

## Muon detectors at LHC: experience from Run-1 operation and extrapolation to Phase-2

---

**Andrea Alici**

*INFN - Bologna*

*E-mail:* [andrea.alici@bo.infn.it](mailto:andrea.alici@bo.infn.it)

**Davide Boscherini\***

*INFN - Bologna*

*E-mail:* [davide.boscherini@bo.infn.it](mailto:davide.boscherini@bo.infn.it)

**Alessandro Cardini**

*INFN - Cagliari*

*E-mail:* [alessandro.cardini@ca.infn.it](mailto:alessandro.cardini@ca.infn.it)

**Martino Gagliardi**

*Università degli Studi e Sezione INFN Torino*

*E-mail:* [martino.gagliardi@to.infn.it](mailto:martino.gagliardi@to.infn.it)

**Gianni Masetti**

*INFN - Bologna*

*E-mail:* [gianni.masetti@bo.infn.it](mailto:gianni.masetti@bo.infn.it)

**Pierluigi Paolucci**

*INFN - Napoli*

*E-mail:* [pierluigi.paolucci@na.infn.it](mailto:pierluigi.paolucci@na.infn.it)

**Giovanni Passaleva**

*INFN - Firenze*

*E-mail:* [giovanni.passaleva@fi.infn.it](mailto:giovanni.passaleva@fi.infn.it)

**Davide Piccolo**

*INFN - LNF*

*E-mail:* [davide.piccolo@lnf.infn.it](mailto:davide.piccolo@lnf.infn.it)

**Alessandro Polini**

*INFN - Bologna*

*E-mail:* [alessandro.polini@bo.infn.it](mailto:alessandro.polini@bo.infn.it)

The performance of the muon detectors of the four LHC experiments is summarized, together with the main problems they had to face during Run-1. The background conditions expected in the future LHC phases up to HL-LHC have also been extrapolated from Run-1 data taking.

*INFN Workshop on Future Detectors for HL-LHC*

*March 11-13, 2014*

*Trento, Italy*

---

\*Speaker.

## 1. Muon detectors at LHC

The INFN involvement in the muon detectors at LHC is vast, being present with more than one detector in each of the four experiments. Table 1 summarizes the Italian contributions to the muon systems together with some details about the realized detectors.

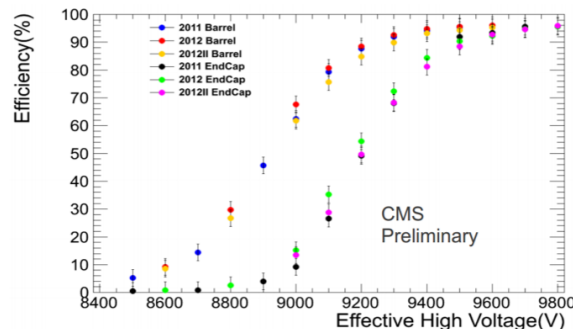
ATLAS		CMS		LHCb		ALICE	
<b>RPC</b>	$ \eta  < 1.05$ 3650 m <sup>2</sup> 370k channels	<b>RPC</b>	$ \eta  < 1.6$ 3000 m <sup>2</sup> 300k channels	<b>MWPC</b>	435 m <sup>2</sup> 122k channels	<b>RPC</b>	$2.5 < \eta < 4$ 144 m <sup>2</sup> 21k channels
<b>MDT</b>	$ \eta  < 2.7$ 5520 m <sup>2</sup> 350k channels	<b>DT</b>	$ \eta  < 1.2$ 1600 m <sup>2</sup> 170k channels	<b>GEM</b>	0.6 m <sup>2</sup> 2.3k channels	<b>CPC</b>	$2.5 < \eta < 4$ 120 m <sup>2</sup> 1000k channels
						<b>MRPC-ToF</b>	$ \eta  < 0.9$ 141 m <sup>2</sup> 153k channels
From 2020							
<b><math>\mu</math>Mega</b>	$1.3 <  \eta  < 2.4$	<b>GEM/RPC</b>	$1.5 <  \eta  < 2.2$				

**Table 1:** Muon detectors in the LHC experiments with INFN involvement. The MRPCs used in the ALICE time-of-flight system are included because of interest in this technology for the muon upgrade. The already planned upgrades for the data taking starting in 2020 are also reported in the last row.

