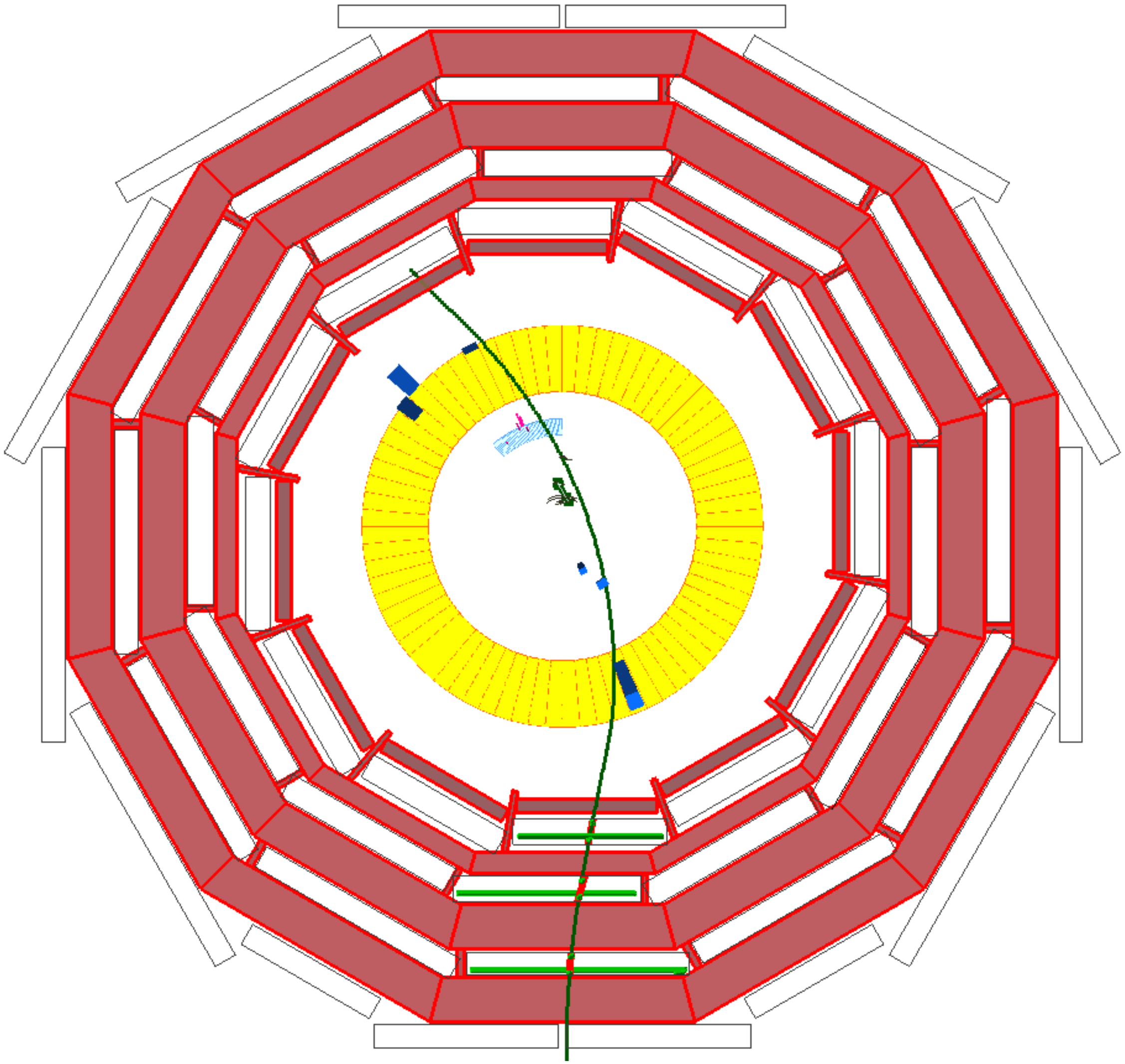
Muon Reconstruction



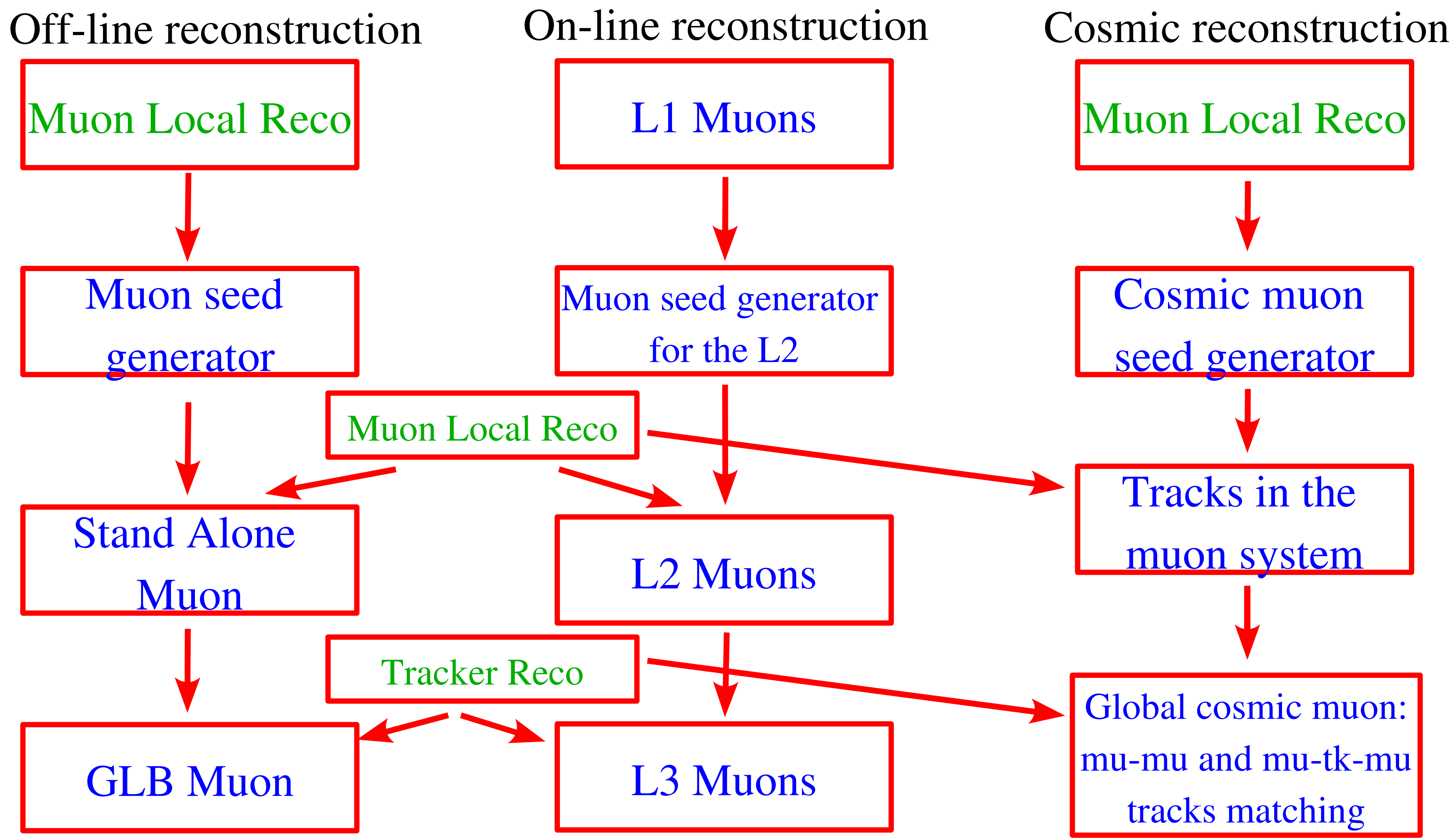
Riccardo Bellan

μ-POG

Outline

- Muon reconstruction strategy
- Muon reconstruction performance
- Cosmic ray reconstruction strategies
- Data analysis of cosmics

The Full Chains

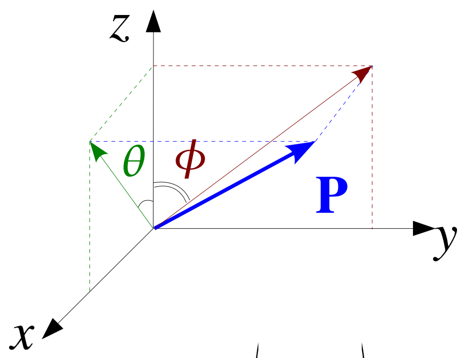


Tracking Infrastructure

- Since the beginning (ORCA times), *very big effort* to maintain the structure of the data formats, of the fitting tools, of the geometry, ... , **as generic as possible**
- This allows as to use **common tools** for all systems (tracker, CSC, DT, RPC)
  - e.g. generic rechit interface, so the fitting tools can take a collection of tracker hits and one of muon segments and fit them all
- Our paradigms are:
  - Whenever possible, use common tools instead of building specific ones
  - If the tool you have built is suitable for both the tracker and the muon reconstruction, then make it a common tool

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



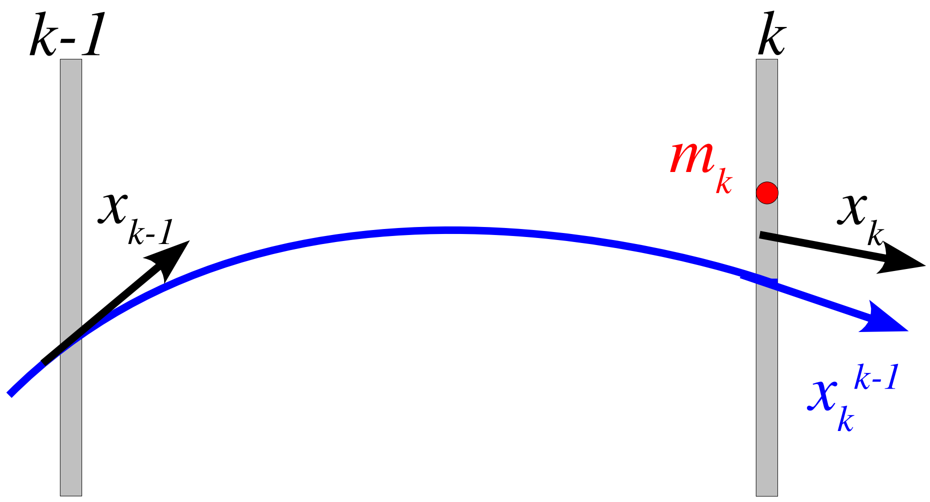
$$x = \begin{pmatrix} q/p \\ \tan\theta \\ \tan\phi \\ x \\ y \end{pmatrix}$$

- The goal is to **reconstruct the trajectory** of many charged particles using *position measurements*

Requirements

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

⇨ **Kalman Filter**



Propagation of the state on the $(k\text{-}1)^{th}$ 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

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

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

smoothed state

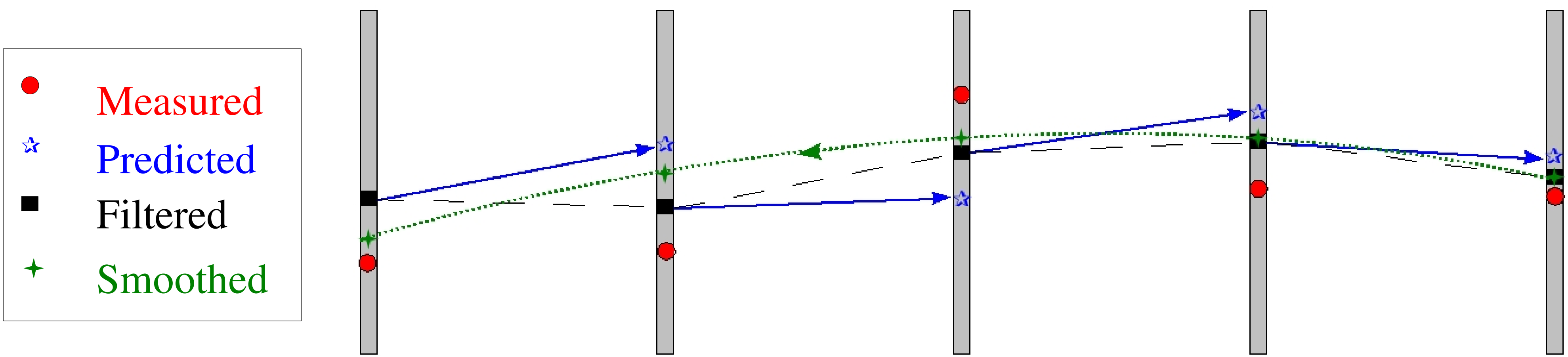
$$x_k^n = x_k + A_k (x_{k+1}^n - x_{k+1}^k)$$

covariance matrix of the smoothed state vector

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

with (smother gain matrix)

