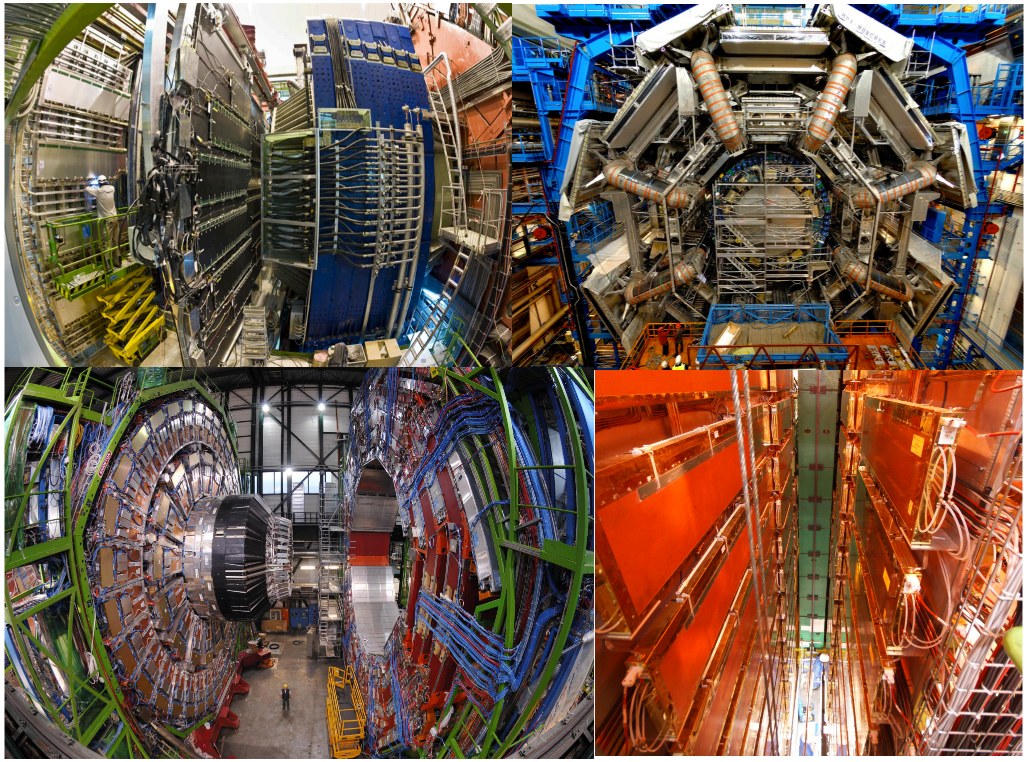


Longevity and Expected Performance of the Existing Muon Systems at the LHC Experiments

Paolo Iengo (ATLAS) with the help of:

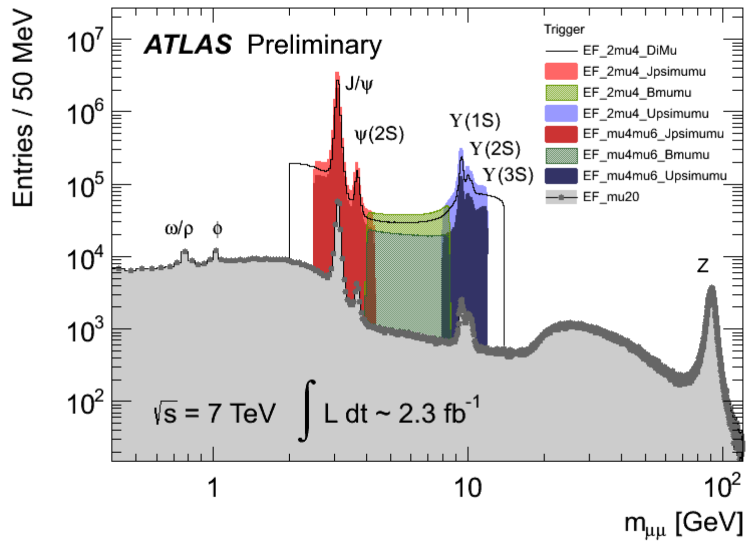
Pascal Dupieux (ALICE)

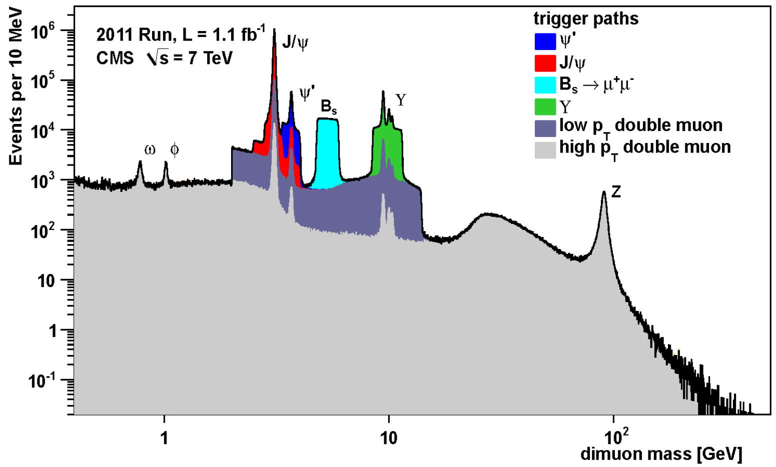
Cristina Fernandez Bedoya (CMS)

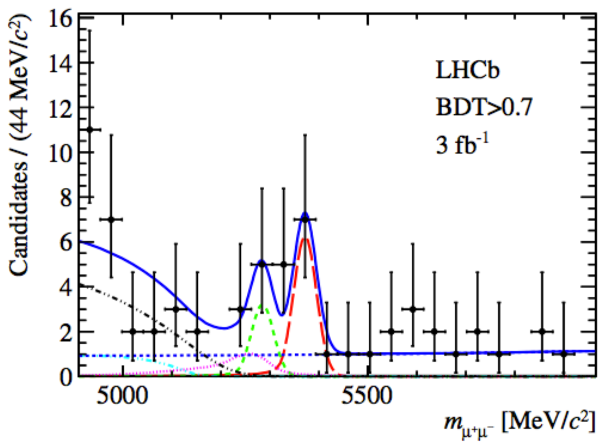
Gaia Lanfranchi (LHCb)

