Micro-Pattern Gaseous Detectors for High Energy Physics

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RD51

Micro Pattern Gaseous Detectors

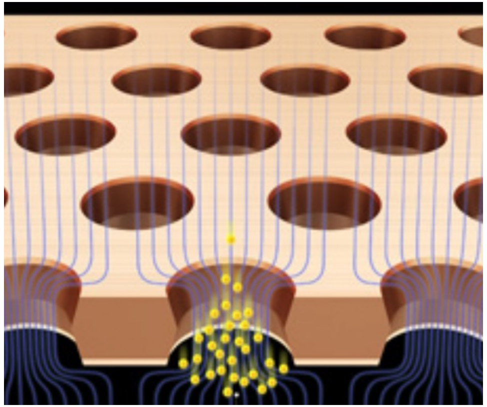
School

CERN

27 November - 1 December 2023

Outline

- Introduction
- Example of current applications of MSGC, GEM, Micromegas
- MPGDs for
    - Upgrade of LHC experiments
    - Experiments at future colliders
- A word on detector longevity



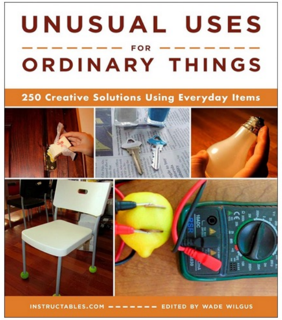
Applications

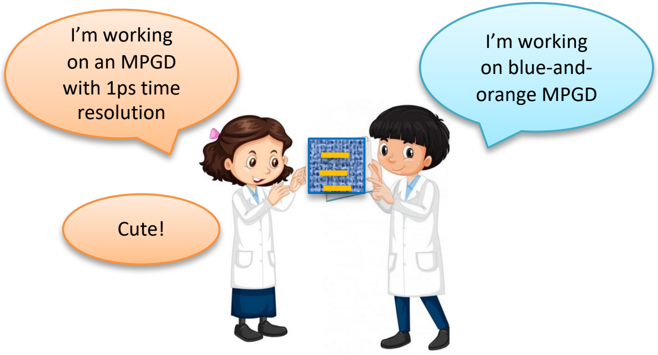
- By now you know EVERYTHING about MPGD !
  → let's look together to their *application* to (some) HEP experiments

Detector R&D

Application driven

Blue Sky





- Application-driven: developments tailored on well-defined requirements, normally coming from the physics case (experiments)
- Blue Sky: new ideas + developments to push forward the performance of currently available technologies (always having in mind possible future applications)

Application = the final goal of the development work

Applications in HEP

HEP detector design

Physics case → Experiment requirements → Detector requirements →

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

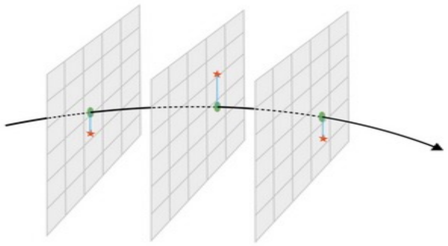
- Detector available 'on the market'
- R&D for specific application

Cutting-edge requirements (often next generation experiments)

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

Measure 10 GeV muon with 1% p_T resolution

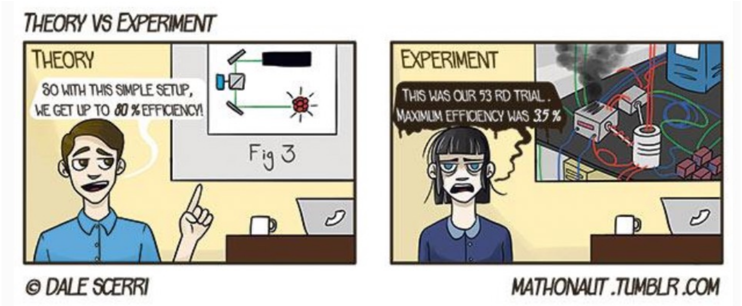
With 3 measurement points L=1 m, B=1 T
➔ $\sigma_x \approx 30\ \mu m$



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

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

Things can even go wrong: selected technology too costly, too complex to build, not reliable enough, finally not meeting the required performance…



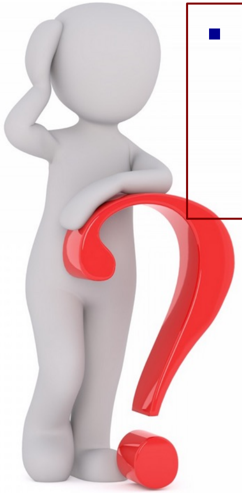
Applications

- 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

Operations

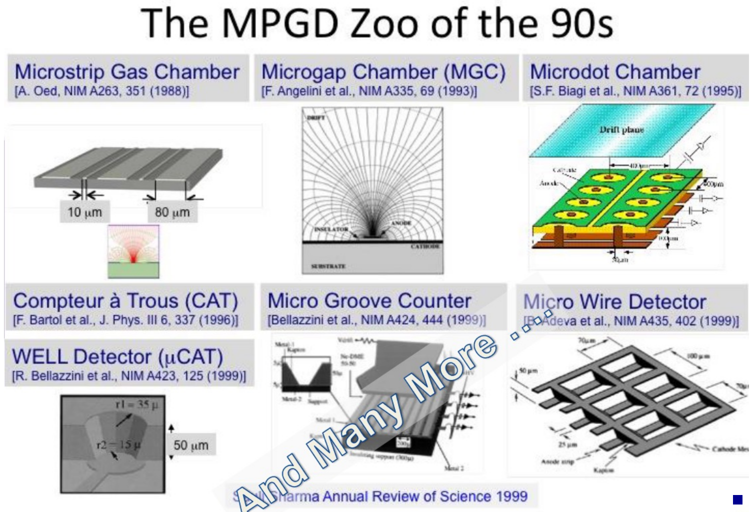
- Gas mixture
  - Drift velocity
  - Diffusion
  - Amplification vs HV stability
  - Aging…

- Aging
  - Gas mixture
  - Materials

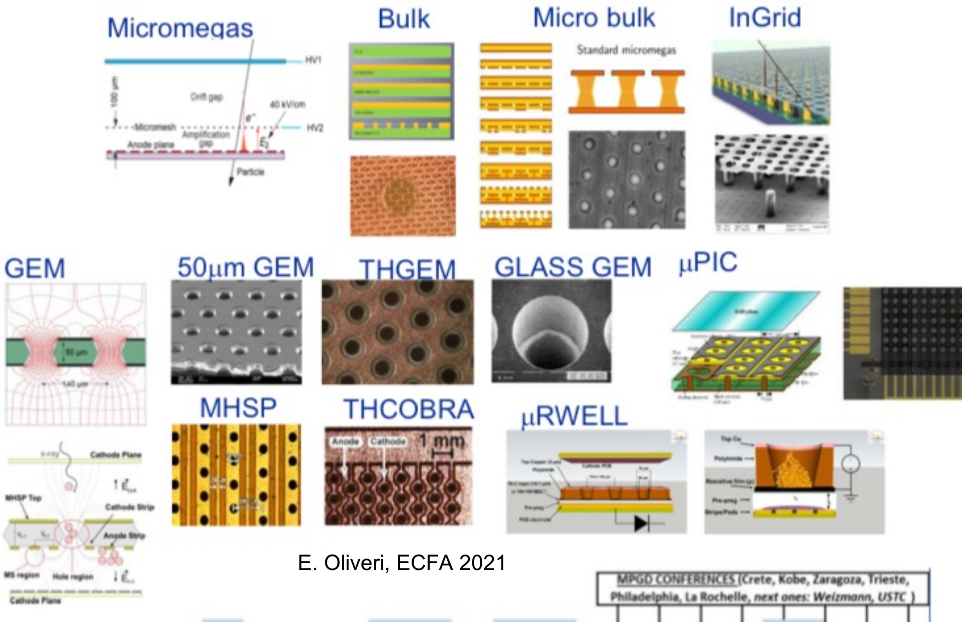
- Spark protection
  - Resistive coating
  - Segmentation
  - Gas mixture

The MPGD evolution

- Since the invention of the MSGC many other MPGD have been developed:
  some very promising, some somewhat less…



A. Sharma (1999)

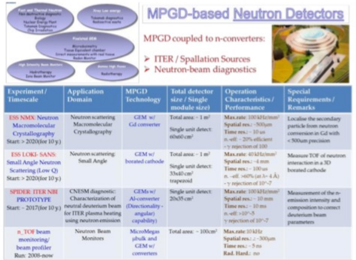


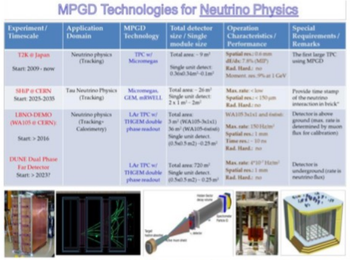
E. Oliveri, ECFA 2021

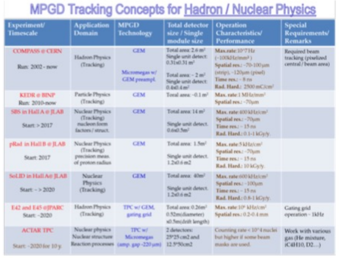
- Today the MPGD family includes a large number of detectors
  - Well established technologies adopted in HEP experiments
  - New ideas, R&D for future experiments or specific applications

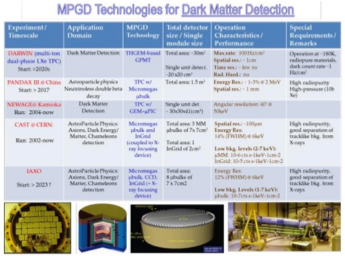
Disclaimer

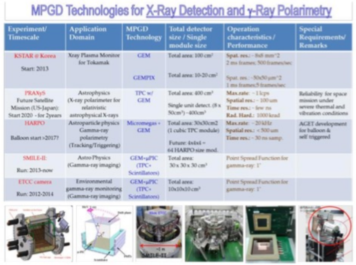
- Impossible to cover all the MPGD HEP applications
- Will show a selected number of representative examples
- What is not mentioned is NOT less relevant!

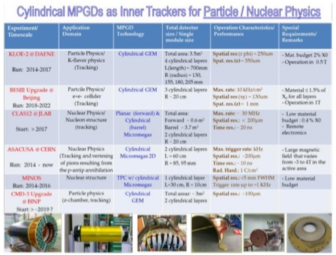


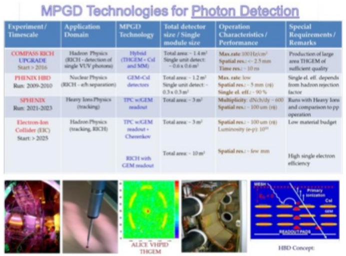












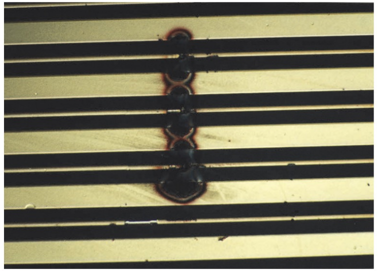
(Out-of-date) list of MPGD applications

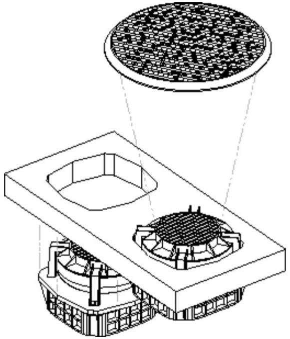
M. Titov, 5th MPGD conference

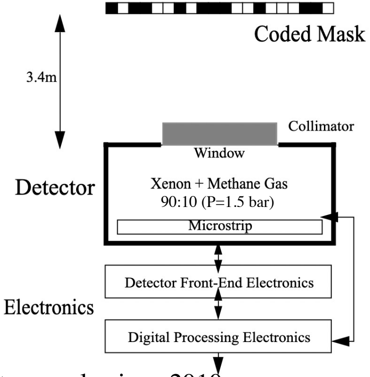
Micro-Strip Gas Chambers (MSGC)

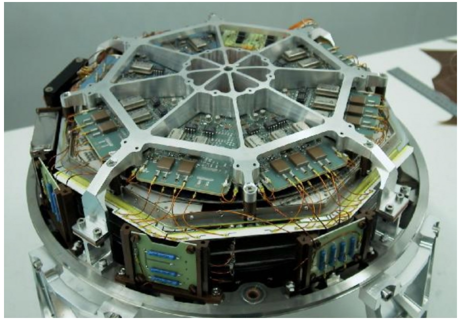
Despite the know limitations due to instability the first introduced MPGD – the MSGC – has been and is still being successfully used in many experiments

Example: the JEM-X detector on board of the INTEGRAL mission of ESA







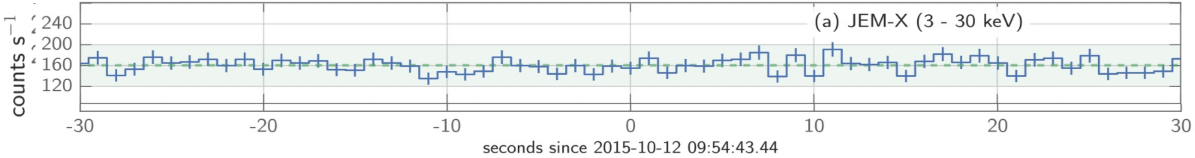


E_{xray} = 3-35 keV

Both MSGC operated simultaneously since 2010

ESA INTEGRAL mission:

Launched in 2002, end of mission: 2029



Light curves from JEM-X count-rates zoomed around the time of LVT151012 trigger provided by the LIGO/Virgo collaboration. The light curve is binned with a time resolution of 1 s. The count-rates of the instrument backgrounds (dashed lines) and the expected level of random fluctuations at 3 σ confidence level (shaded regions) are indicated too. [*Astron.Astrophys.* 603 (2017) A46]

Central Tracker 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

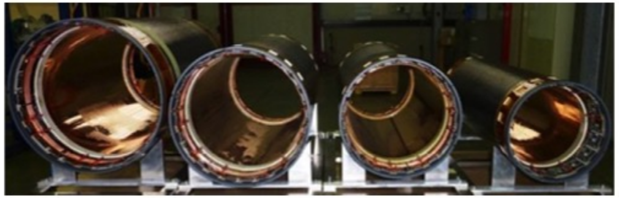
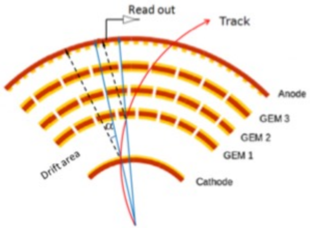


Fig. 2. The four cylindrical-GEM layers before assembling them to build the Inner Tracker.

- KLOE2 @ DAϕNE e^+e^- collider at LNF
  - 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



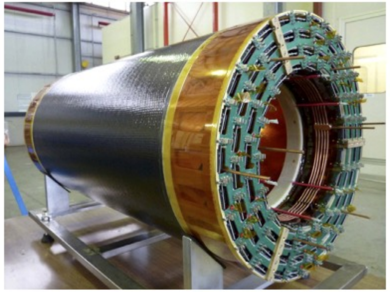


Fig. 1. The Inner Tracker detector before its installation in the KLOE-2 interaction region.

G. Bencivenni et al NIM A 958, 2020

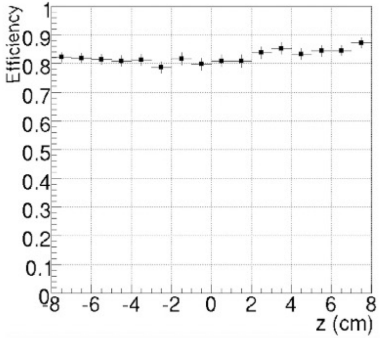


Fig. 3. Two-view efficiency as a function of the longitudinal z-coordinate measured using Bhabha scattering events for IT Layer#1.

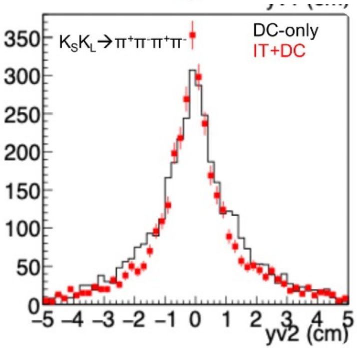
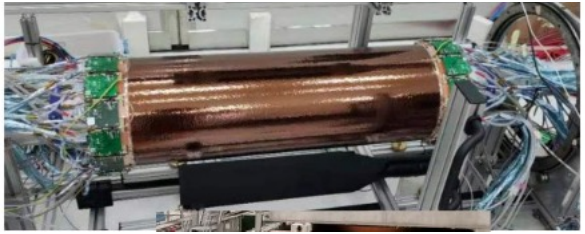


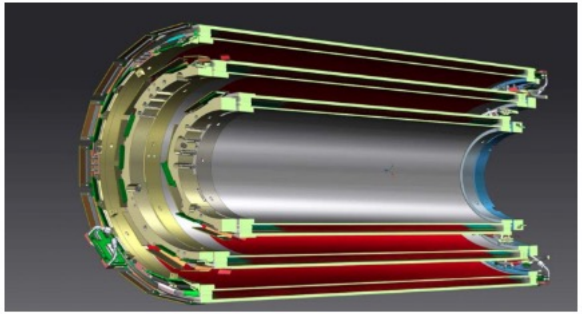
Fig. 4. Comparison between y-coordinate distribution of the two vertices for $K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ events. DC-only reconstruction is the solid histogram, while red points is the integrated IT+DC reconstruction.