## 2. Experience from Run-1: performance and problems

### 2.1 CMS-RPC

The CMS RPC system has been operated with an efficiency of about 95% at the end of 2012. The implementation of the automatic correction of the HV working point for variations of pressure and temperature has played a fundamental role in stabilizing the performance. Three HV scans, carried out in 2011-2012, have shown a remarkable stability of the working conditions by comparing the HV value at 50% efficiency with the HV value at the working point (see fig. 1) [1].



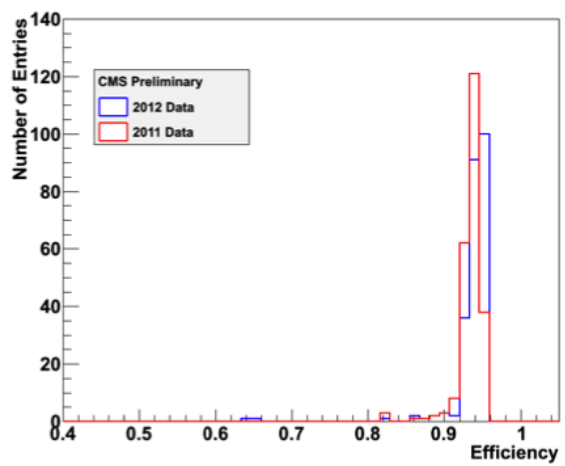
**Figure 1:** HV scans for the CMS RPCs.

The number of dead channels was also kept well under control in the range 2.0-2.5% all over Run-1. The main reasons for dead channels can be summarized as due to noise, electronics problems or HV/LV failures. The failures can be ascribed to chambers with HV off for 1.3%, chambers

operated in single gap mode (instead of double gap mode) for 4.6%, problems with the voltage distribution of the discrimination thresholds for about 1%. Most of the above problems have been fixed during the last long shutdown (LS1). Concerning the gas distribution, leaks caused by fragility in the pipe connections have affected about 0.4% of the chambers, half of them addressed in LS1.

### 2.2 CMS-DT

The CMS Drift Tubes have been operated with 98.5% of active channels at the end of 2012 and a trigger efficiency per chamber of about 93.7% (fig. 2) [2]. Most of the dead channels has

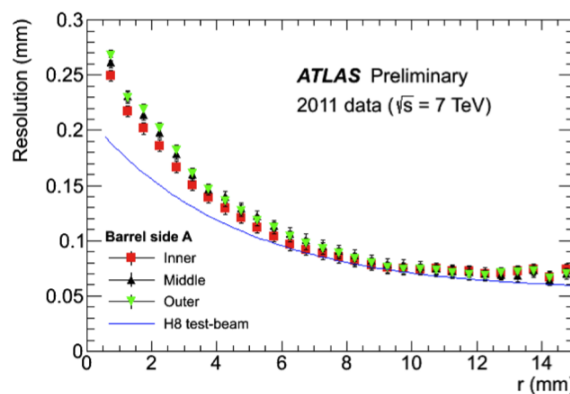


**Figure 2:** Trigger efficiency distribution (per chamber) for the CMS DTs.

been recovered during LS1. No aging effects have been observed up to the end of Run-1.

### 2.3 ATLAS-MDT

The ATLAS Monitored Drift Tubes had quite a successful data taking with an active fraction of readout channels above 99.5% and a good data quality fraction of 99.6%. The spatial resolution was also very similar to the expectations (see fig. 3) [3].

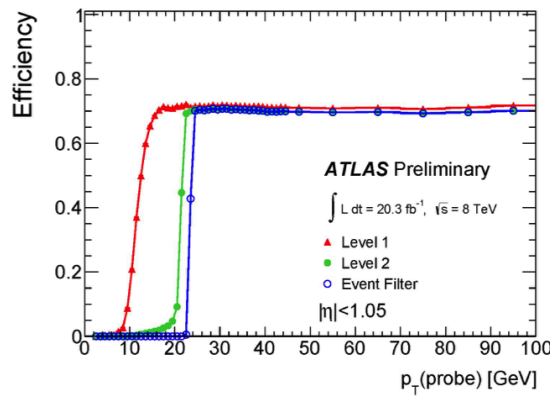


**Figure 3:** Spatial resolution of the ATLAS MDTs as measured in 2011 for the different station types and compared to the test-beam results.

