Micro-Pattern Gaseous Detectors for High Energy Physics

Paolo Iengo
paolo.iengo@cern.ch

DRD1
Gaseous Detectors
School

CERN

November 27 - December 6, 2024

Applications in HEP

HEP detector design

Physics case → Experiment requirements → Detector requirements → Detector available 'on the market' / R&D for specific application

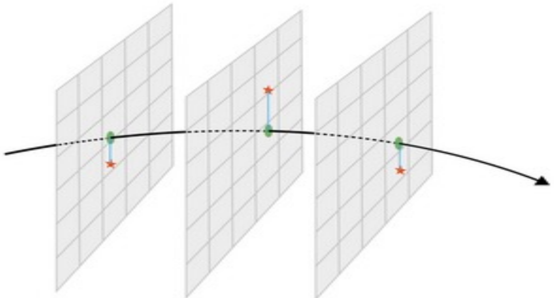
Experiments with 'standard' requirements (often small/medium-size experiments)

Detector available 'on the market'

R&D for specific application

Cutting-edge requirements (often next generation experiments)

- Physics case: Example: $Z \rightarrow \mu^+\mu^-$
- Experiment requirements: Measure 10 GeV muon with 10% p_T resolution
- Detector requirements: With 3 measurement points L=1 m, B=1 T $\rightarrow \sigma_x \approx 300\ \mu m$



Sagitta (s) measurement to determine transverse momentum

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\sigma_x \cdot \frac{8p_T}{0.3BL^2}$$

Applications in HEP

HEP detector design

Physics case → Experiment requirements → Detector requirements → Detector available 'on the market' / R&D for specific application

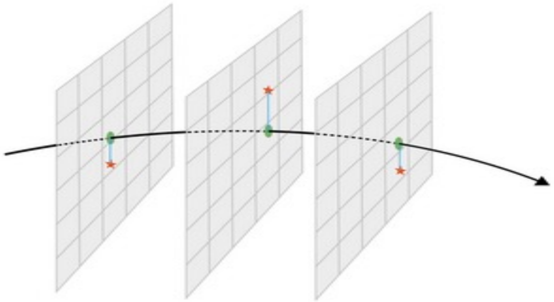
Example: $Z \rightarrow \mu^+\mu^-$

Measure 10 GeV muon with 10% p_T resolution

With 3 measurement points L=1 m, B=1 T
➔ $\sigma_x \approx 300\ \mu m$

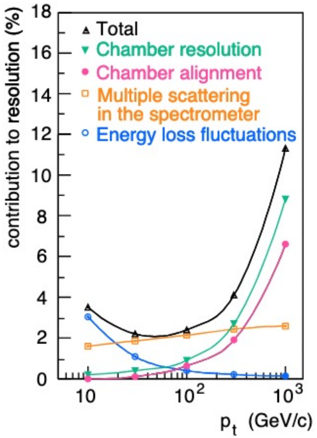
Experiments with 'standard' requirements (often small/medium-size experiments): Detector available 'on the market'

Cutting-edge requirements (often next generation experiments): R&D for specific application



Sagitta (s) measurement to determine transverse momentum

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_s}{s} = \sqrt{\frac{3}{2}}\sigma_x \cdot \frac{8p_T}{0.3BL^2}$$



- Improving σ_x not always worth: other effects contribute to momentum resolution
  - Multiple scattering
  - Chamber alignment
  - …

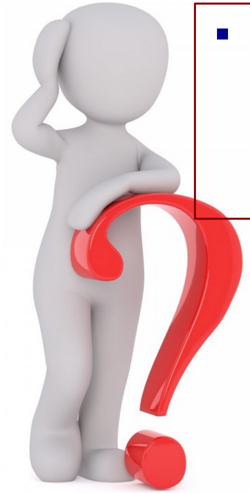
- Other factors affecting the detector choice:
  - Cost
  - Size
  - Long-term operability
  - Maintainability
  - Expertise of the involved teams
  - Contributing Institutes
  - ….

Applications in HEP

- Gaseous detectors are used in and are being developed for many HEP experiments
- Each one challenging one or more performance or construction limits

Construction

- Large detector surface for big experiments
  - Construction technique
  - Industrialisation
  - Maintenance
- Geometry
  - Planar
  - Cylindrical
  - Spherical



Gaseous Detectors

Performance

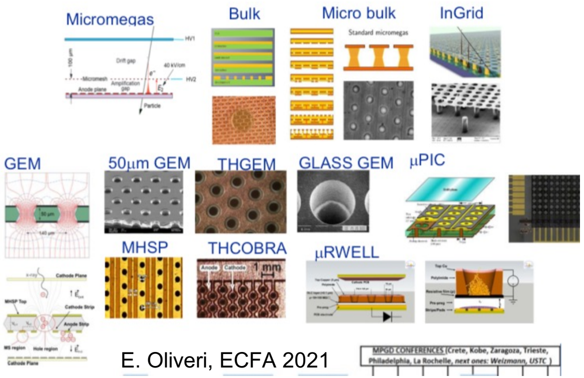
- Time resolution
  - Fast gas
  - Multistage
  - Cherenkov
- Space resolution
  - Granularity
  - Charge sharing
  - Time info (uTPC)
  - Si readout
- Rate capability
  - Space-charge reduction
  - Small-size readout
  - Fast readout
- Spark protection
  - Resistive coating
  - Segmentation
  - Gas mixture

Operations

- Gas mixture
  - Drift velocity
  - Diffusion
  - Amplification vs HV stability
  - Aging…
- Aging/Longevity
  - Gas mixture
  - Materials

Disclaimer

- Today the MPGD family includes a large number of detectors
  - Well established technologies adopted in HEP experiments
  - New ideas, R&D for future experiments or specific applications



E. Oliveri, ECFA 2021

- Impossible to cover all the MPGD HEP applications
  - Will show a selected number of representative examples
  - Focus on LHC experiments and on GEM and Micromegas
  - What is not mentioned is NOT less relevant!

- You can always find something more interesting…

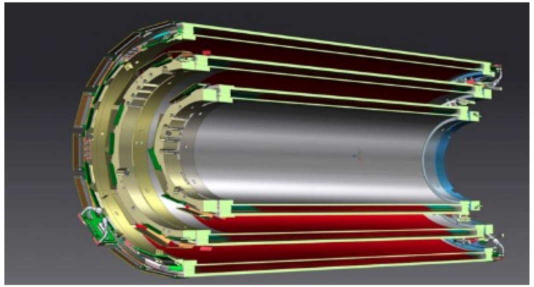
When a man with .45 meets a man with a rifle the man with a pistol's a dead man

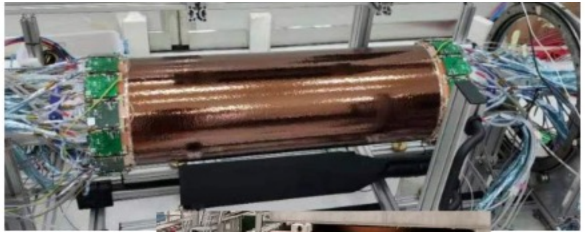
Trackers with MPGD

Cylindrical GEM

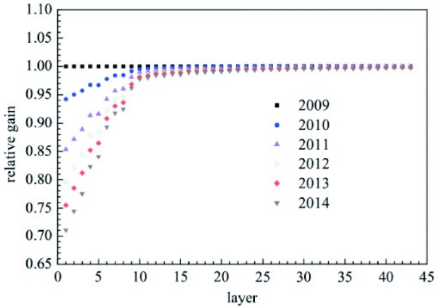
- MPGD suitable for Inner Tracker thanks to their intrinsic light structure → low material budget
- IT exploit mechanical flexibility of MPGD → cylindrical shape

- BESIII @ BEPC II e^+e^- collider 2.0-4.95 GeV cme
  Charmonium and light hadron spectroscopy
- Triple GEM (inspired by C-GEM of KLOE2)
  - Gas: Ar:iC_4H_{10} (90:10)
  - B = 1T → $\sigma(p_T)/p_T$ = 0.5%
  - Material budget: 0.5% X0/layer

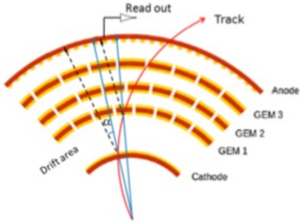


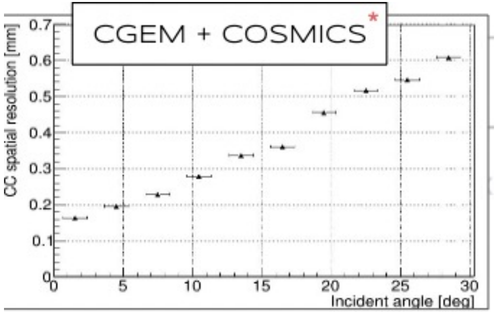


R. Farinelli, MPGD Conference 2022

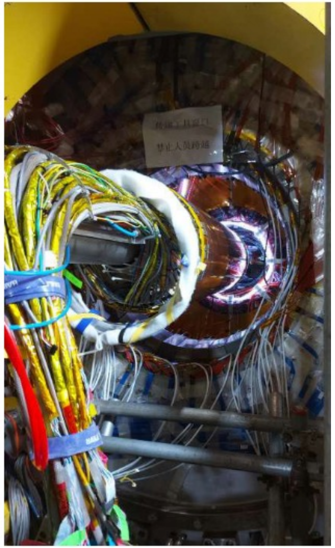


Performance degradation with time of wire-based BES IT
→ replaced by the CGEM





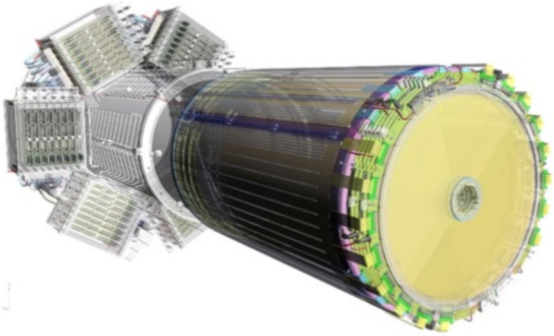
Space resolution of CGEM with cosmics



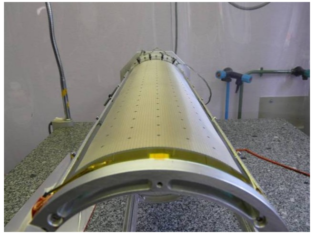
CGEM during installation in BESIII
G. Mezzadri, MPGD Conference 2024

Cylindrical Micromegas

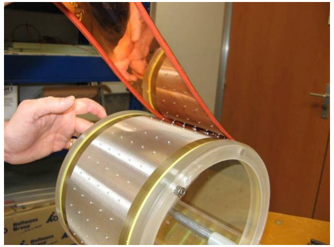
- Micromegas Vertex Traker for CLAS12 @ JLAB
- Nuclear Physics/Hadron Spettroscopy/Deep Processes
- B=5 T magnet
- 11 GeV e^- beam / 30 MHz particle rate



  - Barrel system
  - Gas: Ar:iC_4H_{10} (95:5)
  - 2.9 m2 / 18 units / 6 layers in 10 cm / X_0 ~0.33/layer

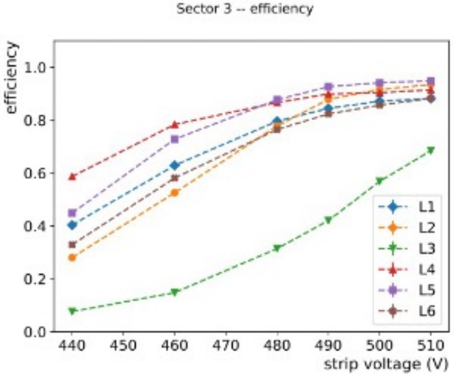


Curved MM bulk

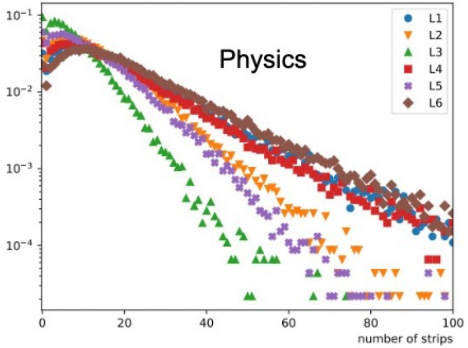


Drift electrode integration

Barrel tracker finalised



Efficiency vs HV
L3: likely gas issue → gas distribution modification

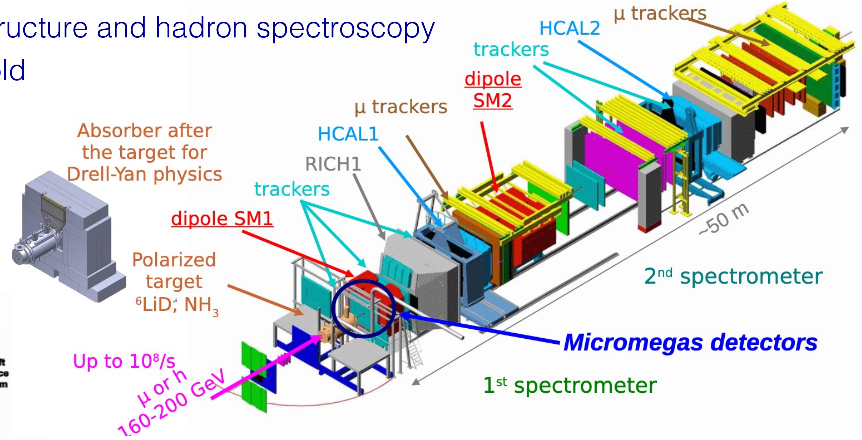


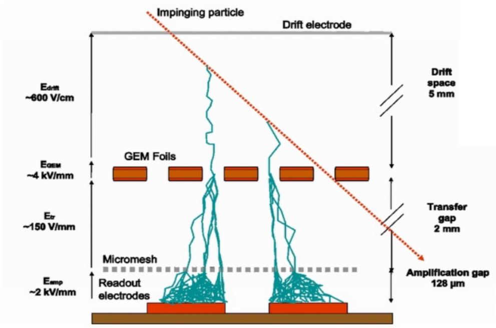
Occupancy for Sector 1 (up to 1.8%)

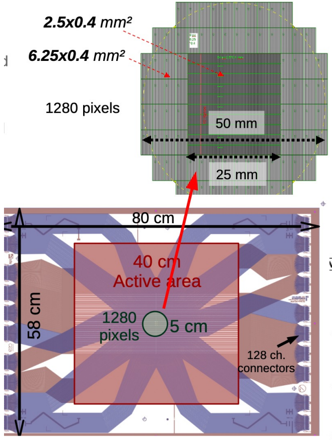
M. Vandenbroucke, MPGD Conference 2022

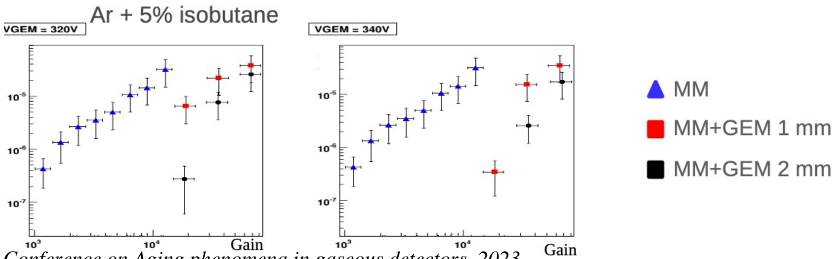
GEM+Micromegas

- COMPASS experiment at CERN (2002-2022): nucleon spin structure and hadron spectroscopy
- Hybrid GEM+MM detector installed in 2014/2015 to replace old MM in view of high intensity pion beam
- 1 GEM foil (gain ~20) effective in reduction of discharge probability
- Readout: small pads in the centre (100 kHZ/cm^2) and strips on the periphery
- Gas Ne:C_2H_6:CF_4 80:10:10

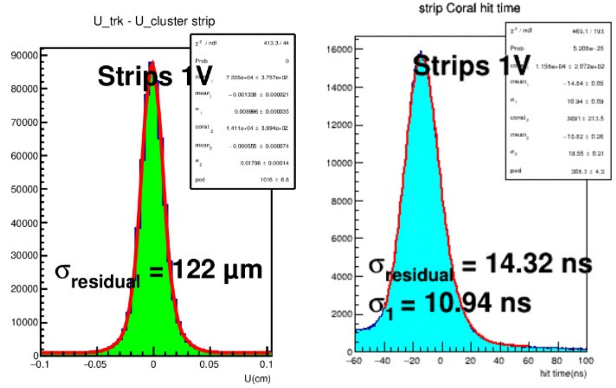








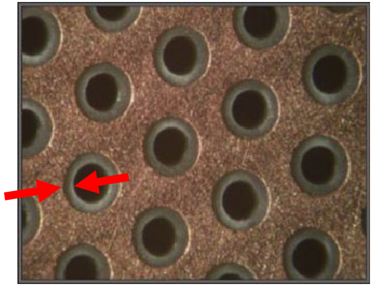
D. Neyret, 3rd Conference on Aging phenomena in gaseous detectors, 2023

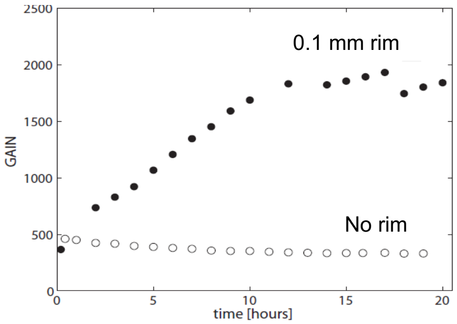


Good tracking and timing performance

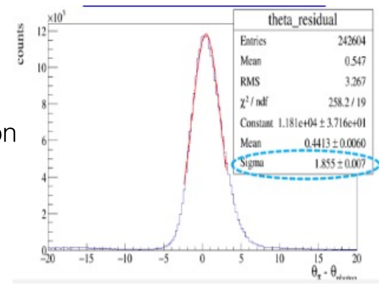
Thick GEM: photon detection at COMPASS

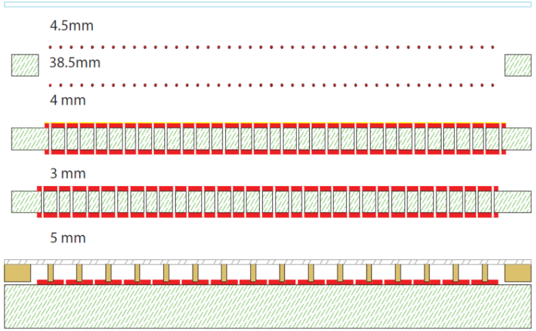
- THGEM: Same principle as GEM but with thick material (FR4)
  - PCB thickness ~ 0.4-3 mm
  - Hole – drilled - diameter ~ 0.2-1 mm
  - Pitch ~ 0.5-5 mm
- Industrial production for large size
- Mechanically self-supporting, robust