Cylindrical GEM

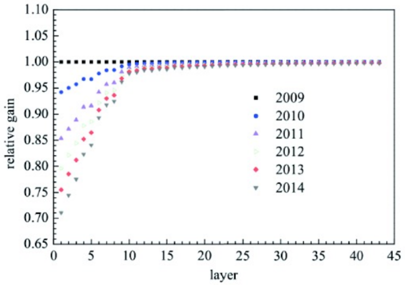
- MPGD suitable for Inner Tracker thanks to their intrinsic light structure → low material budget
- IT exploit mechanical flexibility of MPGD → cylindrical shape

- BESIII @ BEPC II e^+e^- collider
  - Gas: $Ar{:}iC_4H_{10}$ (90:10)
  - B = 1T → $\sigma(p_T)/p_T = 0.5\%$

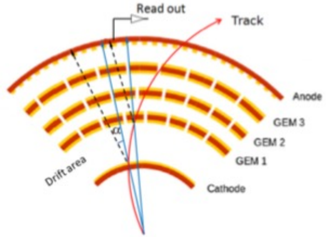


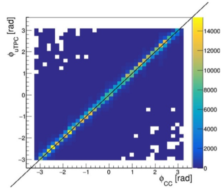


R. Farinelli, MPGD Conference 2022

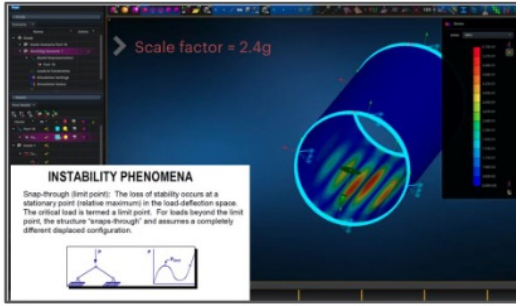


Performance degradation with time of wire-based BES IT (aging)
→ will be replaced by the CGEM

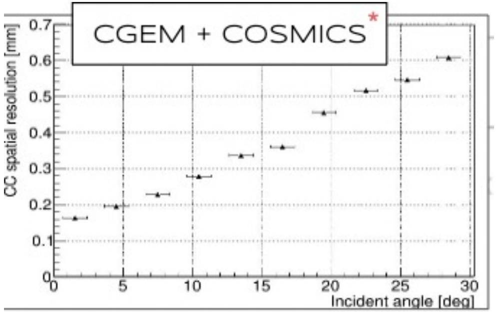




Cosmic event



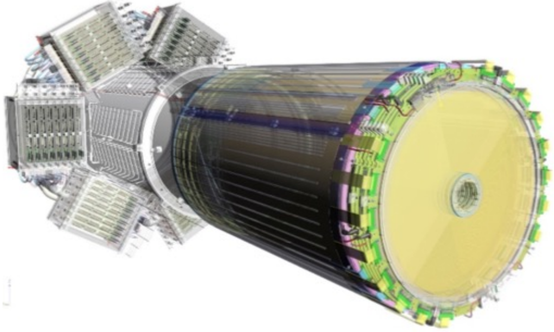
Some instabilities due to buckling of the large external foil solved adding a spacing grid



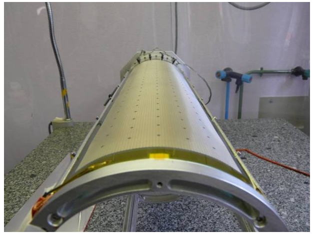
Space resolution with cosmics.
At large angle can be improved by exploting the time information (uTPC, discussd later)

Cylindrical Micromegas

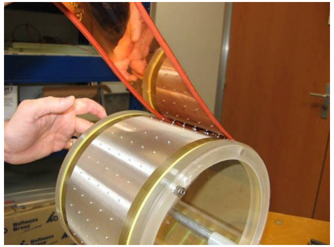
- Micromegas Vertex Traker for CLAS12 @ JLAB
- Nuclear Physics/Hadron Spettroscopy/Deep Processes
- B=5 T magnet
- 11 GeV e^- beam / 30 MHz particle rate



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

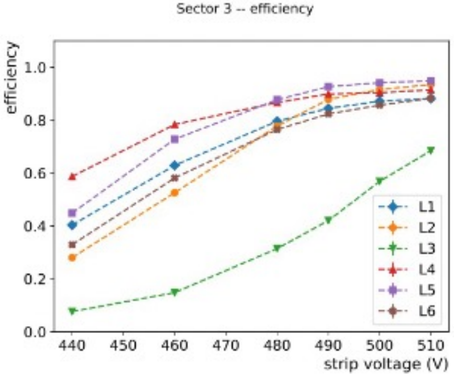


Curved MM bulk

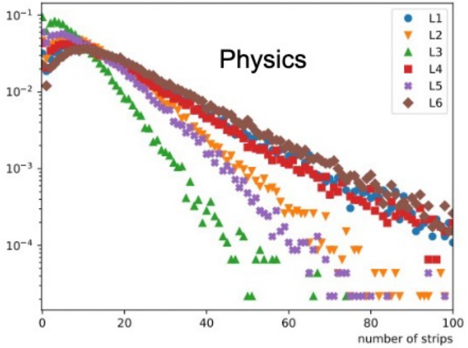


Drift electrode integration

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

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)

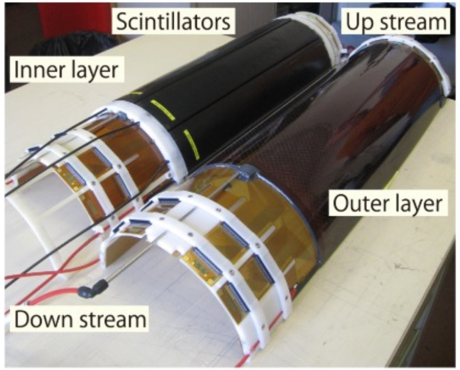


FIG. 6. A picture of the integrated scintillator (left) and Micromegas trac layer (right).

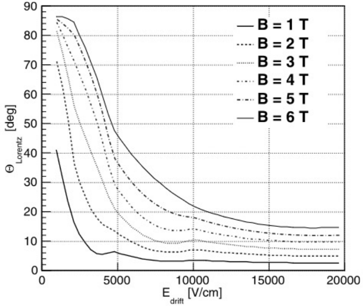
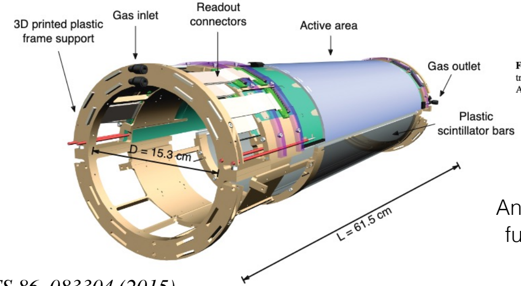


FIG. 8. Lorentz angle as a function of drift electric field for various magnetic field strengths, calculation from Magboltz, using Ar(90%) + Isobutane(10%) gas mixture.



REVIEW OF SCIENTIFIC INSTRUMENTS 86, 083304 (2015)

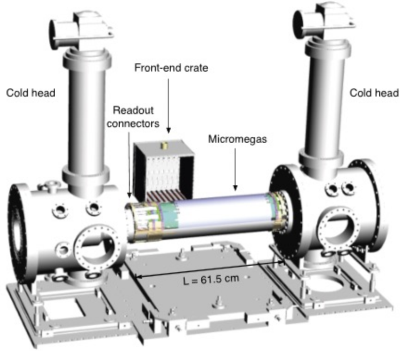


FIG. 1. Technical drawing of the AMT detector installed around the outer vacuum bore of the central trap. The two cold heads, used for the cryogenic trap system, on the sides are also visible. The AMT is surrounded by the double-cusp magnet, which is not shown in this drawing (see Figure 7).

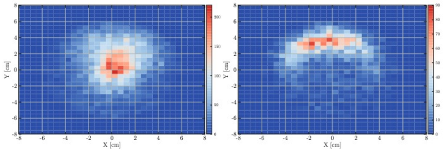


Fig. 4. Reconstructed antiproton annihilation vertex position distribution for antiprotons trapped at the central axis (R = 0 cm radius) of the ASACUSA multi-ring electrode (left) and for antiprotons annihilating on the ASACUSA multi-ring electrode walls at R = 4 cm radius (right).

Antiproton and antihydrogen annihilation events fully reconstructed with ASACUSA Miromegas

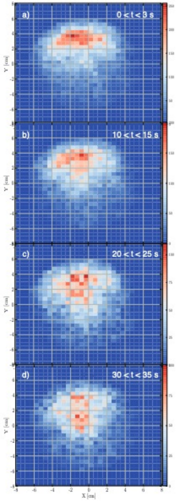
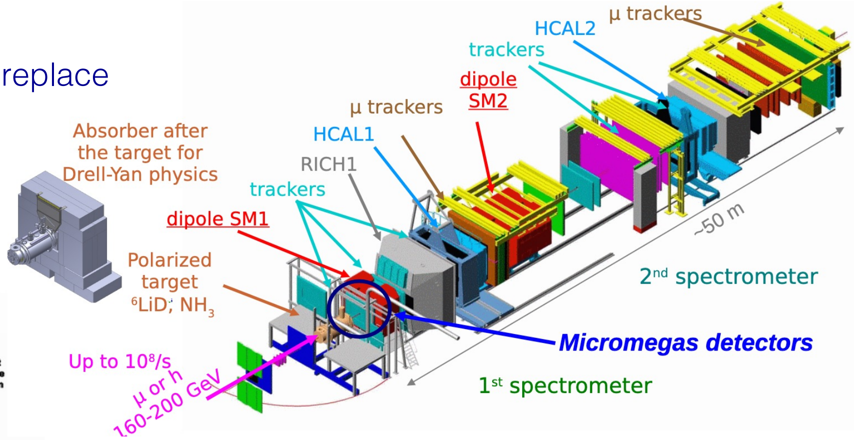


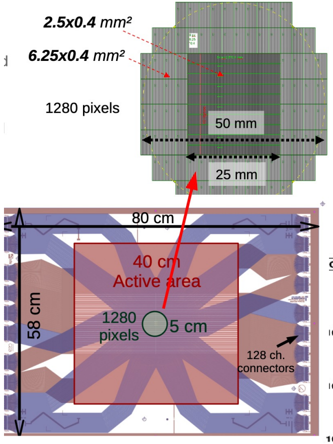
Fig. 6. Radial vertex position distribution, reconstructed by AMT, for various time slices during mixing. The start time of the mixing is t = 0 seconds.

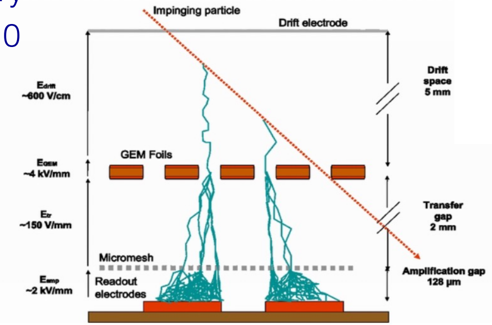
JPS Conf. Proc. , 011010 (2017)

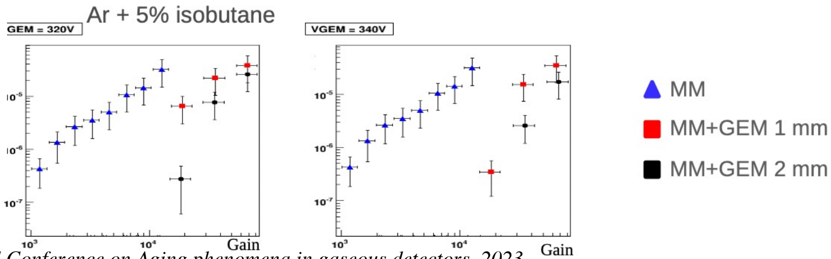
GEM+Micromegas

- COMPASS experiment at CERN (2002-2022)
- Hybrid GEM+MM detector with 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

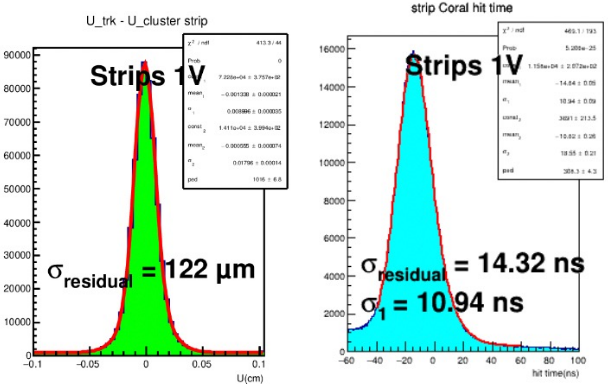








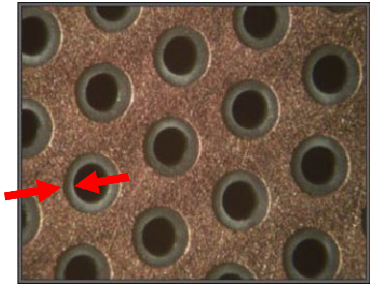
D. Neyret, 3rd Conference on Aging phenomena in gaseous detectors, 2023

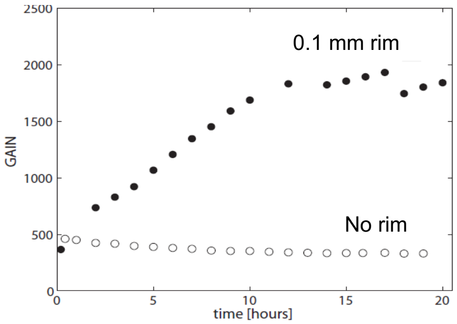


Good tracking and timing performance

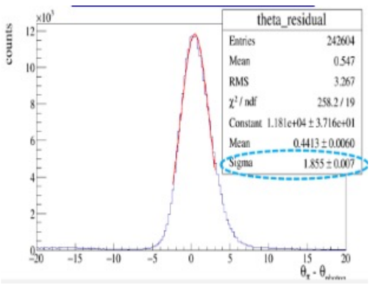
Thick GEM: photon detection at COMPASS

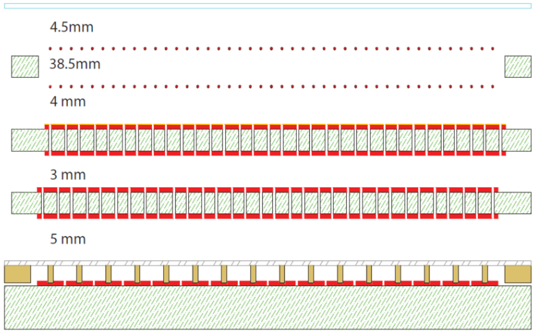
- THGEM: Same principle as GEM but with thick material (FR4)
  - PCB thickness ~ 0.4-3 mm
  - Hole – drilled - diameter ~ 0.2-1 mm
  - Pitch ~ 0.5-5 mm
- Industrial production for large size
- Mechanically self-supporting, robust

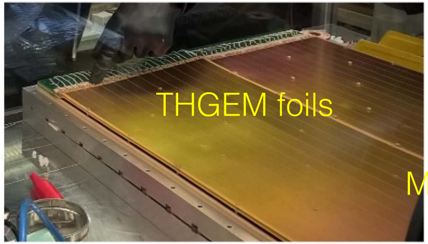


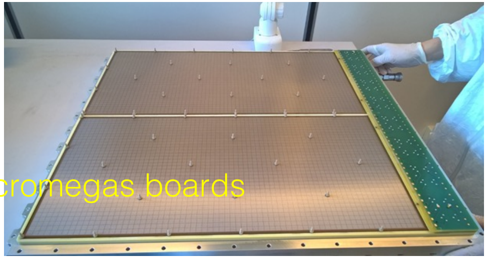


- Successfully used in COMPASS RICH-1 for single-photon detection
  - Hybrid configuration: THGEM+Micormegas; 1.4 m^2
  - eff. gain ~ 15000, gain stability ~5%
  - single γ angular res. 1.8 mrad
  - Gas: $Ar:CH_4$ 50:50 →optimal photoelectron extraction from CsI to gas
  - IBF = 3%

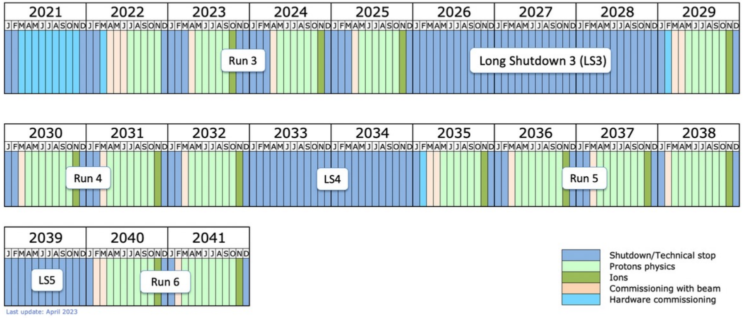


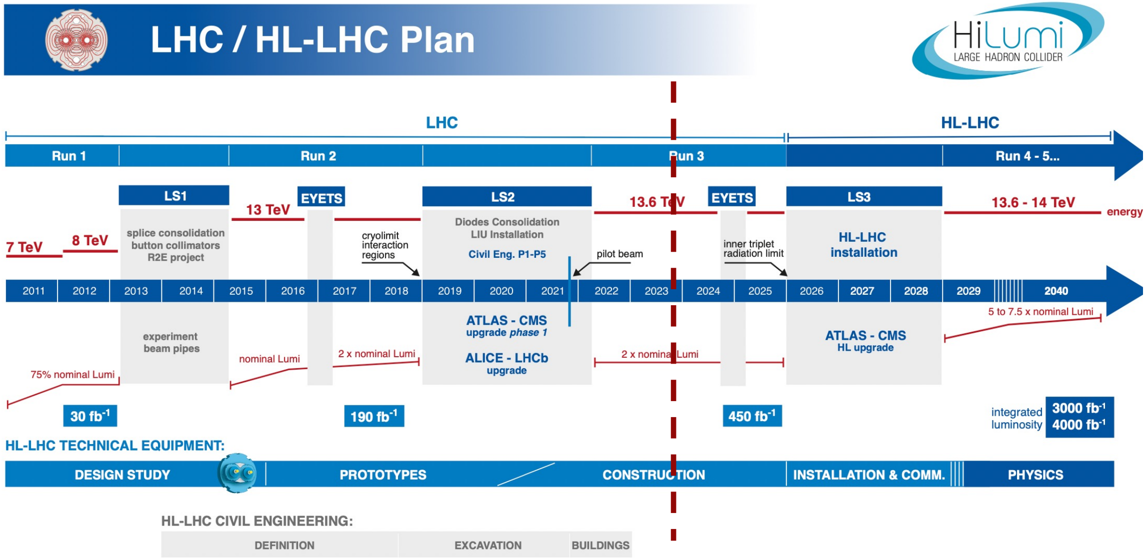






MPGD at LHC



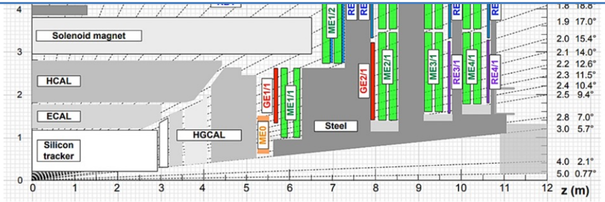


The development of gaseous detectors for HiLumi LHC is driving the effort for (most although not all) technologies proposed for experiments at future colliders

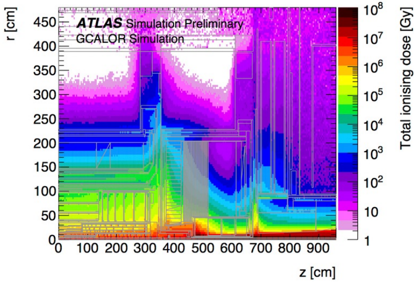
Detector challenges all there:
- High rate
- High radiation
- Pileup

Detector challenges at LHC

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



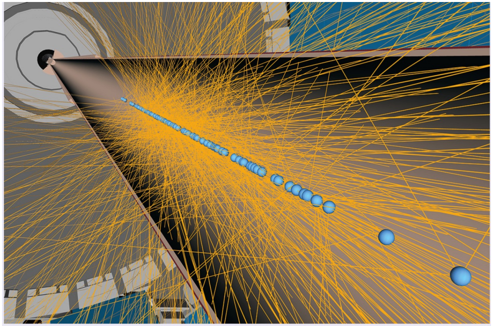
Micro Pattern Gaseous Detectors are becoming a popular choice to cope with rates up to O(MHz/cm^2)



- 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)

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
- 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

ELSEVIER Nuclear Physics B - Proceedings Supplements
Volume 78, Issues 1–3, August 1999, Pages 80-83

High rate tests of microstrip gas chambers for CMS

MSGC proposed for CMS tracker – never used

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
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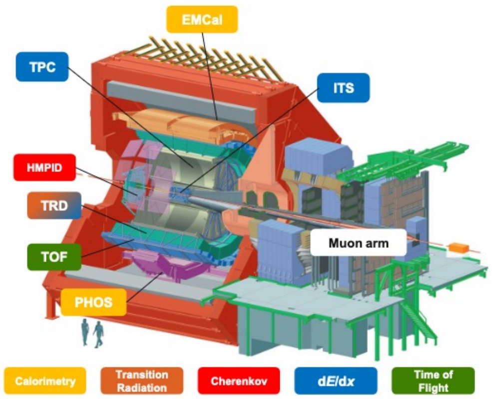
- LHCb
  - MWPC
  - GEM*
  - uRwell***

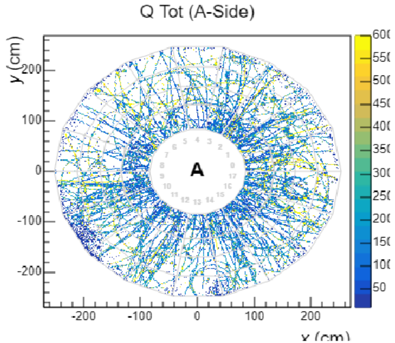
Gaseous detectors at the 4 large LHC experiments

