Muon Reconstruction and Momentum Scale Calibration and Their Application to Standard Model Higgs Searches with the CMS Experiment

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Prelude

- The LHC will give a final answer to the question about the existence of the Higgs boson
  - all the allowed mass range is accessible
    \[ 114 \text{ GeV/c}^2 < m_H < O(1 \text{ TeV/c}^2) \]
  - either confirm or rule out its existence
- A “needle in a haystack”
  - Total inelastic cross section
    \[ \sigma_{\text{tot}} \sim 100 \text{ mb} \]
  - Higgs production cross section
    \[ \sigma_H \sim 1-100 \text{ pb} \] (depending on mass, \( \sqrt{s} \))
- Need for a clear signature
  - high trigger efficiency
  - strong background rejection
The Compact Muon Solenoid

Outside the Solenoid
- ~1.8 T return field, mostly in the Iron Yoke
- muon spectrometer

Inside the Solenoid
- 3.8 T magnetic field
- longitudinal, ~homogeneous
- tracker, ECAL, HCAL
Why Muons?

Muons provide the cleanest signal over the hadronic background

- little interaction with detector material
- the only charged particles that reach the outermost subdetectors

“Golden channel” for the Higgs boson discovery at the LHC

\[ H \rightarrow ZZ^{(*)} \rightarrow 4\mu \]
But, Before...

$$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$$
But, Before...

Muon Reconstruction

\[ H \rightarrow ZZ^{(*)} \rightarrow 4\mu \]
But, Before...

Muon Reconstruction

Muon Momentum Calibration

$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$
Outline

- Algorithms
- Local, Stand-Alone, Global Reconstruction
- Developments in Stand-Alone
- Performance with 2010 CMS Data

Muon Reconstruction

- The MuScleFit Algorithm
- Low Momentum Muons: J/ψ
- Medium/High Momentum Muons: Z

Muon Momentum Calibration

- Signal and Backgrounds
- Selection
- Results on Simulation at 1 fb⁻¹
- Results on 2010 CMS Data

H → ZZ*(*) → 4μ
Part I

Muon Reconstruction
Detectors for Muon Reconstruction

\[ \eta = -\ln \tan \frac{\theta}{2} \]
Detectors for Muon Reconstruction

250 Drift Tube Chambers (DT)

(1D hits, 3D segments)

- 4 stations

Spatial resolution (segments)

~70 μm (in φ)

\[ \eta = -\ln \tan \frac{\theta}{2} \]
Detectors for Muon Reconstruction

**250 Drift Tube Chambers (DT)**

- 4 stations
- Spatial resolution (segments) ~70 µm (in φ)

**540 Cathode Strip Chambers (CSC)**

- 4 stations
- Spatial resolution (segments) 50-250 µm

\[ \eta = -\ln \tan \frac{\theta}{2} \]
Detectors for Muon Reconstruction

250 Drift Tube Chambers (DT)
(1D hits, 3D segments)
- 4 stations
- Spatial resolution (segments) ~70 µm (in φ)

Resistive Plate Chambers (RPC)
(1D hits, fast response < 10 ns)
- 6 stations (barr.)
- 3 stations (endc.)
- Spatial resolution ~1 cm (only φ)

540 Cathode Strip Chambers (CSC)
(2D hits, 3D segments)
- 4 stations
- Spatial resolution (segments) 50-250 µm

\[ \eta = - \ln \tan \frac{\theta}{2} \]
Reconstruction of Muon Tracks

Local Reconstruction → Initial State (seed) → Forward (inside-out) → Backward (outside-in) → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter

Diagram showing a schematic of the CMS detector, including Silicon Tracker, Electromagnetic Calorimeter, Hadron Calorimeter, and Superconducting Solenoid. Iron return yoke interspersed with Muon chambers.
1. Local Reconstruction
Reconstruction of hits and track segments inside a chamber

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Local Reconstruction

Initial State (seed)  Forward (inside-out)  Backward (outside-in)  Ghost suppression  Beam spot constraint  Global Reconstruction

Kalman filter
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Reconstruction of Muon Tracks

1. Local Reconstruction
   Reconstruction of hits and track segments inside a chamber

2. Stand-alone Reconstruction (Level-2)
   Reconstruction of the track inside the muon system
Reconstruction of Muon Tracks

1. Local Reconstruction
   Reconstruction of hits and track segments inside a chamber

2. Stand-alone Reconstruction (Level-2)
   Reconstruction of the track inside the muon system

3. Global Reconstruction (Level-3)
   Reconstruction of the track combining the information from tracker and muon system
Reconstruction of Muon Tracks

1. Local Reconstruction
   Reconstruction of hits and track segments inside a chamber

2. Stand-alone Reconstruction (Level-2)
   Reconstruction of the track inside the muon system

3. Global Reconstruction (Level-3)
   Reconstruction of the track combining the information from tracker and muon system

- I worked in particular on the development of stand-alone muon reconstruction
  ➔ responsible in CMS since 2010
- The following description will be focused on it
Stand-Alone Reconstruction
Seed

