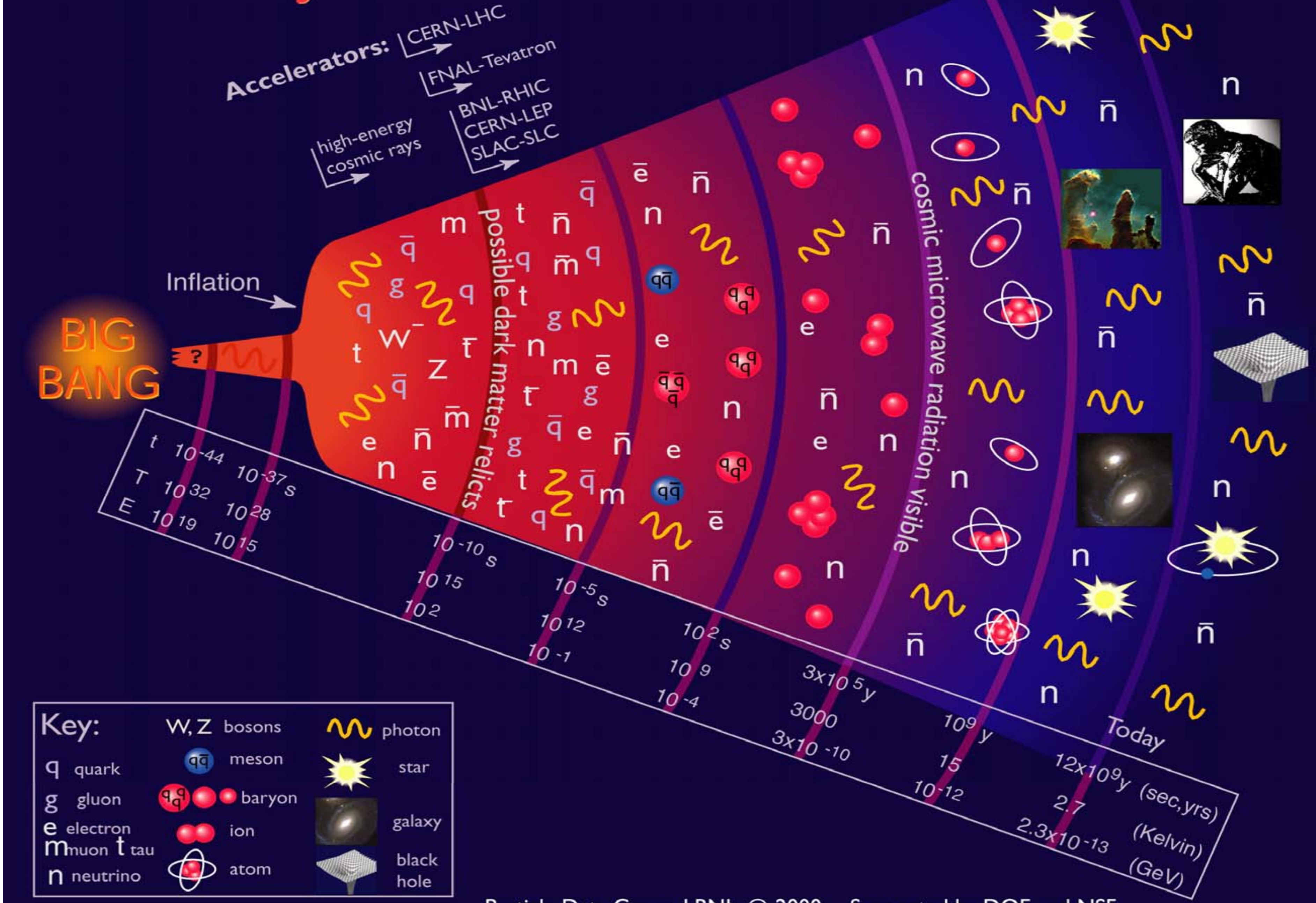


Signal Processing for Particle Tracking in High Energy Physics

Hagit Messer
and David Primor

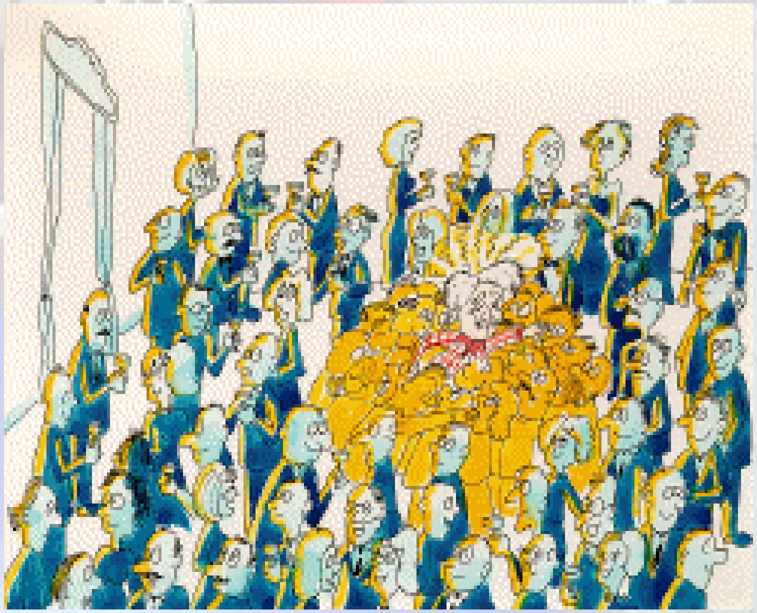
Tel Aviv University

History of the Universe

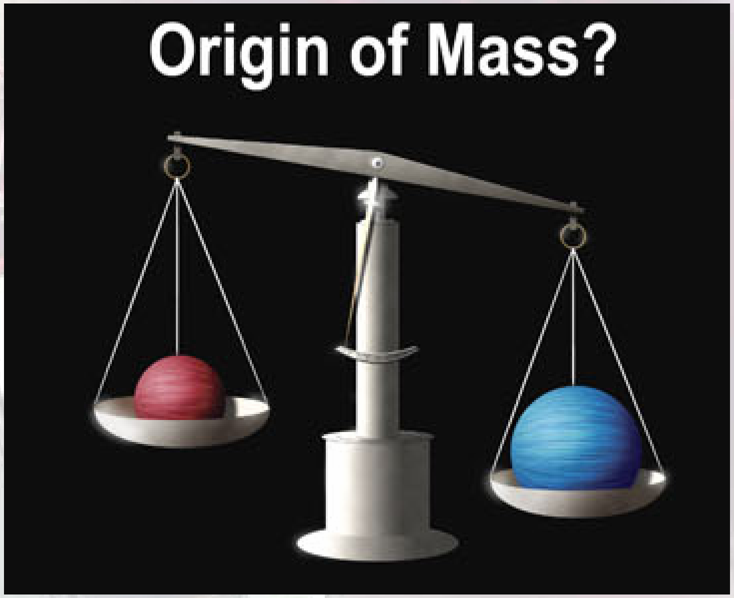


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The Higgs mystery

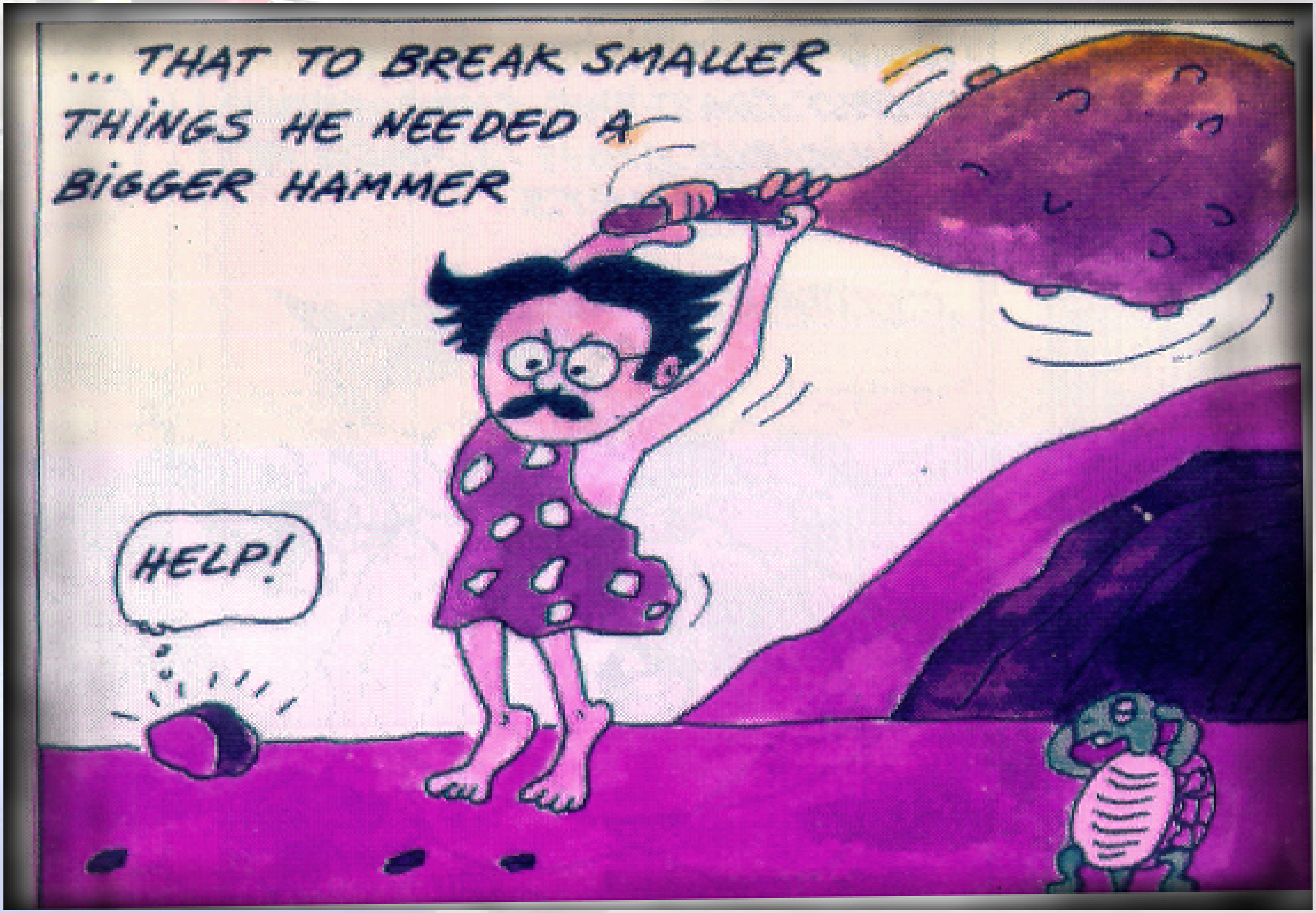


The Higgs Particle couples to all matter in the universe hence acquire it with MASS



In the standard model, for fundamentals particles to have masses, there must exist a particle called the Higgs boson.

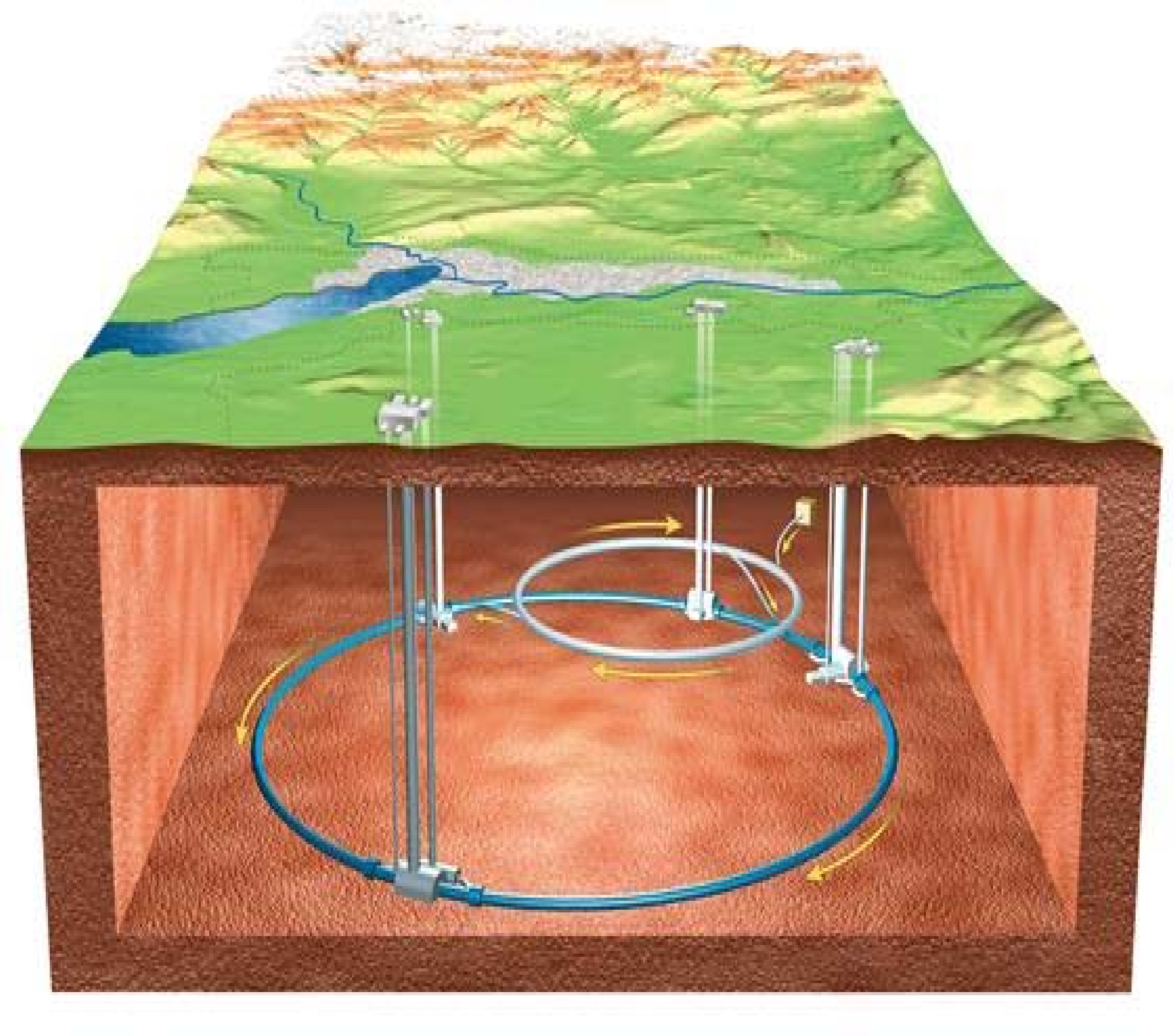
How can we detect particles?



