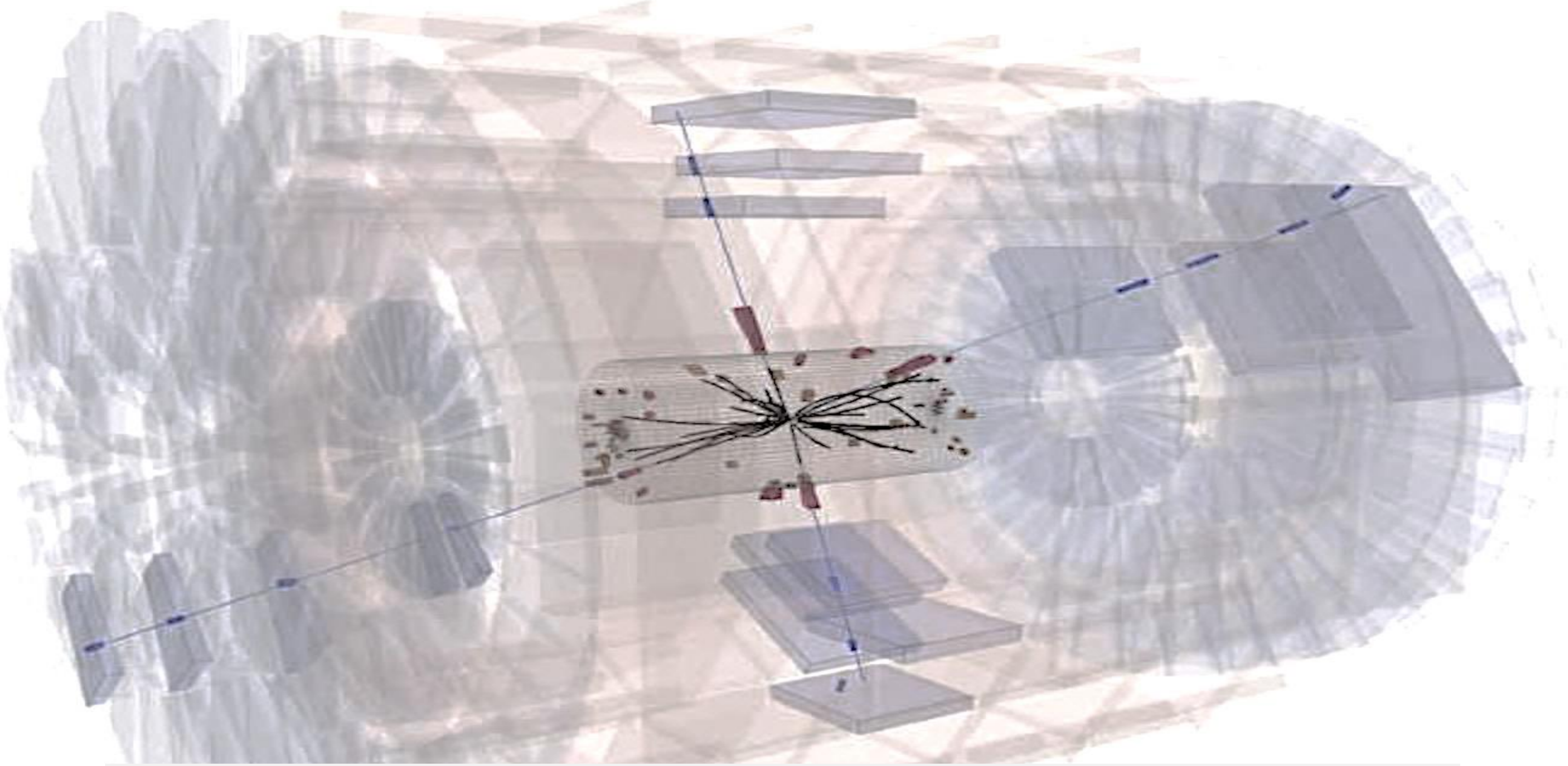

The upgrade of the CMS Muon Spectrometer for HL-LHC

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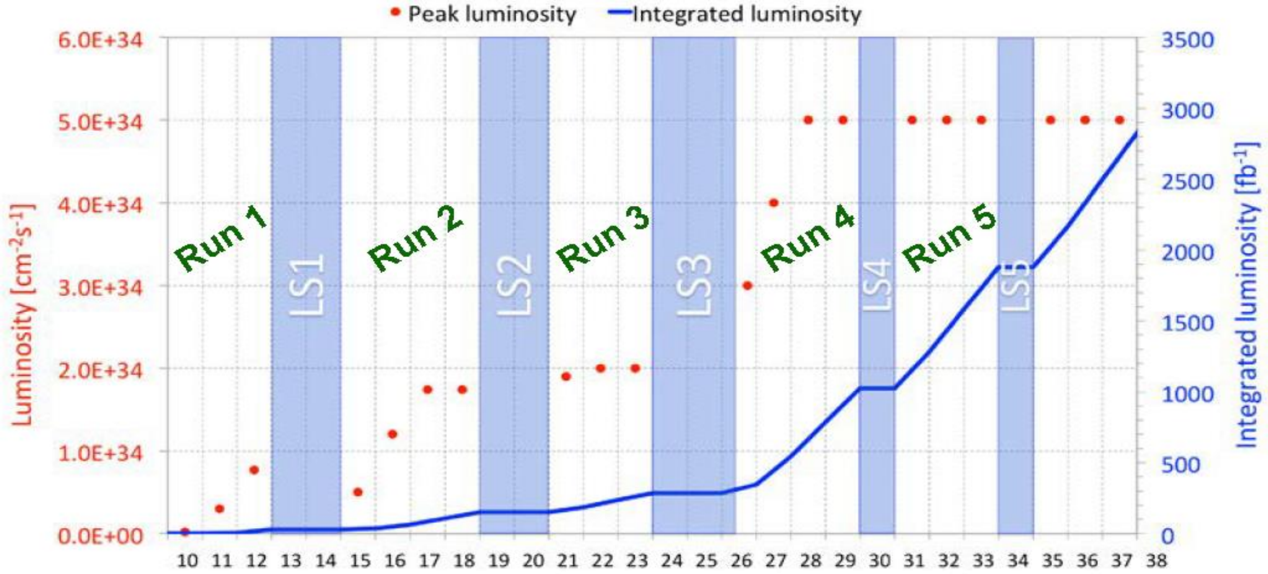
7th ENHEP School on High Energy Physics
26-31 January 2019
Ain Shams University

CMS Upgrade towards HL-LHC



PU ~200

LHC Phase-1
LS2: Upgrade injection to
increase beam brightness

HL-LHC Phase-2
LS3: Upgrade int. Region to
increase beam overplap

CMS Upgrades

- New tracker (4 pixel layers +3 disks)
- New trigger/DAQ:
  - Track information at L1 with extended trigger latency (from 3.2 total of 12.5 μs)
  - Increased L1 bandwidth from 100 kHz to 750 kHz
- Calorimeters with higher granularity
- Upgrade of Muon system

$|\eta| < 3$

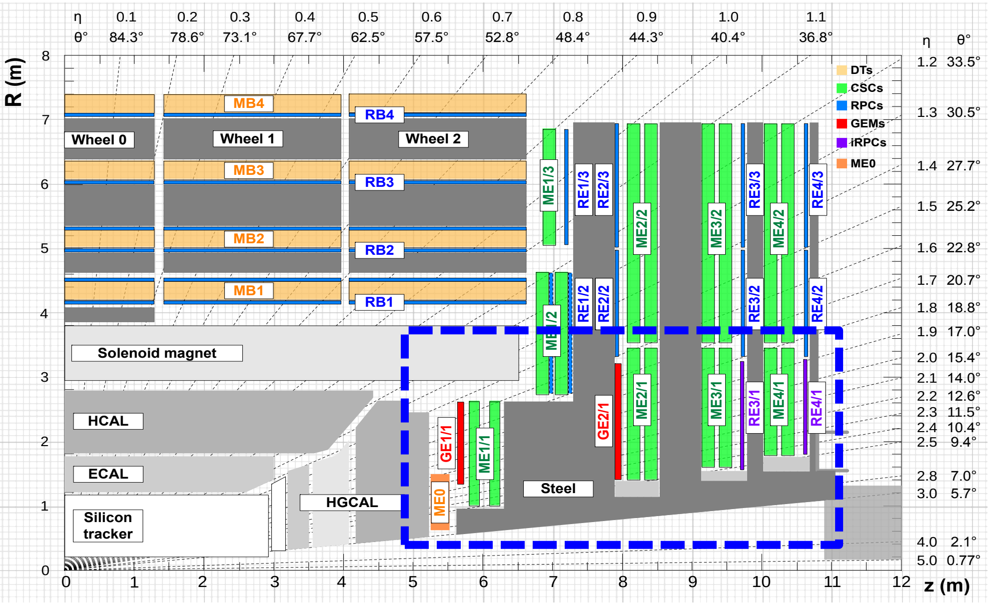
Phase-2 Muon Upgrade overview

Plan for operation in the future decades requires three elements in the Muon upgrade:

1. Upgrades of the existing muon detectors
   - Assess longevity of current detectors/electronics to withstand at HL-LHC
   - Upgrade electronics to ensure longevity, cope with trigger and readout requirements

2. Enhancement of the forward region 1.6<|η|<2.4:
   - Additional GEM and RPC layers with new technology for improved triggering, background rejection.

3. Extension of coverage to the very forward region 2.0<|η|<2.8:
   - new ME0 detector using GEM technology for triggering and tagging: extra coverage and reduced physics backgrounds from “lost leptons”



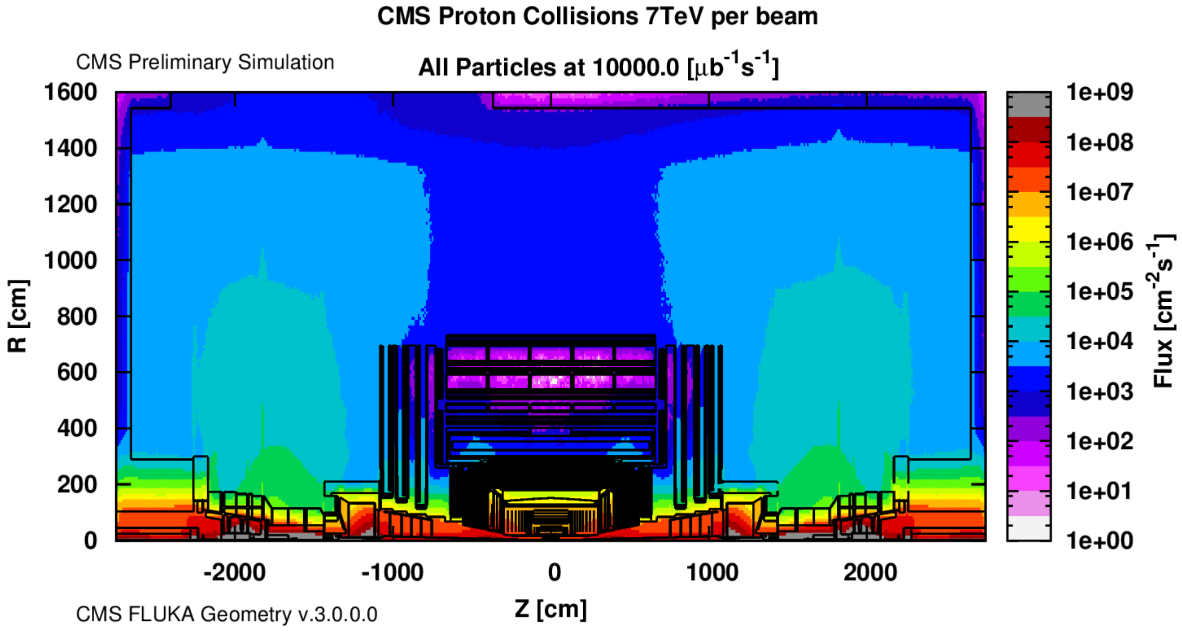
1. Upgrades of the existing muon detectors

- Assess longevity of current detectors/electronics to withstand at HL-LHC

Radiation particles at LHC

Hadronic interactions lead to activation of materials and give rise to neutron backgrounds. Long living neutrons can interact with nuclei and produce photons which further decay to electrons/positrons with some possibility to generate fake signals.

- very high flux→ low detector sensitivity to the neutron and photons required



Monte Carlo estimation of the flux of all particles at CMS using FLUKA. Inelastic collision cross section used for normalization is 80 mb. Used simulation cut offs: Hadrons 1 keV, Muons 1 keV, Neutrons 0.01 meV, Photons 3 keV, Electrons 30 keV. Photons and Electrons have significantly higher cut-offs in some regions (heavy parts). The plot shows the particle flux in the whole CMS cavern for nominal instantaneous luminosity, ($L = 10^{34}$ cm^{-2} s^{-1}) .

Radiation particles at LHC

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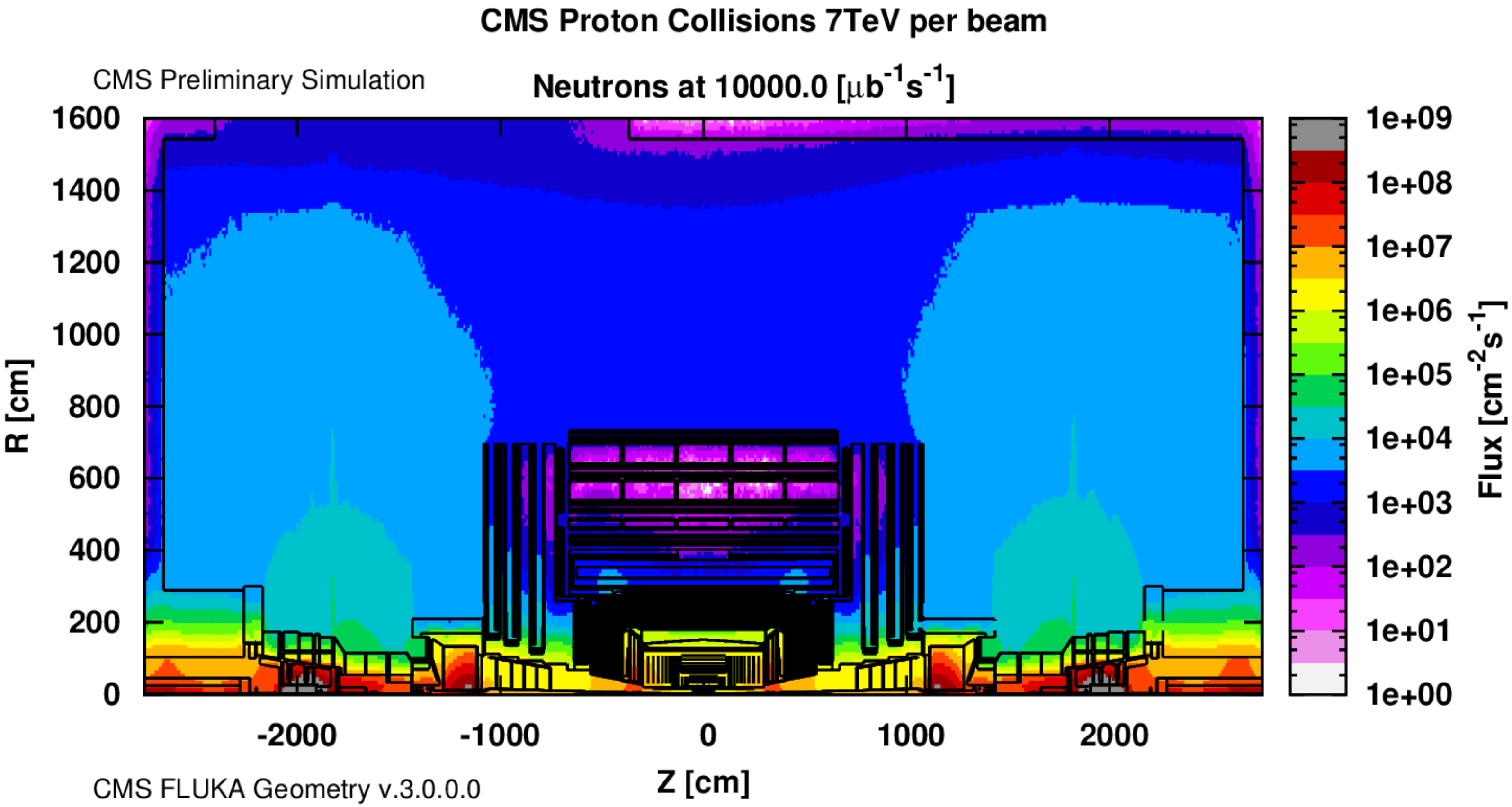


Radiation particles

- **neutrons:** originate as “fast”, O(100) MeV, (the end product of hadron showers) and then “thermalize” down to 0.025 eV via multiple nuclear scattering
- **photons:** 0.1-10 MeV, from nuclear capture of thermal neutrons, followed by nuclear de-excitation
- **electrons/positrons:** 0.1-10 MeV, from photon conversions and Compton scattering
- **minimum ionizing particle (MIPs):** muons (prompt, π/K in-flight decays) and punch-through hadrons

neutrons : photons : e^+/e^- : mips

Although absolute fluxes change dramtically from place to place, the relative fluxes of different species are approximately the same (except for mips):

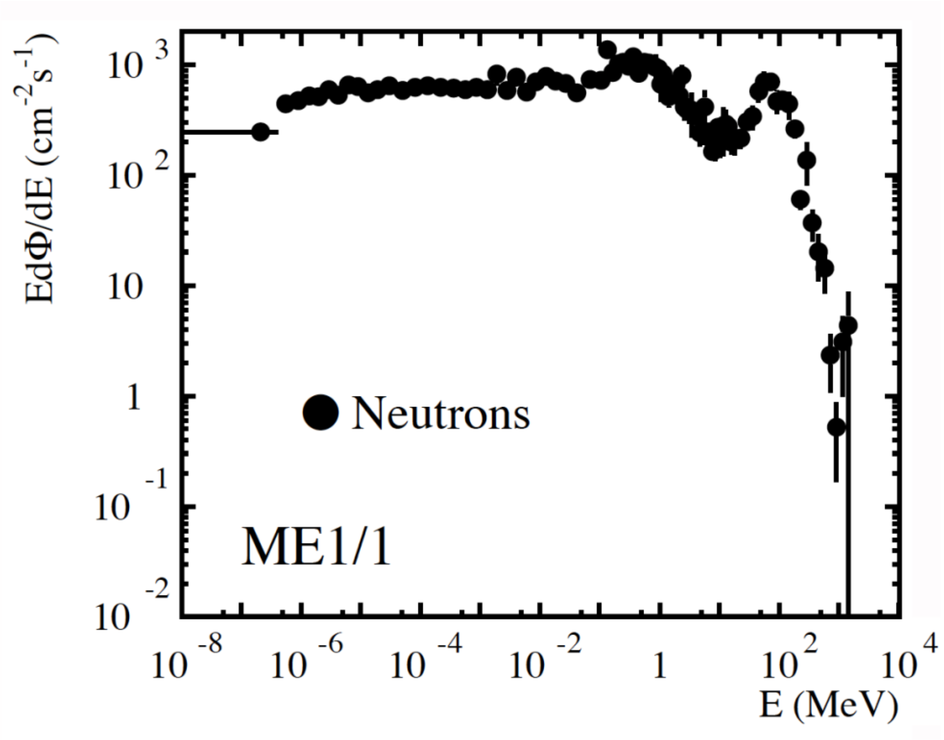
3 : 1 : 0.01 : 0.001-0.01

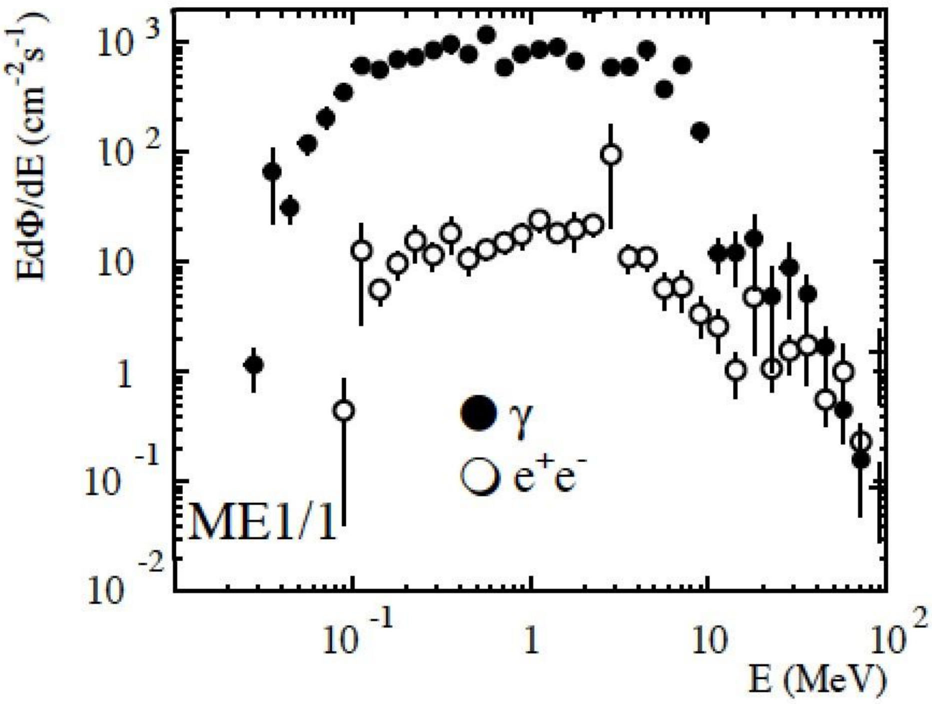
Probability (sensitivity) for different particles to cause a “hit” is almost detector technology independent, approximately:

0.2% : 1% : 20% : 100%

Energy spectra

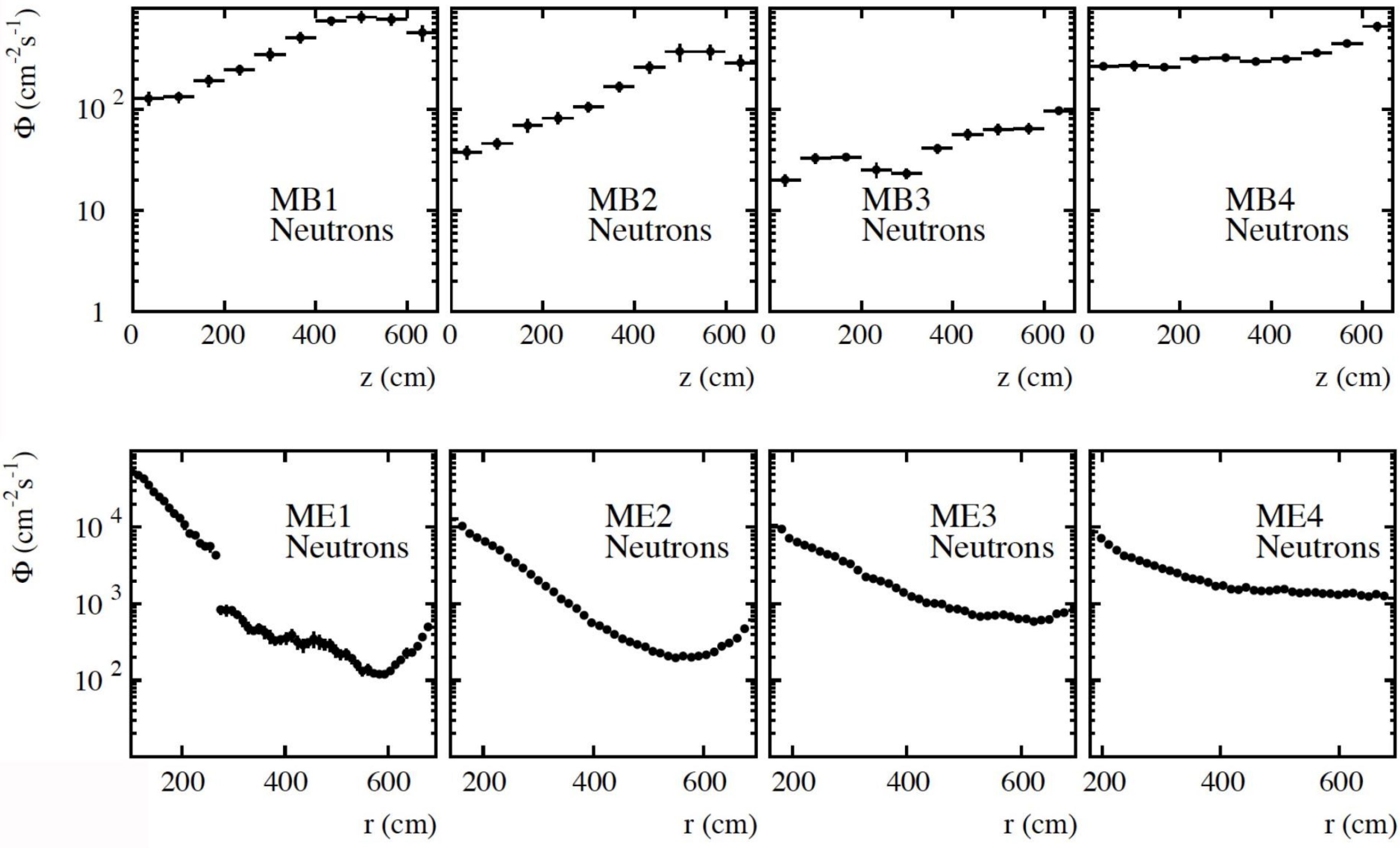
Plots from Muon TDR



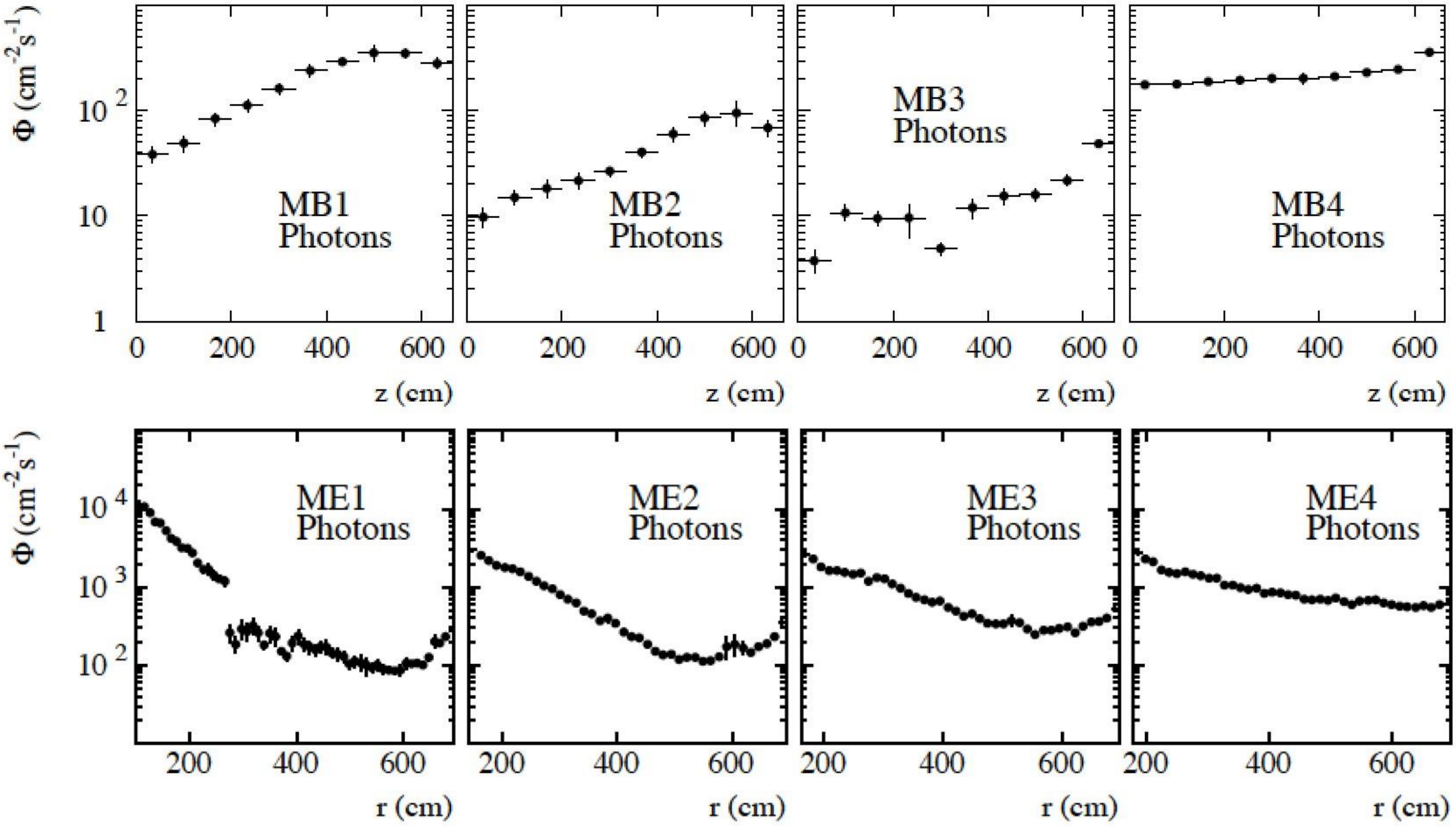


The shapes of the energy spectra of neutrons, photons, e^+/e^- are about the same throughout the muon system

Flux: neutrons (Muon TDR)



Flux: photons (Muon TDR)



Aging and Long Term Operation

The degradation of operating conditions of wire chambers under sustained irradiation are the main limitation to the use of gas detector in high-energy physics.

‘Classical aging effects’ are deposits formed on electrode surfaces by chemical reactions in avalanche plasma near the anode.

During gas avalanches many molecules break up and form free radicals (unionized atomic or molecular particles with one or more unsatisfied valence bonds).

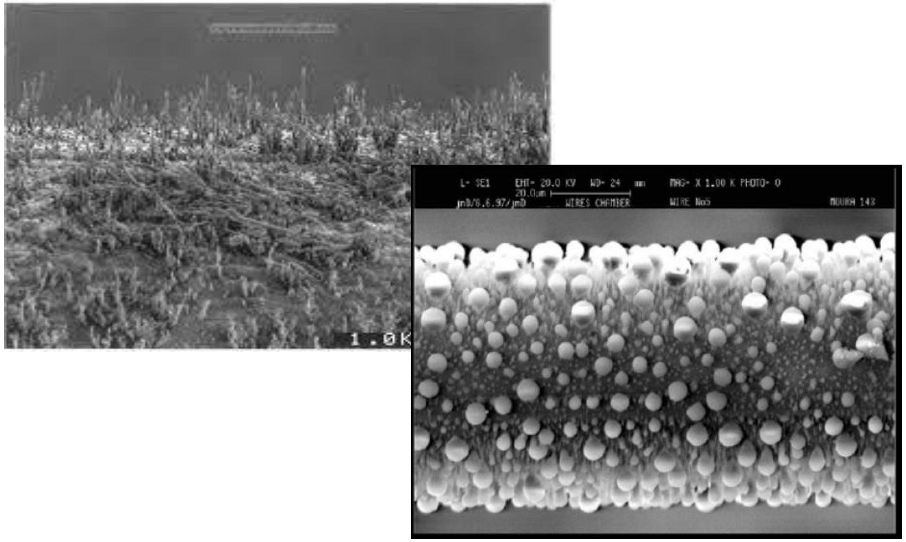
Free-radical polymerization is regarded at the dominating mechanism of wire chamber aging

The integrate charge (per unit area for parallel detector or for unit lenght of the anode wire for wire chambers) during radiation exposure is the relevant quantity Type equation here.

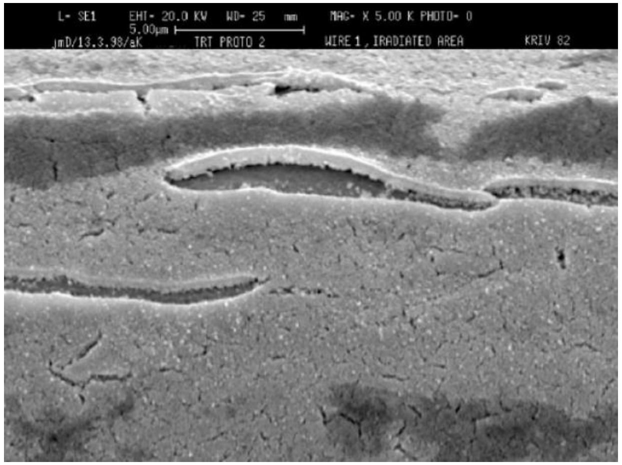
$$\text{Expected int charge}\left(\frac{C}{cm^2}\right) = \left[\varepsilon \frac{Charge}{hit}\right] \times \left[\frac{0.5 \times 10^7}{LHCy} s\right] \times \phi^{Experiment}_{particle} \times \left[n^o LHCy\right]$$

Aging and Long Term Operation: wires

- **polymerization**
  - – wires get effectively thicker:
    - smaller non-uniform gas gain
    - loss of efficiency
  - – long whiskers:
    - can cause spurious pulses
    - and eventual HV breakdown

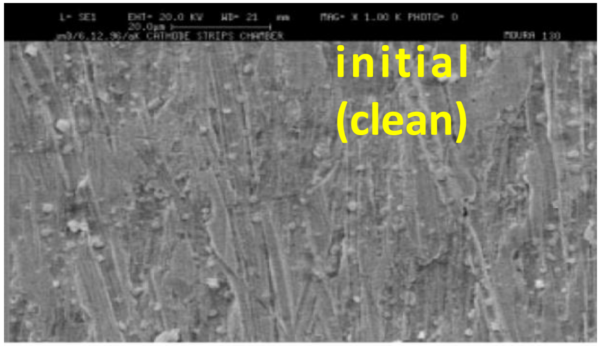


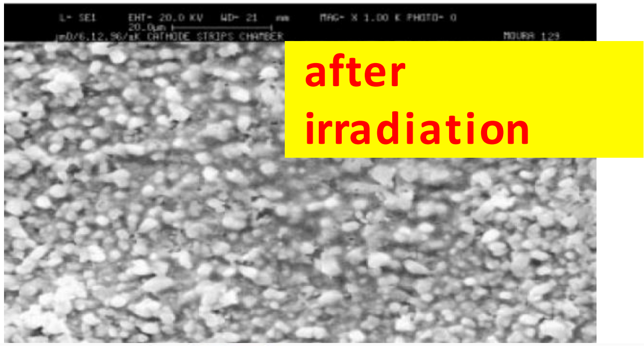
- **oxidation under gold coating:**
  - – wires swell:
    - smaller non-uniform gas gain
    - loss of efficiency
  - – gold coating cracks:
    - sharp edges can cause spurious pulses
    - and eventual HV breakdown



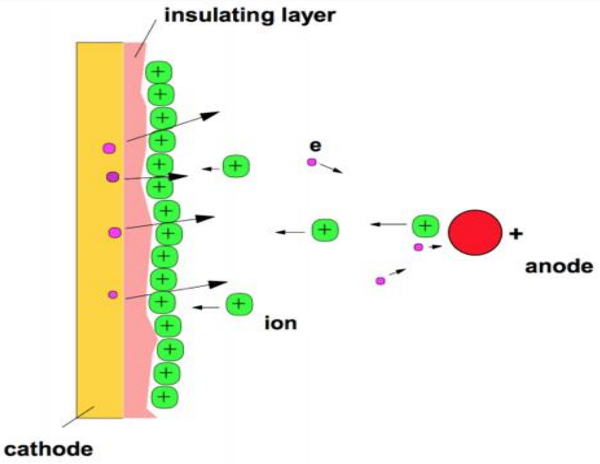
Aging and Long Term Operation: surface

- **Polymerization on surfaces:**
  - increased conductivity:
    - leak currents
    - loss of the proper electric field configuration
  - decreased conductivity; insulating blemishes can charge up and cause:
    - erratic changes of the proper electric field configuration (unstable operation)
    - **self-sustained discharges (Malter currents)**





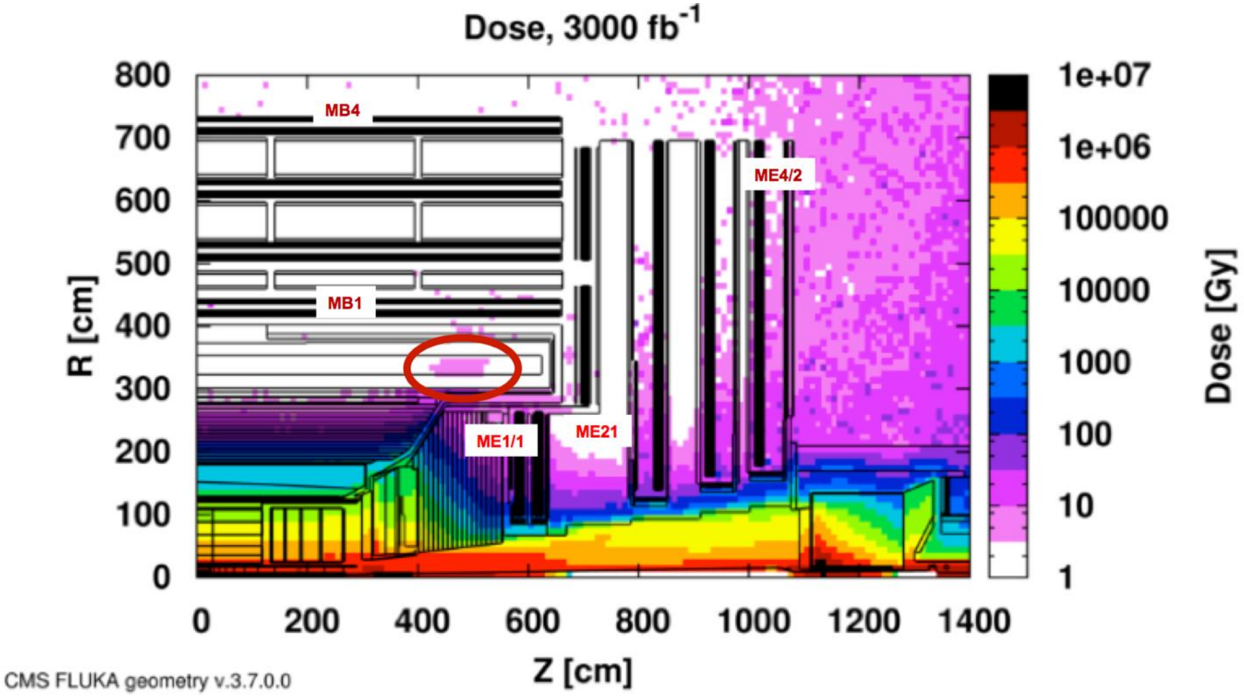
- **Physics:**
  - **self-sustained** discharge **ignited** by high intensity irradiation
  - associated with thin film insulator on cathode which can due to initial dirt (e.g., fingerprints) and due to polymerization build-up



HL-LHC: Assess longevity of detectors/electronics longevity

Different Radiation Environment in different stations

Background – 5x rates and 6x total doses with respect to LHC

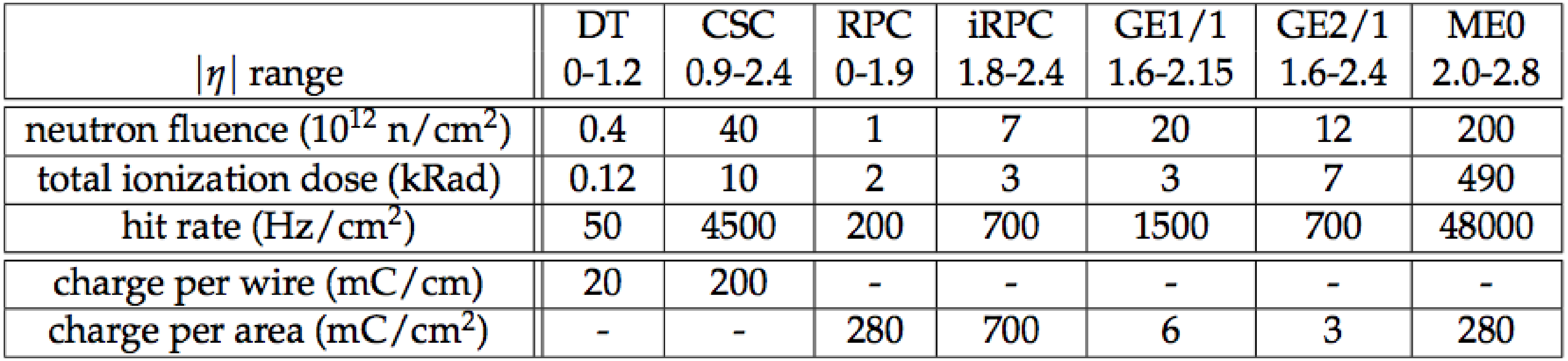


Exceed the design tolerances of several components of the muon system:

- new assessment of the chambers and electronics longevity and performance under accelerated aging tests.

