Muon Phase 2 Upgrade

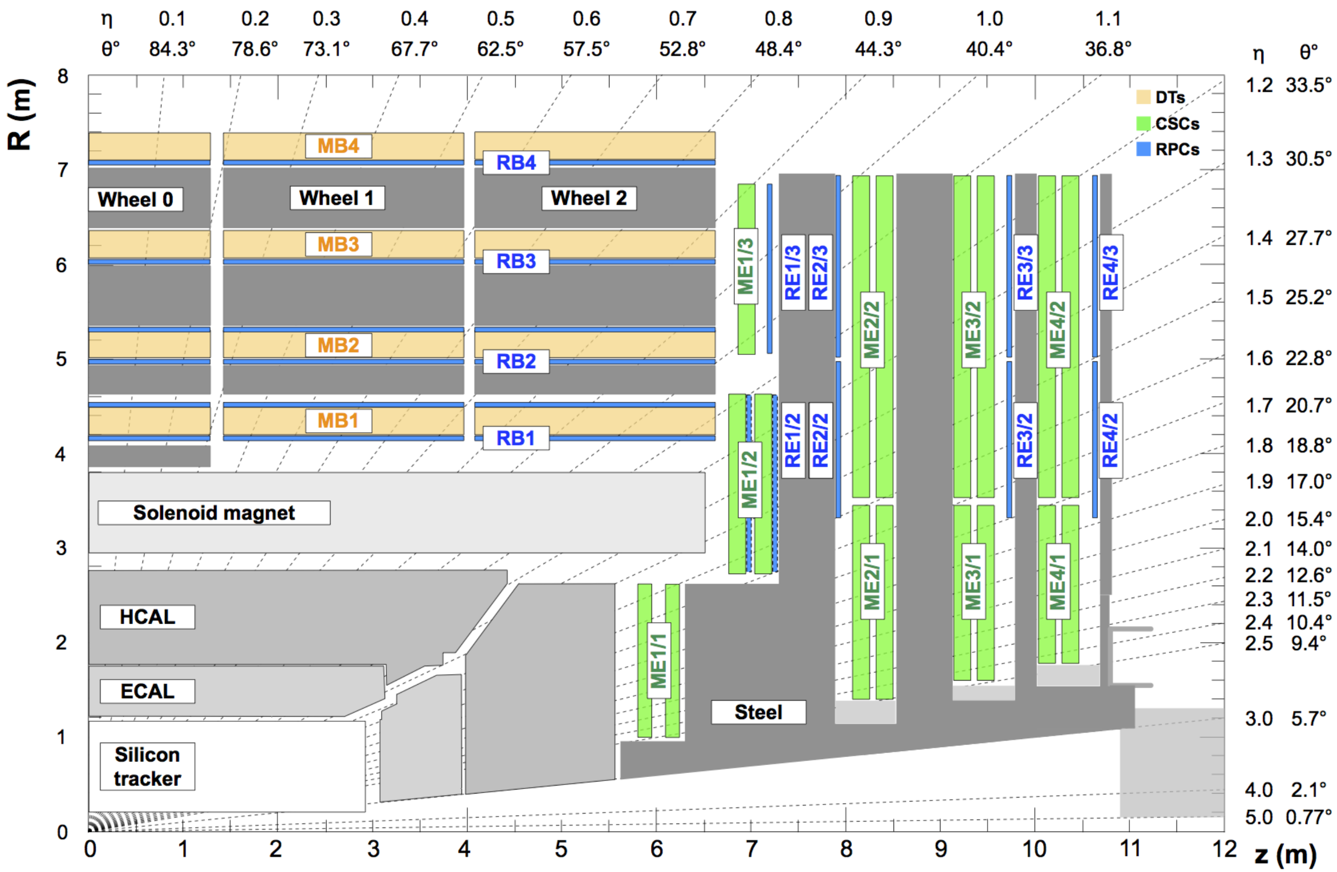
Andrey Korytov

University of Florida

Phase-2 L1 Muon Trigger Algorithms and Muon Upgrade Workshop

November 28, 2018

Current Muon System



DT (drift tubes):
trigger, precision, low rate

CSC (cathode strip chambers):
trigger, precision, high rate

RPC (resistive plate chambers):
trigger, fast

Redundancy (4 stations with 2 detector technologies on the path of a muon in ≈any direction) ensure
- robust trigger
- efficient reconstruction

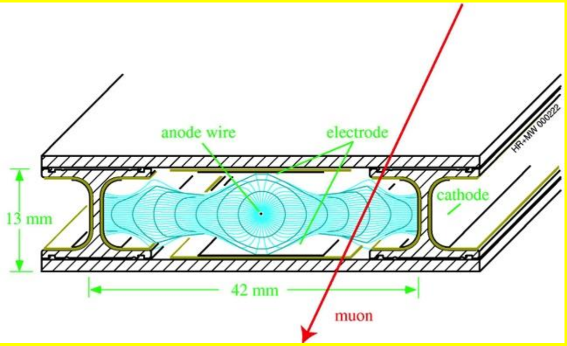
Acceptance: $|\eta| < 2.4$

L1 Trigger: $p_T > 25$ GeV (μ); $p_T > 4$ GeV ($\mu^+\mu^-$, $\Delta R<1.2$)

Reconstruction: $p > 3$ GeV (yes, p), $\delta p_T/p_T \approx$ 1-2% (with the Tracker)