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



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 <u>inside to outside</u> 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 <u>outside to inside</u> 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

<u>For each ("Pre"-) filter step</u>

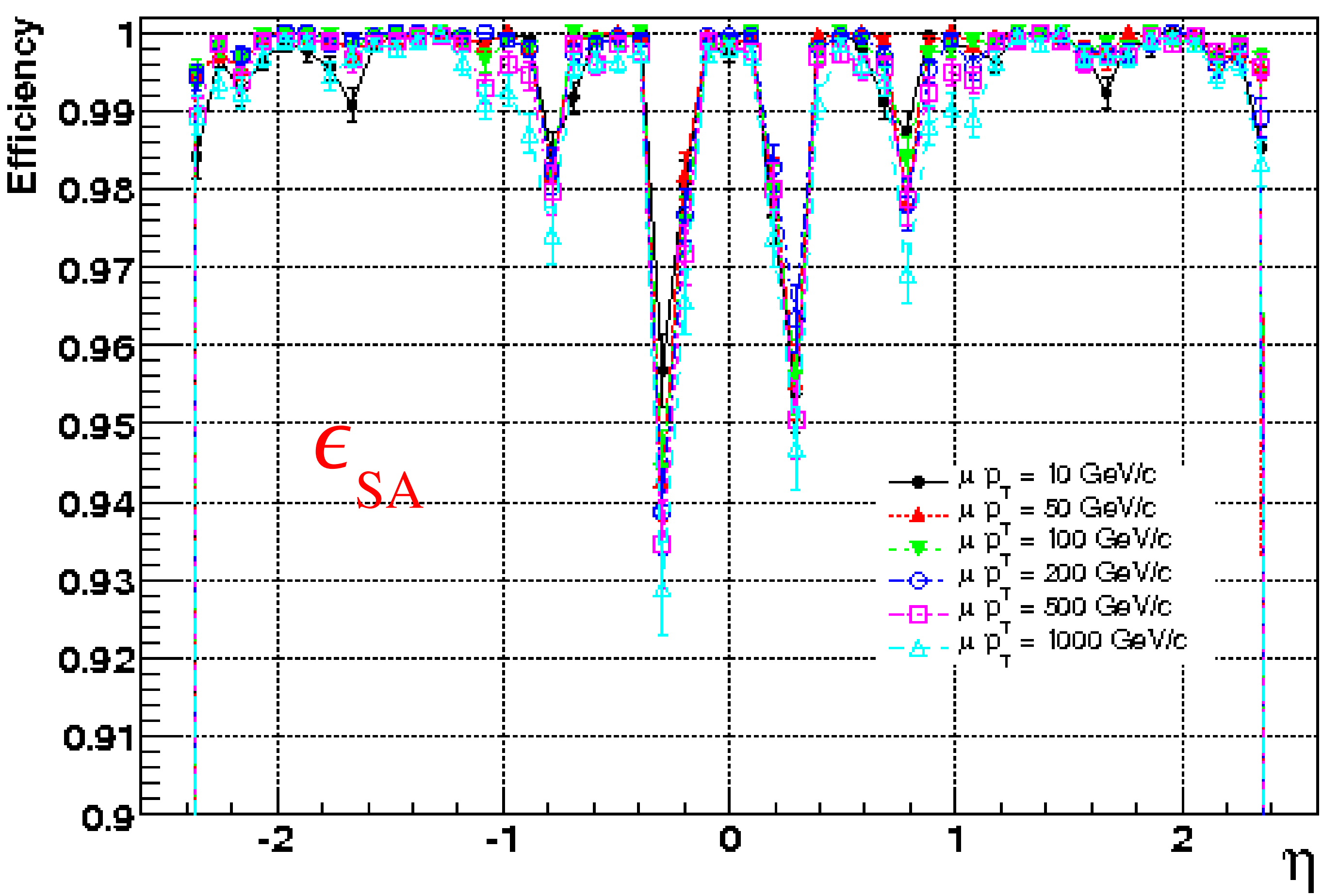
- **Propagation** of the state to the next compatible layer of chamber
- looking for the measurements (segments/hit)
  - **pattern recognition**: choose of the most compatible (on χ^2 basis)
    - possibility to reject all the measurements (there is a χ^2 cut)
  - **updating** (**filtering**) of the 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

DataFormats: Input/output Objects (I)

- Seed for the Stand Alone muon reconstruction
  - Input: CSC and DT segments (no RPC)
  - Output: **TrajectorySeed collection**
- Stand alone muon reconstruction
  - Input: rechits/segments in the muon system (CSC, DT, RPC) and the TrajectorySeed collection
    - I want to stress: **all rechits/segments have the same generic interface**
  - Transient output: Trajectory collection
    - It contains all the fit's information... indeed it is the result of the fit!
    - It has the measurements on all the used layer
  - Persistent output: **reco::Track collections**
    - DataFormat designed to be persistent: minimal disk space usage
    - Two collections: tracks with and without vertex constraint

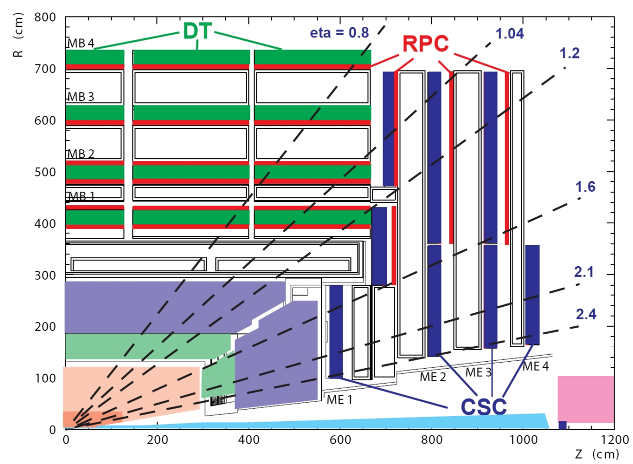
Stand-Alone Muon Reco Efficiency



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

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

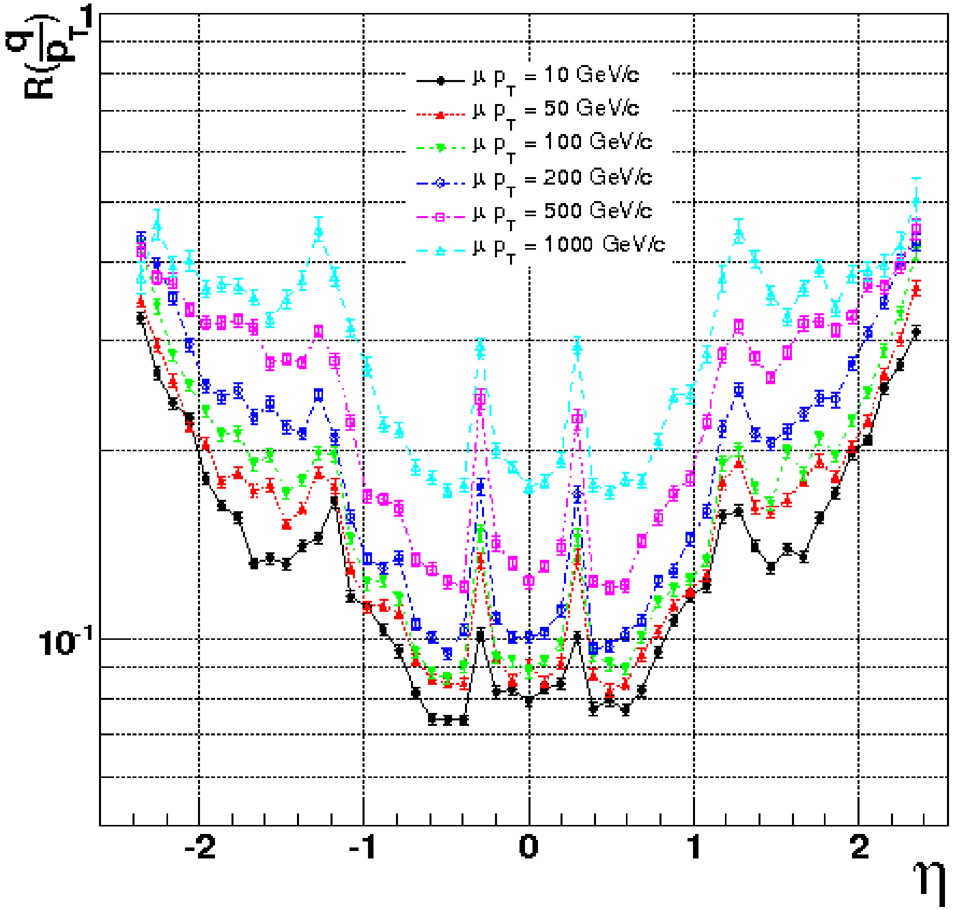
$|\eta| \approx 1.6$ ⇨ transition between two end-cap rings