Background and longevity issues

Very harsh conditions expected at HL-LHC with integral radiation dose parameters and hit rates at the instantaneous luminosity of $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$



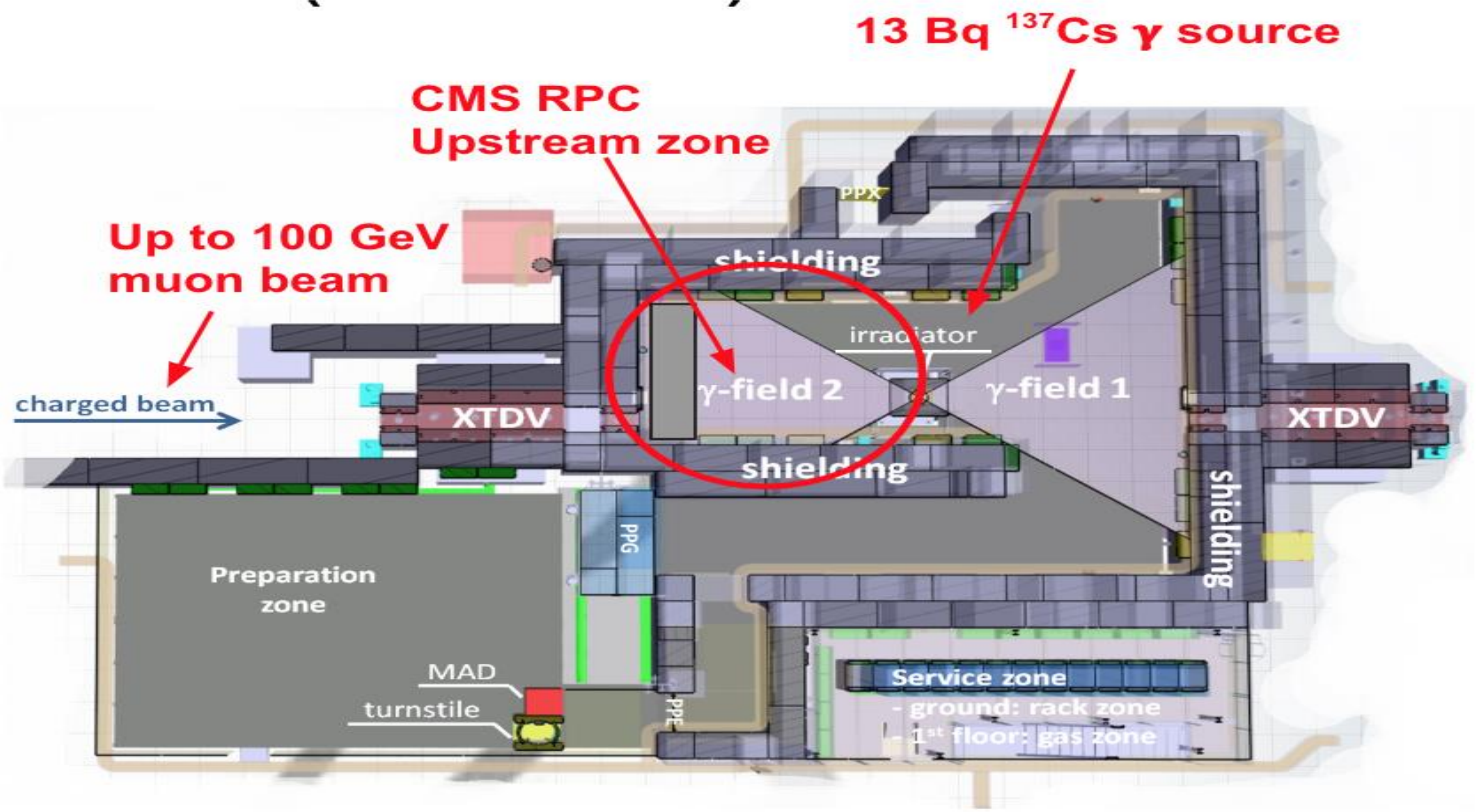
	DT	CSC	RPC	iRPC	GE1/1	GE2/1	ME0
$\lvert\eta\rvert$ range	0-1.2	0.9-2.4	0-1.9	1.8-2.4	1.6-2.15	1.6-2.4	2.0-2.8
neutron fluence (10^{12} n/cm^2)	0.4	40	1	7	20	12	200
total ionization dose (kRad)	0.12	10	2	3	3	7	490
hit rate (Hz/cm^2)	50	4500	200	700	1500	700	48000
charge per wire (mC/cm)	20	200	-	-	-	-	-
charge per area (mC/cm^2)	-	-	280	700	6	3	280

High radiation affects both the detectors and electronics:

- can decrease the gas gain and increase hit-efficiency losses
- radiation damage of the silicon substrate in electronic chips can lead to noisier electronics performance and even fatal failures of entire electronic boards.
- elements of current system date even before 2000, currently 15-20 years old, eventually may need to last 40 years
- must re-certify existing equipment to HL-LHC for the expected integrated radiation doses and signal and background rates.

Muon longevity studies at GIF++

All detectors profit from the **CERN gamma irradiation facility, GIF++:** 662 keV photons emitted by an intense 14 TBq ^{137}Cs source + high momentum particle beam



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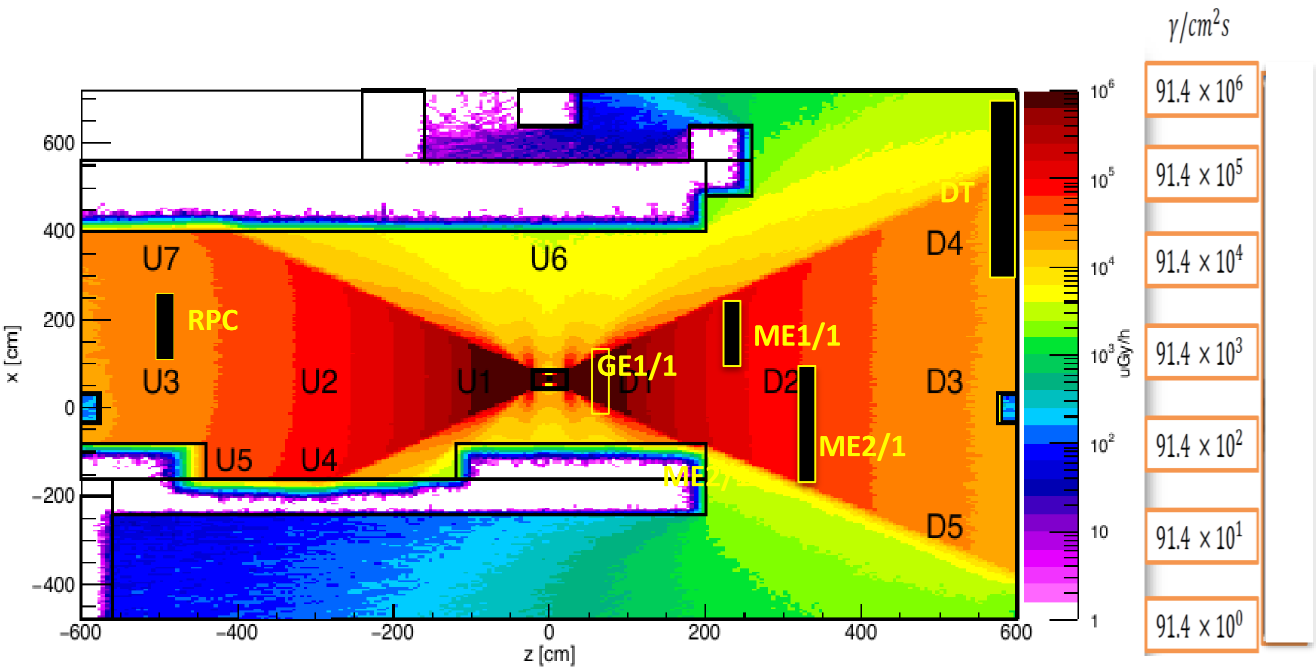


RPC

- RE2 and RE4 chambers and six spare gaps under test: detector performance and dark current/noise will be monitored

CSC

- Irradiate one ME1/1 (higher rate) and one ME2/1.
- Monitoring of gas gain and current. Measure trigger rates at HL-LHC condition.
- Monitor Malter effect.

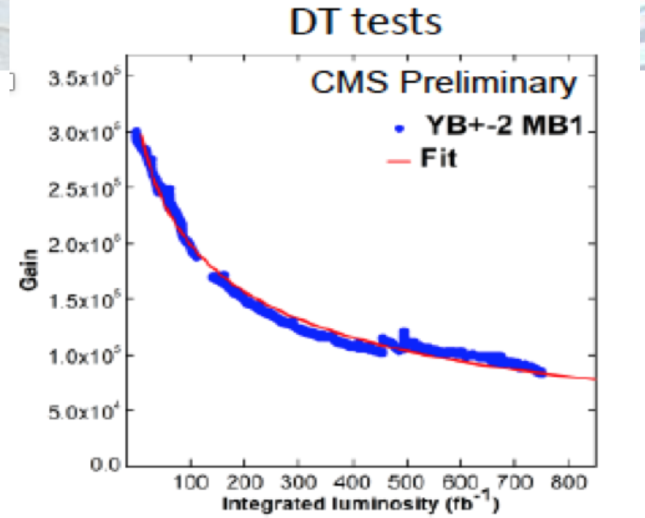
DT

- Study radiation effect on the material: small Drift-tubes are installed at Gif++
- Operated one spare MB1

GEM

- Test GE1/1 triple-GEM chamber at HL-LHC condition
- Also accelerated test with X-ray

Present Detector longevity status



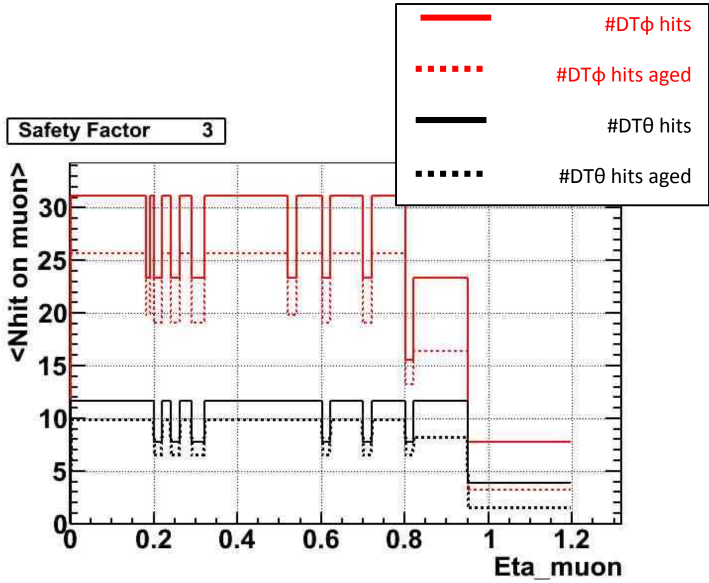
- **DTs (Ar : CO_2)**
  - about 15% of chambers, most exposed to background, could see noticeable gas gain loss but:
    - muon reconstruction will **remain high**, thanks to multiple layers of DTs on the path of a muon

- **CSCs (Ar : CO_2 : CF_4)**
  - longevity test with standard mixture completed: **no gas gain loss up to 3 × HL-LHC**

- **RPCs (i-C_4H_{10} : $C_2H_2F_4$: SF_6)**
  - **no detector degradation effect so far..test continuing**

- **GEM (Ar : CO_2)**
  - At GIF++: 30 x HL-LHC of the GE1/1 expected charge (0.6 of ME0) accumulated.
  - At B904: More than 1 C/cm^2 has been accumulated with X-ray test.

Operation conditions are stable no gas gain change observed

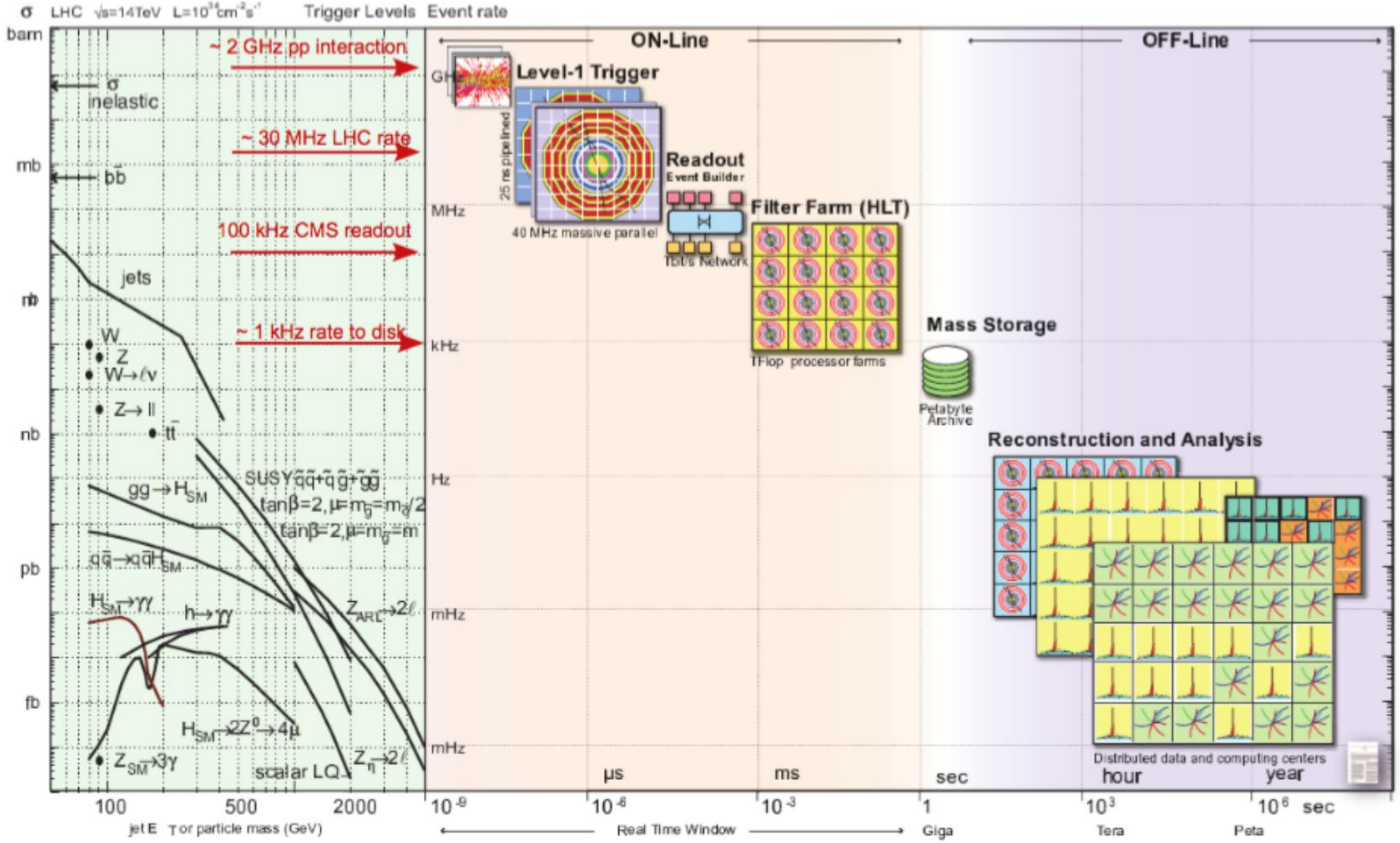


All installed Muon detectors will be kept operational at HL-LHC

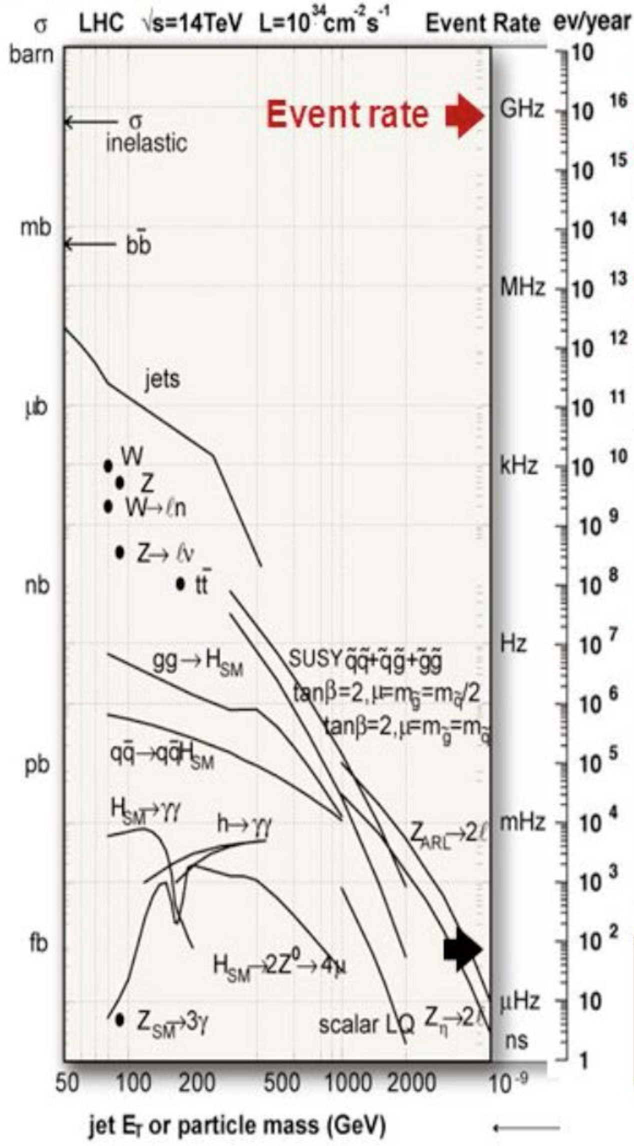
1. Upgrades of the existing muon detectors

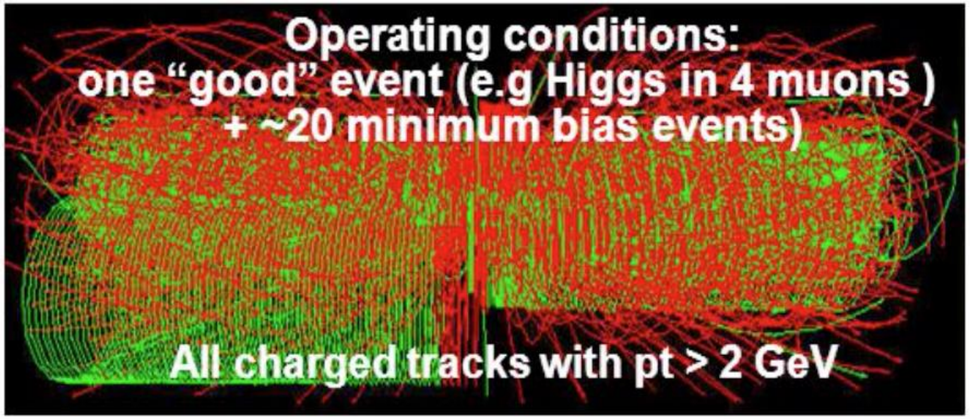
- Upgrade electronics to ensure longevity, cope with trigger and readout requirements

LHC cross section and trigger rates



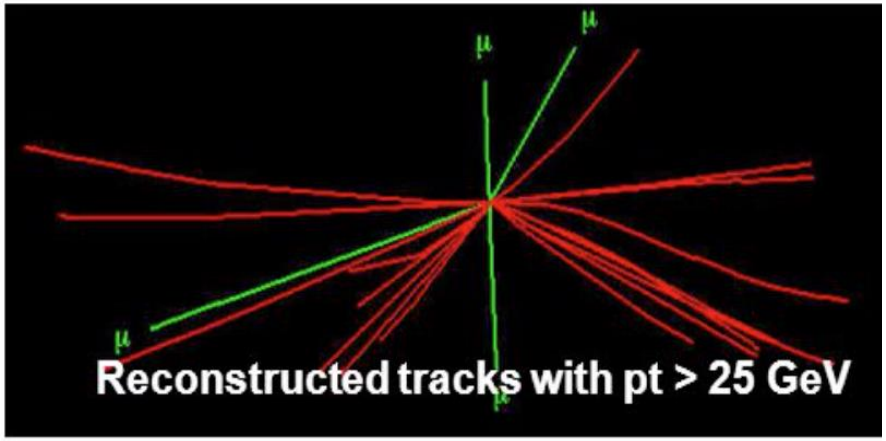
LHC cross section and trigger





Operating conditions:
one "good" event (e.g Higgs in 4 muons)
+ ~20 minimum bias events)

All charged tracks with pt > 2 GeV



Reconstructed tracks with pt > 25 GeV

Event size:	**~1 MByte**
Processing Power:	**~X TFlop**

SM Higgs (125 GeV/c^2):	→0.1 Hz
t t production:	→10 Hz
W→ ℓ ν:	→10^2 Hz
Z→ ℓ ℓ :	→10 Hz
bb production:	→ 10^6 Hz
Inelastic:	→10^9 Hz

Beam crossing every 25 ns

25 pileup event / beam crossing

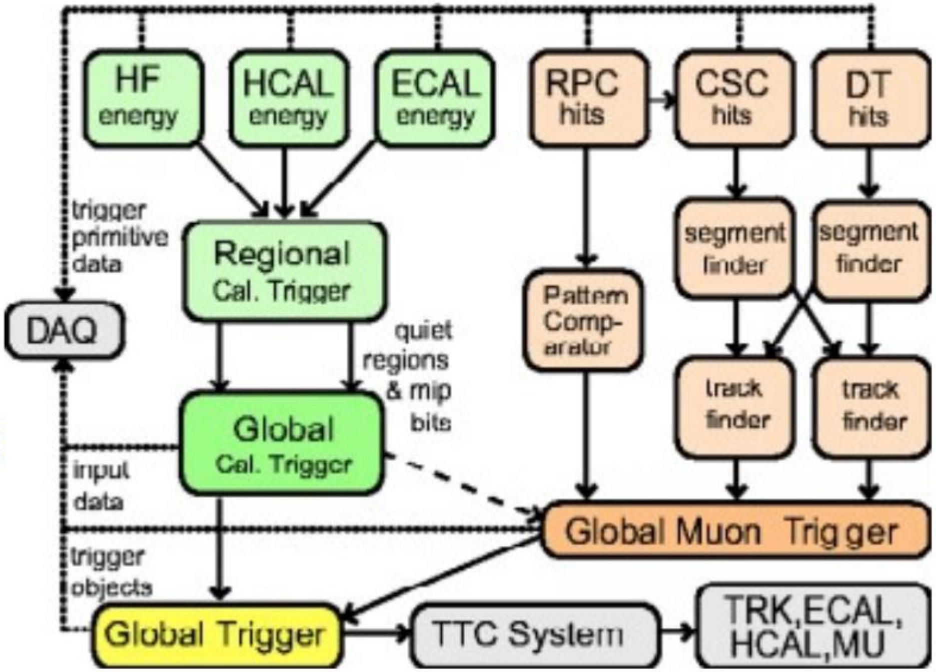
Experiments: need stringent and efficient online selection criteria (trigger)

Level 1 muon trigger

- Why high-momentum leptons?
  - QCD (strong interaction) provides many jets and large energy deposition, but generally not signatures of electroweak processes
  - So signatures with large energy deposition face large QCD backgrounds
  - Electrons, muons, taus are signatures of W, Z bosons, top quarks, higgs bosons, SUSY decays, etc., but are rare from QCD.
- Muons especially:
  - Excellent background reduction possible.
  - Excellent momentum resolution for invariant masses etc.
- Muon triggering:
  - Typical W→⌈⌇ muon transverse momentum <40 GeV/c. Wish to trigger above 15 or 20 GeV/c, typically.

Level 1 trigger

- Custom programmable processors
  - To minimise latency
- Synchronous decision every 25 ns
  - delayed by 3.2 μs = 128 BX (Max depth of pipeline memories)
- Max output ≡ max DAQ input
  - Design: 100 kHz; at startup: 50 kHz
- Only μ detectors and calorimeters
  - e/γ, μ, τ jets, jets, E_T^{miss}, ΣE_T



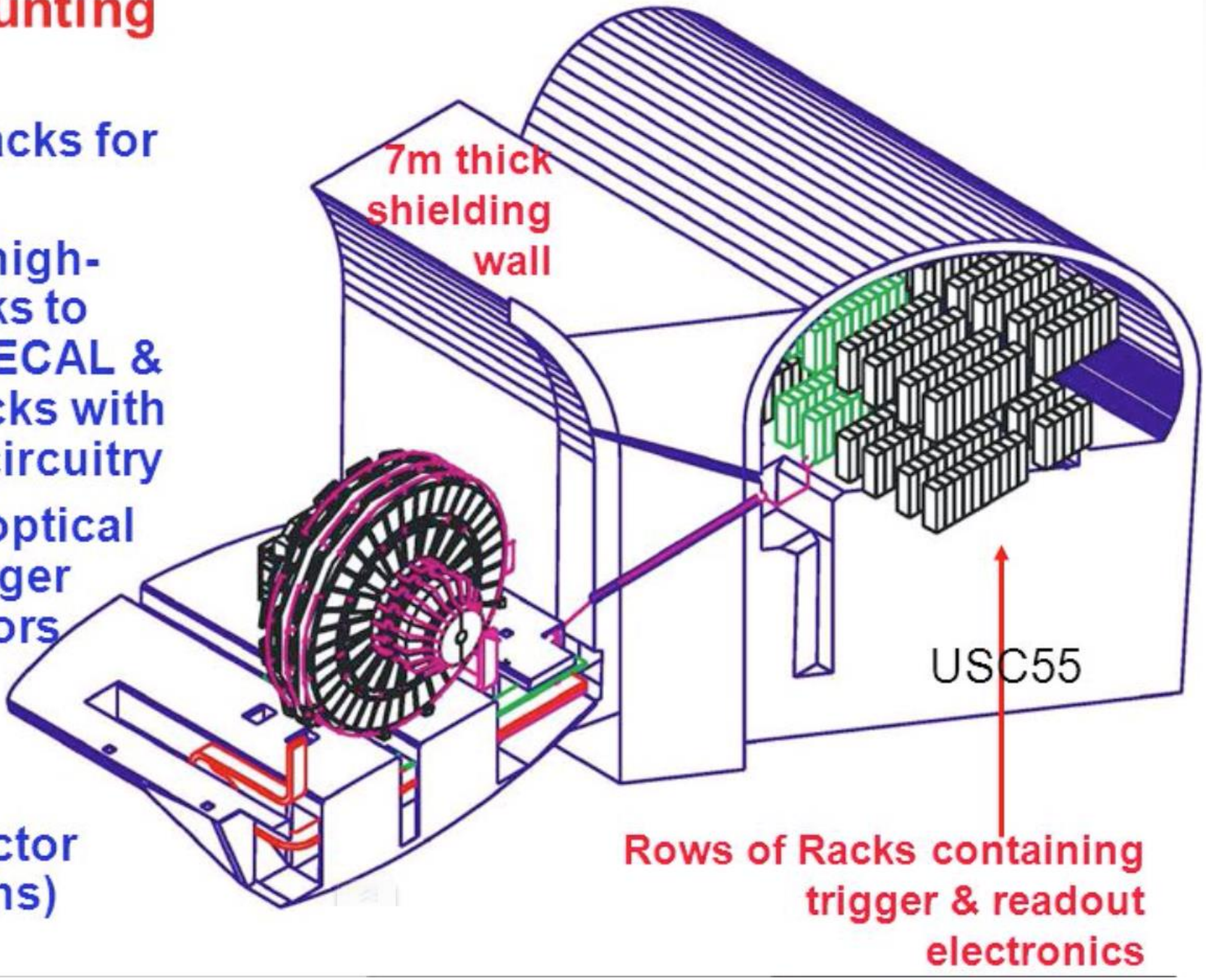
HL-LHC

- New trigger/DAQ:
  - Track information at L1 with extended trigger latency (from 3.2 total of 12.5 μs)
  - Increased L1 bandwidth from 100 kHz to 750 kHz

Level 1 trigger: where?