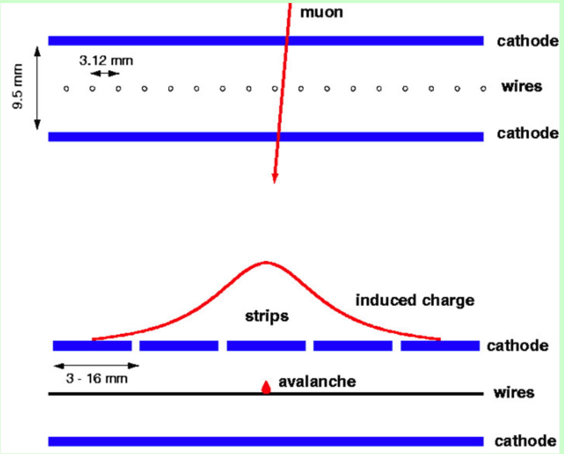
Three technologies

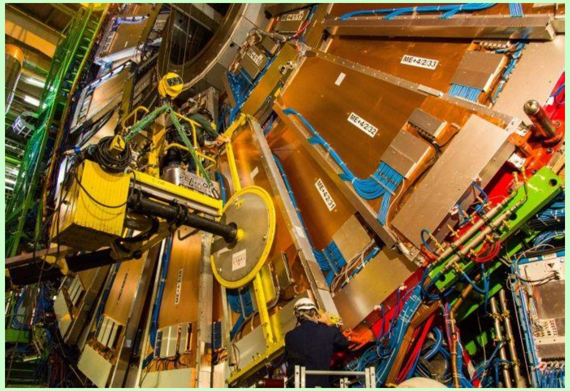
DTs



Sensitive layers area: **18,500 m^2**
Number of channels: **172K**

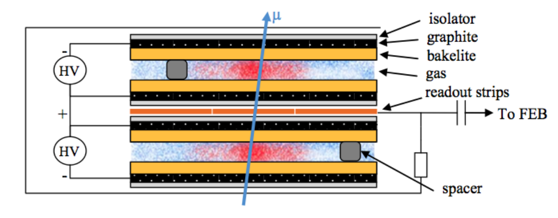
CSCs

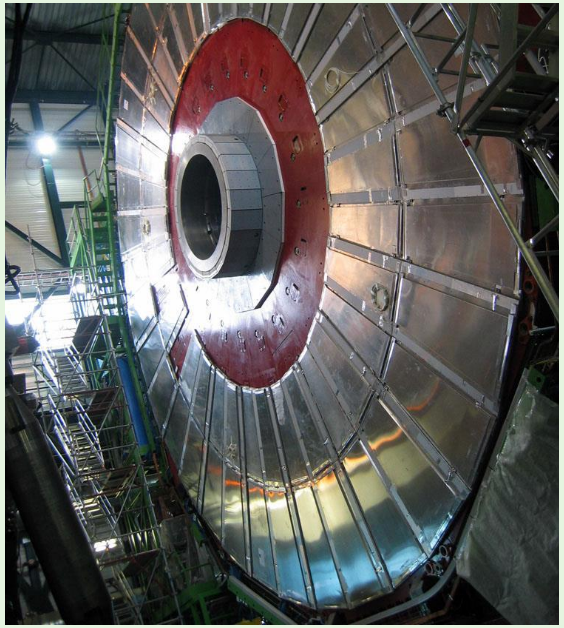




Sensitive layers area: **6,300 m^2**
Number of channels: **477K**

RPCs





Sensitive layers area: **4,000 m^2**
Number of channels: **137K**

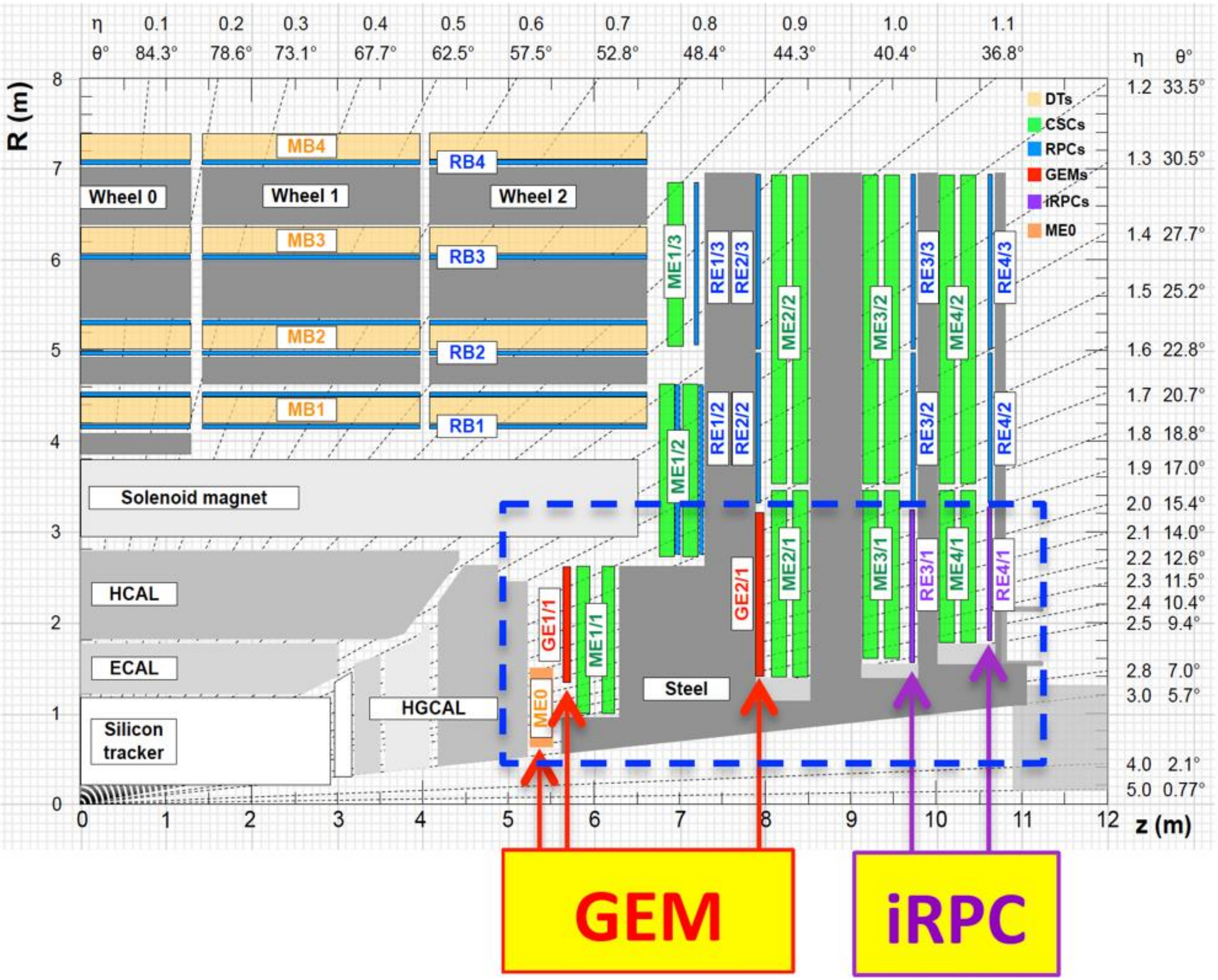
HL-LHC vs LHC

		LHC	HL-LHC	ultimate HL-LHC
Collider	instantaneous luminosity ($cm^{-2}s^{-1}$)	10^{34}	5×10^{34}	7.5×10^{34}
	pileup collisions	30	150	200
	integrated luminosity (fb^{-1})	500	3000	4000
CMS	L1 trigger (kHz)	100	500	750
	L1 trigger latency (μs)	3.6	12.5	

All LHC experiments were designed for the LHC specs

New specs require detector upgrades

Muon System Upgrade



Present DT, CSC, RPC detectors will stay

- **extensive longevity studies**

Electronics of the legacy detectors

- **replace what will fail the HL-LHC L1/DAQ specs**
  - **DT:** replace on-detector/BE electronics
  - **CSC:** selective on-detector board replacements and all BE
  - **RPC:** replace off-chamber readout/control system
- **enhance capabilities of what is being replaced**
  - **DT Trigger:** improved timing, more flexibility
  - **RPC Trigger:** improved timing

Enhance the challenging forward system

- **GE1/1:** 2 extra points
- **ME0:** 6 layers, η coverage is extended from 2.4 to 2.8
- **GE2/1:** 2 extra points
- **iRPC:** 1 extra point per station

Detector longevity

Detector longevity

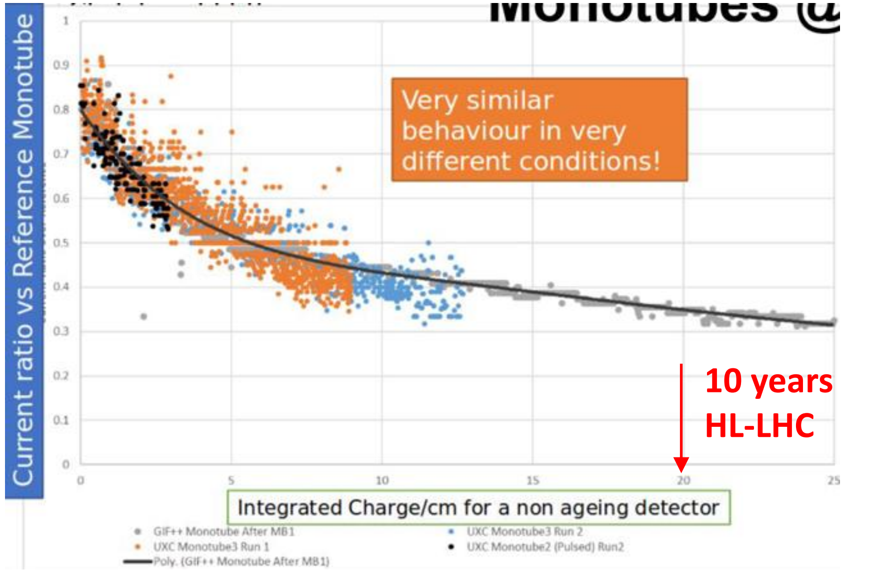
Detector	Maximum Expected Q* at L=3000 fb^{-1}	Accumulated Q (test detectors at GIF++ & B904)	Results obtained with test detectors
DT	20 mC/cm	25 mC/cm	**Gas gain drop is observed (next slide)**
CSC	110 mC/cm	340 mC/cm	No deterioration in performance
RPC **iRPC**	280 mC/cm^2 500 mC/cm^2	425 mC/cm^2 90 mC/cm^2	No deterioration in performance
GE1/1 **GE2/1** **ME0**	6 mC/cm^2 3 mC/cm^2 280 mC/cm^2	1400 mC/cm^2	No deterioration in performance

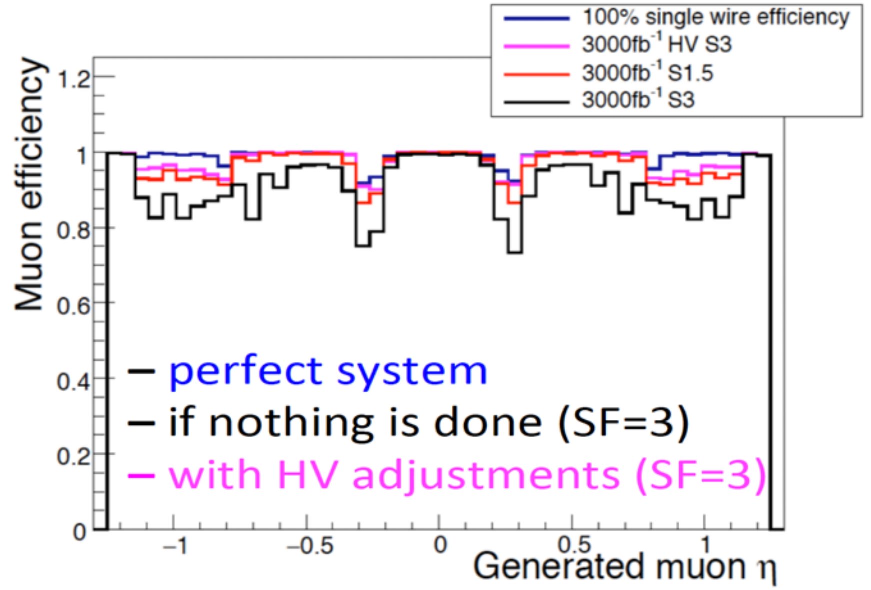
* The maximum expected accumulated charge per wire length or surface area is **for the hottest spots in the system**

DT longevity

- **Hottest spots:**
  - **MB±2/1:** Q~20 mC/cm at nominal HV
  - other DTs will accumulate substantially smaller charge (see backup)
- **Wire aging:**
  - expect gas gain drop by a factor of 3 at 20 mC/cm
  - cause: DT material outgassing
- **Mitigation measures**
  - selectively reduce HV (half the gas gain) to slow down aging and reduce signal discriminator thresholds to keep efficiency intact (implemented)
  - precaution: change from close-loop to open-loop gas flow (implemented)
  - add MB4 shielding (to be implemented in LS2)
  - considering O_2 and H_2O additives having aging-preventive properties
  - **high redundancy in the original DT system design plus new scheme to trigger/readout will keep the trigger/reco efficiency higher than 90%**
- **Need a good model of the net effect for Phase-2 simulation**

  This is a bit more involved than just assumptions on the number of dead channels (often in groups corresponding to one FE board)





Replacement of electronics of the legacy detectors

DT electronics upgrade

MAIN PROBLEM:

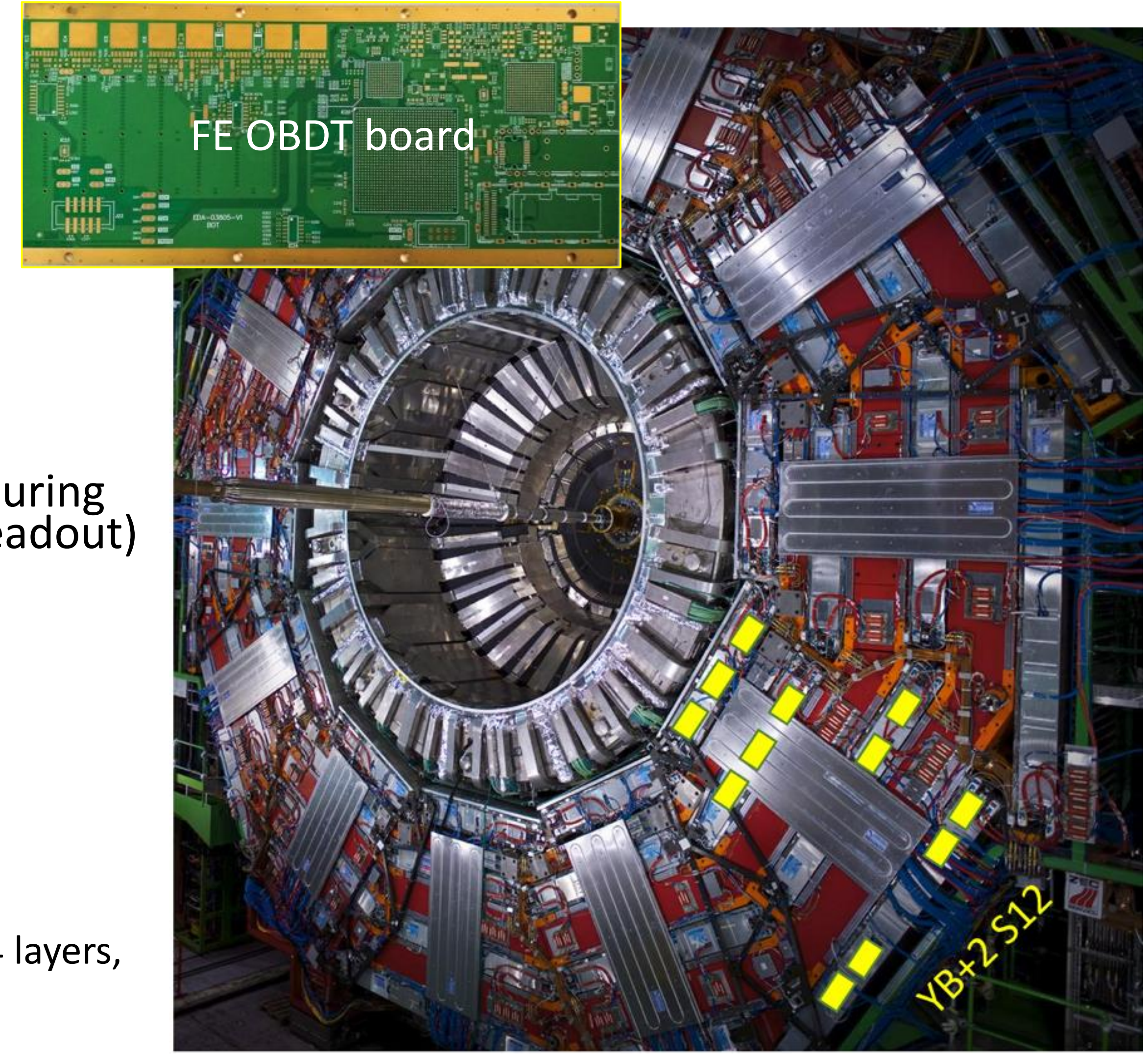
- Readout cannot cope with the new L1/DAQ specs
- Minicrate electronics (FE Trigger/DAQ) are aging

SOLUTION:

- Replace readout system (keep FE analog electronics)

PROTOTYPING STATUS:

- One sector will operate with prototypes of new electronics during LS2 and, partially, into Run 3 (all in parallel with the legacy readout)



ENHANCEMENTS FOR L1 TRIGGER

- better timing (12.5 ns digitization → 1 ns)
  - better suppression out-of-time background
  - better momentum measurement
  - trigger on HSCP (Heavy Slow Charged Particles)
- move trigger primitive logic to back-end electronics:
  - more versatile trigger logic (e.g., TPs can be made from more than 4 layers, easy to mix in RPC hits, more FPGA power in general)
  - more robust w.r.t. potential DT efficiency deterioration
  - easier to maintain/upgrade

CSC electronics upgrade

MAIN PROBLEM:

- Part of readout cannot cope with the new L1/DAQ specs
- Rad-hard issues for ME1/1 electronics

SOLUTION:

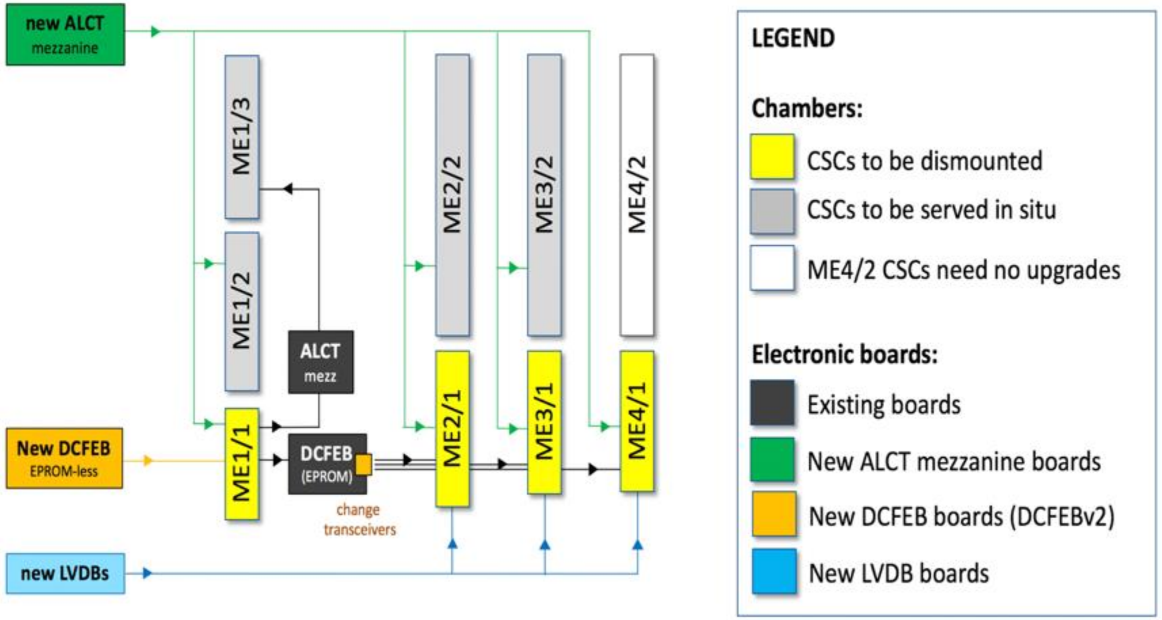
- Replace electronic boards selectively, as needed

STATUS

- All on-detector work is to be done during LS2

ENHANCEMENTS FOR L1 TRIGGER

- more FPGA resources for forming trigger primitives
  - ALCT boards (anode 1D TP): all CSCs
  - TMB boards (cathode 1D TP, (anode)x(cathode) 2D TP): ME*/1 CSCs
- can form joint ME2/1-GE2/1 trigger primitives



RPC electronics upgrade

MAIN PROBLEM

- Readout system will have non-sustainable rate of losing configuration communications at HL-LHC
- Readout system is aging; we will run out of spares

SOLUTION

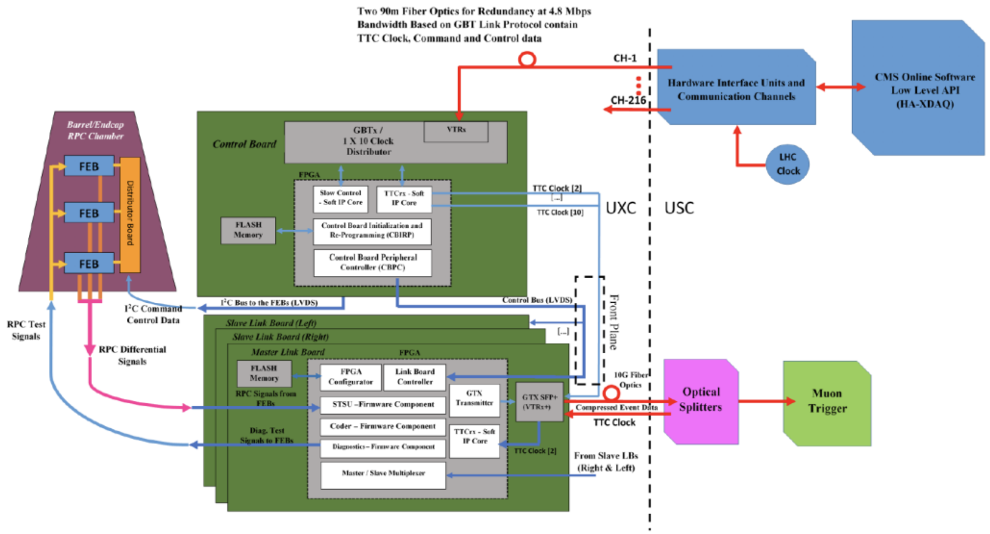
- Replace trigger/readout system (so-called Link System)