CERN – Big Hammers Factory

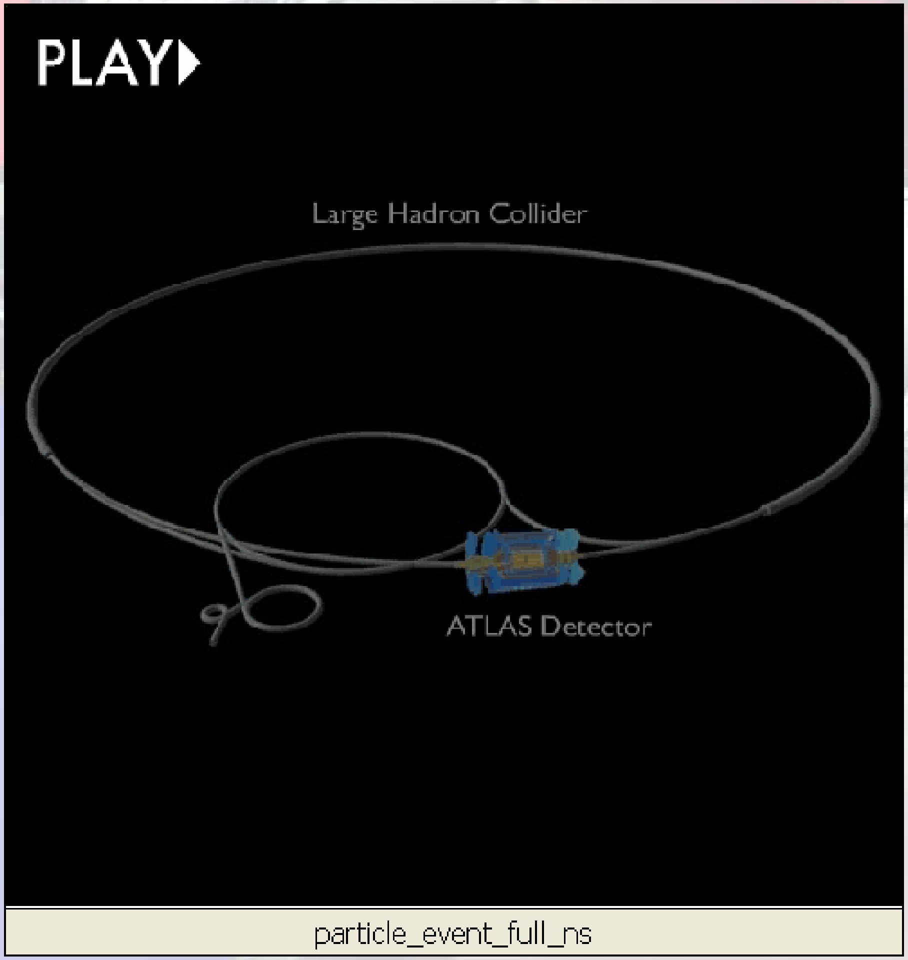
CERN, the European Organization for Nuclear Research, is the world's leading laboratory for particle physics. It has its headquarters in Geneva. At present, its Member States are Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom. India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO have Observer status.

The LHC accelerator

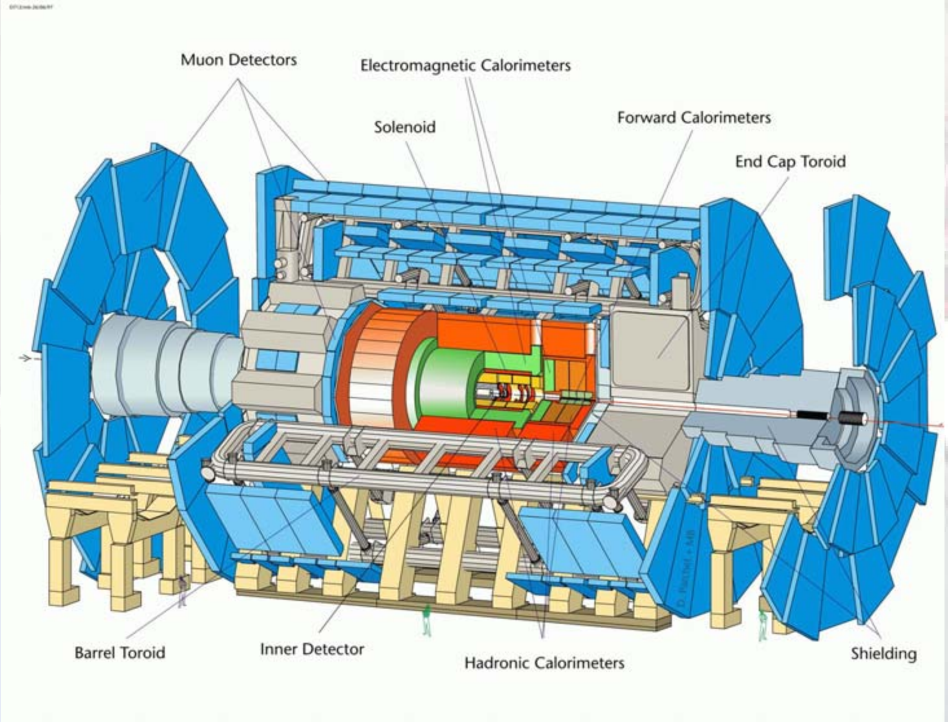


The tunnel is 27 Km long!

The ATLAS detector

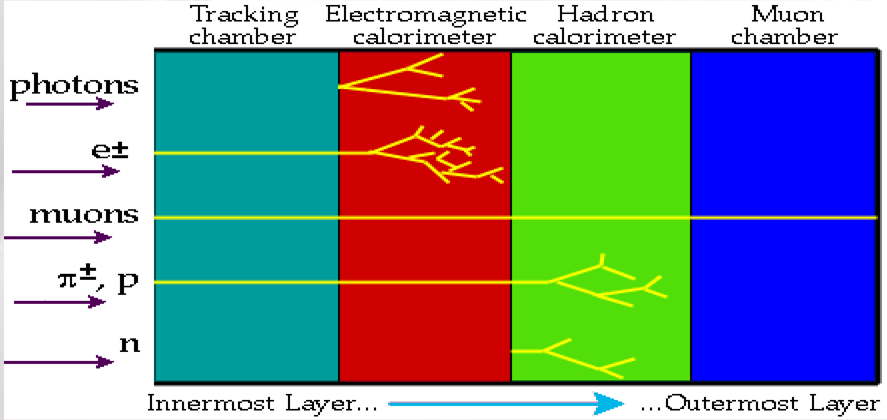


The ATLAS detector

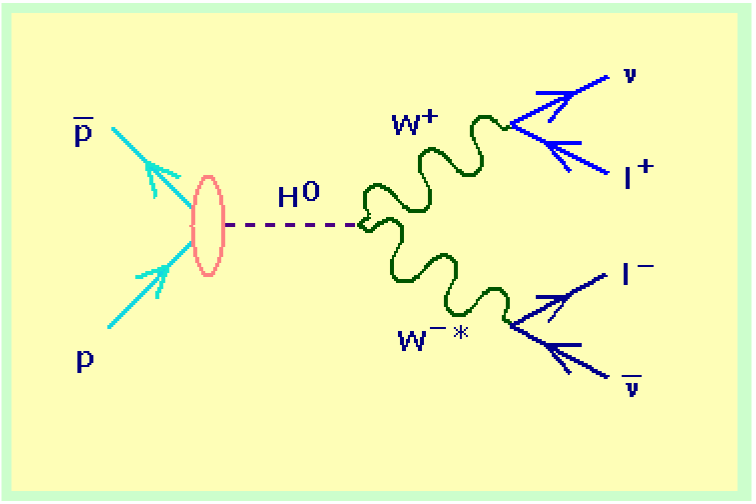


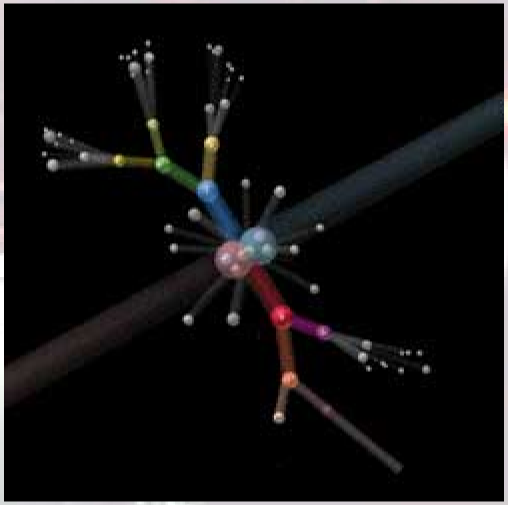
- There is one head to head bunch crossing every 25 nSec

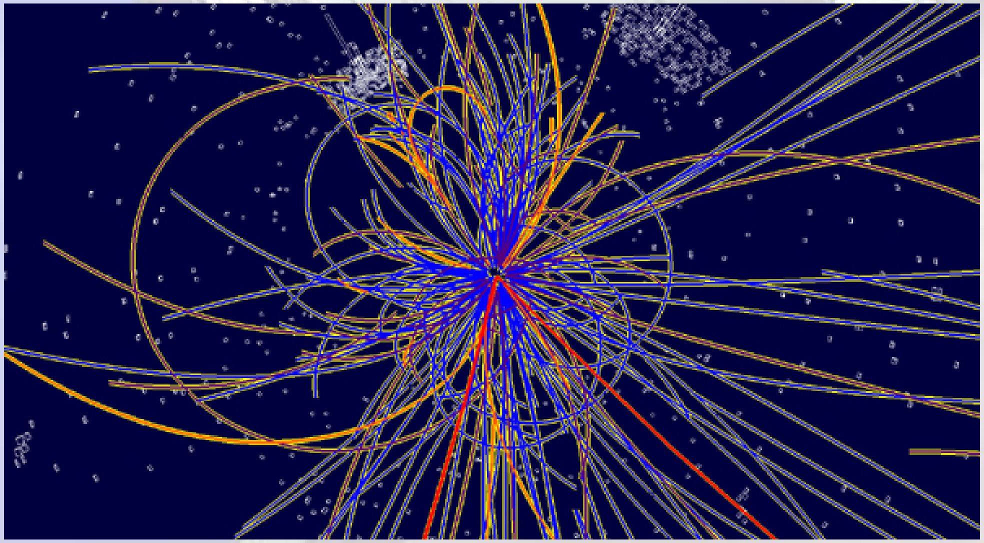
- There are ~23 collisions occurring in each bunch



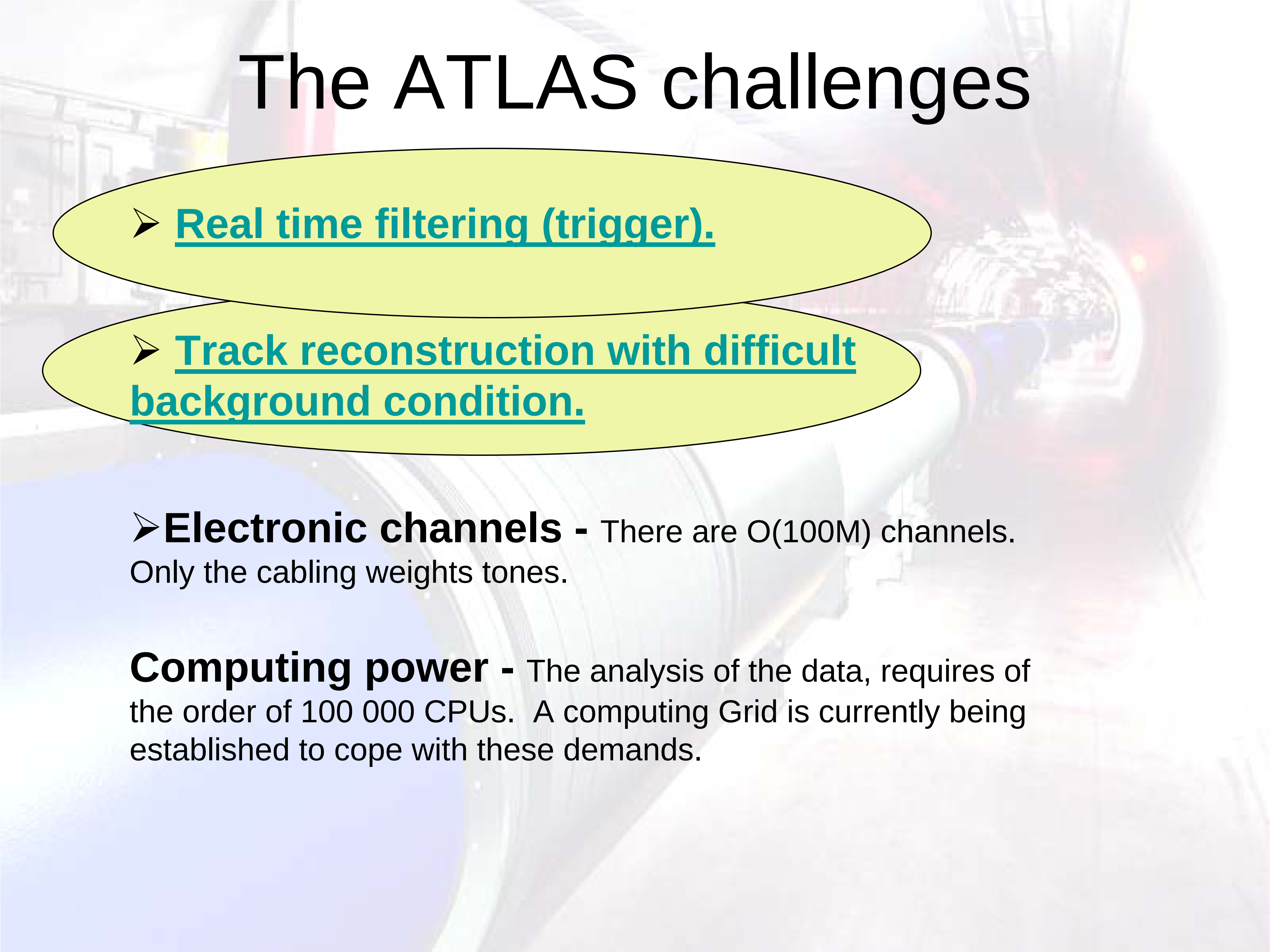
The search for the Higgs







The ATLAS challenges



- **Real time filtering (trigger).**

- **Track reconstruction with difficult background condition.**

- **Electronic channels -** There are O(100M) channels. Only the cabling weights tones.

Computing power - The analysis of the data, requires of the order of 100 000 CPUs. A computing Grid is currently being established to cope with these demands.

