The CMS muon upgrade project

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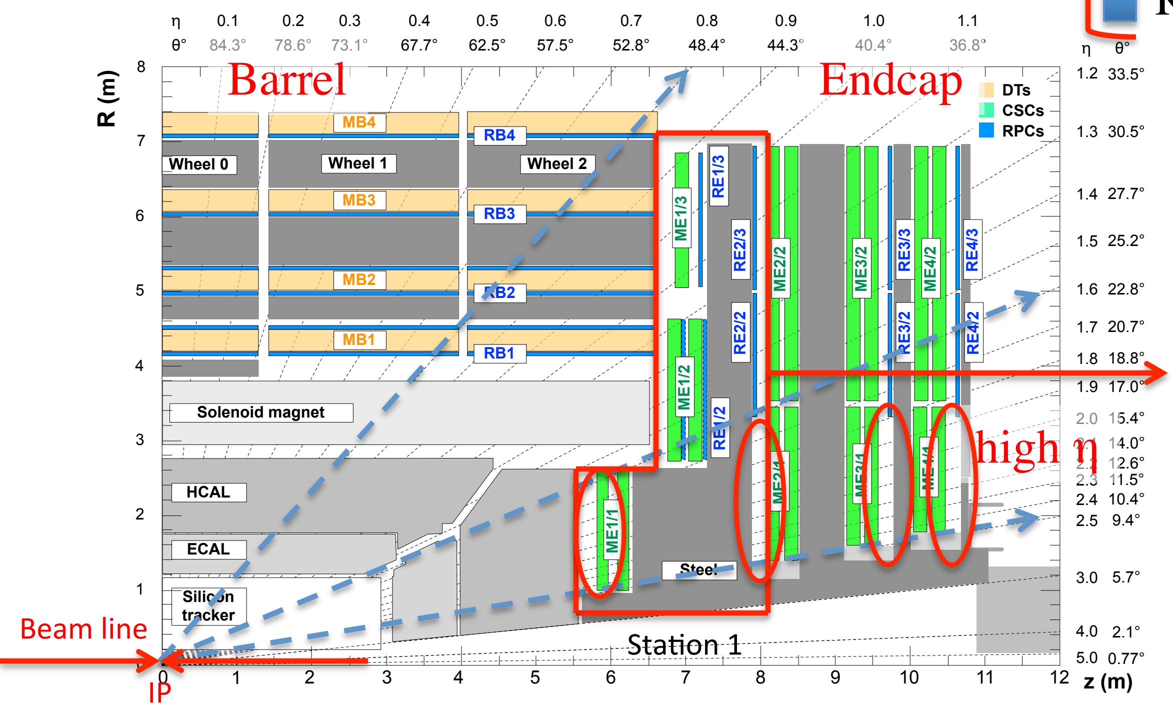
Overview

- The CMS forward muon spectrometer
- The CMS GEM project
- CMS Triple-GEM detectors
- Trigger & Physics performance
- Detector & Electronics R&D
- Belgian contribution
- Planning
- Phase-II upgrades
- Conclusions

The CMS muon forward spectrometer

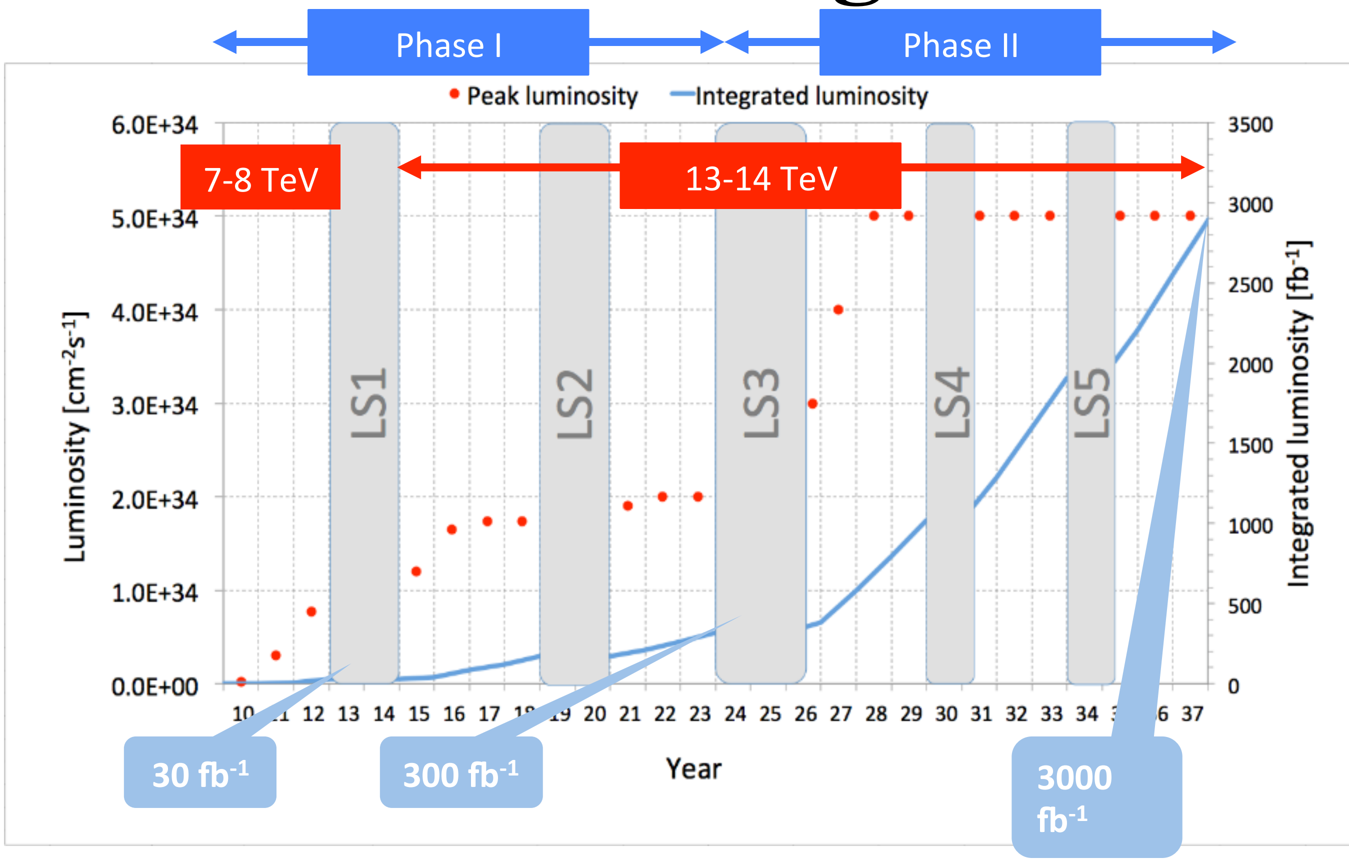
- Highly redundant (4 stations of several layers)
- High performance tracking and triggering
- Use 3 gaseous detector technologies

Drift Tube (DT) – Barrel only
Cathode Strip Ch. (CSC) – Endcap only
Resistive Plate Chamber (RPC)



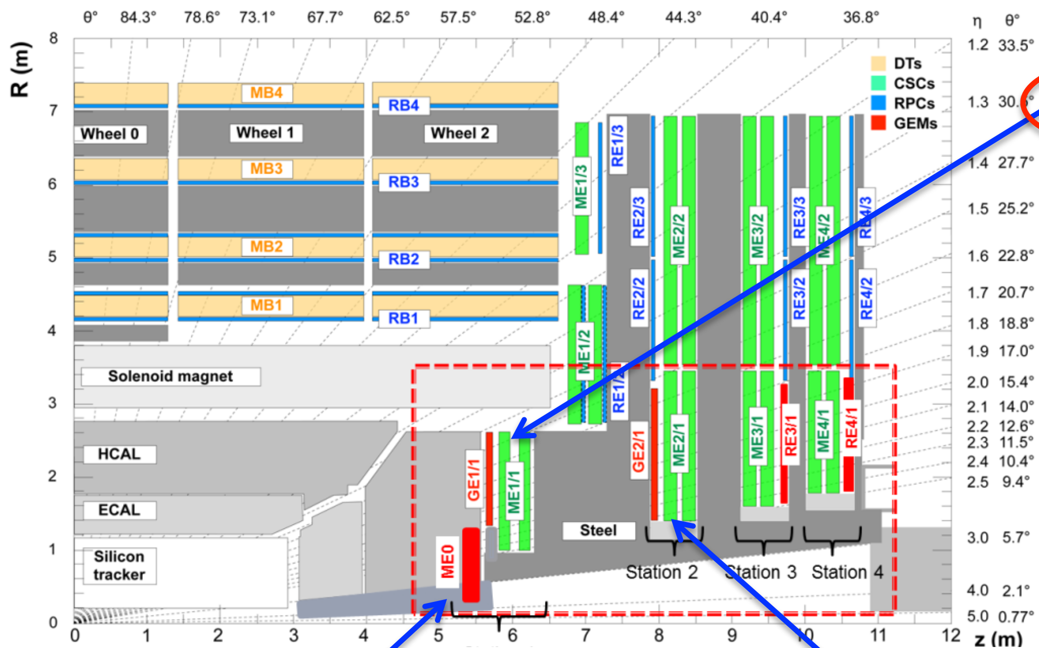
Forward muon spectrometer: $0.8 < |\eta| < 2.4$
The high η region: $1.6 < |\eta| < 2.4$
The high η region is lacking a layer of RPC in each station

Challenges



- The CMS forward region challenges:
  - Lack of redundancy: 1 layer of RPC is missing in each station (|η|>1.6)
  - Particle rate: the highest rates of the system, up to 10 kHz/cm^2 in phase II
  - Electronics: higher occupancy/rate than design spec, irradiation dose
  - Longevity: accumulated charge ~ C/cm^2 at the end of phase II

The CMS GEM project



GE1/1:

- 1.6 < |η| < 2.2
- baseline detector for GEM project
- 36 staggered chambers per endcap, each chamber spans 10°
- One chamber is made of 2 back-to-back Triple-GEM detector
- Will guarantee high trigger performance during late Phase I and throughout Phase II
- Installation: LS2 (2019-20)

ME0:

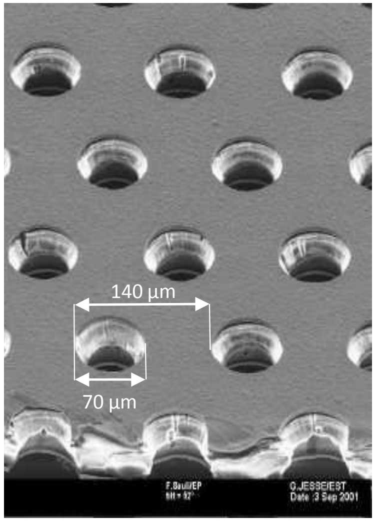
- Muon tagger at highest η
- 2.0 < |η| < 3.5
- 6 layers of Triple-GEM
- each chamber spans 20°
- Installation: LS3 (2023-24)

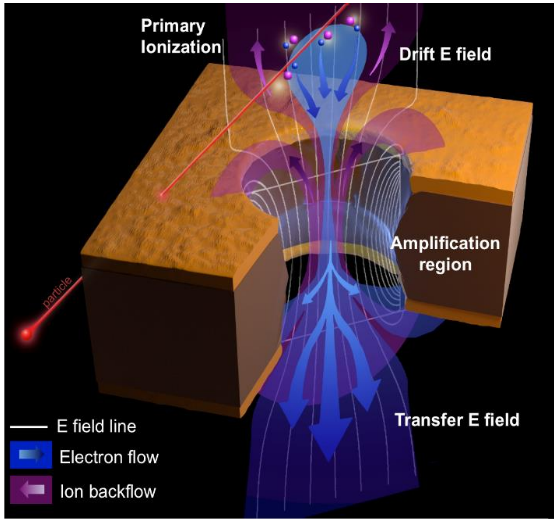
GE2/1:

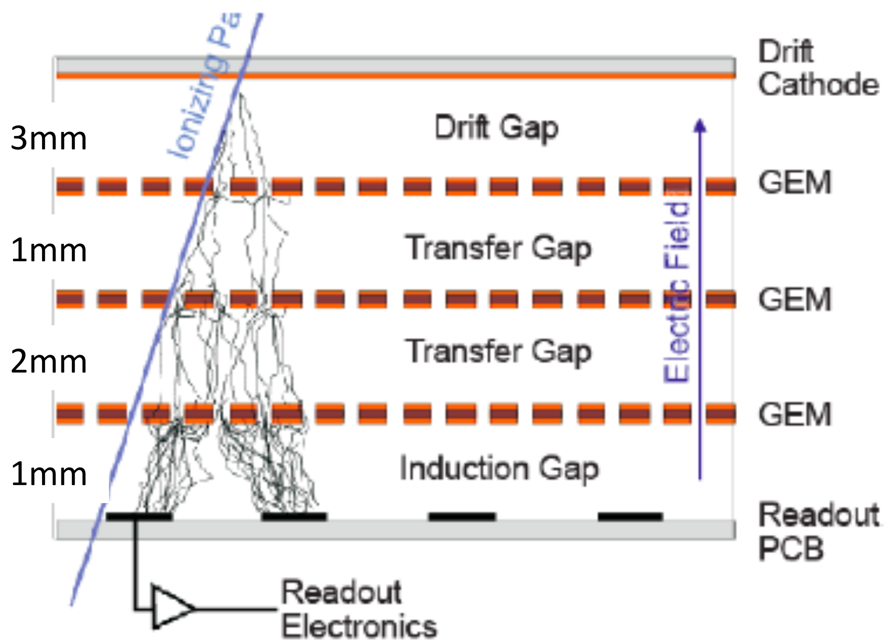
- 1.55 < |η| < 2.45
- 18 staggered chambers per endcap, each chamber spans 20°
- Installation: LS3 (2023-24)

Standard RPCs can't sustain the expected rate at |η|>1.6

TGEM & CMS requirements

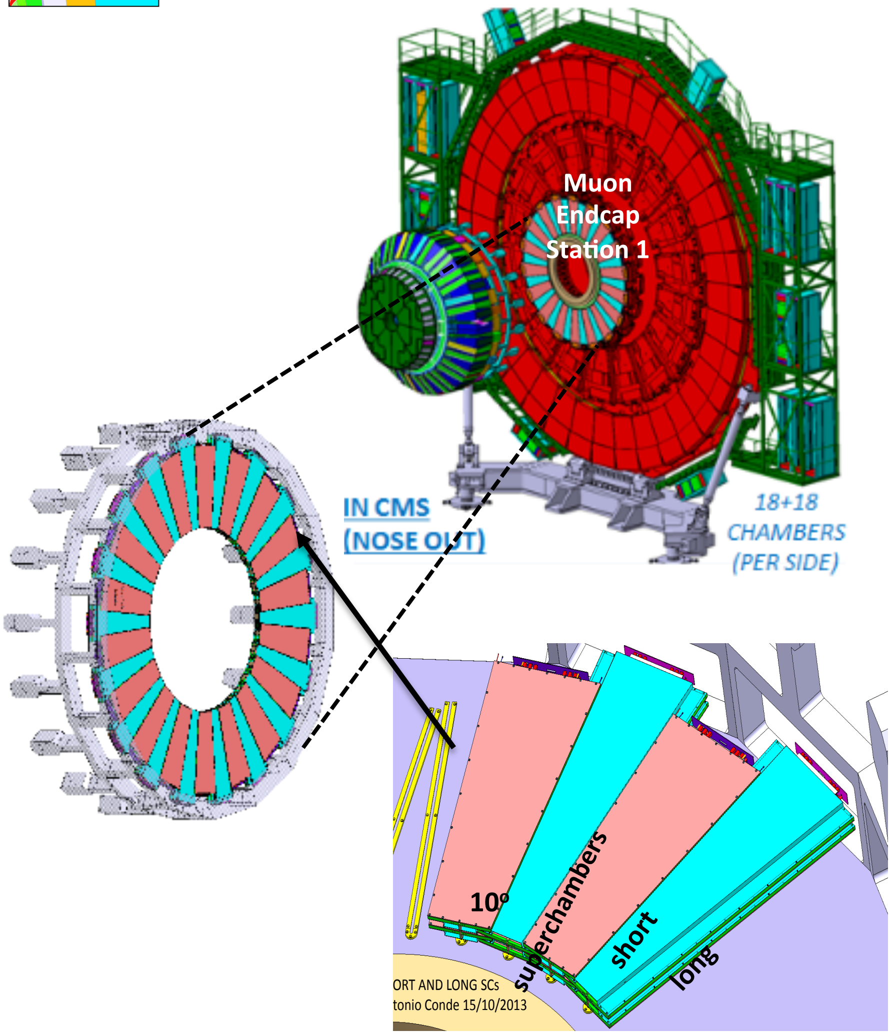




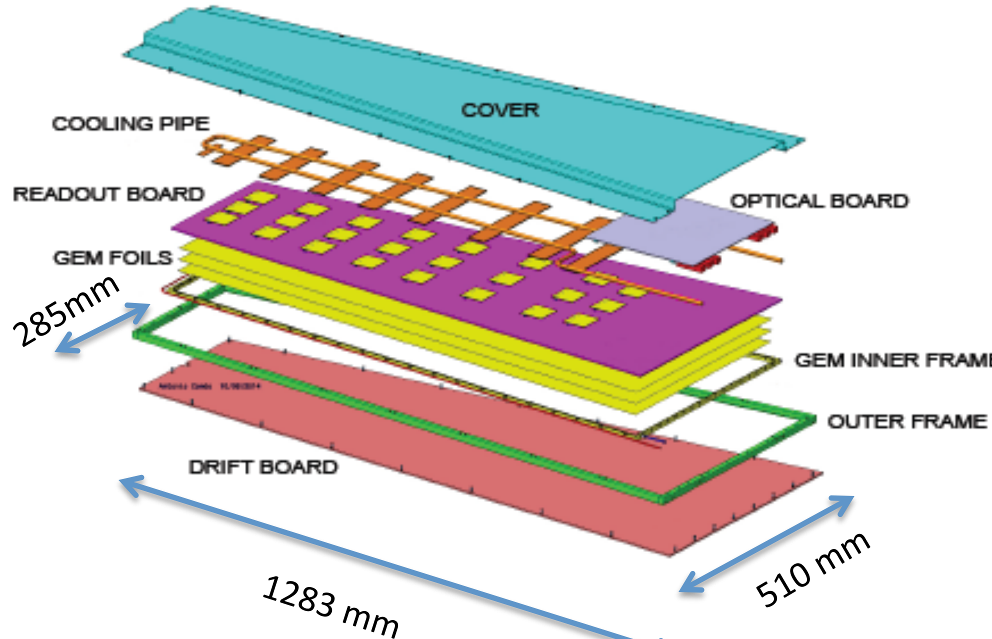


- Maximum geometric acceptance within the given CMS envelope
- Rate capability of 1-2 kHz/cm^2
- Single-chamber efficiency > 98 % for MIP
- Spatial resolution better than 300 μm
- Timing resolution of 10 ns or better for a single chamber.
- Gain uniformity of 10% or better across a chamber and between chambers.
- No gain loss due to aging effects after 200 mC/cm^2 of integrated charge

