Upgrade plans and ageing studies for the CMS muon system in preparation of HL-LHC

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On behalf of the CMS Muon Group

中国物理学会高能物理分会第十届全国会员代表大会暨学术年会
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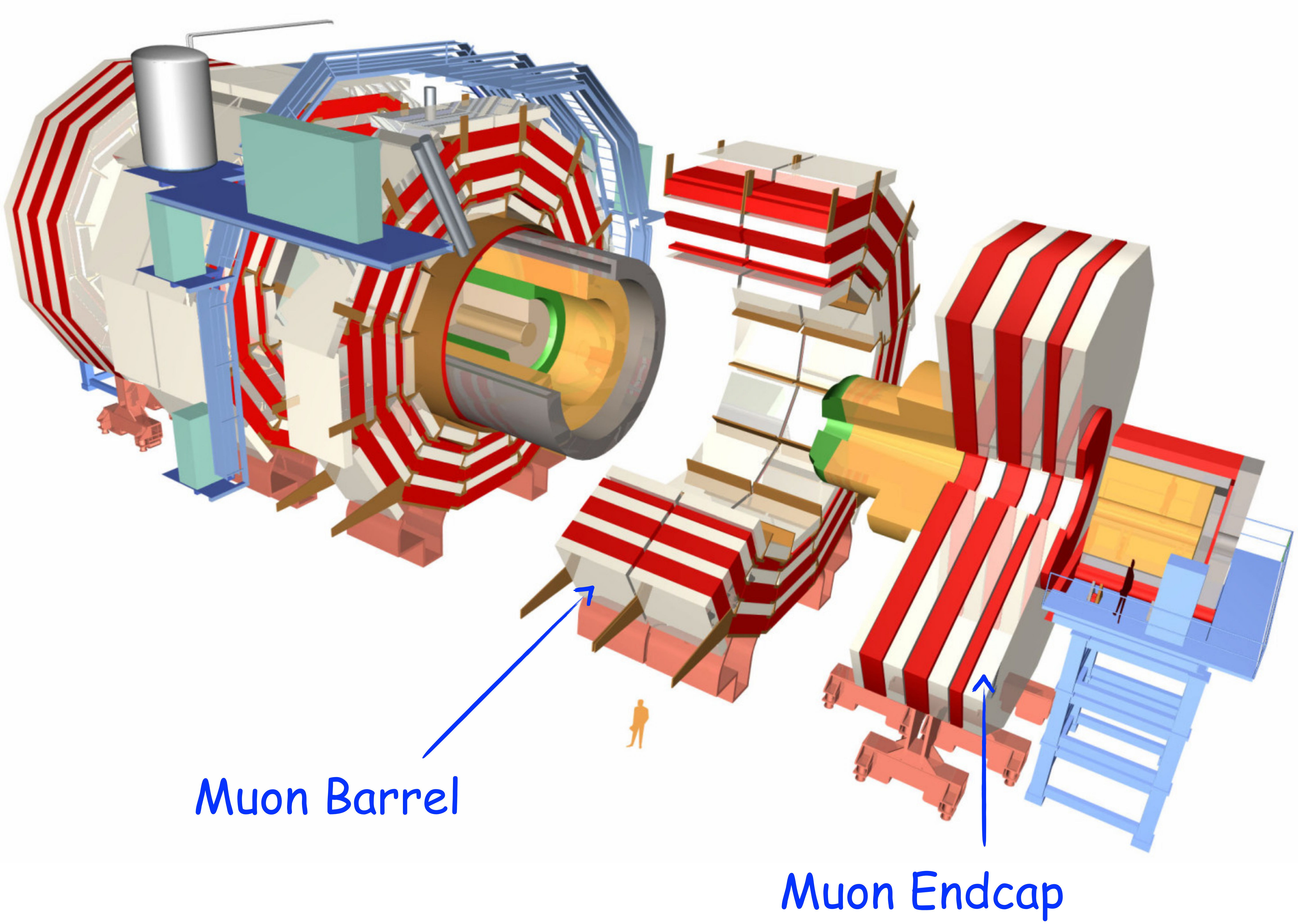
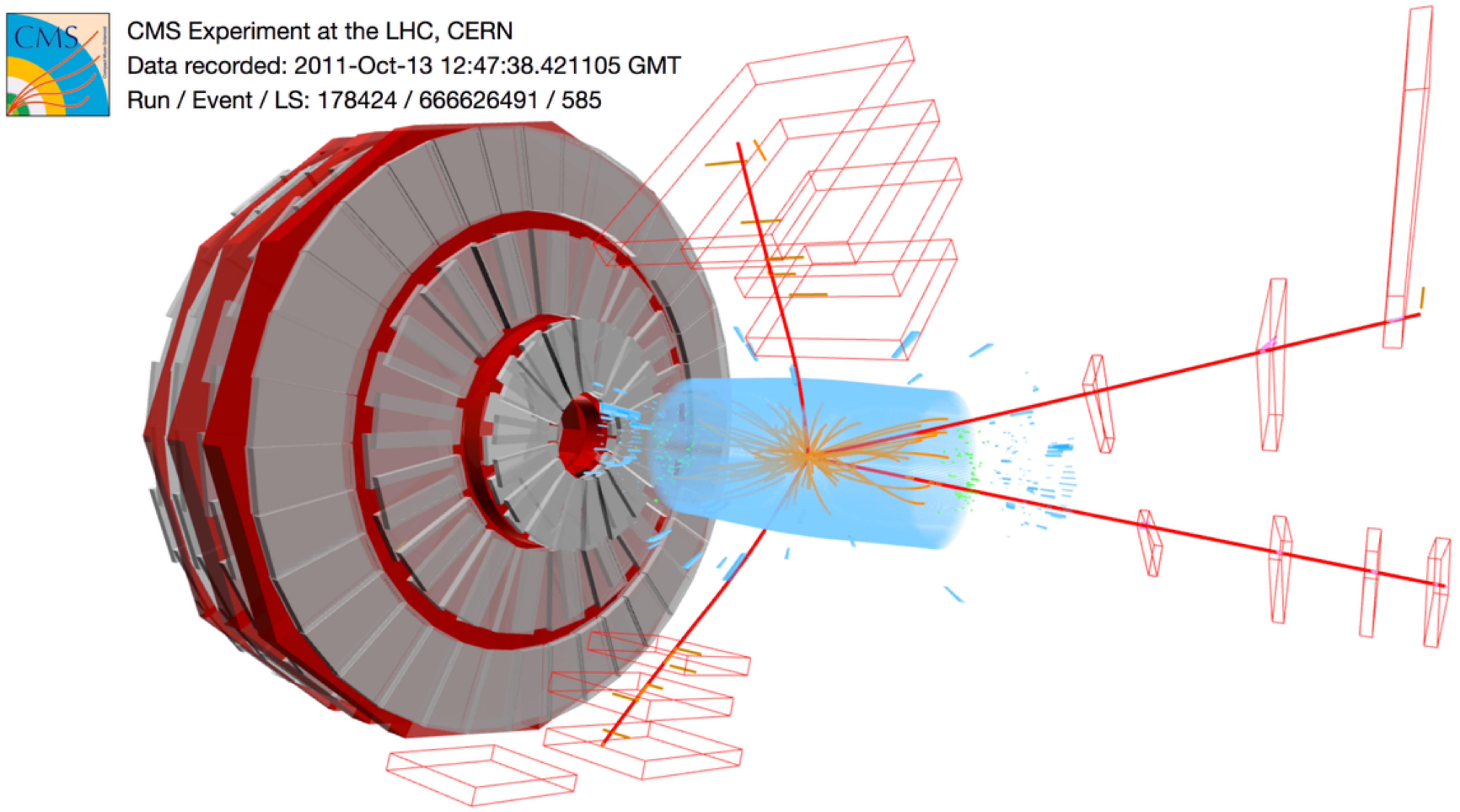
The CMS detector @ CERN LHC

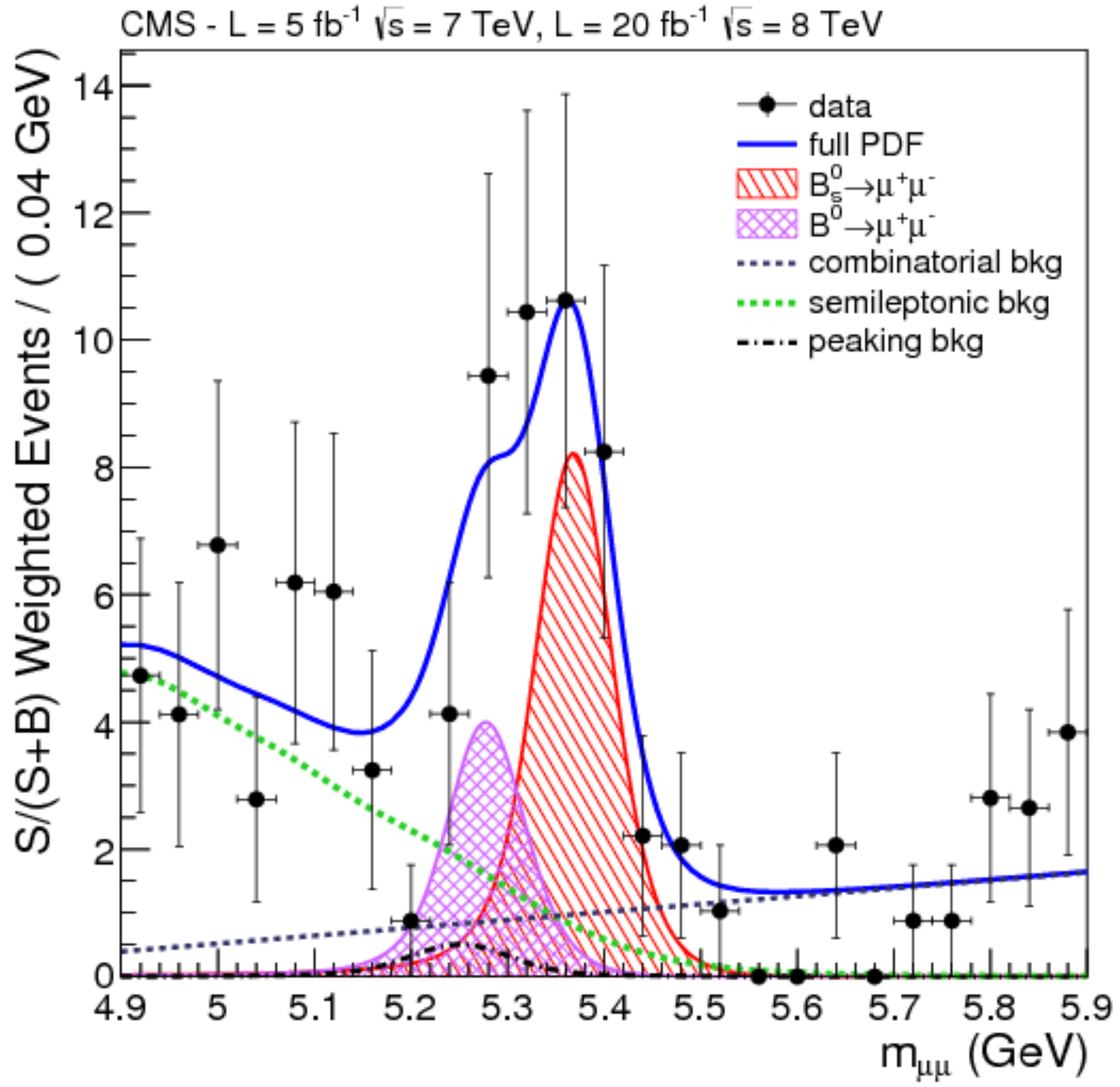


- Hadrons are copiously produced at LHC
- Almost all hadrons, electrons, and photons are absorbed in calorimeters
- Trigger, identification and measurement of muons is of great importance in searching for interesting and rare processes

Higgs -> ZZ -> 4μ
The golden channel



Bs -> 2μ rare decay



The present CMS Muon system

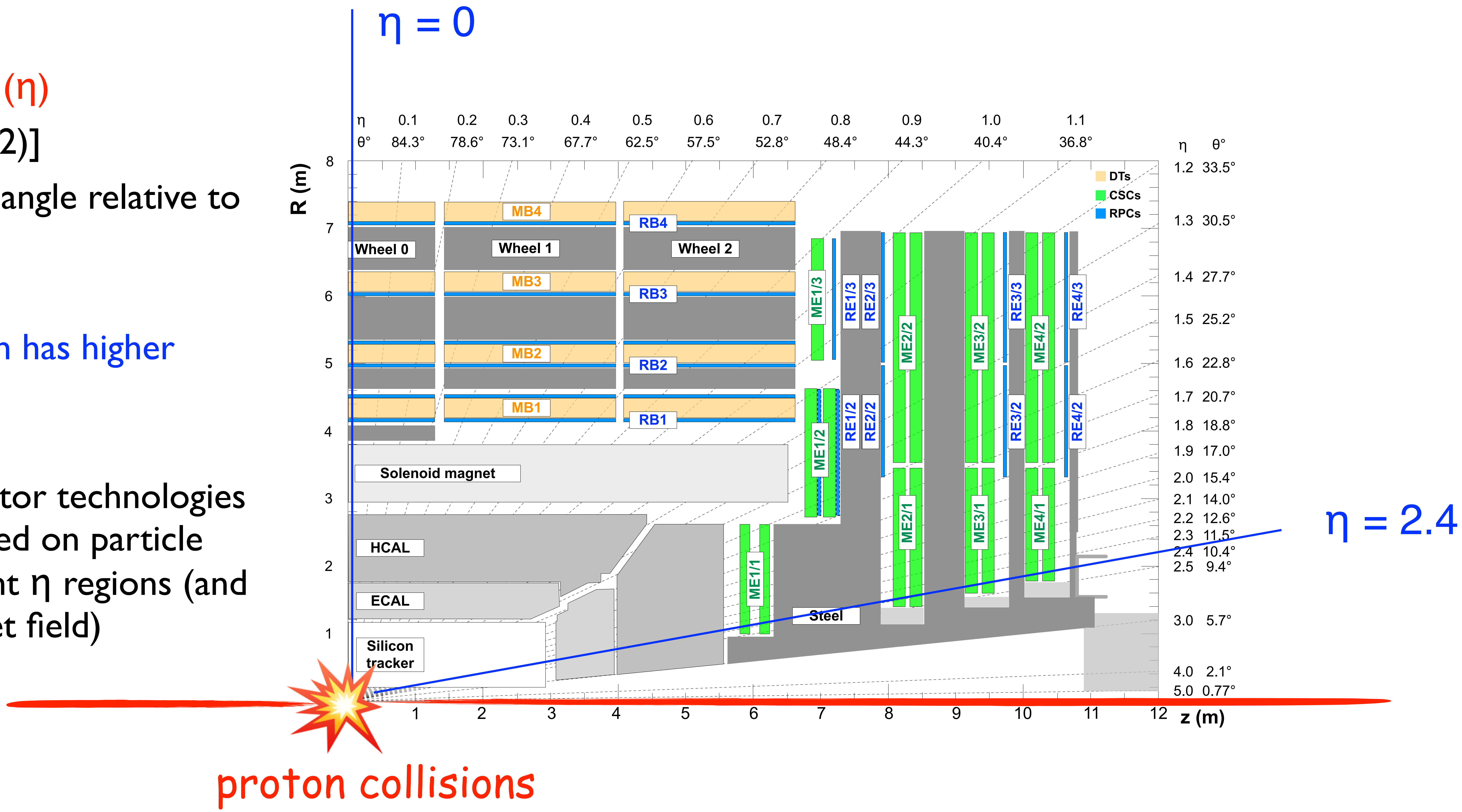
Pseudorapidity (η)

$\eta = -\ln[\tan(\theta/2)]$

where θ is the angle relative to the beam axis

Higher η region has higher particle rate

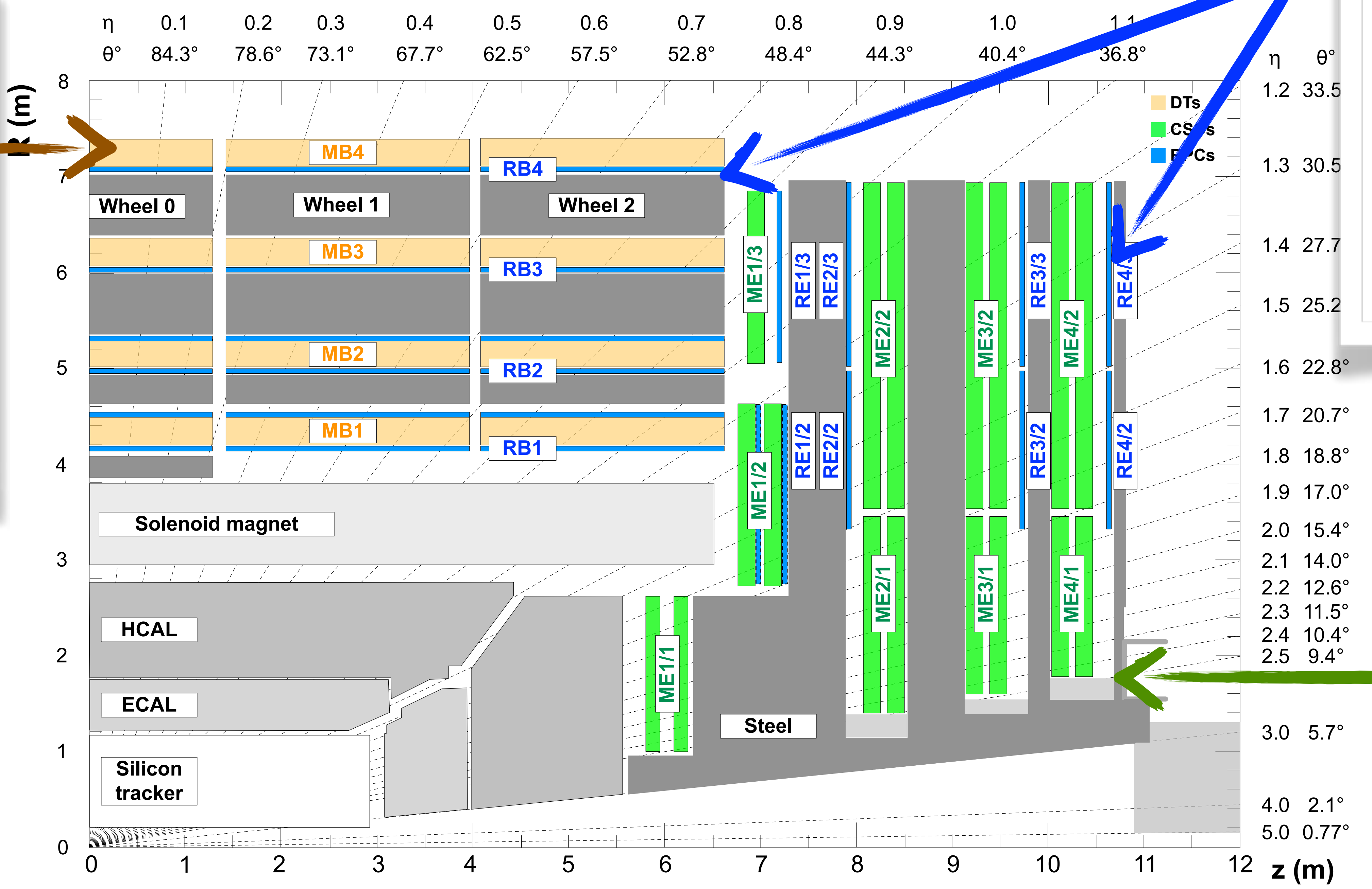
Different detector technologies are chosen based on particle rates in different η regions (and different magnet field)



Three gas detector technologies

Drift Tube (DT):
- 0 < |η| < 1.2
- 250 chambers
- Spatial resolution 100 μm
- Time resolution 2 ns

Low rate



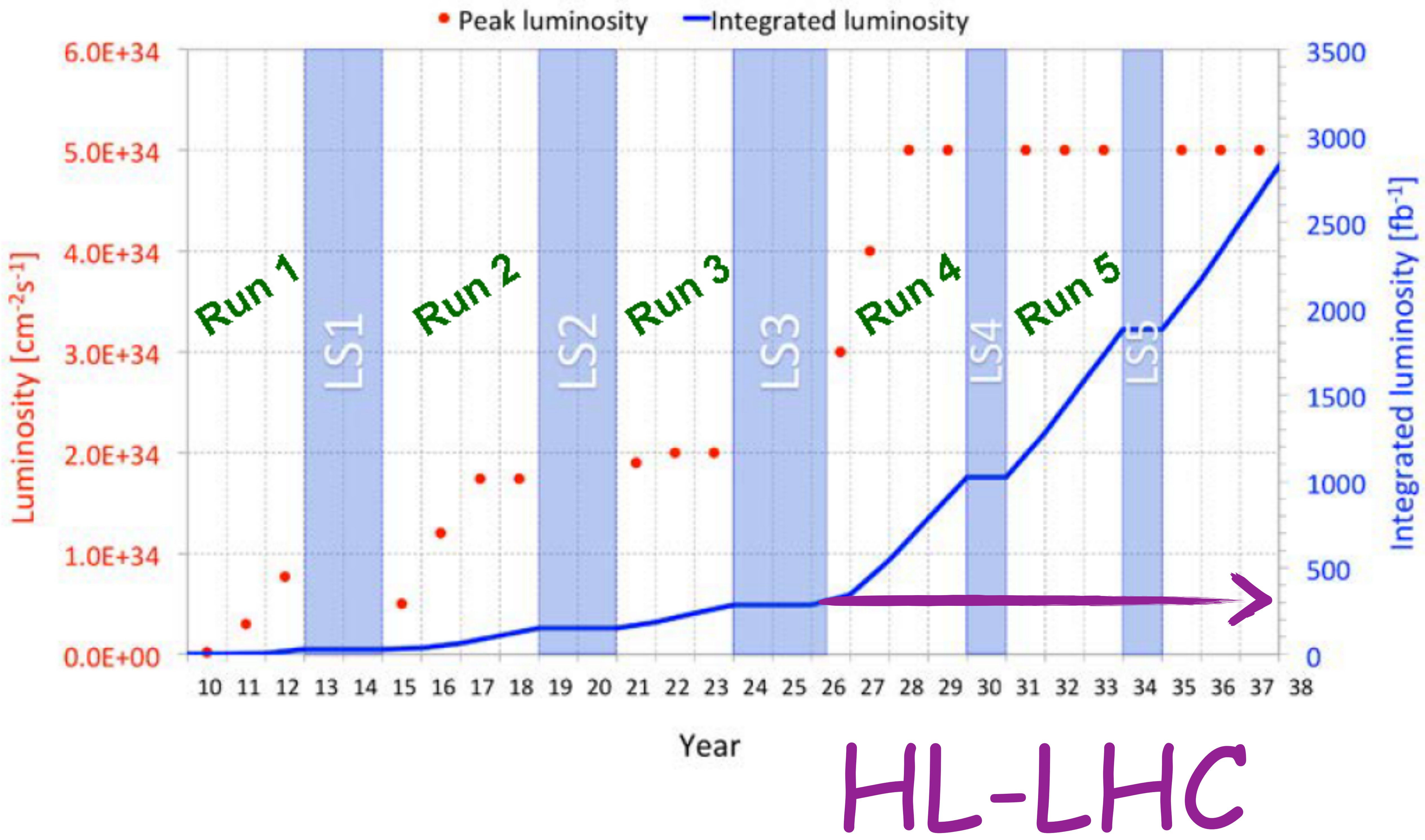
Resistive Plate Chamber (RPC)
- 0 < |η| < 1.8
- 480 (barrel) + 576 (endcap) chambers
- Spatial resolution 0.8-1.3 cm
- Time resolution ~ 2 ns

Cathode Strip Chamber (CSC)
- 0.9 < |η| < 2.4
- 540 chambers
- Spatial resolution 50-140 μm
- Time resolution 3 ns

High rate

- *The trajectory of a muon passes 4 stations, 2 types of detectors (except for the high η region)*
- *Robust trigger and efficient reconstruction*

