Gaseous Detectors for Future Accelerators

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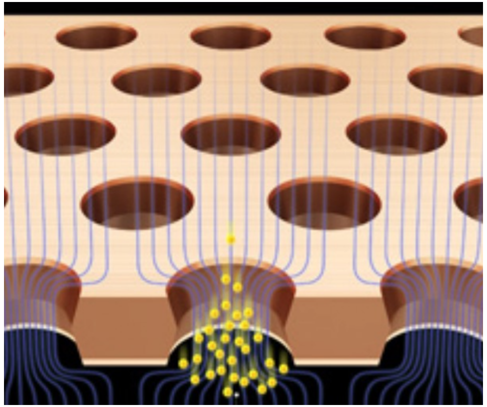
- INFN -

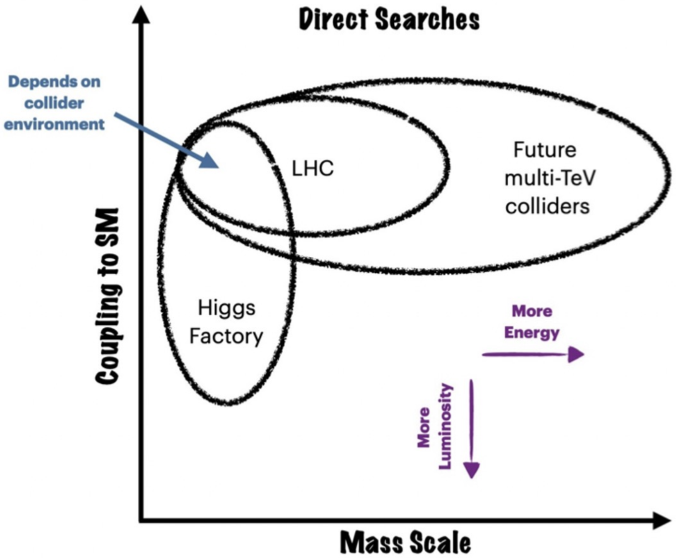
Outline

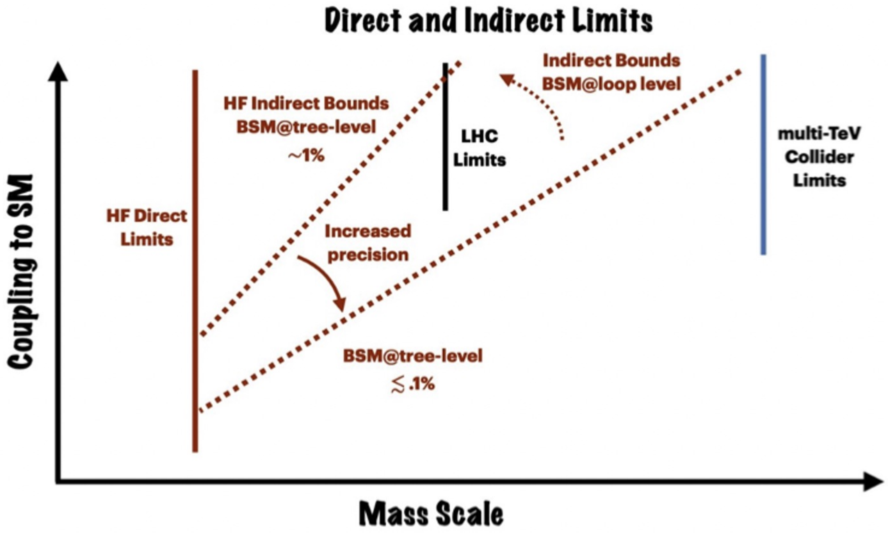
- Introduction: Future Colliders
- Gaseous Detectors for
  - Upgrade of LHC experiments
  - Lepton Colliders
  - Electron-Ion Collider
  - FCC-hh
- Trends and R&D on Gaseous Detectors
- Summary



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.

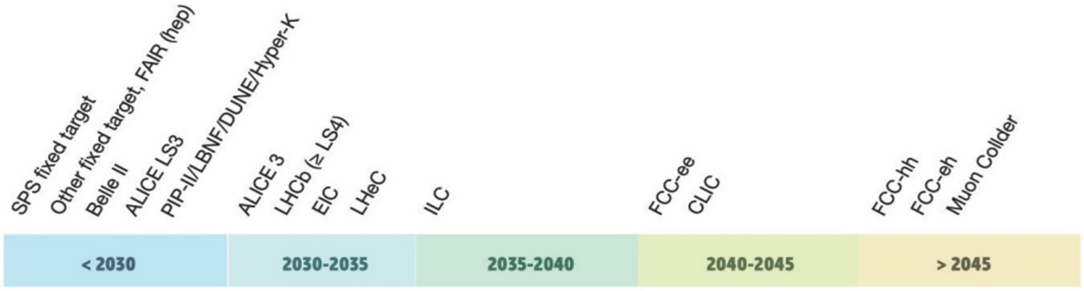
Future Colliders

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	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500 GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	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

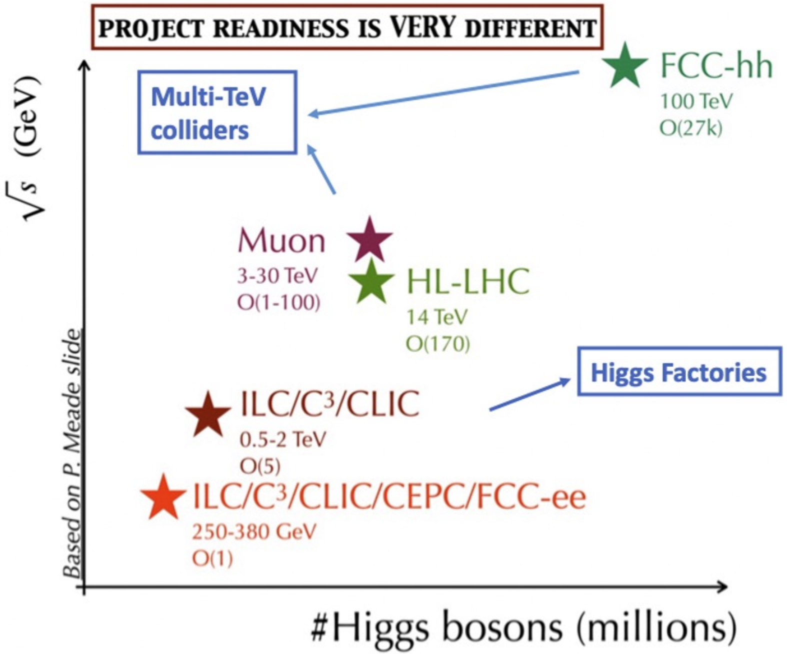
Multi-TeV colliders (> 1 TeV c.o.m. energy)

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	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		



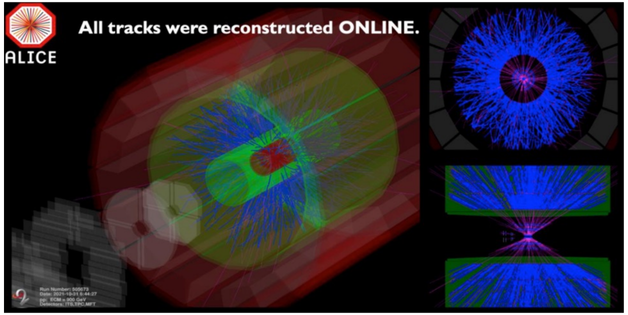
Timeline of future colliders

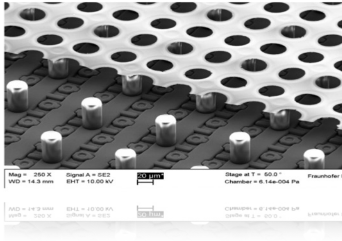
Future Colliders



Detector requirements depend strongly by the machine parameters

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





From micro-patterns to large experiments, gaseous detectors are still largely exploited

Gaseous detectors at LHC

- Gaseous detectors devices are successfully used in HEP since many decades
- They are key detectors 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

Gaseous detectors at the 4 large LHC experiments,
including legacy (Run1, Run2) and Phase1 upgrade (Run3)

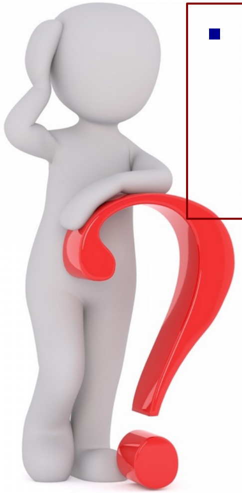
Applications

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

Construction

- Large detector surface for big experiments
  - Industrialisation
  - Maintenance

- Geometry
  - Planar
  - Cylindrical
  - Spherical



Performance

- Time resolution
  - Fast gas
  - Multistage
  - Cherenkov

- Space resolution
  - Granularity
  - uTPC
  - Si readout

- Rate capability
  - Ion background suppression
  - Small-size readout

Operations

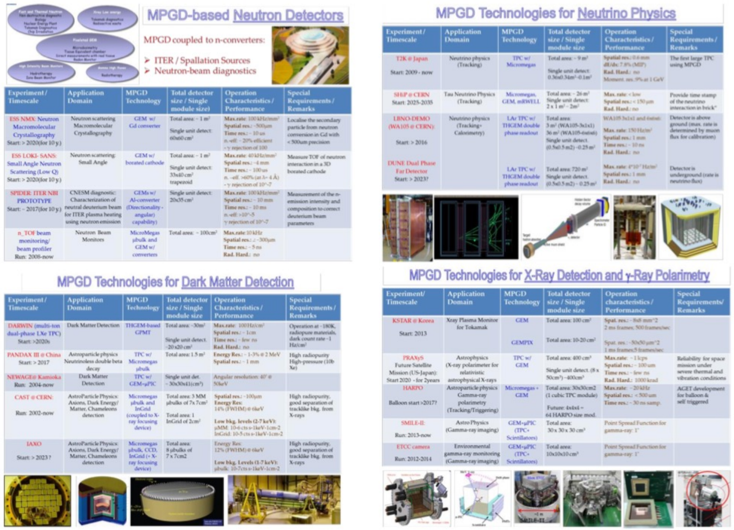
- Gas mixture
  - Drift velocity
  - Diffusion
  - Amplification vs HV stability
  - Aging…

