The CMS Silicon Tracker: from the performance in cosmic runs to the p_T resolution in early data

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- **Introduction**

  Why LHC?

  The Compact Muon Solenoid (CMS)

- **My work on the Tracker: calibration with cosmics**

  The CMS Silicon Strip Tracker

  Calibration

  Data Quality Monitoring

  Tracker commissioning with cosmic muons

- **Measurement of the p_T resolution from the Z line-shape**

  Introduction on the method

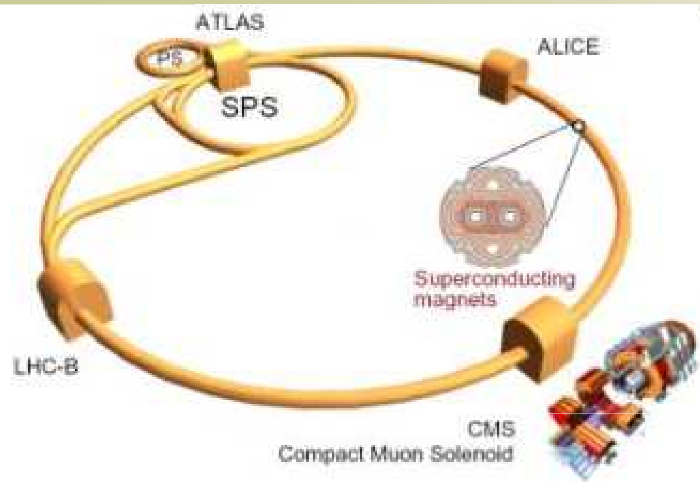
  Ideal scenario

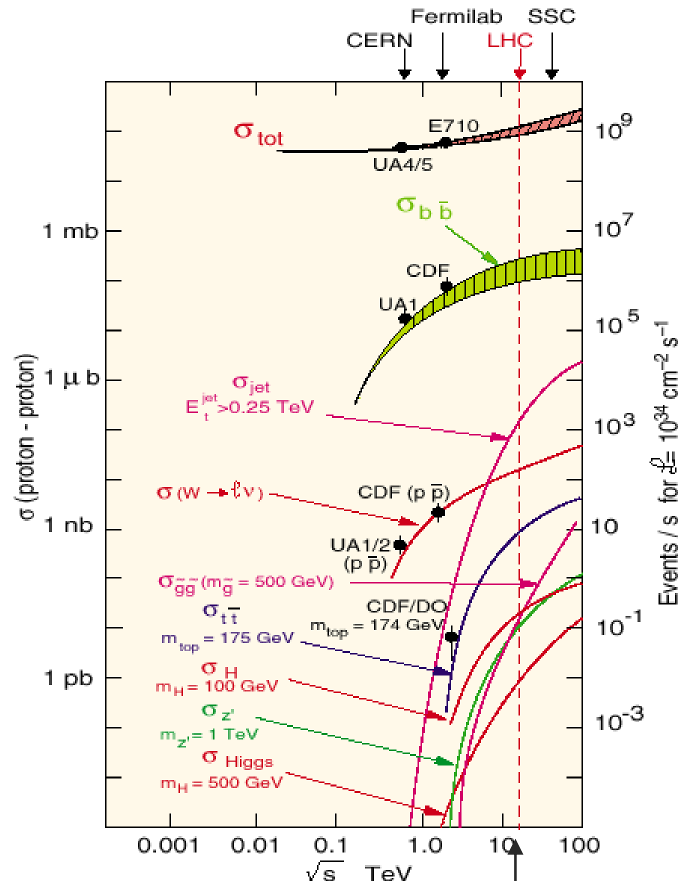
  Early data scenario

  Data driven method for the correction of the MC resolution

Introduction

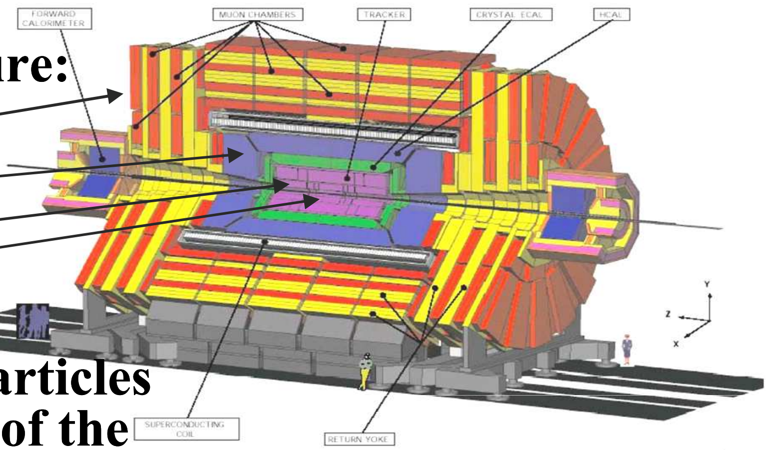
Why LHC?



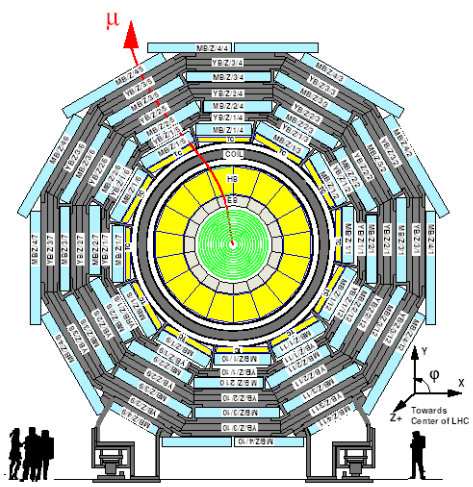


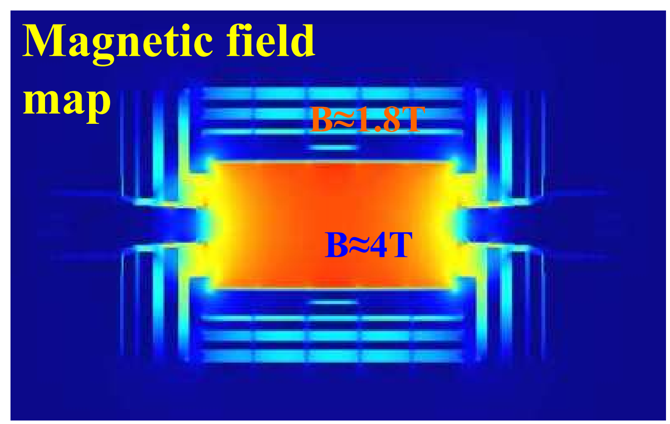
- Energy scales never explored until now… new physics foreseen!
- Higgs search and Electroweak symmetry breaking: crucial points for Standard Model
- Early data: re-discovery of the Standard Model physics (e.g. $Z \rightarrow \mu\mu$, $W \rightarrow \mu\nu$) as
  - Background to new physics searches
  - Fundamental channels to improve PDF knowledge
  - Detector calibration: resolution measurement and momentum scale correction
  - Tuning of Monte Carlo simulation

The Compact Muon Solenoid



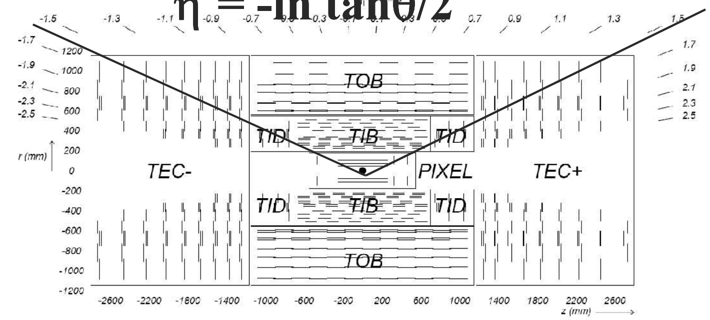
- **Compact cylindrical detector, “onion” structure:**
  - **Muon Chambers (muons trigger)**
  - **Hadronic + Electromagnetic calorimeters**
  - **Silicon Strip Tracker**
  - **Pixel Vertex Detector**
- **Very strong magnetic field (4T) to bend the particles trajectory and permit a precise measurement of the transverse momentum**