Built using one or more track segments in DT and CSC

\[ p_T \text{ parametrized as a function of } \phi \text{ slope of segments: } p_T = A - B/\Delta \phi \]

\[ \Delta \phi \]

Simulated muons with design geometry

\[ \sigma \] of the core of a double Gaussian

resolution

relative bias

mean of the core of a double Gaussian
Stand-Alone Reconstruction
Kalman Filter

Iterative method:
- starts from the initial seed state
- the seed state is propagated to the next layer
- on this layer, the most compatible measurement is found (on a $\chi^2$ basis) and used to update the track parameters
- starting from the new state, the procedure is repeated on each reachable layer

Forward filter
- starts from the seed state
- removes biases from the seed

Backward filter
- starts from the last state of the Forward filter (outermost)
- less affected by seed biases

Initial State (seed) → Forward (inside-out) → Backward (outside-in) → Ghost suppression → Beam spot constraint → Global Reconstruction
Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

- The **ghost suppression** or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same muon)

  ➔ *if two tracks share any hit, only the higher-quality track is kept, based on number of hits, $\chi^2$/d.o.f. and $p_T$*

- The track is extrapolated to the **point of closest approach** to the beam line

  The **beam spot** is constrained to be a point of the track, to improve the $p_T$ resolution (up to 40%)
Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

- The ghost suppression or cleaning removes possible duplicates of the same track (coming from multiple seeds for the same muon)

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Stand-Alone Reconstruction

Initial State (seed) → Forward (inside-out) → Backward (outside-in) → Ghost suppression → Beam spot constraint

Kalman filter

Local Reconstruction

Global Reconstruction

Simulated muons with design geometry

- Resolution
- Relative bias

$q/p_T$ vs $p_T$ [GeV/c]
Global Reconstruction

- The stand-alone track defines a *region of interest* (ROI) in the tracker
- compatible tracker tracks are chosen in the ROI
- for each compatible track, the stand-alone–tracker track pair is refitted, using the whole set of hits (tracker + muon)
- ghost suppression is applied
Global Reconstruction

Local Reconstruction → Initial State (seed) → Forward (inside-out) → Backward (outside-in) → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter

Simulated muons with design geometry

- **resolution**
  - $q/p_T$ vs. Muon $p_T$ [GeV/c]

- **relative bias**
  - $q/p_T$ vs. Muon $p_T$ [GeV/c]
Development of Stand-Alone Reconstruction

I have taken care of the stand-alone reconstruction software and coordinated the works for its development (I was appointed as responsible in 2010)

• monitoring of reconstruction performance
  • in data and simulation

• maintenance and update of the software, following new specific requirements
  • in particular, driven by the data taking

• dedicated studies for the improvement of the algorithms, e.g.
  • optimisation of track fitting and pattern recognition
  • optimisation of criteria for ghost suppression, both in off-line and on-line (trigger) reconstruction
One Example...

In the Kalman filter, the selection of measurements for the fit is crucial to balance between track quality and reconstruction efficiency

- I introduced new criteria for the selection of hits and rejection of outliers
  ➔ improve the measurement resolution without losing efficiency!
One Example...

In the Kalman filter, the selection of measurements for the fit is crucial to balance between *track quality* and *reconstruction efficiency*

- I introduced *new criteria* for the *selection of hits* and *rejection of outliers*
  ➔ improve the *measurement resolution* *without* losing efficiency!

**Stand-alone muons**

\[ \frac{p_{T}^{REC}}{p_{T}^{SIM}} - 1 \]

**Simulated muons with** \( p_{T} = 100 \text{ GeV/c} \)

Shoulder at low \( p_{T} \)
(bremsstrahlung, \( \delta \)-rays)

\[
\frac{(p_{T}^{REC} - p_{T}^{SIM})}{p_{T}^{SIM}}
\]
In the Kalman filter, the selection of measurements for the fit is crucial to balance between track quality and reconstruction efficiency.

- I introduced new criteria for the selection of hits and rejection of outliers
  - improve the measurement resolution without losing efficiency!

**Simulated muons with $p_T = 100$ GeV/c**

---

**Stand-alone muons**

$p_T^{REC} / p_T^{SIM} - 1$
One Example...

In the Kalman filter, the selection of measurements for the fit is crucial to balance between *track quality* and *reconstruction efficiency*.