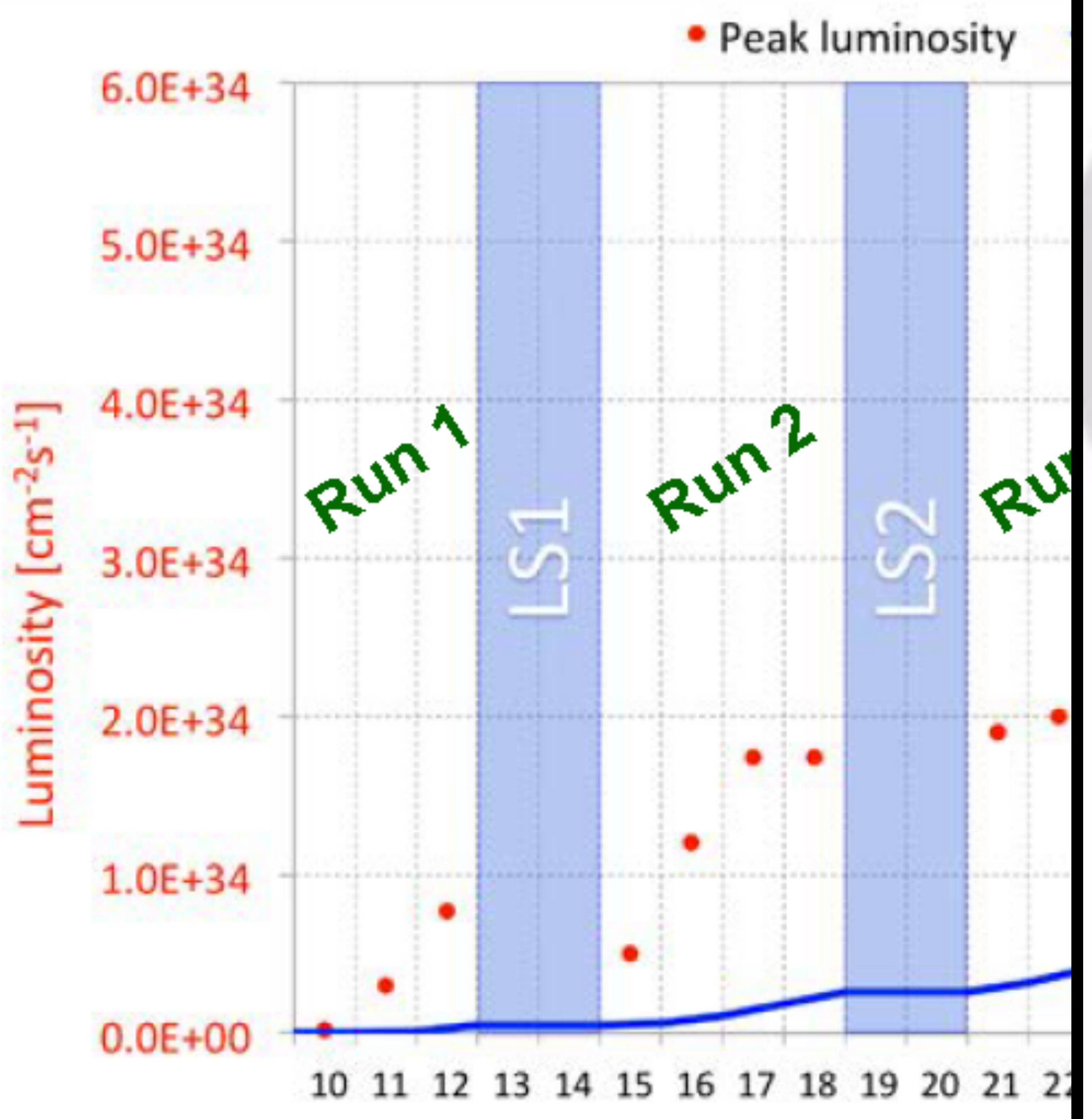
HL-LHC environment defines detector upgrades



	LHC design	HL-LHC design	HL-LHC ultimate
peak luminosity (10^{34} cm^{-2}s^{-1})	1.0	5.0	7.5
integrated luminosity (fb^{-1})	300	3000	4000
number of pileup events	~30	~140	~200

- CMS detector was designed for the LHC specifications
- Higher integrated luminosity - are the present Muon detectors sufficiently radiation hard?
- Higher instantaneously luminosity - the L1 (hardware) trigger rates 500 kHz and latency 12.5 μs would be too high for the Muon system electronics (100 kHz and 3.5 μs as of today)

HL-LHC en… …tor upgrades



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1.0	5.0	7.5
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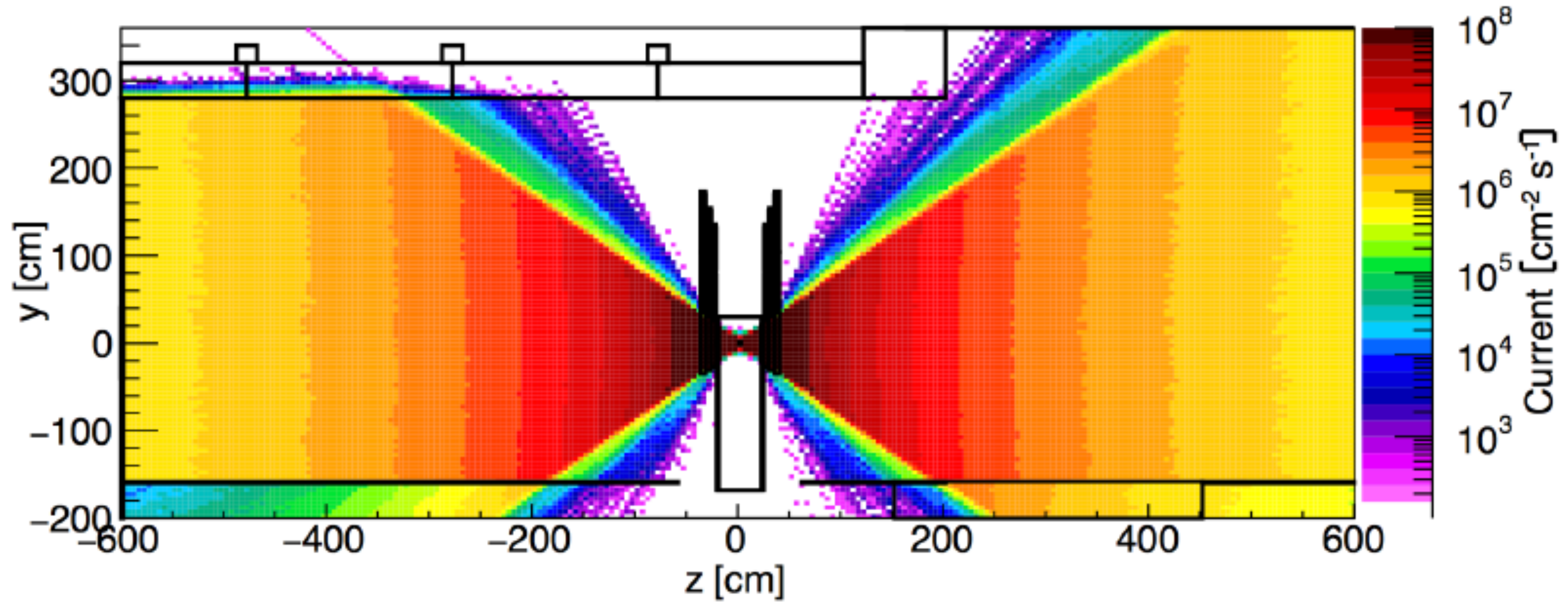
…minosity - the L1 (hardware) trigger
… 12.5 μs would be too high for the
(100 kHz and 3.5 μs as of today)

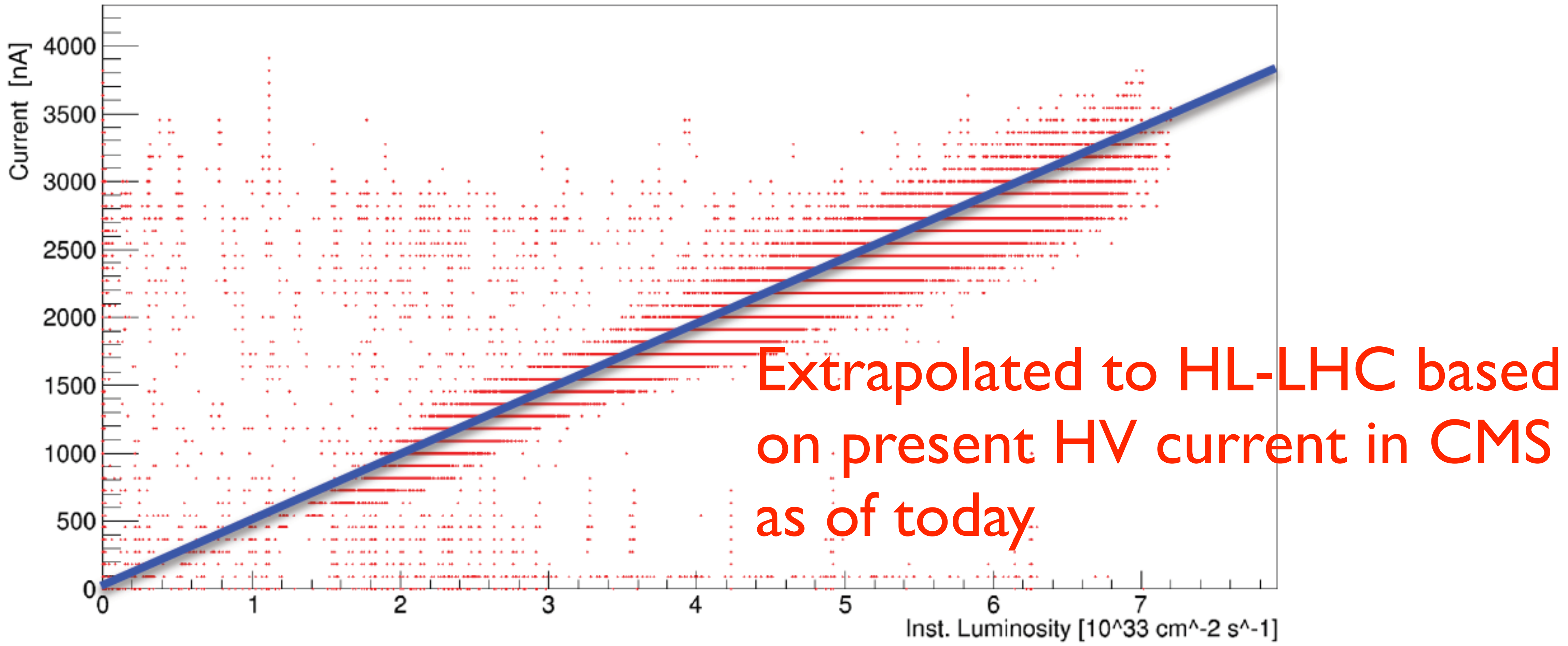
Muon detector longevity

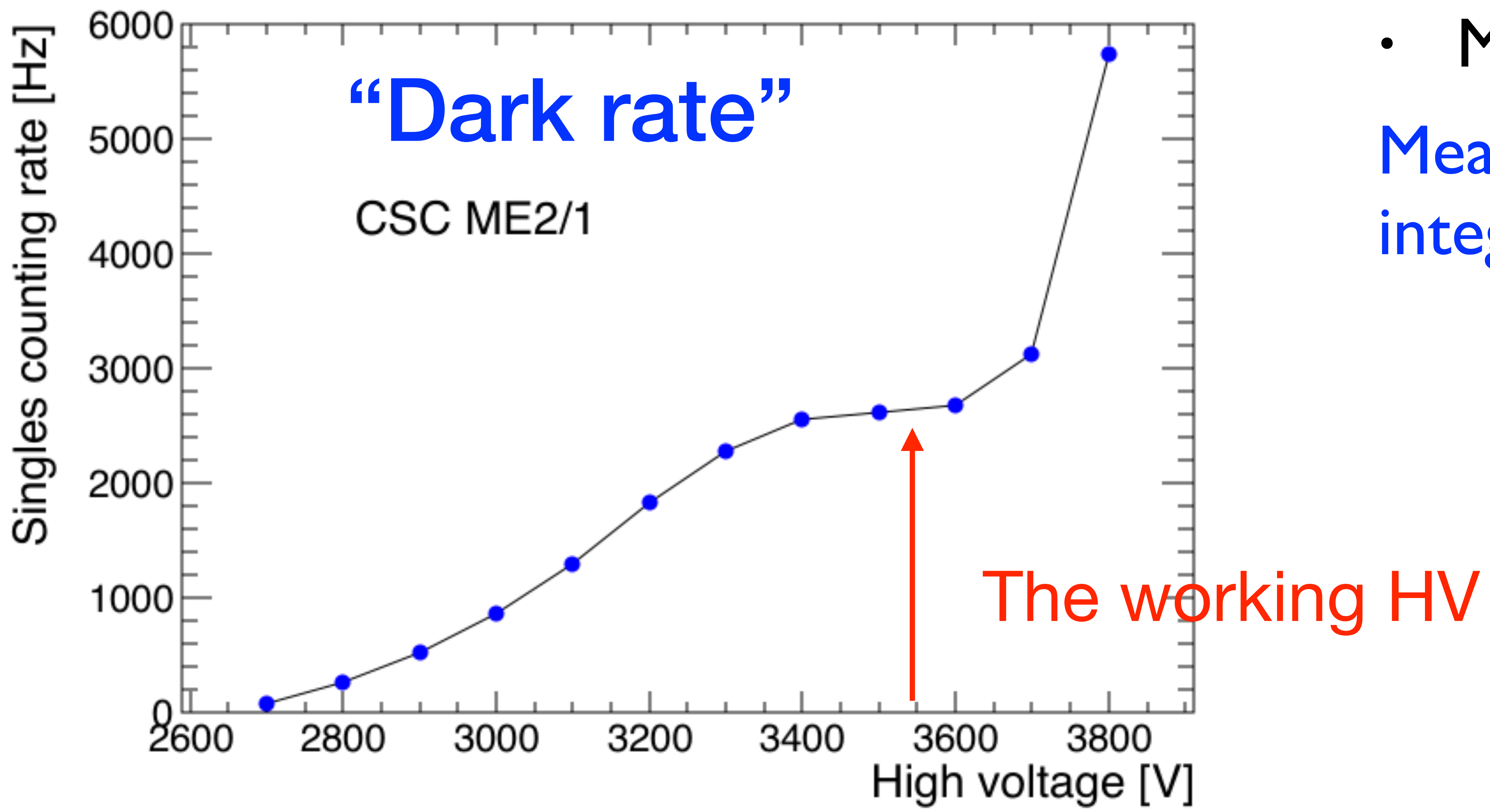
- Exposure to HL-LHC radiation could potentially cause detector deterioration and permanent failure
  - Gas gain decrease, spurious hits, self-sustained discharges, HV breakdown
- DT, CSC, RPC chambers are exposed to high rates at the CERN Gamma Irradiation Facility (GIF++)
  - Accelerated irradiation - accumulated charge per cm of wire or cm2 area is the measure of "radiation exposure"
  - In addition, a safety factor of 3 is applied



GIF++ photon flux map
Cs137, 13.5 TBq, 662 keV photons

Longevity study





- Full-size muon chambers under irradiation
- Same gas flow as in CMS
- Regular measurements to monitor the chambers
  - I vs HV; "Dark rate"; leakage current; resistance between electrodes; etc
- Muon beam test every 2 or 3 months

Measurements are recorded as a function of integrated charge (from 0 to 3xHL-LHC)

Longevity summary

DT

About 15% of chambers (the ones most exposed to background) are expected to see noticeable gas gain decrease

Muon reconstruction efficiency will remain high, thanks to multiple layers of DT on the path of a muon

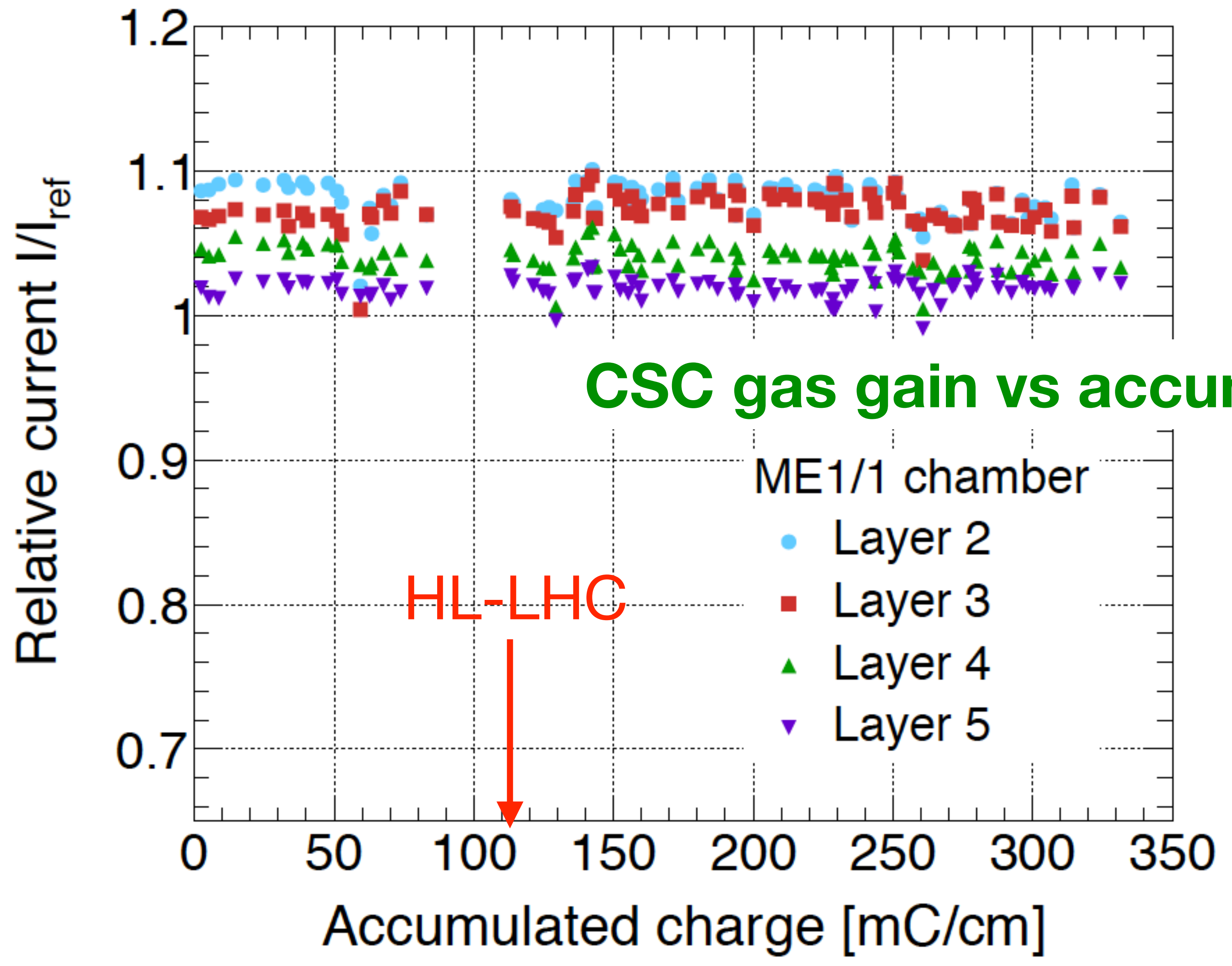
Mitigation measures are being implemented (no gas recirculation, HV adjustment, shielding for chambers, etc)

RPC

No noticeable performance degradation so far (2xHL-LHC); the test is being continued

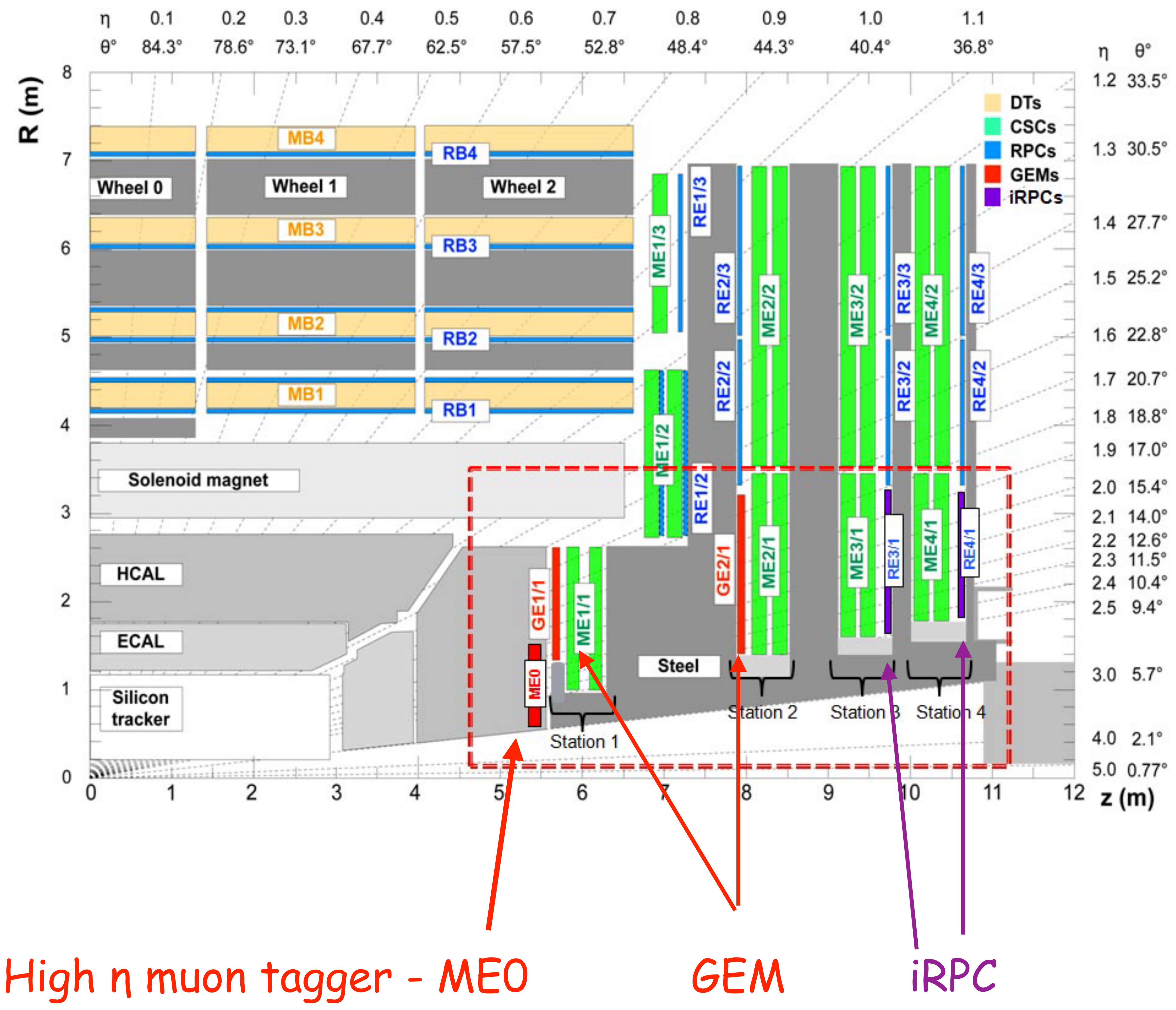
CSC

No noticeable performance degradation up to 3 x HL-LHC (330 mC/cm)



