Progress in the CMS phase-II endcap muon detector upgrade with GEM

Dayong Wang
Peking University

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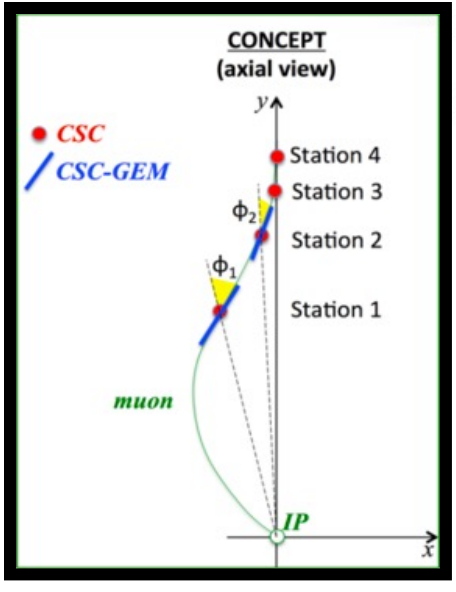
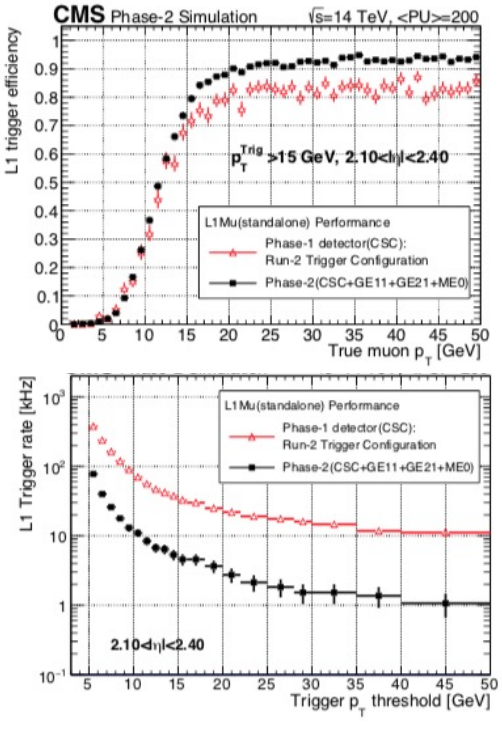
Motivation for CMS GEM Detectors

- **HL-LHC**
  - ~3.5 times higher instantaneous luminosity
  - ~200 p-p interactions per bunch crossing
- **Limits**
  - L1 trigger rate exposion
    - CSCs (current forward muon detector) may misidentify soft muons as high p_T in high radiation environment

    → L1 standalone muon trigger rate becomes uncontrollable
  - Limited forward-muon acceptance
    - Phase2 silicon tracker: $|\eta| < 4.0$
    - Current muon system: $|\eta| < 2.4$ →forward muons identification impossible, limiting physics reach
- **Goals**
  - Keep the L1 trigger threshold
  - Expand the muon acceptance
  - Improve tracking performance in the forward high-η region

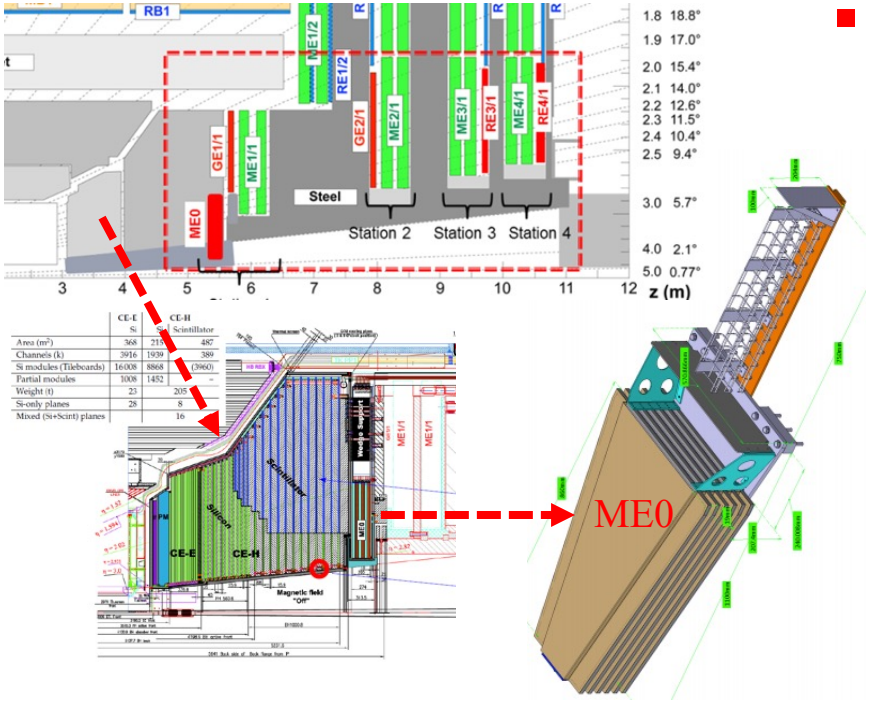




Important physics topics with multiple endcap muons:

- $H \rightarrow ZZ \rightarrow 4\mu$，$H \rightarrow 2\mu$
- Top quark mass in $t \rightarrow J/\psi(\mu\mu)\ \mu + X$
- Double-parton scattering in $pp \rightarrow W+W+$
- $B_{(s)} \rightarrow \mu\ \mu$, LFV decays $\tau \rightarrow 3\mu$
- Precise electroweak mixing angle with Drell-Yan events
- BSM with two SS leptons, displaced muons, HSCP

