Experience from RUN 1 operation: extrapolation to Phase-2

Report from the Muon WG1:

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Outline

- Status of muon detectors in CMS/ATLAS/LHCb/ALICE
- Performance in Run-1
- Problems faced in Run-1
- Extrapolations to HL-LHC running conditions
- Conclusions and perspectives towards HL-HLC

IFD2014 - Trento, 11-13/03/2014

Overview of the italian involvement in muons

Major achievements

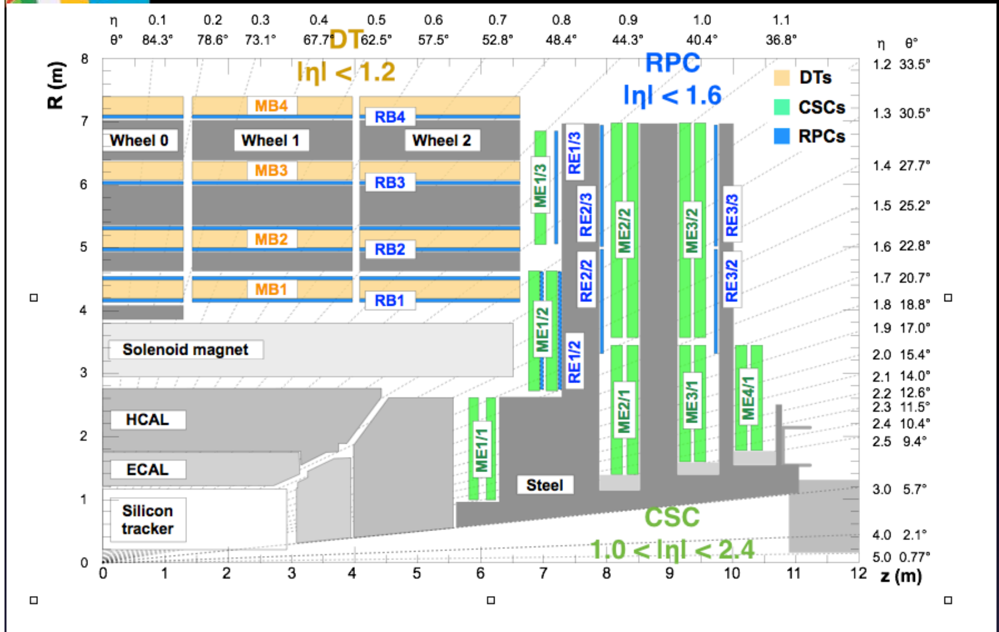
Fundamental contributions of the “italian” muon detectors to the LHC experiments, f.i. ATLAS/CMS Higgs discovery

Muon detectors at the LHC experiments with INFN involvement

ATLAS		CMS		LHCb		ALICE	
RPC	$\|\eta\|<1.05$ $3650\ m^2$ 370k channels	**RPC**	$\|\eta\|<1.6$ $3000\ m^2$ 300k channels	**MWPC**	$435\ m^2$ 122k channels	**RPC**	$2.5<\eta<4$ $144\ m^2$ 21k channels
MDT	$\|\eta\|<2.7$ $5520\ m^2$ 350k channels	**DT**	$\|\eta\|<1.2$ $1600 m^2$ 170k channels	**GEM**	$0.6\ m^2$ 2.3k channels	**CPC** (MWPC)	$2.5<\eta<4$ $120\ m^2$ 1000k channels
		Not a muon detector → *but interesting for future use in muons*				**MRPC-ToF**	$\|\eta\|<0.9$ $141\ m^2$ 153k channels
From 2018							
µMega	$1.3<\|\eta\|<2.4$	GEM/ RPC	$1.5<\|\eta\|<2.2$	*← See next presentation*			

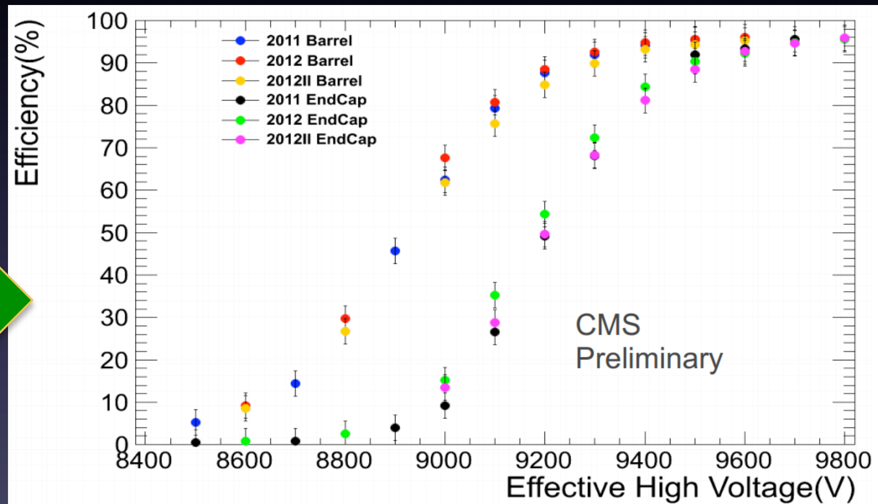
Definitions used in the following text/presentations:
Phase-1 = until LS3
Phase-2 = HL-LHC = after LS3

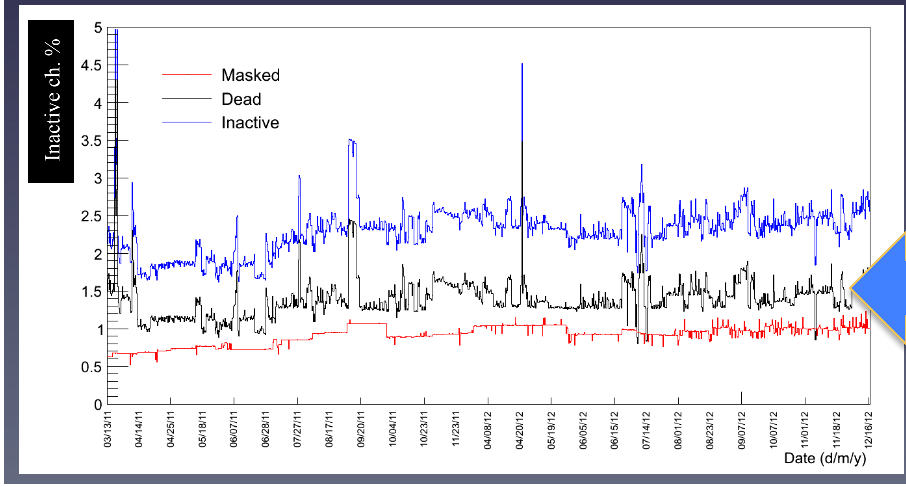
CMS muon system: RPC performance



RPC efficiency ~95% at the end of the 2012
Automatic working point correction versus P/T was fundamental to stabilize the performance

Three HV scans between 2011 and 2012.
Very stable results ($HV_{50\%}$ - HV_{WP})

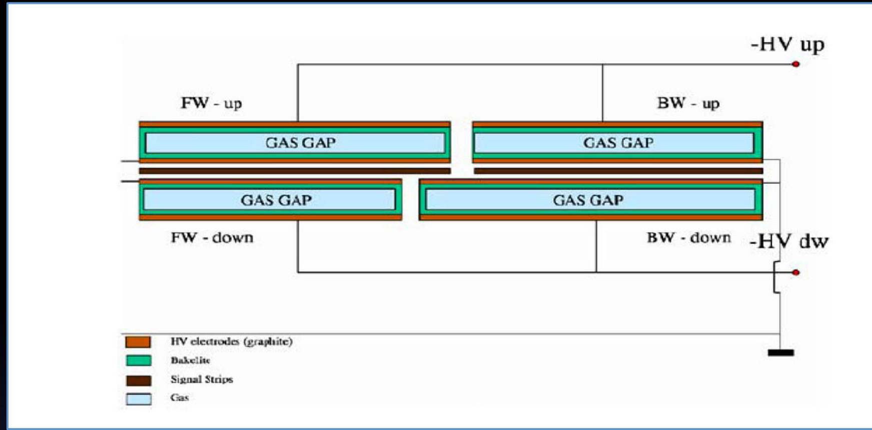




Number of “disconnected” channels was stable between 2 and 2.5 % (noisy channels, electronics problem and HV/LV off channels)

RPC hardware failures during the 2010-2012

RPC system made of chambers with double gaps and a readout panel in between



HV/LV failures:

- 1.3% of chambers OFF at the end of 2012
- 4.6% operated in single gap mode

All repaired during LS1(2013-2014)

Gas Leaks: T and inlet connection fragility

- 16 leaky chambers found in half barrel
  8 successfully repaired
- T connection is the most delicate component
  (used only in barrel)

Total failure of 0.4%

Distribution board and Threshold setting:

~1 % of channels masked for THR

Improved version of distribution board has been installed in the 14 "broken" chambers (3.8%)