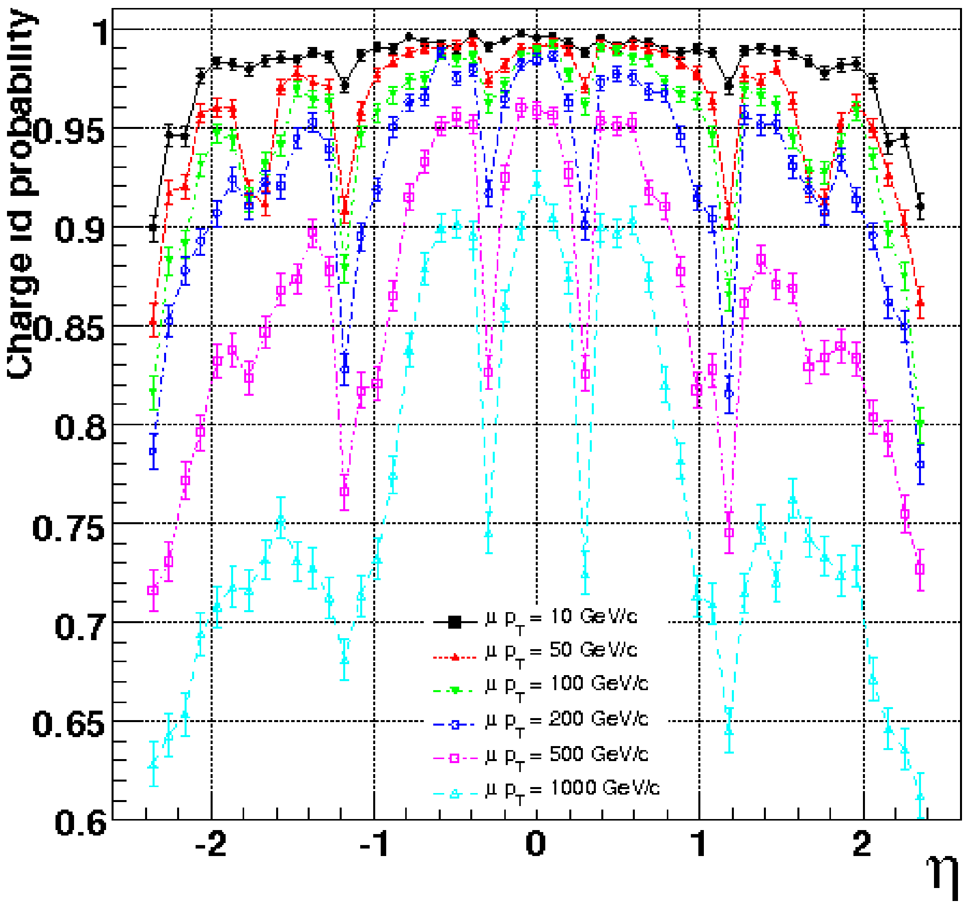


Overall efficiency ~ 99%

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

Global Reconstruction

Two different strategies

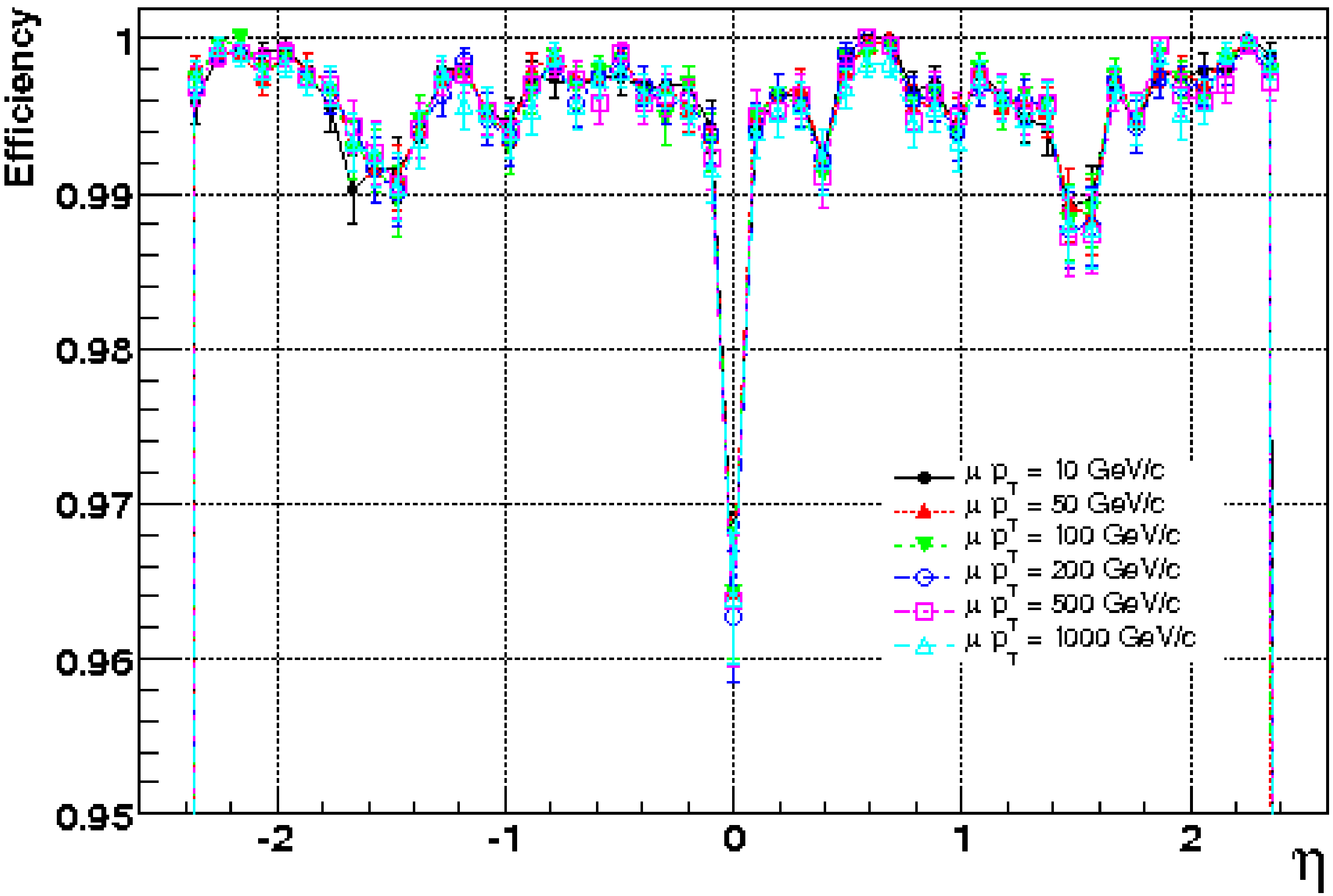
- Track reconstruction inside the tracker and inside the muon system independently
  - **matching** of the two tracks and refit of all hits
- Track reconstruction inside the muon system and then in the tracker
  - the state estimated in the muon system alone is used to open a *region of interest* in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

The reconstruction in the tracker uses the *Kalman Filter approach* as well.

DataFormats: Input/output Objects (II)

- Global muon reconstruction → tracks matching
  - Input: tracker and STA muon's reco::Track collections
  - Transient output: the Trajectory collection corresponding to the global tracks
  - Persistent output: **reco::Track collection** of the tracker+muon system
  - Map to keep *three links*:
    - matched **tracker**'s track alone, **STA** muon tracks, **combined** track
- Final muon object
  - Input: muon's reco::Track collections
  - Output: reco::Muon collection
    - Info from the calorimeters added

Tracker Track Reco Efficiency

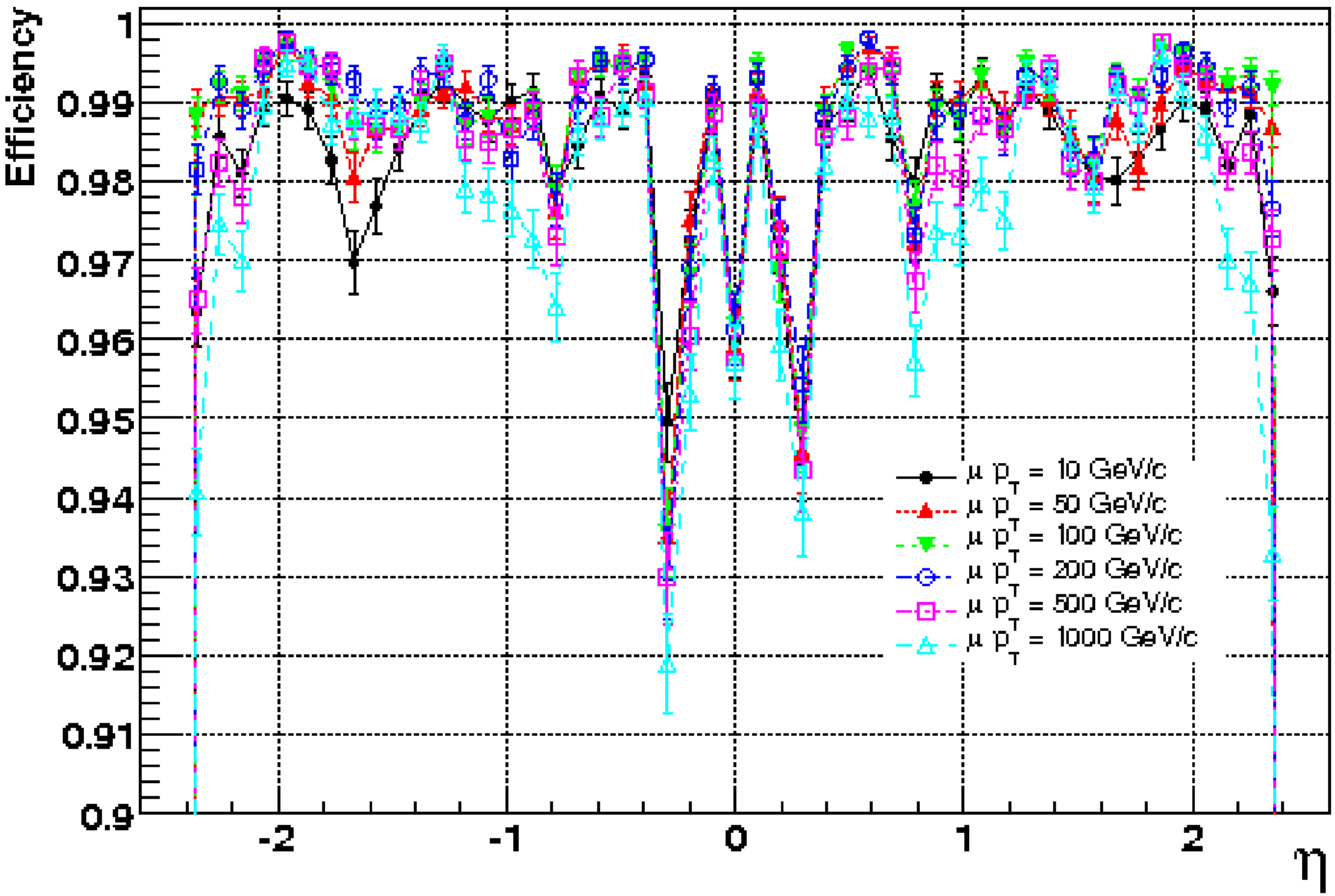


Dips due to geometrical acceptance of the tracker:

- $\eta \sim 0$ half-barrel junction
- $|\eta| \sim 1.5$ barrel-endcap transition