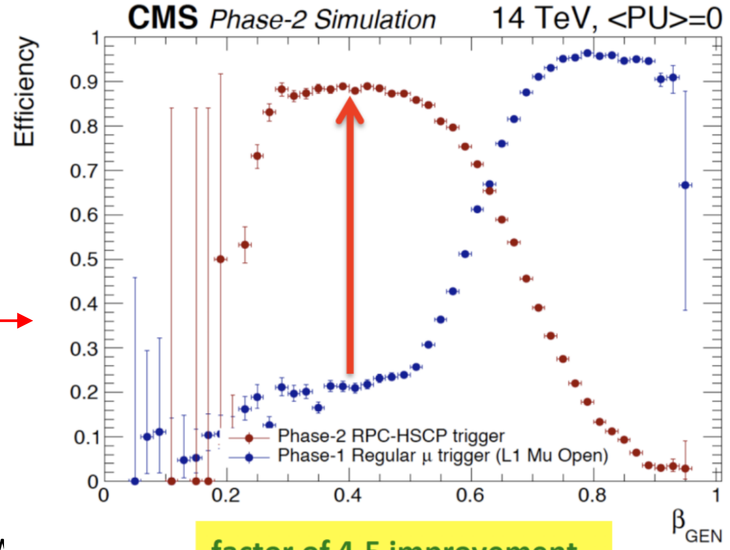
PROTOTYPING STATUS

- First prototype design is due in June 2019

ENHANCEMENTS FOR L1 TRIGGER

- better timing (25 ns digitization → 1.6 ns)
  - better suppression out-of-time background
  - trigger on HSCP
- better integration of RPC hits into RPC+DT TPs





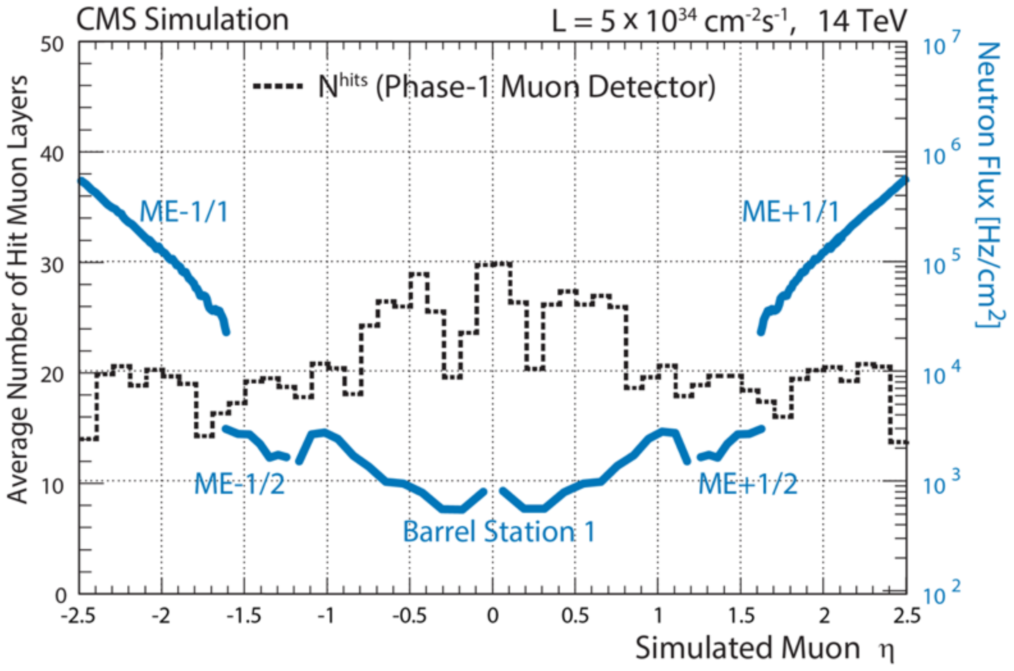
factor of 4-5 improvement

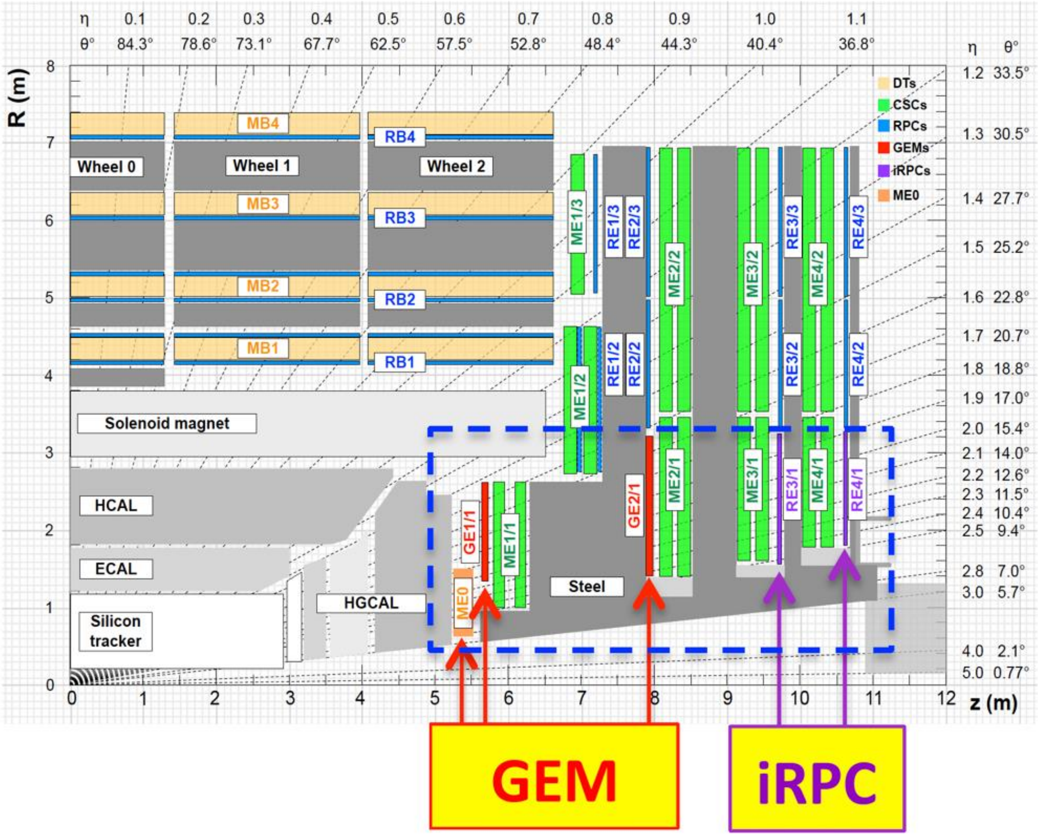
New detectors

New detectors in the forward direction

VERY CHALLENGING FORWARD REGION

- high rates due to n/γ-induced background, punchthrough, and muons
- small bending of muons by magnetic field
- small number of hits per muon in the forward direction (present system); smaller than in the barrel!



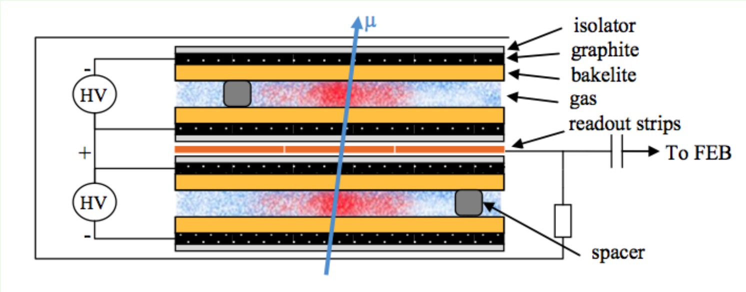


Enhance the forward system by adding:

- **GE1/1:** 2 extra points
- **ME0:** 6 layers (and, opportunistically, η coverage is extended from 2.4 to 2.8)
- **GE2/1:** 2 extra points
- **iRPC:** 1 extra point per station

iRPC (improved RPC) detectors

improved RPC



Conventional double-layer RPC units (1 hit) with critical improvements:

- lower resistivity, smaller gas gain, more sensitive FE: **higher rate capability**
- two-end strip readout with O(0.1) ns time resolution: **true 2D hits with 1 cm localization**

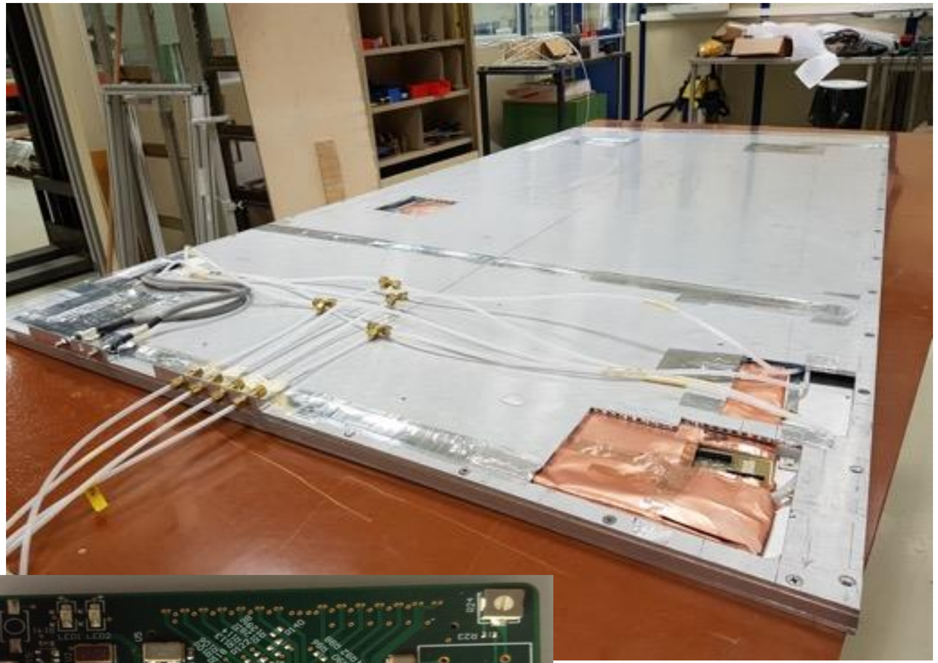
RE3/1 and RE4/1 stations:

Overall area: **90 m^2**

Number of channels: **14K**

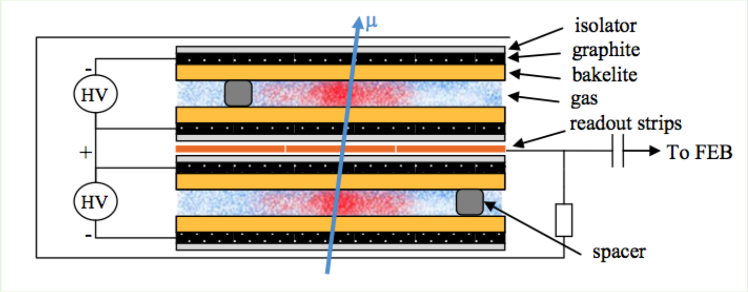
STATUS

- Next iRPC prototype with FEBv3 is due in March 2019



iRPC (improved RPC) detectors

improved RPC



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Overall area: **90 m^2**

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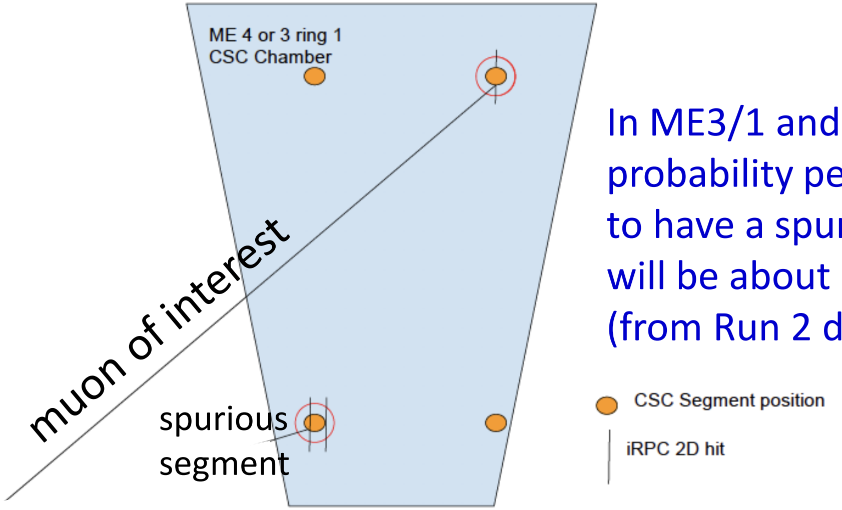
ENHANCEMENTS FOR L1 TRIGGER

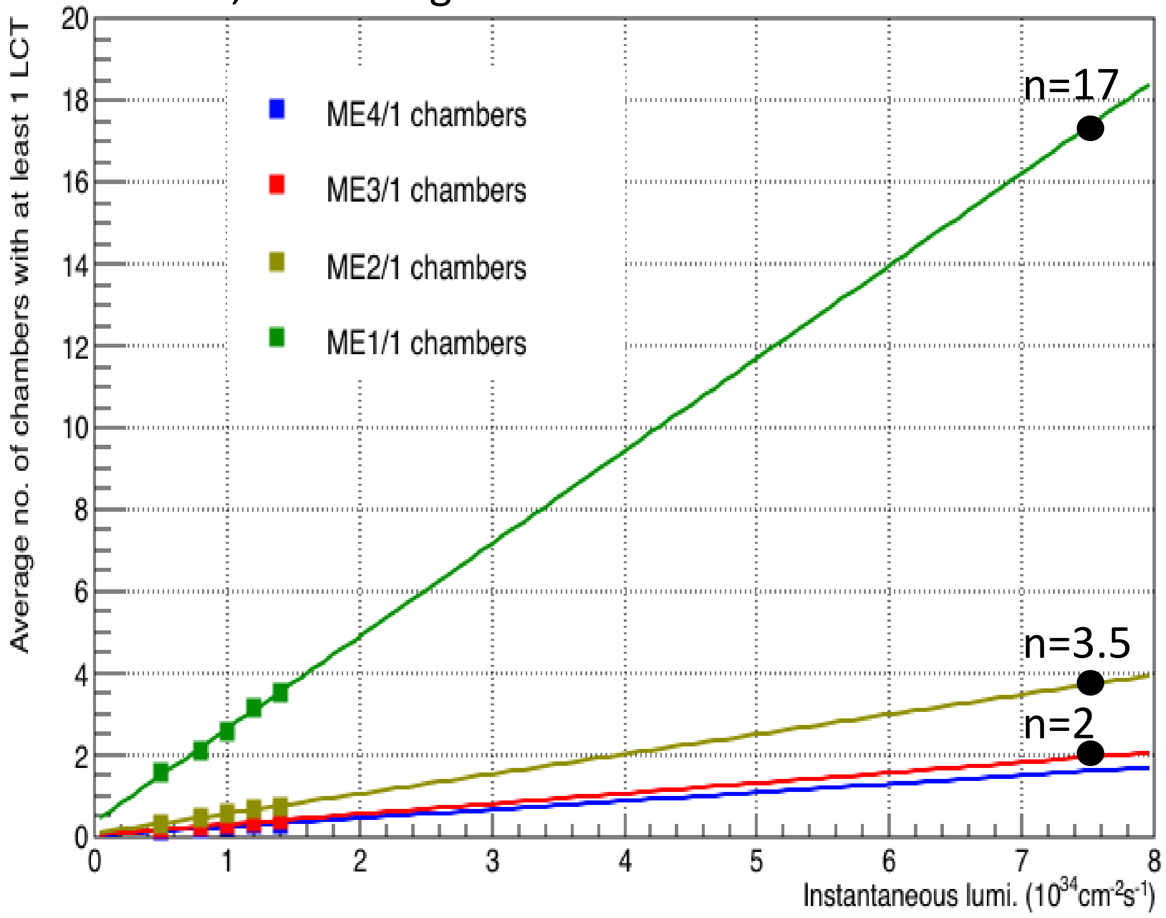
- 2 more muon measurements in the forward direction
- iRPC hits excellent timing of O(1) ns should help suppress out-of-time background
- iRPC hits will help disentangle combinatorial ambiguities in CSCs with multiple muons



In ME3/1 and ME4/1 chambers, probability per chamber to have a spurious segment will be about 10% at HL-LHC (from Run 2 data extrapolation)

Rate of trigger primitives (LCT) in forward CSCs

Run 2, Jian Wang



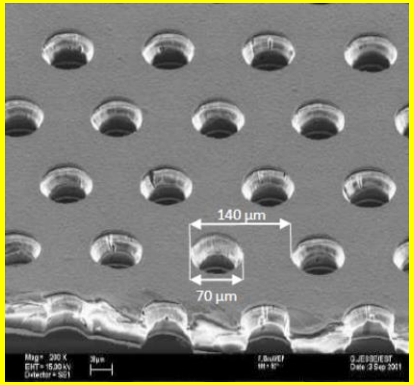
Probability per chamber: p = n/N * 3

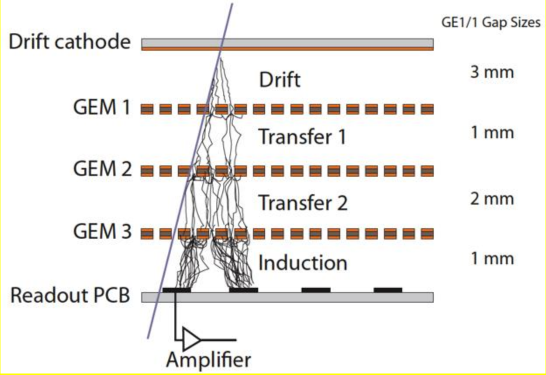
- n - average number of chambers with LCTs per BX
- N – number of chambers of that type
- 3 – accounts for 3 BXs, the time window for LCTs to be possibly associated with the same muon in EMTF

ME1/1:	p~70%
ME2/1:	p~30%
ME3/1 and ME4/1:	p~15%

GEM detectors

GEM – gas electron multiplier





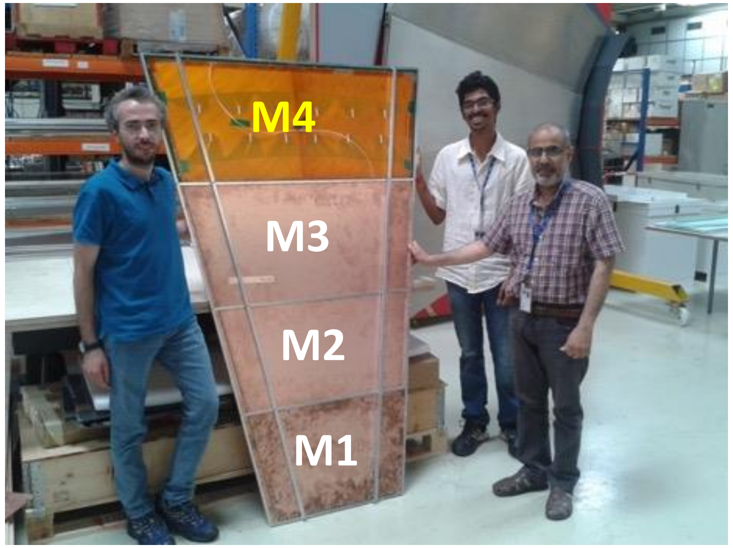
Avalanches in strong electric field concentrated in pin holes
Triplet GEM: **gas gain 10^4**
Operate well in **high rate**
Tests show **excellent longevity**