Need new $C_2H_2F_4$-less gas: R&D mandatory

CMS RPC extrapolations for phase-1 and phase-2

8 TeV **End of Run 2012**	**Max Barrel rate (Hz/cm²)**	**Max Endcap rate (Hz/cm²)**	**Max Barrel integrated charge (C/cm²)**	**Max Endcap integrated charge (C/cm²)**
$L_{ist} = 0.7 * 10^{34}$ $cm^{-2}s^{-1}$ $L_{int} = 27$ fb^{-1}	~10 Hz/cm²	~30 Hz/cm² (|η| ~ 1.6)	~1 mC/cm²	~ 3 mC/cm²

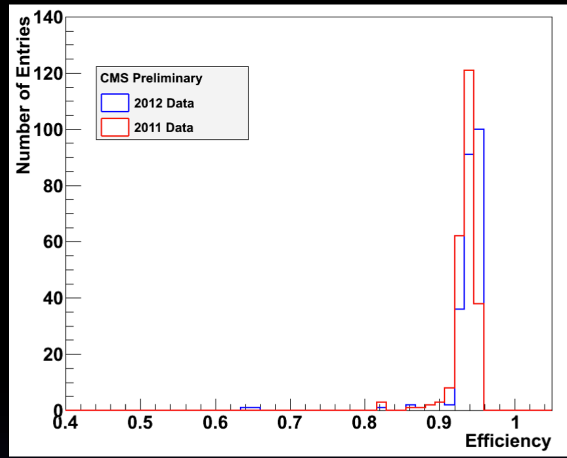
14 TeV **(x1.5 wrt 8 TeV)** **Extrapolation @**	**Max Barrel rate (Hz/cm²)**	**Max Endcap rate (Hz/cm²)**	**Max Barrel integrated charge (C/cm²)**	**Max Endcap integrated charge (C/cm²)**
$L = 3 * 10^{34}$ $cm^{-2}s^{-1}$ Lint = 400 fb^{-1}	~64 Hz/cm²	~180 Hz/cm² (|η| ~ 1.6)	~22 mC/cm²	~67 mC/cm²
$L = 7 * 10^{34}$ $cm^{-2}s^{-1}$ Lint = 3000 fb^{-1}	~150 Hz/cm²	~390 Hz/cm² (|η| ~ 1.6)	~165 mC/cm²	~495 mC/cm²

Aging qualification tests for an integrated charge of **100 mC/cm²**
Both in barrel and endcap chambers the extrapolation to phase-2 exceeds the qualification value

- CMS is studying the possibility to extend the endcap muon region up to η = 2.5
- The two internal disks will be equipped with GEM and the two external with RPC (bakelite or glass)
- The rate will be up to 1 kHz/cm²

CMS: DT performance

CMS – DT:
98.5% active channels at end of 2012
Most of dead channels recovered during LS1



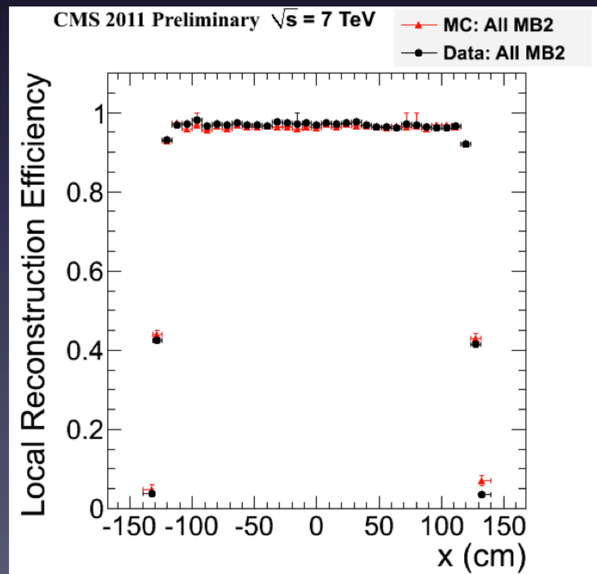
Drift Tubes Local Trigger efficiency / chamber
<efficiency>: 93.5% (2011), 93.7% (2012)

Chambers:
No aging effect observed
No problem expected in chambers or FE electronics at HL-LHC

On-detector electronics:
Irradiation tests needed to qualify for HL-LHC
Access possible only in long shutdowns

Readout electronics
L1 rate limit for the read-out electronics ~300-500 kHz.
New RO boards needed if rate is increased to 500-1000 kHz
Redesign part of the on-detector electronics and move it to radiation-free environment.

R&D needs to start soon in order to be ready for phase-2



Segment reconstruction efficiency measured with the tag-and-probe method on a $Z \rightarrow \mu\mu$ sample

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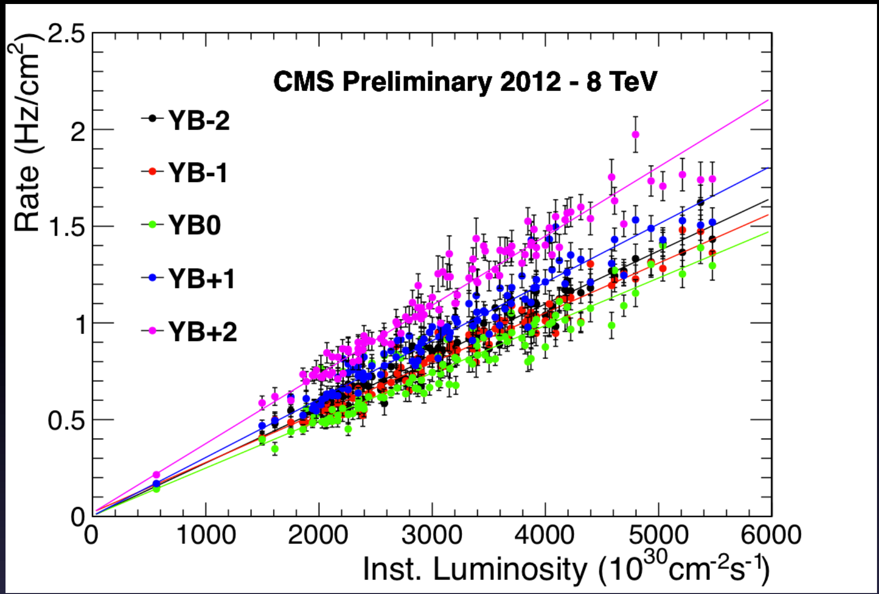
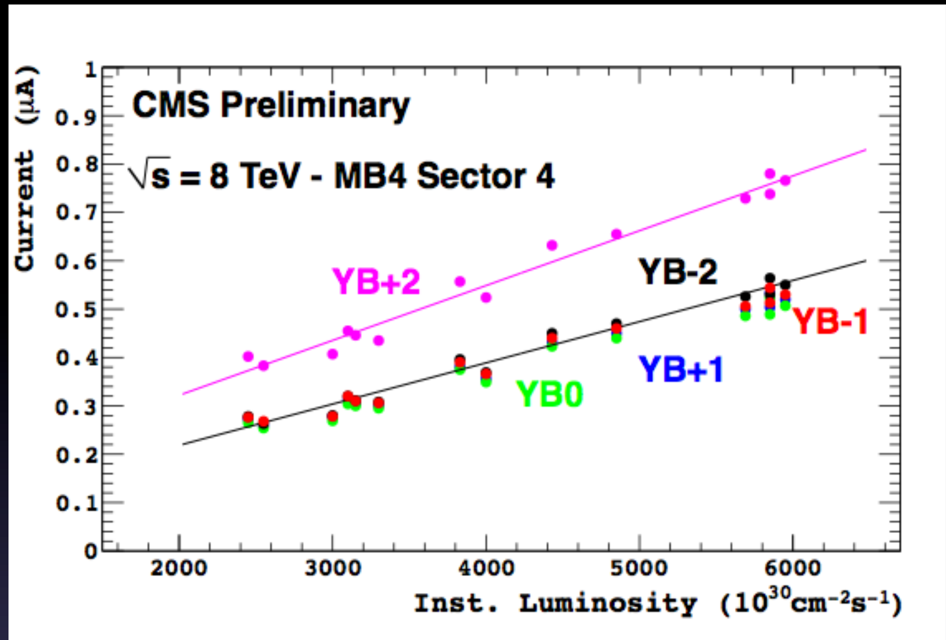
CMS: DT rates VS luminosity