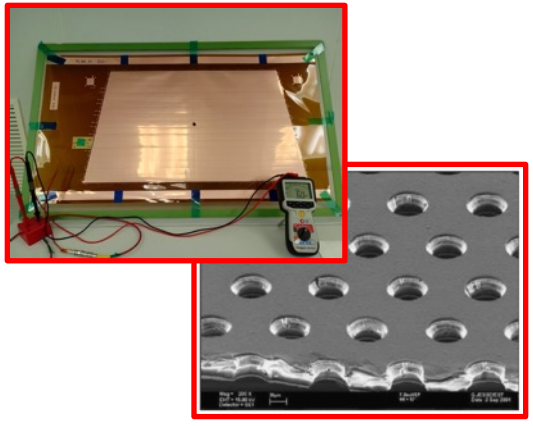
Muon Challenges@HL-LHC: ME0 as example

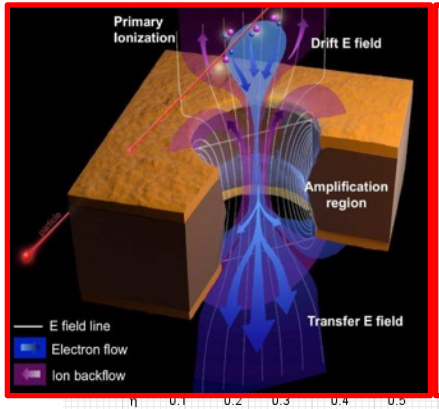


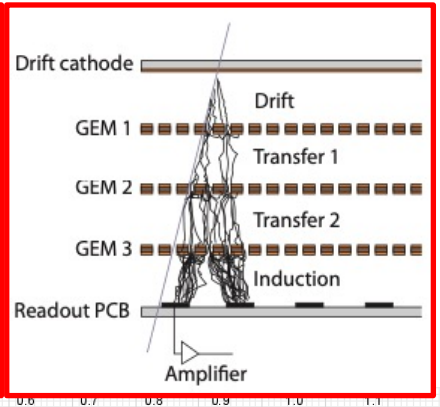
- 6-Layer Triple-GEM stack behind HGCAL (complex environment)
  - 2×18 stacks (20°) covering $2.0 < \eta < 2.8$

- Requirements:
  - 97% module efficiency
  - $< 500\mu$rad space resolution
  - 8-10 ns time resolution
  - $\leq 15\%$ gain uniformity
  - Work in high rate environment: 50kHz/cm^2
  - Survive harsh radiation environment:7.9C/cm^2
  - Discharge rate not impede performance or operation