Underground Counting Room

- Central rows of racks for trigger
- Connections via high-speed copper links to adjacent rows of ECAL & HCAL readout racks with trigger primitive circuitry
- Connections via optical fiber to muon trigger primitive generators on the detector
- Optical fibers connected via "tunnels" to detector (~90m fiber lengths)

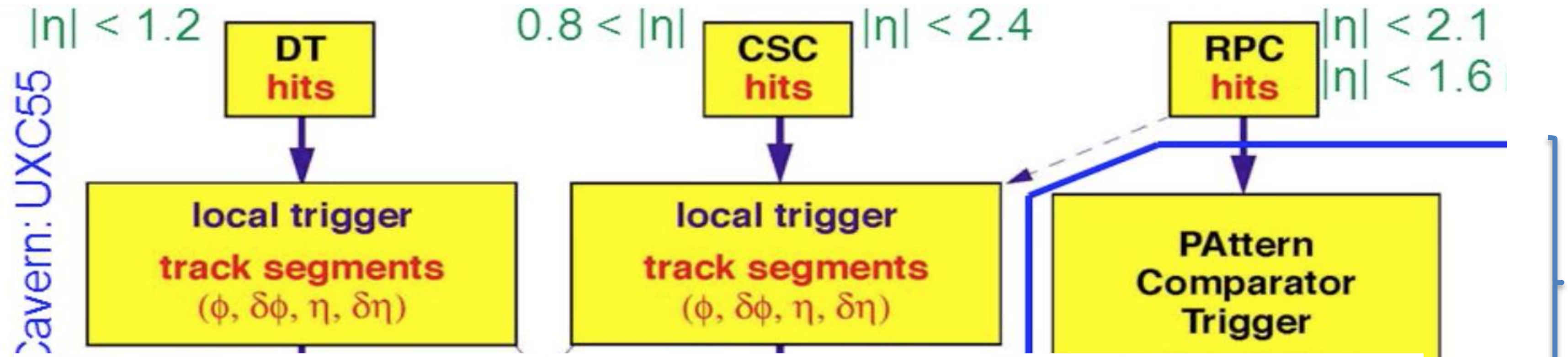


7m thick shielding wall

USC55

Rows of Racks containing trigger & readout electronics

Level 1 trigger LHC



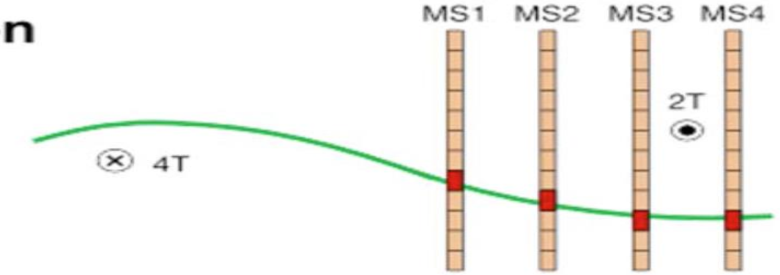
RPC pattern recognition

- Pattern catalog
- Fast logic

Memory to store patterns

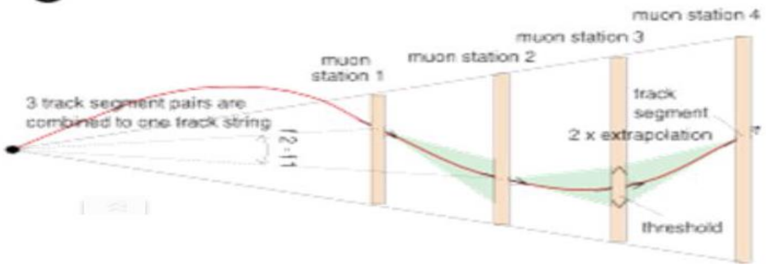
Fast logic for matching

FPGAs are ideal



DT and CSC track finding:

- Finds hit/segments
- Combines vectors
- Formats a track
- Assigns p_t value



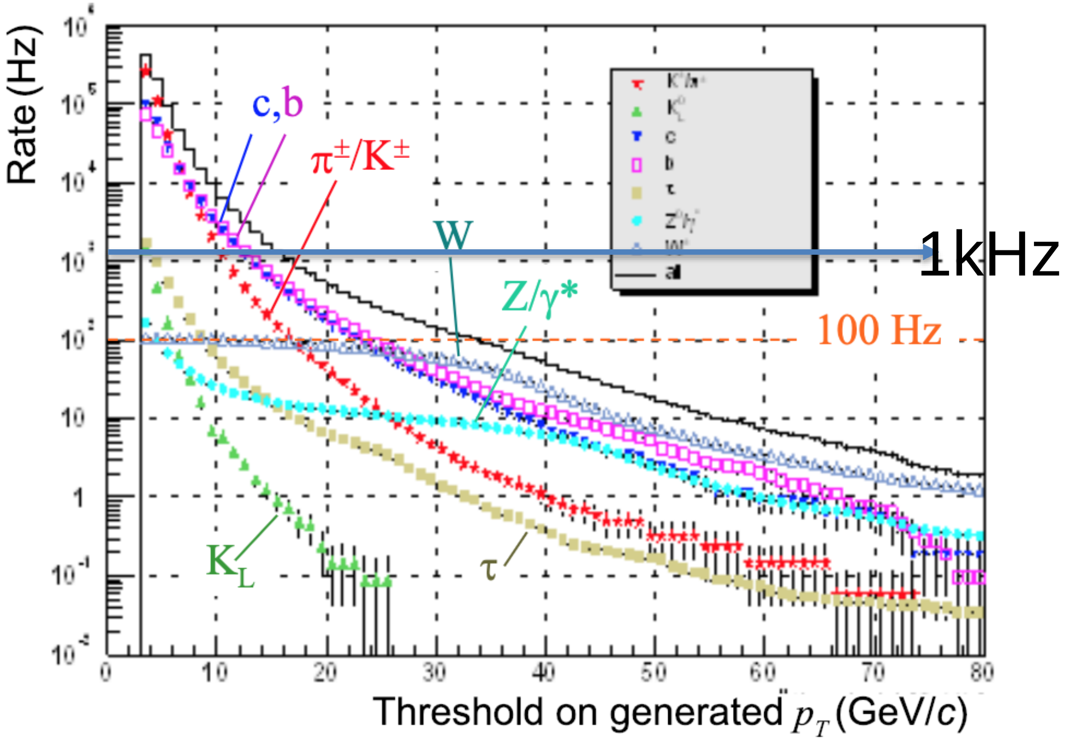
High level trigger (HLT)

- full detector readout, full granularity
  - 100 kHz input rate

- implementation
  - C++ software: same CMSSW releases used for simulation and offline analyses
  - running on a cluster of commercial PCs (*filter farm*)
  - quasi-online, input buffer 1-2 minutes

- constraints
  - ~300 ms *average* processing time to take a decision
  - peak throughput of ~ 6 GB/s aggregated over all streams
  - 1 kHz *average* output rate (limited by offline resources)

Integral rate ($\mathscr{L} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$)



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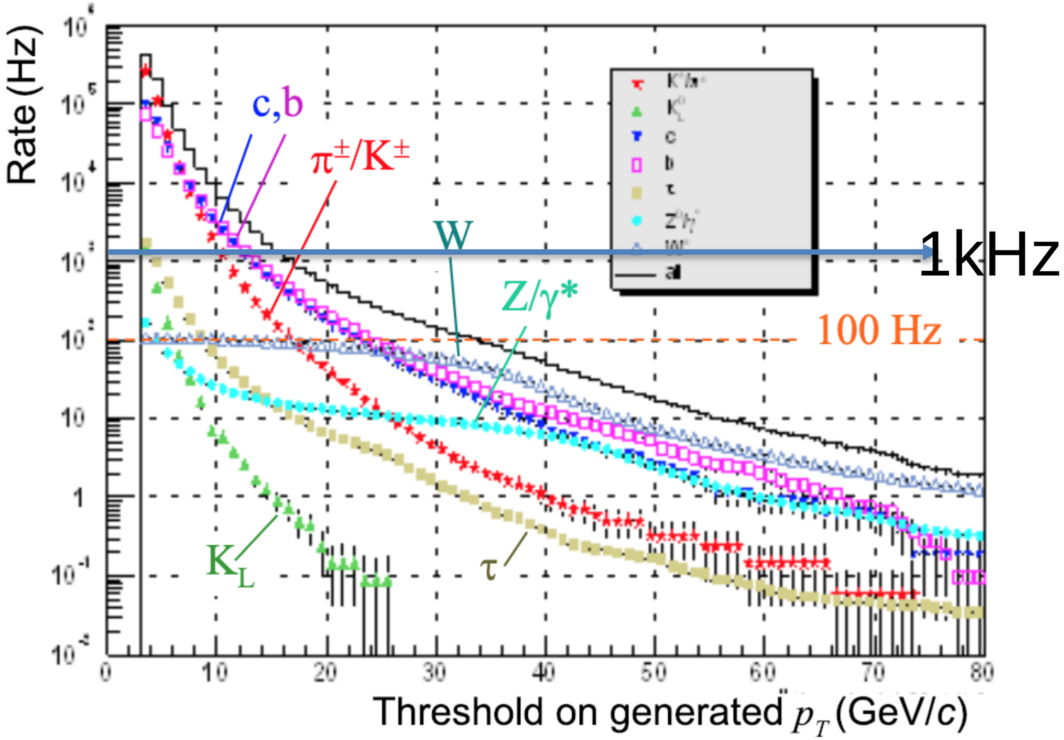
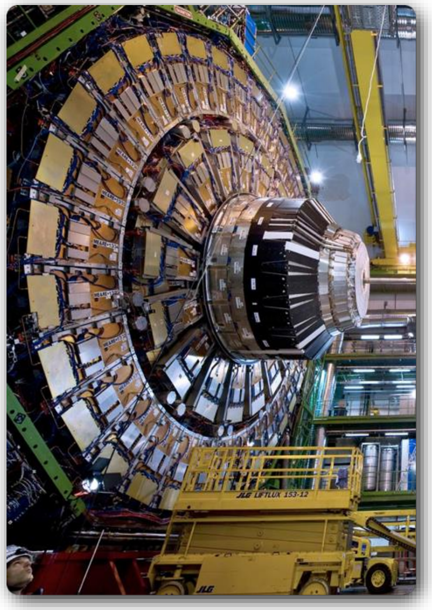


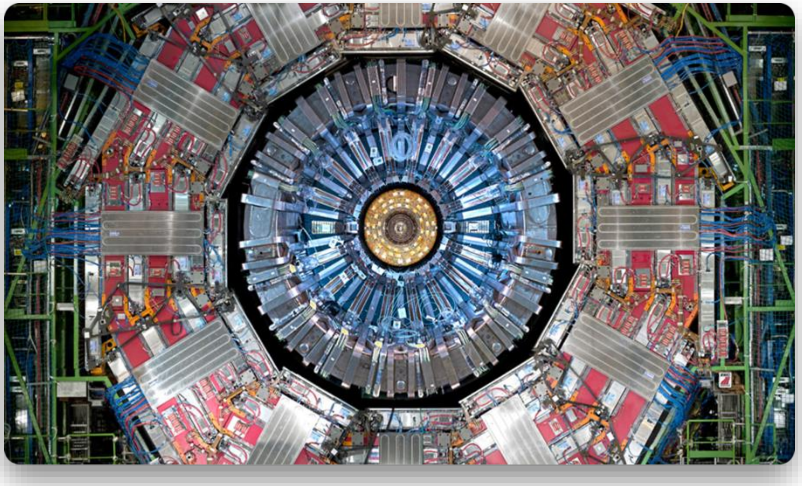
Muon Electronics Upgrade

After initial installation completed in 2009, the Muon system underwent many upgrades in order to recover the initial system descoping and to improve the functionality



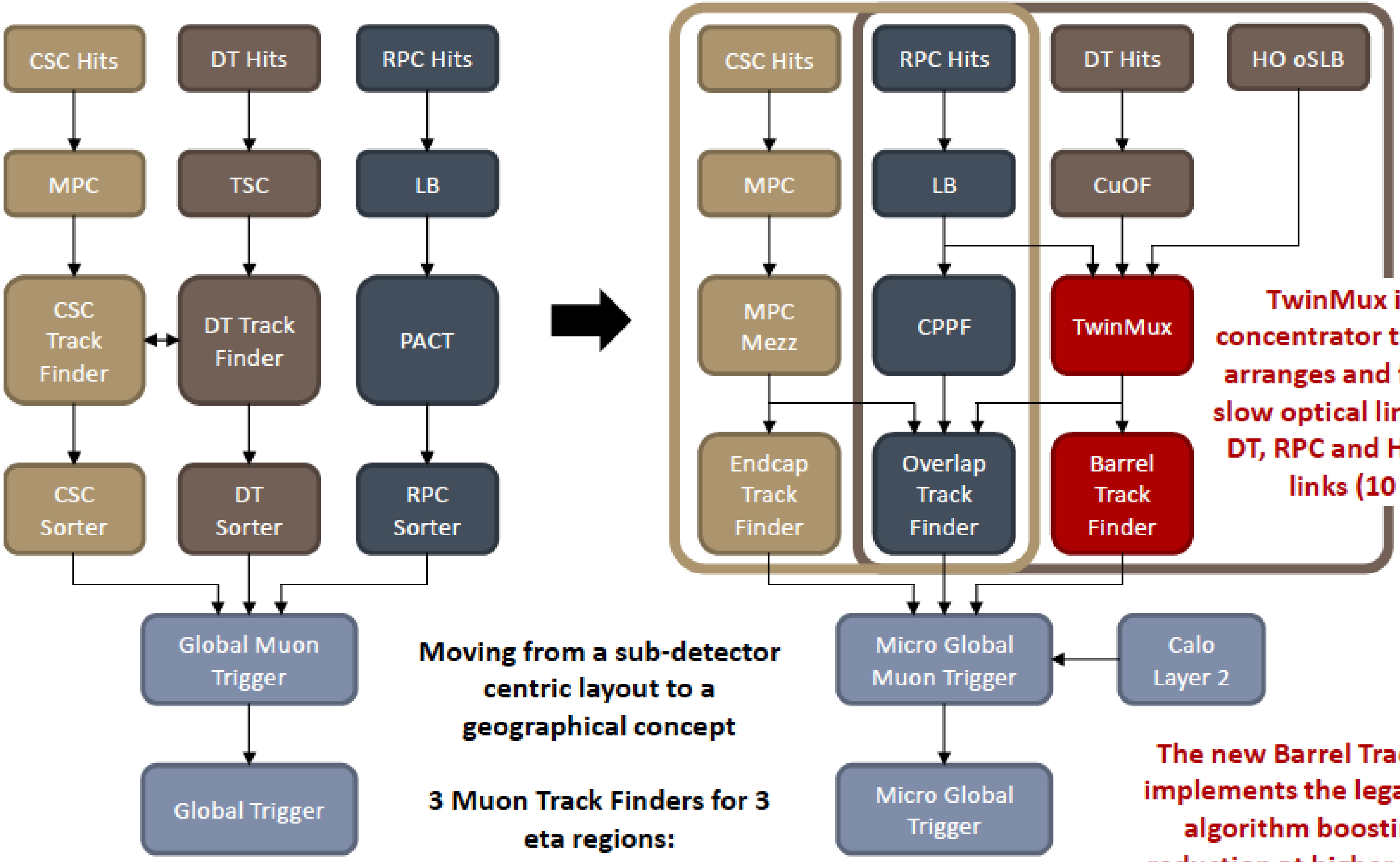
CSC & RPC **+ GEM**
in the endcap

DT and RPC
in barrel



Phase-2 CMS Upgrade: replace on chamber electronics to cope with longevity and operational issues, high rate and latency requirements

L1T Muon Trigger Architecture upgrade evolution after LS1



TwinMux is a data concentrator that merges, arranges and fan-out the slow optical links from the DT, RPC and HO in faster links (10 Gbps)

Moving from a sub-detector centric layout to a geographical concept

3 Muon Track Finders for 3 eta regions:
BarrelMTF OverlapMTF
EndcapMTF

The new Barrel Track Finder implements the legacy trigger algorithm boosting rate reduction at higher efficiency

CMS: Muon L1 trigger flow at Phase2

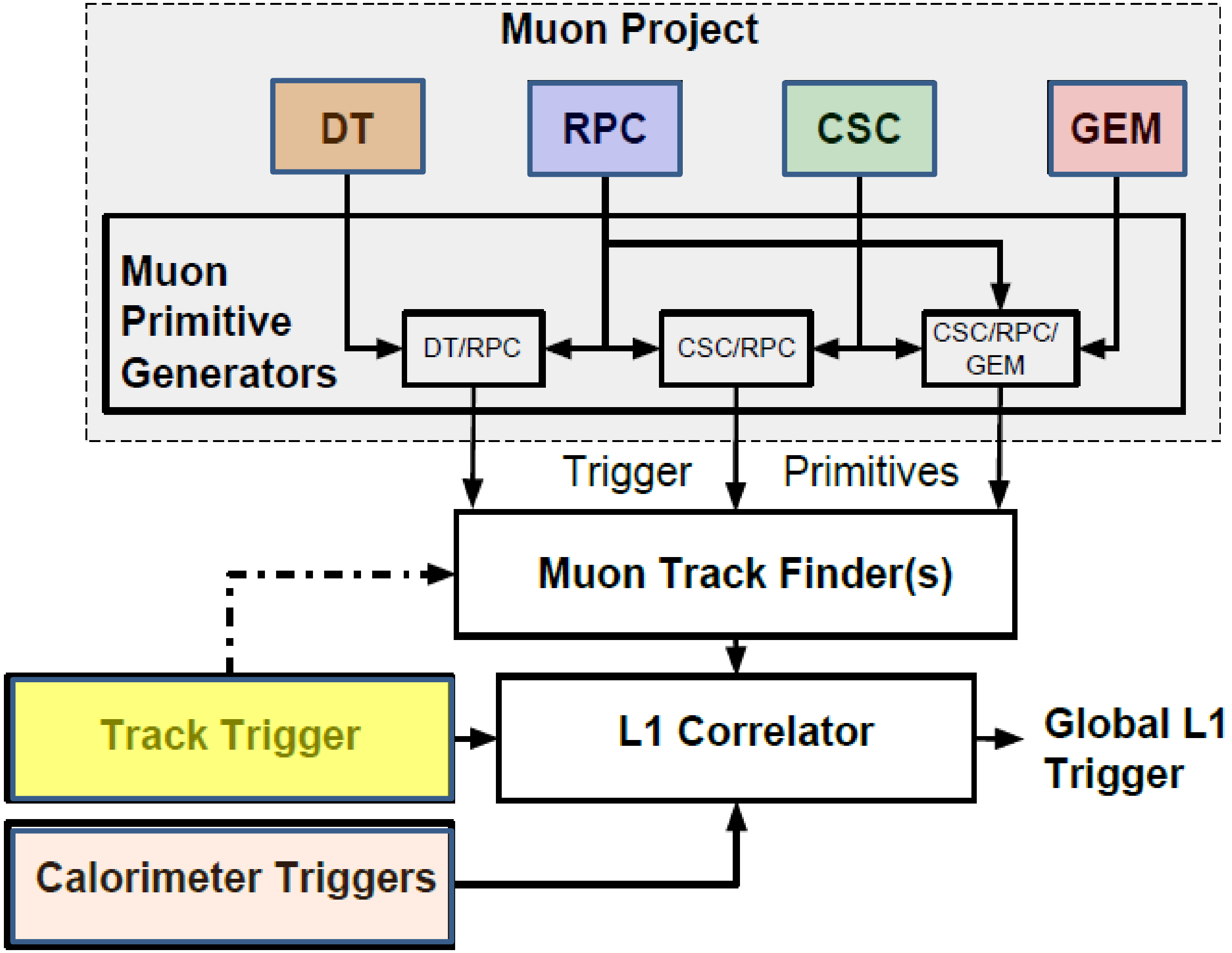
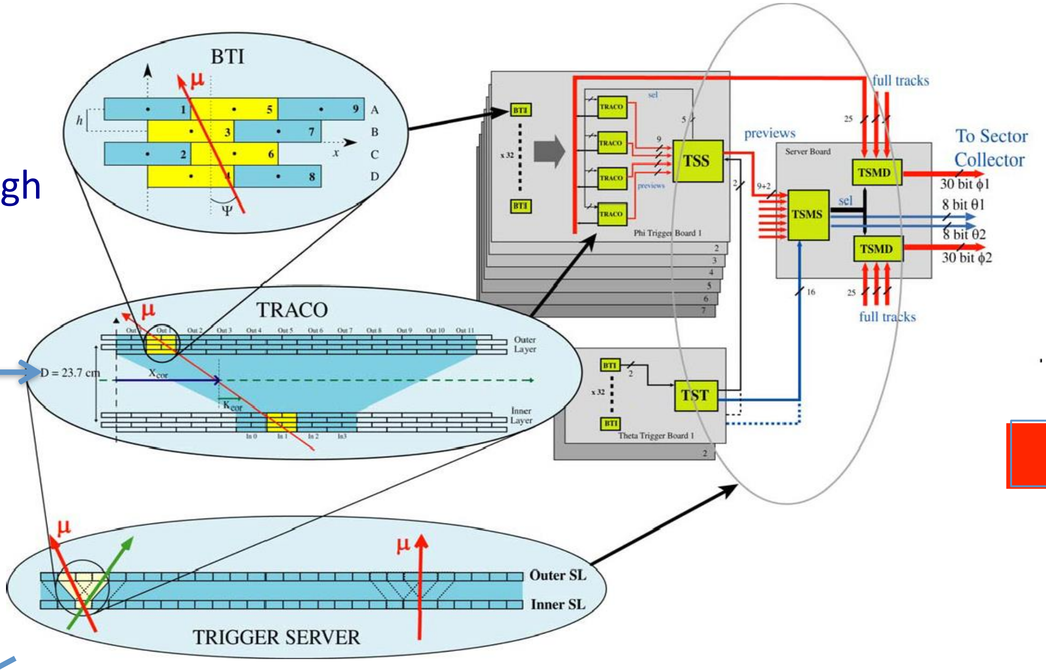


Figure 7.1: Block diagram of the Phase-2 L1 muon trigger data flow.

DT electronics and trigger primitives generation

Trigger boards housed in on-chamber MiniCrates for trigger primitive generation

- A single large synchronous 40 MHz digital system of 55000 ASICs
- Two best muon segments on output from each chamber:



STEP 1

Signals from wires are processed by **Bunch and Track Identifier (BTI)**: Rough track finding within a Super Layer (SL)

STEP 2

TRAck COrrelators (TRACO) Put out two best muon segments from each chamber. Correlate inner and outer superlayers

STEP 3

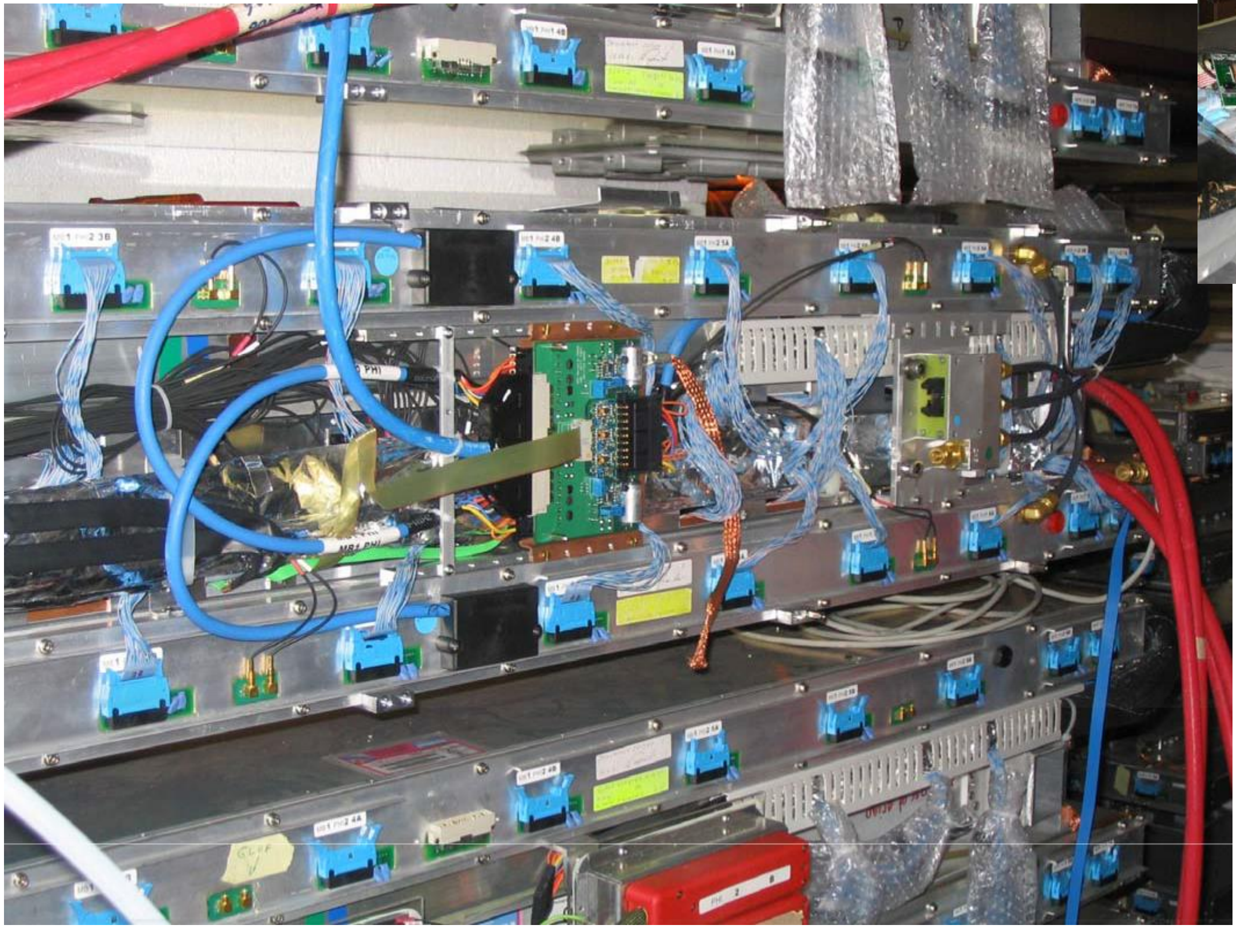
Trigger Server (TS) performs a quality based selection on segments coming from TRACOs

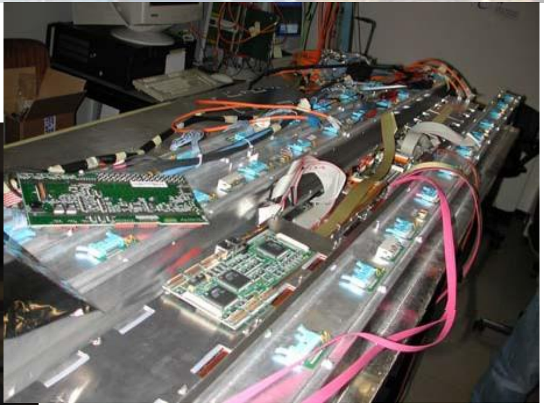
STEP 4

Sector Collector (SC), on balcony, refines the sorting per sector and performs BX alignments before sending data to the track finder

DT minicrates

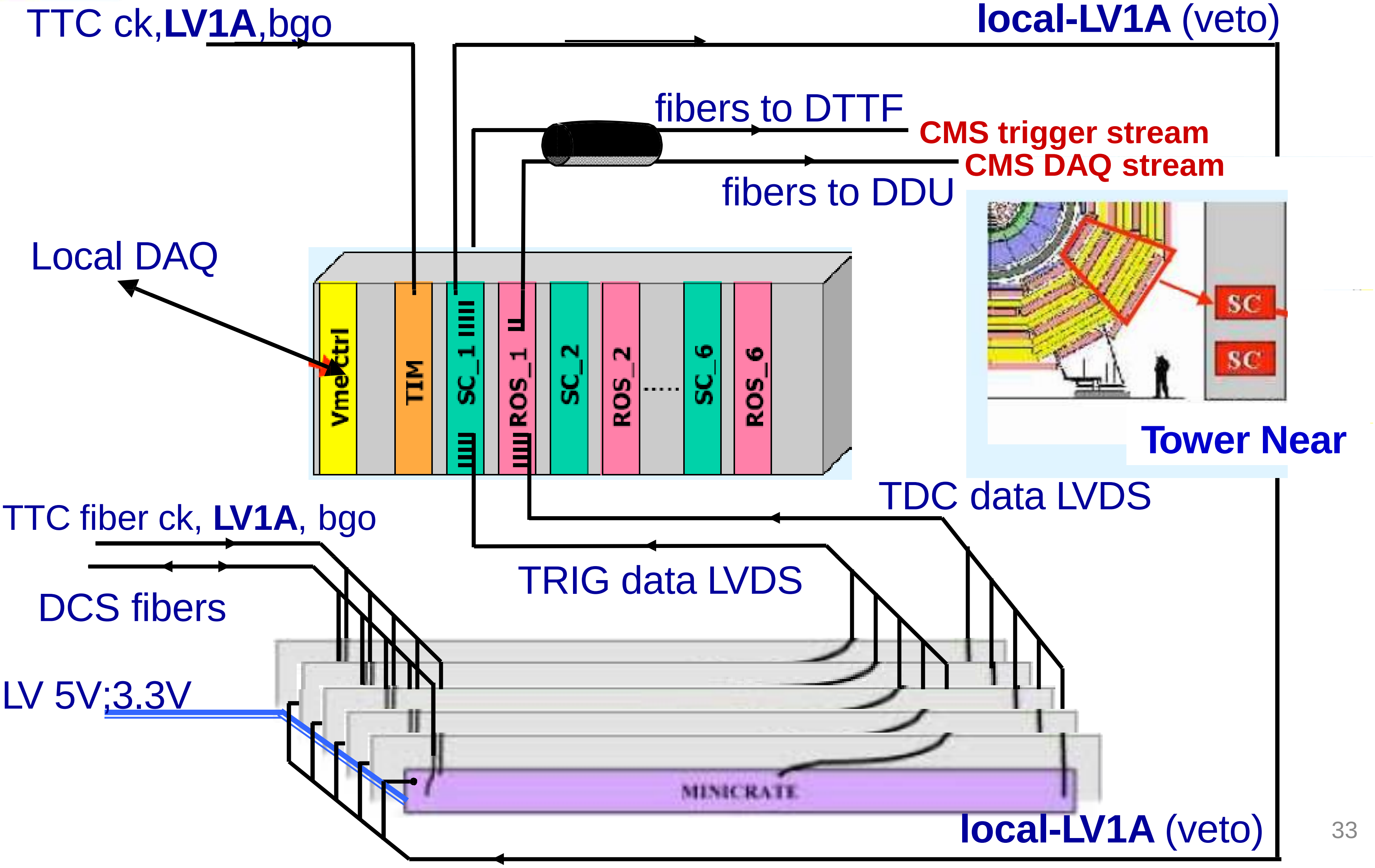
BTI, TRACO, and TS trigger electronics, etc.





An average MC has ~17 boards: 6 ROB, 6 TRB, SB/CCB, LB

DT Sector collector and readout server crates



TTC ck,**LV1A**,bgo

local-LV1A (veto)

fibers to DTTF

CMS trigger stream

CMS DAQ stream

fibers to DDU

Local DAQ

Vme ctrl

TIM

SC_1

ROS_1

SC_2

ROS_2

.....

SC_6

ROS_6

Tower Near

TDC data LVDS

TTC fiber ck, **LV1A**, bgo

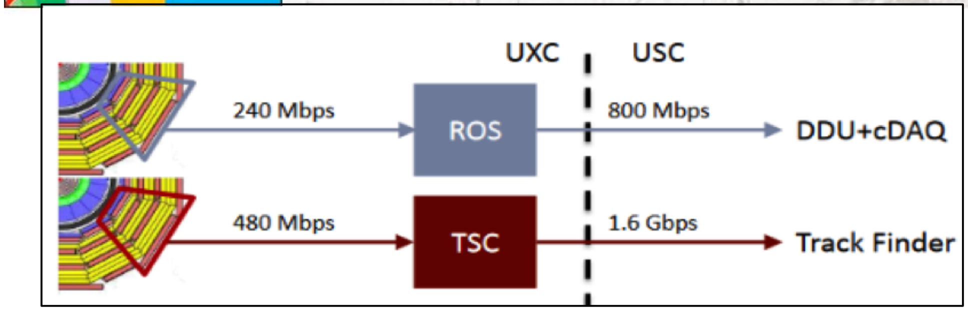
TRIG data LVDS

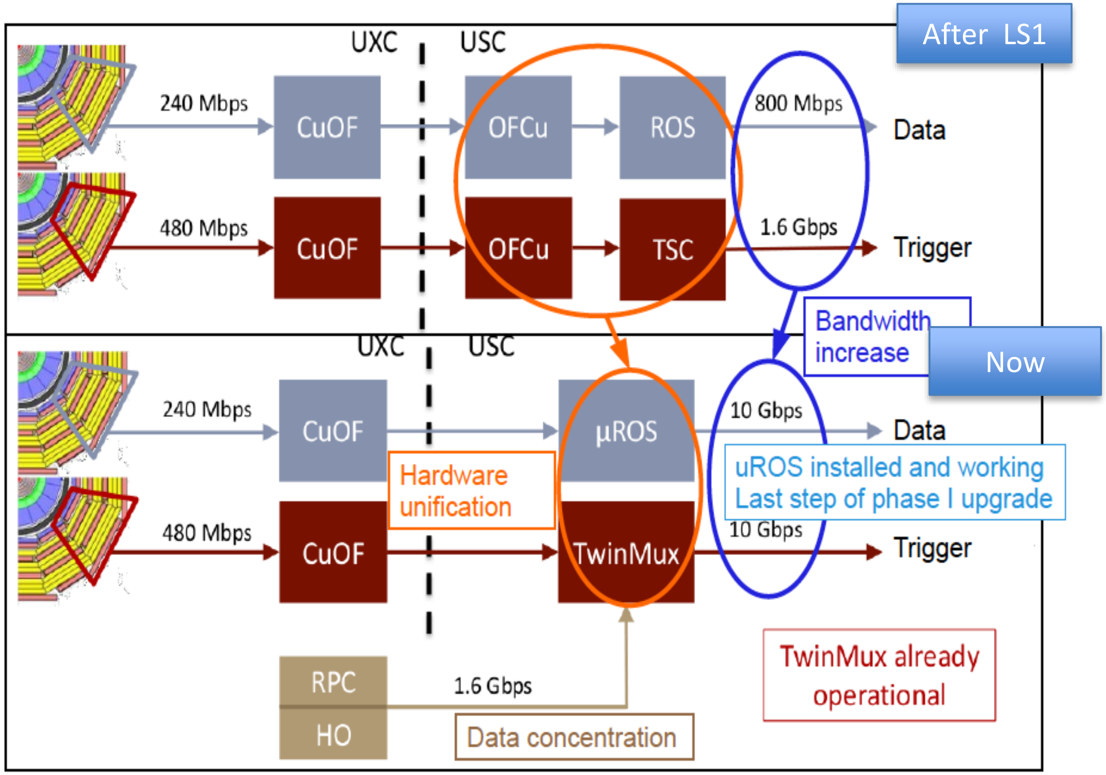
DCS fibers

LV 5V;3.3V

local-LV1A (veto)

DT electronics evolution





After LS1

Bandwidth increase

Now

Hardware unification

uROS installed and working
Last step of phase I upgrade

TwinMux already operational

Data concentration

During LS1 **Trigger Sector Collector** and **Read Out Server** crates have been relocated by simple electronics converting copper signal to optical.

- CuOF does a parallel conversion from copper to optical and OFCu reconverts the signal to copper

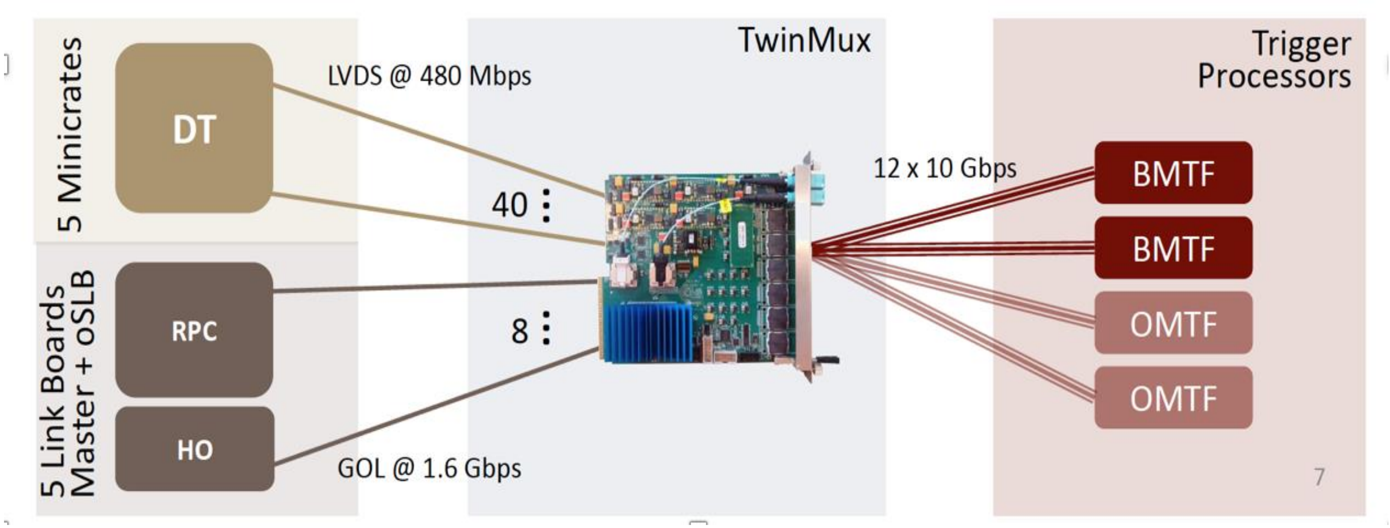
More powerful electronics based on µTCA has replaced the **Trigger Sector Collector** and the **Read Out Server:**

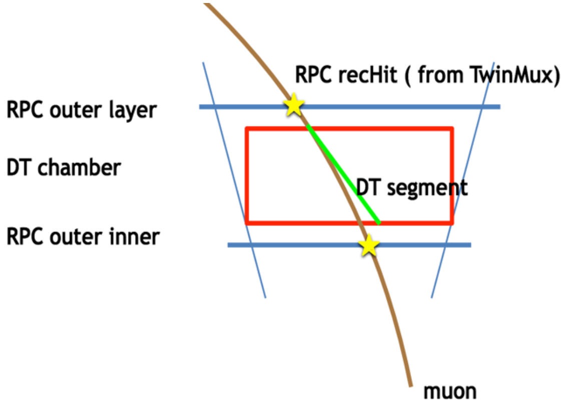
- Such electronics is needed to overcome the limitations from the increase of luminosity in terms of processing speed and trigger rates
- Optical decoupling facilitated the electronics improvement without interfering LHC schedule (optical splitting)

Barrel electronics upgrade after LS1

Readout and trigger electronics moved from VME standard to uTCA standard

- **Trigger (TwinMux):** Build Superprimitives (SP) with DT+RPC information.



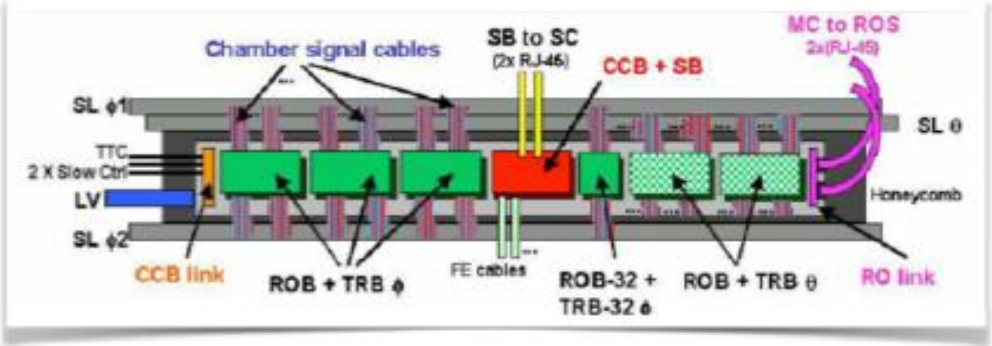


- **Readout (uROS):**
  - Same HW as **TwinMux** but different firmware
  - Installalled in YETS 2017-2018, operating very well in 2018.