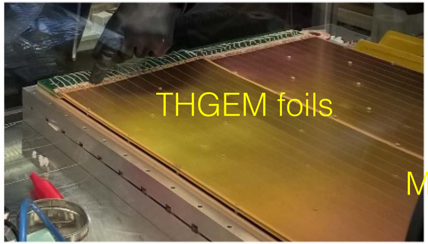


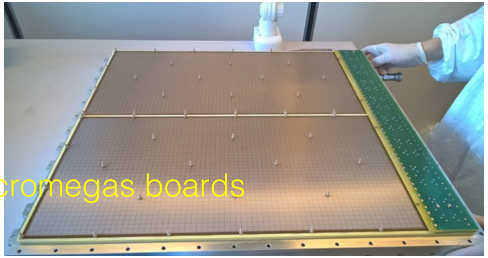


- Successfully used in COMPASS RICH-1 for single-photon detection
  - Hybrid configuration: THGEM+Micormegas; 1.4 m^2
  - eff. gain ~ 15000, gain stability ~5%
  - single γ angular res. 1.8 mrad
  - Gas: Ar:CH_4 50:50 → optimal photoelectron extraction from CsI to gas
  - IBF = 3%

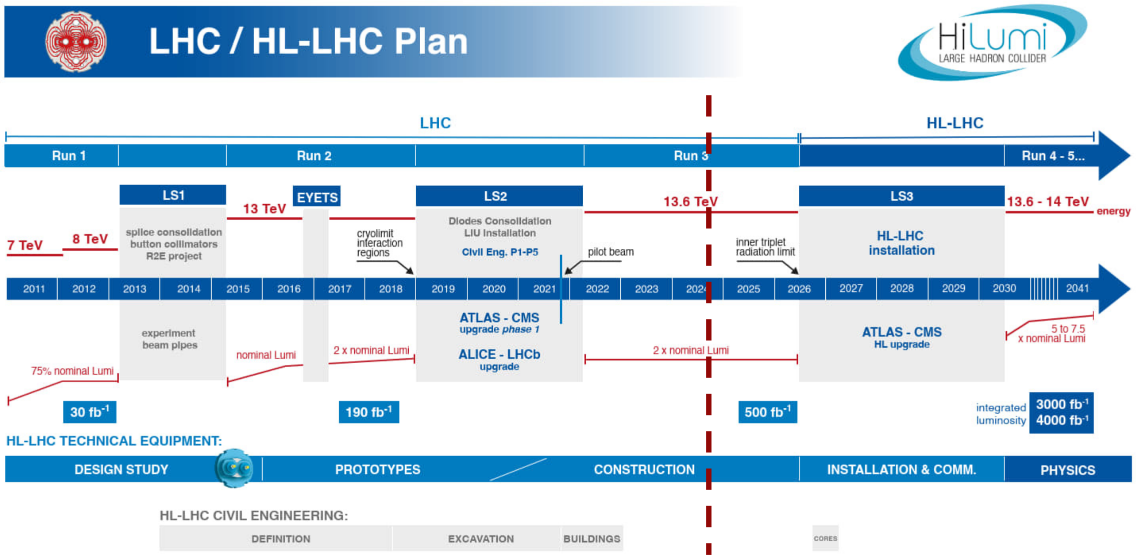








MPGD at LHC



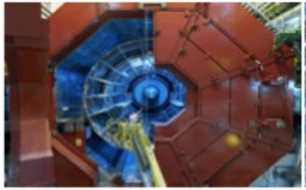
The development of gaseous detectors for High Luminosity LHC has driven the R&D effort for several MPGD technologies

Detector challenges all there:

- High rate
- High radiation
- Pileup

Gaseous detectors at LHC

- Gaseous detectors are key devices in current forefront experiments, e.g. at LHC
- Mostly as central tracker (TPC) and Muon systems




- ALICE
  - CSC
  - MWPC
  - RPC
  - Timing RPC
  - GEM**
- ATLAS
  - MDT
  - CSC*
  - TGC, sTGC
  - RPC
  - Micromegas**
  - TRT straws
- CMS
  - DT
  - CSC
  - RPC, iRPC
  - GEM**
- LHCb
  - MWPC
  - GEM*
  - uRwell***

Gaseous detectors at the 4 large LHC experiments

* Removed after Run2
** Run3 and beyond
*** Proposed for Run4 and beyond

Gaseous detectors at LHC

- Gaseous detectors are key devices in current forefront experiments, e.g. at LHC
- Mostly as central tracker (TPC) and Muon systems

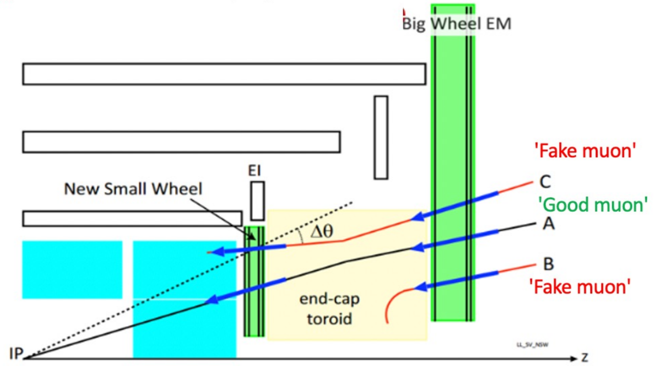
- ALICE
  - CSC
  - MWPC
  - RPC
  - Timing RPC
  - GEM**
- ATLAS
  - MDT
  - CSC*
  - TGC, sTGC
  - RPC
  - Micromegas**
  - TRT straws
- CMS
  - DT
  - CSC
  - RPC, iRPC
  - GEM**
- LHCb
  - MWPC
  - GEM*
  - uRwell***

Gaseous detectors at the 4 large LHC experiments

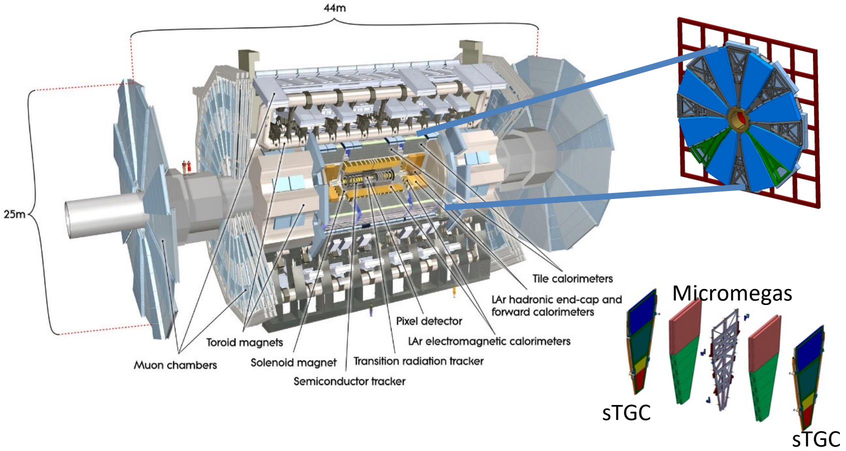
* Removed after Run2
** Run3 and beyond
*** Proposed for Run4 and beyond

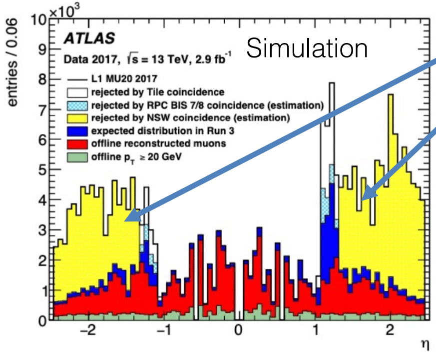
ATLAS Micromegas

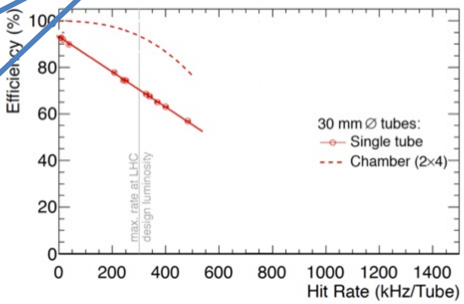
- New Small Wheel: major ATLAS upgrade of Phase1



Run1 & 2: Level 1 End-Cap trigger, dominated by fake trigger events (type B e C)







Efficiency vs rate for ATLAS MDT

Complementary technologies:

- sTGC: good bunch crossing assignment with high radial resolution and rough ϕ resolution from pads
- Micromegas: good offline radial resolution and a good ϕ coordinate due to its stereo strips
- 1280 m² active surface for each technology

ATLAS Micromegas

- ATLAS Micromegas is the largest MPGD-based system ever conceived and built
- Main R&D challenges
  - Spark suppression (see lecture by P. Gasik)
  - Large-area production
  - Precise tracking for inclined tracks

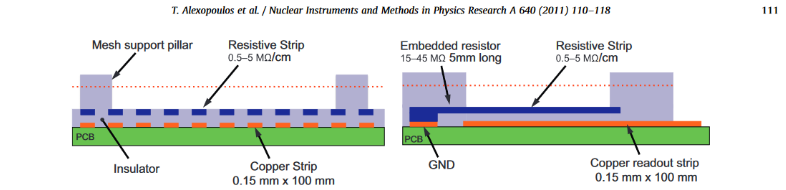
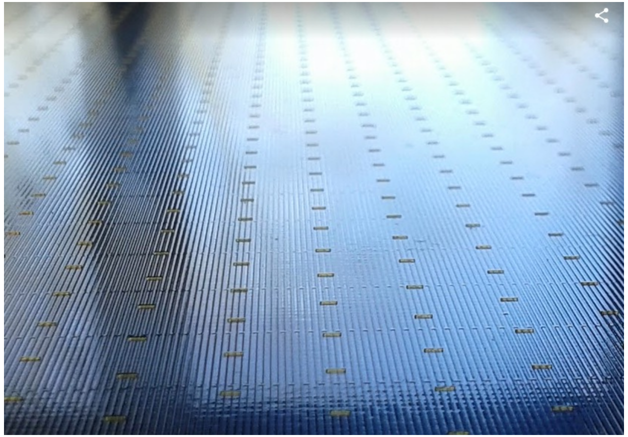
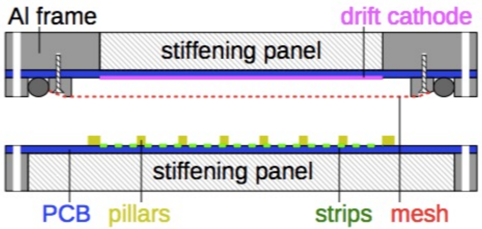


Fig. 1. Sketch of the detector principle (not to scale), illustrating the resistive protection scheme; (left) view along the strip direction, (right) side view, orthogonal to the strip direction.

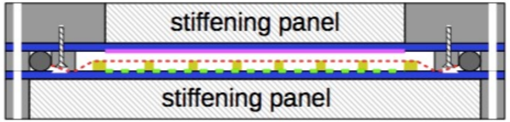
The Micromegas R&D for ATLAS pioneered the resistive MPGD



Micromegas boards fully produced in industry
2500 boards produced→ big technology challenge



Open detector



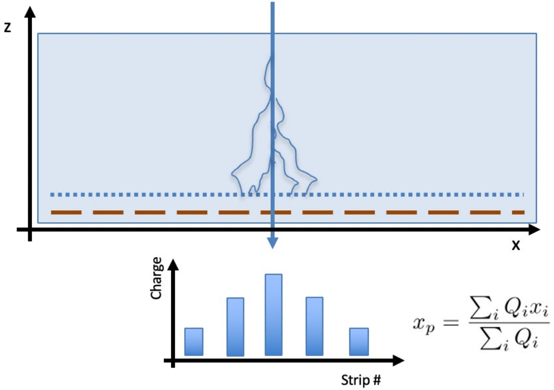
Closed detector

Principle of mechanically floating mesh

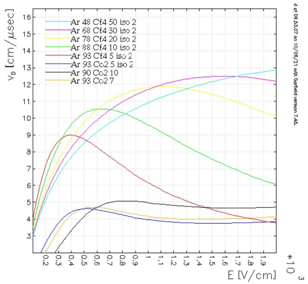
ATLAS Micromegas

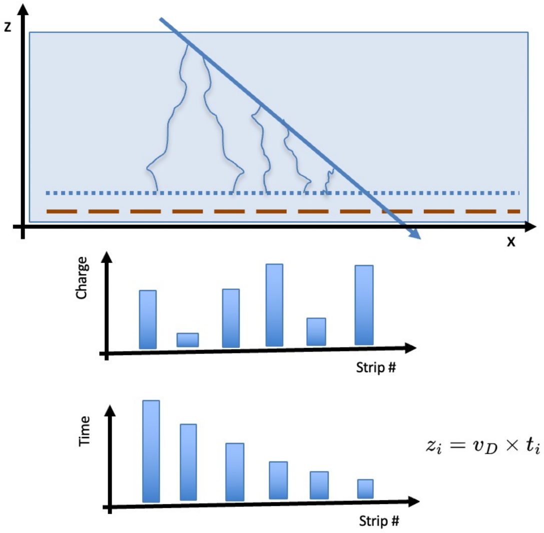
- ATLAS Micromegas is the largest MPGD-based system ever conceived and built
- Main R&D challenges
  - Spark suppression (see lecture by P. Gasik)
  - Large-area production
  - Precise tracking for inclined tracks: same principle as a TPC but in few mm gas

The μTPC reconstruction technique make use of the time information to reconstruct the cluster z coordinate and allows for precise tracking for inclined tracks (see lecture from T. Alexopoulos)



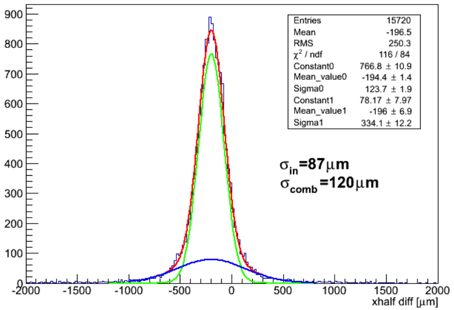
$$x_p = \frac{\sum_i Q_i x_i}{\sum_i Q_i}$$

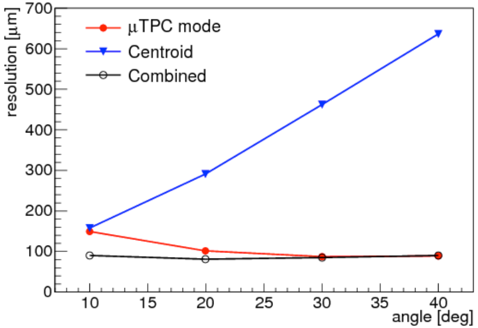




$$z_i = v_D \times t_i$$

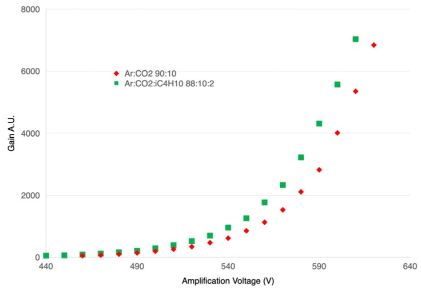
Cluster centroid method works well for perpendicular tracks
It degrades at large angles

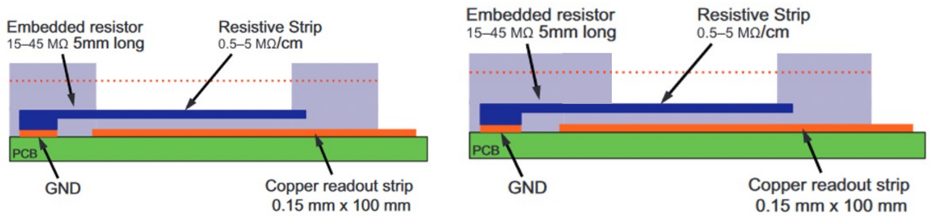




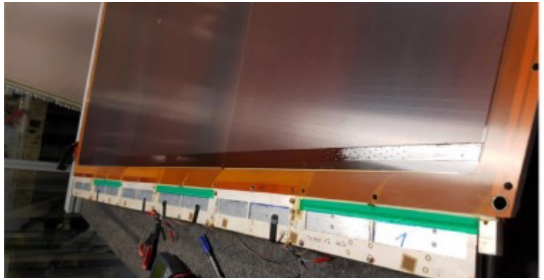
ATLAS Micromegas

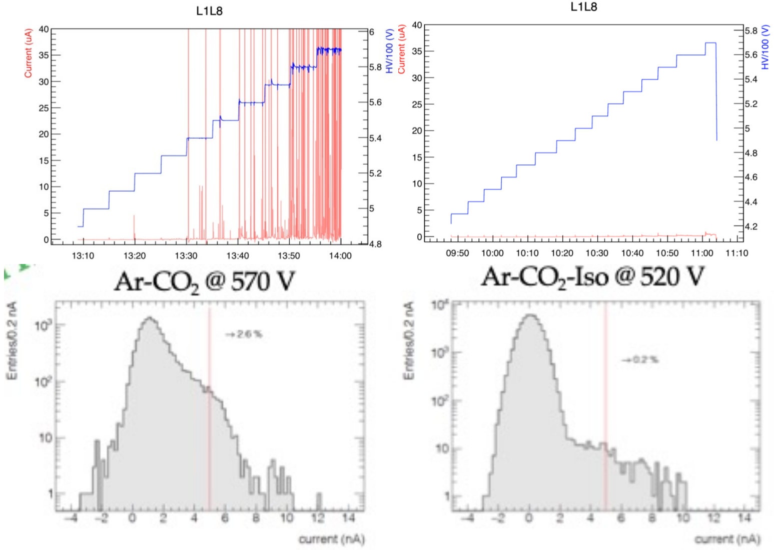
- Several action taken to further suppress HV instabilities, among which:
  - Edge passivation
  - Gas mixture changed from Ar:CO2 93:7 to Ar:CO2:iC4H10 93:5:2
    → reduced voltage at same gain, suppress tail of events with high charge





