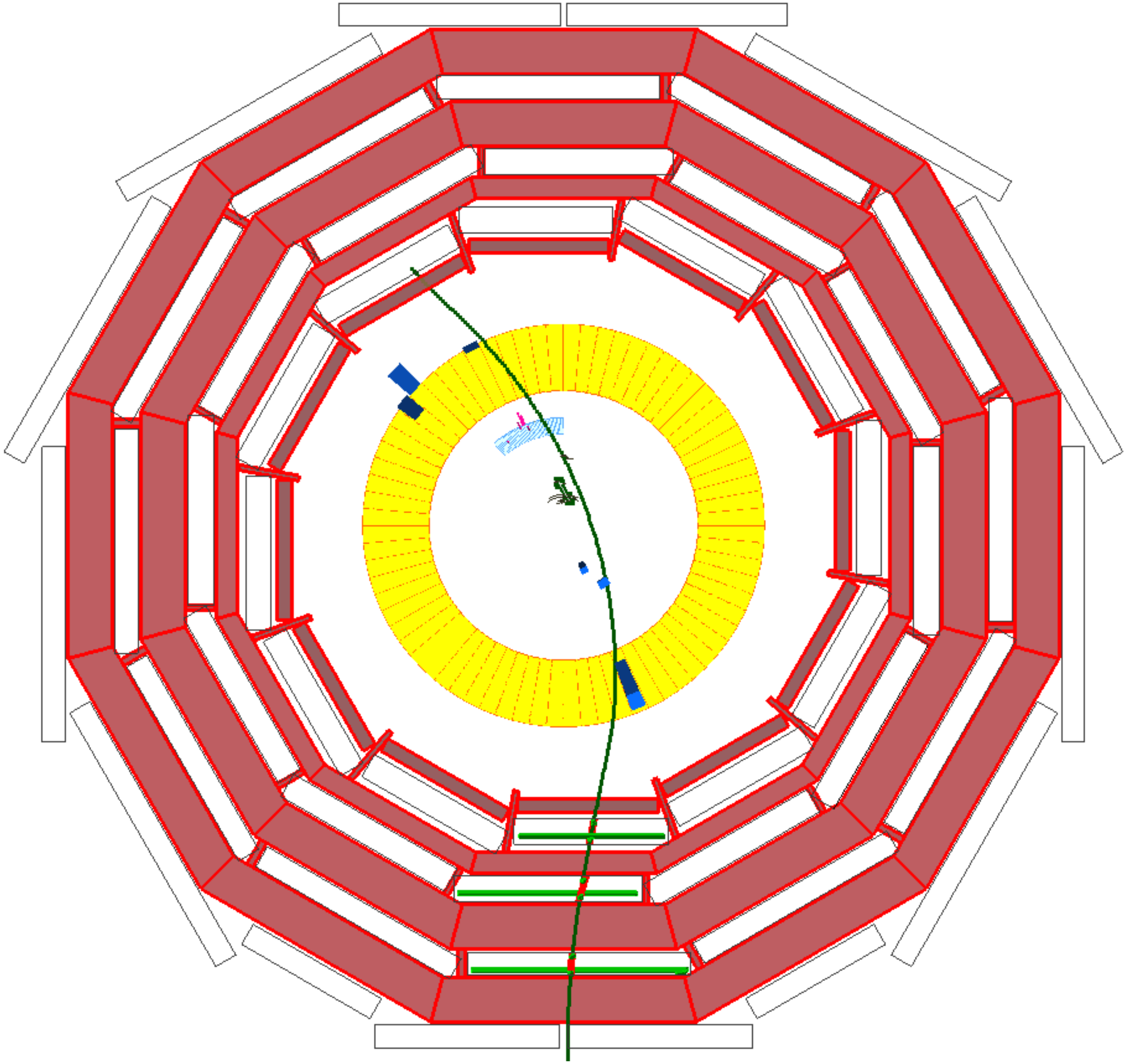
Muon Reconstruction with the *CMS* Detector

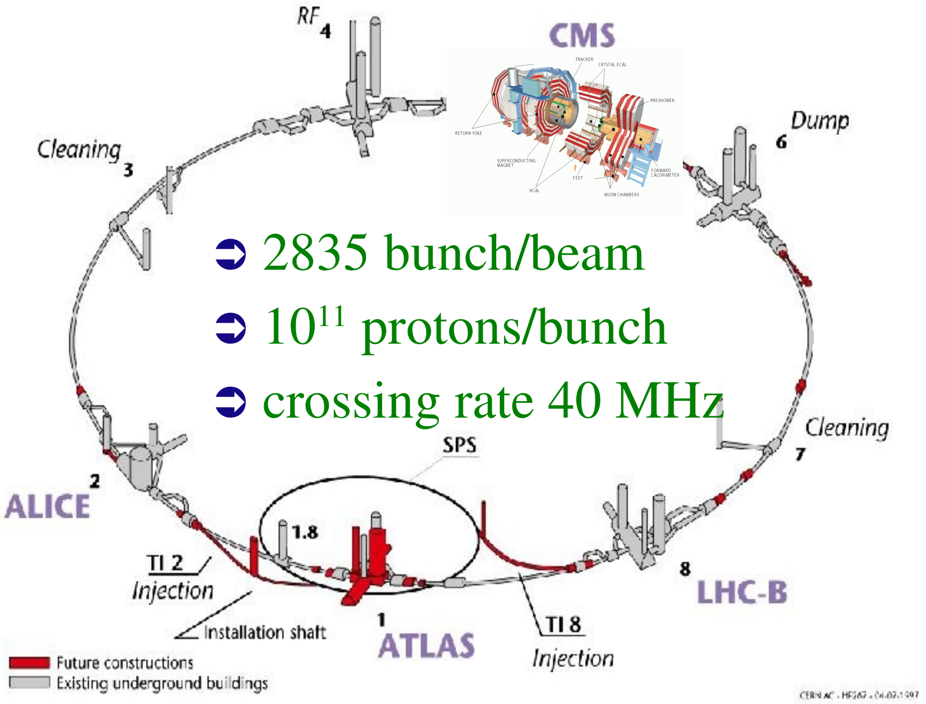


Riccardo Bellan

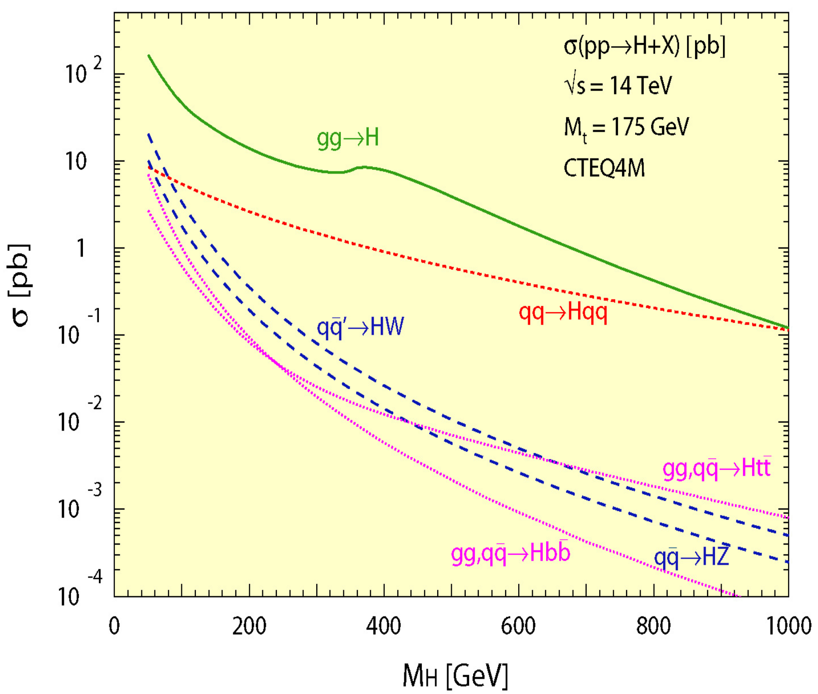
Outline

- Introduction to LHC and CMS
- Muon reconstruction strategy
  - local reconstruction
  - track reconstruction
  - high level trigger
- Muon reconstruction performance
- Torino activities in CMS

Large Hadron Collider (LHC)



- ➲ 2835 bunch/beam
- ➲ 10^{11} protons/bunch
- ➲ crossing rate 40 MHz



Spira et al. hep-ph/9803257

- Requirement on energy
  - span energy regions from 10 GeV to 2000 GeV

⇨ beam energy 7 TeV

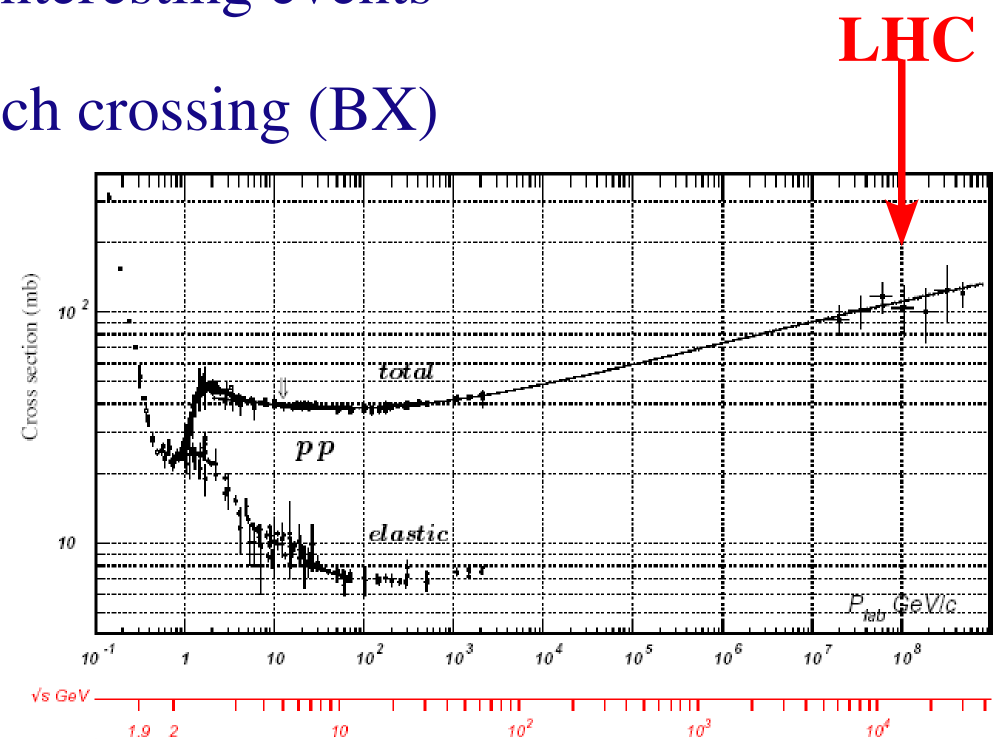
- Requirement on # of good events per year
  - High luminosity

⇨ $L_{low} = 2\times10^{33}\ cm^{-2}s^{-1}$

$L_{high} = 10^{34}\ cm^{-2}s^{-1}$

The Challenges

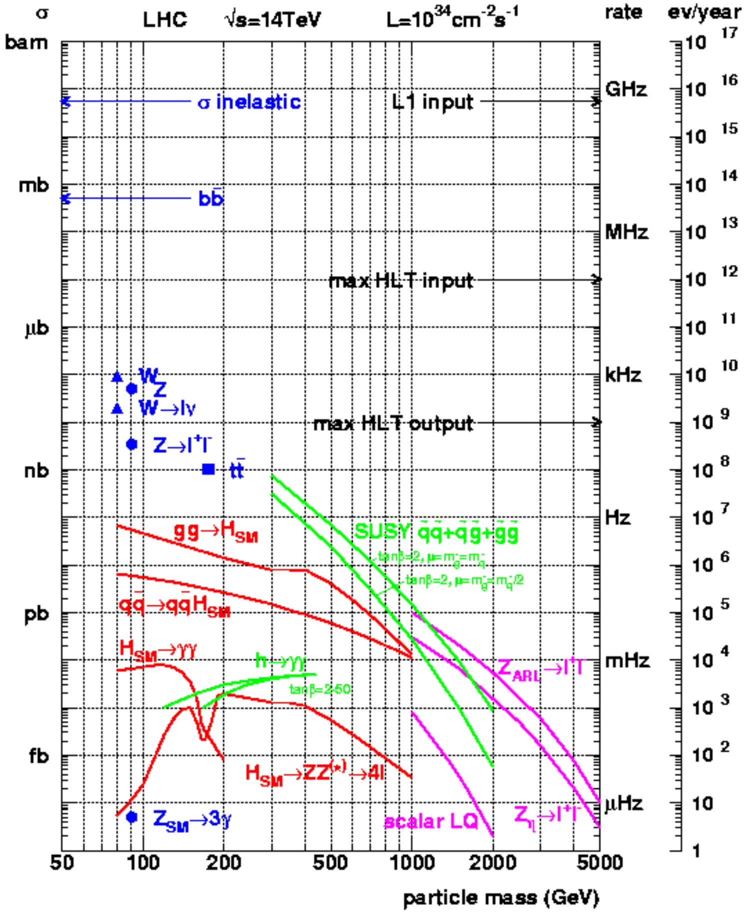
- Very high rate in the detectors
- QCD background surround all the interesting events
- Number of interaction for each bunch crossing (BX)
  - interactions per second:
    - $L_{high} = 10^{34}\ cm^{-2}s^{-1}$
    - $\sigma_{pp}(14TeV) \approx 70$ mb
    - $R \approx 7 \cdot 10^{8}$ Hz
  - events per BX
    - $\Delta t = 25$ ns
    - interaction per BX = 17.5



- Not all the bunches are filled
  - 2835 out of 3564
    - **Interaction / filled BX = 22**

The Discovery pass through the lepton reconstruction

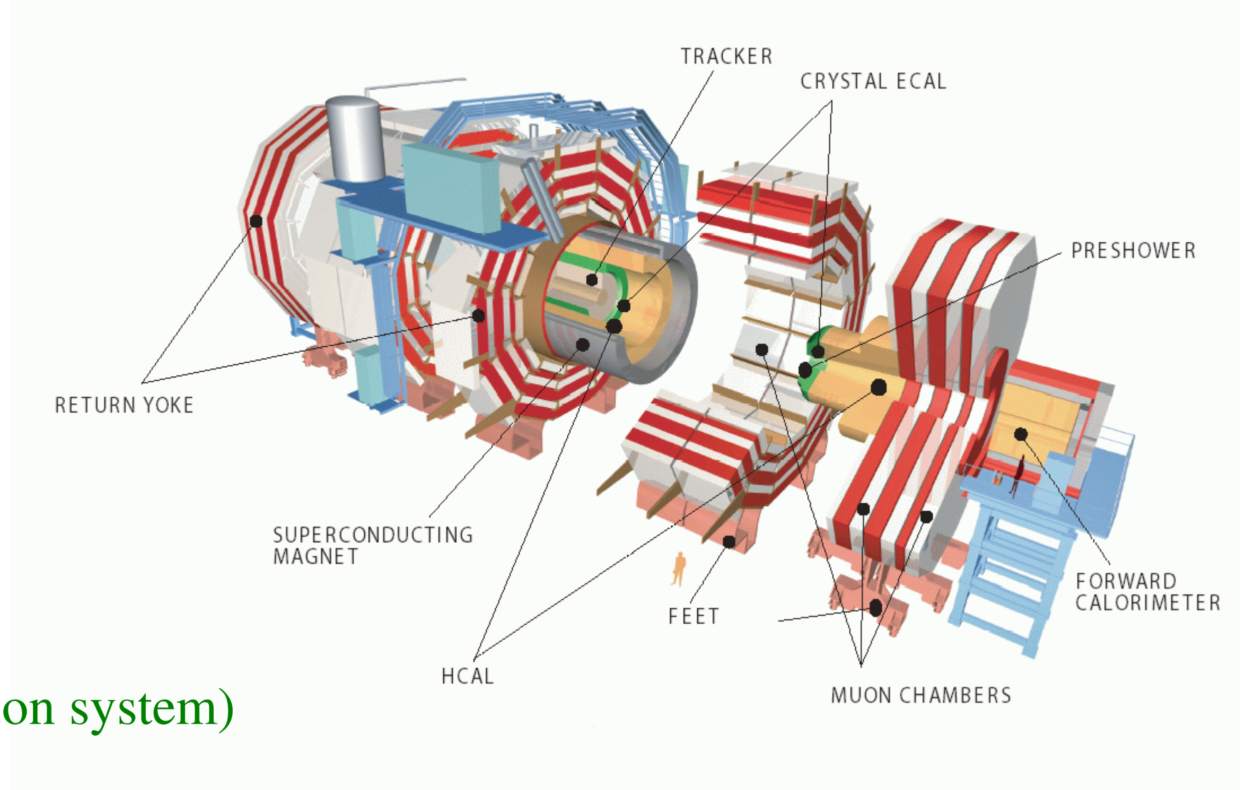
- A good event will contain:
  - top, Higgs, or new physics and...
  - ~22 interaction superimposed to the signal
- In an hadron-hadron collider it is fundamental to design a detector capable to reconstruct leptons with
  - high resolution
  - high efficiency
  - high purity
- The golden channel for the Higgs discovery is
  - pp→H→ZZ→4μ



Compact Muon Solenoid (CMS)

Parameters

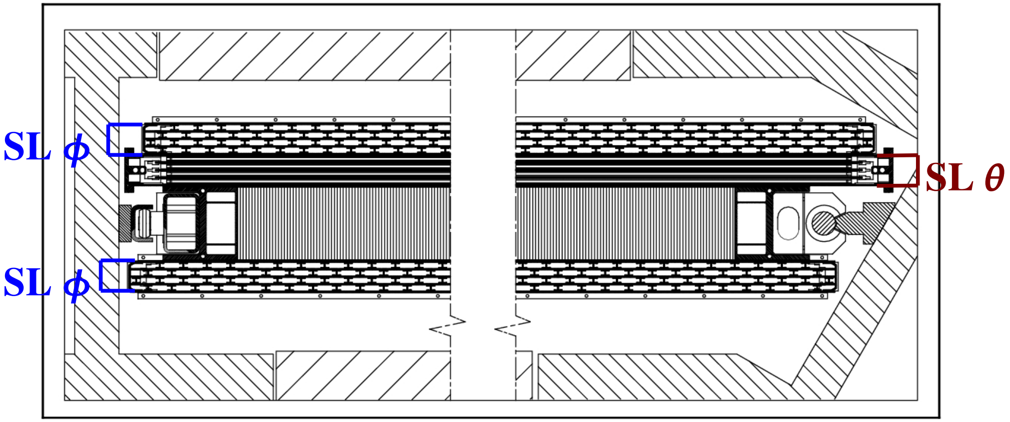
- diameter = 15 m
- length = 21.6 m
- Weight = 12 000 t
- Solenoidal Magnetic field
  - 4 T in the inner barrel
  - 1.8 T in the return yoke (muon system)



Drawback

- from the dimensions
  - finite value of the speed of light means that in 25 ns a particle travels ~7.5 m
- from the detector itself
  - response time (i.e. the drift tubes integrates the signal over 500 ns = 20 BX) from the dimensions

The CMS muon system



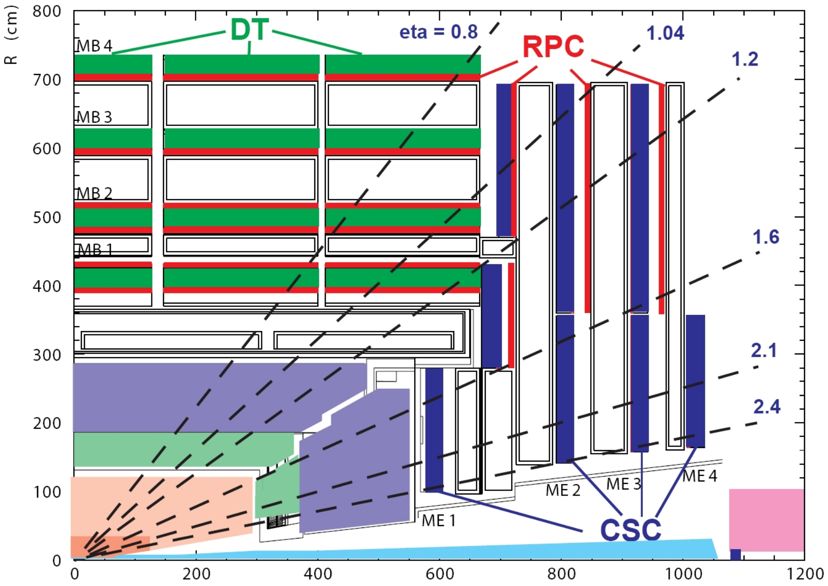
3 Super Layer (2ϕ and 1θ) for the first 3 stations

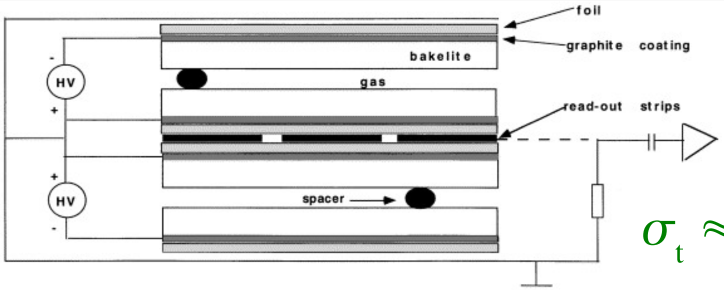
2 Super Layer (2ϕ) for the last station

DT

4 Layer for each Super Layer

$\sigma_x \approx 200\ \mu m$



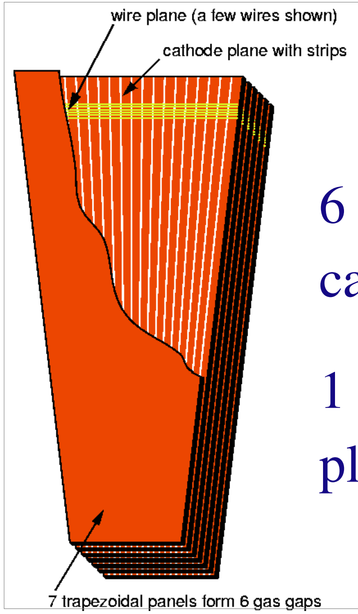


RPC

$\sigma_t \approx 2\ ns$

2 RPC chamber for the first 2 DT stations

1 RPC chamber for the last 2 DT stations and for the CSC chamber till $|\eta|<1.6$



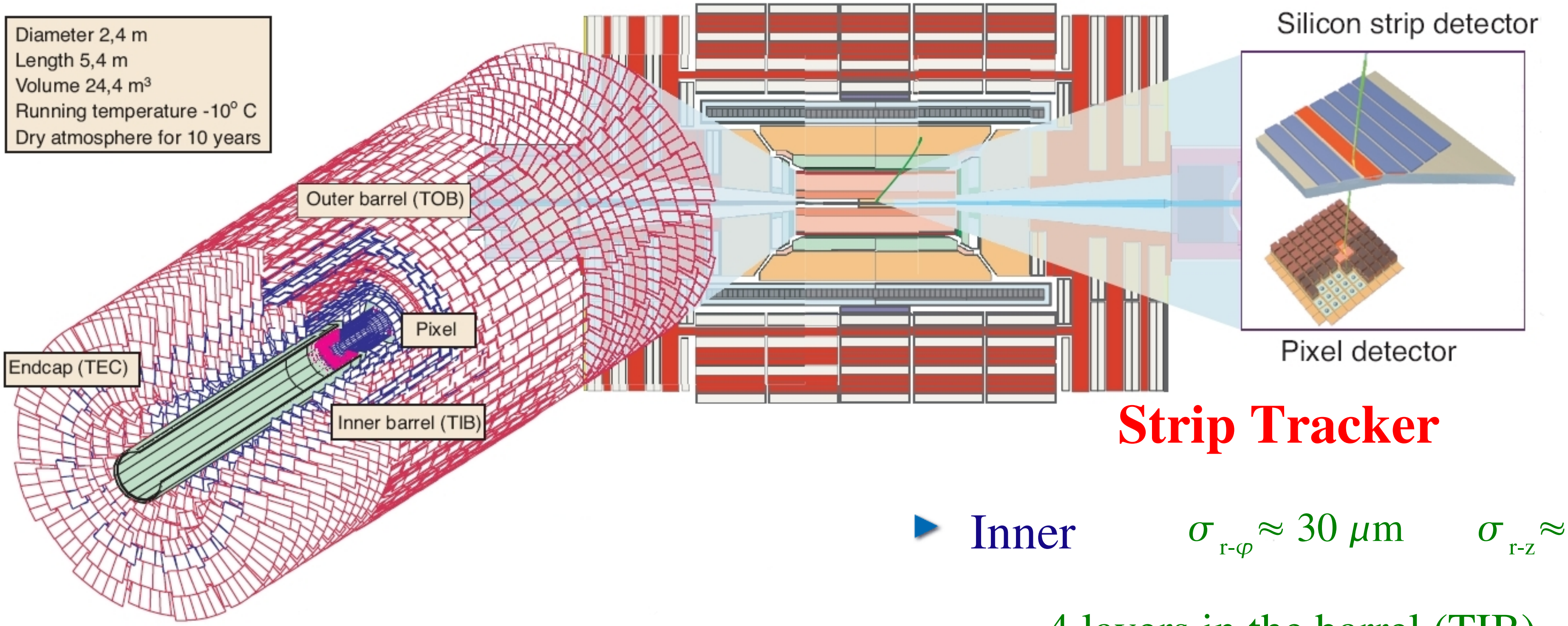
CSC

6 gaps (Layers) for each camber

1 wire plane and 1 cathode plane with strips

$\sigma_x \approx 100\text{-}240\ \mu m$

Tracker Layout



Diameter 2,4 m
Length 5,4 m
Volume 24,4 m³
Running temperature -10° C
Dry atmosphere for 10 years

Pixel Tracker

- 3 Layers in the barrel
- 2 disks for each end caps

$\sigma_{r\text{-}\varphi} \approx 10\ \mu m$ $\sigma_{r\text{-}z} \approx 20\ \mu m$

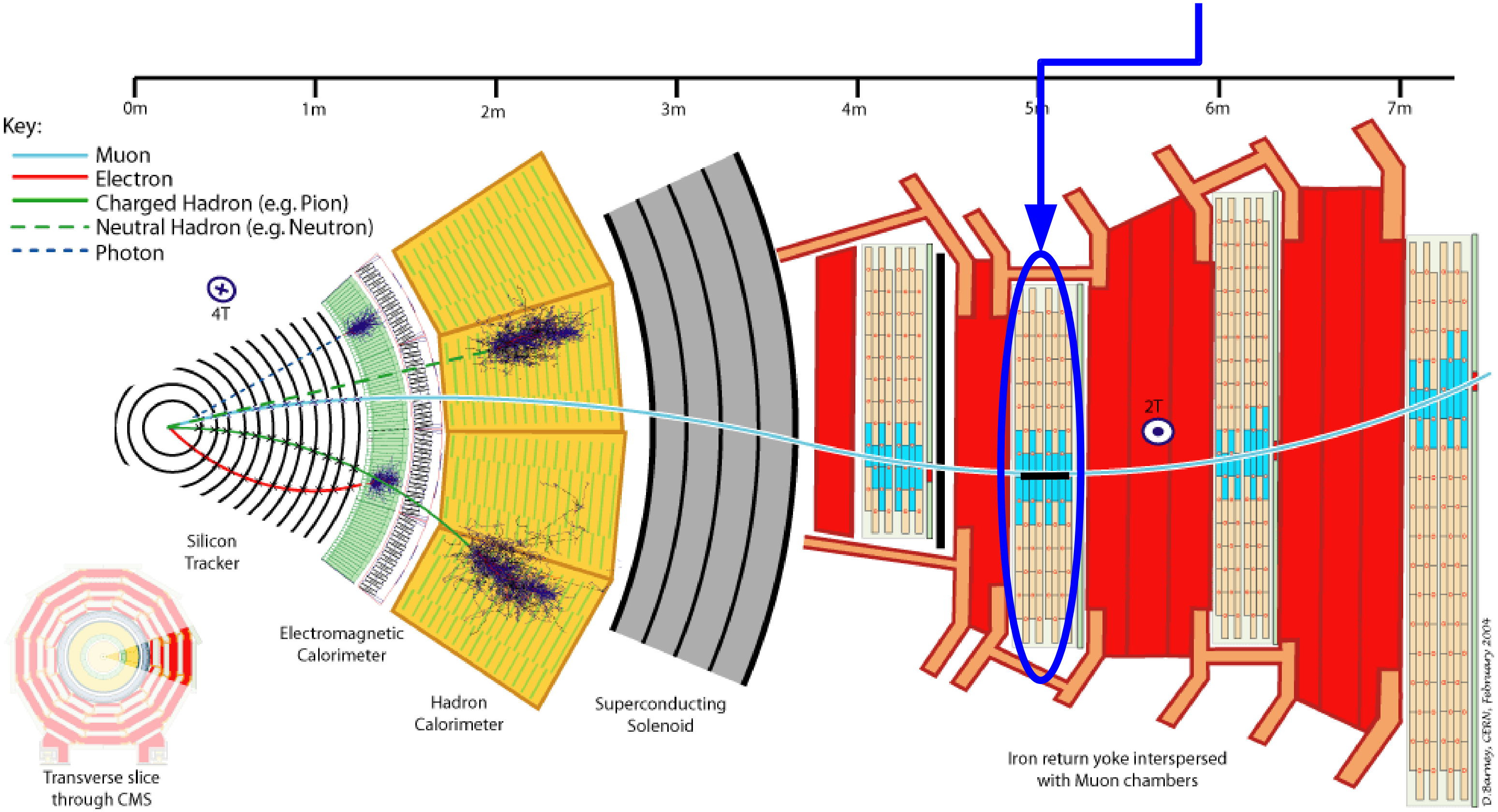
Strip Tracker

- Inner $\sigma_{r\text{-}\varphi} \approx 30\ \mu m$ $\sigma_{r\text{-}z} \approx 230\ \mu m$
  - 4 layers in the barrel (TIB)
  - 3 disks for each endcap (TID)
- outer $\sigma_{r\text{-}\varphi} \approx 40\ \mu m$ $\sigma_{r\text{-}z} \approx 530\ \mu m$
  - 6 layers in the barrel (TOB)
  - 9 disks for each endcap (TEC)

Muon Reconstruction

The muon reconstruction is divided into **three steps**

① Reconstruction of the **hits** and the **track segments** inside a chamber.

