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Study of the muon momentum scale and resolution with MuScleFit on the $\sqrt{s}$ = 7 TeV and 8 TeV datasets

S. Casasso, E. Migliore
Università di Torino and INFN Sezione di Torino

Abstract

This note describes the studies on the momentum scale and on the resolution of the muons reconstructed by the CMS experiment in the 2011 and 2012 proton-proton LHC runs using the MuScleFit algorithm. Both real and simulated data were calibrated using the large sample of dimuons decays from Z bosons. A data-driven validation of the results using dimuons from J/ψ, $\Upsilon(1S)$ and Z decays and an estimate of the systematic uncertainty on the momentum scale for the data collected in 2012 are also presented.

1 Introduction

FIXME Outline of Introduction

- bla-bla on uncertainties in track reconstruction
- definition of the datasets used
- event/track selection
- outline of the structure of the note

2 Calibration strategy

The MuScleFit algorithm [1] uses the spectrum of dimuons from the decay of reference resonances to determine biases in the momentum assigned to charged tracks and to estimate its resolution. For the calibration procedure described in this note, dimuons from the decay of Z bosons were used. The invariant mass spectrum of the dimuons was modeled as the sum of a signal obtained from a NNLO calculation [2], adapted to kinematic cuts close to those used in the selection of reconstructed muons, and an exponentially falling background. The decay constants of the exponential were determined separetely in 9 bins depending on the pseudorapidities of the two muons. **FIXME** expand description of the background model

2.1 Ansatz functions for scale corrections and resolution

The bias in the assignment of the momentum is mainly related to geometrical effects, e.g. deformations of the tracker geometry used in the reconstruction nevertheless present after the alignment procedure. For this reason scale corrections were implemented as corrections to the curvature $\kappa = q/p_T$ of the track. We modeled these corrections with an ansatz function defined in five bins of the muon pseudorapidity:

$$\kappa' = (1 + p_0)\left(\kappa - \frac{\delta}{2} - C_j(\eta, \varphi)\right), \tag{1}$$

where j is an index running on the η bin: [-2.4,-2.1], [-2.1,-1.5], [-1.5,+1.5], [+1.5,+2.1] and [+2.1,+2.4].

The terms in Eq. 1 are:

- p_0 corresponding to a global correction to the scale accounting for effects like inaccurate knowledge of the magnetic field;
- δ representing an absolute bias in the curvature, e.g. a bias on the transverse momentum of the track different for negative and positive muons;
- $C_j(\eta, \varphi)$ accounting for residual misalignment effects in each of the five η bins. The functional form

  $$C_j(\eta, \varphi) = a_{1,j}\sin(\varphi + \varphi_{1,j}) + a_{2,j}\sin(2\varphi + \varphi_{2,j}) + b_j(\eta - \eta_{0,j}) + b_{0,j}$$

  was choosen to model the weak modes more frequently found in the post-alignment geometry, namely the sagitta (described by $a_{1,j}$), the twist (described by b_j) and the elliptical (described by $a_{2,j}$) deformations [1]. The elliptical deformations were considered null everywhere apart from the first and last η bin.

[1] The three weak modes correspond to the following parametric deformations: $r\Delta\varphi = c_s \cos\varphi$ *sagitta*, $\Delta\varphi = c_t z$ *twist* and $\Delta r = r(1 - c_e \cos 2\varphi)$ *elliptical* with c_s, c_t and c_e being the approriate constants.

Table 1 shows the values of the fitted parameters found by MuScleFit. Coefficients $a_{1,j}$, $a_{2,j}$ and b_j with magnitude smaller than 0.000001 GeV^{-1} were considered null. Similarly values of p_0 smaller than 0.0050 were considered zero as they are consistent, within the systematic uncertainty computed in Section 4, with the null value.

The resolution on p_T was modeled as the sum in quadrature of two terms

$$\frac{\sigma(p_T)}{p_T} = q_0 p_T \oplus q_j \tag{2}$$

where the parameters q_j, representing multiple Coulomb scattering effects, were computed separately in 12 equally spaced bins in η.