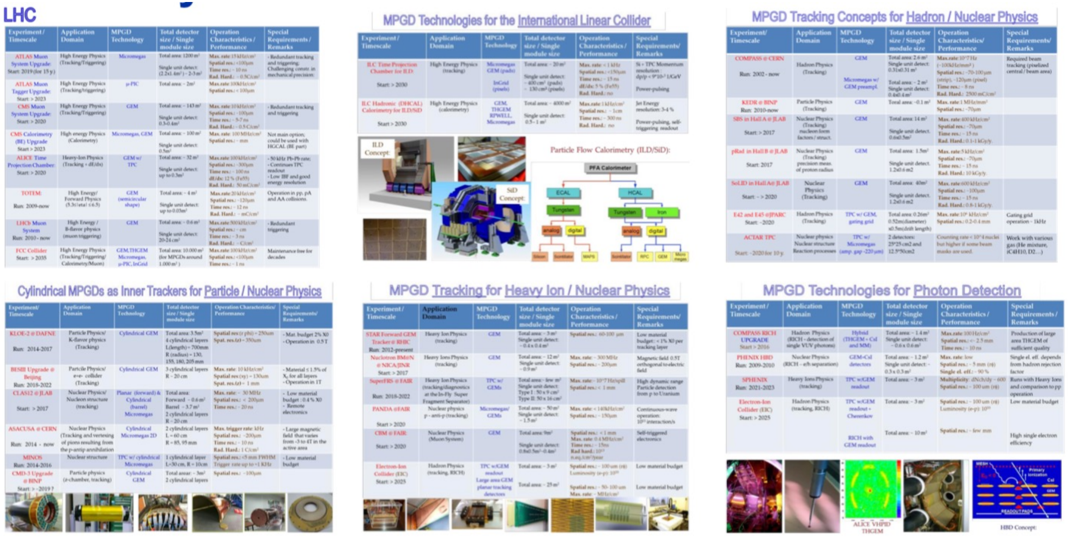
- Aging
  - Gas mixture
  - Materials

- Spark protection
  - Resistive coating
  - Segmentation
  - Gas mixture

Disclaimer

- Impossible to cover all the ongoing efforts on gaseous detectors for future accelerators
- I will show a selected number of representative examples focused on detectors at Colliders
- What is not mentioned is NOT less relevant!

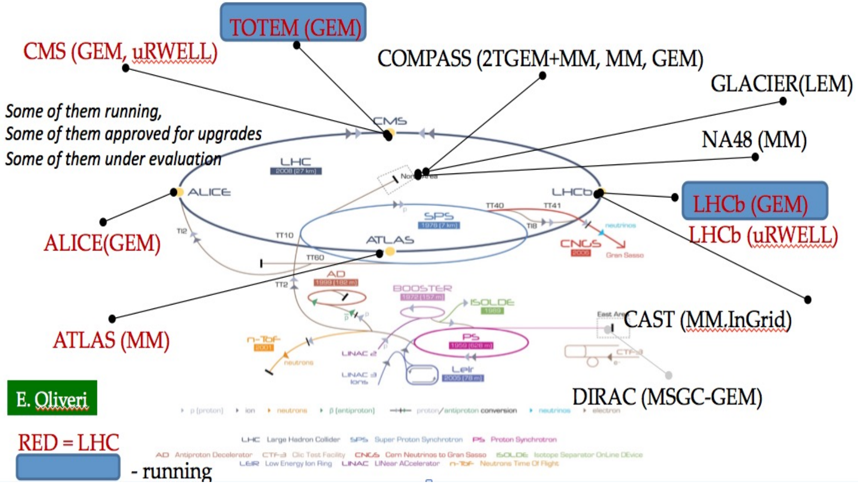




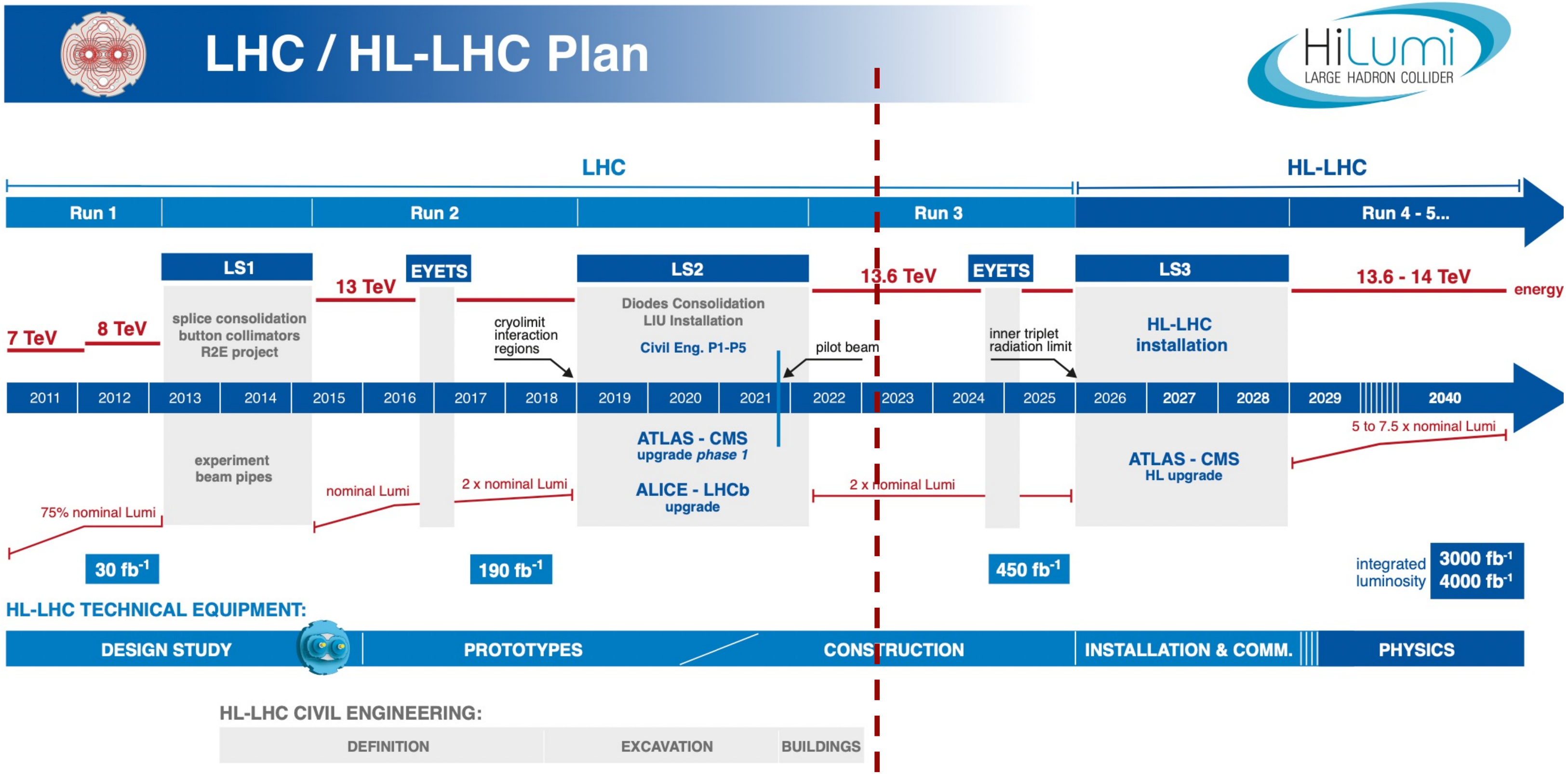
(Out-of-date) list of MPGD application

M. Titov, 5th MPGD conference

LHC experiments upgrade



High Luminosity LHC



HL-LHC

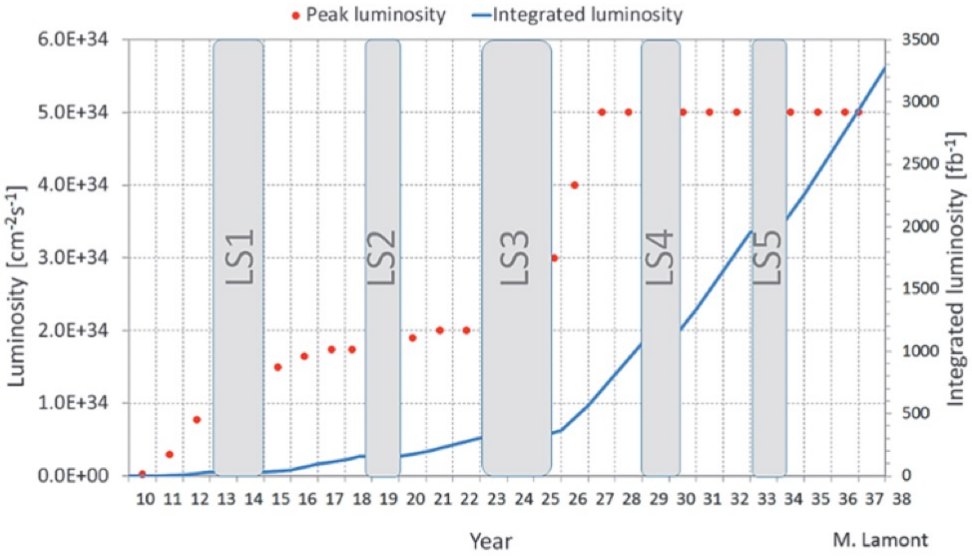


Fig. 7. Peak luminosity (red dots) and integrated luminosity (blue line) vs time till 2035.