CMS GE1/1

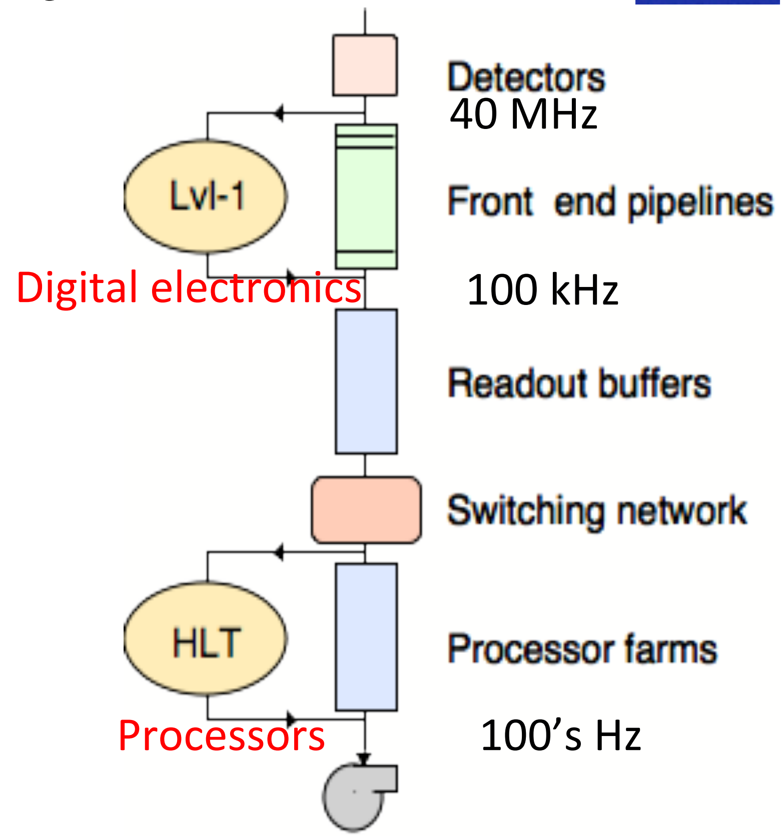


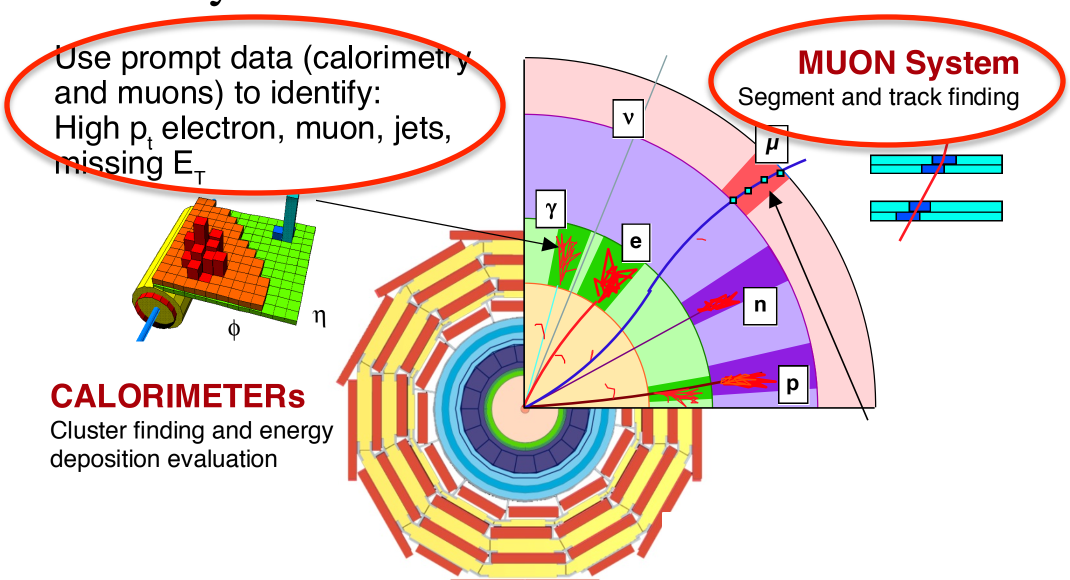
Exploded view of a long GE1/1 TGEM:



CMS Trigger system

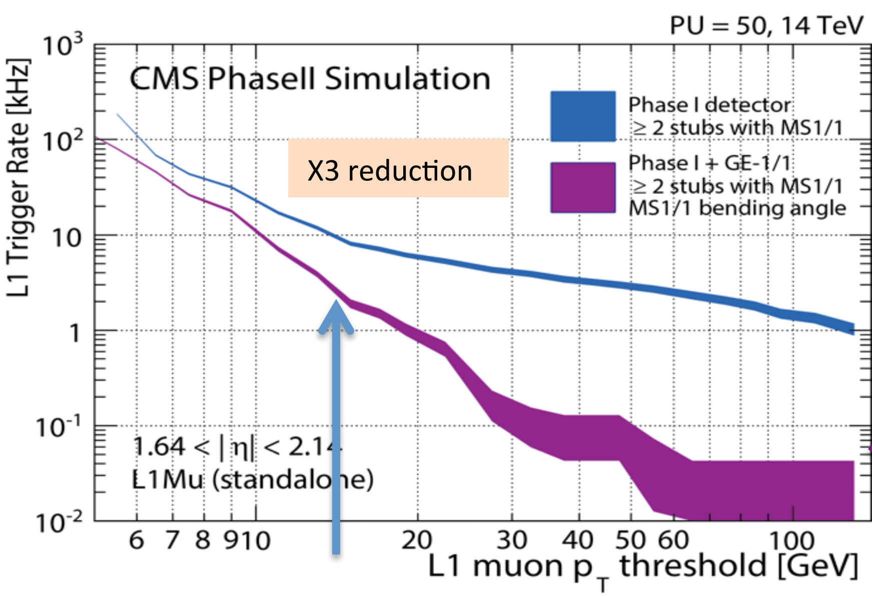
- No (affordable) data acquisition system could read out O(10^7) channels at 40 MHz → 400 TBit/s to read out – even assuming binary channels!
- What's worse: most of these millions of events per second are totally uninteresting: one BEH event every 0.02 seconds
- A *trigger system* must somehow select the more interesting events and tell us which ones to deal with any further

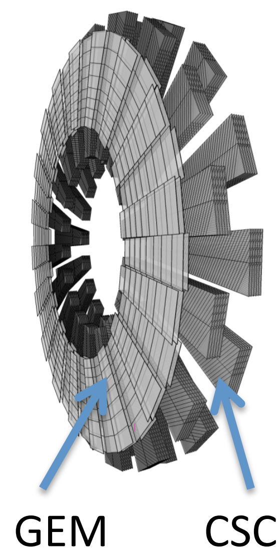


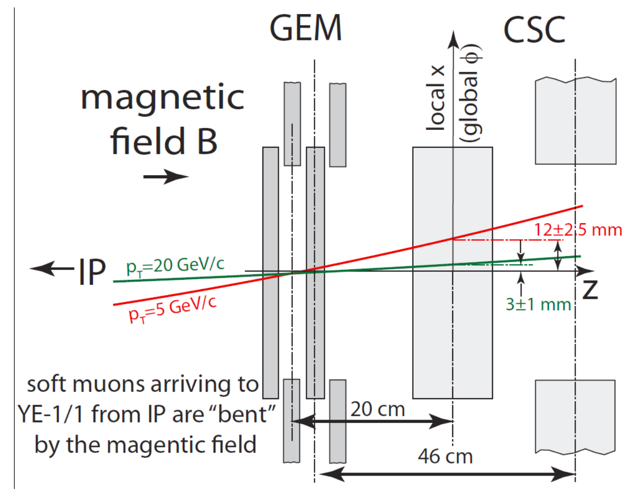


Muon Trigger performance

- At |η|> 1.6 the muon trigger entirely relies on CSC
- L1 trigger rate "flattening" with p_T
  - Soft muons scattering can occasionally be identified as high p_T muons (rare, but lots of soft muons);
  - L1 muon-trigger momentum resolution can be improved by measuring the bending angle with CSC+GEM





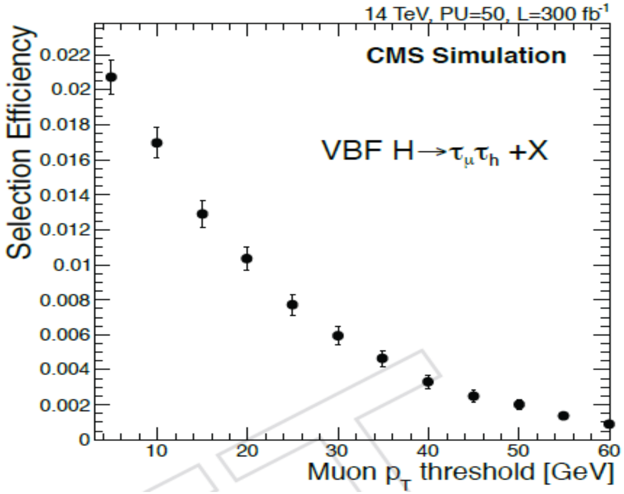


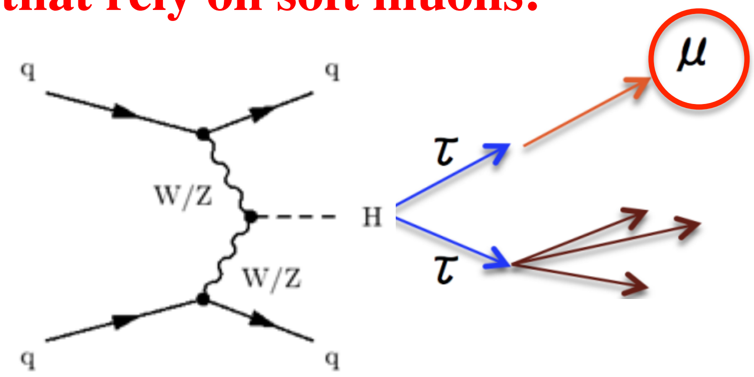
YE-1/1	p_T=5 GeV	p_T=20 GeV
$\Delta x_{Dz=30\ cm}$	12±3mm	3±1mm

Physics performance

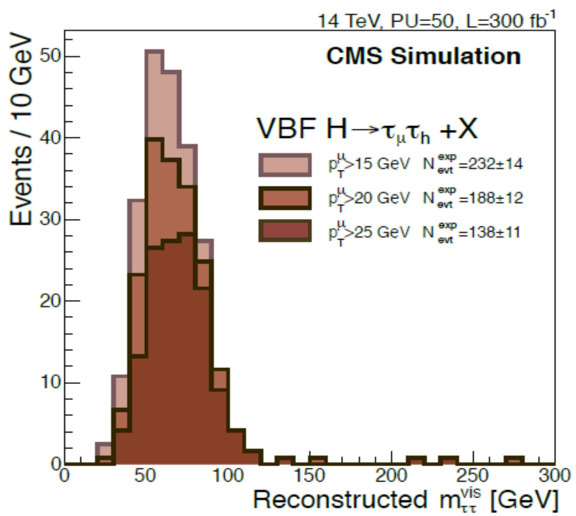
Keeping low trigger thresholds has a large impact on the whole CMS physics program, especially the processes that rely on soft muons.