The main problems faced in Run-1 were the gas leaks due to cracks in the jumpers (connection between tubes) periodically repaired in the shutdowns, with no effect on performance, and an unexpected saturation of the TDC buffers on the chambers with higher rates (endcap inner chambers at small radii). The latter issue caused up to 2.5% efficiency loss in the affected chambers and was likely originated from trigger bursts. A few fixes have been proposed and tested during LS1 (data size reduction, buffer clearings, ...).

## 2.4 ATLAS-RPC

The ATLAS RPC system, the only muon trigger source in the barrel region, has been successfully operated during Run-1, with a trigger efficiency reaching the acceptance value (see fig. 4) [4]. The active readout fraction was about 97%, with a good data quality fraction of 99.8%.



**Figure 4:** Efficiency of the three levels of the ATLAS single muon barrel trigger seeded by the RPCs.

The main issues have been the gas leaks due to cracks in the gas nozzles in about 4% of the gas volumes and weak grounding connections in about 6% of the readout panels which required an enhancement of the Faraday cage of the affected chambers. At the end of 2012, 2.5% of the gas volumes were not operated mainly due to gas leaks.

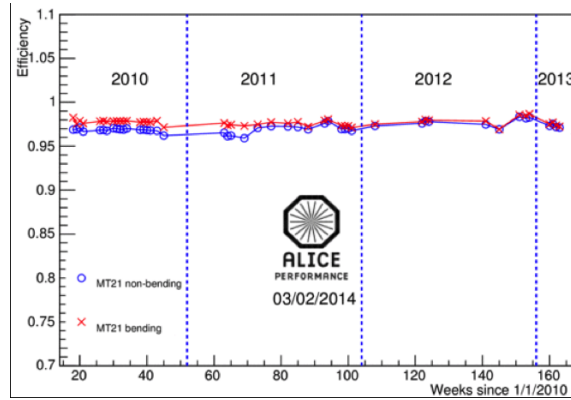
## 2.5 ALICE-RPC

The ALICE muon trigger system, based on bakelite RPCs, have been operated in stable conditions with an efficiency above 95% (fig. 5) [5]. The main issues observed in Run-1 have been an important increase of the dark current on a few chambers not correlated with the integrated charge, and a few problems with the gas tightness due to mechanical stress on in/outlets.

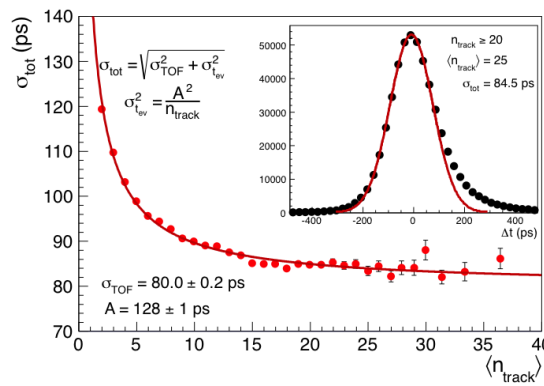
## 2.6 ALICE-MRPC

The ALICE Time-of-flight system, based on multi-gap glass RPCs (MRPCs), has shown very good performance reaching a timing resolution of 80 ps (fig. 6) [6]. It has been included in this study of muon detectors because of a possible interest for a future application in the CMS forward region to exploit its excellent timing for pile-up mitigation.

At the end of Run-1 about 1.6% of MRPCs were off because of HV connector failures. The LV power supplies will be upgraded in LS1 after having exhibited problems due to their operation



**Figure 5:** Efficiency vs time for one of the four ALICE muon trigger stations.

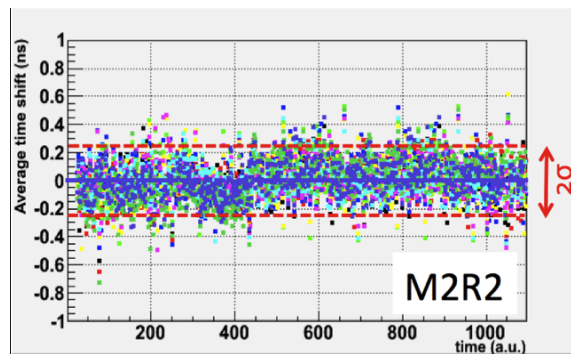


**Figure 6:** Time resolution of the ALICE MRPCs used in the ToF system.

in magnetic field. A few percent of readout channels were also off because of broken or noisy electronics boards.