- I introduced new criteria for the *selection of hits* and *rejection of outliers*.
- *improve the measurement resolution without losing efficiency!*

**Simulated muons with** $p_T = 100$ GeV/c

**Stand-alone muons**

$p_T^{REC} / p_T^{SIM} - 1$

**Global muons**

$p_T^{REC} / p_T^{SIM} - 1$

- higher efficiency
- better resolution
- reduction of non-Gaussian tails

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Performance of Muon Reconstruction with 2010 CMS Data

- I used samples of 2010 CMS data to test the performance of muon reconstruction.
- To compare data and simulations, muons were selected with the same criteria and quality requirements.
- Efficiency was determined with the tag-and-probe technique, using di-muons from:
  - $Z$ boson candidates
  - $J/\psi$ meson candidates (for low momentum: $p_T < 15$ GeV/c)
- Track properties are tested on muons from $Z \rightarrow \mu^+\mu^-$ candidate samples.
- Resolutions of stand-alone tracks are estimated w.r.t. tracker tracks:

\[
\begin{align*}
\frac{q}{p_T} \text{ resolution} &= \frac{(q/p_T)_{STA} - (q/p_T)_{TRK}}{(q/p_T)_{TRK}} \\
\eta \text{ resolution} &= \eta_{STA} - \eta_{TRK} \\
\phi \text{ resolution} &= \phi_{STA} - \phi_{TRK}
\end{align*}
\]

Resolution of tracker tracks is about one order of magnitude better than that of stand-alone tracks.
Muon Reconstruction in 2010 CMS Data

Efficiency

Stand-alone muons

Global muons

including some quality cuts

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Muon Reconstruction in 2010 CMS Data

Resolutions of Stand-Alone Tracks

- $\eta$ resolution
- $\phi$ resolution
- $q/p_T$ resolution
Muon Reconstruction in 2010 CMS Data

Number of Hits

Stand-alone muons

Global muons

$\chi^2$
Part II

Muon Momentum
Scale and Resolution Studies
After the reconstruction, the measurement of muon momentum can be affected by biases, coming from several sources: reconstruction algorithm, limited knowledge of the detector (material budget, alignment), magnetic field.

\[ p_T \text{ relative bias} = \text{mean of the distribution} \]

\[ \frac{p_T^{REC} - p_T^{SIM}}{p_T^{SIM}} \]

fit with a Gaussian

Need to correct these biases and measure the momentum resolution.
MuSCleFit: algorithm for muon momentum scale calibration, using muons from well known resonances ($J/\psi$, $\Upsilon$, $Z$) and a multivariate likelihood
directly corrects the momentum of muons, in order to “force” the mass of the resonance to its expected value

• For a given resonance, construct a model for mass profile:
  \[ P(m, \sigma) = \int L(m' ; M_0, \Gamma) \times Gauss(m-m' ; \mu=0, \sigma) \, dm' \]

• find ansatz function for scale and resolution:
  \[ p_T^{corr} = f(x_i, a_j) \cdot p_T , \quad \sigma(x_i) = g_i(x_k, b_j) \cdot p_T \]
  where \( x_i = p_T, \cotg \theta, \phi \) and \( a_j, b_j \) are free parameters

• from data, compute likelihood:
  \[ -\ln L = - \sum_{\text{events}} \ln P(m(x_i^{(1)}, x_j^{(2)}), \sigma(x_i^{(1)}, x_j^{(2)})) \]

• minimizing \(-\ln L\), one obtains scale correction \( f \) and resolution functions \( g_i \)
My work in the MuScleFit group

- Find suitable ansatz functions for scale correction and resolution in data, using muons from different resonances ($J/\psi$, $Z$) – i.e. different $p_T$ scales
  - find dependencies of scale and resolution on muon kinematics
  - find the best fit strategy

- Provide analysis groups (e.g. $J/\psi$, $\Upsilon$) with
  - momentum scale corrections
  - systematics from momentum scale and resolution

- Evaluate resolution and bias of different muon reconstruction algorithms (tracker, global, stand-alone) and compare to MC expectations
Momentum Calibration Using J/ψ

- Simulated J/ψ → μμ sample with realistic alignment conditions (~ 13 pb⁻¹)
- J/ψ → μμ candidates from 2010 CMS data (~ 19 pb⁻¹)

![J/ψ mass graphs](image)

- Mean of Crystal-Ball fits to mass distributions in each bin
Momentum Calibration Using J/ψ

- Simulated J/ψ → μμ sample with realistic alignment conditions (~ 13 pb⁻¹)
- J/ψ → μμ candidates from 2010 CMS data (~ 19 pb⁻¹)

Mass resolution

σ of Crystal-Ball fits to mass distributions in each bin
J/ψ: Calibration Strategy

- The following ansatz functions are chosen, based on the main features observed in simulation and in data

**Resolution**

\[
\frac{\sigma(p_T)}{p_T} = \begin{cases} 
  f(p_T) + a_3 + a_4 \eta^2 & \text{for } |\eta| \leq a_0 \\
  (|\eta| - a_0) (y_2 - y_1)/(a_1 - a_0) + y_1 & \text{for } a_0 < |\eta| \leq a_1 \\
  f(p_T) + a_5 + a_6 (|\eta| - a_7)^2 & \text{for } a_1 < |\eta| \leq a_2 \\
  f(p_T) + a_8 + a_9 (|\eta| - a_{10})^2 & \text{for } |\eta| > a_2 
\end{cases}
\]

with \( f(p_T) = a_{11} p_T \)  \( \text{linear in } p_T \)