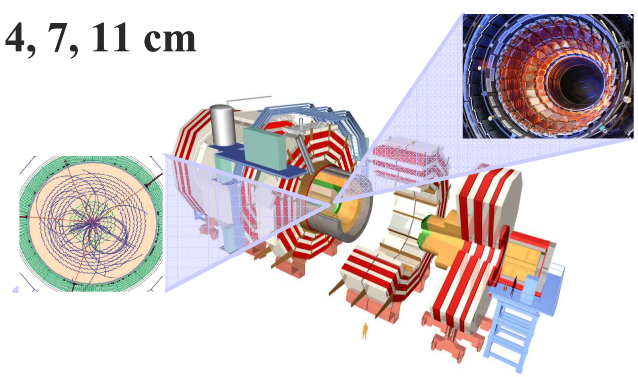
The CMS Tracker: layout

$\eta = -\ln \tan\theta/2$

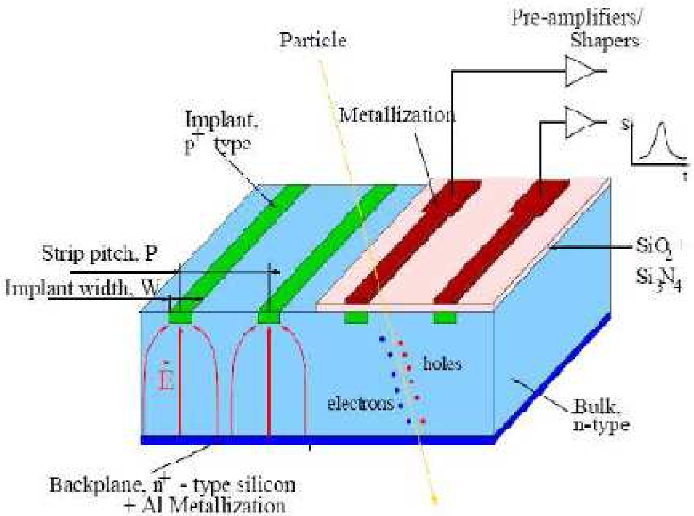


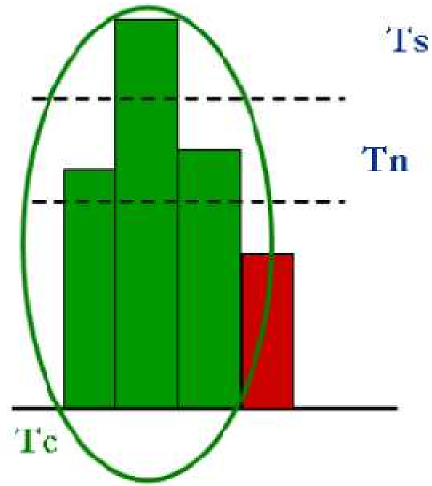
Physics Enviroment	Design Requirements
High particle fluence	Radiation hardness
High track density	High granularity
25 ns bunch crossing	Fast read-out

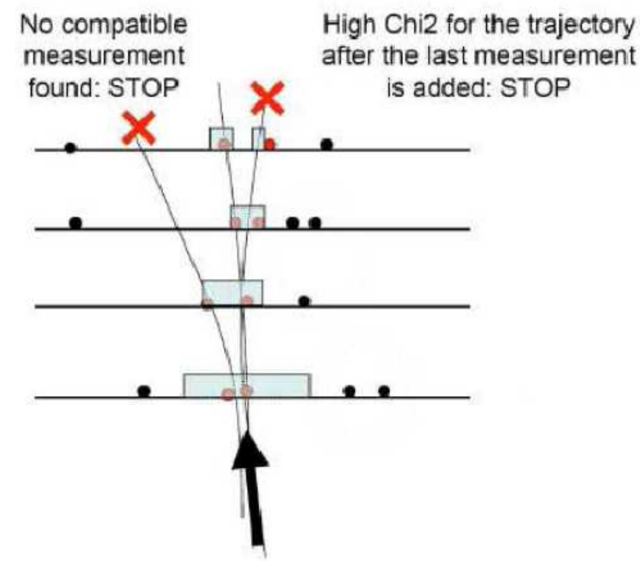
- **Tracking system designed to provide a precise and efficient measurement of the charged particle trajectories in the LHC collisions**
  - **B = 4 Tesla**
  - **Resolution: $\Delta p_t/p_t \sim$ 1-2% ($|\eta|<1.6$)**
  - **Tracking efficiency: $\varepsilon\sim$99% (μ), ~90% hadrons**
- **Silicon Pixels surrounded by Silicon Strip detectors**
  - **Pixels:**
    - **~ 1 m^2 of Si sensors, 65 M channels, 100x150 mm^2 , r = 4, 7, 11 cm**
  - **Strips:**
    - **~ 200 m^2 of Si sensors, 15148 modules, ~10 M channels**
    - **10 barrel layers (TIB,TOB)**
    - **12 end-cap wheels per side (TID,TEC)**



The CMS Tracker: working principle







- **Particle passing through silicon → electron-hole pairs produced**
- **Charge collected, preamplified and shaped by readout chips (APV)**
- **Cluster: group of adjacent strips fired together above some thresholds**
- **Analogical charge collection → hit position as barycenter of the cluster**
- **Tracking based on Kalman Filter technique starting from the hits**

CALIBRATION

The Tracker calibration workflow

Before starting to collect physics data, the detector needs to be fully commissioned and calibrated in order to have the most reliable measurements to be used for physics studies.

- **Gain calibration**
- **Noise measurement**
- **Cluster properties studies**
- **Identification of bad components**
- **Lorentz angle calibration**
- **Tracking performance**
- **Alignment of silicon modules** → **R. Castello's presentation**

Data Quality Monitoring system

- **The Data Quality Monitoring (DQM) constantly controls the status of the detector and of the reconstruction**
  - **capable of running on a variety of online and offline environments, in the control room as well as in remote sites**
  - **Monitored quantities**
    - **Read-Out (Fed errors), Raw Data, Cluster/Hit Properties, Tracks**
    - **Calibration constants used during the reconstruction**
    - **Quality test applied to quickly spot problems during online/offline reconstruction**
  - **Fundamental tool for the calibration**

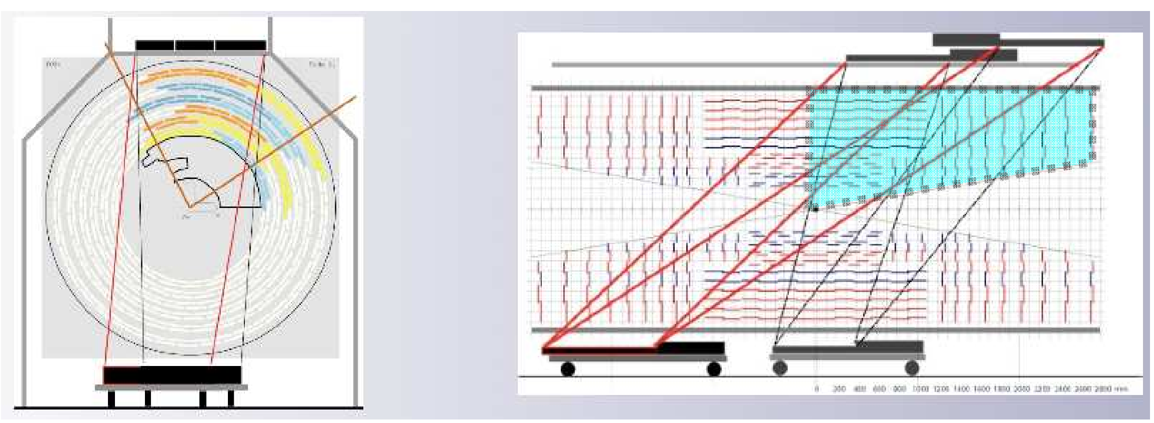
Tracker calibration with cosmic data

- The Tracker Slice Test @ TIF
- CRuZeT/CRAFT @ P5

The Tracker Slice Test

First large scale system test: Tracker Integration Facility (TIF) @ CERN (ground level).

- **~15% of the full detector operated from Feb. to July ’07**
- **@ five operating temperatures (15, 10, -1, -10, -15 °C)**
- **More than 4 M events**
- **Verified HW, SW and calibration procedures in conditions close to the final one**



Trigger:

- **rate: ~6 Hz**
- **Flexible trigger geometry**
- **5 cm lead on bottom scintillator to reject soft muons**

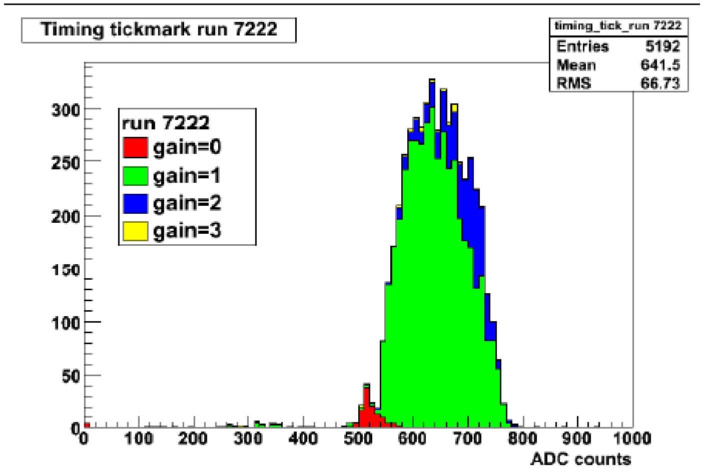
CRuZeT & CRAFT

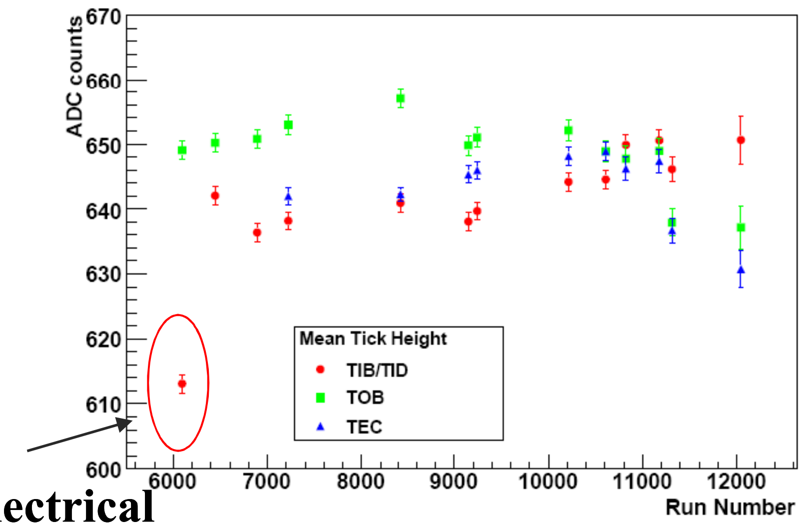
- **Tracker inserted in CMS in December 2007 and fully cabled and tested in the following months**
- **In Global Run with the full CMS in June 2008**
  - **98% of the detector switched on**
  - **Temperature of operation 10°**
  - **~8.5 M cosmic data with and without B field**
  - **Magnetic field OFF in CRuZeT (Cosmic Run @ Zero Tesla) and 3.8 T in CRAFT (Cosmic Run @ Four Tesla)**
  - **Cosmic Trigger configured using muon chambers**