Trigger is a Real Time Challenge

40 TB/sec

level 1 - special hardware

75 GB/sec

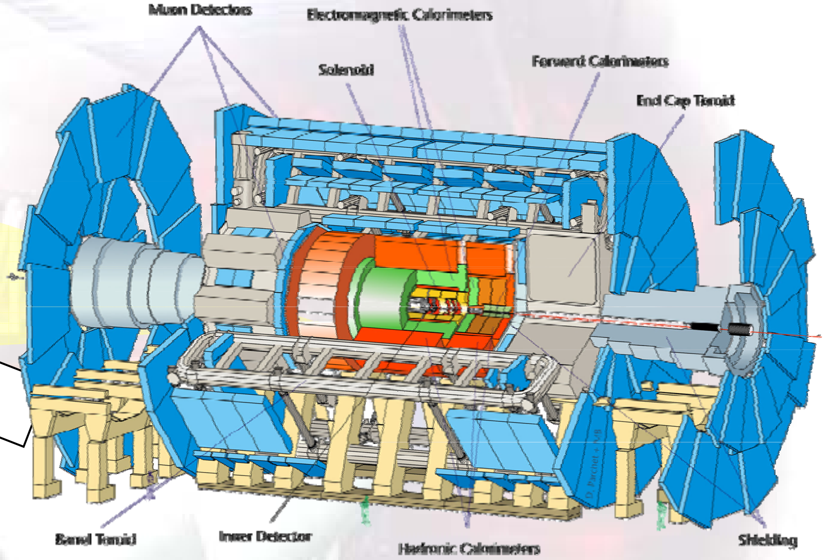
level 2 - embedded processors

5 GB/sec

level 3 - PCs

100-400 MB/sec

data recording &
offline analysis



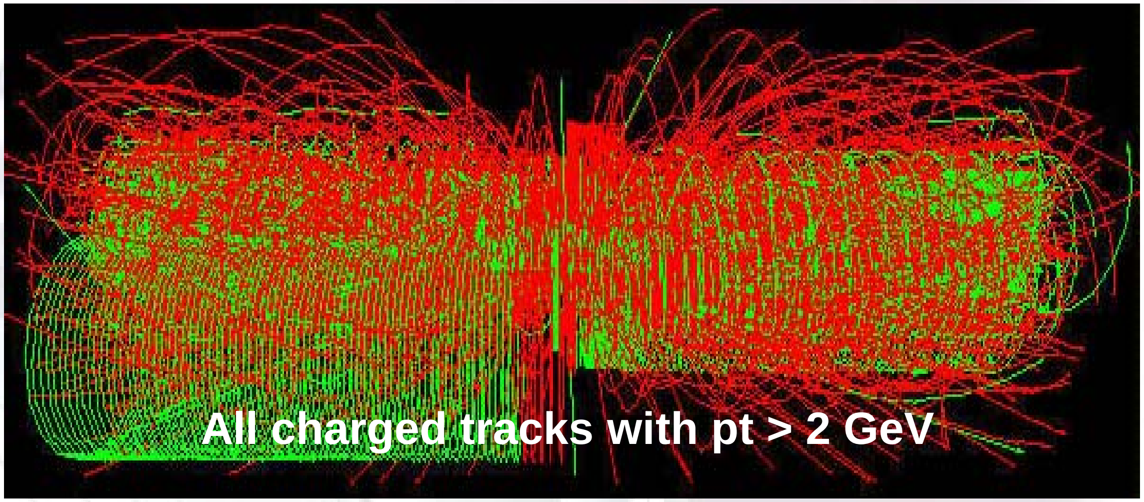
- ➢For off-line processing, an equivalent CD is being written every 1-6 seconds.

- ➢Level 1 trigger detectors perform in real time, transferring filtered data to level 2 with an appropriate time tag.

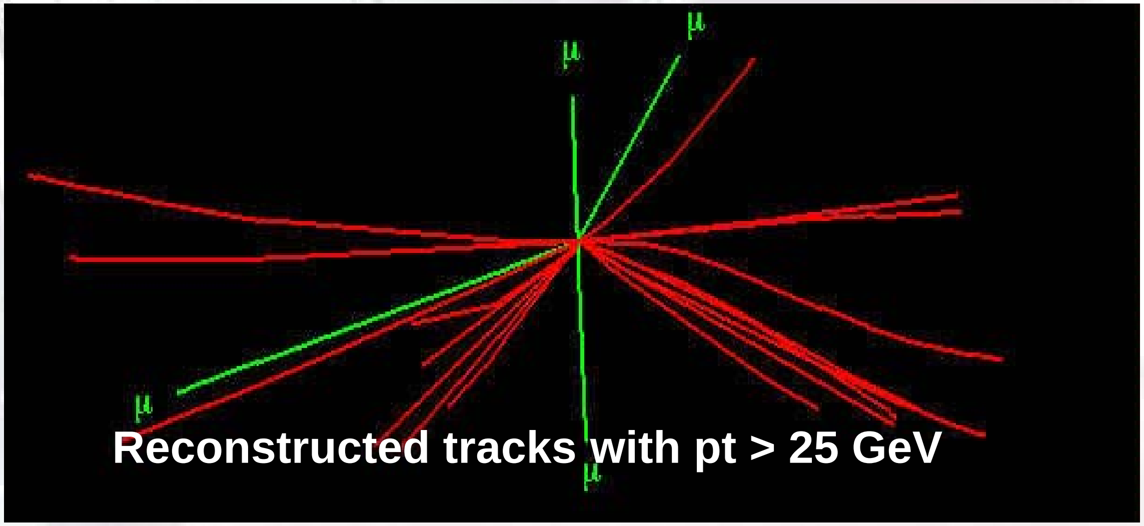
A Higgs→4 Muons

Each event causes many particle tracks, which may or may not include Higgs products.

Particles are filters according to their energy.



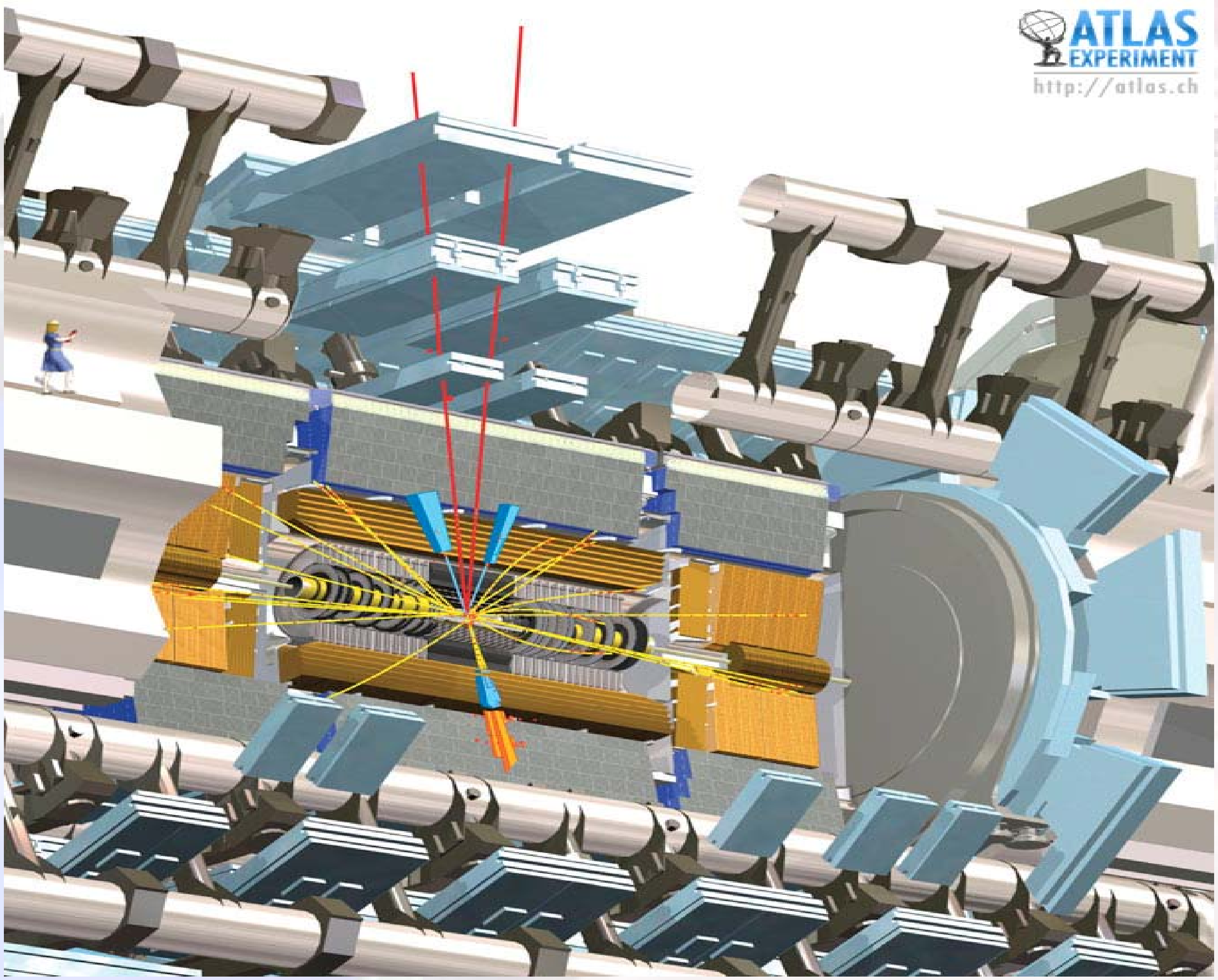
All charged tracks with pt > 2 GeV



Reconstructed tracks with pt > 25 GeV

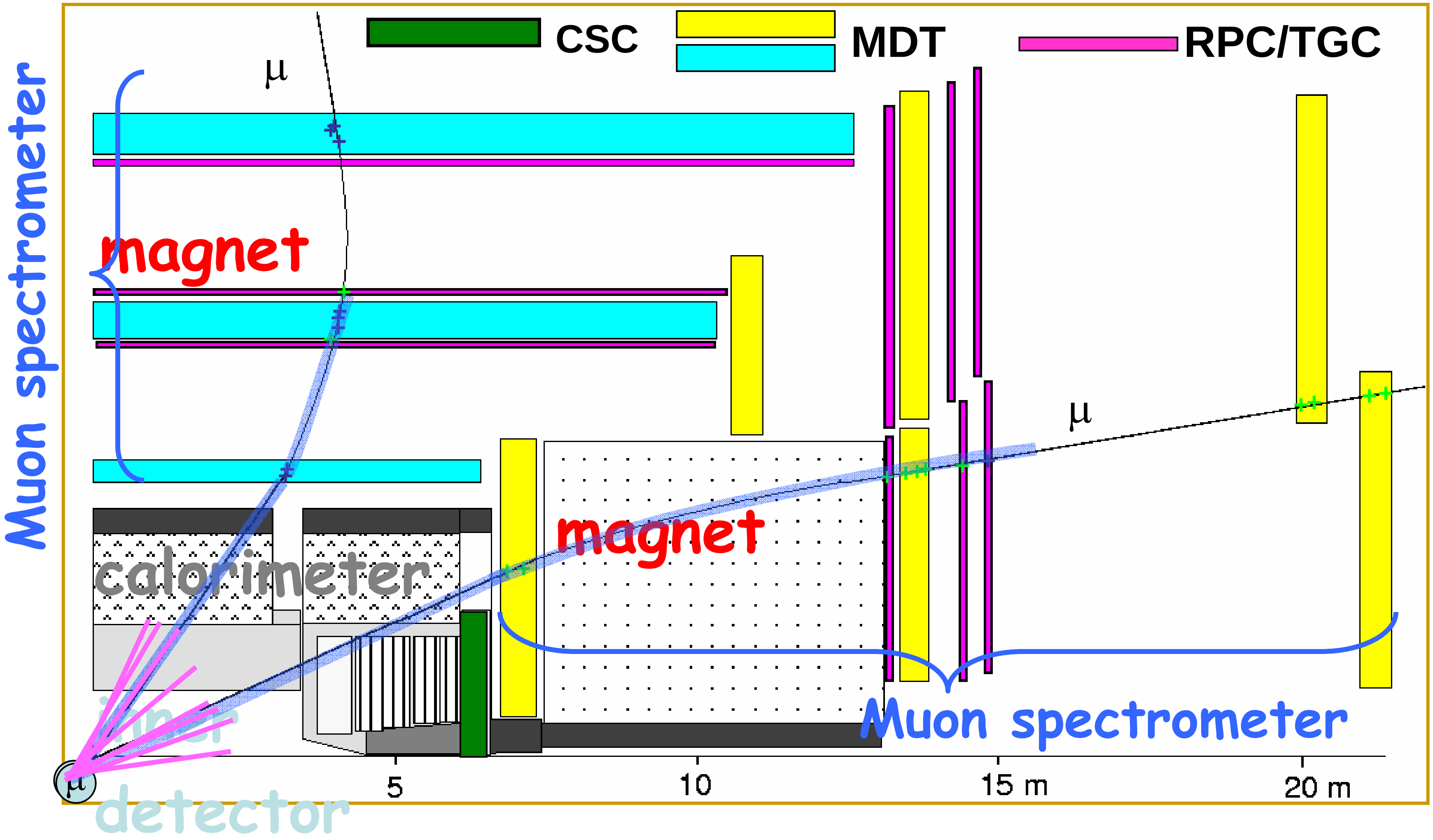
plot from **S. Cittolin**

Track reconstruction



Local vs. global tracking; Track finding vs. track fitting

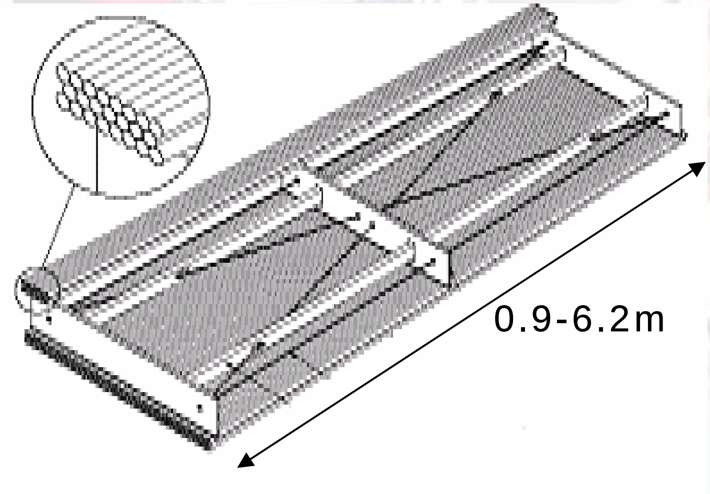
Combined muon reconstruction - example

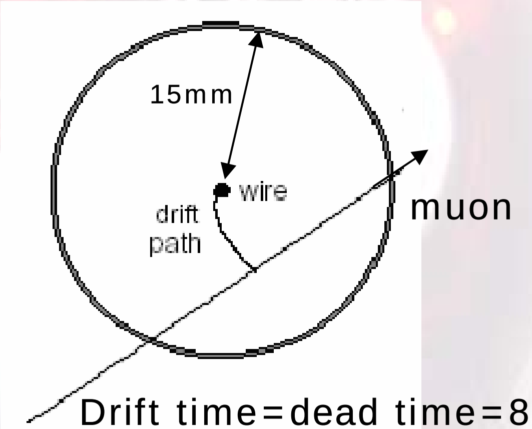


Methods for track finding/fitting

- Hough transform
- Global Least Squares fit
- Kalman filter
- Deterministic annealing filter (DAF)