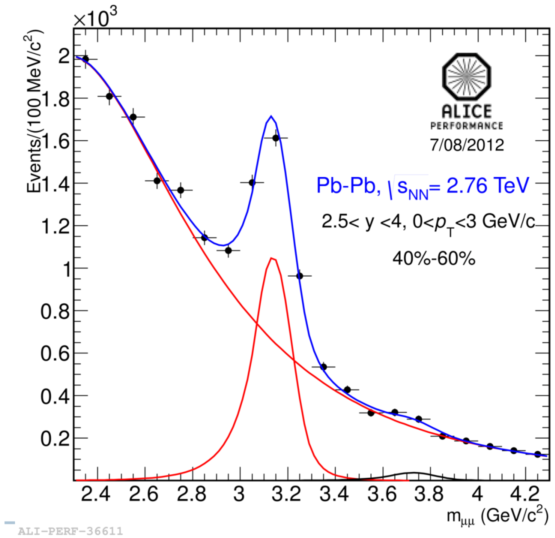
Muon Systems at LHC

- Muon Systems have performed extremely well during the LHC Run1
- Outstanding results in muon channels
- Crucial to keep the same performance (and even improve it) in the future runs to exploit the full physics potential → talk by K. Hoepfner
- How will the detectors behave in the harsher background conditions expected at higher lumnosity and in particular at HL-LHC?
- 10-years old detectors (and frontend electronics) to be operated at least for 10 more years



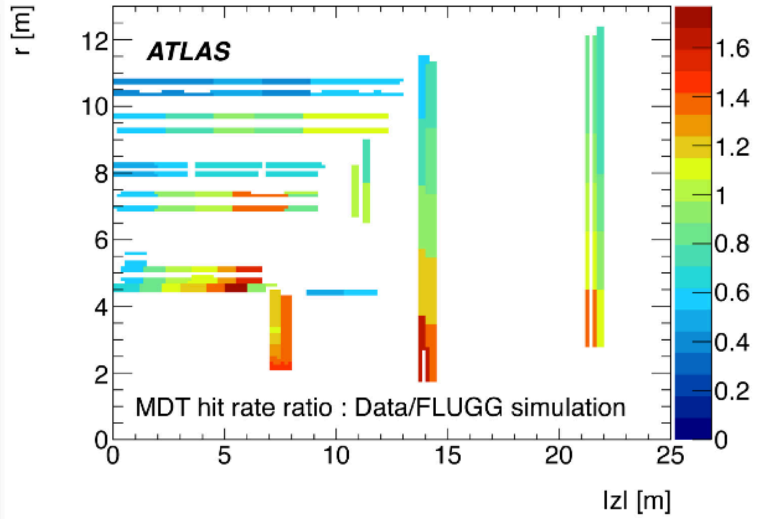


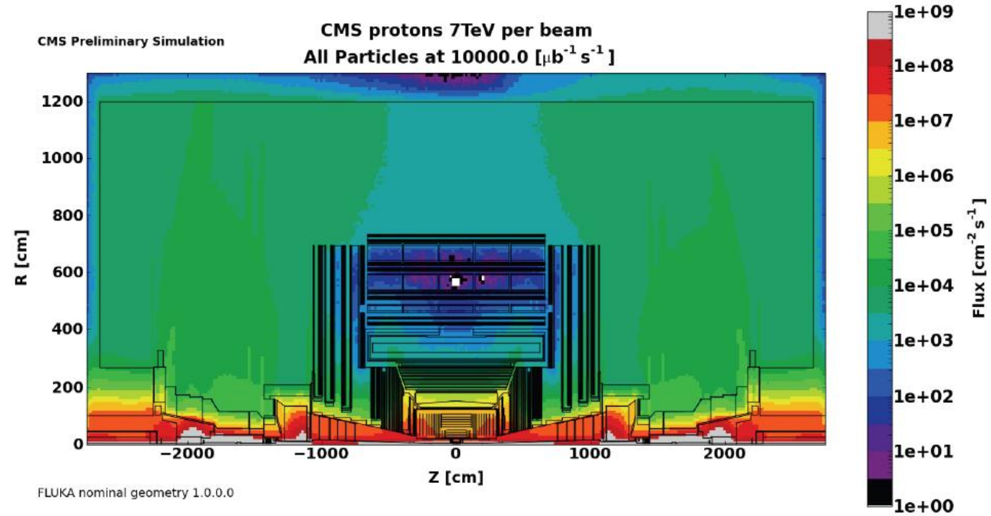




Muon System lifetime

- Muon system lifetime at LHC depends on
  - Detector lifetime
    - Technology, aging properties
    - Location (background level)
    - Sensitivity to neutrons and photons (the main sources of bkg)
    - Working regime (accumulated charge per hit)
  - Frontend electronics lifetime
    - Resistance to irradiation
    - Aging of components
    - Components obsolescence (spares unavailability)
  - Ability to control fake triggers at high rates
    - Majority
    - Single-plane and time resolution
    - Readout electrode segmentation
    - LVL1 track segment reconstruction capability
  - Readout and trigger electronics (→ covered in talk by M. Ishino)





Muon Detectors at LHC: a technologies mosaic

- ALICE
  - CSC
  - RPC
- ATLAS
  - MDT
  - RPC
  - TGC
  - CSC
- CMS
  - CSC
  - RPC
  - DT
- LHCb
  - MWPC
  - GEM

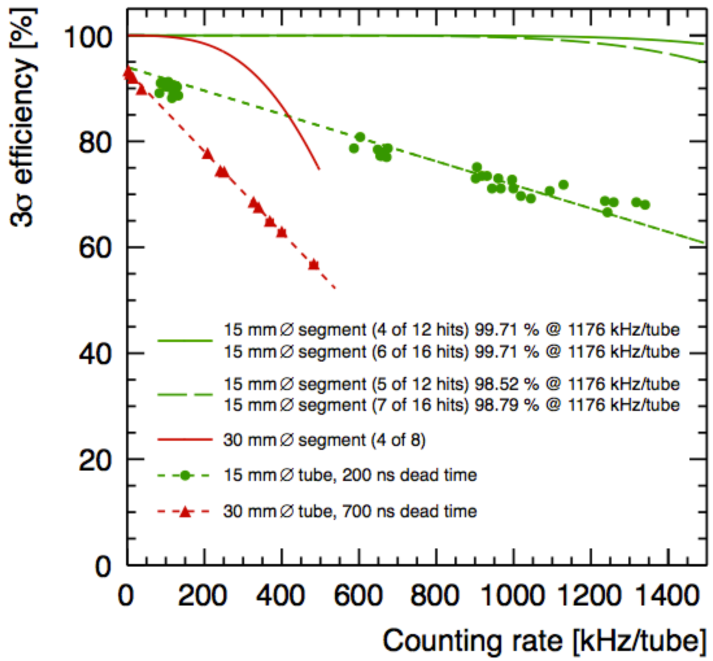
- Big variety of particle detectors with a common point: they are all gaseous detectors
- Two 'basic' technologies: wires/drift chambers and resistive plates (+GEM for LHCb, GEM covered in talk by M. Abbrescia)
- Common aspects on muon detector limitations at HL-LHC:
  - Rate capability
  - Occupancy
  - Trigger rate (fakes)
  - Momentum resolution
  - Aging