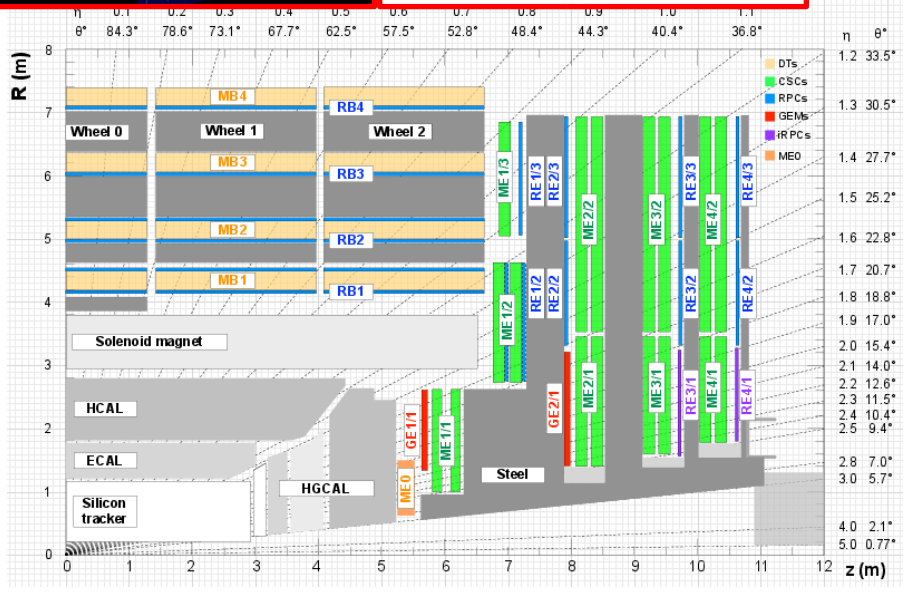
CMS phase-II GEM upgrade projects



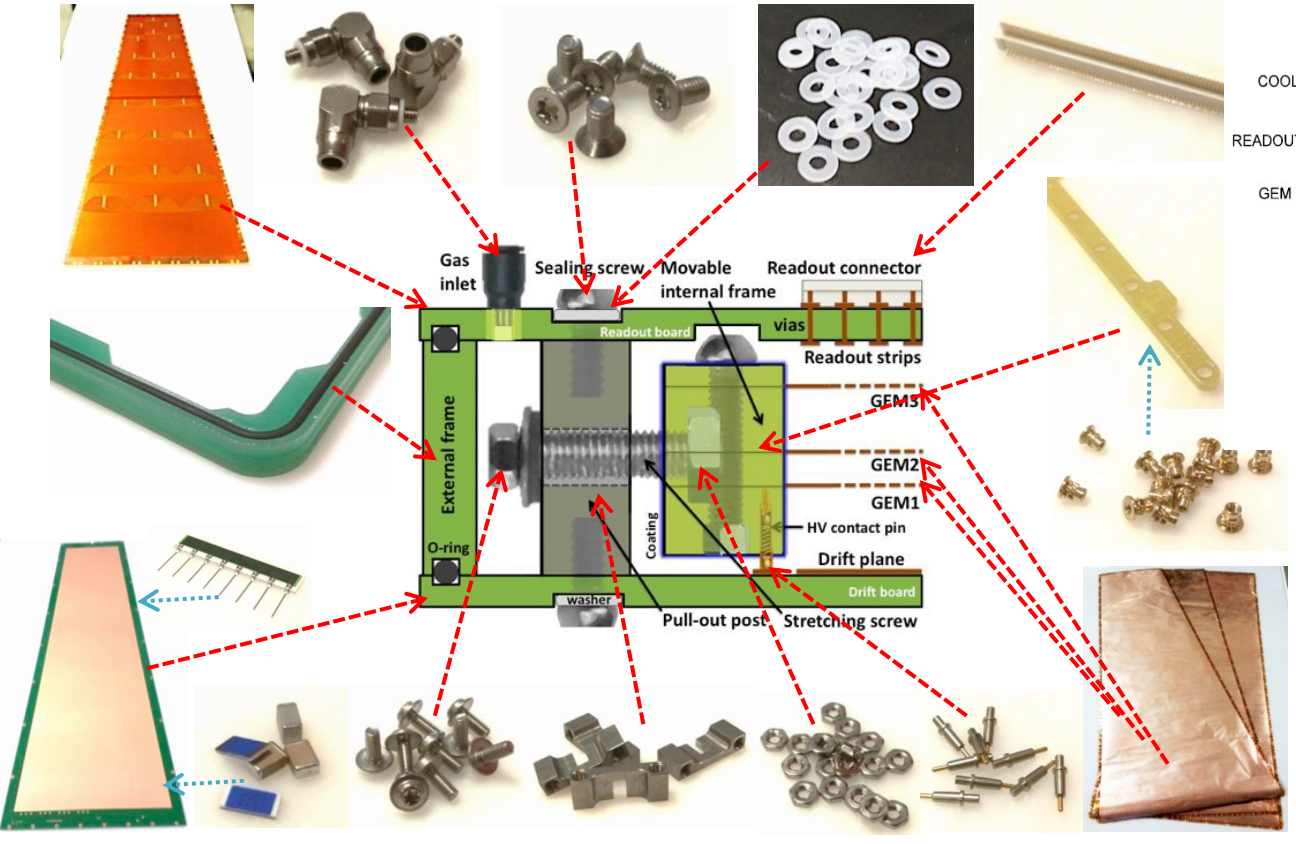


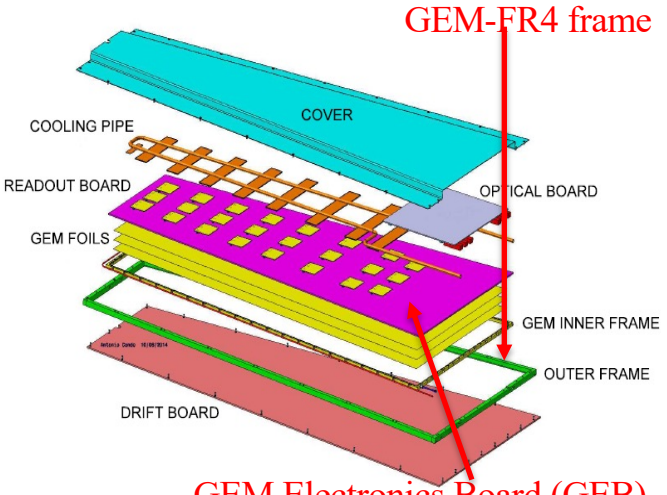


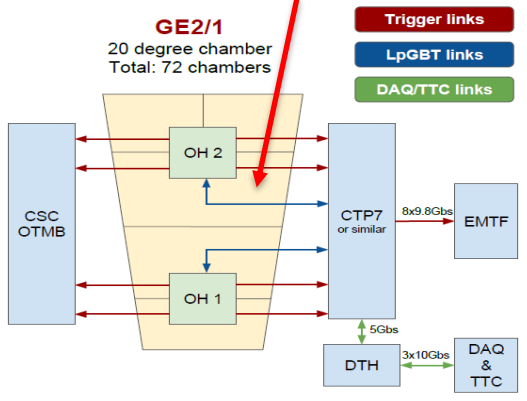
- The use of GEM technology in the endcap muon station will help to maintain or even improve the forward muon triggering and reconstruction in the region | η | > 1.6 in the phase of high luminosity.



Methodology: large-area, glue-less, custom structure and electronics

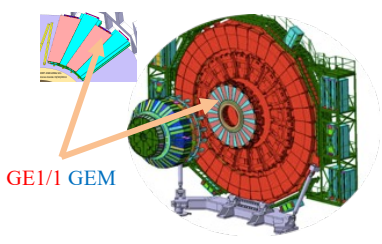


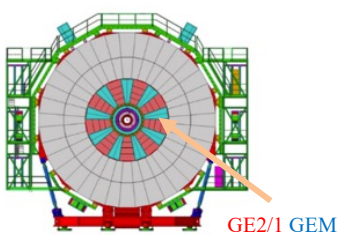


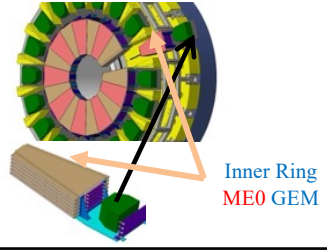


CMS-GEM upgrade: CMS-China contributions

CMS GEM System Phase-II upgrade:





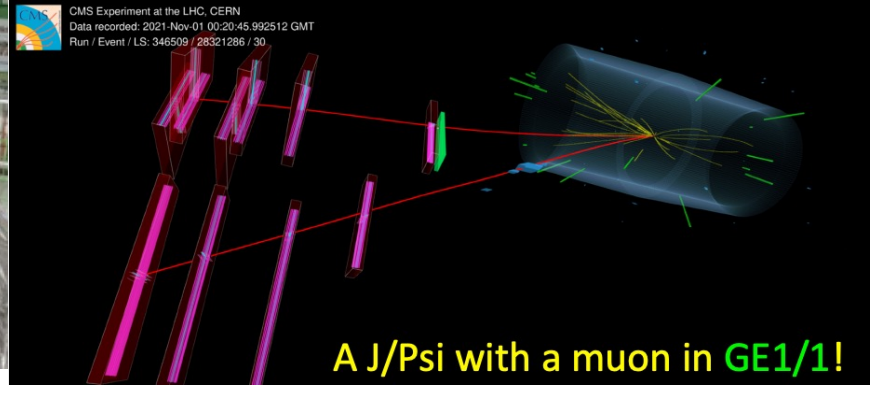


		GE1/1	GE2/1	ME0
Numbers		288（=2×36×4）	288（=2×18×8）	216（=2×18×6）
plan	prototyping	2013-2017	2014-2022	2014-2023
	batch **production**	2017-2019	2022-2030(?)	2024-2026
	Install&commission	2018-2020	2030-(?)	2027-2029
CMS-China **Contributions**		Production and test of all electronic boards(GEB) Participate assembly, test and commissioning at CERN	Design, production and test of all electronic boards(GEB) Assembly and QC of ~1/8 GEM detectors at PKU， Participate assembly, test and commissioning at CERN Production of FR4 frames, mechanical structures, etc	Design, production and test of all electronic boards(GEB)， Assembly and QC of ~1/5 GEM detectors at PKU， Participate assembly, test and commissioning at CERN Production of FR4 frames, mechanical structures, etc