### 2.7 LHCb-MWPC

The Multi-Wire-Proportional-Chambers have been operated with an efficiency above 99.3% without showing any gain variation (see fig. 7) [7]. The integrated charge has not exceeded 0.05

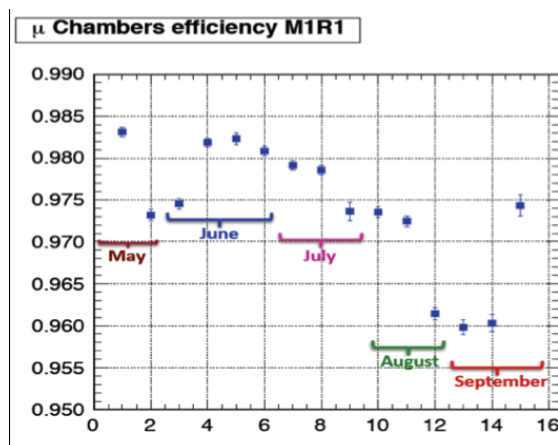


**Figure 7:** Gain variation vs time of an LHCb MWPC for the whole 2011 run period.

C/cm/y (to be compared with the certification value of 0.4 C/cm) with a maximum current  $I_{max}=10$  nA/cm. No major issues were observed in Run-1 and a replacement rate of about 5 MWPCs/year is estimated.

### 2.8 LHCb-GEM

The GEMs have been operated with an efficiency of about 98.7% (fig. 8) up to rates of 0.5 MHz/cm<sup>2</sup>, with a very good stability over the whole 2012 data taking. The integrated charge has not



**Figure 8:** Efficiency of an LHCb GEM chamber over the whole 2012 run period.

exceeded 0.05 C/cm<sup>2</sup>/y (to be compared with the certification value of 1.8 C/cm<sup>2</sup>) with a maximum average current  $\langle I_{max} \rangle = 10$  nA/cm<sup>2</sup>.

After experiencing a few shorts on the detectors, their stability has been improved by equalizing the gain among the three GEM foils with a large reduction of the observed sparks. A CF<sub>4</sub> pollution problem causing gain jumps in correspondence of the bottle change has been observed and reported to the CERN gas group for the required fix.

### 3. Extrapolations up to HL-LHC

The background conditions experienced in Run-1 have been used to extrapolate the running conditions expected in the future LHC running phases up the HL-LHC. The estimates of rates and integrated charges are reported in table 2 for ATLAS [8][9] and CMS, table 3 for ALICE [10], and table 4 for LHCb.

### 4. Conclusions

The muon systems currently used by the LHC experiments have excellently performed during Run-1. The extrapolations from Run-1 to the HL-LHC running conditions indicate that most of the adopted technologies will be able to face the severe background conditions expected in the next years.

However, the RPC aging will exceed the certified values in ATLAS and CMS, whilst in ALICE the upgrade of the front-end-electronics will allow to operate them up to the end of Phase-2. For

POS (IPFD2014) 018

Extrapolation @	ATLAS		CMS	
	RPC (barrel)	MDT (excl. SW)	RPC (endcap)	DT
$\mathcal{L}_{inst}=3 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ $\int \mathcal{L}(t) dt = 500 \text{fb}^{-1}$	120 Hz/cm <sup>2</sup> 60 mC/cm <sup>2</sup>		180 Hz/cm <sup>2</sup> 67 mC/cm <sup>2</sup>	25 Hz/cm <sup>2</sup>
$\mathcal{L}_{inst}=7 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ $\int \mathcal{L}(t) dt = 3000 \text{fb}^{-1}$	280 Hz/cm <sup>2</sup> 360 mC/cm <sup>2</sup>	140 kHz/tube	390 Hz/cm <sup>2</sup> 495 mC/cm <sup>2</sup>	55 Hz/cm <sup>2</sup>
Detector certified for	300 mC/cm <sup>2</sup>		100 mC/cm <sup>2</sup>	

**Table 2:** Extrapolated rates and integrated charges for the most exposed regions of the ATLAS and CMS muon detectors, in the phase-1 and phase-2 expected scenarios.