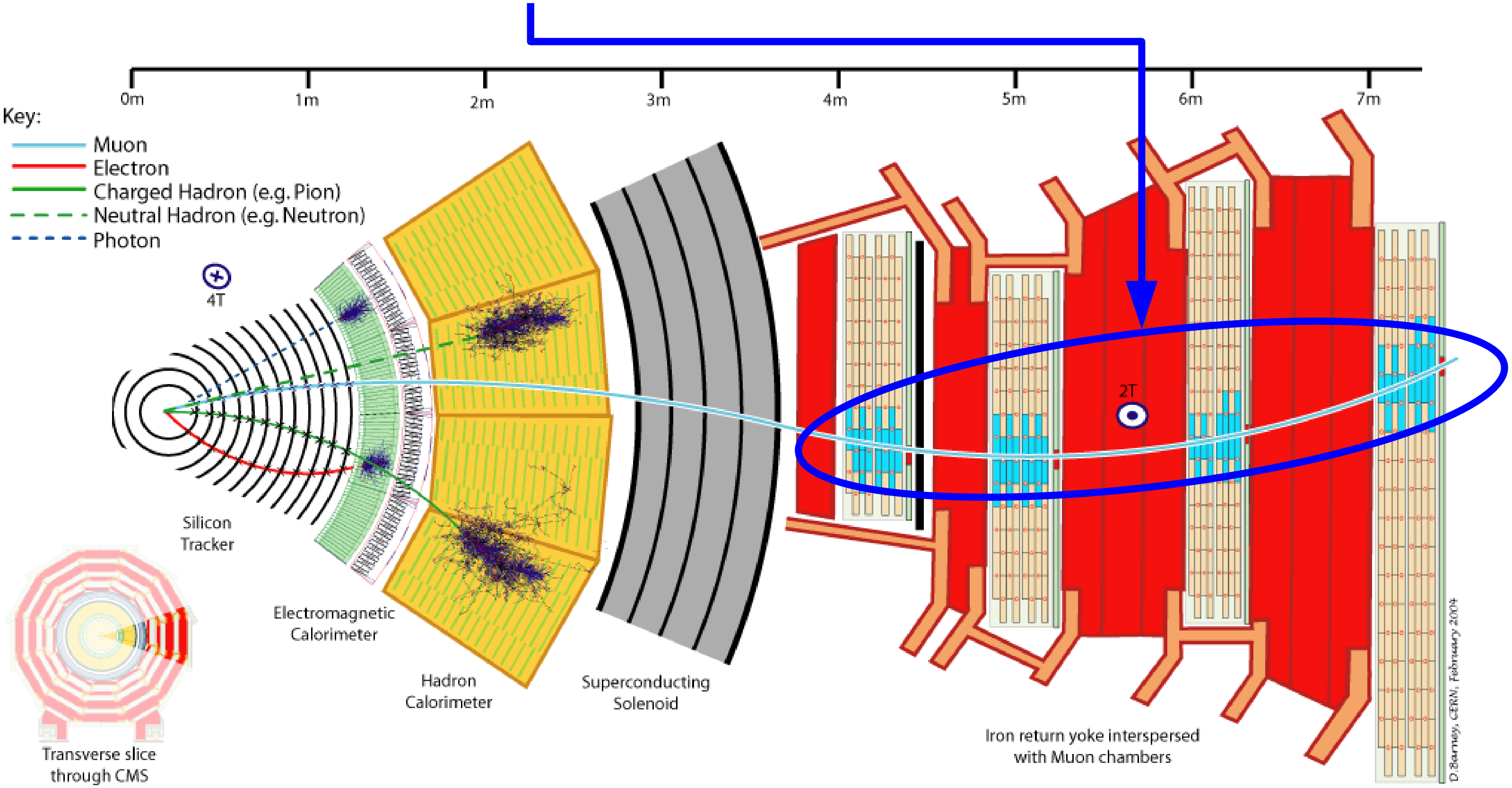


Muon Reconstruction

The muon reconstruction is divided into **three steps**

① Reconstruction of the **hits** and the **track segments** inside a chamber.

② Reconstruction of the **track** inside the **muon system**



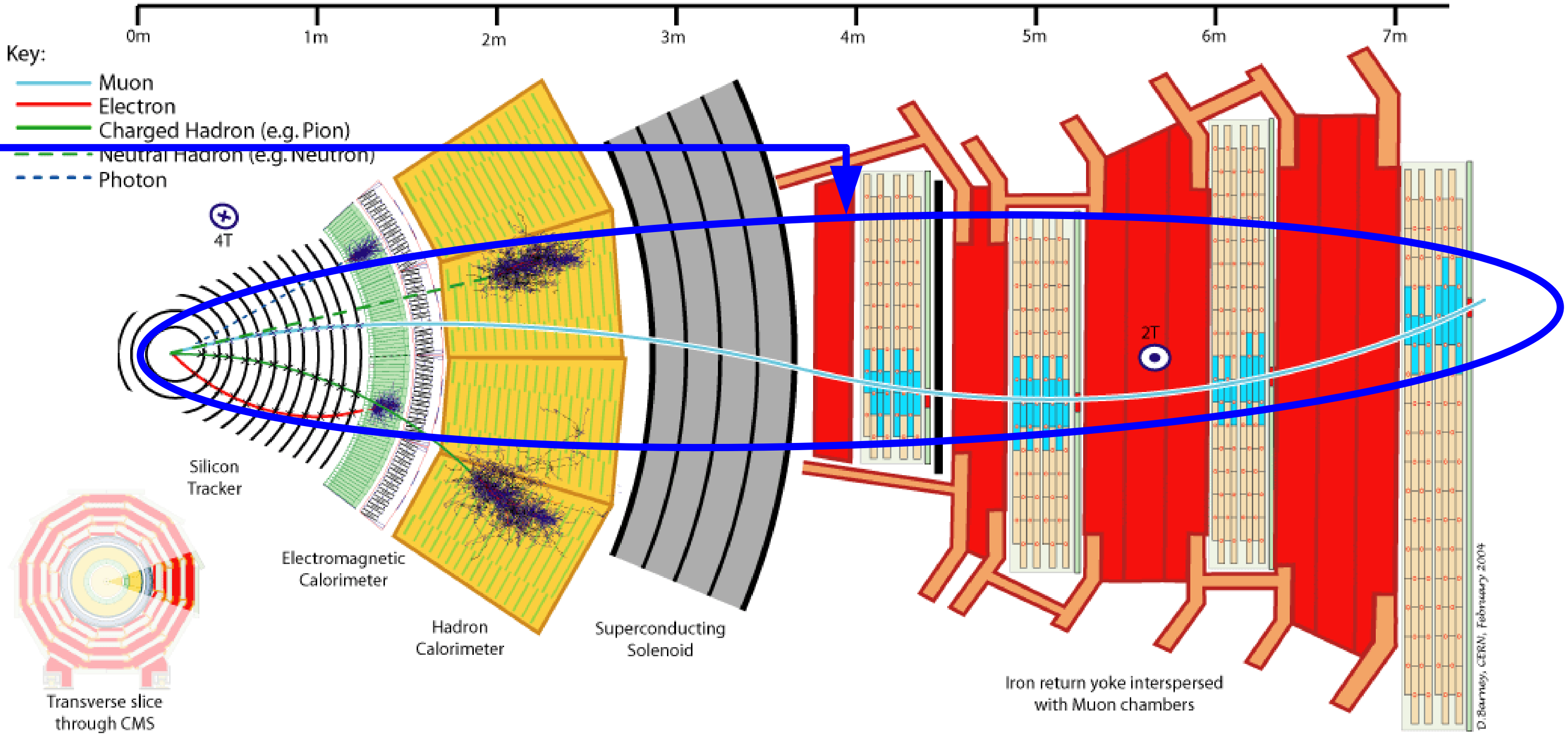
Muon Reconstruction

The muon reconstruction is divided into **three steps**

③ Reconstruction of the track combining the information from the **tracker** *and* **the muon system**

② Reconstruction of the **track** inside the **muon system**

① Reconstruction of the **hits** and the **track segments** inside a chamber.

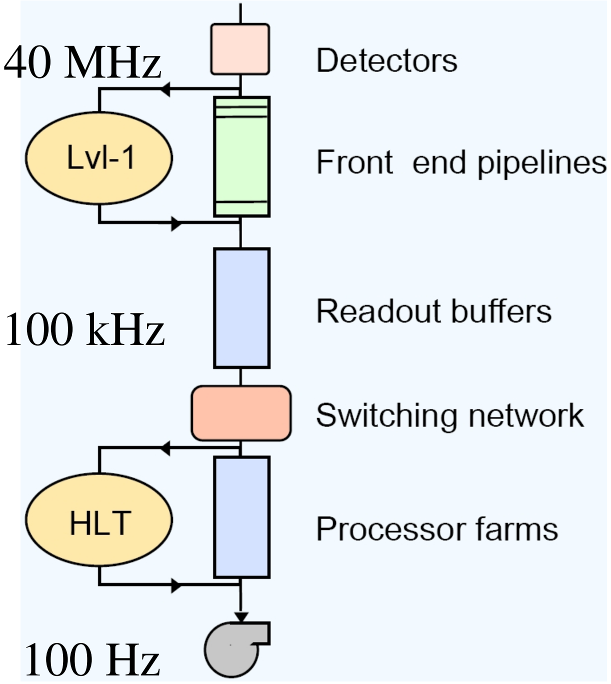


Muon High Level Trigger

L1 – *Hardware*

HLT (**L2**/**L3**) – *Software*

⇨ same algorithms and framework as the **off-line software**!



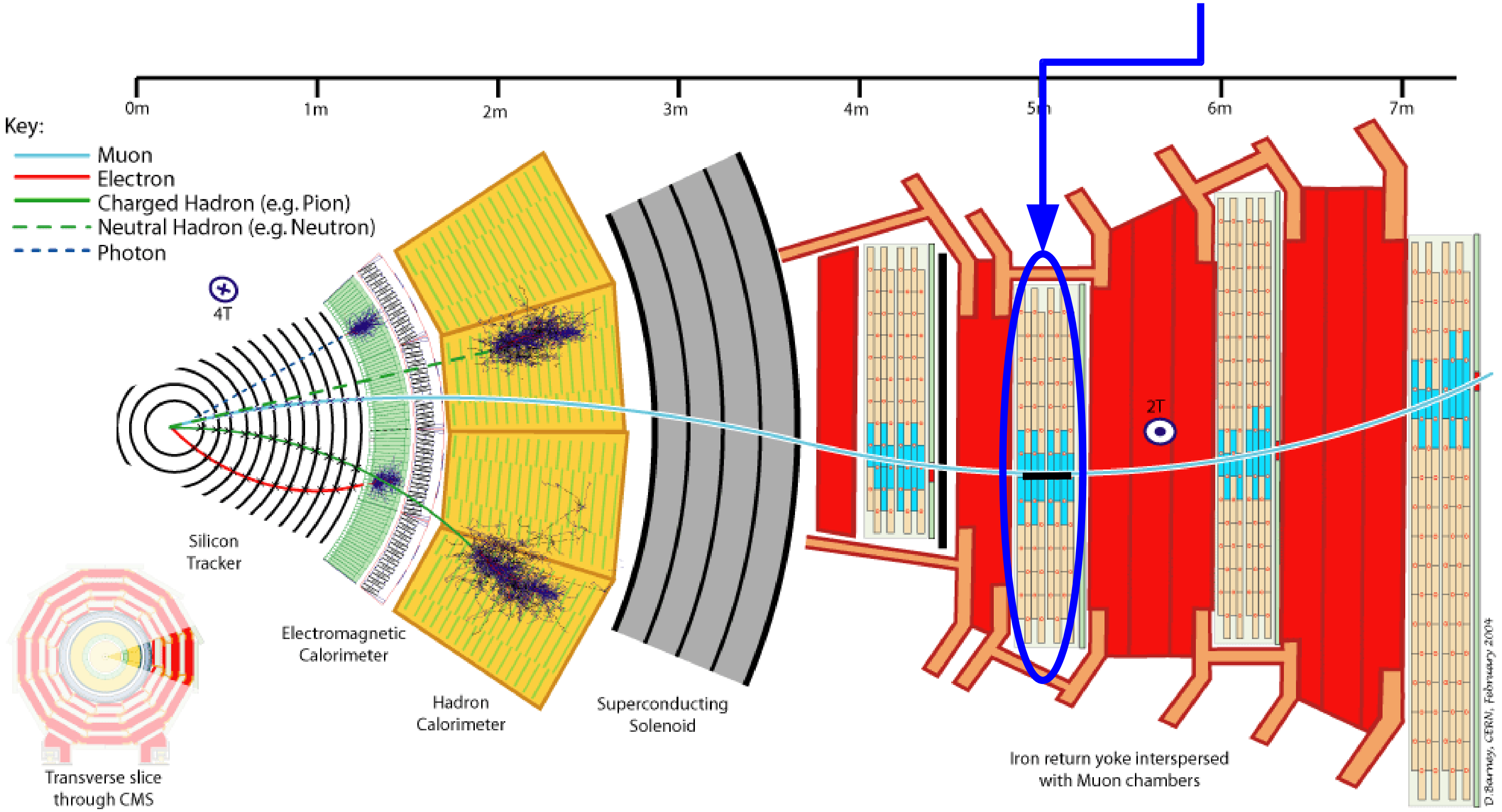
- The reconstruction in the **stand alone muon system** corresponds to the **L2 of the HLT**
  - the seed come from the L1
- The reconstruction inside both the **tracker and the muon detectors** corresponds to the **L3 of the HLT**

Possibility to *specialize* the algorithms (i.e. for speed-up) but all the code is **shared** by the off- and the on- line reconstruction

Muon Reconstruction

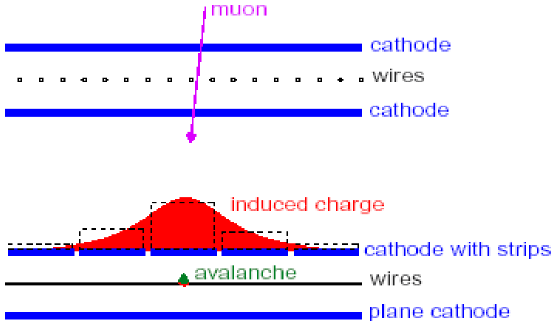
The muon reconstruction is divided into **three steps**

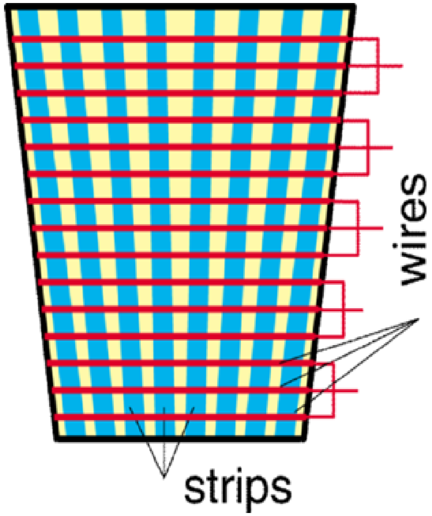
① Reconstruction of the **hits** and the **track segments** inside a chamber.



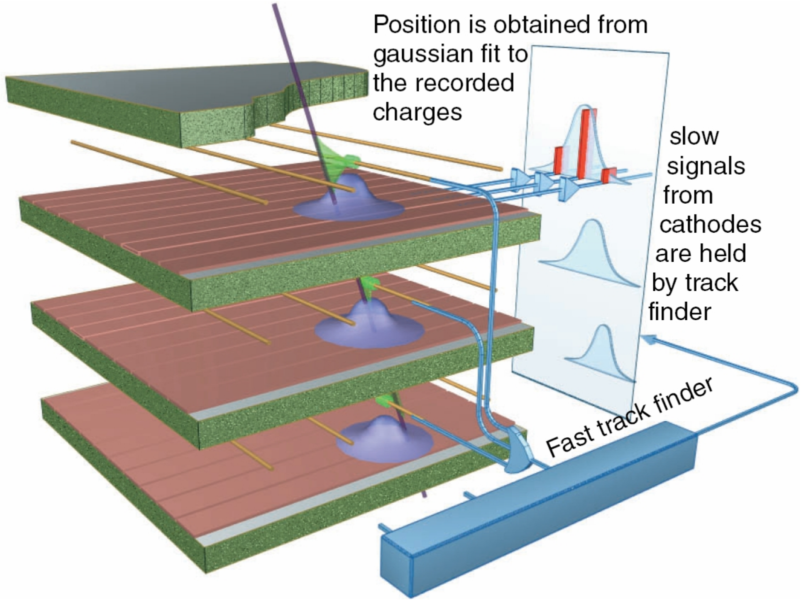
CSC Local Reconstruction

- **ϕ coordinate** measured by strips
  - charge distribution on a cluster of adjacent strips fitted with the Gatti function to determine the centroid



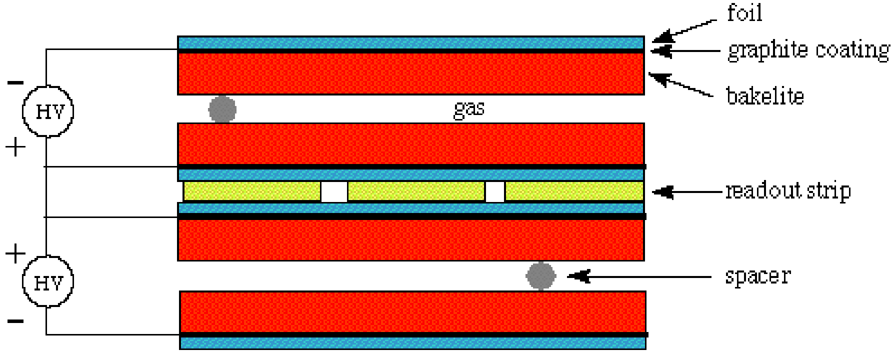


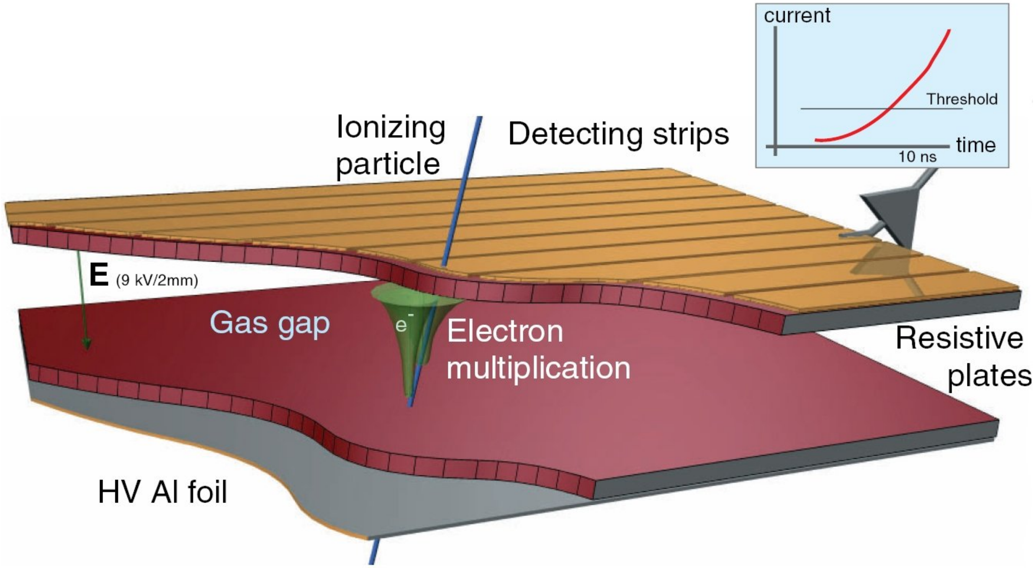
- ***r* coordinate** measured by wires
  - readout in bunches to reduce the number of channel
    - ghosts
- **Fit** of the 2D points in the 6 layers
  - determine the 3D segments



RPC Local Reconstruction

- Double gap chambers
  - strips measure ϕ





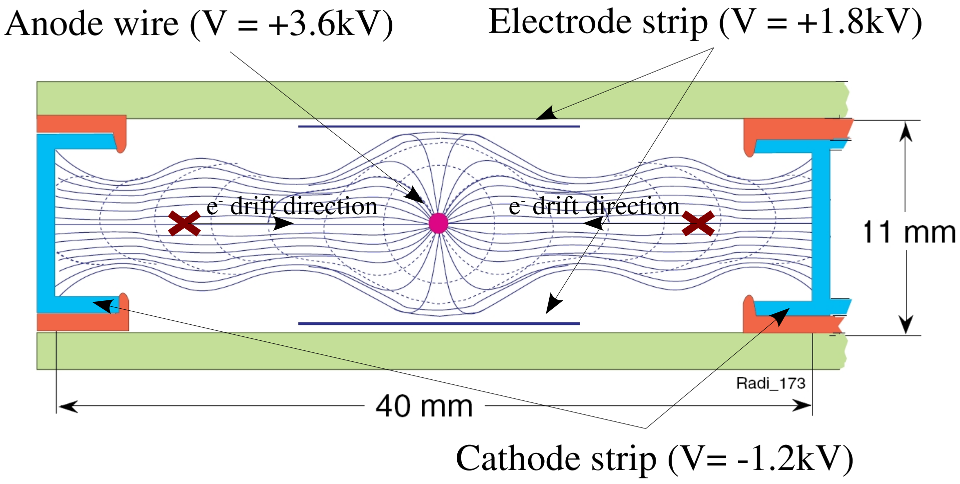
- Measure the 2D points
  - up to 6 points in the barrel and 4 in the endcap

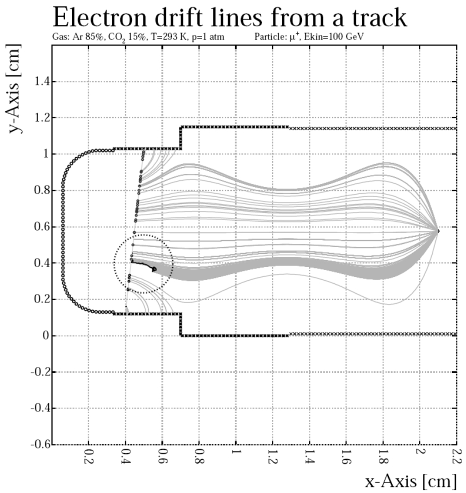
DT Local Reconstruction

It is performed in <u>**three**</u> steps

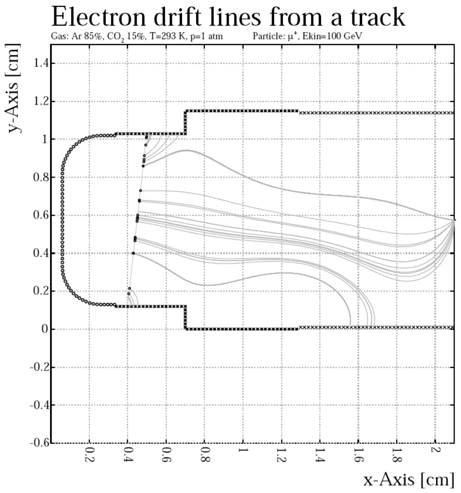
① Reconstruction **inside the cell**

- the drift time is **converted** in a position with respect to the wire. Two different algorithms:
  - <u>constant drift velocity</u> in the whole cell
  - <u>time to distance relation</u> parametrized by *GARFIELD*:
    - $x(t) = f(t,\alpha,B_{wire},B_{norm})$
    - the information about α, B_{wire} and B_{norm} are not available at this step
      ⇨ iterative procedure using the information from the other two steps.
- **1D hit** with left/right ambiguity