Gain calibration

- Aim: to achieve a uniform electronic gain among the readout chips (APV)
- Measurement of the value of the height of synchronization pulses, referred to as tick-marks, generated by the APV
- Equalization of the response of the full electronic chain to a known value (640 ADC)
- Influenced by voltage, temperature → important to monitor stability in time

TIF results

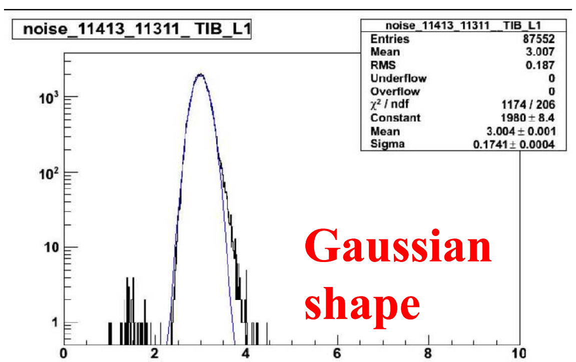


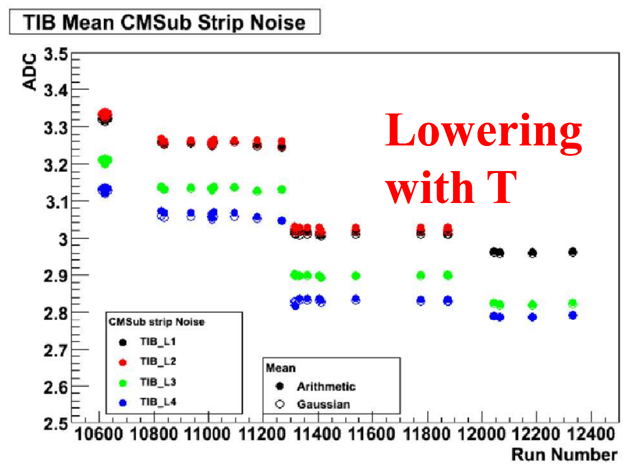


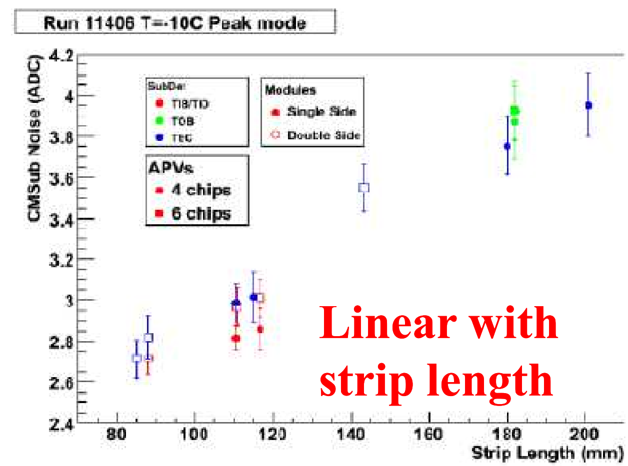
Low electrical gain!

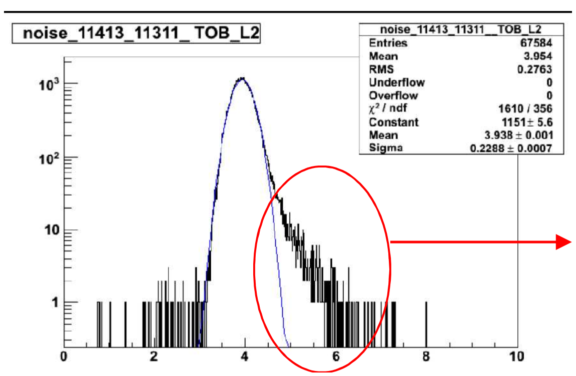
Noise measurement

- Before irradiation, completely determined by the input capacitance load of the APV chips, dominated by the silicon strips.
- Linear dependence on the length of the silicon strips.
- When the modules are mounted on the final support structures (close proximity to each other), other possible sources of noise can arise (grounding loops, cross talk, digital noise, cables…), affecting the final noise performance.







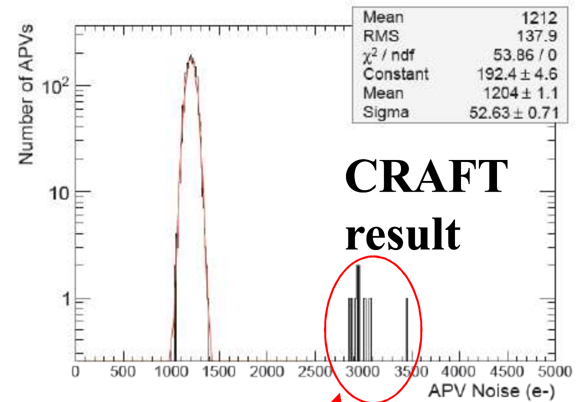


Non Gaussian tails in TOB modules.
After investigation, grounding problem
→ solved

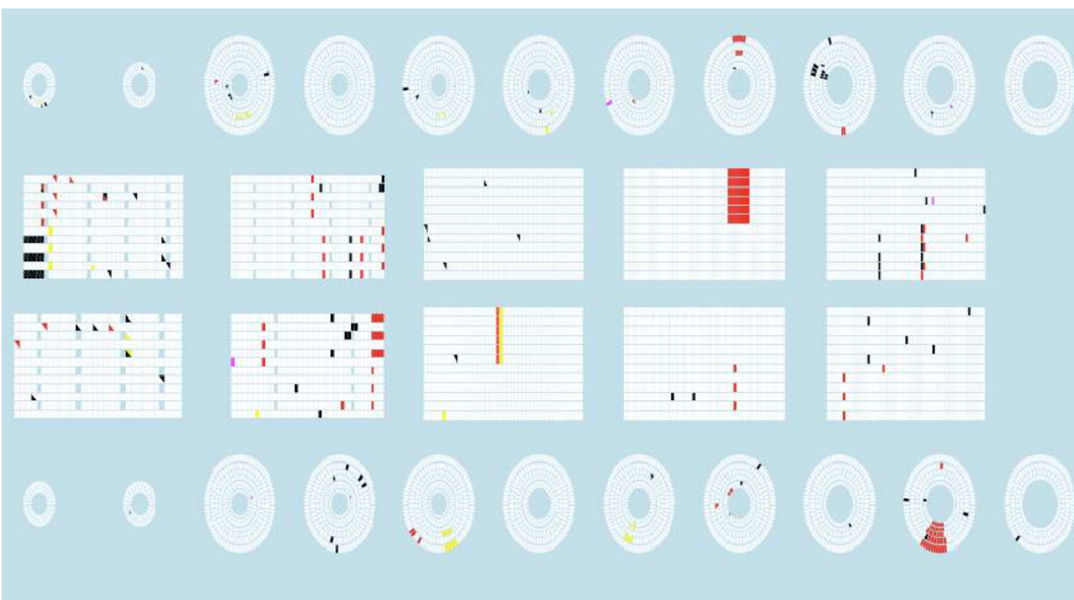
TIF results

Bad components identification

- **Online bad component identification:**
  - **Search for HV errors**
  - **Search for noisy components**
- **Offline bad component identification:**
  - **Search for high occupancy strips or APV**
  - **Search for inefficient components**



Non gaussian behaving strips: HV off



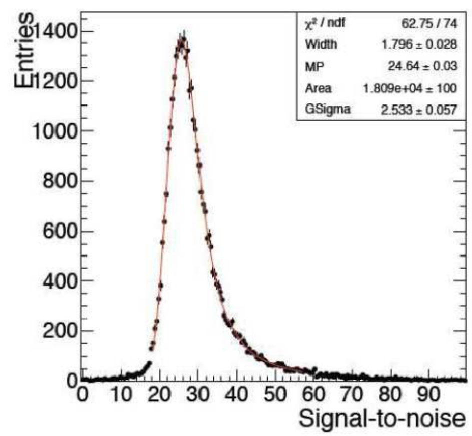
- **Known from commissioning**
- **Online identification**
- **Offline identification**
- **Online + offline**