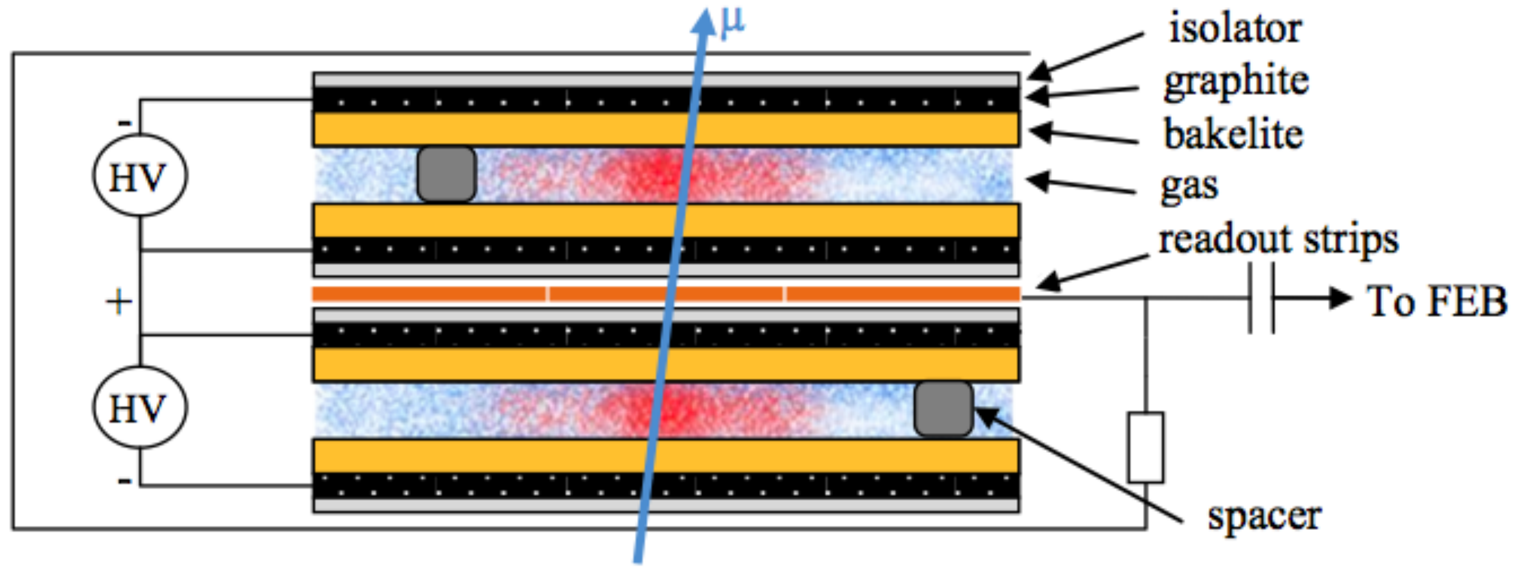
CSC gas gain vs accumulated charge

New detectors in the high η region

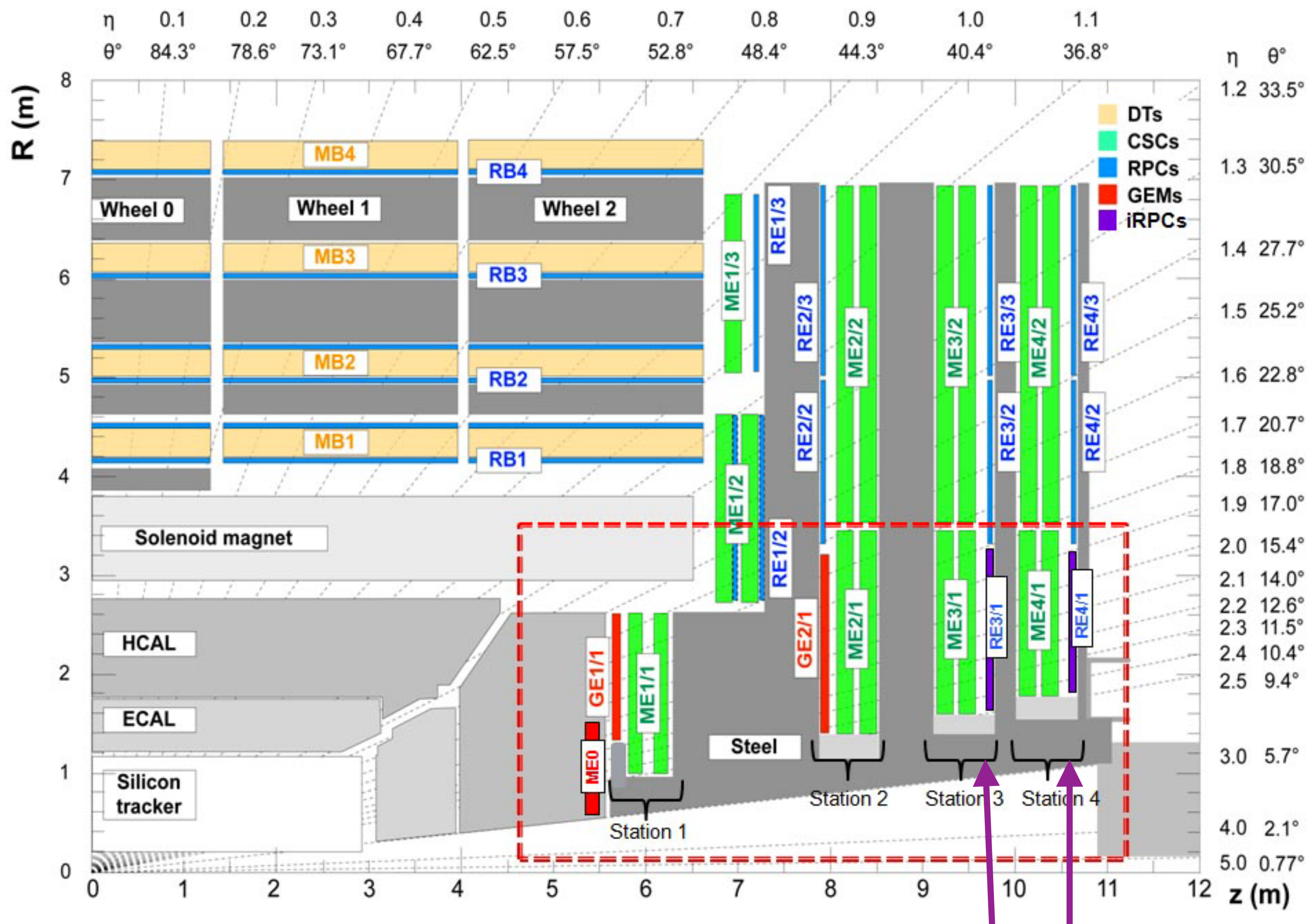


- Very challenging region
  - High rate from random hits, hadron punch-though, and muons
  - Low magnetic field => small bending of muon trajectory
- Despite harsher environment, this region has fewer hits measurement as of today
  - 1.8 < |η| < 2.4 covered only by CSC

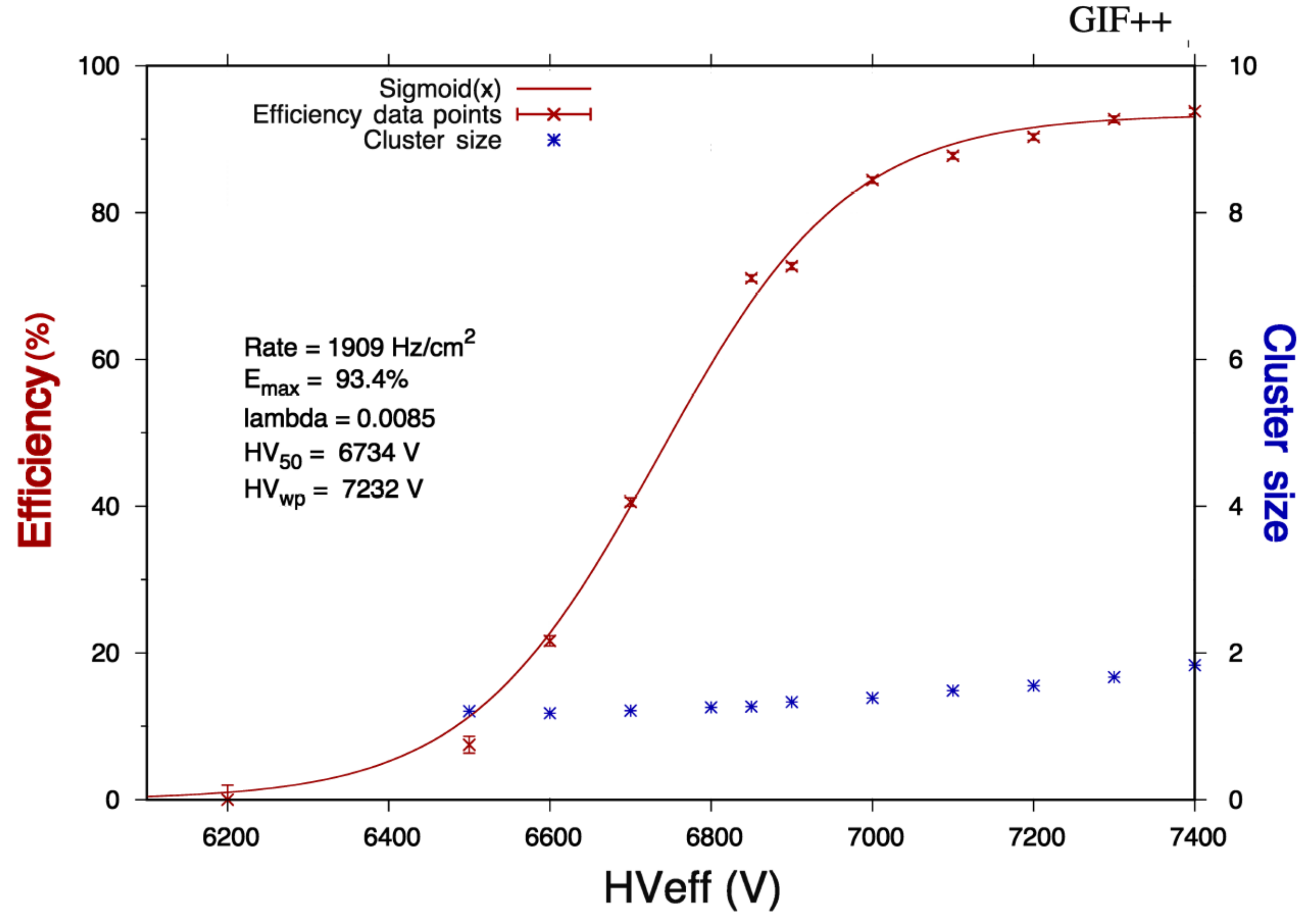
Improved RPC



- Endcap stations 3&4; 1.8 < |η| < 2.4 (RE3/1, RE4/1)
- Double-gap RPC units (same as the present RPC)
- Improved performance
  - Higher rate capability (lower resistivity, smaller gas gain)
  - Two-side strip readout
    - Providing true 2D hits with O(1) cm resolution in both dimensions

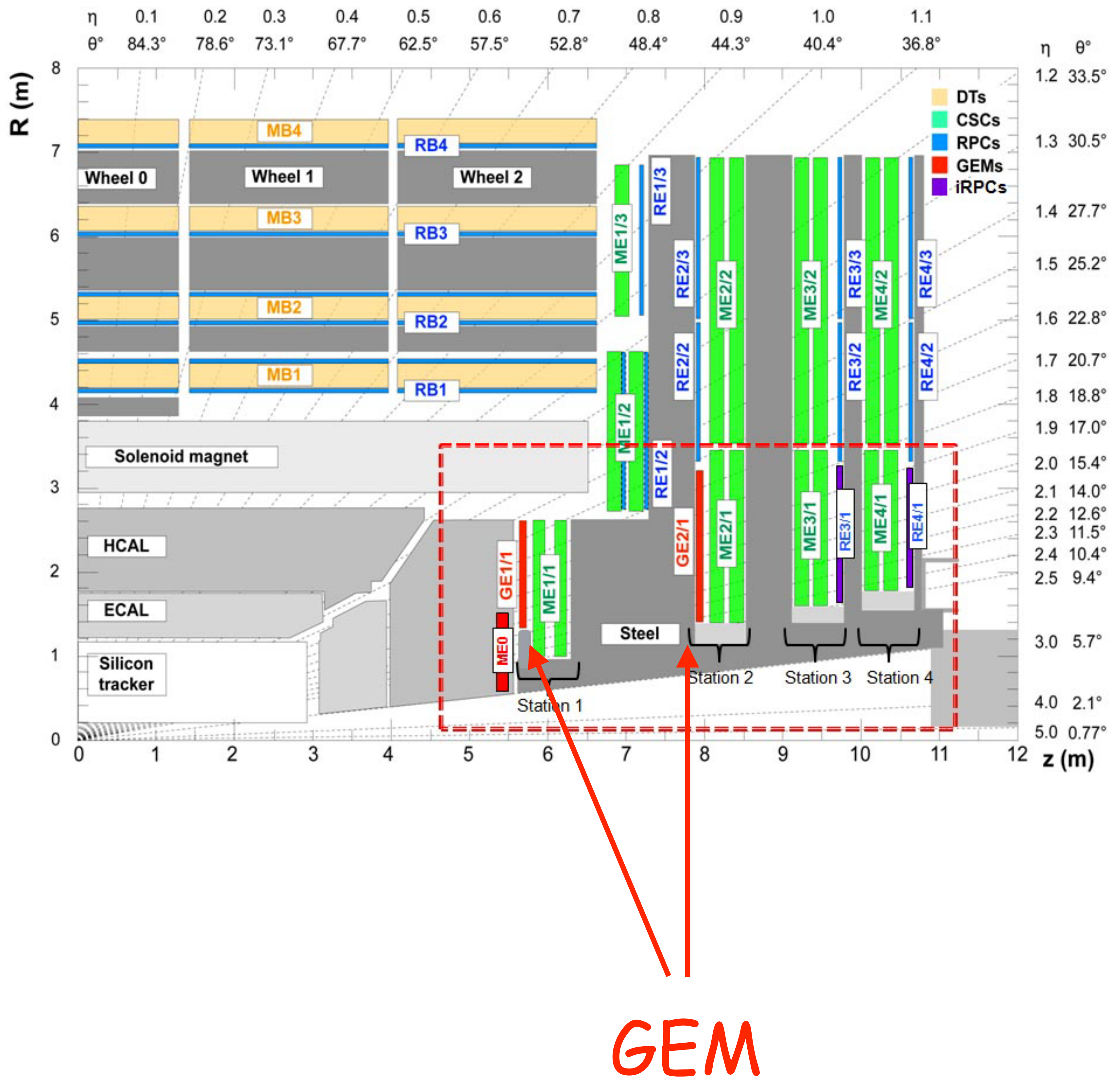


iRPC

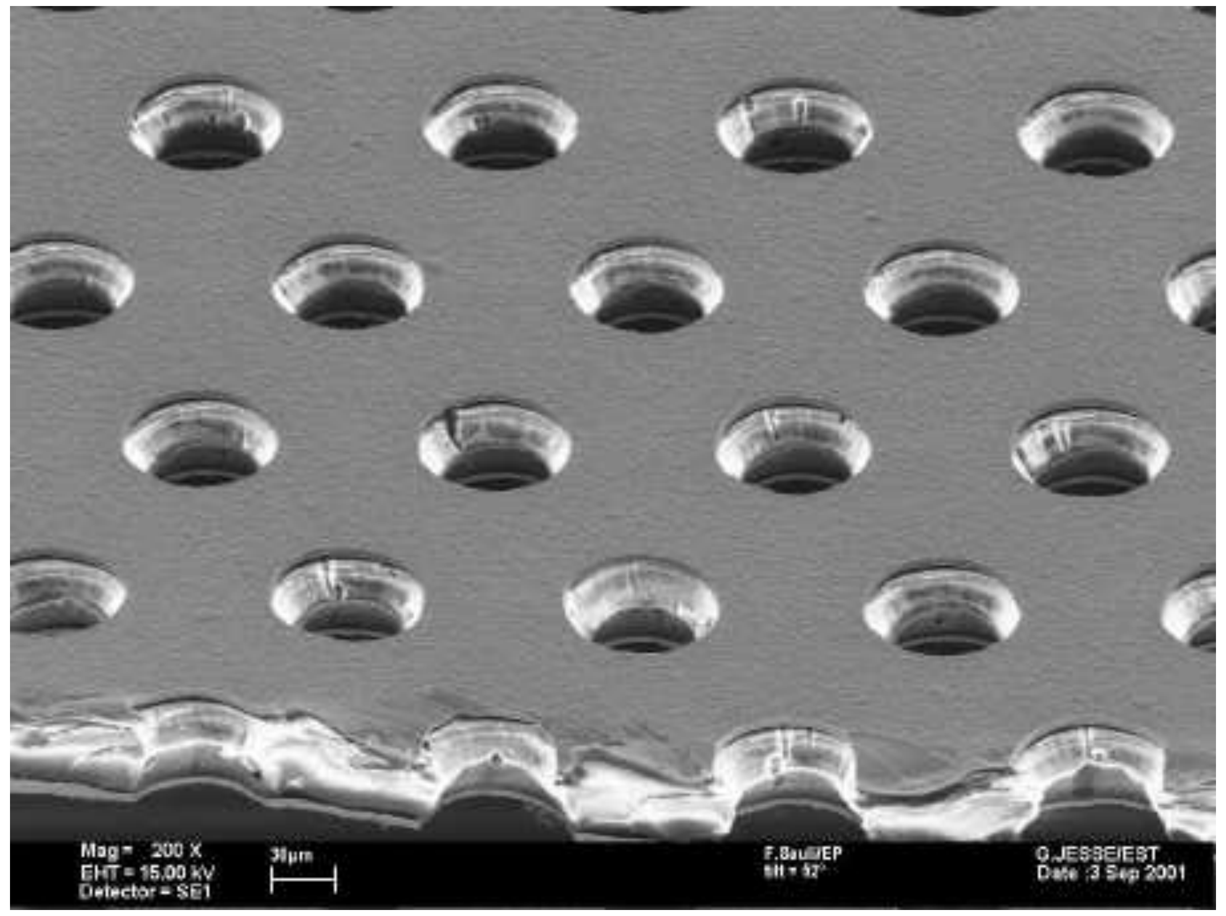


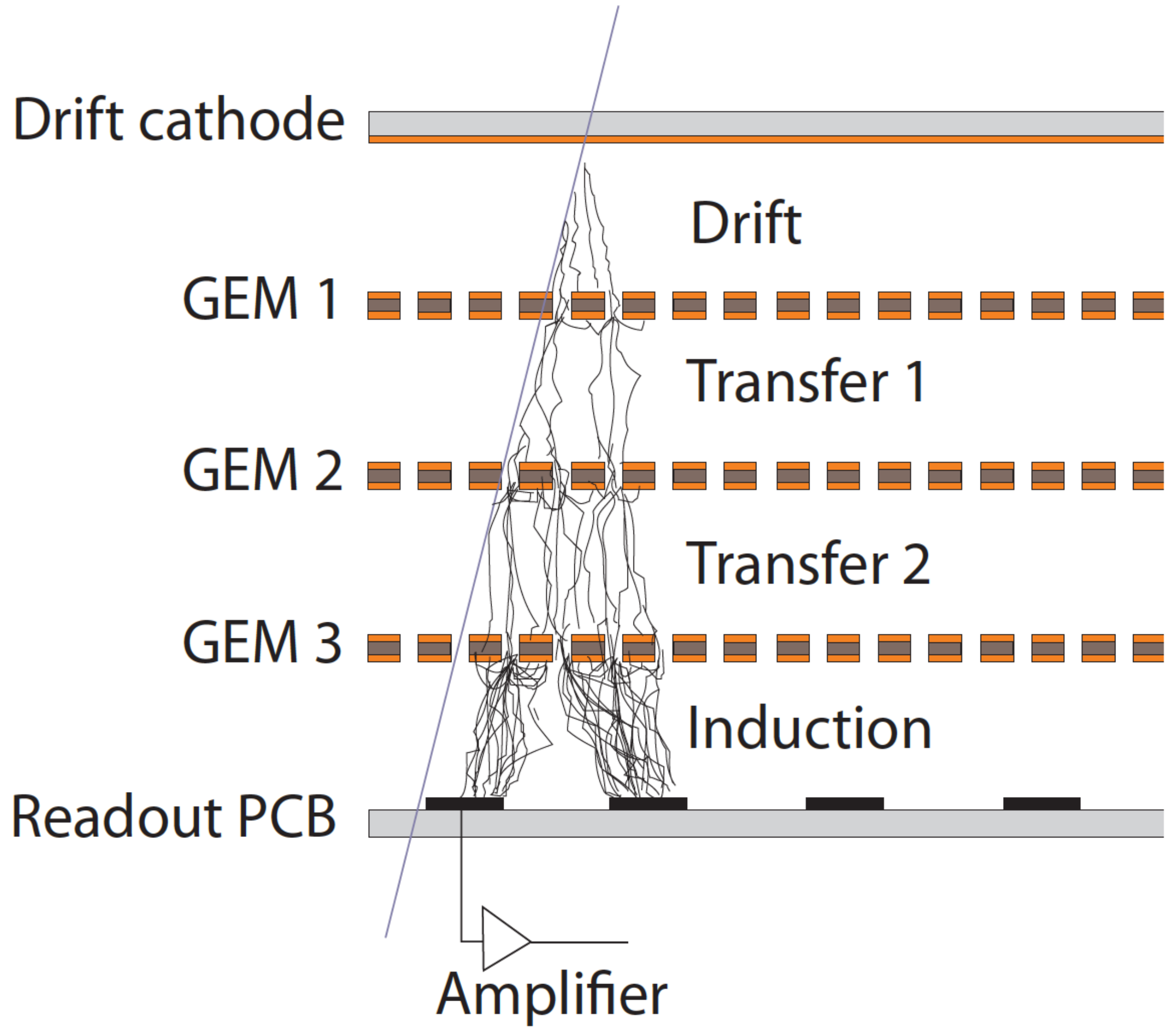
Performs well at
2 kHz/cm2
(3xHL_LHC)

GEM (Gas Electron Multiplier)

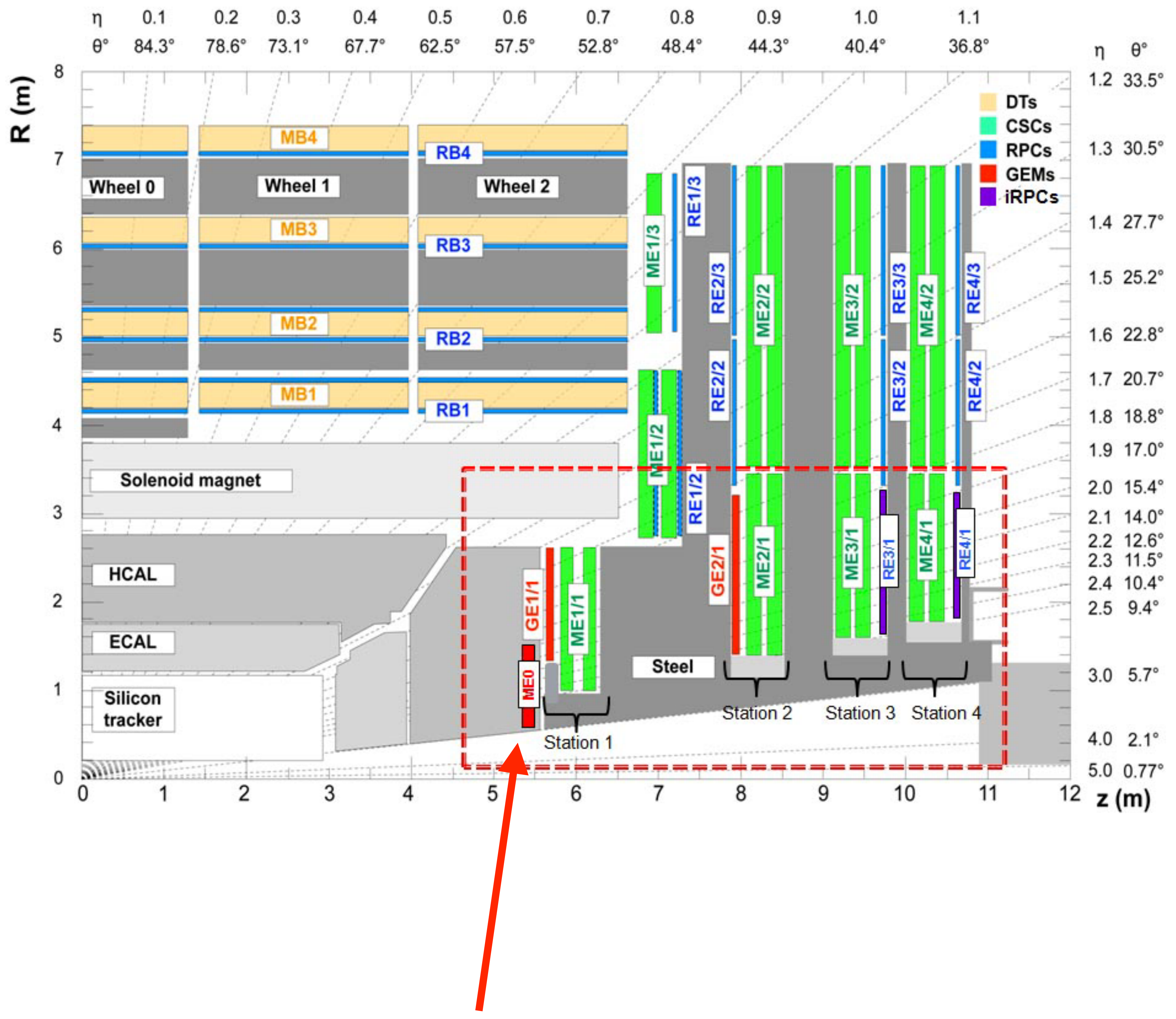


- Avalanches in strong electric filed concentrated in pin holes
- Known to operate reliably at high rate (MHz/cm2); excellent longevity
- Triplet GEM: gas gain 10^4
- Spatial resolution ~ 100 μm
- Two layers triple-GEM to be added at endcap stations 1&2
  - GE1/1: 1.6 < |η| < 2.2
  - GE2/1: 1.6 < |η| < 2.4
- A pilot system of 5 pair GEM chambers were installed in CMS at the beginning of 2017