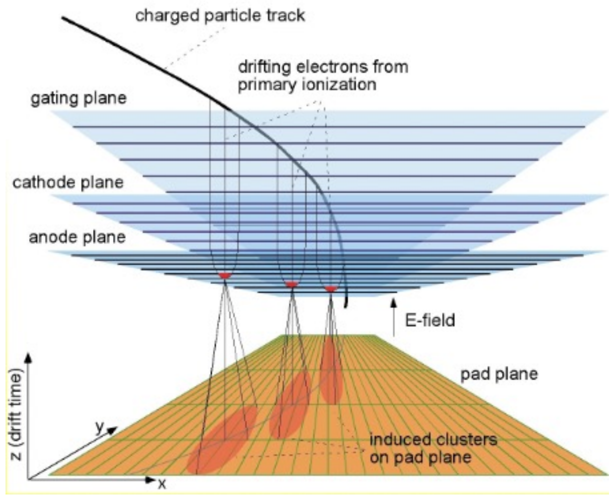
* Removed after Run2
** Run3 and beyond
*** Proposed for Run4 and beyond

ALICE TPC

- Heavy-ion collision experiment @ HLC
- 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

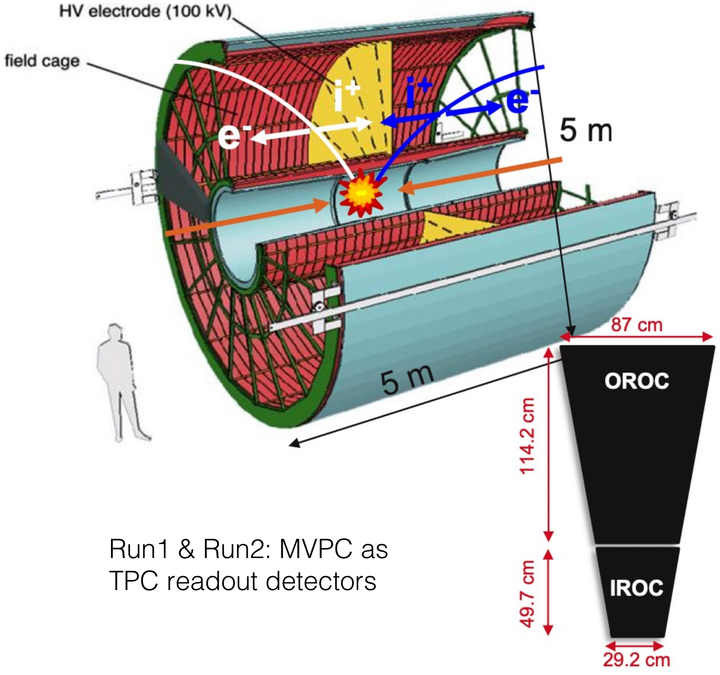






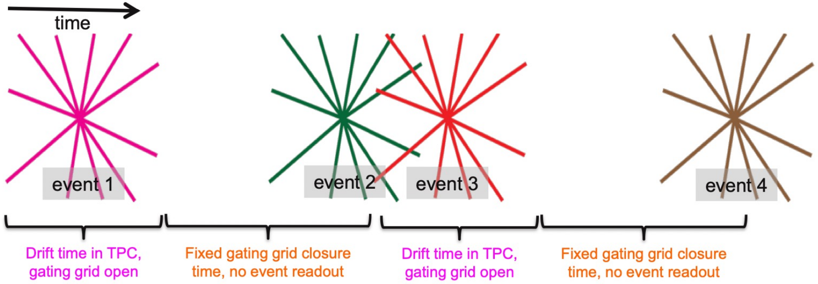
- TPC is the main device in ALICE for tracking and particle identification (PID)
- In a TPC a crucial aspect is the ion backflow suppression: ions from avalanche amplification affect the E field stability in the TPC volume → gating grid

ALICE TPC



Run1 & Run2: MVPC as TPC readout detectors

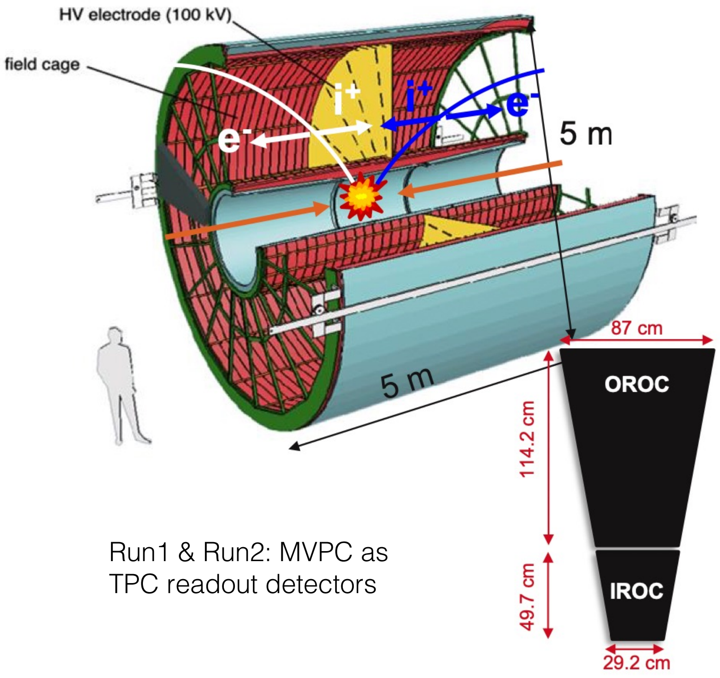
GATED OPERATION IN RUN 1 & RUN 2



- **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)**

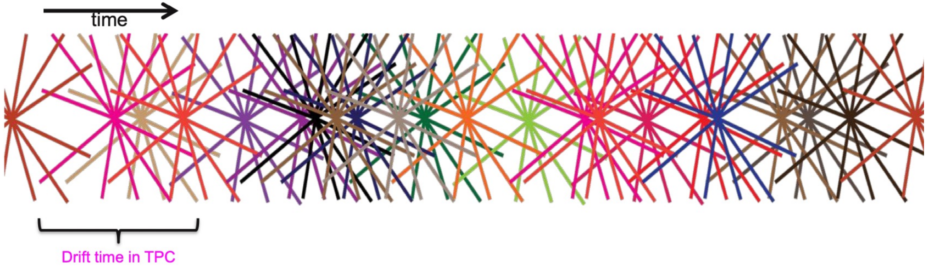
R. H. Munzer CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978

ALICE TPC



Run1 & Run2: MVPC as TPC readout detectors

CONTINUOUS OPERATION IN RUN 3 AND BEYOND

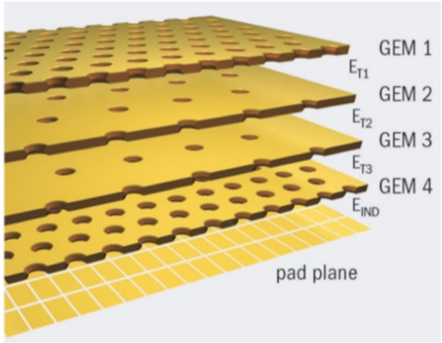


- Maximum drift time of electrons in the TPC: ~100 μs
- Average event spacing: ~20 μs
- Event pileup: 5 on average
- Triggered operation not efficient
- Minimize IBF without the use of a gating grid

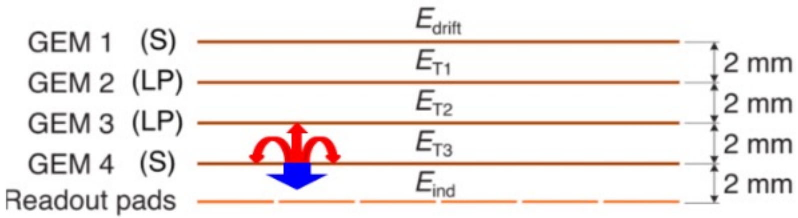
Gated operation used in Run1 & 2 becomes inacceptable in Run3
→ Move to non-gate continuous operation

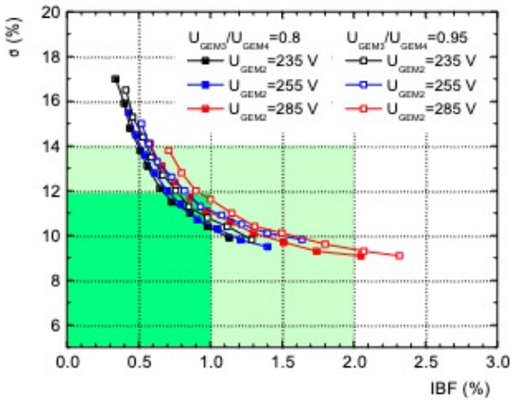
R. H. Munzer CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978

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)





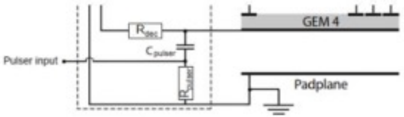
Three measures to suppress the ion back flow into drift region:

- 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

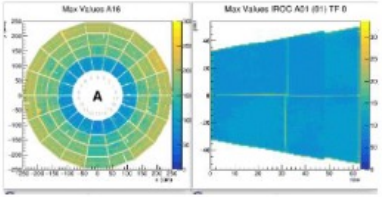
R. H. Munzer CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978

ALICE TPC: calibration, calibration

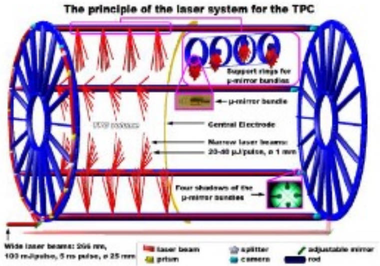
PULSER SYSTEM



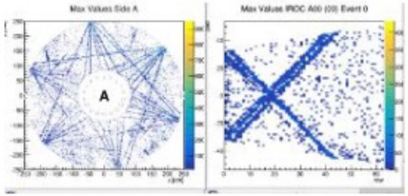
- Pad response measurement
- Common Mode calibration



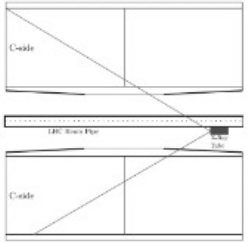
LASER SYSTEM



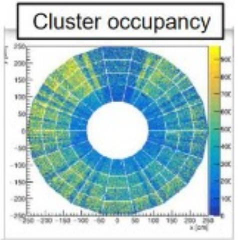
- Alignment
- Drift velocity measurement
- Drift field distortions
- Common Mode calibration



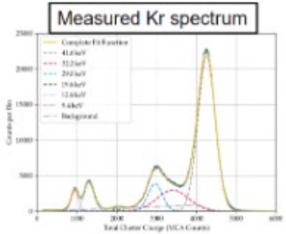
X-RAY



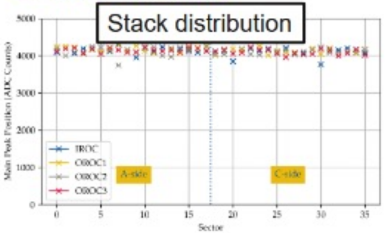
- Full gain map
- Stability



KRYPTON



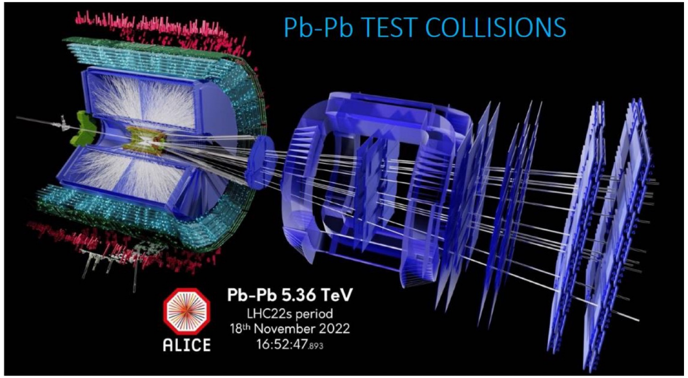
- Energy resolution: σE/E = 12% @ K(α) of 55Fe corresponds to: σE/E = 4.5% @ 41.6 keV (Krypton main peak)
- Gain Equalization



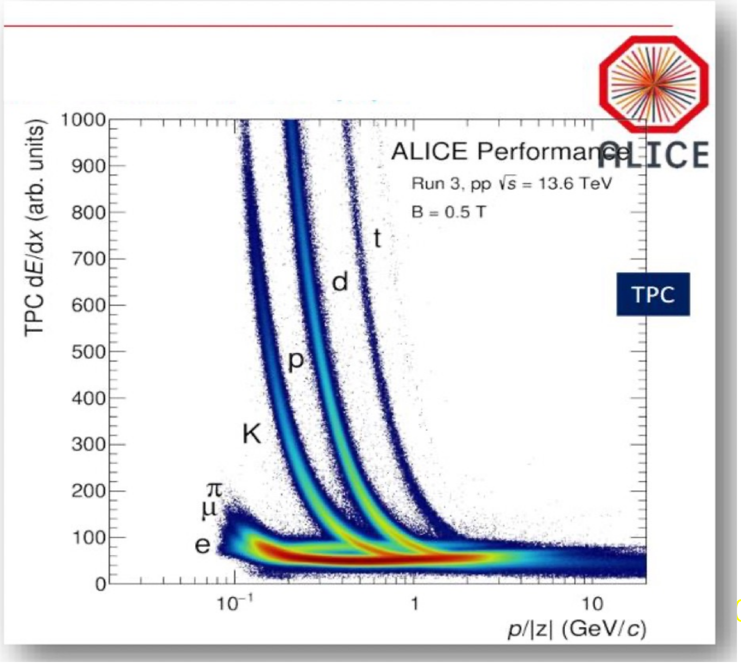
R. H. Munzer, Continuous data taking with the upgraded ALICE GEM-TPC, CERN EP Detector Seminar, 24/6/2022, https://indico.cern.ch/event/1172978/

E. Oliveri, MPGD Conference 2022

ALICE TPC

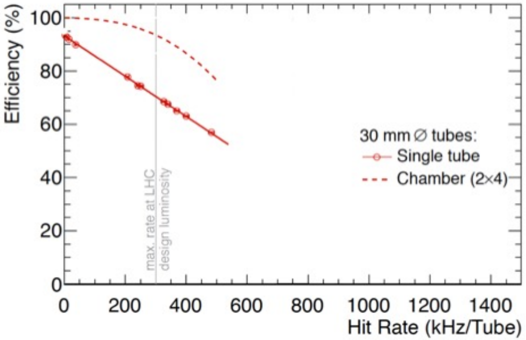


ALICE PERFORMANCE IN 13.6 TeV pp

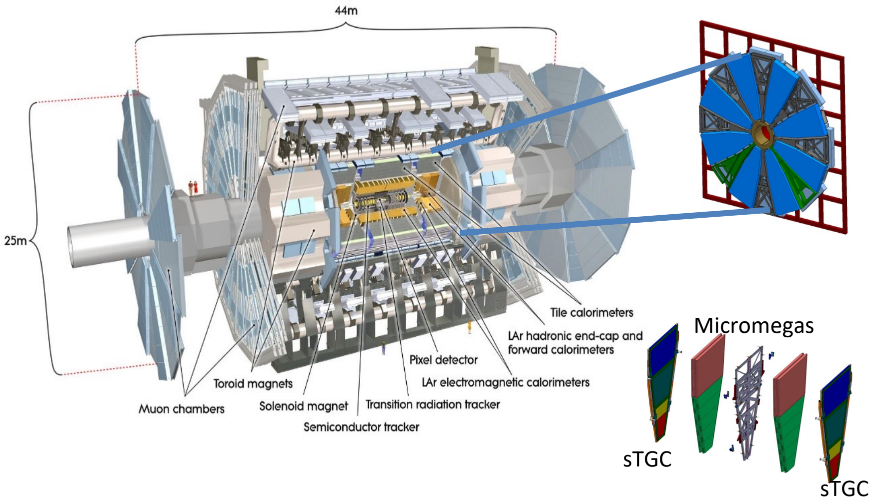


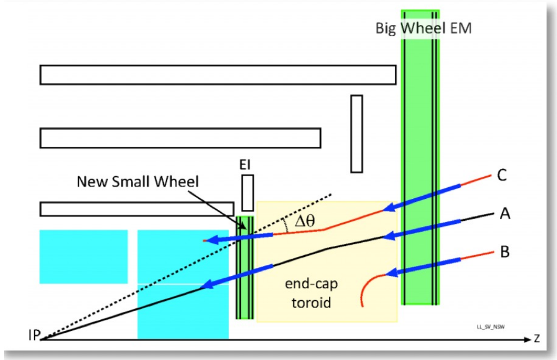
ATLAS Micromegas

- Major ATLAS upgrade of Phase1



Efficiency vs rate for ATLAS MDT





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

- 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 m^2 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
  - Precise tracking for inclined tracks
  - Large-area production

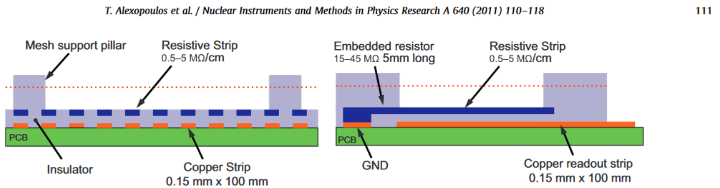
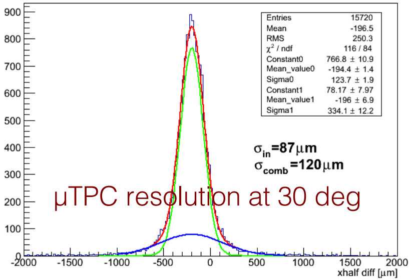
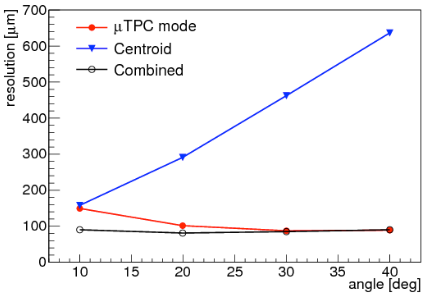
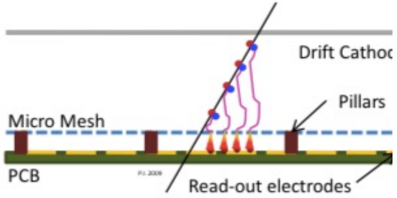


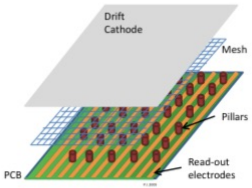
Fig. 1. Sketch of the detector principle (not to scale), illustrating the resistive protection scheme; (left) view along the strip direction, (right) side view, orthogonal to the strip direction.