Overall efficiency more than 99%

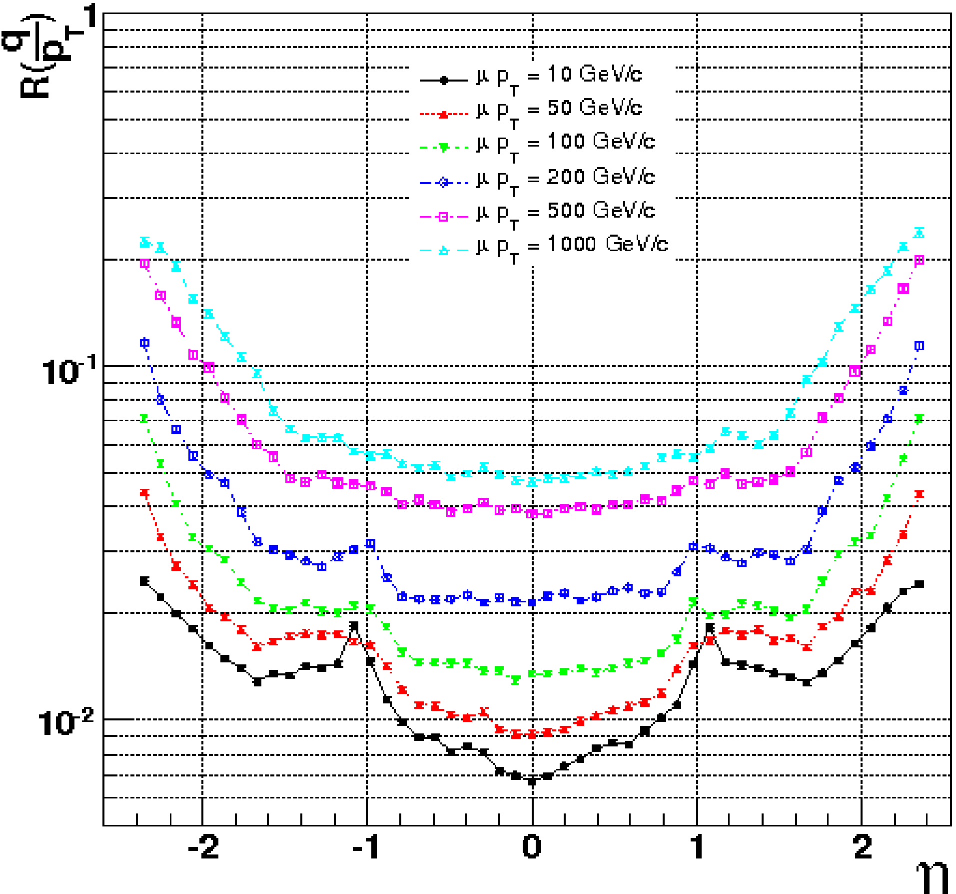
Global Muon Reco Efficiency

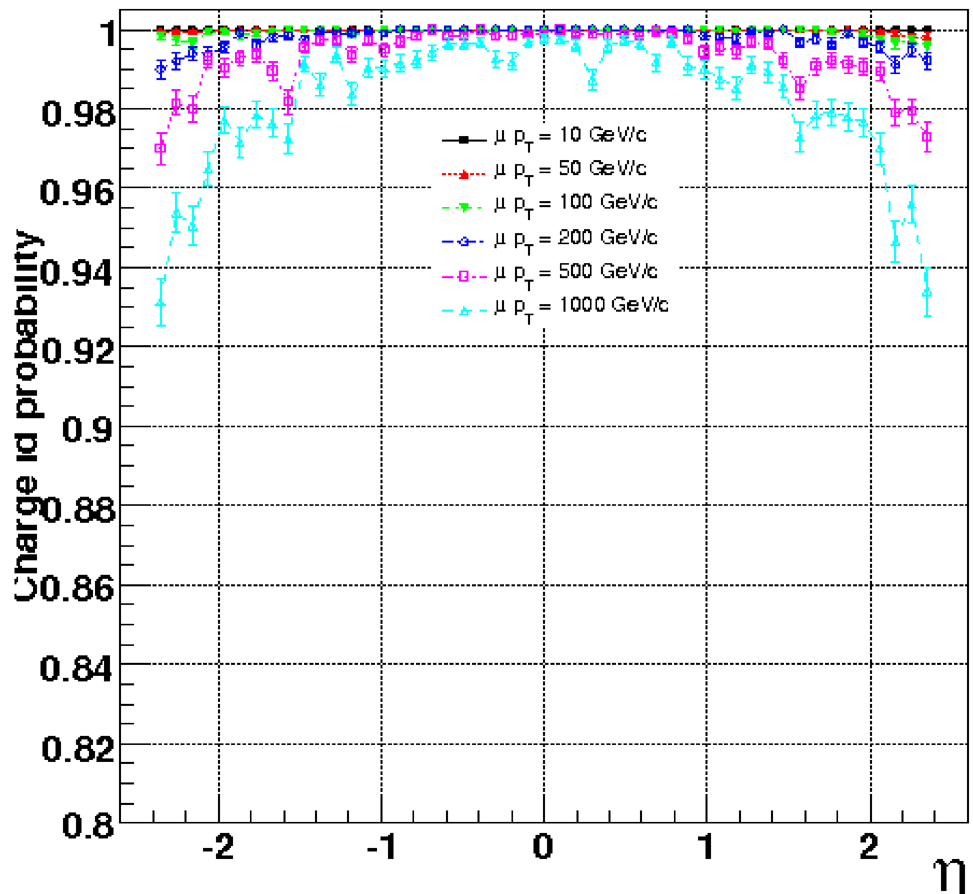


Efficiency strongly depends on the

stand alone muon reconstruction

Resolution



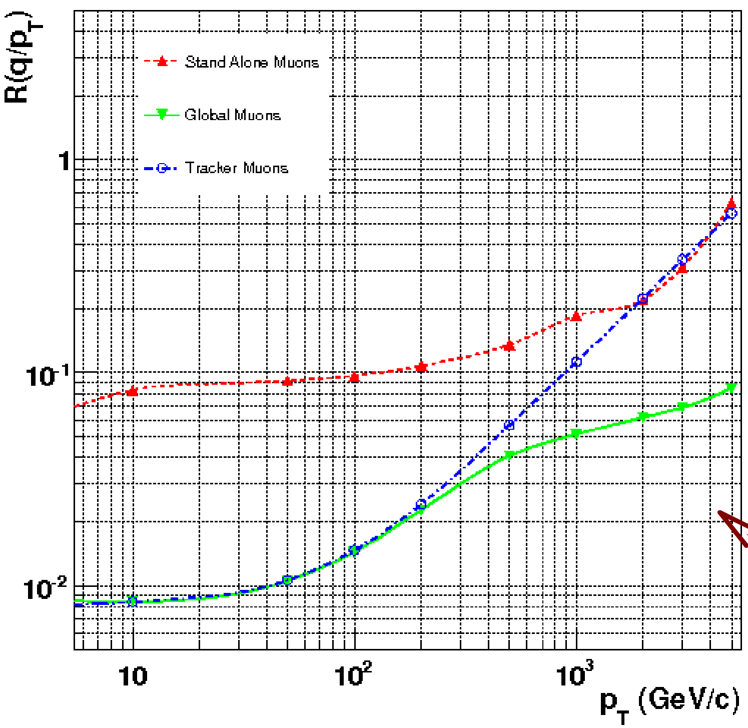


Resolution strongly dependent by the **tracker resolution** (at least for $p_T < 200$ GeV)

0.8% of resolution on q/p_T in the barrel, for μ with $\mathbf{p_T = 50}$ **GeV**

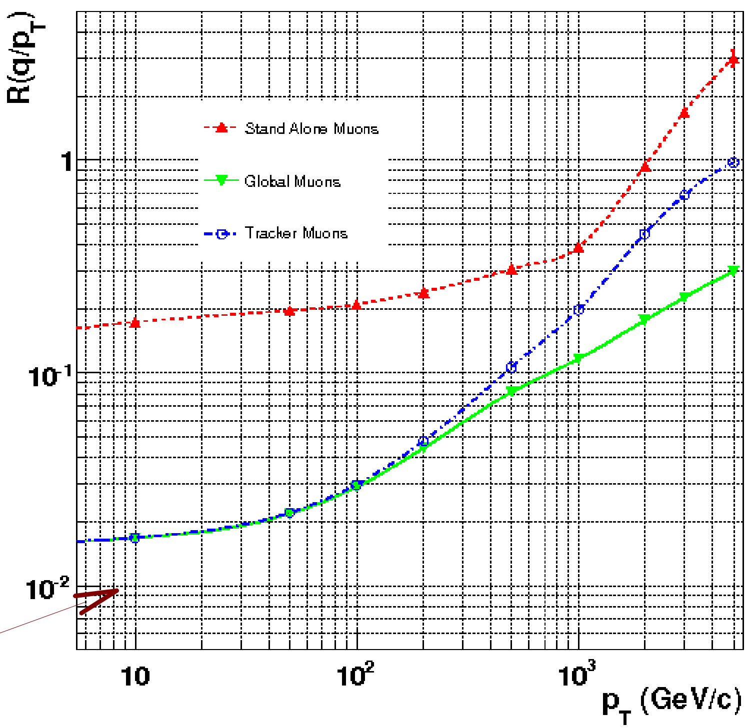
~100 % of charge Id probability, for μ with $\mathbf{p_T = 50}$ **GeV**

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



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

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

Tracking and Alignment

- Possibility to **estimate** the alignment constant using the common tracking/refitting tools
- **Alignment acts at geometry level**:
  - hits are in the local frame of the detectors
  - Correcting the detector position automatically corrects the hit position
  - position/rotation corrections taken from DB
- The tracking tools work **independently** to the alignment constants:
  - Just apply corrections to the geometry model

Cosmic Rays Tracking

- Track reconstruction **a little bit different** w.r.t. the *pp collision* one
- **Specific services** have been developed for this purpose
  - navigation
    - strategy to select the compatible detectors during the pattern recognition
  - track matcher able to join:
    - 2 stand alone tracks
    - 2 stand alone tracks and 1 tracker track
    - 2 stand alone and 2 tracker tracks
  - seed generator for cosmic muons
- The direction on which the energy is lost must be set carefully

Strategies for Cosmic Reconstruction

The user can follow three basic strategies, which should be chosen depending on what is her/his final goal

- Reconstruction with the **dedicated cosmic reconstruction**
  - detectors commissioning
  - alignment
  - study of the cosmic ray distribution (for fun and cross check)
- Reconstruction with the ***pp* collision reconstruction**
  - useful for developers to test the final reconstruction
  - needs special kind of events, i.e. cosmics which pass close to the CMS centre
- **Combination of the two**
  - as for the two items before, but from a different point of view

Cosmic data Analysis

- The maximum effort will be spent to **centrally provide** the first two reconstruction chains and their most popular combination
  - **make life easier** for users and developers
  - **feedback** is crucial
  - create a **community** for the data analysis
- Detector and software commissioning
- Strong interest to test the software which applies the alignment constants and try the data reprocessing
- Monitoring tools

Monitoring of Tracks and Muons (I)

- Separate w.r.t. the sub-detector DQMs
  - two additional “layers”: monitoring of the tracks, monitoring of the muon object
- The tracks in CMSSW are the **same c++** object both for the *silicon tracker*, the *muon spectrometer* and the *whole tracking system*
- Tracker group already has a track monitor which can be extended with our contribution. An initial agreement with the tracker community have been reached
  - we will monitor **stand alone** and **global muon tracks**
  - activity from muon POG side started this week
  - Tracking DQM foreseen for next GR

Monitoring of Tracks and Muons (II)

- Muon object monitoring will be separated from the tracking monitoring, as it is **muon specific**
  - energy deposits in the calorimeters
  - comparison between the three types of tracks inside the muon object, ...

Summary

- The algorithms for the muon reconstruction perform very well
  - **high performance** on simulated data
  - tested on many types of sample. Are currently used in CMS for all analyses which involve muons.
- The algorithms have been **successfully** tested on real data
  - the reconstruction of cosmics muons need to became "*systematic*"
  - **validation** of the reconstruction work-flow, **from raw data to muon object, passing though alignment**, will be the main goal to reach before the *pp* data taking

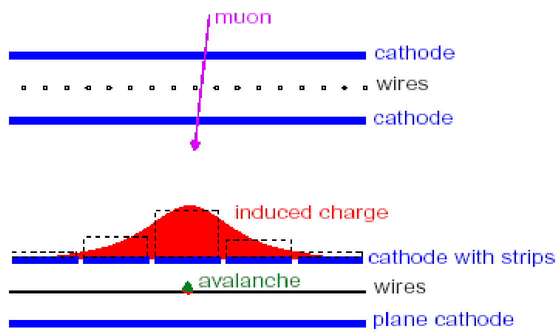
Back-Up Slides

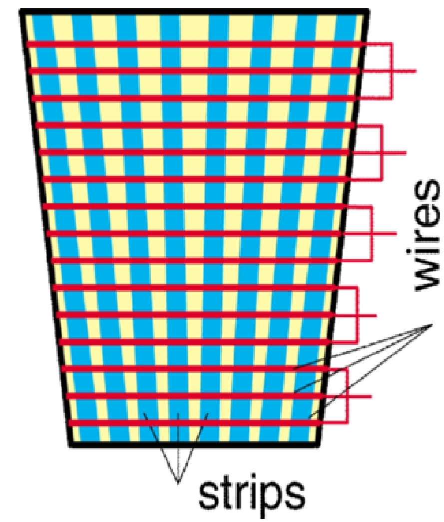
Samples

- 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)
- $Z \to \mu^+ \mu^-$
  - 350k events
- Local Reconstruction
  - Local with 150
  - Track with 16X