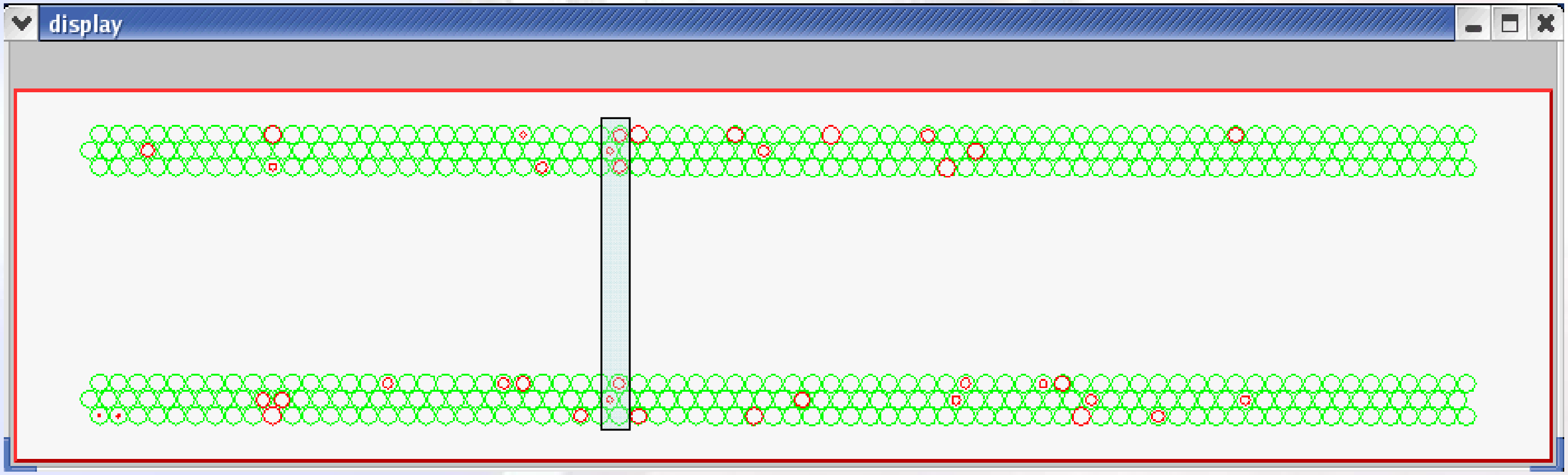
Local tracking in the MDT detector



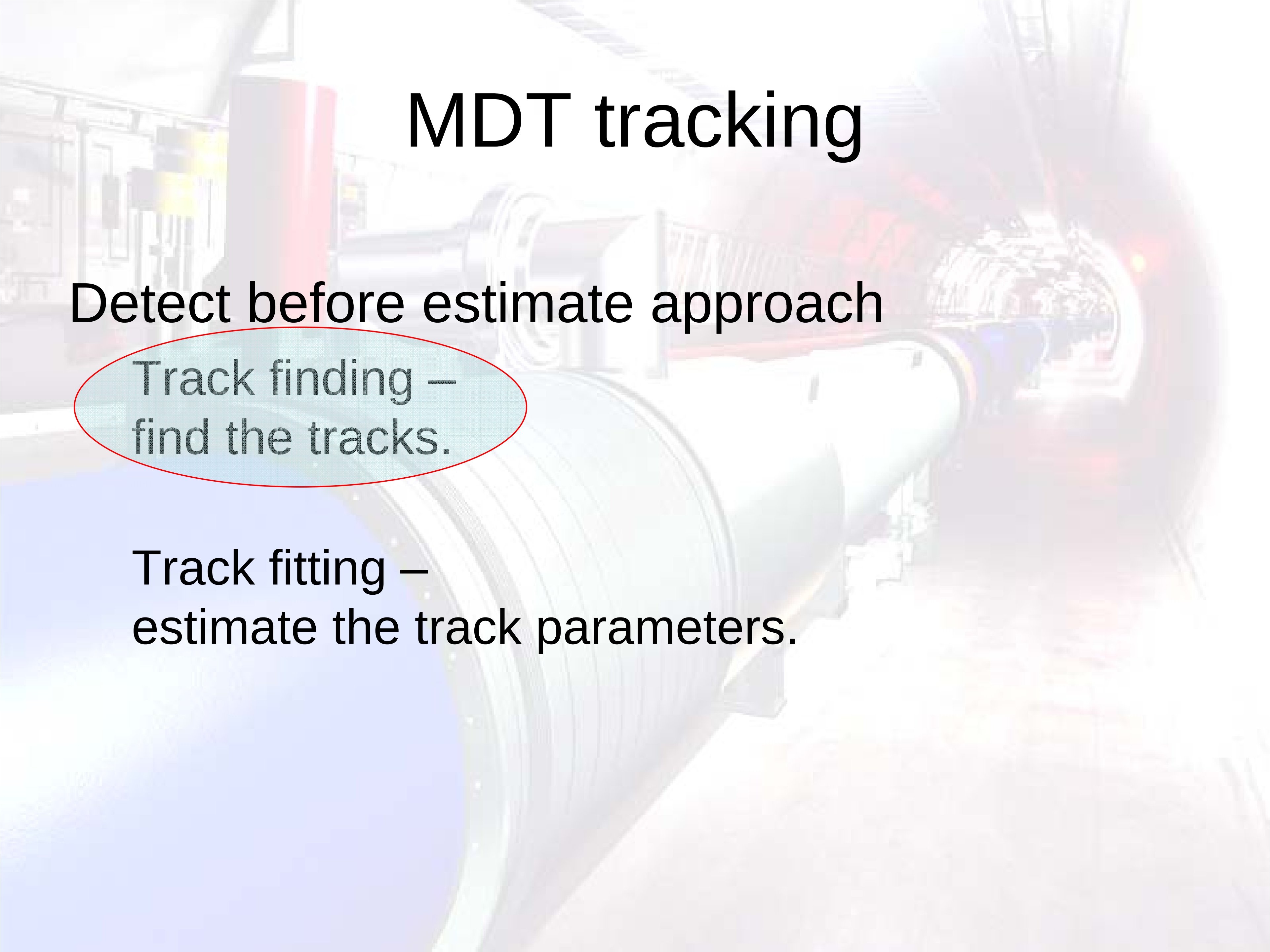


Drift time=dead time=800ns

About 370,000 tubes in ATLAS



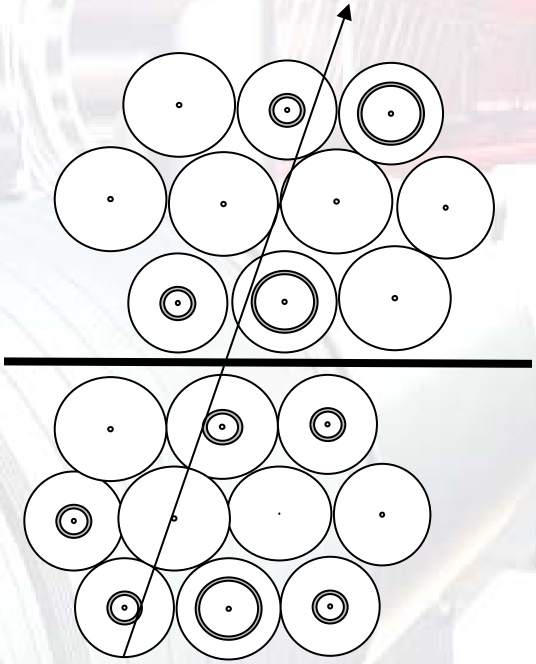
MDT tracking



Detect before estimate approach

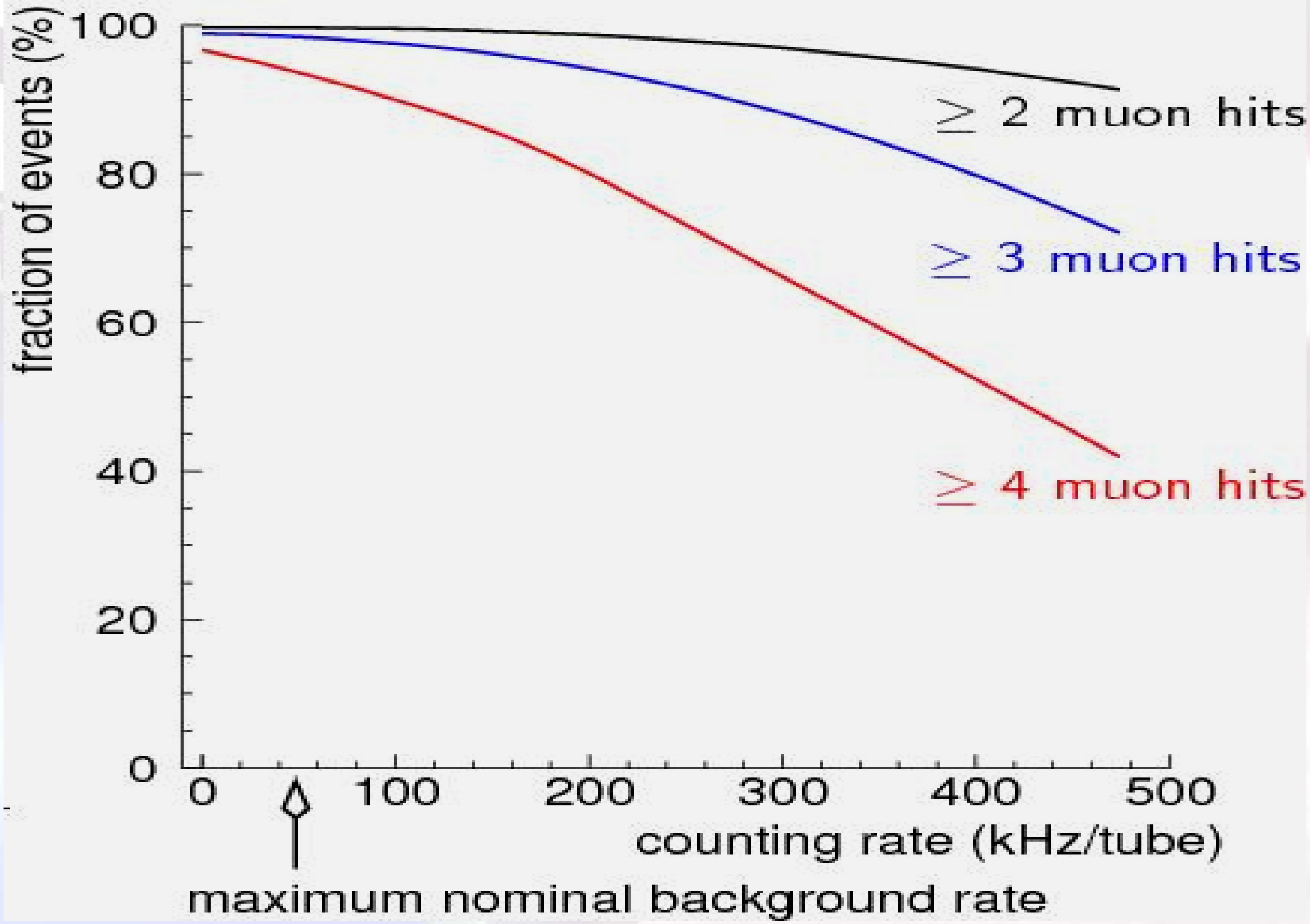
- Track finding –
  find the tracks.
- Track fitting –
  estimate the track parameters.

The common approach: 4 out of 6



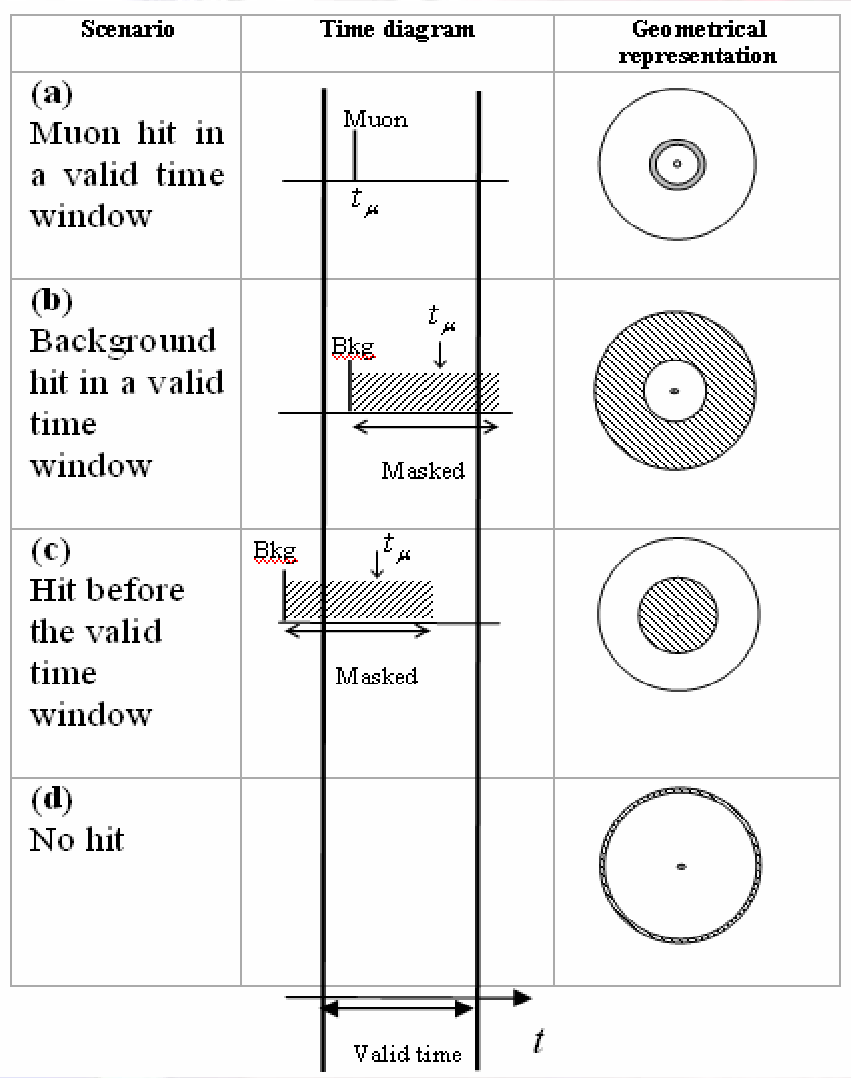
One should find all possible lines that are tangent to a minimal subset of drift radii

The effect of noisy background



4/6 => low Pd; 2/6 => high Pfa

The different scenarios



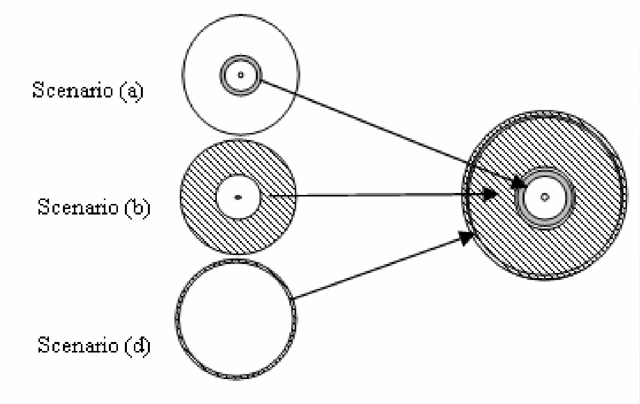
Scenario	Time diagram	Geometrical representation
(a) Muon hit in a valid time window		
(b) Background hit in a valid time window		
(c) Hit before the valid time window		
(d) No hit		