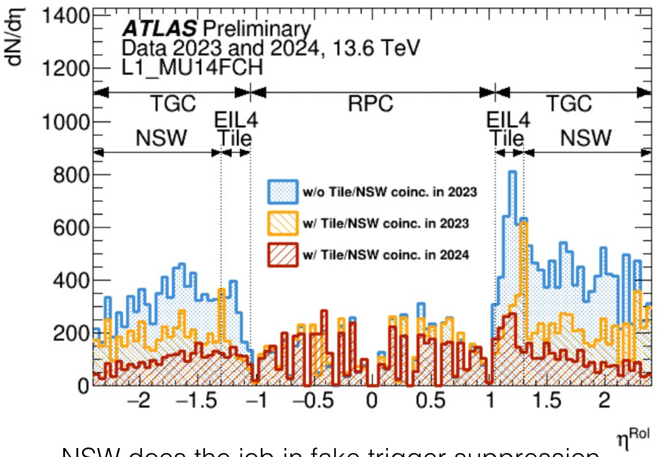
Passivation technique: increase the minimum distance between the active area and the HV line (DOCA= Distance Of Closest Approach)
→ increase of minimum resistance

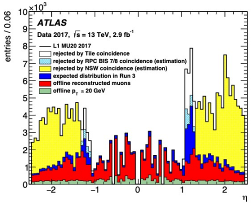




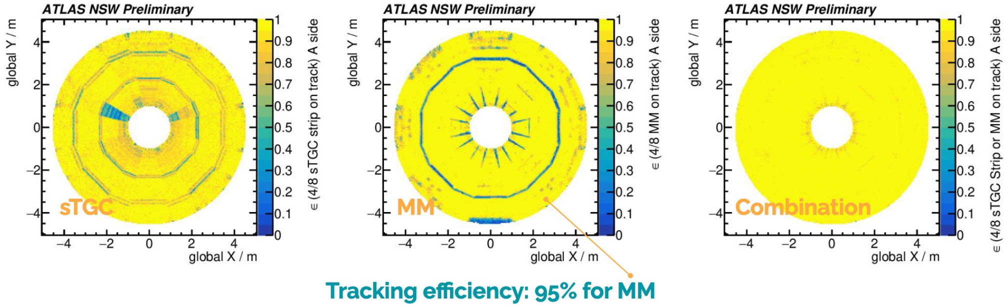
HV stability improved by adding 2% of iC_4H_{10}

ATLAS Micromegas

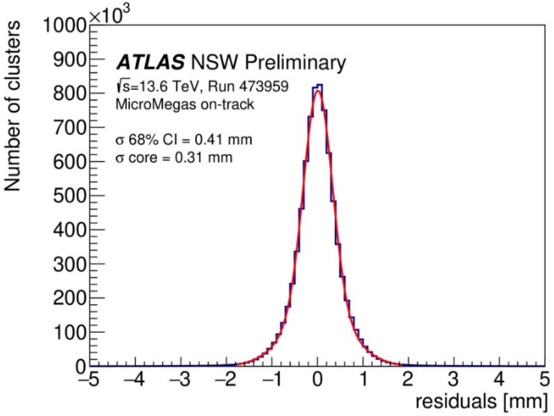


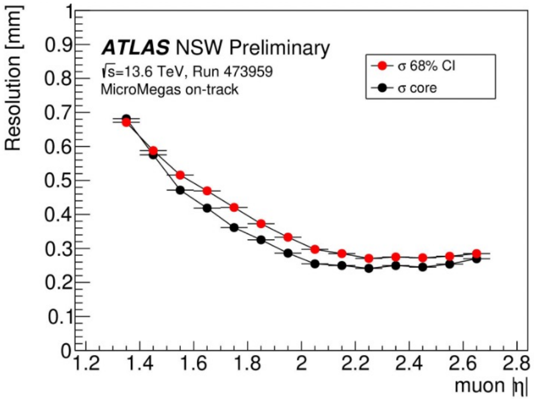


NSW does the job in fake trigger suppression



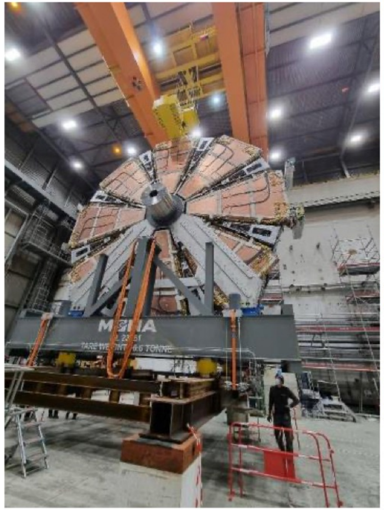
S. Francescato, MPGD Conference, 2024

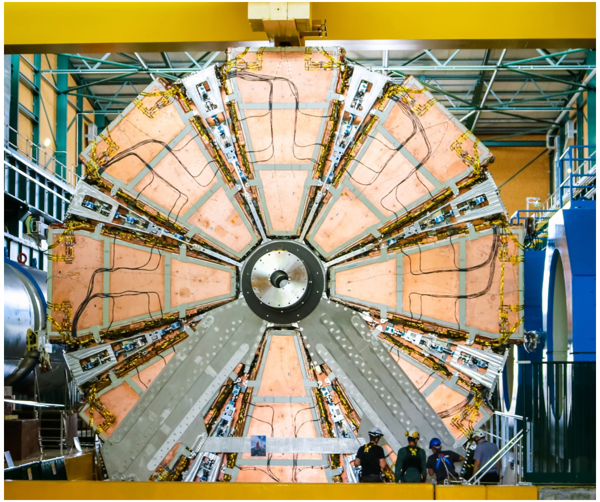


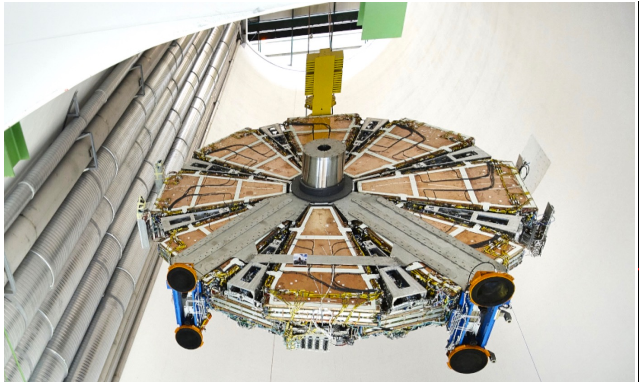


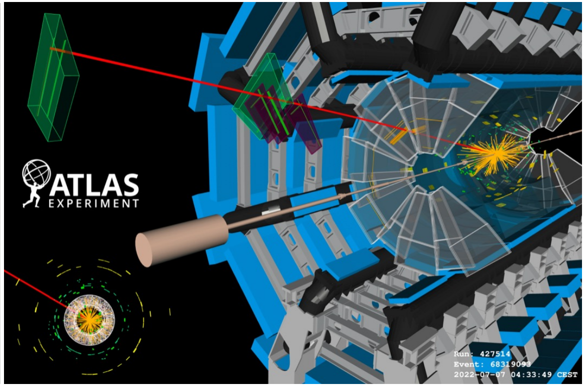
Resolution vs track impact angle with cluster centroid in pp collision in ATLAS (no alignment correction, no time correction)

ATLAS Micromegas



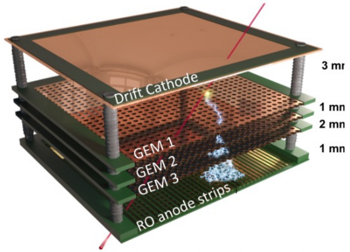


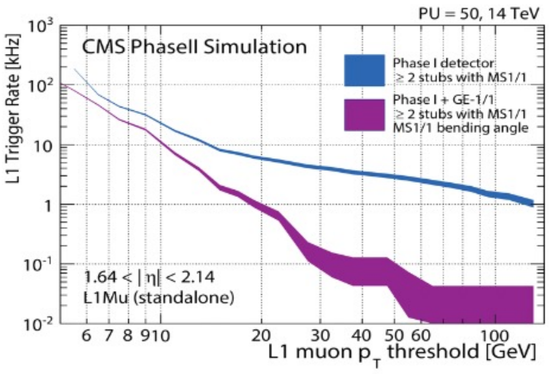


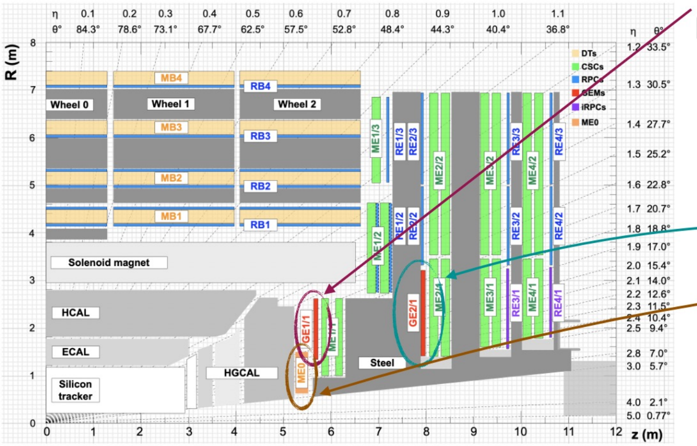


CMS GEM

- GEM End-cap: Improve muon tracking and trigger performance in forward region. Extend coverage to η=2.8
- Project on several phases
  - Slice test → Run2
  - GE1/1 → Inner endcap Muon station → Phase1
  - GE2/2 → Second endcap Muon station → Phase 2
  - ME0 → High rapidity region (|η|=2.03-2.8) → Phase 2
- Triple GEM 3/1/2/1 configuration
- Gas: Ar:CO_2 70:30

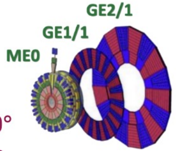






Phase-1 upgrade : GE1/1

- 1.55 < |η| < 2.18
- 36 staggered chambers per endcap, each chamber spans 10°
- Installed in 2019-2021, recording LHC Run-3 data since 2022



Demonstrator: 4 +1 GEM 'super-chambers' installed and successfully operated in Run2

Phase-2 upgrade: GE2/1 & ME0

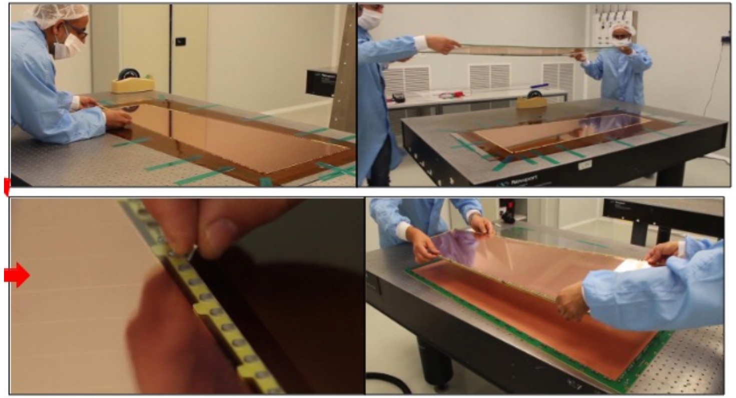
- 1.55 < |η| < 2.45
- 18 staggered chambers per endcap, each chamber spans 20°
- Few chambers installed, fully installation: after LS3

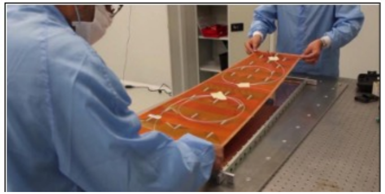
- the only Muon station at the highest η: 2.0 < |η| < 2.8.
- 6 layers of Triple-GEM, each chamber spans 20°
- Installation: LS3 (2027)

Y. Hong MPGD conference 2024

CMS GEM

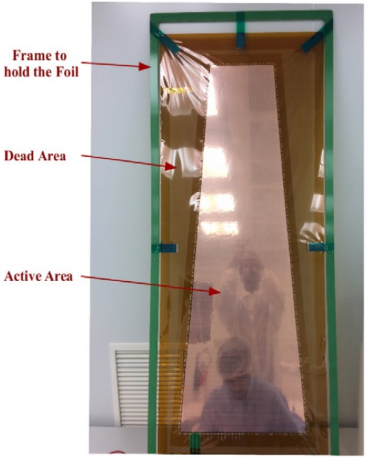
- GE1/1: 2 wheel each of
  - 72 detectors → 36 'super-chambers'
  - Total active surface ~50 m^2

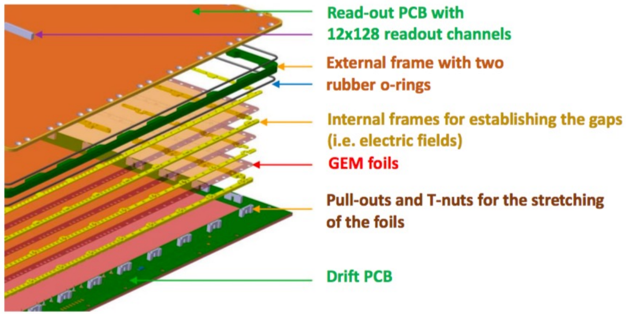


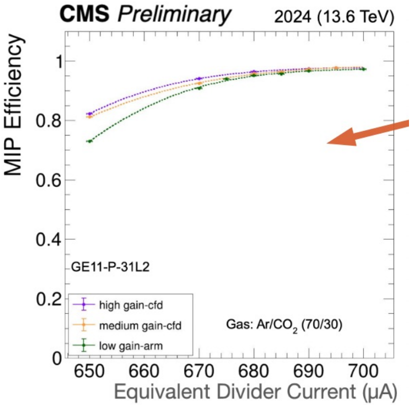


Foils stretched against the "pull out" and chamber closed placing the Readout Board

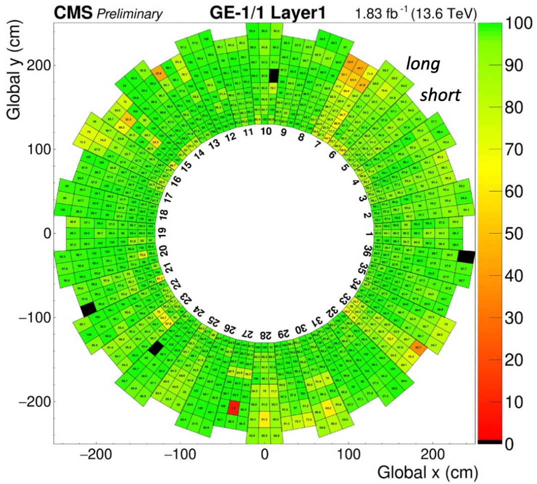
M. Bianco CERN EP Detector Seminar, 08/7/2022







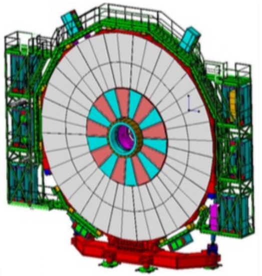
Y. Hong MPGD conference 2024

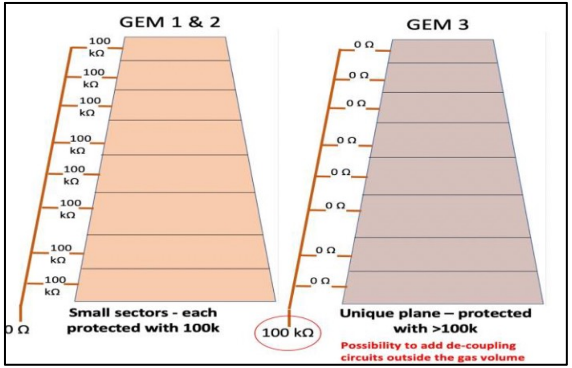


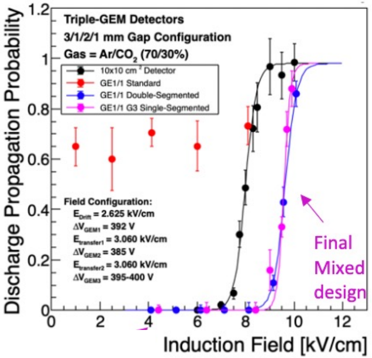
P. Verwilligen MPGD conference 2022

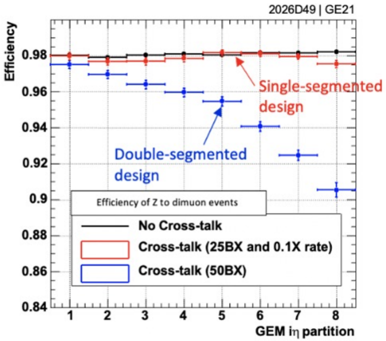
CMS GEM

- GE2/2: 2 end-caps each of
  - 36 chambers on 2 layers
  - 4 modules/chamber → 288 modules
  - Total active surface ~110 m^2



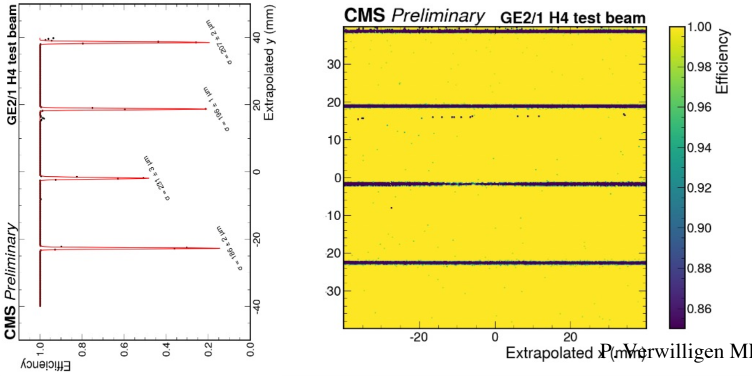






Double segmentation is an effective way to limit the discharge propagation probability: segmentation of power line with decoupling resistors following the GEM foil segmentation

But an increase of cross-talk has been observed with double segmentation on all three foils, reducing the performance



P. Verwilligen MPGD conference 2022

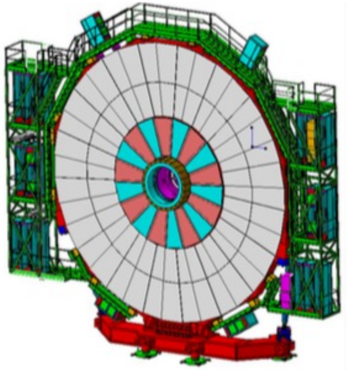
Solution found with mixed design:
Double segmented foils 1 and 2