The Micromegas R&D for ATLAS pioneered the development of resistive MPGD

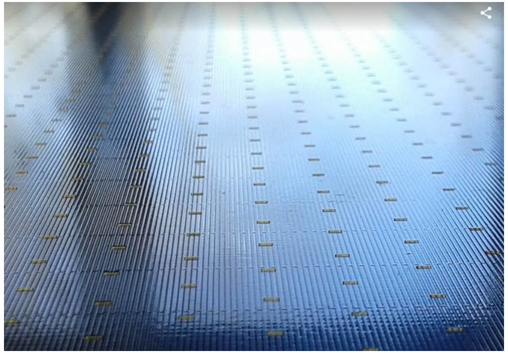








The uTPC reconstruction technique allows for precise tracking at large impact angle

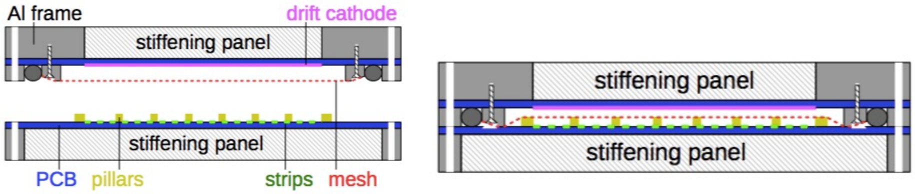


Micromegas boards fully produced in industry

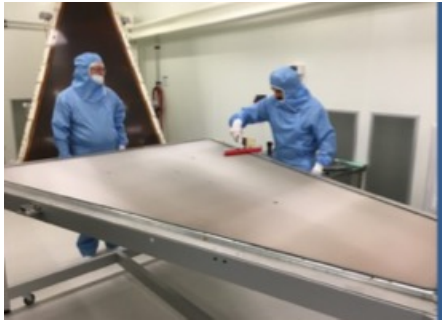
2500 foils produced→ big technological challenge

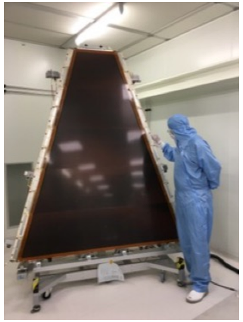
ATLAS Micromegas

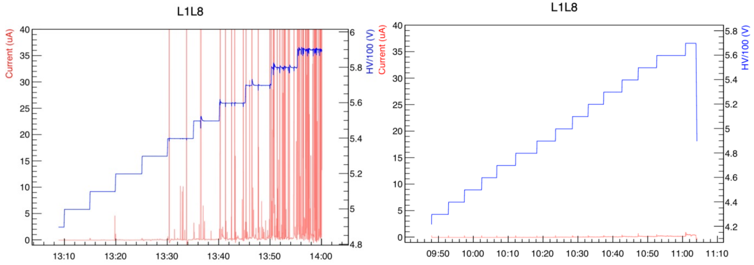
- ATLAS Micromegas is the largest MPGD-based system ever conceived and built
- 2.1 M readout channels readout with VMM chip
- 128 detectors
- Ar:CO2 93:7 → Ar:CO_2:iC_4H_{10} 93:5:2
- Mesh mechanically floating (no bulk)
  → detector can be reopened

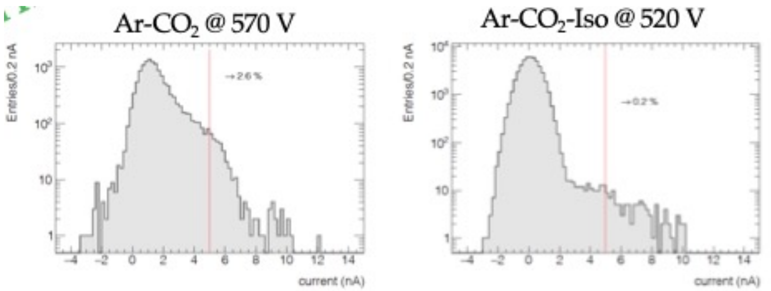


Principle of mechanically floating mesh



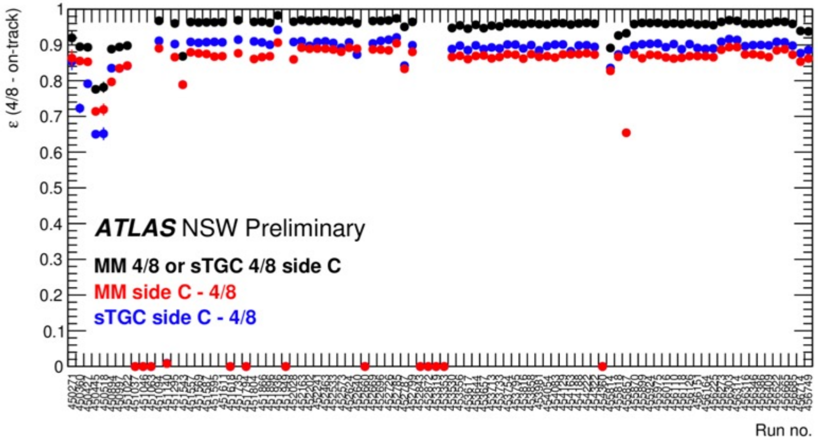




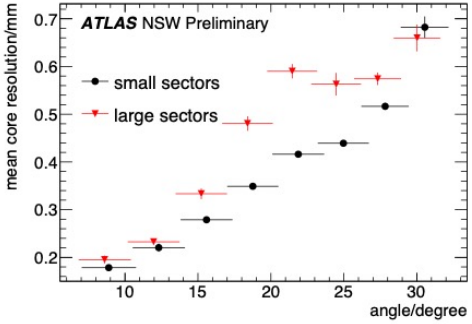


HV stability improved by adding 2% of iC_4H_{10}

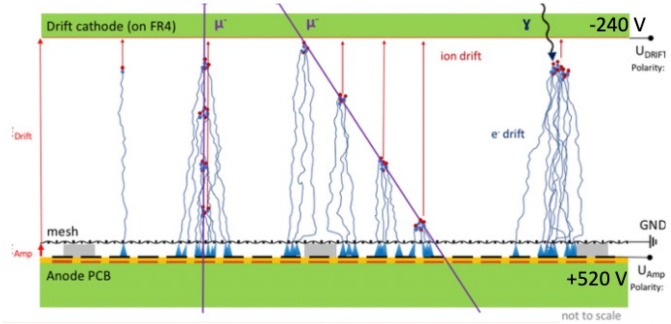
ATLAS Micromegas



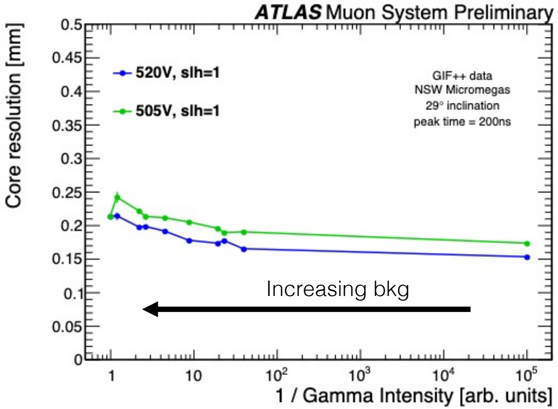
NSW efficiency vs run number in Run3



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

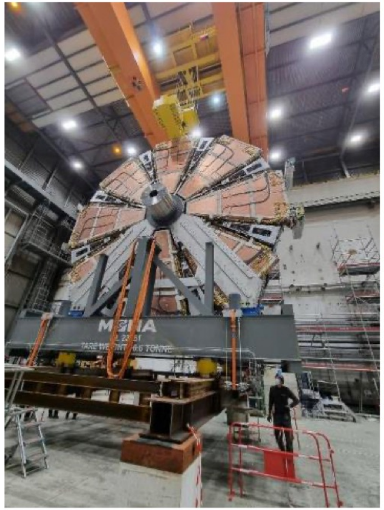


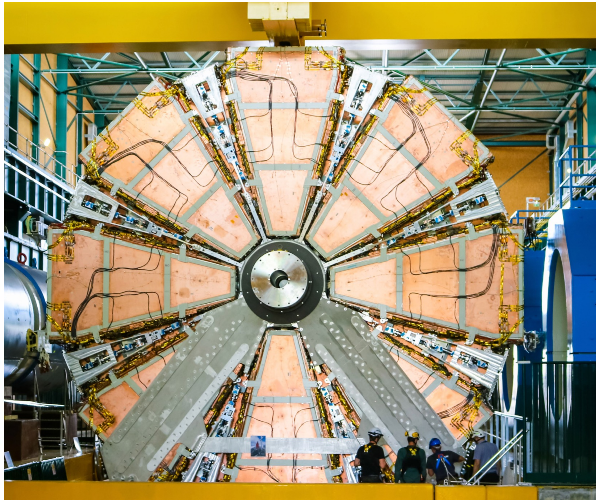
V. D'Amico, 3rd Conference on Aging phenomena in gaseous detectors, 2023

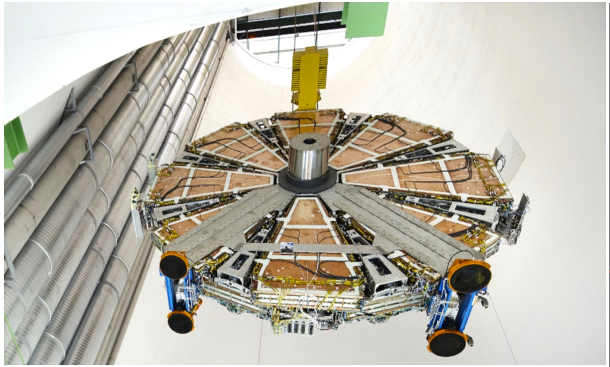


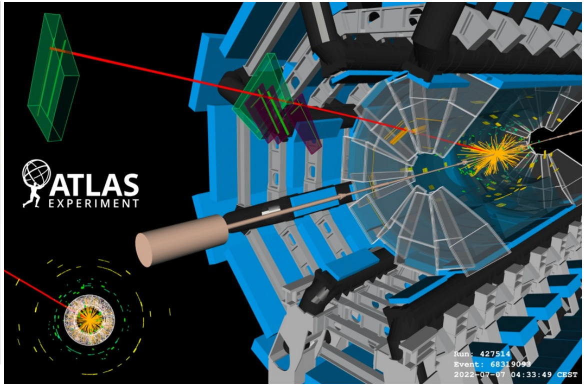
Resolution for 29deg. muon track with cluster-time projection method
as function of photon background

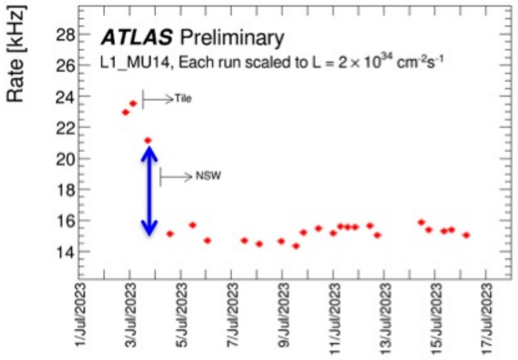
ATLAS Micromegas





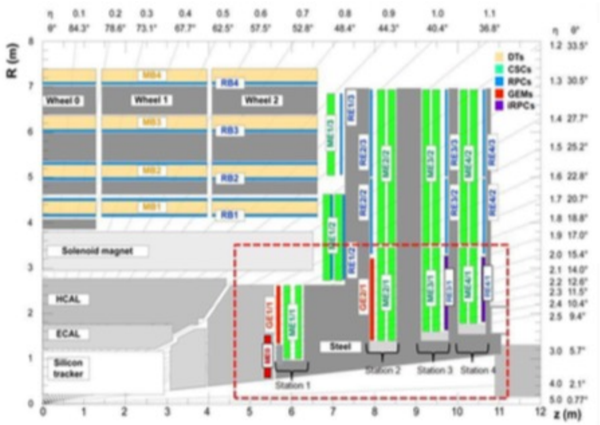


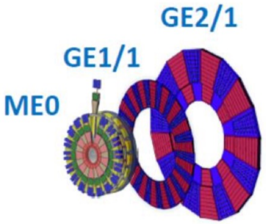


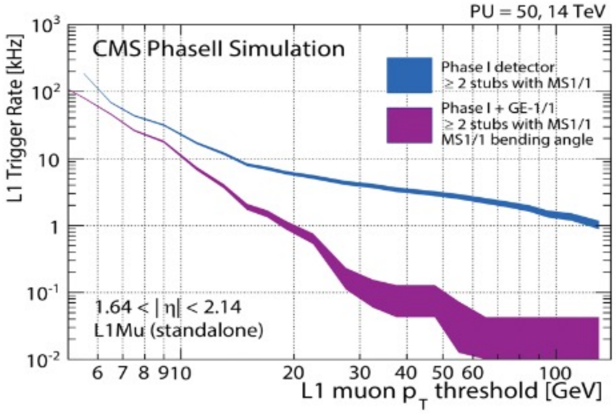


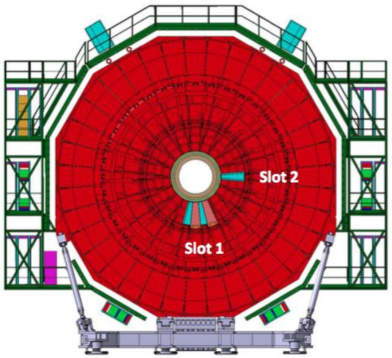
CMS GEM

- GEM End-cap: 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
- Gas: Ar:CO_2 70:30



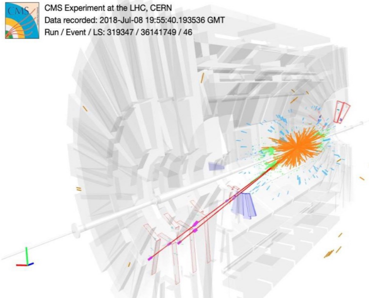






M. Bianco CERN EP Detector Seminar, 08/7/2022

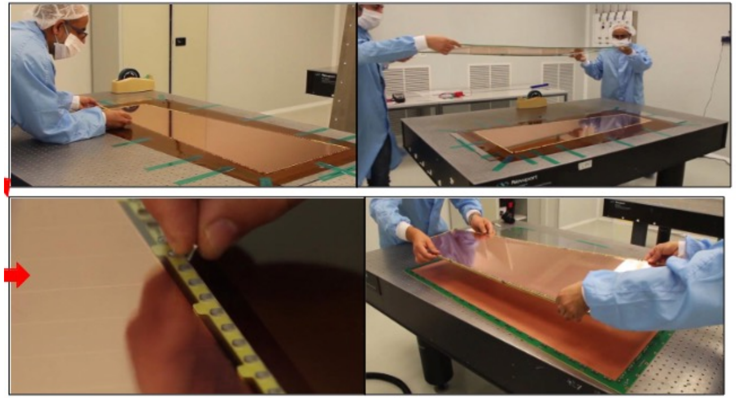
Demonstrator: 4 +1 GEM 'super-chambers' installed and successfully operated in Run2

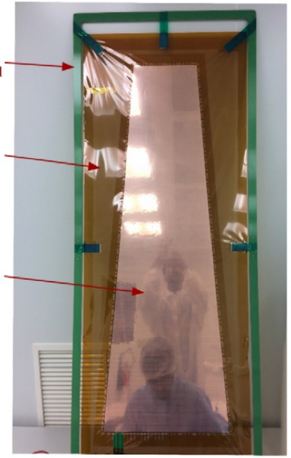


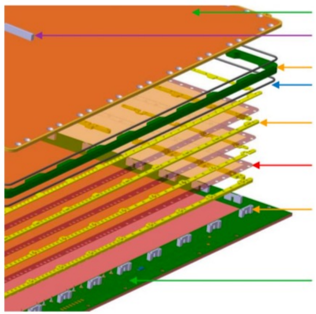
Valuable experience to spot operation problems and implement improvement in the GE2/2 detectors

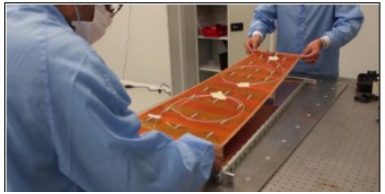
CMS GEM

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

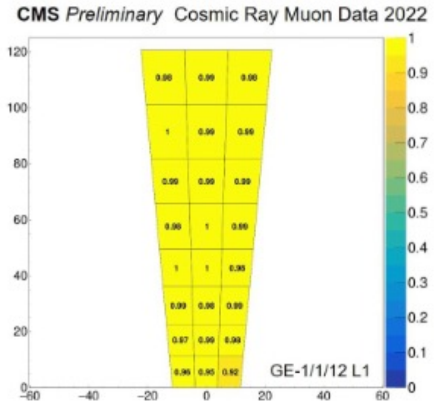








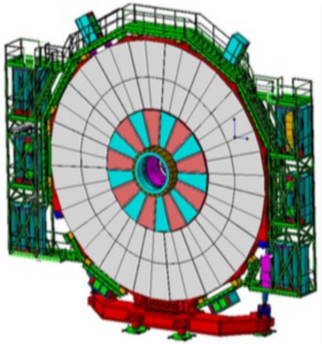
Foils stretched against the “pull out” and chamber closed placing the Readout Board

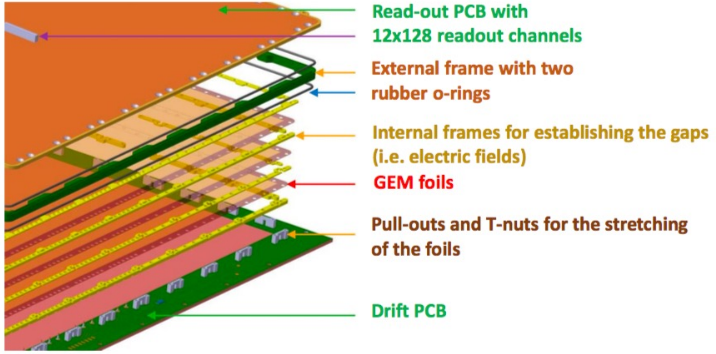


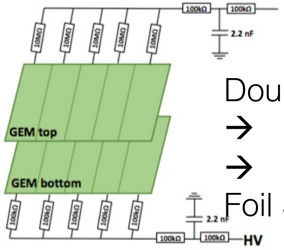
M. Bianco CERN EP Detector Seminar, 08/7/2022

CMS GEM

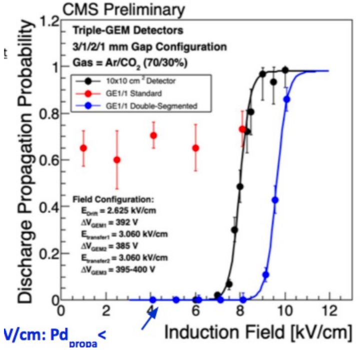
- GE2/2: 2 end-caps each of
- 36 chambers on 2 layers
- 4 modules/chamber → 288 modules
- Total active surface ~110 m^2

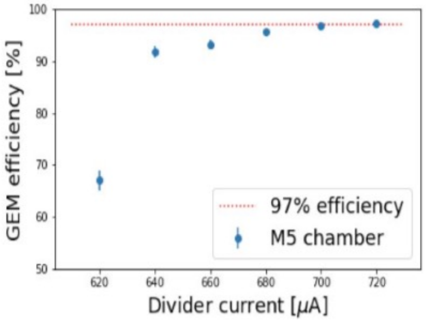


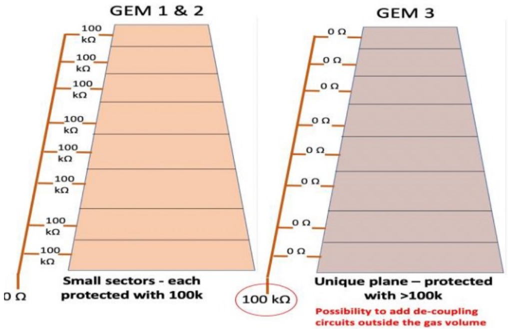


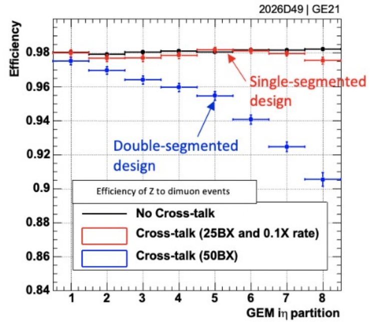


Double segmented foils 1 and 2
→ Discharge propagation suppression
→ Good efficiency reached
Foil 3 single segmented to reduce HF noise





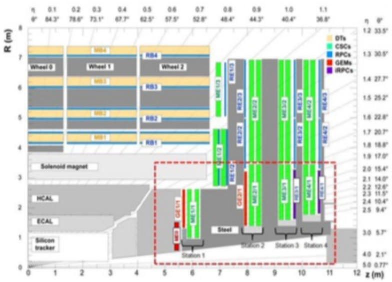


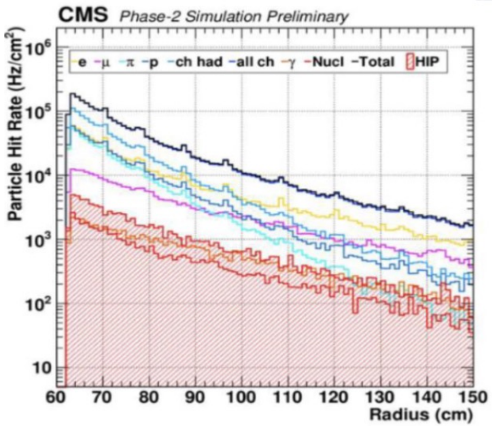


CMS GEM

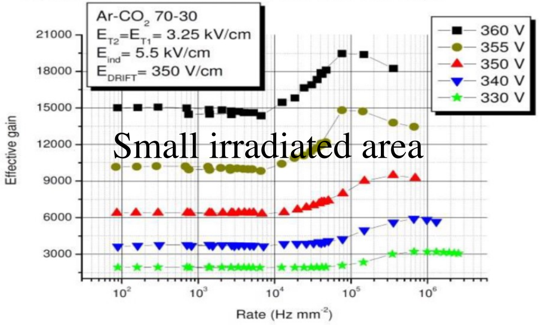
- ME0: 2 end-caps each of
- 6 modules x 18 stations → 216 modules
- Module area 0.296 m^2 → total active area: 64 m^2