Example: $H \rightarrow \tau\tau \rightarrow \mu\tau_{hadr} + X$



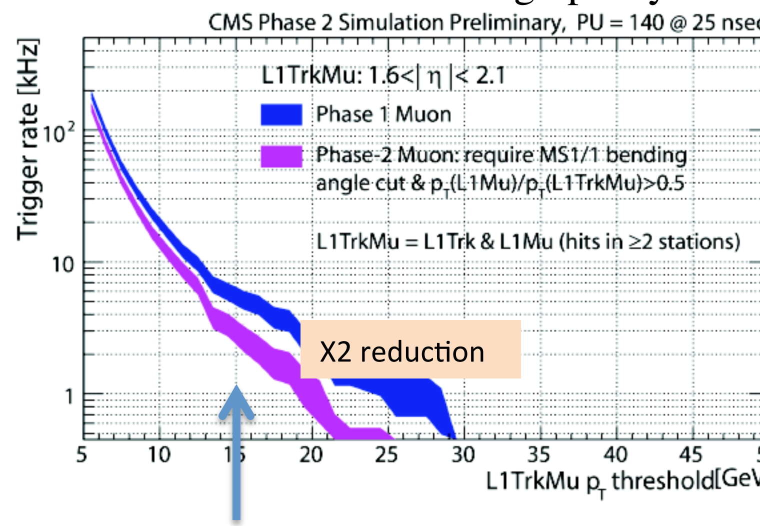


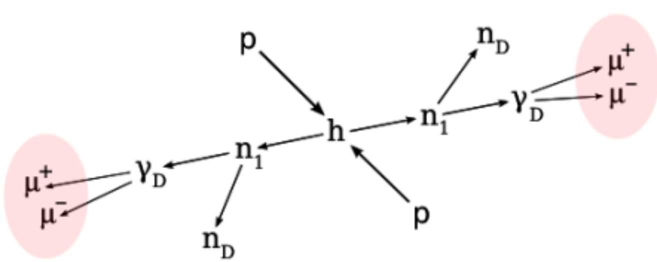
- **23% of events** have a muon candidate reaching GE1/1
- Event yield increases by:
  - **35%** if the threshold is reduced from **25 to 20 GeV**
  - **68%** if it is reduced from **25 to 15 GeV/c**

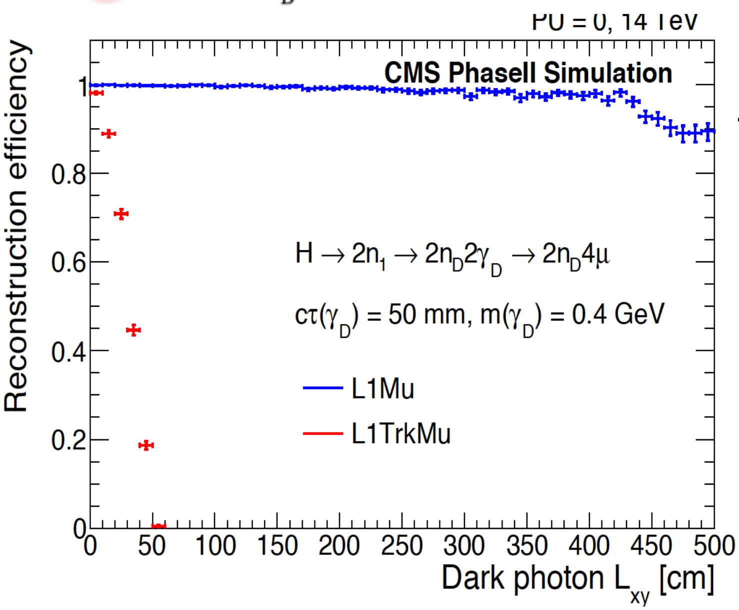


Physics performance @ Phase II

- Preserving the standalone muon triggering and reconstruction capabilities is a must in the HL-LHC era
  - The new tracker triggering, matching inner tracks and muon tracks enables ultra-high purity muon trigger with low thresholds

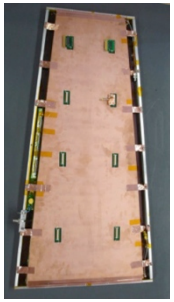






- **Preserving CMS sensitivity to physics with displaced lepton topologies arising from decays of long-lived new particles in Phase-II uniquely relies on standalone muon trigger**

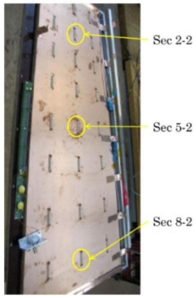
Detector R&D



2010

Generation I

The first 1m-class detector ever built but still with spacer ribs and only 8 sectors total. Ref.: **2010 IEEE (also RD51-Note-2010-005)**



2011

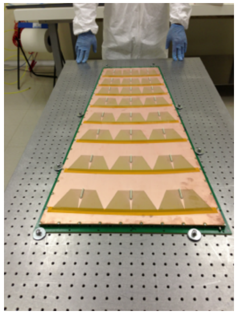
Generation II

First large detector with 24 readout sectors (3x8) and 3/1/2/1 gaps but still with spacers and all glued. Ref.: 2011 IEEE. Also **RD51-Note-2011-013.**

2012

Generation III

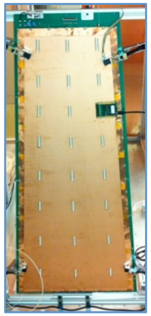
The first sans-spacer detector, but with the outer frame still glued to the drift. Ref.: **2012 IEEE N14-137.**



2013

Generation IV

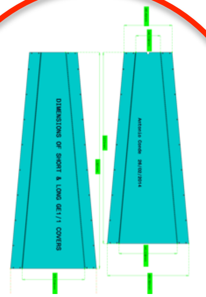
First detector with complete mechanical assembly; no more gluing parts together! **Upcoming papers from MPGD 2013; And IEEE2013.**



2014

Generation V

Very close to what we will install in CMS. Features re-designed stretching apparatus that is now totally inside gas volume. **Upcoming test beam campaign for final performance measurements.**

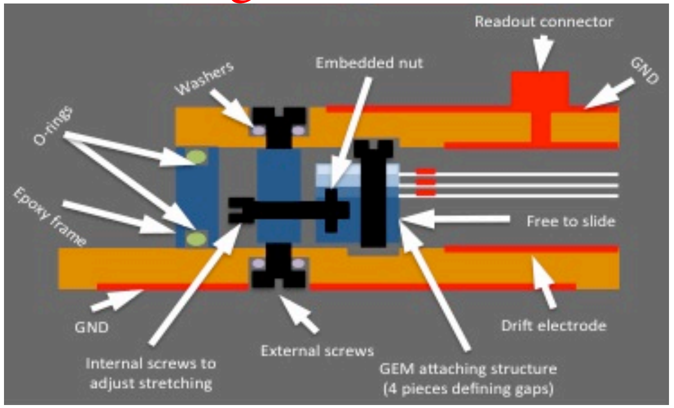


2014/2015

Generation VI

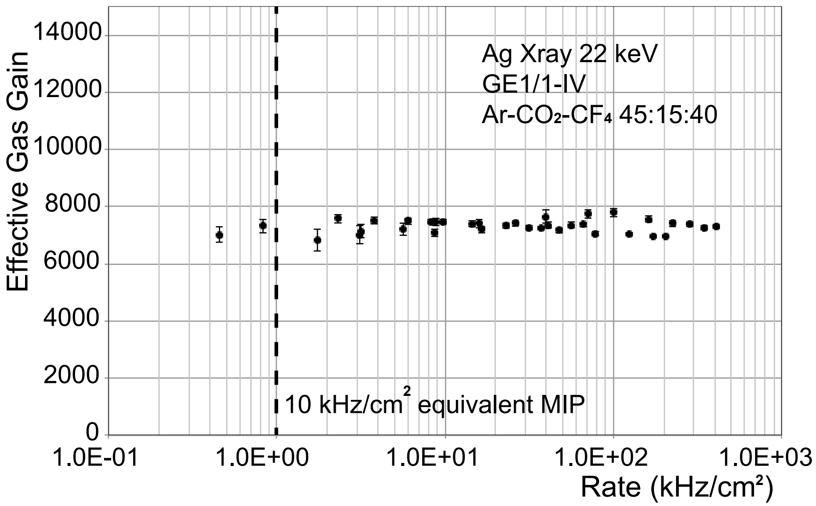
Latest detector design; **what we will install in CMS.** Optimized final dimensions for maximum acceptance and final eta segmentation. **Upcoming test beam campaign for DAQ chain stress test!**

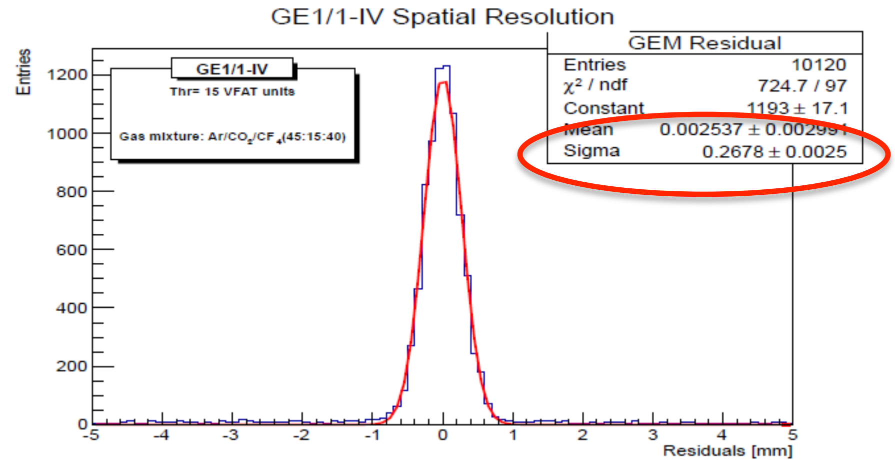
- GEM foil production uses single mask technology for wet etching
  - Dramatically reduces foil production costs and large sizes to be manufactured
- Performance same as that of double mask
- Mechanical foil stretching procedure
  - Construction time reduced from week(s) to two hours per chamber