GE1/1, GE2/1 stations: 2 layers of triplet-GEM units
ME0: 6 layers of triplet-GEM units
Overall area (triplet-GEM): **220 m^2**
Number of channels: **1.5M**

STATUS

- GE1/1 will be installed in LS2
- Final GE2/1 prototype (detector+electronics) – Dec 2018
- Final ME0 prototype comes in 2021

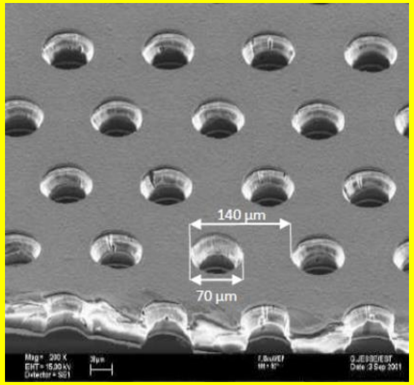
GE1/1 chamber

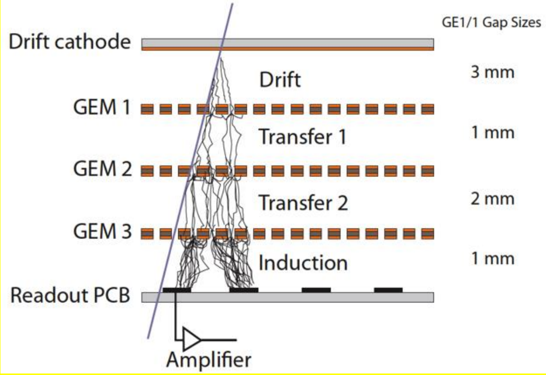


GE2/1 chamber

GEM detectors

GEM – gas electron multiplier





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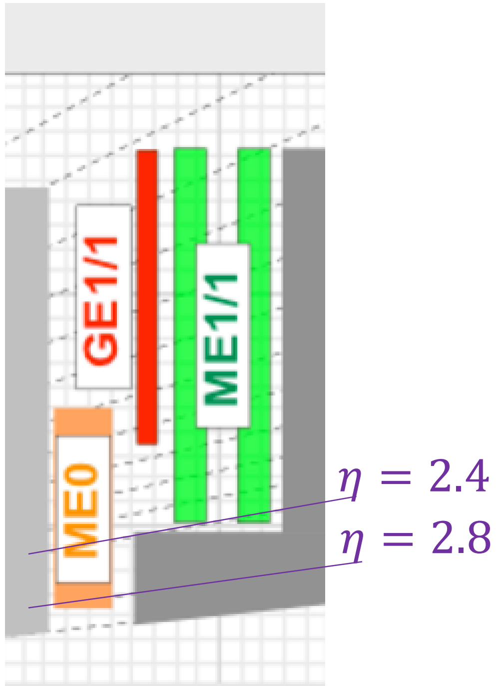
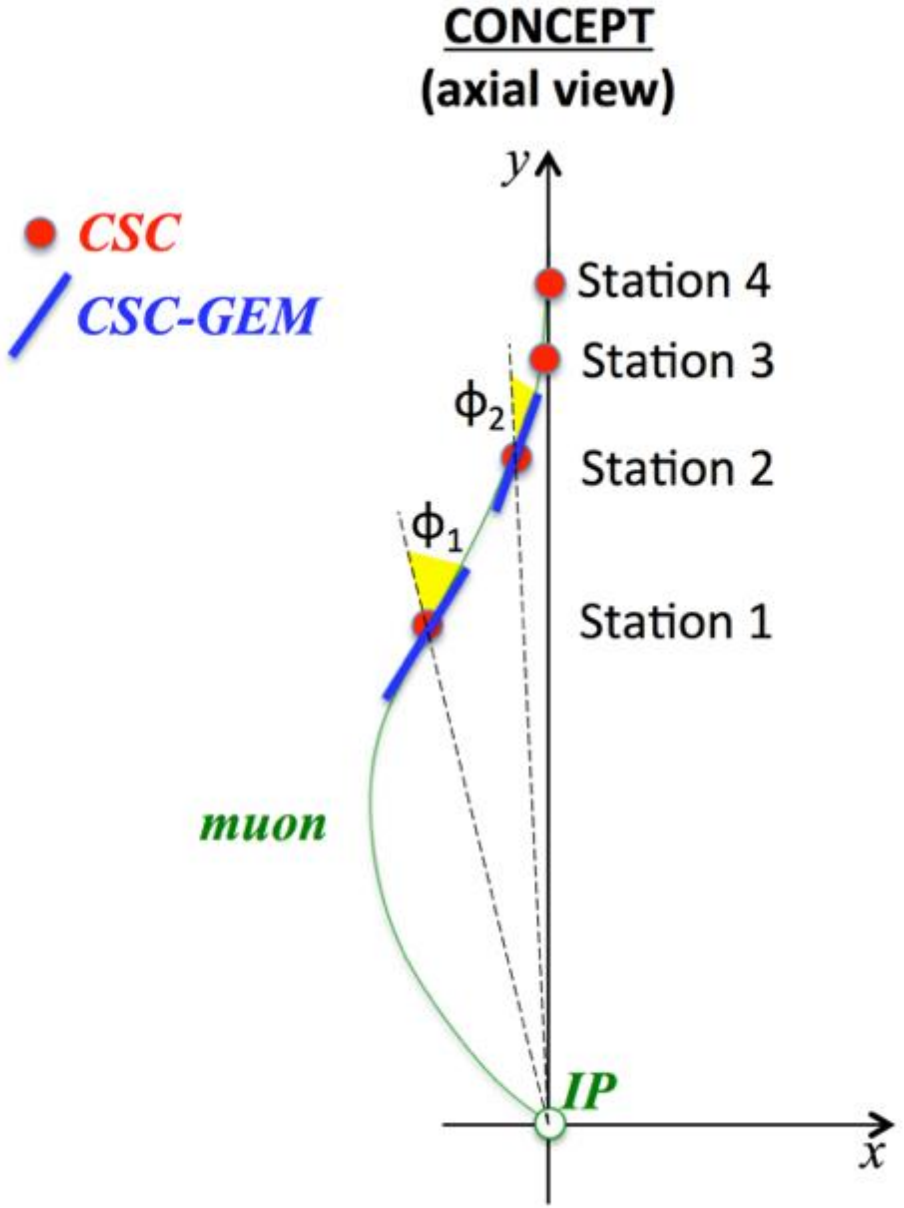
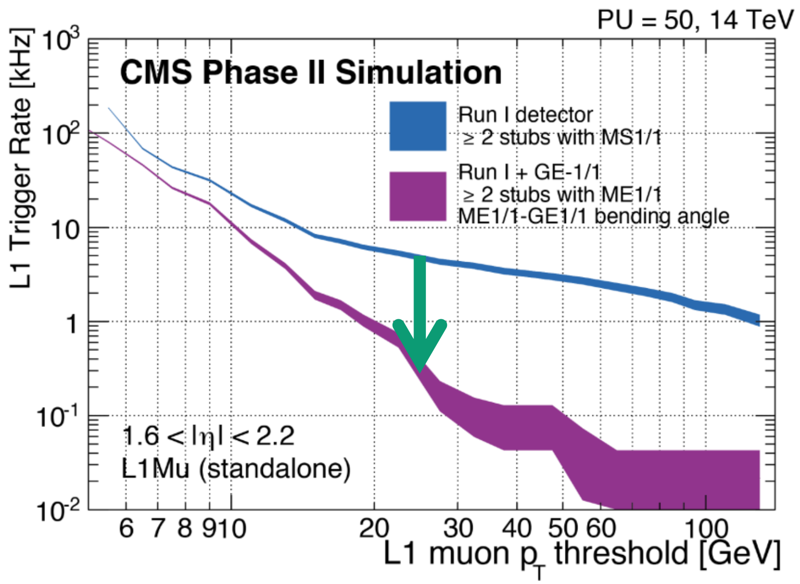
ENHANCEMENTS FOR L1 TRIGGER

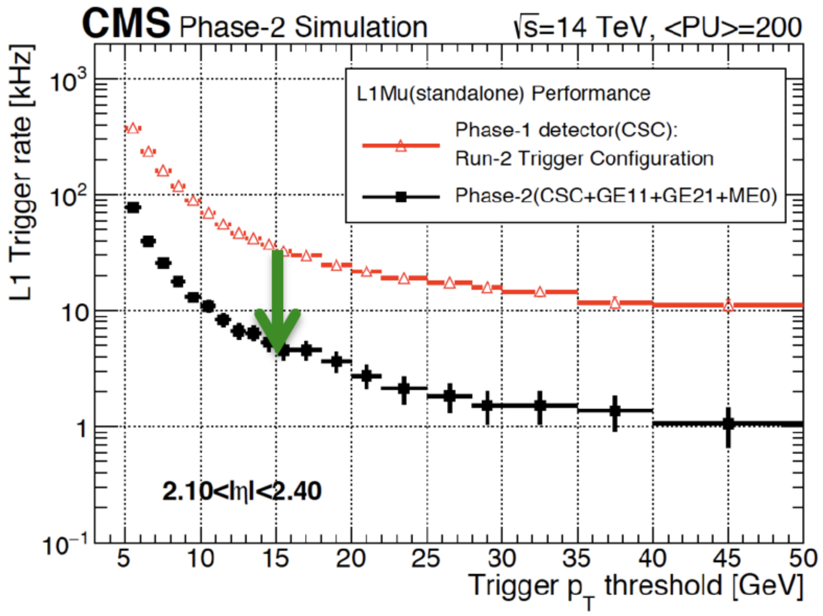
- more muon measurements in the forward direction
- GEM hits help disentangle combinatorial ambiguities in CSCs with multiple muons
- GEM-CSC tandems in the 1st and 2nd muon stations allow for muon track "bending angle" measurements:
  - sharpen muon trigger efficiency turn-on
  - reduce trigger rate
- ME0 extends eta from 2.4 to 2.8, which enhances sensitivities for searches for and measurements of processes with muons in the forward region (getting these muon at trigger level is a challenge!)