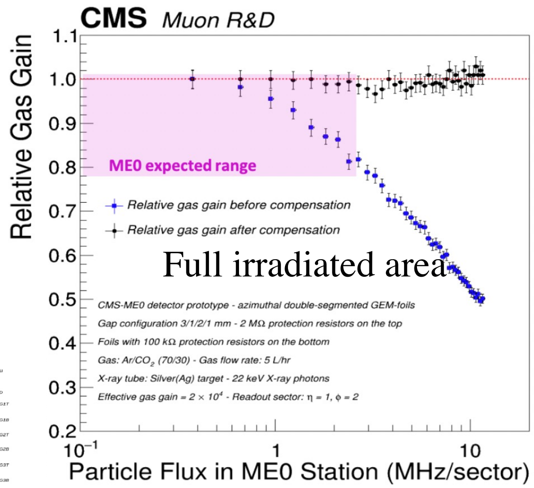
Forward region → expected rate up to ~150 kHz/cm^2





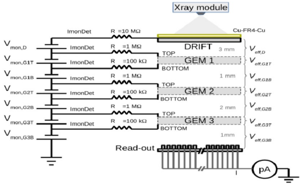
https://cds.cern.ch/record/1316179/files/CERN-THESIS- 2006-088.pdf

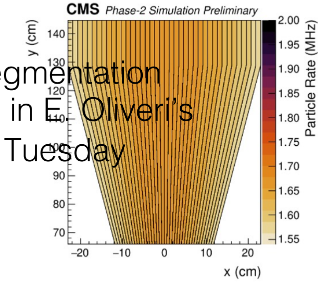




Voltage-drop compensation: Promising results for triple GEM working with stable gain at particle flux of O(MHz/sector)

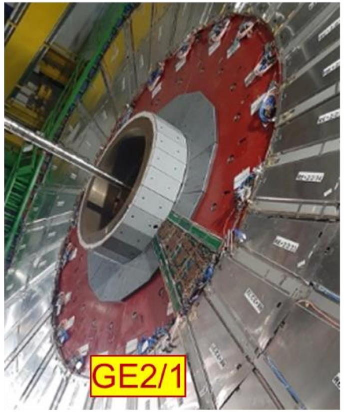
Effect of voltage drop on the protection resistor not visible when irradiating a small detector surface

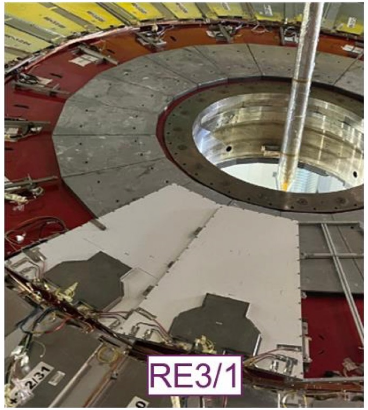


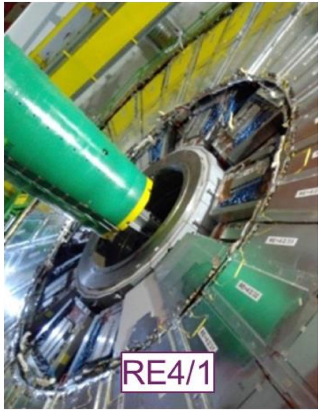


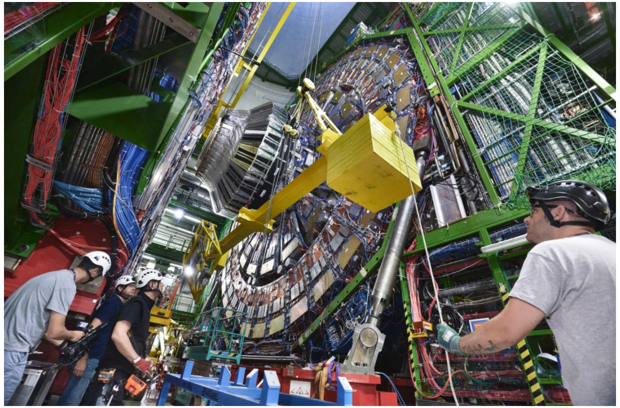
Vertical segmentation discussed in E. Oliveri's lecture on Tuesday

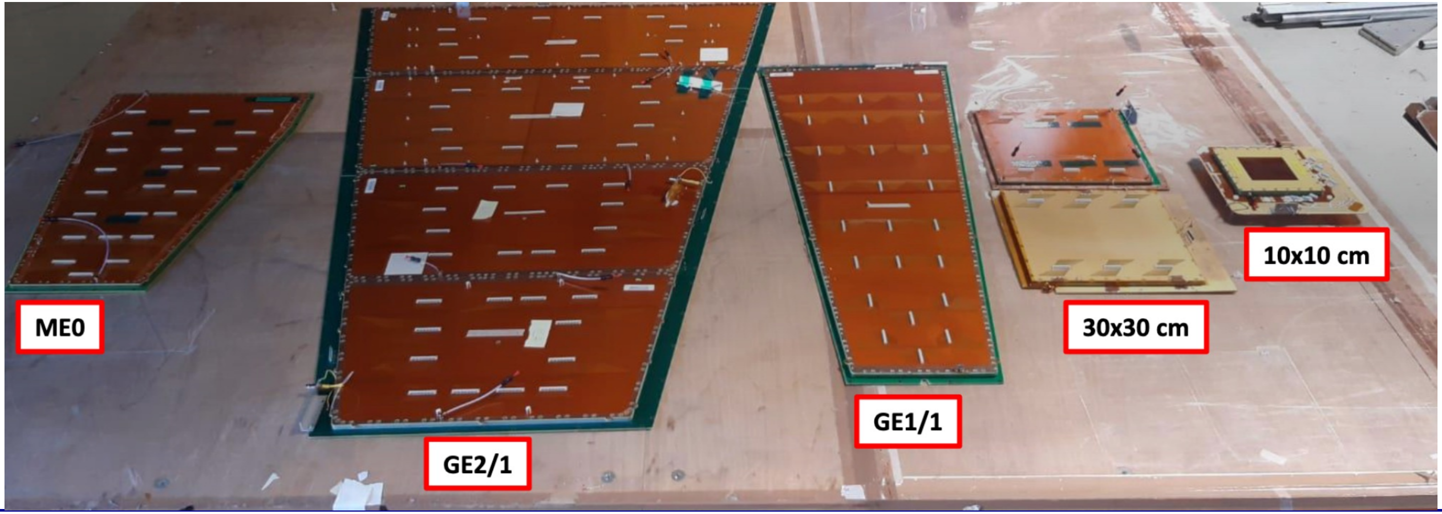
CMS GEM



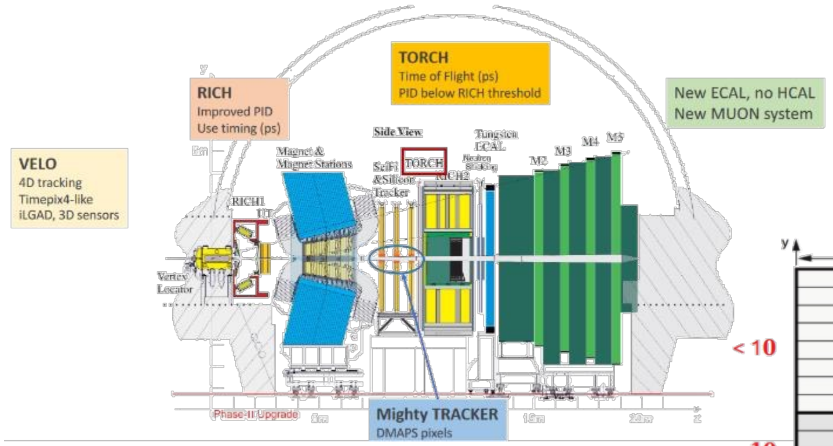








LHCb µRwell



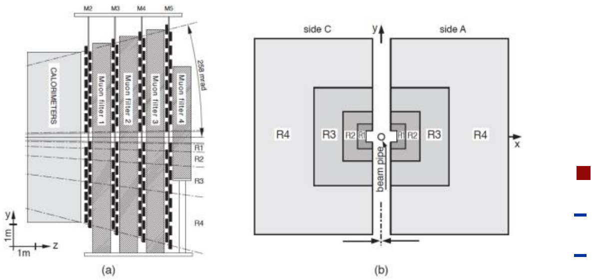
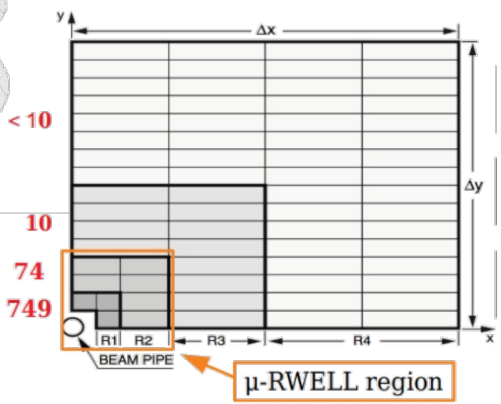


Figure 4.15: (a) Side view of the LHCb muon system for the Phase-I Upgrade. (b) Station layout with the four regions R1–R4 indicated.

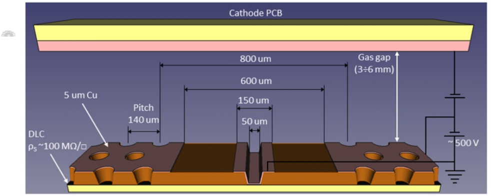
- LHCb Upgrade of the Muon system for Run5 and beyond
- Rate up to 750 MHz/cm^2 on detector single gap
- Efficiency quadrigap >=99% within a BX (25 ns)
- Stability up to 1C/cm^2 in 10y
- Gain=4000



Rates (kHz/cm^2)	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 (m^2)	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

- uRWELL for R1/R2
- 4 gaps/chamber
- 76 detectors, size 30x25 to 74x31 cm^2
- 90 m2 detector (130 m2 DLC)
- Gas: Ar:CO2:CF4 (45:15:40)



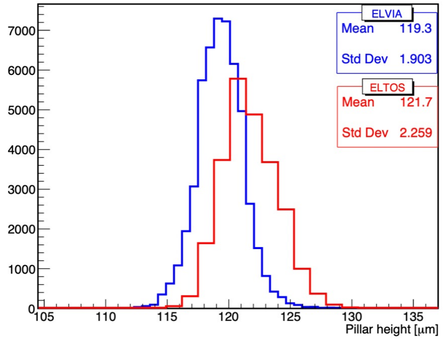
PEP technique, more in E. Oliveri's lecture on Tuesday

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

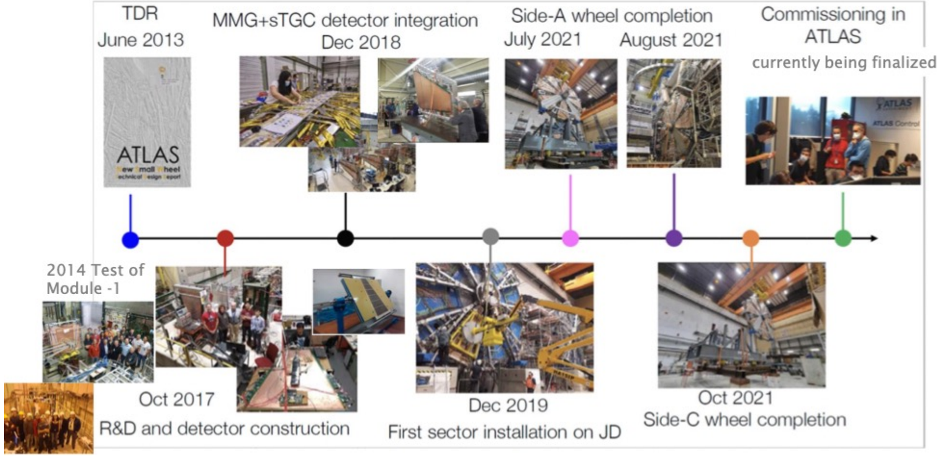
Distribution of the pillar height of the Micromegas boards for ATLAS



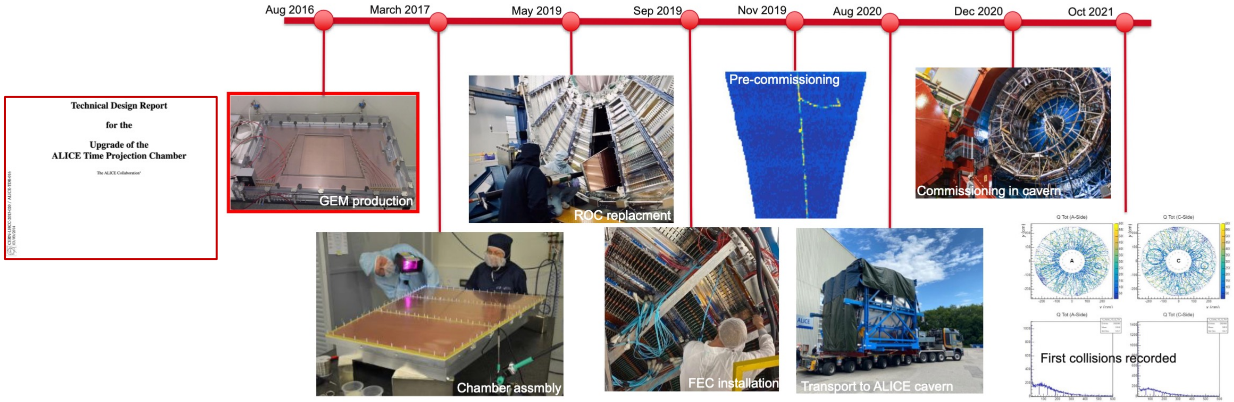
Large detectors → large problems!
Many components → high probability of having problems!

Detector experts inspecting an MPGD board at the production site

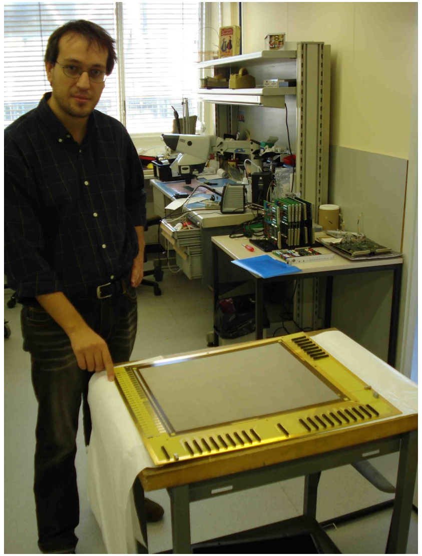
It’s a long, long way…



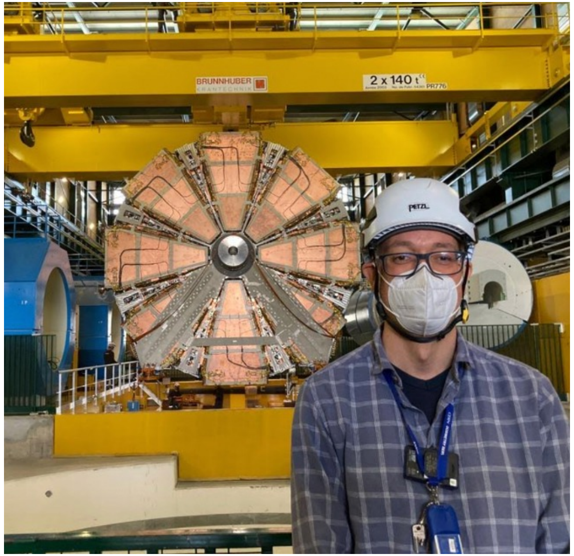
- Examples: ATLAS and ALICE
- Technical Design Report in 2013
- Installation in 2021/2022



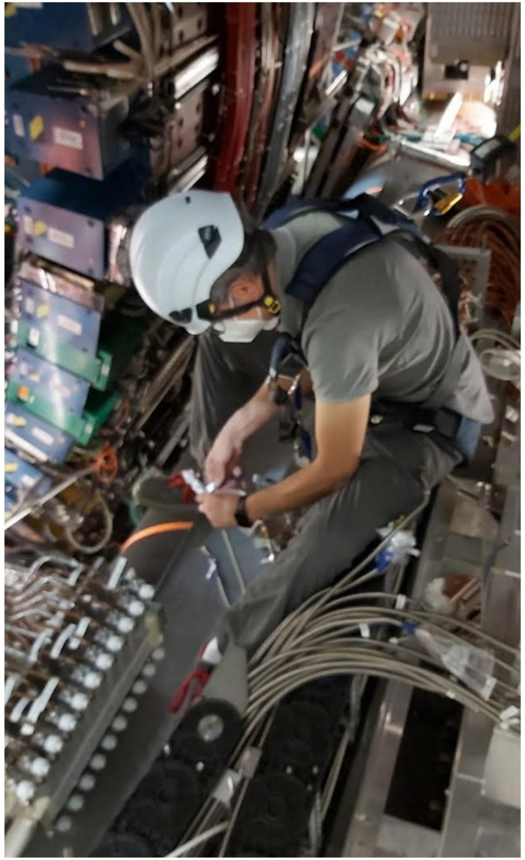
It’s a long, long way…



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



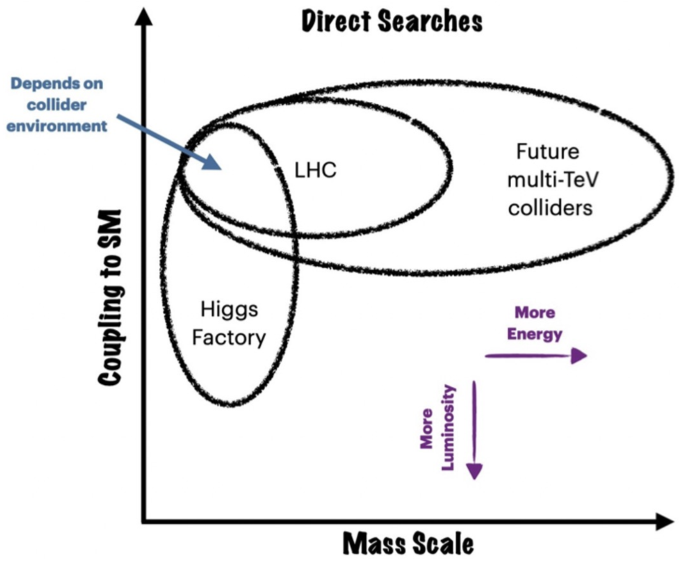
2022 Project compoletion: Largest Micromegas system ever built (1280 m^2)

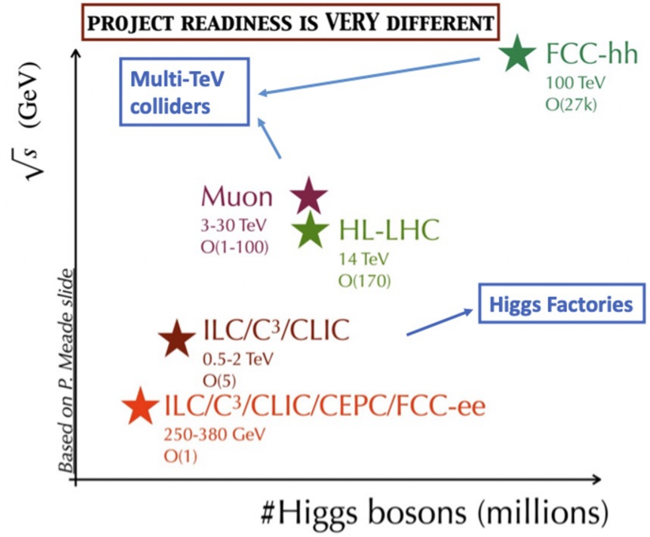


From SM Lagrangian to plumbery work… waiting for physics

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.