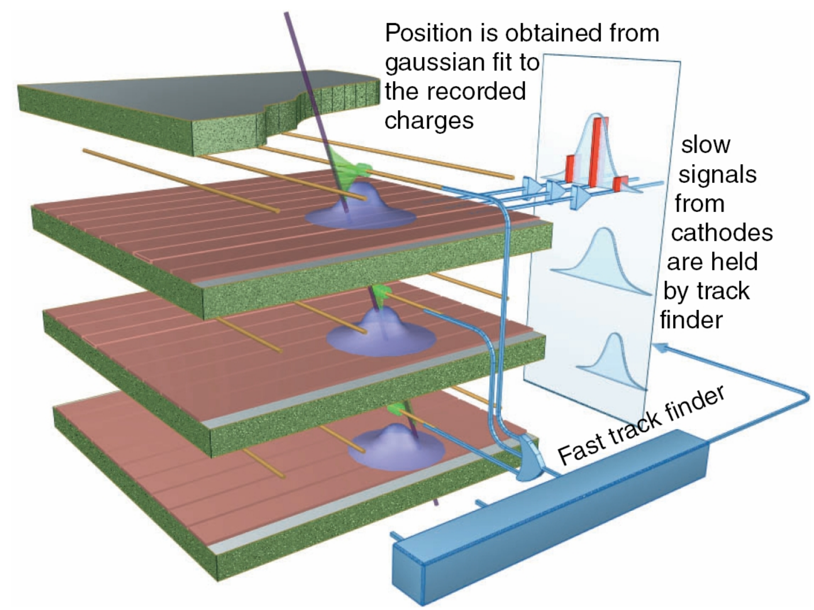
CSC Local Reconstruction

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





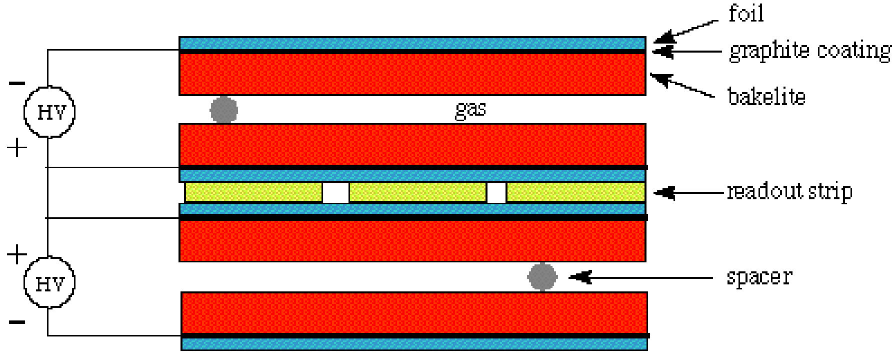
- ***r* coordinate** measured by wires
  - readout in bunches to reduce the number of channel
    - ghosts

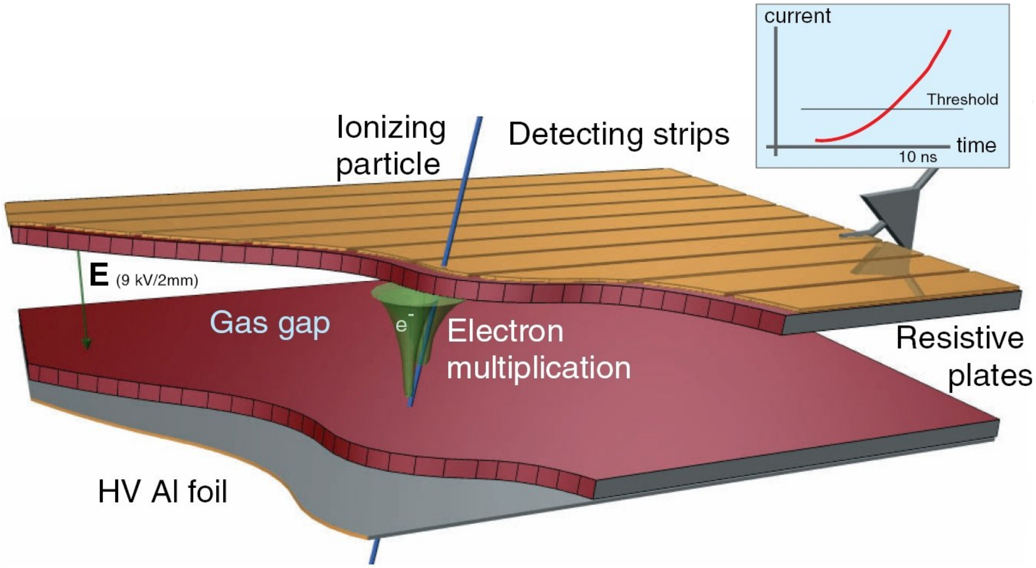


- **Fit** of the 2D points in the 6 layers
  - determine the 3D segments

RPC Local Reconstruction

- Double gap chambers
  - strips measure ϕ





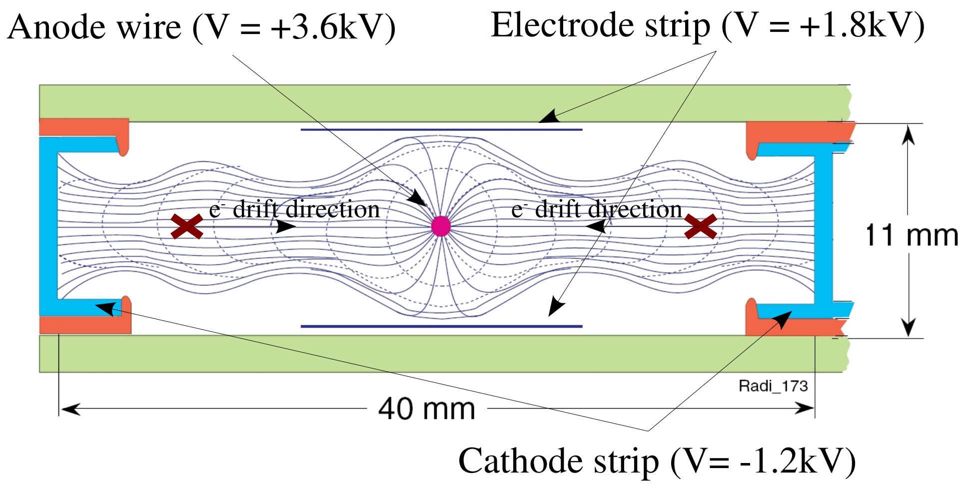
- Measure the 2D points
  - up to 6 points in the barrel and 4 in the endcap

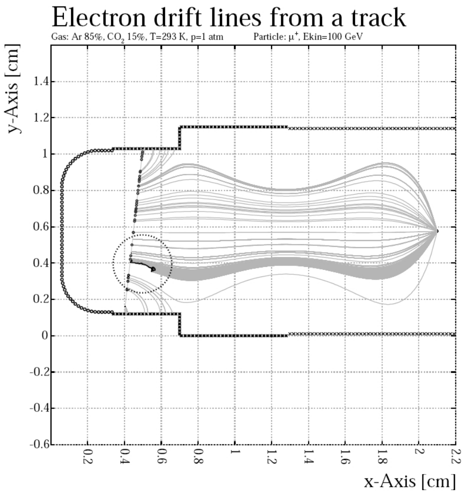
DT Local Reconstruction

It is performed in **three** steps

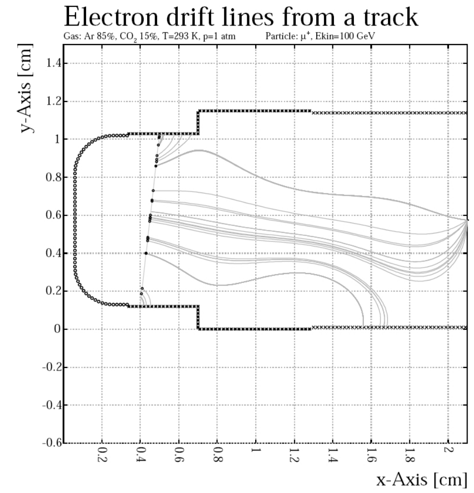
① Reconstruction **inside the cell**

- the drift time is **converted** in a position with respect to the wire. Two different algorithms:
  - constant drift velocity in the whole cell
  - time to distance relation 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





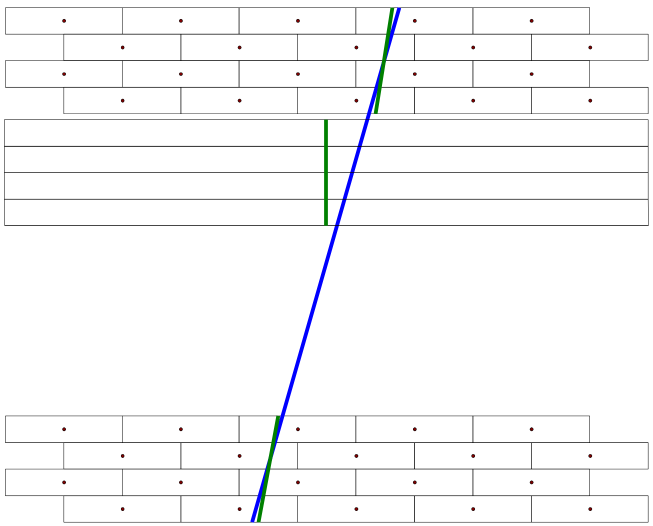
$B_{wire} = 0$ T



$B_{wire} = 0.4$ T

DT Local Reconstruction

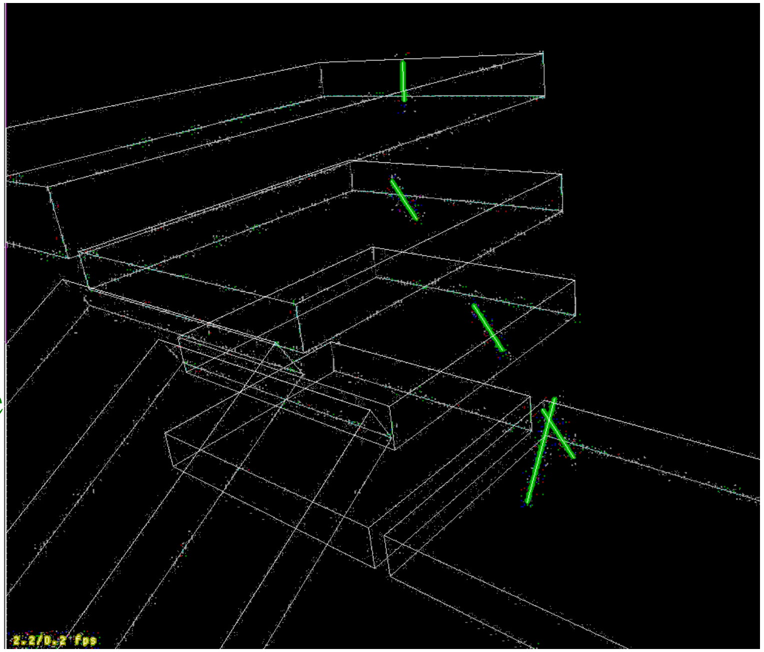
② Reconstruction in the ***R-φ*** and ***R-θ*** view **independently**



- **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**

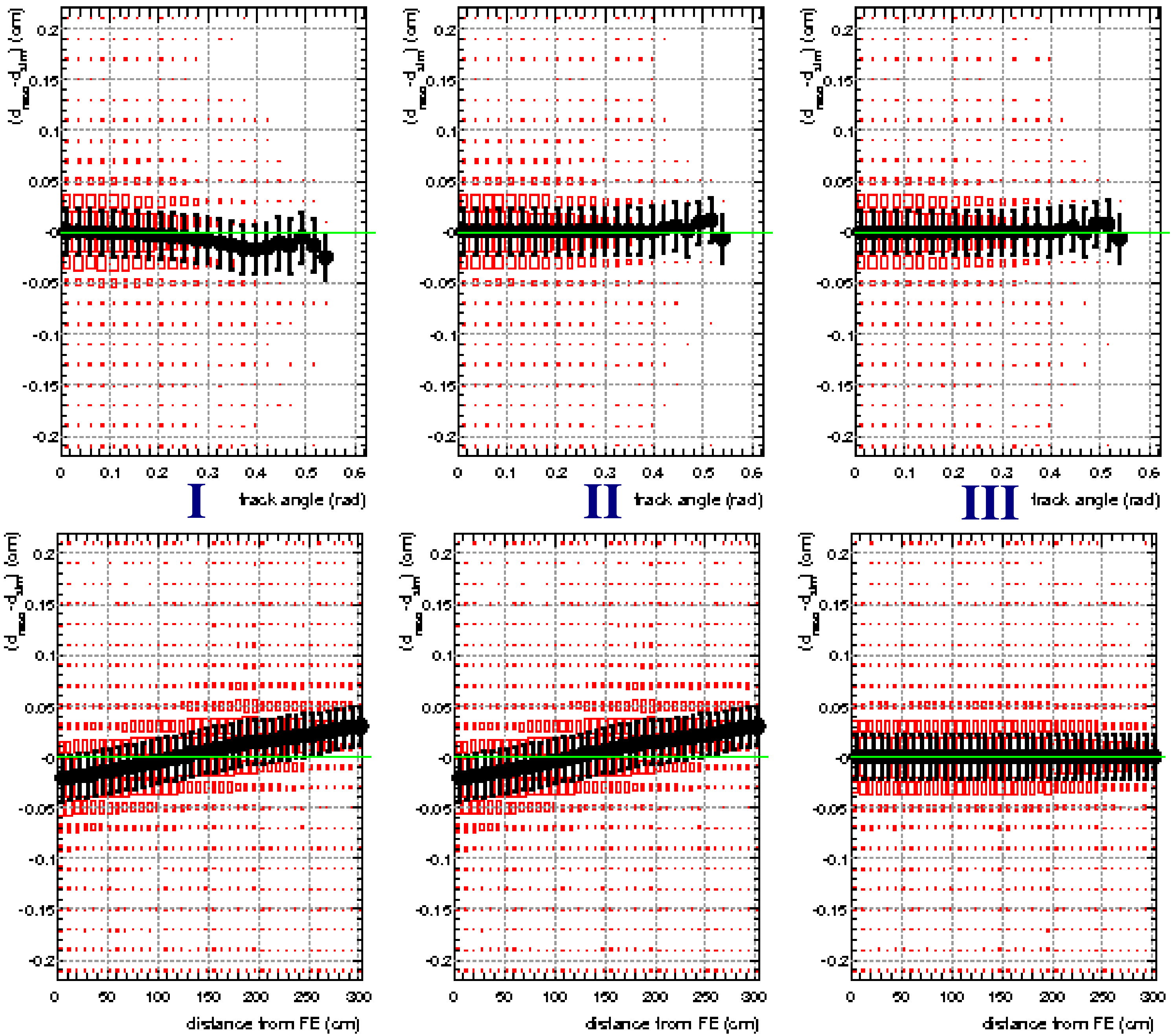
- the two projection are **combined** together
- **update** of the position if the 1D hits using the knowledge on B_{wire} and B_{norm} ⇨ refit of the updated hits
- **3D segment**