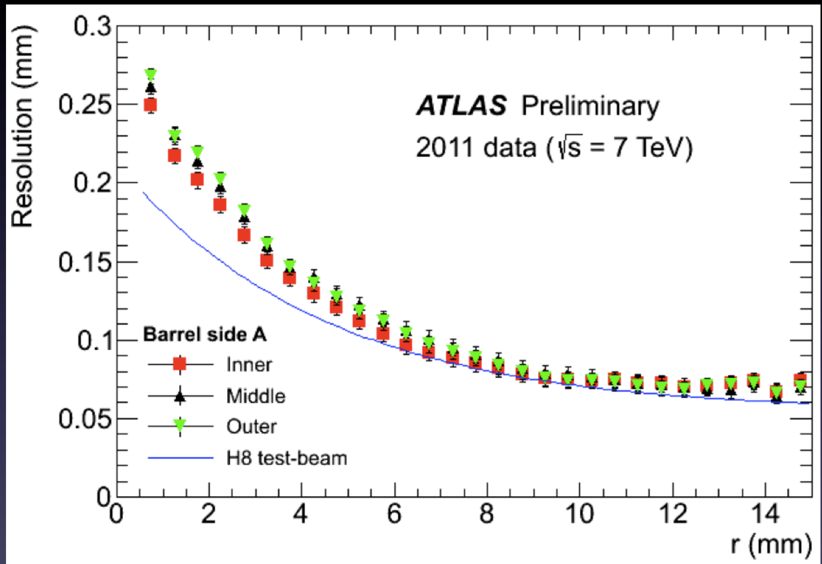


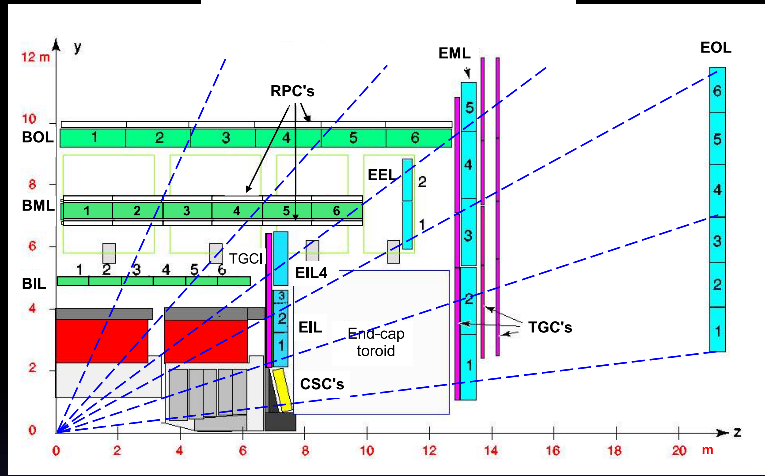
With a linear extrapolation, the expected maximum background rate will not exceed 5 Hz/cm^2 at $L = 10^{34}\ cm^{-2}s^{-1}$ and E_{cm}= 8 TeV (or 8 Hz/cm^2 at E_{cm}= 14 TeV)

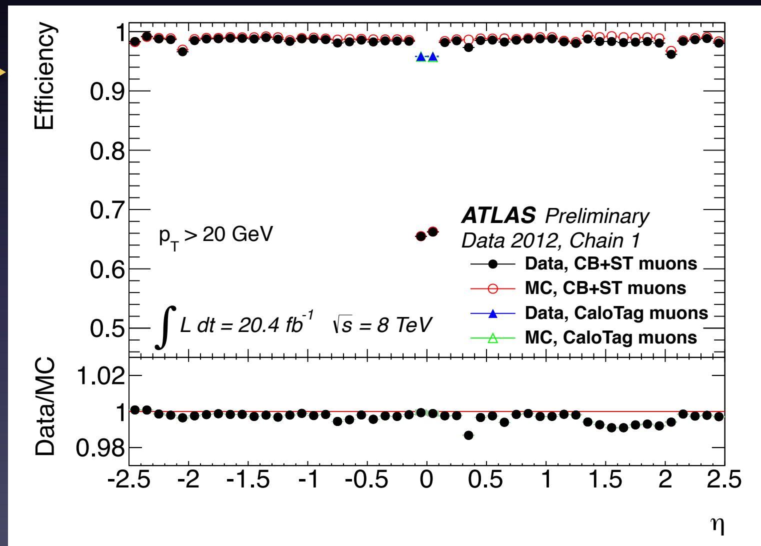
ATLAS MDT experience in Run-1

MDT (BARREL+ENDCAP)

- Good data quality fraction: 99.6%
- Active fraction of readout channels: >99.5%
- High reconstruction efficiency
- Spatial resolution as expected







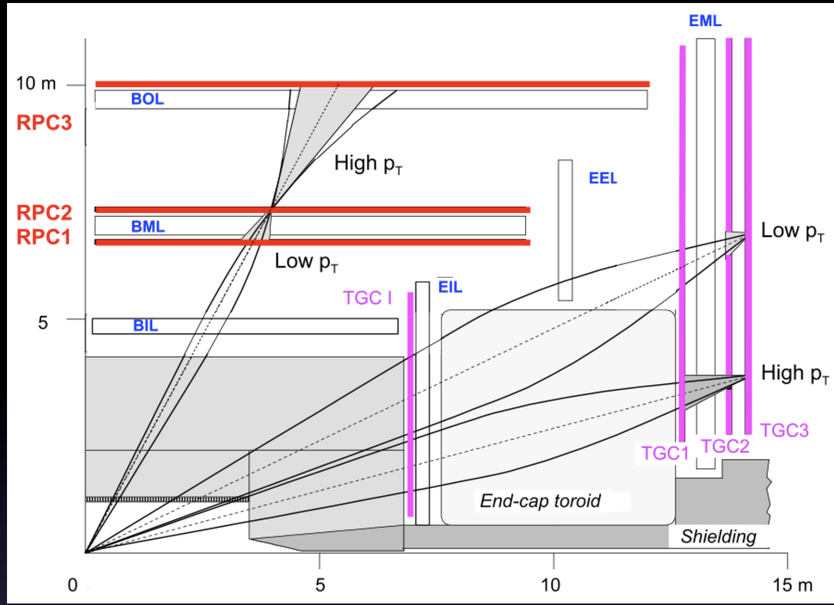
MDT problems

- gas leaks from jumpers (connection between tubes) in EO chambers
  periodically repaired during shutdowns, no effect on performance
- unexpected saturation of the TDC buffers on endcap inner chambers at small radii
  probably due to trigger bursts, reproduced in lab and few solutions proposed
  2.5% efficiency loss in EI chambers

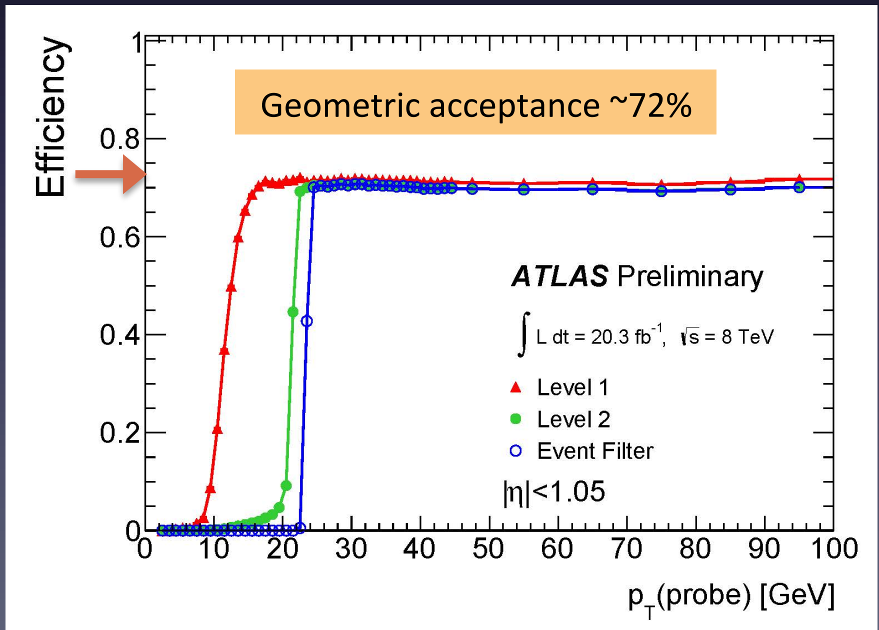
ATLAS RPC system: description and performance

RPC system (barrel region of ATLAS)

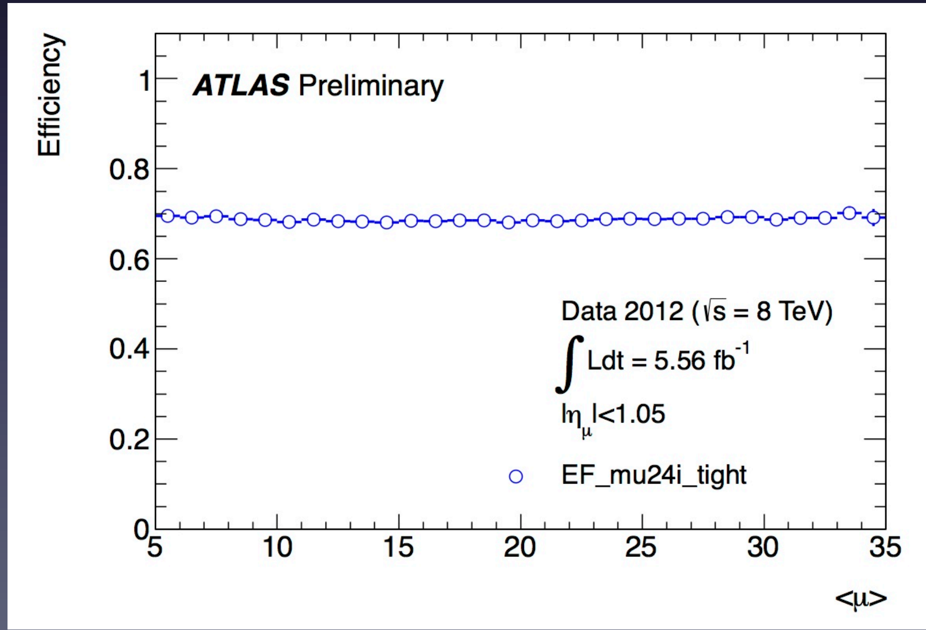
- 3 double layers of 2mm gas gaps (plastic laminate) operated in avalanche mode