中国组负责生产的GE2/1和ME0的FR4外框架和超模块结构部件(320+360套)均已按计划完成并通过CERN检测

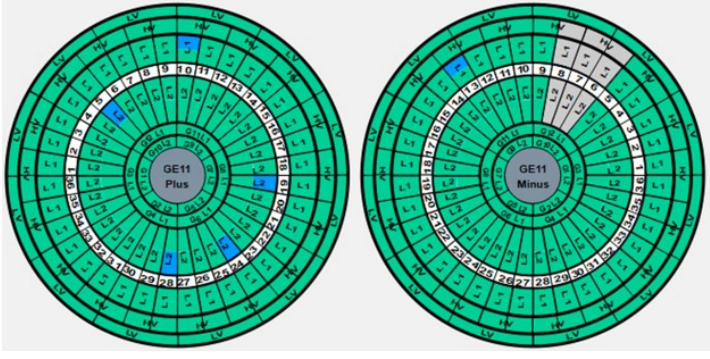
GE1/1 timeline and successful running

NIMA 972 (2020) 164104



GE1/1 Performances in Run 3

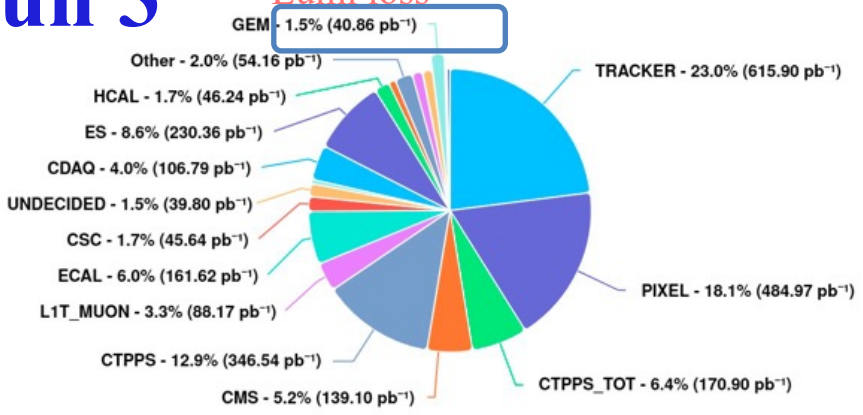
- **GE1/1 detector was installed during LS2:**
  - Total of 144 chambers have been operating since beginning of Run 3.
  - Currently, 138 chambers are active; 3 SCs were extracted in YETS 24/25.

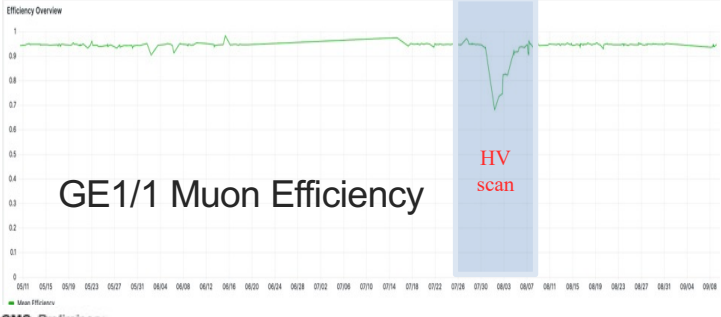


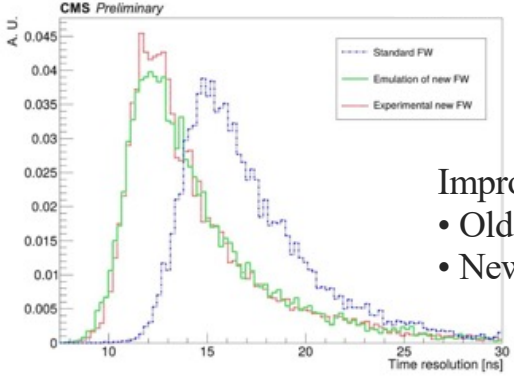
- **GE1/1 Chambers operate smoothly:**
  - Muon detection efficiency: 94–95%
  - Time resolution improved to 12.3 ns.
  - Luminosity loss: approximately 1.5%
  - GEM information has been integrated into the Level-1 trigger.

CMS-GEM, JINST 20(2025) P05035

Lumi loss



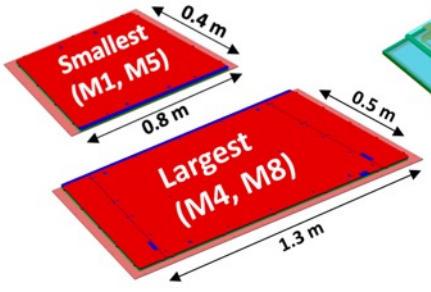




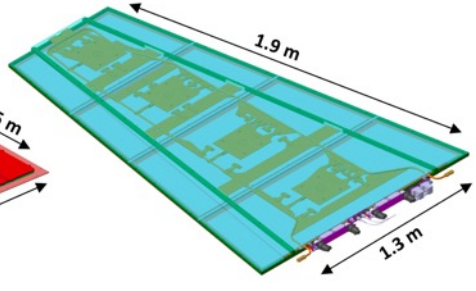
Improvement of mode value
- Old firmware: 15.3 ns
- New firmware: 12.3 ns

GEM detector design feathers: GE2/1 and ME0

- The full GE2/1 system: 72 chambers (36 per end-cap)
  - 4 triple-GEM modules per chamber = 288 modules in total
  - The chambers are arranged in two layers
- Two different types of chambers
  - On-Yoke= FRONT-type (module types M1-M4)
  - Off-Yoke= BACK-type (module types M5-M8)