Residual on Hit Position (I)

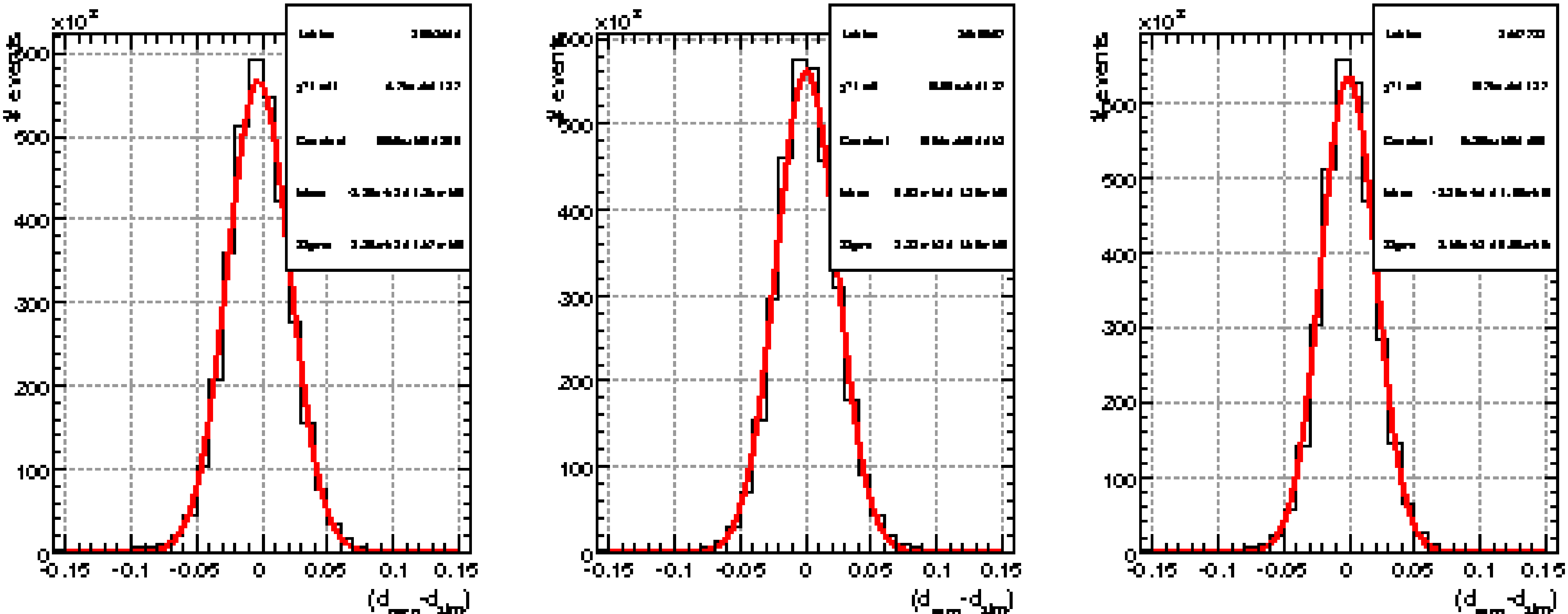
R-ϕ

Step:



Residual on Hit Position (II)

R-ϕ

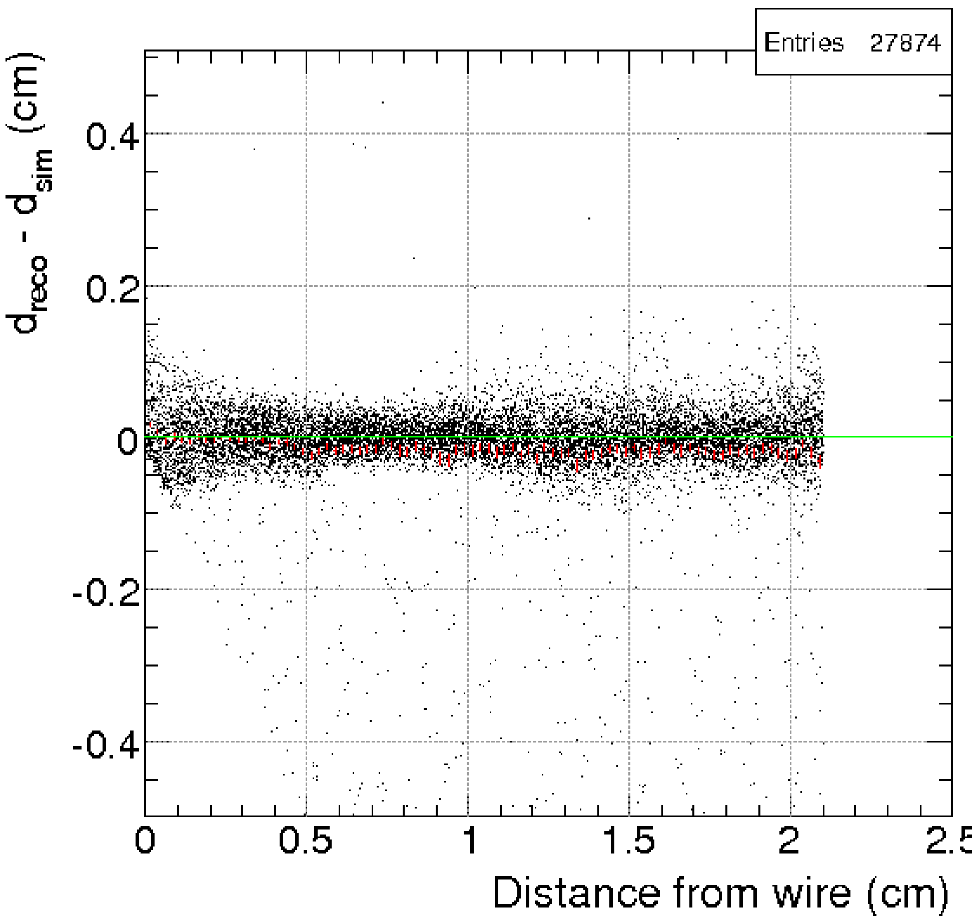


Step: **I** **II** **III**

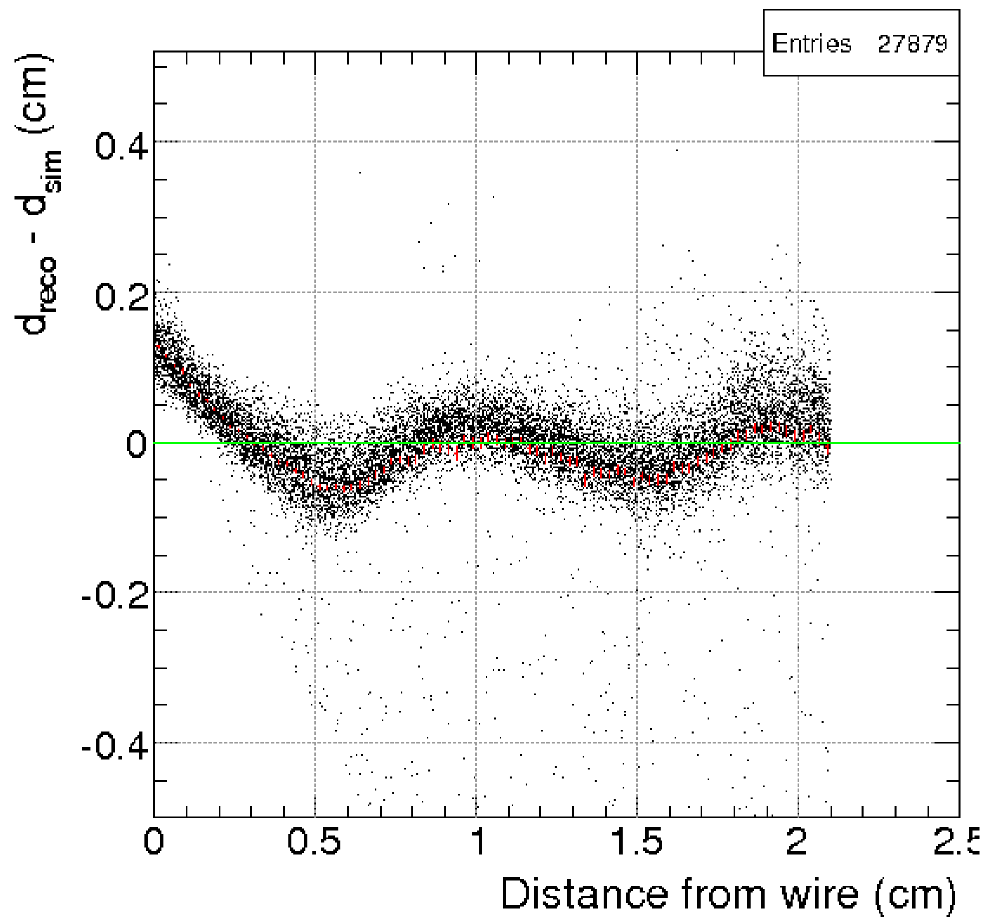
I	II	III
$\sigma \approx 238\ \mu m$	$\sigma \approx 232\ \mu m$	$\sigma \approx 210\ \mu m$