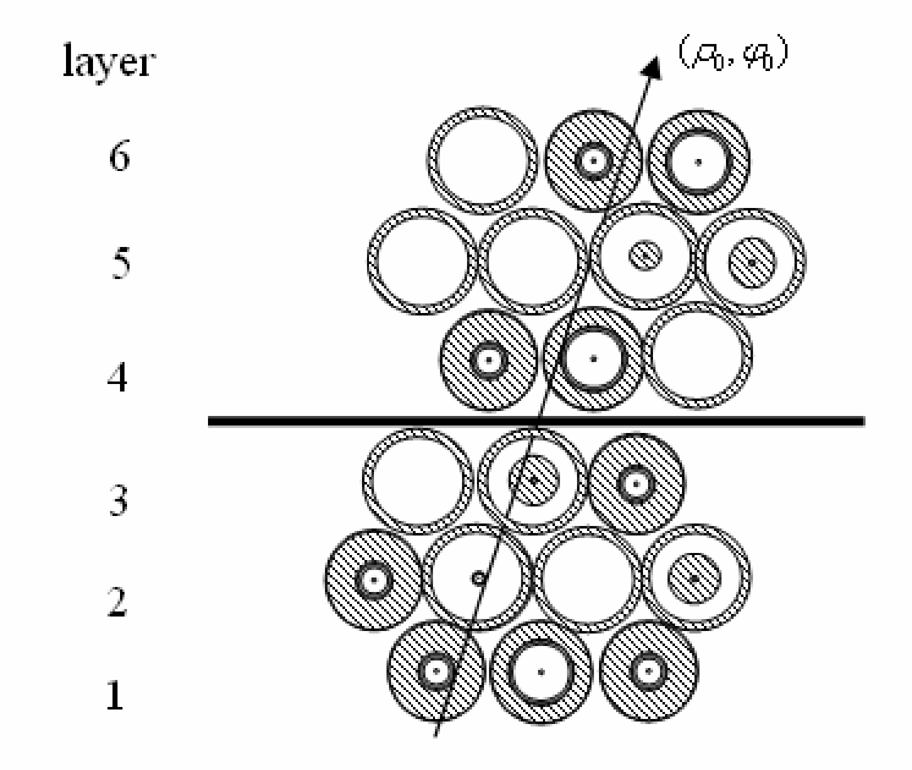
Geometrical representation of the track finding problem

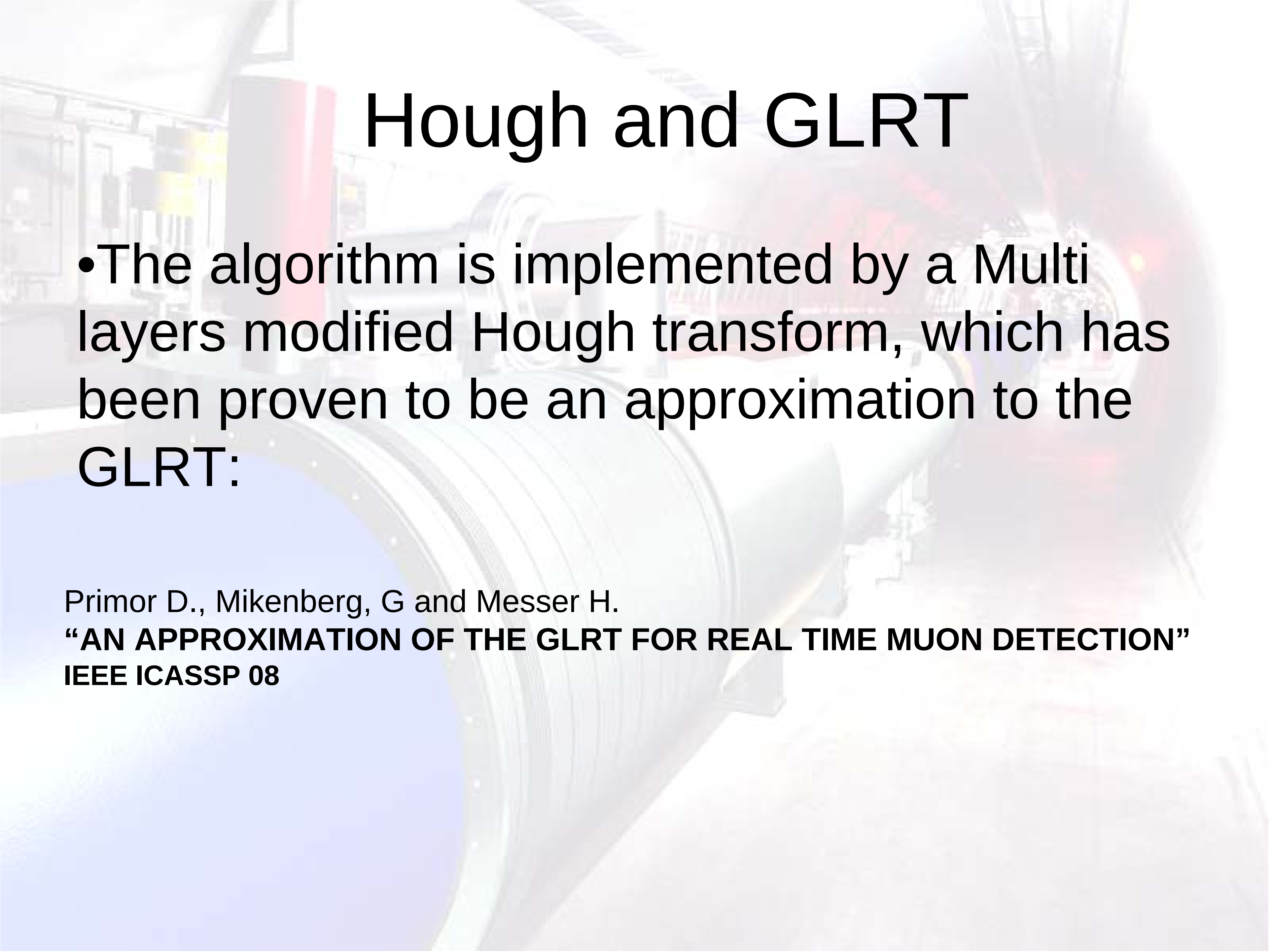
sum of the i-th basic scenarios the track crosses

$$H_i(\rho_0,\varphi_0)=\begin{cases} 3 & i=1 \qquad \text{(scenario (a), layers 1,2,4)} \\ 1 & i=2 \qquad \text{(scenario (b), layer 6)} \\ 1 & i=3 \qquad \text{(scenario (c), layer 3)} \\ 1 & i=4 \qquad \text{(scenario (d), layer 5)} \end{cases}$$

$$\boxed{\Lambda(\rho,\varphi)=\sum_{i=1}^{4} H_i(\rho,\varphi)\cdot w_i > \lambda}$$







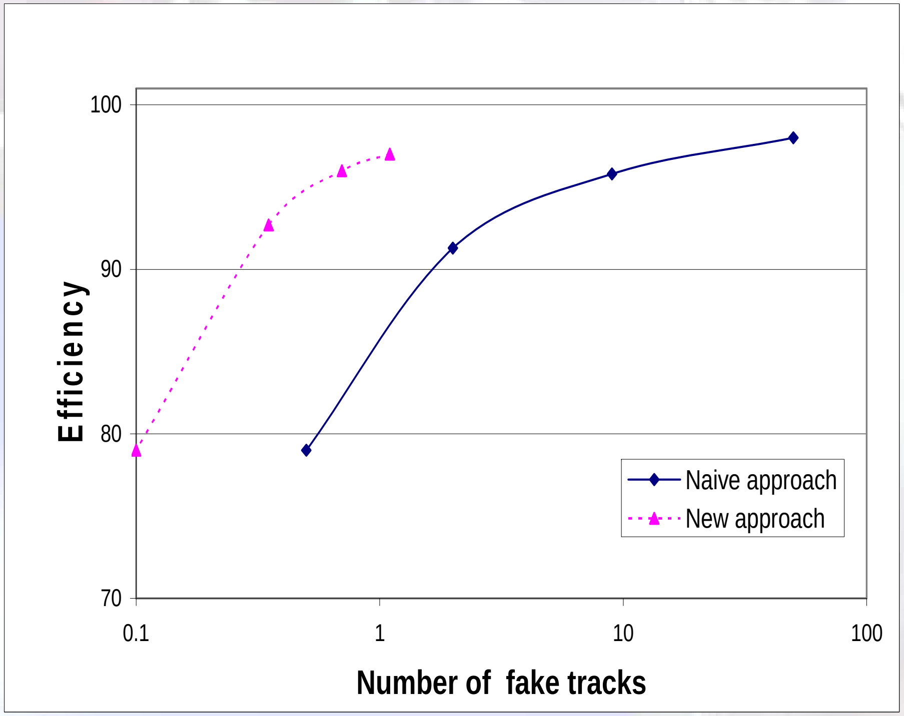
Hough and GLRT

- The algorithm is implemented by a Multi layers modified Hough transform, which has been proven to be an approximation to the GLRT:

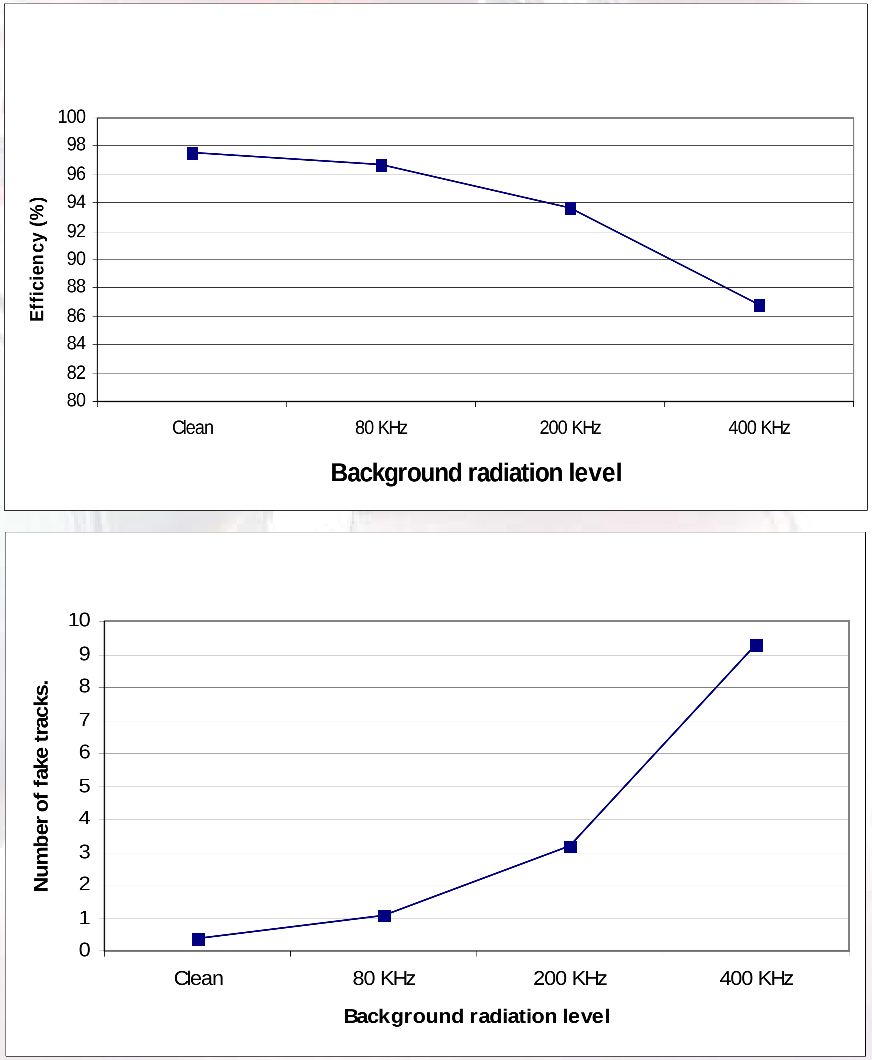
Primor D., Mikenberg, G and Messer H.
“AN APPROXIMATION OF THE GLRT FOR REAL TIME MUON DETECTION”
IEEE ICASSP 08