**Scale correction**

\[
p_T^{corr} = p_T \cdot (1 + A + B f(|\eta|) + C_{q,h} |\phi| \sin(2\phi + D_{q,h}))
\]

with \( f(|\eta|) \)  \( \text{tabulated from the actual mass vs. } |\eta| \text{ distribution (by-point function)} \)

**Exponential background**

\[\rightarrow \text{different in } (\eta (\mu^+), \eta (\mu^-)) \text{ bins} \]
J/ψ: Mass After Correction

Before corrections
After corrections

mean of Crystal-Ball fits to mass distributions in each bin
**J/ψ: Line-Shape After Correction**

**Before the correction**

- Events / (8 MeV/c²)
- Mass [GeV/c²]
- $N_{J\psi} = 266772 \pm 312$
- $k = -0.67226 \pm 0.0050$
- $N_{bg} = 1398400 \pm 1268$
- $f_{\text{GB}} = 0.3892 \pm 0.0016$
- Peak value = $(3091.989 \pm 0.044)$ MeV/c²
- $\sigma = 0.030263 \pm 0.000066$
- $\alpha = 9.3 \pm 7.5$
- $n = 0 \pm 230$
- $\sigma_z = 0.054016 \pm 0.000078$

**After the correction**

- Events / (8 MeV/c²)
- Mass [GeV/c²]
- $N_{J\psi} = 264318 \pm 422$
- $k = -0.66609 \pm 0.0052$
- $N_{bg} = 1396450 \pm 1326$
- $f_{\text{GB}} = 0.389 \pm 0.012$
- Peak value = $(3094.974 \pm 0.047)$ MeV/c²
- $\sigma = 0.03021 \pm 0.00030$
- $\alpha = 1.798 \pm 0.029$
- $n = 100 \pm 64$
- $\sigma_z = 0.05408 \pm 0.00040$

**Peak value**

- $(3091.989 \pm 0.044)$ MeV/c²
- $(3094.974 \pm 0.047)$ MeV/c²

**Fit with**

- Crystal-Ball + Gaussian, exponential background

**+3 MeV/c² shift**

**Compatible with PDG J/ψ mass:**

- $(3096.916 \pm 0.011)$ MeV/c²

- ~ $2$ MeV/c² shift is expected (due to the function used for the fit)


J/ψ: $p_T$ Resolution

**Resolution function after the fit**

The gray band accounts for statistical and systematic uncertainties

**Parametrisation:**

$$
\frac{\sigma(p_T)}{p_T} = \begin{cases} 
  f(p_T) + a_3 + a_4 \eta^2 & \text{for } |\eta| \leq a_0 \\
  (|\eta| - a_0) (y_2 - y_1)/(a_1 - a_0) + y_1 & \text{for } a_0 < |\eta| \leq a_1 \\
  f(p_T) + a_5 + a_6 (|\eta| - a_7)^2 & \text{for } a_1 < |\eta| \leq a_2 \\
  f(p_T) + a_8 + a_9 (|\eta| - a_{10})^2 & \text{for } |\eta| > a_2
\end{cases}
$$
Momentum Calibration Using Z

- Simulated $Z \rightarrow \mu\mu$ sample with realistic alignment conditions ($O(100 \text{ pb}^{-1})$)

- $Z \rightarrow \mu\mu$ candidates from 2010 CMS data ($\sim 30 \text{ pb}^{-1}$)

![Z mass plots](image)

**mean of Voigtian fits to mass distributions in each bin**
Z: Calibration Strategy

Ansatz functions:

- **Resolution**

\[
\frac{\sigma(p_T)}{p_T} = \begin{cases} 
  f(p_T) + a_2 \eta^2 & \text{for } |\eta| \leq a_0 \\
  f(p_T) + a_3 (|\eta| - a_4)^2 & \text{for } \eta < -a_0 \\
  f(p_T) + a_5 (|\eta| - a_6)^2 & \text{for } \eta > a_0 
\end{cases}
\]

with \( f(p_T) = a_1 + 1.8 \cdot 10^{-4} p_T \) fitted on simulation

- **Scale correction**

\[
p_T^{corr} = b_0 + b_1 p_T + q b_2 \eta + q b_3 \sin(\phi + b_4)
\]

\( q = \text{charge} \)

- **Exponential background**

\( \rightarrow \) the background level is very low, a single exponential function is used
Z: Mass After Correction

Before corrections

After corrections

mean of Voigtian fits to mass distributions in each bin
Z: Line-Shape After Correction

**Before the correction**

**After the correction**

**Mean of the fit**

- Before: \( (90.874 \pm 0.028) \text{ GeV/c}^2 \)
- After: \( (90.781 \pm 0.028) \text{ GeV/c}^2 \)

\(-0.1 \text{ GeV/c}^2\) shift

\( \sigma = 1.52 \rightarrow 1.45 \text{ GeV/c}^2 \)

\( \sim 4.6\% \) improvement in resolution from momentum correction

fit with a Voigtian profile, exponential background

peak of Z resonance expected at the LHC:

\( \sim 90.7 \text{ GeV/c}^2 \), due to PDFs and FSR
Part III

Standard Model Higgs Boson
Searches in the 4 Muons Channel
The Higgs mass ($m_H$) is a free parameter of the SM, but it’s related to known parameters through virtual corrections ($\sim \log m_H$).