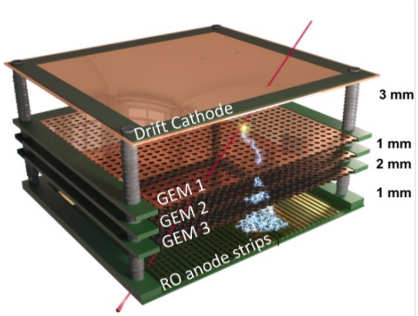
→ Discharge propagation suppression
→ Good efficiency reached

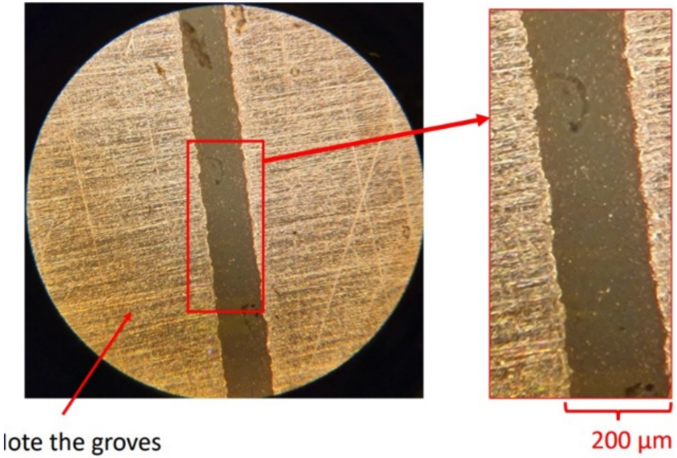
Foil 3 single segmented to reduce cross-talk

CMS GEM

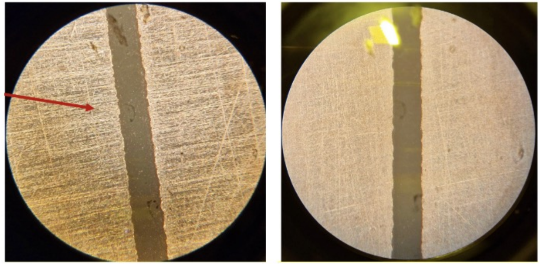
- GE2/2: 2 end-caps each of
  - 36 chambers on 2 layers
  - 4 modules/chamber → 288 modules
  - Total active surface ~110 m^2







Solution found with proper chemical cleaning:
Procedure established, all produced modules have to be refurbished

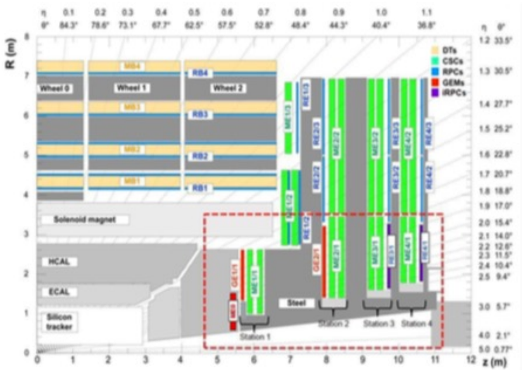


Problems observed during detector testing allowed to identify the presence of microscopic (a few µm) copper dust between strips

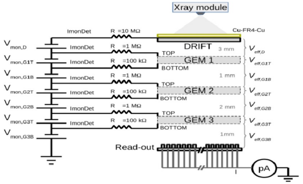
CMS GEM

- ME0: 2 end-caps each of
- 6 modules x 18 stations → 216 modules
- Module area 0.296 m^2 → total active area: 64 m^2

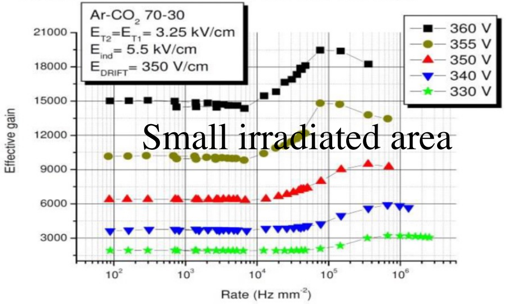
Forward region → expected rate up to ~150 kHz/cm^2

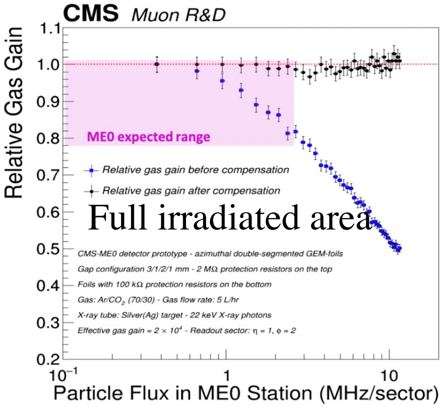


Effect of voltage drop on the protection resistor not visible when irradiating a small detector surface
With full-area irradiation the current increases, and so the voltage drop does
→ efficiency drop at high rate
Can be recovered with HV tuning on each sector (voltage-drop compensation)



https://cds.cern.ch/record/1316179/files/CERN-THESIS- 2006-088.pdf



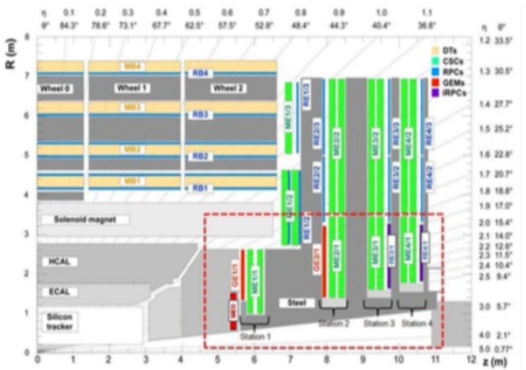


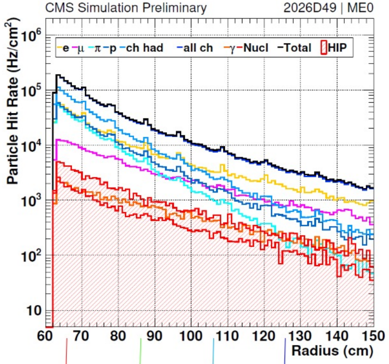
P. Verwilligen MPGD conference 2022

CMS GEM

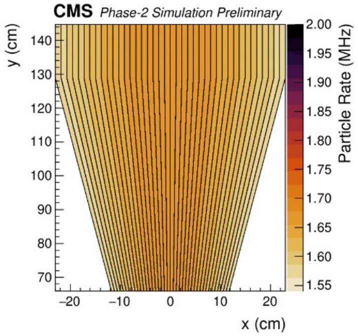
- ME0: 2 end-caps each of
- 6 modules x 18 stations → 216 modules
- Module area 0.296 m^2 → total active area: 64 m^2

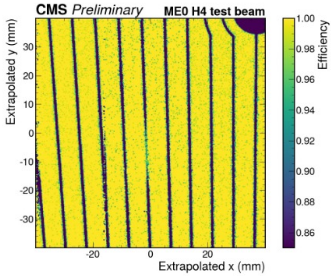
Forward region → expected rate up to ~150 kHz/cm^2

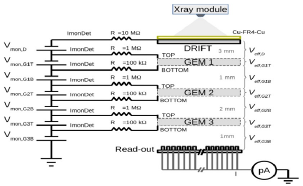


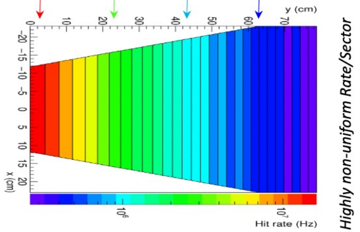


Effect of voltage drop on the protection resistor not visible when irradiating a small detector surface
With full-area irradiation the current increases, and so the voltage drop does
→ efficiency drop at high rate
Can be recovered with HV tuning on each sector (voltage-drop compensation)







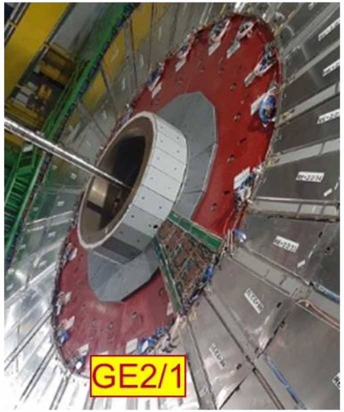


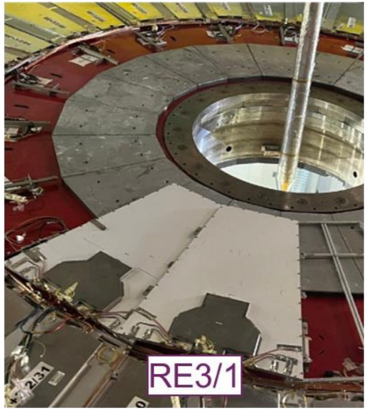
With standard GEM segmentation the section are subject to very unequal irradiation, following η

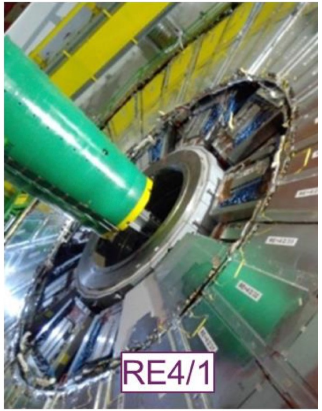
New design: vertical segmentation
→ Rates on HV sectors equalized
→ Uniform voltage-drop compensation
→ Good efficiency at the cost of increasing segmentation (more dead areas)

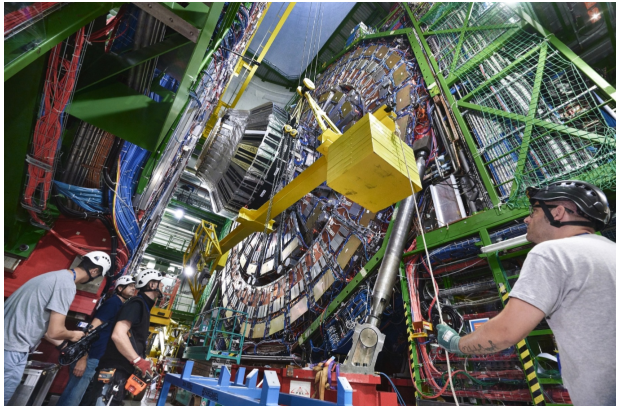
P. Verwilligen MPGD conference 2022

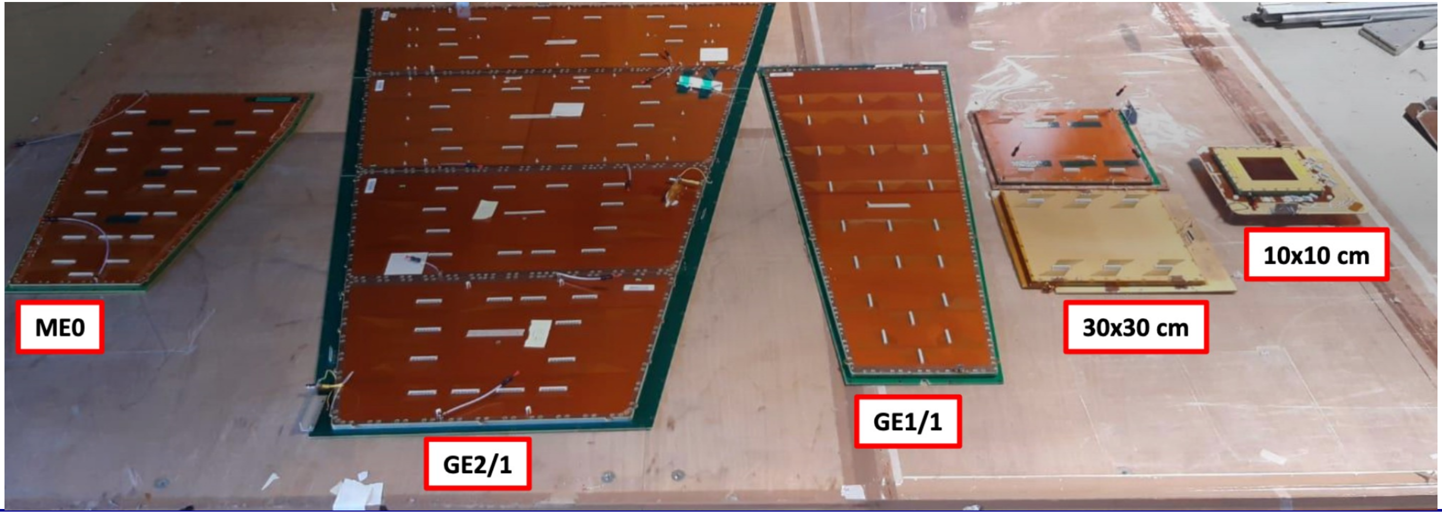
CMS GEM



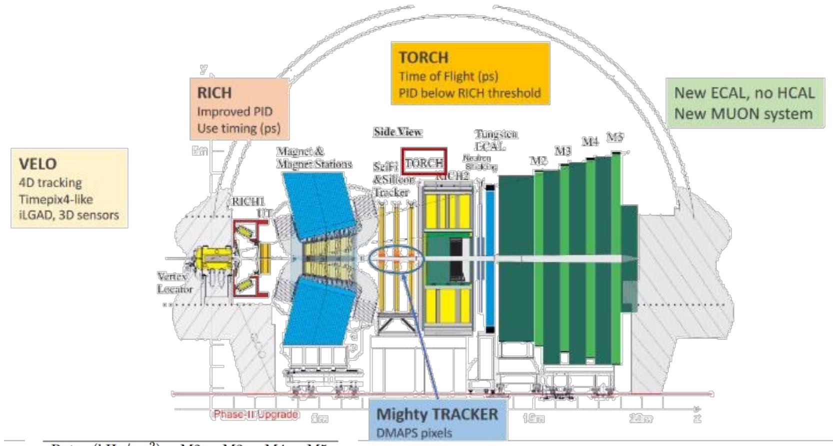




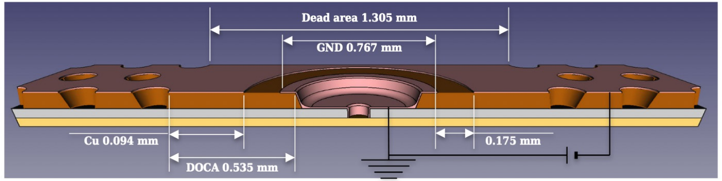




LHCb µRwell



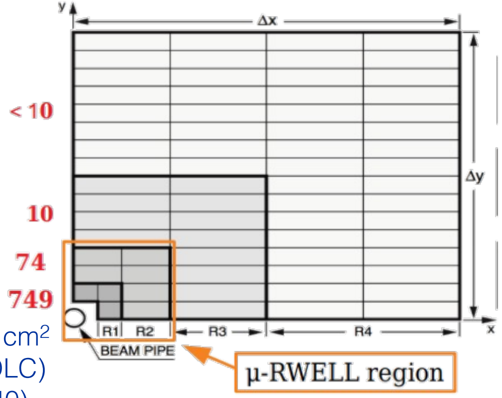
- LHCb Upgrade of the Muon system for Run5 and beyond
  - Rate up to 750 MHz/cm² on detector single gap
  - Efficiency quadrigap >=99% within a BX (25 ns)
  - Stability up to 1C/cm² in 10y
  - Gain=4000

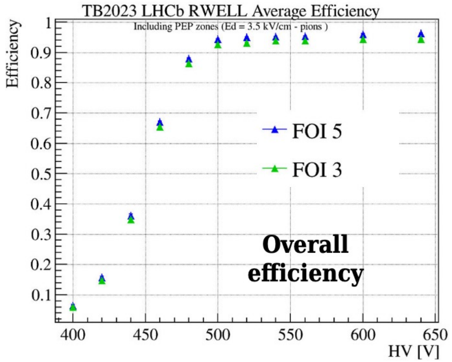


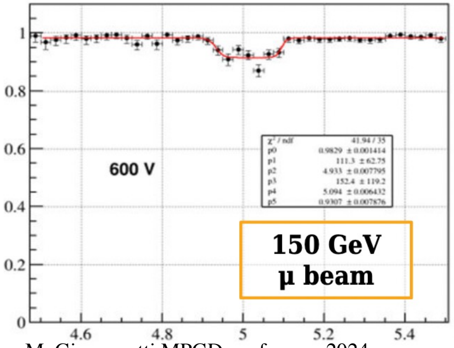
DLC connection to ground with metalized vias from the top Cu layer down to the pad-readout, producing ~2% dead area

Rates (kHz/cm²)	M2	M3	M4	M5
R1	749	431	158	134
R2	74	54	23	15
R3	10	6	4	3
R4	8	2	2	2

Area (m²)	M2	M3	M4	M5
R1	0.9	1.0	1.2	1.4
R2	3.6	4.2	4.9	5.5
R3	14.4	16.8	19.3	22.2
R4	57.6	67.4	77.4	88.7







M. Giovannetti MPGD conference 2024

- uRWELL for R1/R2
  - 4 gaps/chamber
  - 76 detectors, up to 74x31 cm²
  - 90 m2 detector (130 m2 DLC)
  - Gas: Ar:CO2:CF4 (45:15:40)
  - Patterning-Etching-Plating

TPC: intro

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

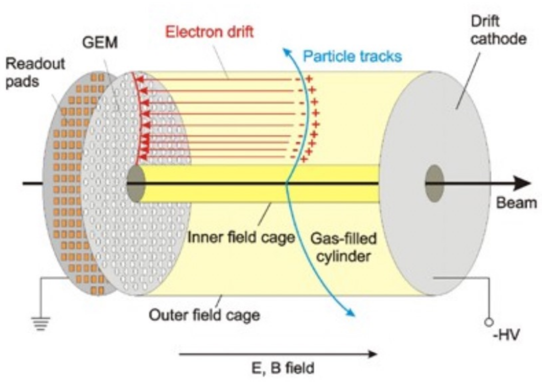
Lawrence Berkeley Laboratory
Berkeley, California 97420

Abstract

A new approach to the problems of track recognition and momentum measurement of high energy charged particles is described, and a detector particularly suitable for PEP energies is discussed.