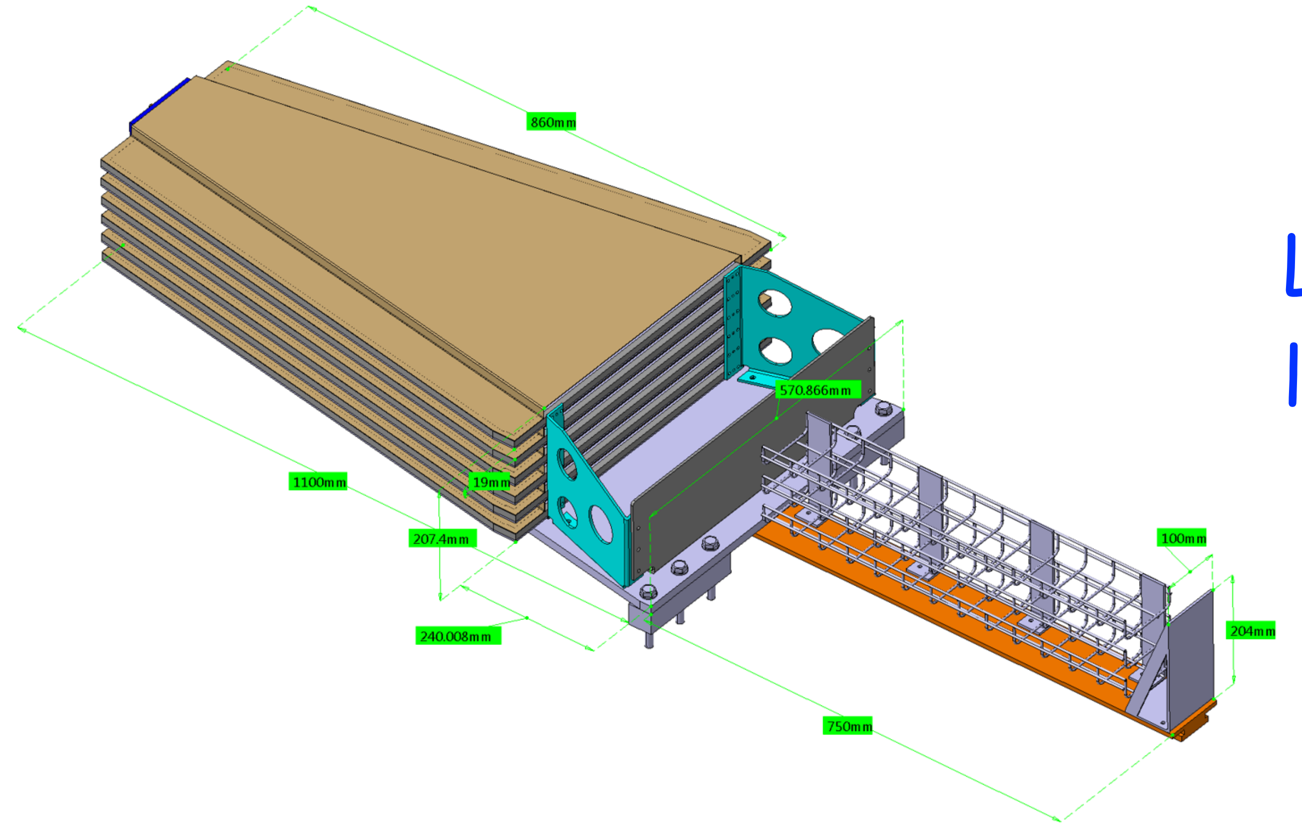


ME0 - high η muon tagger



High η muon tagger - ME0

- The same technology as GE1/1, GE2/1
- Six layers - providing "segments"
  - Muons of high p despite low pT
- Covers very high η region: 2.0 < |η| < 2.8
  - 2.0 < |η| < 2.4: CSC-ME0 tandem largely reduces trigger rate
  - 2.4 < |η| < 2.8: enlarged muon geometrical acceptance
    - Taking advantage of the extended acceptance of upgraded CMS inner pixel detector
    - Could be used not only in offline, cut also in trigger



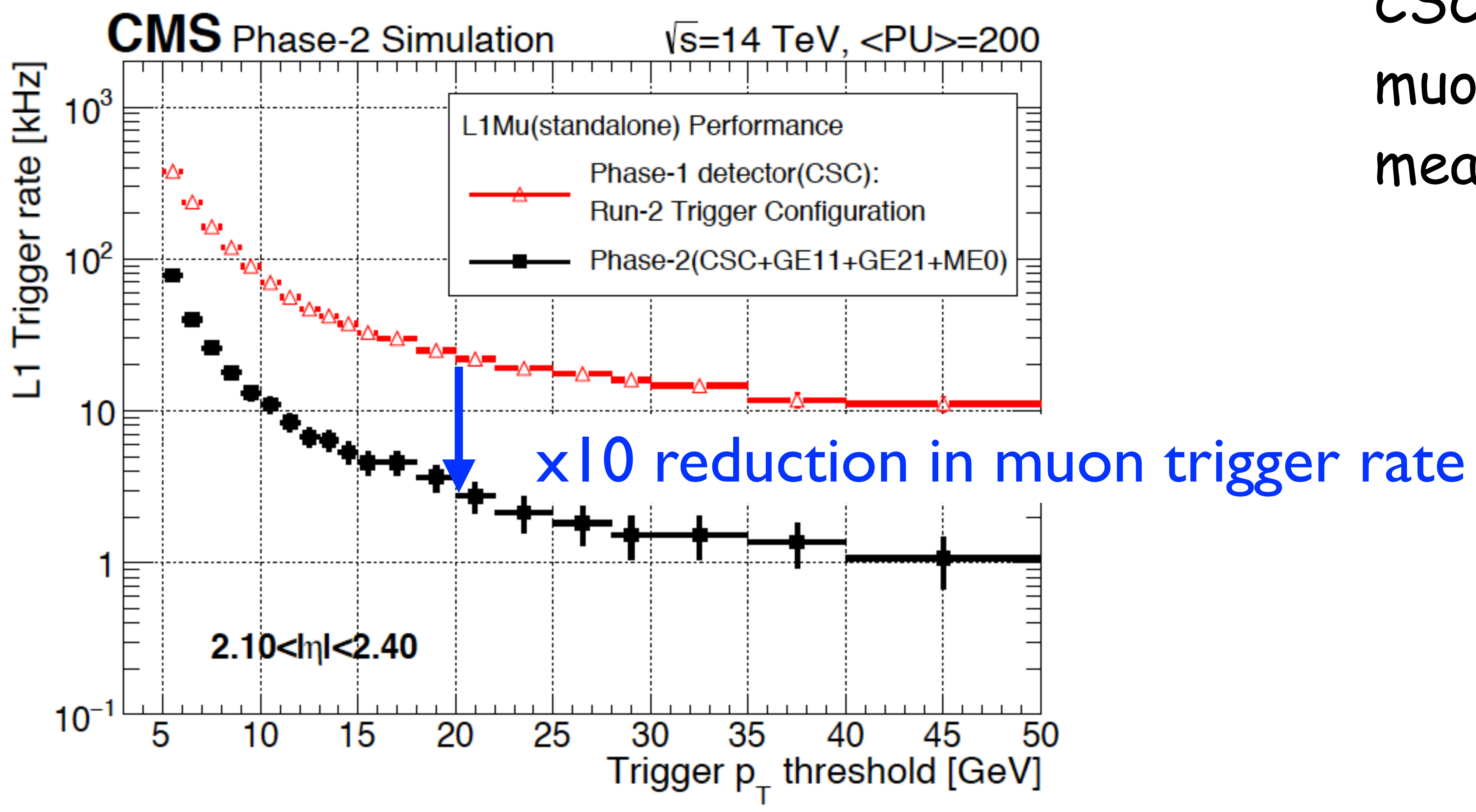
Layout of six layer stack

Muon trigger improvement

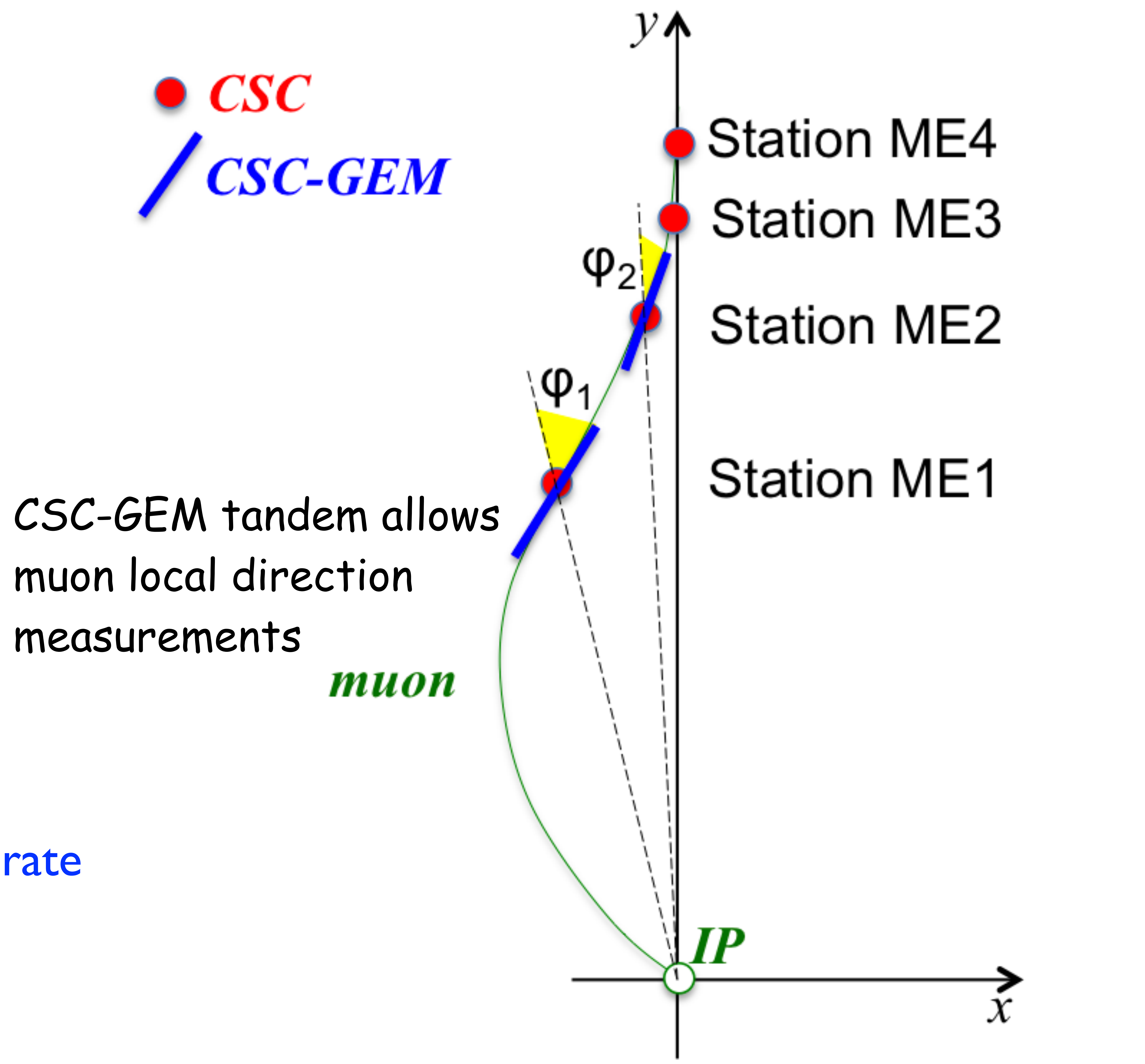
- CSC-GEM tandem (in endcap stations 1&2) improves trigger-level muon momentum measurement
- Background has steeply falling momentum spectrum

==> Trigger rate reduction

(otherwise raising trigger thresholds would harm physics acceptance)

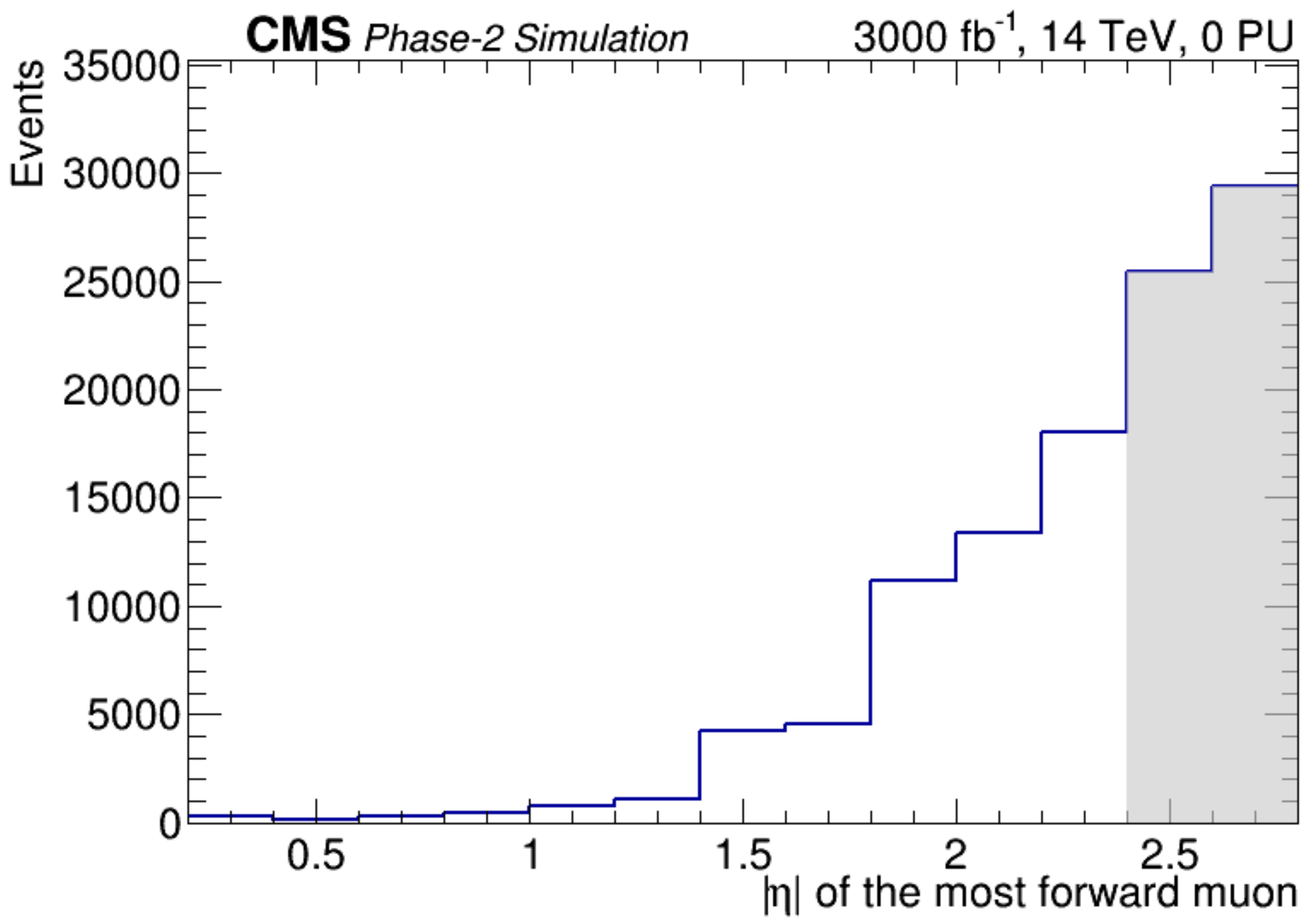


Schematic view of a muon trajectory from the collision point



Physics performance by examples

Benefit from extended muon acceptance

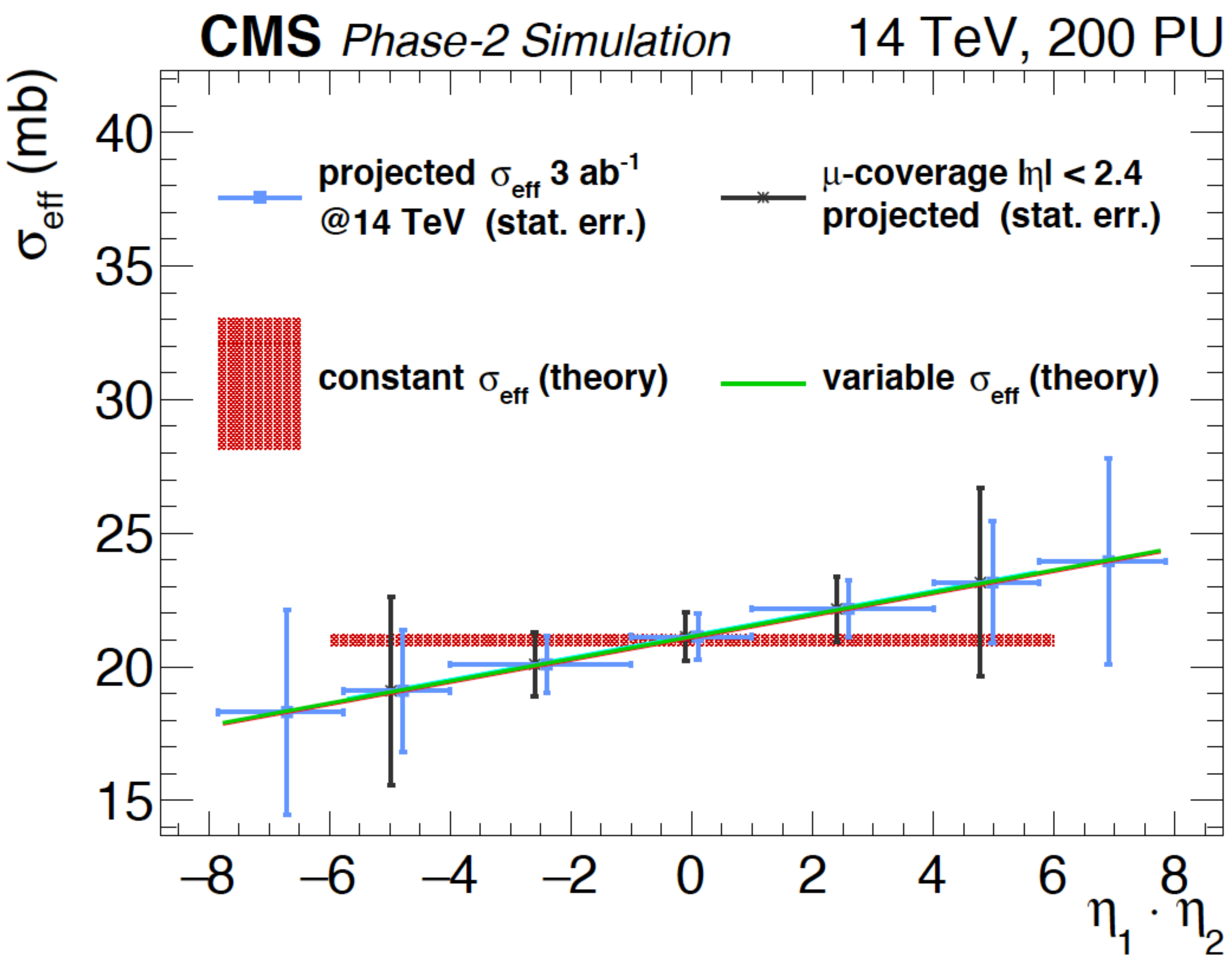


Lepton flavor violating τ->3μ search

- τ-lepton produced at LHC are of boosted to high η region (the dominant source is D/B mesons decay to tau)
- With ME0 detector, the signal acceptance is doubled at reconstruction level
- ME0 muon segments can also be used in trigger (in a multi-object trigger pattern)
- Sensitivity gain 17% by adding ME0 detector

Physics performance by examples

Benefit from extended muon acceptance



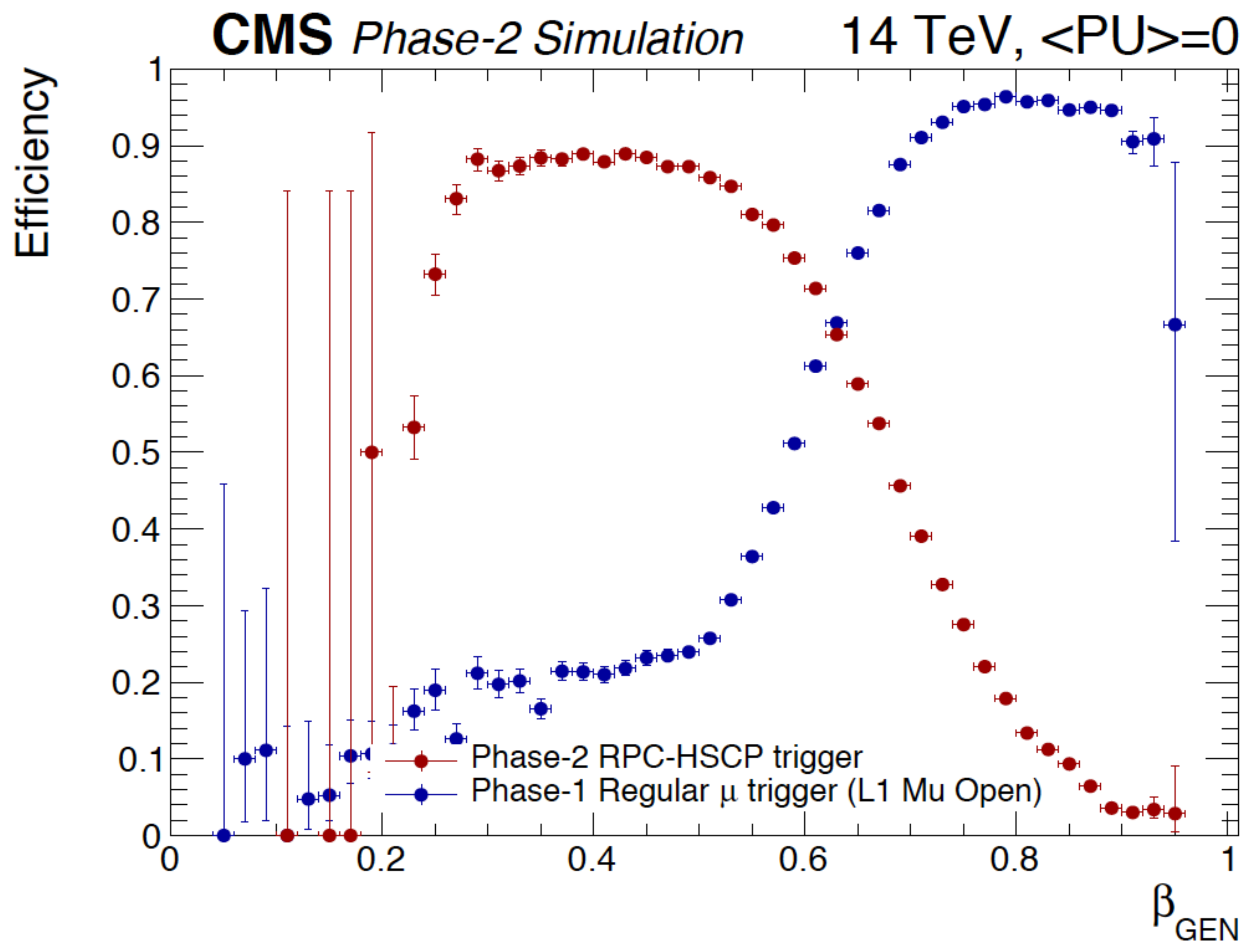
Double parton scattering pp->W+W-

- Events with both muons in the highest eta directions are the best in discriminating between different theoretical models
- Sensitivity gain 50% by adding ME0 detector

Physics performance by performance

Trigger on unconventional signals

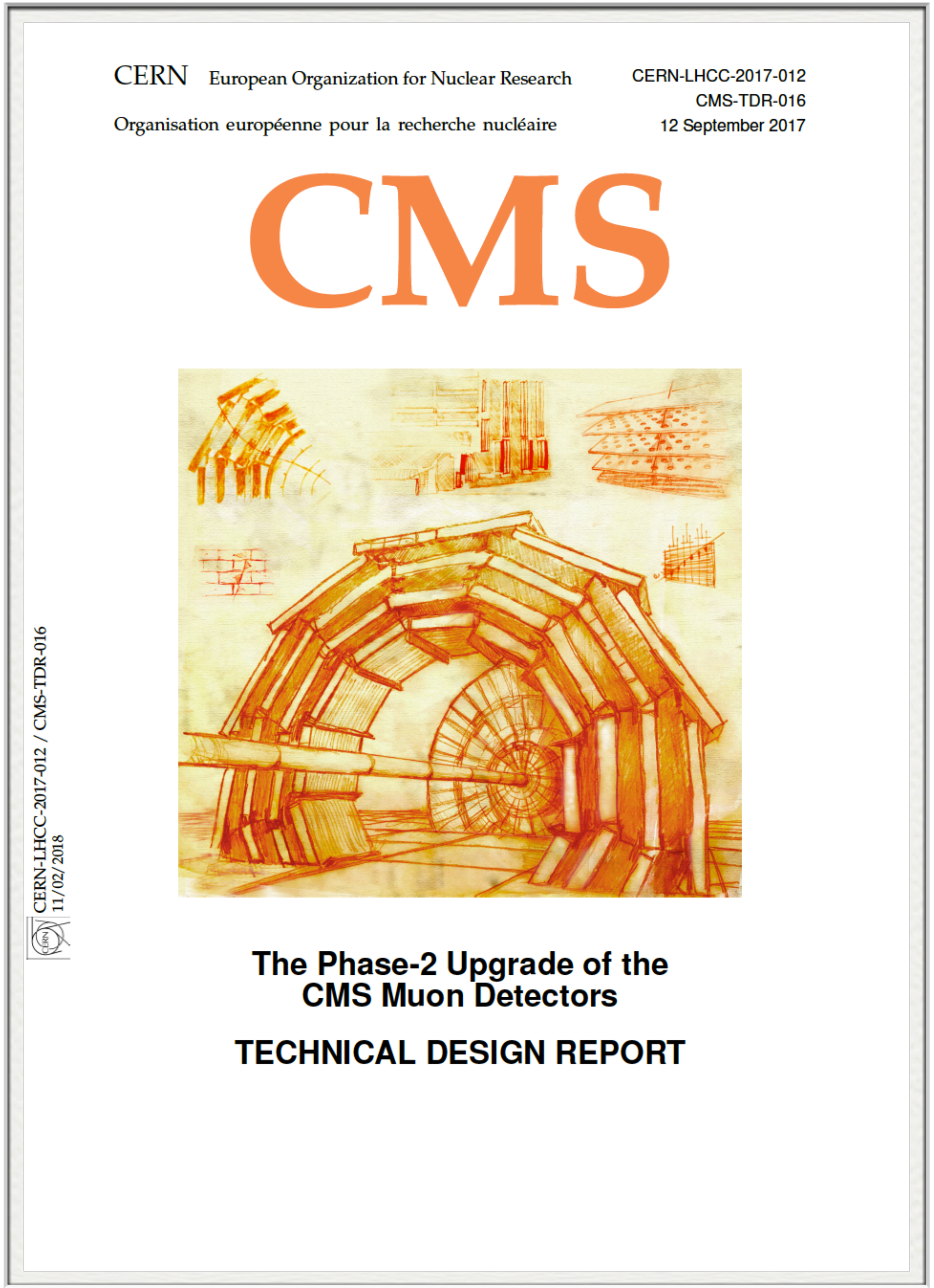
Trigger efficiency on HSCP with RPC timing