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

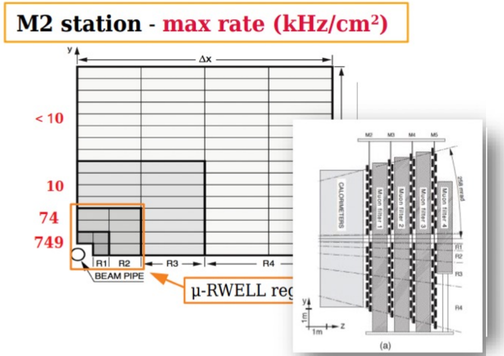
All challenges already here:

- High rate
- High radiation
- Pileup

High rate

- Increase in luminosity → rate increase
- Extend the coverage to high eta region → rate increase

LHCb M Stations



CERN-LHCC-2021-012 ; LHCB-TDR-023, Framework TDR for the LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era, https://cds.cern.ch/record/2776420/

CMS ME0

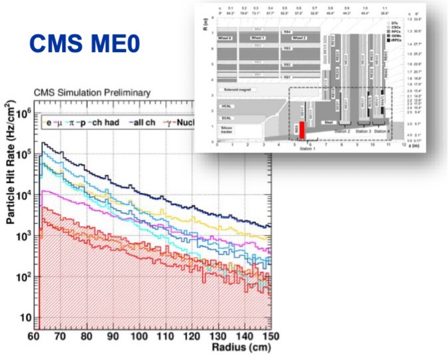
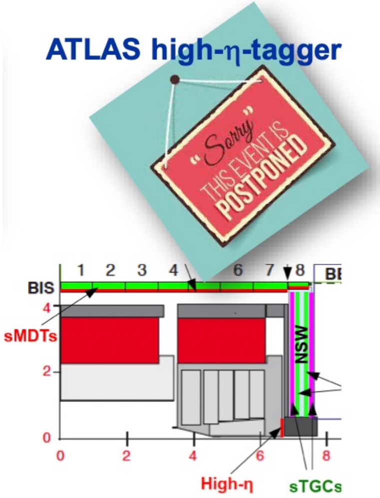


Fig. 2. Expected background flux in the ME0 environment as a function of the distance from the LHC beam line.

Rate capability of large-area triple-GEM detectors and new foil design for the innermost station, ME0, of the CMS endcap muon system, arXiv:2201.09021

ATLAS high-η-tagger



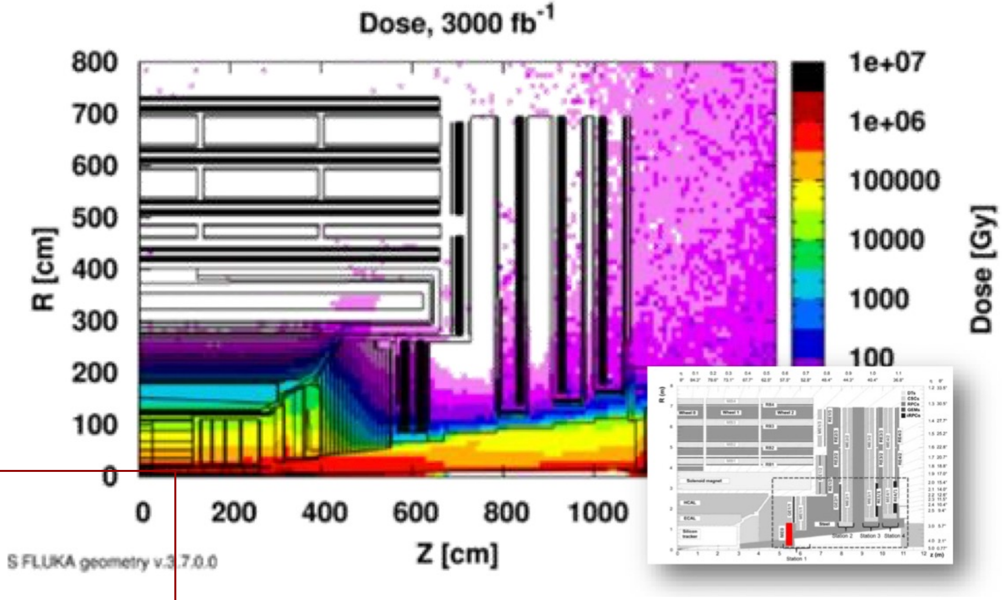
Rate Capability (@ inner radius R = 25 cm): up to 10 MHz/cm2)

CERN-LHCC-2017-017 ; ATLAS-TDR-026, Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer, http://cds.cern.ch/record/2285580/

To cope with rates up to1 MHz/cm² Micro Pattern Gaseous Detectors are becoming a popular choice
Wire chambers, drift tubes and RPC remain a valid option for rates up to O(10-100 kHz/cm²)

High radiation

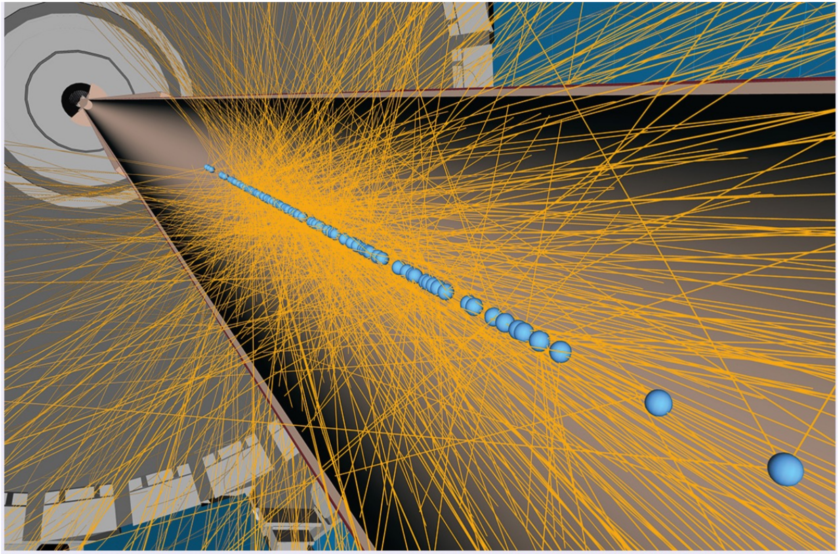
Annual dose delivered to the detector per year in the HL-LHC era will be similar to the total dose of all operations from the beginning of the LHC program to the start of LS3



Detector challenges:

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

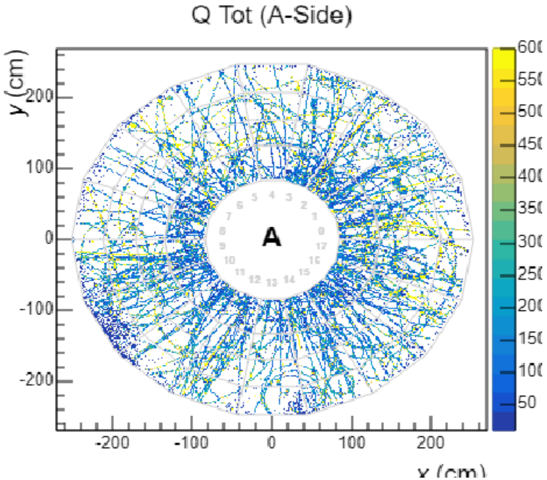
Pileup



ATLAS simulated tt event at 14 TeV at HL-LHC
- 200 pileup interaction in the same BC
- 2000 reconstructed tracks

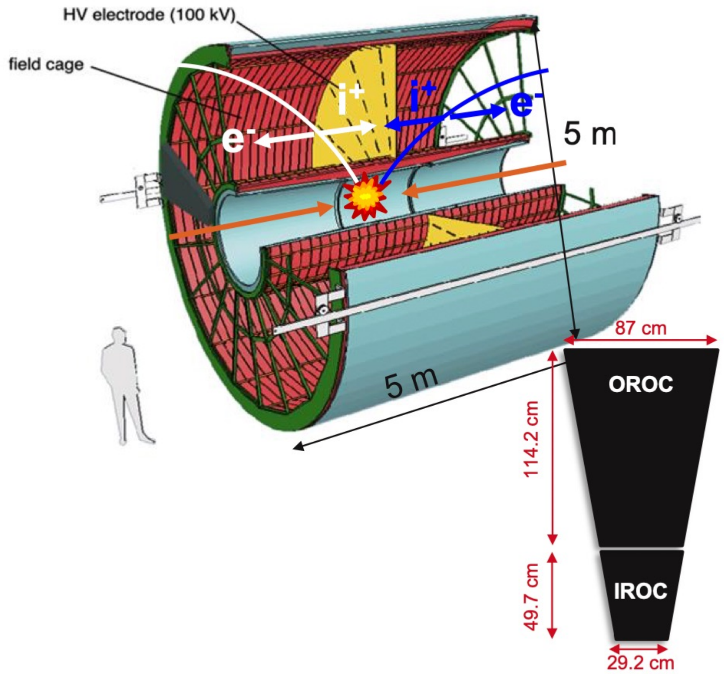
Pileup impacts track identification and reconstruction, adds extra energy to the calorimeter, hide "isolated" leptons, impact trigger and offline reconstruction...