Time to distance relation parametrized by *GARFIELD*

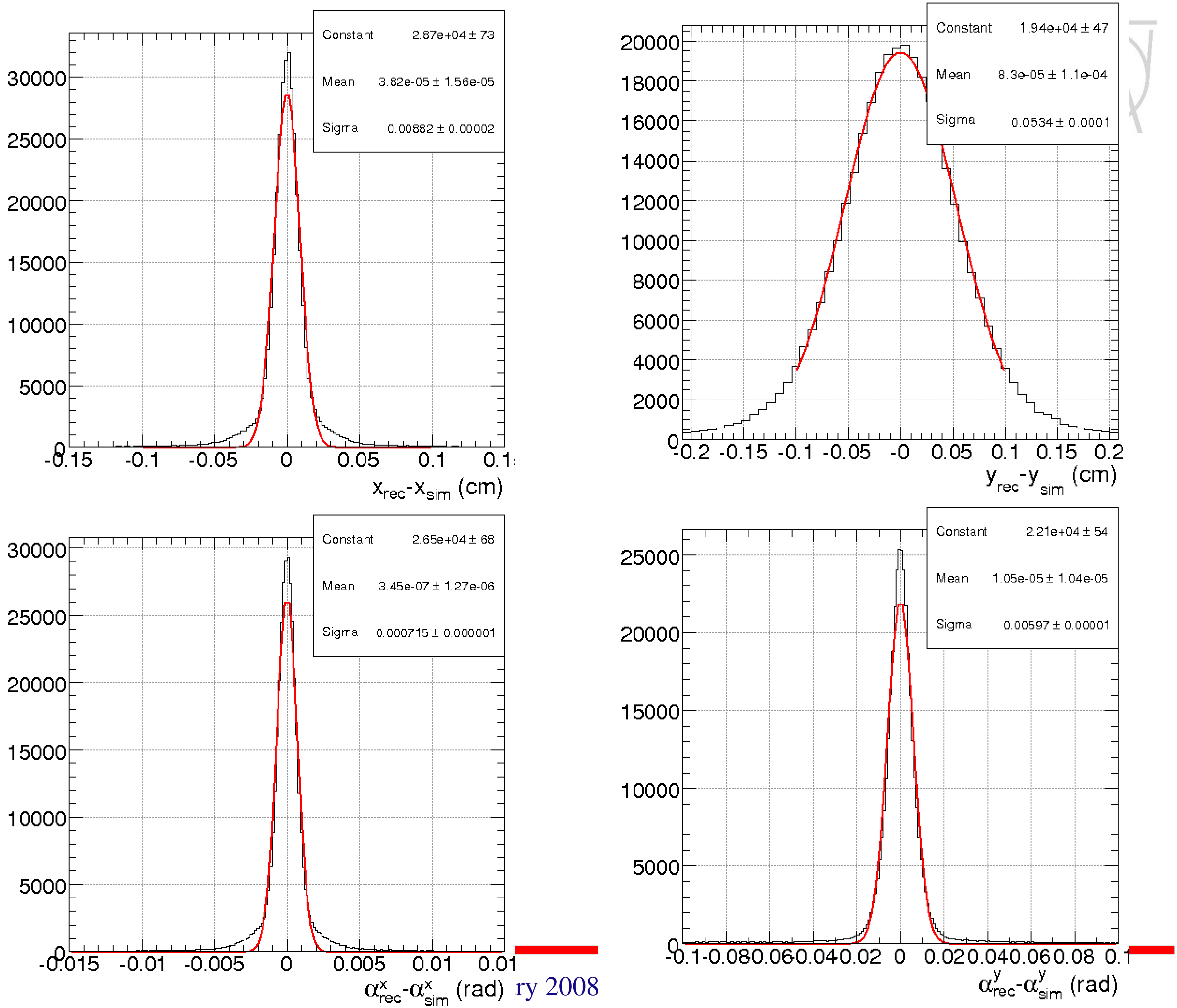
Algorithm Comparison



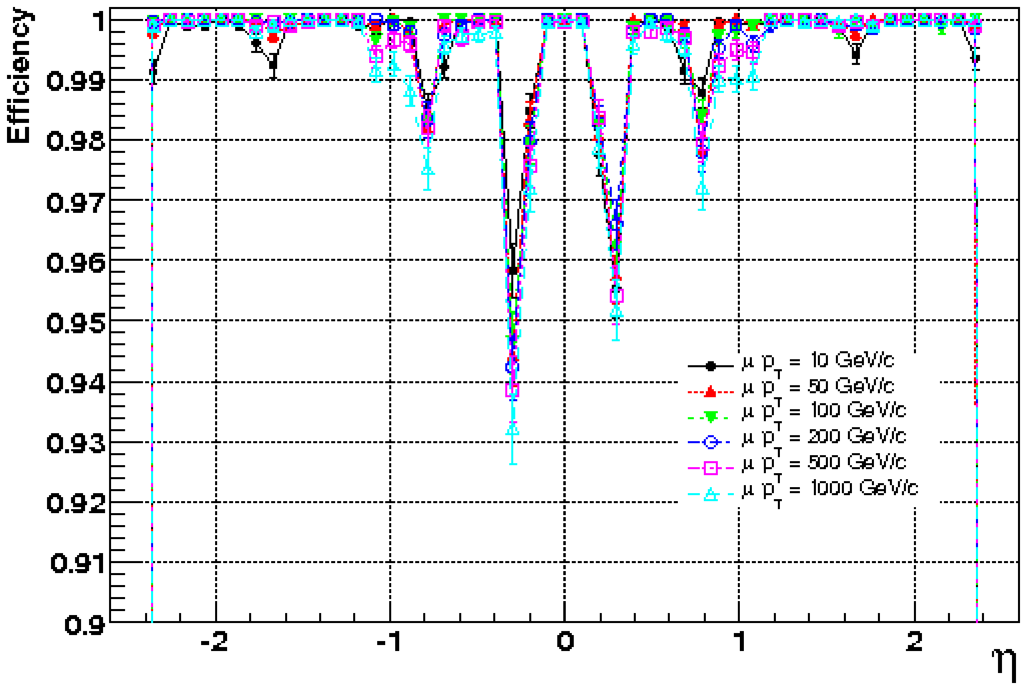
Parametrised time-to-distance relationship



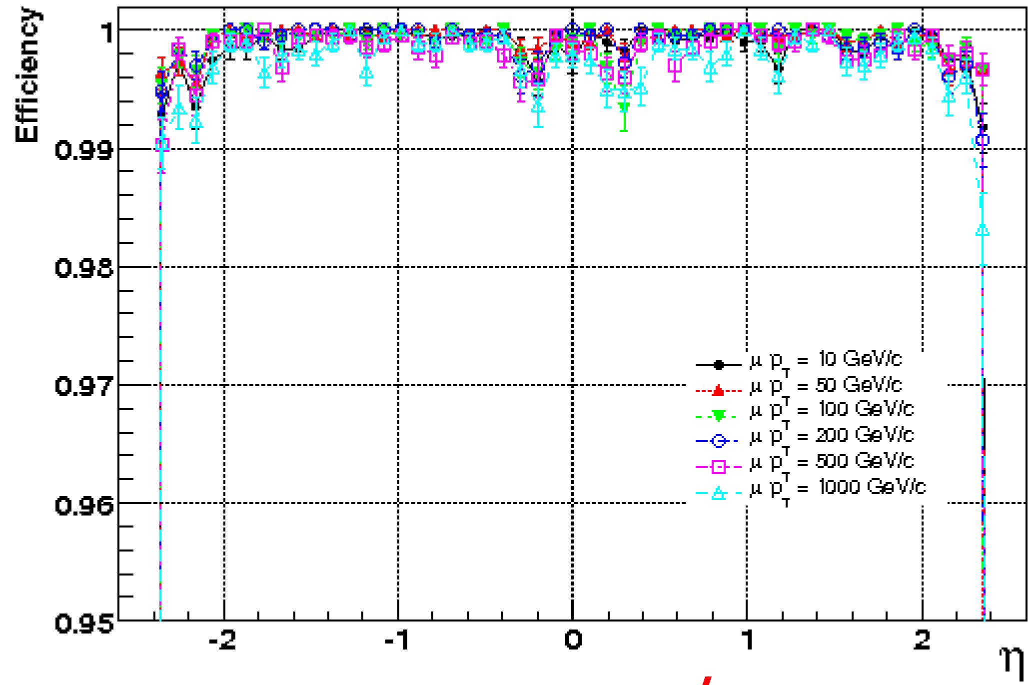
Constant drift velocity


Constant 2.87e+04 ± 73
Mean 3.82e-05 ± 1.56e-05
Sigma 0.00882 ± 0.00002
x_rec-x_sim (cm)
Constant 1.94e+04 ± 47
Mean 8.3e-05 ± 1.1e-04
Sigma 0.0534 ± 0.0001
y_rec-y_sim (cm)
Constant 2.65e+04 ± 68
Mean 3.45e-07 ± 1.27e-06
Sigma 0.000715 ± 0.000001
α^x_rec-α^x_sim (rad)
Constant 2.21e+04 ± 54
Mean 1.05e-05 ± 1.04e-05
Sigma 0.00597 ± 0.00001
α^y_rec-α^y_sim (rad)