- Adding GEM makes it possible to build trigger-level muons without assuming muons come from the collision point
  - Trigger on highly displaced muons
- The upgraded RPC link system fully exploits the RPC time resolution
  - Allowing better suppression of out-of-time background
  - Enabling to identify patterns of delayed hits from one station to the next, with a precision of ~1 ns
    - Trigger on Heavy Stable Charge Particles

Summary

- CMS Muon system upgrade
  - Present DT, CSC, RPC detectors will stay
  - Electronics to be selectively replaced to meet HL-LHC requirements
  - The high η region to be enhanced with additional iRPC, GEM and ME0 detectors
  - Upgraded detector capabilities open windows for new physics opportunities
- CMS Muon Upgrade TDR is published
- Installation starts in the Long Shutdown 2 (2019-2020); continues in Year-End-Techinical-Stops; and finishes in the Long Shutdown 3 (2024-mid 2026)
- Chinese CMS groups contribute to CMS muon detector upgrade (PKU, Beihang, SYSU, Tsinghua)



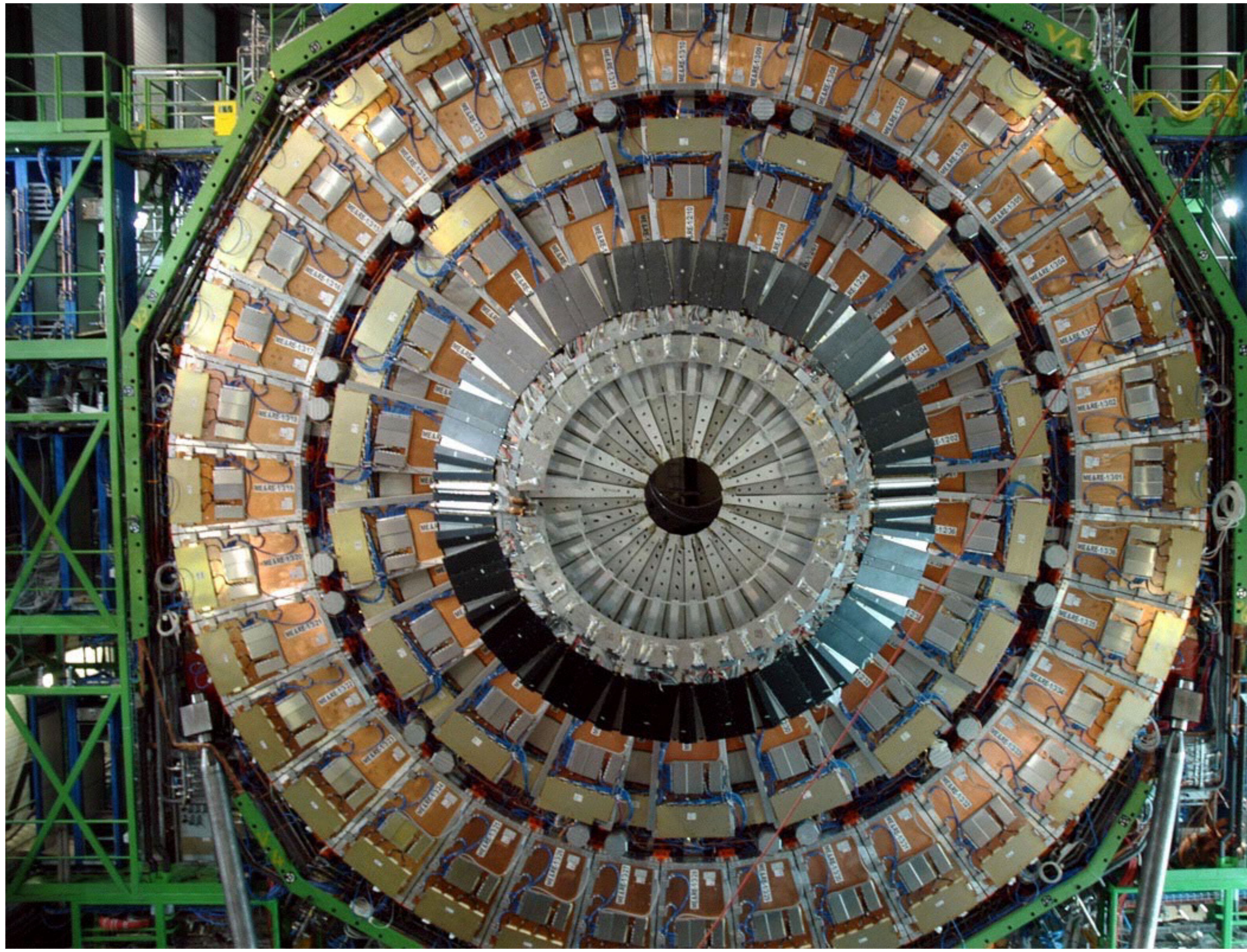
Back-up

CV

- 2005 南京大学 本科
- 2011 中科院高能所 博士

- 2012-2014, Universite Libre de Bruxelles (Belgium) Post-doc
  - CMS experiment, physics analysis
    - High mass Higgs
    - Higgs invisible decay
    - Higgs width via off-shell
  - 2014-2016 "Higgs off-shell" sub-group co-convenor of LHC Higgs Cross Section Woking Group

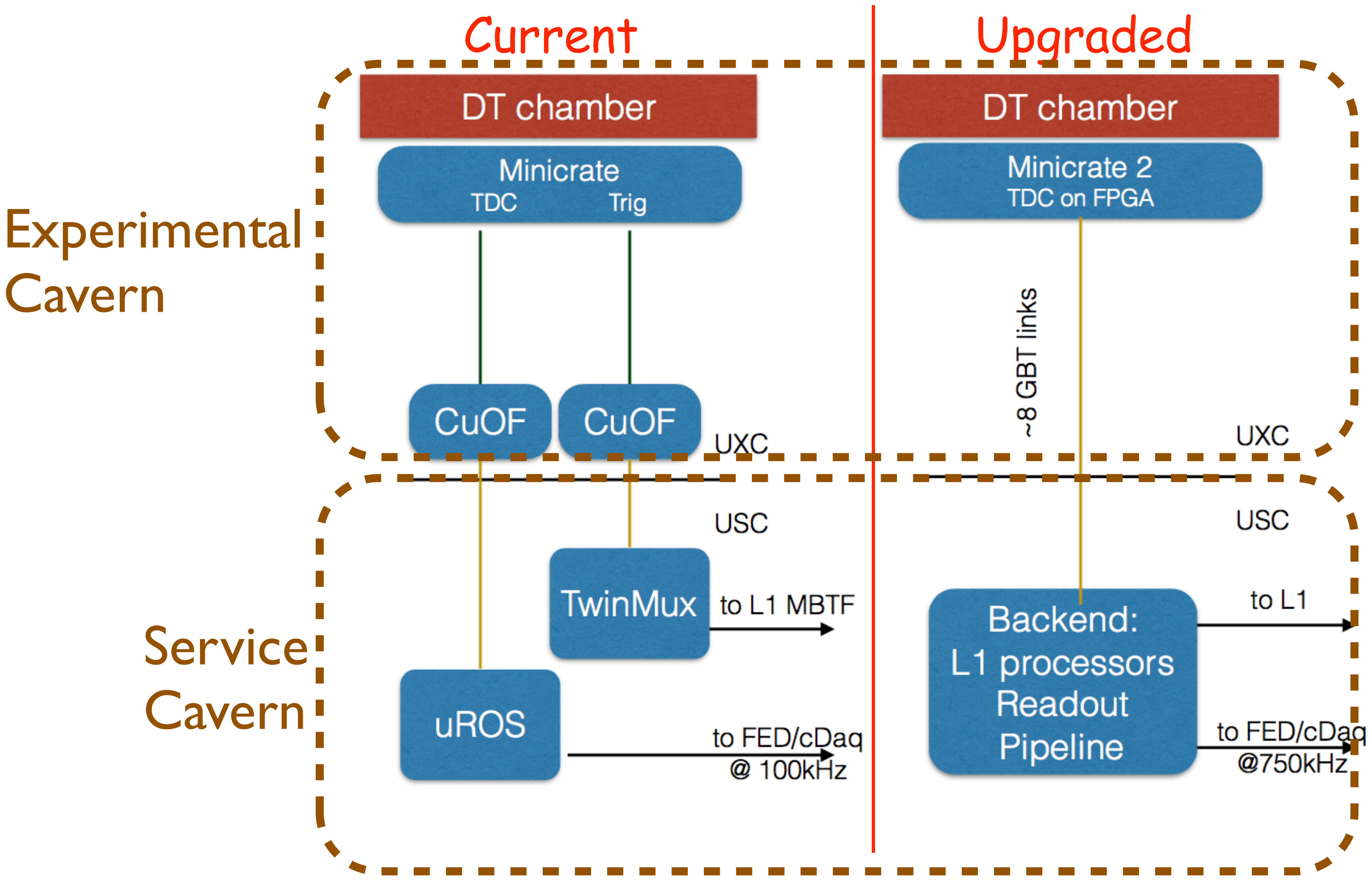
- 2015 - present, University of Florida, Post-doc (Based at CERN)
  - CMS experiment, Endcap-Muon detector
  - 2016 - present, CMS Endcap Muon detector Run Co-ordinator
    - 24/7 responsible for detector operation, data-taking, trouble shooting

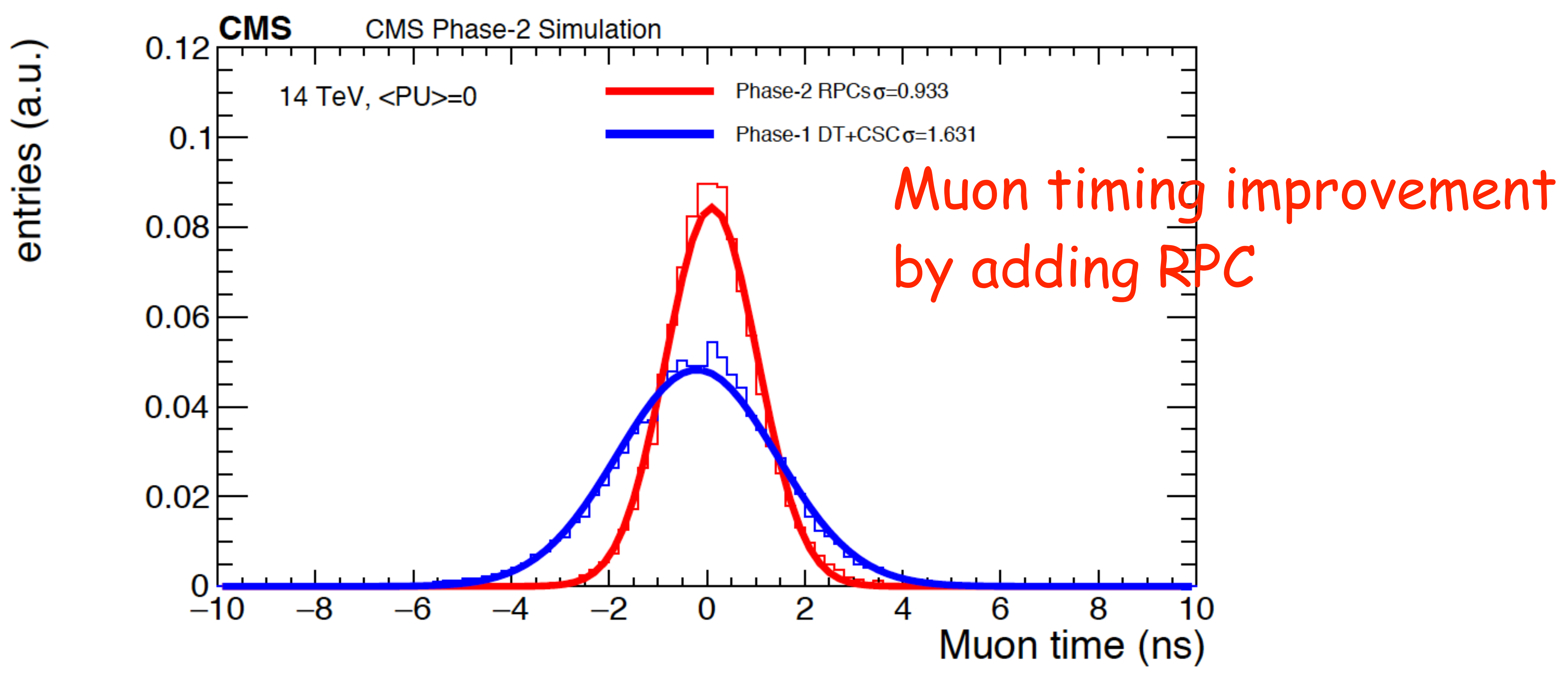


Electronics upgrade

- DT
  - New on-chamber electronics, to cope with higher rate and radiation
  - New trigger logic system to be in the service cavern - easier to maintain
- CSC
  - Selective replacement of electronics for inner ring chambers - Cathode FE board in station 1 moved to stations 2,3,4, while newer generation boards installed in station 1
- RPC
  - The “link system” (connecting the FE board to the trigger processors) to be replaced
    - For convenience of operation and maintenance
    - To fully exploits the intrinsic time resolution ~1.5 ns

DT electronics

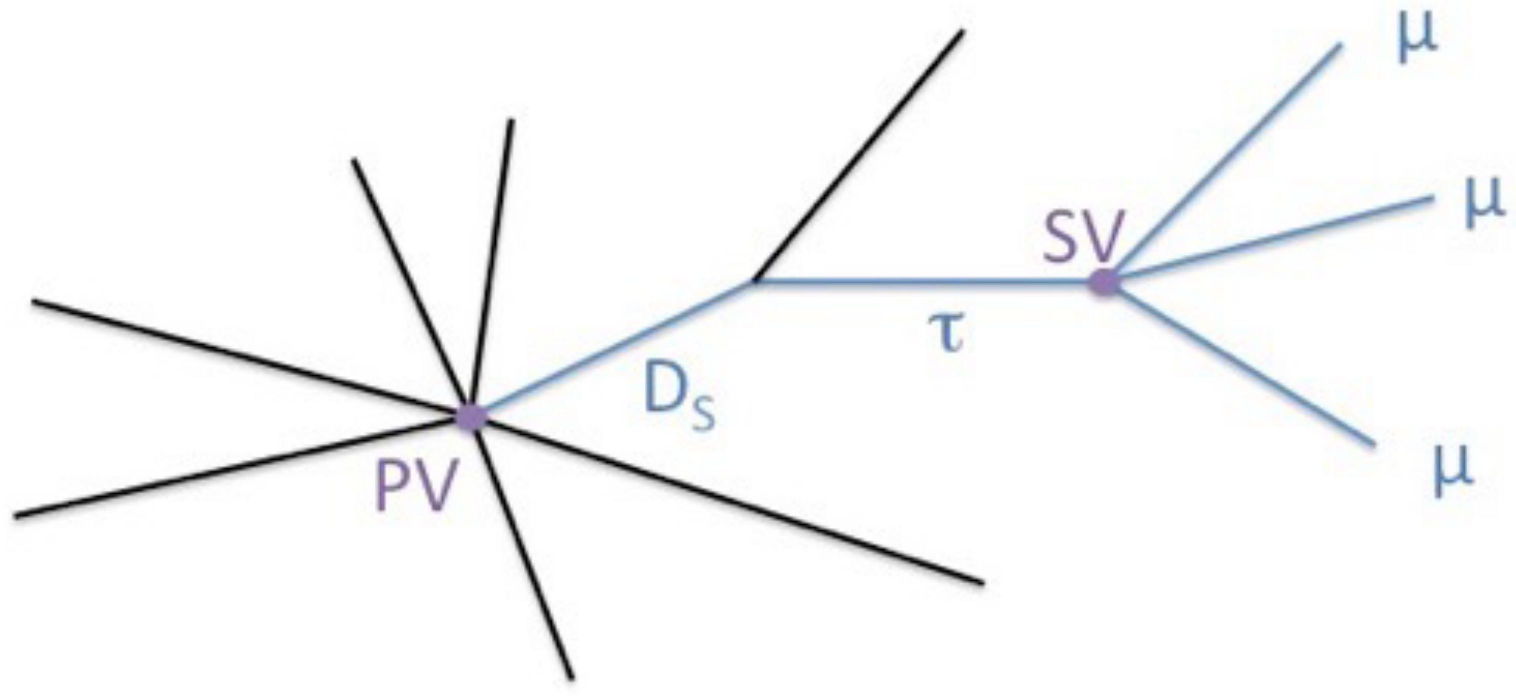


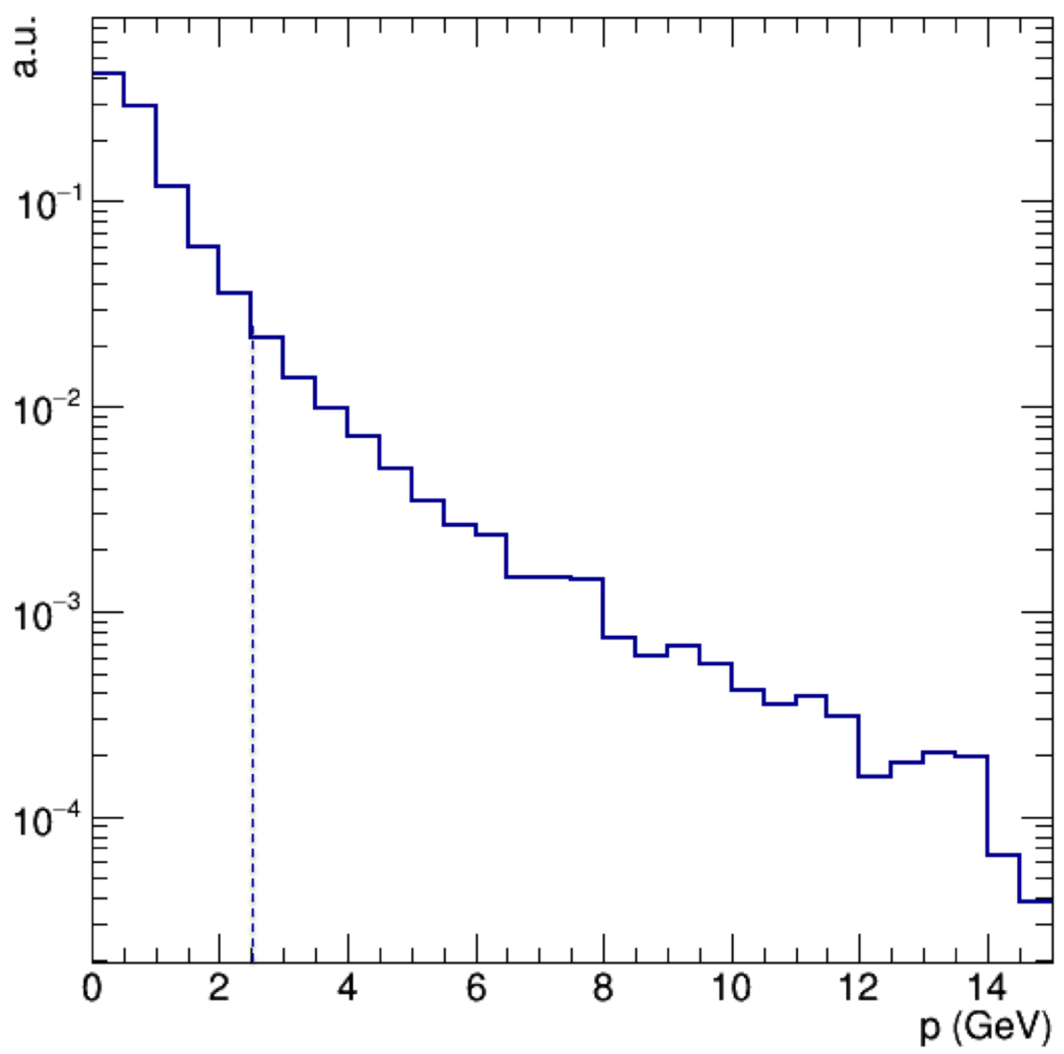


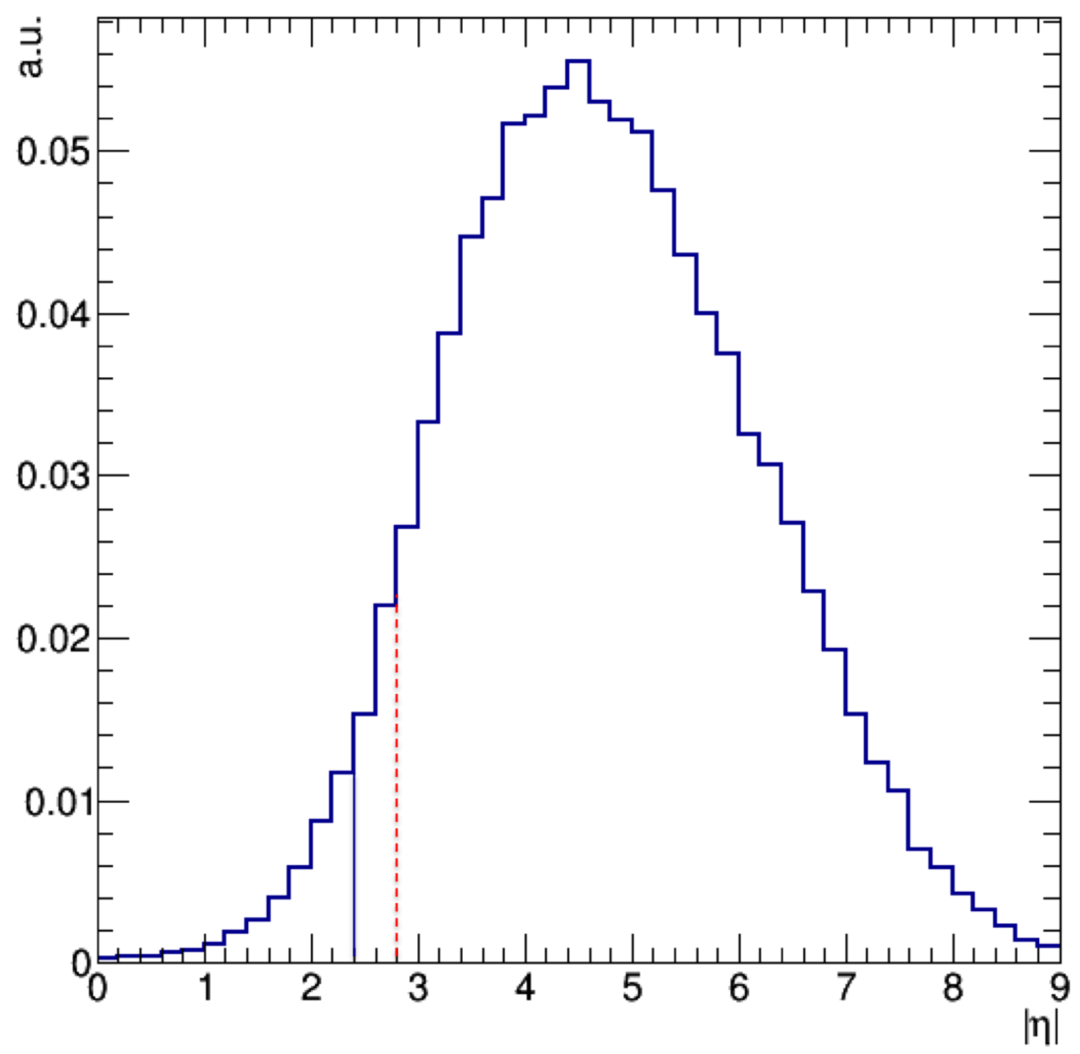
Physics performance by examples

Lepton flavor violating τ->3μ search

- No fundamental law forbids Charged Lepton Flavor Violation
- Experiments have been built for decades to search for CLFV (MEG, COMET, Mu2e, etc)
- CLFV τ-lepton decay could be studied at colliders
  - τ->3μ relatively clean signature at LHC
  - The world best limit: Belle: 2.1*10^(-8) @ 90 CL
- τ produced at LHC are boosted to high η region (dominant source being D/B decay to τ)
- Only 2% (4%) in the present (upgraded) muon detection fiducial region