Muon p_T with CSC+GEM tandems

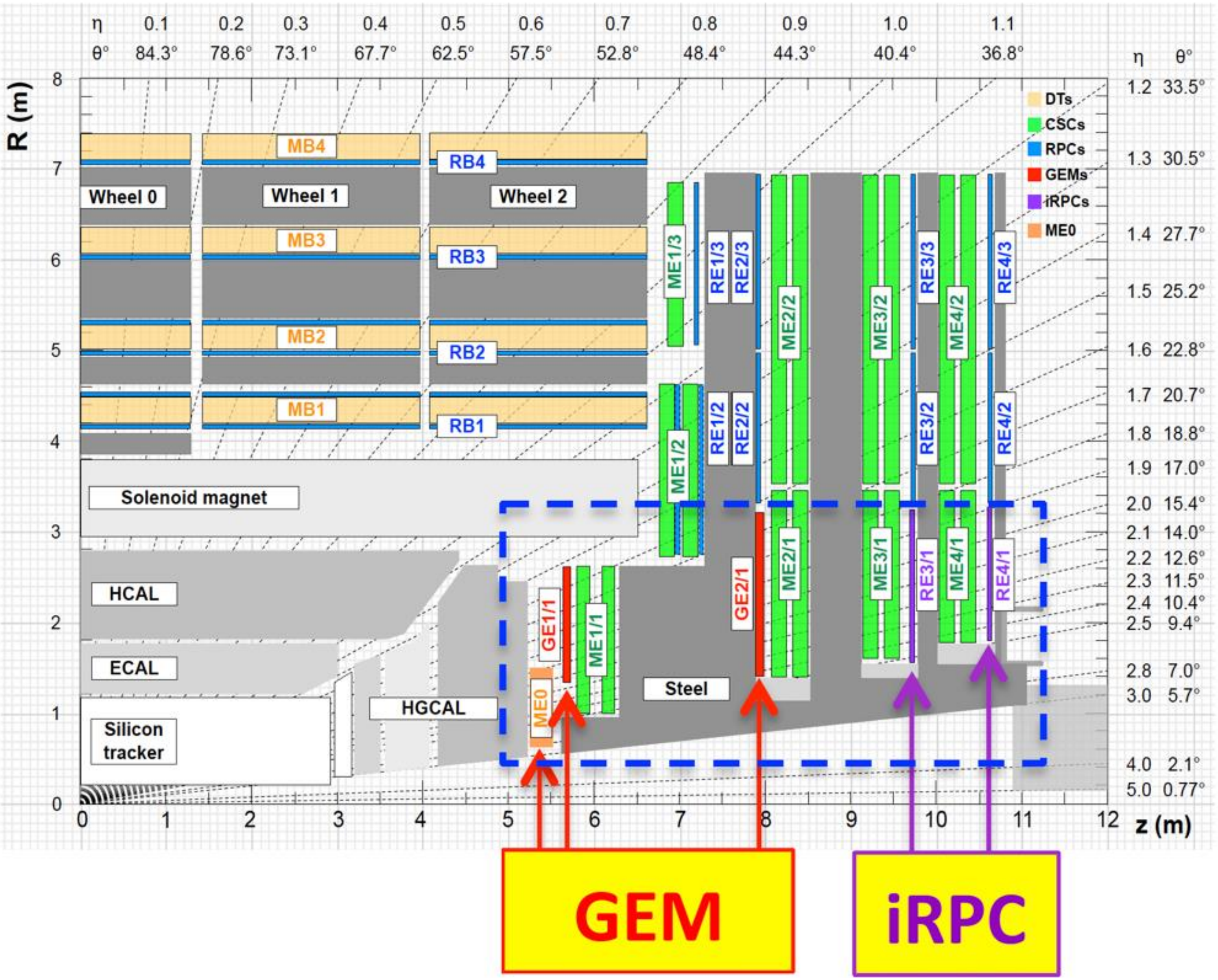








Summary (form the L1 trigger perspective)

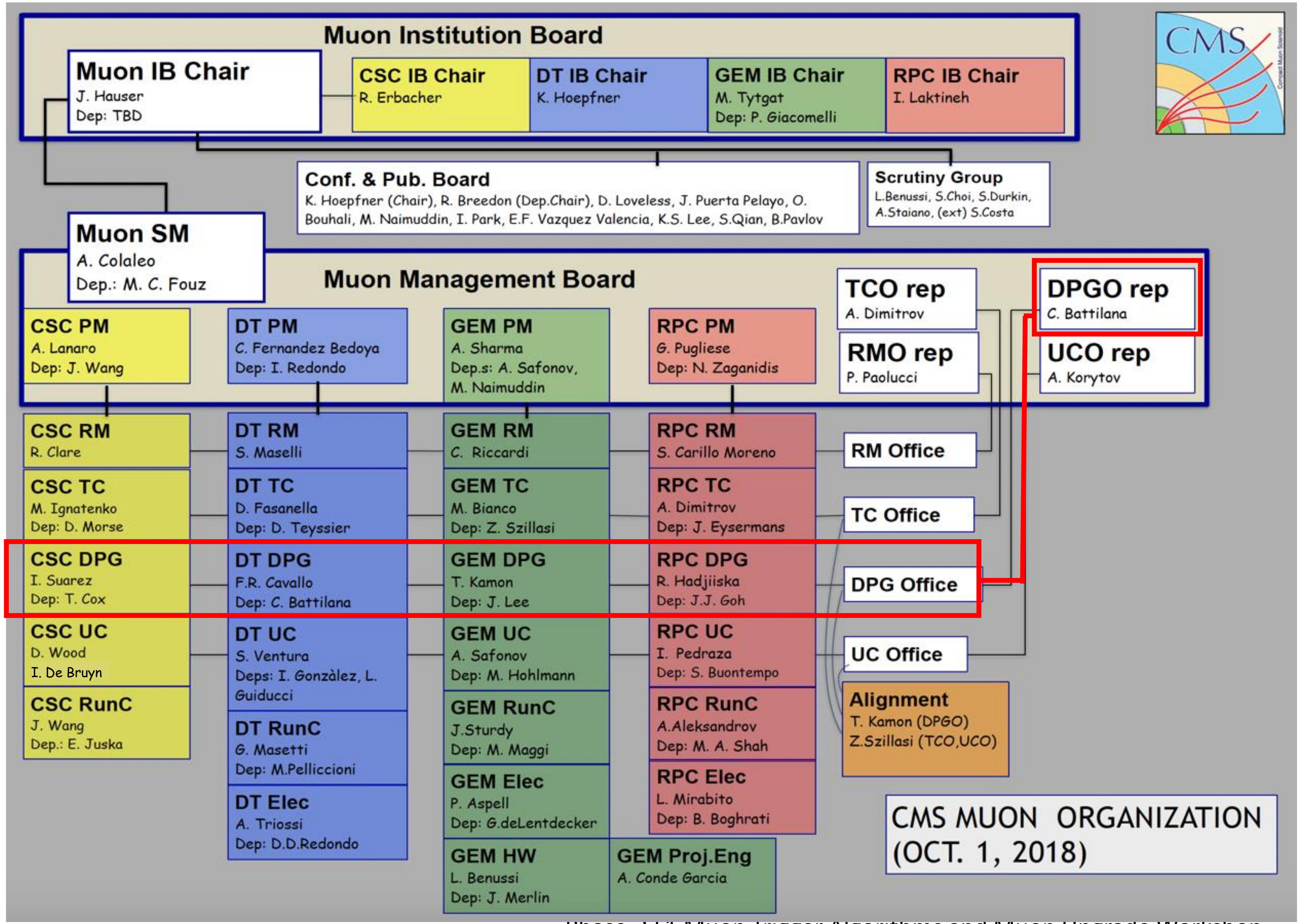


DT, CSC, RPC electronics will be upgraded to cope with HL-LHC L1/DAQ requirements. New electronics will have considerably enhanced L1 trigger capabilities.

New GEM and iRPC detectors will make triggering in the challenging forward region far more robust.