**Experimental constraints**

- $m_H > 114.4$ GeV/c$^2$ (LEP exclusion)
- $m_H \neq 158-175$ GeV/c$^2$ (Tevatron exclusion)
- $m_H < 158$ GeV/c$^2$ (global EW fit)

**Theoretical constraints**

- $m_H \lesssim 1$ TeV/c$^2$
The “Golden Channel”

For high Higgs masses ($m_H > 2m_Z$):

- $H \rightarrow W^+W^-$ main decay channel
- $H \rightarrow ZZ$ has $BR(H \rightarrow WW) \approx 3 \times BR(H \rightarrow ZZ)$

But $Z$ can decay in 2 charged leptons

- clean signature over the hadronic background
- good resolution on Higgs mass

So: $H \rightarrow ZZ \rightarrow 4\ell$ ($\ell = e, \mu$) is the “golden channel” for a Higgs discovery at the LHC

$$\sigma_{NNLO} \times BR(H \rightarrow ZZ \rightarrow 4\ell) = 1 - 16 \text{ fb}$$

(here $\ell = e, \mu, \tau$)

signature: 4 leptons in the final state with
- high $p_T$
- isolated (not inside a jet of hadrons)
- prompt (emerging from the primary vertex)
Main Backgrounds

- **Irreducible** (same final state as the signal)
  - $ZZ^{(*)} \rightarrow 4\ell$

- **Reducible** (2 leptons from jets)
  - $Zbb \rightarrow 4\ell + X$
  - $tt \rightarrow 4\ell + X$

- **Other backgrounds:** $n$-jets (QCD), $W + n$-jet, $Z + n$-jet

\[ \ell = e, \mu, \tau \]

\[ \sigma_{\text{NLO}} \times BR = 4.80 \text{ pb} \]

\[ \sigma_{\text{NLO}} \times BR = 2.93 \text{ pb} \]

\[ \sigma_{\text{NLO}} \times BR = 16.71 \text{ pb} \]
Main Backgrounds

- **Irreducible** (same final state as the signal)
  - $ZZ^{(*)} \rightarrow 4\ell$
  - $\ell = e, \mu, \tau$

  \[ \sigma_{NLO} \times BR = 4.80 \text{ pb} \]

- **Reducible** (2 leptons from jets)
  - $Zbb \rightarrow 4\ell + X$
  - $\sigma_{NLO} \times BR = 2.93 \text{ pb} \]

  $\ell = e, \mu, \tau$

- $\bar{t}t \rightarrow 4\ell + X$
  - $\sigma_{NLO} \times BR = 16.71 \text{ pb} \]

- **Other backgrounds**: $n$-jets (QCD), $W + n$-jet, $Z + n$-jet

- In the following, a prospective analysis for the $4\mu$ final state is presented, for a centre-of-mass energy of 7 TeV and integrated luminosity of 1 fb$^{-1}$

- Two parallel analyses, for the $4e$ and $2\mu2e$ final states, are performed using the same strategy

- Combined results of the three channels are shown in the conclusion
Preliminary Selections

1. Trigger

   single and double muon triggers
   (no isolation)

2. Skimming

   – suppress QCD, W+jets, Z+jets events
   – based on $p_T$ cuts

3. Preselection

   – reduce fake muons and lower QCD
   – require 2 $\mu^+\mu^-$ pairs with cuts on
     2-muon and 4-muon invariant mass

![Graph showing events vs. $m(Z_1 Z_2)$]
Selection: Isolation

**Isolation variable**

momentum / energy of tracks inside a cone around the muon

**Selection applied on variable**

\( \mu \text{Iso}_{2\text{ least}} \ = \ \text{sum of the isolation of the 2 least isolated muons} \)
**Impact parameter significance:**

\[ S_{IP} = \frac{IP^{3D}}{\sigma_{IP^{3D}}} \]

**Cuts applied to the 2 highest \( S_{IP} \) muons**

(muons from \( b \)-jets have higher \( S_{IP} \))
Selection: Isolation vs. $p_T$

- A $p_T$-dependent isolation cut proves more effective on $Zbb$ background

The bidimensional distributions
isolation variable vs $p_T$ of muons
show a very strong rejection power