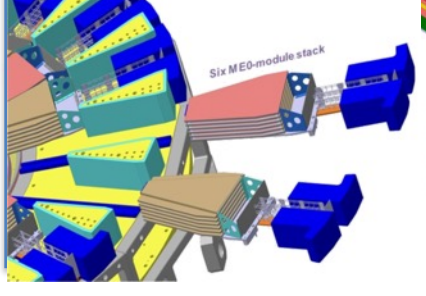


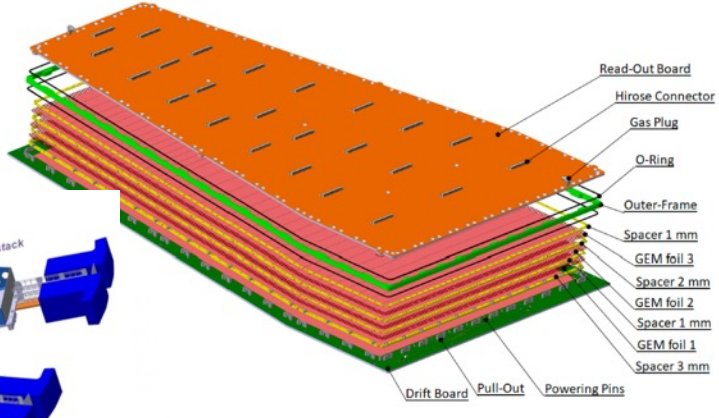
8 slightly different triple-GEM modules (M1 to M8)



Off-Yoke (M1 to M4) and On-Yoke (M5 to M8) chambers

- ME0 system: 216 chambers (108 per end-cap)
  - 6 triple-GEM modules per stack
  - 18 stacks per endcap
- Harsh environment and limited space
  - Rate Capability: >150kHz/cm2
  - Longevity: Need to survive integrated charge up to 7.9C/cm^2.





GEM assembly and test schemes(GE2/1 and ME0)

CERN

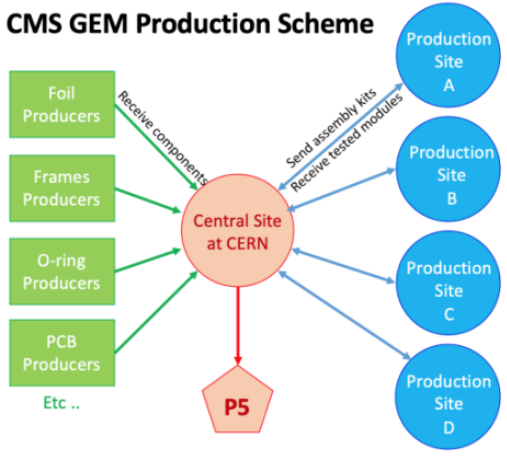
- QC 1: material inspection
- QC 2: GEM foils test (fast + long)

Production sites (e.g. PKU)

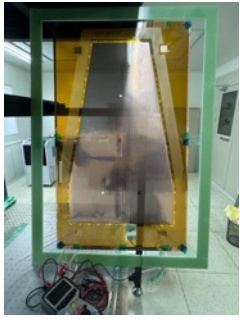
- QC 2: GEM foils test (fast)
- Assembly preparation + Assembly
- QC 3: gas leak test
- QC 4: HV test
- QC 5: gas gain calibration

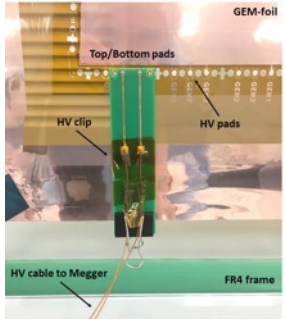
CERN

- QC 6: HV stability test
- QC 7: electronics connectivity test
- QC 8: cosmic ray test



QC2 (ME0 chamber)





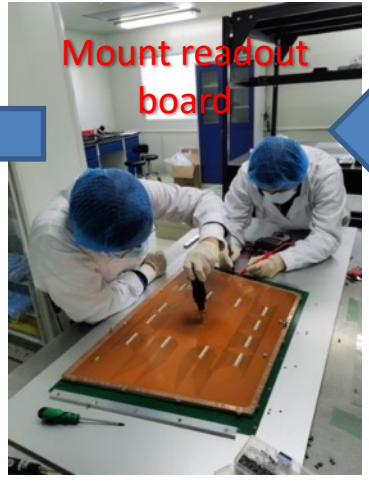
short impedance test

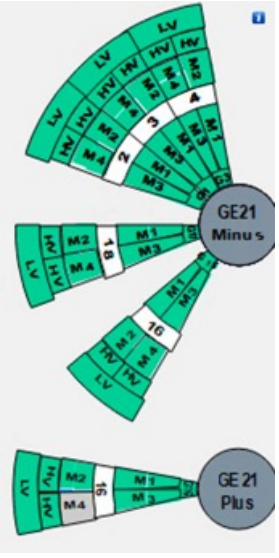
The certified set up for GEM assembly and QC

- Some assembled chambers are sent from CERN for testing procedures
- The final CMS GEM assembly site certification was achieved in 2021-22

GE2/1 M5 assembly at PKU lab(2022-23)

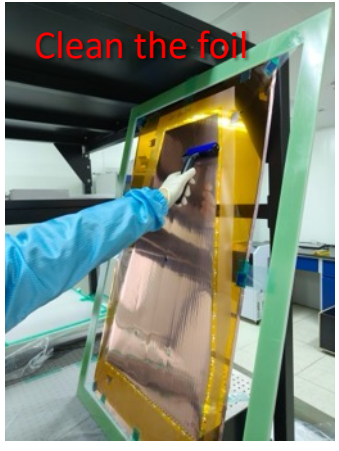
two batches of 15 GE2/1 M5 modules were produced at PKU