Detector challenges:
- High space granularity
- High time granularity → 4d reconstruction
- Low material budget (central regions)

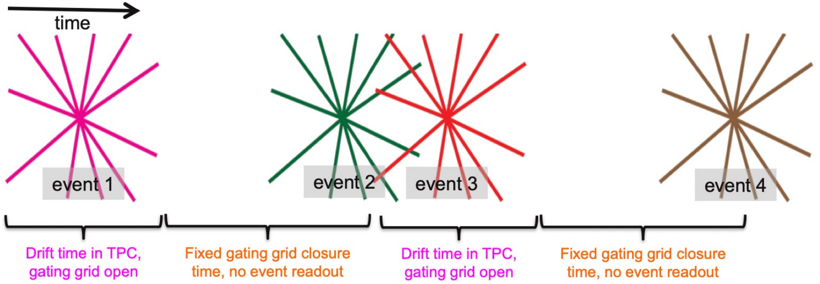


ALICE TPC

ALICE TPC



GATED OPERATION IN RUN 1 & RUN 2

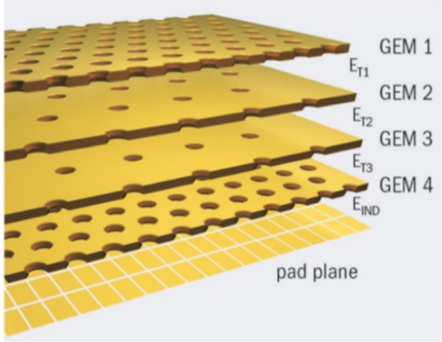


- **Multi Wire Proportional Chamber readout**
- A pulsed gating grid is used to prevent back-drifting ions from the amplification stage to distort the drift field (ion backflow (IBF) suppression ~10^{-5})
- 100 μs electron drift time + 200/400 μs gate closed (Ne/Ar) to minimize ion backflow and drift-field 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)**

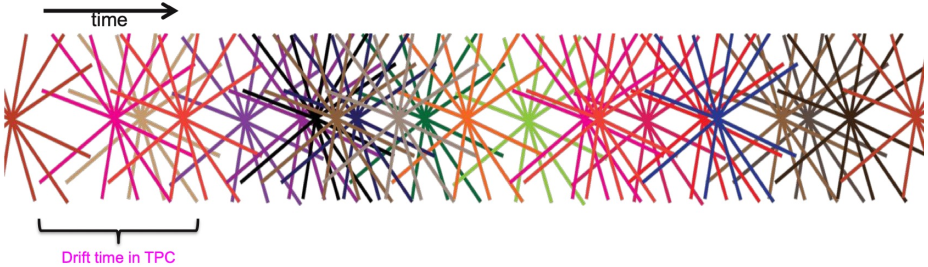
Gated operation used in Run1 & 2 becomes inacceptable after Run3 (current run) and beyond

- Mandatory to identify a stable amplification stage with reduced IBF and good energy resolution → move to non-gated, continuous operation

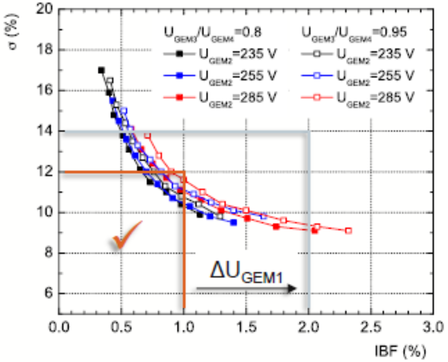
ALICE TPC



CONTINUOUS OPERATION IN RUN 3 AND BEYOND

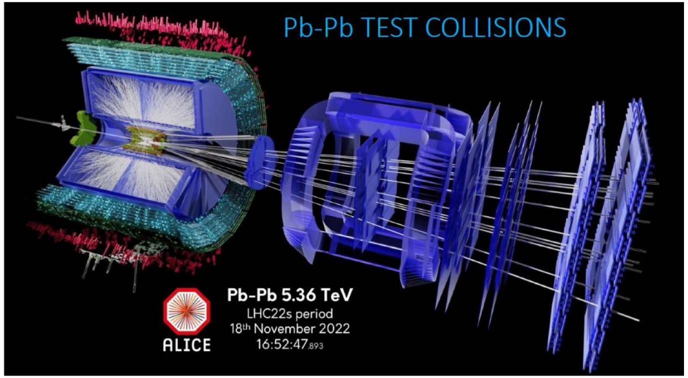


- Maximum drift time of electrons in the TPC: ~100 μs
- Average event spacing: ~20 μs
- Event pileup: 5 on average
- Triggered operation not efficient
- Minimize IBF without the use of a gating grid

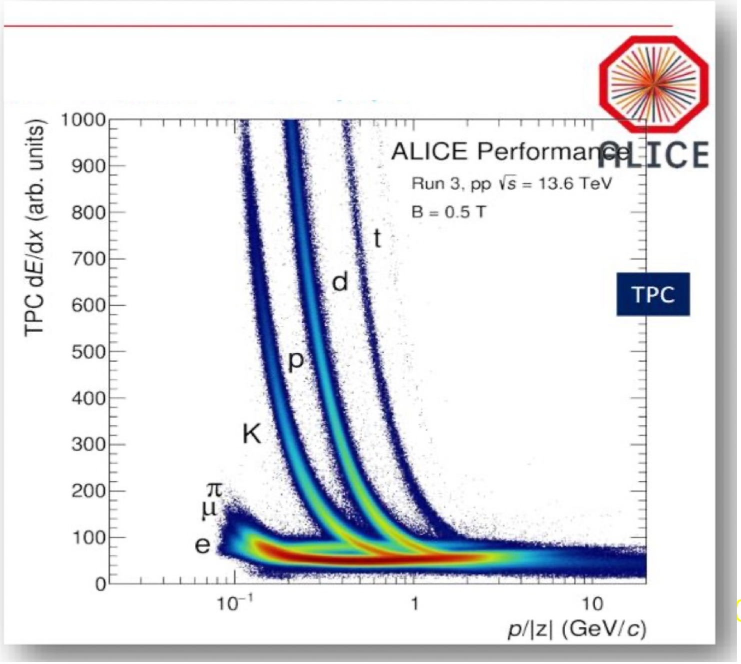


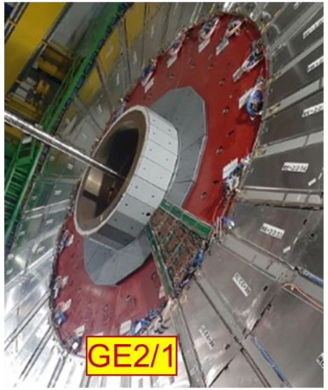
- ALICE: ungated GEM-based TPC
- Cascade of 4 GEM foils → reduction of Ion backflow from ~5% (3 GEM) to <1%
- Continuous operation at >50 kHz Pb-Pb
- PID with dE/dx: fine tuning of geometry and HV sharing between foils; Energy resolution ~5-8 %
- TPC volume: ~90 m^3; Active GEM area: ~32 m^2
- B=0.5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

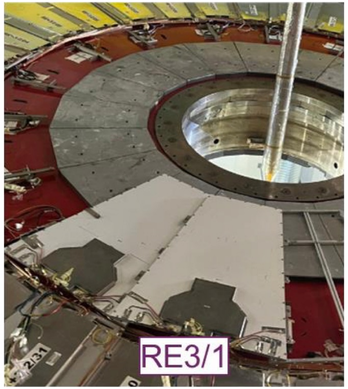
ALICE TPC

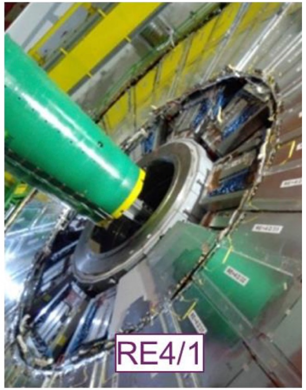


ALICE PERFORMANCE IN 13.6 TeV pp





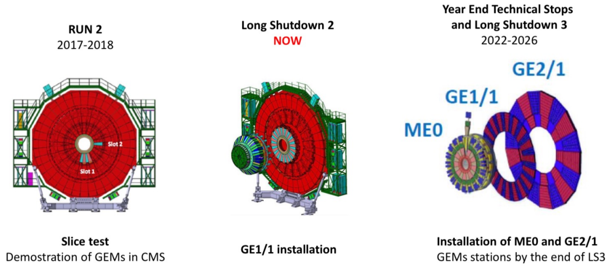




CMS GEM

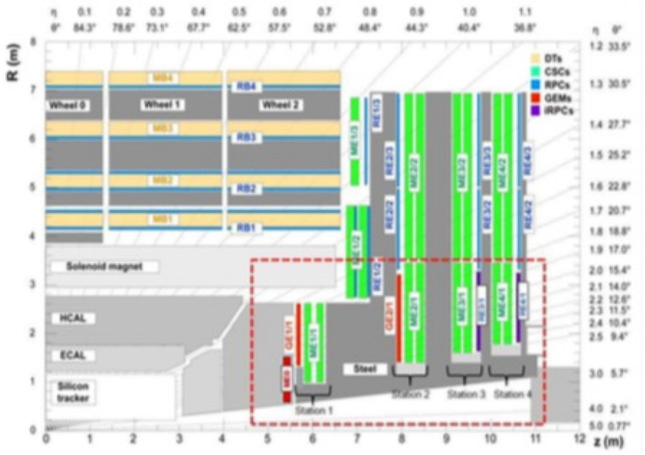
CMS GEM

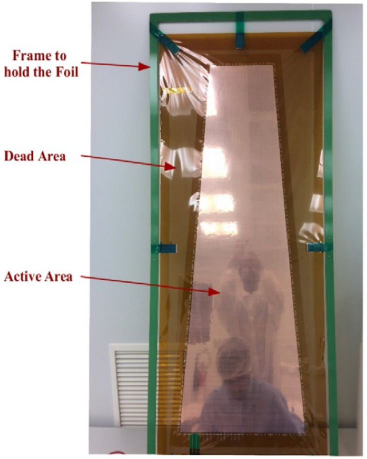
- GEM End-cap: Project on several phases
- 'Slice test' → Run2
- GE1/1 → Inner endcap Muon station → Phase1
- GE2/2 → Second endcap Muon station → Phase 2
- ME0 → High rapidity region (|η|=2.03-2.8) → Phase 2
- Gas: Ar:CO_2 70:30