Results for test beam data

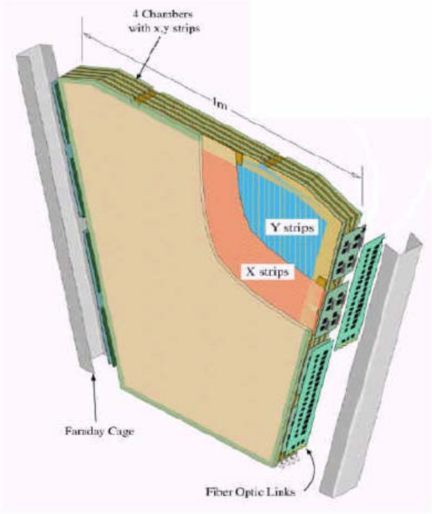
Radiation background of 80KHz/tube

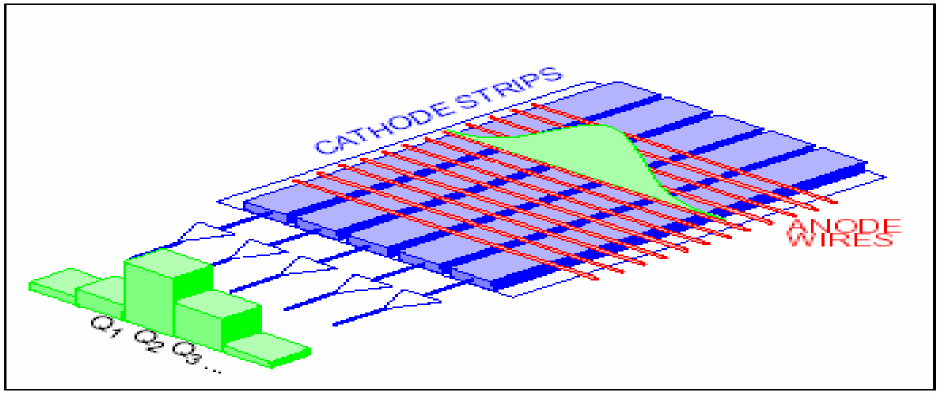


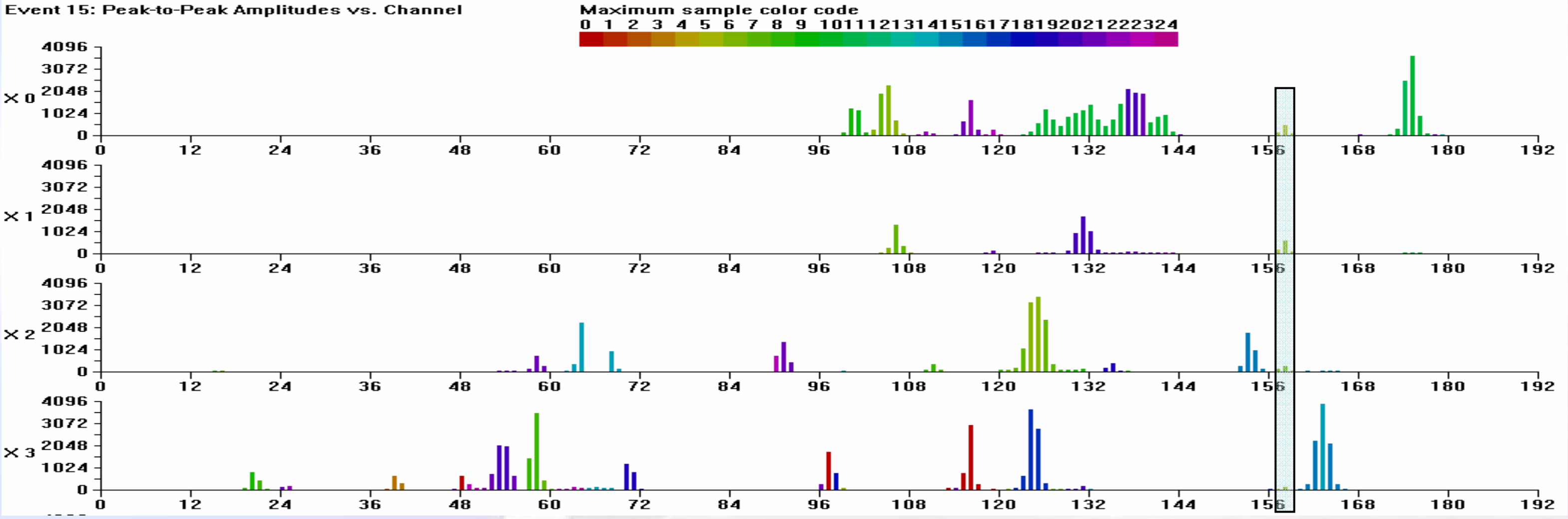
Performance of the proposed method for different radiation background



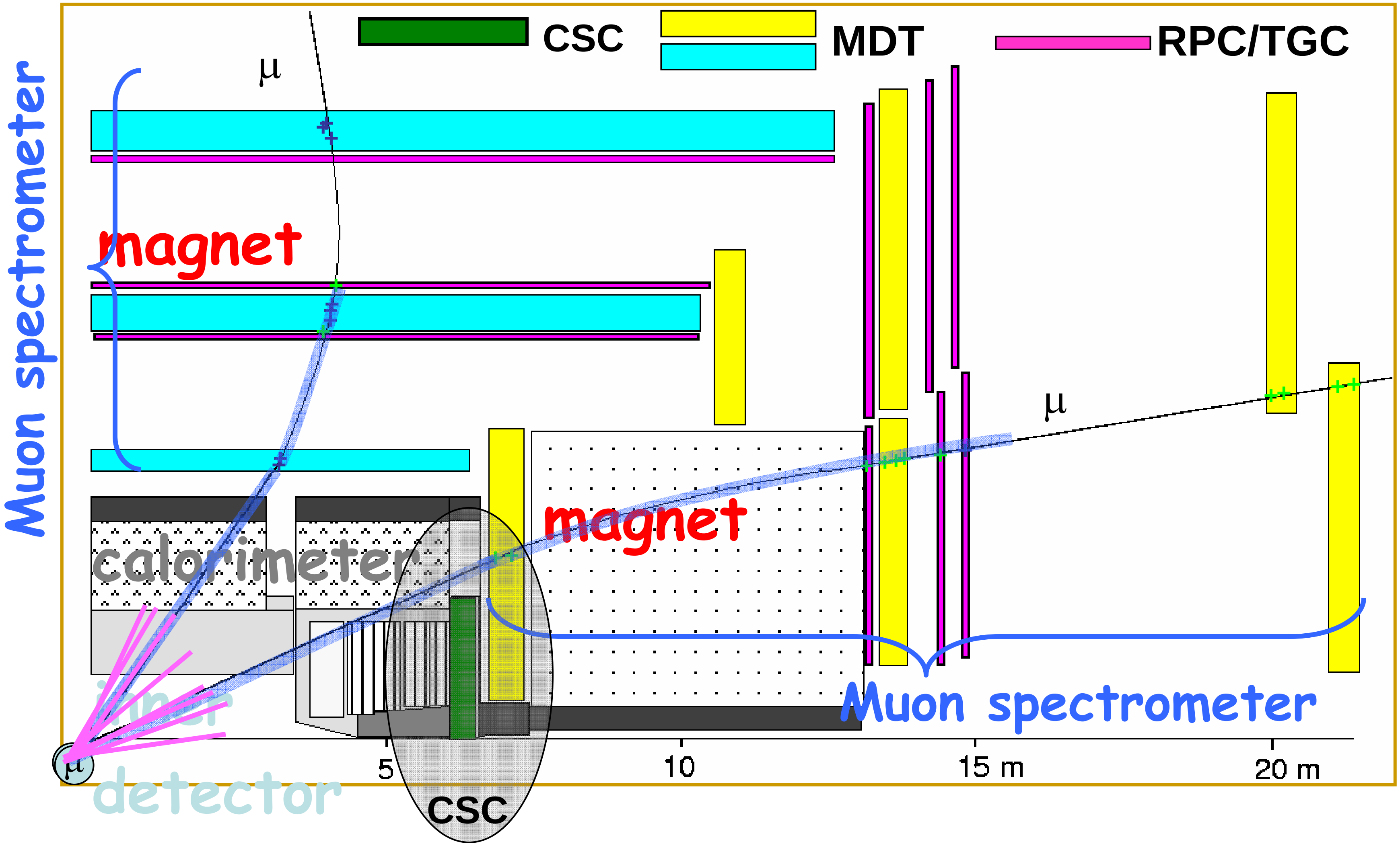
Local tracking in the CSC detector





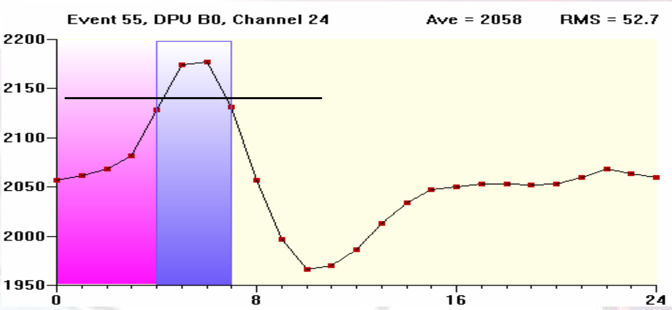


Combined muon reconstruction - example



The proposed approach

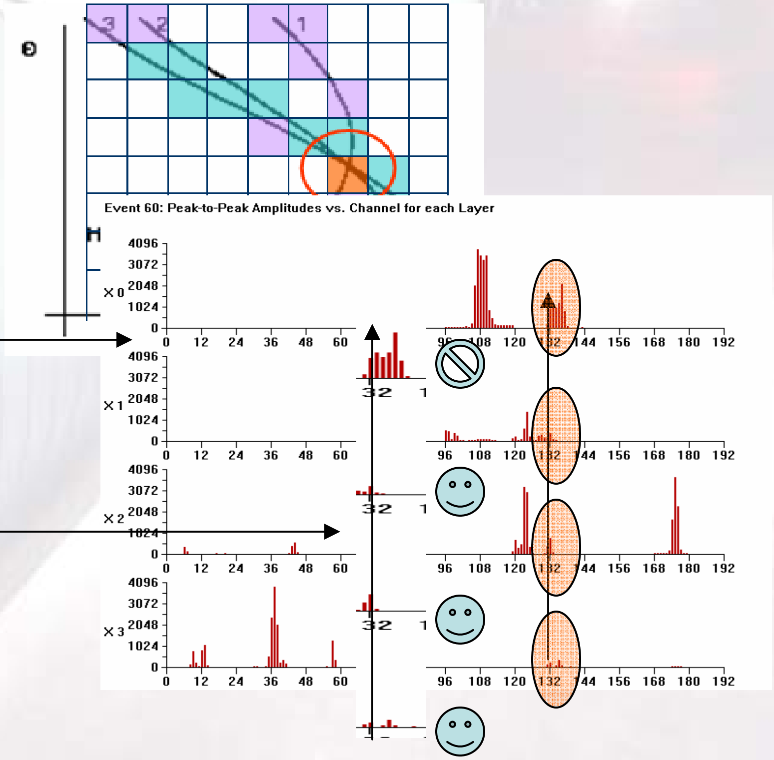
Activity detection within time interval



Track finding

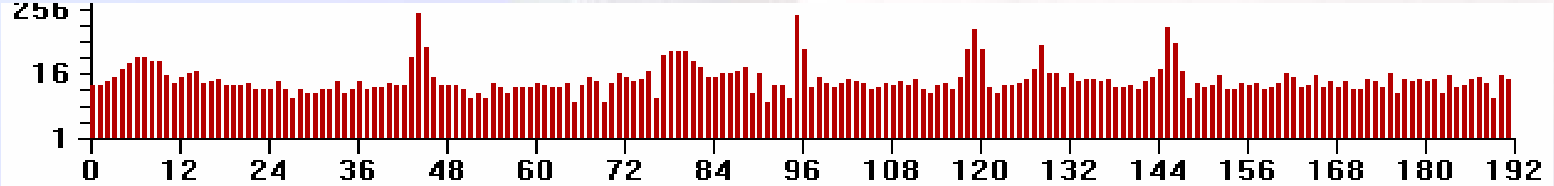
Cluster classification and localization

Line fitting



The detect-before-estimate approach

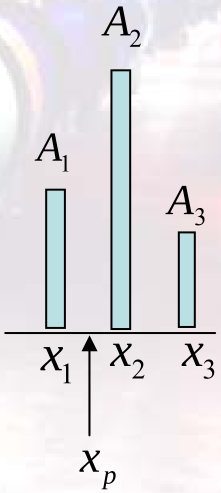
- With the presence of background the number of particle hits is much larger.
- Estimation of each cluster parameters before finding the track is unreasonable.
- We use a Hough Transform to “detect before estimate”.



The conventional hit position estimation

- The ratio algorithm

$$x_2 - \hat{x}_p = \begin{cases} \dfrac{A_2 - A_1}{A_2 - A_1} & A_1 > A_3 \\ \dfrac{A_2 - A_3}{A_2 - A_1} & A_3 > A_1 \end{cases}$$

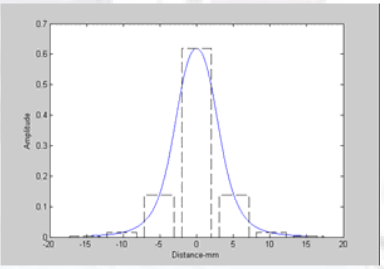


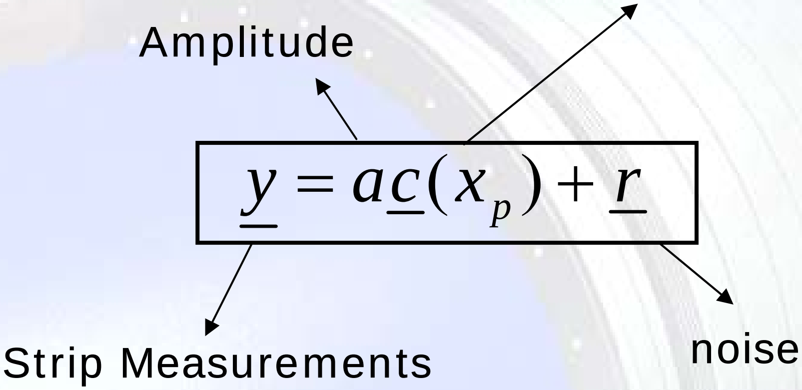
- The COM algorithm:

$$\hat{x}_p = \sum_{i=1}^{N} x_i A_i / \sum_{i=1}^{N} A_i$$

The LS approach

Matheison dist.





Amplitude

$$\boxed{\underline{y} = a\underline{c}(x_p) + \underline{r}}$$

Strip Measurements

noise

$$\underline{y} = [y(0), y(1), ..., y(N-1)]$$

$$\underline{r} = [r(0), r(1), ..., r(N-1)]^T$$

$$\underline{c}(x_p) = [S(0-x_p), S(1-x_p), ..., S(N-1-x_p)]^T$$

$$\boxed{\hat{x}_p = \arg\max_{x_p} \frac{(\underline{y}^T \underline{c}(x_p))^2}{\underline{c}(x_p)^T \underline{c}(x_p)}}$$

The EM algorithm*

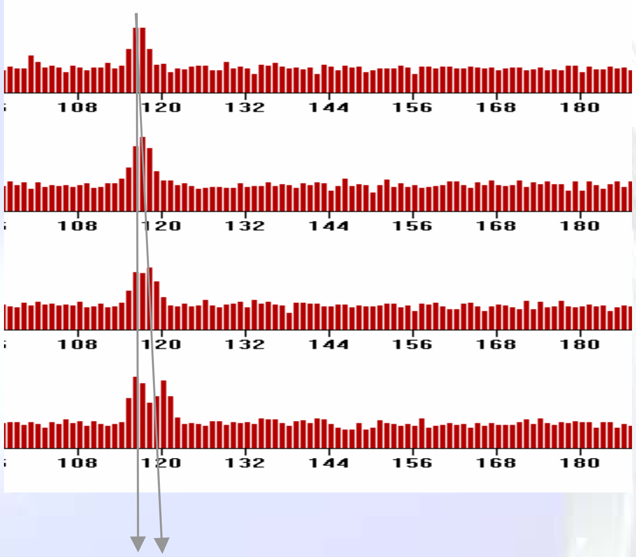
The use of the EM algorithm for the CSC MUON detection

in the next poster session “Detection & Estimation”

$$\boxed{\underline{y} = \mathbf{C}(\underline{x})\underline{a} + \underline{r}}$$

$$\mathbf{C}(\underline{x}) = \begin{bmatrix} S(0-x_{p1}) & S(0-x_{p2}) & \cdots & S(0-x_{pM}) \\ S(1-x_{p1}) & S(1-x_{p2}) & & \\ \vdots & & \ddots & \\ S(N-1-x_{p1}) & & & S(N-1-x_{pM}) \end{bmatrix}$$

$$\underline{a} = [a_1, a_2, \ldots, a_M]^T \qquad \underline{x} = [x_{p1}, x_{p2}, \ldots, x_{pM}]^T$$



$$\underline{\hat{y}}_{m,k} = a_{m,k}\underline{c}(x_{p_m,k}) + \frac{\sigma_m^{\;2}}{\sigma^2}(\underline{y} - \underline{c}(x_{p_m,k})a_{m,k})$$

$$\hat{a}_{m,k+1} = \frac{\underline{\hat{y}}_{m,k}{}^T \underline{c}(x_{p_m,k+1})}{\underline{c}(x_{p_m,k+1})^T \underline{c}(x_{p_m,k+1})}$$