Exclusive LVL1 muon trigger for the barrel region and measurement of non-bending coordinate



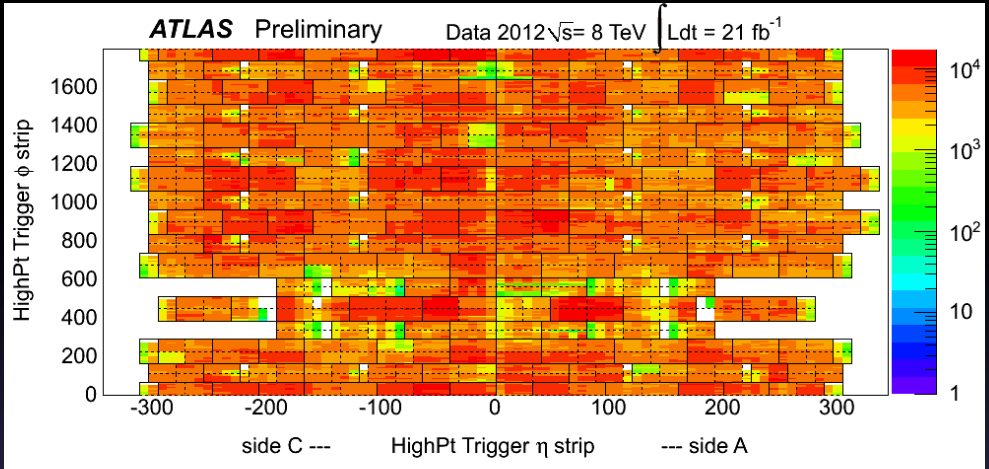
barrel muon trigger efficiency VS p_T



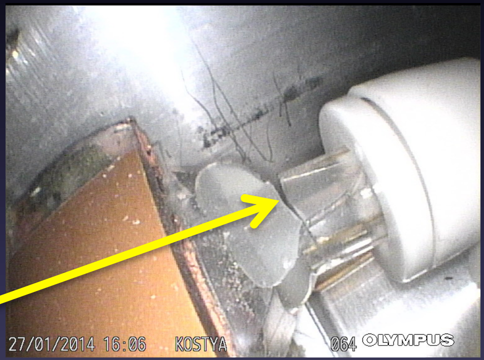
barrel muon trigger efficiency VS pile-up

ATLAS RPC experience in Run-1

Stable running with **99.8% of good data fraction**
Active readout fraction ~97% over the entire Run-1



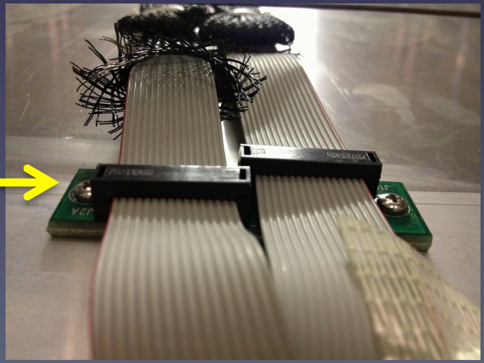
$\eta - \phi$ spatial coincidence for the high-p_T triggers integrated over the full 2012 data sample



RPC operational issues

- **gas leaks in 4% of volumes**
  due to mechanical stress induced by piping on gas inlets
  repair campaign ongoing

- **weak grounding connection** affecting ~6% of readout panels
  → enhancement of Faraday cage

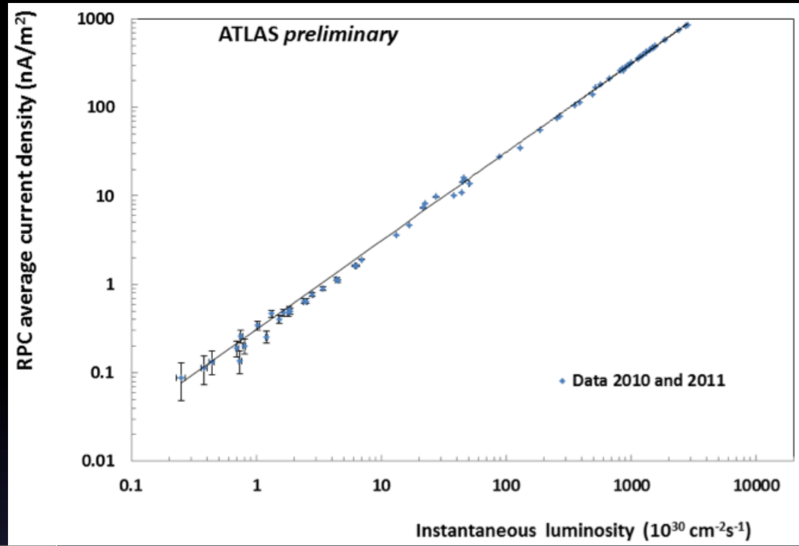


- **2.5% of gas volumes disconnected** at the end of 2012 due to
  gas leaks (mainly), high gap currents

ATLAS RPC expected rates at L=10^{34} cm^{-2}s^{-1}

Measured correlation of RPC current with luminosity

Linear correlation observed
over a few orders of magnitude



ATLAS RPC BM extrapolated average rate density — RPC unit Id. along Z direction — *ATLAS preliminary*

Sector Φ Id.	-7	-6.2	-6.1	-5	-4	-3.2	-3.1	-2.2	-2.1	-1.2	-1.1	01.01	01.02	02.01	02.02	03.01	03.02	4	5	06.01	06.02	7	Average (Hz/cm²)
01.01	40	42	37	36	29	19	14	17	13		9	8	9	14	15	16	18	26	36	34	36	30	23
01.02		38	35	38	28	21	16	18	16		10	9	10	15	17	17	19	28	40	35	39	38	24
2		16	26	24	18	14	12	10	9	7	7	6	7	9	10	13	12	18	26	25	21		15
03.01		37	37	38	26	18	16	15	14	9	9	9	10	16	16	16	17	26	38	34	36		23
03.02		38	36	39	27	19	16	18	15	11	10	10	9	16	17	19	19	26	38	33	37		23
4		14	23	23	20	14	12	9	10	7	7	6	7	10	10	12	14	20	24	23	20		15
05.01	35	27	27	32	21	13	13	16	15	9	9	9	10	15	20	13	15	22	31	24	24	27	19
05.02		29	29	28	18	14	15	16	16	10	8	9	10	14	16	13	16	21	29	32	32		19
6		16	24	25	19	13	12	11	11	8	7	6	8	10	10	12	14	21	24	26	22		15
07.01	34	37	34	35	25	21	17	16	15		10	10		15	18	16	20	24	35	34	37	32	24
07.02		40	33	30	16	18	14	16	13		10	10		13	16	15	20	15	39	35	32	36	21
8		15	25	24	20	13	11	10	9	7	7	6	7	8	9	11	14	20	24	24	22		15
09.01	28	39	32	37	26	20	15	17	14		7	9		13	16	16	18	25	35	34	36	28	23
09.02		40	33	35	25	19	14	14	13		8	10		13	14	13	18	24	35	32	35		22
10		16	26	26	18	11	11	9	9	6	6	5	7	9	9	10	11	18	24	25	23		14
11.01	29	37	31	30	20	14	11	12	10		6	5		10	11	12	13	19	29	28	33	22	18
11.02		25	23	20	14	11	9	7	7		5	5		7	8	8	10	13	19	21	23	32	13
12						14	13	10	9	6	5	5	6	9	11	13	14						9
13.01	40	37	34	30		17	13	12	11	6	6	6	7	11	12	11	16		30	33	37	30	19
13.02		37	33	28		14	12	13	11	6	7	7	7	12	13	12	15		27	29	35	31	18
14						15	18	10	8	6	5	5	6	8	10	17	15						10
15.01	25	23	25	19	14	11	9	9	7		5	5		7	8	10	12	14	19	22	23	24	13
15.02	34	24	21	31	20	16	12	13	10		6	6		10	13	14	15	20	31	24	27		18
16		16	27	27	21	13	11	8	9	8	7	7	7	9	8	11	13	21	26	26	21		15
Average (Hz/cm²)	34	25	29	29	21	15	13	12	11	7	7	7	8	11	12	13	15	21	29	28	28	29	17

RPC rates @ L= 1×10^{34} cm^{-2}s^{-1}, E_{cm}=13TeV
(extrapolation from 0.6×10^{34} cm^{-2}s^{-1}, E_{cm}=8TeV)
<rate>= 17 Hz/cm², rate$_{max}$= 40 Hz/cm²

Integrated charge at the end of Run-1:
<Q> = ~1 mC/cm², Q_{max} = ~3 mC/cm²

ATLAS extrapolations for phase-1 and phase-2

Rates and integrated charges in the **RPCs**

	Average rate (Hz/cm²)	Max rate (Hz/cm²)	Average integrated charge (mC/cm²)	Max integrated charge (mC/cm²)
Extrapolation @ L = 3 * 10^{34} $cm^{-2}s^{-1}$ Lint = 400 fb^{-1}	~50	~120 ($\lvert\eta\rvert$ ~ 1.0)	~20	~50
Extrapolation @ L = 7 * 10^{34} $cm^{-2}s^{-1}$ Lint = 3000 fb^{-1}	~120	~280 ($\lvert\eta\rvert$ ~ 1.0)	~150	~360