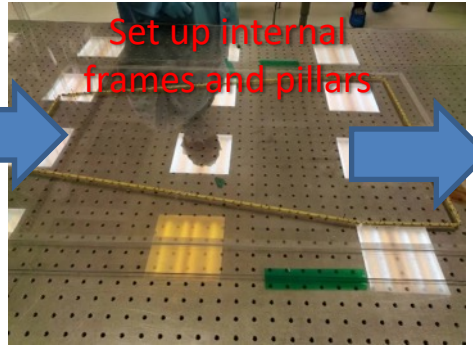


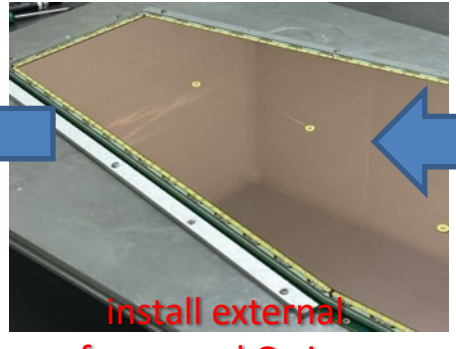


- 目前有6个测试用GE2/1探测器安装在CMS上，5个在− endcap，1个在+ endcap
- 生产推迟到2028年后，安装计划待定

Quickly adapted to ME0 assembly procedures

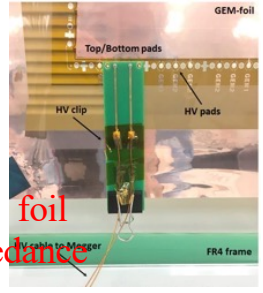




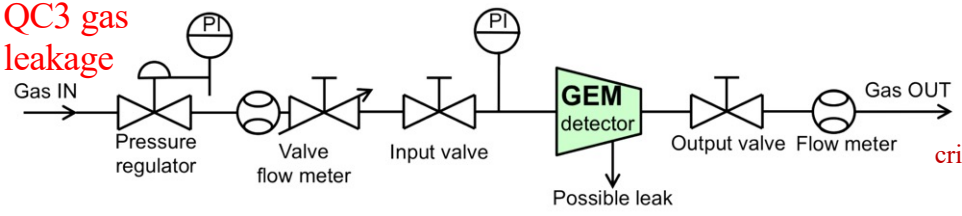


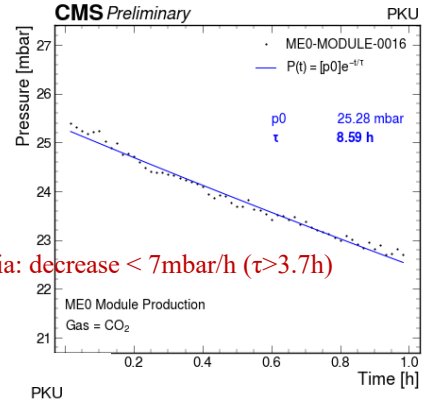
ME0 Module QC test @PKU Lab

QC2 foil impedance



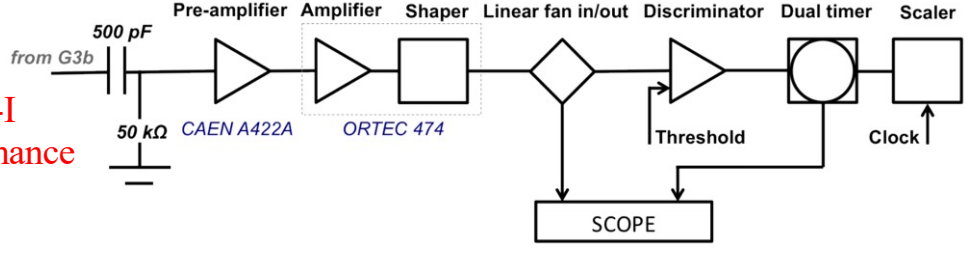
QC3 gas leakage

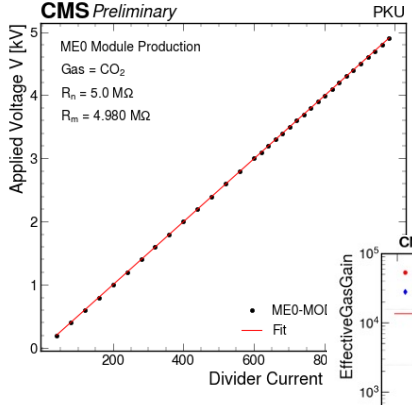




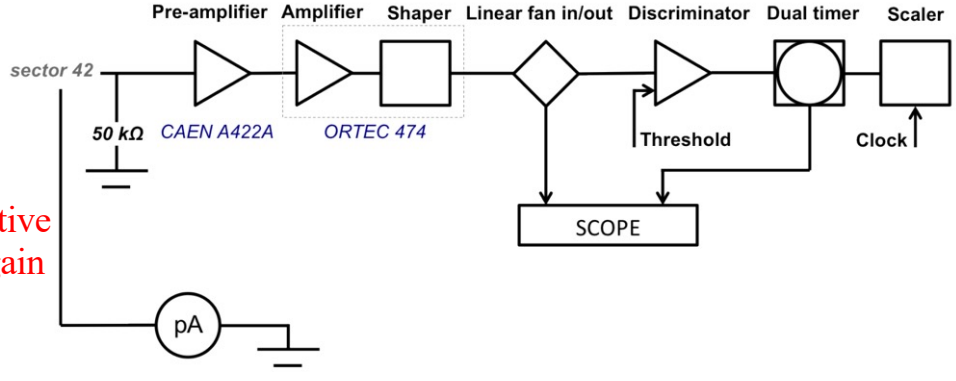
criteria: decrease < 7mbar/h (τ>3.7h)