The 3$^{rd}$ and 4$^{th}$ muon, sorted by decreasing $p_T$
- are inside $b$-jets
- have a softer $p_T$ spectrum

\[ \mu \text{Iso}_2 \text{least} = A - B \, p_T \]
Selection: Dimuon Invariant Mass

**Definition of Z:**

- $Z_1$: the muon pair closest to the nominal $Z$ mass
- $Z_2$: the 2 remaining muons with the highest $p_T$

**After preselection**

![Histograms showing CMS data and theoretical predictions for $m(Z_1)$ and $m(Z_2)$](image)

**Data**

- $L \approx 32$ pb$^{-1}$

**CMS Data**

- $L \approx 32$ pb$^{-1}$

**Normalised area**

- $H_{150}$ GeV/c$^2$
- $ZZ +$ jets
- $Z\bar{b}/c\bar{b} +$ jets
- $t\bar{t} +$ jets
- $Z +$ jets
- $W +$ jets
- QCD
Results

A narrow peak emerges over the continuum of the remaining ZZ background.
Results

At 7 TeV with 1 fb⁻¹, neither discovery nor exclusion are possible, for all the mass range.

Lines: extrapolations of a similar analysis at √s = 10 TeV

Stars: results of this analysis

A narrow peak emerges over the continuum of the remaining ZZ background.

Higgs mass [GeV/c²]

Higgs mass [GeV/c²]

Higgs mass [GeV/c²]
Results on Data (32 pb⁻¹)

After HLT + skimming

After preselection

After full selection

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At $\sqrt{s} = 7$ TeV, $L = 32$ pb⁻¹:

$\text{Prob (1 evt } ZZ \rightarrow 4\mu) = 0.08$

$\text{Prob (1 evt } ZZ \rightarrow 4\ell) = 0.23$

all isolated, with $S_{IP} \sim 0$
4µ Golden Event
Conclusions

- **Muon Reconstruction**
  - Reconstruction algorithms
  - Stand-alone reconstruction and its improvements
  - Test of muon reconstruction performance on 2010 LHC data and comparison with simulations

- **Muon Momentum Scale Calibration**
  - Algorithm developed for momentum calibration
  - Application of the algorithm to J/ψ and Z samples from 2010 CMS data
  - Scale corrections and resolution measurements in different $p_T$ ranges

- **Higgs Boson Searches in the Four Muons Channel**
  - Development of a prospective analysis for a low luminosity scenario
  - Expected results on simulations at 7 TeV energy and 1 fb$^{-1}$ luminosity
  - Application of this analysis to 2010 CMS data and first results
Thanks for the attention!
Acknowledgements

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A nonna Maria era eferente mondo.
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Backup slides
Stand-Alone Reconstruction

It is estimated in different ways in the the off-line and on-line (trigger) reconstruction:

- **on-line**: input from Level 1 trigger
- **off-line**: built from one or more track segments

\[ p_T = A - B/\Delta \phi \]
Stand-Alone Reconstruction

**seed**

- **Initial State (seed)**
  - **Forward (inside-out)**
  - **Backward (outside-in)**
  - **Ghost suppression**
  - **Beam spot constraint**

Kalman filter

It is estimated in different ways in the off-line and on-line (trigger) reconstruction:

- **on-line**: input from Level 1 trigger
- **off-line**: built from one or more track segments
  
  \[ p_T = A - \frac{B}{\Delta \phi} \]

---

**Muon seed efficiency vs \( \eta \)**

**Muon seed efficiency vs \( \phi \) (|\( \eta \)| < 2.4)**

**Muon seed efficiency vs \( p_T \) (|\( \eta \)| < 2.4)**

- Simulated muons
- Design geometry
- Flat \( \eta \), |\( \eta \)| < 2.5
- \( p_T = 5-1000 \) GeV/c
Stand-Alone Reconstruction seed

\[
\frac{(q/p_T)_{\text{MEAS}} - (q/p_T)_{\text{SIM}}}{(q/p_T)_{\text{SIM}}}
\]

Fit with a double Gaussian

- the narrow Gaussian for the core of the distribution
- the large Gaussian accounts for tails (mult. scattering)

From the core distribution

- mean: \(q/p_T\) relative bias
- \(\sigma\): \(q/p_T\) resolution

\(\chi^2 / \text{ndf} = 864.5 / 193\)

\(\text{Const}_1 = 1575 \pm 17.3\)

\(\mu_1 = -0.06728 \pm 0.00119\)

\(\sigma_1 = 0.1371 \pm 0.0020\)

\(\text{Const}_2 = 400.4 \pm 15.4\)

\(\mu_2 = -0.09537 \pm 0.00307\)

\(\sigma_2 = 0.3995 \pm 0.0053\)

up to \(~40\%\) at low \(p_T\)