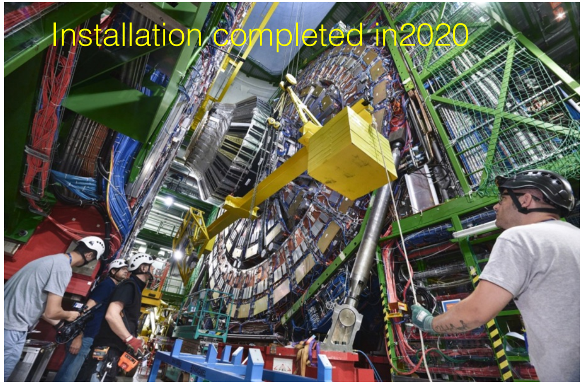


S. Calzaferri INSTR20

- Demonstrator: 4 GEM installed and successfully operated in CMS in Run2
- GE1/1 2 wheel each of
  - 72 detectors → 36 'super-chambers
  - Total active surface ~50 m^2

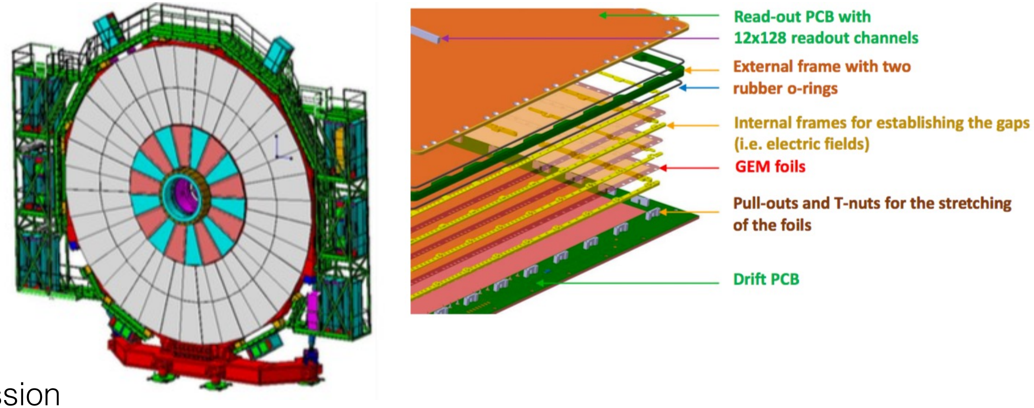


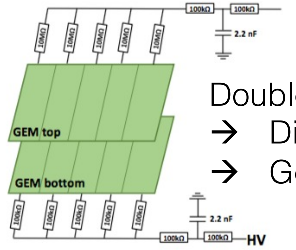




CMS GEM

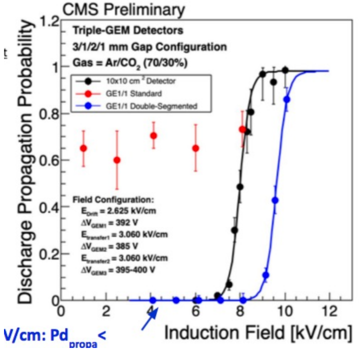
- GE2/2: 2 end-caps each of
- 36 chambers on 2 layers
- 4 modules/chamber → 288 modules
- Total active surface ~110 m^2

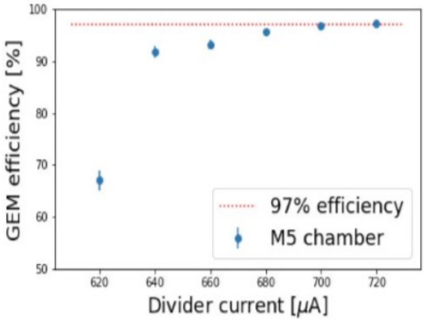


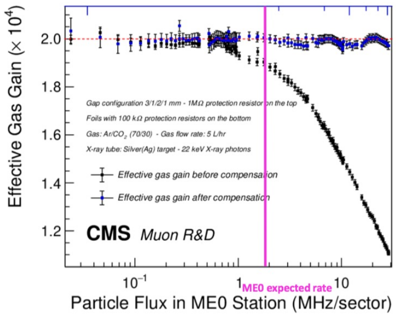


Double segmented foils 1 and 2
→ Discharge probability suppression
→ Good efficiency reached

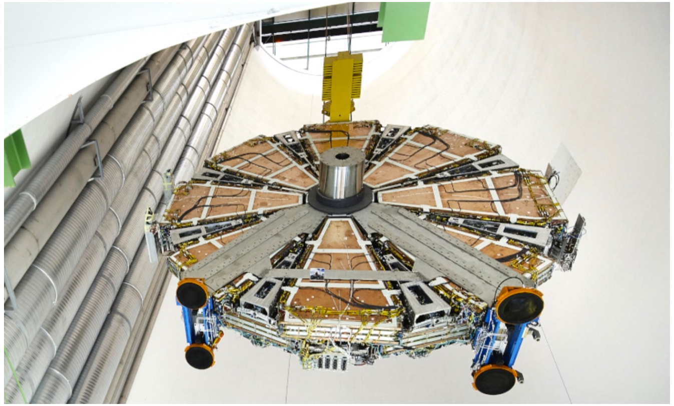
- ME0: 2 end-caps each of
- 6 modules x 18 stations → 216 modules
- Module area 0.296 m^2 → total active area: 64 m^2







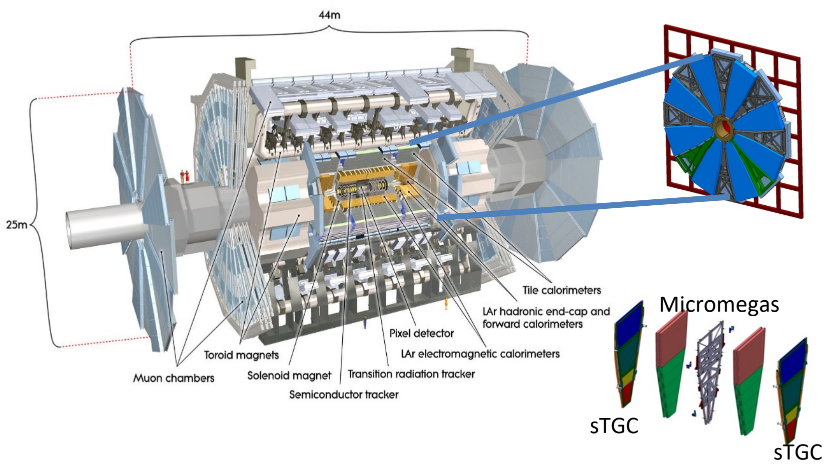
Voltage-drop compensation: Promising results for triple GEM working with stable gain at particle flux of O(MHz/sector)

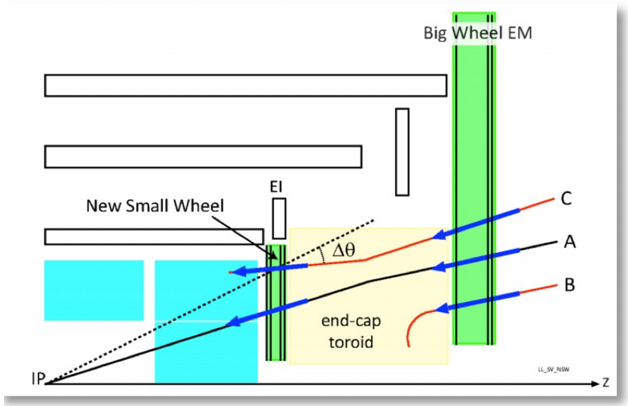


ATLAS

ATLAS New Small Wheel

- Major ATLAS upgrade of Phase1



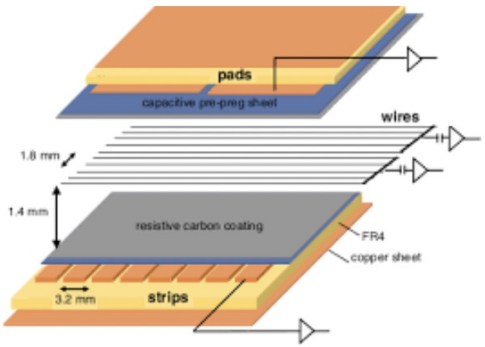


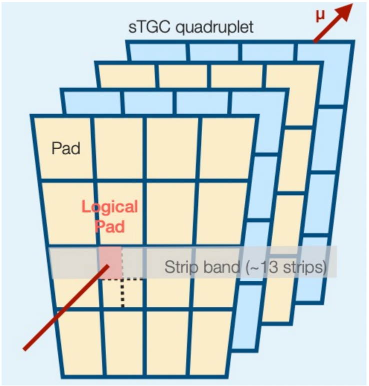
Run1 & 2: Level 1 End-Cap trigger, dominated by fake trigger events (type B e C)