Performance limitation due to high bkg rate
→ instantaneous luminosity

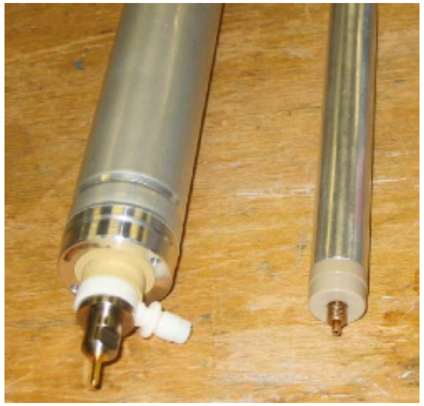
Progressive reduction of the performance due to ageing
→ integrated luminosity

Drift chambers: rate limitation

- Example: the ATLAS Monitored Drift Tube
  - 30 mm diameter tubes
  - Ar:CO2 @ 3 bar



- Rate limitation
  - Voltage (gain) drop due to space charge effect
  - Other factors affecting the rate capability
    - Occupancy
    - Pulse width
    - Dead time

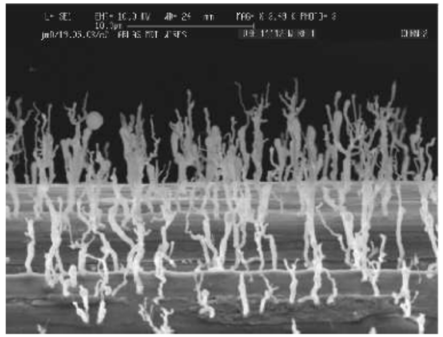


- Rate capability increased by changing the geometry (30mm → 15mm diameter)
- smallMDT to be used for consolidation of the ATLAS Muon Spectrometer (elevator and feet regions)

- Given the geometry the wire chambers have an 'intrinsic' rate limit
- Will the current detector geometry work at higher background level?

Wire chambers: aging

- Aging of wire chambers is being studied since decades
- Main ageing effects:
  - Formation of 'whiskers' on the anode wires, mostly made of silicon compounds
  - Distortion of pulse height spectra, gain loss, noise rate etc



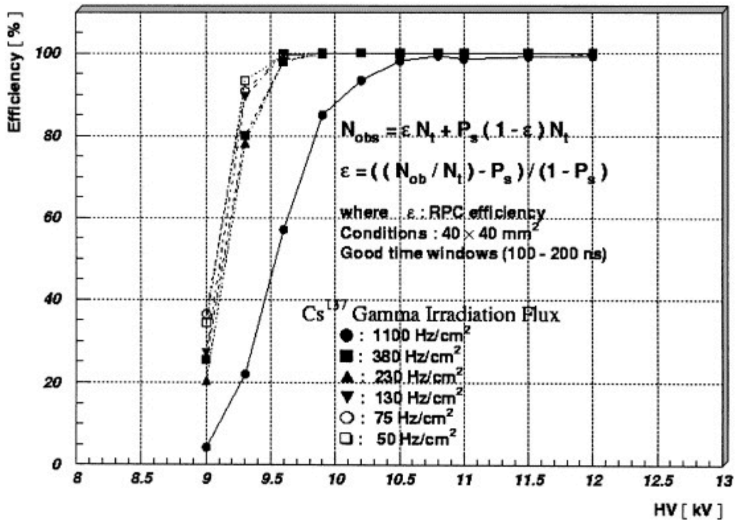
- Wire chambers for LHC have been designed and built according to general prescriptions to reduce aging effects:
  - No hydrocarbons in gas mixtures in drift chambers
  - No silicon material in the chambers and in the gas connections
  - Careful material selection (outgassing, radiation effects etc.)

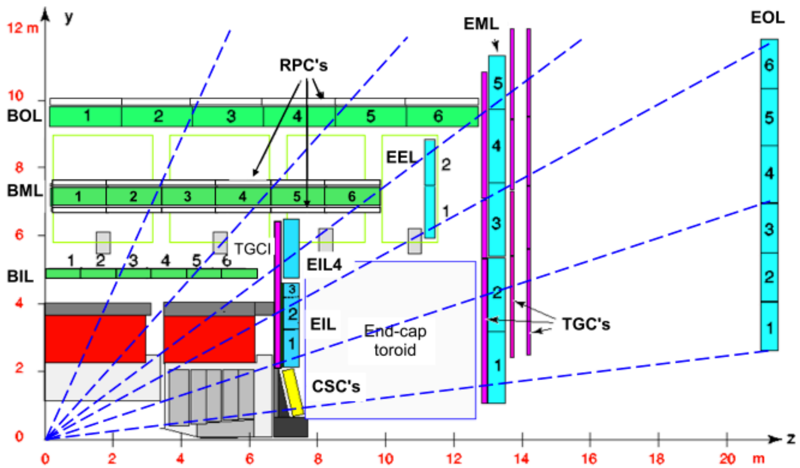
No aging effect which can compromise the detector performance expected up to HL-LHC

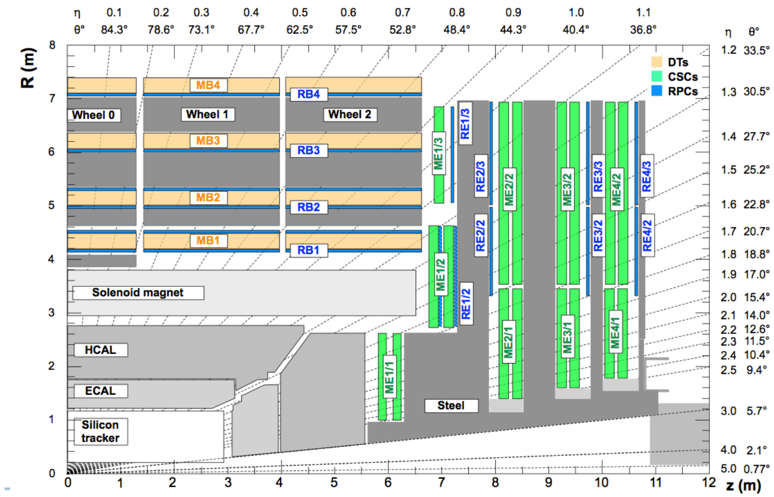
- Still some potential sources of problems
  - Pollution of the gas mixture (especially for large systems where gas re-circulation is needed)
  - Materials not always qualified up to the maximum expected radiation at HL-LHC
  - Radiation level at HL-LHC can exceed the 'expected' one (already true after LS1)