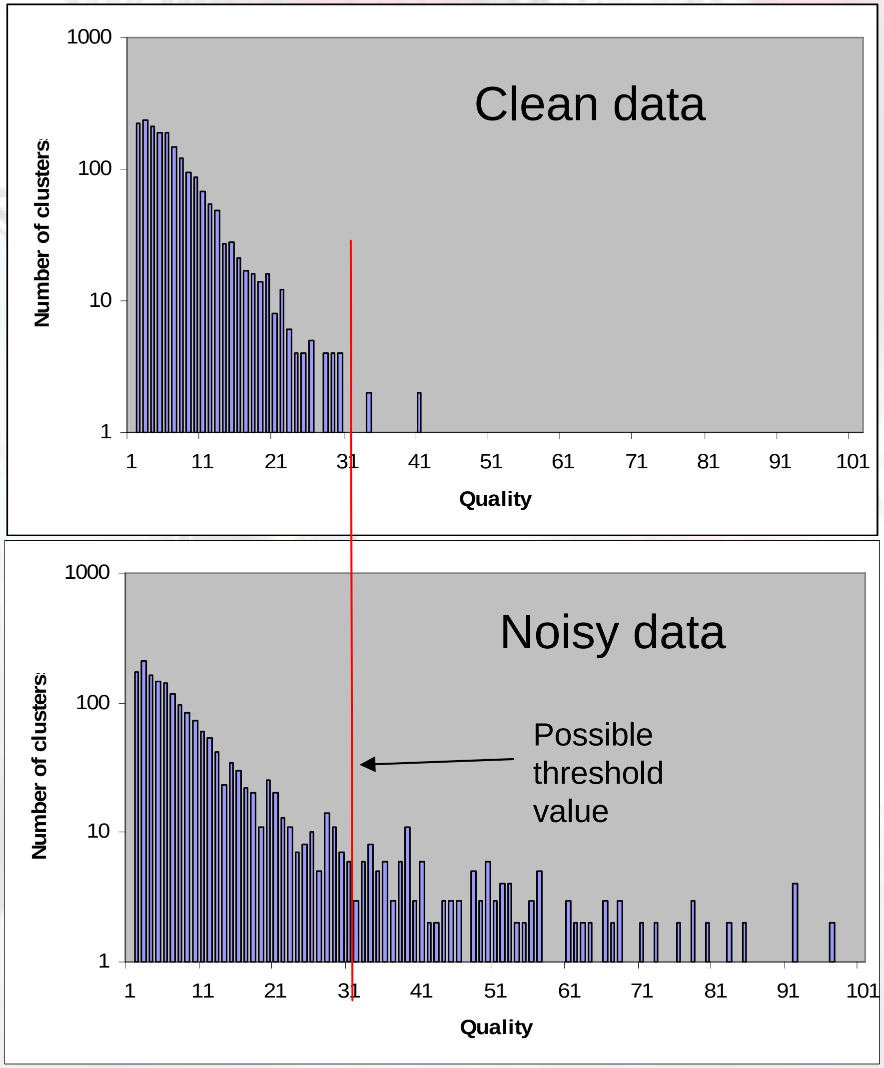
$$\hat{x}_{p_m,k+1} = \arg\max_{x_{p_m}} \frac{(\underline{\hat{y}}_{m,k}{}^T \underline{c}(x_{p_m}))^2}{\underline{c}(x_{p_m})^T \underline{c}(x_{p_m})}$$

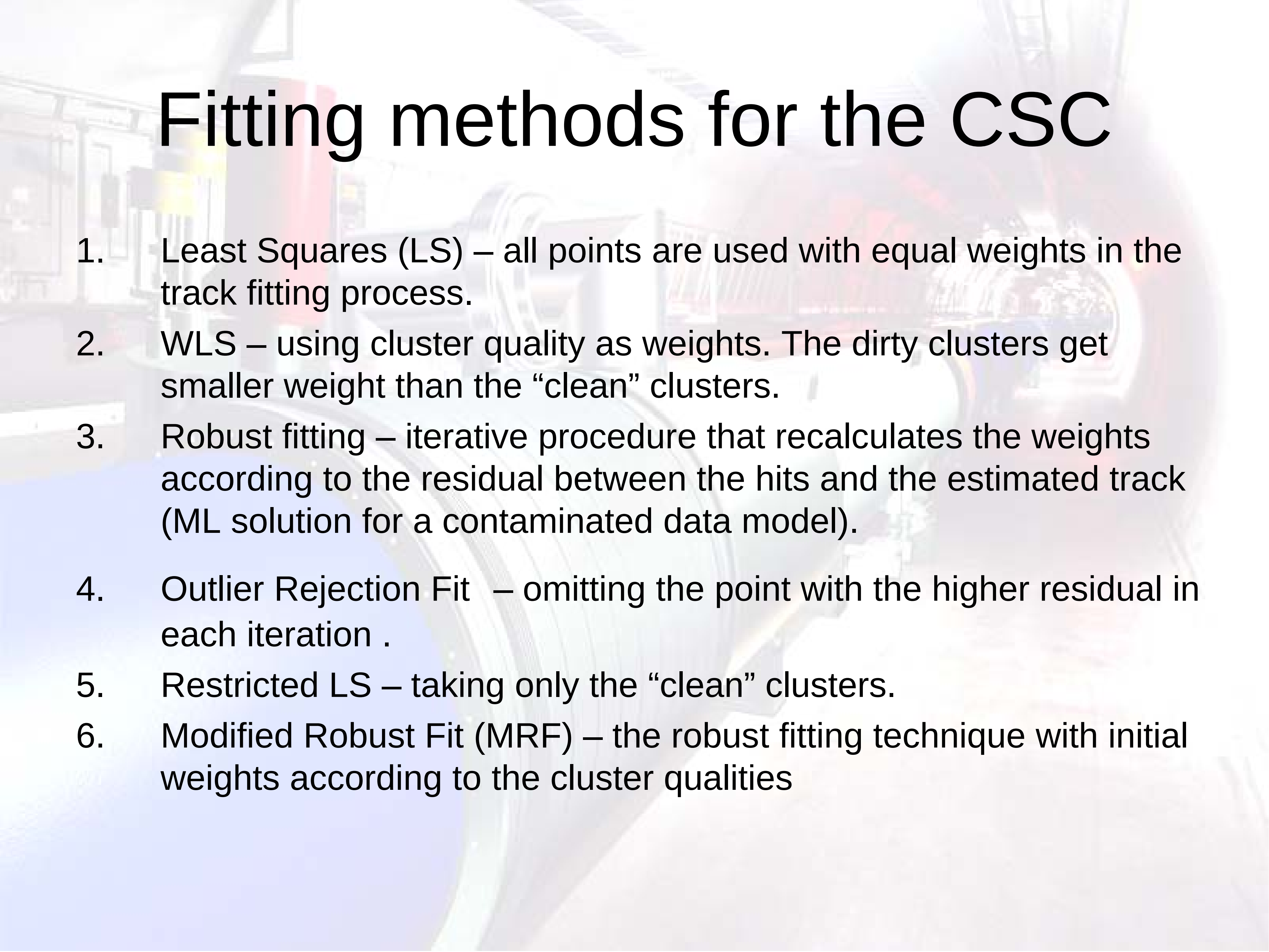
Quality of clusters

Off line threshold setting
based on the test beam data

$$\boxed{\underline{y} = a\underline{c}(x_p) + \underline{r}}$$

$$\boxed{Q \equiv | \underline{y} - \hat{a}\underline{c}(\hat{x}_p) |^2 > \lambda'}$$

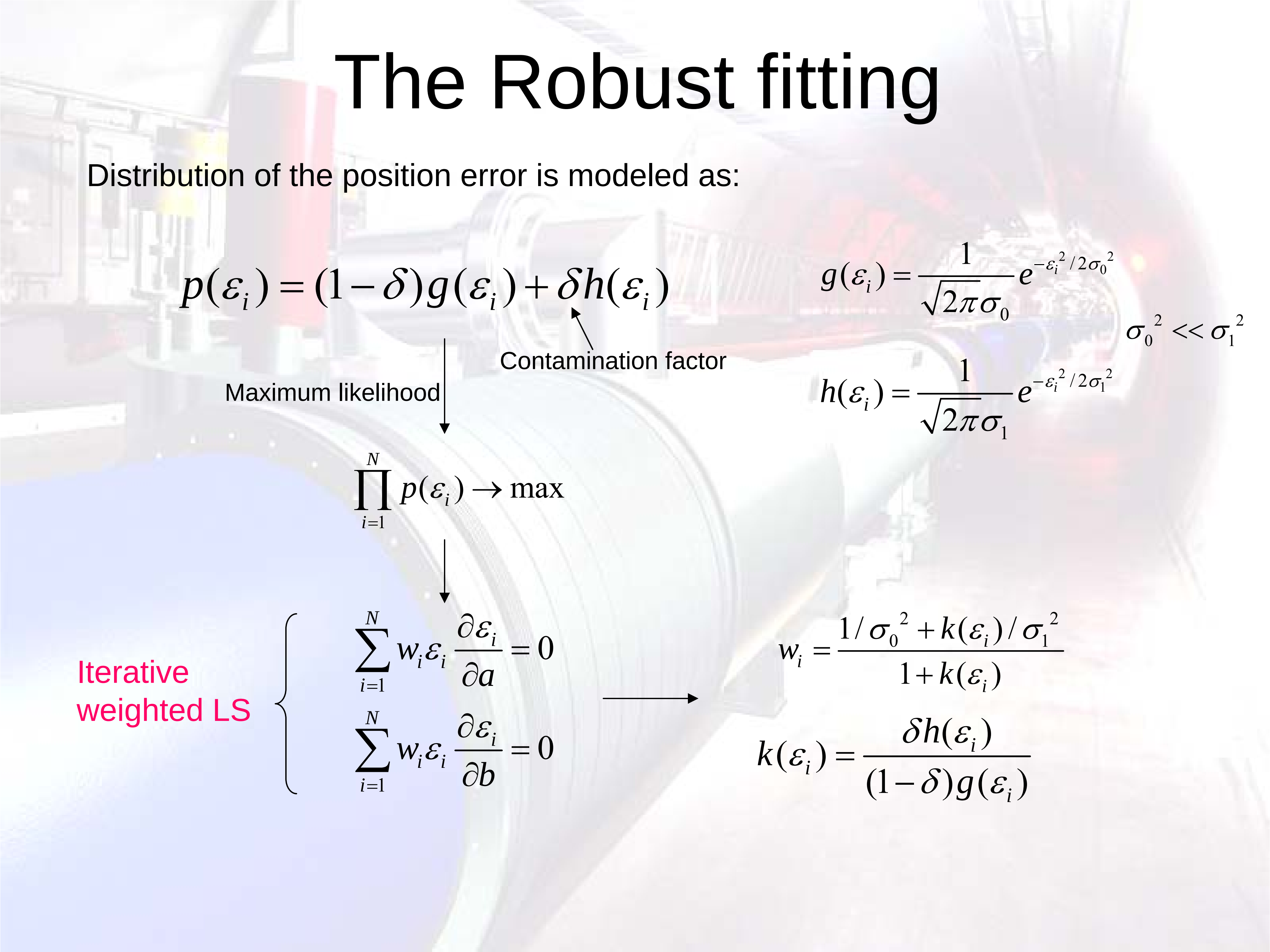




Fitting methods for the CSC

1. Least Squares (LS) – all points are used with equal weights in the track fitting process.
2. WLS – using cluster quality as weights. The dirty clusters get smaller weight than the “clean” clusters.
3. Robust fitting – iterative procedure that recalculates the weights according to the residual between the hits and the estimated track (ML solution for a contaminated data model).
4. Outlier Rejection Fit – omitting the point with the higher residual in each iteration .
5. Restricted LS – taking only the “clean” clusters.
6. Modified Robust Fit (MRF) – the robust fitting technique with initial weights according to the cluster qualities

The Robust fitting



Distribution of the position error is modeled as:

$$p(\varepsilon_i) = (1-\delta)g(\varepsilon_i) + \delta h(\varepsilon_i)$$

Contamination factor

$$g(\varepsilon_i) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{-\varepsilon_i^2/2\sigma_0^2}$$

$$\sigma_0^2 << \sigma_1^2$$

$$h(\varepsilon_i) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\varepsilon_i^2/2\sigma_1^2}$$