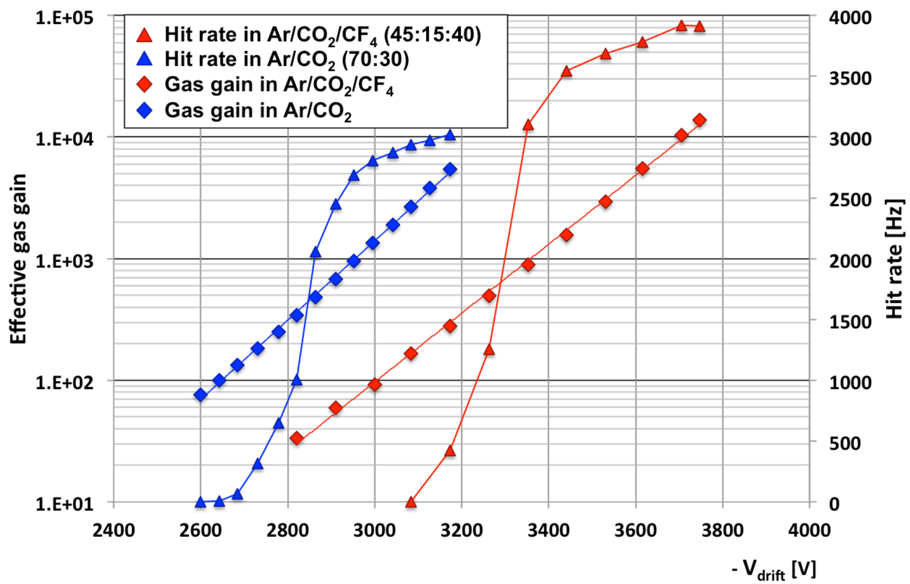


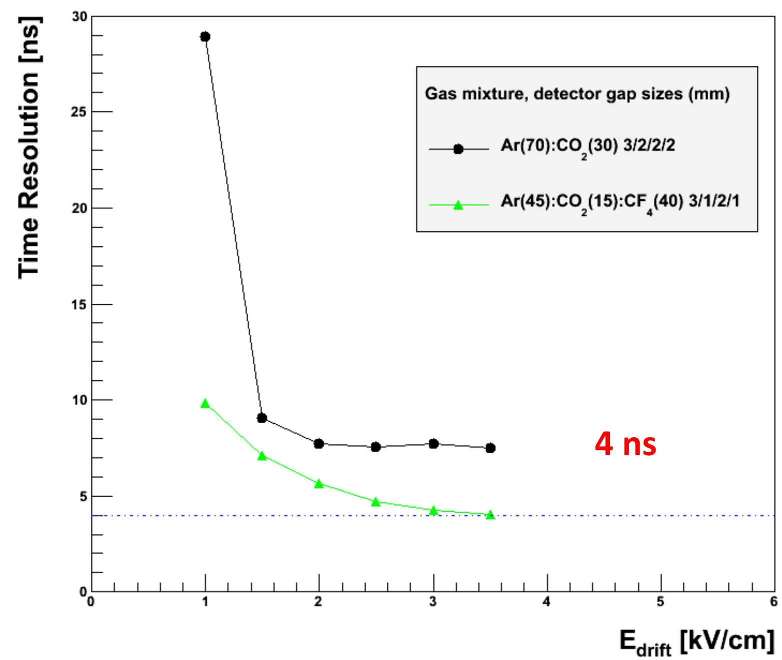
Performances

Over the years numerous tests, also with beam (CERN/FNAL), have been performed



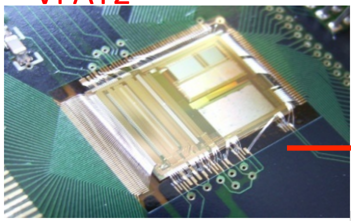


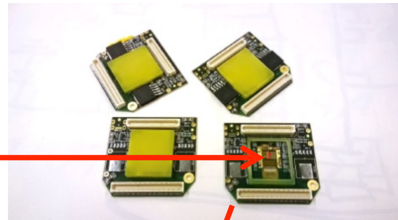


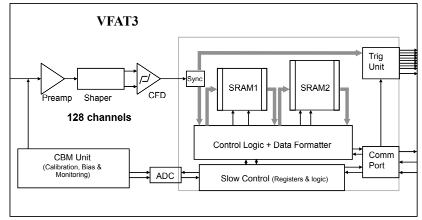


GE1/1 Trigger & DAQ

VFAT2

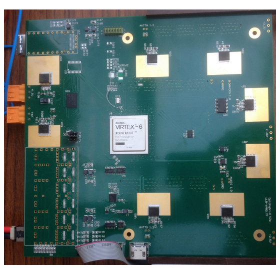


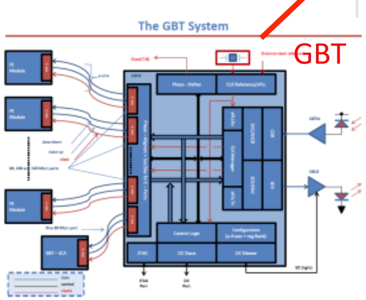




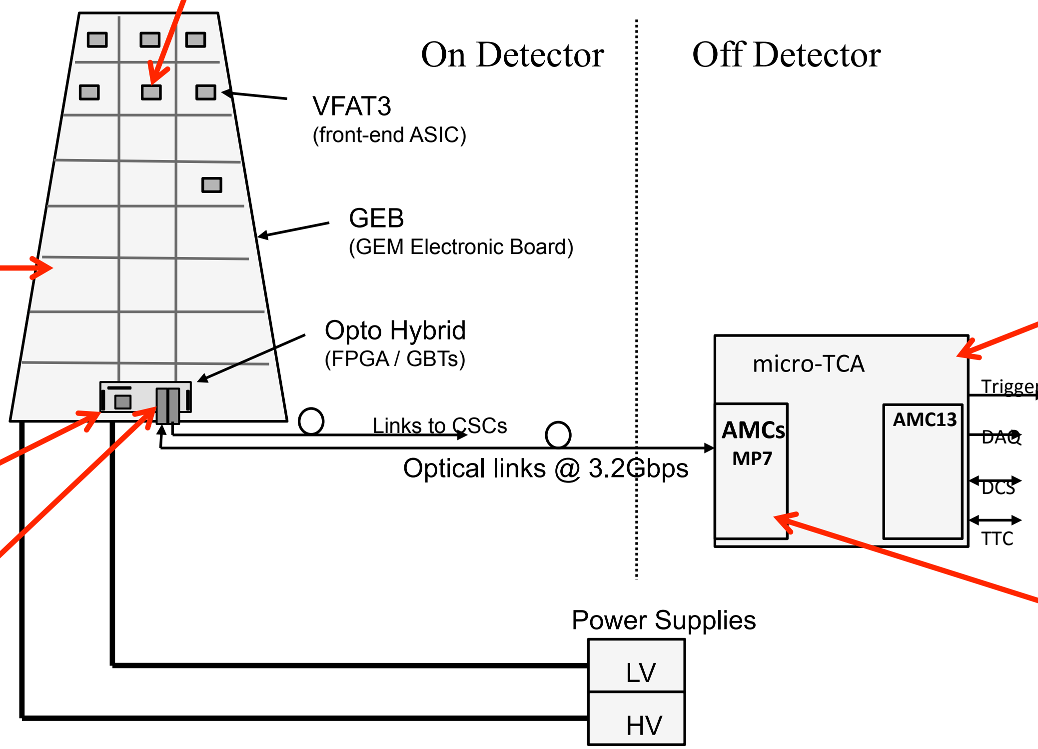
GEM Electronic Board (GEB)

Opto-Hybrid (OH)



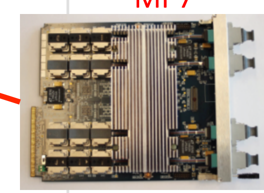


GBT



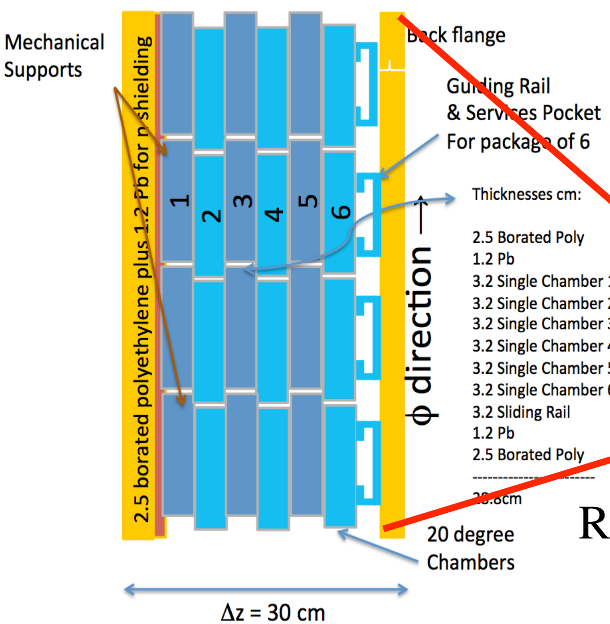
µTCA
AMC13, MCH

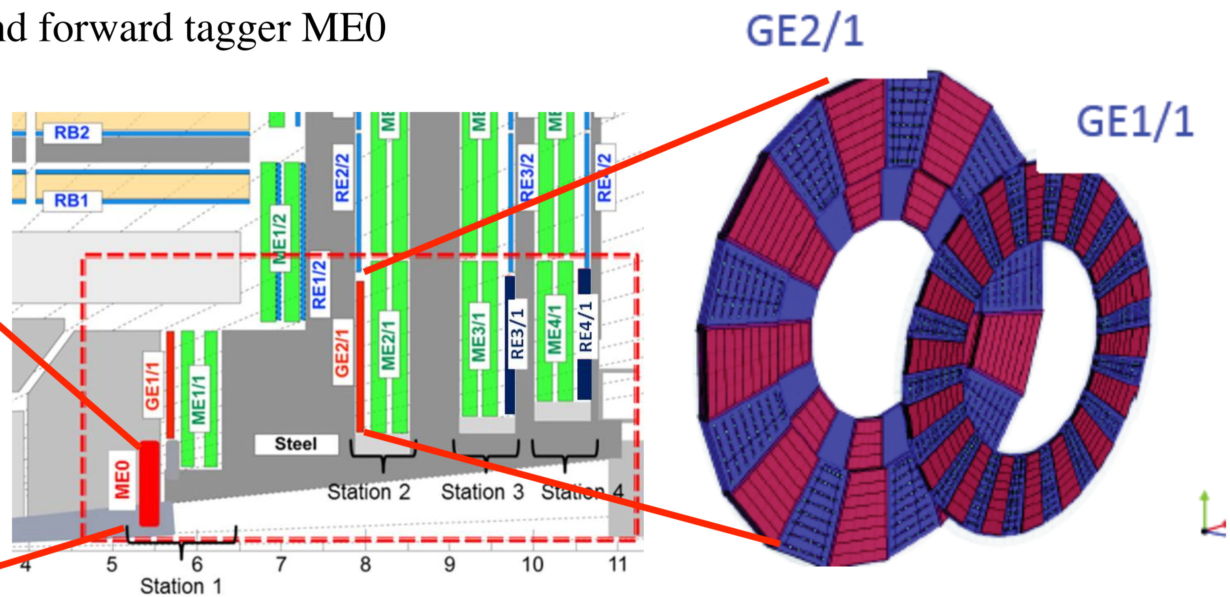
MP7



Schedule & next steps

- GE1/1 upgrade project approved by CERN Resource Board in Sept. 2015
- Slice test
  - 4 Super-Chambers will be installed during 2016 LHC End of Year Technical Stop (YETS 2016)
  - GE1/1 data integrated to CMS DAQ
  - Goals: reduce commissioning period at the full installation, gain experience in integration
- Full installation in LS2 (2019-2020)
  - 144 Super-Chambers
- LHC Phase II (LS3, 2023)
  - 2nd GE station (GE2/1) and forward tagger ME0
  - iRPCs