Aging qualification tests for 100 Hz/cm² for 10-year LHC running and an integrated charge of **300 mC/cm²**

In most exposed RPC chambers the extrapolation to phase-2 exceeds the qualification value

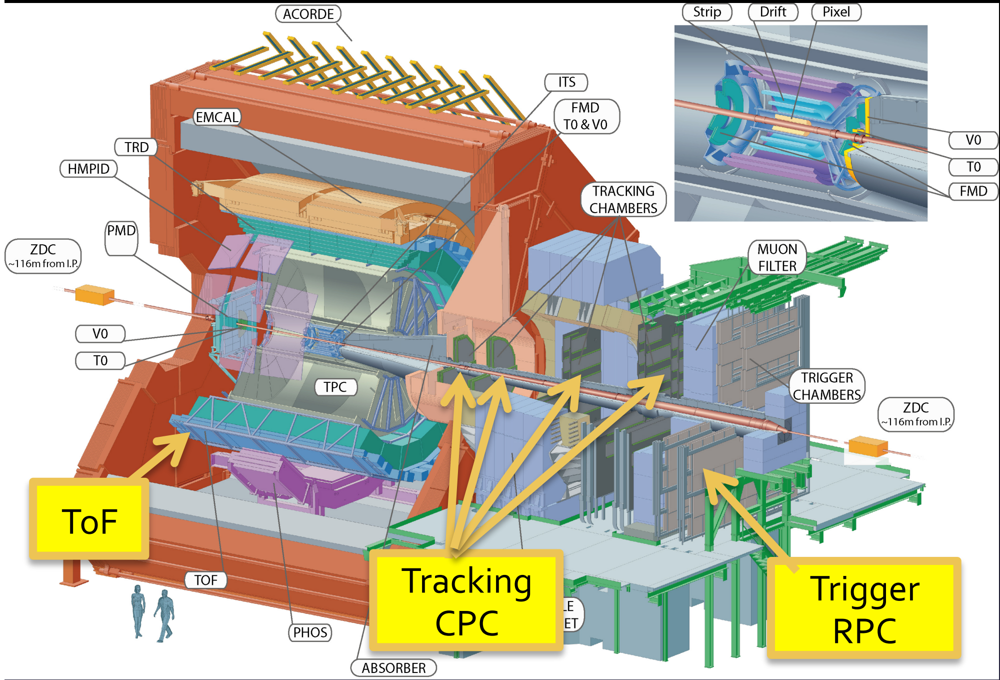
→ lower HV with lower FE thresholds + improve gas flow distribution + proposal to equip the inner barrel layer with RPCs is under discussion

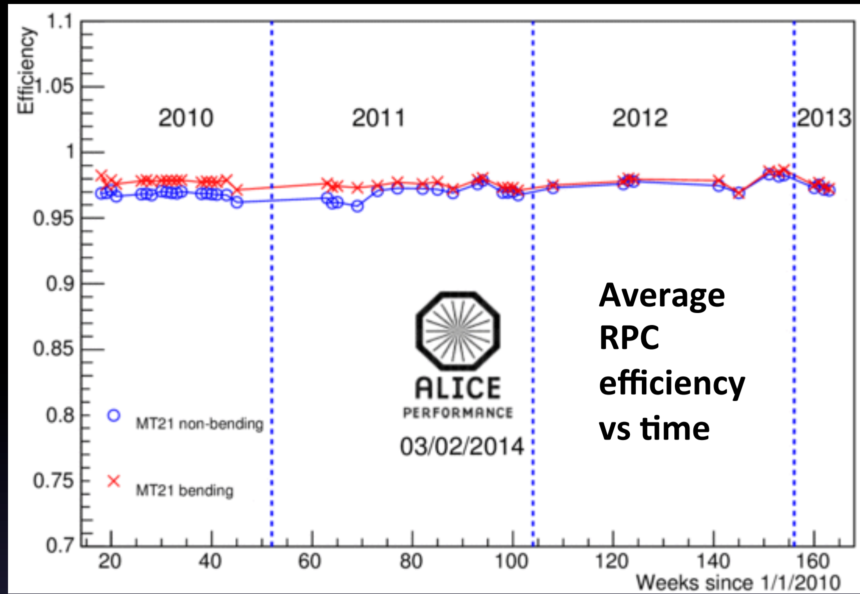
Rates and performance of **MDTs** chambers at L=7 x 10^{34} $cm^{-2}s^{-1}$ (extrapolated from data)

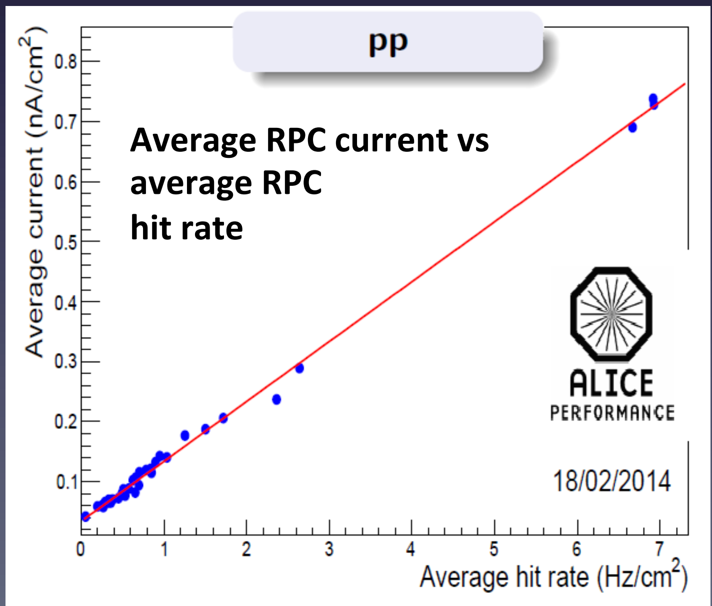
All MDT rates at acceptable levels

MDT tube location	Tube length	Expected hit rate	Hit rate / tube	Occup-ancy	Tube eff.	Link sat. @200kHz	Buf. occ. @25μs absol.	Buf. occ. @25μs relative
		Hz/cm^2	kHz	%	%	%		%
BW, inn	150	273	123	9	91	75	147	58
BW, mid	240	196	141	11	90	82	169	66
BW, out	430	91	117	9	92	73	141	55
OW, inn	202	70	42	3	97	45	51	20
OW, mid	298	56	50	4	96	48	60	23
OW, out	500	42	63	5	95	53	76	30
BI	260	105	82	6	94	60	98	38
BM	353	98	104	8	93	68	125	49
BO	494	63	93	7	93	65	112	44

ALICE muon trigger (bakelite RPCs): performance and issues







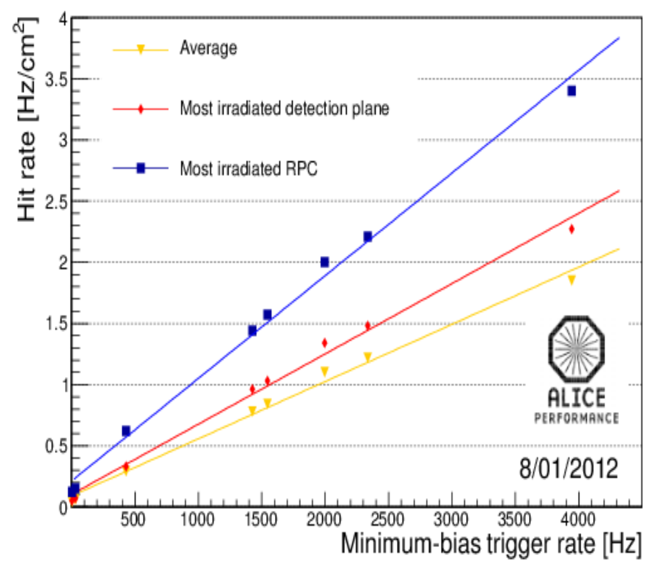
Performance:

- Efficiency: stable and uniform (>95%)
- Cluster size and dark current stable

Issues:

- Important increase of dark current on few chambers not correlated with integrated charge
- Few problems with gas tightness (mechanical stress on beaks at in/outlets)