Extrapolation @	ALICE	
	RPC	MRPC
Pb-Pb at $\mathcal{L}_{inst}=6.5 \cdot 10^{27} \text{cm}^{-2} \text{s}^{-1}$	55 Hz/cm <sup>2</sup>	105 Hz/cm <sup>2</sup>
p-p at $\mathcal{L}_{inst}=10^{31} \text{cm}^{-2} \text{s}^{-1}$	15 Hz/cm <sup>2</sup>	26 Hz/cm <sup>2</sup>
End of Phase-1	290 Mhits/cm <sup>2</sup>	1.9 mC/cm <sup>2</sup>
End of Phase-2	500 Mhits/cm <sup>2</sup>	2.8 mC/cm <sup>2</sup>
Detector certified for	~ 500 Mhits/cm <sup>2</sup> (without FEE upgrade)	~ 10 mC/cm <sup>2</sup>

**Table 3:** Extrapolated rates for the most exposed regions of the ALICE muon and time-of-flight detectors, in the phase-1 and phase-2 expected scenarios.

Extrapolation @	LHCb	
	MWPC	GEM
$\mathcal{L}_{inst}=4 \cdot 10^{32} \text{cm}^{-2} \text{s}^{-1}$	0.05 C/cm/y	0.05 C/cm <sup>2</sup> /y
$\mathcal{L}_{inst}=2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$	0.20 C/cm/y	0.25 C/cm <sup>2</sup> /y
Detector certified for	~ 0.4 C/cm	~ 1.8 C/cm <sup>2</sup>

**Table 4:** Integrated charges for the most exposed regions of the LHCb muon detectors, extrapolated at the phase-1 and phase-2 expected scenarios.

ATLAS and CMS, further irradiation tests are envisaged, together with a strategy for operating the current RPC systems in safer conditions.

The MWPCs in LHCb will also exceed the certified aging values; a possible replacement with GEMs is being considered.

## References

- [1] CMS Collaboration, *The performance of the CMS muon detector in proton-proton collisions at  $\sqrt{s} = 7 \text{ TeV}$  at the LHC*, 2013, JINST 8 P11002, <http://inspirehep.net/record/1240504>
- [2] CMS Collaboration, *Muon DPG (DT/CSC/RPC) Approved Results*, <https://twiki.cern.ch/twiki/bin/view/CMSPublic/MuonDPGResults>
- [3] Iodice M., Pontecorvo L. for the ATLAS Collaboration, *MDT resolution plots*, 2011, ATLAS-PLOT-MUON-2011-006, <http://atlas.web.cern.ch/Atlas/GROUPS/MUON/PLOTS/ATLAS-PLOT-MUON-2011-006/>
- [4] ATLAS Collaboration, *Performance of the ATLAS muon trigger in pp collisions at  $\sqrt{s}=8 \text{ TeV}$* , 2014, arXiv:1408.3179

- [5] M. Fontana for the ALICE Collaboration, *Performance of the ALICE muon trigger RPCs during LHC Run I*, 2014, JINST 9 C08019
- [6] Akindinov A., Alici A., Agostinelli A. et al. *Performance of the ALICE Time-Of-Flight detector at the LHC*, 2013, Eur. Phys. J. Plus 128: 44
- [7] LHCb Collaboration, *LHCb Detector Performance*, 2014, <https://cds.cern.ch/record/1978280/files/arXiv:1412.6352.pdf>
- [8] ATLAS Collaboration, *Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment*, 2012, <https://cds.cern.ch/record/1502664>
- [9] Aielli G., Boscherini D., Polini A. for the ATLAS Collaboration, *RPC Cavern Background Plots*, 2014, <https://cds.cern.ch/record/1753443?>
- [10] B. Joly et al. for the ALICE Collaboration, *Upgrade of the ALICE muon trigger electronics*, 2014, JINST 9 C09013