R&D ongoing: geometry, background rates, radiation hardness…

Belgian Contributions to GE1/1

- UGent
  - Team leader: M. Tytgat
  - Main activities: detector R&D, freon-free gas mixtures R&D
  - Commitment: detector production and Quality Control
  - Responsibilities: CMS GEM Collab. Board Chair
- ULB
  - Team leader: G. De Lentdecker
  - Main activities: Trigger & DAQ electronics R&D, Z'->$\mu\mu$ analysis
  - Commitment: design and production of Trigger & DAQ electronics
  - Responsibilities: Trigger & DAQ electronics group co-convener

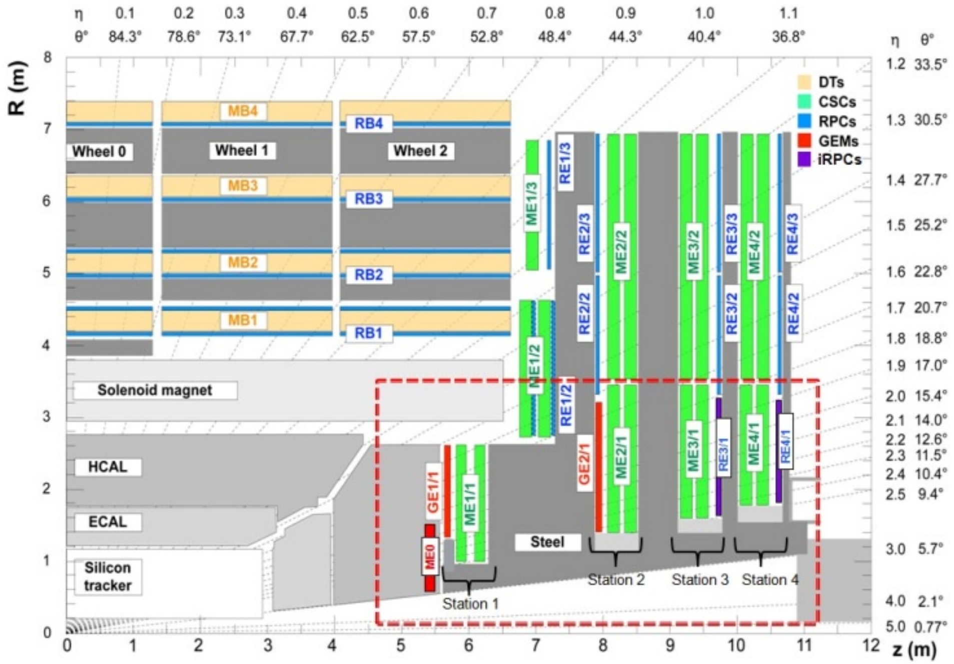
Belgian Contributions

- UGent is active in CMS-RPC since 2007; M. Tytgat RPC deputy project manager 2010-2015; RPC Upgrade Manager 2015-…
- UGent was co-initiator of the CMS-GEM project in 2009; M. Tytgat GEM deputy project manager 2009-2015; GEM IB Chair 2015-…)
- Past and present hardware activities @ UGent
  - LS1 - RPC RE4: assembly & QC site @ UGent, installation, commissioning
  - LS2 - GE1/1: detector R&D, assembly & QC site @ UGent, installation, commissioning
  - LS3 – iRPC: new geometries (thin gap, multi-gap …), new materials (low resistivity glass, new Bakelite), new Front-End electronics, Eco-friendly gas mixtures
  - LS3 – GE2/1, ME0: R&D on back-to-back GEMs, μ-Well
- ULB joined CMS GEM in 2011
  - Large experience with GEM (CMS Tracker R&D, Large LC TPC prototypes)
  - Large experience of Trigger & DAQ electronics design (LC TPC, ICE^3, ARA)
  - LS2 - GE1/1: design and production of Trigger & DAQ electronics
  - LS3 – GE2/1, ME0: no commitment yet.

Phase II RPC muon upgrade

Extension of forward endcaps in the 1.8<|η|<2.4 region with RPCs:

- RE3/1-RE4/1
- Improved RPC performance needed to handle ~2kHz/cm^2



- Rate capability to be improved wrt. present RPC design: study new, low resistivity electrode materials, detector geometries and improved Front End electronics
- Option under study includes improved time resolution below 100ps

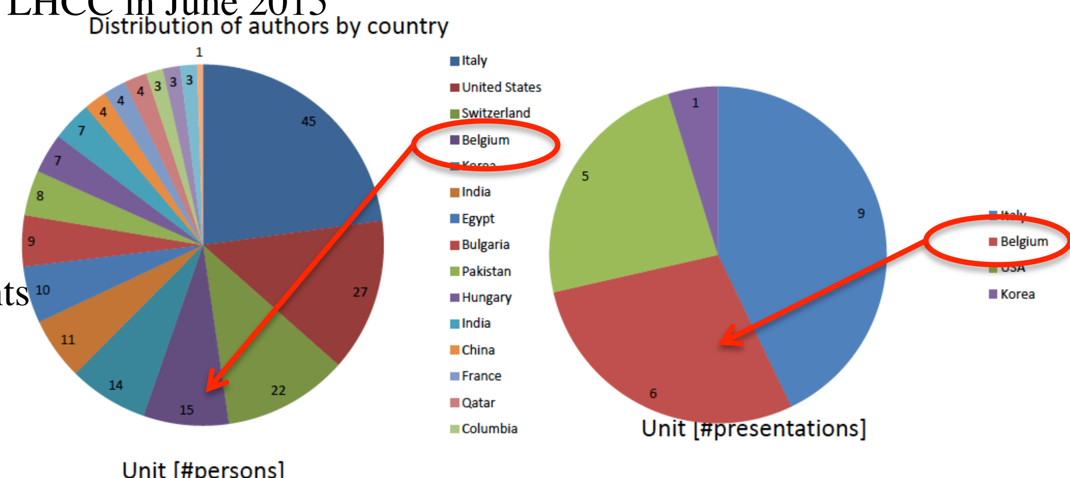
Conclusions

- Forward muon region is the most difficult part of the CMS muon spectrometer
  - Rate, background noise, irradiation dose
  - Currently the less redundant region
  - This region ($1.6 < |\eta| < 2.4$) region 1/3rd of the muon spectrometer coverage
    - Impact on all the CMS physics program is huge

- This region requires several upgrades spread over the consecutive Long Shutdowns
  - GE1/1 (LS2)
  - GE2/1 & ME0 (LS3)
  - RE3/1 & RE4/1 (LS3)

- GE1/1 upgrade approved by CERN Research Board in September 2015
  - Technical Design Report (TDR) approved LHCC in June 2015

- Belgian contributions to GE1/1
  - 2 complementary teams:
    - Detector – Electronics R&D
  - Very active
  - Important responsibilities and commitments



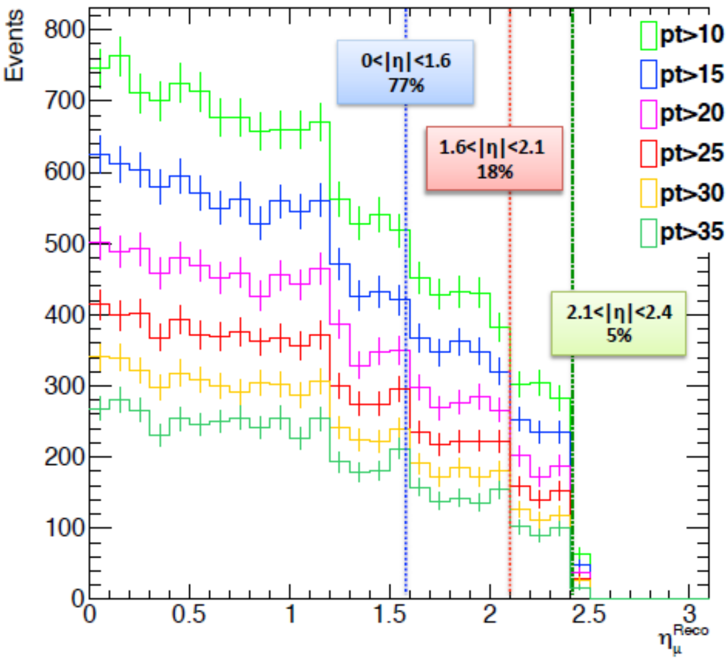
- Belgian contributions to iRPC
  - Ugent working on iRPC and new detector technologies, alternative gas mixtures
  - Responsibilities: M. Tytgat, iRPC Upgrade Coordinator

BACK-UP

GE1/1 physics

- **Redundancy** in $1.5 < |\eta| < 2.2$ region with additional GEMs
  - ~20% of interesting physics channels ($H\rightarrow4\mu$, $Z\rightarrow2\mu$, $H\rightarrow\tau\tau$) in GE1/1 region
- **Lowering the trigger threshold**
  - in $H\rightarrow\tau\tau$ yields gain in sensitivity :
    - $H\rightarrow \tau(\mu\nu\nu)\tau(\text{had})$
    - $H\rightarrow \tau(\mu\nu\nu)\tau(\mu\nu\nu)$