The aging of the DT electronics

In “Minicrates”, located at the ends of DT chambers

- Up to 17 boards of six different types,
- ~100W power consumption



Local functionalities and processing :

- Trigger primitive generation
- Data readout pipeline
- Slow Controls (front-end and monitoring)

Original CMS specs:

- pipeline buffering and throughput sized for 3.2us latency and lumi <2*10^34cm-2sec-1

Access for maintenance difficult:

- most chambers need detector opening
- lot of CMS cabling running over the MiC

An ageing, complex system with increasing cumbersome maintenance needs and a maximum sustainable event rate topping at ~300kHz

Overview of DT electronics upgrade in Phase-2

Electronics need **to be upgraded**

- ➡ Limited to **L1 rate of 300 kHz**

  Need at least 500 kHz for the HL-LHC

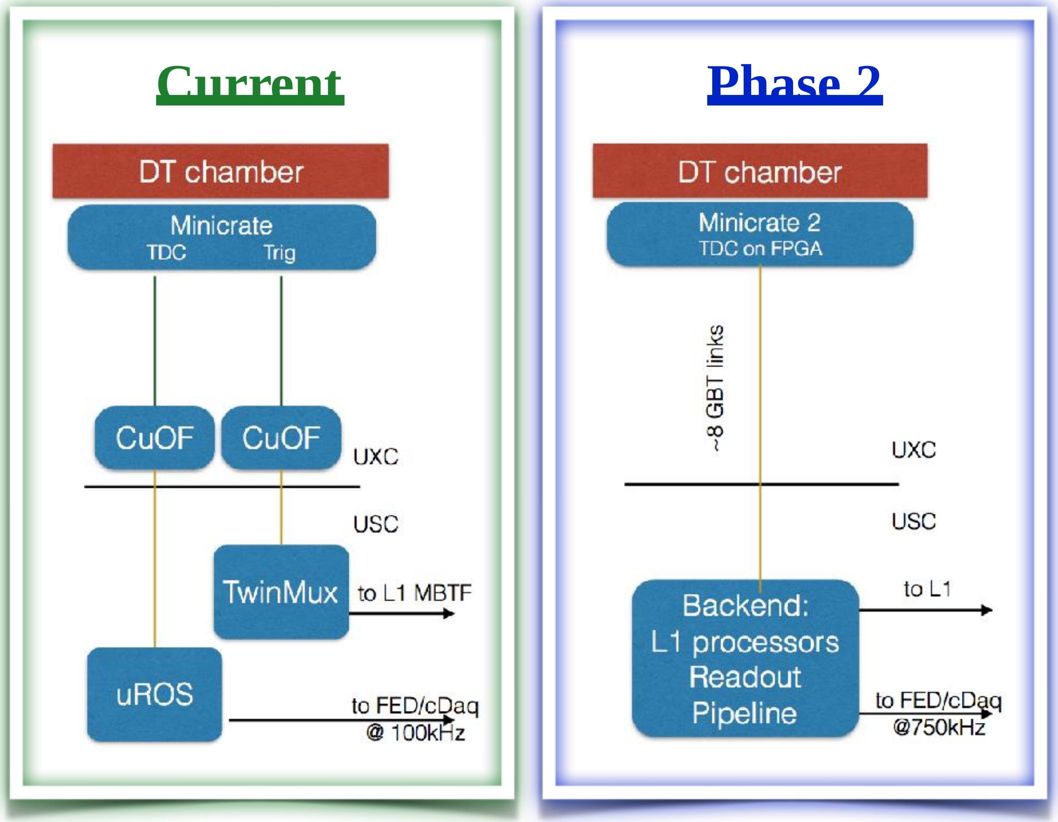
  - ➡ Designed for **TIDs corresponding to 500 fb^{-1}**
  - ➡ Buried in iron yoke → **difficult maintenance**
  - ➡ **Not robust against single-hit inefficiency**

  Due to trigger primitives generated locally

  Aging of DTs could lead to significant chamber trigger inefficiency

Phase-2 electronics **move complexity to USC**

- ➡ **Same analog front end**
- ➡ **New on-detector board: OBDT**



➡ **Trigger primitive generation in new back-end electronics in USC (underground control room**

DT On detector electronics for Phase-2

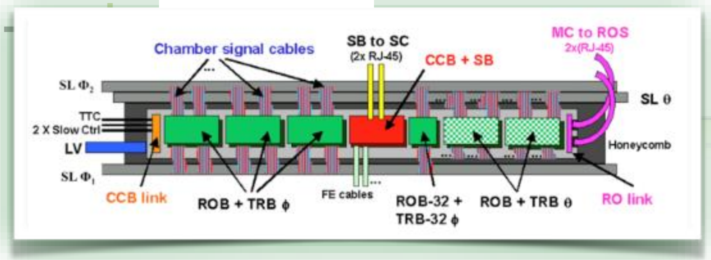
DT chamber

Minicrate
TDC Trig

DT chamber

Minicrate 2
TDC on FPGA

Current



1 minicrate per chamber

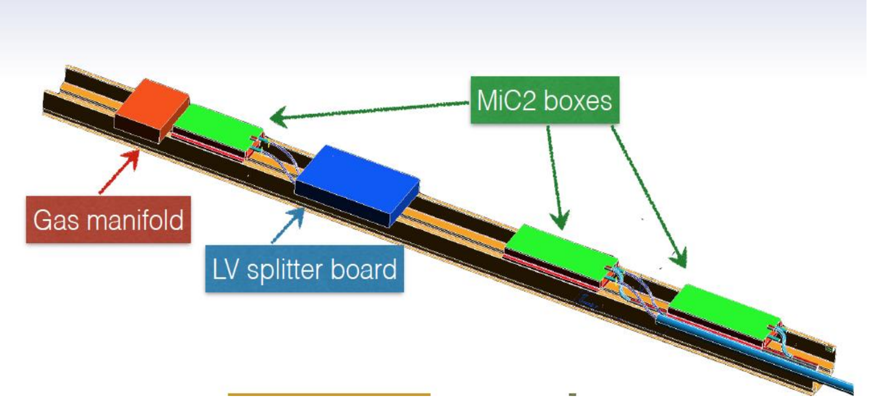
Phase 2

UXC

3-5 OBDTs per chamber

One single type of board

- New MiC2 designed over one single type of board (OBDT) that contains:
    - time digitization (required resolution achievable with FPGAs)
    - optical transmission (profit from CERN developments)
    - reduced slow control



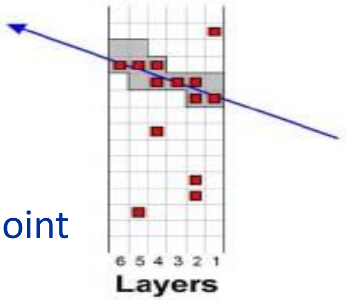
CSC electronics and trigger primitives generation

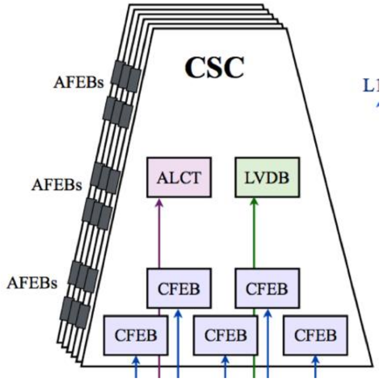
- Wires spaced at 3.2mm, drift times 0-50 ns with small tail up to 75ns
- 6 layers of information for both anodes and cathodes

ALCT board:

- FPGA looks for a pattern of hits every 25 ns
- Anodes “non-bend plane”

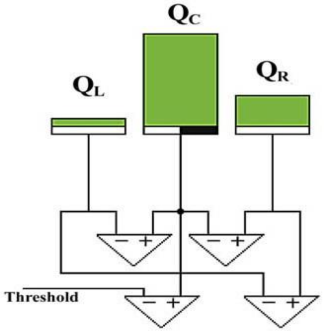
  Pattern the same for all muons from interaction point
- Bunch ID
- Fine delay adjustment (2.2ns steps) for times-of-flight
- Time history (16 bx) recorded for each wire group

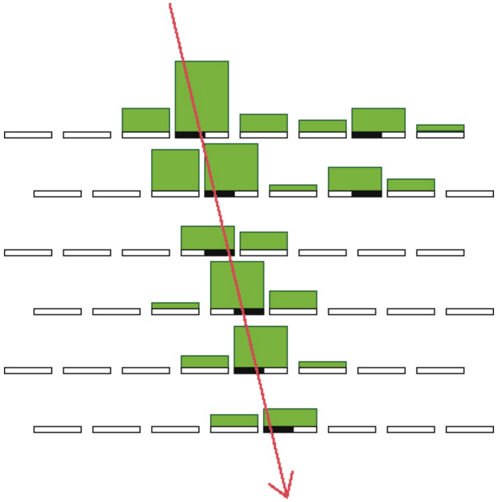




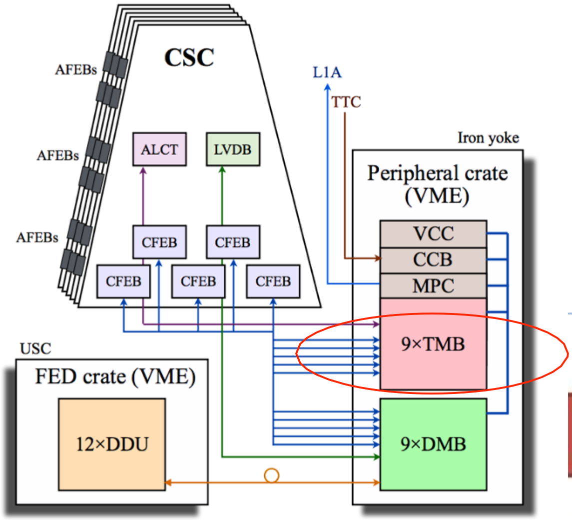
CFEB:

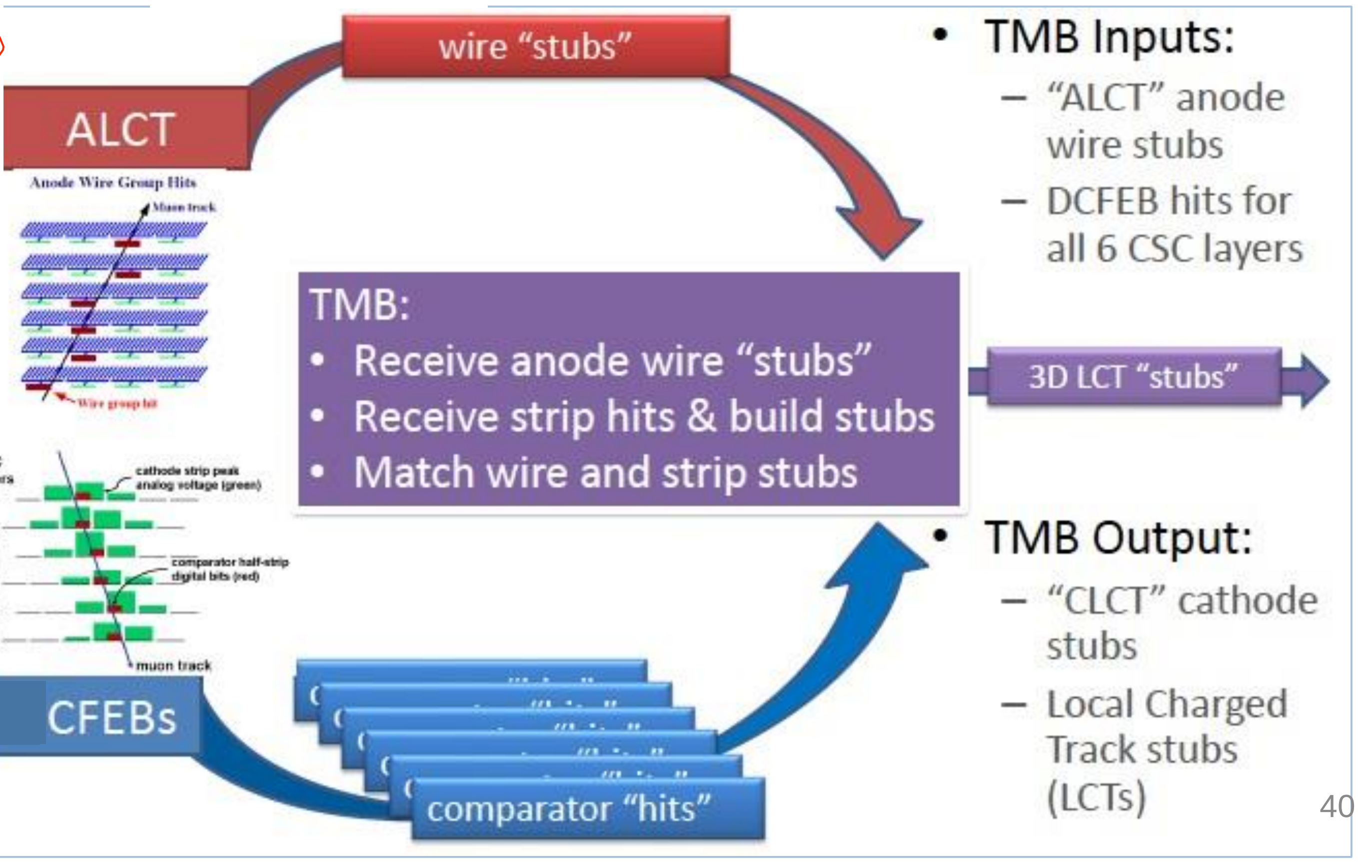
- Serves 6 (planes) x 16 strips
- Amplifiershaper (τ = 100 ns)
- Precision charge information stored every 50 ns
- Comparator ASIC finds half-strips hit
- FPGA (programmable) finds 6-layer patterns
  - Patterns are different, depending on Pt of the muon
  - Pt threshold around 3 GeV/c





CSC Trigger Mother Board



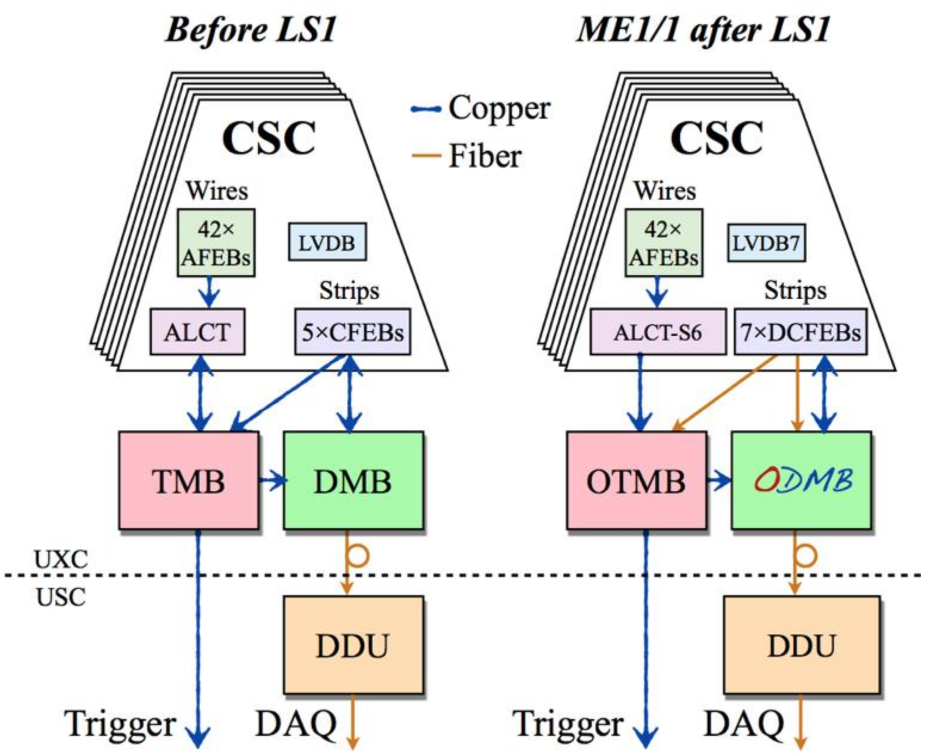


TMB:

- Receive anode wire "stubs"
- Receive strip hits & build stubs
- Match wire and strip stubs

- TMB Inputs:
  - "ALCT" anode wire stubs
  - DCFEB hits for all 6 CSC layers
- TMB Output:
  - "CLCT" cathode stubs
  - Local Charged Track stubs (LCTs)

CSC Upgrade in LS1: ME1/1 chamber



New DMB is capable of handling 7 DCFEBs
➡ Data received via seven 3.2 Gb/s links
➡ Powerful Virtex-6 FPGAs stores data in internal FIFOs.
Same 1.6 Gb/s output link to DDU

DCFEBs continuously digitize strip signals
➡ Signals stored in deep buffers inside powerful Virtex-6 FPGA

Trigger/readout data sent via 3.2 Gb/s links to OTMB/ODMB

ALCT mezzanine upgraded
➡Based on more powerful Spartan 6 FPGA (ALCT-LX150 (it has a Spartan-6 LX150 FPGA), capable of improved algorithms

TMB upgraded (OTMB) with much more powerful Virtex-6 PFGA
➡ Also increased bandwidth from DCFEBs with 3.2 Gb/s optical link

CSC Electronics Upgrade for Phase-2

On chamber Electronics:

Cathode Front End Board (CFEB) will be update with Digital CFEB in all ME234/1 chambers

- DCFEBv2 very similar to DCFEB (installed in 2013-14 in ME1/1 ring)

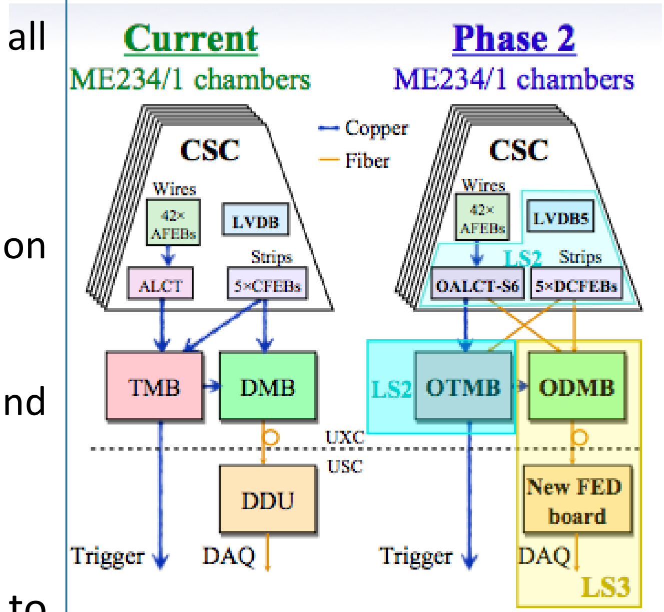
DCFEB will be updted to xDCFEB in ME1/1 chamber:

- Main difference with respect to DCFEBv1 is increased radiation hardness

Anode local charged Track (ALCTs)

- designs based on ALCT mezzanine boards installed in ME1/1 and ME4/2 during LS1
- New ALCT with Optical link in ME1234/1 (LX100/LX150)
- Current ALCT from ME1/1 to ME1/3

Low Voltage Distributor Boards will be update to provide power to new DCFEBs and ALCTs



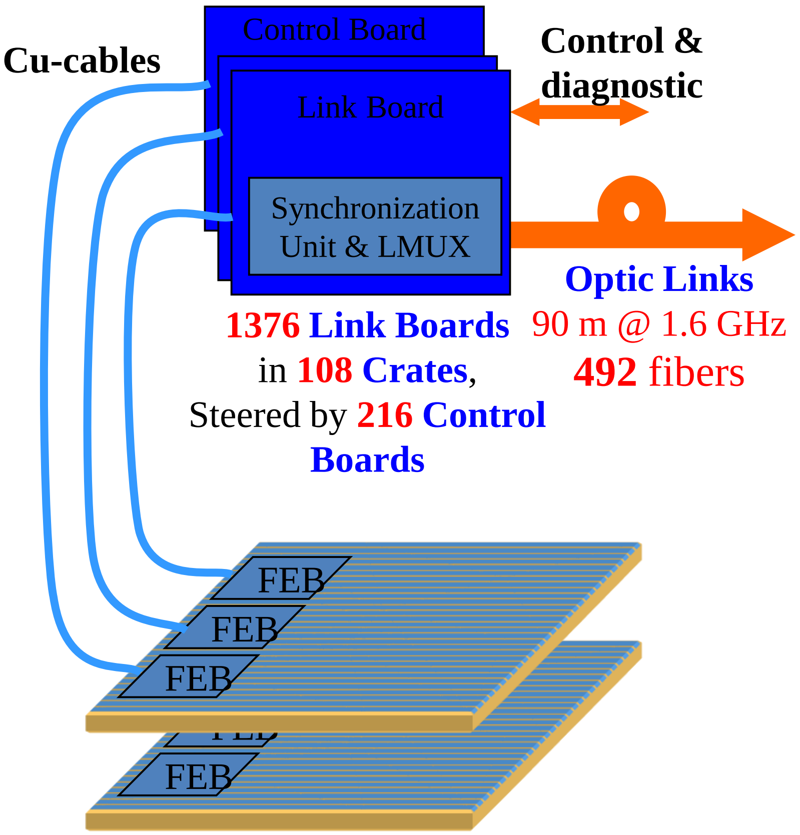
Off chamber Electronics:

Trigger Motherboard (TMB): replaced with Optical TMB in order to receive DCFEB trigger data; increased algorithmic power

Data Mother Boards (DMB): replaced with Optical DMBs

- **based on** new generation **Artix-7 FPGAs**
- new optical fibers at 6.4 Gb/s

RPC Link System Upgrade in Phase-2



1376 Link Boards in **108 Crates**, Steered by **216 Control Boards**

90 m @ 1.6 GHz
492 fibers

Resistive Plate Chambers
Up to 6 layers of detectors.
480 chambers in Barrel, **648** in Endcap

Off-detector electronics: consists of Link and Control Boards ("Link System") and is located in crates on the balconies around CMS.

Motivation for Upgrade:

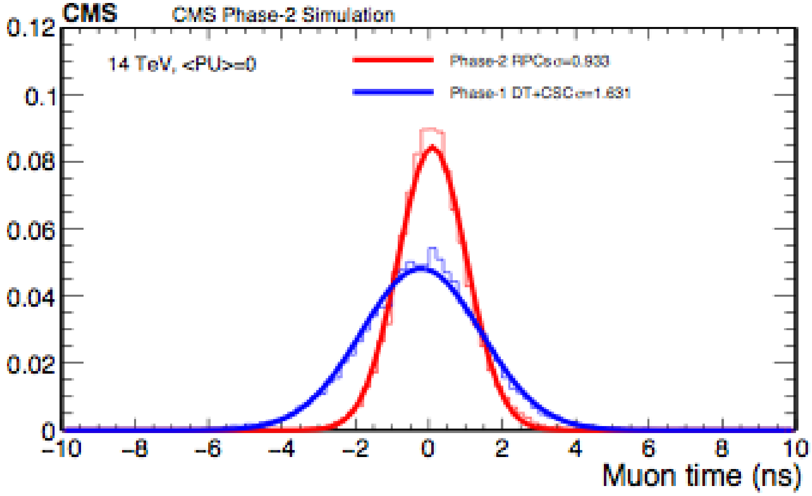
- **Operation issues:**
  - the CBs are connected into ring configuration. If one CB fails then the entire ring does not work, leading to a loss of 6 % of the system.
- **Maintenance:** Not enough spares available (rely on old ASICs)
- **Low speed data transmission links (**1.6 Gbps)

Electronics will be replaced during Long Shutdown3.

RPC New Link System Design

New LB and CB

- Back compatible with the present Link Boxes. Signal cables from the chambers will be not removed.
- Based on Xilinx 7 FPGAs (replace ASICs)
- RPC signal sampling frequency will be 640 MHz clock from the present 40 MHz clock
  - **Time resolution will be improved: from 25 ns to 1.6 ns. Impact on muon trigger and offline reconstruction.**
- Background hits out of time could be removed and synchronization facilitated
- More robust
- Higher bandwidth (10 Gbps output, lpGBT and VL+)



2. Enhancement of the forward region $1.6<|\eta|<2.4$:

Additional GEM and RPC layers with new technology for improved triggering, background rejection.

HL-LHC: Muon requirements in endcap region

Very challenging region:

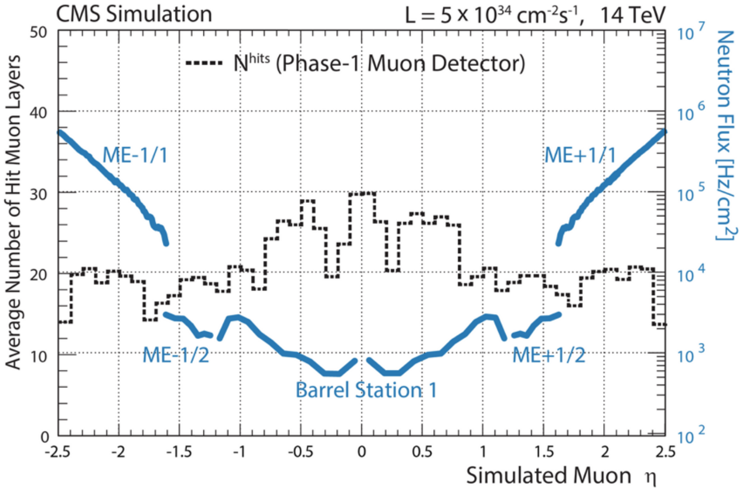
- High rates: muons, background hits, punchthrough
- Small bending of muons by magnetic field
- Currently only CSC chambers at high η

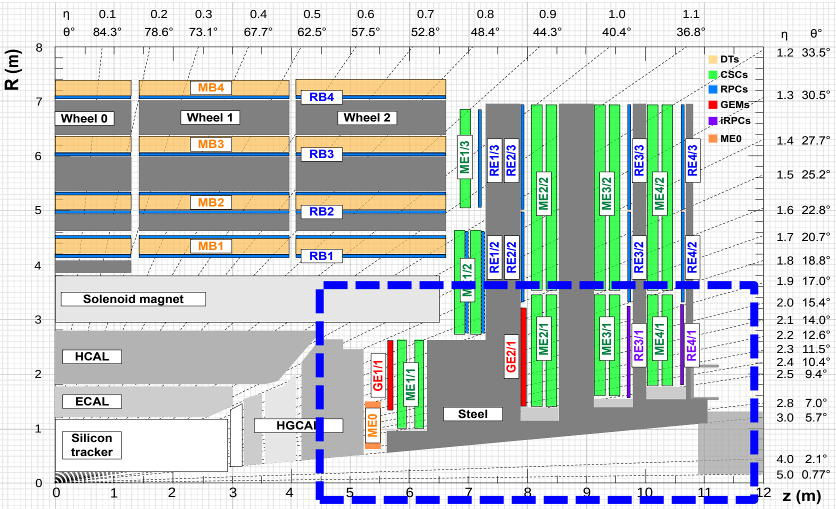
Event reconstruction capabilities (trigger and offline) require, particularly in forward region:

- to enhance redundancy, to increase # of measurements with good spatial and time resolution, to solve track reconstruction ambiguities.

Extended acceptance

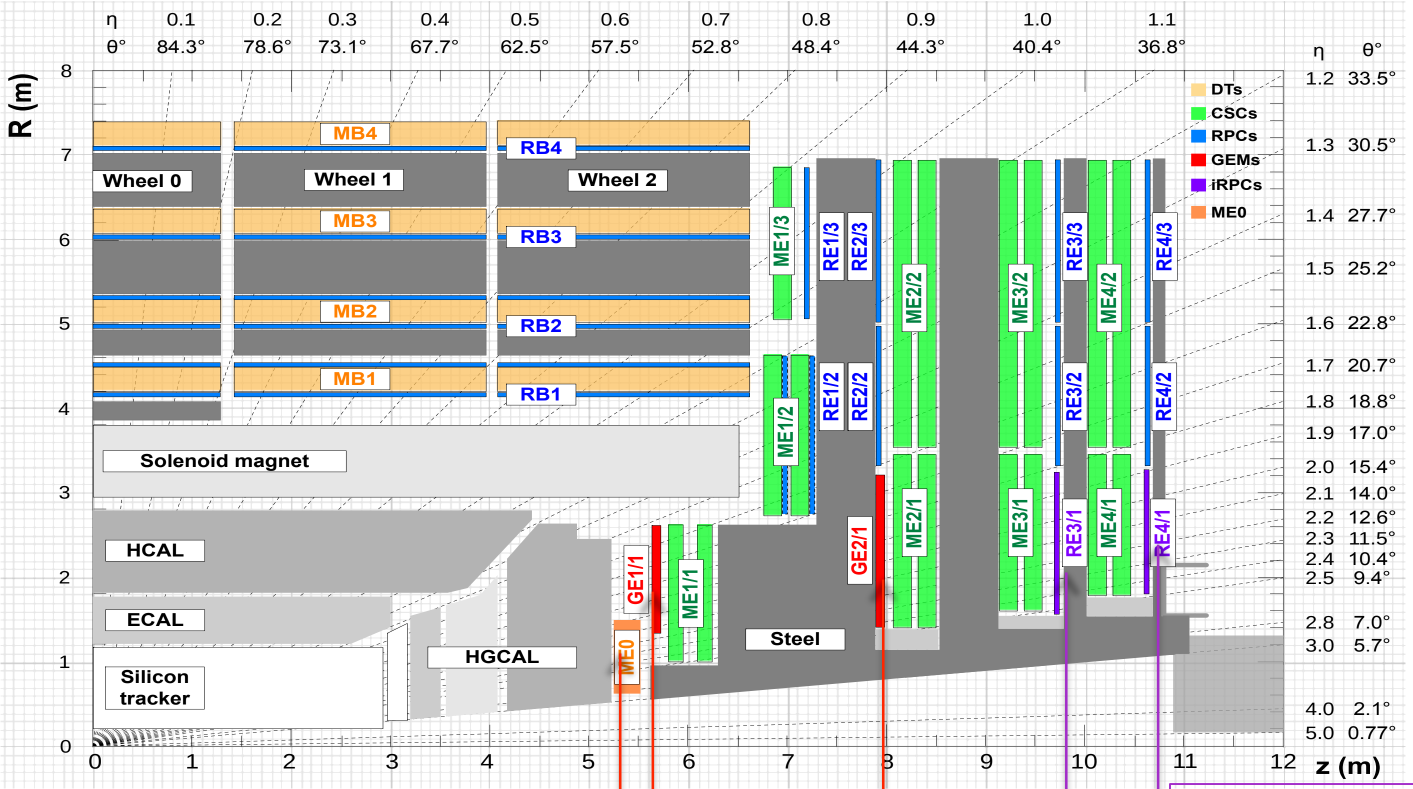
- to complement the wider tracking and calorimeter coverage and to reduce physics backgrounds from “lost leptons”





Enhancement and extension of the forward region

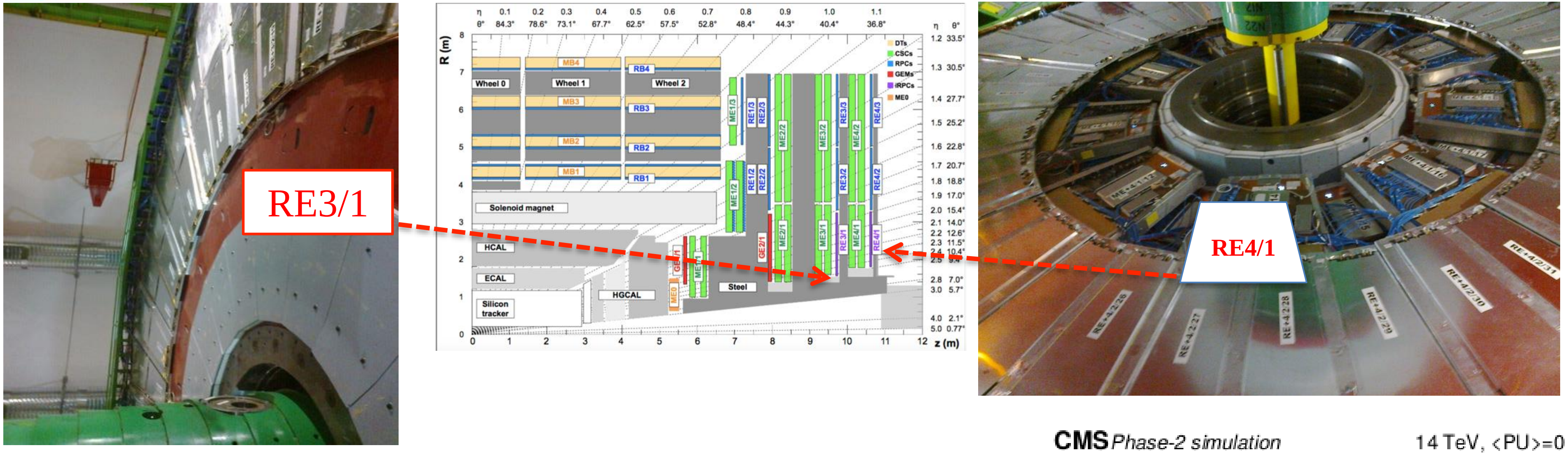
UPGRADE: augment the system with new detectors.



improved RPC (iRPC)

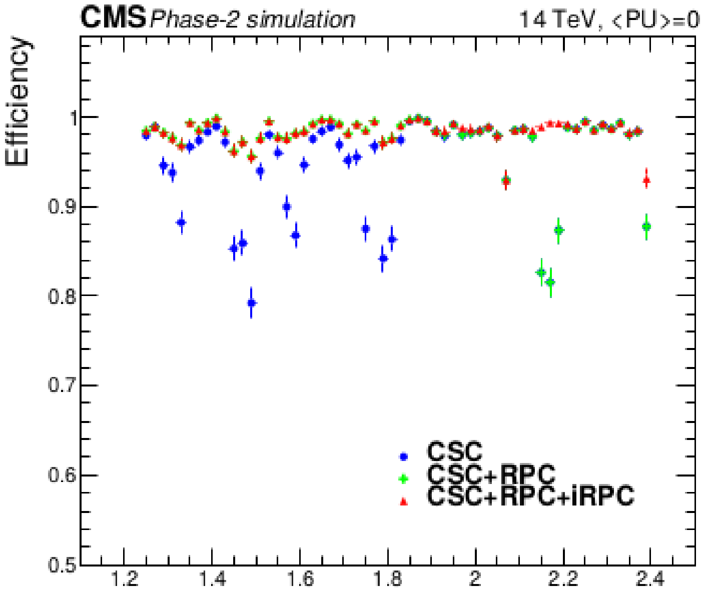
GEM detectors

Forward muon system enhancement: improved RPC in RE3/1 and RE4/1



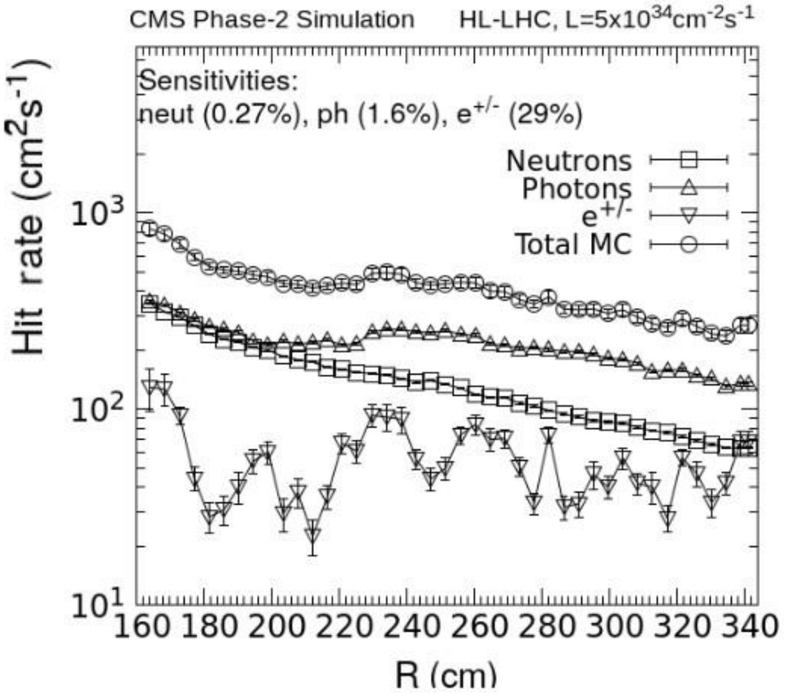
New 72 chambers (RE3/1 and RE4/1), related electronics and services to extend the coverage in |η| to 1.8 < |η| < 2.4 using an improved design of RPCs (iRPCs) in order to:

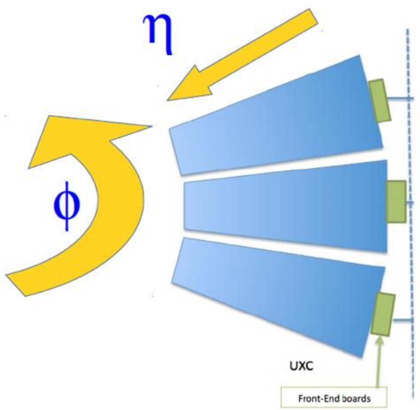
- handle the particle rates foreseen at HL-LHC (2 KHz/cm^2 including safety factor 3)
- restore redundancy L1 muon trigger.