ALICE muon trigger (bakelite RPCs): extrapolation to Run 2, 3 and 4



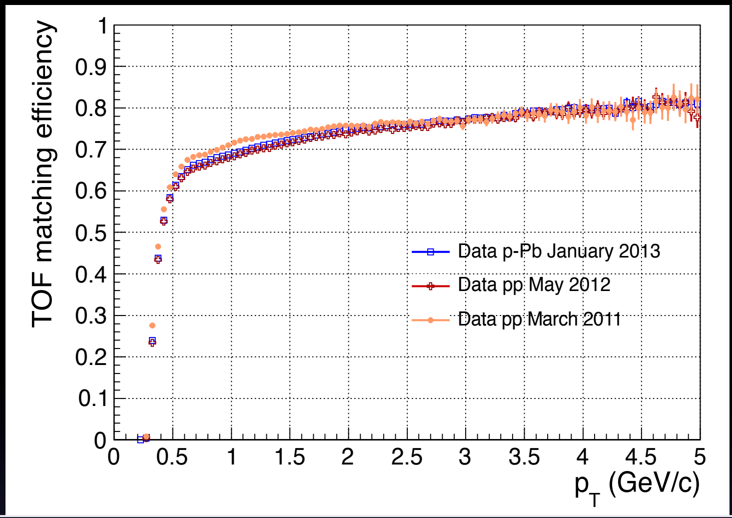
Based on the measured correlation between luminosity and counting rate (extrapolation + energy rescaling)

	Average rate or Average integrated hits (charge)	**Max rate or Max integrated hits (charge)**	**Rate capability or Certified integrated hits (charge)**
Pb-Pb at $L_{inst} = 6.5 * 10^{27}\ cm^{-2}s^{-1}$	30 Hz/cm²	55 Hz/cm²	~60 Hz/cm²
p-p at $L_{inst} = 10^{31}\ cm^{-2}s^{-1}$	9 Hz/cm²	15 Hz/cm²	~60 Hz/cm²
End of Run 2	165 Mhits/cm² (17 mC/cm²)	290 Mhits/cm² (29 mC/cm²)	~500 Mhits/cm² (~50 mC/cm²)
End of Run 4	300 Mhits/cm²	500 Mhits/cm²	~500 Mhits/cm² (~50 mC/cm²)

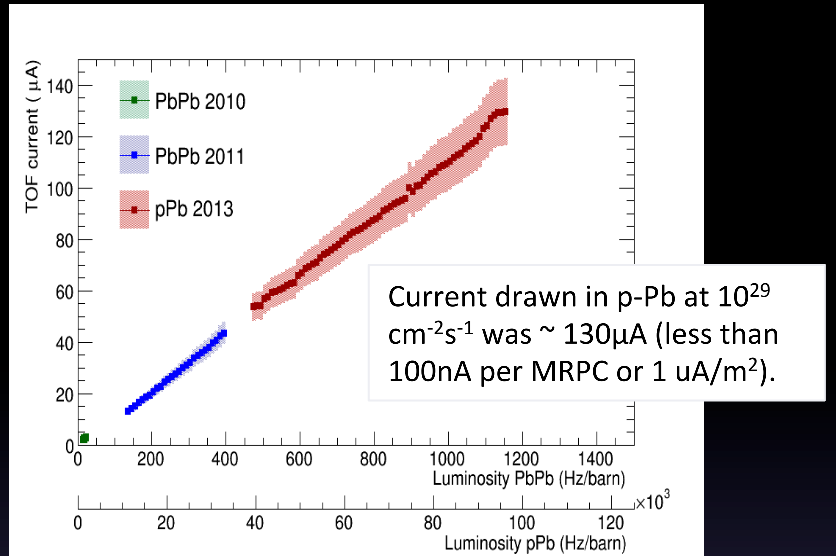
Operation in Run 3 and Run 4 at limit of detector capabilities

→ upgrade FEE electronics to change running mode (now maxi avalanche, charge/hit ~100 pC)

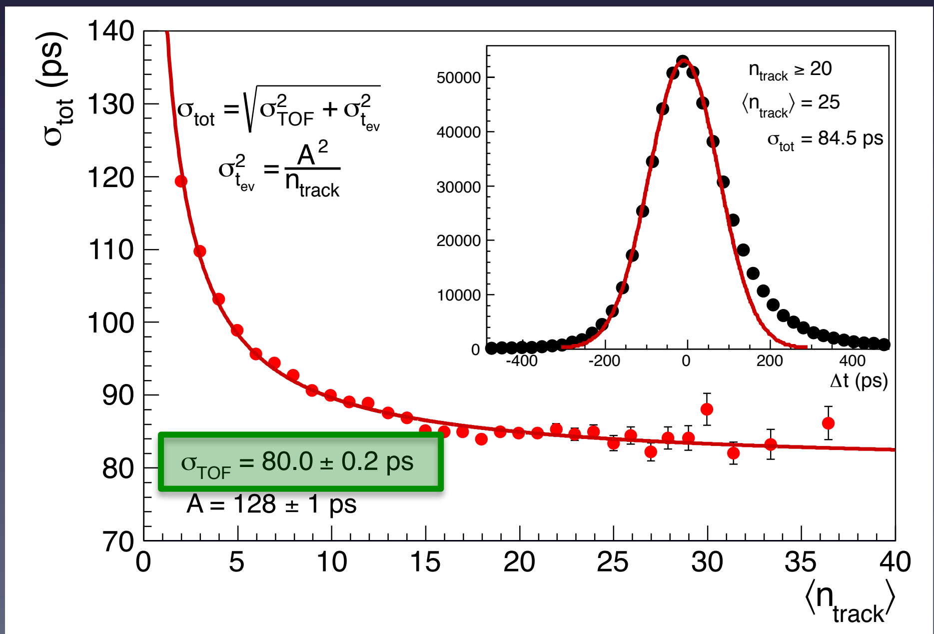
ALICE TOF (glass MRPCs): performance and issues



TOF matching efficiency wrt reconstructed tracks as expected and stable throughout the years



Linear increase of MRPC current with luminosity
No anomalies due to abnormal noise



Performance:

- Excellent timing resolution: **80 ps** considered for pile-up mitigation

Issues:

- **1.6%** of MRPCs OFF at end of Run 1 due to HV connector failures
- Troubles with LV power supplies in B-field Upgraded with new design validated in 2012
- Few % of readout channels OFF due to broken or noisy readout electronics boards

NO UPGRADE FORESEEN

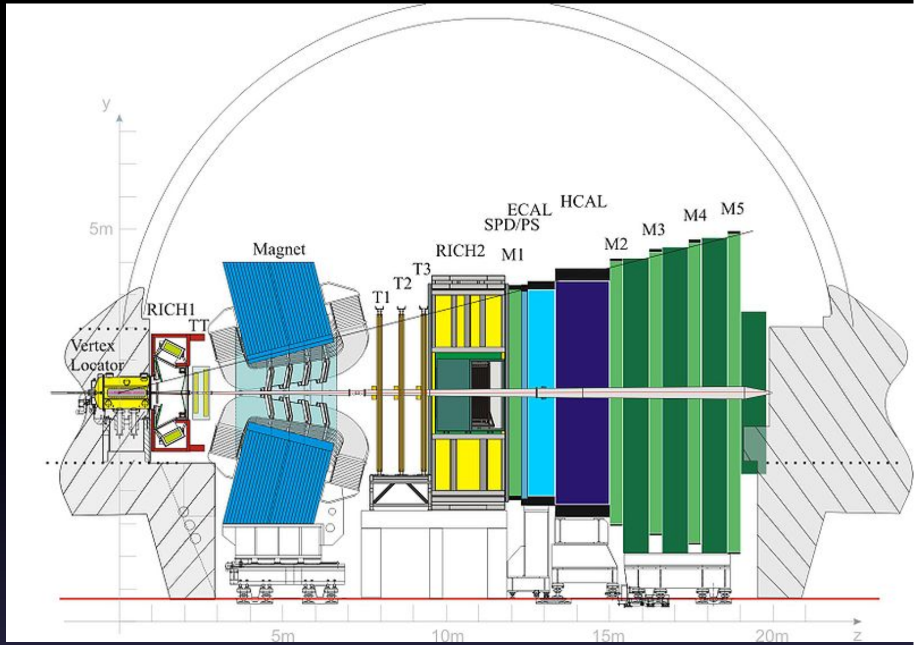
LHCb Muon System

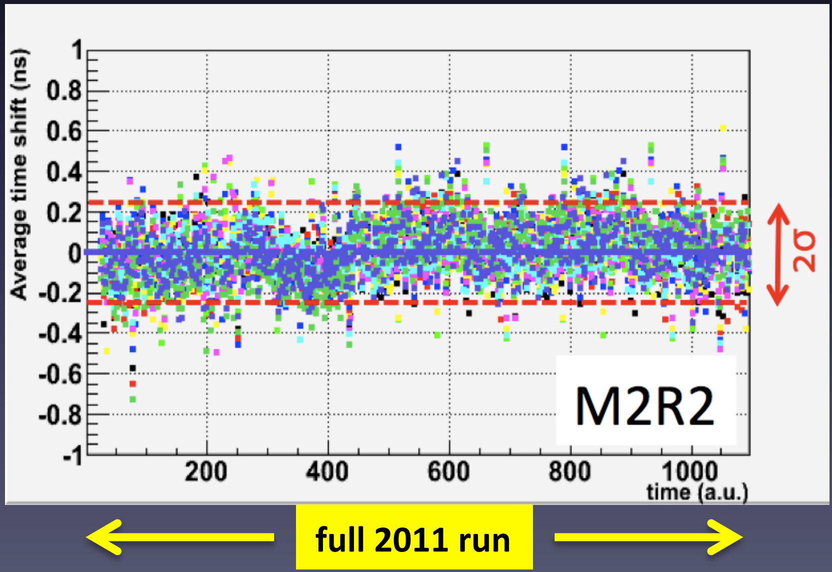
MWPC

- Rates up to **O(100) kHz/cm2** at nominal L=4x10^{32} cm^{-2}s^{-1} and E_{cm}=8 TeV
- Efficiency >99.3% everywhere