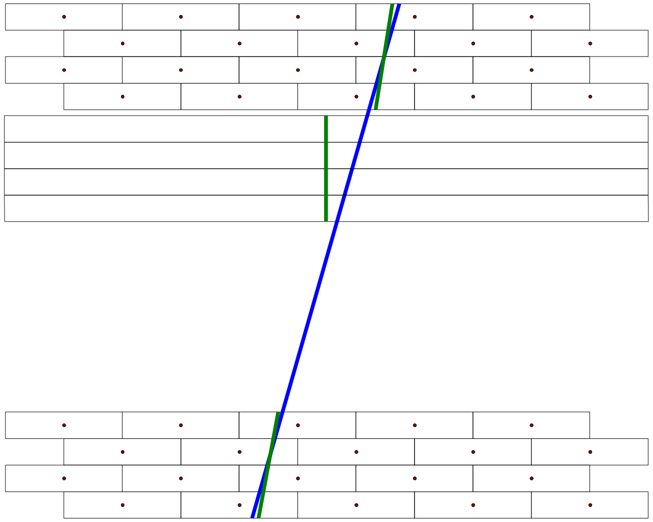
$B_{wire} = 0$ T



$B_{wire} = 0.4$ T

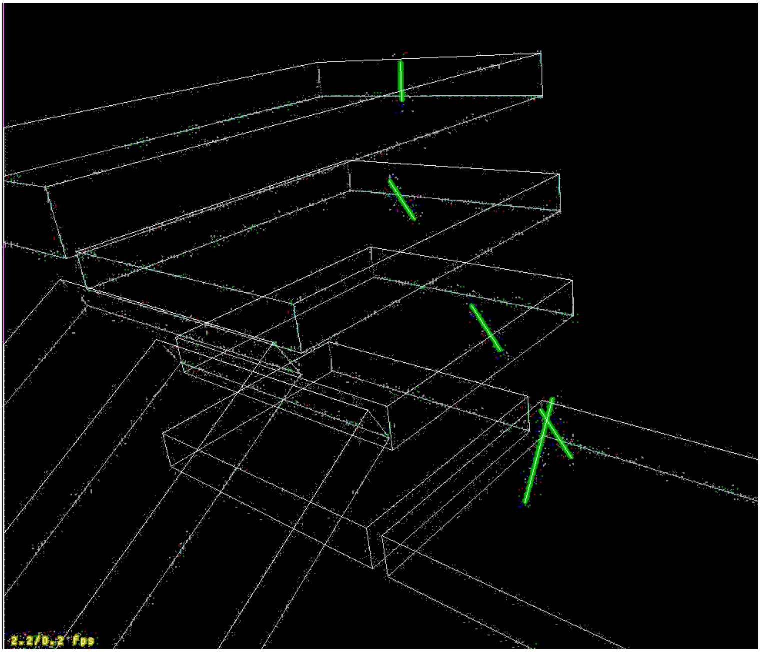
DT Local Reconstruction

② Reconstruction in the ***R-ϕ*** and ***R-θ*** view **independently**



- **pattern recognition** and left/right ambiguity solved using the best χ^2 estimation ⇨ fit of the hits
  - up to 8 hits in the R-ϕ view
  - up to 4 hits in the R-θ view
- **update** of the position if the 1D hits using the impact angle (α) ⇨ refit of the updated hits
- **2D segment**

③ Reconstruction **in the chamber**



- the two projection are **combined** together
- **update** of the position if the 1D hits using the knowledge on B_{wire} and B_{norm} ⇨ refit of the updated hits
- **3D segment**

Torino Activities in the DT Community

- All MB4 chambers built in Torino
- The aluminium plates for all chamber type have been prepared in Torino
- The electrodes of all chamber type have been assembled in Dubna, under Torino resposibility, which also provided the relevant tools
- Design and realisation of the DDU of the Drift Tubes
- Management of the chamber production DB
- Commissioning started in 2005
  - Chambers installation in the return yoke
  - Test of the chambers with cosmics

Torino Activities in the DT Community

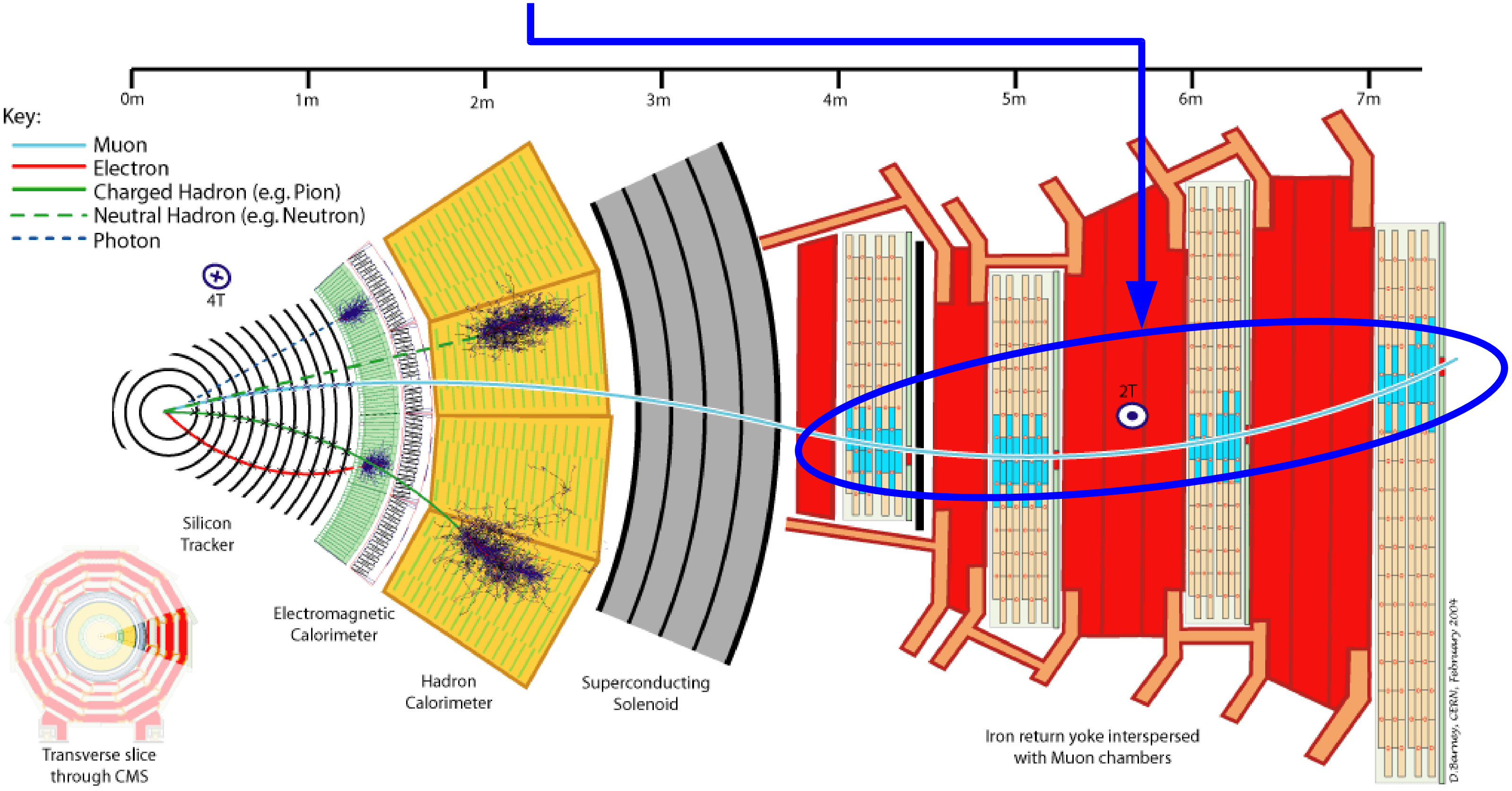
- Algorithms and services of the Local Reconstruction
- Data Quality Monitoring
- Calibration
- Simulation of the drift tube response
- Analysis of noise profiles

Muon Reconstruction

The muon reconstruction is divided into **three steps**

② Reconstruction of the **track** inside the **muon system**

① Reconstruction of the **hits** and the **track segments** inside a chamber.



Tracking – Basic Concept

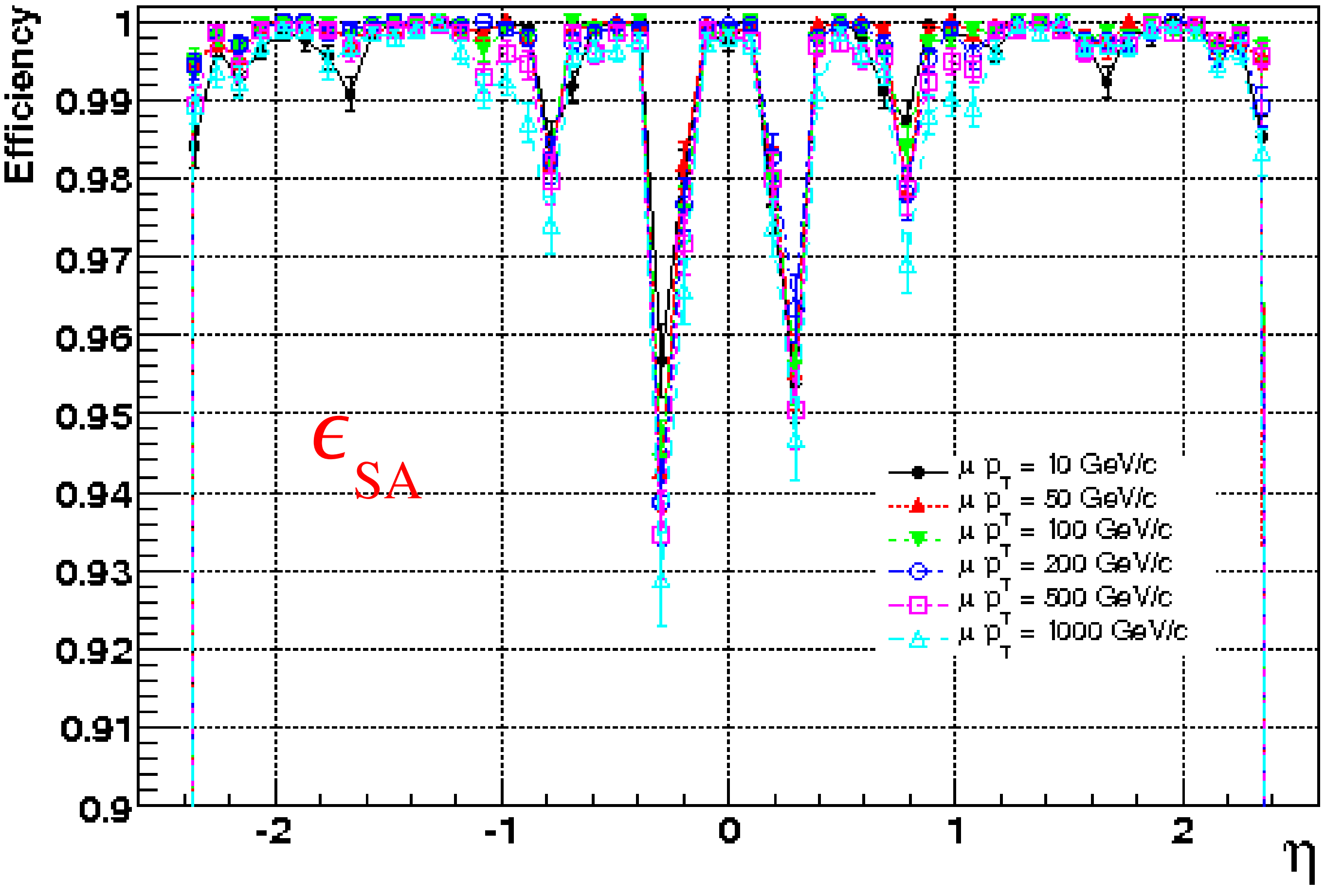
- In magnetic field the trajectory of a charged particle is an **helix**
  - **5 parameters**
    - charge/momentum, direction and position on a given surface
  - Strong magnetic field is required for high p_T measurement
- The goal is **reconstruct the trajectory** of many charged particles using *position measurements*

Requirements

- **Multiple scattering** and **energy loss estimation**
- Need to
  - perform the **pattern recognition**
  - have the *best* and the *fast* estimation as possible

⇨ **Kalman Filter**

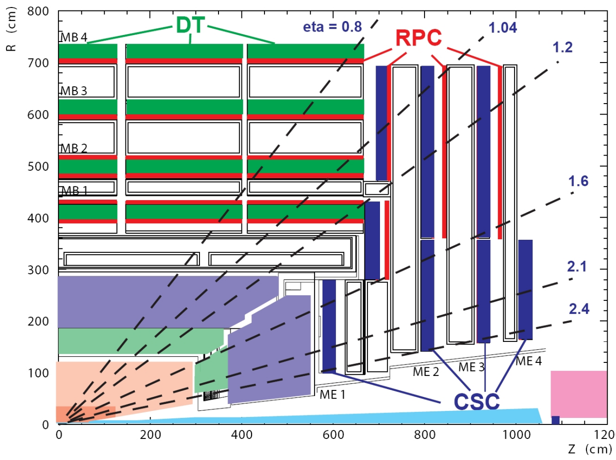
Stand-Alone Muon Reco Efficiency



$|\eta| \approx 0.3$ ⇨ gap between wheel 0 and ±1

$|\eta| \approx 0.8$ ⇨ beginning of overlap region

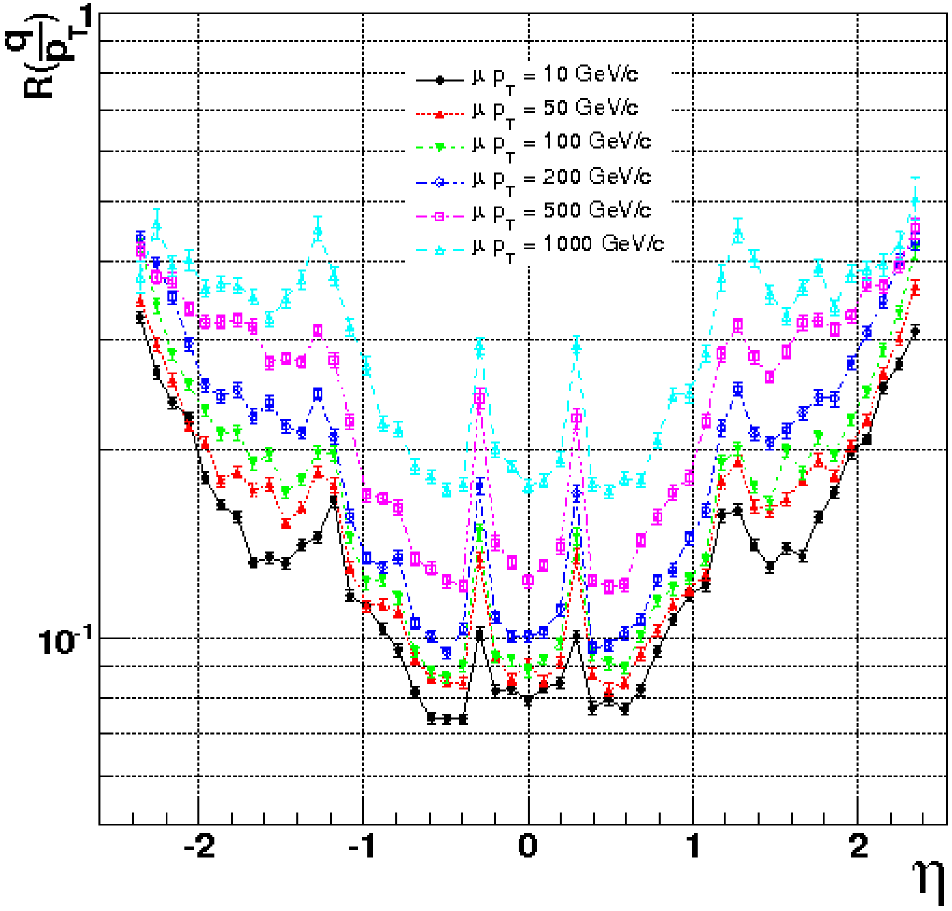
$|\eta| \approx 1.6$ ⇨ transition between two end-cap rings



Overall efficiency ~ 99%

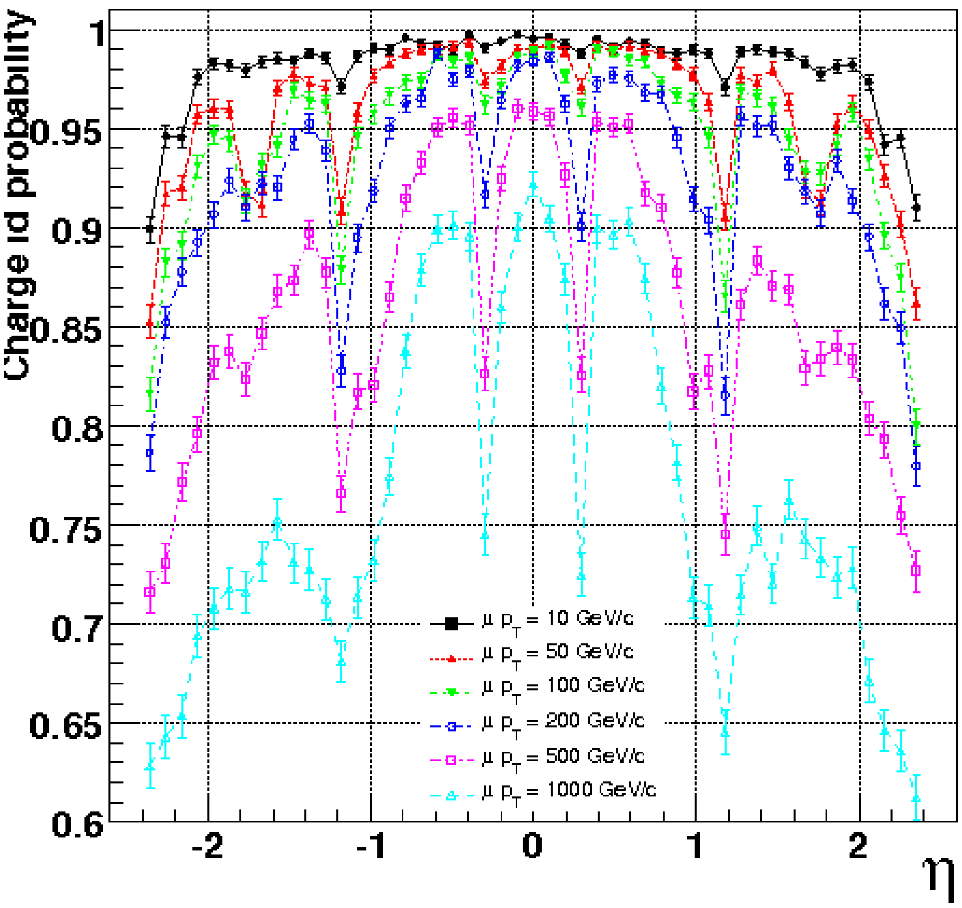
Resolution

Design performance reached



9% in the barrel

for muons with $p_T = 50$ GeV



98% of charge Id probability

for muons with $p_T = 50$ GeV

Torino Activities in the Stand Alone Reco

- Responsibility of the track reconstruction using CSC, DT and RPC
- Algorithms and services (geometry, data formats, ...), used by the track reconstruction, written by the Torino group

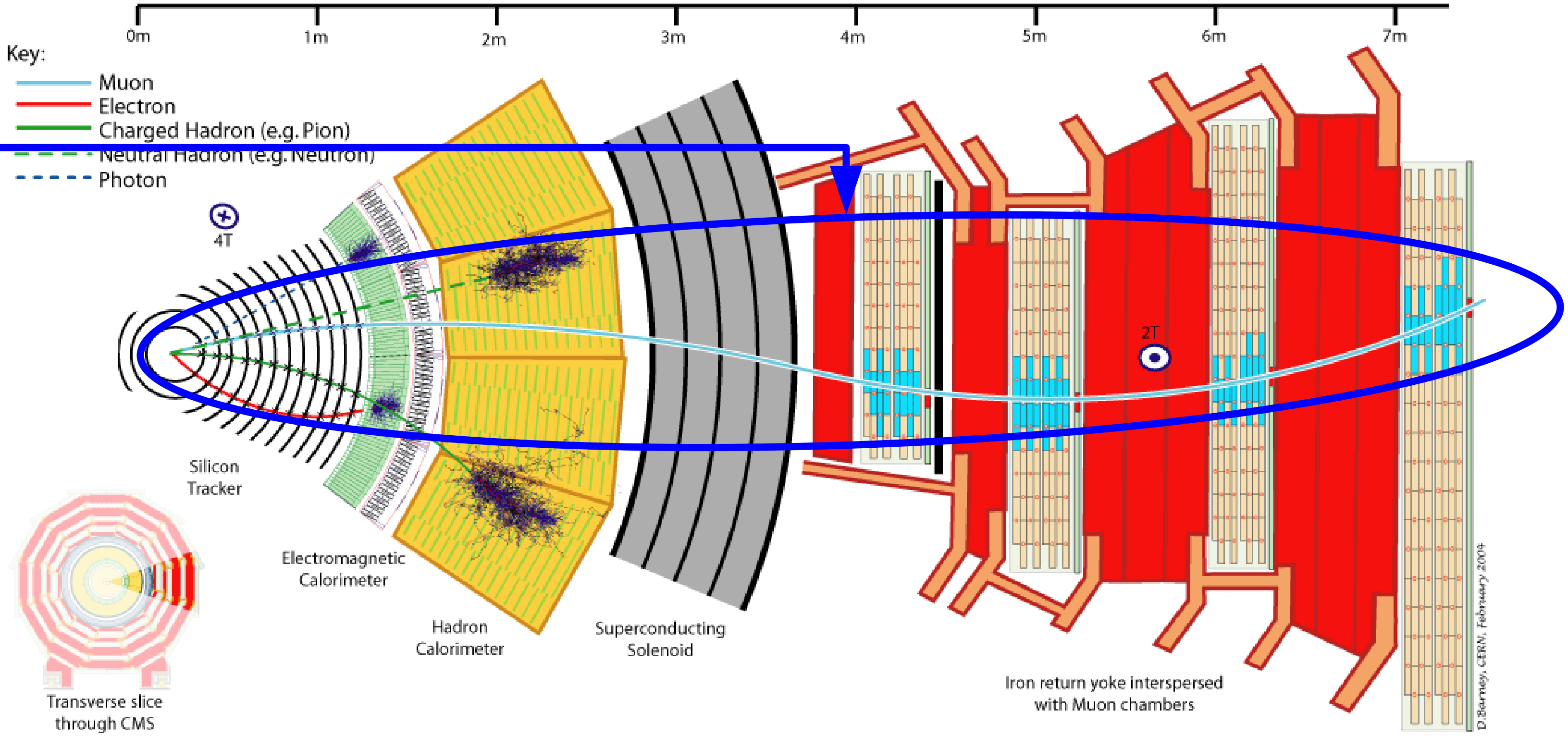
Muon Reconstruction

The muon reconstruction is divided into **three steps**

③ Reconstruction of the track combining the information from the **tracker** *and* **the muon system**

② Reconstruction of the **track** inside the **muon system**

① Reconstruction of the **hits** and the **track segments** inside a chamber.



Global Reconstruction

Two different strategies

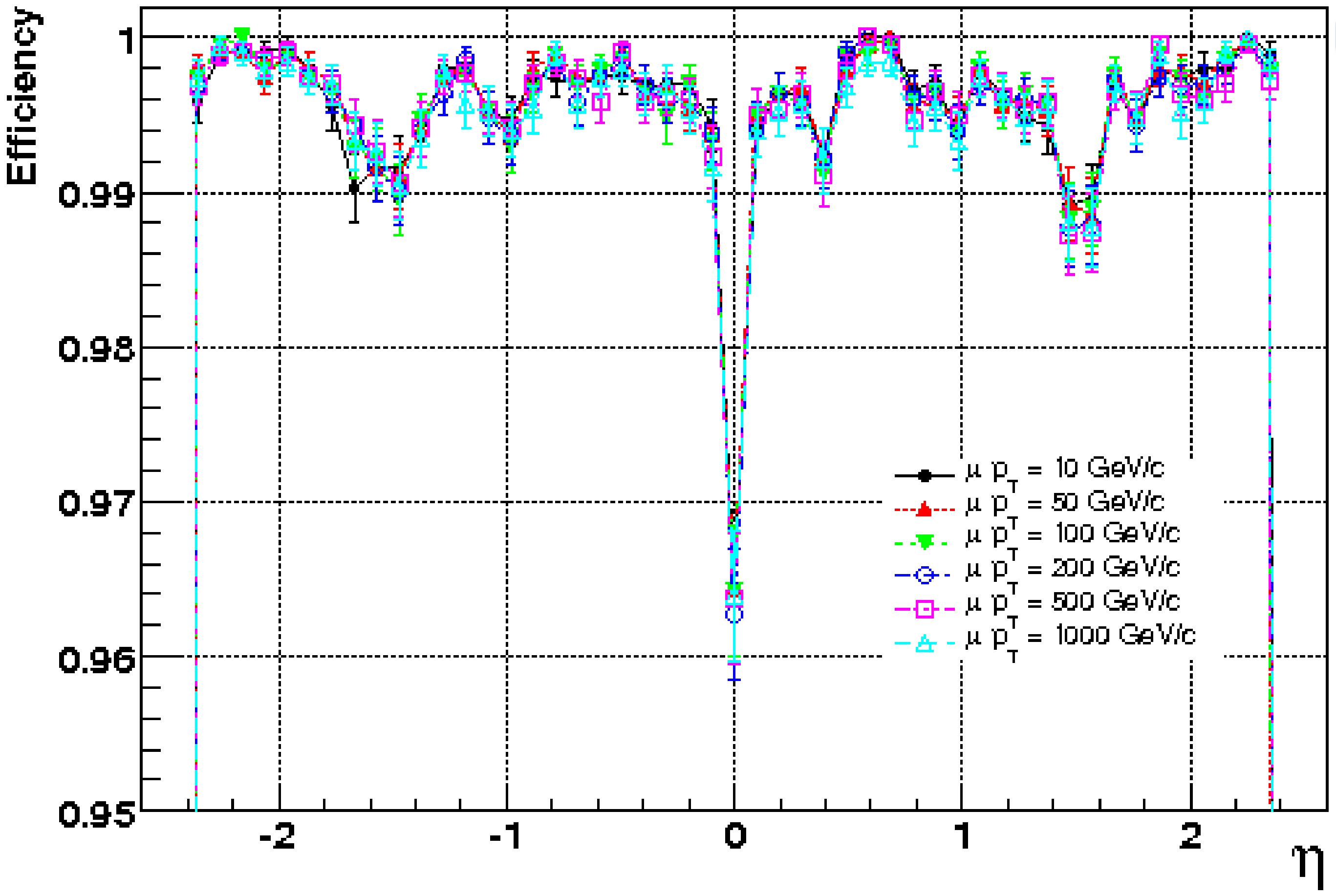
- Track reconstruction inside the tracker and inside the muon system independently
  - **matching** of the two tracks and refit of all hits
- Track reconstruction inside the muon system and then in the tracker
  - the state estimated in the muon system alone is used to open a *region of interest* in the tracker
  - the tracker tracks are built
  - **matching** of the two tracks and refit of all hits

The reconstruction in the tracker (*1st strategy*) uses the *Kalman Filter approach* as well.