\(~10\%\) at 1 TeV/c

Simulated muons
Stand-Alone Reconstruction seed

Built using one or more track segments in DT and CSC

\[ \rho_T \text{ parametrized as a function of } \phi \text{ slope of segments: } \rho_T = A - B/\Delta\phi \]
Stand-Alone Reconstruction

seed

$q/p_T$ resolution:

\[
\frac{(q/p_T)_{\text{MEAS}} - (q/p_T)_{\text{SIM}}}{(q/p_T)_{\text{SIM}}}
\]

Fit with a double Gaussian

- the narrow Gaussian for the core of the distribution
- the large Gaussian accounts for tails (mult. scattering)

From the core distribution

\[
\sigma
\]

$q/p_T$ resolution

\[
\text{mean}
\]

$q/p_T$ relative bias
Stand-Alone Reconstruction

seed

\[ \frac{(q/p_T)_{\text{MEAS}} - (q/p_T)_{\text{SIM}}}{(q/p_T)_{\text{SIM}}} \]

Fit with a double Gaussian

the narrow Gaussian for the core of the distribution

the large Gaussian accounts for tails (mult. scattering)

$q/p_T$ resolution:

- Initial State (seed)
- Forward (inside-out)
- Backward (outside-in)
- Ghost suppression
- Beam spot constraint
- Global Reconstruction

Kalman filter

Initial State (seed)

Forward (inside-out)

Backward (outside-in)

Ghost suppression

Beam spot constraint

Global Reconstruction

Local Reconstruction

$q/p_T$ resolution:

- Mean of the core distribution
- \( \sigma \) of the core distribution

relative bias

resolution

up to \(~40\%\) at low \(p_T\)

\(~10\%\) at 1 TeV/c

Simulated muons
Stand-Alone Reconstruction

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter
Stand-Alone Reconstruction
Kalman filter

Iterative method:
- starts from the initial seed state
- the seed state is propagated to the next layer
- on this layer, the most compatible measurement is found (on a $\chi^2$ basis) and used to update the track parameters
- starting from the new state, the procedure is repeated on each reachable layer

Forward filter
- starts from the seed state
- segments in DT and CSC, and individual points in RPC are fitted
- removes possible biases from the seed

Backward filter
- starts from the last state of the Forward filter (outermost)
- individual points in DT, CSC and RPC are fitted
- not affected by possible seed biases
The ghost suppression or cleaning removes possible duplicates of the same track (coming from multiple seeds for the same muon)

⇒ if two tracks share any hit, only the highest-quality track is kept, based on number of hits, $\chi^2$/d.o.f. and $p_T$
**Z: Comparison Tracker-Global (I)**

- **Z mass**
  - ▼ Inner tracks
  - ■ Global tracks
Z: Comparison Tracker-Global (II)

Mass resolution

- ▼ Inner tracks
- ■ Global tracks
Reconstruction of Muon Tracks

1. Local Reconstruction
   Reconstruction of hits and track segments inside a chamber

2. Stand-alone Reconstruction (L2)
   Reconstruction of the track inside the Muon System

3. Global Reconstruction (L3)
   Reconstruction of the track combining the information from Tracker and Muon System

The track is built from position (direction) measurements with an iterative method called Kaman filter, which provides

- pattern recognition → collection of hits
- best estimation of track parameters → minimum $\chi^2$
- fast reconstruction → well-suited also for HLT
Stand-Alone Seed Performance

- **Efficiencies**
  - Detector acceptance (cracks betw wheels)
  - Detector acceptance (services chimneys)

- **Simulated muons**
  - Design geometry
  - Flat $\eta$, $|\eta| < 2.5$
  - $p_T = 5\text{–}1000 \text{GeV/c}$

- **Mean of the core distribution of a double Gaussian**
  - up to ~ 40% at low $p_T$
  - ~10% at 1 TeV/c

- **Relative bias**

- **Resolution**

- **Detector acceptance**
  - (services chimneys)

- **Seed efficiency**

- **Graphs**
  - Muon $p_T$ [GeV/c]
  - Muon $\phi$ [°]
  - Muon $p_T$ [GeV/c]
Stand-Alone Reconstruction
Kalman Filter

Iterative method:

- starts from the initial seed state
- the seed state is propagated to the next layer
- on this layer, the most compatible measurement is found (on a $\chi^2$ basis) and used to update the track parameters
- starting from the new state, the procedure is repeated on each reachable layer

Forward filter

- starts from the seed state
- segments in DT and CSC, and individual points in RPC are fitted
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- not affected by possible seed biases
The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same muon)

→ *if two tracks share any hit, only the highest-quality track is kept, based on number of hits, $\chi^2$/d.o.f. and $p_T$*
Stand-Alone Reconstruction

Beam Spot Constraint

The track is extrapolated to the *point of closest approach* to the *beam line*.