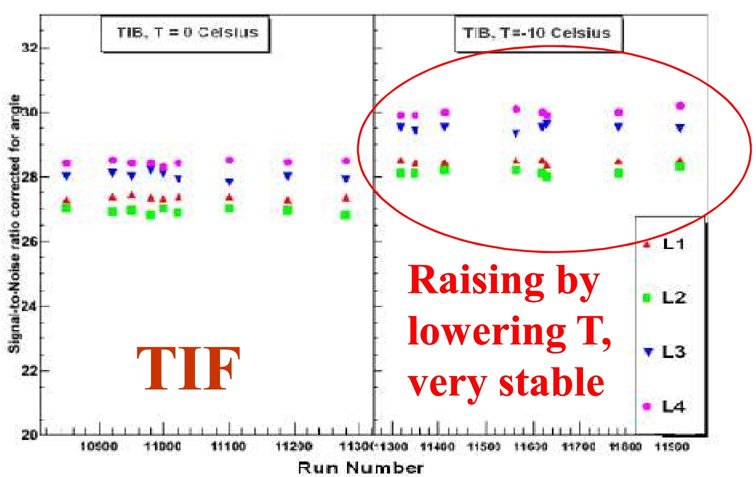
Currently: 2.7% of strips masked

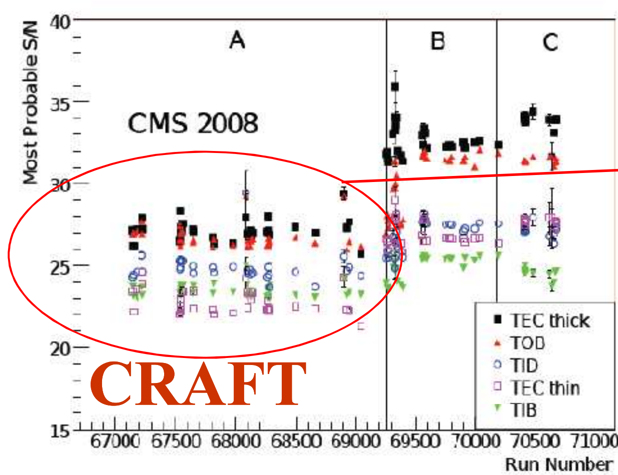
Cluster/hit properties studies

- Signal-to-noise renormalized to the detector thickness EXCELLENT parameter to monitor the stability of the tracker during data taking
- S_{ren} = S/K where K particle path length in the silicon. Landau distribution.
- $N = \sqrt{\Sigma_i N_i^2/n_{strips}}$. Gaussian distribution.
- Independent on gain
- S_{ren}/N largest possible
  - in order to reduce fake hits rate
  - will get worse for radiation damage

Fit: Landau ⊕ Gaussian



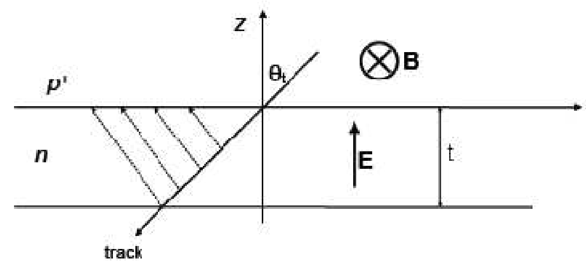




Wrong synchronization with the trigger caused low S/N

Lorentz angle calibration

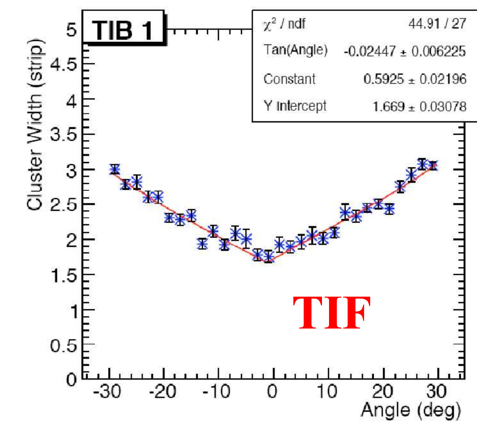
- $\vec{E}$ perpendicular to the strips $\Rightarrow$
  - if B = 0 charges drift in E direction
  - if B $\neq$ 0 diffusion path influenced by B
- Net effect $\Rightarrow$
  - Shift in the hit position
  - Change in the cluster width

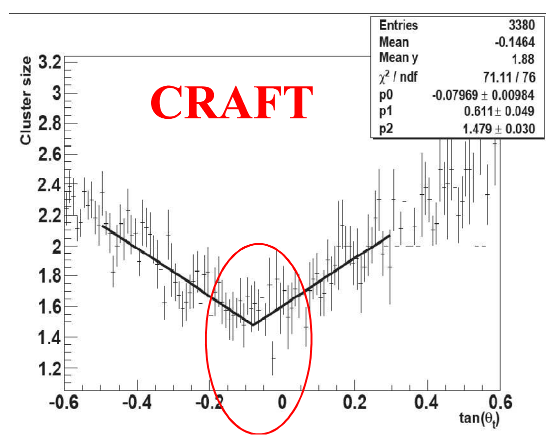


$$< clusterwidth >= a + \left|\frac{t}{p} \cdot b \cdot (\tan\theta_t - \tan\Theta_L)\right|$$

where

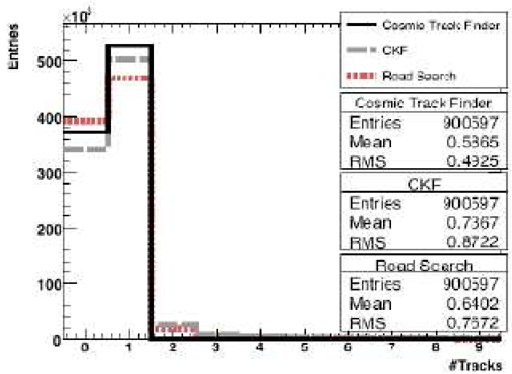
- t = detector thickness
- p = detector pitch
- a, b = coefficients expressing the carrier diffusion and the electronic capacitive coupling between nearby channels
- Θ_L = Lorentz angle
- θ_t = track angle

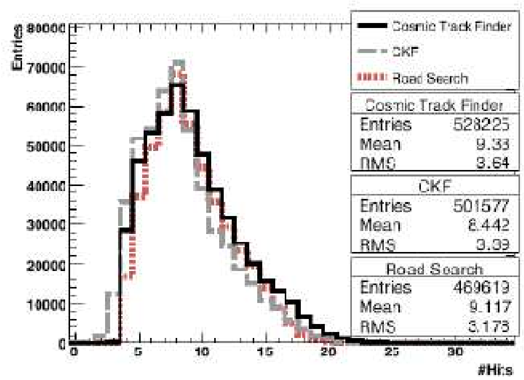


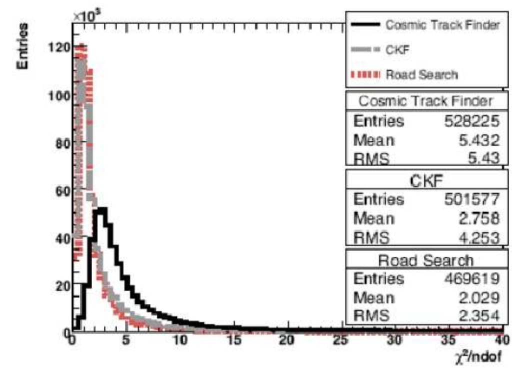


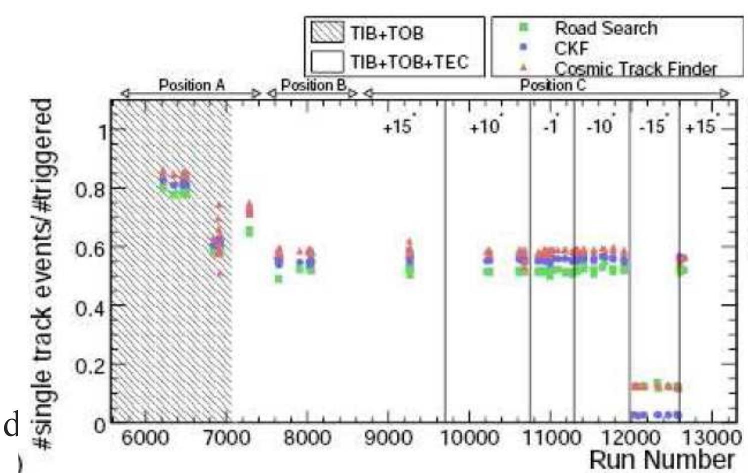
Track properties (I): TIF

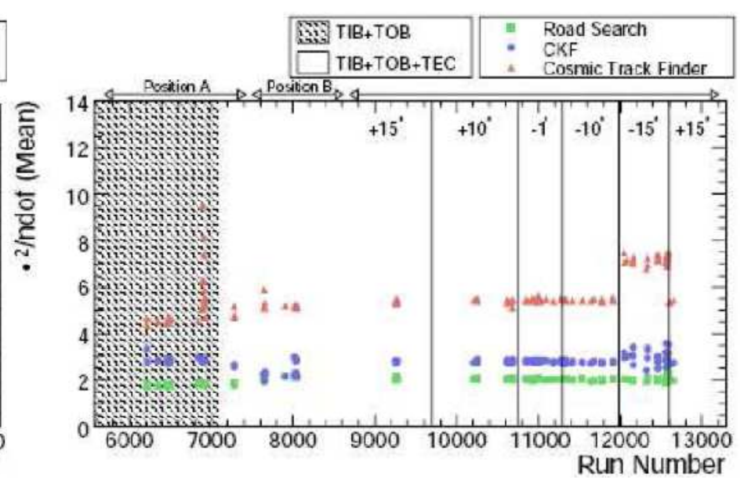
- **Three tracking algorithm, similar performances**
- **Number of tracks, number of hits per track, χ^2 of the track, η, φ**
- **Monitoring stability in time**