The central idea is the utilization of a large methane-filled drift chamber placed in a strong magnetic field, with the drift field oriented parallel to the magnetic field. In this configuration transverse diffusion of the ionization electrons can be very substantially suppressed by the magnetic field. This in turn leads to the possibility of measurement accuracies on the order of 100 microns after one meter of drift.

At the same time, the detector can provide truly 3-dimensional spatial data, free from the ambiguities characteristic of conventional techniques involving spatial projections. The reconstruction efficiency can be expected to approach 100%, even for events of the highest multiplicities.



$$\sigma_L = \sqrt{2Ld}$$

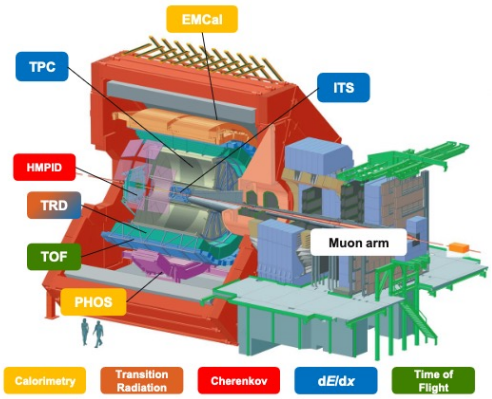
$$\sigma_T = \frac{\sigma_L^2}{1+\omega^2\tau^2}$$

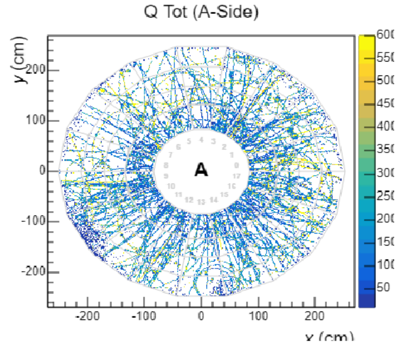
σ = r.m.s. normal distance
$d = vl/3$ = diffusion coeff.
l = electron mean free path
v = electron speed
t = total time
$\omega = eB/m_e$ = cyclotron frequency
τ = mean collision time

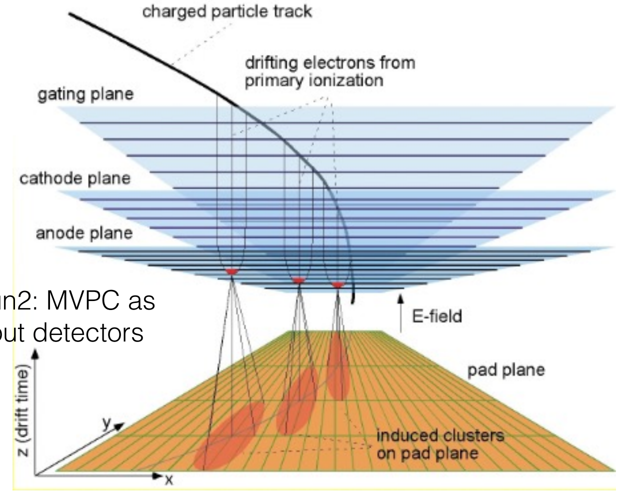
- The magnetic field B parallel to E limit the transverse diffusion
- 3D track reconstruction with a single device
- Good particle identification capability with dE/dx when readout with a proportional detector
- Stability of the operation crucial: E-field distortion, T variation etc affect the performance
- Continuous and precise calibration needed
- TPC originally coupled with MWPC, nowadays MPGD are widely used

ALICE TPC

- Heavy-ion collision experiment @ LHC
- Major upgrade in LS2
- Physics goal: high precision measurement of rare events at low p_T
  - Low S/B ratio → hw trigger not efficient at low p_T
  - Large data sample required for rare-events → acquire all Pb-Pb collisions



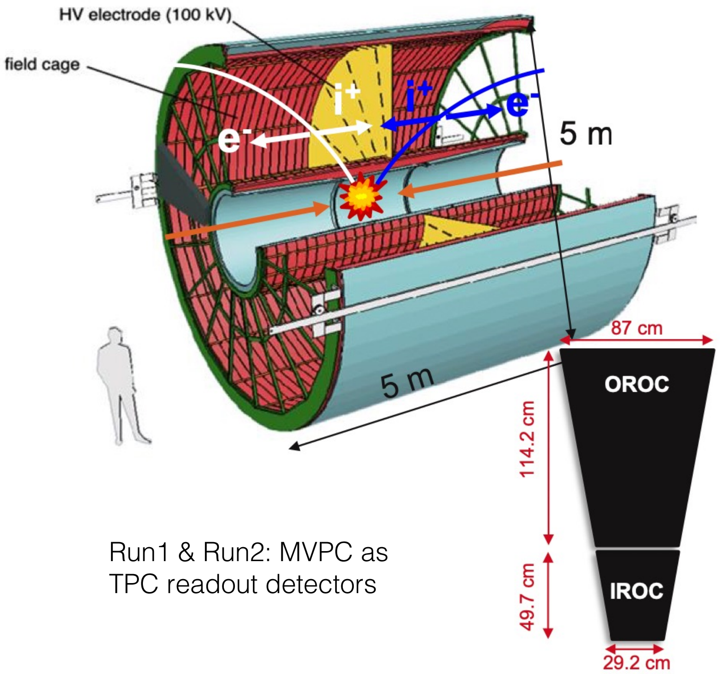




Run1 & Run2: MVPC as TPC readout detectors

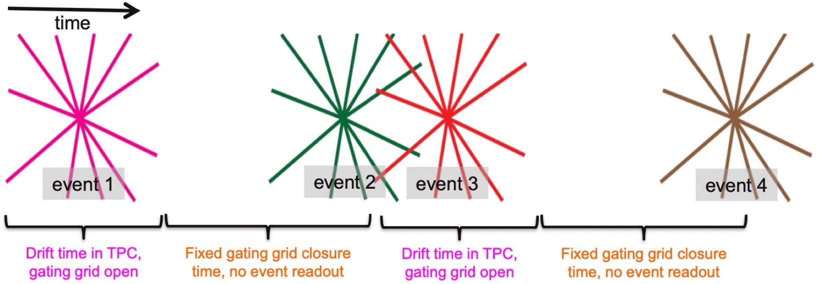
- TPC is the main device in ALICE for tracking and particle identification (PID)
- In a TPC a crucial aspect is the ion backflow suppression: ions from avalanche amplification affect the E field stability in the TPC volume
- Reminder: ions are ~1000 times slower than electrons In a large volume TPC ions from different events will pile-up → large space charge density
- A gating grid is used to suppress the ion tail

ALICE TPC



Run1 & Run2: MVPC as TPC readout detectors

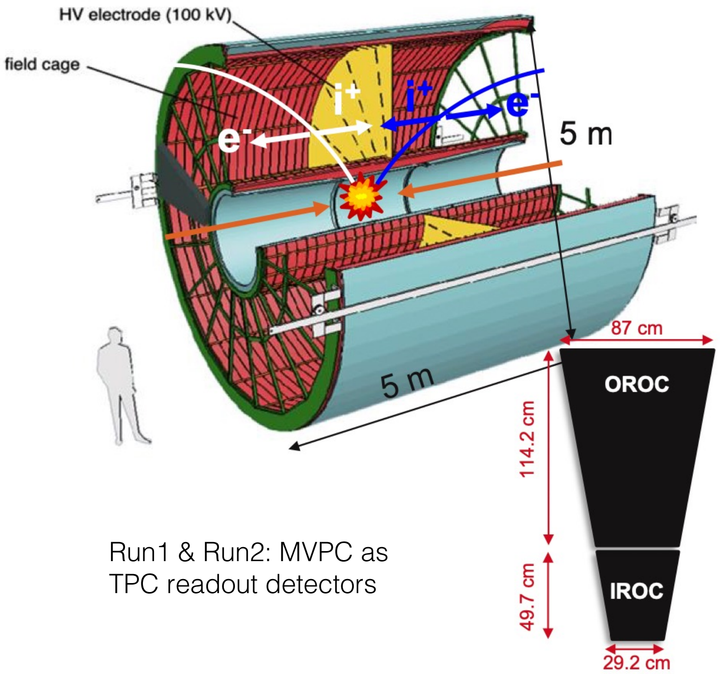
GATED OPERATION IN RUN 1 & RUN 2



- **Multi Wire Proportional Chamber readout**
- A pulsed gating grid is used to prevent back-drifting ions from the amplification stage to distort the drift field (ion backflow (IBF) suppression ~10^{-5})
- 100 µs electron drift time + 200/400 µs gate closed (Ne/Ar) to minimize ion backflow and drift-field distortions
- **300/500 µs** in total limits the maximal readout rate to **few kHz** (in pp)
- Limitation of readout electronics: ~kHz in Run 2 **(2017 pp: 2040 Hz)**

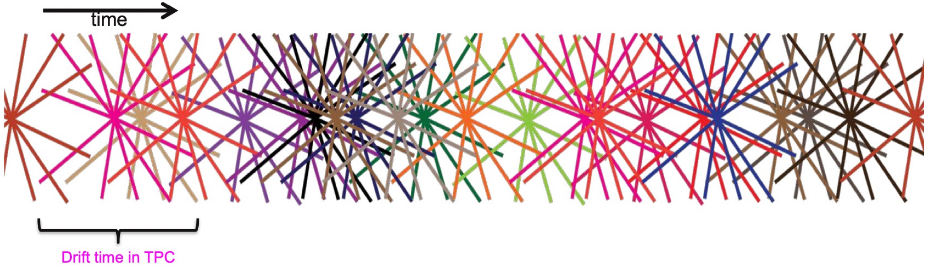
R. H. Munzer CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978

ALICE TPC



Run1 & Run2: MVPC as TPC readout detectors

CONTINUOUS OPERATION IN RUN 3 AND BEYOND



- Maximum drift time of electrons in the TPC: ~100 μs
- Average event spacing: ~20 μs
- Event pileup: 5 on average
- Triggered operation not efficient
- Minimize IBF without the use of a gating grid

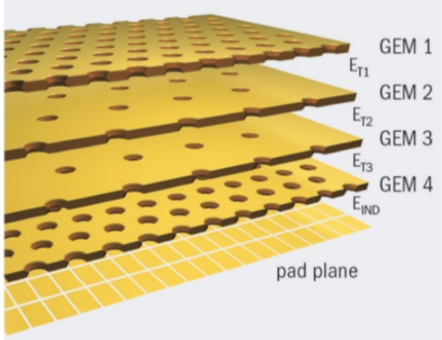
Gated operation used in Run1 & 2 becomes inacceptable in Run3

→ Move to non-gate continuous operation

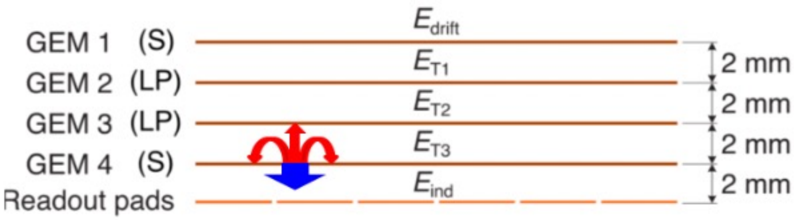
→ Detector design to suppress ion back-flow

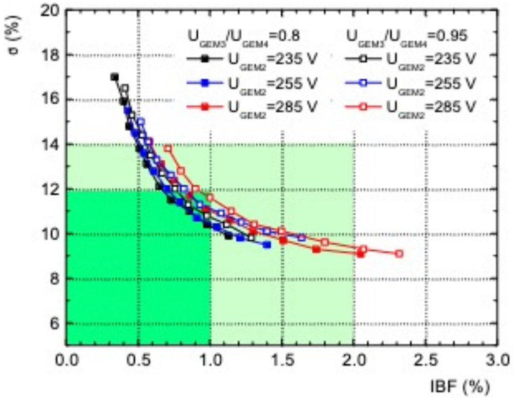
R. H. Munzer CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978

ALICE TPC



- ALICE: ungated GEM-based TPC
- Continuous operation at >50 kHz Pb-Pb
- Cascade of 4 GEM foils → reduction of Ion backflow from ~5% (3 GEM) to <1%
- PID with dE/dx: fine tuning of geometry and HV sharing between foils; Energy resolution ~5-8 %
- TPC volume: ~90 m^3; Active GEM area: ~32 m^2
- B=0.5 T; Gas: Ne:CO_2:N_2 (90:10:5)



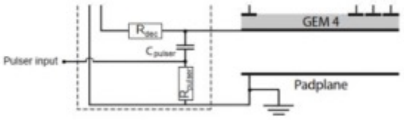


Three measures to suppress the ion back flow into drift region:
- Low gain in GEM 1, highest in GEM 4
- Two layers of large pitch (LP) foils (GEM2 and GEM 3) block ions from GEM 4
- Very low transfer filed ET3 (100 V/cm) between GEM3 and GEM4

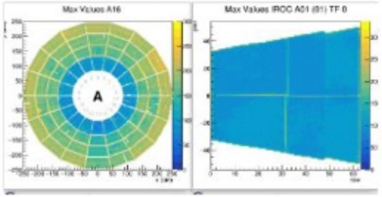
R. H. Munzer CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978

ALICE TPC: calibration, calibration

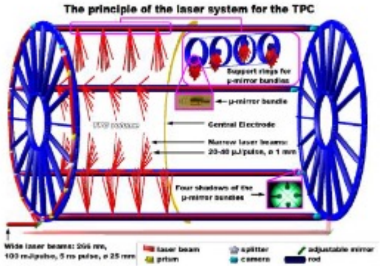
PULSER SYSTEM



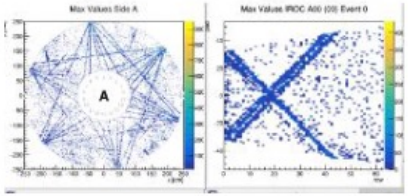
- Pad response measurement
- Common Mode calibration



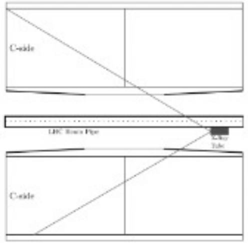
LASER SYSTEM



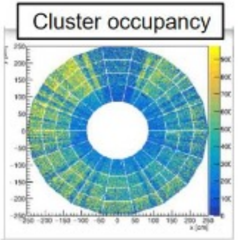
- Alignment
- Drift velocity measurement
- Drift field distortions
- Common Mode calibration



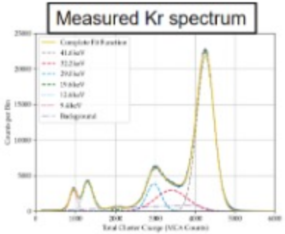
X-RAY



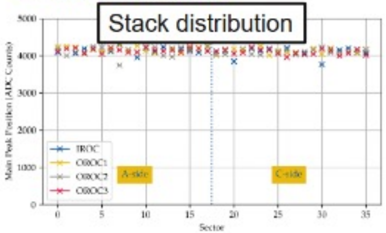
- Full gain map
- Stability



KRYPTON



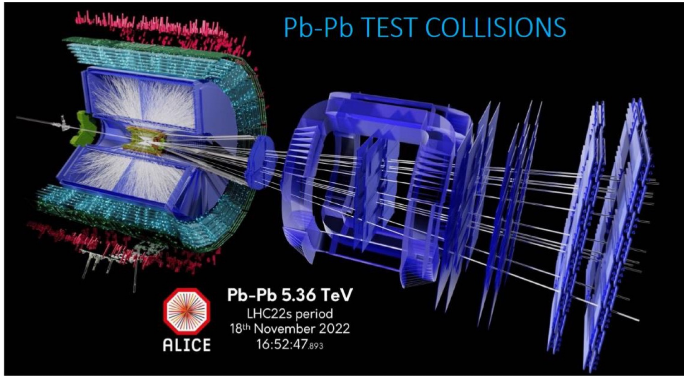
- Energy resolution: σE/E = 12% @ K(α) of 55Fe corresponds to: σE/E = 4.5% @ 41.6 keV (Krypton main peak)
- Gain Equalization



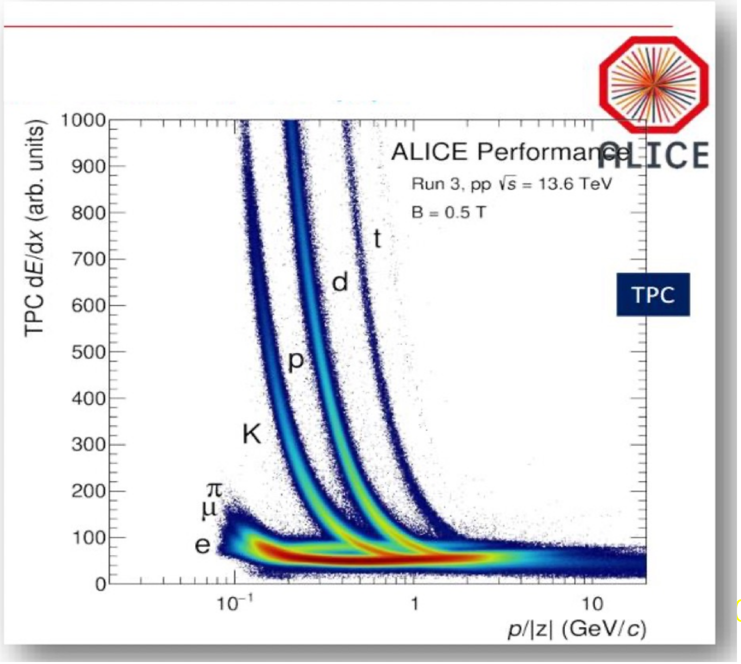
R. H. Munzer, Continuous data taking with the upgraded ALICE GEM-TPC, CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978/

E. Oliveri, MPGD Conference 2022

ALICE TPC



ALICE PERFORMANCE IN 13.6 TeV pp



Quality, quality, quality !

- Quality control during detector construction is crucial
- Any defect will be a weak point during operations
- Detectors, components and services expected to run for many years (>20 in LHC) in harsh environments with sometime limited possibility for maintenance and replacement

MPGDs have an amplification cell of 50-100 μm
→ defects of few μm can lead to malfunctioning (sparks, shorts) an entire section of your detector

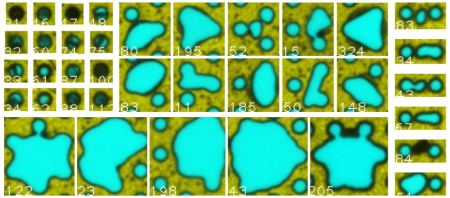
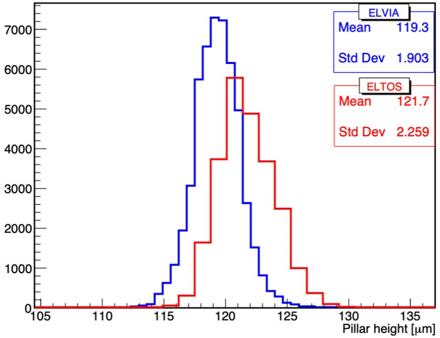


Figure 15. Collage of typical defects identified during the Advanced QA, including blocked (16 images at top left) and over-etched holes.