RPC rate limitation

- RPC rate capability depends on the resistivity of the plates
- For material (bakelite, $10^{10}\ \Omega$ cm) used in RPCs of the present muon systems of LHC experiments, detectors can stand up to <1 kHz/cm^2
- OK for HL-LHC
  - ATLAS: RPCs in barrel
  - CMS: RPCs also in endcaps but shielded by iron yoke
  - ALICE: expected rates very limited
- No concerns about rate capability

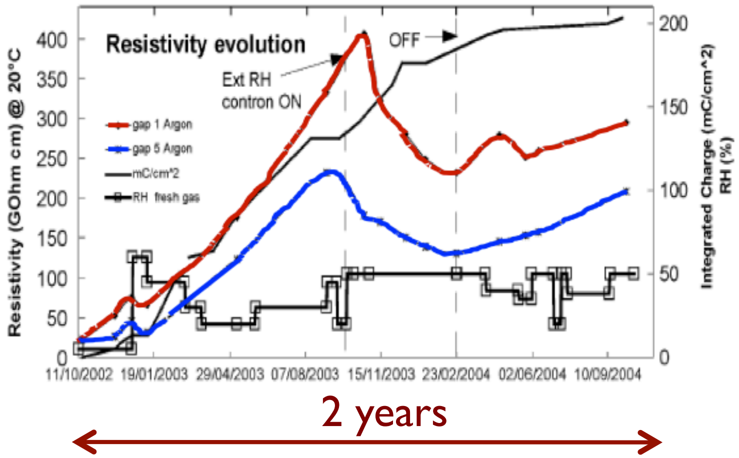


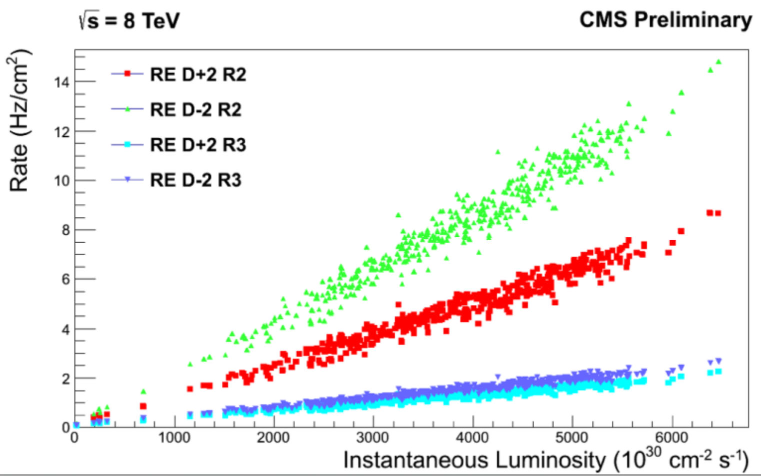




RPC aging

- Intense R&D programs conducted in recent years (with positive interactions across LHC experiments) to understand the aging of bakelite RPCs; max integrated charge 0.4 C/cm^2
- Main effects:
  - Resistivity evolution: progressive reduction of plates humidity
  - Increase of dark current: degradation of plates surface due to F- radicals and HF
- Appropriate solutions were implemented to avoid (and recover!) the aging effects:
  - Add H_2O vapour in the gas mixture
  - Reduction of fluoride compounds





- So far (max integrated charge of 3 mC/cm^2) no sign of aging in the bakelite RPCs
- An unforeseen problem: tetrafluorethane banned in EU (from 2017, already now in France)
  R&D studies for finding new operating gas mixtures already started

Max expected hit rates and integrated charges

Numbers refer to the hottest regions extrapolating the behavior of the present systems

	ATLAS				CMS			LHCb		ALICE		
Lumi	**CSC**	**MDT**	**RPC**	**TGC**	**CSC**	**DT**	**RPC**	**Lumi**	**MWPC**	**Lumi Pb-Pb**	**RPC**	
7x10^{33}cm^{-2}s^{-1} 25 fb^{-1}	20	10	3	21	3	0.1	3	4x10^{32}cm^{-2}s^{-1} 3 fb^{-1}	40	4x10^{26} cm^{-2}s^{-1} 150ub^{-1}	8	Int. charge
	770	280	13	100	170	2	14		4x10^{4}		3	Max. hit rate
1x10^{34}cm^{-2}s^{-1} 100 fb^{-1}	80	40	11	84	12	0.35	12	4x10^{32} cm^{-2}s^{-1} 8 fb^{-1}	100	2x10^{27} cm^{-2}s^{-1} 1nb^{-1}	<10	Int. charge
	1100	400	18	140	250	3	20		4x10^{4}		20	Max. hit rate
3x10^{34}cm^{-2}s^{-1} 350 fb^{-1}	280	140	38	280	41	1.2	42	1x10^{33} cm^{-2}s^{-1} 23 fb^{-1}	300	6x10^{27} cm^{-2}s^{-1} 10nb^{-1}	30$\rightarrow$10	Int. charge
	3300	1200	54	430	750	9	60		1x10^{5}		125	Max. hit rate
7x10^{34}cm^{-2}s^{-1} 3000 fb^{-1}	2400	1200	330	2450	350	10	360	2x10^{33} cm^{-2}s^{-1} 46 fb^{-1}	600			Int. charge
	7700	2800	130	1000	1700	20	140		2x10^{5}			Max. hit rate

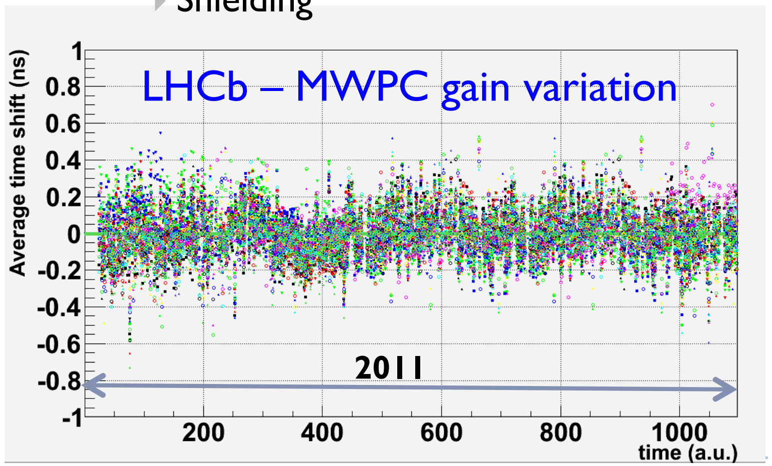
Integrated charge in mC/cm^2 (mC/cm for MWPC)
Max. hit rate in Hz/cm^2