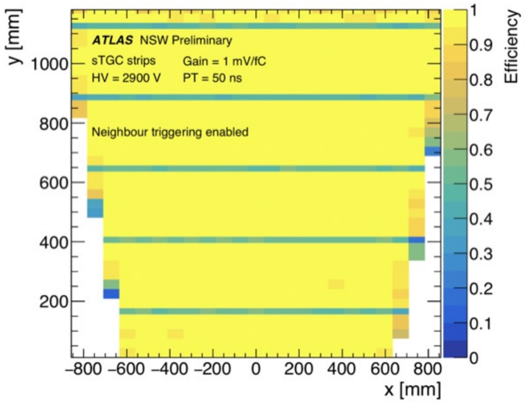
- Complementary technologies are used for triggering and for track reconstruction.
  - sTGC: good bunch crossing assignment with high radial resolution and rough ϕ resolution from pads
  - Micromegas: good offline radial resolution and a good ϕ coordinate due to its stereo strips
  - 1280 m^2 active surface for each technology

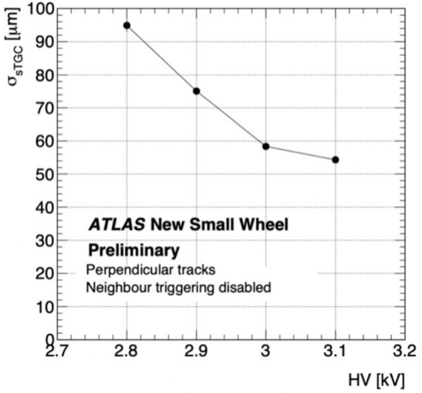
ATLAS sTGC

- Small Strips Thin Gap Chambers (sTGC)
  - Two cathode boards
  - Gold-Tungsten wires between the cathode boards
  - 380k channels
  - 192 detectors
  - CO_2+n-Penthane









ATLAS Micromegas

- ATLAS Micromegas is the largest MPGD-based system ever conceived and built
- 2.1 M readout channels
- 128 detectors
- Gas: $Ar:CO_2$ 93:7 → $Ar:CO_2:iC_4H_{10}$ 93:5:2

T. Alexopoulos et al. / Nuclear Instruments and Methods in Physics Research A 640 (2011) 110–118 111

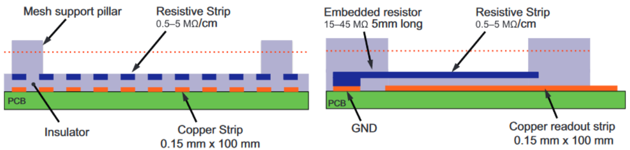
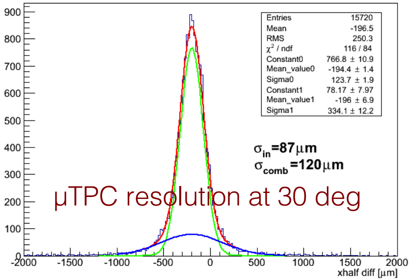
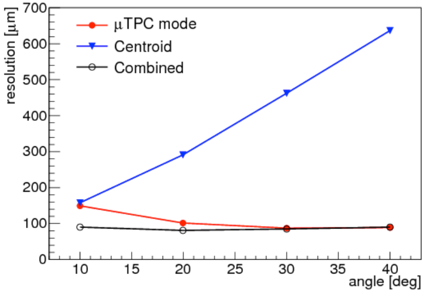
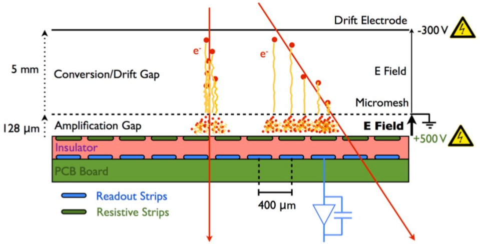


Fig. 1. Sketch of the detector principle (not to scale), illustrating the resistive protection scheme; (left) view along the strip direction, (right) side view, orthogonal to the strip direction.

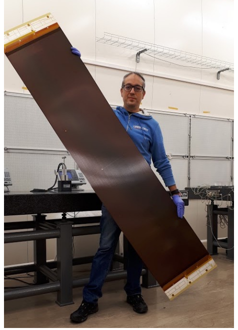
The Micromegas R&D for ATLAS pioneered the development of resistive MPGD

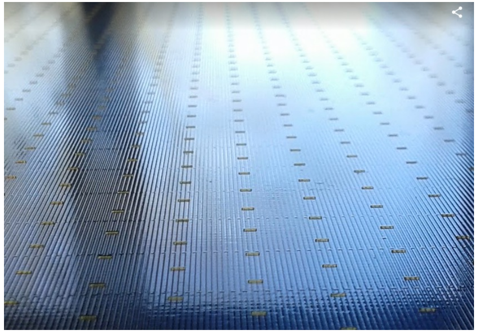






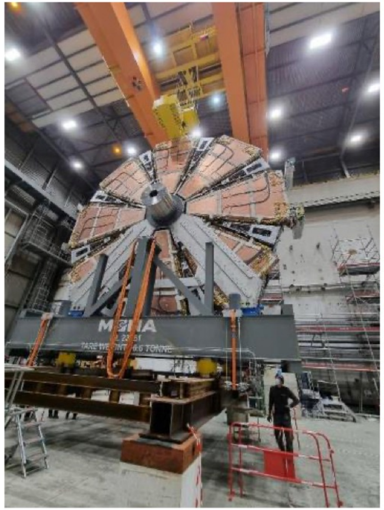
- The uTPC reconstruction technique allows for precise tracking at large impact angle





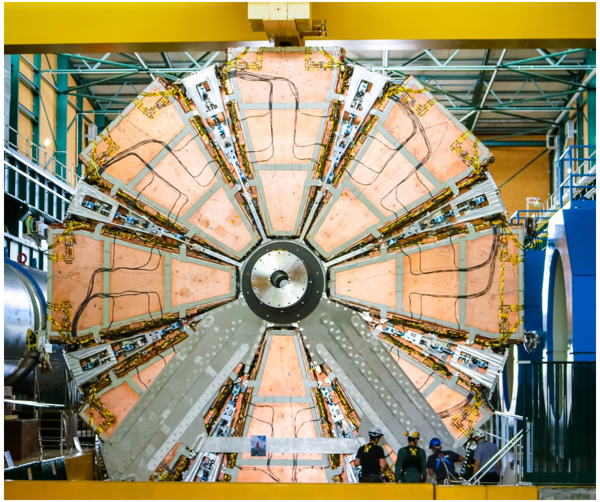
- Micromegas boards fully produced in industry
- ~2500 foils produced→ big technological challenge

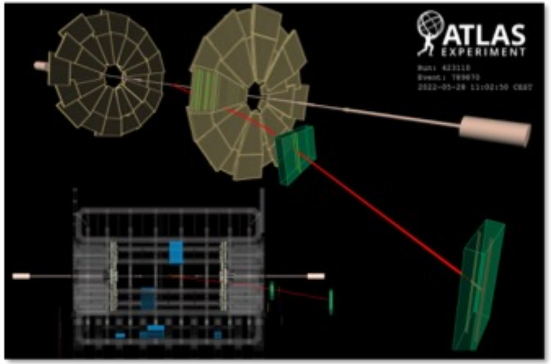
ATLAS NSW


MGHA


14/10/2021
CONVOI EXCEPTIONNEL

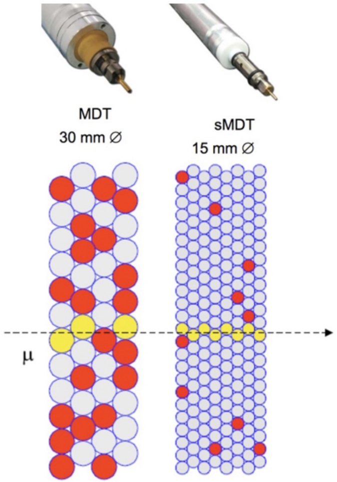

08/11/2021

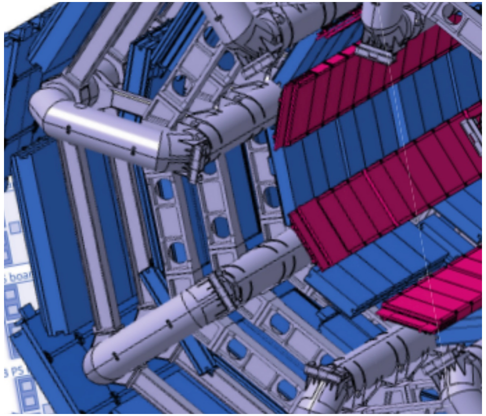



ATLAS
EXPERIMENT

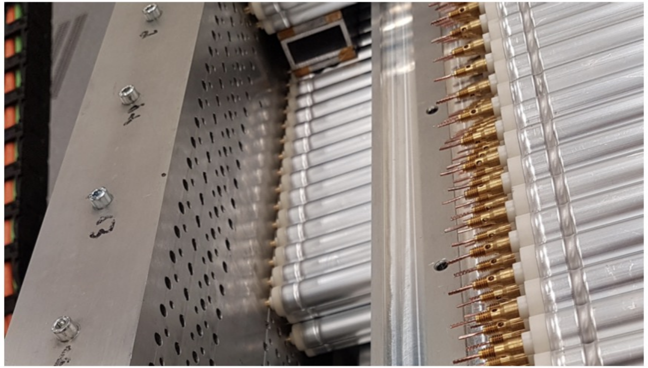
ATLAS Phase2 BI - sMDT

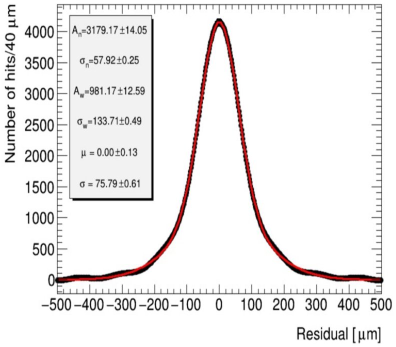
- The Phase-2 BI project
  - Replacement of the inner barrel MDT BIL with new detectors: sMDT and iRPC
  - iRPC layer to be added to BIS