Torino Activities in the TK Community

- Production and test of TIB and TID modules @Torino (500 modules = 3.6 m^2)
- Integration of the 6 TIDs @ Torino (6.9 m^2)
- Integration of TIB/TID into TK @ CERN
- Pre-commissioning of TK @ CERN (March/July 2007)
  - 4.5 M events with 1/8 of TK with final PS/DAQ/safety
- Integration of TK into CMS
- Test of TK and commissioning of TK in CMS (-next-)
- Global run of CMS and TK/DT data analysis (-next-)
- Software tasks:
  - TK alignment
  - analysis of detector performances (clustering, S/N, noise, dead channels,...)
  - material budget evaluation

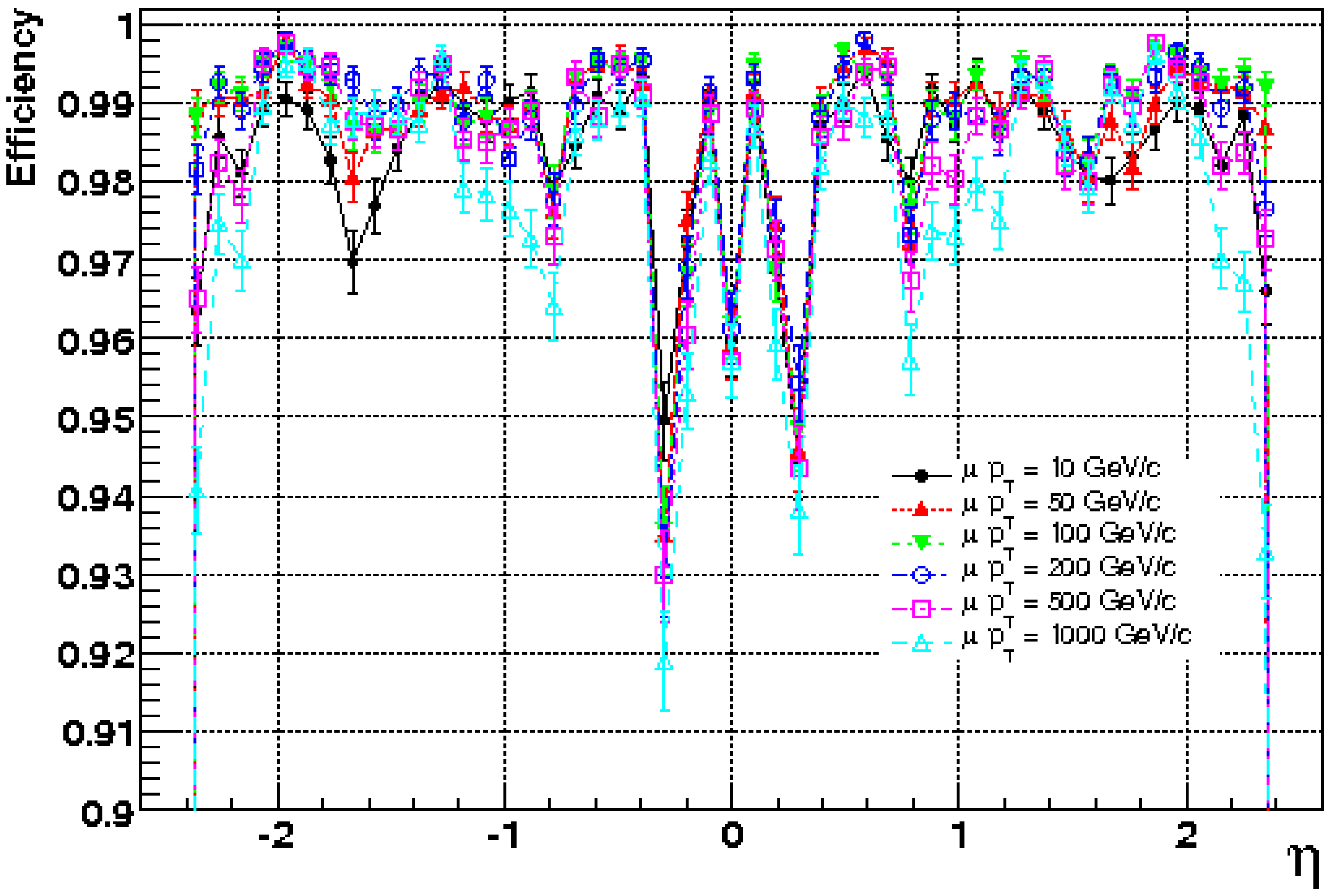
Tracker Track Reco Efficiency



- Dips due to geometrical acceptance of the tracker:
  - η~0 half-barrel junction
  - $|\eta|$~1.5 barrel-endcap transition

Overall efficiency more than 99%

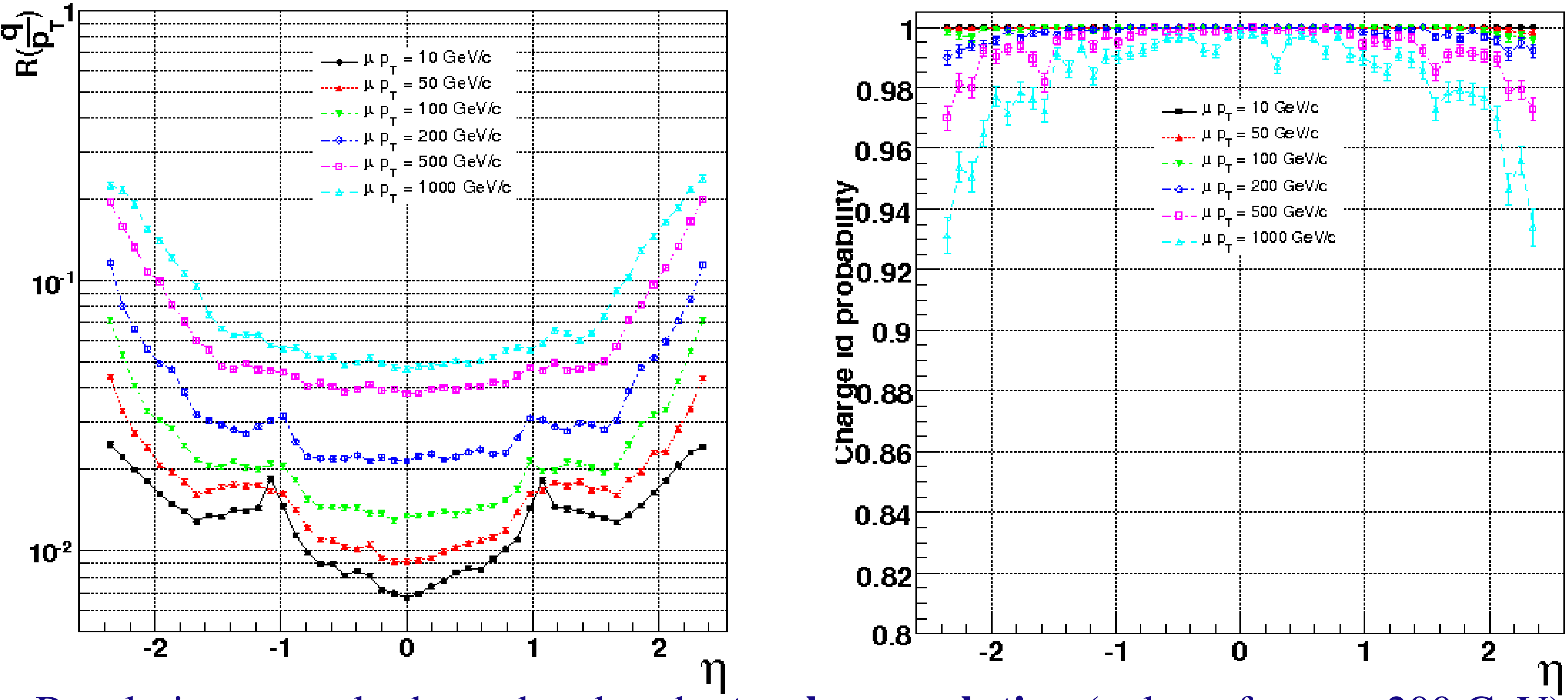
Global Muon Reco Efficiency



Efficiency strongly depends on the

stand alone muon reconstruction

Resolution

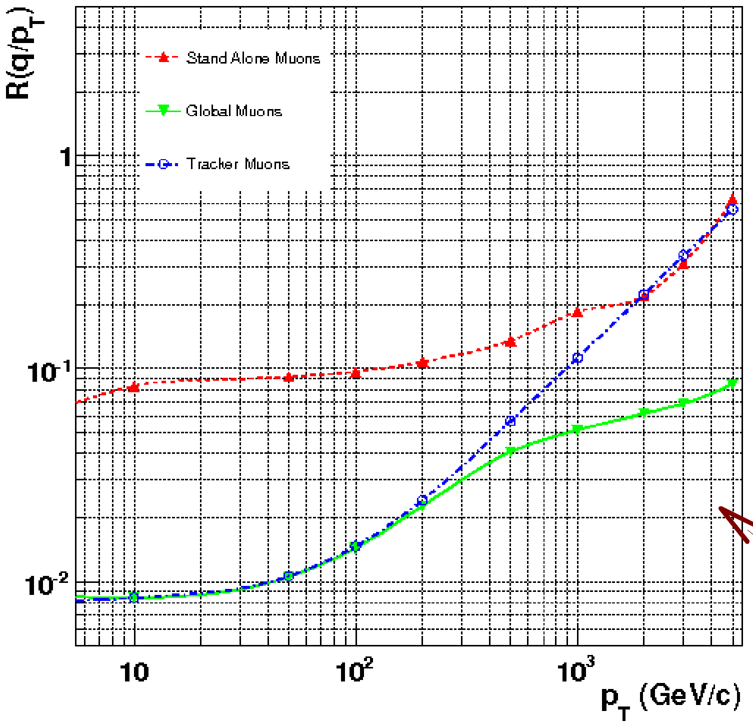


Resolution strongly dependent by the **tracker resolution** (at least for p_T < 200 GeV)

0.8% of resolution on q/p_T in the barrel, for *μ* with **p_T = 50 GeV**

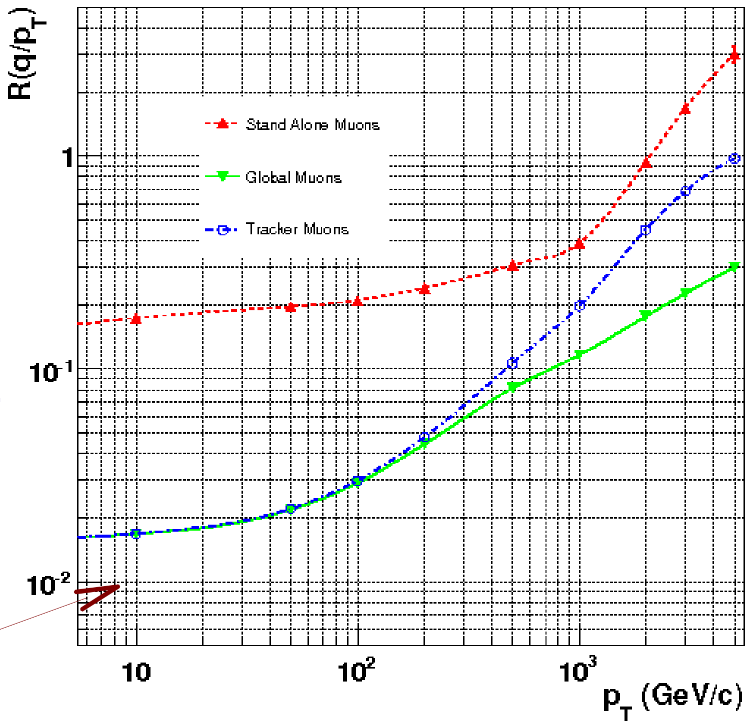
~100 % of charge Id probability, for *μ* with **p_T = 50 GeV**

Stand Alone and Global



Up to 100-200 GeV the resolution is **dominated by the tracker**. For high pt muons the reconstruction inside the **muon system plays a key role**.

barrel   endcap

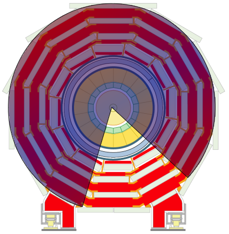


$$\frac{\delta p_T}{p_T} = \underbrace{\frac{0.0136}{\beta}\sqrt{\frac{X}{X_0}}\frac{1}{0.3BL}\sqrt{\frac{4A_N}{N}}}_{\text{Multiple scattering} \rightarrow \text{const}} \oplus \underbrace{\frac{\sigma \cdot p_T}{0.3BL^2}\sqrt{4A_N}}_{\text{Measurement}}$$

$$A_N = \frac{180N^3}{(N-1)(N+1)(N+2)(N+3)}$$

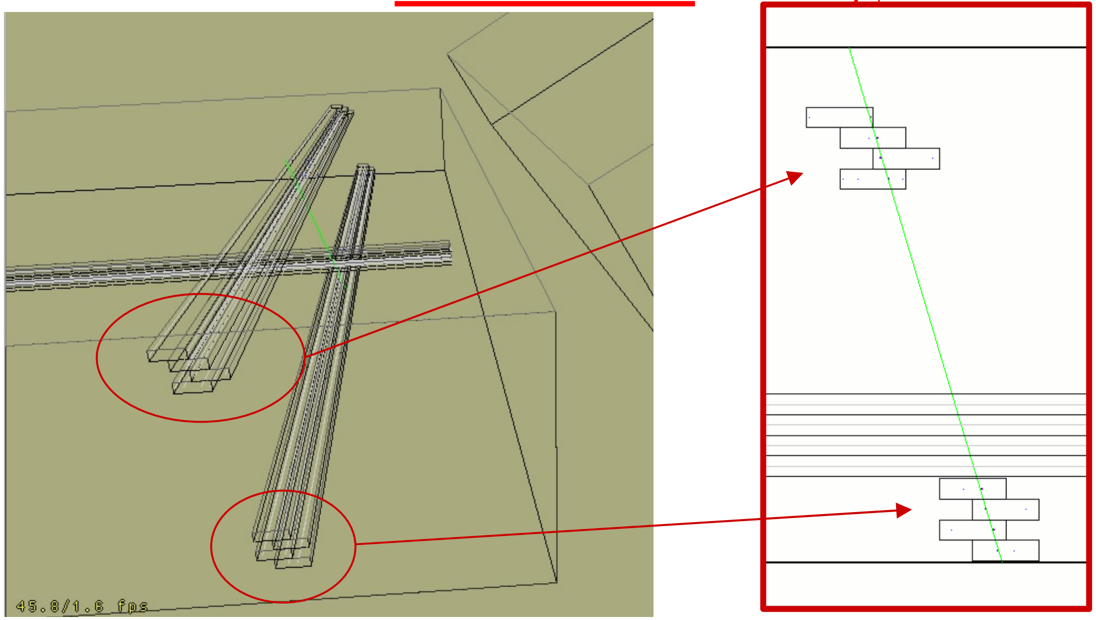
Magnet Test and Cosmic Challenge

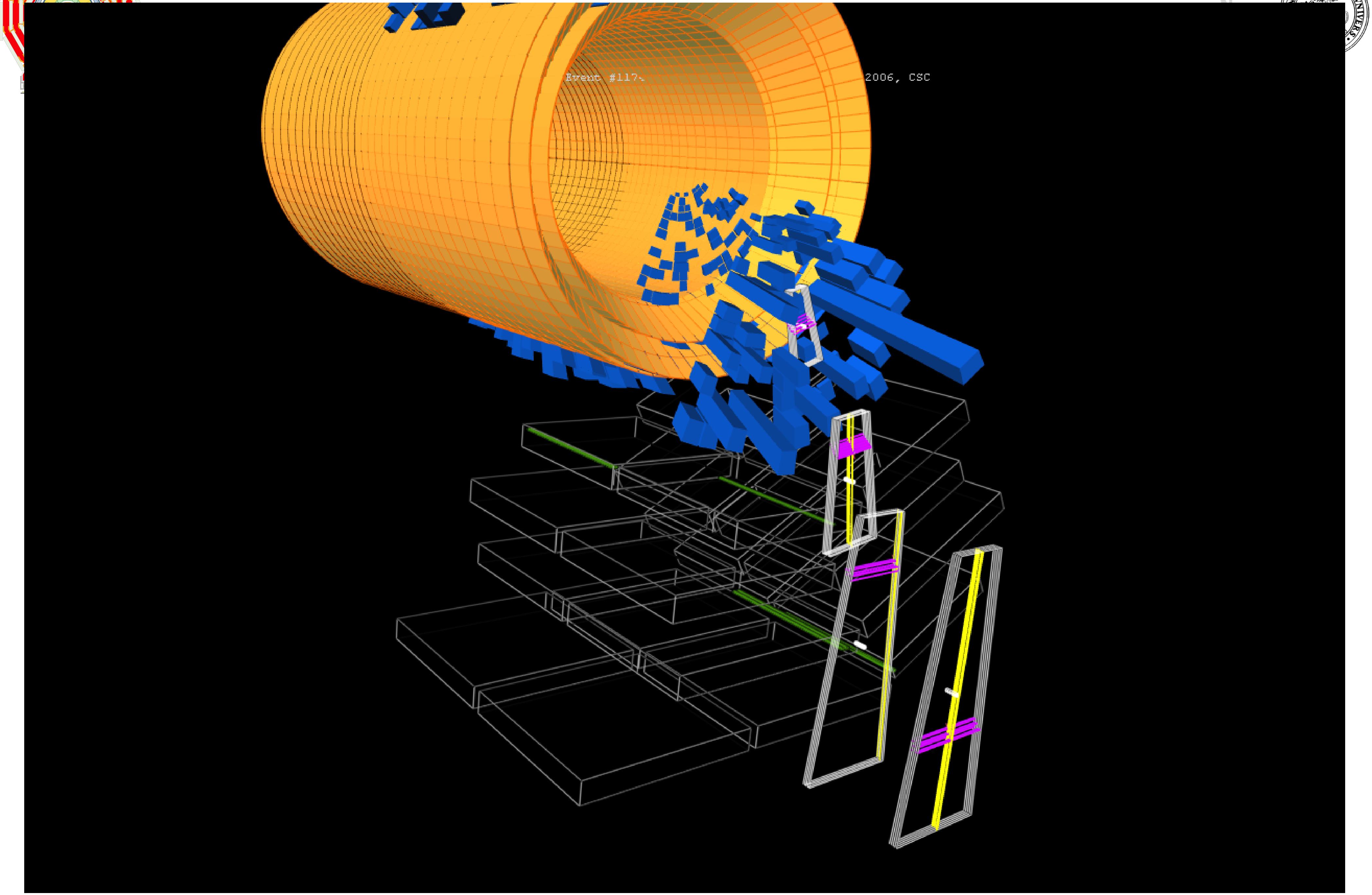
- During the summer '06 the CMS collaboration **turned on the magnet** and **took data** from cosmic rays using three sectors of the detector

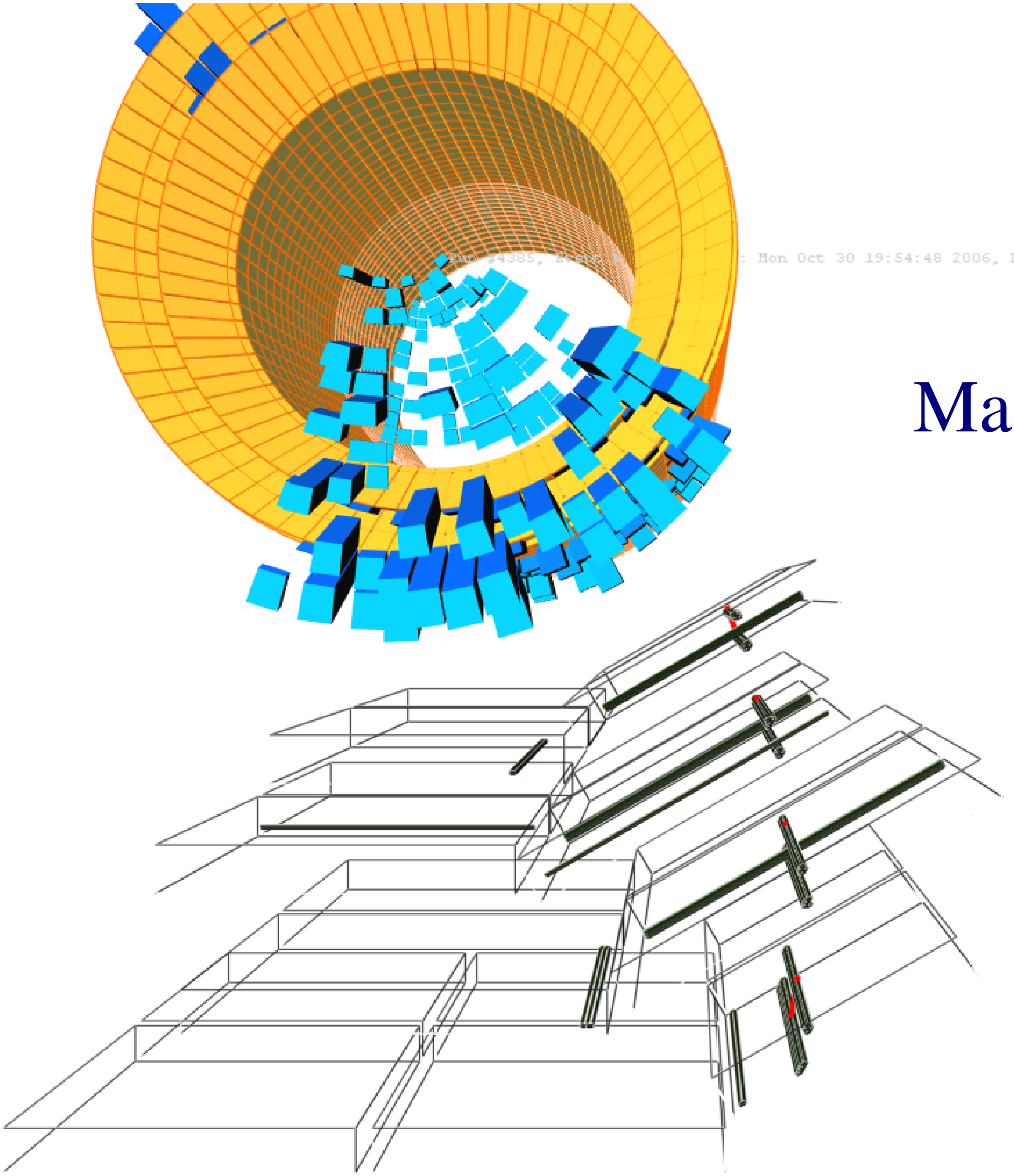


- Since the day “0” the local reconstruction has been working well
  - Unpaking, calibration (and DB access), segment reconstruction
  - debugging and parameters tuning

⇨ Can **<u>read</u>** the detector and **<u>reconstruct</u>** the segments inside a chamber!




Event #117
2006, CSC

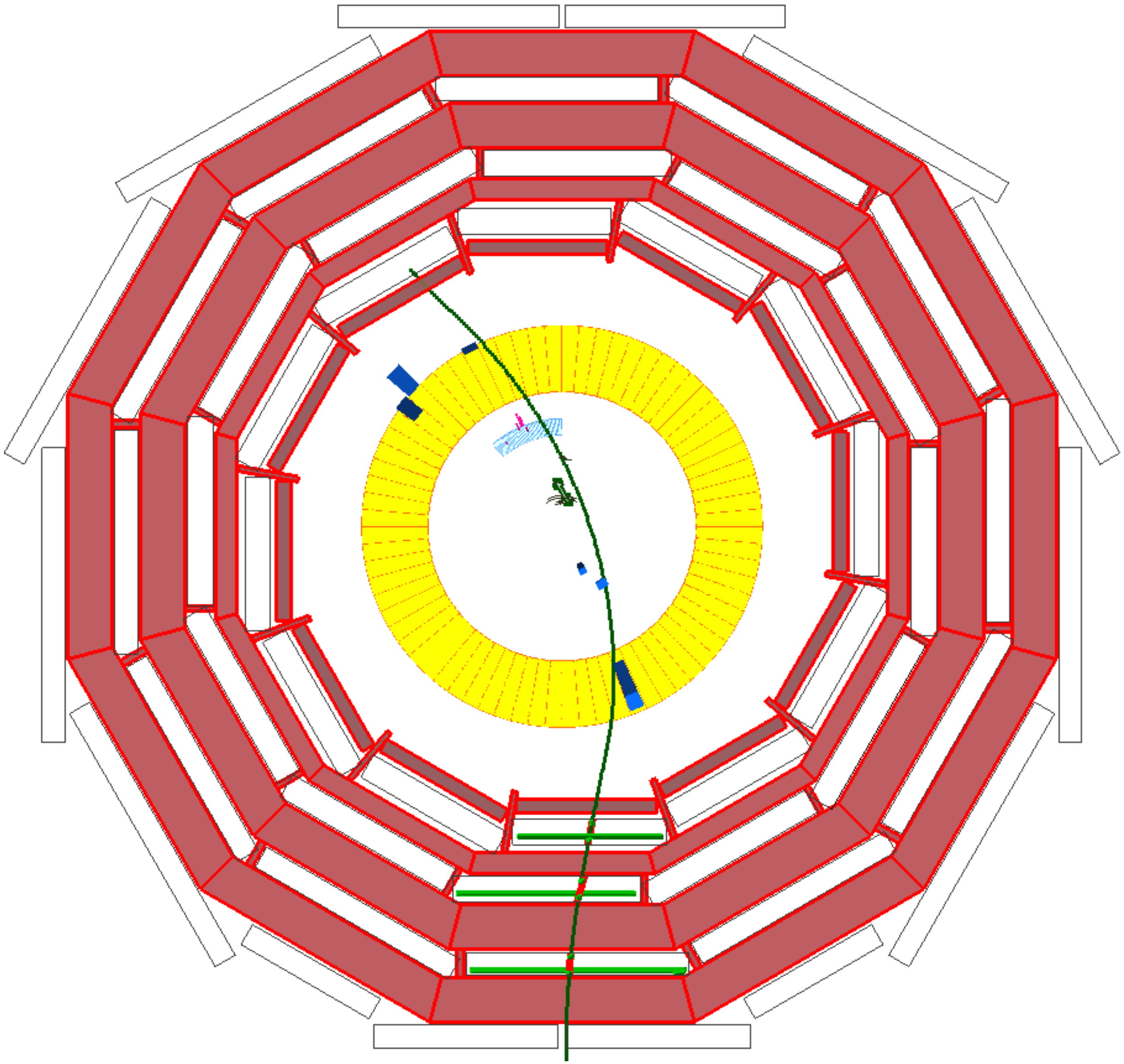


Magnet turned **ON**!