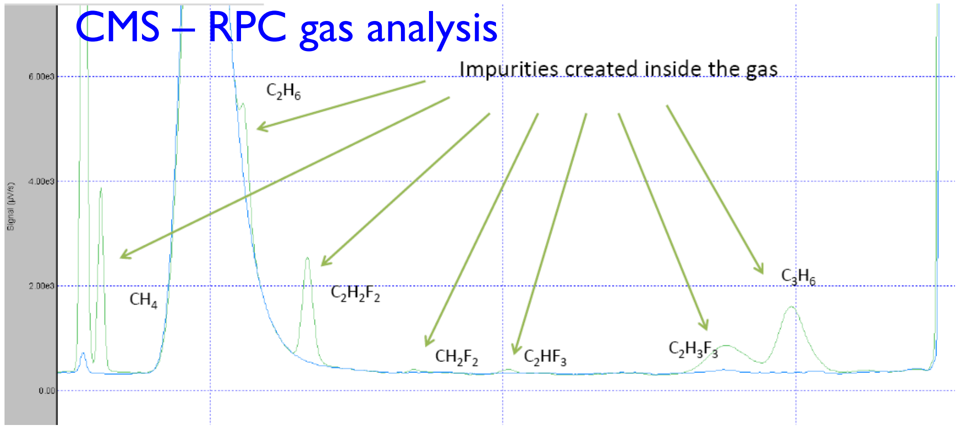
Additional tests needed on some detectors to assess their behavior during all HL-LHC

→ Common test facility (GIF++) strongly needed

Possible actions for increasing system longevity

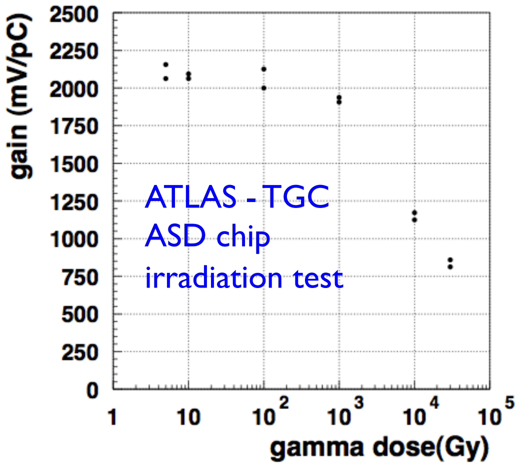
- System longevity can be estimated according to R&D studies, early detector operations, extrapolation of working conditions; but (negative) surprises are always possible
- Two key points
  - Continuous monitor of all the working parameters to spot as early as possible detector weakness or unexpected failures
    - Cracks of gas inlets, aging of plastic material, etc.
    - Gas composition (pollution)
  - Prepare actions to reduce impact of detector performance degradation
    - Regulation of gas flux and composition
    - Working point (HV adjustment)
    - Shielding

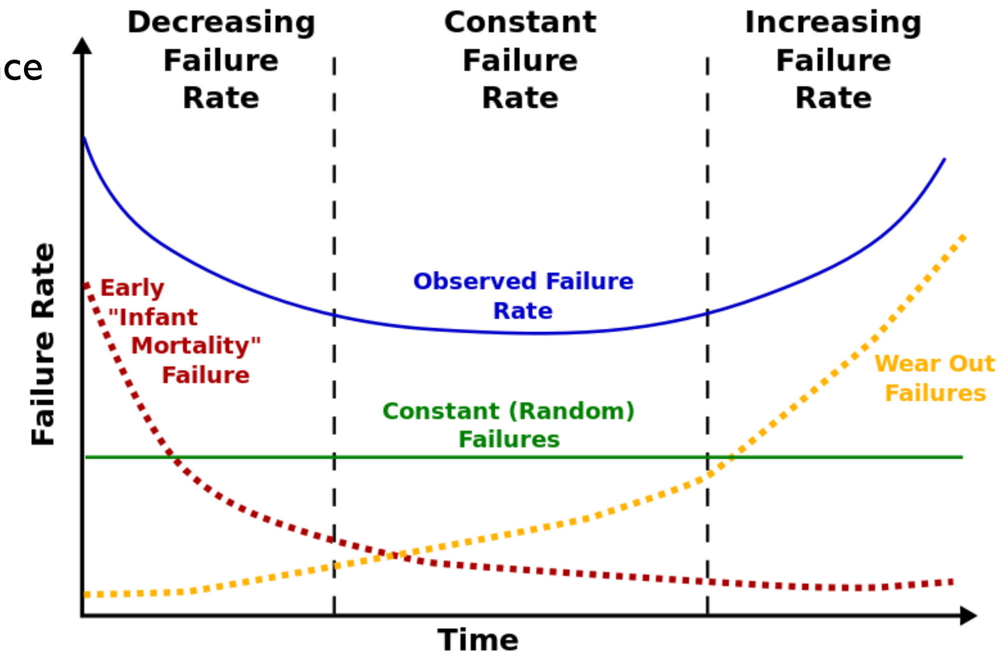




Front-end electronics

- Aging
- Radiation tolerance
- Readout speed
- Trigger rates
- Component obsolescence
- Accessibility



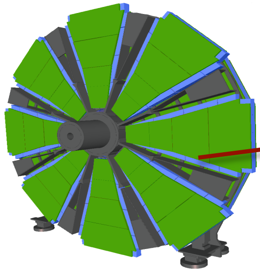


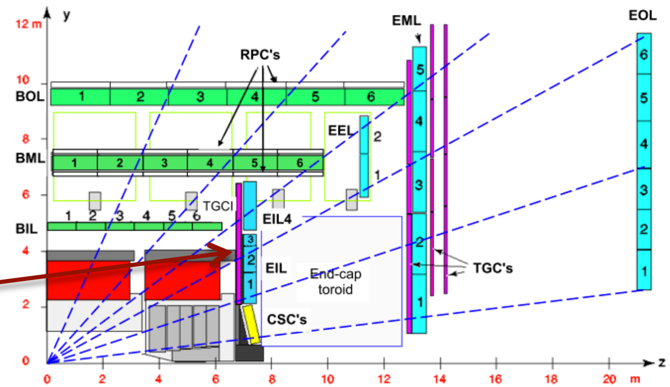
- Frontend electronics for LHC is expected to work for lifetime much longer than common devices
- R&D tests and experience from first years of operation are positive and do not give any indication of early wear out
  - Burn-in and lifetime tests showed no wear out
  - Failure rates during operations low for all LHC muon systems
  - Radiation tests performed in many cases up to the HL-LHC
  - Additional radiation tests are needed for specific components (→ common test facilities)