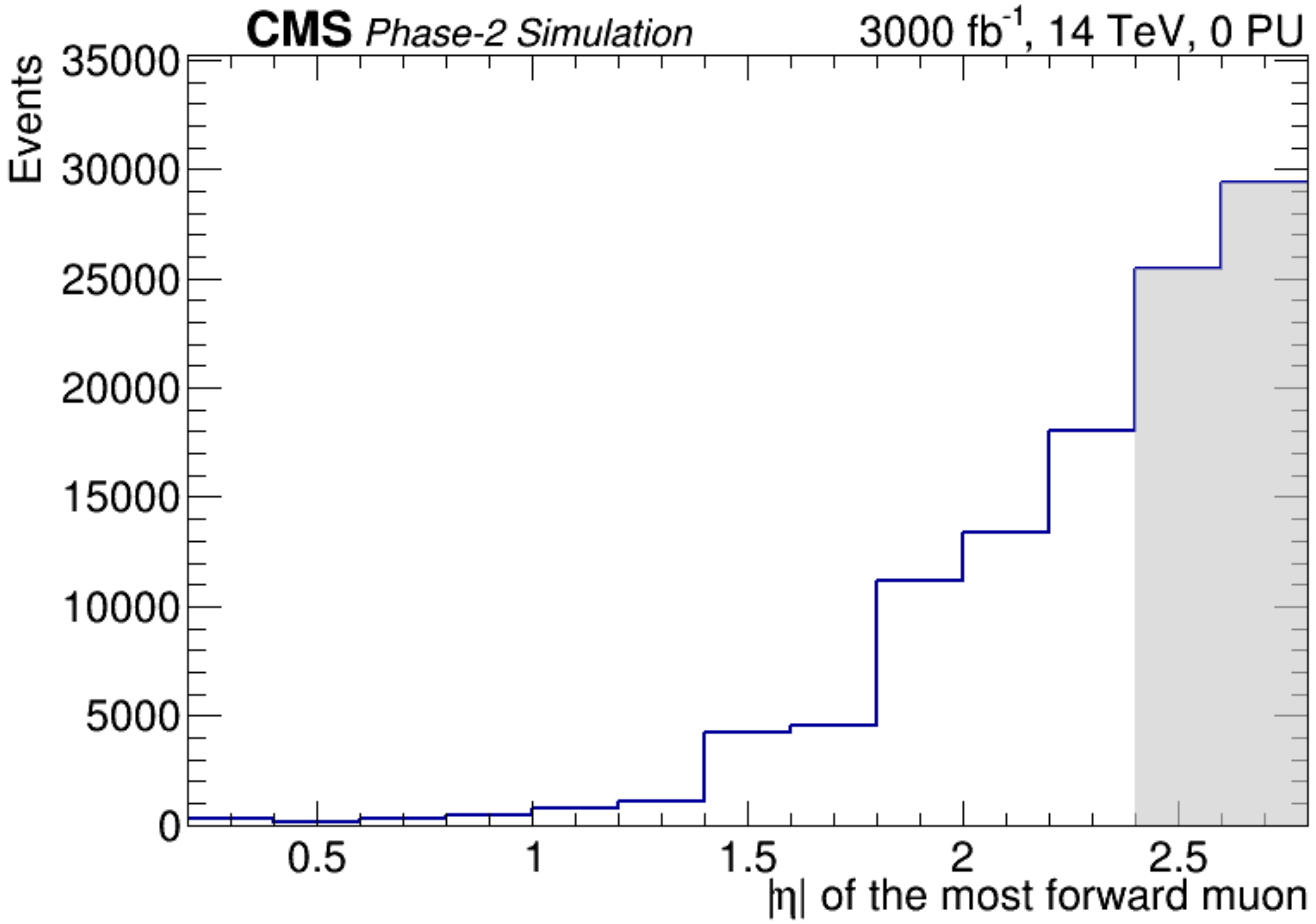




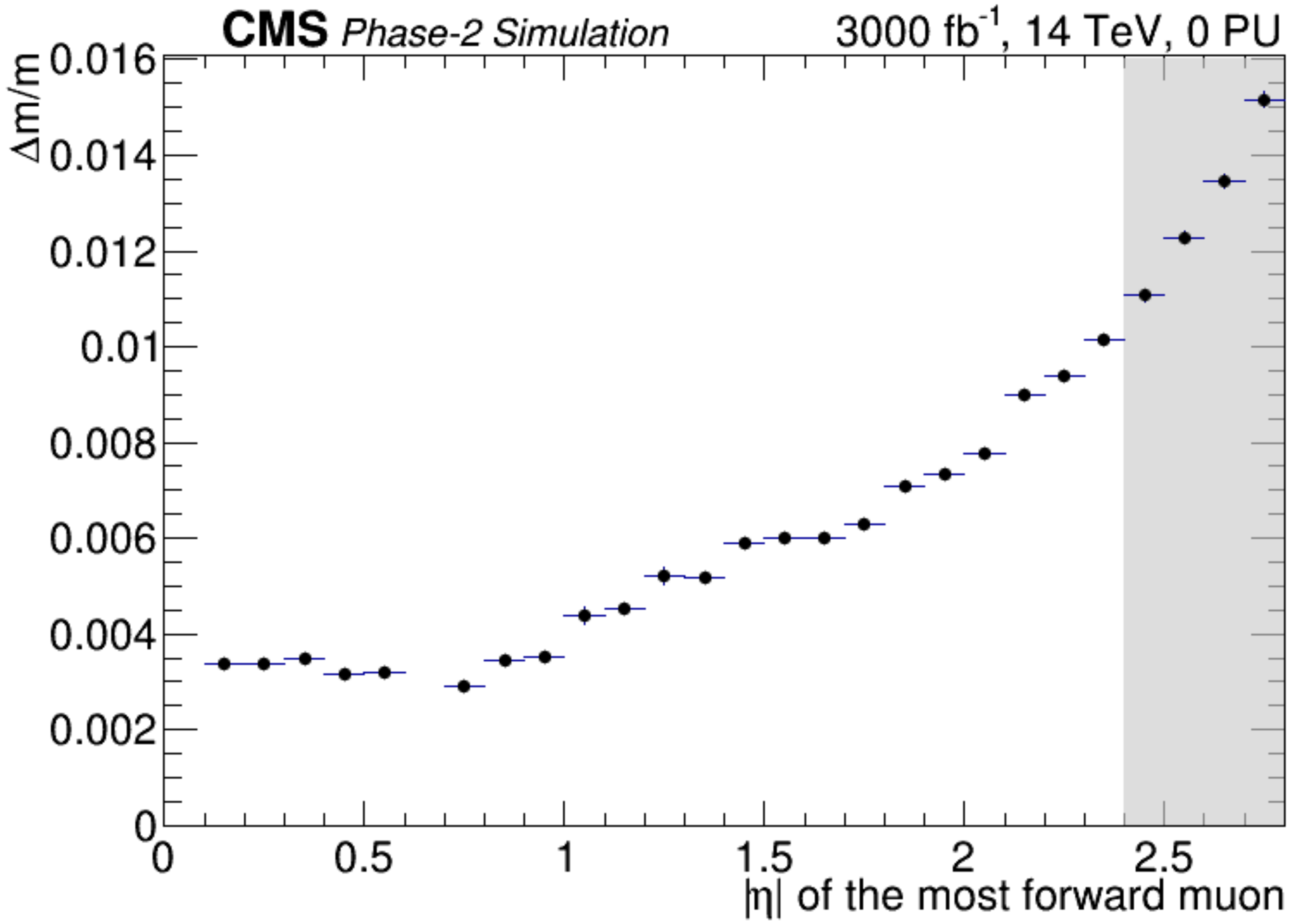


Lepton flavor violating τ->3μ search

Using τ->3μ as a benchmark, worked together with ME0 software team to optimise the reconstruction of ME0 muons in pile-up 200 environment

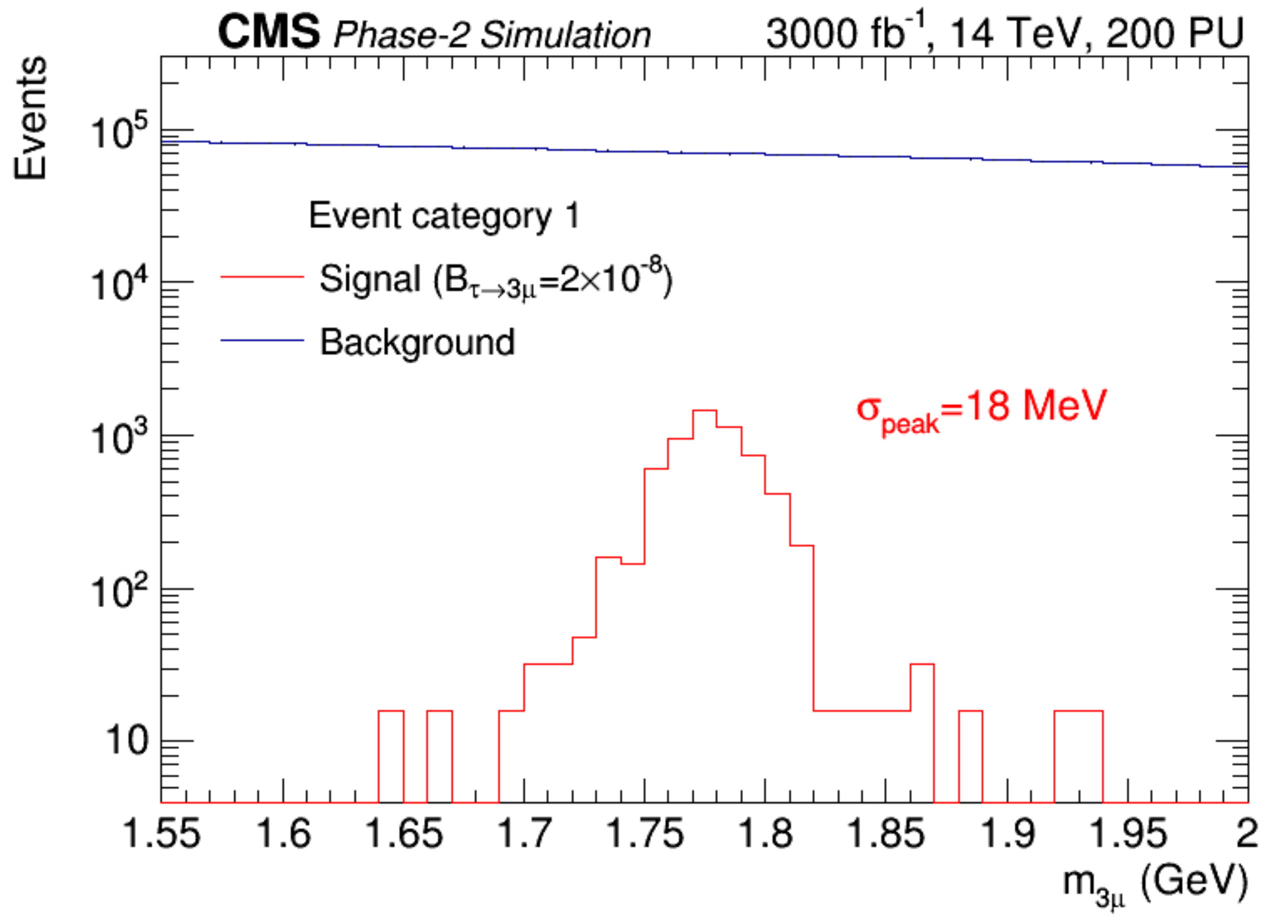


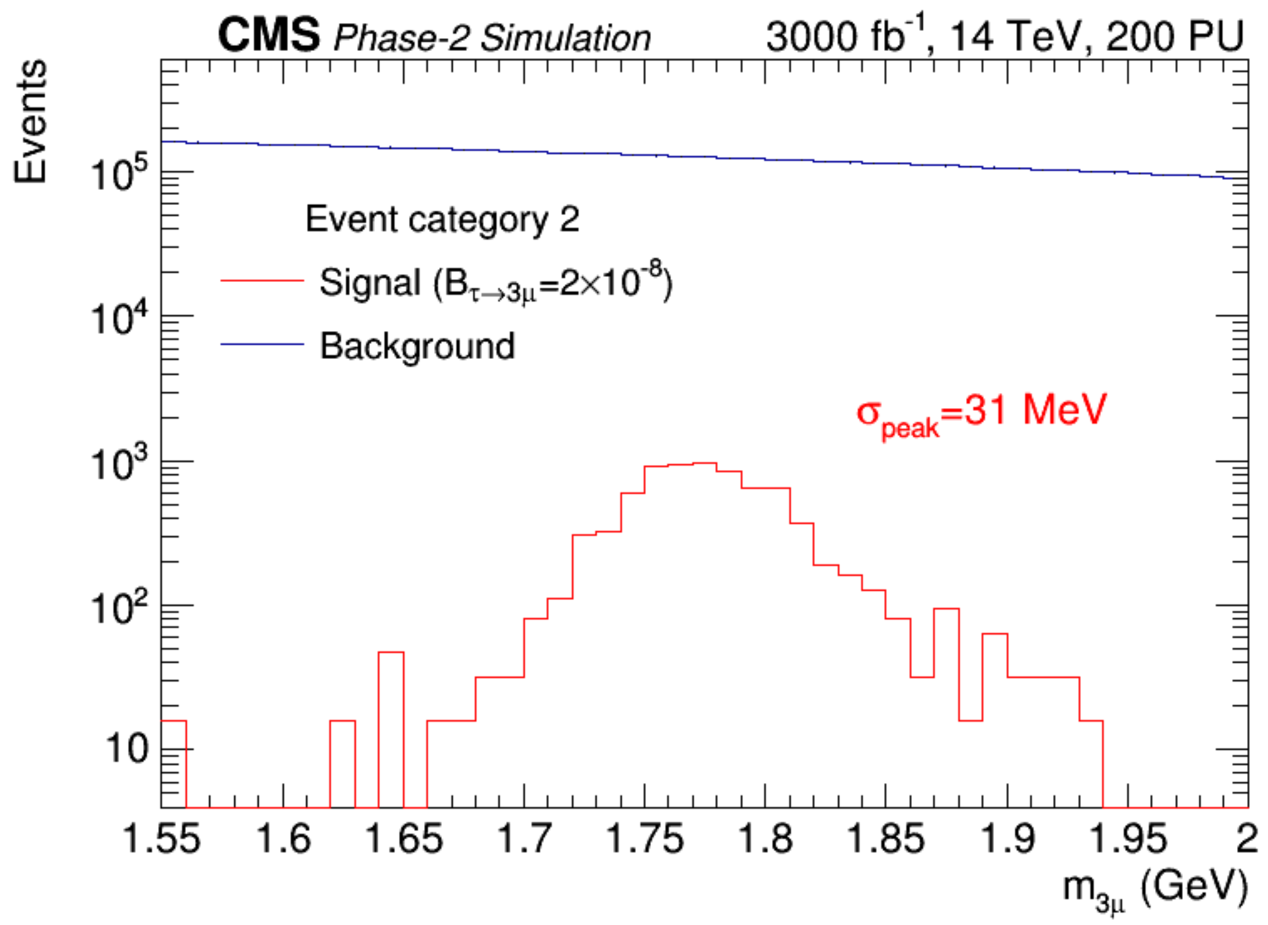
- With ME0 detector, the signal acceptance is doubled at reconstruction level
- ME0 muon segments can also be used in trigger (in a multi-object trigger pattern)



- But of course, these "extended" muons have worse momentum resolution

Lepton flavor violating τ->3μ search





	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4 580	3 640
Trimuon mass resolution	18 MeV	31 MeV
$B(\tau\to3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau\to3\mu)$ 90%C.L. limit	3.7×10^{-9}	
$B(\tau\to3\mu)$ for 3σ-evidence	6.7×10^{-9}	
$B(\tau\to3\mu)$ for 5σ-observation	1.1×10^{-8}	

- Signal acceptance is almost doubled by adding ME0
- The events using ME0 have worse mass resolution, but similar S/B
- Gain in sensitivity is 17%

GEM discharge

- Triple-GEM, achieves high gain without very high HV
- The multiplication takes place “several” mm away from the readout electronics
- “use of protection resistors to limit the energy available in case of a discharge”
- the asymmetric distribution of charge-amplifying electric fields over the three GEM foils

Measurements of the discharge probability

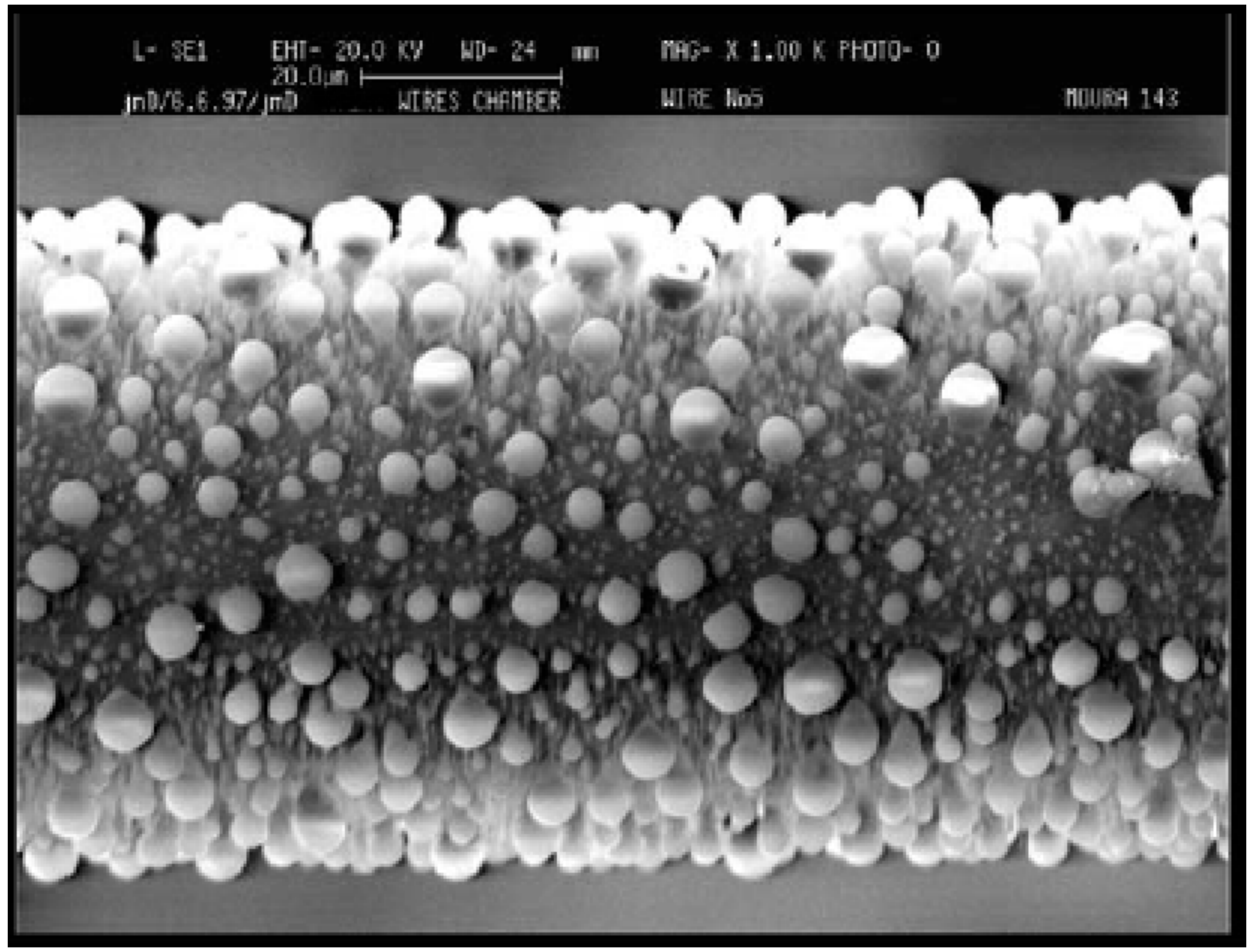
Table 6.6: Expected number of discharges seen in GE1/1, GE2/1, and ME0 detectors after ten years of HL-LHC operation. The calculations use the maximum neutron fluence in the hottest region of the detector and we assume that all neutrons with energy higher than 1 MeV can induce heavily ionising particles.

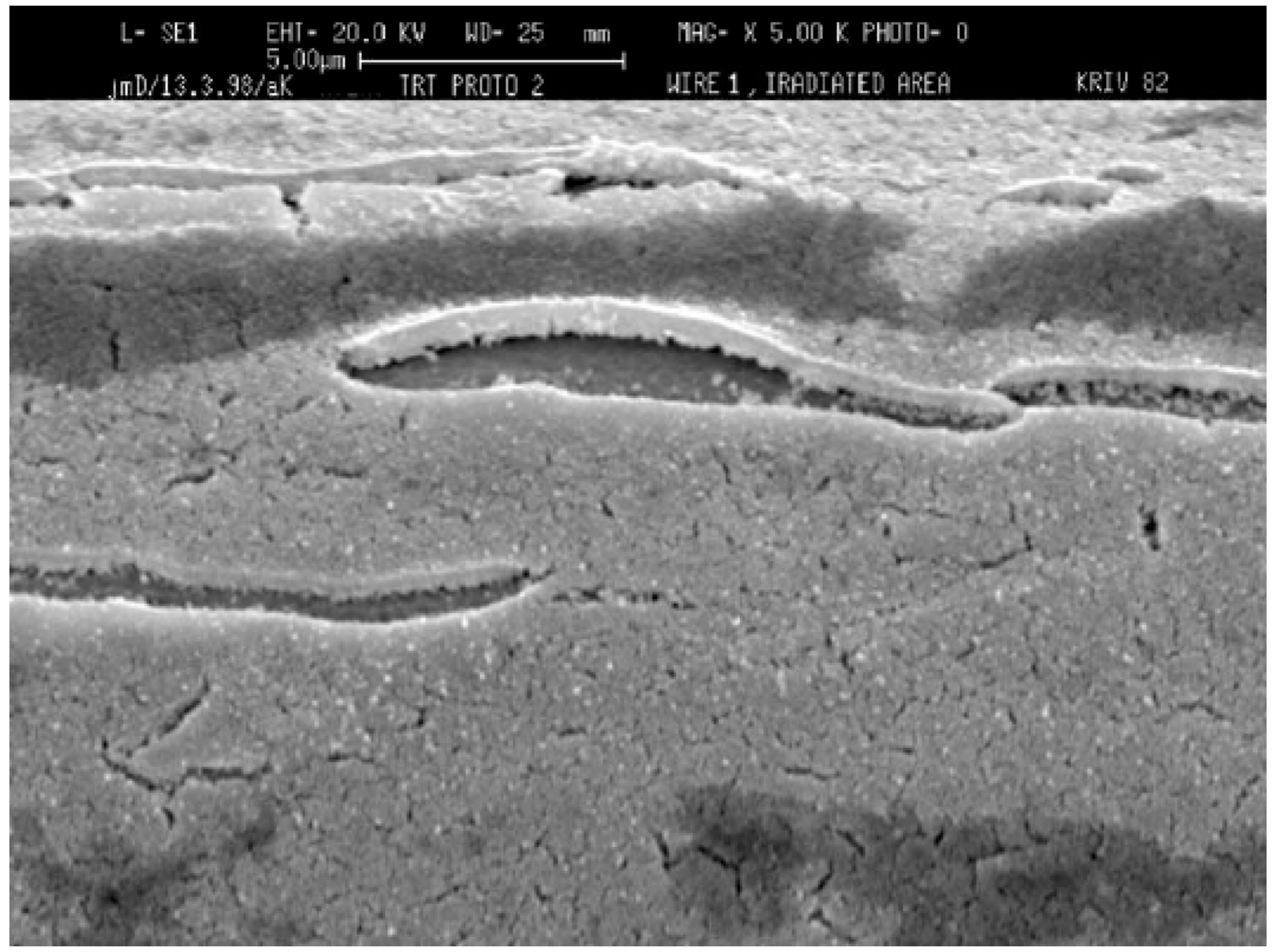
GEM Station	**Expected number of discharges** (using P = 10^{-10} from test with alphas) [$1/cm^2$]	**Expected number of discharges** (using the preliminary upper limit 2.85×10^{-9} measured at CHARM) [$1/cm^2$]
GE1/1	0.6	17.0
GE2/1	0.4	11.7
ME0	7.9	224.8

Gas detector longevity

- Exposure to HL-LHC radiation could potentially cause detector deterioration and permanent failure
  - Gas gain decrease, spurious hits, HV spike/ breakdown self-sustained discharges
- Radiation particles: neutrons, photons, electrons, muons, charged hadrons
  - Main source of hits are neutron-induced photons
- Gas polymerisation
  - gas mixture, impurity, flow
  - chamber material; wire diameter