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

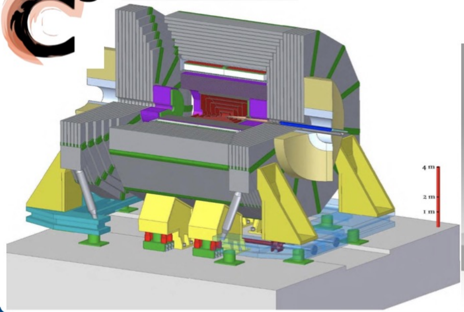
Multi-TeV colliders (> 1 TeV c.o.m. energy)

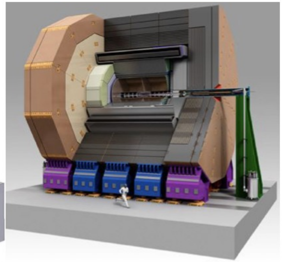
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5	2052	2058
		3.0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

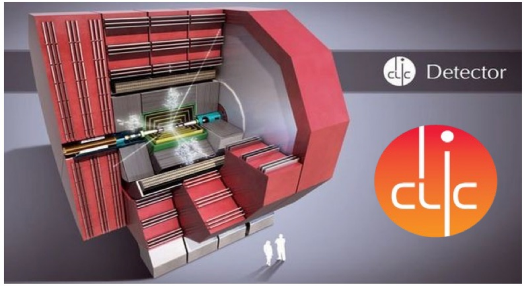
Detector requirements depend strongly by the machine parameters

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

Experiments proposed for future colliders



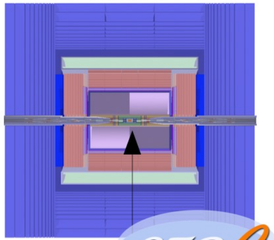




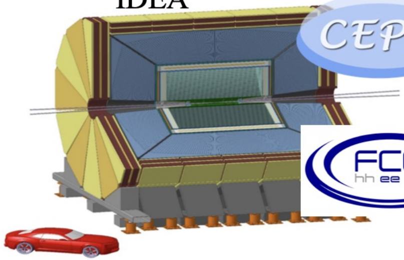
ALLEGRO

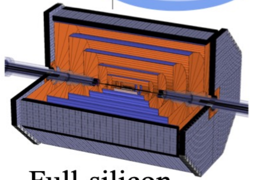
CRD's

ILD like



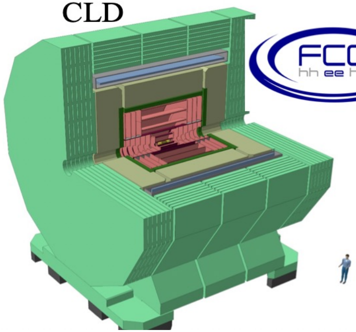
IDEA

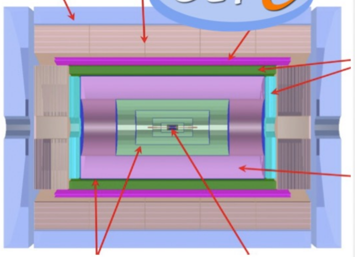




Full-silicon

CLD





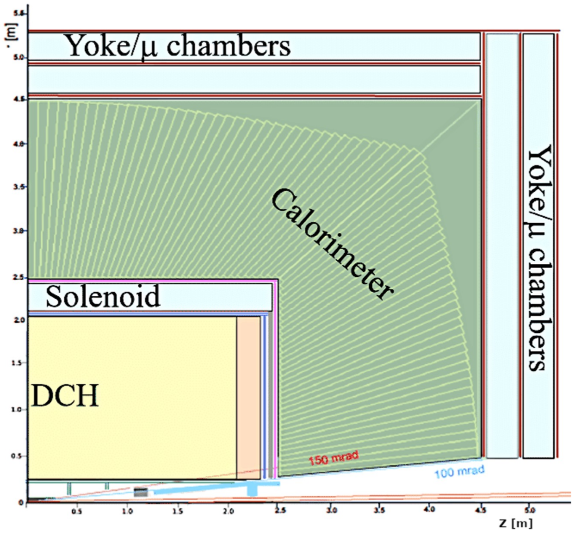
4th CEPC concept

MPGD for future experiments

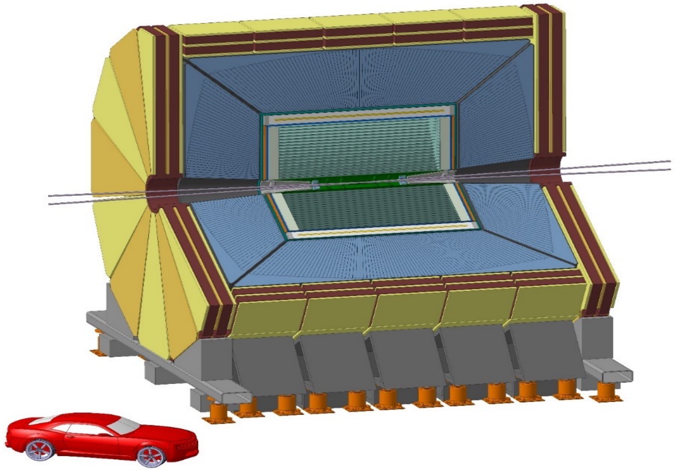
Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirement
FCC-ee and/or CEPC IDEA PRESHOWER DETECTOR START: >2030	Lepton Collider Tracking	μ-RWELL	Total area: 225 m2 Single unit detect: (0.5x0.5 m2) ~0.25 m2	Max. rate: 10 kHz/cm2 Spatial res.: ~60-80 μm Time res.: 5-7 ns Rad. Hard.: <100 mC/cm2	
FCC-ee and/or CEPC IDEA MUON SYSTEM START: >2030	Lepton Collider Tracking/Triggering	μ-RWELL RPC	Total area: 3000 m2 Single unit detect: ~0.25 m2	Max. rate: <1 kHz/cm2 Spatial res.: ~150 μm Time res.: 5-7 ns Rad. Hard.: <10 mC/cm2	
FCC-ee and/or CEPC IDEA PRESHOWER DETECTOR START: >2030	Lepton Collider Tracking	μ-RWELL	Total area: 225 m2 Single unit detect: (0.5x0.5 m2) ~0.25 m2	Max. rate: 10 kHz/cm2 Spatial res.: ~60-80 μm Time res.: 5-7 ns Rad. Hard.: <100 mC/cm2	
MUON COLLIDER MUON SYSTEM START: > 2050	Muon Collider	RPC or new generation fast Timing MPGD	Total area: ~ 3500m2 Single unit detect: 0.3-0.4m2	Max.rate: <100 kHz/cm2 Spatial res.: ~100μm Time res.: <10 ns Rad. Hard.: < C/cm2	Redundant tracking and triggering

Lepton colliders

- In Lepton Colliders gaseous detectors are still the optimal choice for inner trackers → low material budget
- The example is the IDEA detector concept
  - Proposed for large lepton colliders (FCC-ee, CEPC)



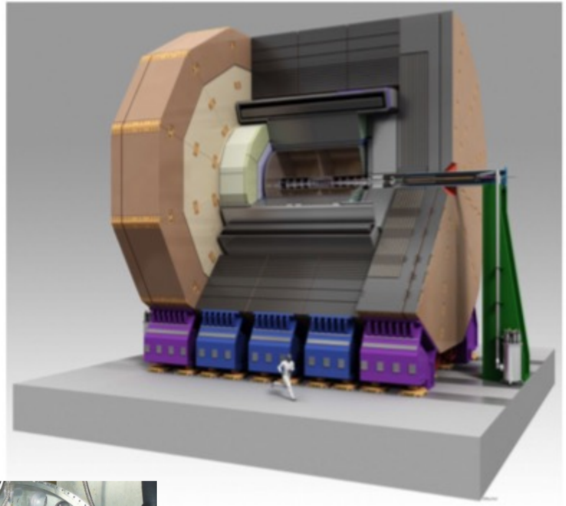
- Tracker:
  - Si pixel vertex detector
  - Drift Chamber (DCH)
  - Si wrappers (strips)
- µRWELL for pre-shower detector and Muon system inside the magnet retour yoke
- Superconducting solenoid 2T,30cm,~0.7X0 ,0.16λ@90°

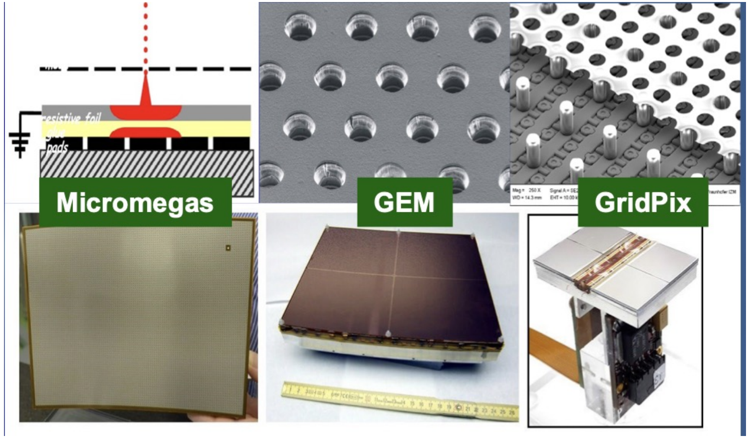


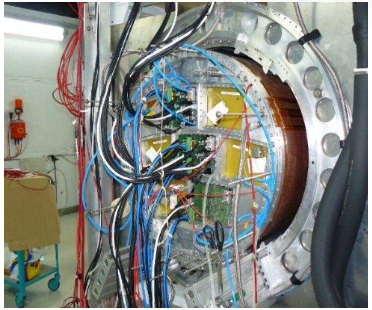
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

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.





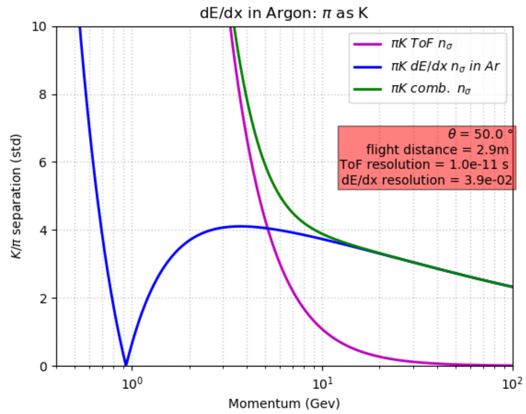


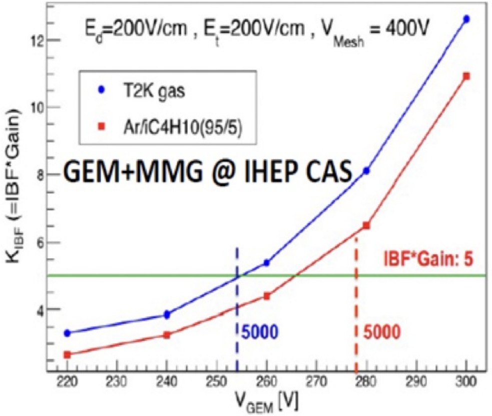
First development of large scale GridPix detector

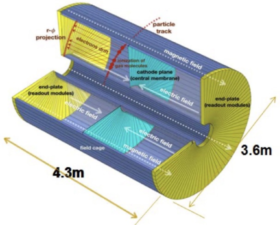
~10 m^2 detector surface. Three option under study: Micromegas / GEM / GridPix

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

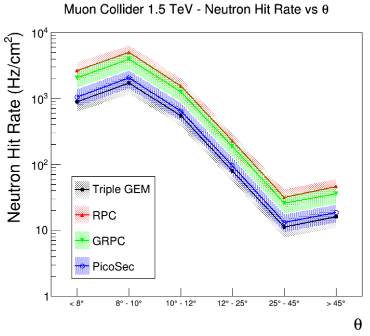
- Running a TPC @ Z pole @ $2x10^{36}$ cm^{-2} s^{-1} is not trivial
- The ion backflow is an issue
- The positive ions of 22 000 Zs will accumulate in the TPC volume
- Continuous DAQ and tracking needed for real-time corrections for space point distortions → experience from ALICE!

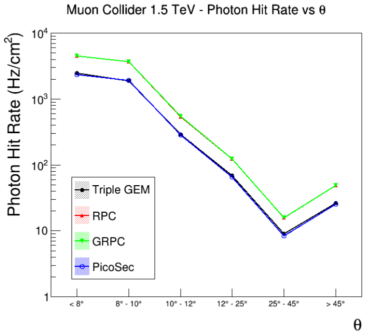
TPC for CEPC: promising results in IBF suppression for hybrid GEM+MM technology (tested by ALICE in the past)

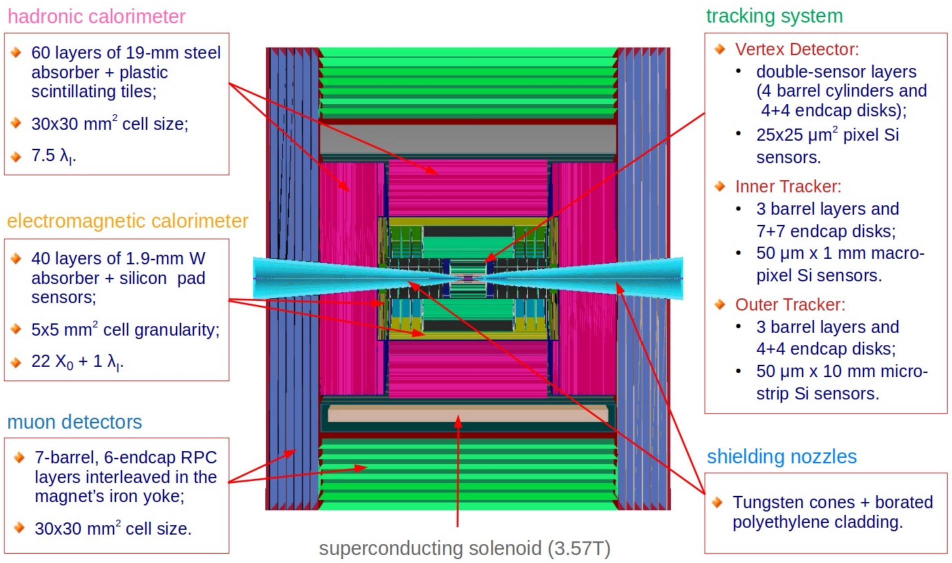
Muon Collider

- Gaseous detectors (RPC) considered for Muon system, interleaved in an iron yoke

- Targets 100 um space and 1 ns time resolutions
- Space resolution and rate capability challenging for RPC → exploring other options: GEM, Micromegas, mRPC, PicoSec...



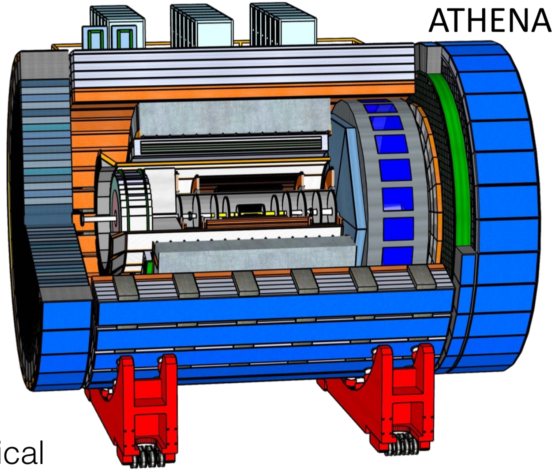




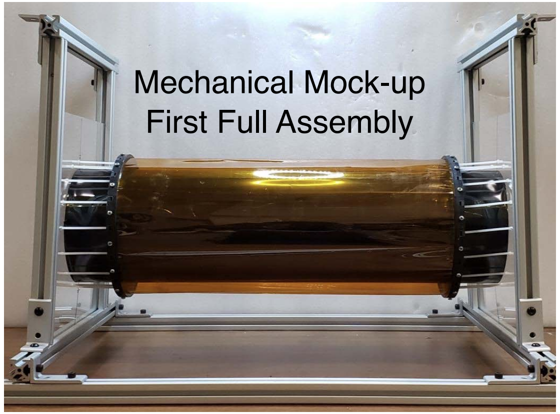
- Picosec detector can reach <1 ns time resolution at high rates
- Lower material budget compared to RPC → smaller sensitivity to neutrons aand photons → R&D started
- Very high energy muon momentum reconstruction in 10 TeV collisions remain challenging

Electron-Ion Collier Trackers

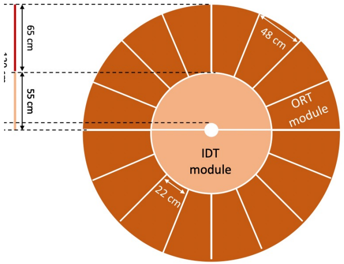
- 3 proto-colloborations: ATHENA, CORE, ECCE
  → ATHENA as example
- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements
- Excellent PID (pi/K/p)
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c



ATHENA

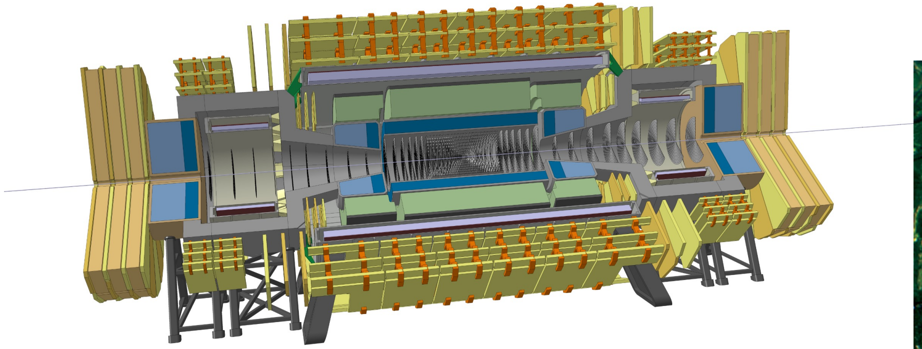


- Outer barrel tracker uses cylindrical Micromegas
- Endcap tracker uses planar u-RWELL
- Envision capacitive-sharing pad readout: Vertical stack of pads layers → reduce readout channels
- GEM or μRWELL proposed as forward tracker in CORE as well