Muon system lifetime: ATLAS

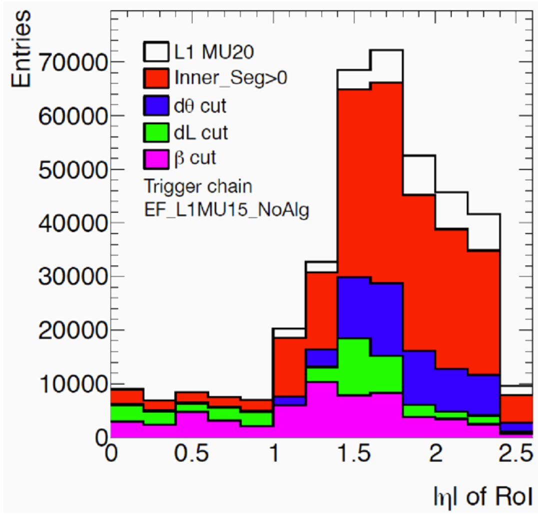
- The innermost endcap regions ('small wheels') will be replaced in Phase1 with New Small Wheels
  - New detector technologies (small strip TGC and Micromegas) offering
    - Higher rate capability
    - Stronger fake trigger rejection
    - Sharper trigger thresholds
    - Compliance with HL-LHC

More in talks by
M. Abbrescia and M. Ishino



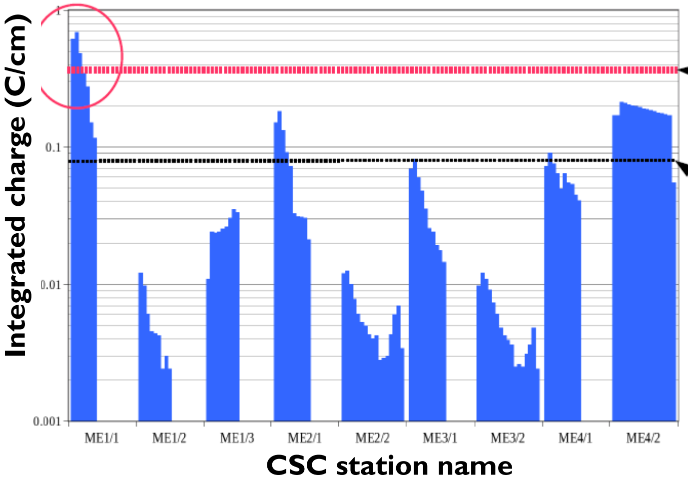


- HL-LHC scenario
  - Present detectors (plus Phase-1 upgrade) are expected to work
  - Some marginalities on trigger performance: better angular resolution needed for sharpening the thresholds
  - Possible improvements:
    - Replacement of the TGC in the inner ring of the second endcap stations
    - Use of the MDT information at LVL1 (→change of frontend elx)
    - Use of charge centroid measurement for RPC (→change of readout elx)
    - Add a fourth trigger layer in the innermost barrel region

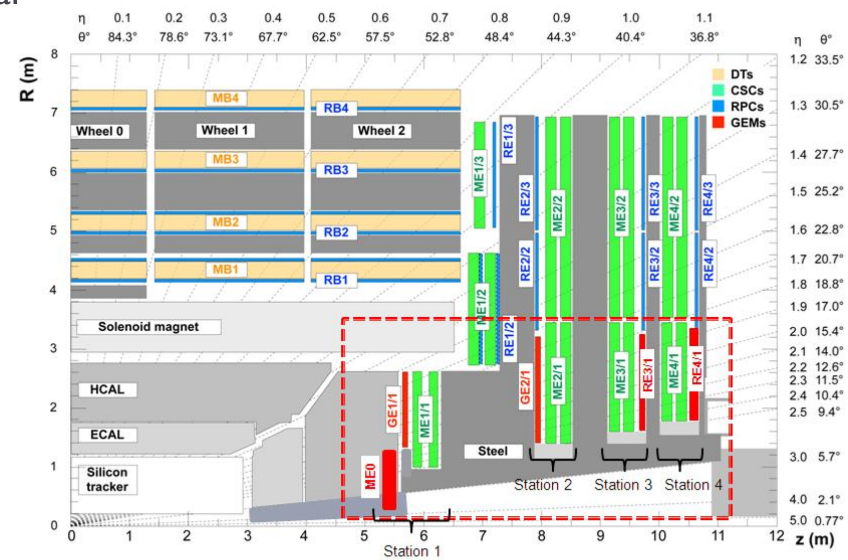


Muon system lifetime: CMS

- System improvements are being considered in the hottest regions
  - Add a shielding layer during LS1
  - Add GEM layers to complement CSC in the highest | η | regions