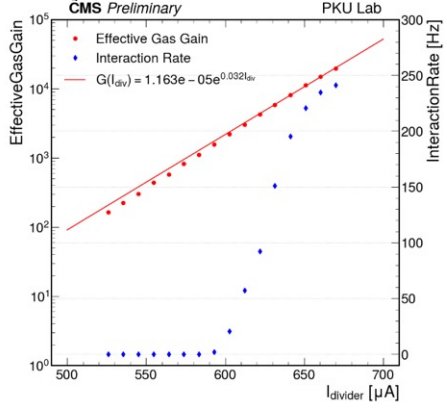
QC4 V-I performance





QC5 effective gas gain



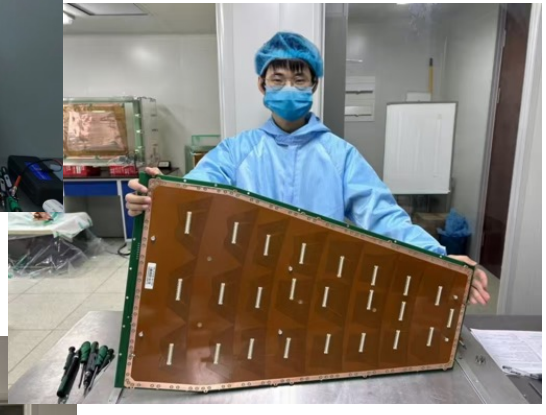


ME0 assembly : 4 batches of 40 chambers finished

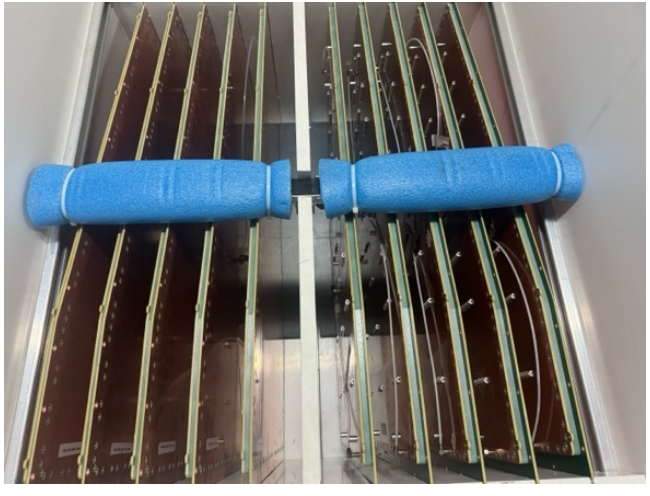

(1st July-Sep, 2024)

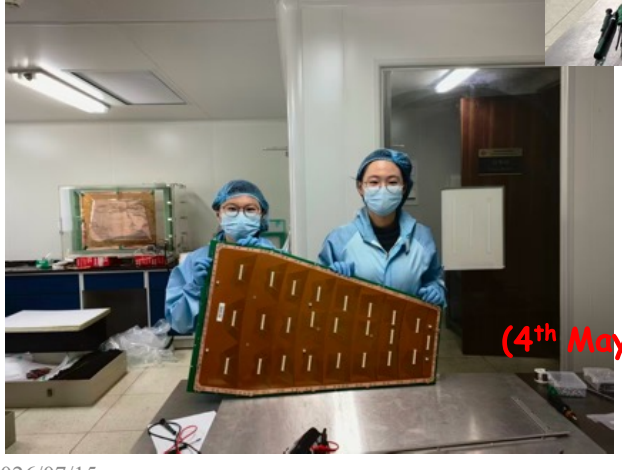
- Assembly and QC test of the four batches of ME0 is completed.
- All the ME0 GEMs are sent back to CERN for further testing.

(2nd Apr.-Jun. 2025)

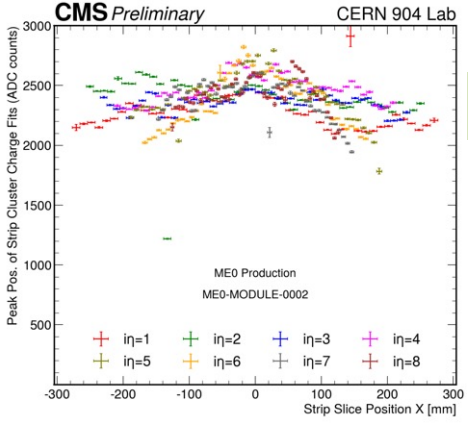


(3rd Nov2025.-Jan. 2026)



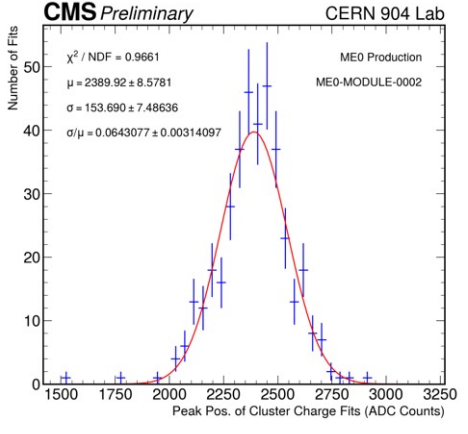

(4th May-Jun. 2026)

ME0 module performance tests at CERN



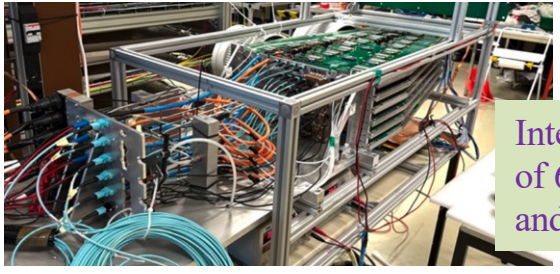
Gain uniformity

不同位置处得到的增益



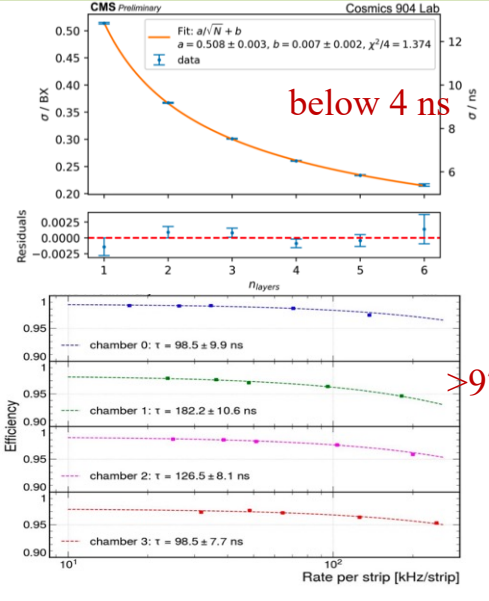
Gain Uniformity
= σ/μ < 15%

使用上图中的数据点
拟合得到的曲线



Integration test
of 6-ME0 stack
and electronics

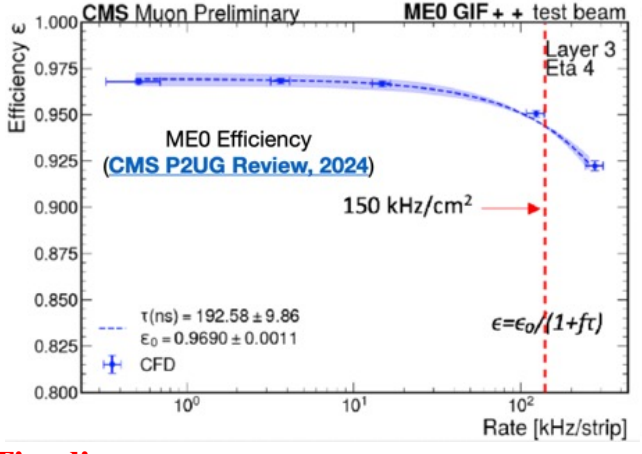
Cosmic and beam test: time resolution and efficiency