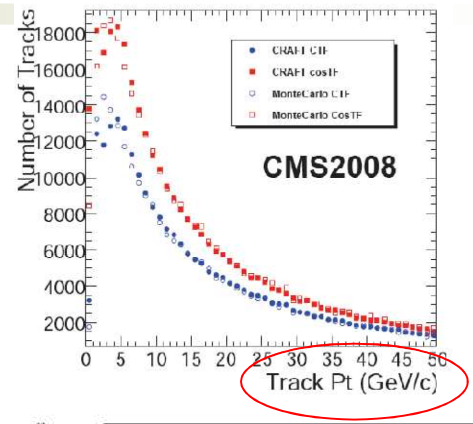


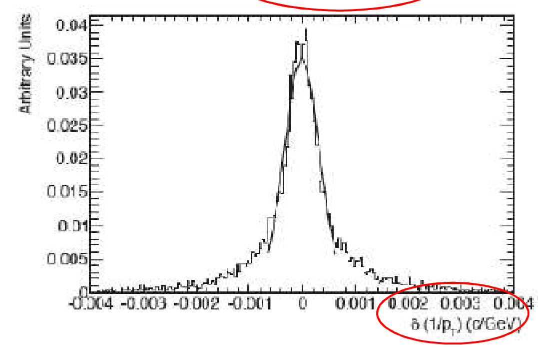


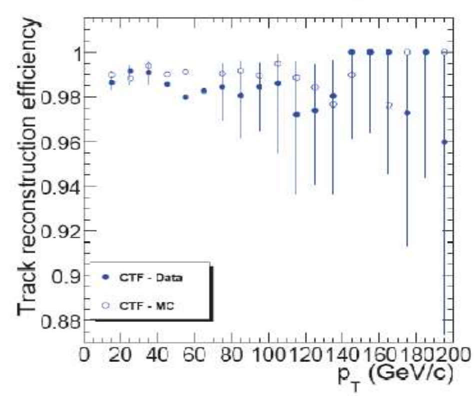


Track properties (II): CRAFT

- Magnetic field ON →
  - first possible estimate of the p_T of the particle!!!
  - first possible estimate of the p_T resolution!!!
    - Tracks pointing to the interaction vertex
    - Track split in two legs
    - Projection of track parameters at the point of closest approach to the beam pipe
    - Residuals calculated: $\delta x = (x_1 - x_2)/\sqrt{2}$
- Measurement of the tracking efficiency with inside-out method (as in LHC collision!)







Measurement of p_T resolution from the Z line-shape

… and data driven correction of the Monte Carlo resolution on p_T

Measurement of p_T resolution from early data

Basic idea

- Comparison between the observed invariant mass lineshape and the expected one:
  - Mass lineshape width → measurement of the resolution
  - Mass peak shift → bias in the momentum scale
- Dependence on the track parameters

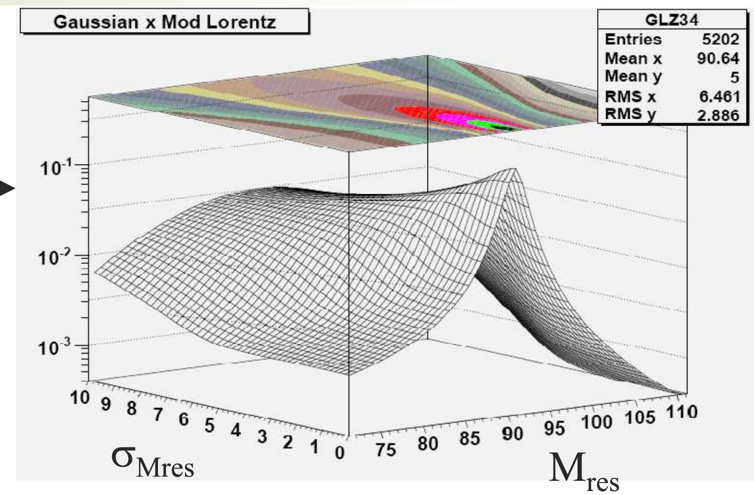
probabilistic approach necessary.

- Estimation directly from data using a likelihood minimization

$$-\ln L = -\sum_{k=1}^{N_{ev}} \ln(P(m_k, s_k))$$

Resolution measurement

- **Input:**
  - **probability distributions $f(M_{res},\sigma_{Mres})$**
  - **ansatz functions for resolution, scale (vs muon kinematics)**



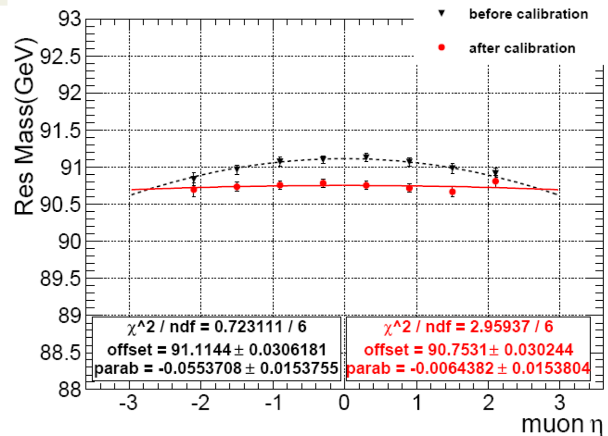
- **For each event the algorithm**
  - **takes the reconstructed mass *m* with its resolution *s* estimated from the ansatz function**
  - **calculates the probability associated to these two values (*m*, *s*) using the probability distributions $f(M_{res},\sigma_{Mres})$**
  - **use this probability value to construct the likelihood**
  - **minimizes the likelihood with respect to the parameters of the ansatz functions.**
- **Output: full set of parameters for resolution and scale**

Samples and cuts

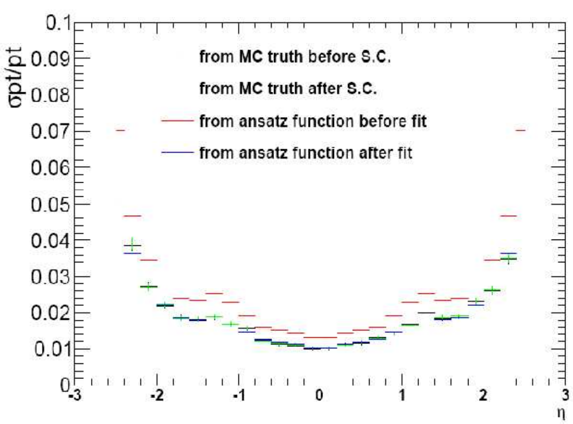
- An ideal MC $Z \rightarrow \mu\mu$ sample generated with Sherpa (CTEQ6l) and reconstructed in an ideal scenario
- A "fake data" $Z \rightarrow \mu\mu$ sample from the same generated sample reconstructed in a realistic scenario after 10 pb^{-1} with:
  - misalignment scenario after CRAFT alignment (the one at the startup)
  - real tracker noise condition, using noise values measured during CRAFT
  - list of bad component found during CRAFT excluded from the reconstruction
- Global muons (muons reconstructed in tracker + muon chambers) → inner tracker track p_t measurement
- Only muons with $p_t > 20$ GeV (too poor statistics below)
- ~5000 Z survive after these cuts, after 10 pb^{-1} data collected

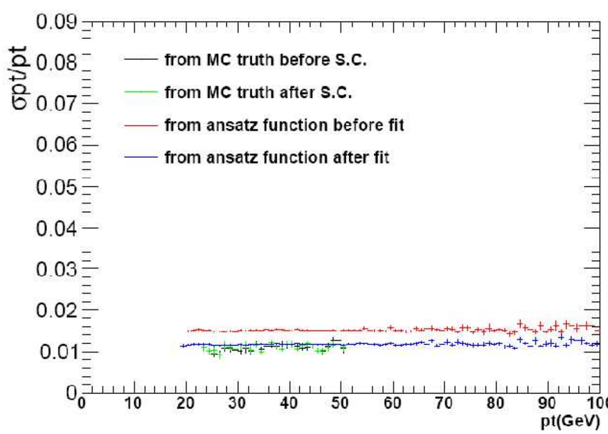
Resolution measurement on ideal MC

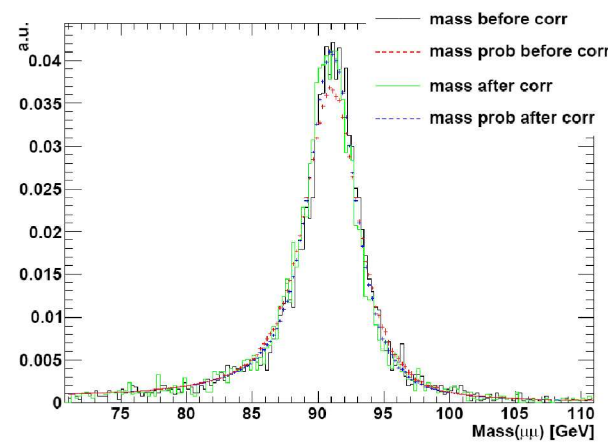
- **Momentum scale correction applied (no strong bias, linear in p_T)**