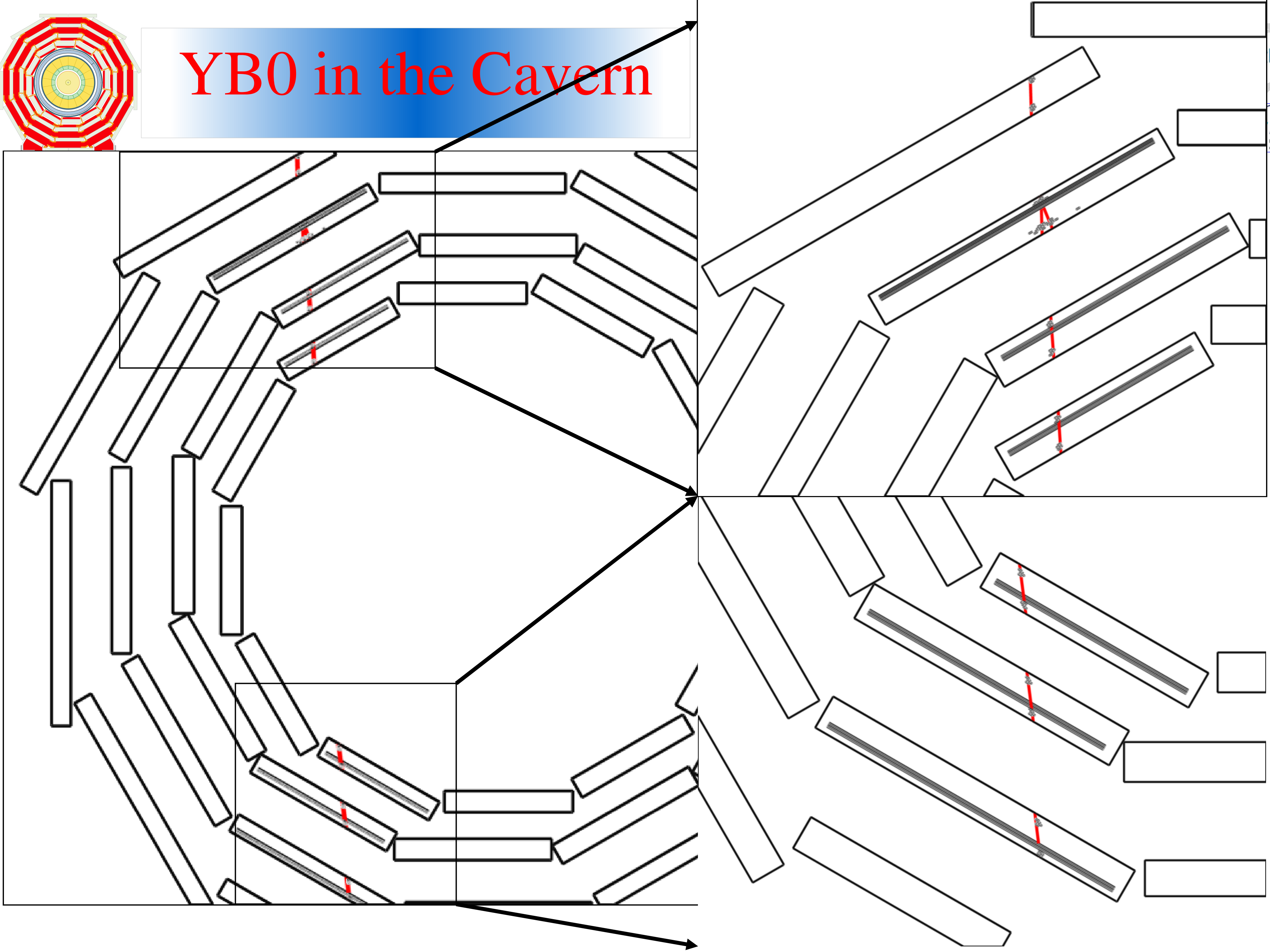
Magnet Test and Cosmic Challenge

Few week later the **track reconstruction** was tried wi the **real data** and ...

We got the **first real reconstructed muon** in the **CMS detector**!!

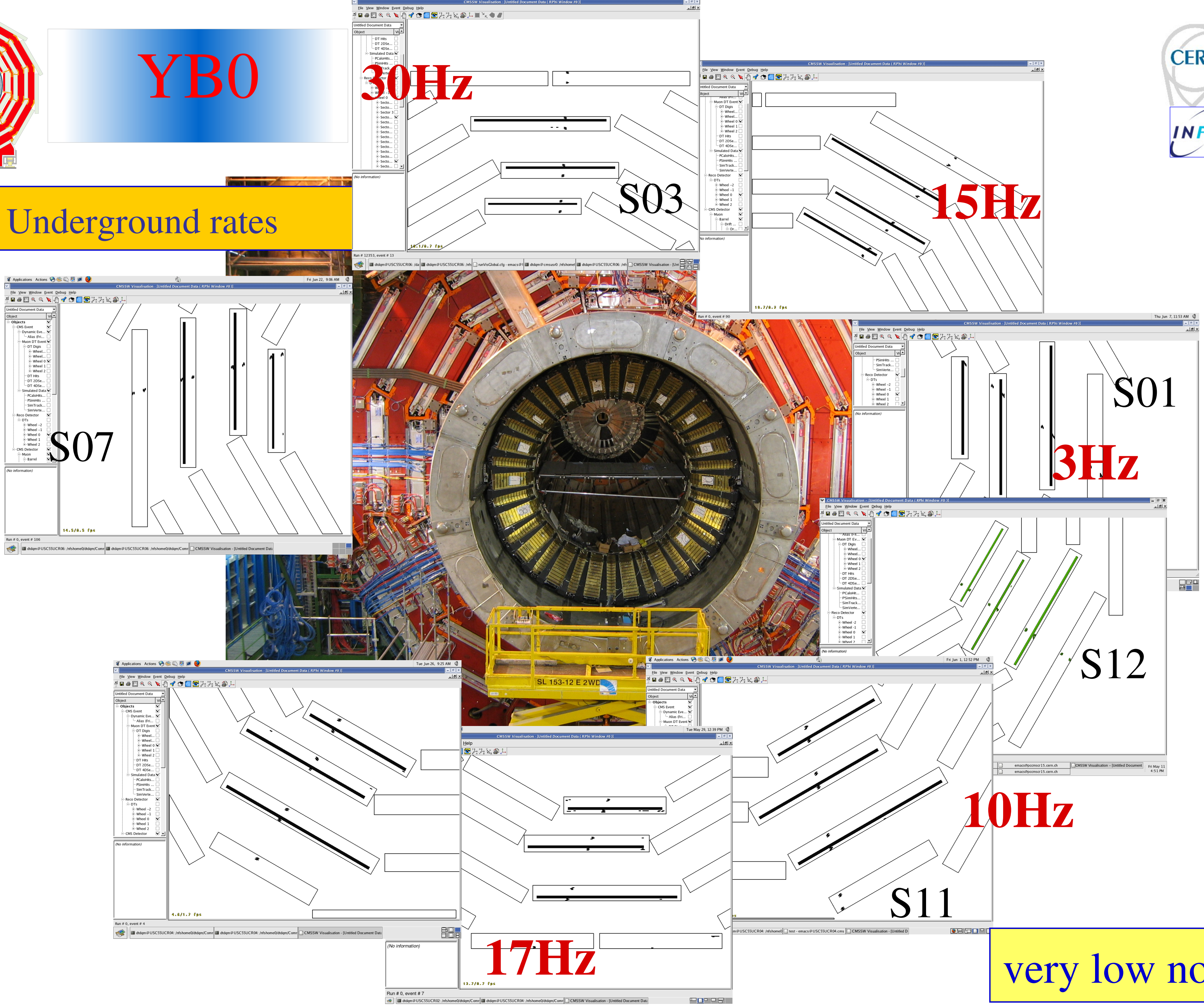


YB0 in the Cavern



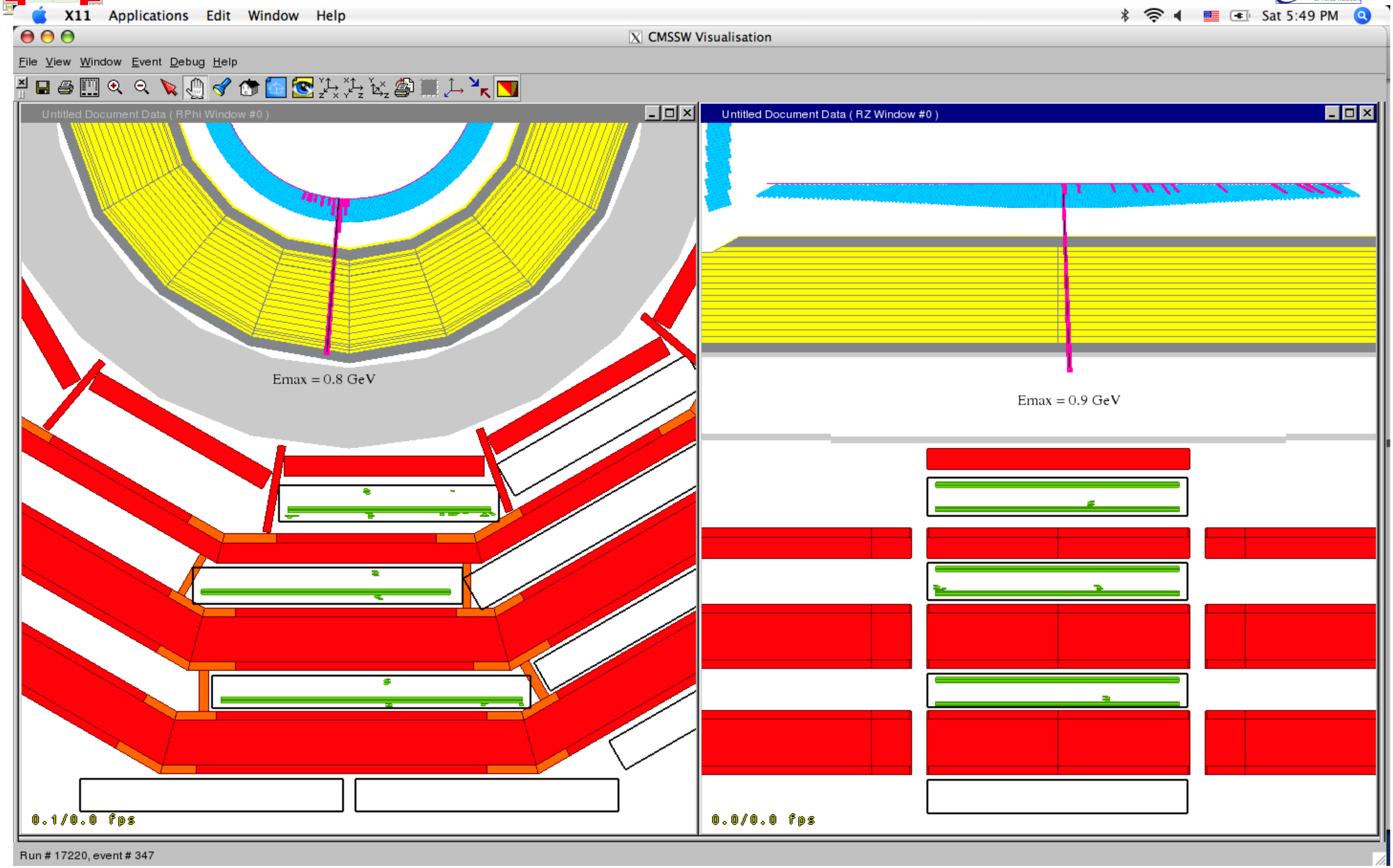
YB0

Underground rates



very low noise!

We are starting to see CMS!



Emax = 0.8 GeV

Emax = 0.9 GeV

```
0.1/0.0 fps
0.0/0.0 fps
Run # 17220, event # 347
```

Torino Activities in the ECAL Community

- Production and test of Motherboard and calibration of VFE
- Integration of the front-end electronics of all the 36 Barrel Super Modules
- Software development for front-end monitoring and safety check (DCU)
- Detector commissioning and integration
- Barrel installation and final cabling
- Final commissioning and setting-up as DAQ experts
- Electron test beams:
  - run coordination of Barrel and Endcap data taking in 2006-2007
  - dedicated precise measurement of beam energy
  - linearity and resolution studies
- In-situ inter-calibration exploiting ϕ-symmetry of minimum bias and jet events

Torino Activities on Physics with Muons

- Coordination of the Higgs Physics Analysis Group
- Coordination of the Muon Physics Object Group
- Coordination of the Muon Software and Muon Software Commissioning
- Calibration of muon momentum scale
- Important role in:
    - $Z \rightarrow \mu\mu$
    - $H \rightarrow ZZ \rightarrow 4\mu$ and $H \rightarrow ZZ \rightarrow 2e\,2\mu$
    - Vector Boson Fusion channels
- Dedicated study on
    - lepton isolation, low pT muon, muon fake rate, HLT

Summary

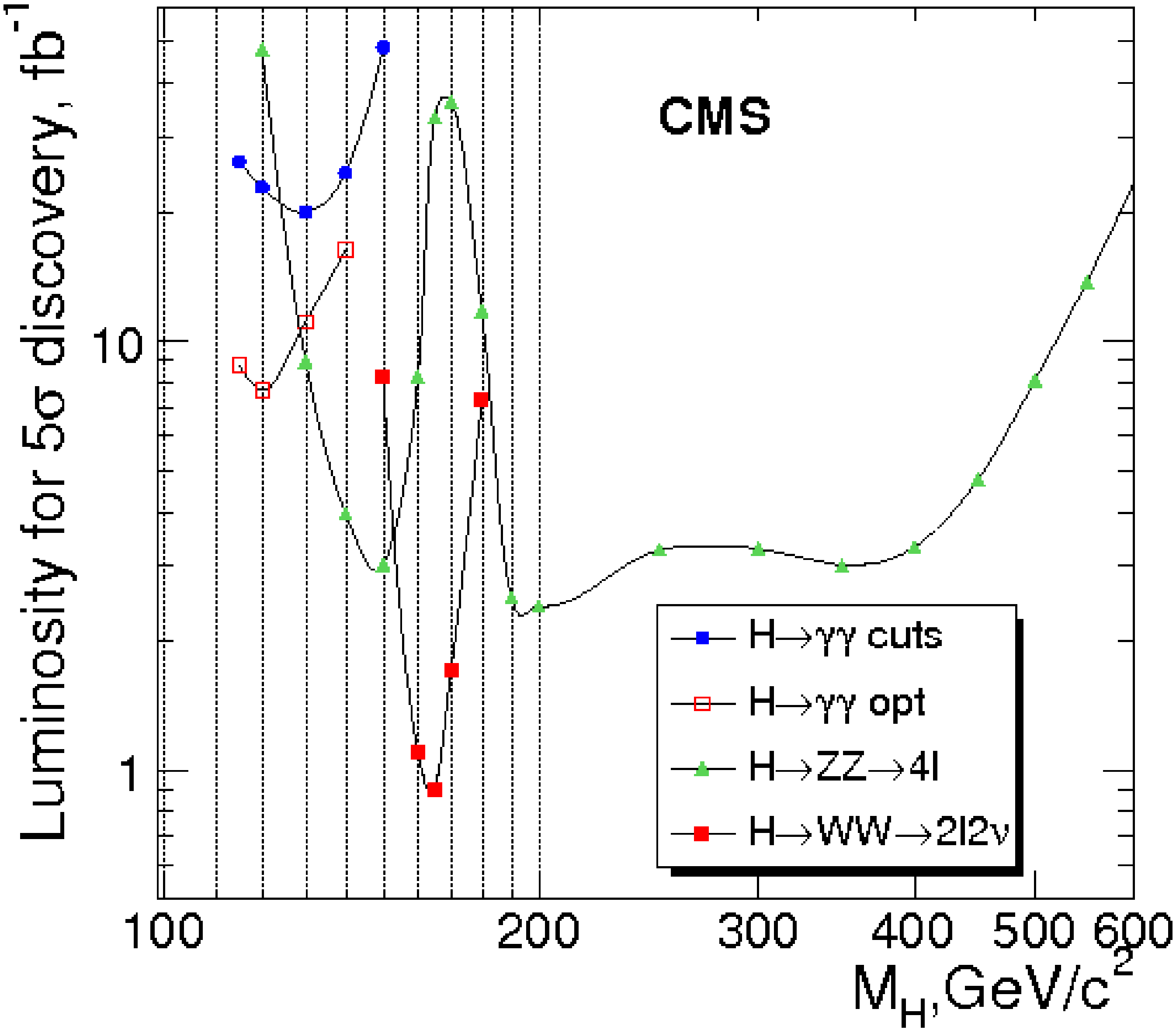
- The algorithms for the muon reconstruction perform very well
  - **high performance**
  - tested on many types of sample. Are currently used in CMS for **all kind of analysis** which involve muons.
- The algorithms have been successfully tested on real data
  - the *muon reconstruction* and the *high level trigger* are **ready for the data taking!**
- **Key role of Torino in the master piece of the reconstruction**

Back-Up Slides

Samples

- Used samples of single muon with different transverse momenta (both signs)
  - 100k events of 5 GeV, 10 GeV, 50 GeV, 100 GeV, 200 GeV, 500 GeV, 1 TeV
  - 70k events of 2 TeV, 40k events of 3 TeV, 20k events of 5 TeV
  - 400k events of 1-200 GeV (flat)
- $Z\rightarrow\mu^{+}\mu^{-}$
  - 350k events
- Local Reconstruction
  - Local with 150
  - Track with 16X

Higgs Discovery at CMS



The CMS muon system

Three types of **gas detector** with trigger capability

- Drift Tube (DT) in the barrel region ($|\eta|<1.2$)
  - $\sigma_x \approx 200\ \mu m$
- Cathode Strip Chamber (CSC) in the endcap region ($0.8<|\eta|<2.4$)
  - $\sigma_x \approx 100\text{-}240\ \mu m$
- Resistive Plate Chamber (RPC) both in the barrel and in the endcap
  - $\sigma_t \approx 2$ ns

precise position resolution

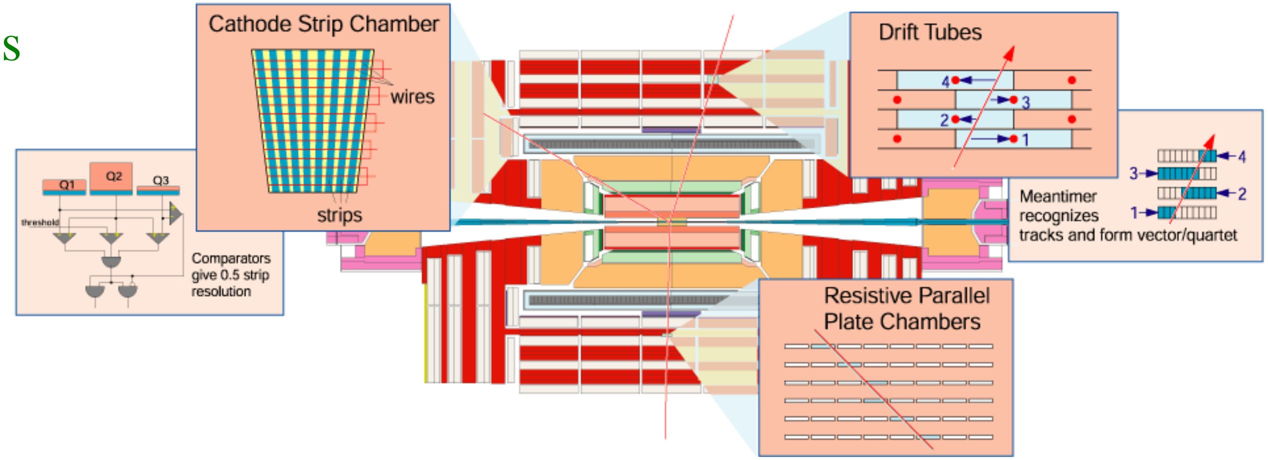
↓

momentum measurement

good resolution on time

↓

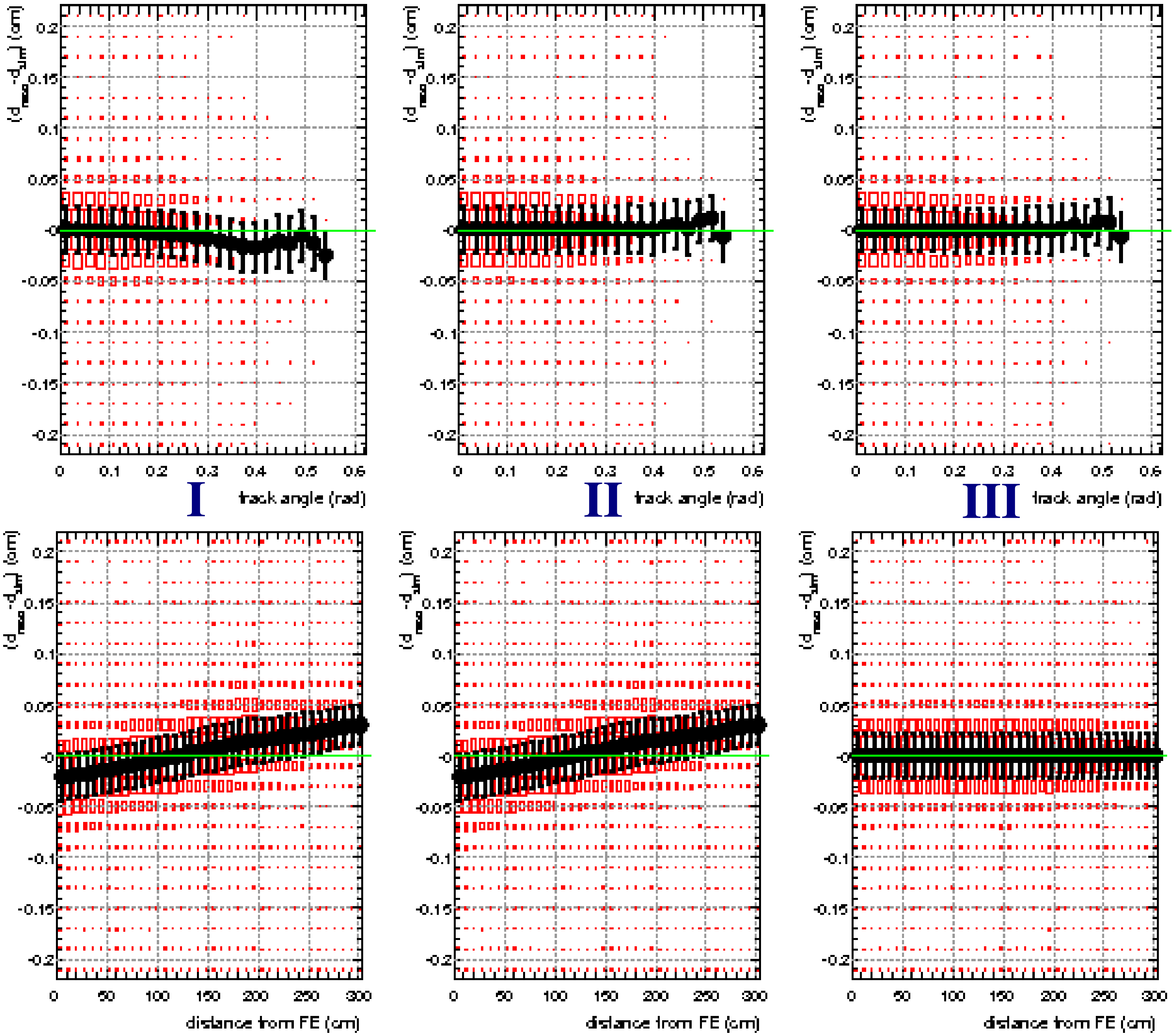
BX assignment



Residual on Hit Position (I)