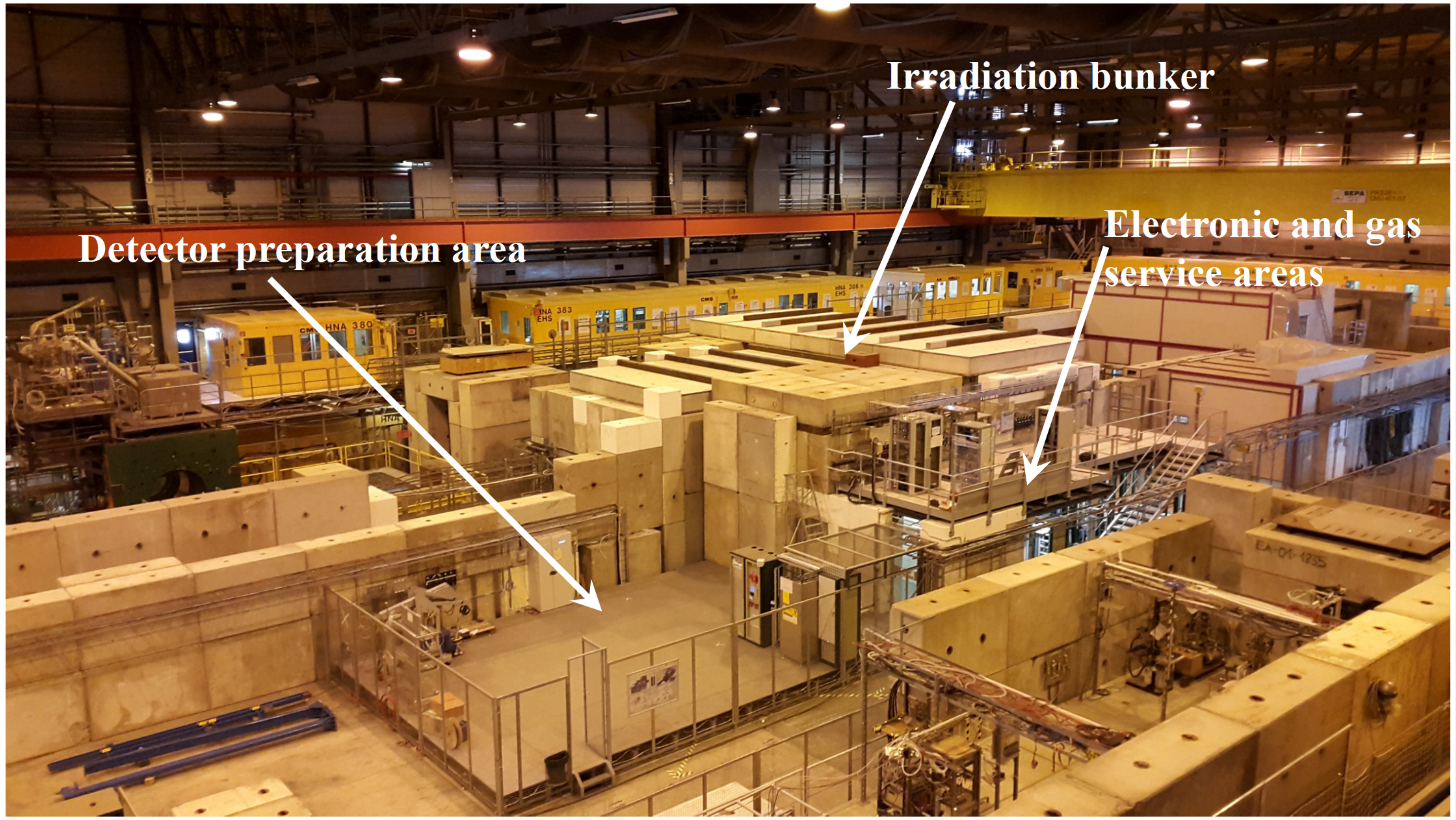
Deposition on wires



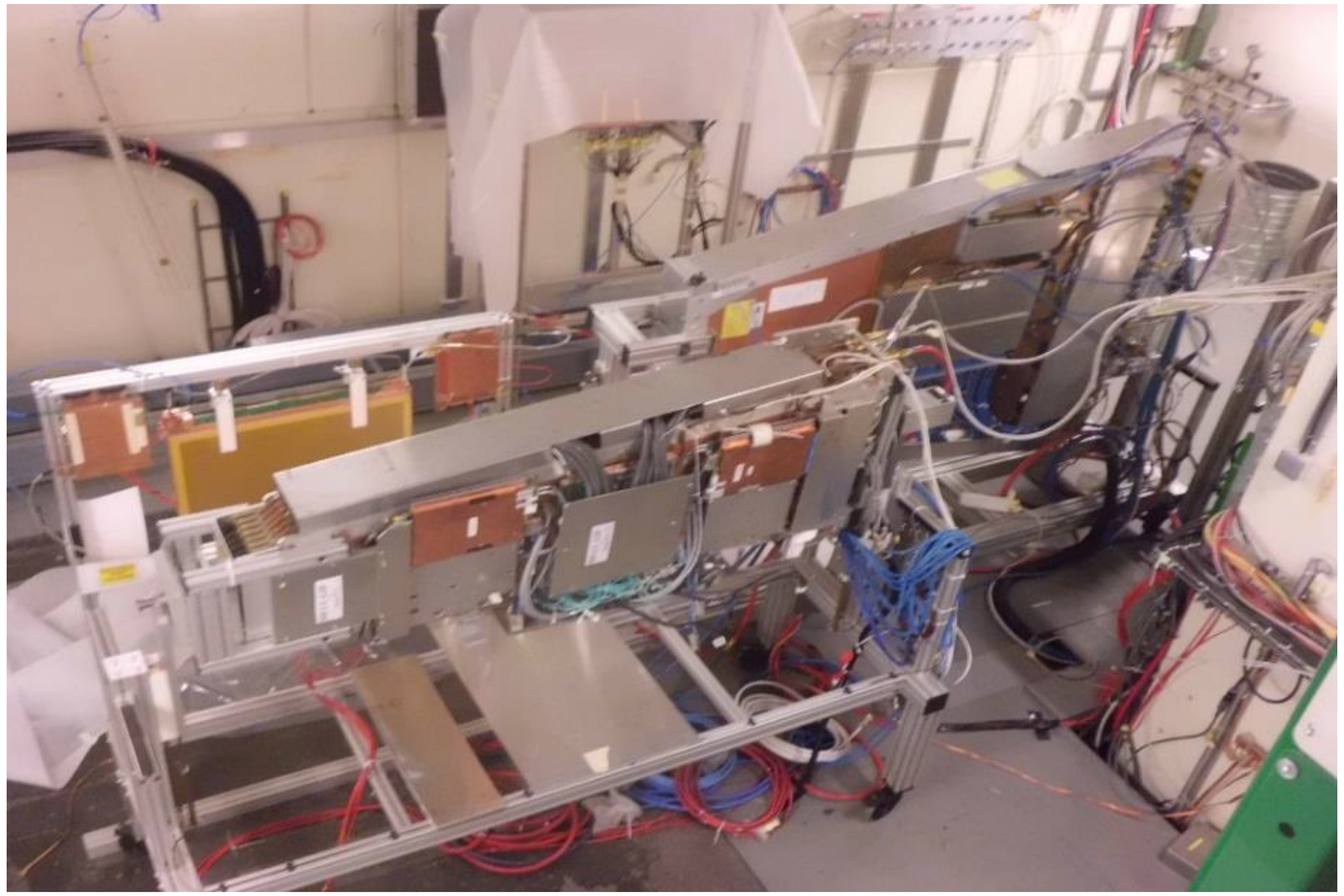


Breakdown of coating

CERN Gamma Irradiation Facility (GIF++)
Cs137, 13.5 TBq, 662 keV photons

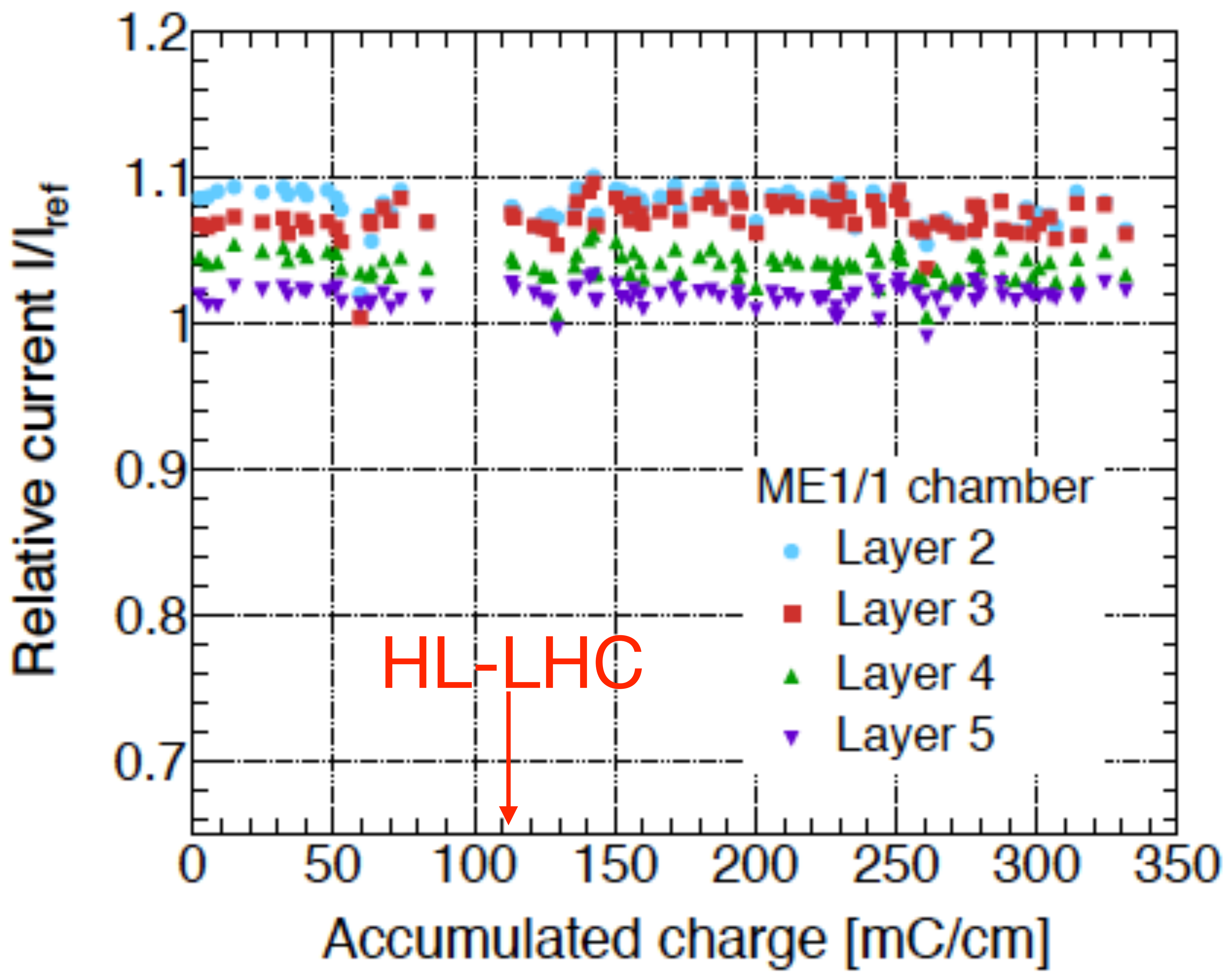


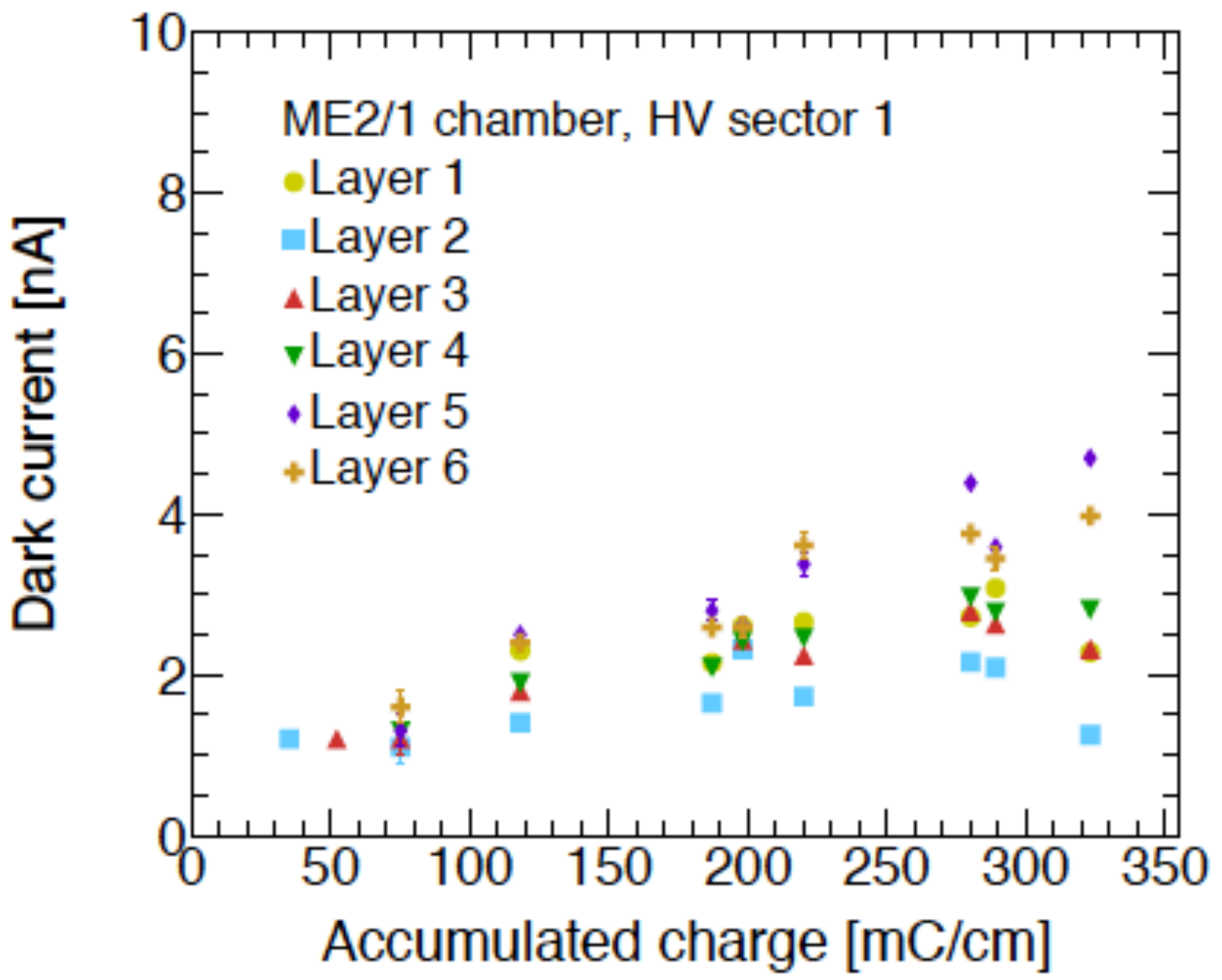
Electronics



CSC chambers

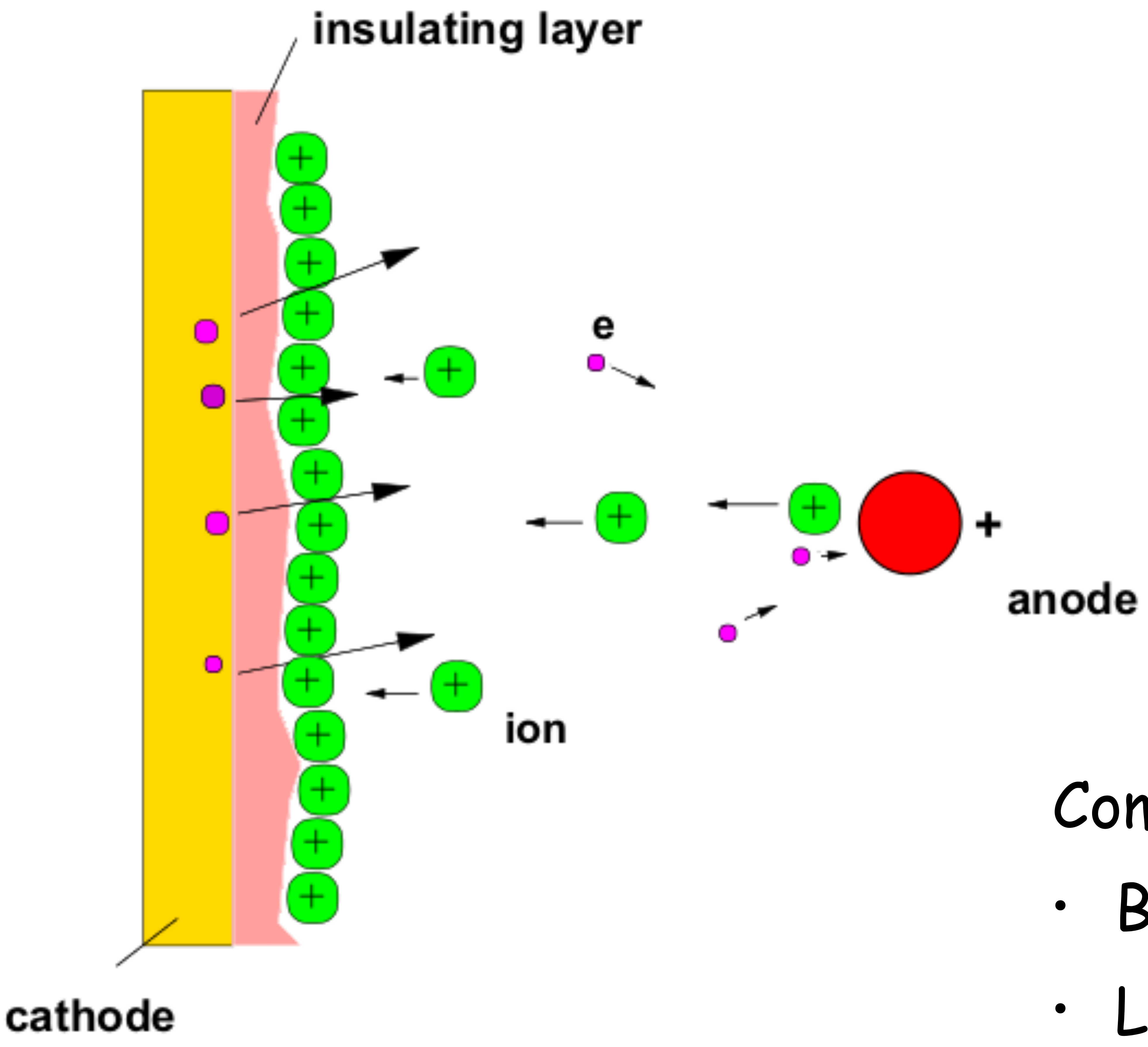
Measurements vs integrated charge

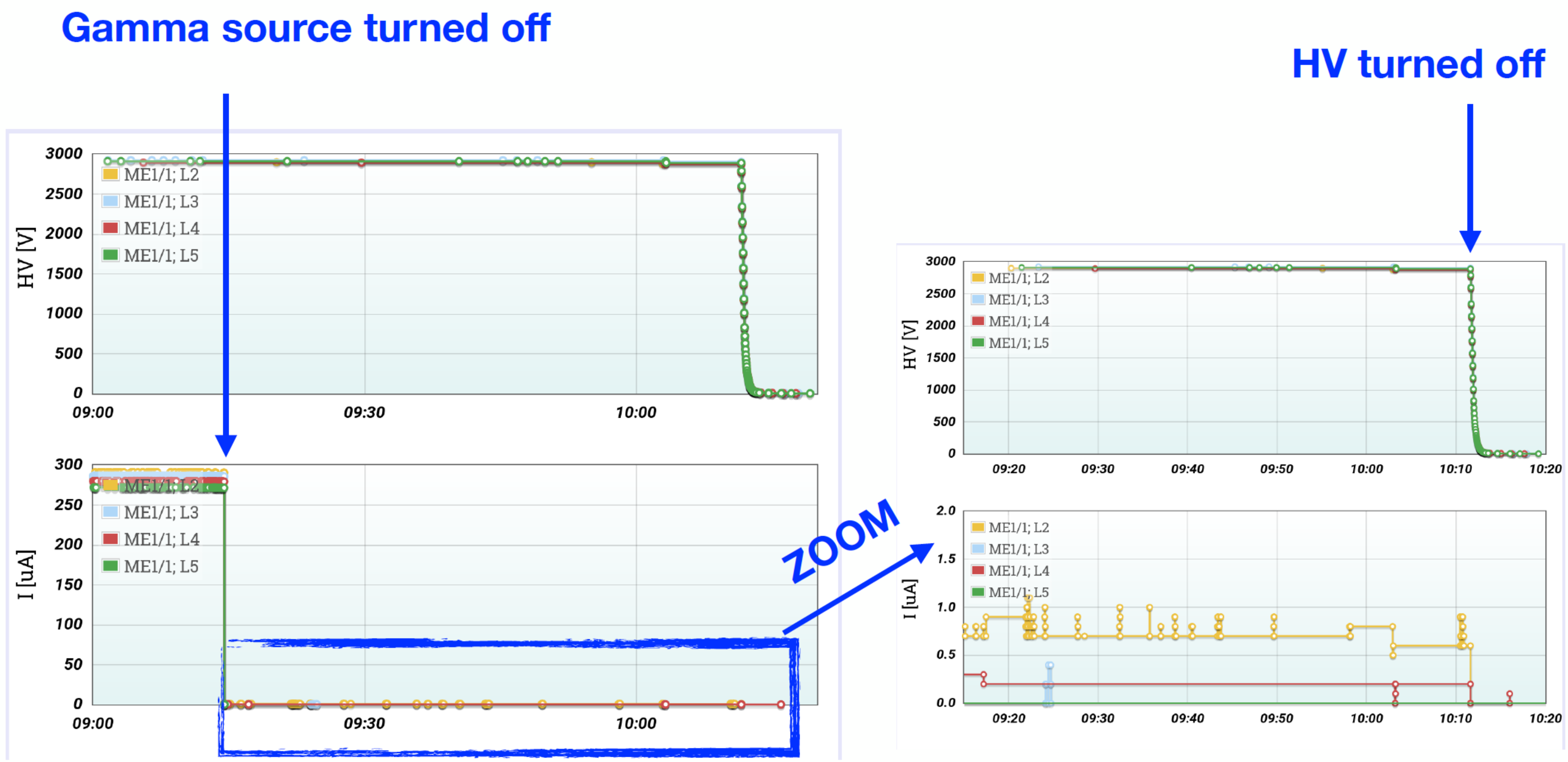




No noticeable performance degradation up to 3 x HL-LHC (330 mC/cm)