The *beam spot* is constrained to be a point of the track, to improve the $p_T$ resolution.

\[ \sigma \text{ of the core of a double Gaussian fit to the distribution} \]

\[ \frac{(q/p_T)_{\text{REC}} - (q/p_T)_{\text{SIM}}}{(q/p_T)_{\text{SIM}}} \]

\[ |\eta| < 0.8 \]

- no update at vertex
- updated at vertex

Simulated muons

Some % improvement at low $p_T$

Up to 30-40% at 1 TeV/c
Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

- The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same muon)

  ➔ *If two tracks share any hit, only the higher-quality track is kept*, based on *number of hits*, $\chi^2$/d.o.f. and $p_T$

- The track is extrapolated to the *point of closest approach* to the beam line

  The *beam spot* is constrained to be a point of the track, to improve the $p_T$ resolution

  Some % improvement at low $p_T$ up to 30-40% at 1 TeV/c
Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

- The ghost suppression or cleaning removes possible duplicates of the same track (coming from multiple seeds for the same muon)

\[ \text{if two tracks share any hit, only the higher-quality track is kept, based on number of hits, } \chi^2/d.o.f. \text{ and } p_T \]

- The track is extrapolated to the point of closest approach to the beam line

The beam spot is constrained to be a point of the track, to improve the $p_T$ resolution

- Some % improvement at low $p_T$
- Up to 30-40% at 1 TeV/c
Development of Stand-Alone Reconstruction

- Development and maintenance of the reconstruction software in the muon spectrometer (*stand-alone reconstruction*)
  - development and optimisation of algorithms for *pattern recognition* and *track fitting*
  - improvement of criteria for *ghost track suppression*
  - specialisation for *on-line reconstruction* (HLT)

- Monitoring of *reconstruction performance* on data and simulation (*stand-alone and global* reconstruction)

- Drift Tube chambers
  - DT calibration (responsibility of the CMS Torino group)
  - Since Dec. '09, *contact person* for the operation of the DT FEDs (part of the read-out electronics, designed and produced in Torino)
Some Examples (II)

- Ghost suppression strategy and criteria improved, in particular to cope with the new features of fitting algorithms
  ➔ ghost rate decreases, without affecting stand-alone and global efficiencies

- MC – single-$\mu$ - $p_T = 10$ GeV/c
- MC – $J/\psi \rightarrow \mu\mu$

- Stand-alone ghost rate
- Global efficiency
- Default ghost suppression
- New cleaning criteria
Some Examples (II)

In the *trigger* reconstruction, the initial state (seed) comes from the *Level-1* trigger electronics. The same muon can produce multiple Level-1's $\Rightarrow$ multiple seeds $\Rightarrow$ *ghost tracks*

Ghost suppression is crucial:

- reject ghosts
- do not affect the efficiency

$\Rightarrow$ *ghost suppression specialised for on-line reconstruction*

![Graphs showing efficiency vs. $p_T$ for different seeds and muons in two different suppression methods.](image)
Performance of Reconstruction in Simulations
Stand-Alone Muons

Efficiencies

Detector acceptance

Bias up to ~2-3%

Resolution

Relative bias
Performance of Reconstruction in Simulations
Global Muons

- Global efficiency
- Muon $p_T$ [GeV/c]
- Muon $\eta$
- Muon $\phi$ [°]
- Efficiency
- $q/p_T$, resolution
- $q/p_T$, relative bias

Efficiencies:
- < 0.1% up to 500 GeV/c
The grey band accounts for statistical and systematic uncertainties.

Systematic error is estimated as the difference between the resolution function fit on MC and the MC truth.
Momentum Calibration Using $Z$

- Simulated $Z \rightarrow \mu\mu$ sample with realistic alignment conditions ($O(100 \text{ pb}^{-1})$)

- $Z \rightarrow \mu\mu$ candidates from 2010 CMS data (~30 pb$^{-1}$)

Z mass

mean of Voigtian fits to mass distributions in each bin
Momentum Calibration Using Z

- Simulated $Z \rightarrow \mu\mu$ sample with realistic alignment conditions ($O(100 \text{ pb}^{-1})$)

$\downarrow$ $Z \rightarrow \mu\mu$ candidates from 2010 CMS data ($\sim 30 \text{ pb}^{-1}$)

Mass resolution

![Graphs showing Z resolution vs muon $\eta$ and $p_T$ in data and simulation, with Gaussian $\sigma$ of Voigtian fits to mass distributions in each bin](Images/Graphs.png)
Results on Data (32 pb$^{-1}$)

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<tr>
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</tr>
</tbody>
</table>

At $\sqrt{s} = 7$ TeV, $L = 32$ pb$^{-1}$:

- $\text{Prob (1 evt } ZZ \to 4\mu) = 0.08$
- $\text{Prob (1 evt } ZZ \to 4\ell) = 0.23$
- $\text{Prob (1 evt } H \to 4\mu) = 0.032$
- $\text{Prob (1 evt } H \to 4\ell) = 0.099$

After HLT + skimming

After preselection

After full selection