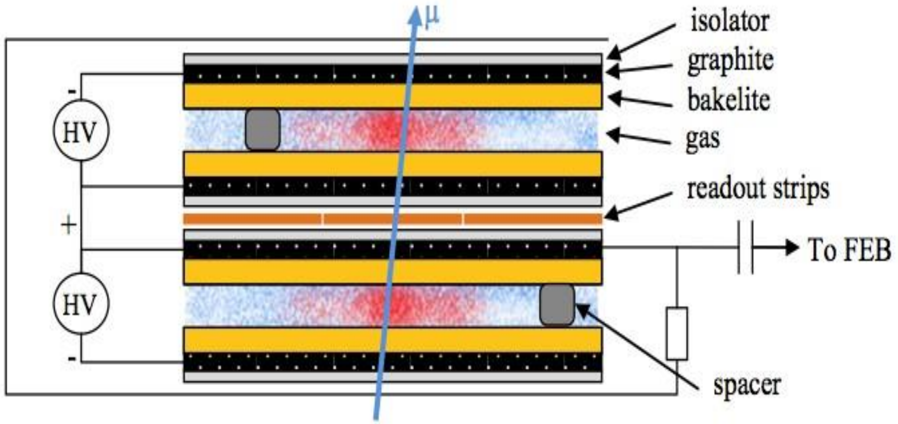
Requirements for the iRPC chambers

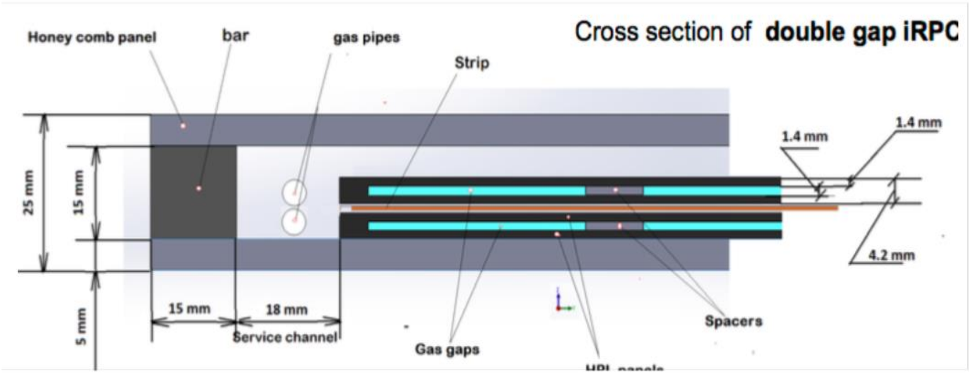
	Present system	**iRPC**
|η| coverage	0 – 1.9	1.8 – 2.4
Max expected rate (Safety factor SF = 3 included)	600 Hz/cm²	2 kHz/cm²
Max integrated charge at 3 ab⁻¹ (SF = 3 included)	~ 0.8 C/cm²	~ 1.0 C / cm²
ϕ granularity	~ 0.3 ˚	~ 0.2˚
η resolution	~ 20 cm	~ 2 cm
time resolution	1.5 ns	< 1 ns





Requirements for the iRPC chambers





- Resistivity of HPL: 1 - 6e10 (RPC) → < 2e10 Ω cm (iRPC)

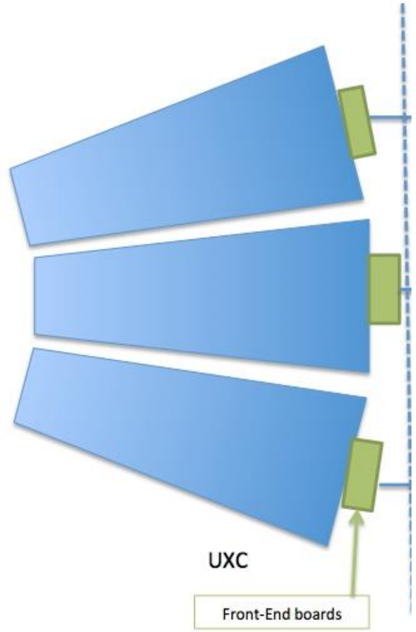
- Gap/electrode thickness: 2.0 mm (RPC) → 1.4 mm (iRPC)

→ Reduce the pick up charge and operational voltage. Less ageing.
→ Reduce recovery time.
→ Efficiency of extracting pickup charge.

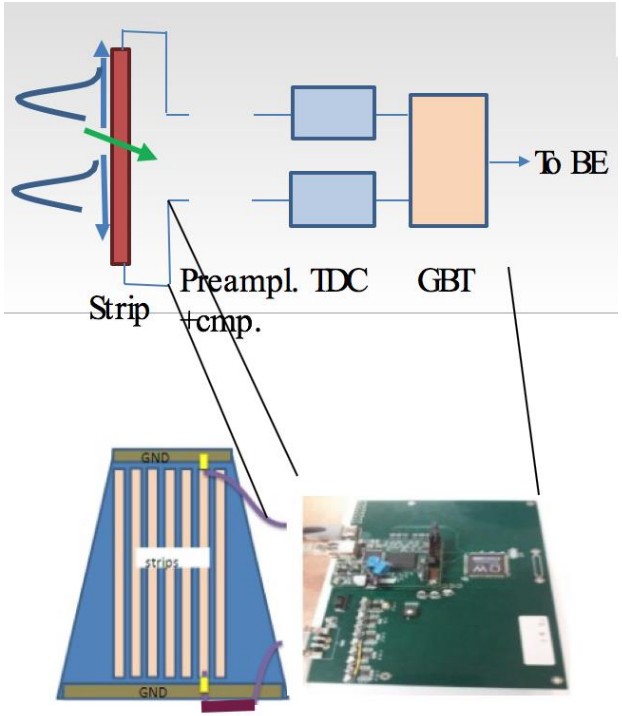
- Electronic threshold : 150 fC (RPC) → 50 fC (iRPC)

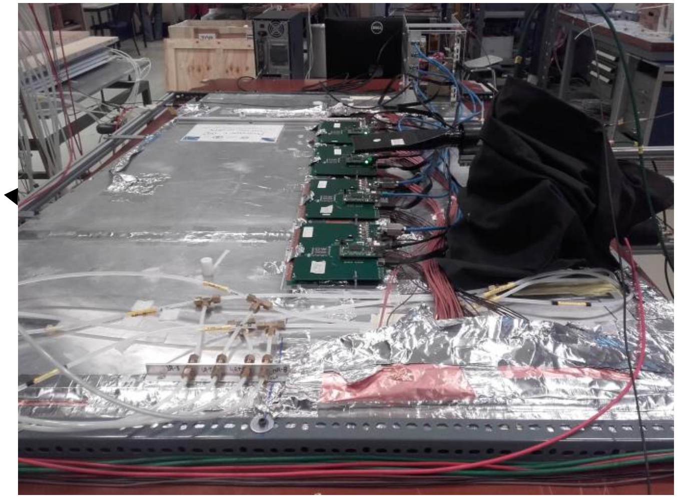
→ Better sensitivity to reduced charge.

iRPC Electronics



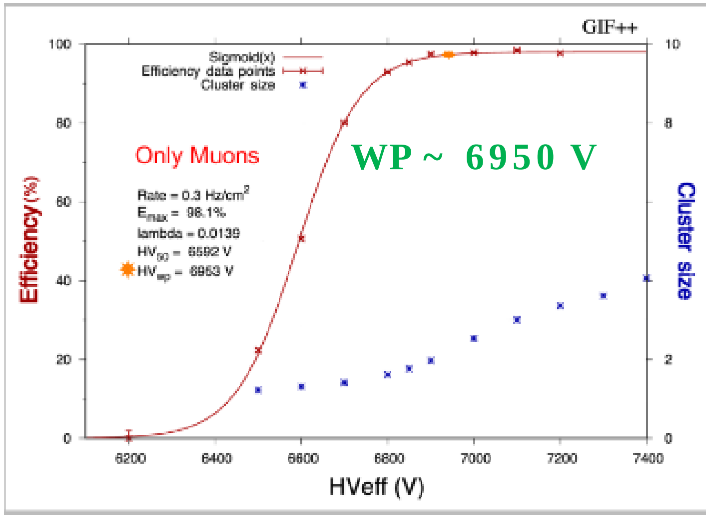
- Electronics scheme of the project with 2 sided readout: 2 cm resolution in |η| with limited number of channels.
- Based on OMEGA ASIC in TSMC 130 nm (Petiroc) with 64 chan/chip.
- TDC implemented in FPGA
- Both sides are connected at the same PETIROC to reduce jitter
- New power system, new services

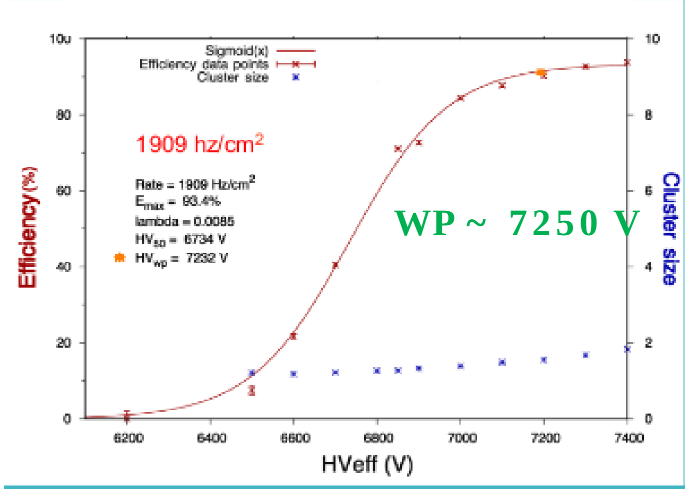


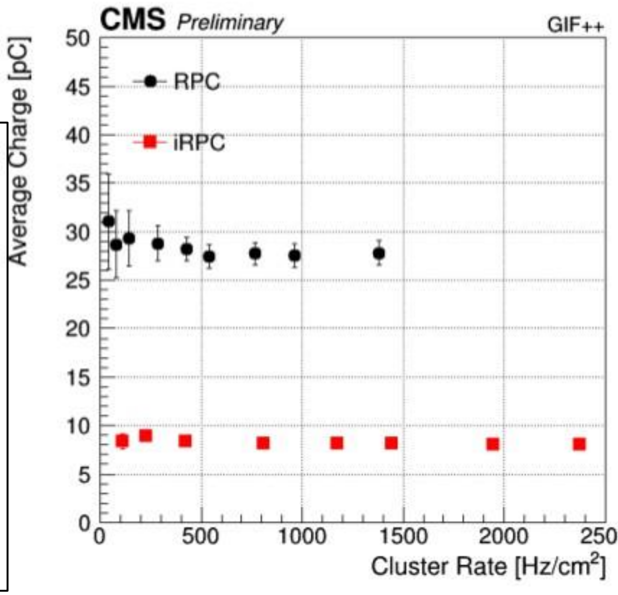


FULL SIZE PROTOTYPE

Validation of iRPC detector

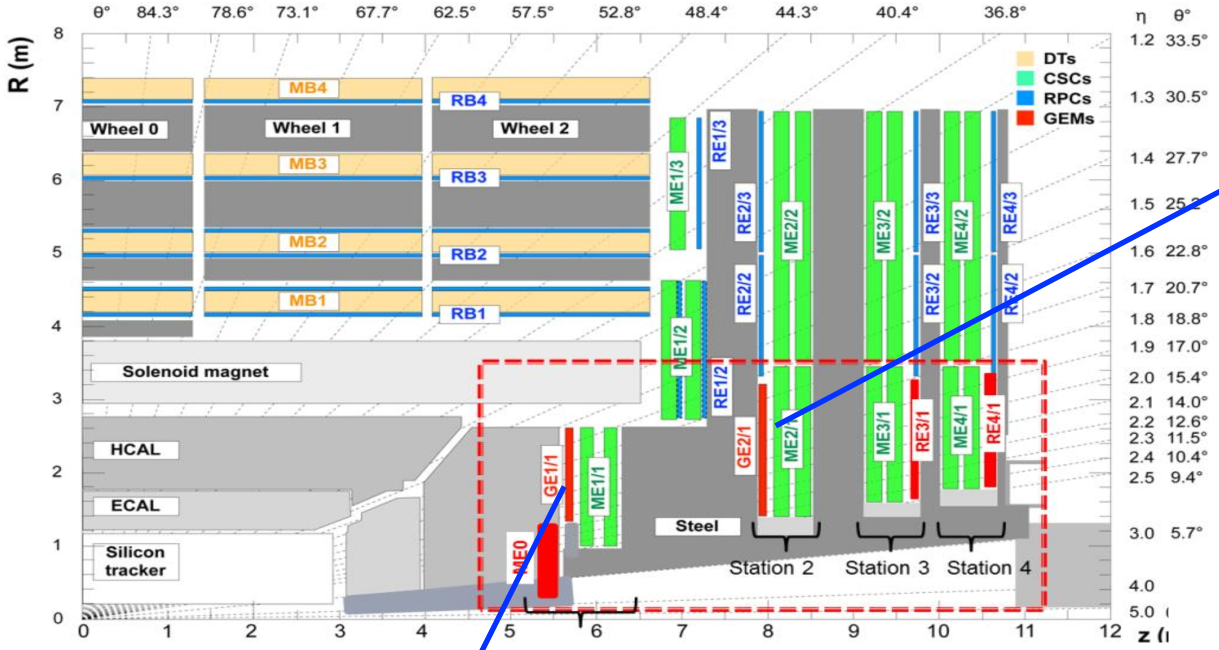






- No background, only muons: 98 % efficiency at Working Point (WP) ~ 7 kV.
- Background of 2 kHz/cm^2: 94% efficiency with WP + 300 V.
- The average charge (or the gain) within the gap is constant at WP optimized for each rate. The iRPC charge is 3 times lower than for RPC.

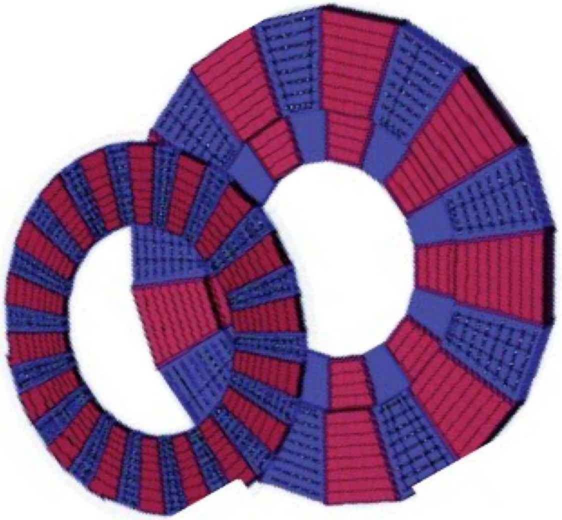
Forward muon system enhancement: GEM project



GE2/1:

Trigger and reconstruction

- 1.6 < |η| < 2.4
- 18 staggered SC per endcap, each **Triple-GEM** chamber spans 20° → 72 chambers each divided in 4 modules: 288 chambers
- **Installation in YETS 2021/22, 2022/23**

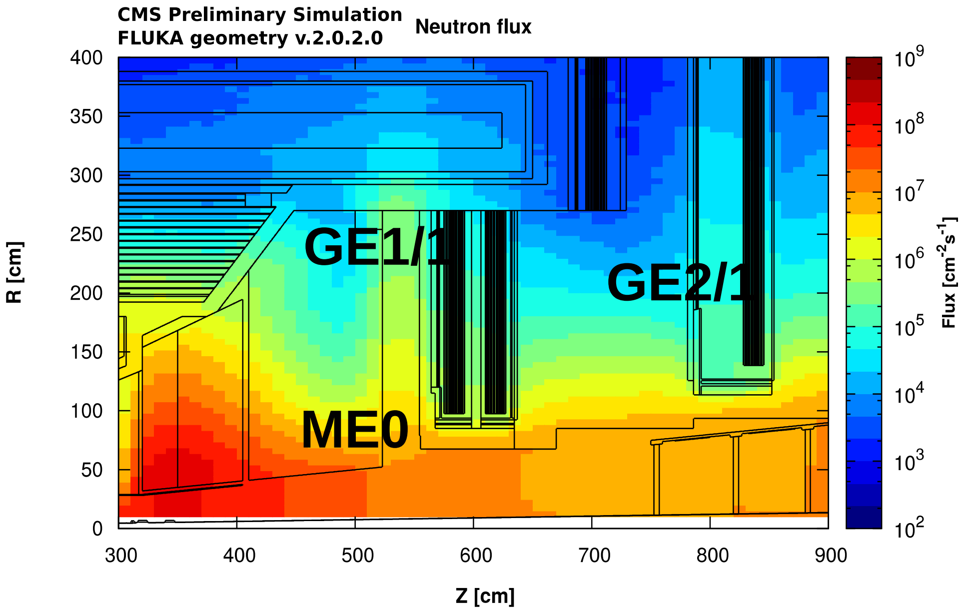


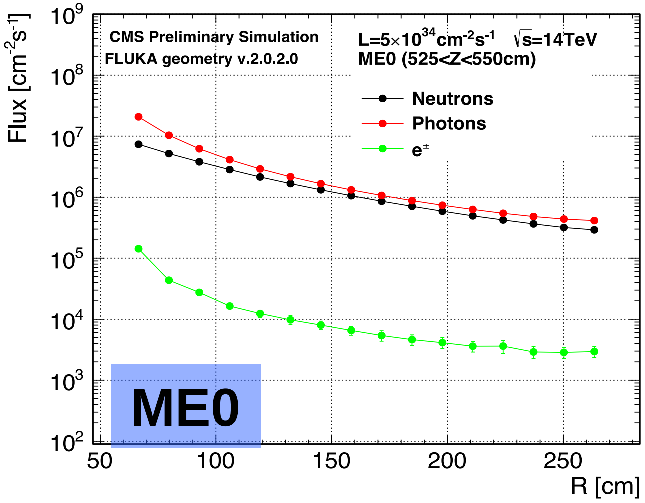
GE1/1:

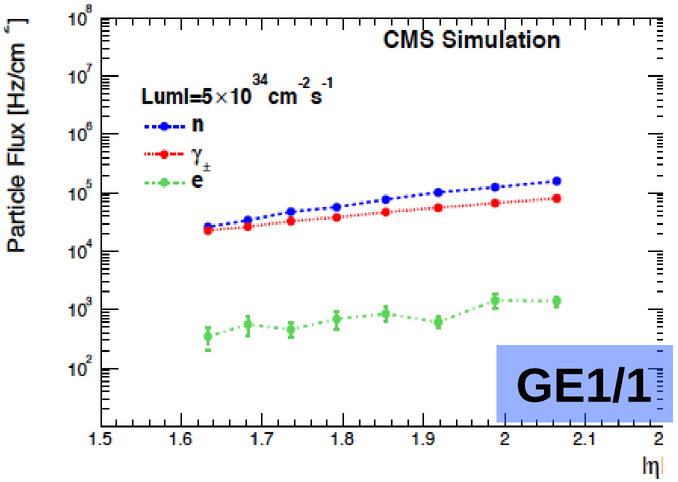
Trigger and reconstruction

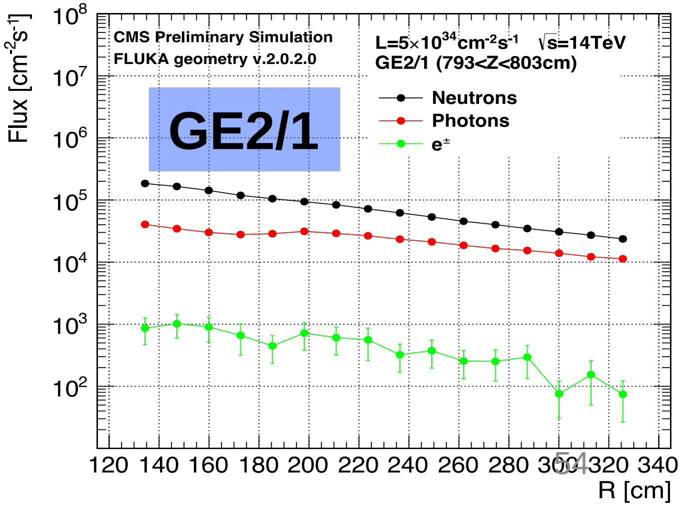
- 1.5 < |η| < 2.2
- 36 staggered super-chambers (SC) per endcap, each **Triple-GEM** chamber spans 10° → 144 chambers in total
- **Installation: LS2 (2019-21)**

The background in forward region

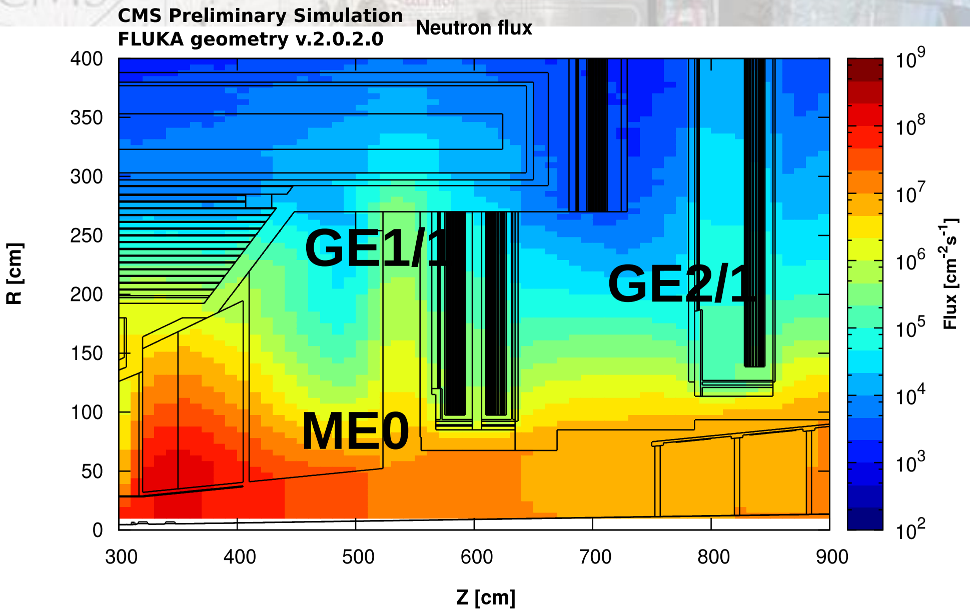




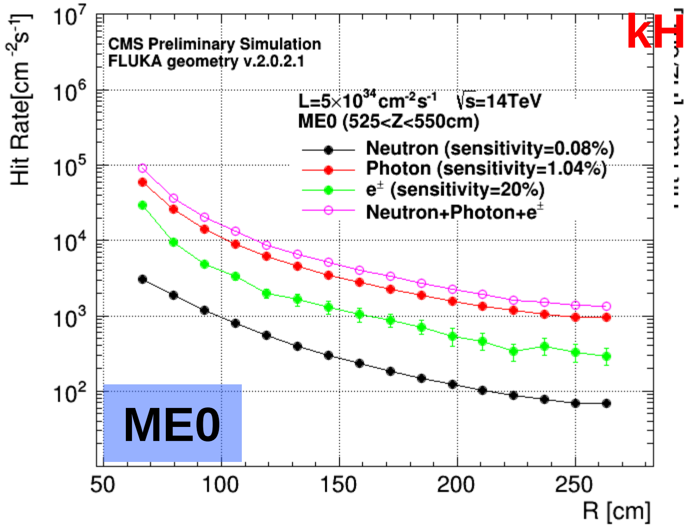


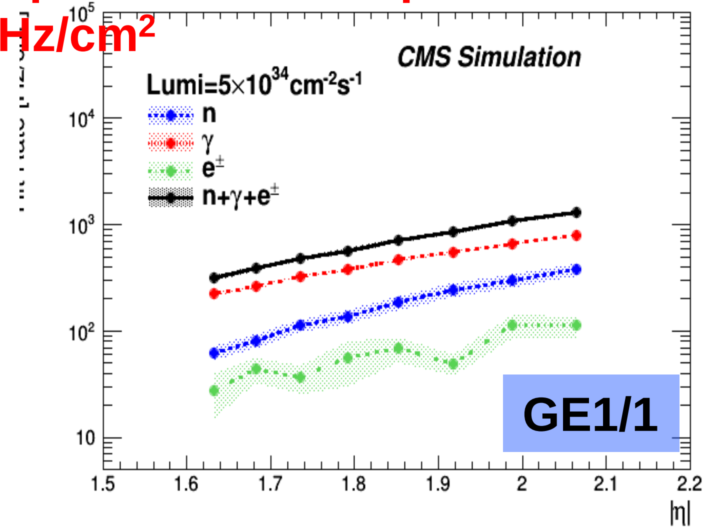


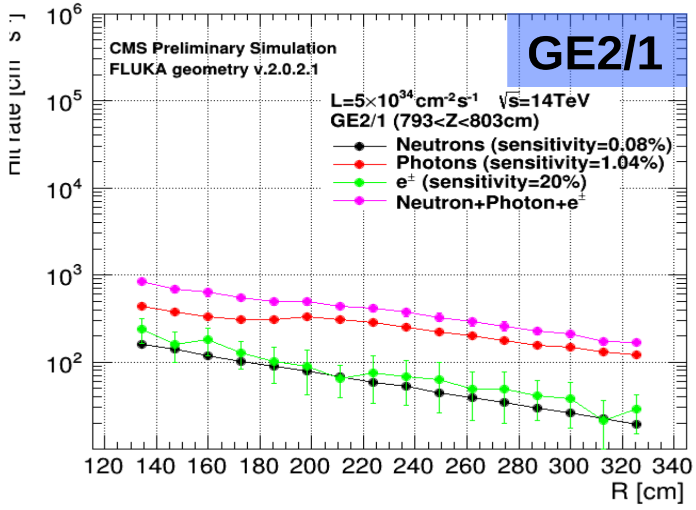
The background in forward region



- Expected hit rate up to 100's Hz – 100's kHz/cm^2







The GE1/1 and GE2/1 detectors

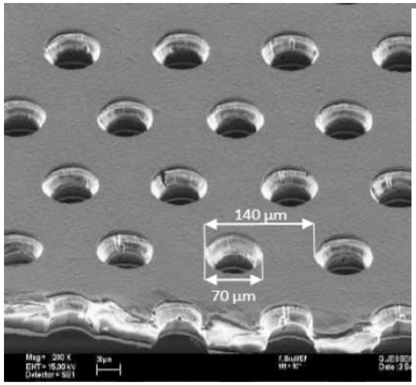
Two additional detectors with good spatial resolution for triggering and reconstruction purpose

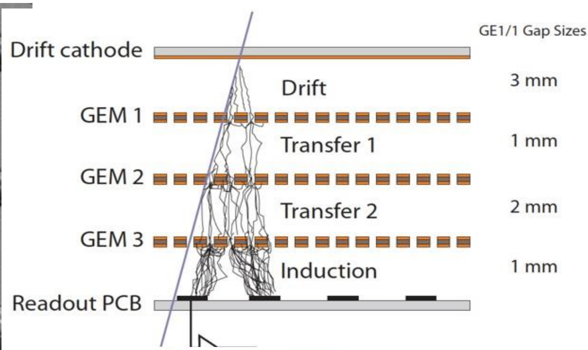
Based on triple-GEM technology:

- high gas gain 10^4
- High spatial resolution O(100 µm)
- Rate capability to MHz/cm2
- very resistant to aging

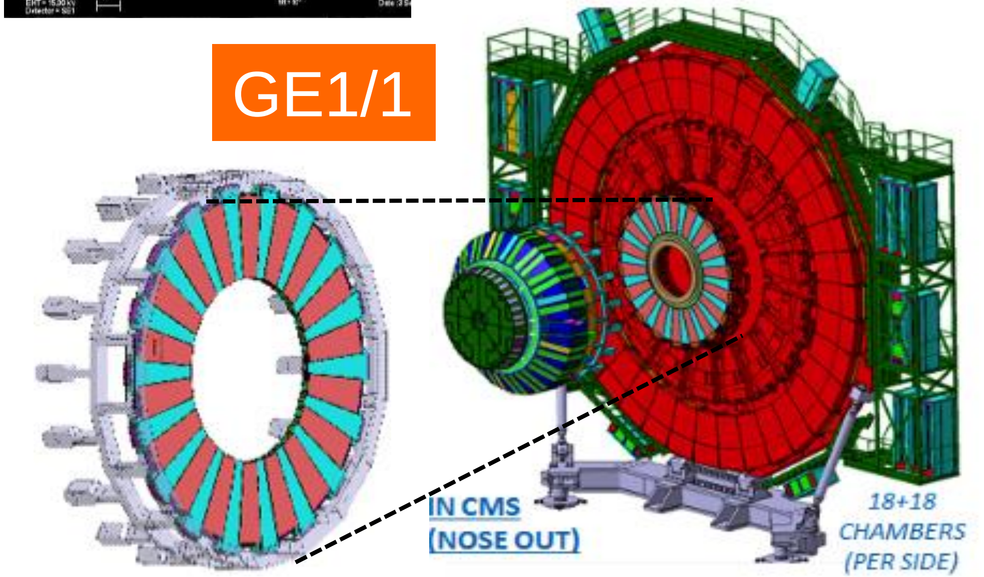
Two layers of triple-GEM (super-chamber) to be installed in front of existing CSC chamber: signals to be used in conjunction with CSC trigger primitives

- GE1/1 consists of 72 10° triple-GEM super-chambers
  - Covers 1.6 < |η| < 2.2 and it would be installed already in LS2 (2019-2020)
  - A slice of the system (5 superchambers installed since Spring 2017.
- GE2/1 consists of 36 20° triple-GEM super-chambers
  - Covers 1.6 < |η| < 2.4
    to installed already in YETS (2021/2022) and YETS (2022/2023)



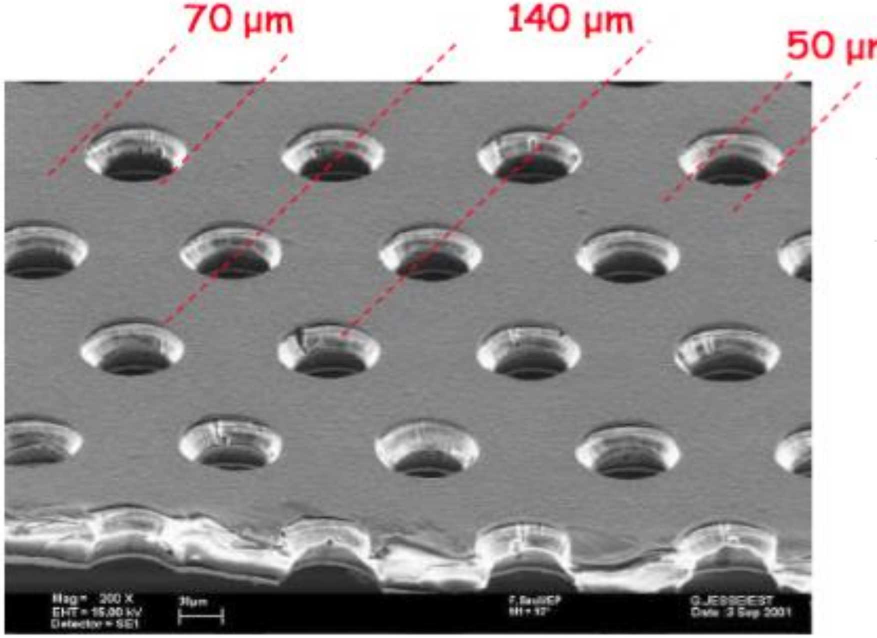


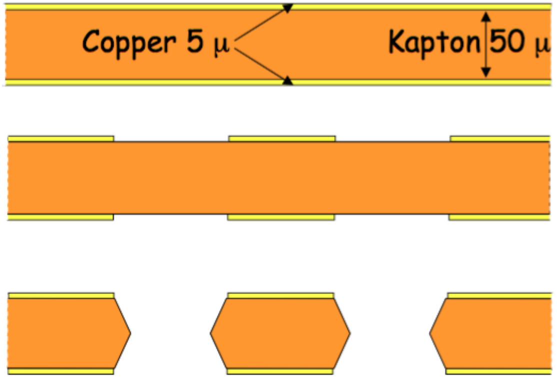
GE1/1



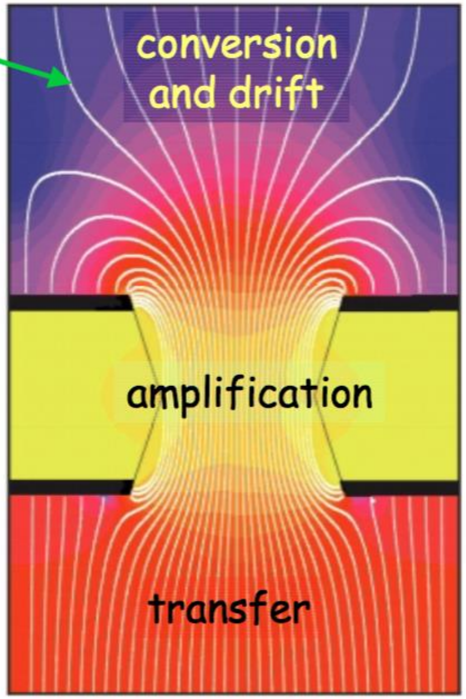
The GEM working principle

- 50 µm thick kapton foil, copper clad on each side and perforated by an high surface-density of bi-conical channels;
  - Kapton is a high-resistivity material
- By applying a potential difference between the two copper sides an electric field as high as 100 kV/cm is produced in the holes acting as multiplication channels.
- Potential difference ranging between 400 - 500 V



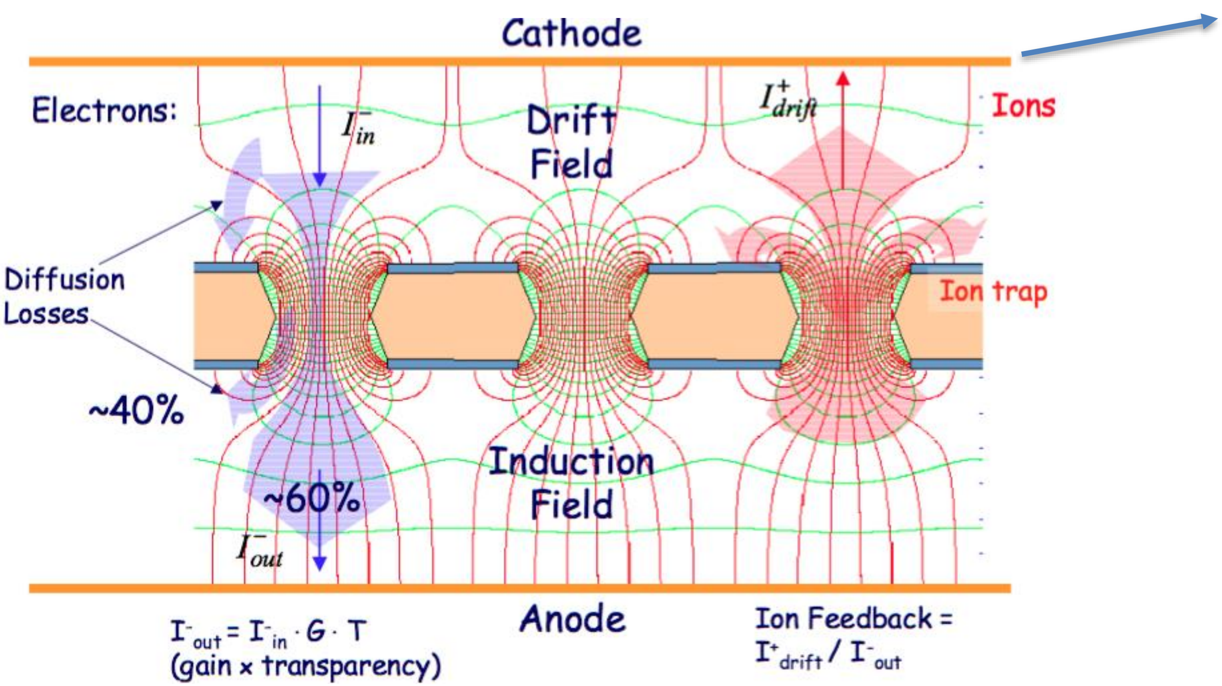


Copper etching by chemical solution
kapton etching using the copper mask



The Single GEM working principle

1. Electrons are collected on patterned readout board.
2. All readout electrodes are at ground potential.
3. Positive ions partially collected on the GEM electrode