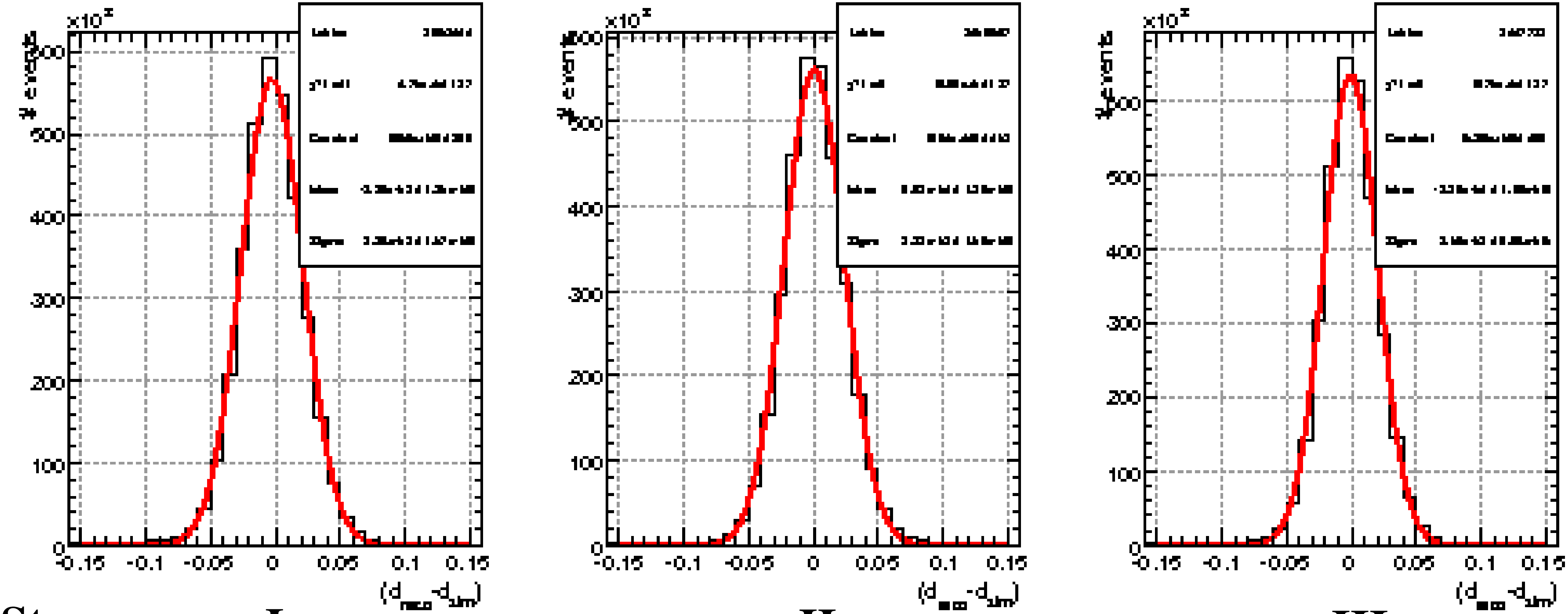
R*-*ϕ

Step:



Residual on Hit Position (II)

R-ϕ



Step: I II III

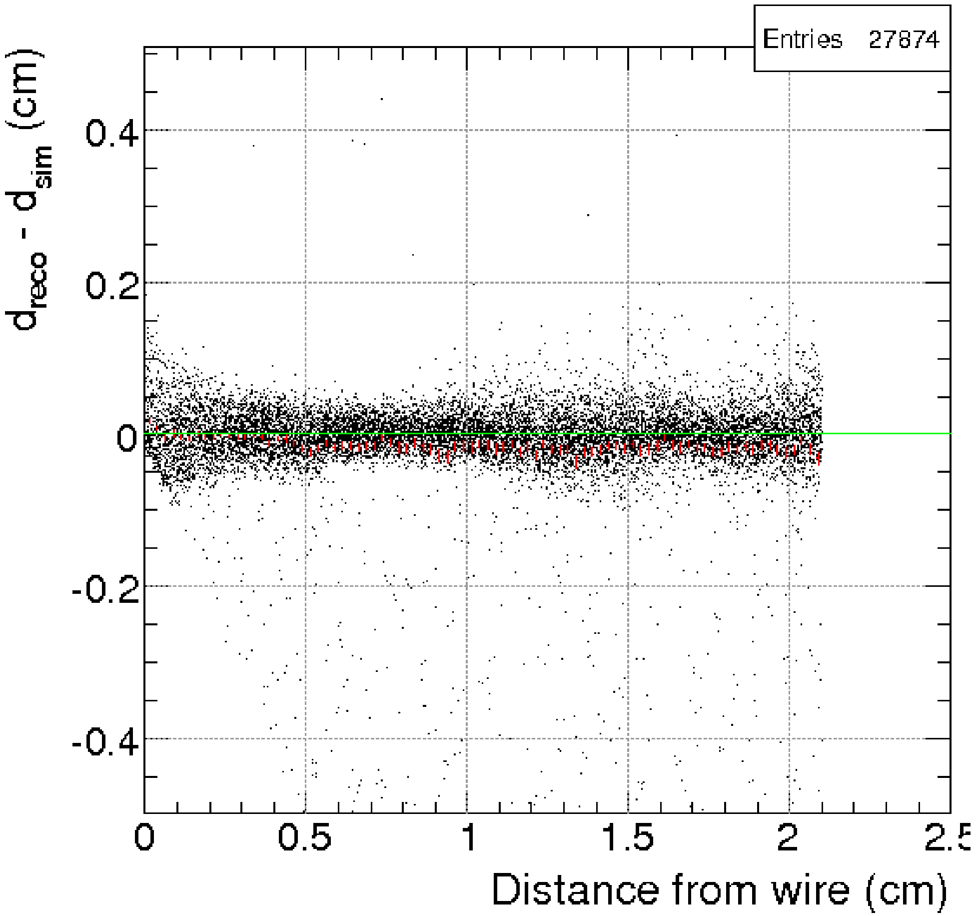
$\sigma \approx 238\ \mu\mathrm{m}$

$\sigma \approx 232\ \mu\mathrm{m}$

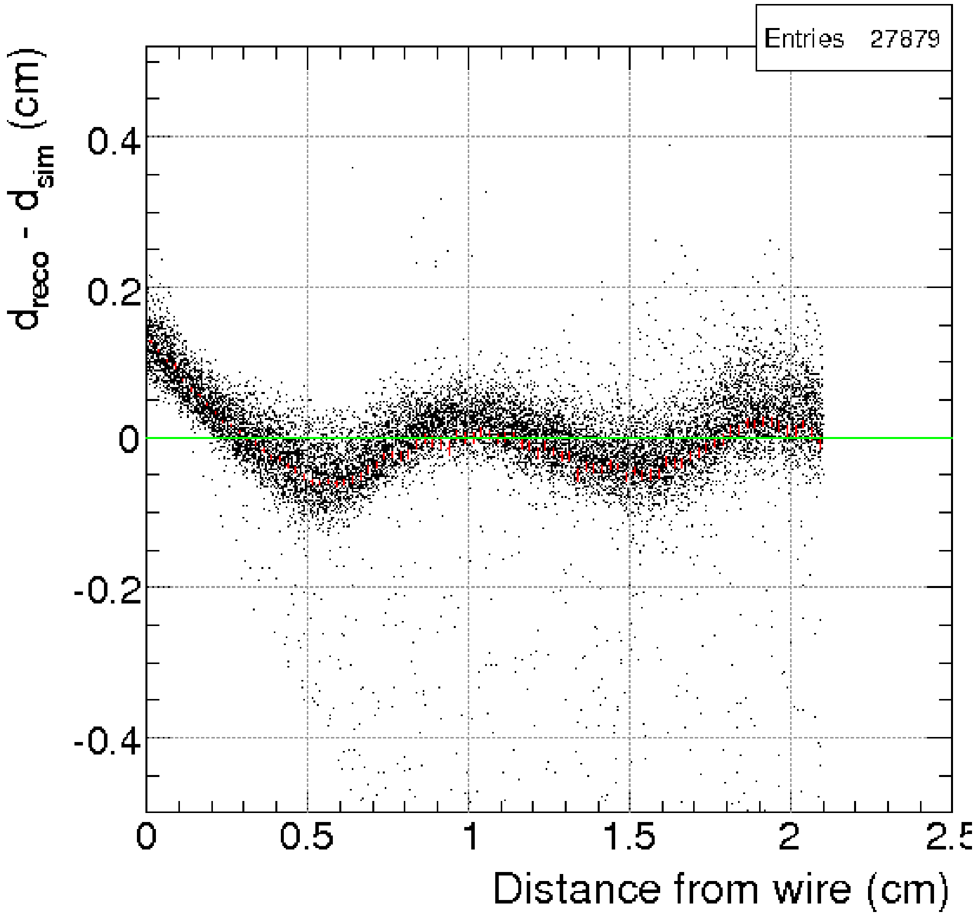
$\sigma \approx 210\ \mu\mathrm{m}$

<u>Time to distance relation</u> parametrized by *GARFIELD*

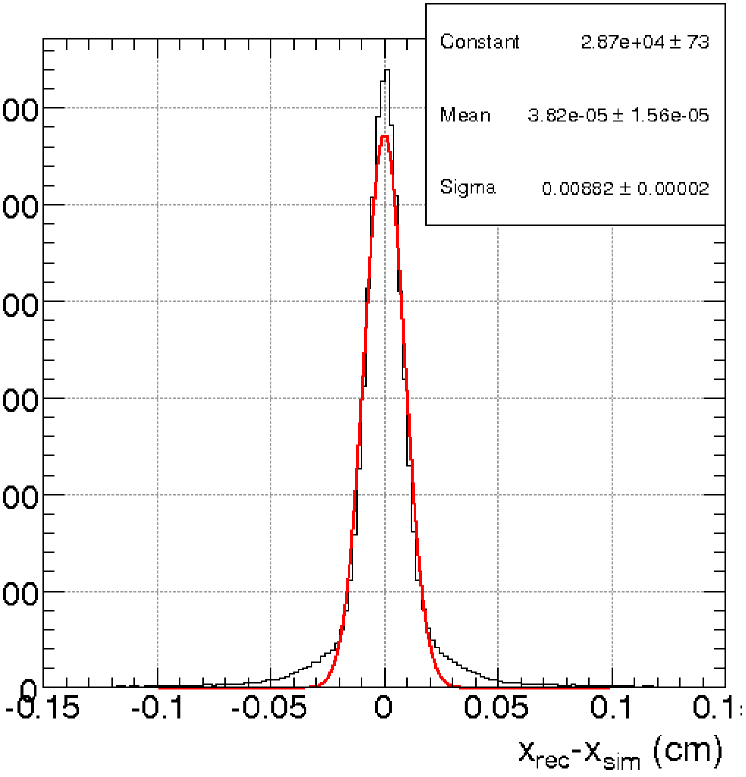
Algorithm Comparison

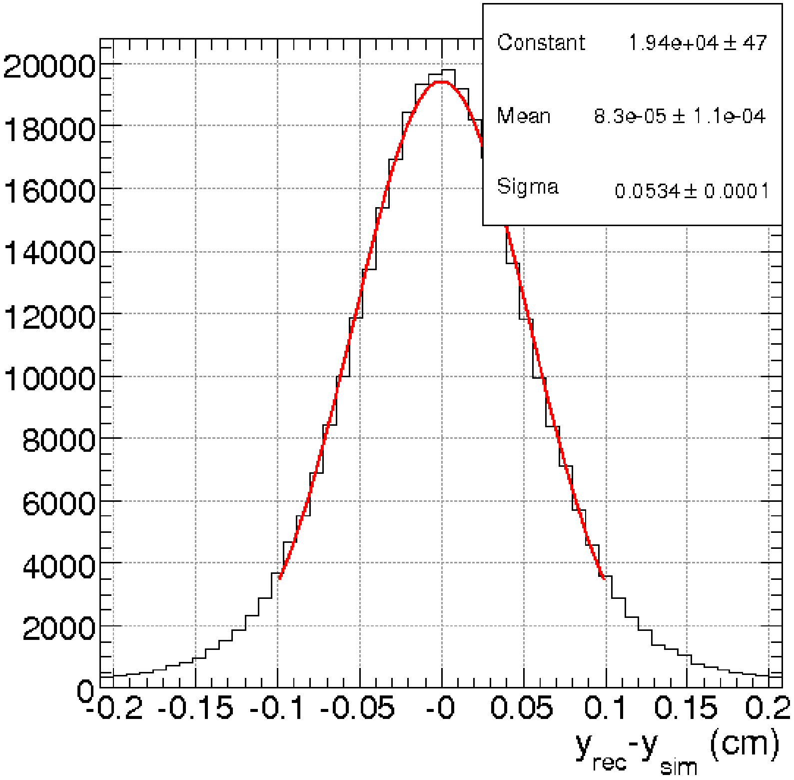


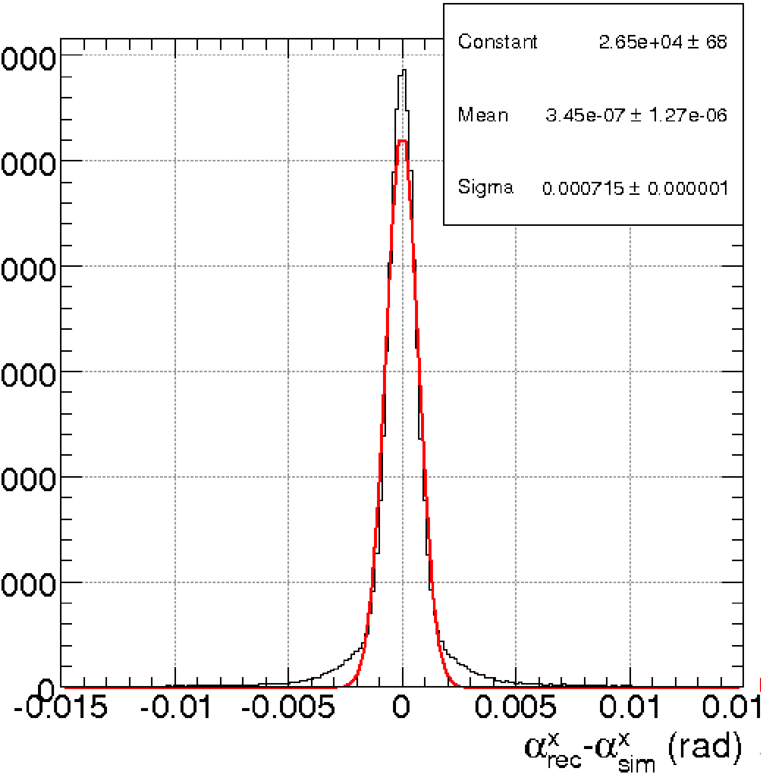
Parametrised time-to-distance relationship

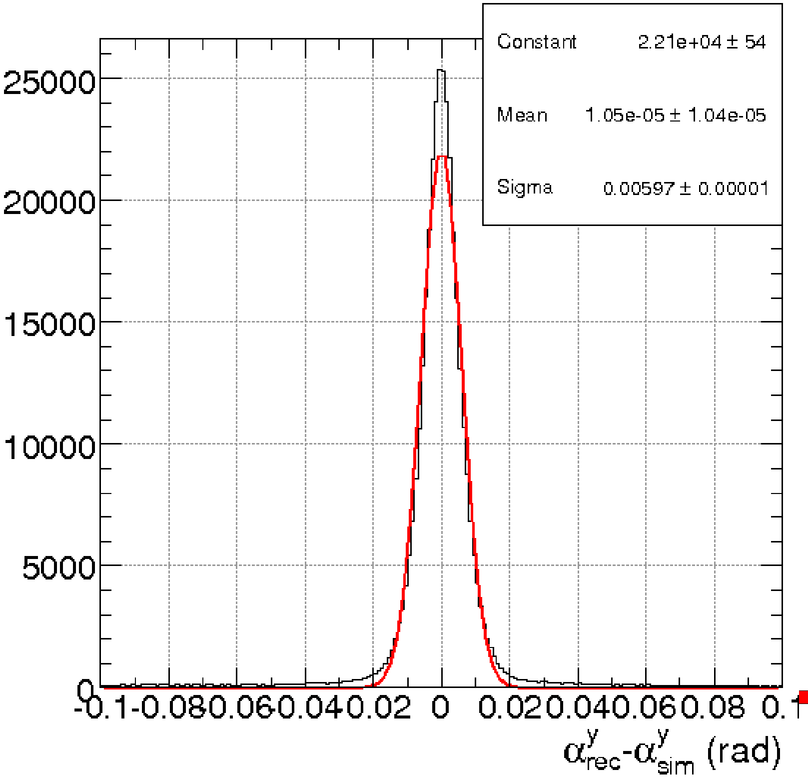


Constant drift velocity

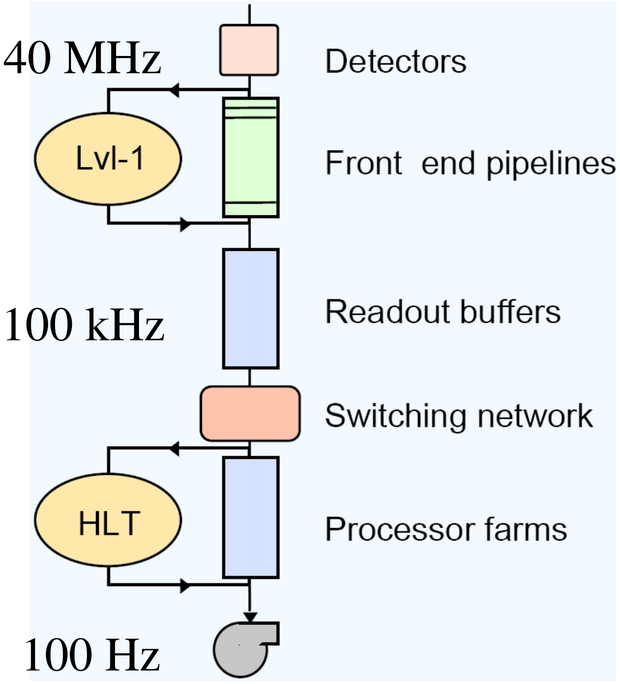

Constant 2.87e+04 ± 73
Mean 3.82e-05 ± 1.56e-05
Sigma 0.00882 ± 0.00002
30000
25000
20000
15000
10000
5000
0
-0.15
-0.1
-0.05
0
0.05
0.1
0.1
$x_{rec}-x_{sim}$ (cm)

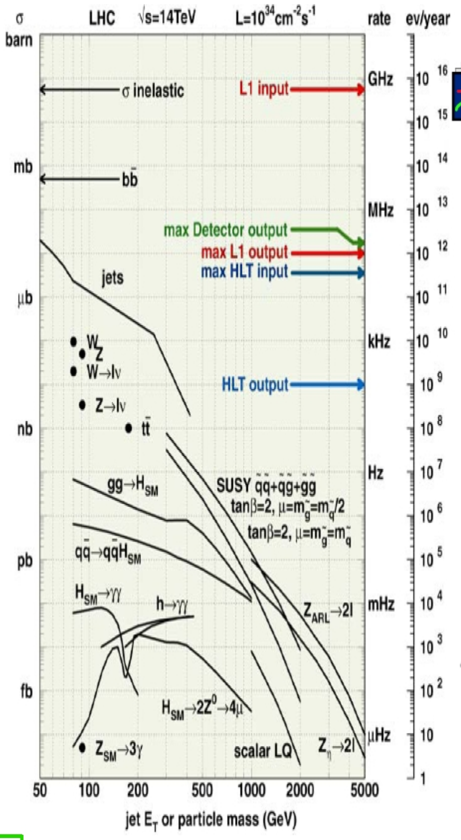

Constant 1.94e+04 ± 47
Mean 8.3e-05 ± 1.1e-04
Sigma 0.0534 ± 0.0001
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-0.2
-0.15
-0.1
-0.05
-0
0.05
0.1
0.15
0.2
$y_{rec}-y_{sim}$ (cm)

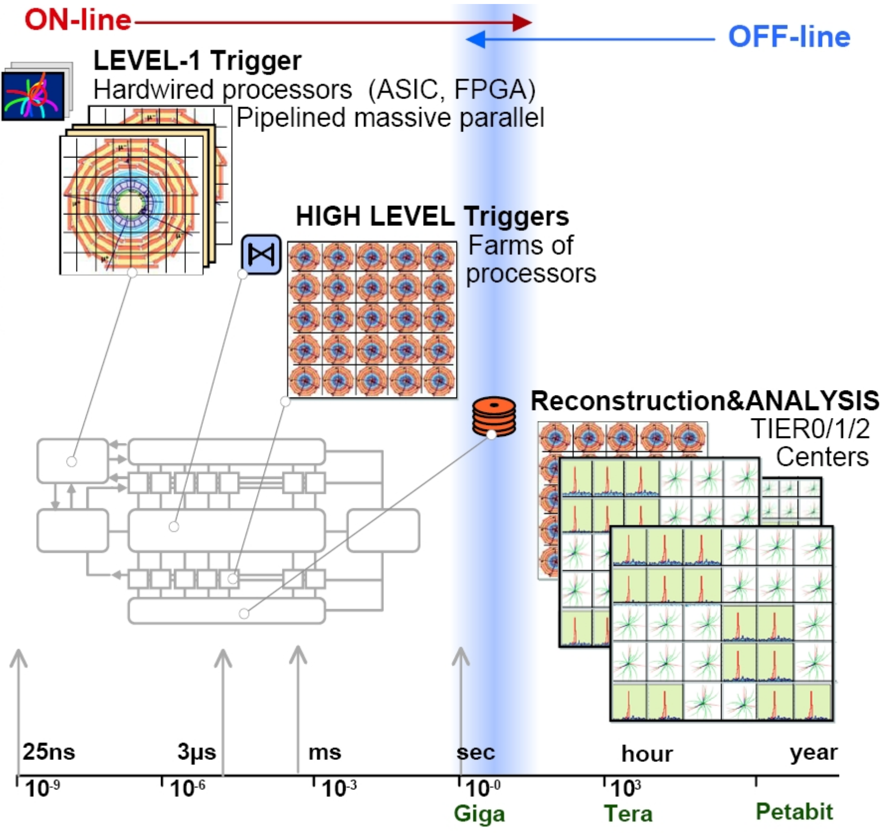

Constant 2.65e+04 ± 68
Mean 3.45e-07 ± 1.27e-06
Sigma 0.000715 ± 0.000001
30000
25000
20000
15000
10000
5000
0
-0.015
-0.01
-0.005
0
0.005
0.01
0.01
$\alpha^x_{rec}-\alpha^x_{sim}$ (rad)

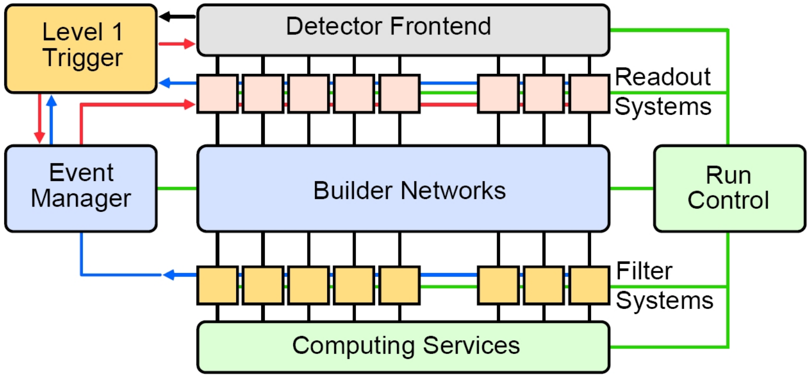

Constant 2.21e+04 ± 54
Mean 1.05e-05 ± 1.04e-05
Sigma 0.00597 ± 0.00001
25000
20000
15000
10000
5000
0
-0.1-0.080.060.040.02
0
0.020.040.060.08
0.1
$\alpha^y_{rec}-\alpha^y_{sim}$ (rad)

CMS Trigger









L1 – *Hardware*

HLT (**L2**/**L3**) – *Software*

⇨ same algorithms and framework as the **off-line software**!