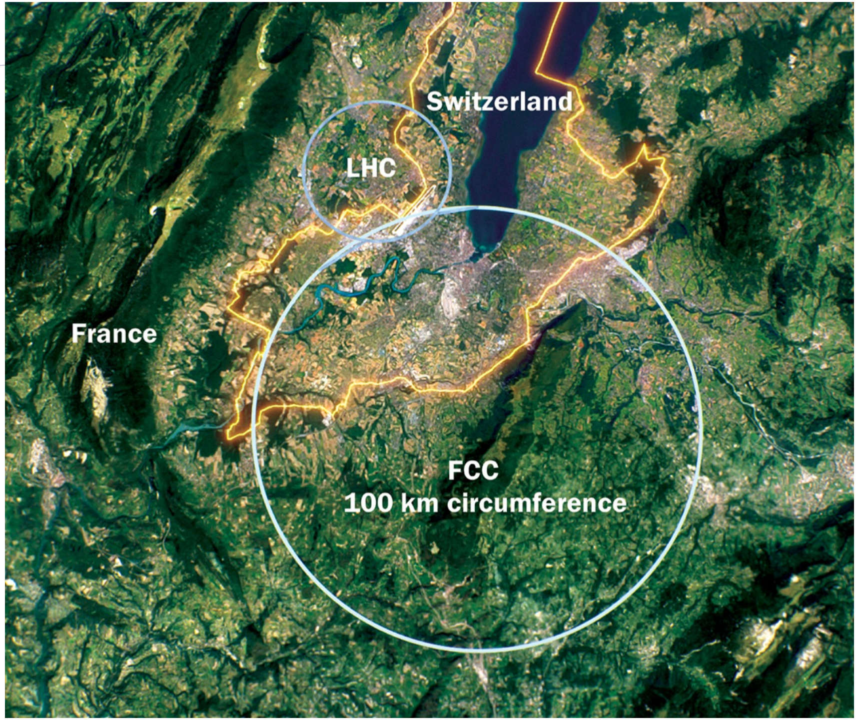


CORE EIC GEM prototype
U-V srtrip redout

FCC-hh

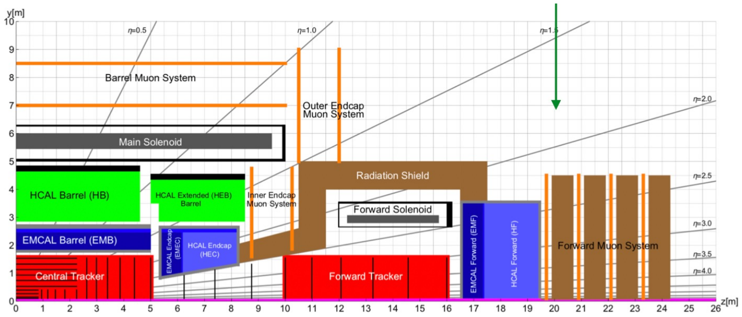


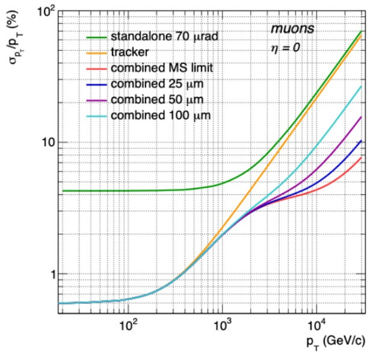
parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L} \times 10^{34}$	$cm^{-2}s^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
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

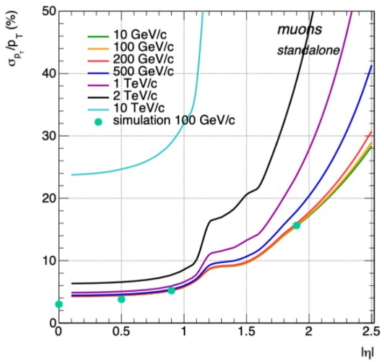


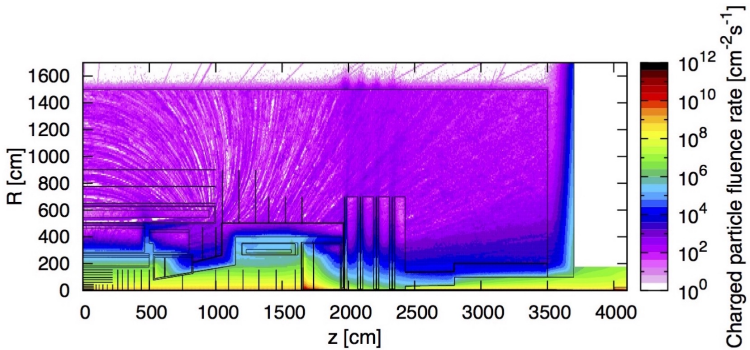
Gaseous Detectors at FCC-hh

- 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)





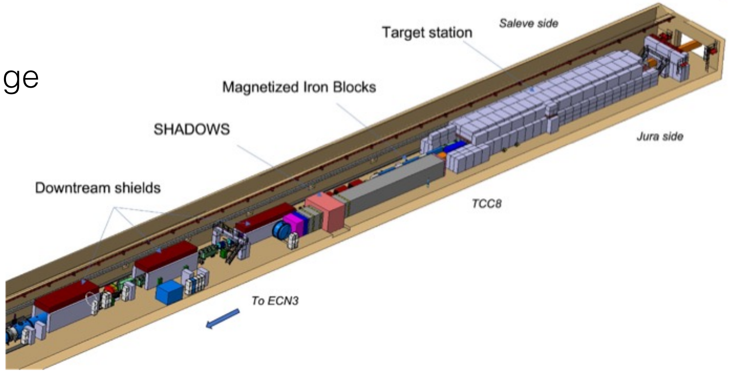




- Gas detectors like the ones employed for HL-LHC (sMDT) are good candidates for the muon systems
- Different choices for Barrel&Outer EC and Inner EC
- Dedicated R&D needed to exploit recent trends in frontier gaseous detectors: sub-ns time res., O(1)MHz/cm2 rate capability, longevity, eco-friendly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

SHADOWS

- SHADOWS: Proposed beam-dump experiment at CERN NA
- Search for feebly interacting particles (FIPs) in 0.1-10 GeV mass range
- Muons from IP main source of background → need of a veto system:
  - ~10 kHz/cm^2 max rate
  - 2D tracking capability with resolution <1mm
  - High efficiency
  - Time resol ~10 ns
- Proposed to use DLC resistive pad Micromegas



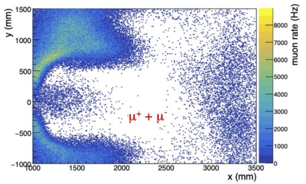
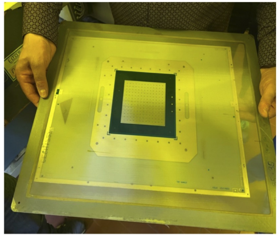
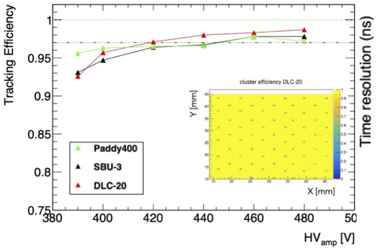
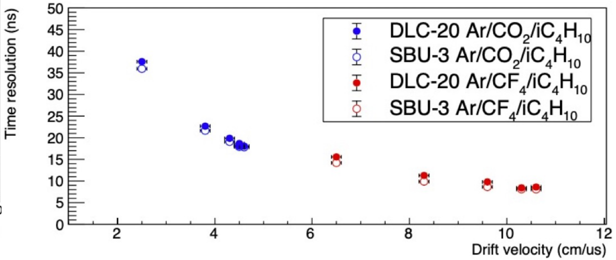
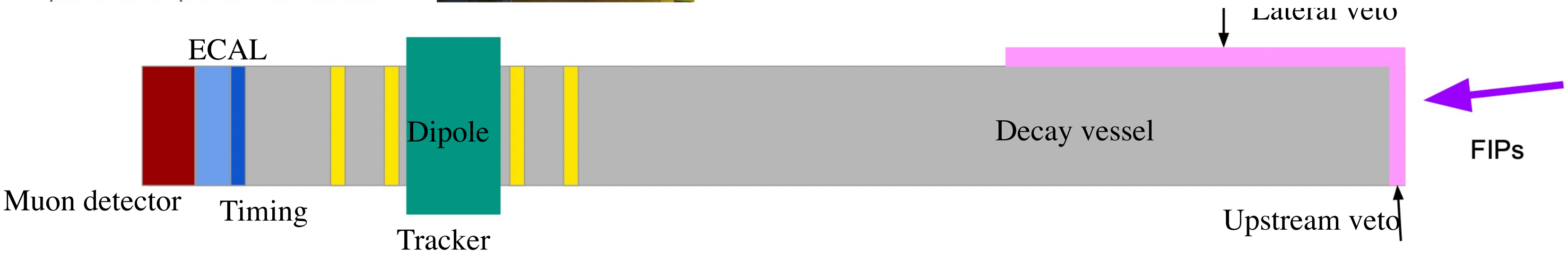


Figure 41. Expected muon rate in the upstream veto of the SHADOWS detector.



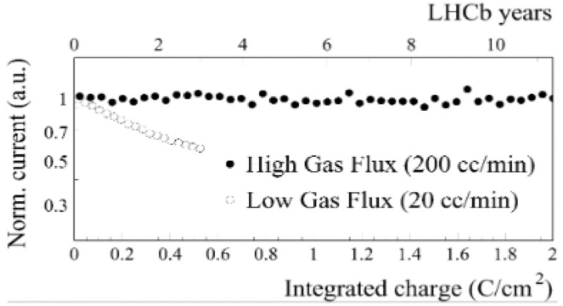




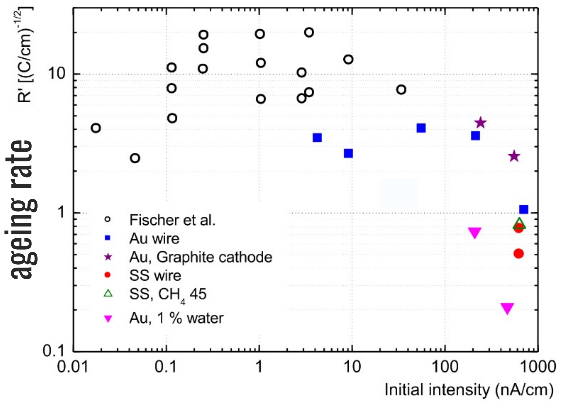


Gaseous detector longevity

- 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 stydu missing for MPGD (to my knowledge)

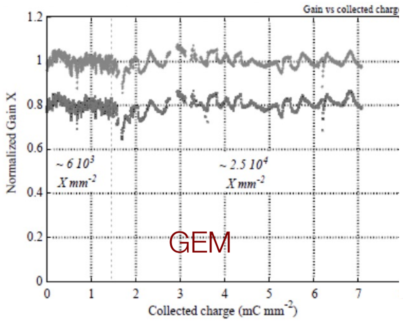


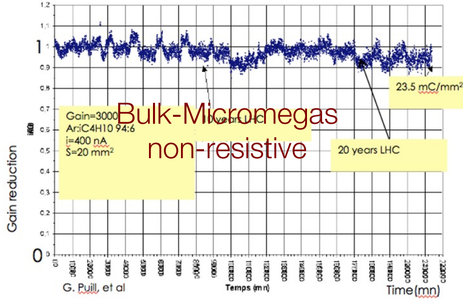
Gaseous detector longevity

- 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

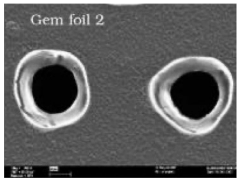
- New materials (resistive coating) and challenging detector operations (high rates, large integrated charge) calls for dedicated studies

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

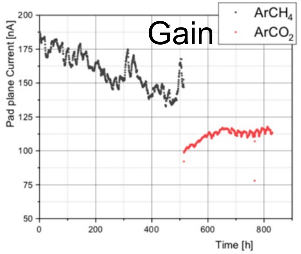


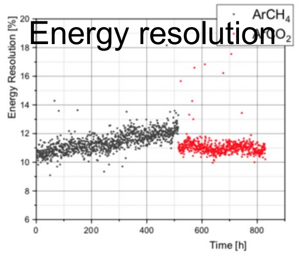


Resistive Micromegas (ATLAS-like): 3-years exposure at GIF++
Total collected charge ~0.3 C/cm^2 → No sign of aging in Ar:CO2

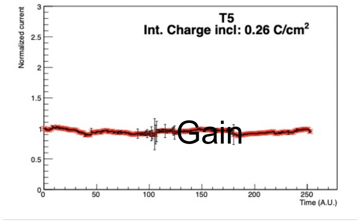


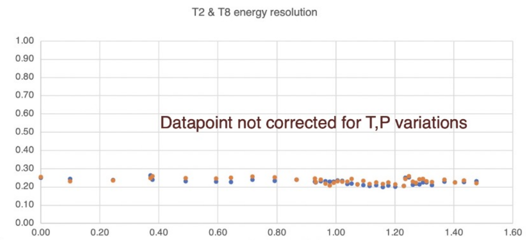
Etching effect on Triple-GEM operated with CF4-based mixture at low flow

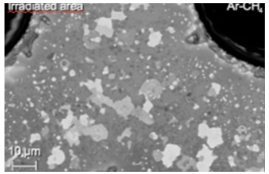




Aging in ALICE GEM prototype operated with hydrocarbons (CH4) in Ar 95% mixture. Aging stops when CH4 is replaced with CO2







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

Summary

- Road to the Nobel Prize for a detector physicist

1. Invent a smart detector
2. Make sure it is used in frontier experiments
3. Make sure one of the experiments makes a breakthrough discovery in Physics

γ-rays and the highest-energy particles. At the current stage of high-energy physics, however, simply making use of the location of free electrons near the wires of proportional chambers and the drift-time of the electrons provides an image of configurations rivalling in complexity those provided by bubble chambers. This is shown in fig. 10, the image of an event generated in the ALEPH detector installed at one of the intersections of LEP, the large e^+e^- collider operated at CERN.

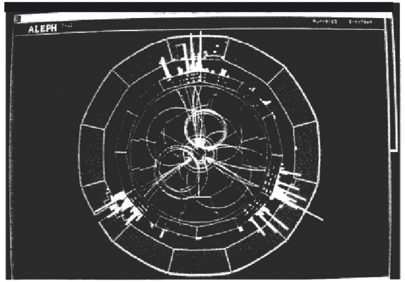
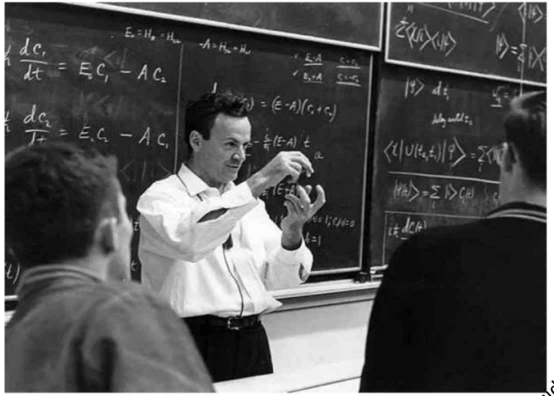


Fig. 10: Image of an e^+e^- collision obtained at the ALEPH experiment at LEP using an instrument making use of the drift-time in a large volume and the read-out of coordinates projected in a wire chamber. Auxiliary outside detectors provide the information on the energy of the particles, the trajectory of which was displayed.

Georges Charpak – Nobel Lecture. NobelPrize.org.
https://www.nobelprize.org/prizes/physics/1992/charpak/lecture/



G. Isidori, ECFA meeting July 2022

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

No Nobel prize (yet) for MPGDs…

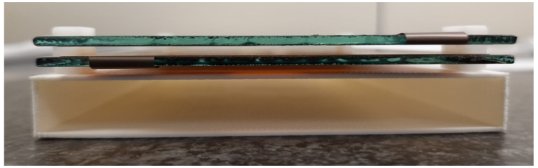
Thank you!

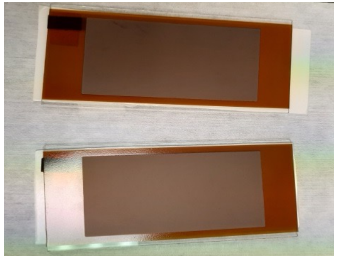
Additional Material

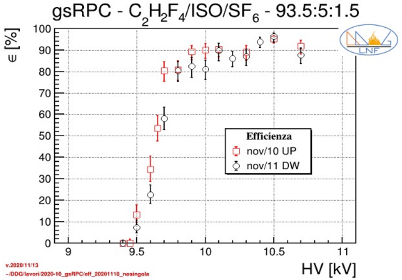
MPGD as RPC

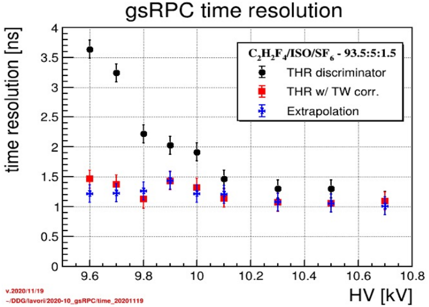
- The resistive coating of PCB allows to develop RPC-like structures for time resolution comparable to RPC (~ ns)
- Main difference with RPC: surface vs planar resistivity
  - Resistive pattern possible
  - Tuning of resistivity
- Some activities ongoing to explore the potential

- sRPC: surface RPC
  - Standard DLC on substrate
  - σ_t = 1 ns reached

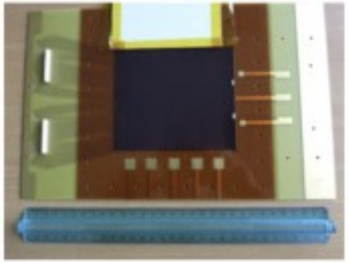


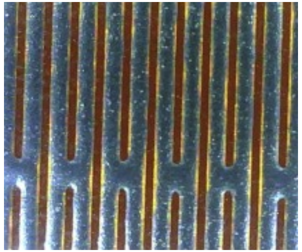


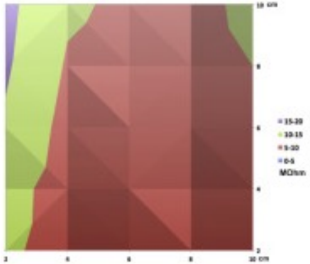


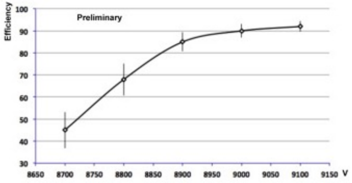


- RSD: Resistive Strip Detector
  - First prototype with screen-printed resistive strips
  - Good resistivity uniformity reached
  - Promising performance



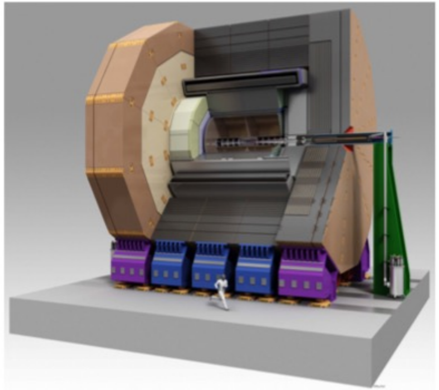






MPGD for future experiments: TPC for ILC

- TPC for ILC

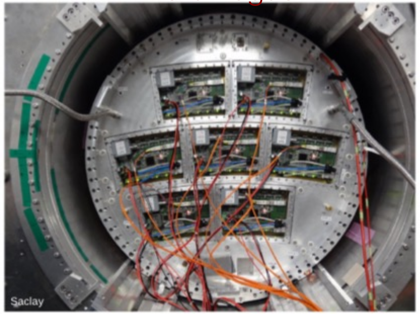


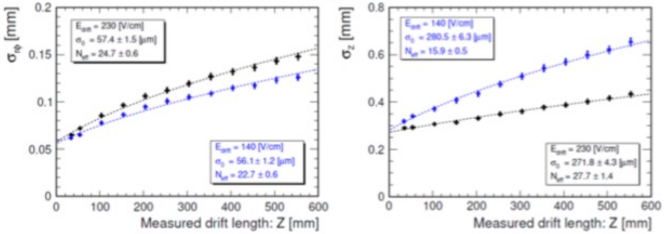
Parameter			
Geometrical parameters	r_{in} 329 mm	r_{out} 1808 mm	z $\pm$ 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq 0.05\ X_0$ including outer fieldcage in r		
	$< 0.25\ X_0$ for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times 10^6$/1000 per endcap		
Pad pitch/ no.padrows	$\simeq 1\times 6\ mm^2$ for 220 padrows		
σ_{point} in $r\phi$	$\simeq 60\ \mu m$ for zero drift, $< 100\ \mu m$ overall		
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)		
2-hit resolution in $r\phi$	$\simeq 2$ mm		
2-hit resolution in rz	$\simeq 6$ mm		
dE/dx resolution	$\simeq 5$ %		
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)		

In addition: very high efficiency for particle of more than 1 GeV.

These requirements can not be fulfilled by conventional wire-based read out. New Micropattern-based readouts have to be applied.