Backup

Project Organization



Highlighted are the people coordinating simulation, emulation, reconstruction

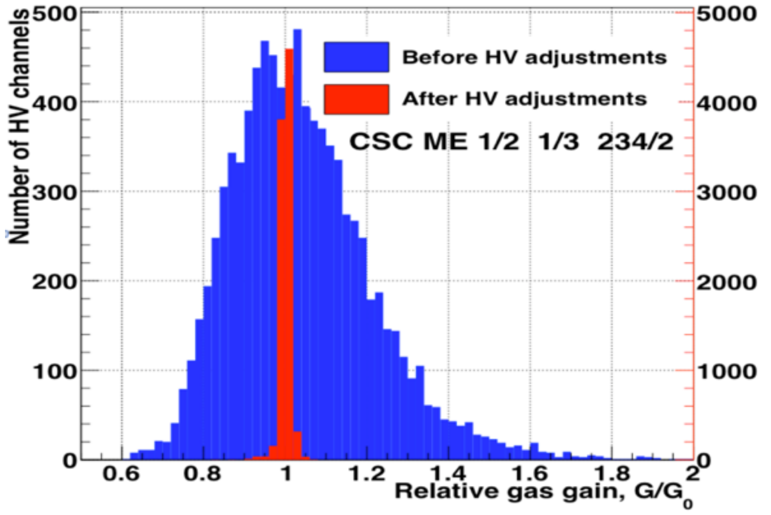
DTs: expected accumulated charge

Table 3.1: Estimated integrated charge in mC/cm up to the end of HL-LHC operations (3000 fb^{-1}) based on measured currents as a function of instantaneous luminosity corrected for the effect of the MB4 top shielding and of operating at 3550 V. No safety factor was included. The quoted uncertainty includes instantaneous luminosity measurement (5%) and stability among fills (3%).

	Wheel-2	Wheel-1	Wheel 0	Wheel +1	Wheel+2
MB4 S4	3.6 ± 0.3	3.7 ± 0.3	3.1 ± 0.2	3.4 ± 0.2	4.3 ± 0.4
MB4 S3-S5	3.4 ± 0.4	2.1 ± 0.2	2.7 ± 0.2	3.0 ± 0.2	3.5 ± 0.3
MB4 S1-S7	7.0 ± 0.4	5.0 ± 0.3	3.8 ± 0.2	4.6 ± 0.3	6.0 ± 0.2
MB4 S12-S8	4.8 ± 0.3	3.0 ± 0.2	2.2 ± 0.2	2.6 ± 0.2	3.7 ± 0.2
MB1	9.9 ± 0.6 17.0 ± 0.7 (3600 V)	4.4 ± 0.3	1.6 ± 0.2	4.2 ± 0.3	10.0 ± 0.6 16.0 ± 1 (3600 V)
MB2	2.1 ± 0.2	0.90 ± 0.05	0.50 ± 0.03	0.80 ± 0.05	2.0 ± 0.2
MB3	0.4 ± 0.1				

CSCs at P5

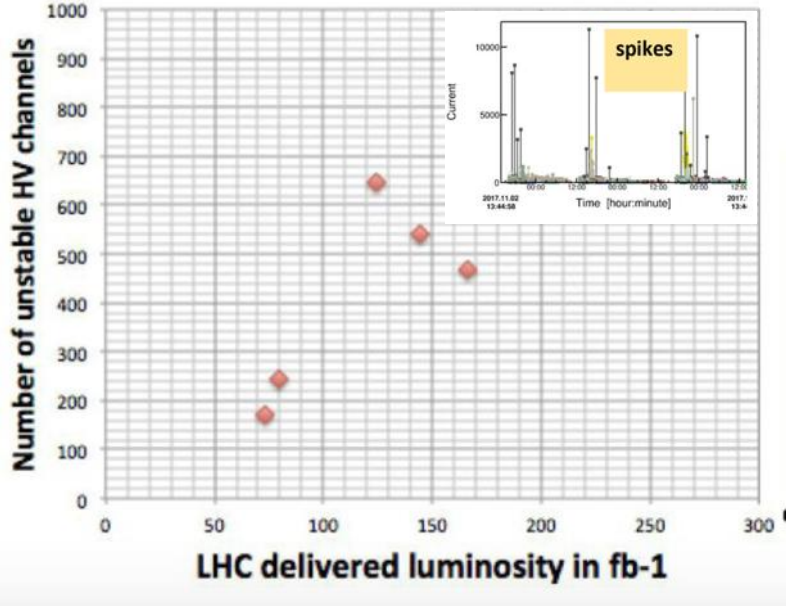
CSC efficiency, space and time resolution are stable since early running



Gas gains are now equalized:

- no chambers run at too high gas gain and, thus, run unnecessary fast their longevity resource
- no chambers run at too low gas gains, which gives room to reduce gas gain

Current instabilities:

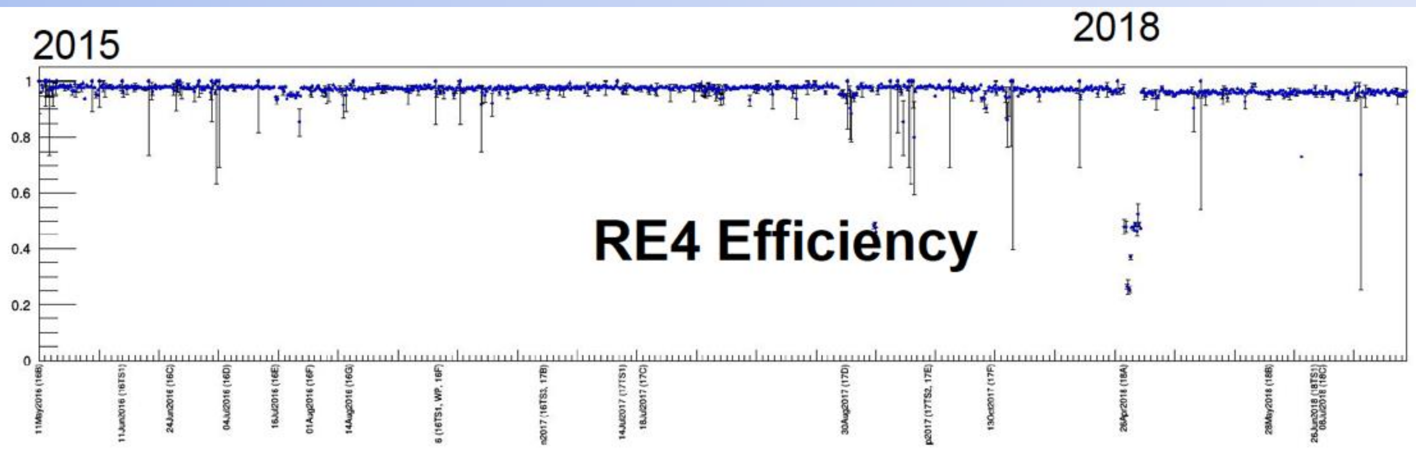


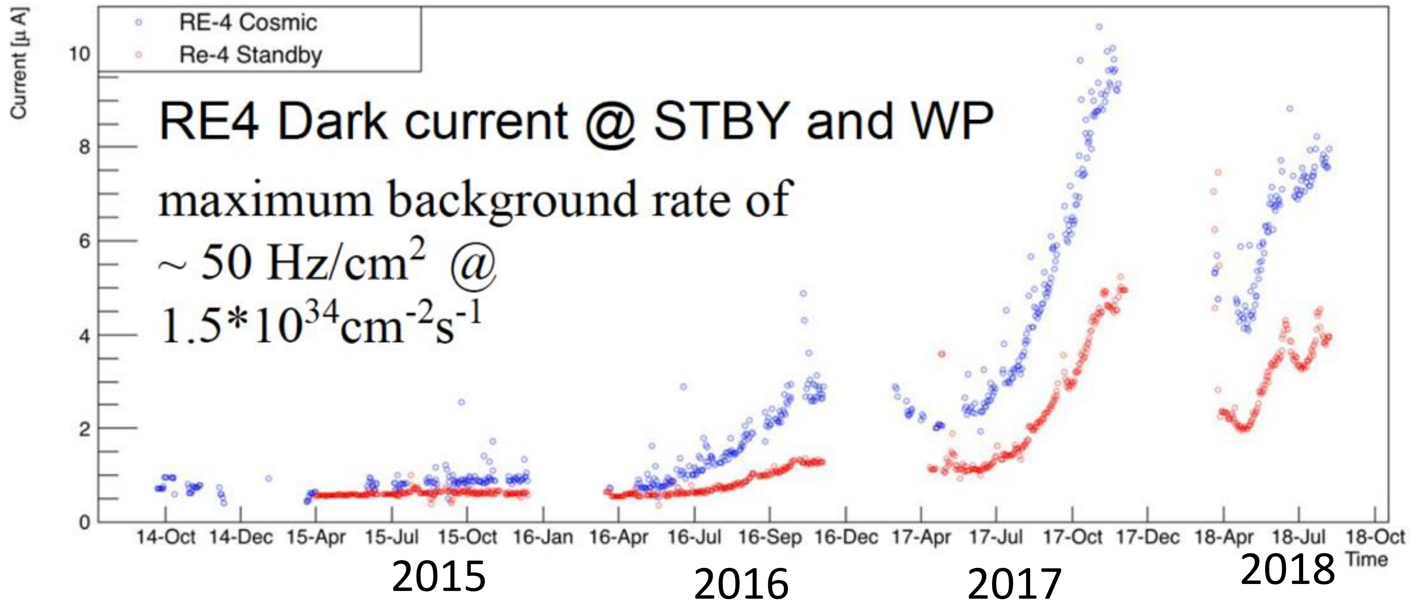
- Observed in Run 2 an increase in occurrences of current spikes and some Malter currents (self-sustained discharges ignited at high hit rates).
- The fraction of “flaky” HV channels seems to have stabilized over the last year at O(5%) of about 12,000 HV channels. Channels with Malter are a small fraction (1-6%) of unstable channels.
- A full characterization of the Malter effect, the use of regeneration techniques, the study of the plasma chemistry and the spectroscopy of the affected materials are actively pursued at CERN GIF++, PNPI, Dubna, Sarov, and Belgrade

RPCs at P5

Stable performance:

efficiency, cluster size





Observe an increase of dark currents in the most exposed RPC stations, partially recovered during breaks (TS & YETS)