- **Resolution Function: basic function**
  - **constant in p_T**
  - **by point in η (single muon simulation)**
  - **2 parameters**
- **Comparison of the resolution from the fit of the ansatz function and the usual MC truth resolution $(pt_{reco}-pt_{gen})/pt_{gen}$. Excellent agreement between resolutions vs p_T and η from MC truth and from the algorithm**

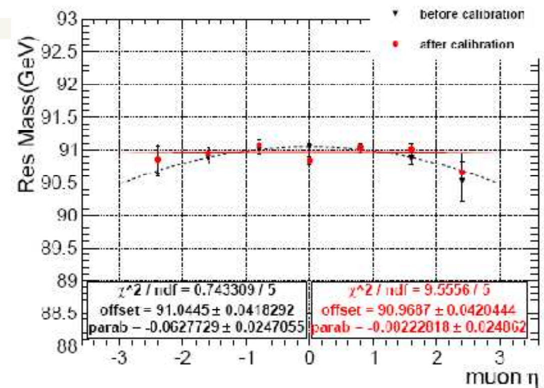


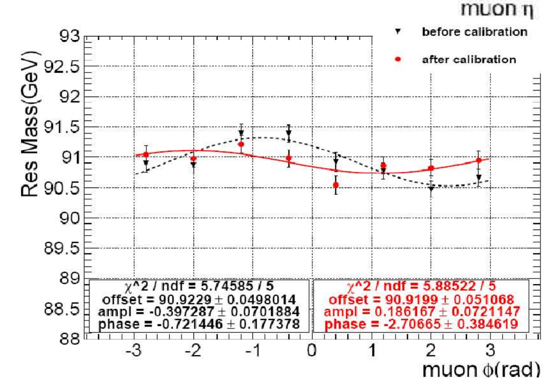




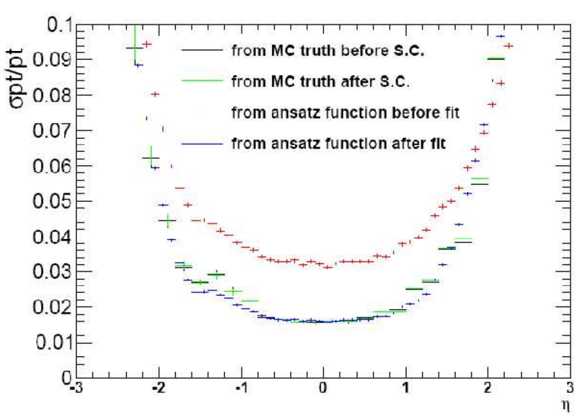
Resolution measurement on "fake data"

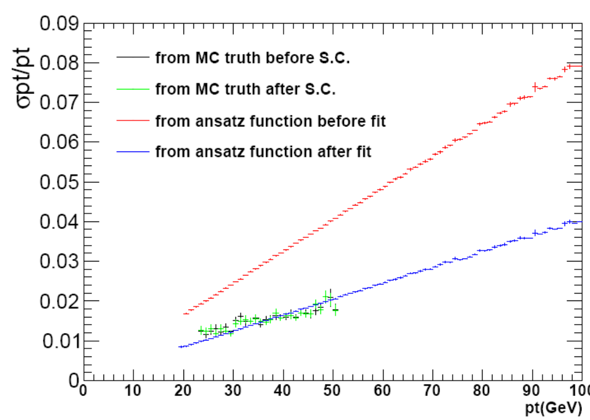
- **Momentum scale correction more complicated:**
  - **linear in p_T**
  - **parabolic in η**
  - **sinusoidal in φ**
- **Resolution Function:**
  - **linear in p_T**
  - **parabolic in η, separated regions for barrel and endcaps**
  - **7 parameters**

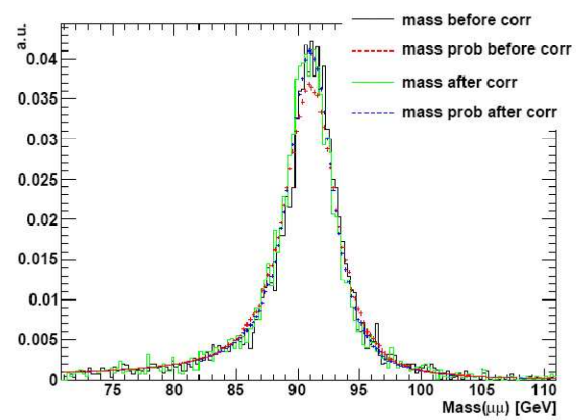




$$\sigma_{pT}/p_T = b_0 \times p_T + \begin{cases} b_1 \times \eta^2 & |\eta| > 0.6 \;\&\; |\eta| < 1.3 \\ b_2 \times (|\eta| - b_3)^2 & \eta > 1.3 \\ b_4 \times (|\eta| - b_5) + b_6 \times (|\eta| - b_5)^2 & \eta < \text{-}1.3 \end{cases}$$







Correction of the MC resolution

- Basic idea: correct the MC resolution on muon momentum in order to reproduce the resolution measured on a real data sample $\Rightarrow$ fundamental to compare data with a realistic MC!
- Hypothesis 1: all the effects introduced in the reconstruction by a real condition detector wrt the ideal detector can be summarized in an additional gaussian smearing
- Hypothesis 2: uncorrelated gaussians ($\Rightarrow$ resolutions):

$$\sigma_{data}^2 = \sigma_{MC}^2 + \sigma_{add}^2$$

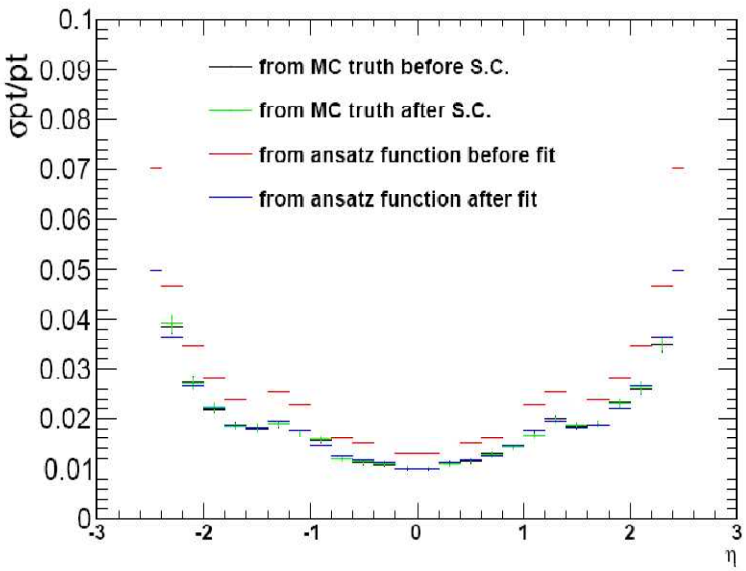
$$\Downarrow$$

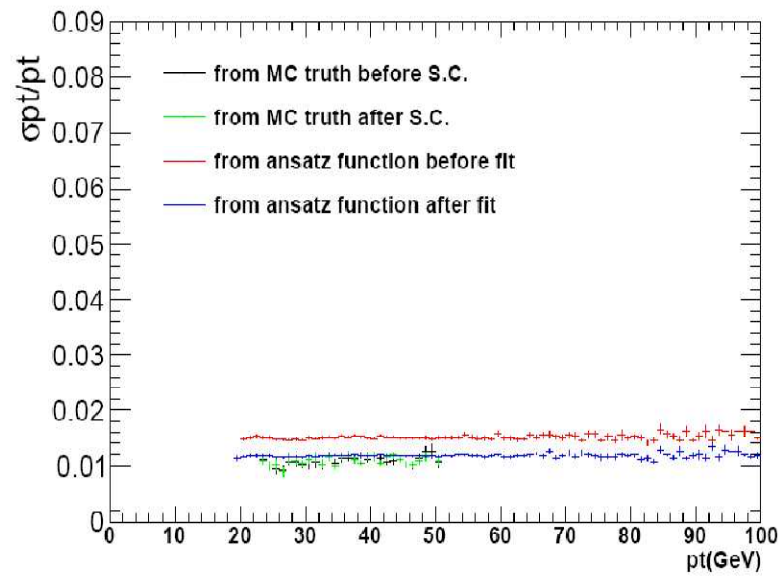
- Smearing the muon transverse momentum by a Gaussian function:

$$p_t' = p_t * G(1, \sqrt{(\sigma_{data}^2 - \sigma_{MC}^2)}) \qquad (1)$$

Resolution measurement on smeared MC

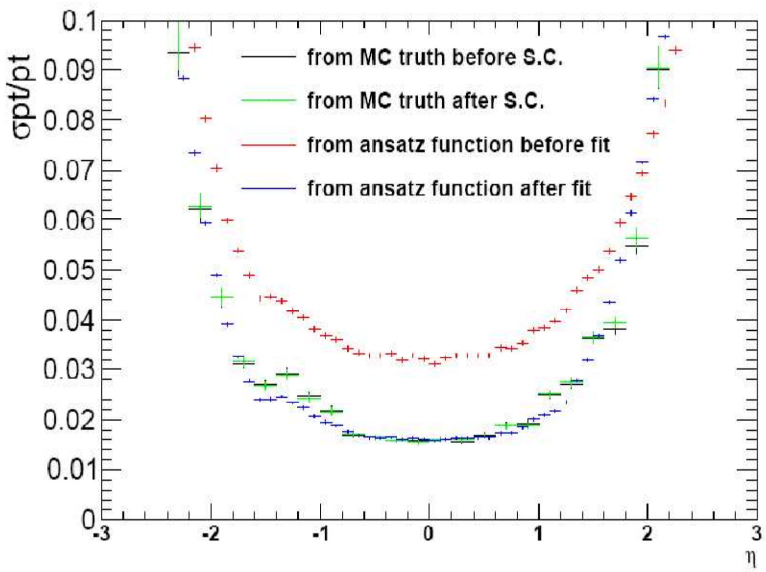
Resolution on IDEAL sample

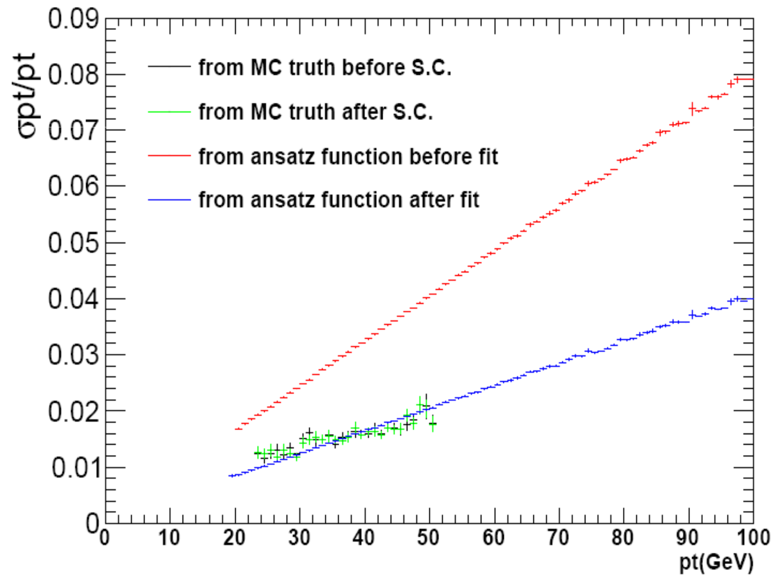




Resolution measurement on smeared MC

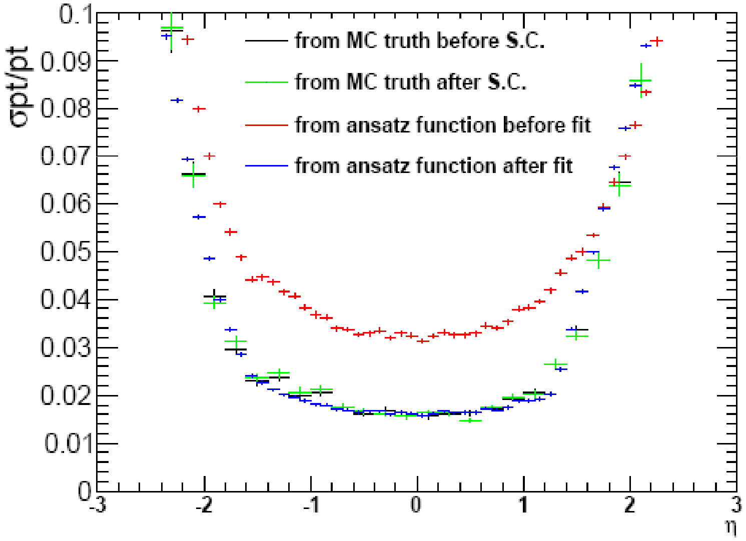
Resolution on REALISTIC sample

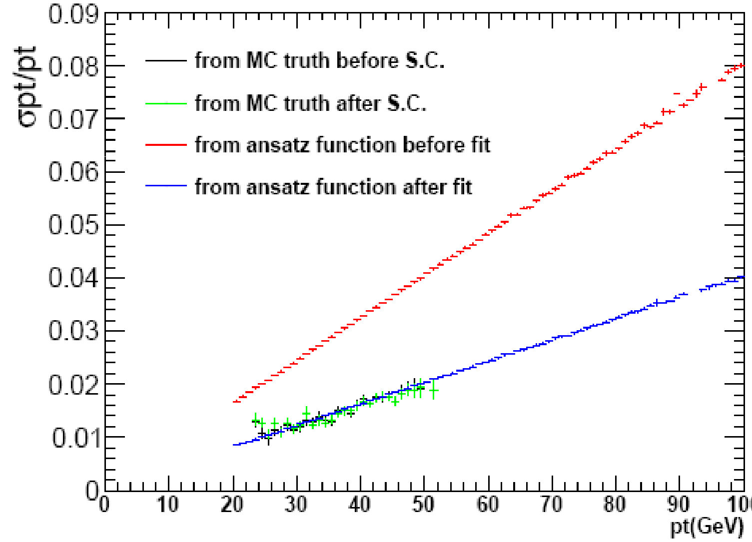




Resolution measurement on smeared MC

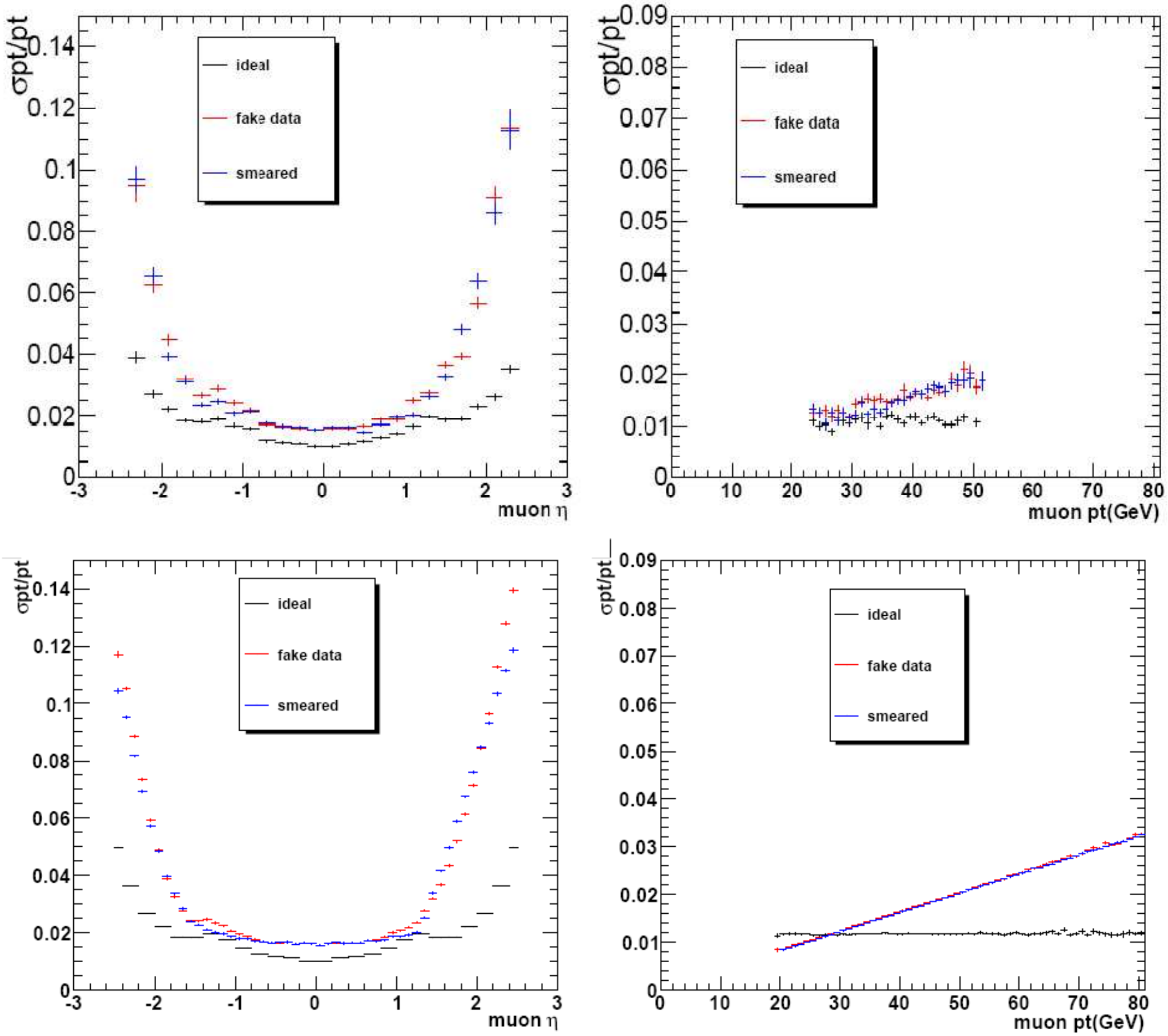
Resolution on SMEARED sample!





The resolution ansatz function is capable to reproduce resolution from reco – gen comparison also for smeared MC events!