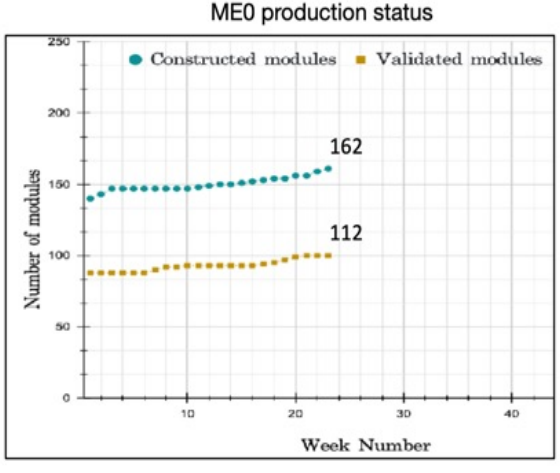


>97%

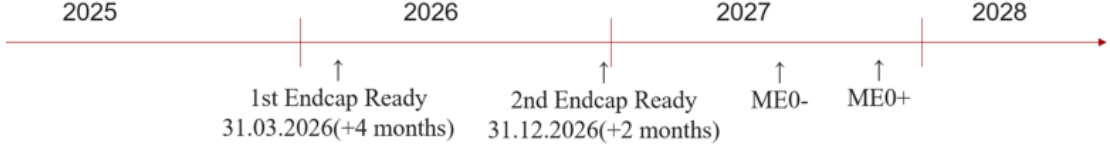
ME0 Production and Performance Validation Status

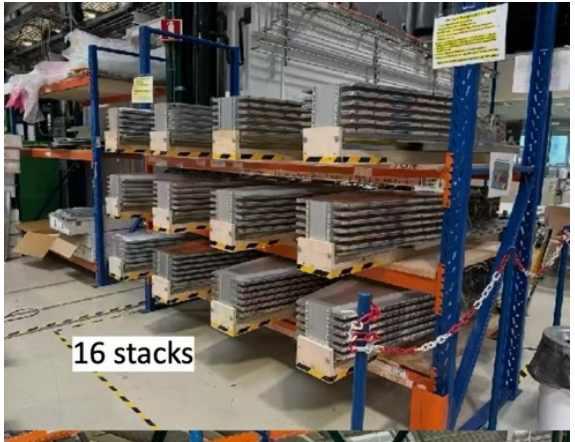
- 16 stacks assembled, including 12 fully validated
- More than one endcap equivalent of modules validated
- Efficiency plateau of approximately 97% at GIF++
- Stack timing resolution below 4 ns under high-rate background





Timeline：

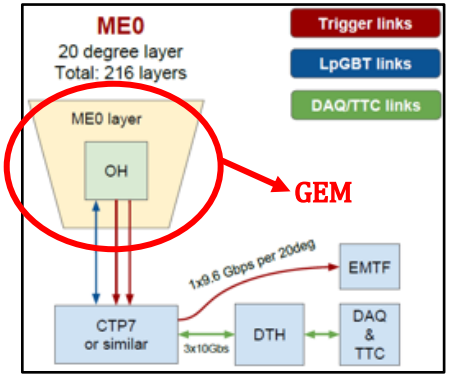




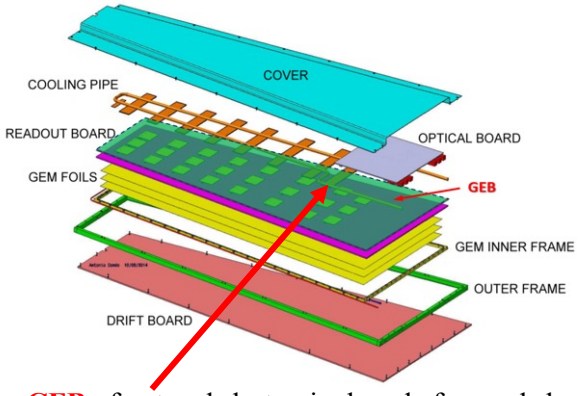
➢ the installation of **ME0-** will be at **Sep-08 2027(+8 months)** and **ME0+** at **Nov-29 2027 (+10 months)**.

GEM Electronics Boards（GEB）

Zhe Li et al JINST 20(2025) P12006



DAQ system of CMS-GEM



GEB: front-end electronics board of upgraded CMS-GEM (GE1/1, GE2/1, ME0)

Function of GEB :

Carrier of front-end and back-end electronics system; front-end signal transmission carrier; provide direct shielding for GEM detectors

Tasks of CMS China group:

- Production and test of GE1/1 GEB
- Design、production and test of ME0 (510) and GE2/1 GEBs(336)
- Development of automatic tester

Milestone of ME0 GEBs production and test(total:510):

- 1st batch of 15 sets of ME0 GEBs produced on Jan. 2023, completed test at CERN in Apr. 2024
- 240 sets of the remaining GEBs production completed in Feb. 2024, 2nd batch of 95 sets of GEBs tested in China and shipped to CERN in April 2024
- 3rd batch of 145 sets of GEBs tested at China completed in Nov. 2024, shipped to CERN ~end of Nov. 2024

Acceptance test at CERN: make sure no damage in shipment.

➢ By May 2026, all of ME0 GEBs has been tested by PKU group with acceptance criteria, all qualified.

Summary

- CMS Phase-II upgrade add three endcap muon stations based on GEM technology. It is one of the largest scale applications in HEP.
  - GE1/1 is successfully built, installed and commissioned in LHC Run-3 and good performances have been achieved.
  - ME0 production is ongoing and progress well.
  - GE2/1 chambers were partially produced and project was postponed.
- CMS-China contribute substantially and progress well
  - Local GEM lab has been certified as one of CMS-GEM production sites.
  - Several batches of GE2/1 M5 and ME0 chambers have been successfully assembled and tested.
  - Design, production and test of all GE2/1(338) and ME0(510) GEB boards have been finished in high quality
  - Other contributions: FR4 frames, mechanical structures, etc
- Could meet HL-LHC challenges and help to maintain/enhance physics!

GE2/1 electronics overview