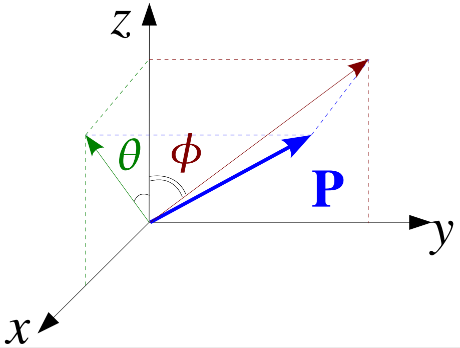
Kalman Filter

- **Filtering**
  - estimation of the "present" state vector, based up all "past" measurement
- **Prediction** (propagation)
  - estimation of the "future" state vector at a future time
- **Smoothing**
  - estimation of the state vector at some time in the "past" based on all measurements taken up to the "present" time

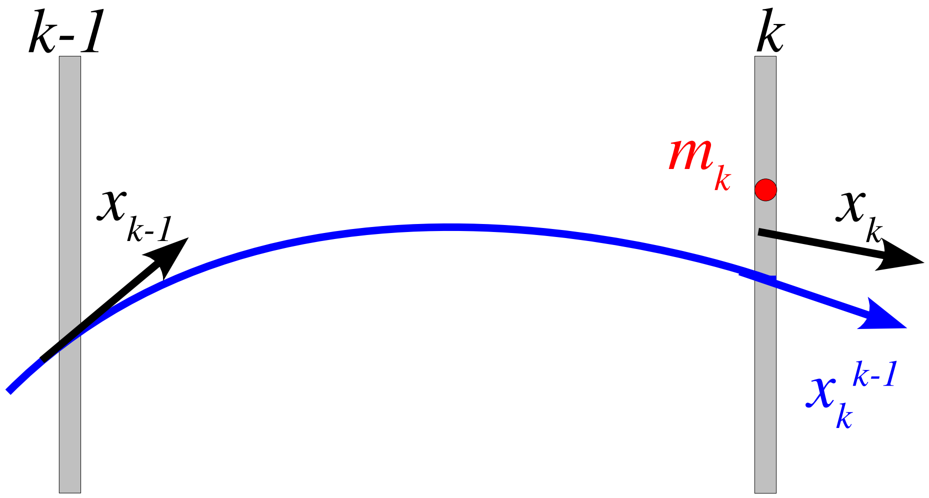
For the tracking of the charged particle the state vector is often parametrized as

$$x = \begin{pmatrix} q/p \\ \tan\theta \\ \tan\phi \\ x \\ y \end{pmatrix}$$

with



Kalman Filter



Propagation of the state on the (*k*-*1*)th layer (black arrow) on the *k*th layer

predicted state (blue arrow)

$$x_k^{k-1} = F_{k-1} x_{k-1}$$

extrapolated covariance matrix

$$C_k^{k-1} = F_{k-1} C_{k-1} F_{k-1}^T + M_{MS,k-1}$$

Relation between the state and the measurement space

$$m_k = H_k x_{k,true} + \epsilon_k$$

Minimizing the χ^2

$$\chi^2 = (H_k x_k - m_k)^T V^{-1} (H_k x_k - m_k)$$

we can find the equations for the **filtering**

updated state (black arrow on k)

$$x_k = x_k^{k-1} + K_k (m_k - H_k x_k^{k-1})$$

updated covariance matrix

$$C_k = (1 - K_k H_k) C_k^{k-1}$$

with

$$K_k = C_k^{k-1} H_k^T (V_k + H_k C_k^{k-1} H_k^T)^{-1}$$

Kalman Filter

Once all the measurements have been filtered, the **smoothing** can be performed. As the filtering it is an iterative process

smoothed state

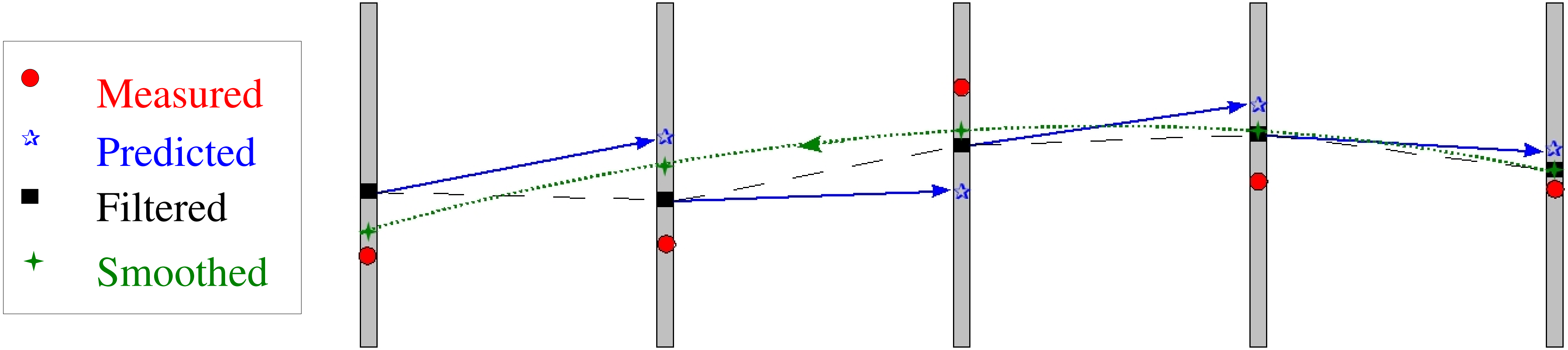
$$x_k^n = x_k + A_k \left(x_{k+1}^n - x_{k+1}^k \right)$$

covariance matrix of the smoothed state vector

$$C_k^n = C_k + A_k \left(C_{k+1}^n - C_{k+1}^k \right) A_k^T$$

with (smother gain matrix)

$$A_k = C_k F_k^T \left(C_{k+1}^k \right)^{-1}$$



The Kalman Filter needs a **seed** to start the iteration process

Stand Alone Muon System

- **Seed** state estimation
  - from the local segments reconstruction for the off-line reconstruction
  - from the L1 trigger in the on-line reconstruction
- **“Pre”-filter** from inside to outside using the DT/CSC segment granularity (1D hits for the RPC)
  - “Pre”-filter needed to avoid possible bias from the seed
  - Best state estimation **on the outermost** (used) layer
- **Filter** from outside to inside using the best state from the “Pre”-filter and:
  - the segment for the pattern recognition
  - the 1D hit for the trajectory updating
  - Best state estimation **on the innermost** (used) layer

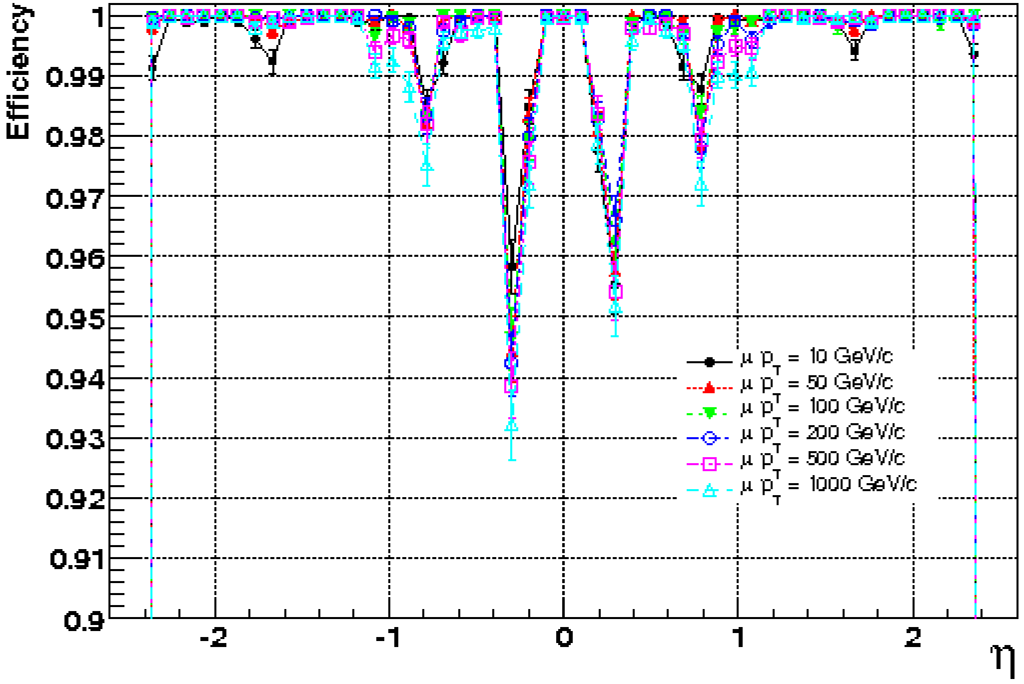
Stand Alone Muon System

For each ("Pre"-) filter step

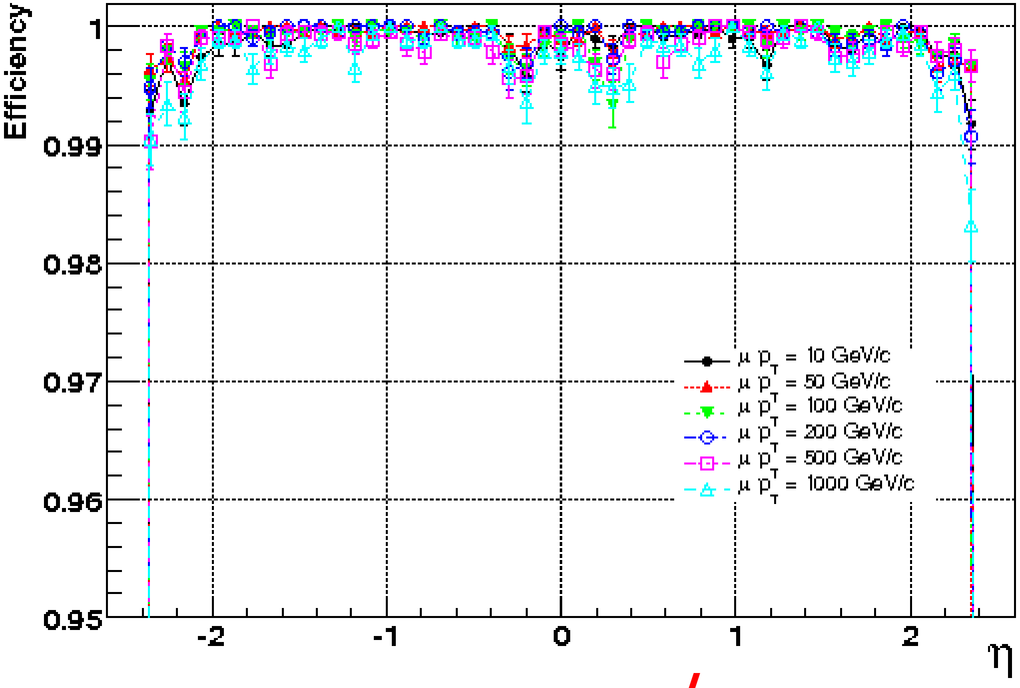
- **Propagation** of the state to the next compatible layer of chamber
- looking for the measurements (segments/hit)
  - **pattern recognition**: choose of the most compatible (on χ^2 basis)
    - possibility to reject all the measurements (there is a χ^2 cut)
  - **updating** (**filtering**) of the state vector with the measurement
    - if the state and the measurement are not on the same plane, another propagation is performed

- Ghost suppression
- Extrapolation to the PCA and updating at vertex
  - update of the track parameters

Stand-Alone Muon Reco Efficiency

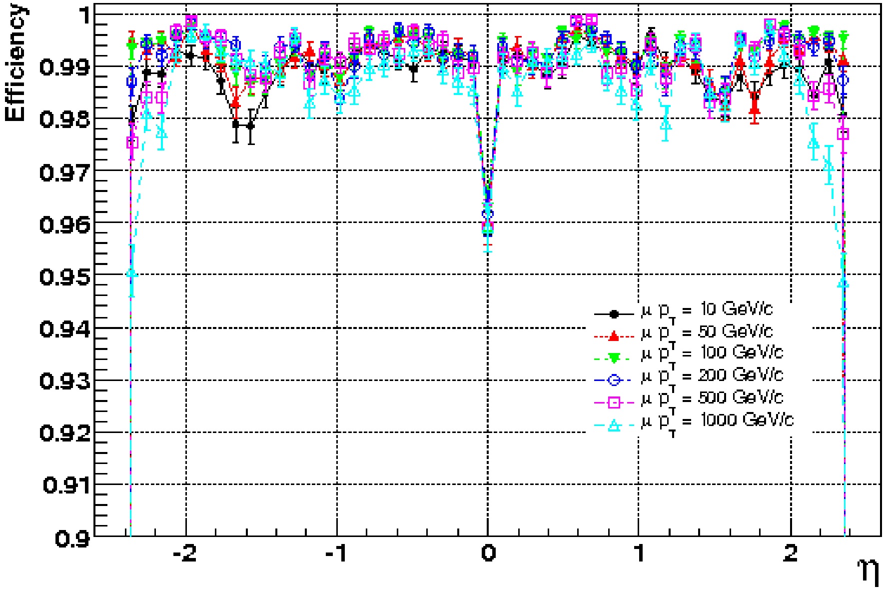


ϵ_{Seed}

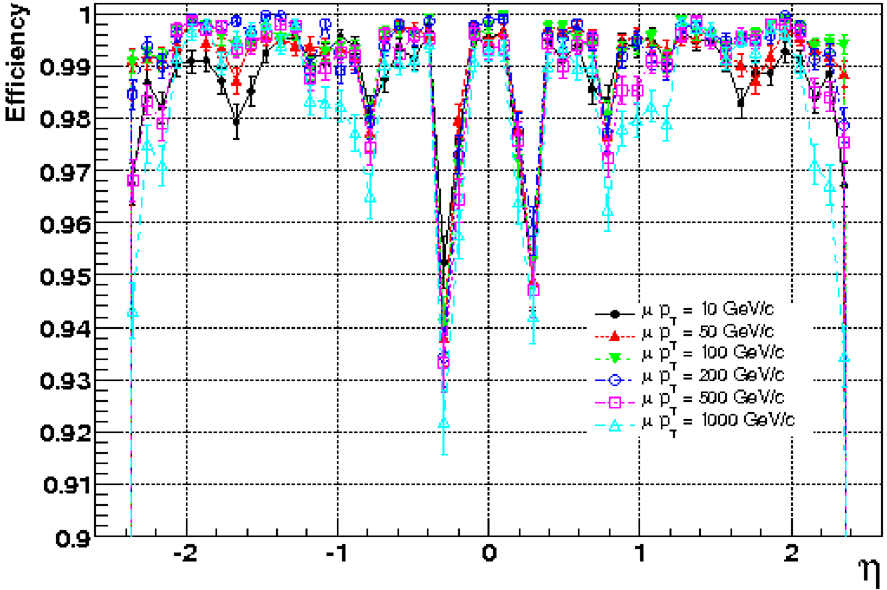


$\epsilon_{\text{SA-Seed}} = \epsilon_{\text{SA}} / \epsilon_{\text{Seed}}$

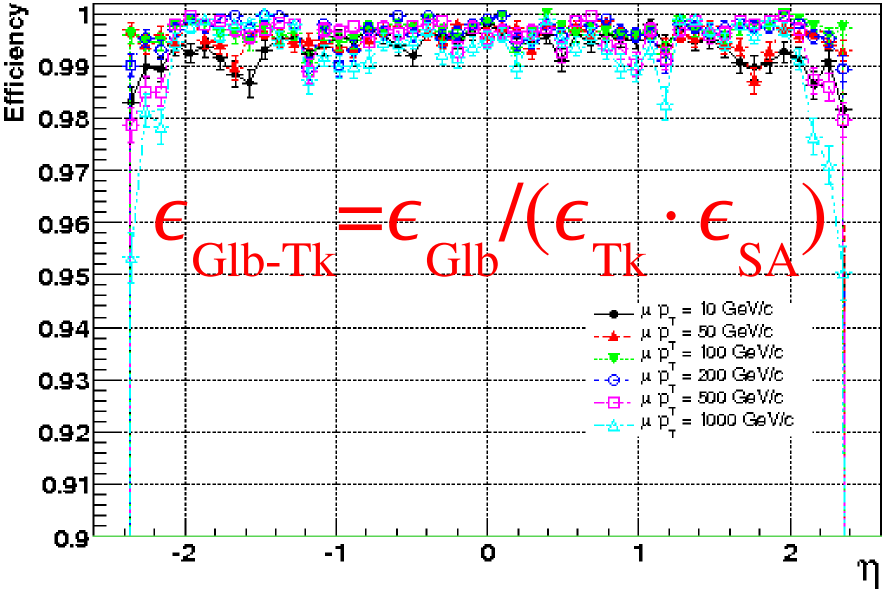
Global Muon Reco Efficiency



$\epsilon_{\text{Glb-Sta}} = \epsilon_{\text{Glb}} / \epsilon_{\text{SA}}$

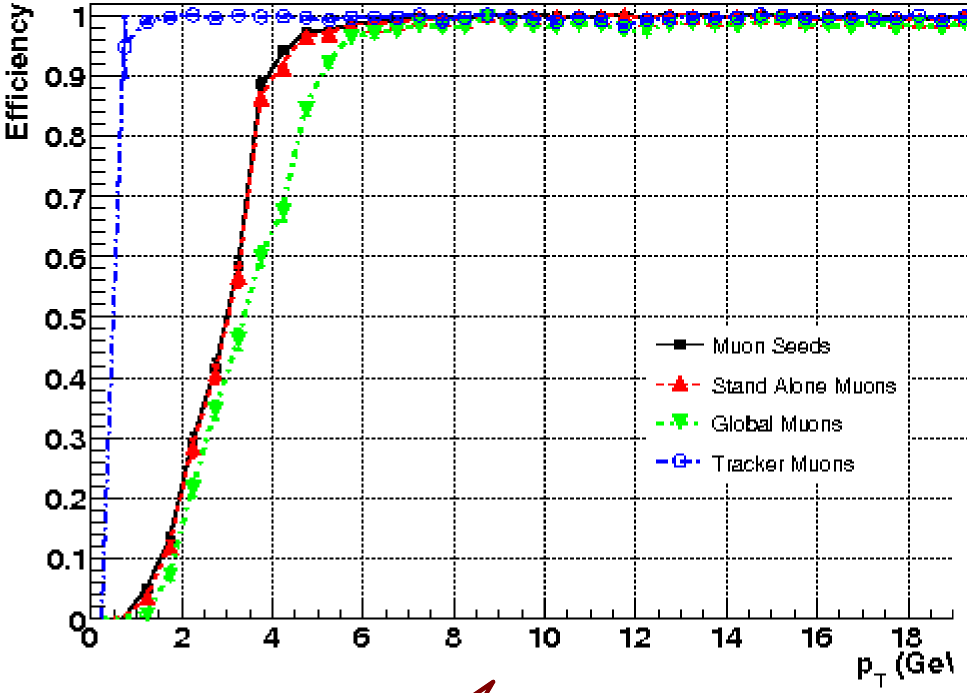


$\epsilon_{\text{Glb-Tk}} = \epsilon_{\text{Glb}} / \epsilon_{\text{Tk}}$



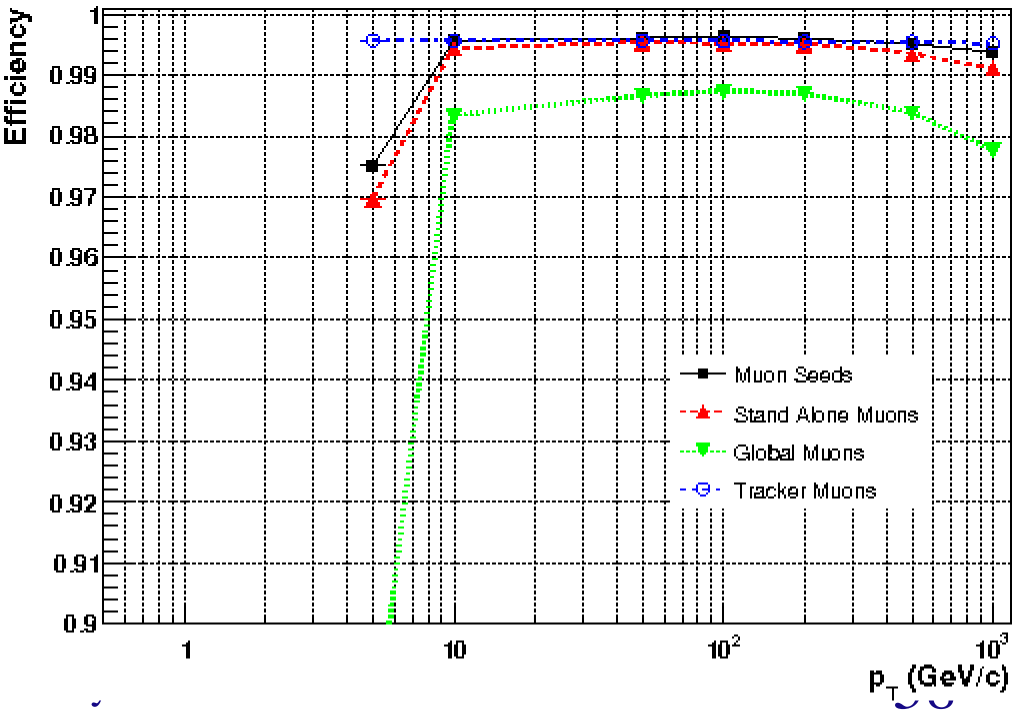
$\epsilon_{\text{Glb-Tk}} = \epsilon_{\text{Glb}} / (\epsilon_{\text{Tk}} \cdot \epsilon_{\text{SA}})$