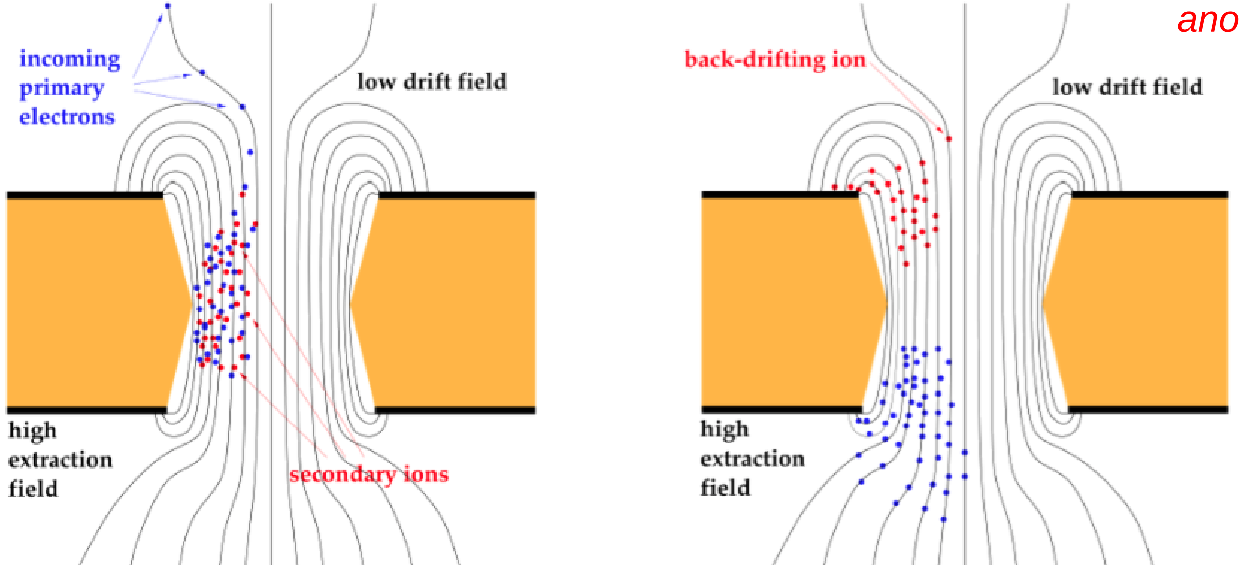


- To study gain in GEM we have to analyze which are the mechanisms of charge amplification
- We identify three electric fields: *drift field, moltiplication field, induction field*

Ion Backflow suppression

- Natural IBF suppression:
  - Asymmetric mobility [low for ions – high for electrons]
    - Electrons move to larger fields in the amplification channel
    - More ions are produced at the edges → trajectory ends on top electrode
  - Asymmetric field [drift – induction]
    - Many field lines end on top electrons (ion capture)
    - Transfer region allows for good electron extraction

Ion backflow=ratio of positive ions reaching the drift electrode to the electron charge detected at the anode



Ions are re-absorbed by the walls!!!

electrons are lost on the lower face of the GEM electrode,

1. The electric fields (drift and induction) play a crucial role to define the so called *Transparency*
2. Another important parameter is the geometry of holes

Gain Determination

$$\epsilon^{coll} = \frac{electrons\ collected\ in\ the\ holes}{electrons\ produced\ above\ the\ holes}$$

Collection efficiency

$$\epsilon^{extr} = \frac{electrons\ extracted\ from\ the\ holes}{electrons\ produced\ in\ the\ holes}$$

Extraction efficiency

$$G_{int} \propto e^{\overline{\alpha} \Sigma V_{GEM}}$$

Intrinsic gain

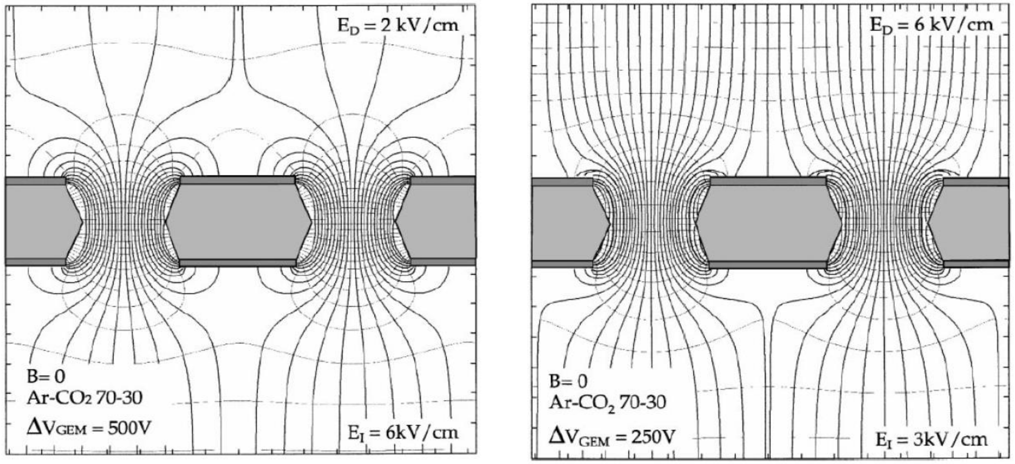
$$G_{eff} = G_{intr} * \varepsilon^{coll} * \varepsilon^{extr} = G_{intr} * T$$

Effective gain

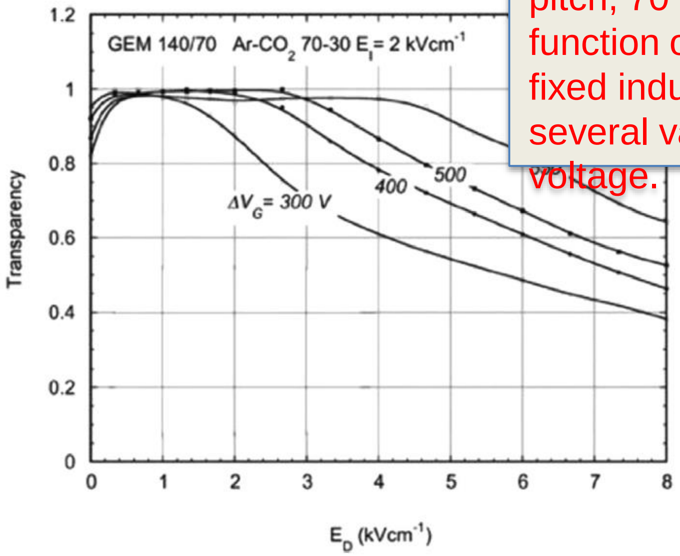
Since a field-dependent fraction of the multiplying electrons is lost on the lower face of the GEM electrode, the useful or effective gain, defined as ratio of the detected to the primary ionization charge, is always lower than the real gain of the multiplier.

GEM detector parameters

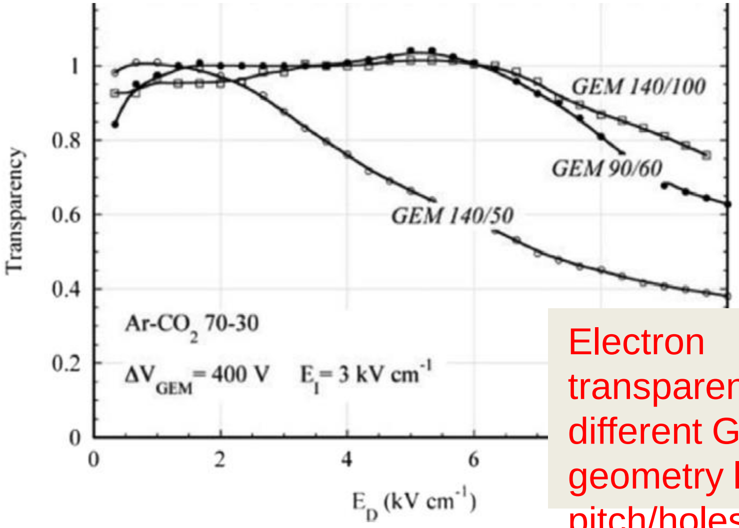
Electron transparency dependence vs Different drift and induction electric field



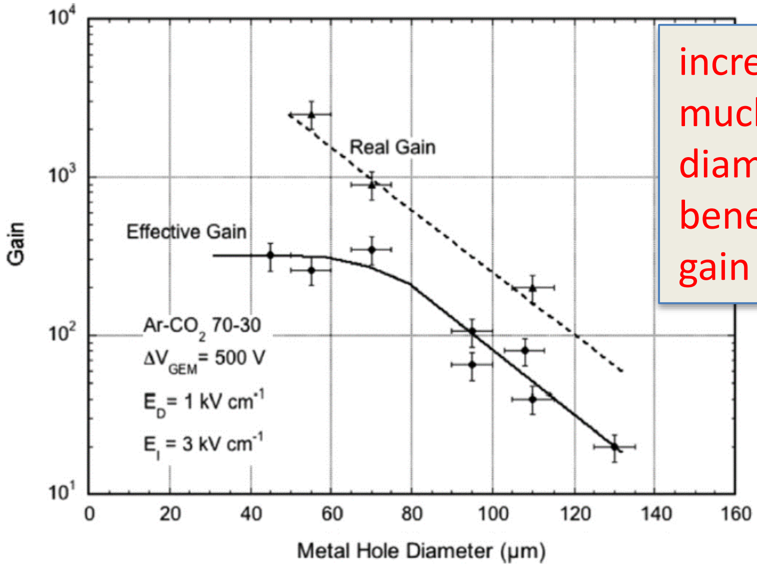
(a) (b)



Electron transparency of a standard GEM electrode (at 140 um pitch, 70 um holes) as a function of drift field for fixed induction field, for several values of GEM voltage.



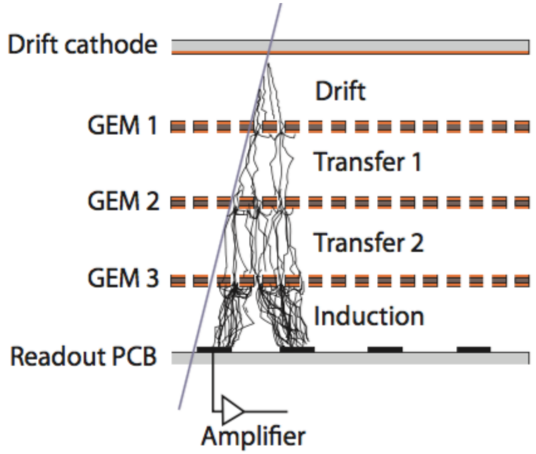
Electron transparency for different GEM geometry labeled as pitch/holes diameter.



increade too much the hole diametr is not beneficial on the gain value

Single vs Triple GEM

With an appropriate choice of the fields, the fraction of amplified electrons transferring to the gas gap following a first electrode can be injected and multiplied in a second foil, and yet again in a cascade of GEM electrodes

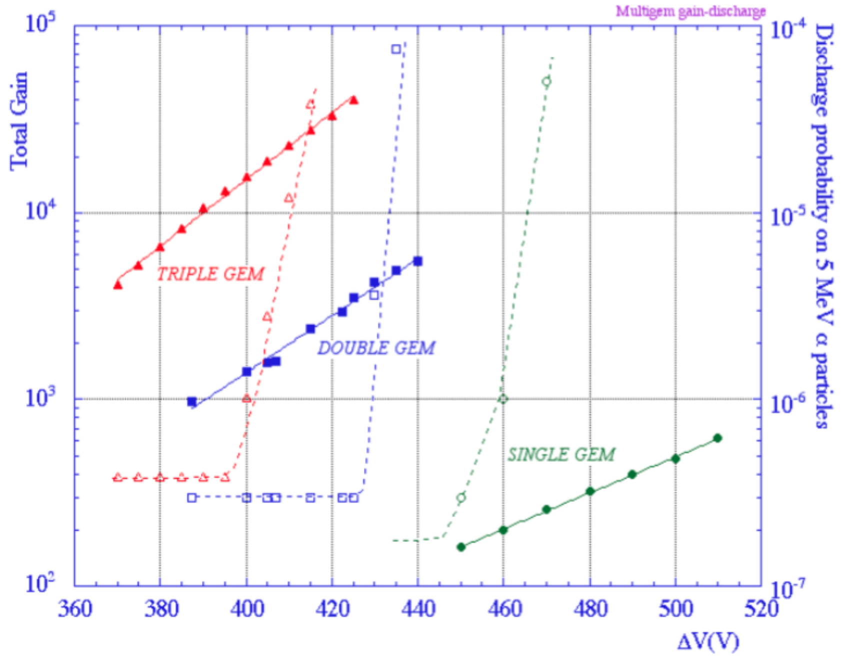


GE1/1 Gap Sizes	Typical Potentials	Typical Voltages	Typical El. Fields [kV/cm]
	3200 V		
3 mm		770 V	2.6
	2430 V		
		380 V	64.0
	2050 V		
1 mm		300 V	3.0
	1750 V		
		370 V	62.0
	1380 V		
2 mm		600 V	3.0
	780 V		
		350 V	60.0
	430 V		
1 mm		430 V	4.3
	0 V		

- Discharge probability on exposures to α particles is strongly reduced

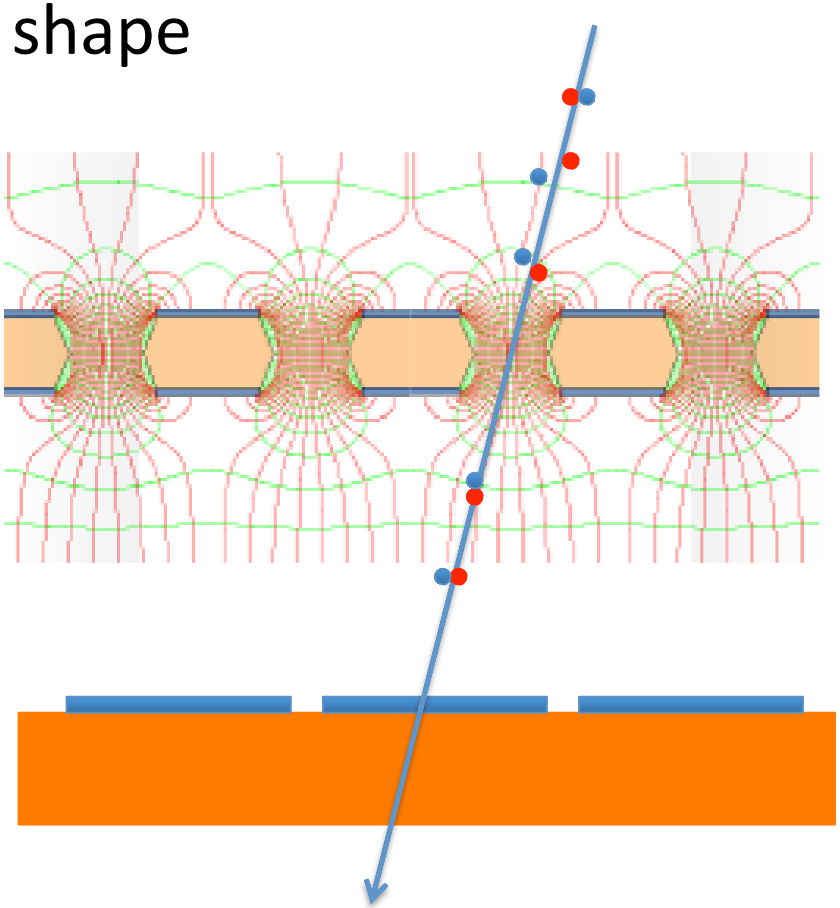
Multiple structures provides equal gain at lower voltage

Measurements with alfa particle

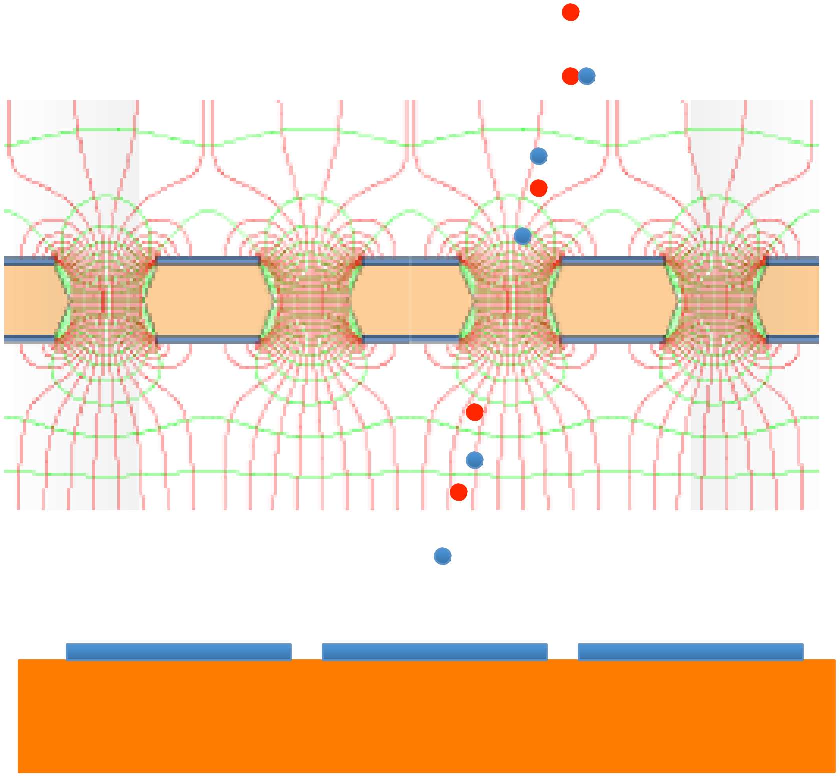


Signal in Triple-GEM detectors

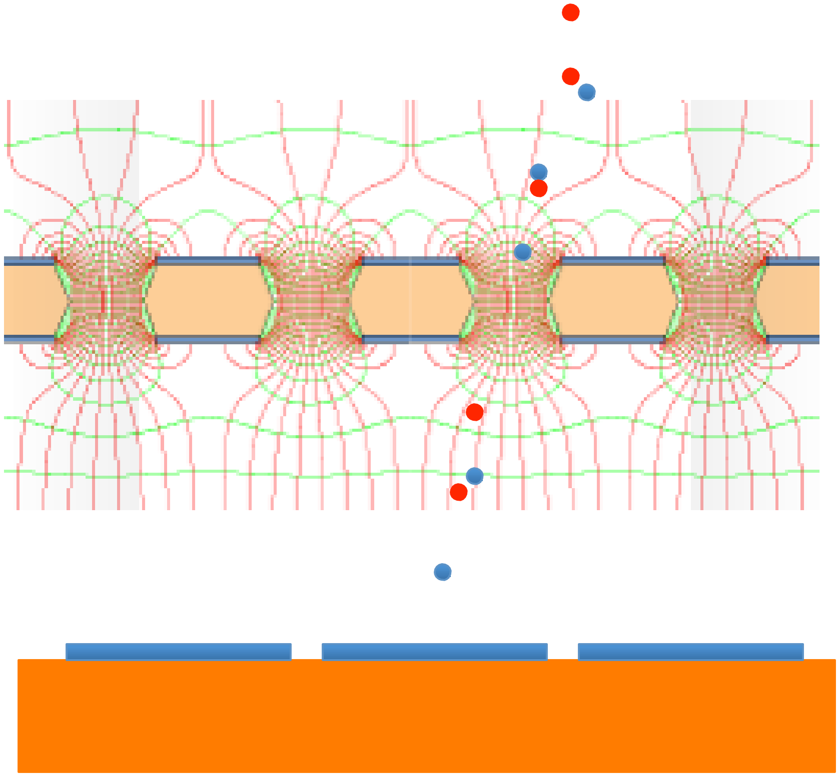
- understand the detector signal shape



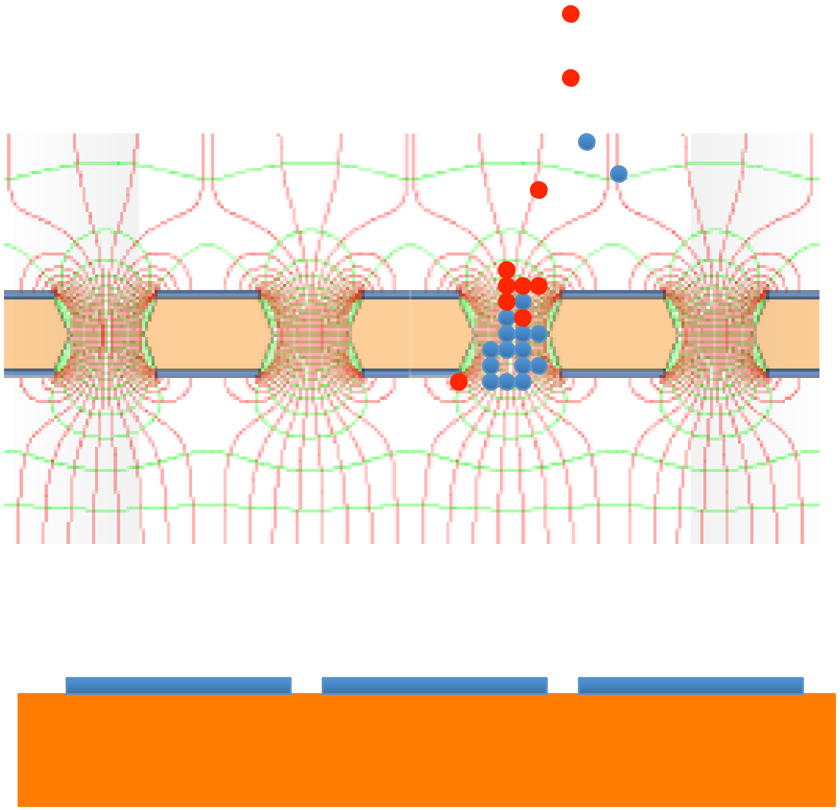
Signal in Triple-GEM detectors



Signal in GEM detector

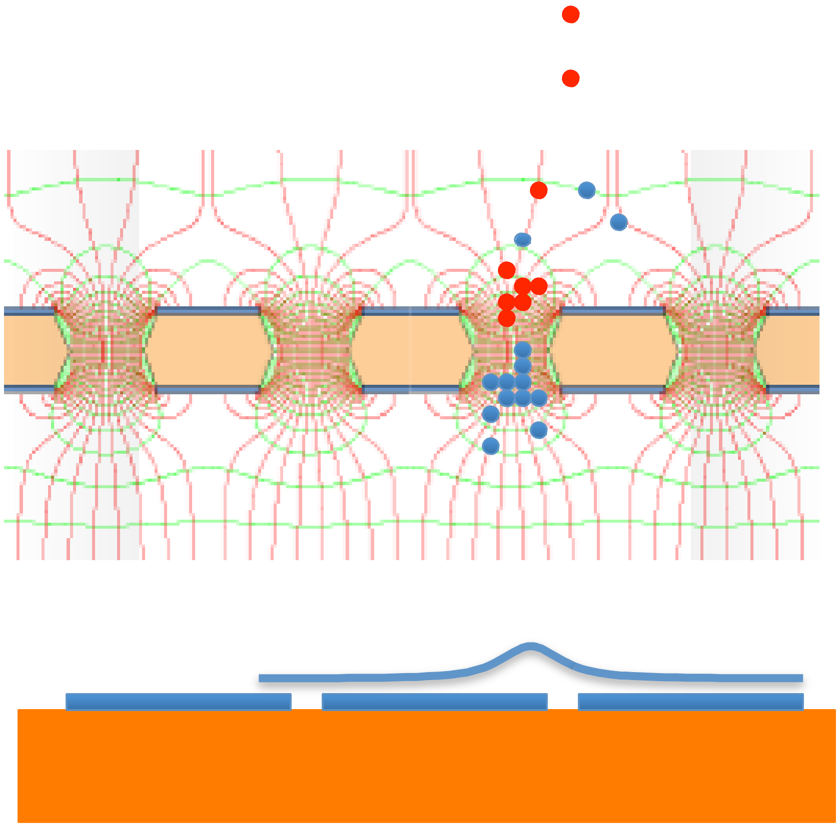


Signal in GEM detector



Signal in GEM detector

the signal induction is caused by the motion of the electrons towards the electrode;



Signal in GEM detector

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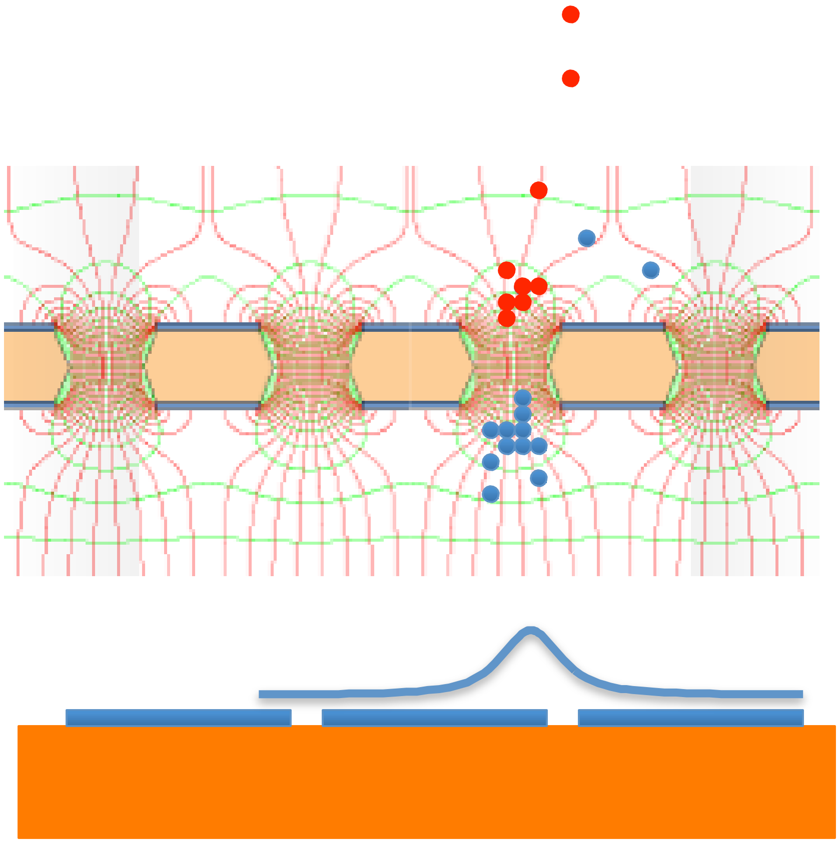
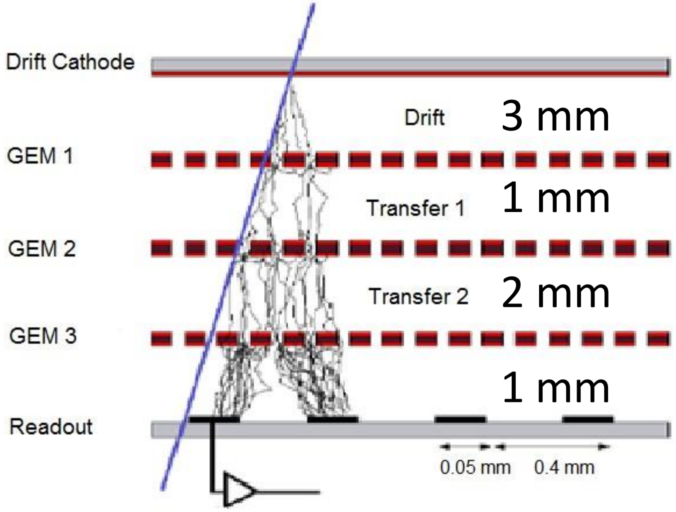
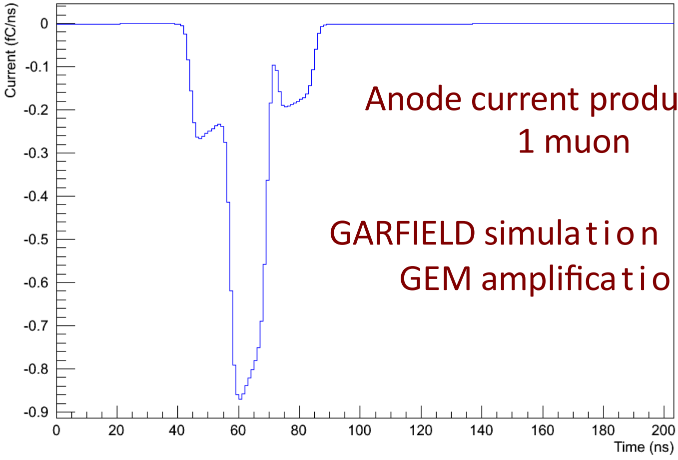


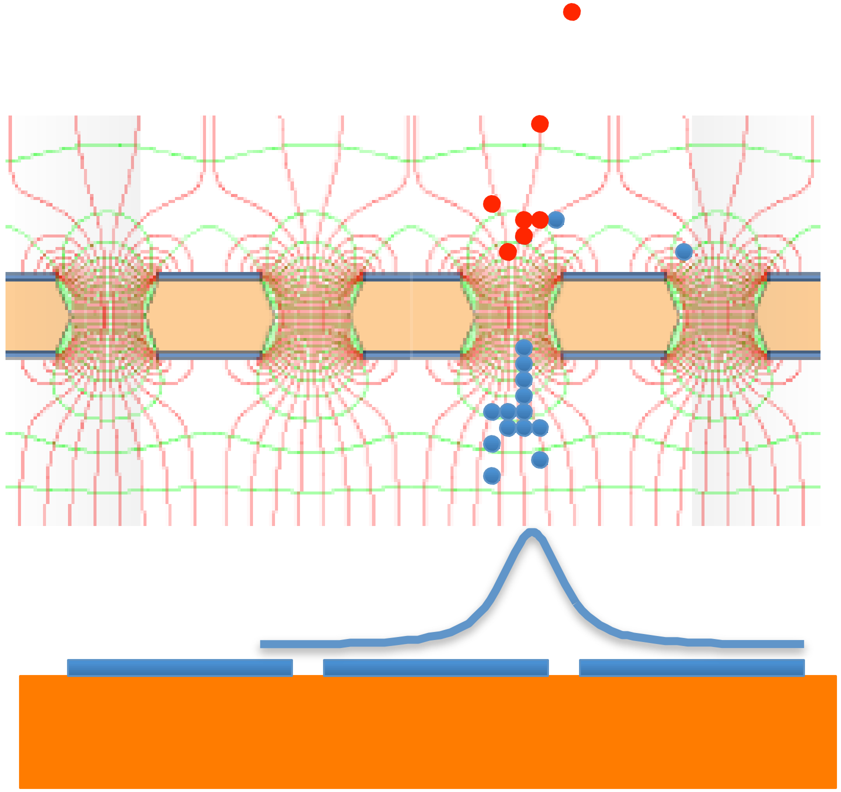
Signal in Triple-GEM detectors





Anode current produced by 1 muon

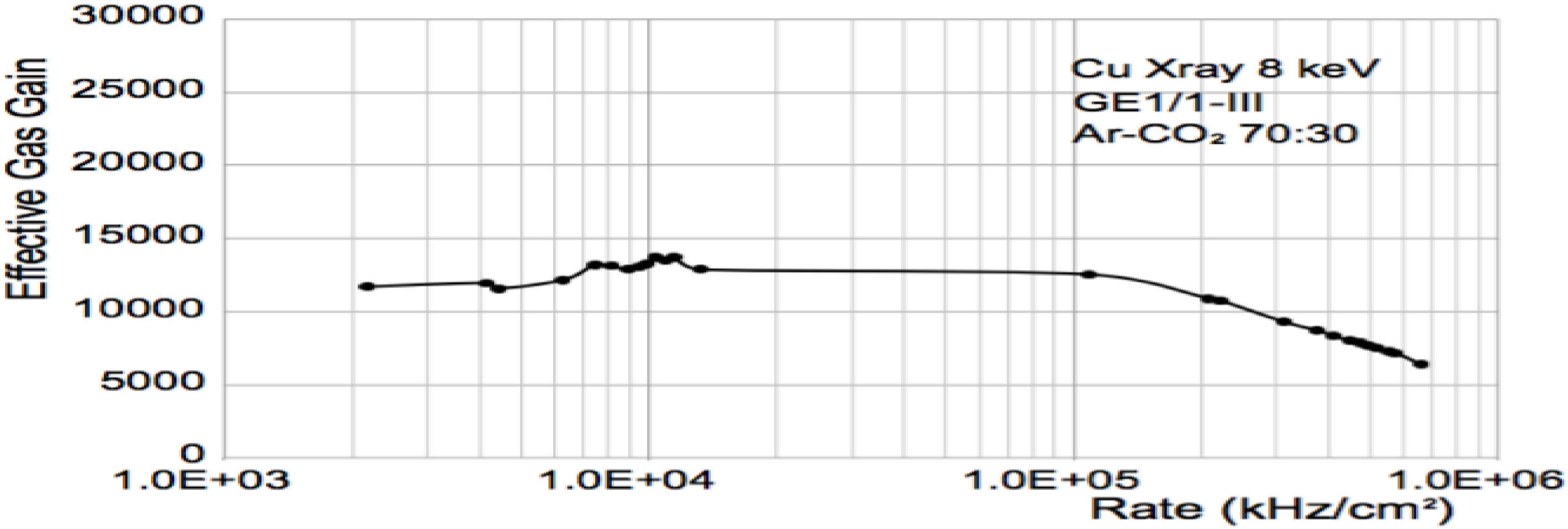
GARFIELD simulation including GEM amplification



- signal length: ~60 ns
- detector capacitance: 10-30 pF
- charge range (MIP): 4-110 fC

Rate capability

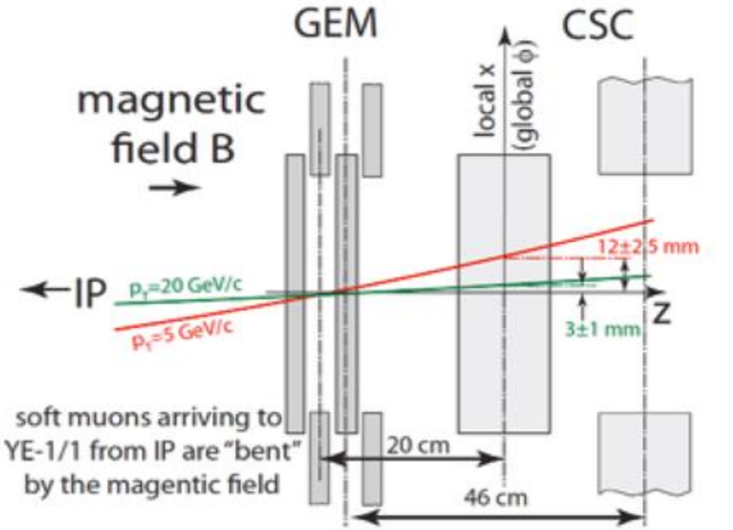
- A systematic study of rate dependence of gain in multi-GEM devices in a range of operating conditions and geometry has shown the gas gain to keep constant wrt to the rate;