2.2 Fit strategy

The maximization of the likelihood was performed in two steps. First, all the parameters of the correction function, with the exception of the global scale p_0, were estimated for realistic values of the resolution function. In the second step the parameters of the resolution function were determined together with the global scale p_0. The fitted parameters were found to be stable against further iterations of the maximization procedure.

3 Validation of the results

- data-driven validation of 2012 corrections
- datasets
- definition of eta, pT bins for the different resonances
- description of the functions used for the fits
- smearing of the resolution in the simulation
- results

The corrections computed with MuScleFit were validated by comparing the poistion of pole and the resolution extracted from the spectra of dimuons from three reference resonances: J/ψ, $\Upsilon(1S)$ and Z. The models used to fit the resonances are detailed in Table 2.

4 Study of the systematic uncertainties

The validation procedure described in the previous section is used for estimating the systematic error on the post-correction momentum of the muons.

There are two common use cases for defining a systematic error on the momentum scale:

- *Case I*: analyses where the spectrum in the data is compared with a model known from the simulation. Here the systematic error is indicated by the residual discrepancy between the the post-correction spectrum in the data and in the simulation.
- *Case II*: analyses aiming to perform an absolute measurement of the momentum of the muon, e.g. not relying on a model for the expected spectrum. In this case, values of observables built from the measured momenta, namely invariant masses, differing from standard references are indications of systematic errors.

<u>Case I</u>: We define the systematic error Δp_T related to the remaining discrepancy between the

data and the simulation as:

$$\frac{\Delta p_T}{p_T} = \frac{M_{DATA} - M_{MC}}{M_{DATA}} \tag{3}$$

The above relation between momentum and masses holds under the hypothesis that the systematic errors are fully correlated between the two muons. The fractional difference on the mass is shown as a function of $|\eta|$ of one of the two muons in Figure 1. The fractional differ-