Maximum likelihood

$$\prod_{i=1}^{N} p(\varepsilon_i) \rightarrow \max$$

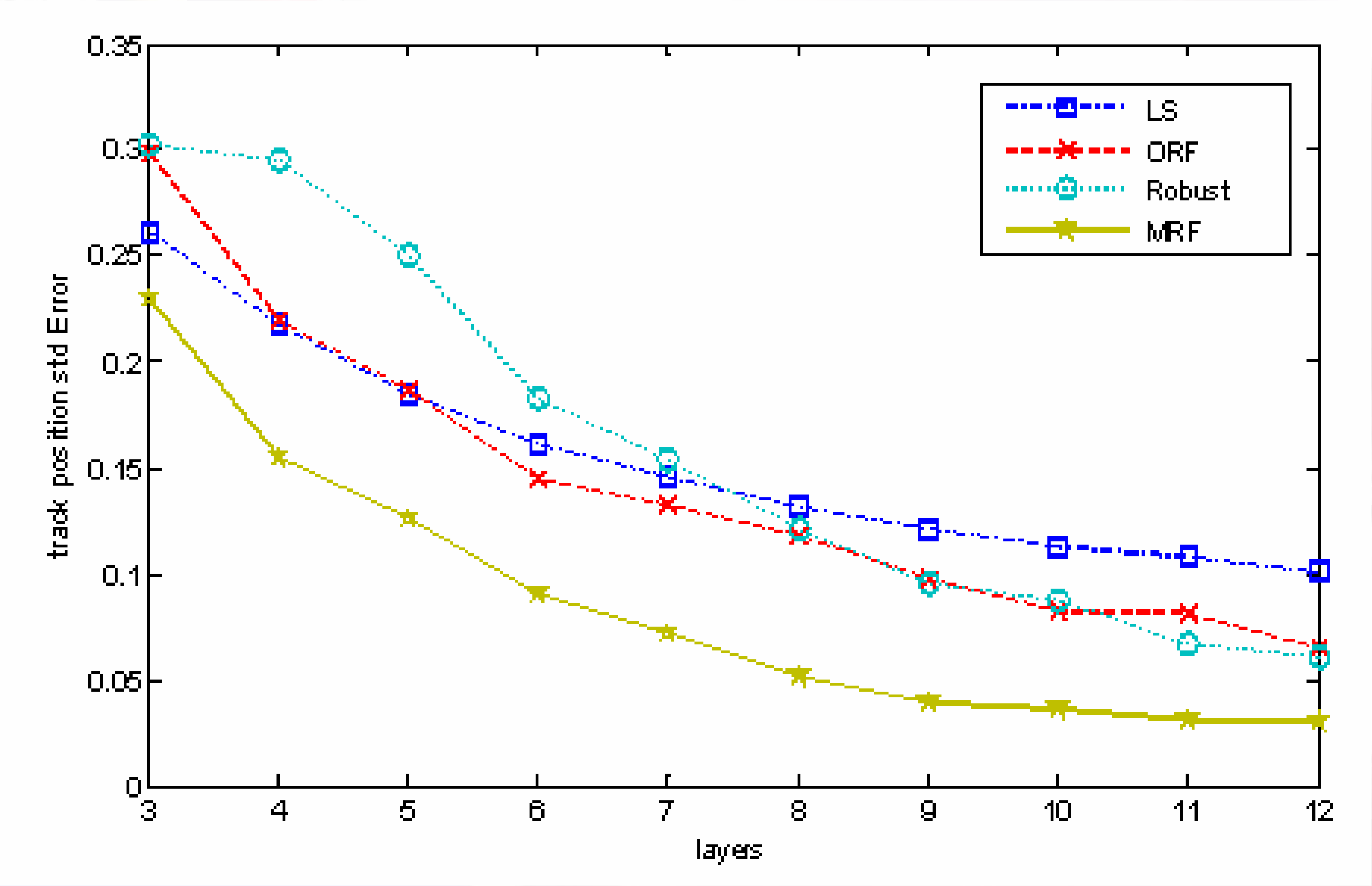
Iterative weighted LS

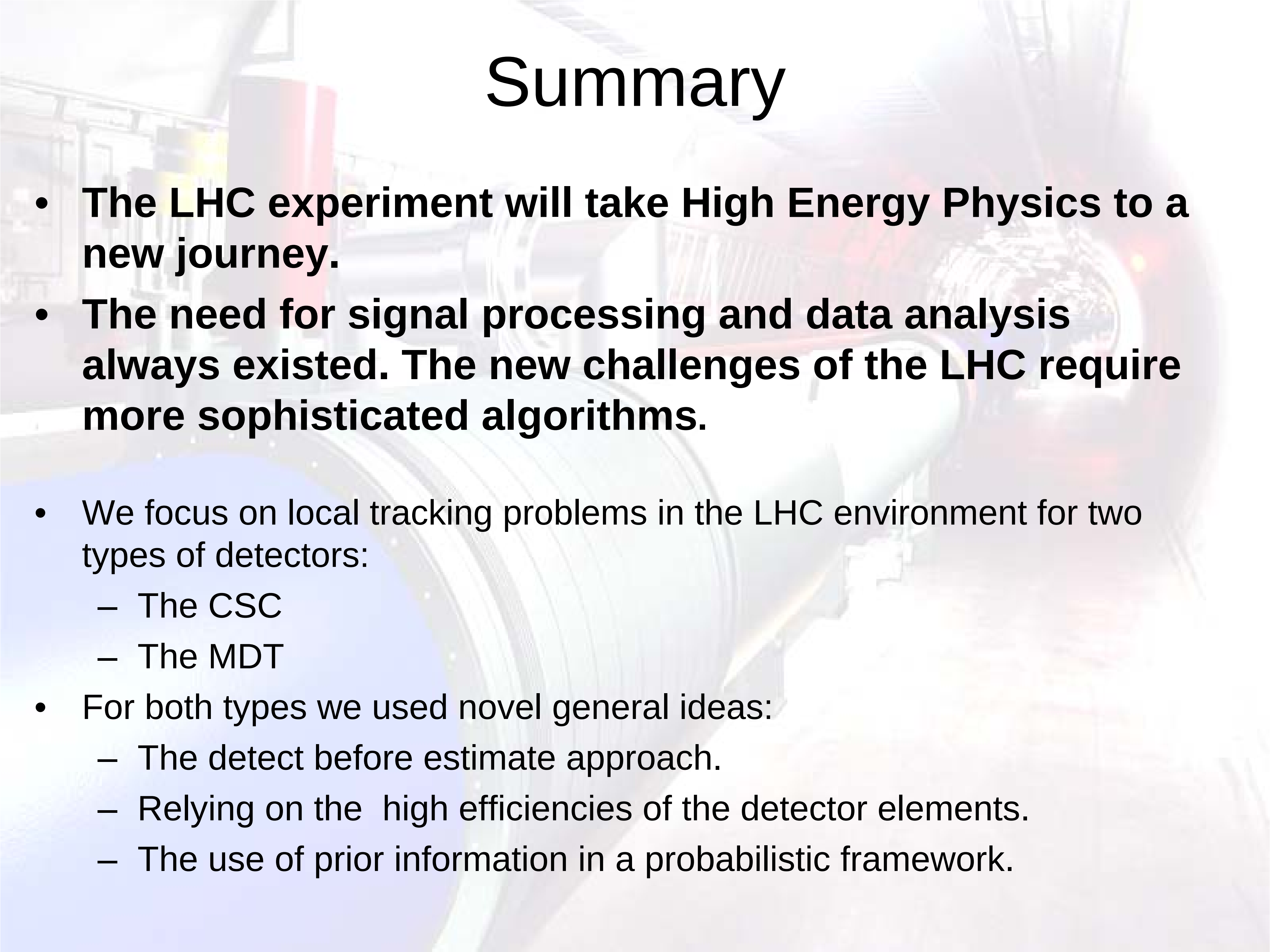
$$\left\{ \begin{array}{l} \sum_{i=1}^{N} w_i \varepsilon_i \frac{\partial \varepsilon_i}{\partial a} = 0 \\ \sum_{i=1}^{N} w_i \varepsilon_i \frac{\partial \varepsilon_i}{\partial b} = 0 \end{array} \right. \longrightarrow$$

$$w_i = \frac{1/\sigma_0^2 + k(\varepsilon_i)/\sigma_1^2}{1+k(\varepsilon_i)}$$

$$k(\varepsilon_i) = \frac{\delta h(\varepsilon_i)}{(1-\delta)g(\varepsilon_i)}$$

Fitting performance for number of layers

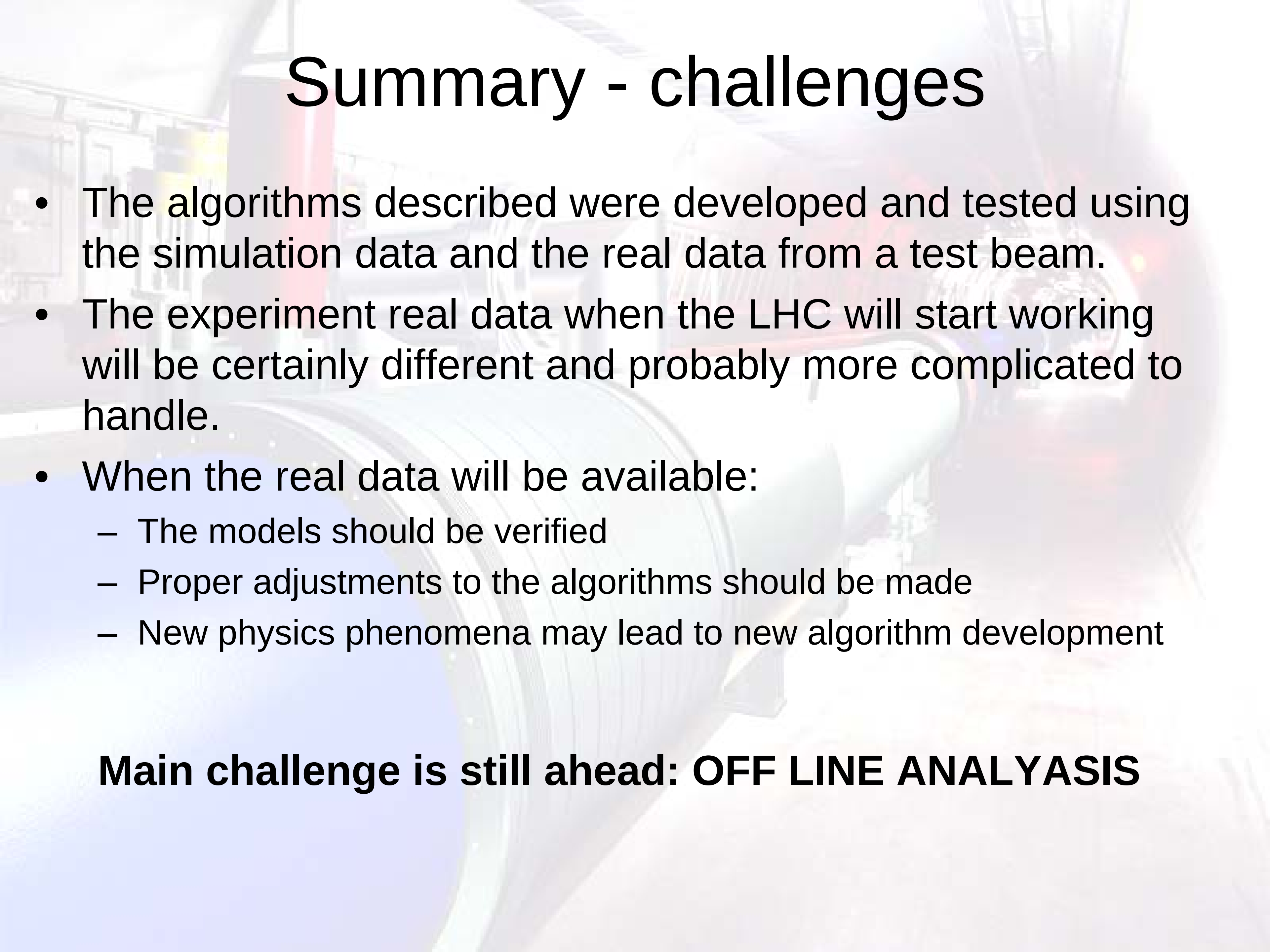




Summary

- **The LHC experiment will take High Energy Physics to a new journey.**
- **The need for signal processing and data analysis always existed. The new challenges of the LHC require more sophisticated algorithms.**

- We focus on local tracking problems in the LHC environment for two types of detectors:
  - The CSC
  - The MDT
- For both types we used novel general ideas:
  - The detect before estimate approach.
  - Relying on the high efficiencies of the detector elements.
  - The use of prior information in a probabilistic framework.

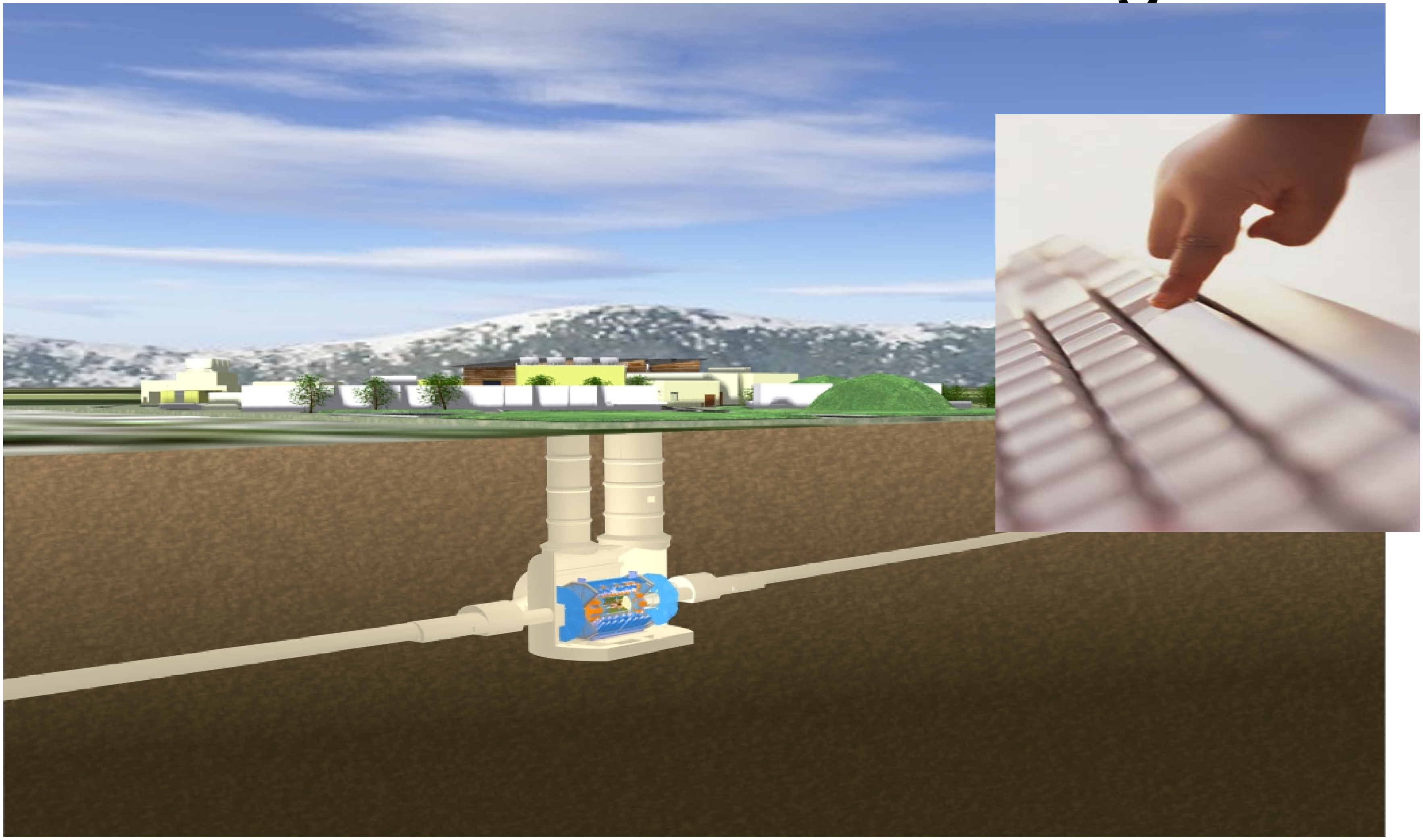


Summary - challenges

- The algorithms described were developed and tested using the simulation data and the real data from a test beam.
- The experiment real data when the LHC will start working will be certainly different and probably more complicated to handle.
- When the real data will be available:
  - The models should be verified
  - Proper adjustments to the algorithms should be made
  - New physics phenomena may lead to new algorithm development

Main challenge is still ahead: OFF LINE ANALYASIS

OK – lets start running*



*The accelerator is expected to have first injections in August 2008 and collision data before the end of the year (at 10 TeV and in 2009 at 14TeV)

Papers

Papers published in scientific journals and conferences:

1. Primor, D., Mikenberg, G., and Messer, H. Muon Detection in the ATLAS CSC Detector, *IEEE transaction on Nuclear Science*, 54:3, 635-642, June 2007
2. Primor, D., Kortner, O., Mikenberg, G., and Messer, H. A novel approach to track finding in a drift tube chamber. *Journal of Instrumentation (JINST),* P01009, 30/1/2007.
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