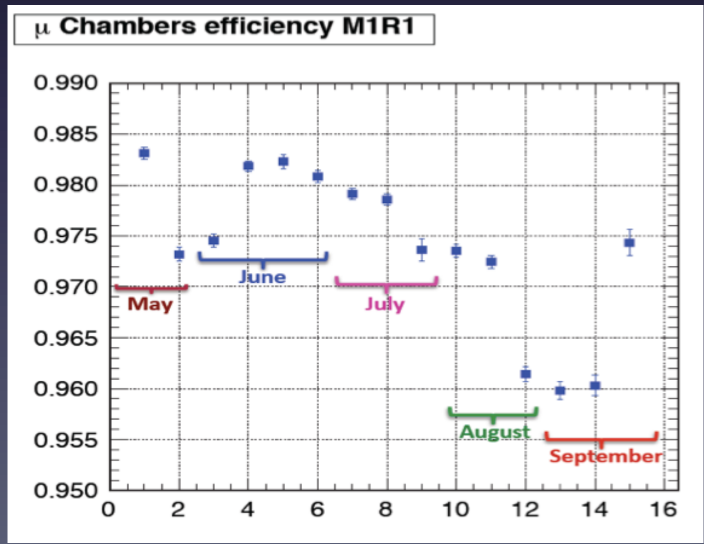
GEM (first LHC detector using this technology)

- Rates up to **0.5 MHz/cm2** at nominal L=4x10^{32} cm^{-2}s^{-1} and E_{cm}=8 TeV
- Efficiency ~98.7%





MWPC:
No gain variation observed → no aging



GEM efficiency stability in time in 2012

LHCb experience in Run-1

Integrated currents

MWPC

- Tested up to **0.4 C/cm** of wire
- Integrated charges not exceeding 0.05 C/cm per year (2011) with I_{max}=10 nA/cm

GEM

- Tested up to **1.8 C/cm^2**
- Integrated charges not exceeding 0.05 C/cm^2 per year (2012) with $\langle I \rangle_{max}$=10 nA/cm^2
  Total 2010+2011+2012 → 0.12 C/cm^2

Issues

MWPC

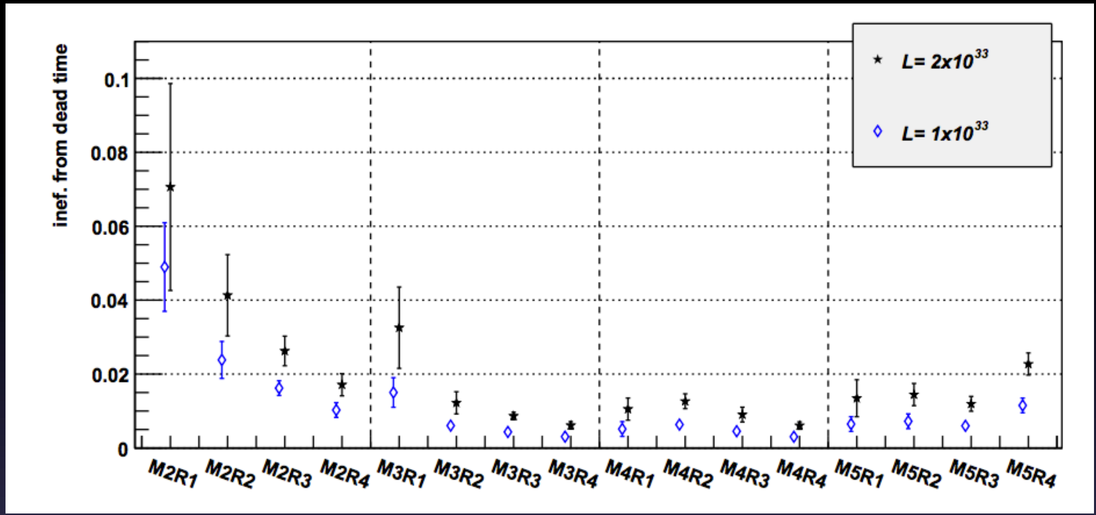
- No major issues observed – MWPC is a reliable technology
- Extremely low MWPC replacement rate (on average 5 MWPC/year)
  Replacement of a muon chamber can be done in a short end-of-the-year shutdown

GEM

- First GEM shorted on a few detectors
  → gain sharing equalized between 3 GEM foils to improve stability and reduce sparks
  G~6000 (435V/425V/415V) → G~4300 (3x415V)
- CF4 pollution problem being investigated by the CERN gas group
  all GEM gain jumps in correspondence to CF4 bottle change

LHCb upgrade

- LHCb upgrade (@ LS2): L=4e32 → L=2e33 and M1 will be removed
- System already tested at L=1e33 – no major problems on detectors' performances



- No space-charge effects observed on MWPCs, not expected in GEMs
- Efficiency reduction only due to higher occupancies → higher dead time
- Currently used detector technologies appears adequate for the upgrade data taking conditions

@ LS2: new muon readout electronics to achieve 40 MHz readout

@ >LS2 (still under discussion):
new detectors for M2 and M3 inner regions (innermost: triple-GEM; outside: MWPCs with cathode pad readout) with optimized readout to reduce channel occupancies

Extrapolation Summary

	ATLAS		CMS	
Extrapolation @	RPC (barrel)	MDT	RPC (endcap)	DT
L = 3 * 10^{34} $cm^{-2}s^{-1}$ Lint = 500 fb^{-1}	120 Hz/cm^2 60 mC/cm^2		180 Hz/cm^2 67 mC/cm^2	25 Hz/cm^2
L = 7 * 10^{34} $cm^{-2}s^{-1}$ Lint = 3000 fb^{-1}	280 Hz/cm^2 **360** mC/cm^2	140 kHz/tube	390 Hz/cm^2 **495** mC/cm^2	55 Hz/cm^2
Detector certified for	300 mC/cm^2	(excl. SW)	100 mC/cm^2	

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

	LHCb	
Extrapolation @	MWPC	GEM
L = 4 * 10^{32} $cm^{-2}s^{-1}$	0.05 C/cm/y	0.05 $C/cm^2/y$
L = 2 * 10^{33} $cm^{-2}s^{-1}$	**0.20** C/cm/y	0.25 $C/cm^2/y$
Detector certified for	~0.4 C/cm	~1.8 C/cm^2

Most exposed MWPCs in LHCb could be replaced by GEMs

RPC aging will exceed the certified values, GIF++ aging tests needed

Conclusions

All the muon detectors performed very well in Run-1
New TDAQ schemes will impose changes of electronics

DT no aging expected, need to qualify on-detector electronics for HL-LHC, replace readout electronics → **R&D on electronics**

MDT no aging expected (replaced by µMega in Small Wheels), replace FE electronics → **R&D on electronics** (no EoI from italian groups)

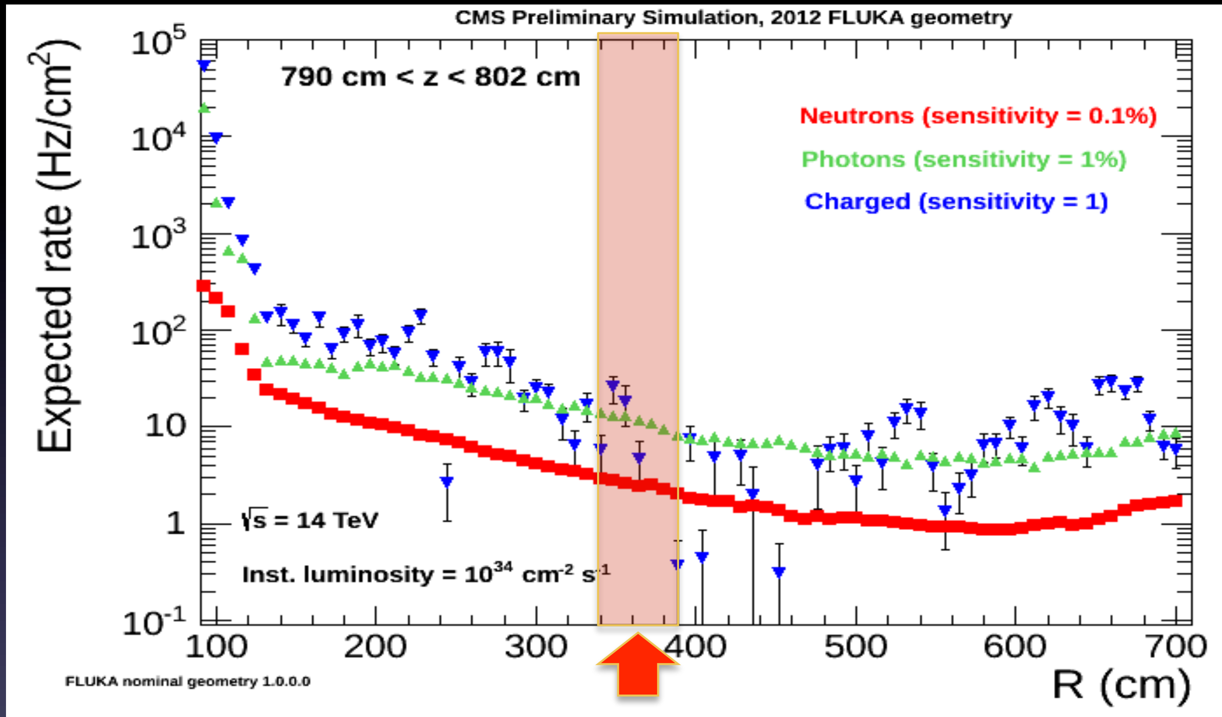
MWPC and GEM in LHCb adequate for upgrade phase (most irradiated MWPC replaced with GEM?), new readout electronics to run at 40MHz → **R&D on electronics**