Example of defective GEM holes identified during QC of ALICE GEM foils
JINST 16 (2021) P03022

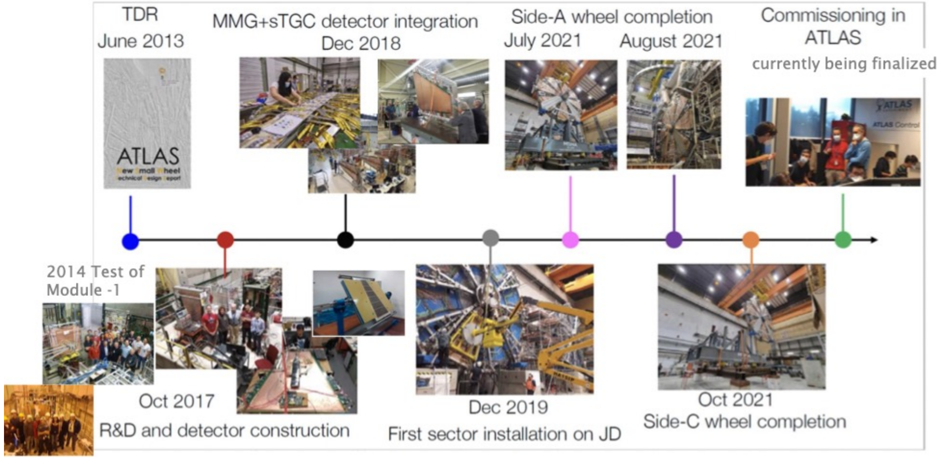


Distribution of the pillar height of the Micromegas boards for ATLAS
JINST 18 (2023) 09 C09014

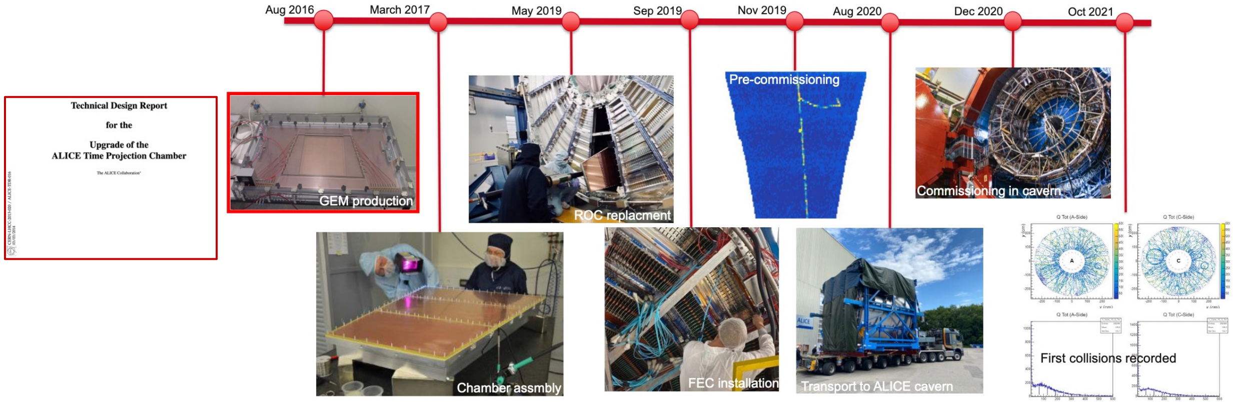
Detector experts inspecting an MPGD board at the production site

Large detectors → large problems!
Many components → high probability of having problems!

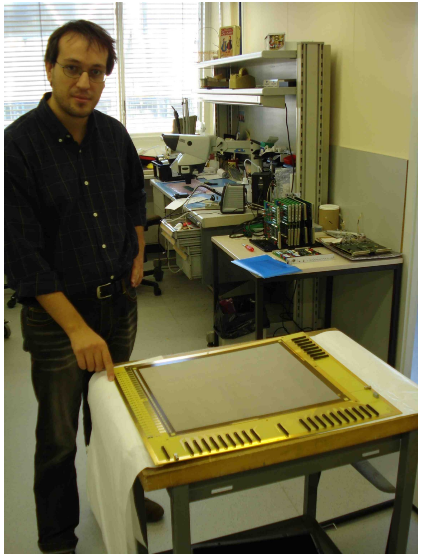
It's a long, long way…



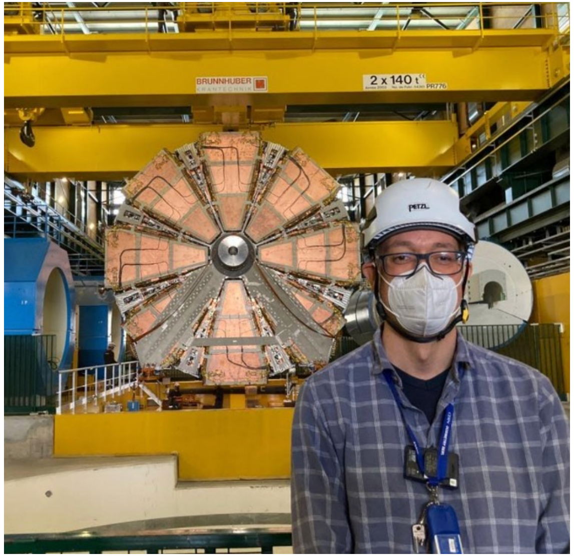
- Examples: ATLAS and ALICE
- Technical Design Report in 2013
- Installation in 2021/2022



It’s a long, long way…

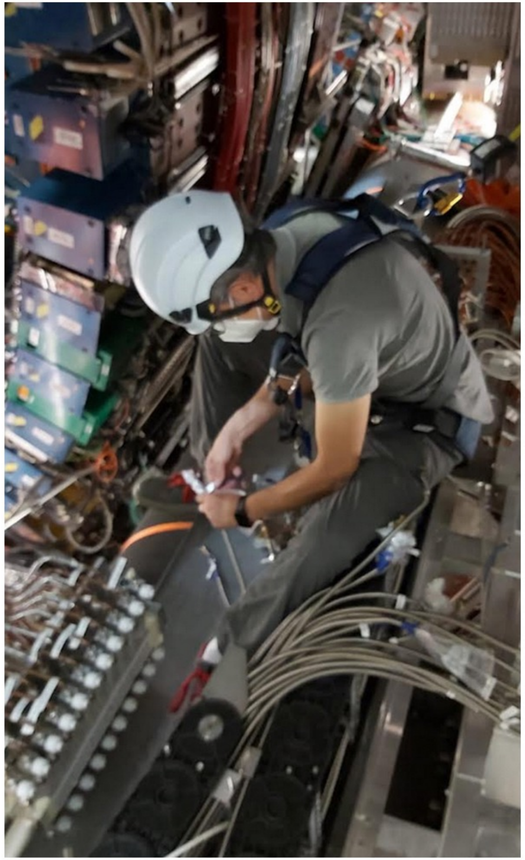


2007 R&D phase: Largest Micromegas ever built (0.24 m^2)



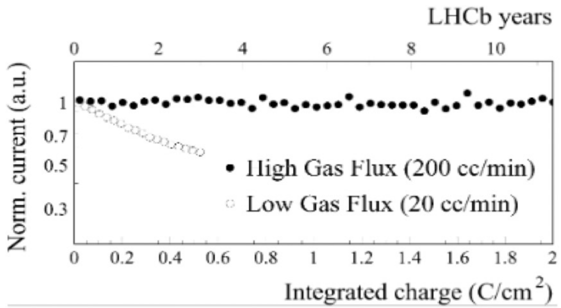
2022 Project completion: Largest Micromegas system ever built (1280 m^2)

Acrobatic plumbery, part of a detector physicist work!

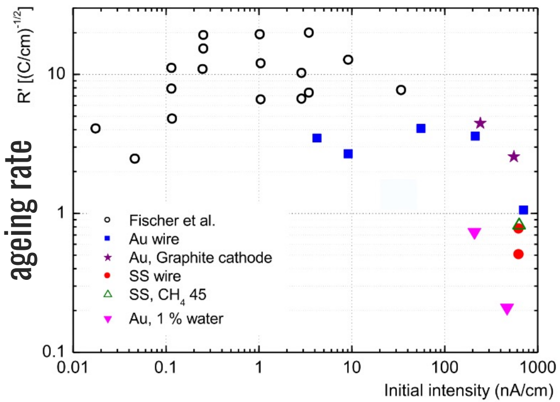


Gaseous detector longevity

- Ageing phenomena in gaseous detectors can be the subject of a dedicated conference:
  3rd International Conference on Detector Stability and Aging Phenomena in Gaseous Detectors:
  6-10 Nov. 2023 CERN (https://indico.cern.ch/event/1237829/)



- Main source of classical ageing:
  - Degradation of material with integrated charge / time
  - Chemical effects of gas compounds
- Ageing is however a subtle phenomena, depending on many parameters (gas mixture, materials, operating conditions, rates…) and detector ageing must be studied for each specific application
- Example: relevance of controlling the operation parameters (e.g. gas flow) in GEM. LHCb test
- Ageing test must be long-term: acceleration might mitigate the aging effect known from wire chambers
  Equivalent study missing for MPGD (to my knowledge)

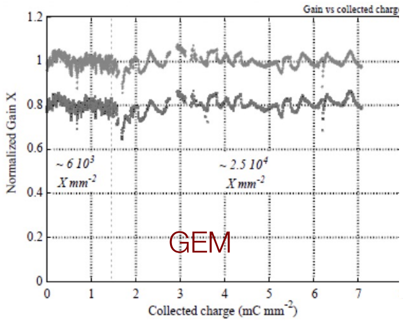


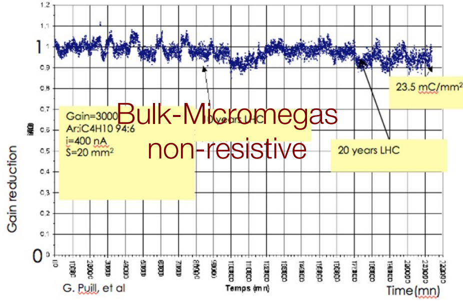
Gaseous detector longevity

- MPGD better behavior compared with wire chambers
- Confirmed with accelerated tests as well as, more recently, with long-term aging tests on GEM, Micromegas and other MPGD with excellent results

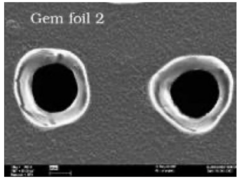
- New materials (resistive coating) and challenging detector operations (high rates, large integrated charge) calls for dedicated studies

- Effects of hydrocarbons must be re-evaluated for the specific application

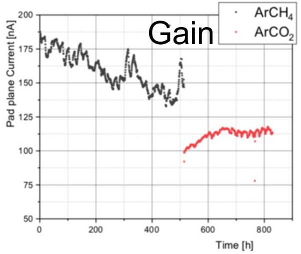


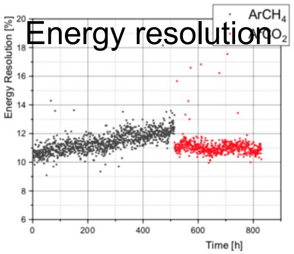


Resistive Micromegas (ATLAS-like): 3-years exposure at GIF++
Total collected charge ~0.3 C/cm^2 → No sign of aging in Ar:CO2

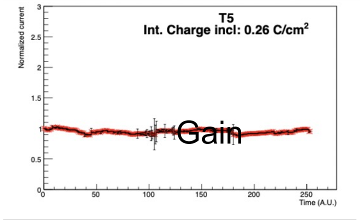


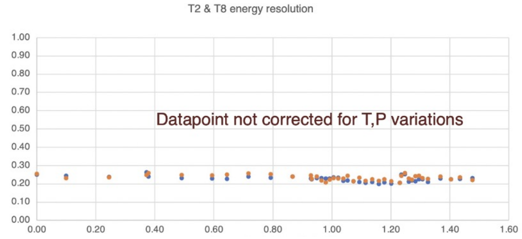
Etching effect on Triple-GEM operated with CF4-based mixture at low flow

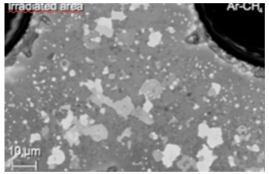




Aging in ALICE GEM prototype operated with hydrocarbons (CH4) in Ar 95% mixture. Aging stops when CH4 is replaced with CO2





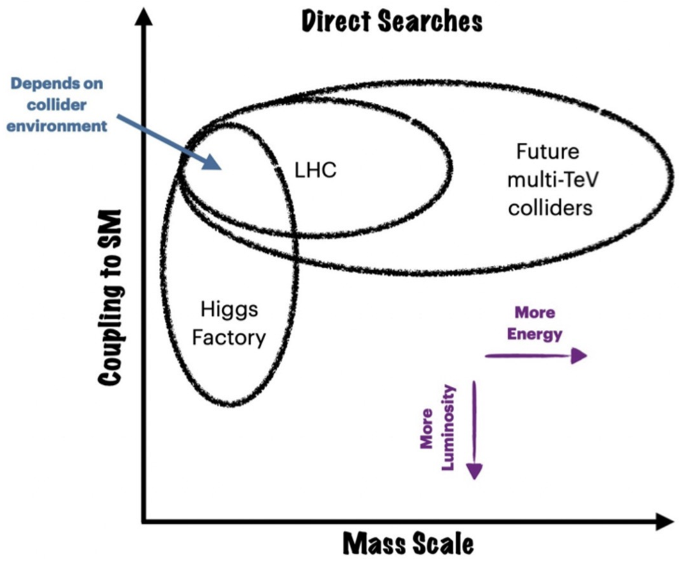


Test with 2% of iC4H10. Results from accelerated test (up to >1C/cm2) and from long-term test at GIF++ : no aging observed

A look to the future

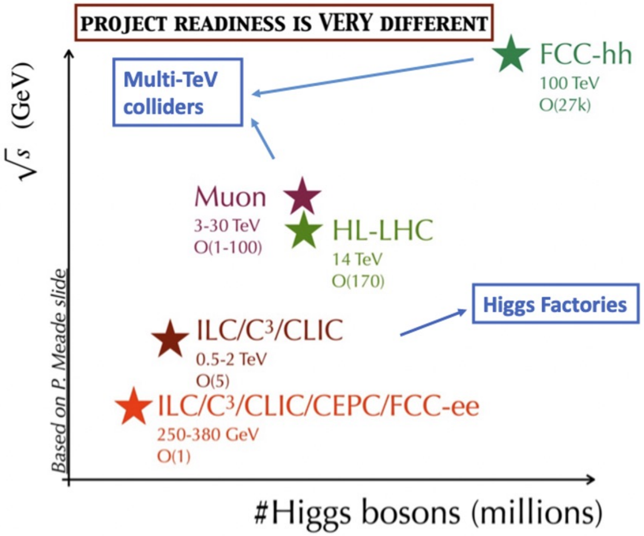
Quest for New Physics

- New physics can be at low as at high mass scales,
- Naturalness would prefer scales close to the EW scale, but LHC already placed strong bounds around 1-2 TeV.



Higgs coupling measurements and direct searches will complement each other in exploring the 1-10 TeV scale and beyond.