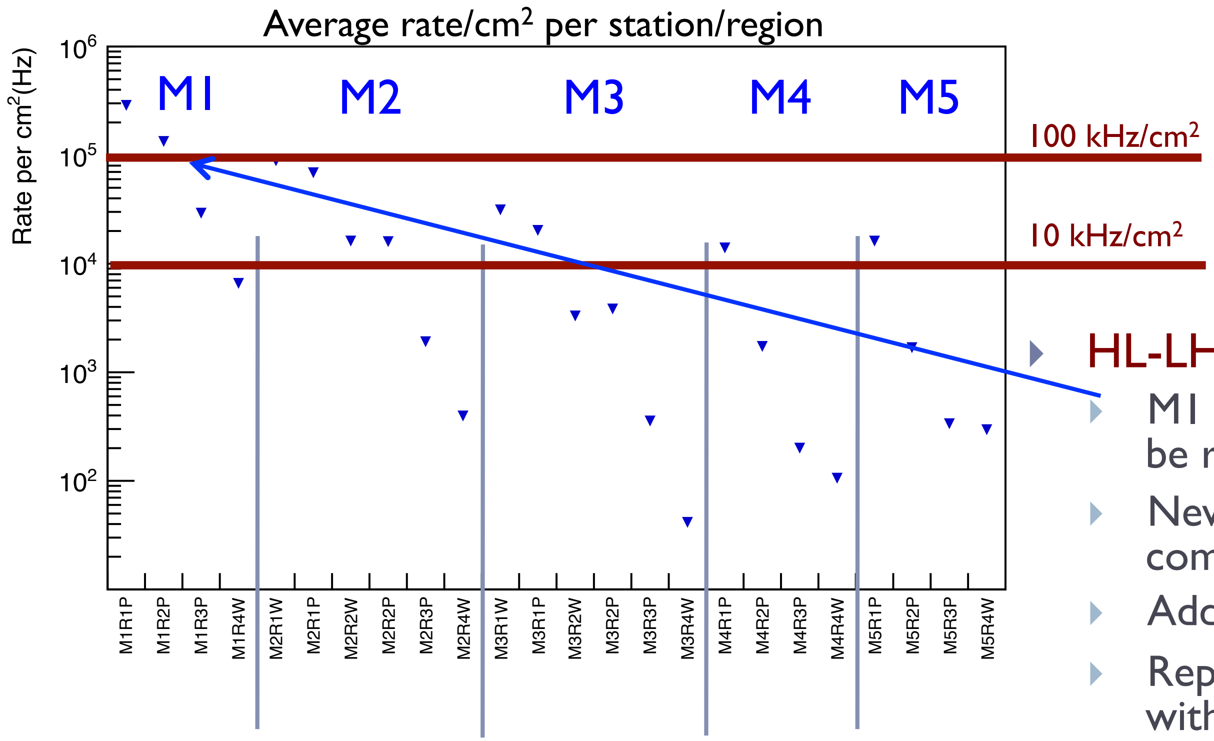


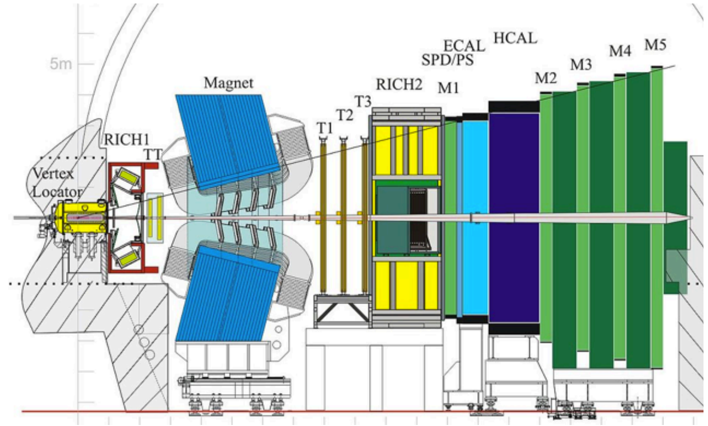
- HL-LHC scenario:
  - No evident degradation is expected at HL-LHC
  - Few limited hot areas in the detector look marginal → additional irradiation tests needed
  - Gas quality is a key point: R&D in new mixtures to be launched
  - Specific actions to mitigate detector concerns
    - RPC resistivity
    - HV adjustment
    - Materials outgassing
    - Gas mixture and flows tuning
  - For most part no concerns about front-end electronics so far:
    - R&D for a new DT minicrate ongoing (more in talk by M. Ishino)



Muon system lifetime: LHCb

- Muon system tested up to 10^{33} at 8 TeV with encouraging results
- No space-charge effect observed
- Final evaluation of performance in the upgrade conditions are ongoing

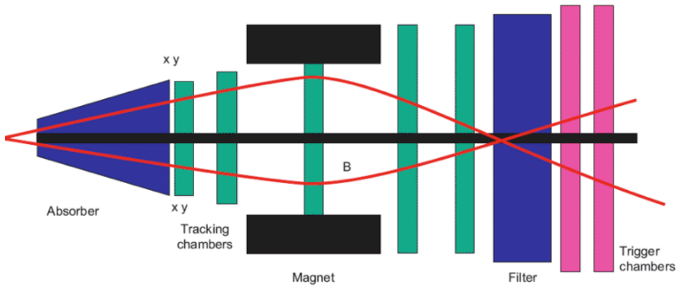




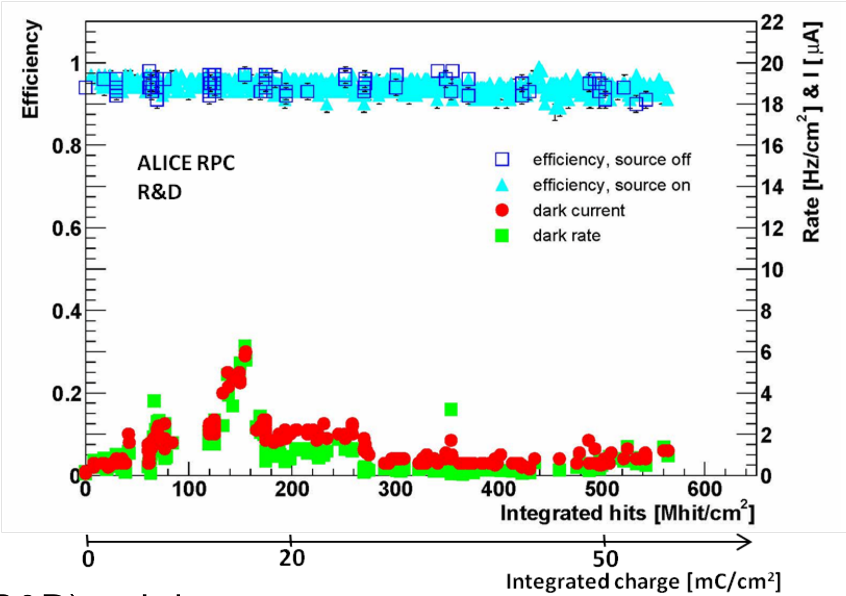
- HL-LHC scenario
  - M1 station (in front of the calorimeter) to be removed in LS2
  - New off-detector readout electronics compliant with 40 MHz – LS2
  - Add shielding – LS2
  - Replacement of the innermost stations with GEM or new MWPC after LS2

Muon system lifetime: ALICE

- All muon detectors are expected to work with full efficiency at HL-LHC → no detector upgrade foreseen
- No deterioration expected
- Readout electronics not able to sustain the 100kHz rate of Pb-Pb collisions



- HL-LHC scenario:
  - Add a CMOS pixel-sensor detector system in the Muon Spectrometer acceptance (Muon Forward Tracker) →discussed in the tracker session
  - Replace the readout electronics of CSC and RPC towards a deadtime-free
  - Replace the front-end electronics of the CSC with new cards based on S-ALTRO chip
  - Change RPCs working regime from maxi-avalanche to saturated avalanche mode (as in ATLAS and CMS)
    - Save a factor ~3-5 in integrated charge (>50 mC/cm^2 from R&D) and short term max hit rate capability (up to 200 Hz/cm^2)
    - New frontend electronics with analog signal amplification capability