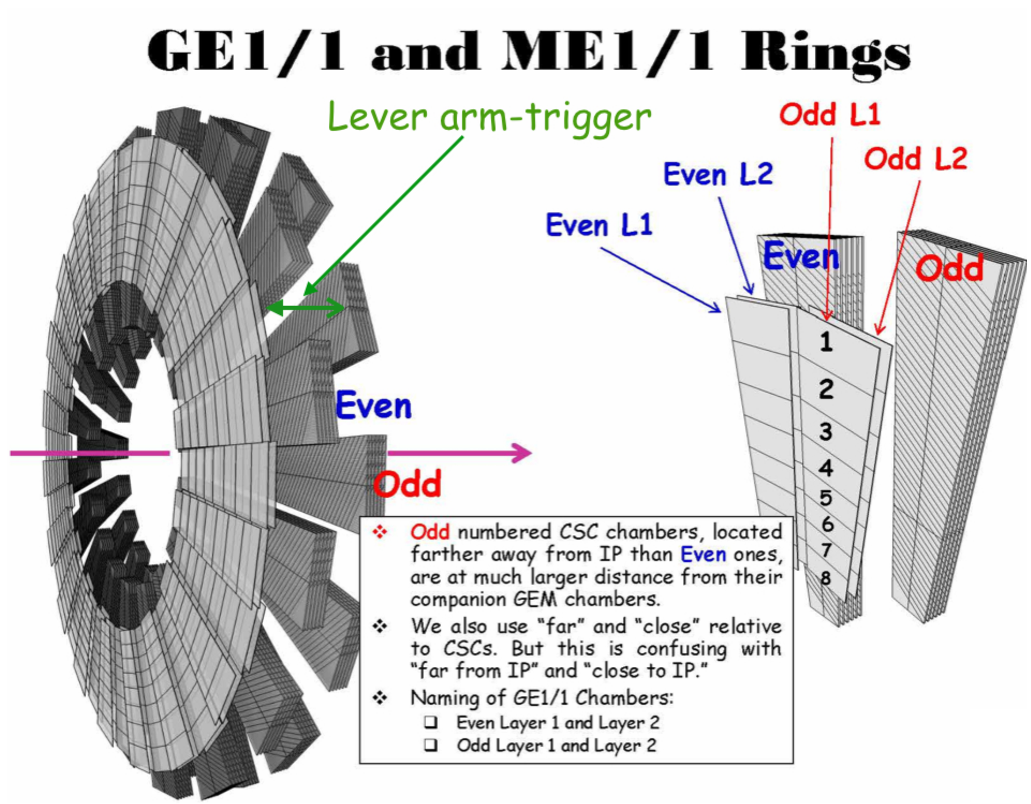
    } μ are soft, $<p_T>$~15 GeV
    - Lowering trigger pT from ~20 GeV (post-LS1 plan) to ~15 GeV = ~20% gain



- Challenge of **the forward region**. Impact of PU on muon reconstruction. Fraction of non-prompt muons in forward region increases dramatically with 140 PU.

The GE1/1 system

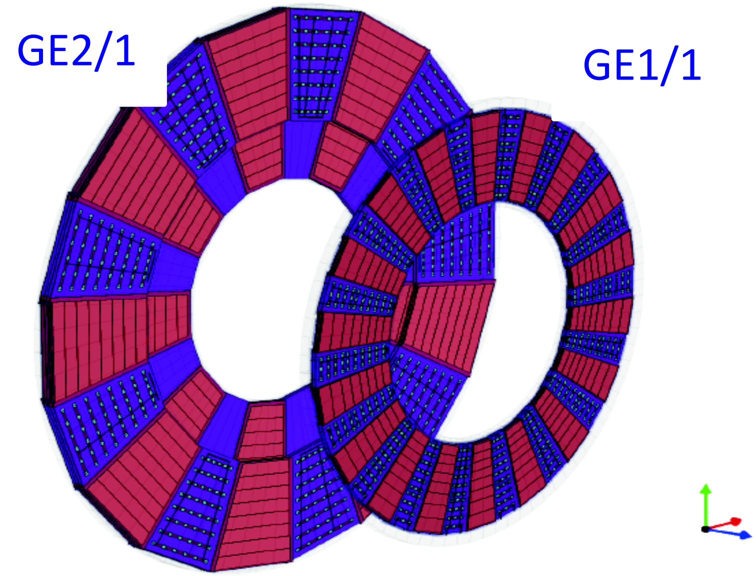
- $1.55 < |\eta| < 2.18$
  - Short and long chambers for maximum coverage
- 36 superchambers (SC) per side of CMS
  - Each chamber spans 10° in φ
  - 2 chambers/SC
  - 144 chambers total
- Total foil area ~140m^2



Four years of R&D has given us five prototype generations; each an improvement of the last!!!

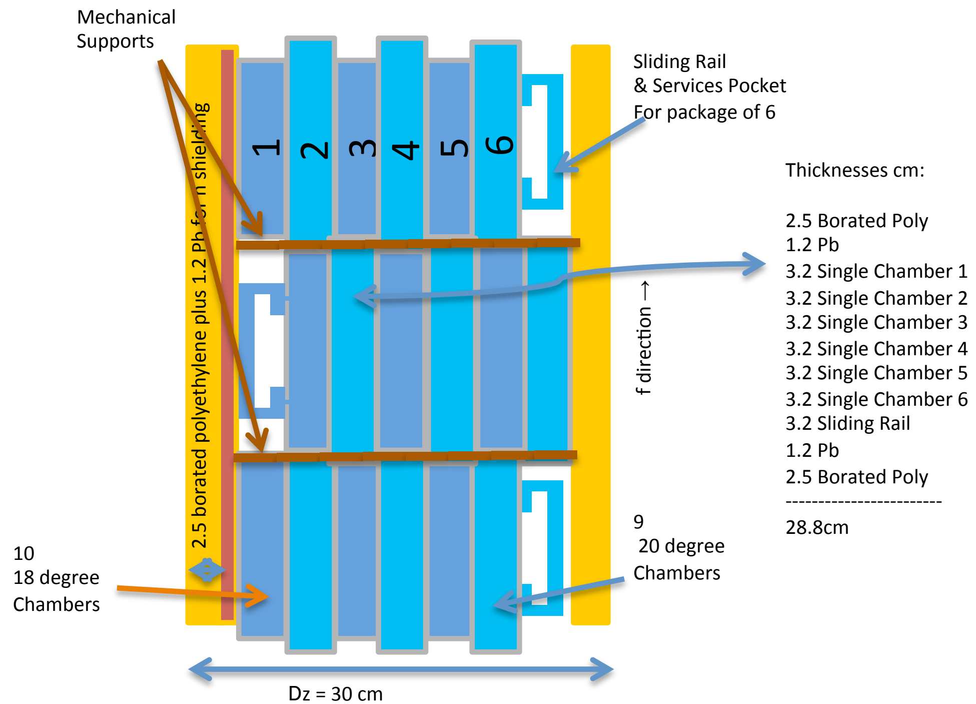
The GE2/1 system

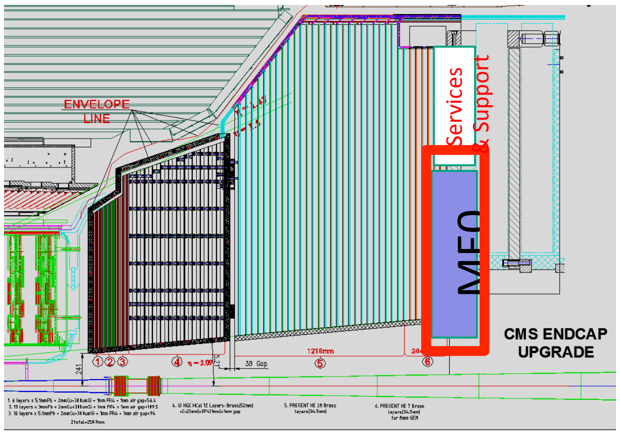
- 1.55 < | η | < 2.45
  - Short and long chambers
  - Each chamber spans 20° in φ
  - 2 chambers/SC
  - 144 chambers total
- Targeting 2 rings of double-layered triple-GEM
  - one ring with 8 and one ring with 12 η partitions
- Total foil area ~145m^2



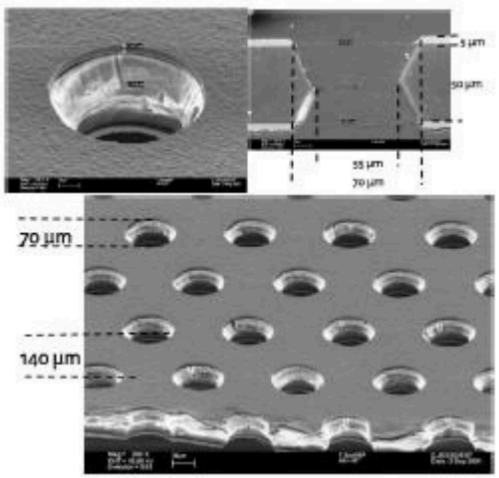
The ME0 system

- 2.0 < |η| < 3.5
  - 20° wedges affixed to back of upgraded CMS HCAL endcap
- Six layers of triple-GEM detectors
  - Design ongoing
- **Significantly increases muon acceptance for high profile analyses**
  - e.g. H→ZZ→4μ
- Total foil area ~144m^2