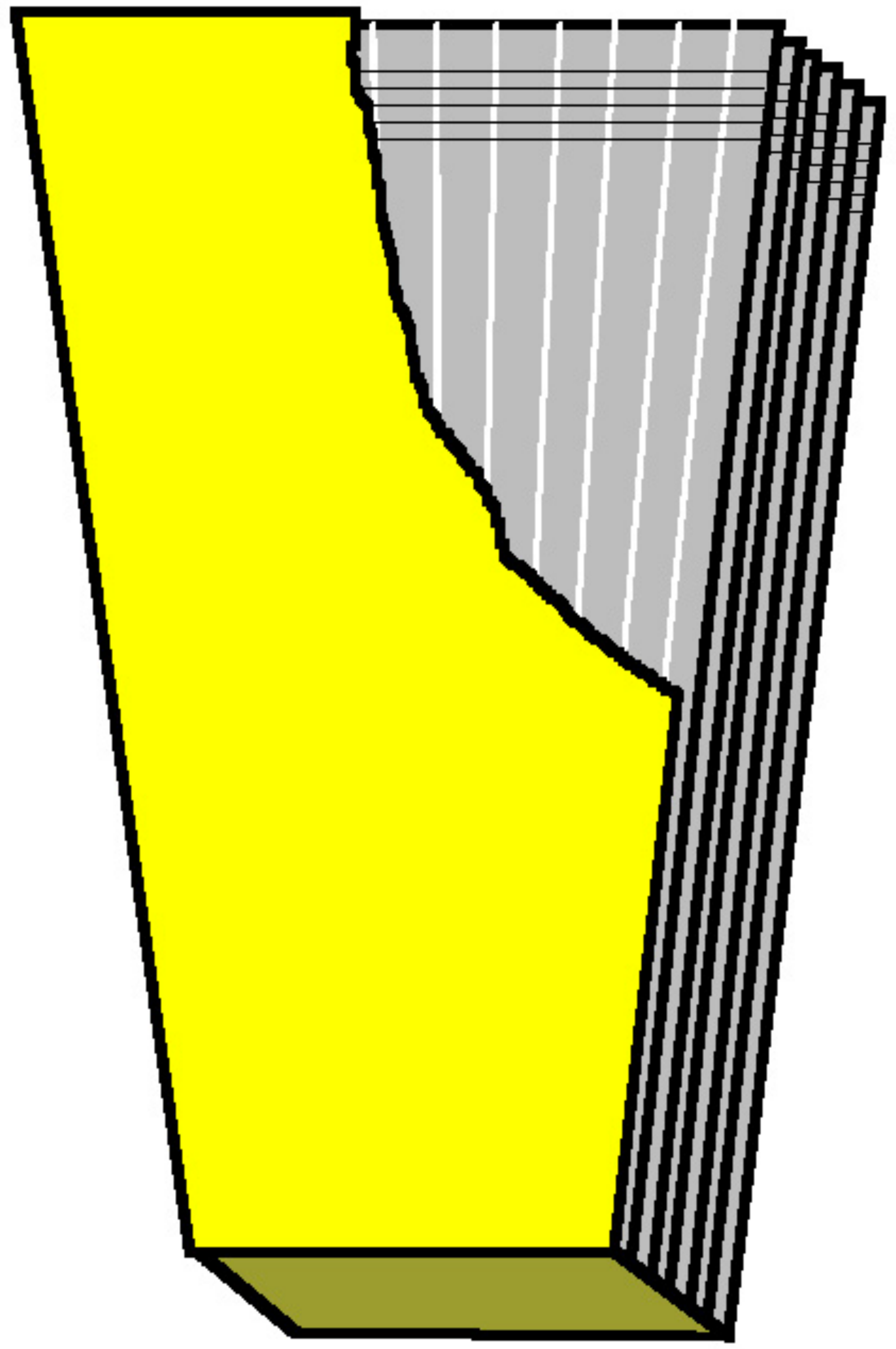
Malter current

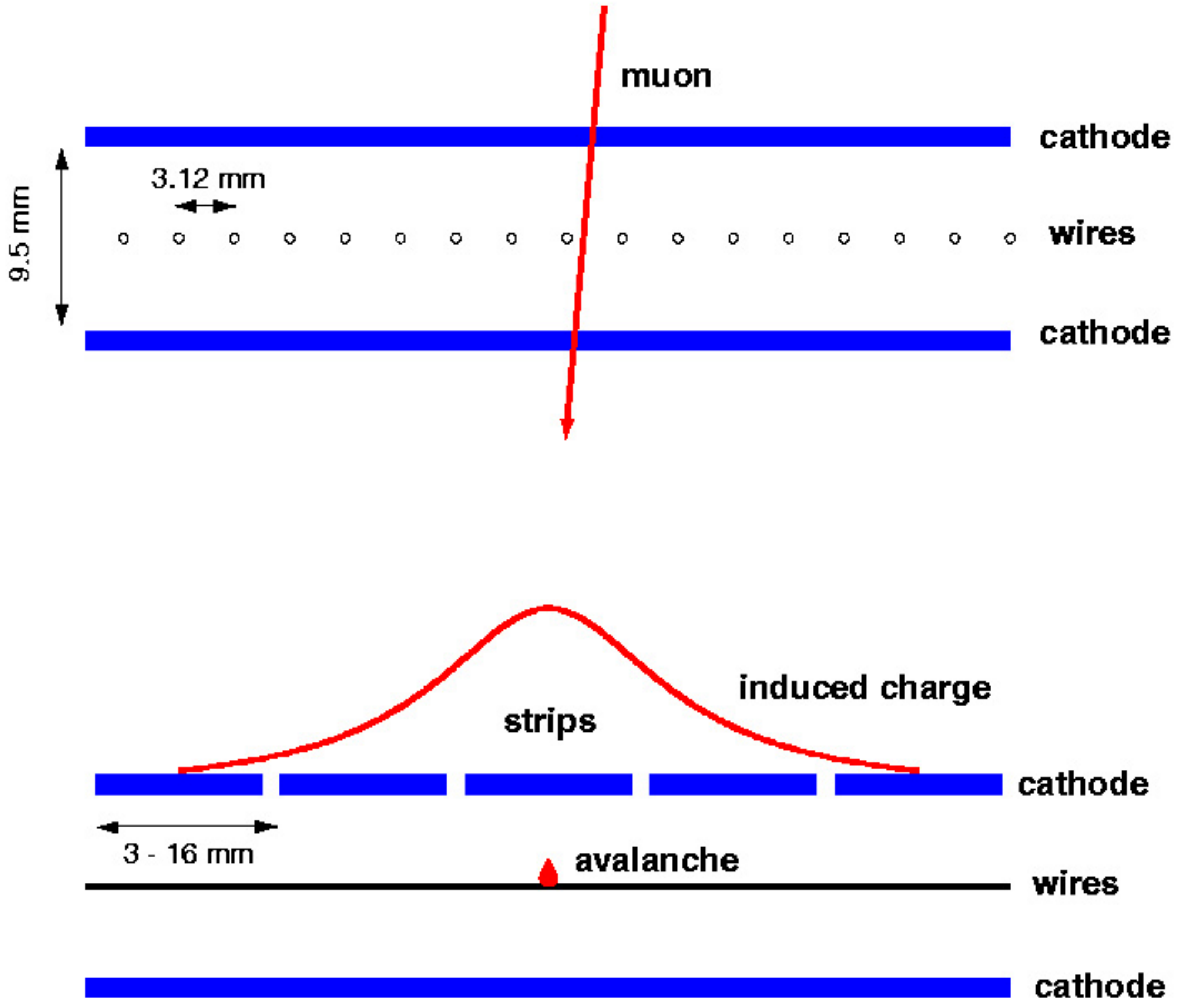




Common in gas detectors. Different measures are taken:

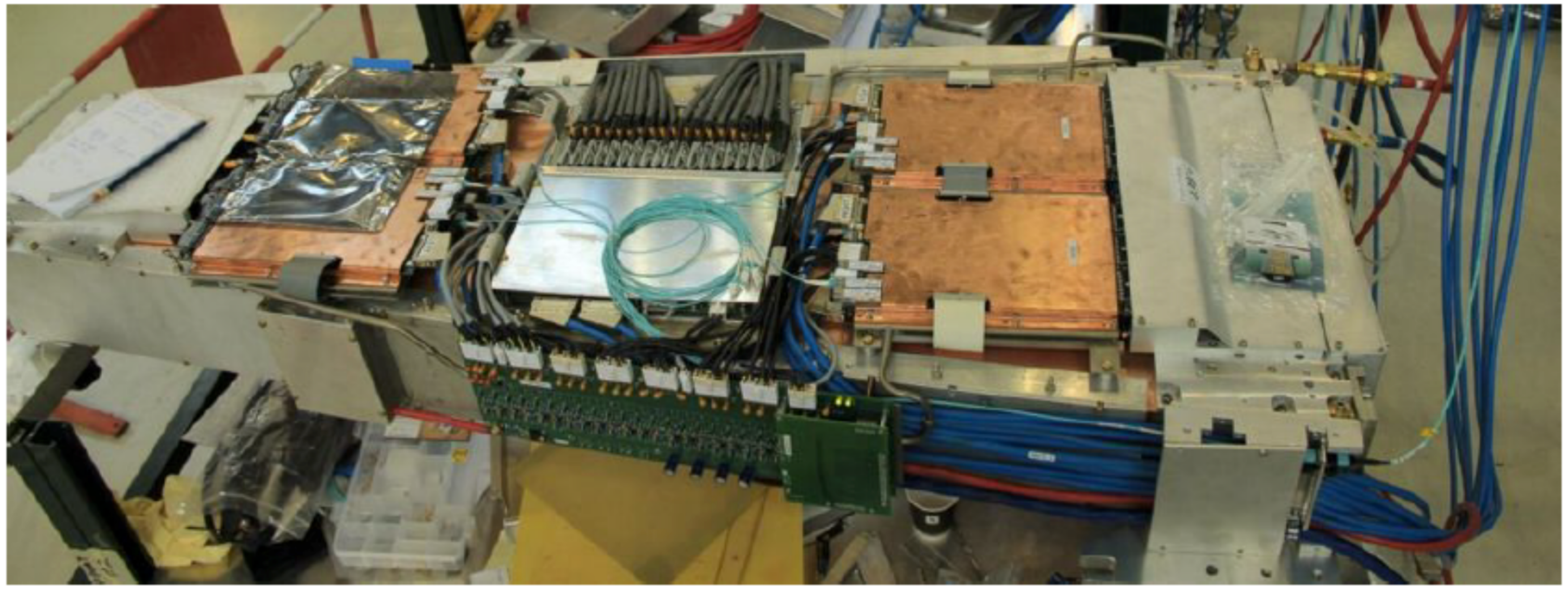
- BES: to add 0.2% vapor
- LHCb: to raise to HV
- CMS: to train the chamber with reversed HV

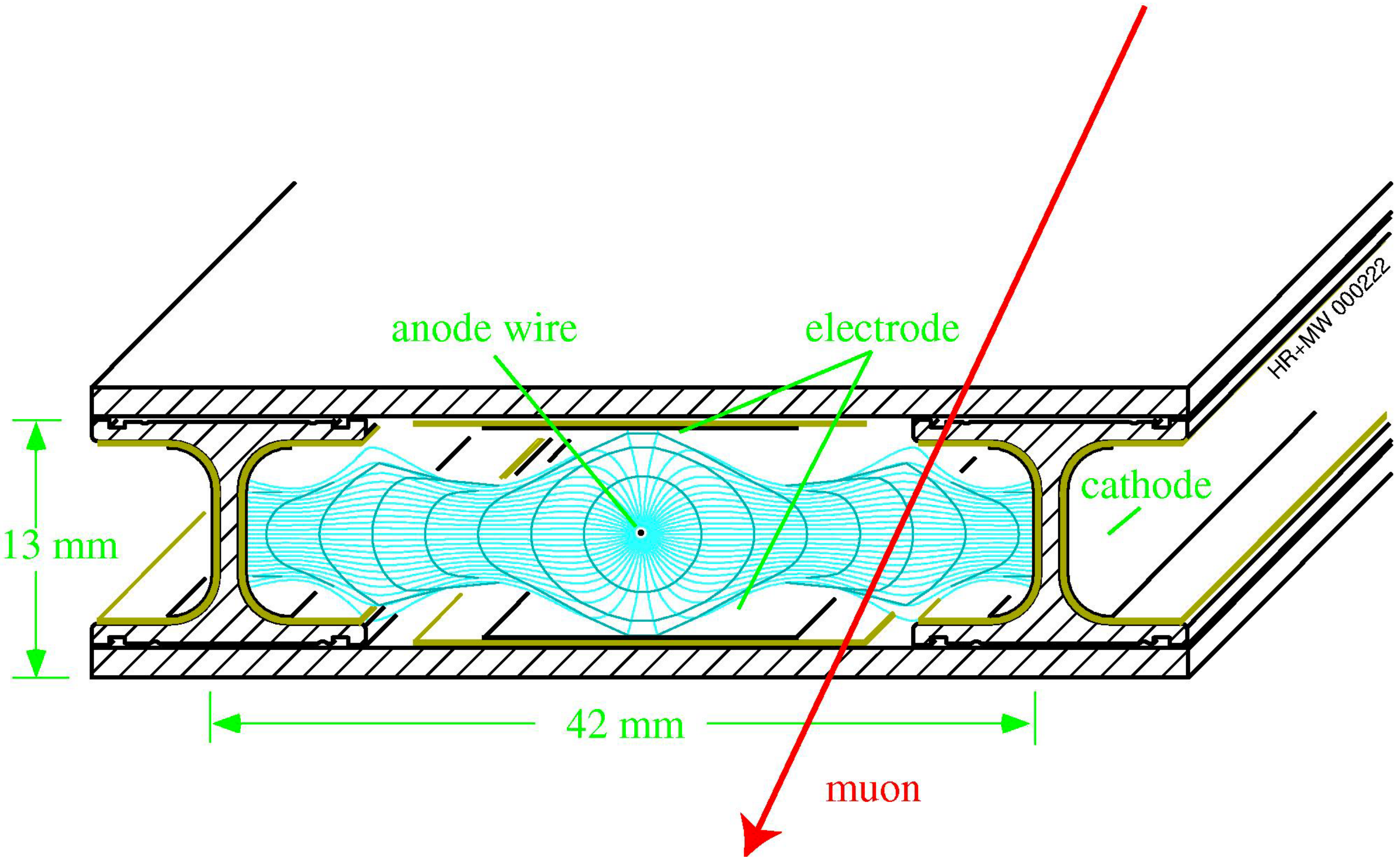


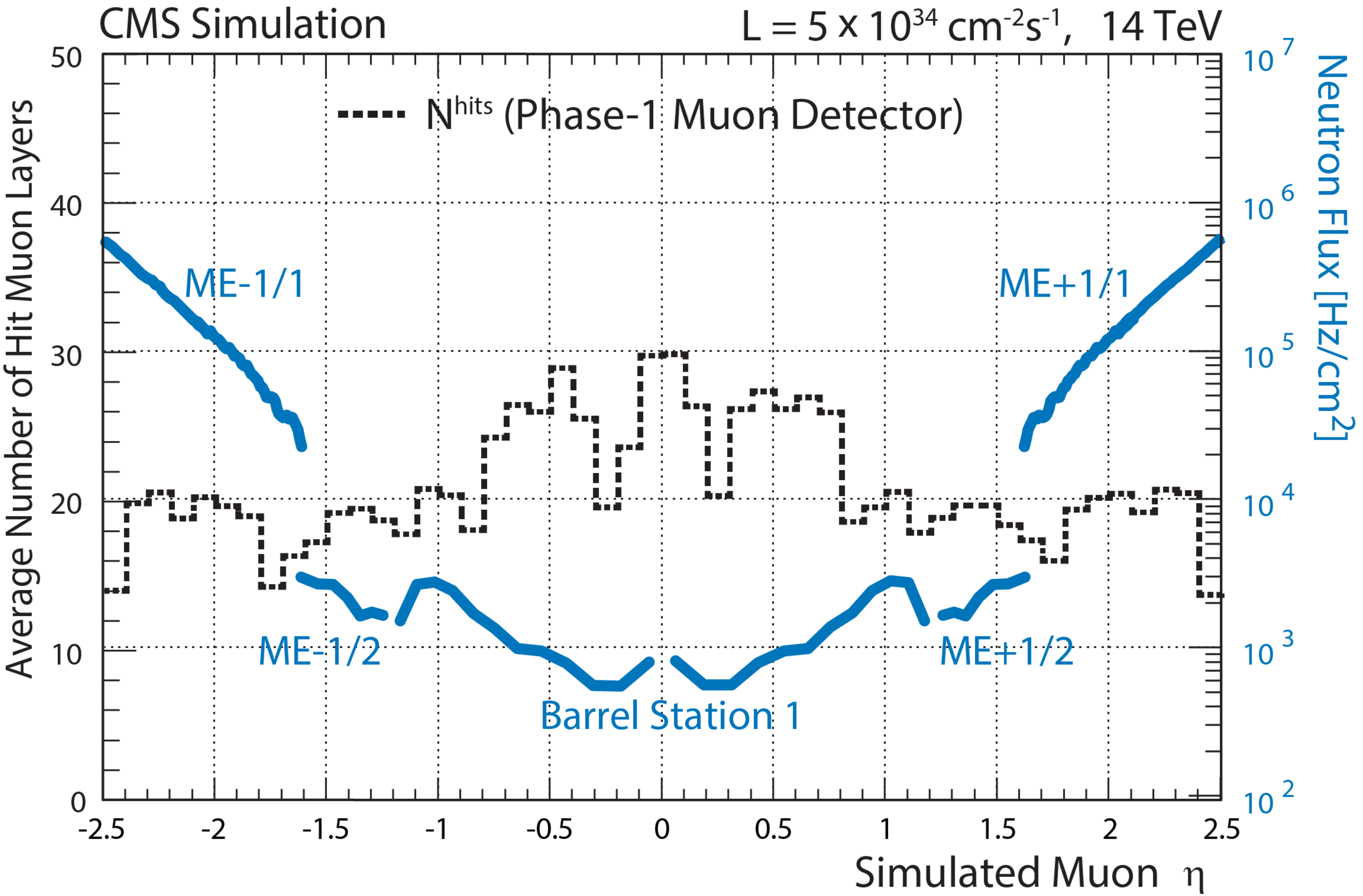


Cathode Strip Chamber

- 6 layers of alternating strips and wires
- Ionization of gas causes avalanche
- Filled with circulating gas (Ar, CO2, CF4)
- On-chamber electronics readout strip and wire signals

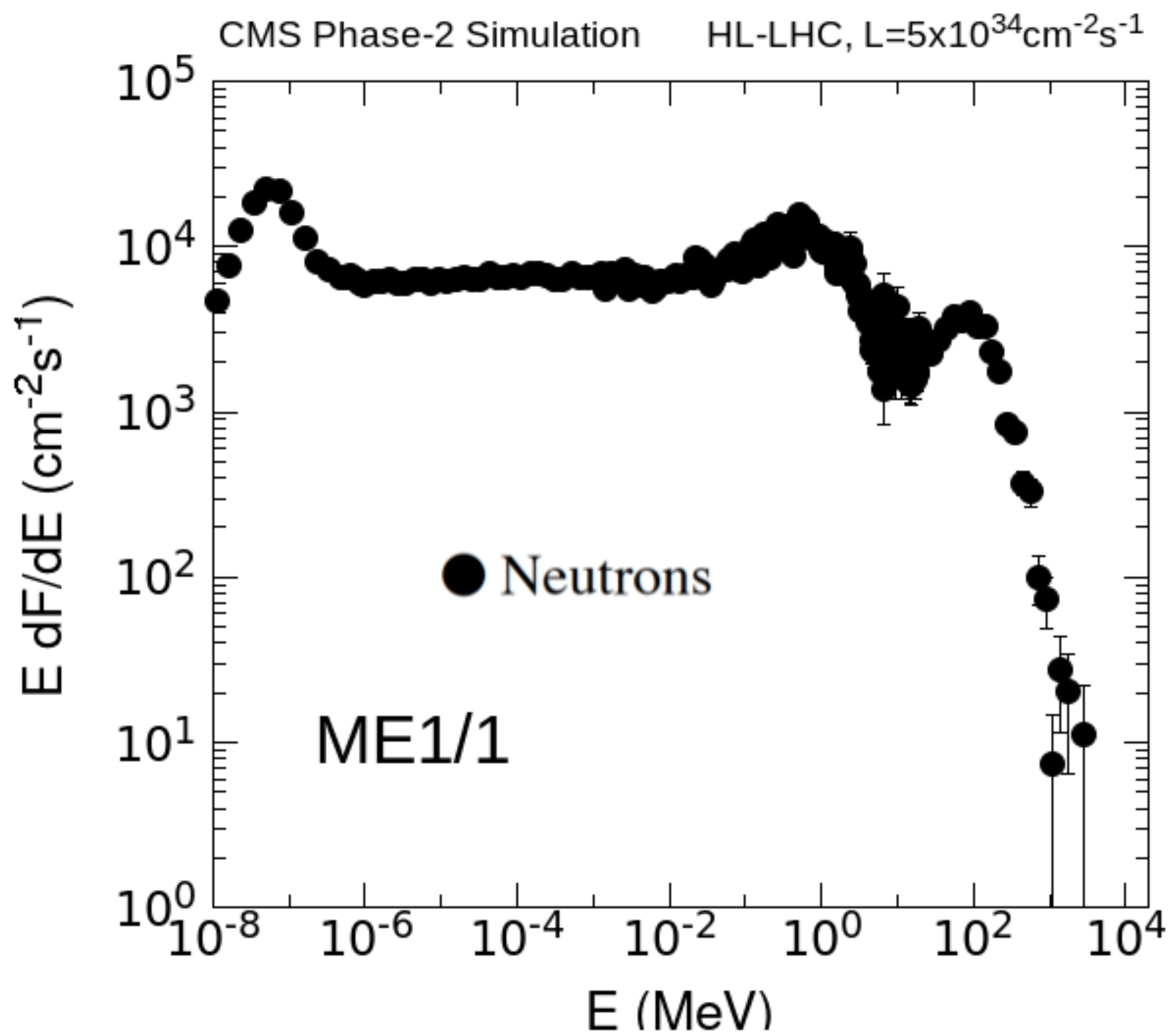


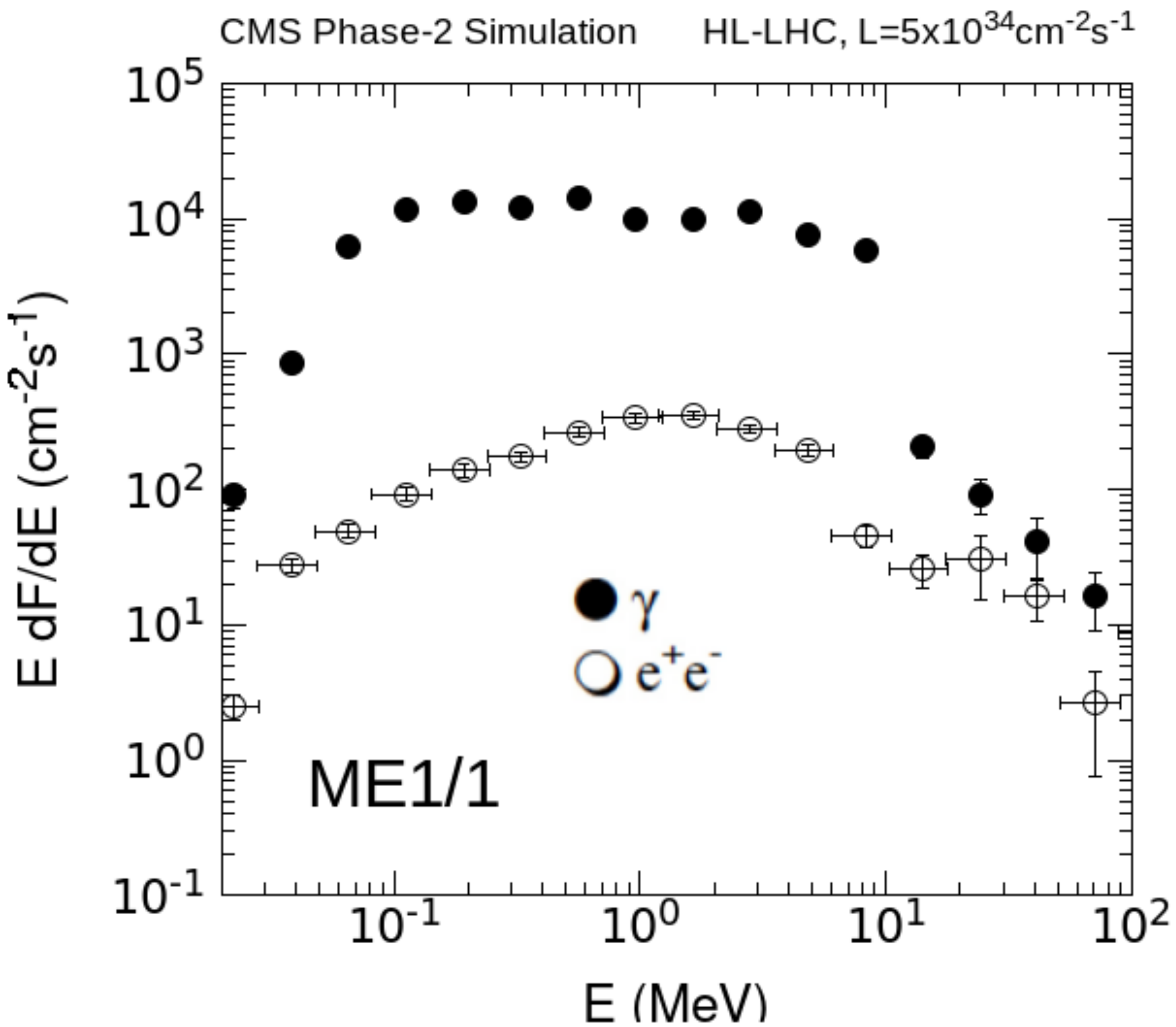

anode wire
electrode
HR+MW 000222
cathode
13 mm
42 mm
muon



CMS Simulation
L = 5 x 10^34 cm^-2s^-1, 14 TeV
N^hits (Phase-1 Muon Detector)
Average Number of Hit Muon Layers
Neutron Flux [Hz/cm^2]
ME-1/1
ME+1/1
ME-1/2
ME+1/2
Barrel Station 1
Simulated Muon η
0
10
20
30
40
50
10^2
10^3
10^4
10^5
10^6
10^7
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

	HL-LHC needs	CMS 2017	CMS upgraded
Level-1 trigger accept rate (kHz)	500	DT: < 300 CSC: < 250	DT: $\gg 500$ CSC: 4000
Level-1 latency (μs)	12.5	DT: 20 CSC: 3.6	DT: $\gg 12.5$ CSC: 28.8
Total DAQ data transfer rate (Gbit/s)	DT: 1082 CSC: 1026	DT: 42 CSC: 230	DT: 3600 CSC: 2764


CMS Phase-2 Simulation
HL-LHC, L=5x10^34cm^-2s^-1
E dF/dE (cm^-2s^-1)
E (MeV)
Neutrons
ME1/1


CMS Phase-2 Simulation
HL-LHC, L=5x10^34cm^-2s^-1
E dF/dE (cm^-2s^-1)
E (MeV)
γ
e+e-
ME1/1

Eco-friendlier gas

- New regulations
  - In 2014, the European Commission adopted a new regulation limiting the total amount of important fluorinated greenhouse gases (F-gases) that can be sold in the EU from 2015 onward and phasing them down in steps to one-fifth of 2014 sales in 2030
- CSC and RPC F-gas footprint
  - 1700 m3/hr of CO_2 equivalent (yearly, 12K cars)
  - F-gases used by CSC and RPC prevent ageing and ensure reliable operation
- Solutions
  - new eco-friendlier gas options -> RPC explore operation with CF_3I, $C_3H_2F_4$ (GWP 0,4)
  - F-gas consumption reduction -> CSC explore operation with 2% CF_4
  - Other measures being explored

Electronics longevity

- Radiation damage of the silicon substrate in the electronic chips leads to noisier electronics performance, and even failure of entire boards
- The relevant quantities are the integrated neutron flux, measured by the number of neutrons per cm2, and the total ionization dose (TID).
- Single event effects (SEE) causes electronics circuits to fail
    - Temporary: memory or communication signal bit flips in programmable electronic elements; can be restored by reloading those memory chips or recycling power
    - Permanent damage
- Tested at CERN High-energy AcceleRator Mixed filed (CHARM) or outside CERN
    - CHARM: mixture of neutron, photon, electron, charged hadron
    - neutron spectrum up to 100 MeV