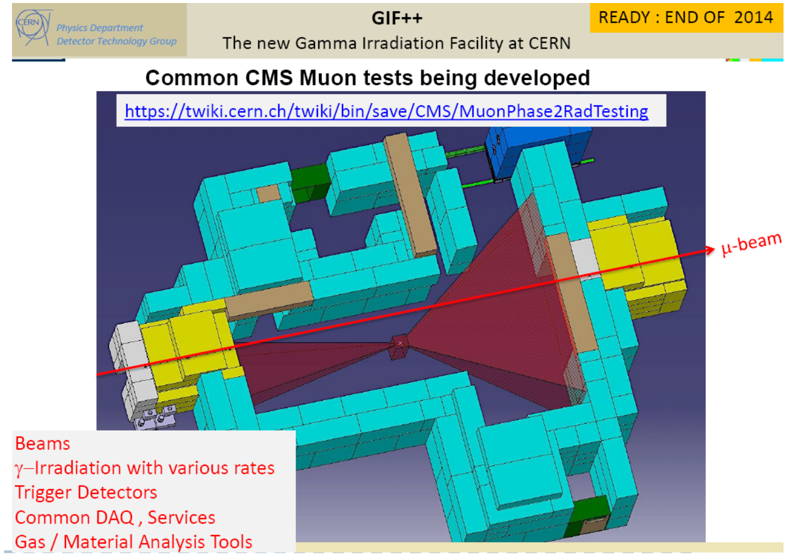


Common test facility: GIF++

- Common R&D efforts on detectors and electronics already made for some of the present muon systems → positive collaboration and better use of resources
- Additional tests are crucial to verify performance and aging properties in conditions as close as possible to HL-LHC
  - High rate, high flux of neutrons and photons
  - For long time (not all the effects are just related to the integrated dose)
  - Other tests might be needed (e.g. chemical analysis of pollutants)

A similar environment for all detectors

A common test facility



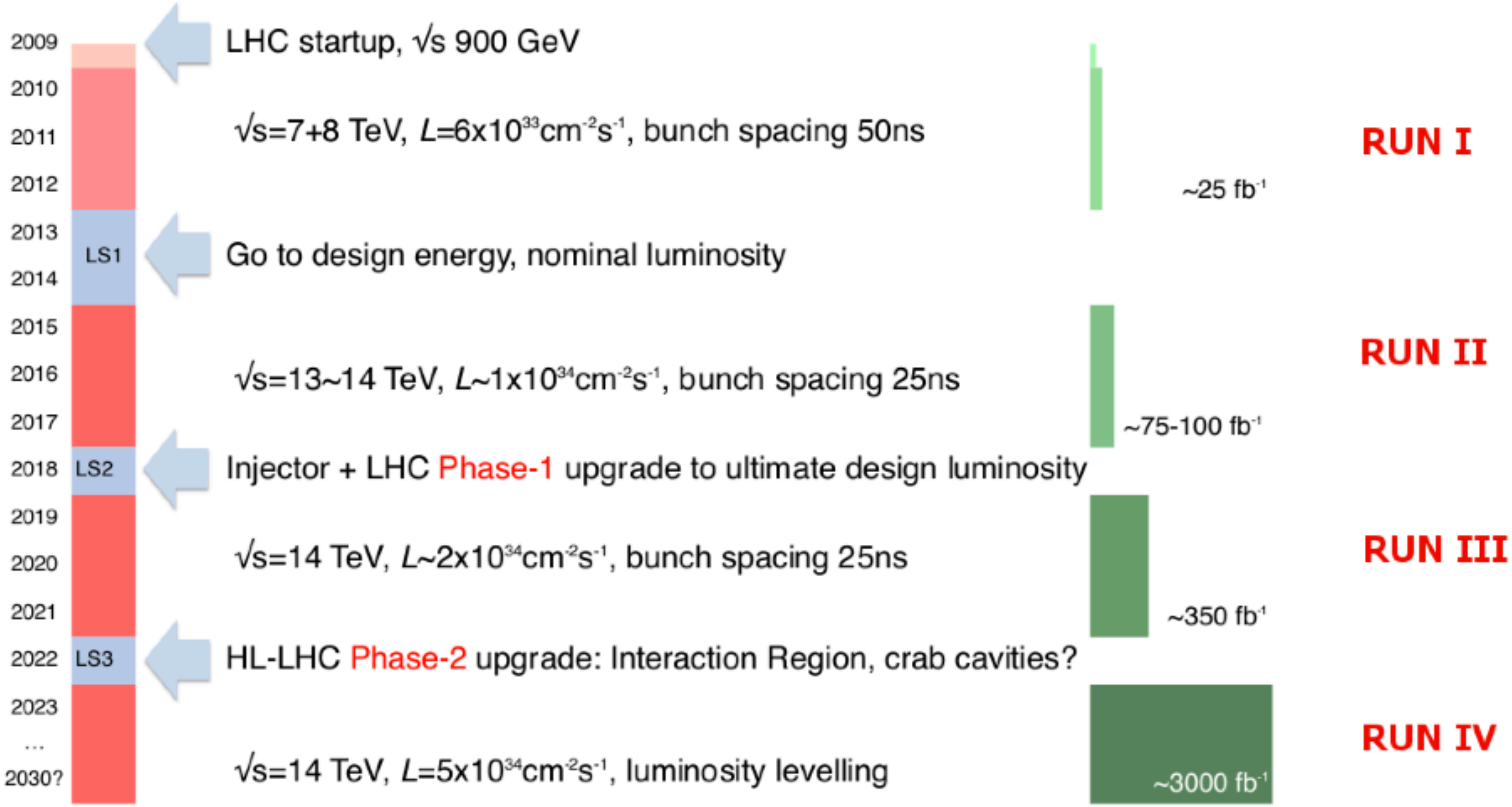
Summary and Conclusions

- Excellent performance of the existing muon systems during the first running period
- Most of the detectors should operate safely at HL-LHC except for some detectors in the hottest regions
- Front-end electronics is expected to survive the HL-LHC, but some to be replaced or improved to enhance the system performance
- Availability of test facilities is crucial for pushing further aging and irradiation studies on both detectors and electronics
- In spite of their age, the muon systems of the LHC experiments are in good shape and (with the upgrade improvements) ready to collect 100 times more luminosity for new physics results …

…by continuing the huge effort of

- mantaining the systems
- verifying their evolution with time
- invest on R&D for upgrades

Additional Material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2030?
LS1
LS2
LS3
LHC startup, √s 900 GeV
√s=7+8 TeV, L=6x10^33cm^-2s^-1, bunch spacing 50ns
Go to design energy, nominal luminosity
√s=13~14 TeV, L~1x10^34cm^-2s^-1, bunch spacing 25ns
Injector + LHC Phase-1 upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34cm^-2s^-1, bunch spacing 25ns
HL-LHC Phase-2 upgrade: Interaction Region, crab cavities?
√s=14 TeV, L=5x10^34cm^-2s^-1, luminosity levelling
~25 fb^-1
~75-100 fb^-1
~350 fb^-1
~3000 fb^-1
RUN I
RUN II
RUN III
RUN IV

wire plane (a few wires shown)
cathode strip plane
7 trapezoidal panels forming 6 gas gaps
Cross plate
Multilayer
In-plane alignment
Longitudinal beam
Anode wire
Electrode strips
Cathode strip
Drift lines
Isochrones
Cathode Strips
Anode Wires
Read-Out
μ
Pick-up strip
Graphite layer
+HV
1.8 mm
50 μm wire
1.4 mm
1.6 mm G-10