Comparison between ideal MC, "fake data" and smeared MC: σ_{pT} vs p_t and η

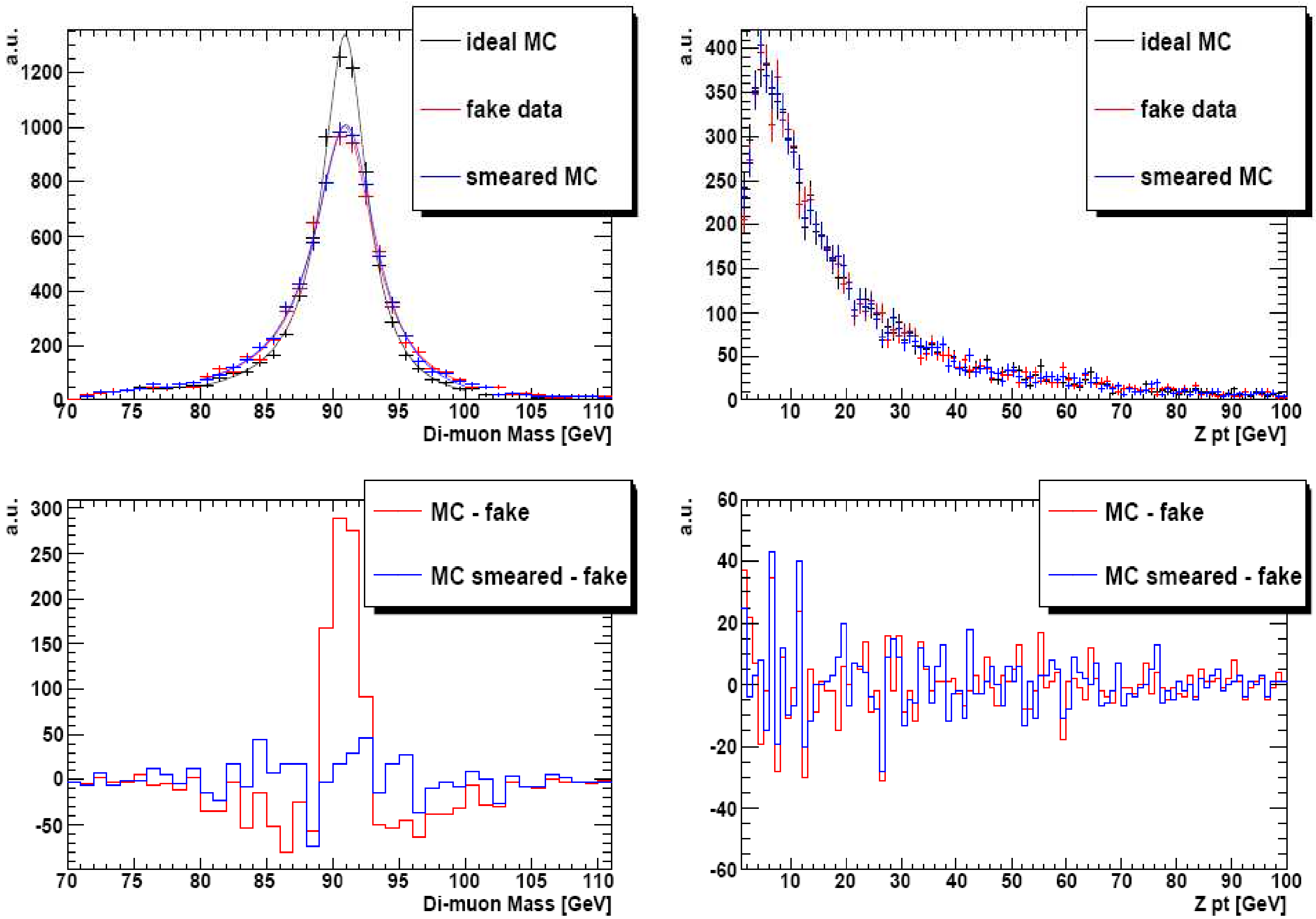


→ Control plots from MC truth.

Excellent agreement between the smeared MC and the fake data resolution

→ Resolution estimation from likelihood minimization.

Effect on the Z kinematics



Evident broadening of the Z di-muon mass in the case of fake data and smeared MC with respect to ideal MC!

No visible effect on Z transverse momentum

Conclusions

- **The tracker has been described in all its aspects: from the calibration and local reconstruction, to the effects that residual miscalibration and misalignment can have on the physics measurements.**
- **A big effort has been done in the last few years to ensure the most reliable physics measurements to be done in the very early phase of the data taking.**
- **Already with 10 pb^{-1} data we are able to correct the muon momentum scale and to measure resolution on transverse momentum.**
- **The smearing method seems to reproduce quite well the "data" behavior starting from ideal MC $\Rightarrow$ fundamental in order to have a realistic Monte Carlo!!**
- **Looking forward for the high energy collisions!!!**

Thank you for your attention!

Back up slides

Likelihood construction

- **Decay muons cross detector material ⇒ measured muon kinematics bring to a reconstructed Z mass which is a resolution-smeared view of the B-W line-shape**

$$P(m,s) = \int dx \frac{\sigma(x)}{s} e^{-\frac{(x-m)^2}{2s^2}}$$ **($\sigma(x)$ = Z mass B-W)**

- **This probability is used to construct a likelihood function:**

$$-\ln L = -\sum_{k=1}^{N_{ev}} \ln(P_s(m_k, s_k) + P_b(m_k))$$

signal **bkg**

where *m* and *s* are parameterized in function of the observable quantities:**

$$m = m(P_{T,1}^{corr}, \phi_1, \cot\theta_1;\ P_{T,2}^{corr}, \phi_2, \cot\theta_2)$$ **measured mass**

$$s = \sqrt{\left(\frac{\partial m}{\partial P_T}\right)^2 \sigma_{P_T}^2 + \left(\frac{\partial m}{\partial \phi}\right)^2 \sigma_\phi^2 + \left(\frac{\partial m}{\partial \cot\theta}\right)^2 \sigma_{\cot\theta}^2}$$ **expected resolution**

** $E = \sqrt{P_T^2(1+\cot^2\theta) + m_\mu^2}$; $P_x = P_T \cos\phi$; $P_y = P_T \sin\phi$; $P_z = P_T \cot\theta$.

Scale correction and resolution measurement

- **Hypothesis on a scale factor:**

$$P_T^{corr} = F(\vec{x};\vec{\alpha})\,P_T$$

- **F → ansatz function for the momentum scale**
- **x → kinematic variables on which the momentum scale depends**
- **α → parameters of the scale correction function, to be extracted from the likelihood minimization**

$$s = \sqrt{\left(\frac{\partial m}{\partial P_T}\right)^2 \sigma_{P_T}^2 + \left(\frac{\partial m}{\partial \phi}\right)^2 \sigma_\phi^2 + \left(\frac{\partial m}{\partial \cot\theta}\right)^2 \sigma_{\cot\theta}^2}$$

ansatz

where

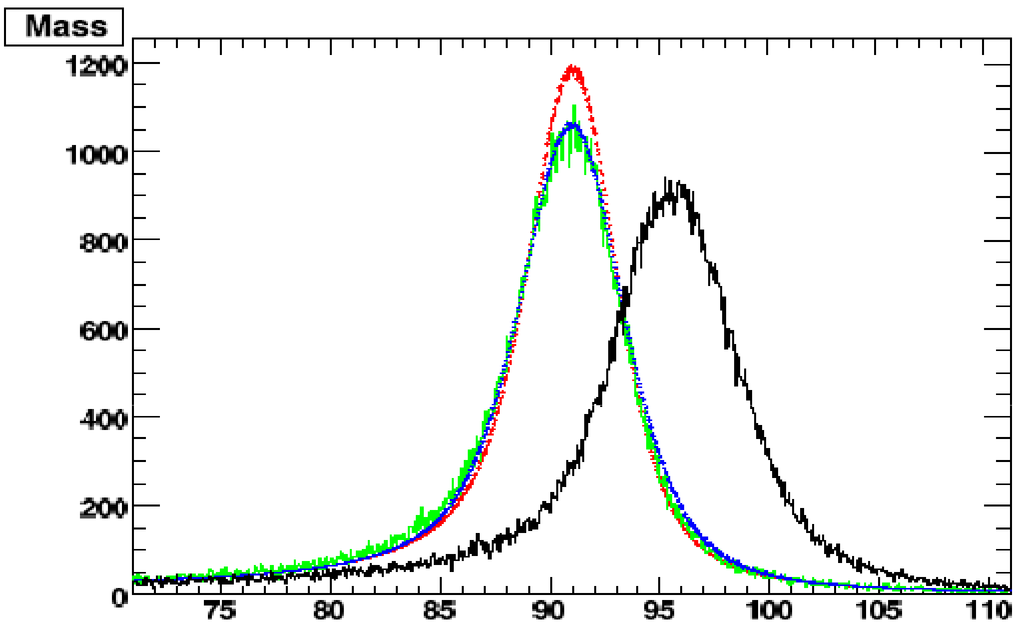
$$\sigma_{P_T} = G_1(\vec{x};\vec{\beta});$$

$$\sigma_\varphi = G_2(\vec{x};\vec{\gamma});$$

$$\sigma_{\cot\theta} = G_3(\vec{x};\vec{\delta});$$

- **G2, G3, γ, δ predetermined by Monte Carlo single muon simulations and ~ negligible.**
- **G1 → ansatz function for the resolution on the muon momentum**
- **β → parameters of the p_T resolution, to be extracted from the likelihood minimization**

Example of possible biases



- Dimuon mass probability before scale correction and resolution measurement
- Observed dimuon mass before scale correction
- Observed dimuon mass after scale correction
- Dimuon mass probability after momentum scale correction and resolution measurement

Strong bias in muon momentum scale evident from dimuon mass distribution