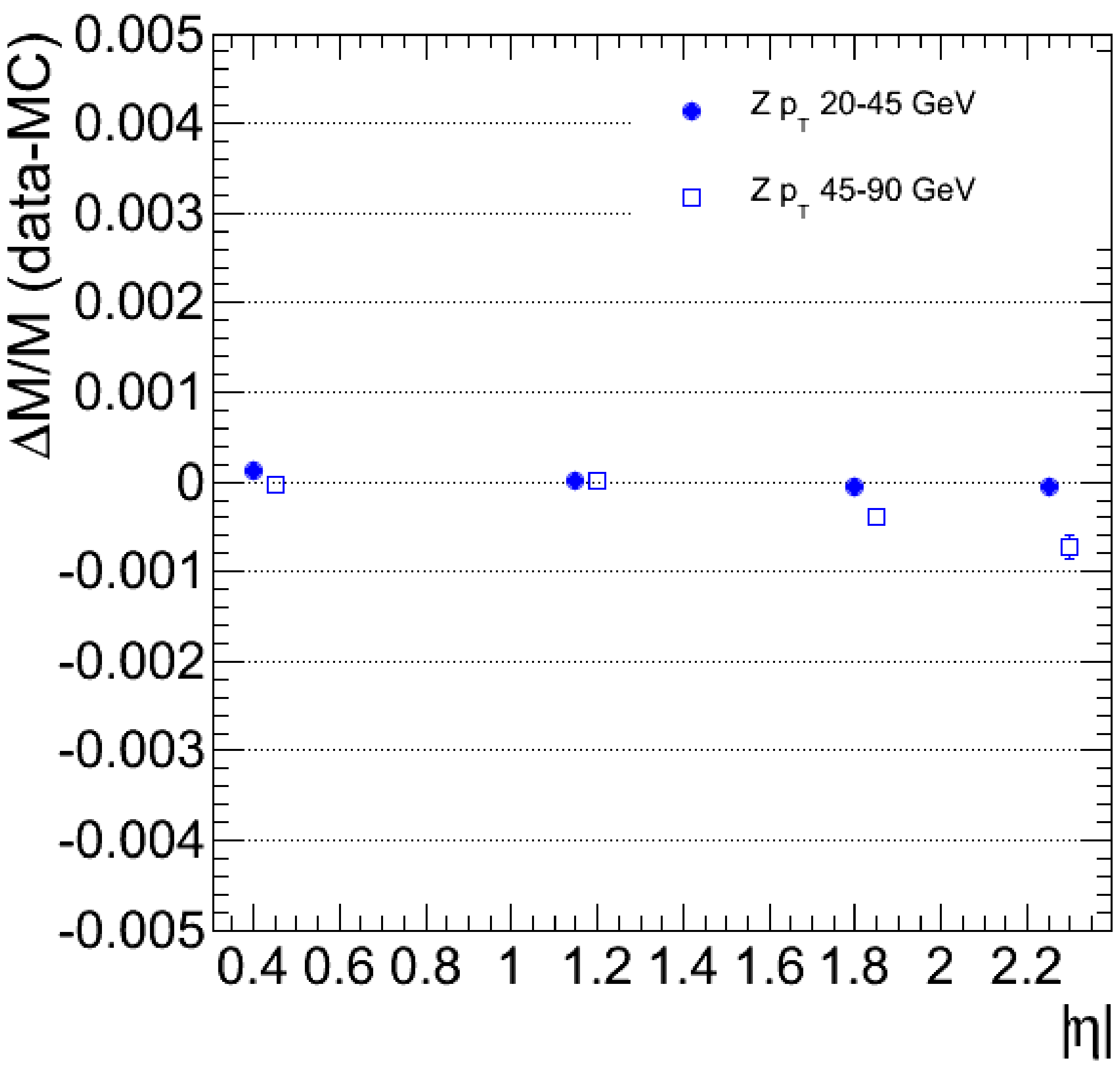

Figure 1: Fractional difference $\frac{M_{DATA}-M_{MC}}{M_{DATA}}$ for dimuons from Z bosons decays as a function of the $|\eta|$ of one the two muons (averaged on the second).

ence is everywhere well within $\pm$0.0010 with the largest value being around -0.0010, for the point in the large $|\eta|$ and p_T bin. Conservatively we assign a $\pm$0.0005 uncertainty everywhere apart from this point where a $\pm$0.0010 uncertainty is assumed.

<u>Case II</u>: The systematic error on p_T has an additional contribution that we evaluate using the simulation where we take as estimator the discrepancy between the values of the mass of the Z

boson extracted from the spectra of the dimuons and the world average reported by the Particle Data Group (PDG) [3]:

$$\frac{\Delta p_T}{p_T} = \frac{M_{MC} - M_{PDG}}{M_{PDG}} \tag{4}$$

The above relation between momentum and masses holds under the hypothesis that the systematic errors are fully correlated between the two muons. We checked the behaviour of the fractional mass difference defined in Eq. 4 against p_T and $|\eta|$ of one of the two muons using simulated events reconstructed in *realistic* conditions. Discrepancies from the PDG values, can orginate from a poor parametrization of the dimuon spectrum or from biases on the muon momentum not entirely corrected by the calibration procedure. Since a not null value of the fractional mass difference will translate directly into the second contribution of the *Case II* error, to disentangle the two effects we used a set of simulated events reconstructed assuming a perfect knowledge of the calibration and alignment conditions, hereafter referred to as *ideal* conditions, but with the same set of dead channels as in real data. Possible biases in the measured momentum due to approximations in the track reconstruction (e.g. mismodelling during the reconstruction of the interaction of the charged particle with the material or with the magnetic field) were the same as in the standard track reconstruction. In this case no corrections were applied to the reconstructed muons. Details on the samples used for this test are given in Table 3. Figure 2 shows the fractional difference on the mass as a function of $|\eta|$ of one of