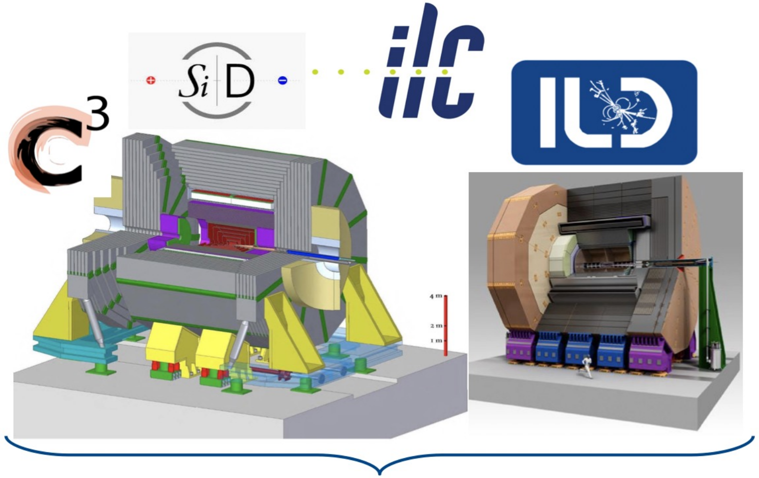
Several future colliders under study

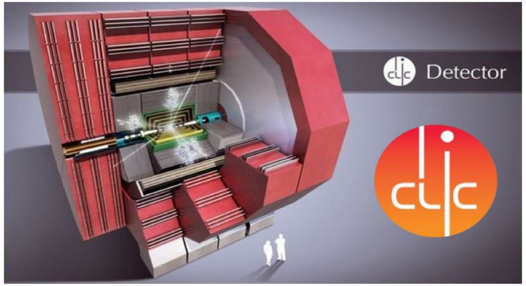


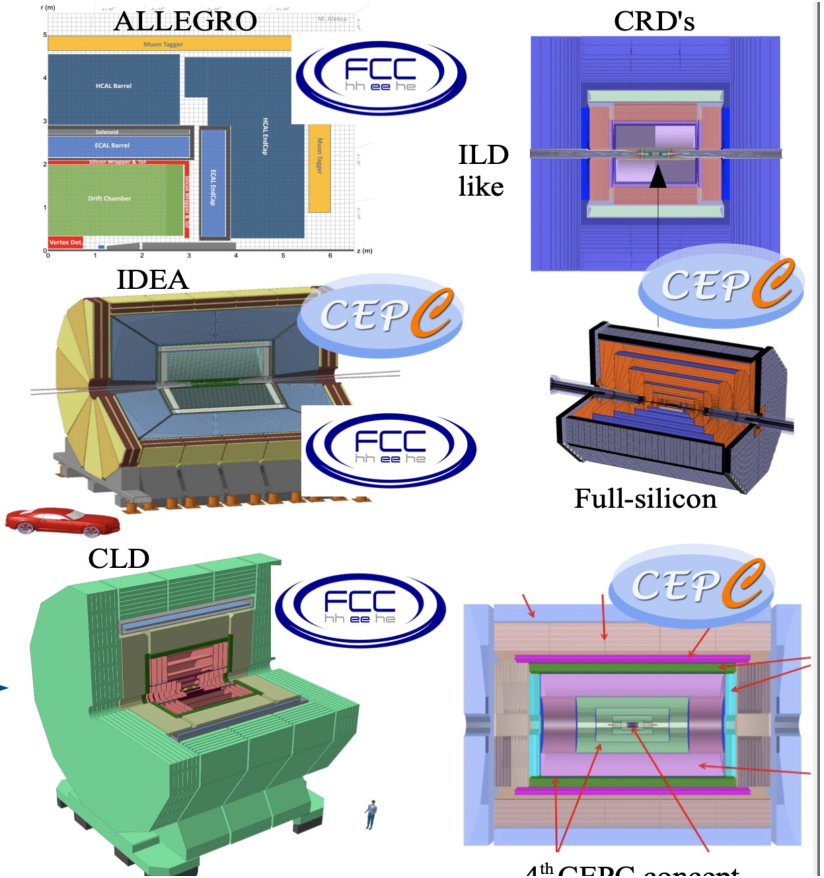
Detector requirements depend strongly by the machine parameters

- Hadron Colliders → high pile-up, high rate
- Lepton Colliders → cleaner environment

Experiments proposed for future colliders

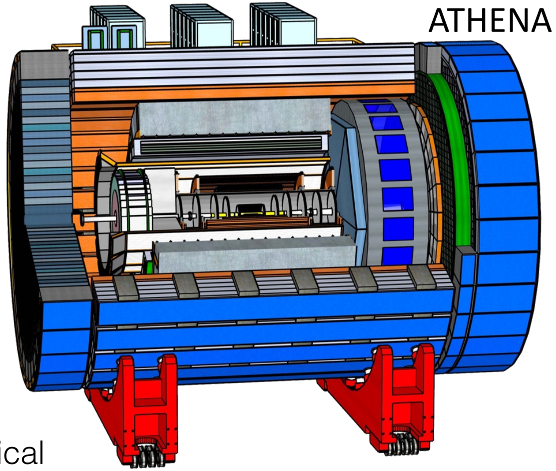


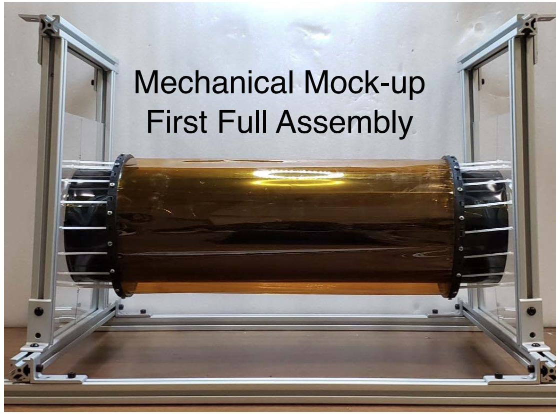




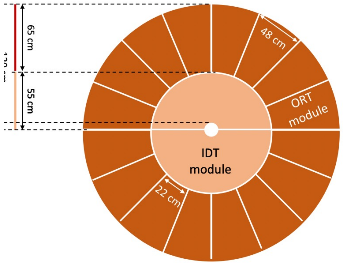
Electron-Ion Collier Trackers

- 3 proto-colloborations: ATHENA, CORE, ECCE
  → ATHENA as example
- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements
- Excellent PID (pi/K/p)
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c





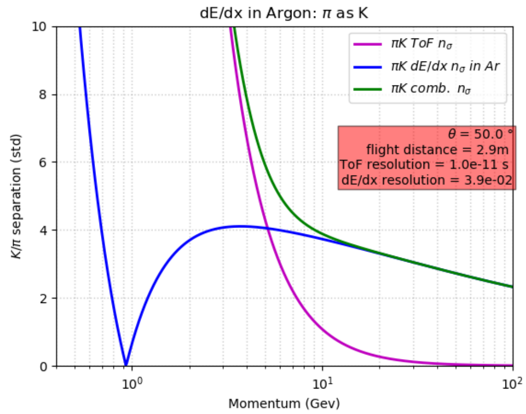
- Outer barrel tracker uses cylindrical Micromegas
- Endcap tracker uses planar u-RWELL
- Envision capacitive-sharing pad readout: Vertical stack of pads layers → reduce readout channels
- GEM or µRWELL proposed as forward tracker in CORE as well

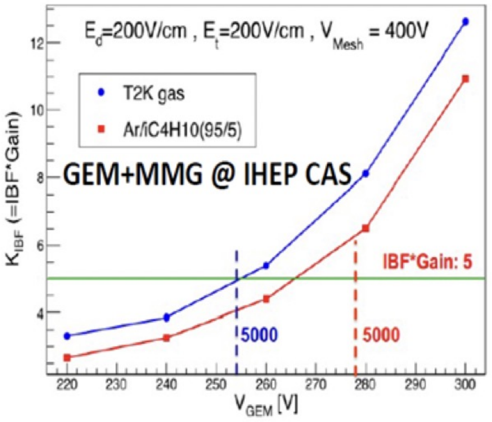


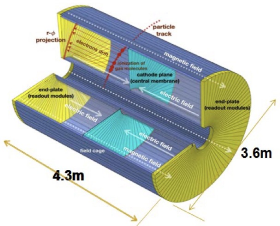
CORE EIC GEM prototype
U-V srtrip redout

TPC at electron circular colliders

- The ILD collaboration is considering to adapt the TPC concept to a circular collider
  - Baseline gas: Ar:CF_4:iC_4H_{10} 95:3:2 → excellent dE/dx
  - For cluster counting He is needed (larger cluster separation)







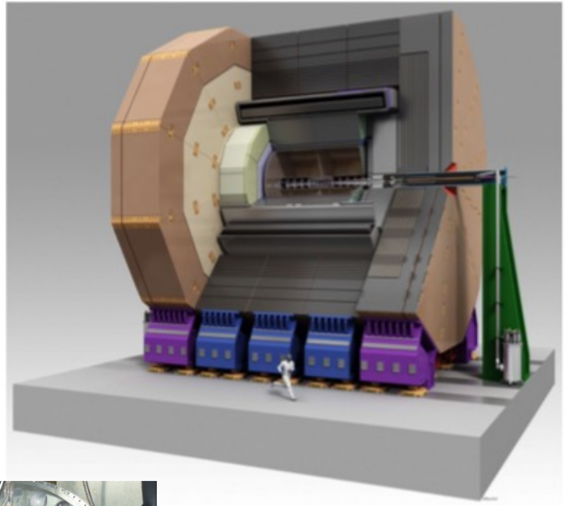
CEPC TPC

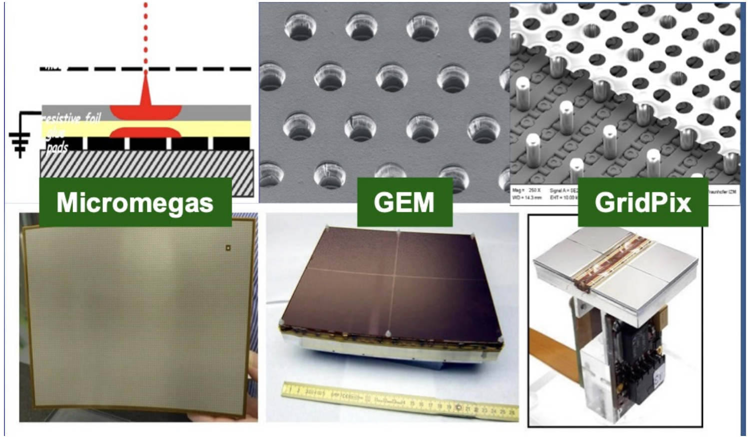
- Running a TPC @ Z pole @ 2×10^{36} cm^{-2} s^{-1} is not trivial
- The ion backflow is an issue
  - The positive ions of 22 000 Zs will accumulate in the TPC volume
  - Continuous DAQ and tracking needed for real-time corrections for space point distortions → experience from ALICE!

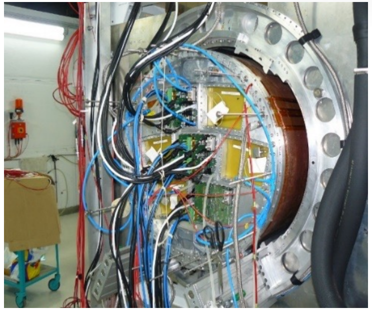
TPC for CEPC: promising results in IBF suppression for hybrid GEM+MM technology (tested by ALICE in the past)

TPC at electron linear colliders

- A TPC ideally combines dE/dx measurement and low material budget, allowing a continuous measurement of the tracks.
  A strong magnetic field aligned with the TPC drift field limits diffusion and allows charged track momentum measurement.
- Together with silicon (vertex) detectors, it provides excellent performance in resolution
- TPC is the main tracker for the ILD detector concept. At ILC, it profits from a beam time structure allowing power switching and gating.



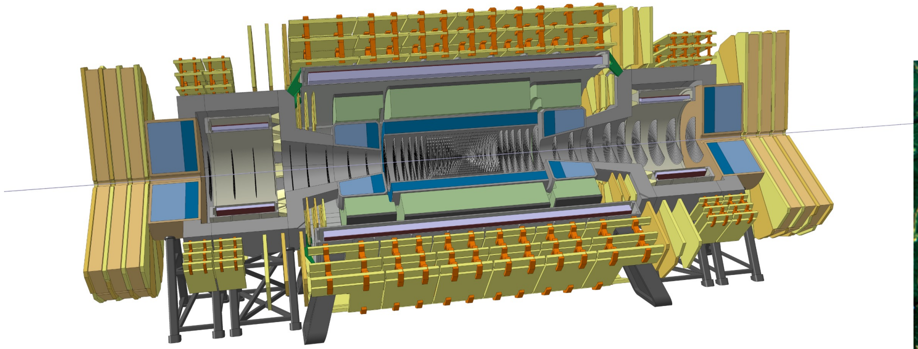




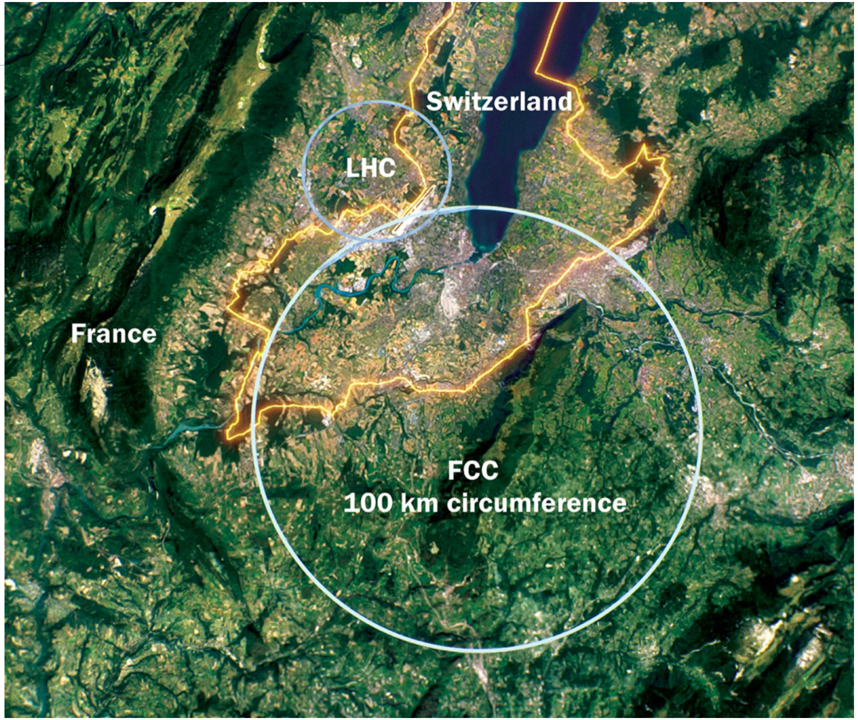
First development of large scale GridPix detector

~10 m^2 detector surface. Three option under study: Micromegas / GEM / GridPix

FCC-hh

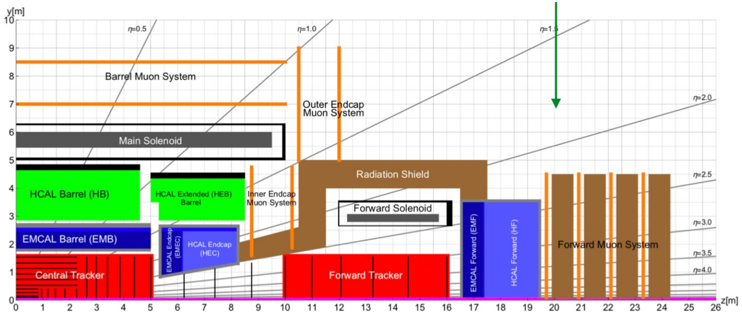


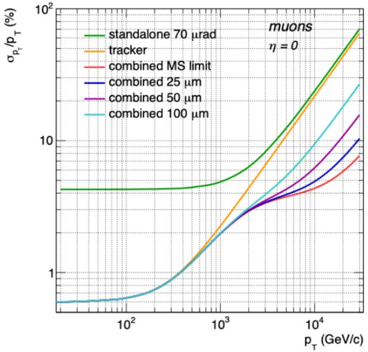
parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L}$ $\times 10^{34}$	$\text{cm}^{-2}\text{s}^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76

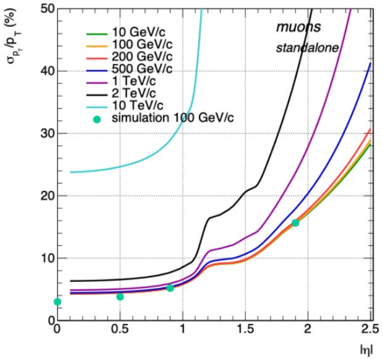


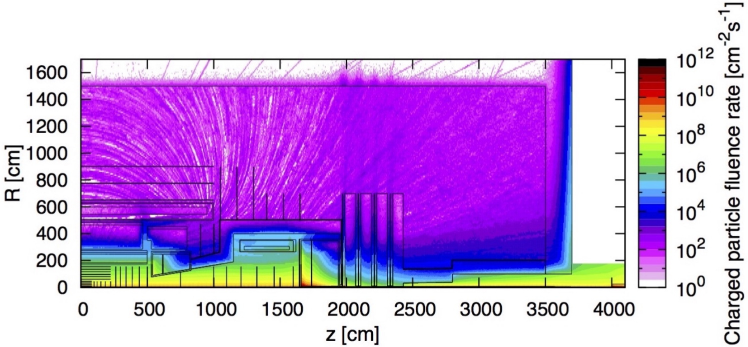
Gaseous Detectors at FCC-hh

- Gaseous detectors in Muon systems (Barrel and forward)
- No standalone muon performance required
  → Muon system providing Muon ID and trigger capability
- Requirement for combined muon momentum resolution: 10% for momenta of 20 TeV/c at η = 0.
- In forward muon system, standalone momentum measurement and triggering can only be achieved when using a forward dipole (like ALICE, LHCb)









- Gas detectors like the ones employed for HL-LHC (sMDT) are good candidates for the muon systems
- Different choices for Barrel&Outer EC and Inner EC
- Dedicated R&D needed to exploit recent trends in frontier gaseous detectors: sub-ns time res., O(1)MHz/cm2 rate capability, longevity, eco-friendly gas etc.

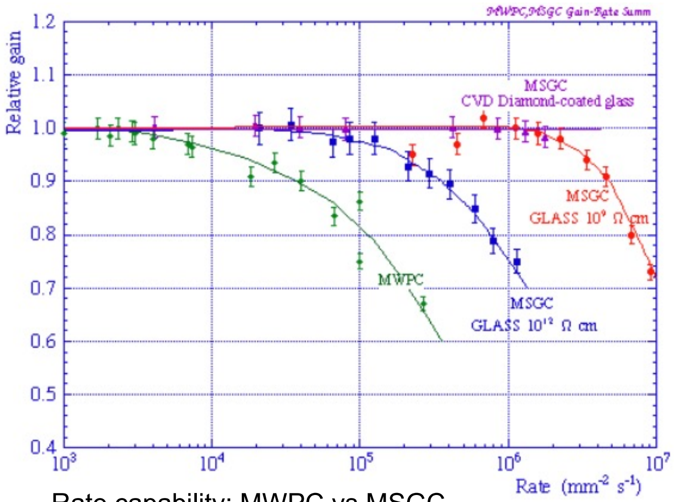
Thank you!