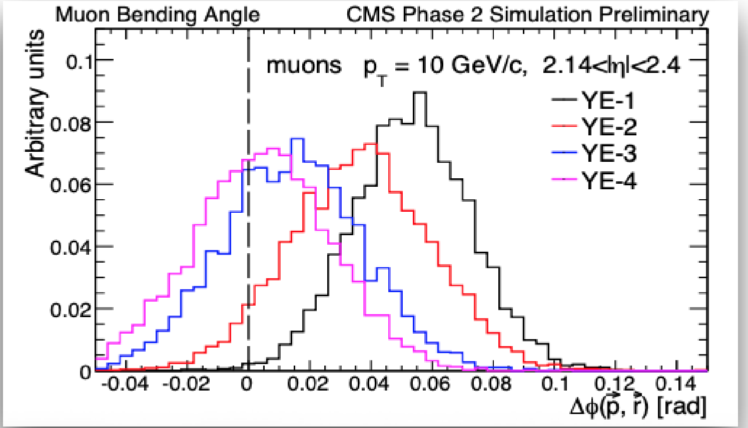


Gas gain is observed to be constant over four orders of magnitude of incident particle rate up to 100 MHz/cm2.
In HEP experiment a maximum rate on the order of 10 kHz/cm2 is expected

CMS GEM-CSC bending requirements

- Forward muon trigger for |η|>1.6 relies entirely on the CSC system
  - Largest particle rates are expected here
- Momentum measurement is driven by the magnetic field and multiple scattering
  - Bending in CSCs is too small for a good measurement at high η
- A GEM detector in front of CSC can measure the muon bending angle in magnetic field
  - Keep the rate under control (bottom right) and add redundancy



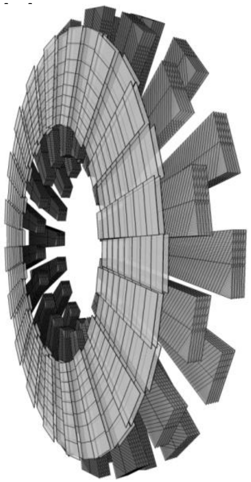


- Bending angle in station 1,2 is large enough; station 3,4 insufficient for good measurement

Adding detector in front of CSC to measure the muon bending angle in magnetic field in the each station, keeps the rate under control and ac redundancy:

✓ Requirement high rate capability

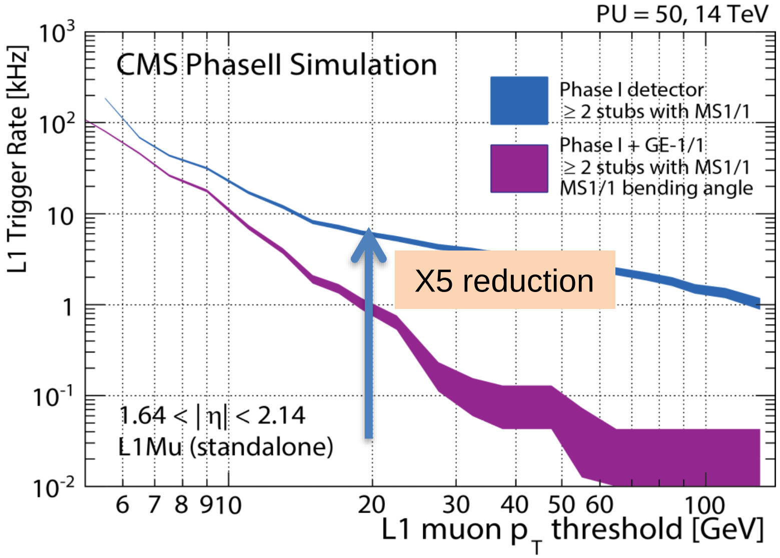
✓ precise Δϕ meas.→spatial resolution



CMS GEM-CSC bending: GEM requirements and performance

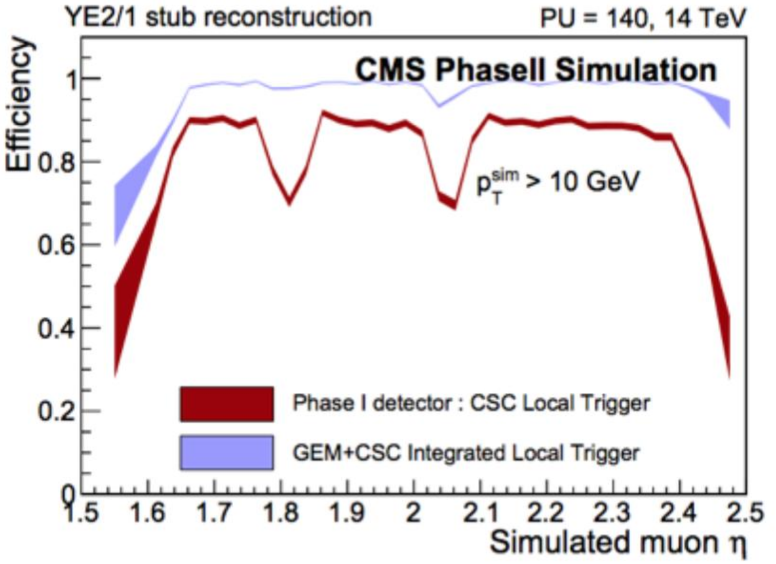
Adding detector in front of CSC to measure the muon bending angle in magnetic field in the each station, keeps the rate under control and adds redundancy:

- ✓ Requirement high rate capability
- ✓ precise $\Delta\phi$ meas.→spatial resolution



GEM detector main characteristics:

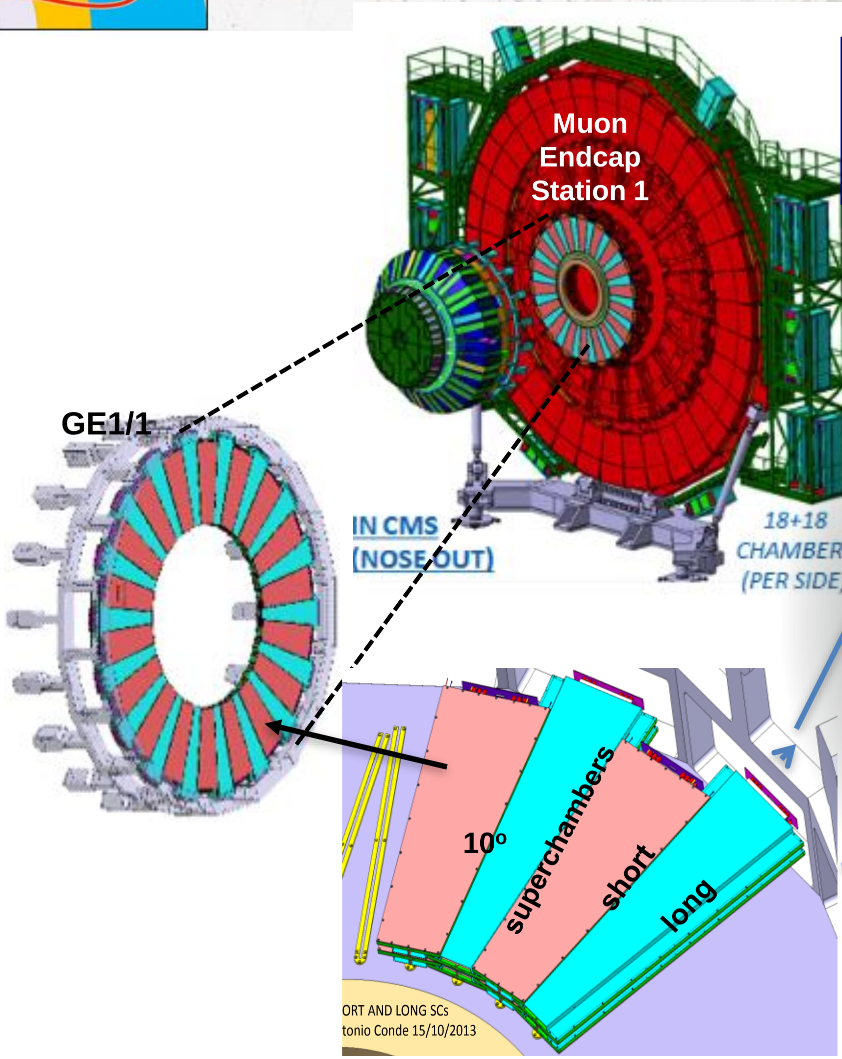
- ✓Excellent rate capability: up to 10^5/cm^2
- ✓ Gas mixture: Ar/CO$_2$ – not flammable
- ✓Angular resolution 500 mrad or better
- ✓Time resolution 8-10 ns
- ✓Gain uniformity of 15% or better across the module
- ✓No gain loss due to aging effect after 10 years of operation at HL-LHC
- ✓Large areas ~1 m x 2m with industrial processes
- ✓Long-term operation in COMPASS, TOTEM and LHCb

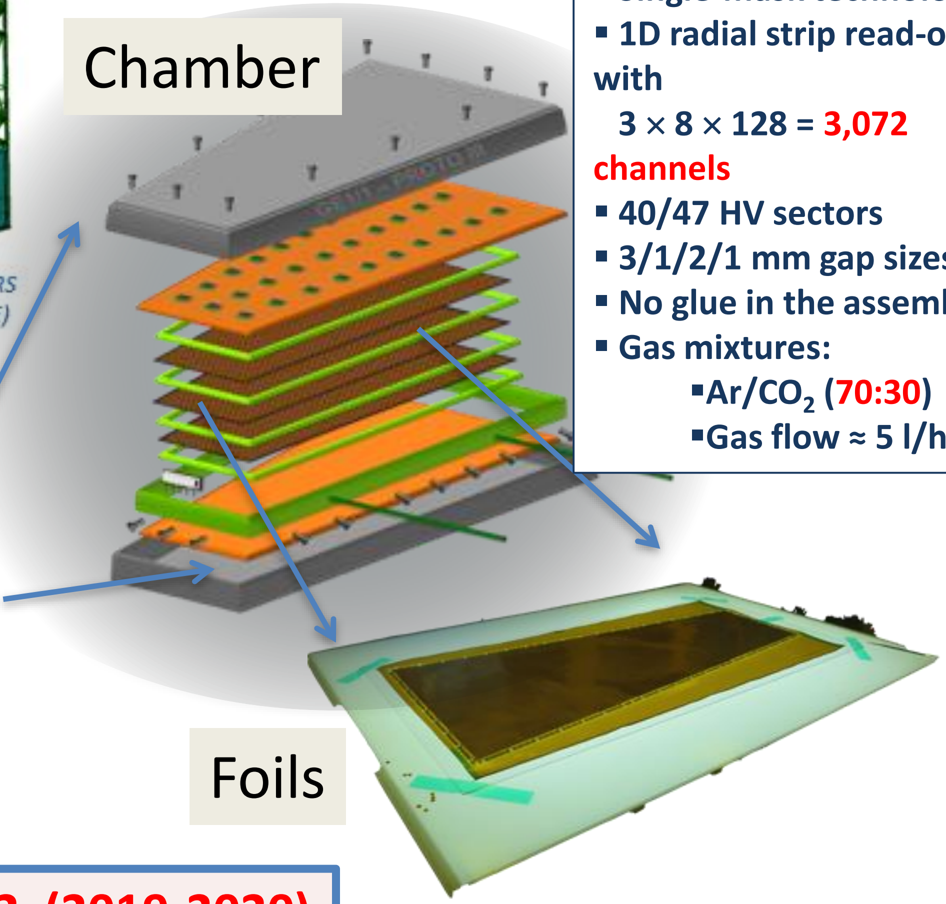


GEM GE1/1 Project Status

GE1/1 in high-η region $1.5<|\eta|<2.2$

36 superchambers in each endcap (144 modules)





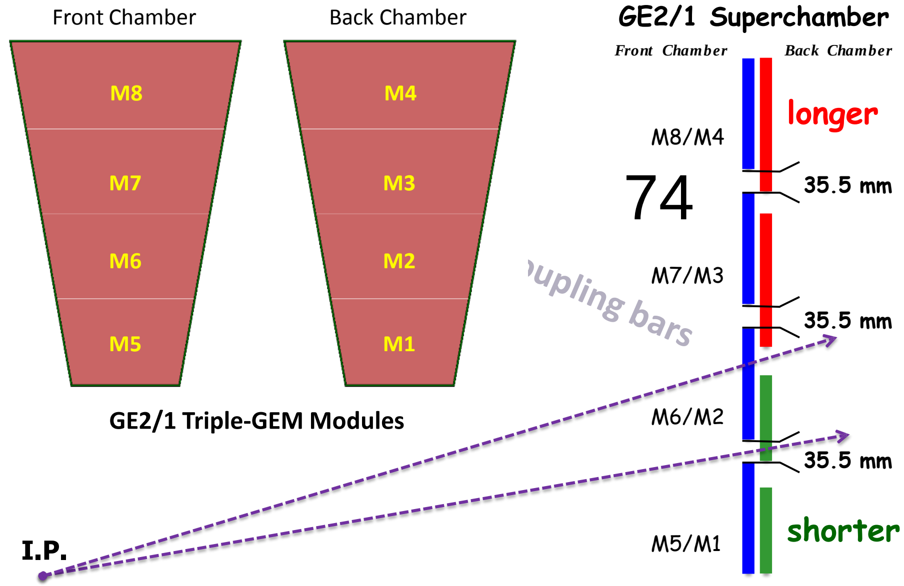
- Single-mask technology
- 1D radial strip read-out with
  $3 \times 8 \times 128 = 3{,}072$ channels
- 40/47 HV sectors
- 3/1/2/1 mm gap sizes
- No glue in the assembly
- Gas mixtures:
  - Ar/CO$_2$ (70:30)
  - Gas flow ≈ 5 l/h

Installation in LS2 (2019-2020)

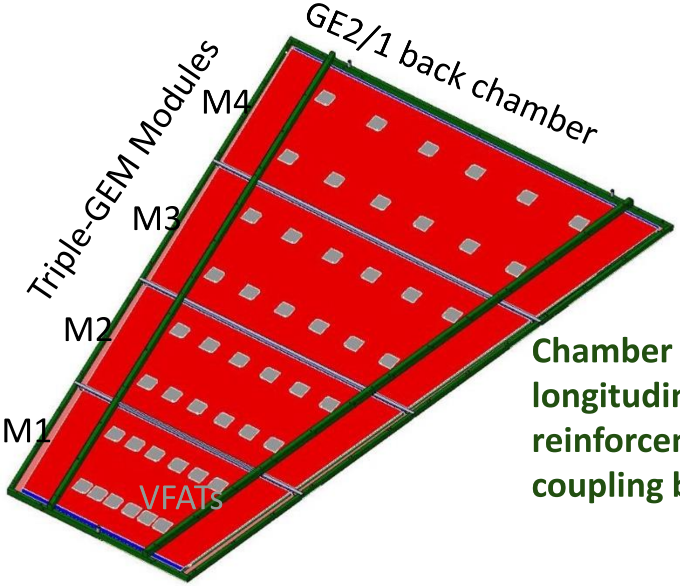
GE2/1 design

GE2/1 consists of 20° 36 triple-GEM super-chambers and covers 1.6 < |η| < 2.4

- **GE2/1 chambers** made up of **4 modules**
  - Different shape but similar size to single ME0 chamber
  - **Modules have different lengths → non-projective**
- **GE2/1 superchambers** made up of **2 chambers**

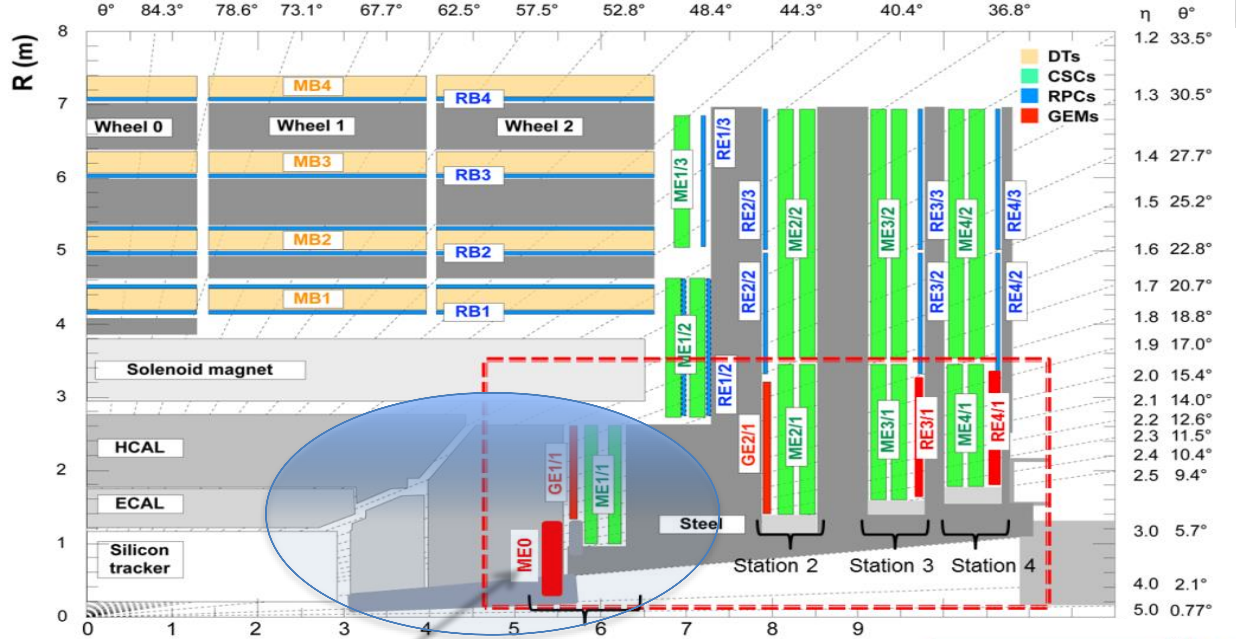


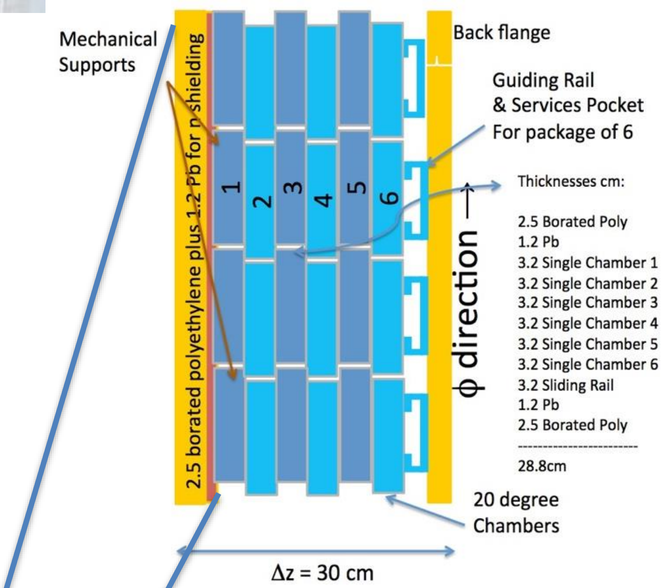
GE2/1 Triple-GEM Modules



Chamber frame with longitudinal reinforcement bars & coupling bars

Forward muon system enhancement: GEM project

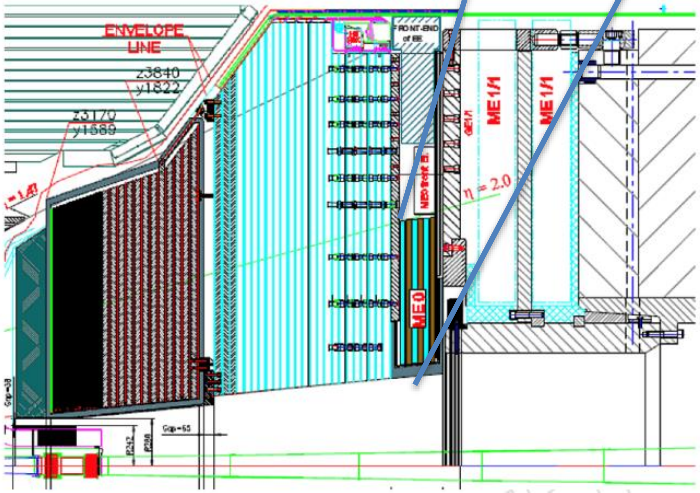




Thicknesses cm:

2.5 Borated Poly
1.2 Pb
3.2 Single Chamber 1
3.2 Single Chamber 2
3.2 Single Chamber 3
3.2 Single Chamber 4
3.2 Single Chamber 5
3.2 Single Chamber 6
3.2 Sliding Rail
1.2 Pb
2.5 Borated Poly

28.8cm



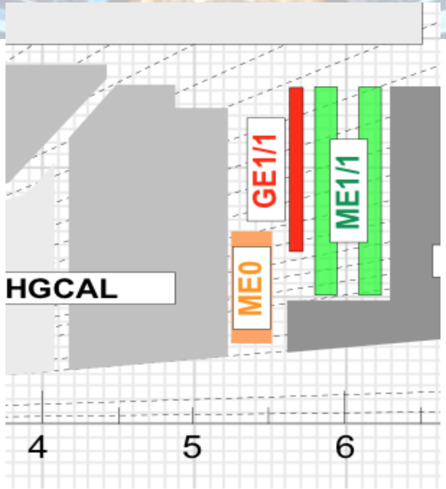
ME0:

Triggering and reconstruction

- 2 < |η| < 2.8
- 36 wedges of 6 layers **Triple-GEM**
- each chamber spans 20˚
- **Installation: LS3 (2024-26)**

The ME0 Detector

New station to efficiently identifying and triggering muons, low in transverse momentum (but large in momentum) while maintaining a low rate of background in the harsh HL-LHC conditions up to η=2.8. Installation scheduled in LS3.



- ME0 consists of 6 layers of triple-GEMs arranged in 20^0 super-module wedges: 216 chambers.

High granularity and spatial segmentation for:

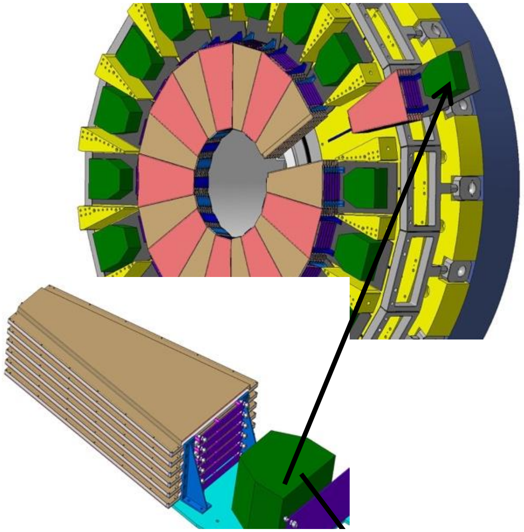
- Position and bending measurement of the muon stubs for efficient matching of the offline pixel tracks.

Multi-layered structure to:

- improve local muon track reconstruction
- discriminate muon (segment) against neutrons (uncorr hits).

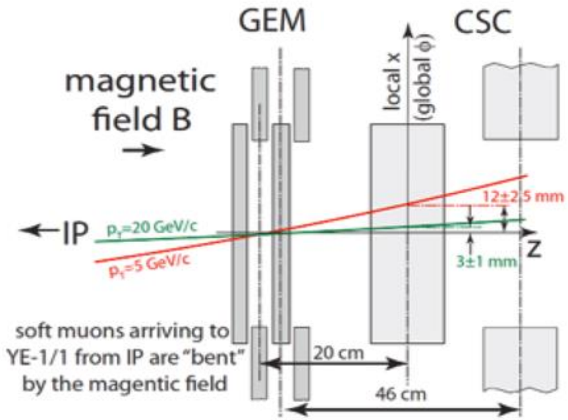
Large lever arm between ME0 and CSC (ME1/1) up to η~2.4

- Allows large trigger rate reduction



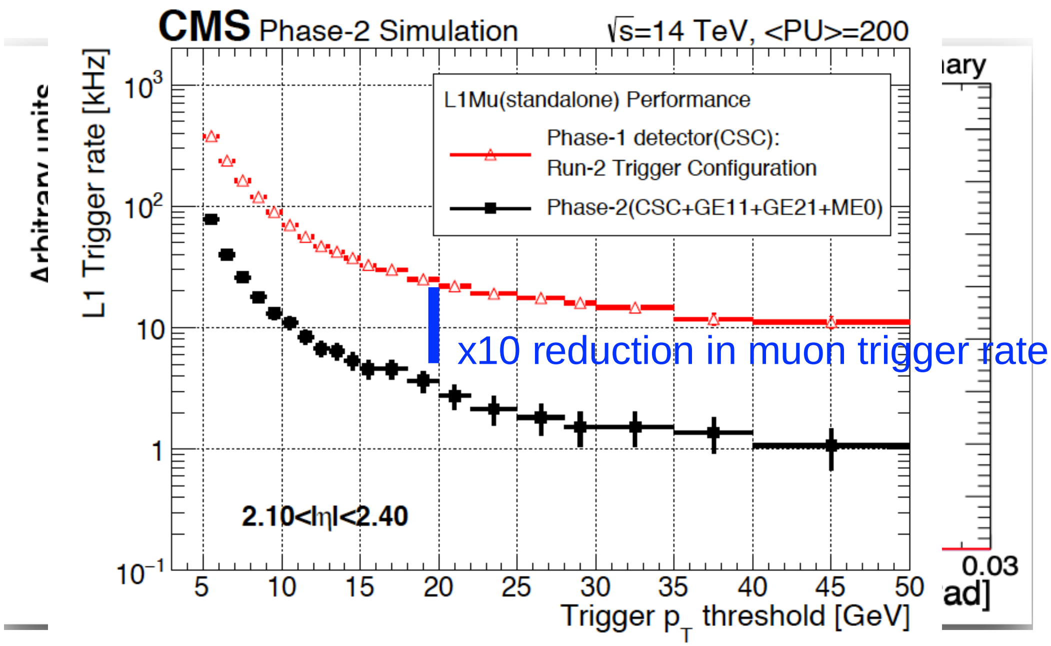
Muon trigger improvement

CSC-GEM tandem improves trigger-level muon momentum measurement, by providing the local direction measurement



Background has steeply falling momentum spectrum

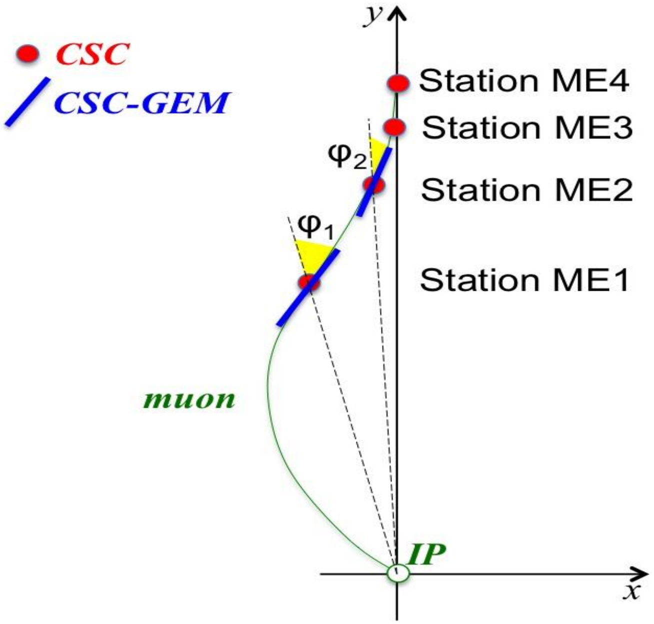
- Trigger rate reduction (otherwise raising trigger threshold would harm physics acceptance)



x10 reduction in muon trigger rate

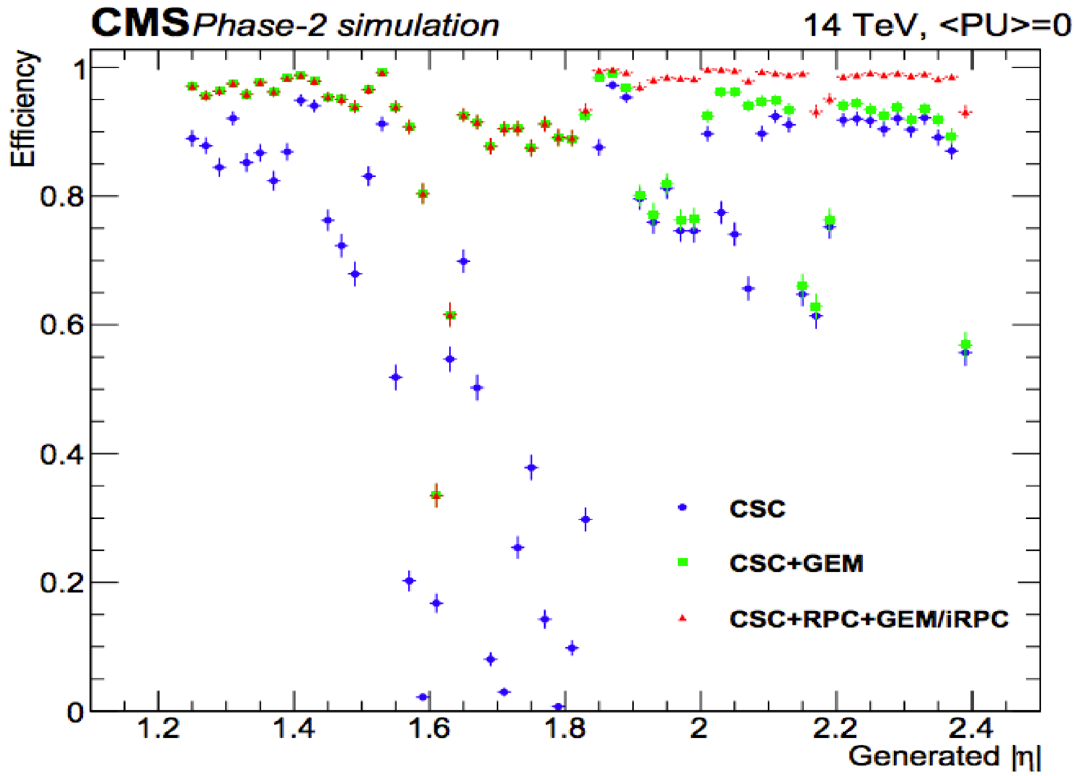
Very good separation between soft and hard muon

Schematic view of a muon trajectory from the collision point



Standalone L1 Trigger: efficiency

Level-1 muon track finding efficiency in the endcap region benefits from the addition of GEM and iRPC in the high η region.

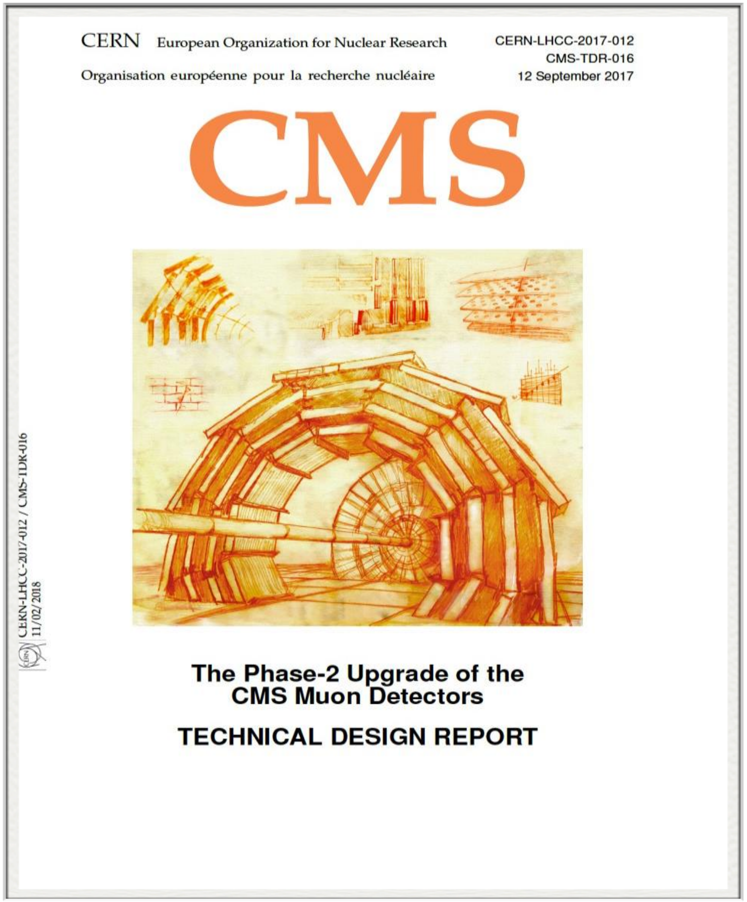


→iRPC additional hits recover the efficiency losses due to acceptance gaps in this region

→ GEM and iRPC hits allows considerably higher efficiency in comparison to a L1 trigger based on CSC detectors alone.

Summary

- The CMS Muon system is performing very well
  - many upgrades have followed the initial installation made the system very robost
- Some electronics need to be replaced to meet HL-LHC requirements.
- The high η region to be enhanced with additional GEM and iRPC detectors.
- Upgraded detector capabilities open windows for new physics opportunities.
- Installation starts in the Long Shutdown2 (2019-2020); continues in Year-End-Techinical-Stops; and finishes in the Long Shutdown 3 (2024-mid 2026)
- CMS Muon Upgrade TDR is published



CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CERN-LHCC-2017-012
CMS-TDR-016
12 September 2017

CMS

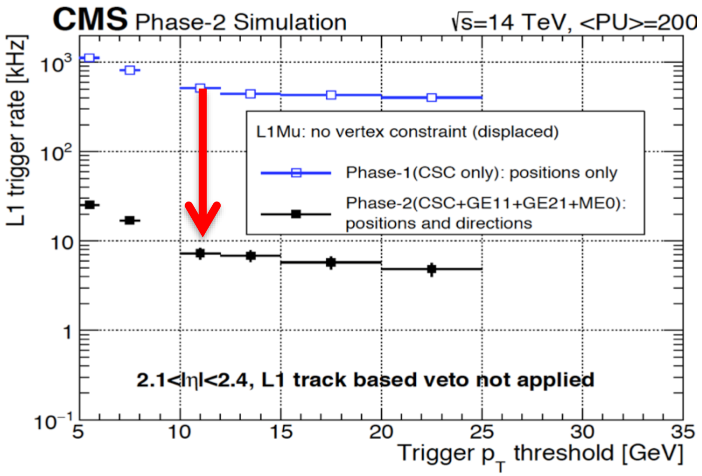
CERN-LHCC-2017-012 / CMS-TDR-016
11/02/2018

The Phase-2 Upgrade of the CMS Muon Detectors

TECHNICAL DESIGN REPORT

For any question/information contact me at Anna.Colaleo@cern.ch

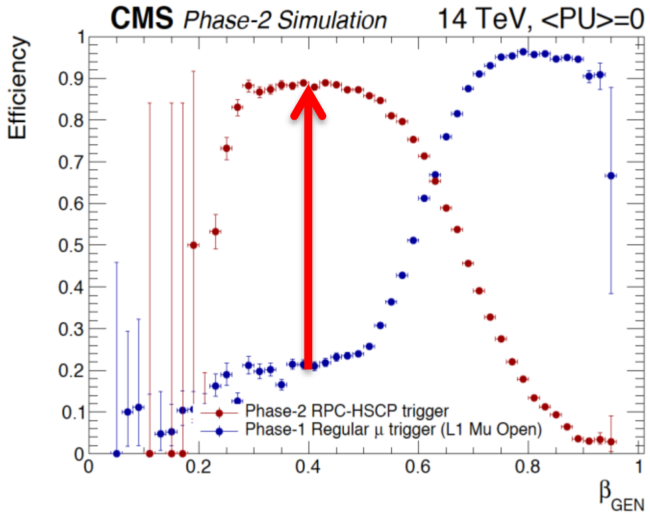
New physics search: triggering on unconventional signals



Trigger on highly displaced muons

Adding GEM makes it possible to build trigger- level muons without assuming muons come from the proton collision point

factor of 50 improvement



Trigger on Heavy Stable Charge Particles

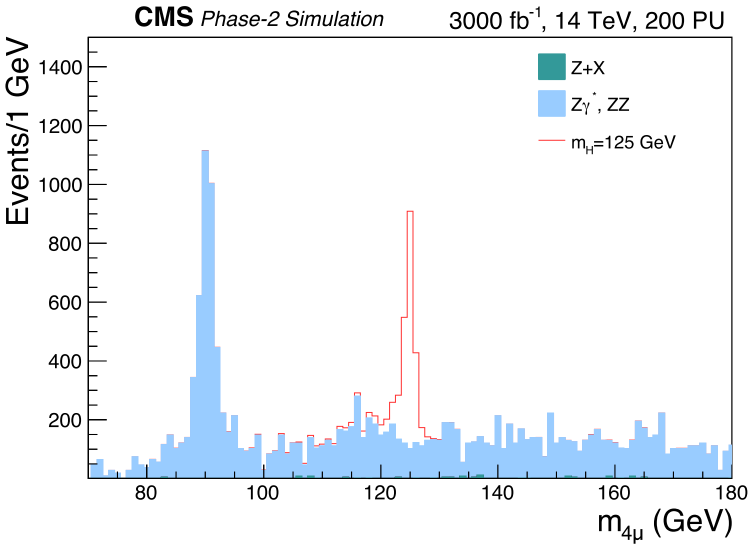
The upgraded RPC link system fully exploits the RPC time resolution, enabling to identify patterns of delayed hits from one station to the next, with a precision of ~1 ns

up to a factor 4-5 improvement

Extended muon acceptance

Many BSM searches and SM measurements benefit from extended muon acceptance:

- 5σ- observation limit on BR(**τ→3μ**) = 1.1 x 10^{-8} @ 90% CL (x2 Belle limit)
- H → ZZ → 4μ: 17% more signal, with a very good background rejection

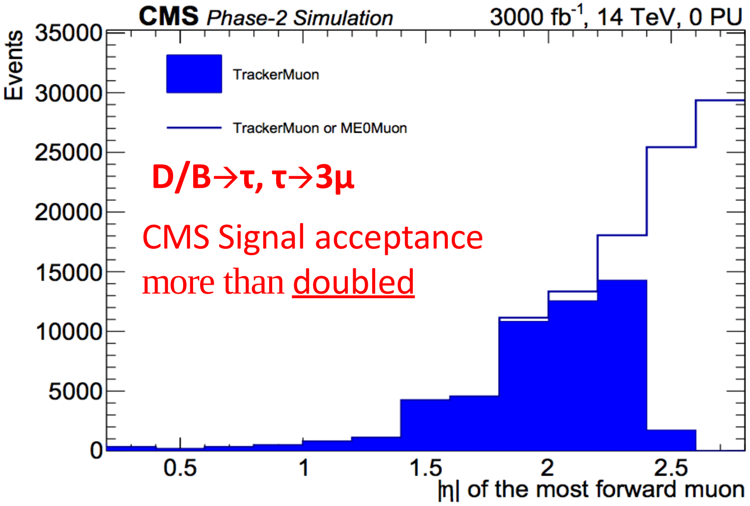


Help in suppressing background such as WZ.