Stand-Alone Muon Reco Efficiency

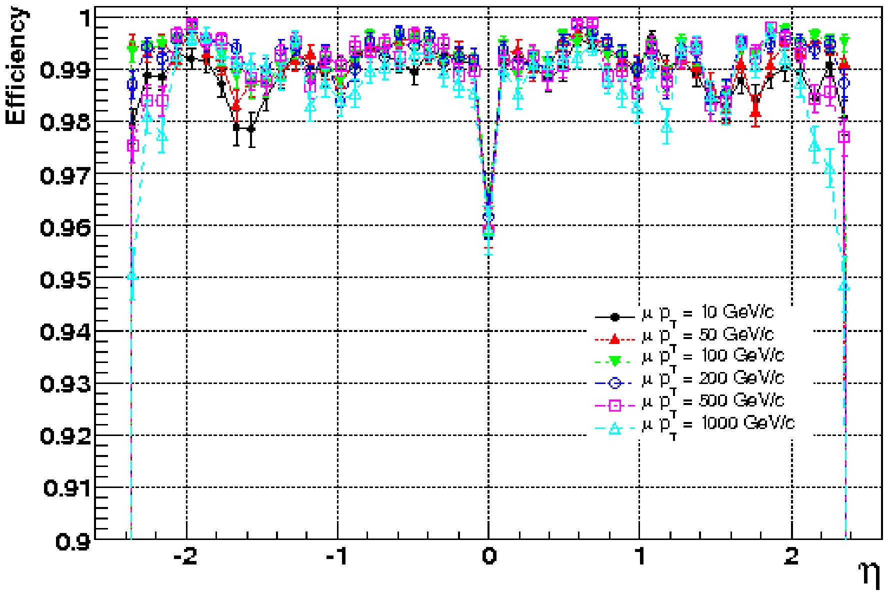


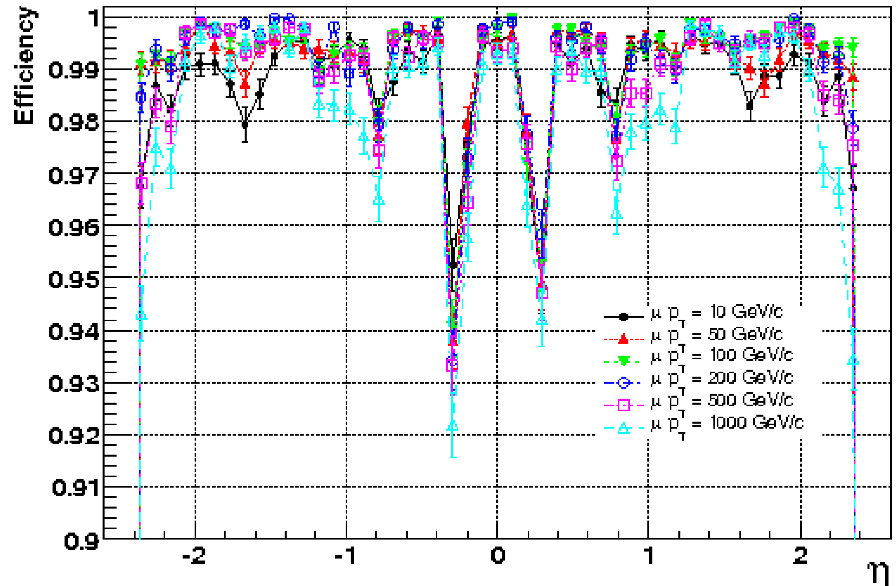
ϵ_{Seed}



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

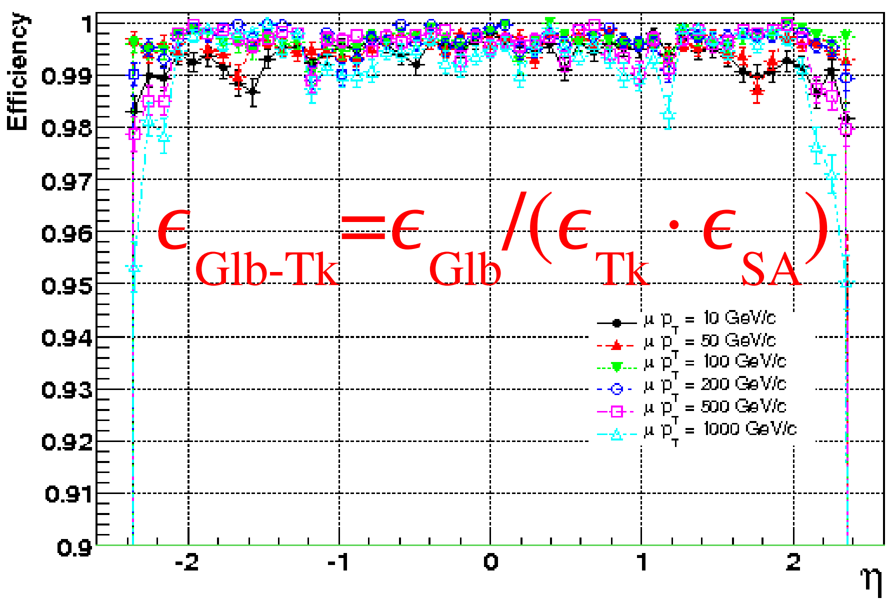
Global Muon Reco Efficiency





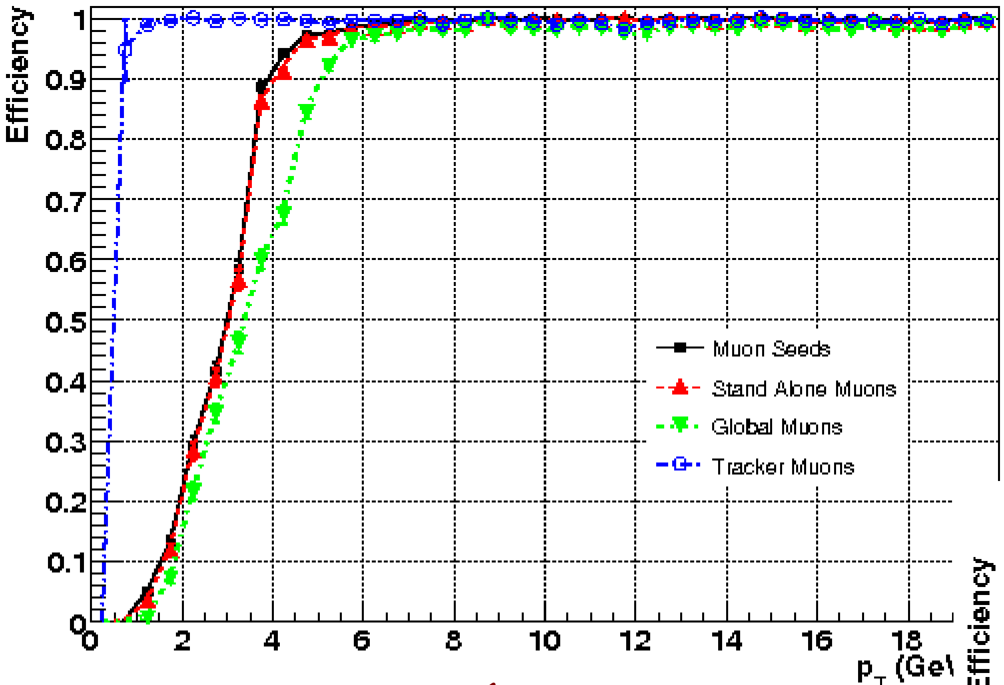
$\epsilon_{Glb\text{-}Sta} = \epsilon_{Glb} / \epsilon_{SA}$

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

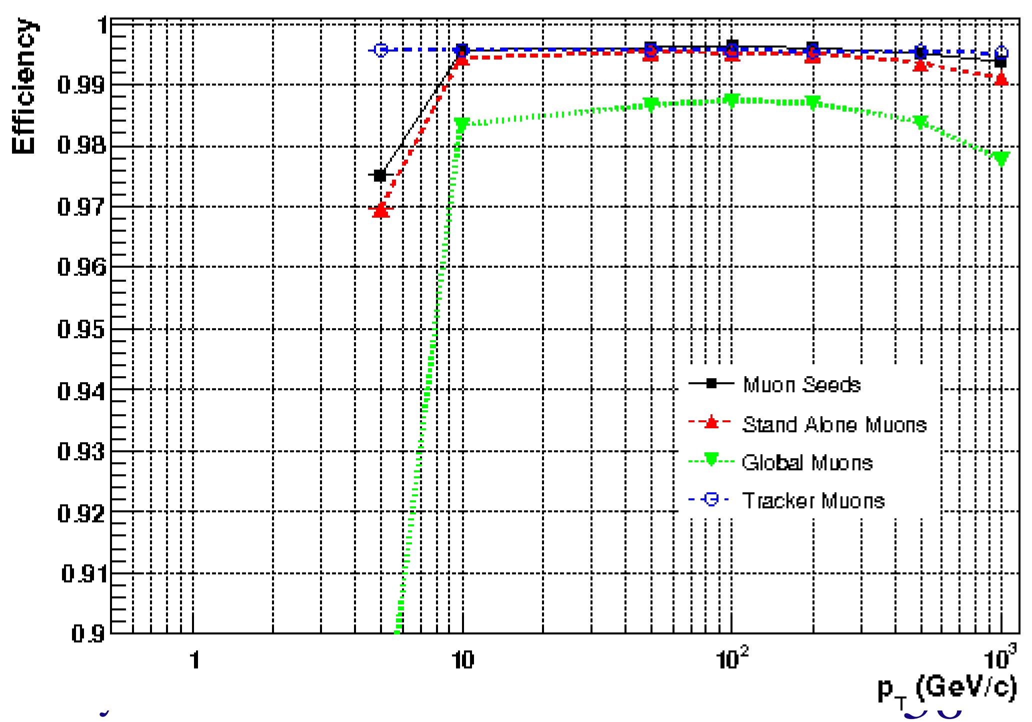


$\epsilon_{Glb\text{-}Tk} = \epsilon_{Glb} / (\epsilon_{Tk} \cdot \epsilon_{SA})$

Stand-Alone and Global Efficiency

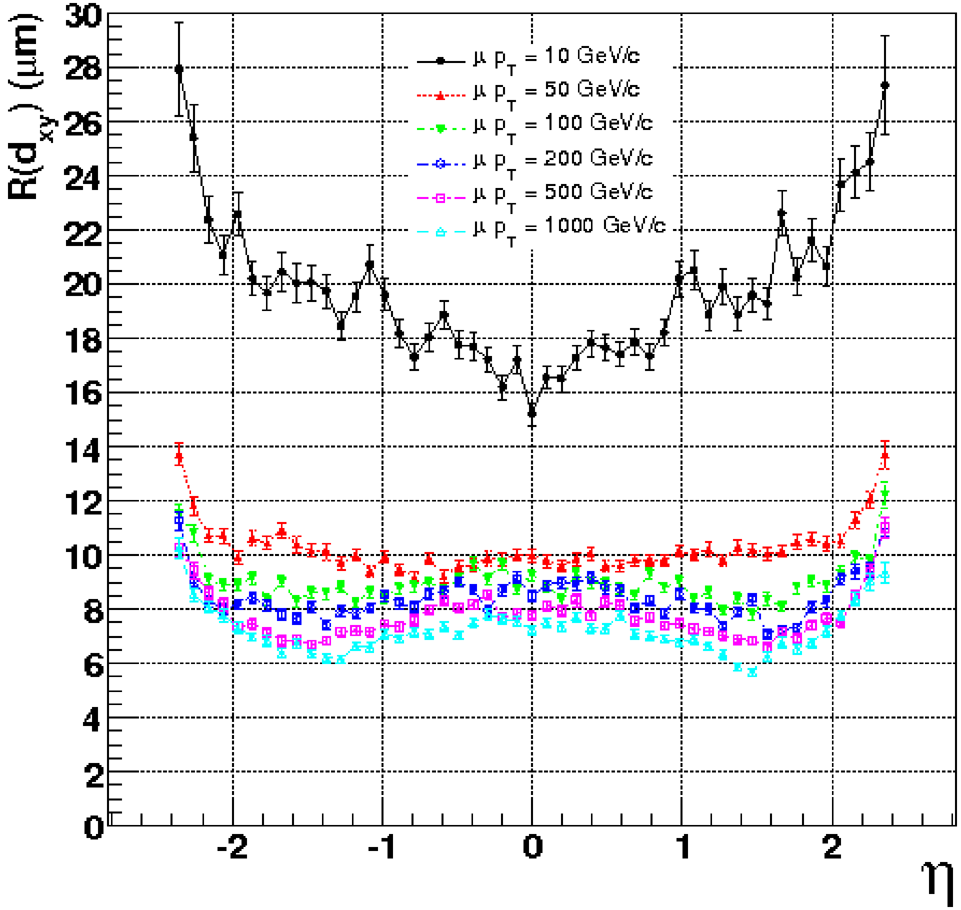


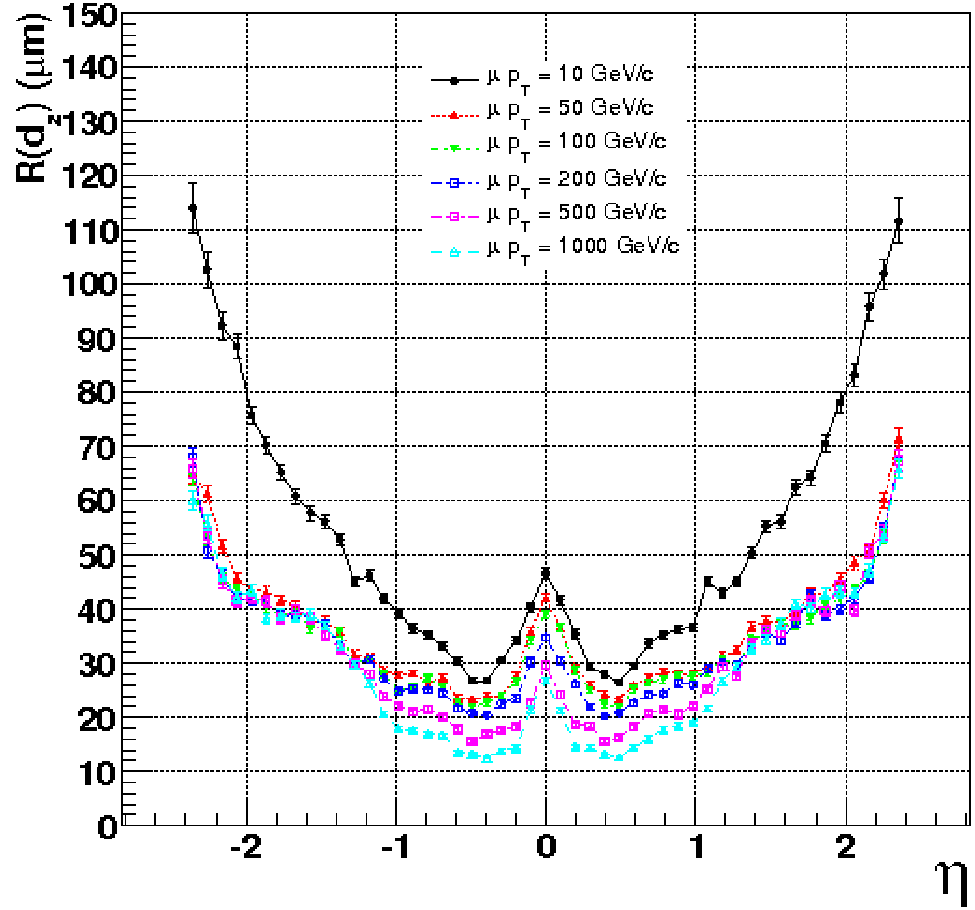
Low p_T region



Whole p_T region

Resolution on the Impact Parameters





Muon Reconstruction Efficiency