Additional Material

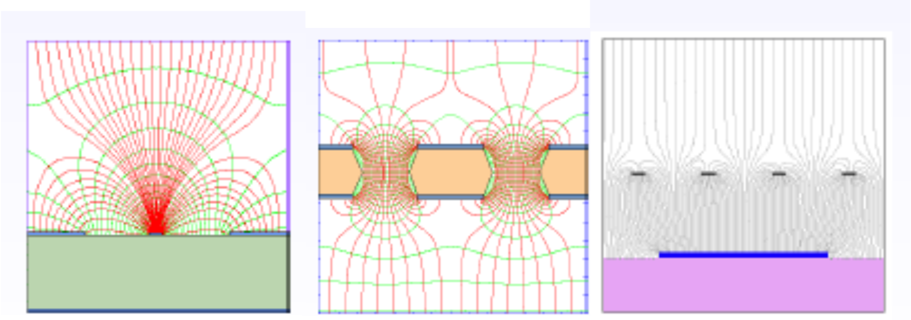
MPGD: increasing the rate capability

- Separation between ionization and amplification regions
- Short (~100 µm) ions drift path → fast ions collection
- → Higher rate capability
- → Granularity, fine space resolution

Construction based on printed circuit board production (photolithography, etching)



Rate capability: MWPC vs MSGC



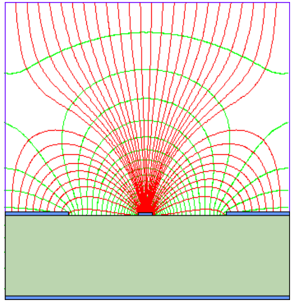
MSGC
A. Oed (1988)

GEM
F Sauli (1997)

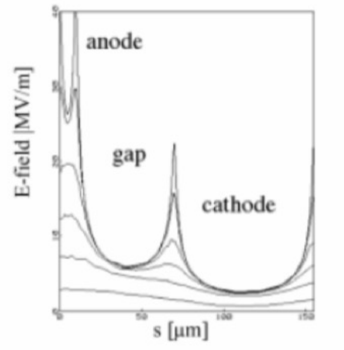
Micromegas
I. Giomataris,
G. Charpak (1997)

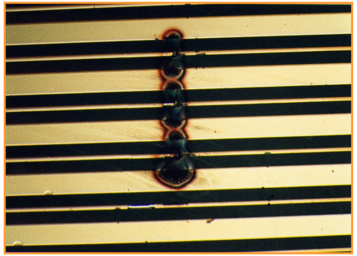
The first challenge: disruptive discharges

- Even in device of good quality, when the avalanche reaches a critical value ~10^7 e^- (Raether limit) a breakdown appear in the gas, often referred as 'spark'
→ limit on max gain for stable operation

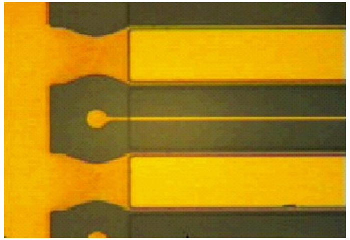


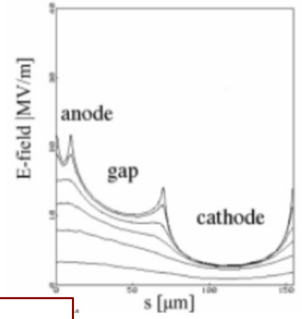
- Example: Gain ~ 10^4; Ionisation gap ~1 cm
Avalanche size Q = # of e^- primaries x Gain
  - MIP: Q = 10^2 x 10^4 = 10^6 → OK
  - p of ~MeV: Q = 10^4 x 10^4 = 10^8 → discharge
  - Field emission from cathode strip: Q = 10^4 x 10^4 = 10^8 → discharge





Passivation of the cathode edges (1999/2000)
→ MSGC operational

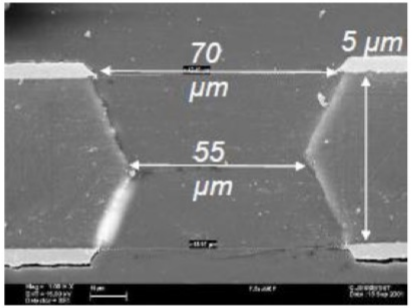


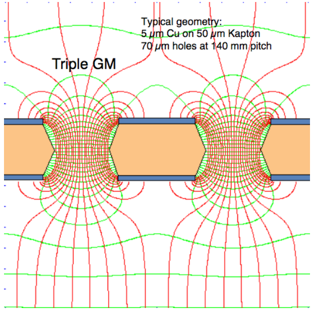


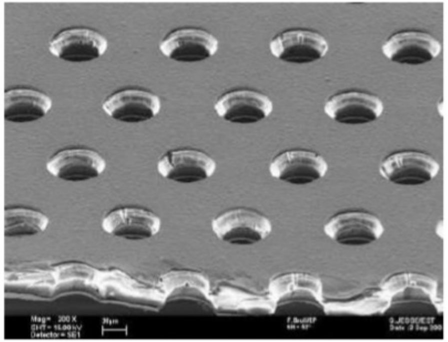
Other spark protection/reduction mechanisms adopted in other MPGD → more on that later

Gas Electron Multipliers

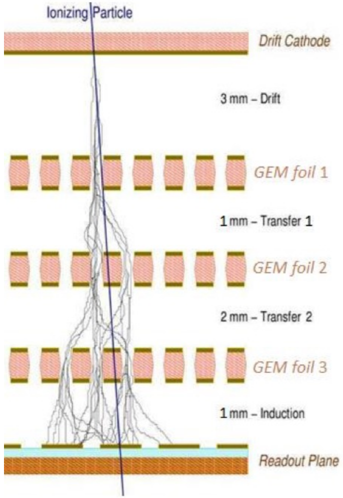
- GEM
- Thin (~50 μm) metal-clad polymer foil chemically perforated with high density of holes (~100/mm^2)
- Preamplification and charge transfer preserving the ionisation pattern



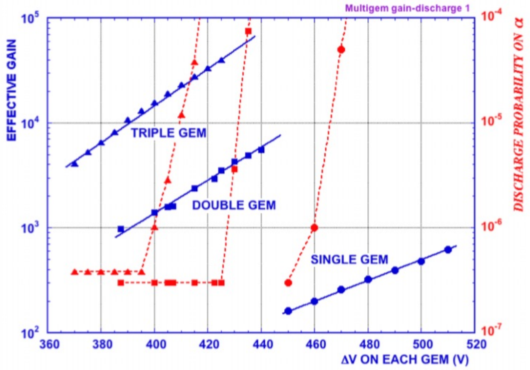




- GEM foils in cascade → high gain before discharges
- Multi-stage → triple GEM



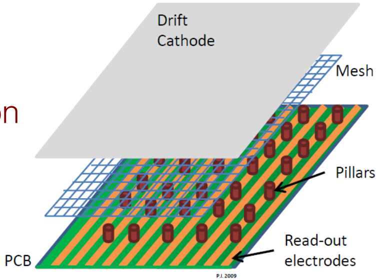
DISCHARGE PROBABILITY ON EXPOSURE TO 5 MeV α (from internal 220Rn gas)

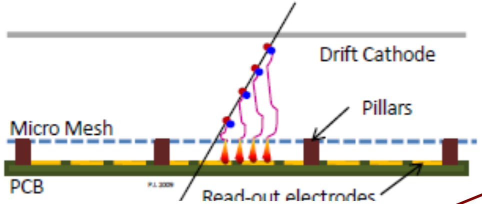


S. Bachmann et al, NIMA 479(2002)294

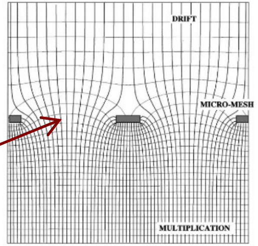
MICRO MEsh Gas Structure

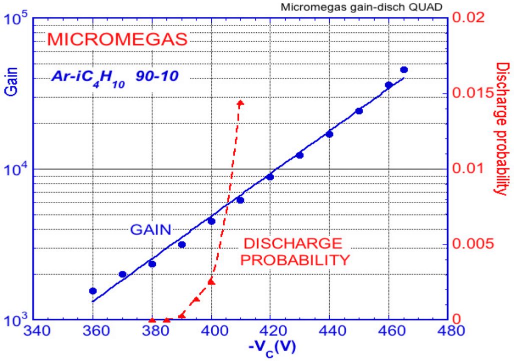
- Parallel-plate with small (~100 µm) amplification gap
- Thin metallic mesh separating the ionisation and amplification regions
- Rate capability and energy resolution of parallel plates



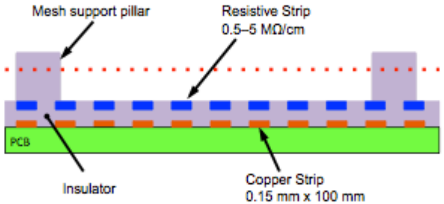


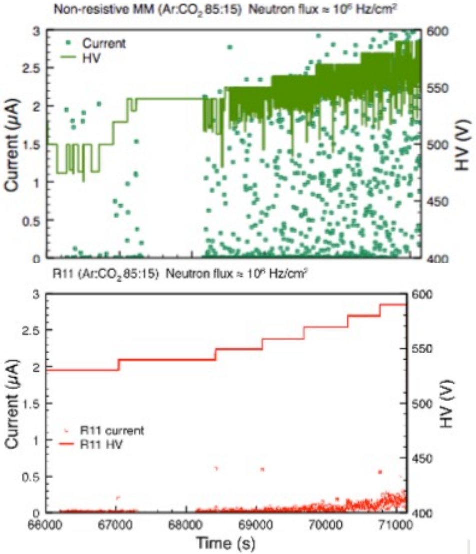
Funnel field lines:
high transparency to electrons





- The introduction of a resistive protection (R&D for ATLAS) permits to largely suppress he discharge intensity → spark-immune Micromegas
- Opened the road to the development of resistive MPGD





- Standard (non-resistive) Micromegas successfully used in HEP experiments
- Still with non-negligible discharge rate

Cylindrical GEM

- MPGD suitable for Inner Tracker thanks to their intrinsic light structure → low material budget
- IT exploit mechanical flexibility of MPGD → cylindrical shape

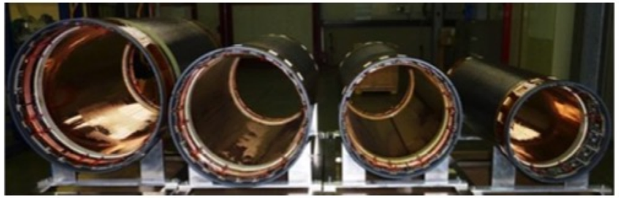


Fig. 2. The four cylindrical-GEM layers before assembling them to build the Inner Tracker.

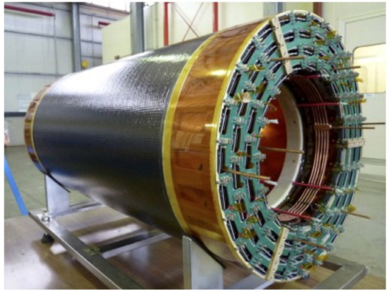
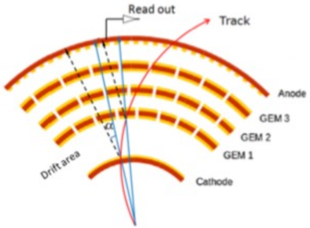


Fig. 1. The Inner Tracker detector before its installation in the KLOE-2 interaction region.

G. Bencivenni et al NIM A 958, 2020

- KLOE2 @ DAϕNE e^+e^- at ϕ peak collider at LNF
  Kaon and light meson (η, ω) physics
  - First development of cylindrical GEM for colliders
- Triple Gem
  - 0.5 T B field
  - Gas: Ar:iC_4H_{10} (90:10)
  - X-V readout strips



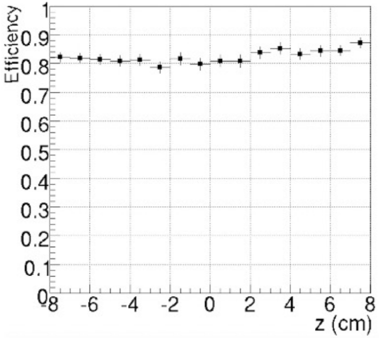


Fig. 3. Two-view efficiency as a function of the longitudinal z-coordinate measured using Bhabha scattering events for IT Layer#1.

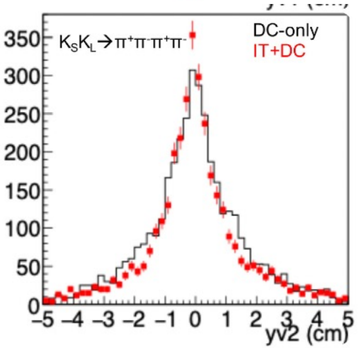


Fig. 4. Comparison between y-coordinate distribution of the two vertices for $K_SK_L \rightarrow \pi^+\pi^-\pi^+\pi^-$ events. DC-only reconstruction is the solid histogram, while red points is the integrated IT+DC reconstruction.

Cylindrical Micromegas

- ASACUSA – Antimatter experiment @ CERN
- Inhomogeneous B field 0-4 T
- 2 Micromegas layers 413 mm long
  r_1 = 78.5 mm r_2 = 88.5 mm
- Gas: $Ar{:}iC_4H_{10}$ (90:10)

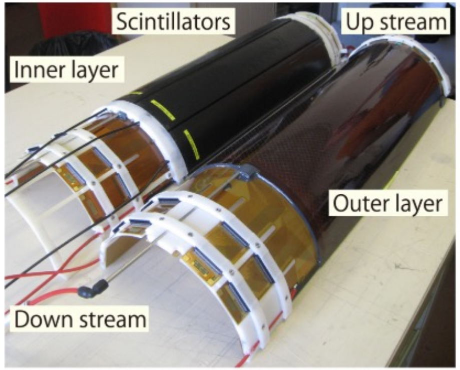


FIG. 6. A picture of the integrated scintillator (left) and Micromegas trac layer (right).

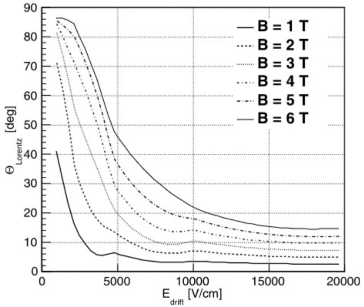
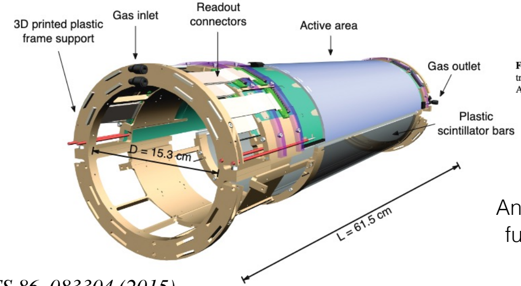


FIG. 8. Lorentz angle as a function of drift electric field for various magnetic field strengths, calculation from Magboltz, using Ar(90%) + Isobutane(10%) gas mixture.



REVIEW OF SCIENTIFIC INSTRUMENTS 86, 083304 (2015)

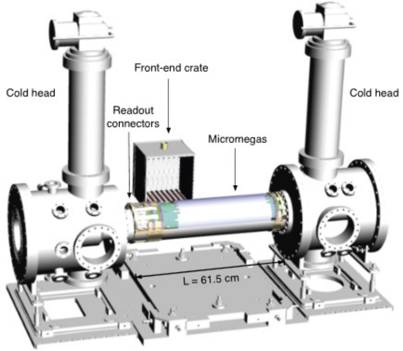


FIG. 1. Technical drawing of the AMT detector installed around the outer vacuum bore of the central trap. The two cold heads, used for the cryogenic trap system, on the sides are also visible. The AMT is surrounded by the double-cusp magnet, which is not shown in this drawing (see Figure 7).

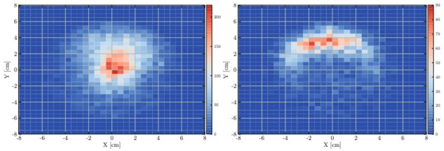


Fig. 4. Reconstructed antiproton annihilation vertex position distribution for antiprotons trapped at the central axis (*R* = 0 cm radius) of the ASACUSA multi-ring electrode (left) and for antiprotons annihilating on the ASACUSA multi-ring electrode walls at *R* = 4 cm radius (right).

Antiproton and antihydrogen annihilation events fully reconstructed with ASACUSA Miromegas

JPS Conf. Proc. , 011010 (2017)

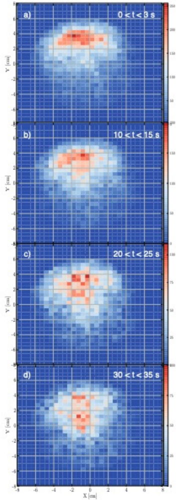
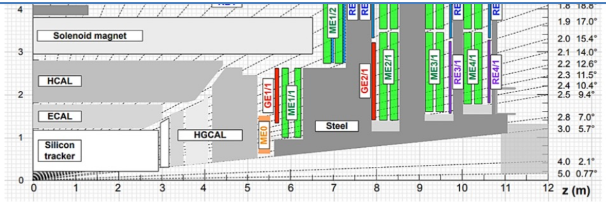


Fig. 6. Radial vertex position distribution, reconstructed by AMT, for various time slices during mixing. The start time of the mixing is *t* = 0 seconds.

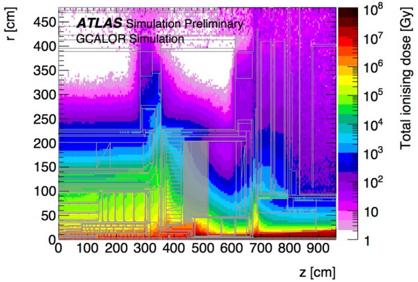
Detector challenges at LHC

- High-rate capability
  - Increase in luminosity
  - Extend the coverage to forward regions



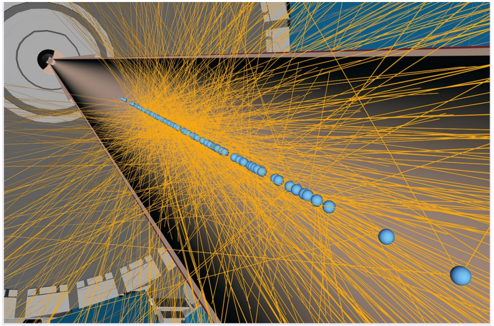
Micro Pattern Gaseous Detectors are becoming a popular choice to cope with rates up to O(MHz/cm^2)

- High radiation
  - Annual dose at HL-LHC ~ total dose of Run1+Run2



Detector challenges:

- Detector longevity (aging)
- Material validation
- Radiation tolerant front-end electronics
- Sensitivity to low energy neutrons and photons



- Pile-up
  - Up to 200 interaction in the same BC
  - Up to 2000 reconstructed tracks!

Detector challenges:

- High space granularity/resolution
- High time resolution → 4d reconstruction
- Low material budget (central regions)

Future Colliders

Higgs-boson factories (up to 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1} /IP
HL-LHC	pp	14 TeV		3
ILC & C^3	ee	250 GeV	$\pm 80/\pm 30$	2
		350 GeV	$\pm 80/\pm 30$	0.2
		500 GeV	$\pm 80/\pm 30$	4
		1 TeV	$\pm 80/\pm 20$	8
CLIC	ee	380 GeV	$\pm 80/0$	1
CEPC	ee	M_Z		50
		$2M_W$		3
		240 GeV		10
		360 GeV		0.5
FCC-ee	ee	M_Z		75
		$2M_W$		5
		240 GeV		2.5
		$2\ M_{top}$		0.8
μ-collider	$\mu\mu$	125 GeV		0.02

Multi-TeV colliders (> 1 TeV c.o.m. energy)

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5	2052	2058
		3.0 TeV	$\pm 80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

Detector requirements depend strongly by the machine parameters

- Hadron Colliders → high pile-up, high rate
- Lepton Colliders → cleaner environment