Ex. WZ→ μμμ decays signature, with two same-sign leptons and third non-reconstructed muon:

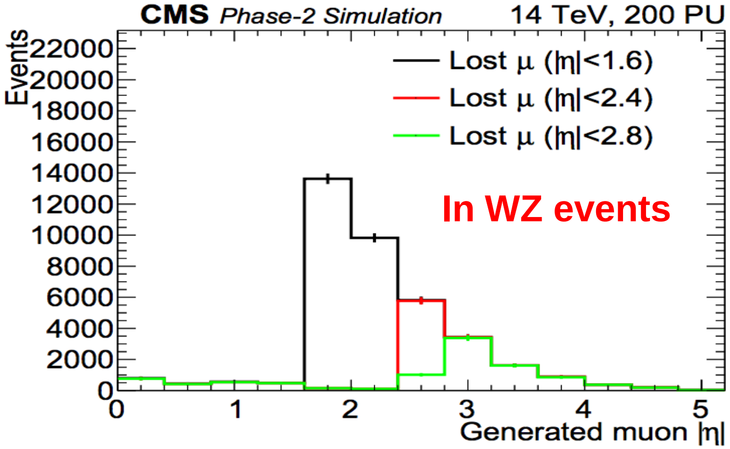
- extended coverage up to 2.8 in η allows more efficient reconstruct and veto of WZ→ μμμ decays

|η| of the most forward muon (p>2.5 GeV)



D/B→τ, τ→3μ

CMS Signal acceptance more than <u>doubled</u>



In WZ events

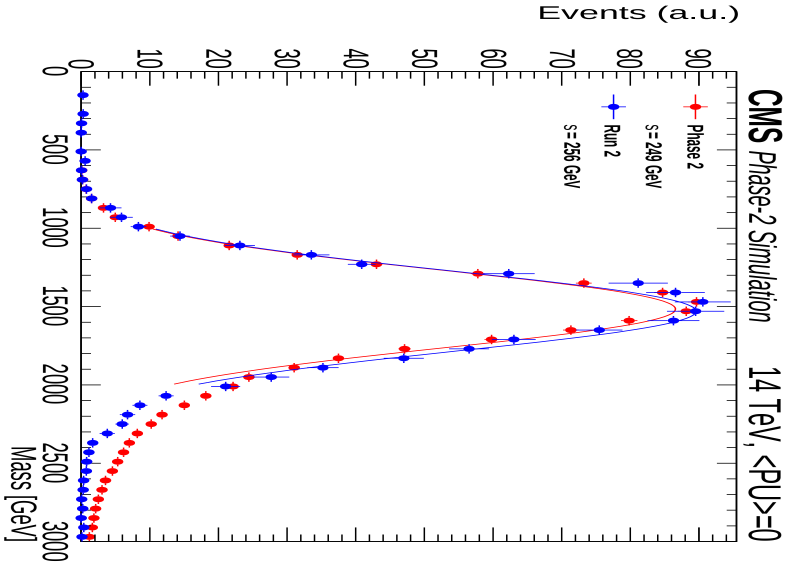
Slow-moving muon-like particles

Search for heavy “colorless” charged particles (HSCP) with masses larger than O(1) TeV and very long lifetimes (β ~ 0.3–0.5):

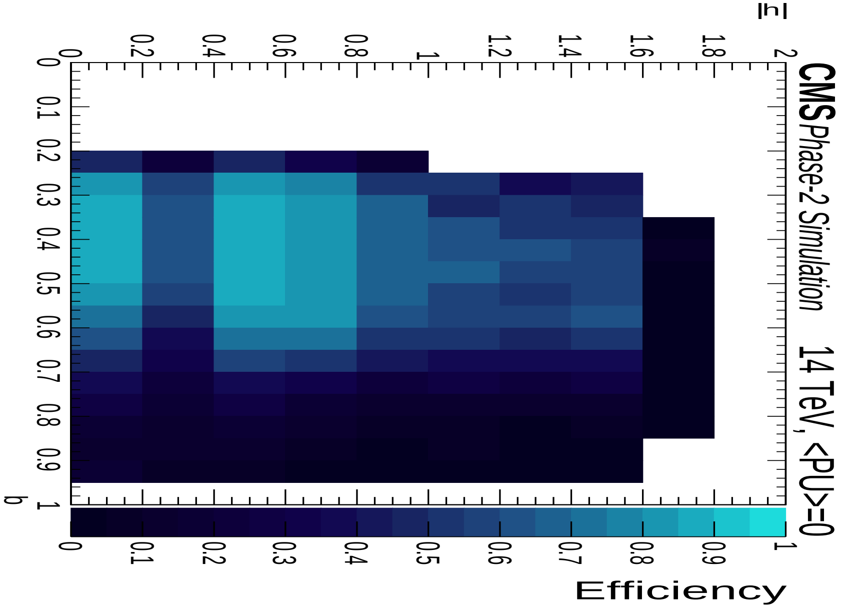
→ slow muons emerging from IP.

Upgraded RPC electronics with precision timing allows to trigger on such slow “muons”

- provide already at trigger level a mass resolution achieved only offline in Run2
- with β < 0.5 can be triggered with nearly 90% efficiency for η < 1.4.



1.6 TeV stau: mass resolution



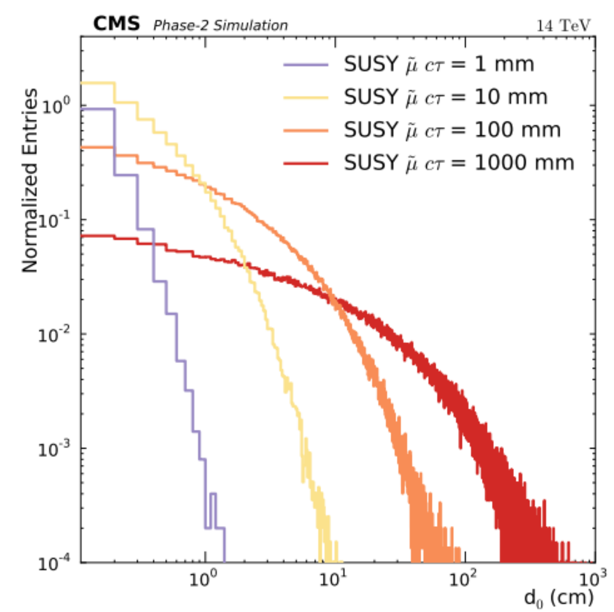
Displaced signatures

Several new physics models predict long-lived particles would potentially lead to displaced signatures, decay outside the tracker volume

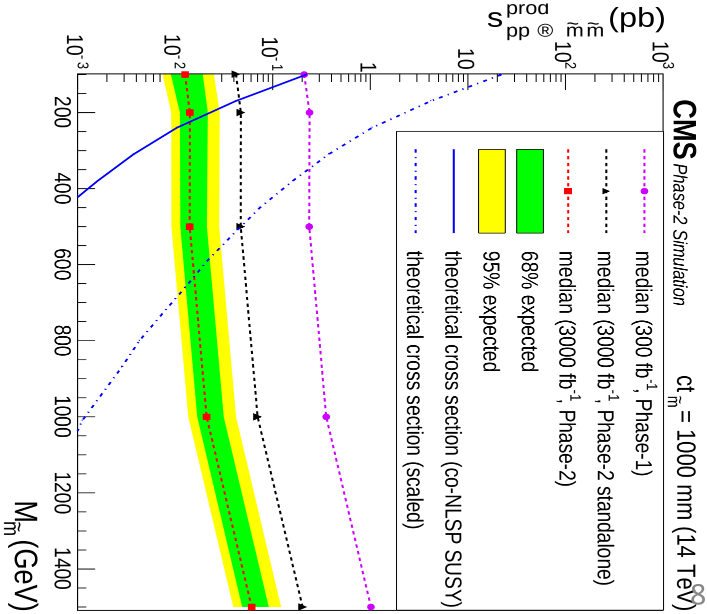
- Trigger and tracking algorithms using position of the primary vertex not efficient in reconstructing tracks with such large impact parameters

- Stand-alone capabilities of the muon system constitute the only possibility for detection of the signature:

    → Additional GEM detectors in combination with CSC in improved algorithms permit to efficient triggering on displaced muon tracks and increase the physics sensitivity for many searches.

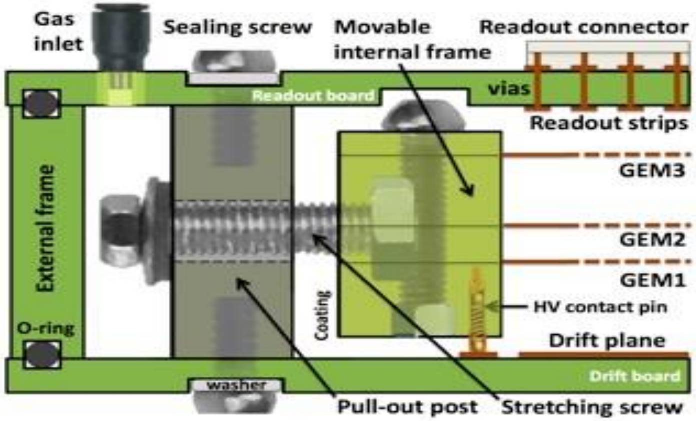


Ex. Improved upper limits on pair production of hypothetical particles, decaying $\tilde{\mu} \rightarrow \mu + X$ with lifetime distance cτ = 100 cm, as a function of the sparticle mass.



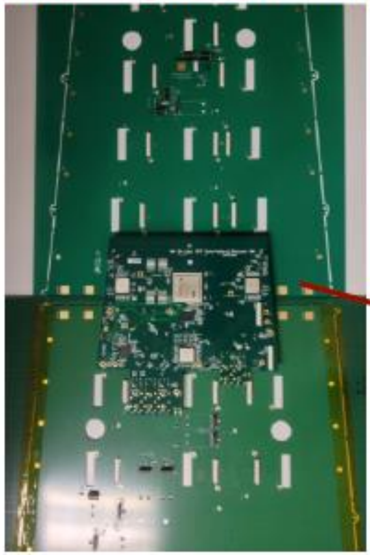
GE1/1 Chamber construction

- GE1/1 chambers introduced a novel technique of GEM chambers construction, which avoid the usage of glue
- GE1/1 chambers are realizing using GEM foils stretched by means of moveable FR4 frame (internal). Cathode and Readout electrode made by standard single layer PCB. Electrical signal extracted by “vias” on PCB trough 130 pins Panasonic connectors
- The internal frames are controlled by “stretching screws”
- The tightness of the chambers is assured by an external FR4 frame sealed with o-ring
- Chamber assembly have to be performed in clean room (at least class 1000) to avoid GEM foils contamination
- GE1/1 Mass production started in April 2017. Production completed!

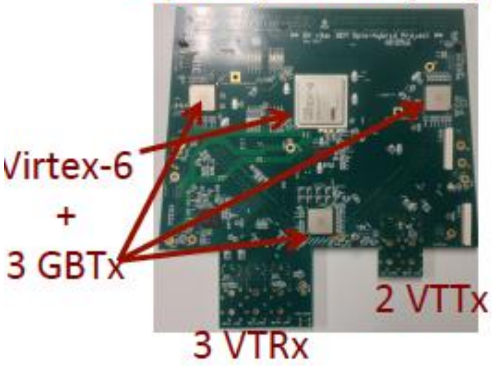


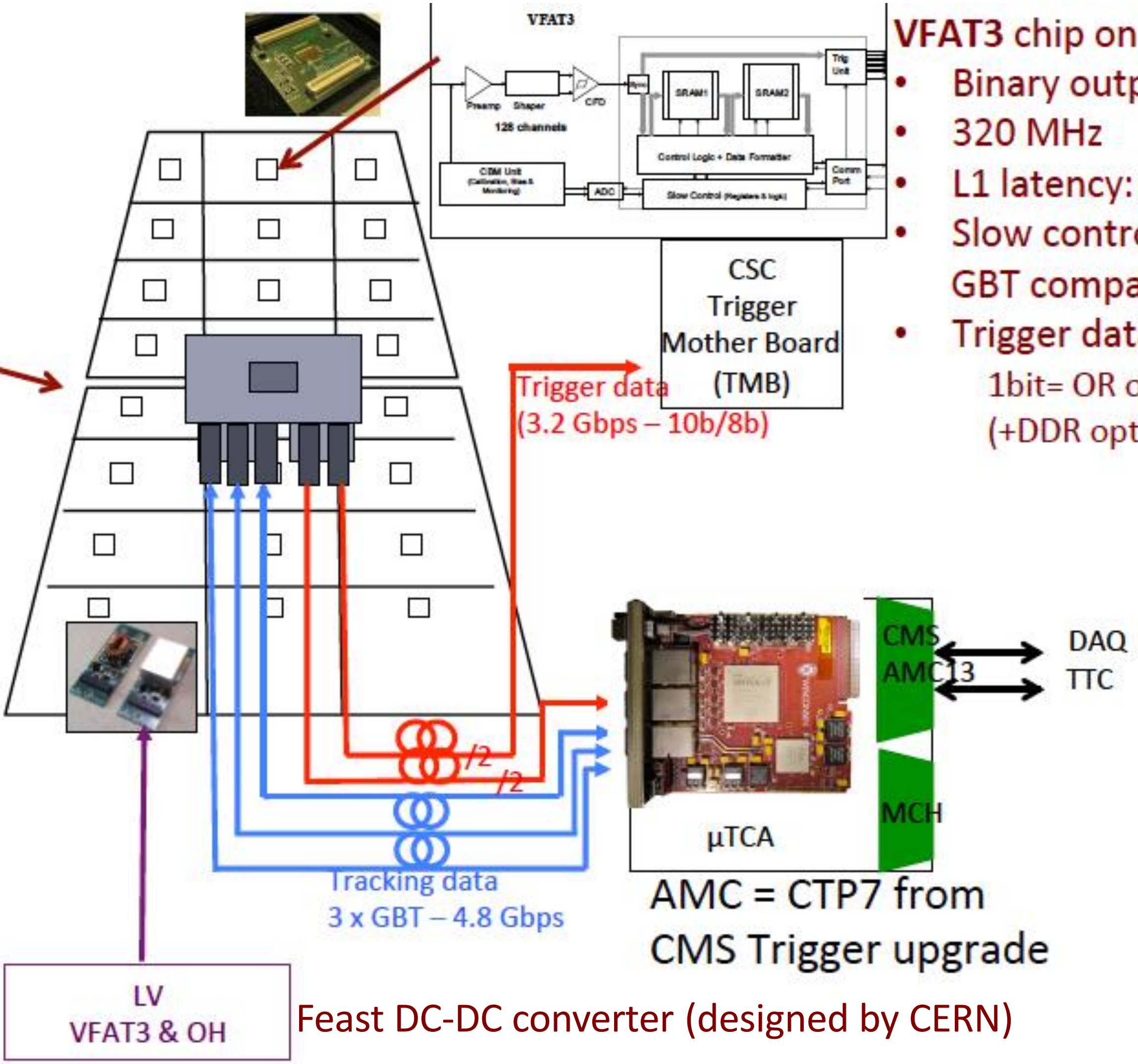
GEM Electronics

2-pieces GEB v3 (1.2m)



Opto-hybrid v3 (OH)





VFAT3 chip on hybrid:

- Binary output, CFD
- 320 MHz
- L1 latency: up to 12 µs
- Slow control: ePort, GBT compatible
- Trigger data:
  1bit= OR of 2 strips
  (+DDR option)

AMC = CTP7 from CMS Trigger upgrade

Feast DC-DC converter (designed by CERN)

Time Resolution

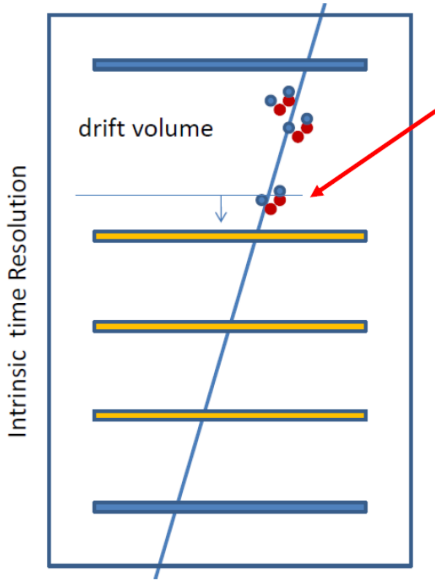
- The time resolution is dominated by fluctuations of the nearest distance of the primary ionisation processes to the region where the gain is acquired, d_{near}.
- Defining N as the average number of primary clusters generated by an ionising particle inside the gas, this distance follows a classical exponential distribution

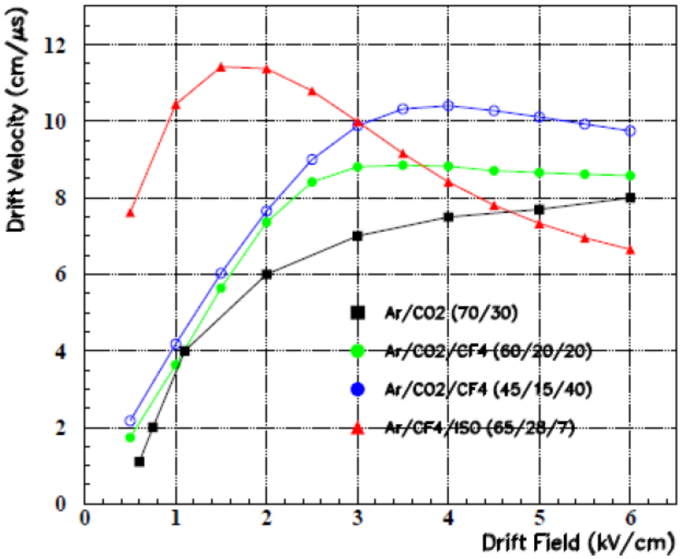
$$d = \exp(-Nx)/N$$

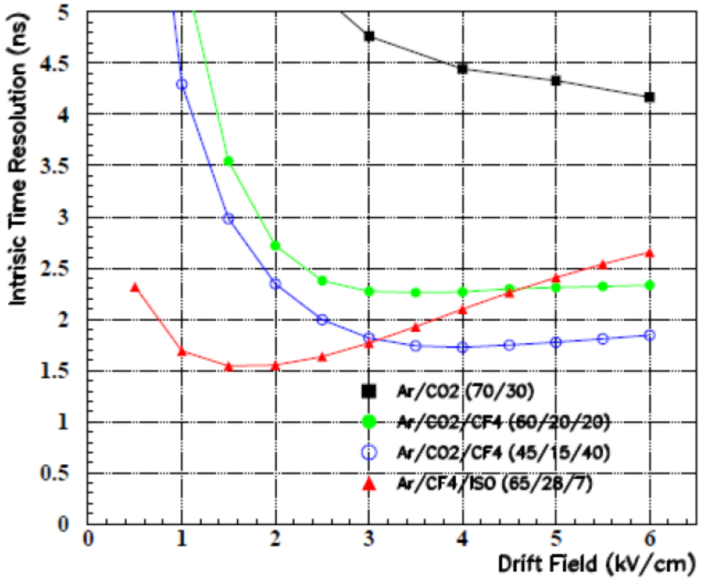
- The contribution of the time resolution to the drift velocity is

$$\sigma_t = 1/N * v_D$$

- Typical values for gases employed in MPGDs are $N = 3$(electrons-ion)/mm and $v_d \sim 0.12$ mm/ns leading to **few-10 ns time resolution** with the best choice of gas mixtures and operating voltages

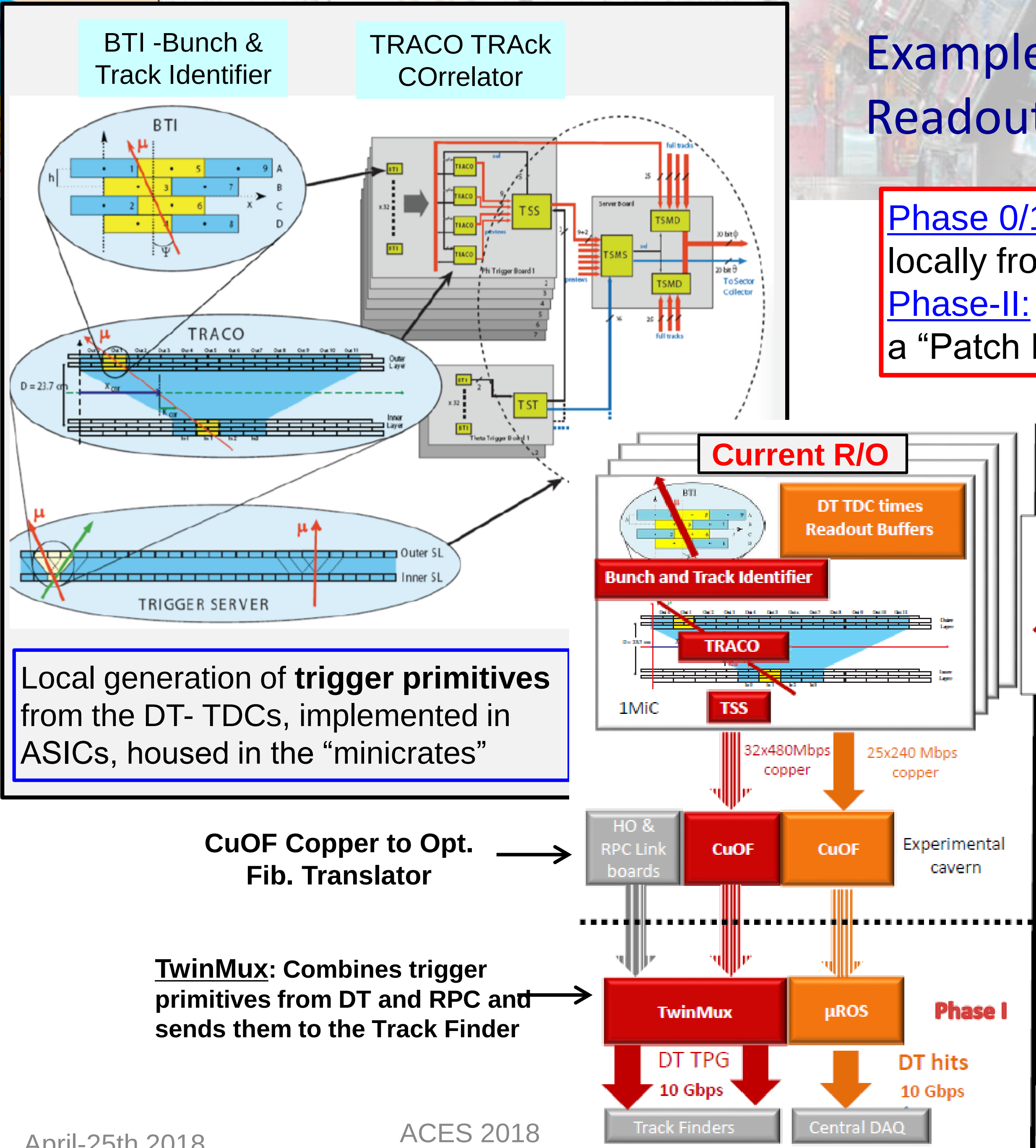






Example: upgrade of the DT Readout for Phase-II

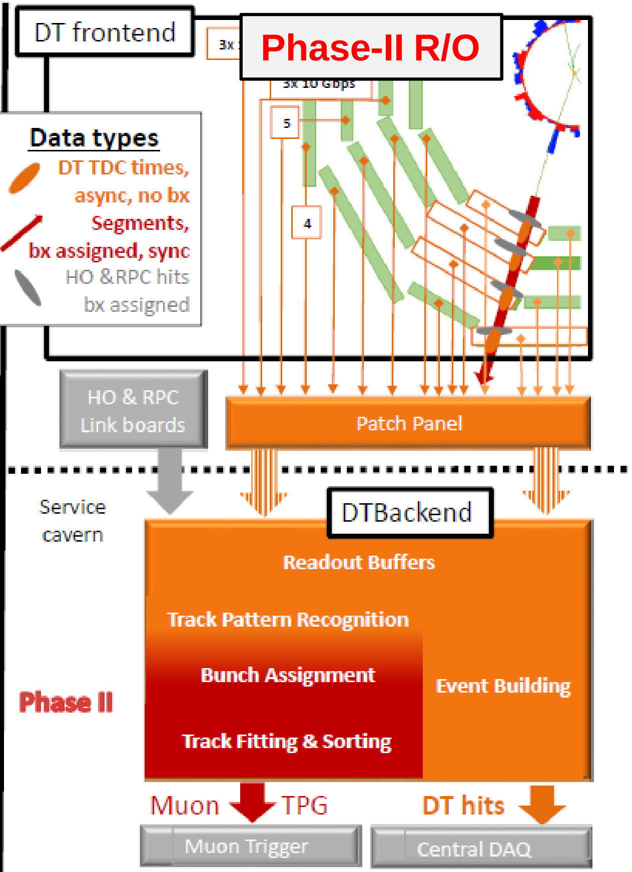
Phase 0/1: Trigger primitives constructed locally from the TDC readings of the DTs
Phase-II: The bare TDC readings are sent via a "Patch Panel" to USC for processing



Local generation of **trigger primitives** from the DT- TDCs, implemented in ASICs, housed in the "minicrates"

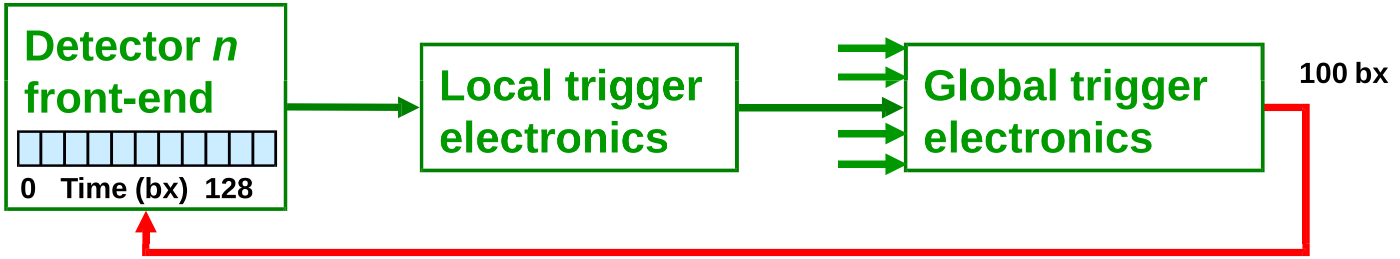
CuOF Copper to Opt. Fib. Translator

TwinMux: Combines trigger primitives from DT and RPC and sends them to the Track Finder



LHC trigger overview

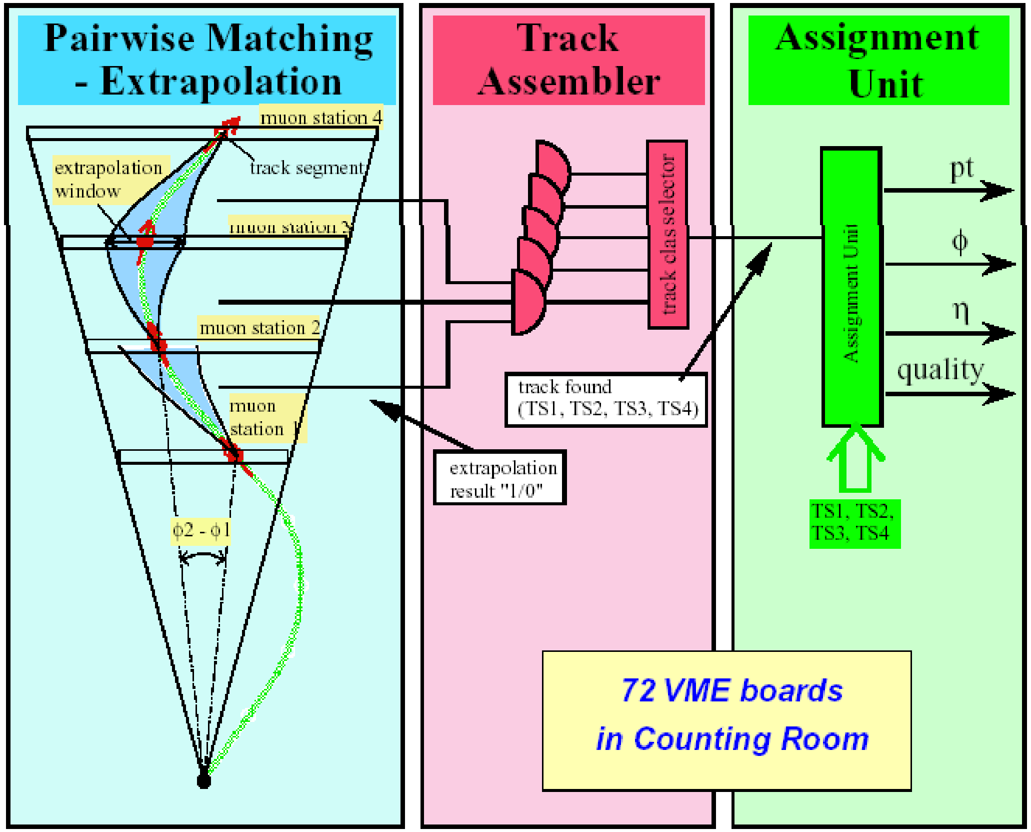
- Triggering takes *much* more time than the 25ns between crossings (bx)
  - Speed of light *c* = 7.5 m / bx
  - Calculations:
    - Electrons, photons, and jets: energy clusters are calculated
    - Missing-Et: all calorimeter energies are summed
    - Muons: tracks are found and Pt calculated
  - Path to electronics cavern is ~100 m (not straight-line)
- Therefore, store temporary data while trigger does its calculations…



- New trigger/DAQ:
  - Track information at L1 with extended trigger latency (from 3.2 total of 12.5 μs)
  - Increased L1 bandwidth from 100 kHz to 750 kHz

Barrel muon track finder

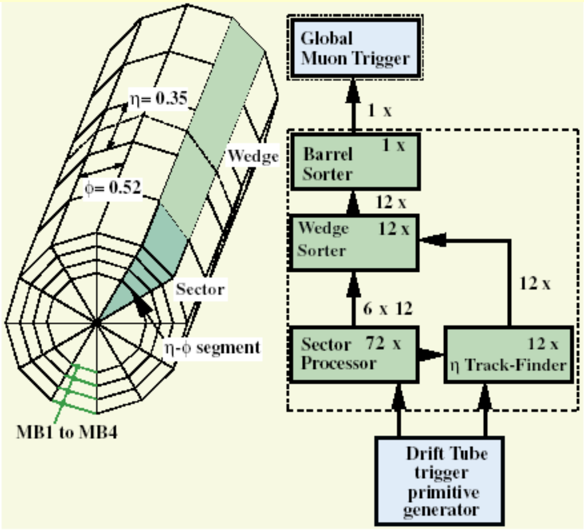
Sector Processor (PHI Track Finder)



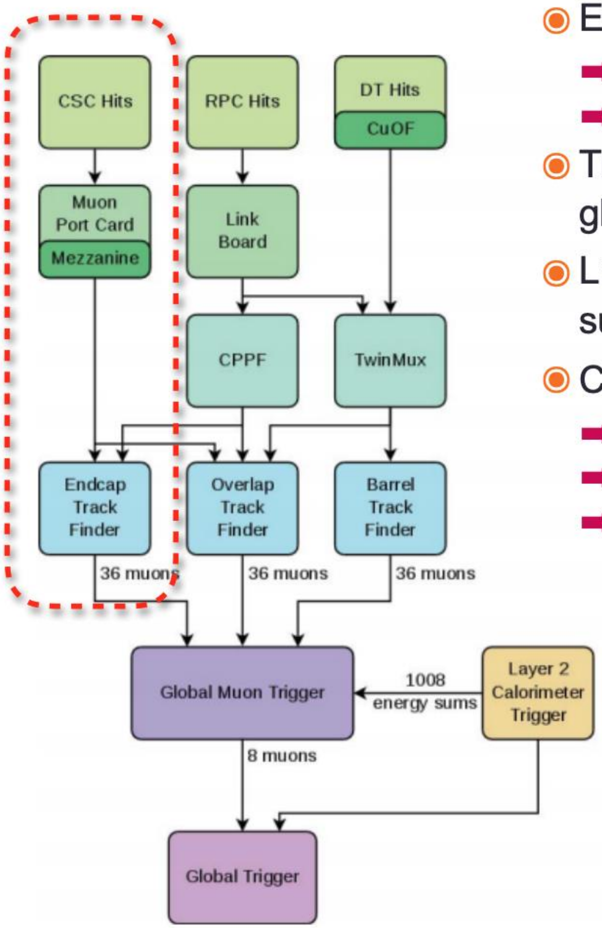
72 VME boards

in Counting Room

- Accepts DT segments from 4 stations in a sector **+ neighbours**
- Accepts also CSC segments in “overlap” | region
- Combines segments into full tracks
- Assigns Pt,| ,∏quality to each muon track



Endcap Muon Track Finder(EMTF)



- EMTF builds muon tracks by combining LCTs from all 4 stations
  - ➡ EMTF receives LCTs through muon port card (MPC)
  - ➡ RPC hits could be optionally used
- Tracks from ETMF are sent to global muon trigger and finally to global trigger
- L1 accept(L1A) is made by global trigger and sent back to subsystem for readout
- CSC data readout, setup in P5 by default:
  - ➡ ALCT board: ALCT+L1A to read out wire digi, Anode trigger
  - ➡ (O)TMB: CLCT+L1A to read out comparator digi, cathode trigger, LCT
  - ➡ (D)CFEB: preCLCT+L1A to read out strip digi