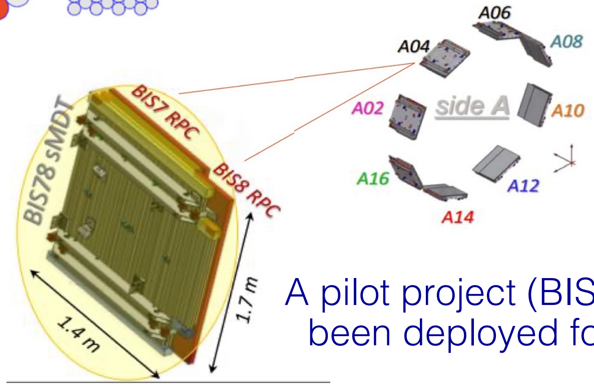




- 30 mm → 15 mm:
  - increase rate capability
  - reduce geometrical encumbrance
- Well established technology, excellent performance



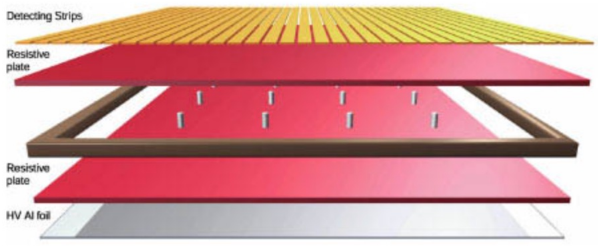




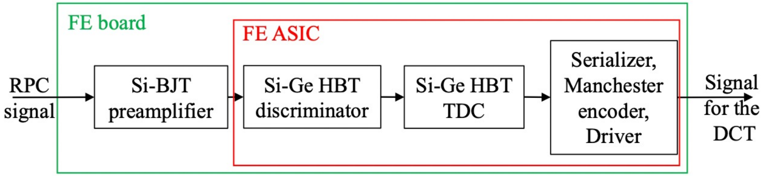
A pilot project (BIS7-8) has been deployed for Run3

ATLAS Phase2 BI - iRPC

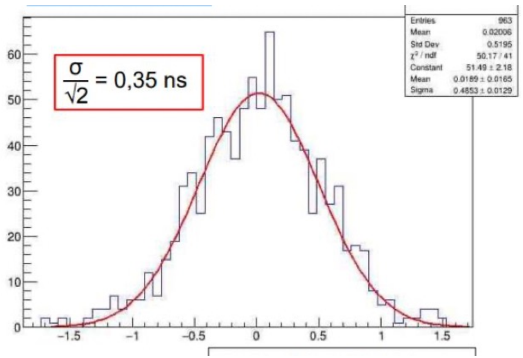
- Improved RPC:
  - Reduced electrode thickness 1.4 mm
  - Resistivity $5x10^{10}$
  - Gas gap 1 mm / chambers with 3 layers
  - Rate capability or longevity x10
  - Tme resolution <400 ps

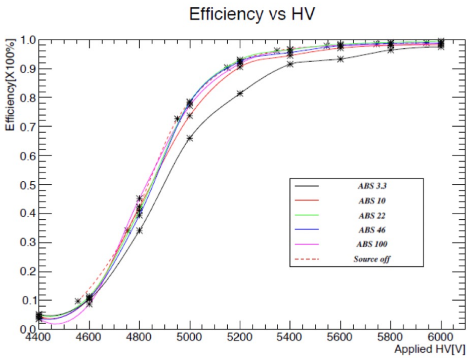


Transfer amplification from gas to FE electronics
→ new FE with new chip, threshold as low as 1 fC



Silicon BJT for the discrete component preamplifier
Full custom ASIC in IHP BiCMOS technology

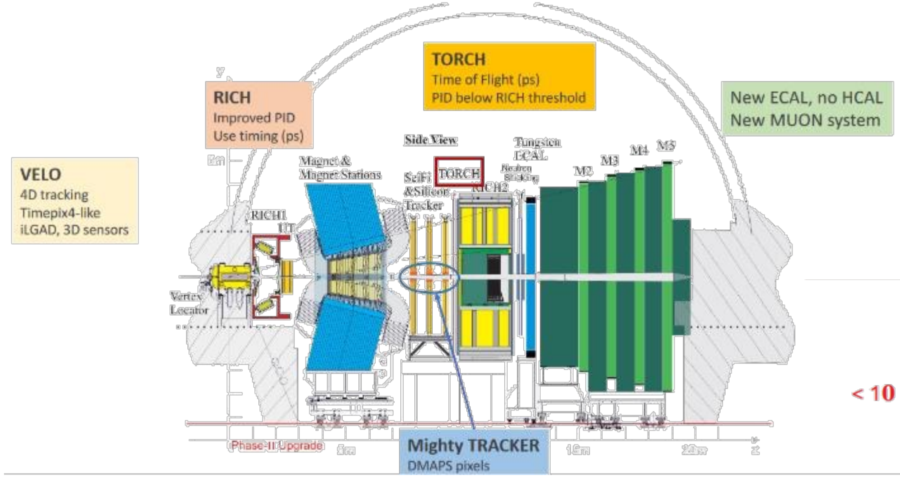




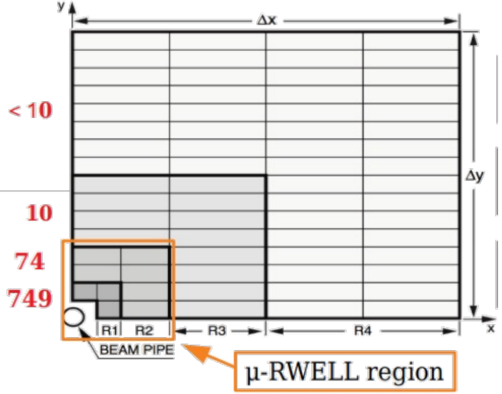
iRPC also used in CMS for Phase2 upgrade: extension of the RPC coverage to 1.9<|eta|<2.4

LHCb

LHCb Run5 Muon system



- LHCb Upgrade of the Muon system for Run5 and beyond
- Rate up to 1 MHz/cm2 on detector single gap
- Rate up to 700 kHz per electronic channel
- Efficiency quadrigap >=99% within a BX (25 ns)
- Stability up to $1C/cm^2$ in 10y at M2R1
- 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

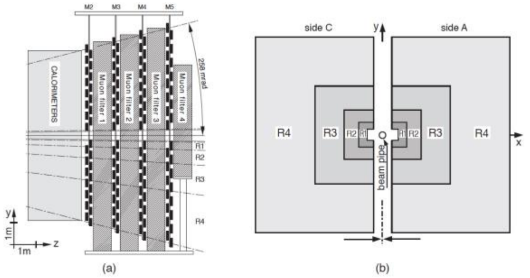
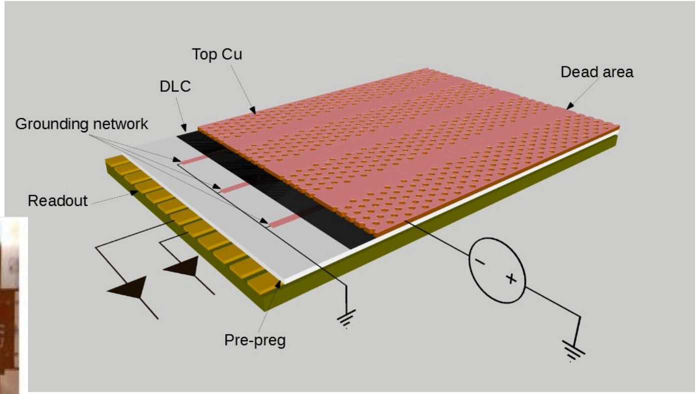


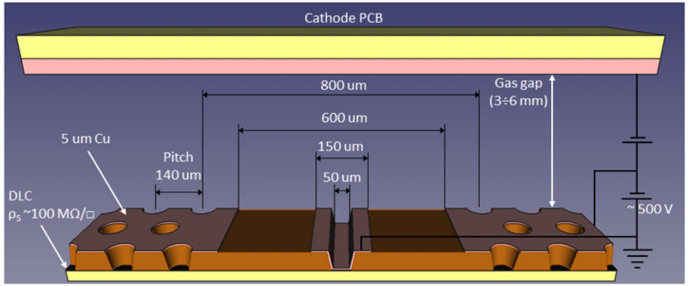
Figure 4.15: (a) Side view of the LHCb muon system for the Phase-I Upgrade. (b) Station layout with the four regions R1–R4 indicated.