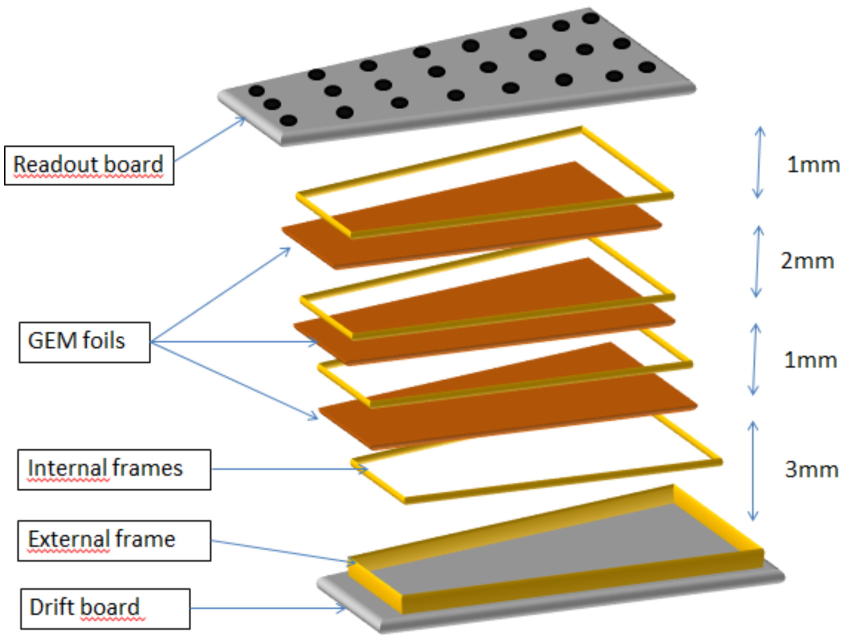


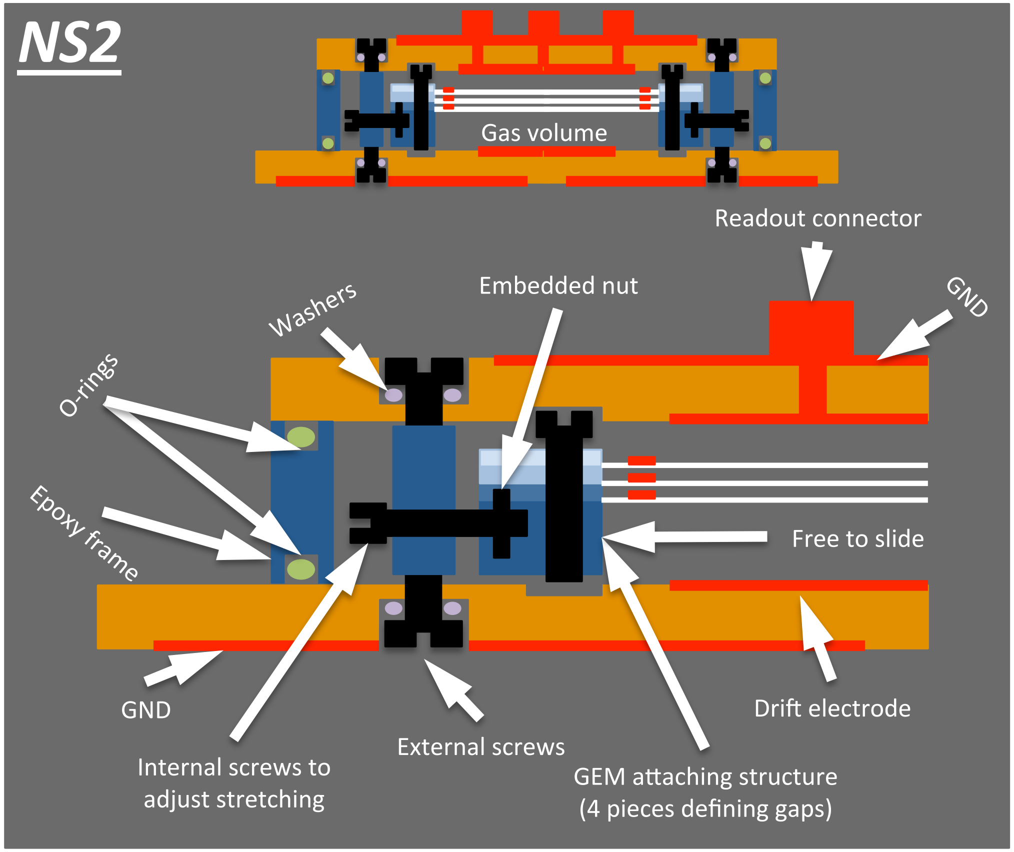


Current focus: GE1/1 & GE1/1-v5 proto



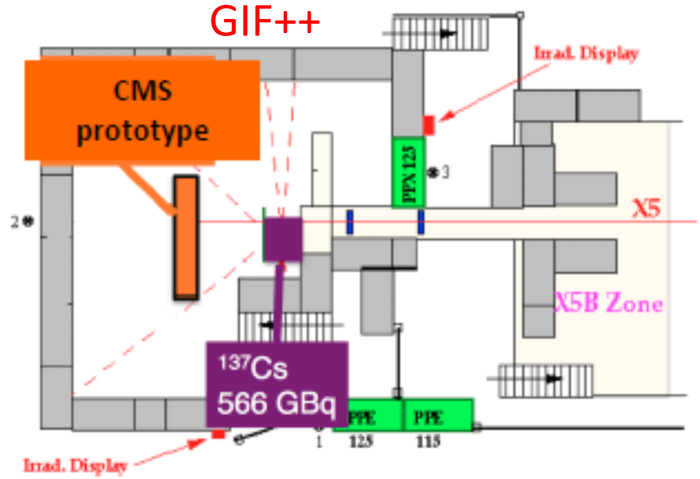
- Triple-GEM foils 5:50:5 μm for Cu:Kapton:Cu
  - 70 μm diam.; 140 μm pitch
- Gap configuration (in mm): 3/1/2/1
- NS2 assembly technology; no spacers or glue!

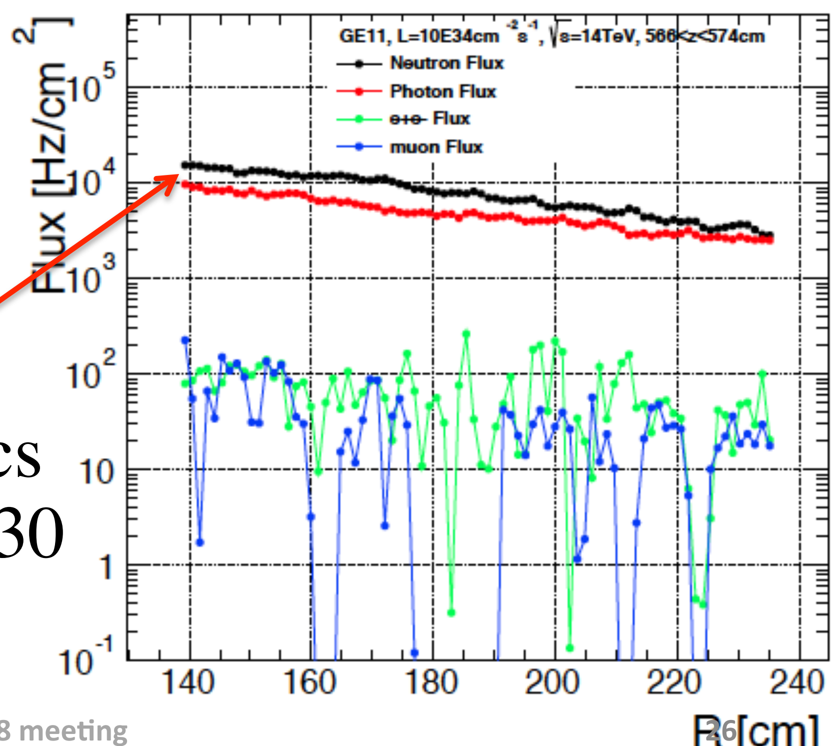




Radiation conditions

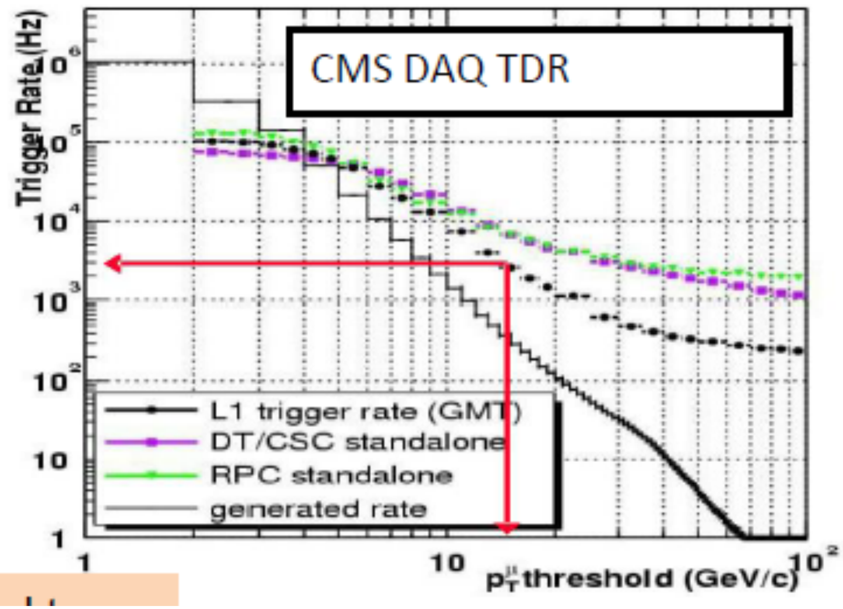
- Detector and electronics longevity is a concern:
- Past irradiation studies for DTs, CSCs and RPCs need to be repeated at higher doses at GIF++ facility
- HL-HLC rate expectations (5 E34)
  - DT: 50 Hz/cm²
  - RPC background rate:
    - barrel ~ 50 Hz/cm²
    - endcap ~ 100 Hz/cm²
  - CSCs and GEMs: a few kHz/cm²
- Note: CSC ME1/1 new electronics have been exposed to dose up to 30 krad (30 years of HL-LHC)

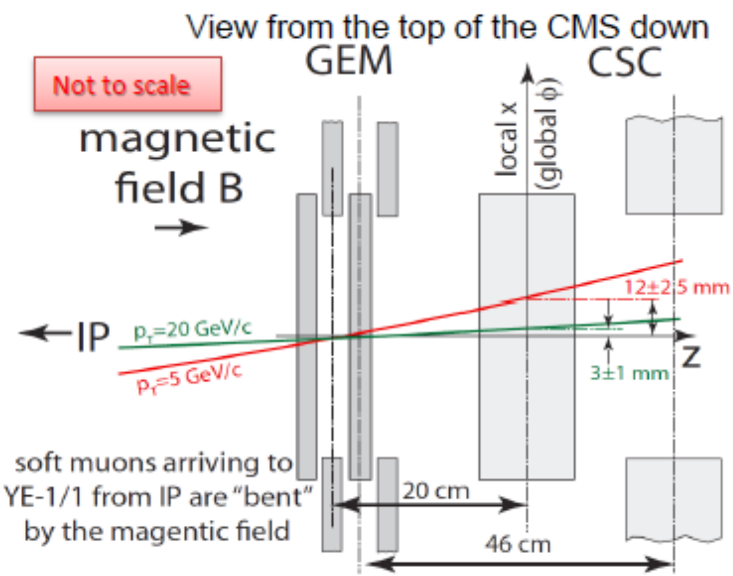




Impact of GE1/1 on L1 muon Trigger

- Scattering of soft muons in the iron yoke flattens the trigger rate curve
  - Promotion of low-p_T muon to high-p_T
- Additional muons stations can help to reduce the trigger rate
- Efficiency of single muon trigger at 20 GeV is about 85% in high eta region





- Additional GEM detector in front of ME1/1 can measure muon bending angle in magnetic field.
- By letting the GEM and CSC **talk to each other** we get a powerful new tool
  - **Rate reduction with GEM-CSC bending angle**

  Typical trigger rate reduction for 20GeV muon: **20kHz/cm² to 2kHz/cm²**
  - **Stub efficiency recovery in ME1/1 CSC TMB**