RPC will reach the aging qualification limits in the regions with highest background
Need **aging tests (GIF++)**
R&Ds aimed to improve the RPC radiation tolerance started (ATLAS/CMS/ALICE)
R&D for the replacement of $C_2H_2F_4$ with a low-GWP gas started (ATLAS/CMS/ALICE)
New on-detector electronics (ATLAS), new FE electronics (ALICE) → **R&D on electronics**

Backup Slides

CMS: RPC rate simulation at 10^{34} cm^{-2}s^{-1}

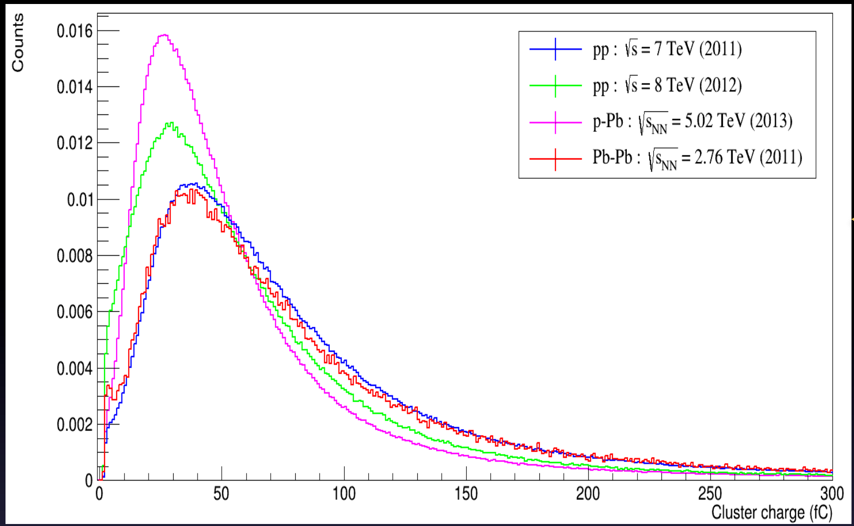
Rate simulation for Endcap RE2 at 10^{34} cm^{-2}s^{-1}

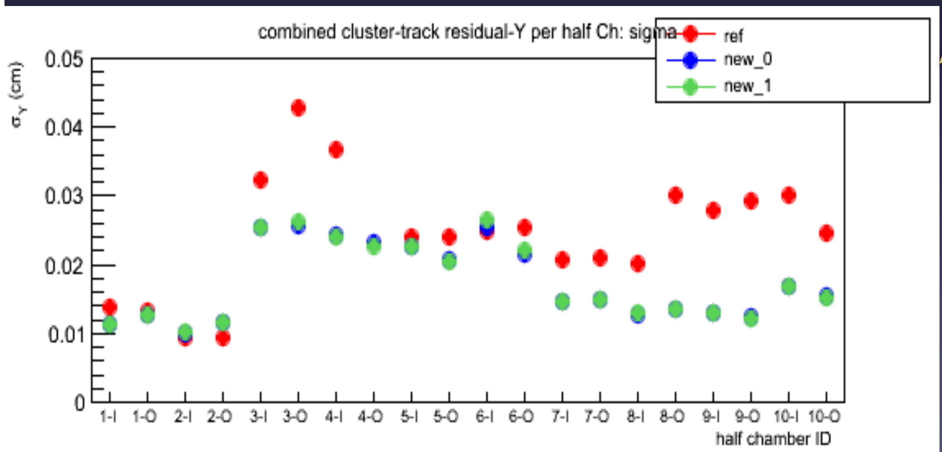


RE2 ring 3 roll C

Expected rate at 10^{34} cm^{-2}s^{-1}: ~40 Hz/cm^2
Good agreement with measurement extrapolations

ALICE muon tracking (Cathode Pad Chamber): performance in Run-1

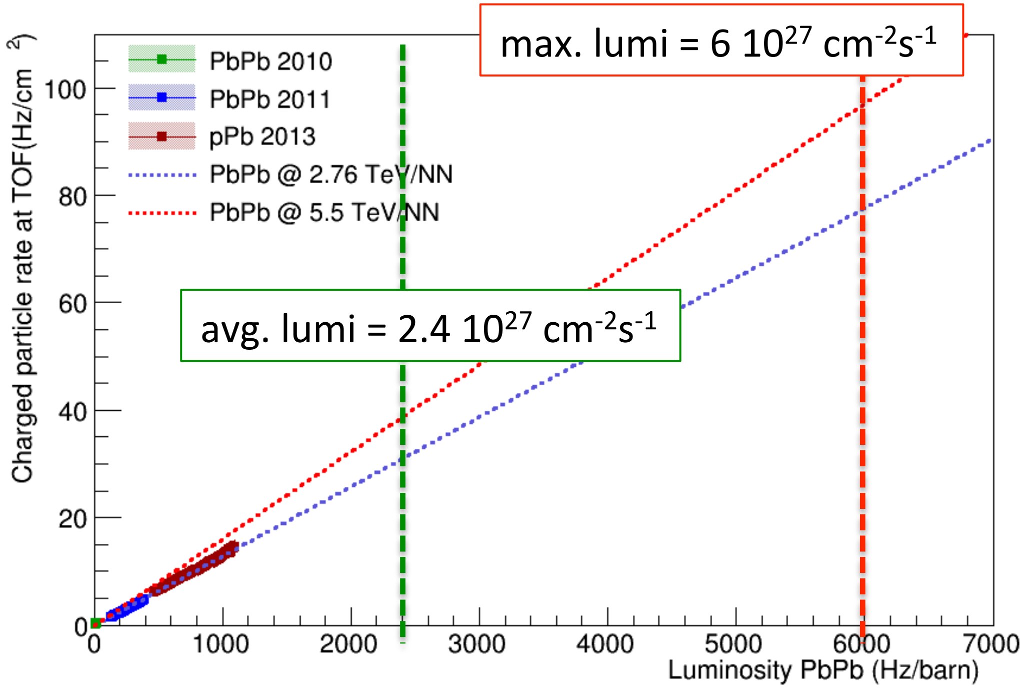


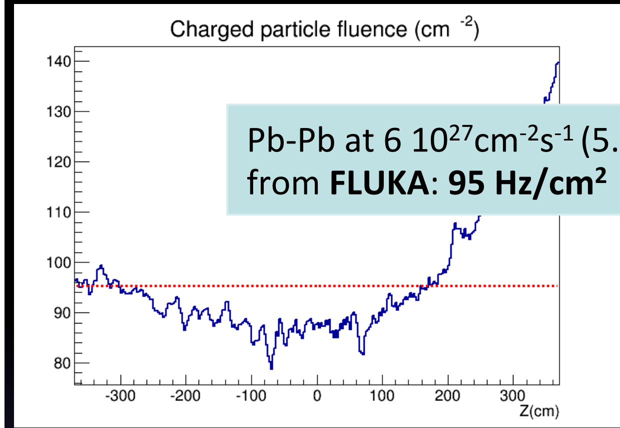


- The Muon Tracking detector managed to collect high precision data for physics analysis.
- The cluster charge distribution over different data taking periods are very similar.
- The variation of the peak of cluster charge distribution is due the different voltage setup.
- The Muon Tracker achieved position resolution of 250µm and 800µm in the bending and non-bending planes, respectively.
- Most importantly, Muon Tracker managed to measure the J/Ψ and Υ resonances at mass resolution of ~70 MeV and ~100 MeV, respectively, which was the design criteria of the detector.

No need of R&D

ALICE TOF (glass MRPCs): extrapolated background





Pb-Pb at 6 10^{27} $cm^{-2}s^{-1}$ (5.5 TeV/NN) from **FLUKA**: **95 Hz/cm²**

ALICE ToF MRPC

		Max rate	Max charge
Measured @	p-Pb at L_{inst} = 10^{29} $cm^{-2}s^{-1}$	14 Hz/cm²	
	End of Run-1		0.2 mC/cm²
Extrapolation @	Pb-Pb at L_{inst} = 6.5 * 10^{27} $cm^{-2}s^{-1}$	95 Hz/cm²	
	p-p at L_{inst} = 10^{31} $cm^{-2}s^{-1}$	26 Hz/cm²	
	End of Phase-1		1.9 mC/cm²
	End of Phase-2		2.8 mC/cm²
Detector certified for		1 kHz/cm²	~10 mC/cm²

NO UPGRADE FORESEEN