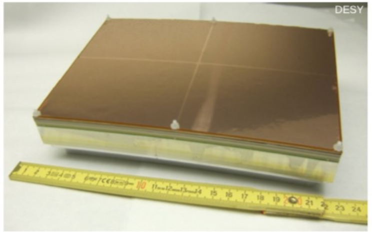
Micromegas

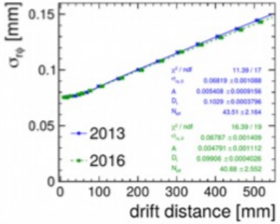


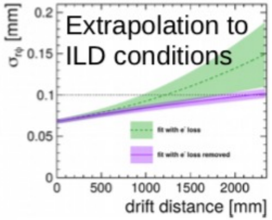


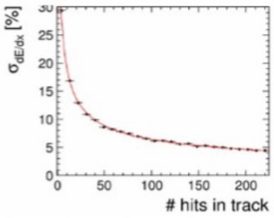
- Several options under study: GEM, Micromegas, GridPix

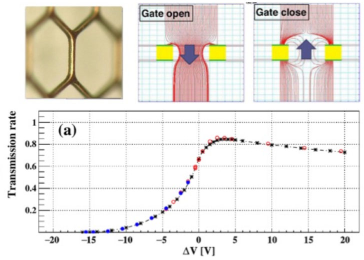
GEM





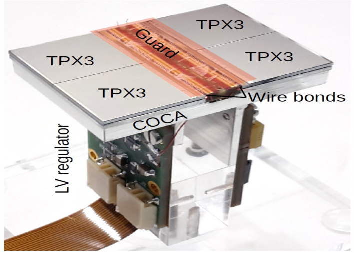


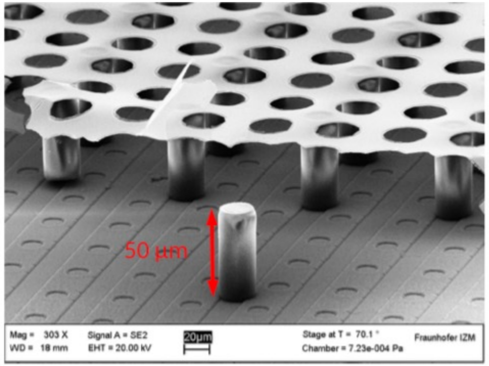


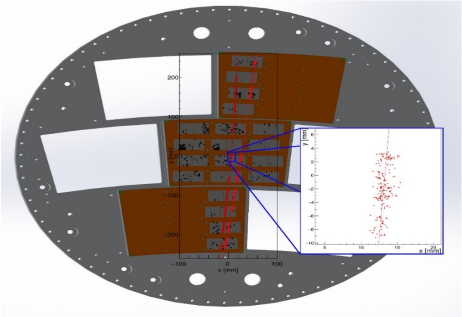


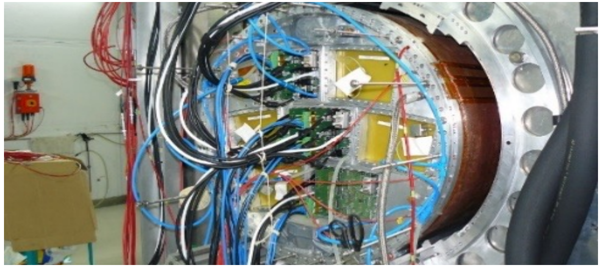
MPGD for future experiments: TPC for ILC

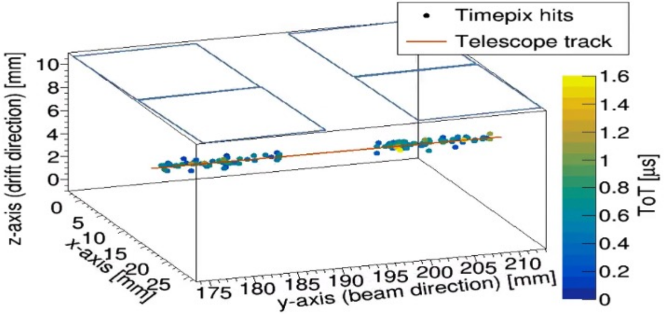
- Gridpix option → first large application
  - Bump bond pads are used as charge collection pads
- Offers:
  - Lower occupancy → easier track reco
  - Improved dE/dx (4% seems possible)
- Needs:
  - ~120 chips/module on 240 modules/endcap ($10m^2$)→ ~60k GridPixels
- Demonstrator of mass production:
  - One module equipped with 160 GridPix ($320 cm^2$)
  - Very promising results: a GridPix-based TPC possible!









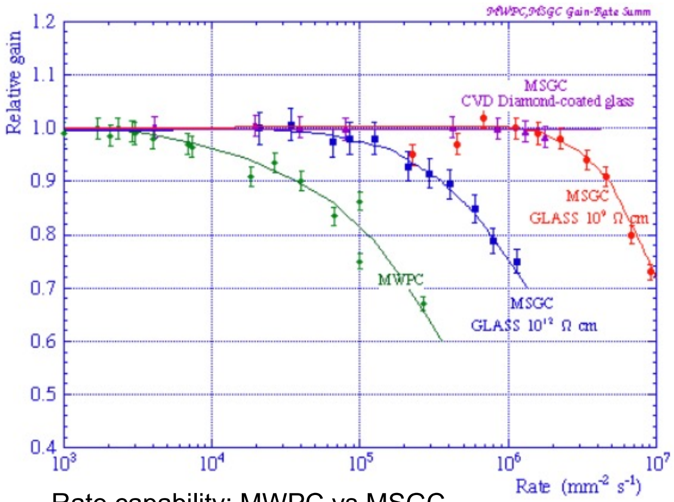


MPGD proposed for calorimetry at ILC too

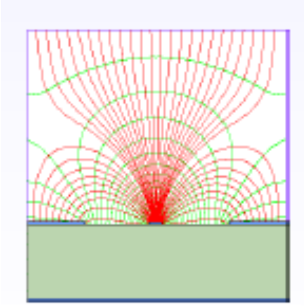
MPGD: increasing the rate capability

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

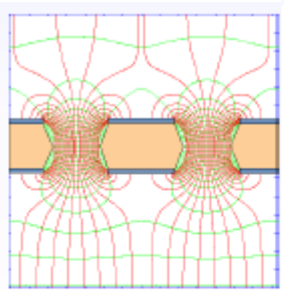
Construction based on printed circuit board production (photolithography, etching)



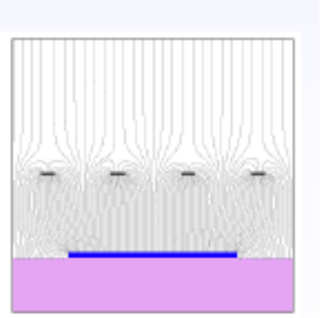
Rate capability: MWPC vs MSGC



MSGC
A. Oed (1988)



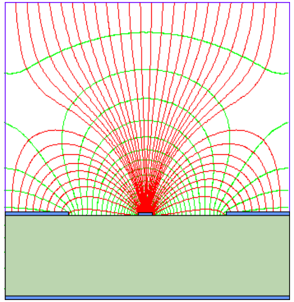
GEM
F Sauli (1997)



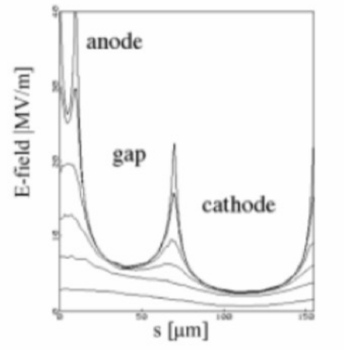
Micromegas
I. Giomataris,
G. Charpak (1997)

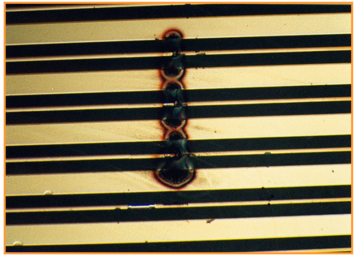
The first challenge: disruptive discharges

- 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

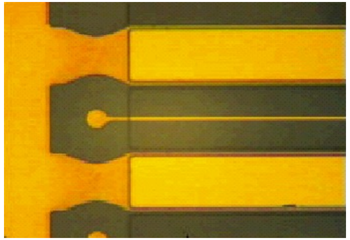


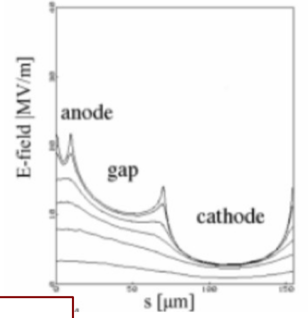
- Example: Gain ~ 10^4; Ionisation gap ~1 cm
  Avalanche size Q = # of e^- primaries x Gain
  - MIP: Q = 10^2 x 10^4 = 10^6 → OK
  - p of ~MeV: Q = 10^4 x 10^4 = 10^8 → discharge
  - Field emission from cathode strip: Q = 10^4 x 10^4 = 10^8 → discharge





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

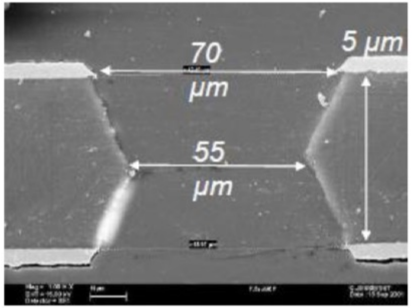


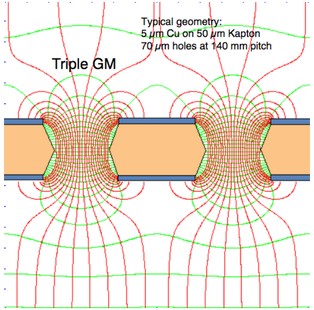


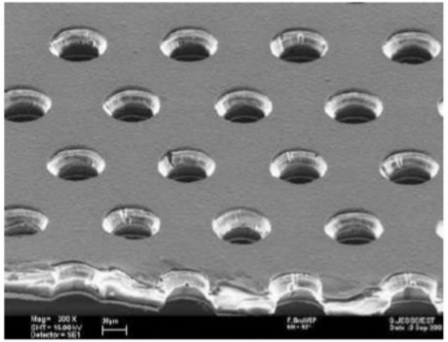
Other spark protection/reduction mechanisms adopted in other MPGD → more on that later

Gas Electron Multipliers

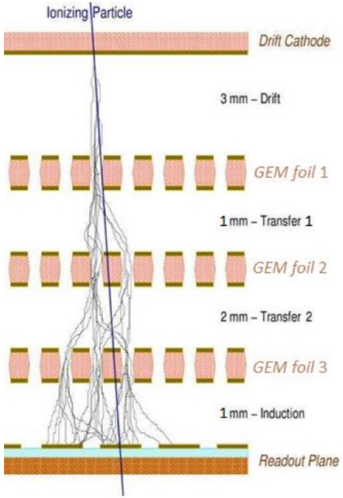
- GEM
- Thin (~50 μm) metal-clad polymer foil chemically perforated with high density of holes (~100/mm^2)
- Preamplification and charge transfer preserving the ionisation pattern



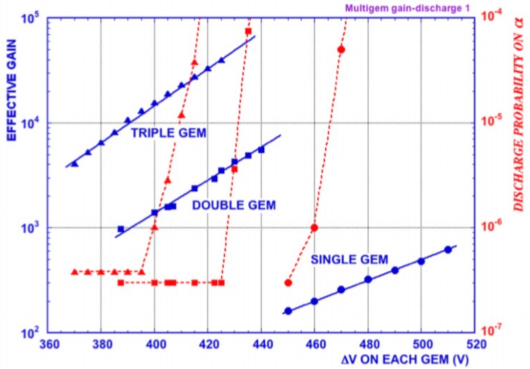




- GEM foils in cascade → high gain before discharges
- Multi-stage → triple GEM



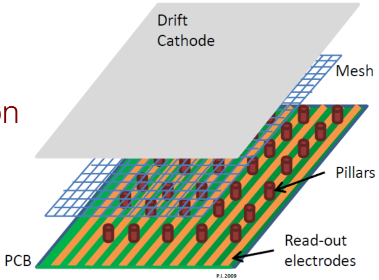
DISCHARGE PROBABILITY ON EXPOSURE TO 5 MeV α (from internal 220Rn gas)

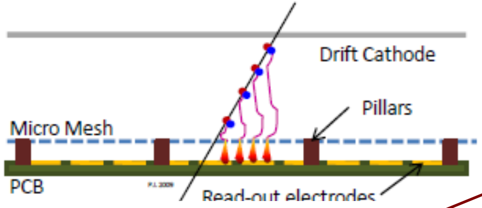


S. Bachmann et al, NIMA 479(2002)294

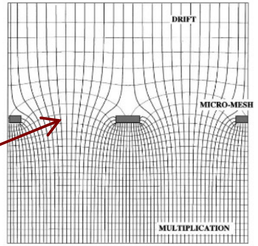
MICRO MEsh Gas Structure

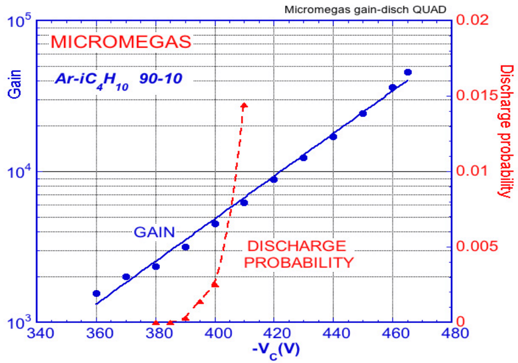
- Parallel-plate with small (~100 μm) amplification gap
- Thin metallic mesh separating the ionisation and amplification regions
- Rate capability and energy resolution of parallel plates



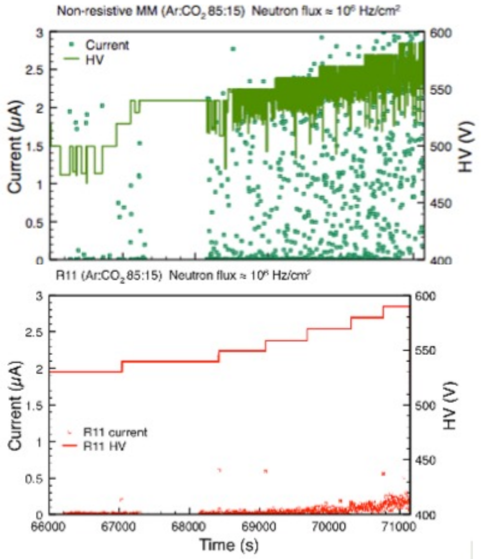


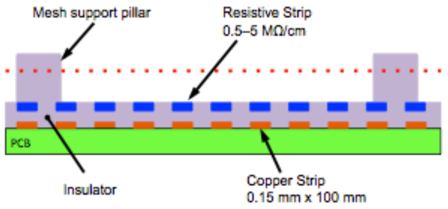
Funnel field lines:
high transparency to electrons





- 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



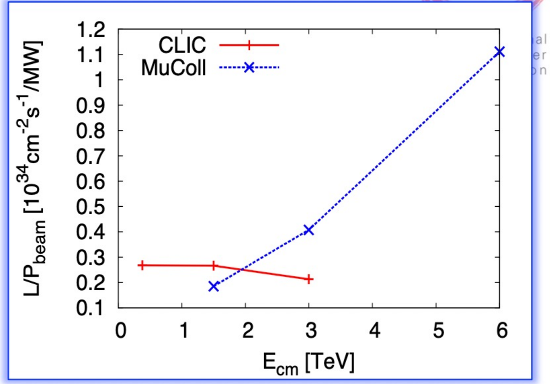


- Standard (non-resistive) Micromegas successfully used in HEP experiments
- Still with non-negligible discharge rate

Muon Collider: a new concept facility

Muons do not suffer from synchrotron radiation in this energy range

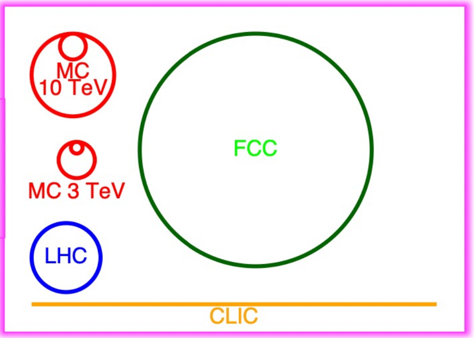
High center of mass energy & high luminosity & power efficient:
luminosity increase per beam power



C. Accettura et al. "Towards a muon collider"

Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	$1 \times 10^{34}\,cm^{-2}\,s^{-1}$	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	1×10^{12}	2.2	1.8	1.8
Repetition rate	f_r	Hz	5	5	5
Total beam power	$P_- + P_+$	MW	5.3	14	20
Longitudinal emittance	ε_l	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_\perp$	µm	25	25	25
IP bunch length	σ_z	mm	5	1.5	1.1
IP beta-function	$\beta^*_\perp$	mm	5	1.5	1.1
IP beam size	$\sigma_\perp$	µm	3	0.9	0.6

Compact:
cost effective
& sustainable

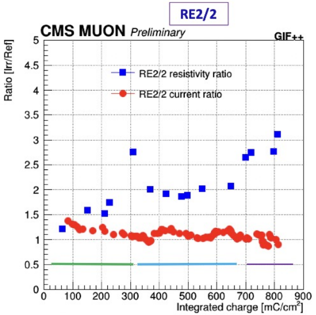


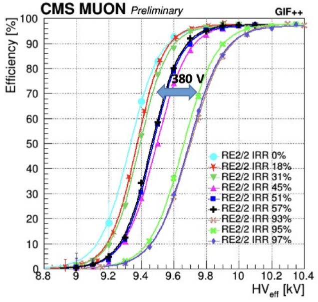
Integrated luminosity: $\sqrt{s} = 3$ TeV 1 ab^{-1} 5 years one experiment
$\sqrt{s} = 10$ TeV 10 ab^{-1} 5 years one experiment

October 17, 2023 Donatella Lucchesi 2

Gaseous detector longevity

- Ageing behavior of traditional gaseous detectors (wire chambers, RPC) well known
- Bakelite RPC
  - Surface degradation mainly due to F- radicals combining in HF → increase of dark current.
    Mitigation: reduce F-based gas components; increase gas flow
  - Increase of bulk resistivity → increase in working point
    Mitigation → restore rH value. Effect can be fully controlled



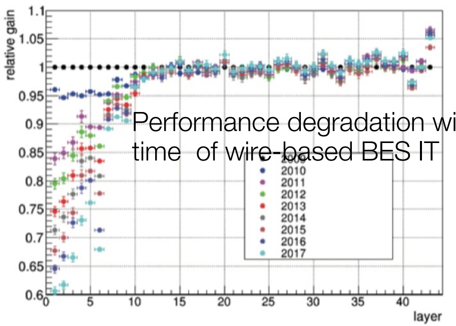


- Wire chambers
  - Deposits (whiskers) on the wire surface → distortion of pulse height spectra, gain loss, noise rate
    Mitigation: no hydrocarbons, no silicon material

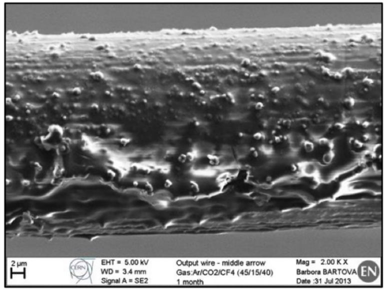
8. Conclusions on Gases

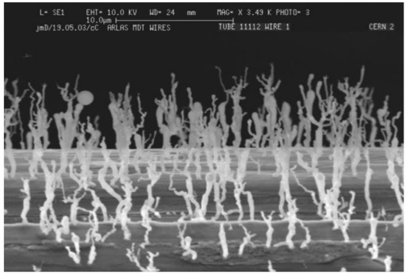
A. If we obtain regular purity gases, a basic conclusion of the workshop is that *Noble gas + hydrocarbon* mixture should not be trusted for more than[11,18,21,46] 0.01–0.05 C/cm. The Noble gas + CO_2 mixture appears to behave about ten times better.[11,21,46]

J.Va'Vra, Nucl.Instr.and Meth.A252 (1986) 547.



Performance degradation with time of wire-based BES IT





Typical aging phenomena on wire chambers