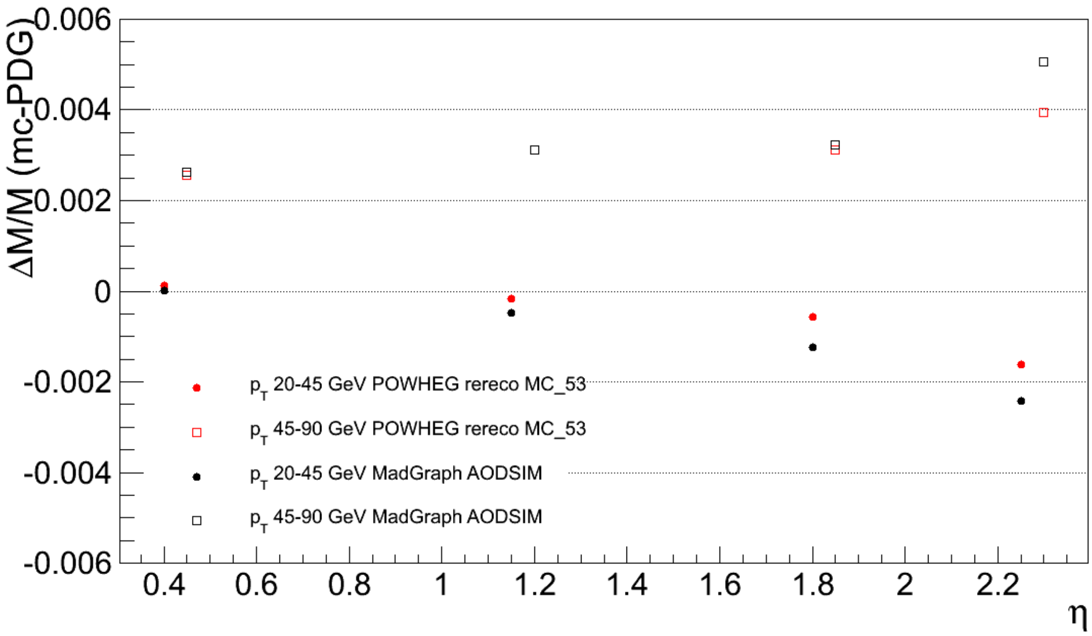

Figure 2: Fractional difference $\frac{M_{MC}-M_{PDG}}{M_{MC}}$ (tbc) for dimuons from Z bosons decays as a function of the $|\eta|$ of one the two muons (averaged on the second).

the two muons in two different ranges of p_T. For p_T in the range [20,45] GeV, values form the realistic simulation (post-correction) are about -0.0005 for $|\eta|$ <1.5 increasing up to -0.0020 at the largest $|\eta|$. A similar trend is observed for points from the simulation in ideal conditions. For p_T in the range [45,90] GeV there is approximately a +0.0020 bias growing up to +0.0050 at the largest $|\eta|$ bin.

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Based on this analysis, the systematic errors estimated for the different p_T and $|\eta|$ ranges are those summarized in Table 4.

References

[1] S. Bolognesi, M. A. Borgia, R. Castello et al., "Calibration of track momentum using dimuon resonances in CMS", CMS Analysis Note 2010/059, (2010).

[2] S. Dittmaier and M. Huber, "Radiative corrections to the neutral-current Drell-Yan process in the Standard Model and its minimal supersymmetric extension", *JHEP* **1001** (2010) 060, doi:10.1007/JHEP01(2010)060, arXiv:0911.2329.

[3] Particle Data Group Collaboration, "Review of Particle Physics (RPP)", *Phys.Rev.* **D86** (2012) 010001, doi:10.1103/PhysRevD.86.010001.

Table 1: Values of the fitted parameters for the scale correction (Eq. 1) for data and simulation samples at 7 TeV and 8 TeV. The five sections in the lower part of the table correspond to the five η bins [-2.4,-2.1], [-2.1,-1.5], [-1.5,+1.5], [+1.5,+2.1] and [+2.1,+2.4]. The values of the b_0 parameters are fixed to guarantee the continuity of the correction function at the boundaries between the η bins.