Stand-Alone and Global Efficiency

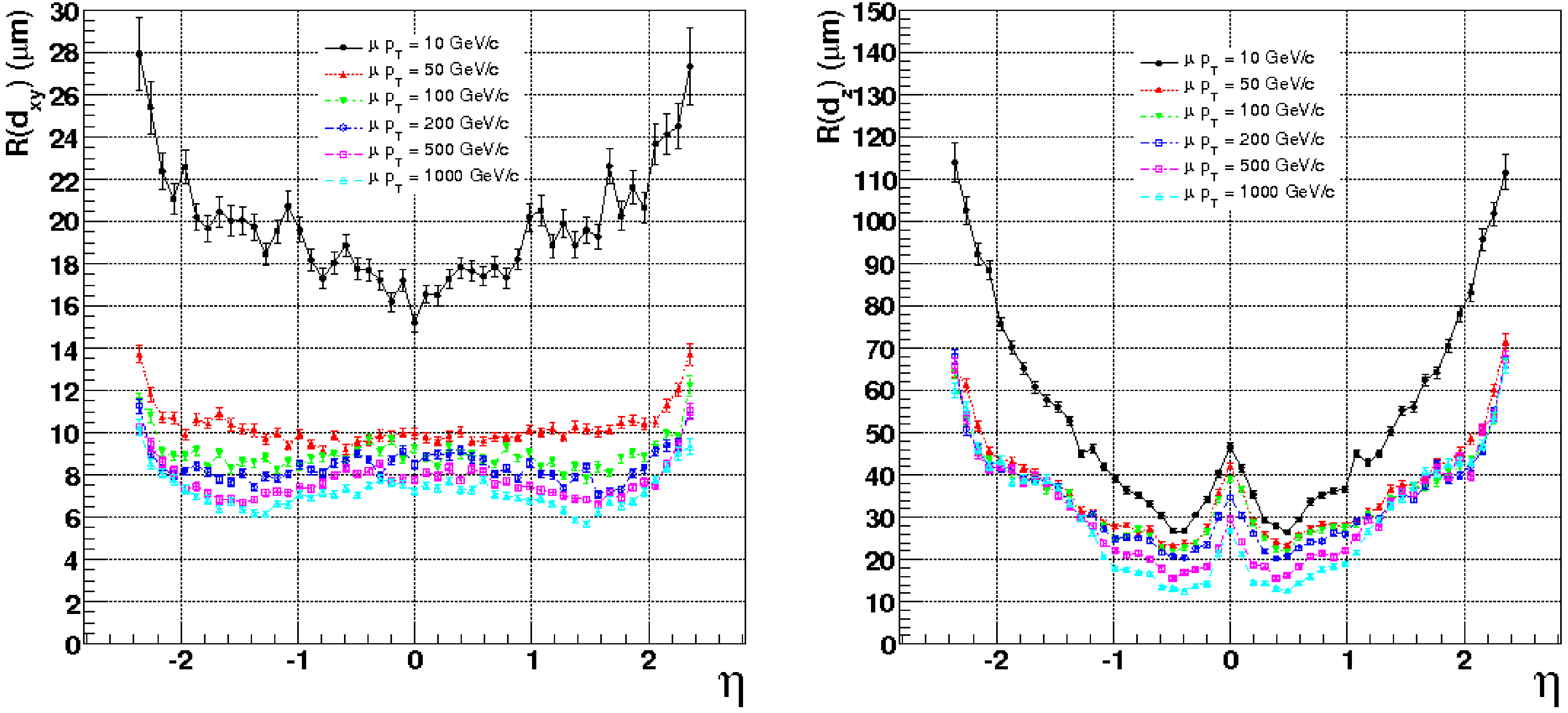


Low p_T region

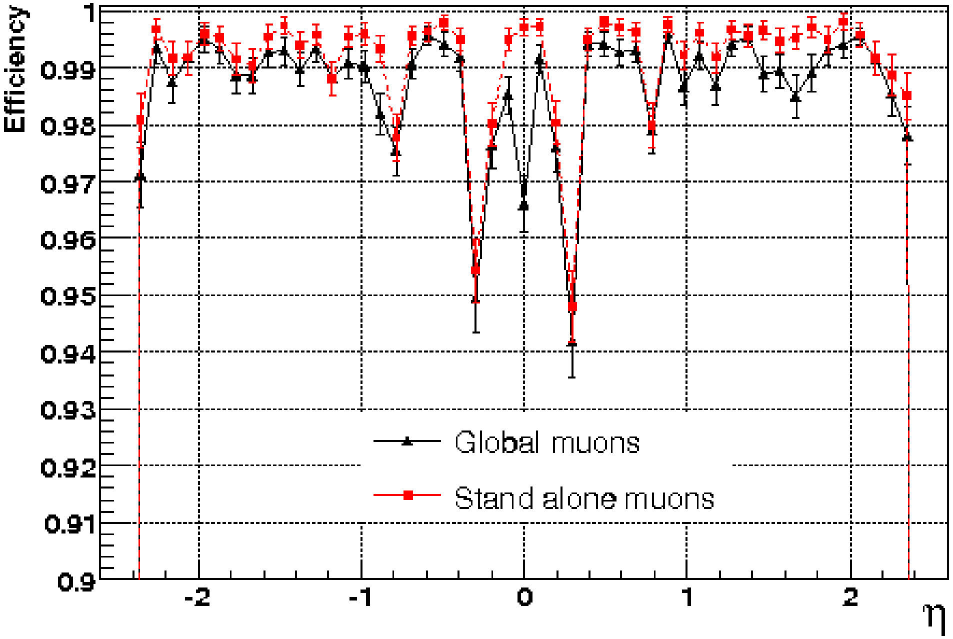
Whole p_T region

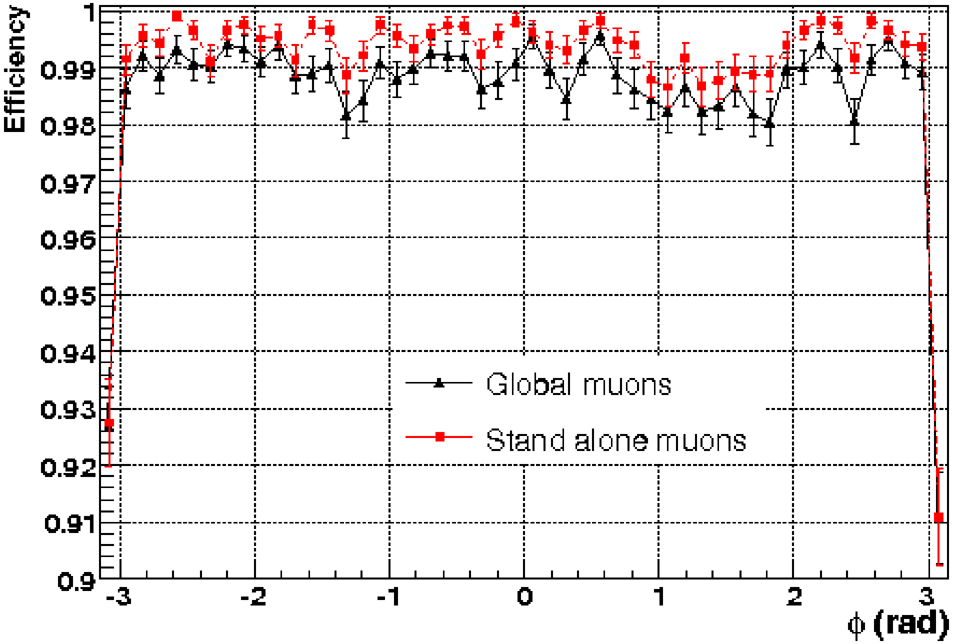


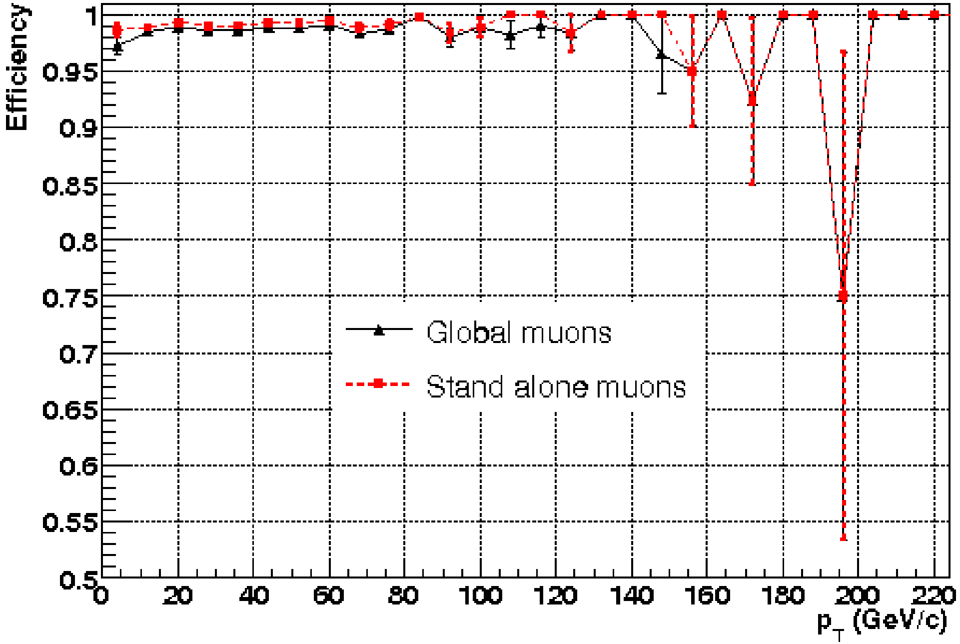
Resolution on the Impact Parameters



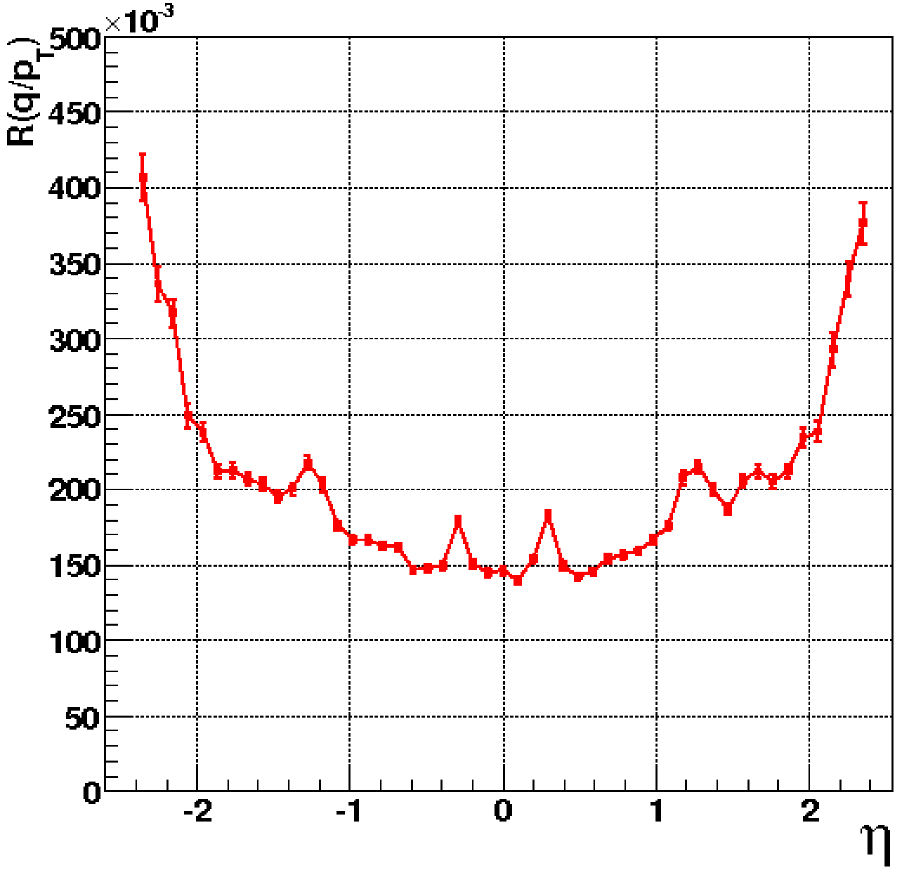
Muon Reconstruction Efficiency



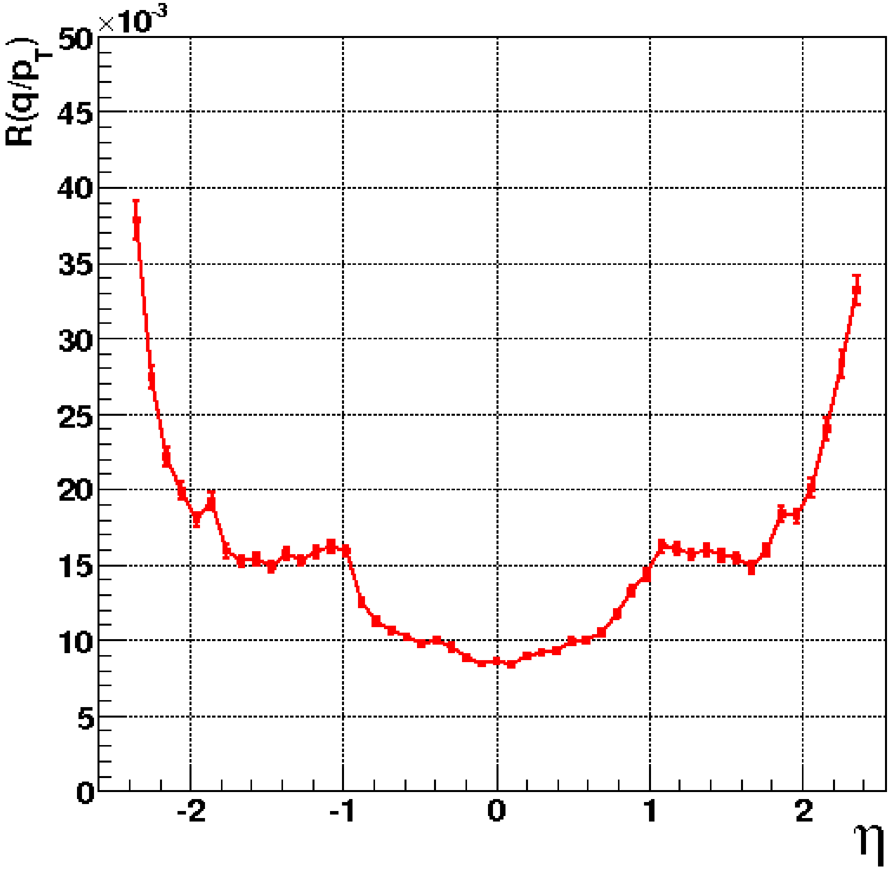




Resolution on q/pT



Stand alone

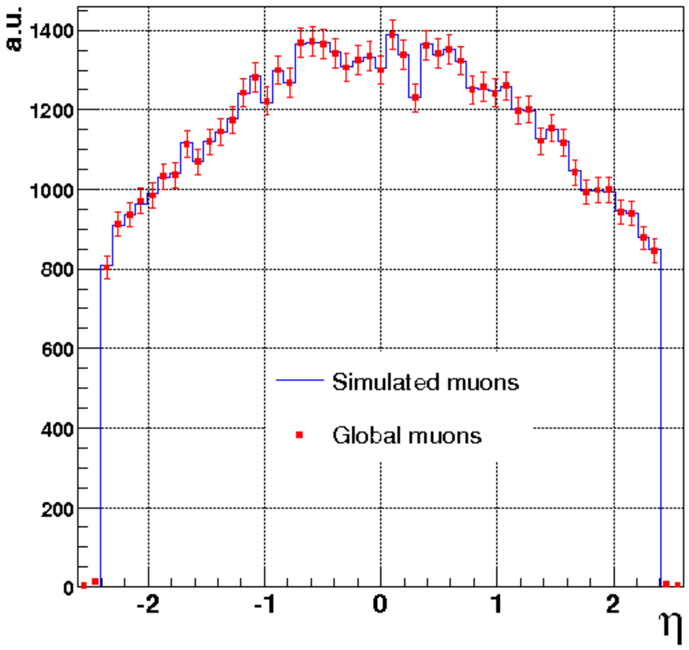


Global

$Z \rightarrow \mu^+\mu^-$

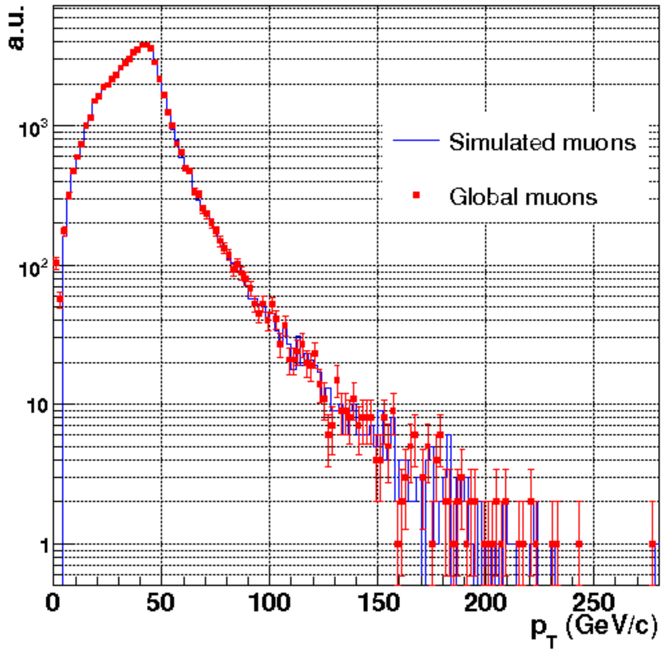
- It is an important signature for the vector boson scattering channel
- It will be one of the first channels investigated at LHC
  - It is a benchmark for the reconstruction and the detector

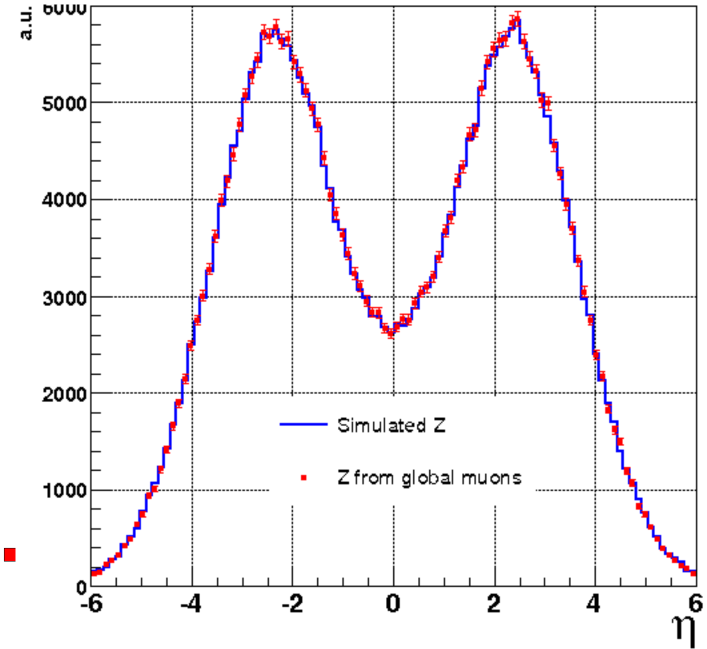
η and p_T Distributions



μ

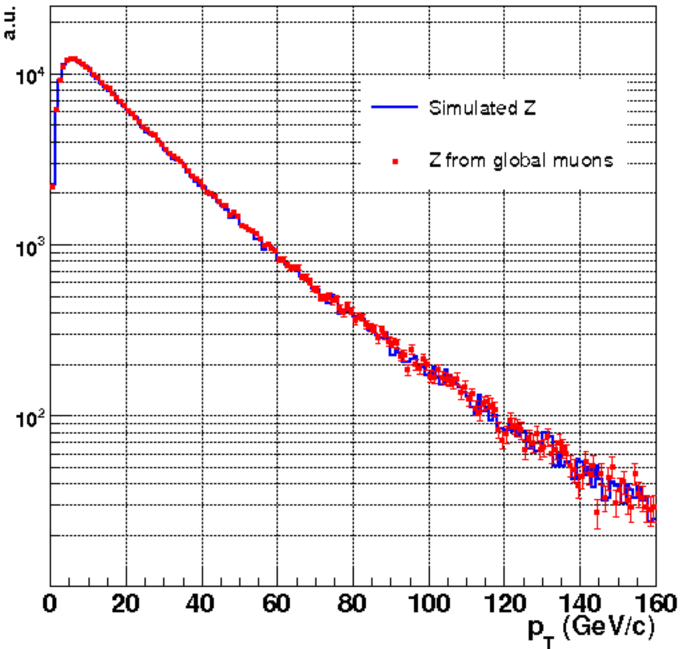
Parameter of μ	Resolution **Global**
p_T (%)	**1,6**
η	**$2,8 \cdot 10^{-4}$**
ϕ **(mrad)**	**0,16**



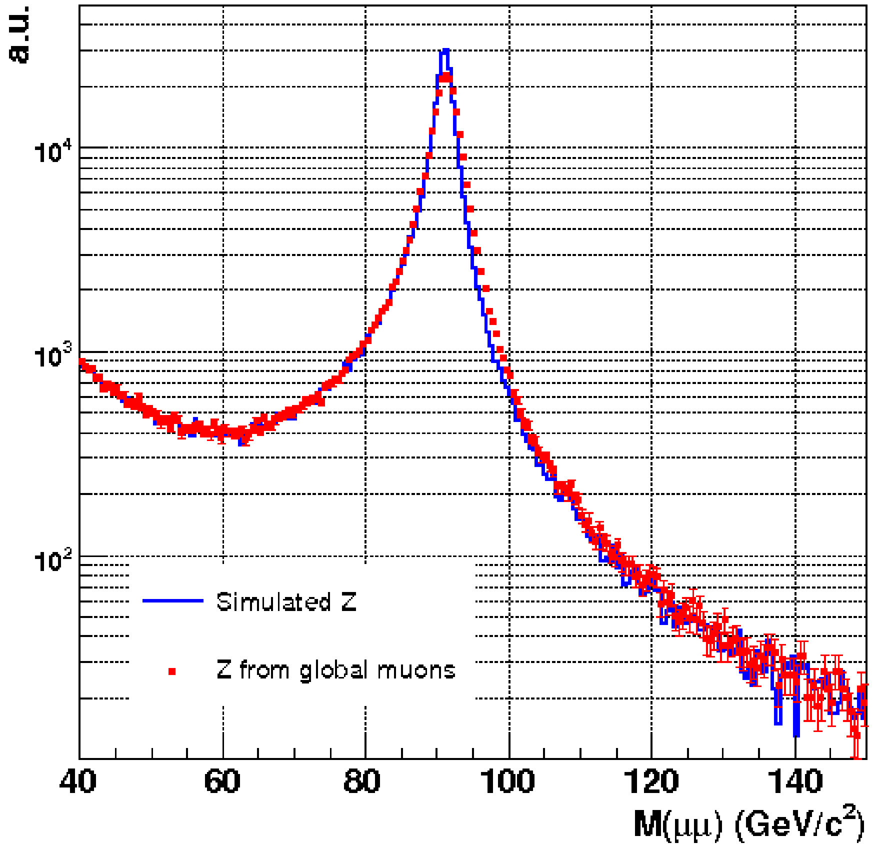


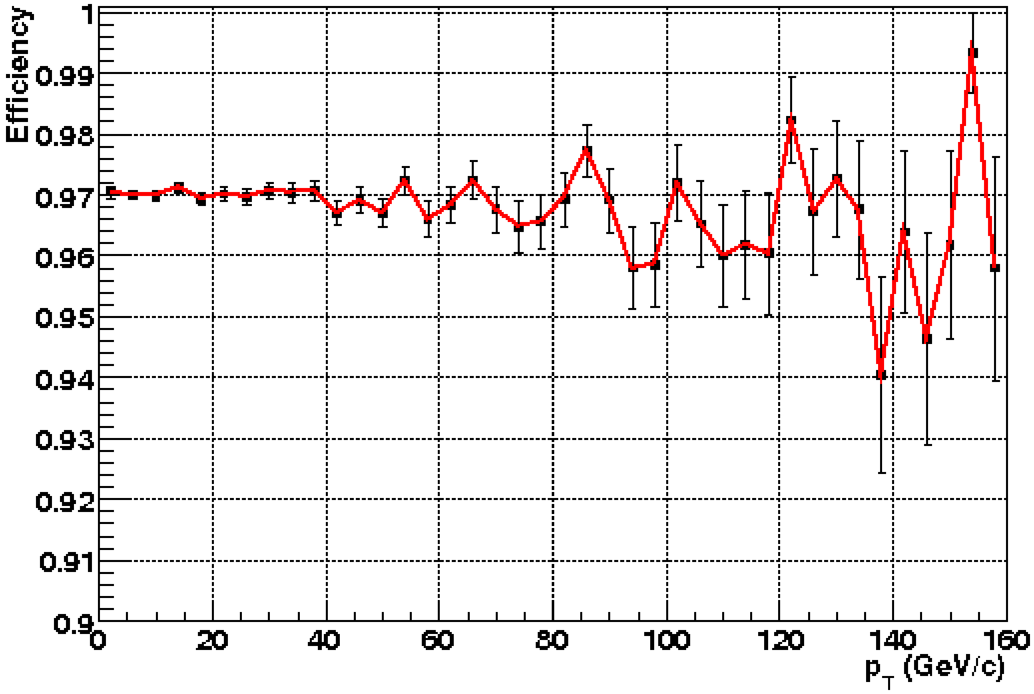
Z

Parameter of Z boson	Resolution **Global**
p_T (%)	**3,8**
η	**0,026**
ϕ **(rad)**	**0,026**



Z Boson Inv Mass and Reco Efficiency





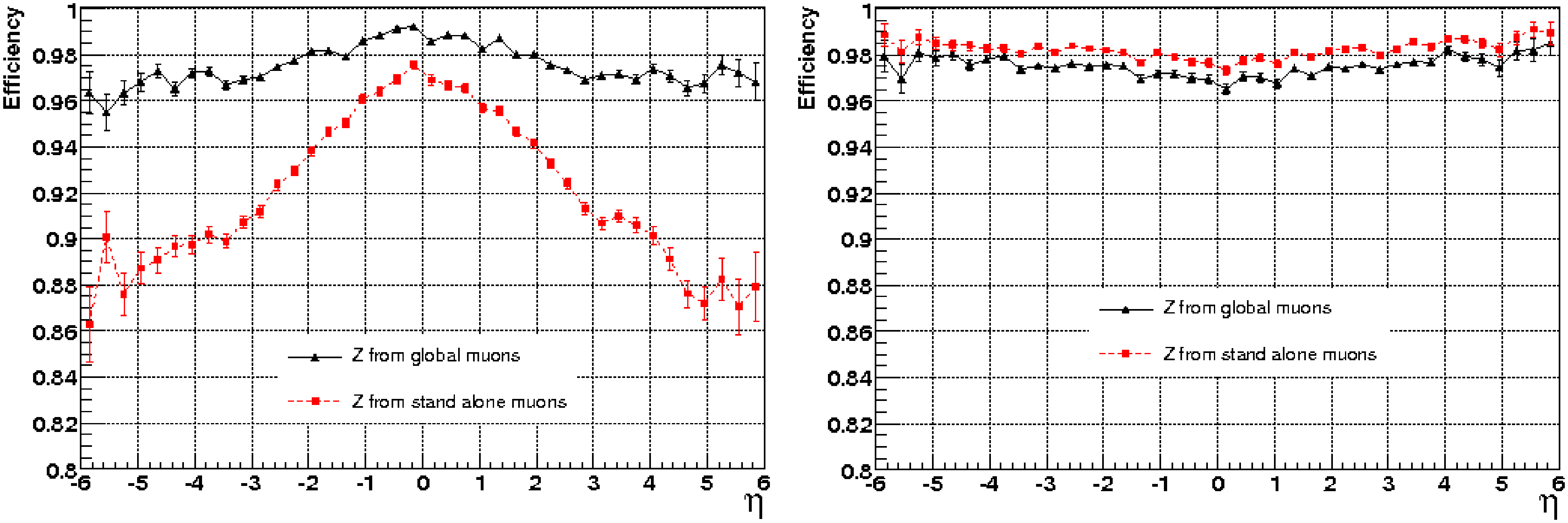
Overall efficiency ~ 97%

$m_Z = (91.089 \pm 0.005)$ GeV

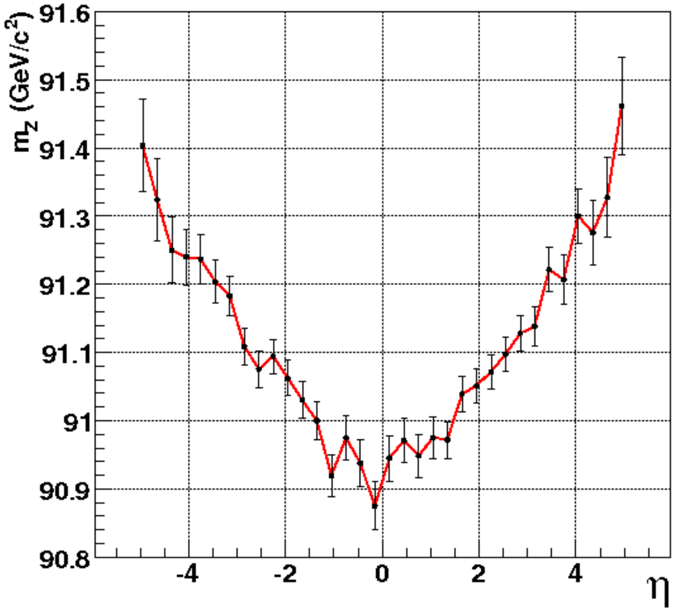
$\delta m_Z / m_Z = 1.06\%$

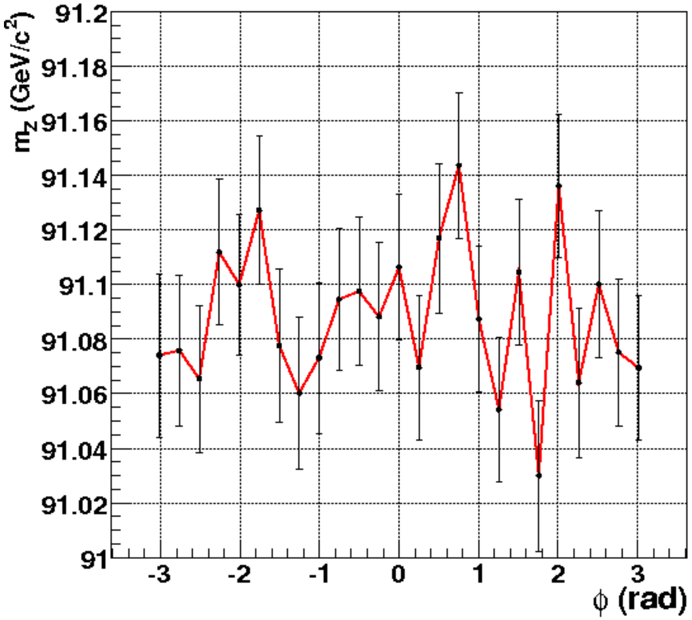
$\Gamma^*_Z = (3.84 \pm 0.01)$ GeV

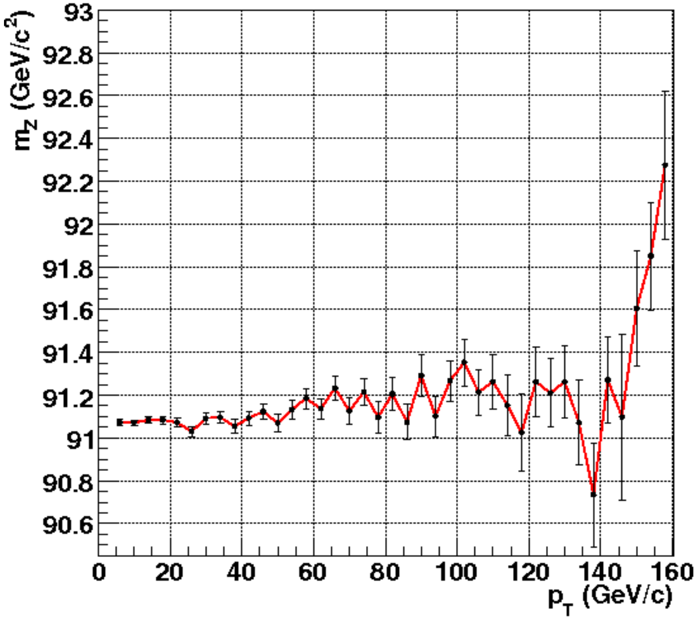
Z Boson Reconstruction Efficiency



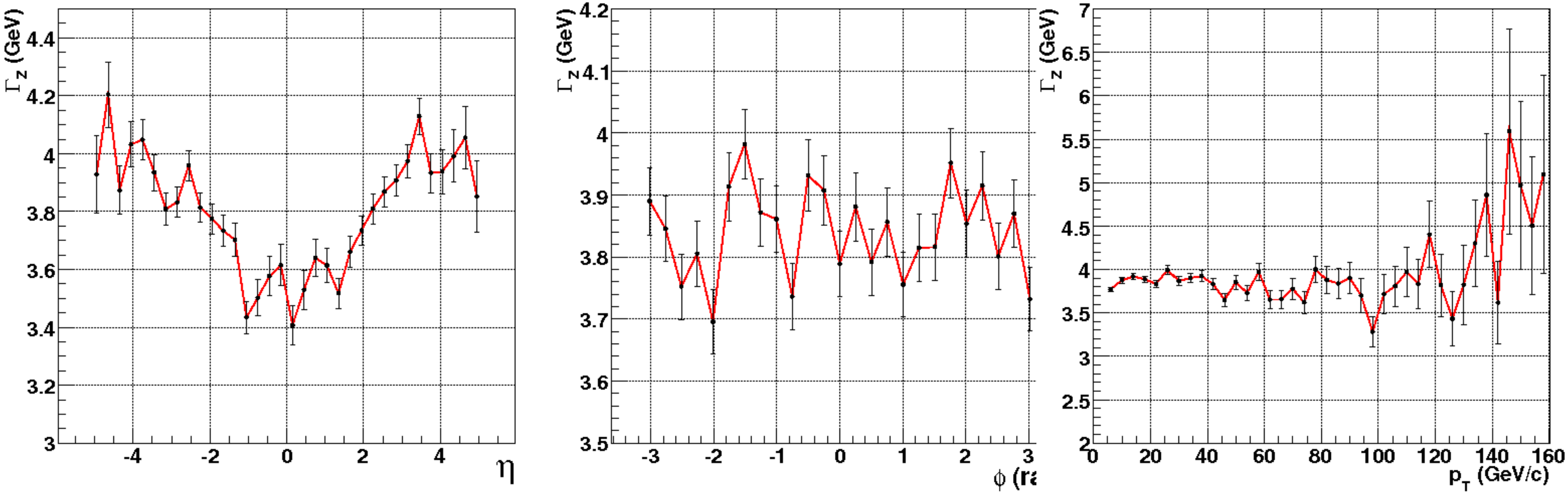
Z Boson Invariant Mass







Width of the Z peak



Resolution on m_Z