Sample	2011_DATA_44X	2011_MC_44X	2012ABC_DATA_ReReco_53X	2012D_DATA_ReReco_53X	2012_MC_53X_smearReReco
p_0	-0.00122	0.00000	-0.00139	-0.00135	0.00000
δ	0.00004	0.00004	0.00004	0.00004	0.00005
a_1	0.00080	0.00022	0.00028	0.00025	0.00027
ϕ_1	1.33254	0.28482	1.21602	1.21894	0.14179
a_2	0.00041	0.00030	0.00019	0.00017	0.00023
ϕ_2	1.79848	-1.68476	1.78374	1.93410	-1.71046
b	-0.00013	-0.00007	-0.00004	-0.00005	0.00000
b_0	0.00010	-0.00001	0.00003	0.00004	-0.00002
a_1	0.00009	0.00006	0.00002	0.00000	0.00001
ϕ_1	1.17708	-1.13170	0.26269	0.15297	-1.04015
b	-0.00024	0.00003	-0.00008	-0.00009	0.00004
b_0	-0.00004	0.00000	-0.00002	-0.00002	0.00000
a_1	0.00015	0.00007	0.00007	0.00007	0.00007
ϕ_1	-1.30574	-1.75023	-1.24722	-1.39464	-1.64733
b	0.00003	0.00000	0.00001	0.00001	0.00000
a_1	0.00001	0.00013	0.00002	0.00001	0.00003
ϕ_1	0.89885	-1.40495	0.21788	1.17093	-1.68410
b	-0.00018	0.00000	-0.00003	-0.00003	0.00000
b_0	0.00004	0.00000	0.00002	0.00002	0.00000
a_1	0.00058	0.00014	0.00021	0.00032	0.00018
ϕ_1	1.85334	-1.42615	1.94164	1.89407	-0.94791
a_2	0.00028	0.00001	0.00012	0.00008	0.00012
ϕ_2	-0.84138	0.78290	-1.10183	-1.23759	0.38600
b	-0.00020	-0.00001	-0.00008	-0.00010	0.00000
b_0	-0.00006	0.00000	-0.00001	0.00000	0.00000

Table 2: PDFs

Resonance		Fit Range [GeV]	Signal pdf	Background pdf
J/ψ	DATA	[2.9,3.3]	$CB(x,\mu,\sigma)$	3^{rd} order Bern. pol.
	MC	[2.9,3.3]	$CB(x,\mu,\sigma)$	3^{rd} order Bern. pol.
$\Upsilon(1S)$	DATA	[8.7,11.0]	$CB_{(}x,\mu_1,\sigma) + CB(x,\mu_2,\sigma) + CB(x,\mu_3,\sigma)$	4^{th} order Bern. pol.
	MC	[8.8,10.0]	$CB_{(}x,\mu,\sigma)$	4^{th} order Bern. pol.
Z	DATA	[75,105]	$BW \otimes CB$	$\exp(a_0 + a_1 x + a_2 x^2)$
	MC	[75,105]	$BW \otimes CB$	$\exp(a_0 + a_1 x + a_2 x^2)$

Table 3: Datasets

Dataset	MC generator	Data-Tier	events	Corrections applied
DYJetsToLL	MadGraph	AODSIM	2.95 M	MuScleFit
DYToMuMu	POWHEG	AODSIM	8.60 M	MuScleFit
DYToMuMu	POWHEG	START_53 from RECO	0.59 M	MuScleFit
DYToMuMu	POWHEG	MC_53 from RECO	0.59 M	nocorrections

Table 4: Estimated systematic uncertainties on the momentum scale post-correction of muons reconstructed in the data. Second column corresponds to *Case I* systematics, while the sum of second and third columns corresponds to *Case II* systematics described in the text.

$\frac{\Delta p_T}{p_T}$	MC - PDG	DATA - MC
p_T <45 GeV, 0< $\lvert\eta\rvert$ <1.5	$\pm$0.0005	$\pm$0.0005
p_T <45 GeV, 1.5< $\lvert\eta\rvert$ <2.4	$\pm$0.0020	$\pm$0.0005
p_T >45 GeV, 0< $\lvert\eta\rvert$ <2.0	$\pm$0.0030	$\pm$0.0005
p_T >45 GeV, 2.0< $\lvert\eta\rvert$ <2.4	$\pm$0.0050	$\pm$0.0010