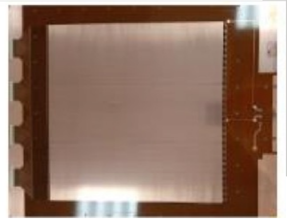
R1/R2 uRWELL (4 gaps/chamber)
R3/R4 MWPC (alternative solutions for R4 are RPC or Scintillating-tile+WLS+SiPM)

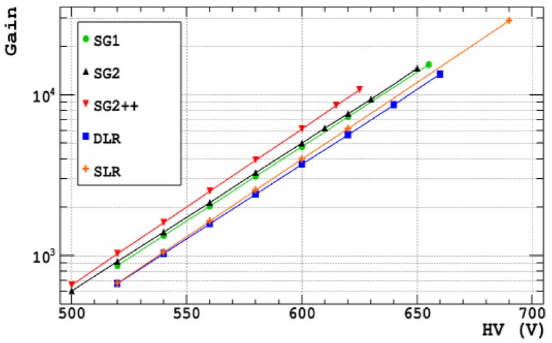
uRWELL for LHCb

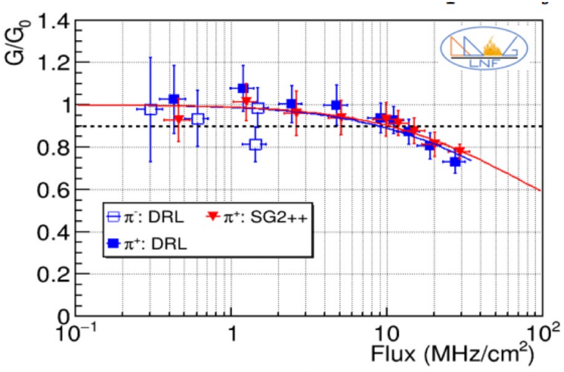
- uRWELL for LHCb
  - 76 detectors, size 30x25 to 74x31 cm2
  - 90 m2 detector (130 m2 DLC)
  - Gas: Ar:CO2:CF4 (45:15:40)

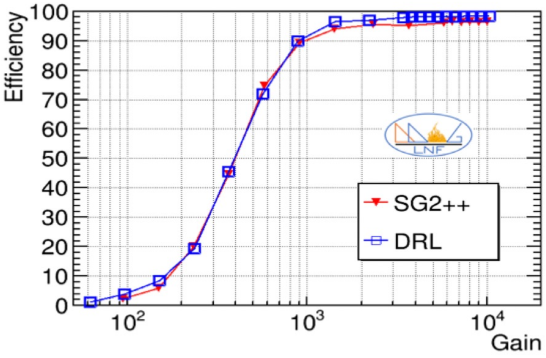








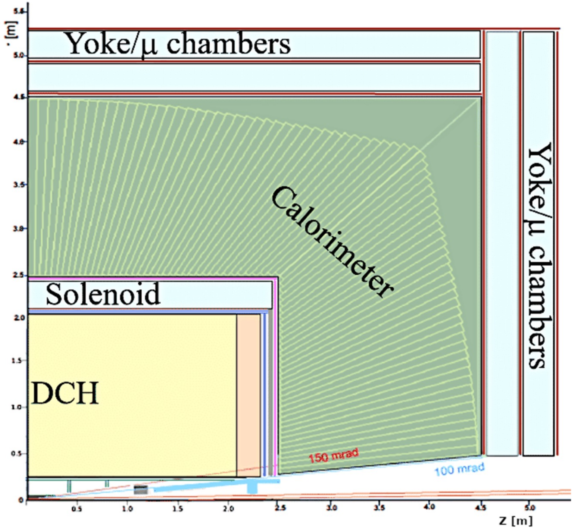




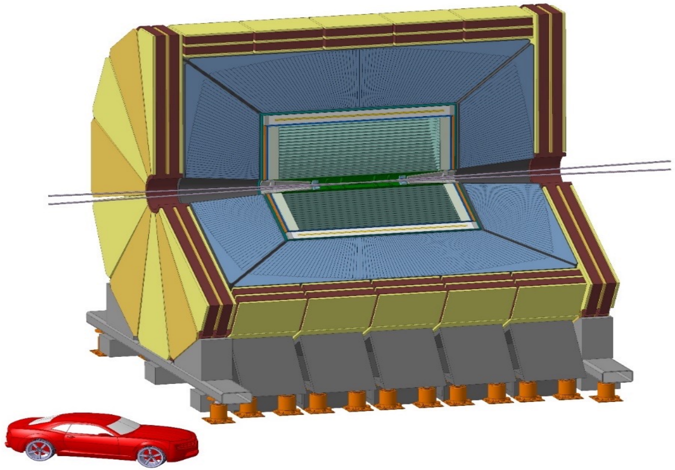
Lepton Colliders

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)
- U-RWELL for pre-shower detector and Muon system inside the magnet retour yoke
- Superconducting solenoid 2T,30cm,~0.7X0 ,0.16λ@90°

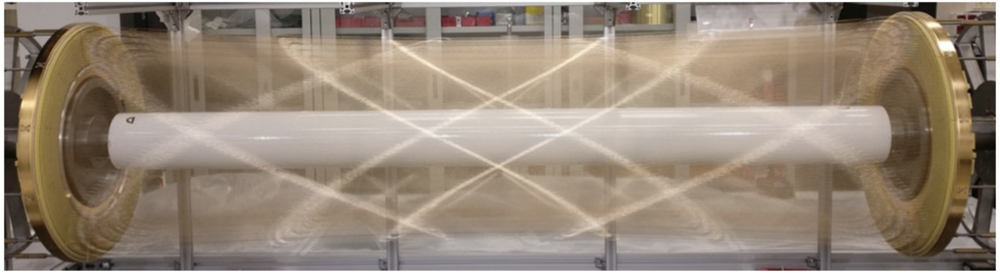


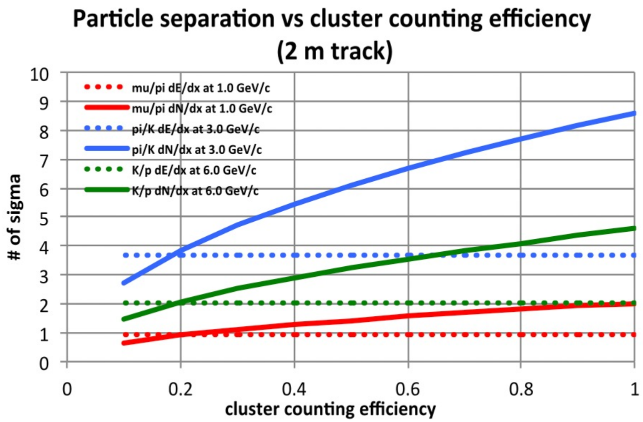
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV})\sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	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	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

IDEA Drit CHhamber

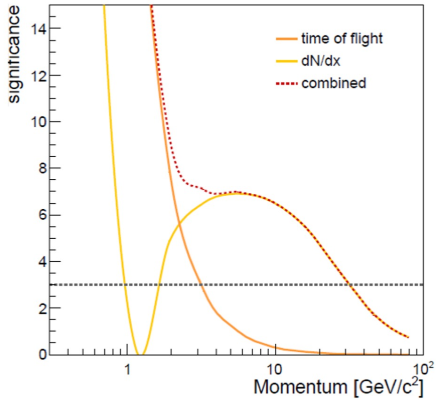
- Developed from previous DCH: MEG II
  - Compromise between granularity and transparency
  - High momentum resolution
  - Ultra light detector
  - Assisted by Si wrappers
  - Dimensions: L=400mm ; R=35÷200cm
  - Total thickness: 1.6% of X0 at 90°
  - 112 layers for each 15° azimuthal sector

MEG-II DCH



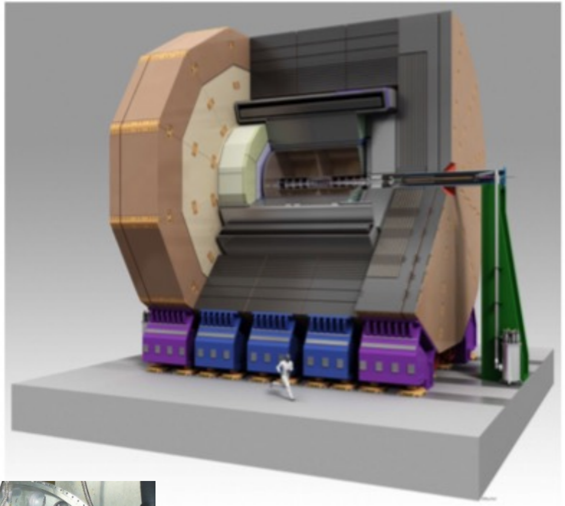


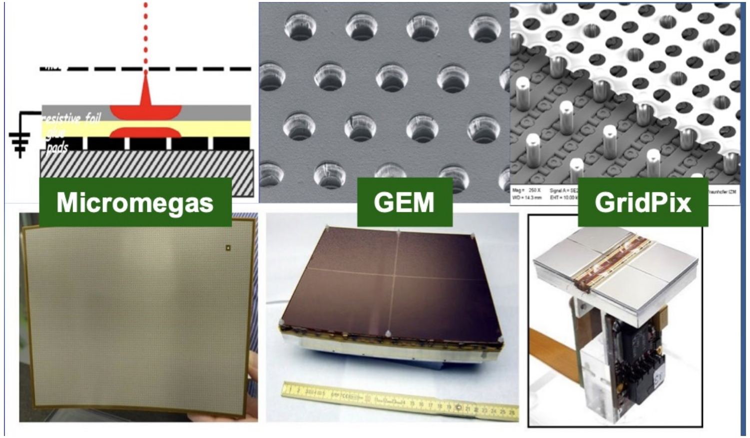
- Particle ID with cluster counting
  - Tracks with rather low pT (<50 GeV)
  - Gas: He:iC4H10 (09:10) → ionisation signals few ns; drift time 350 ns
  - Fast redout (GHz sampling)
  - PID with dNcl/dx expected to be better than dE/dx except for 0.75<p<1.05 (recoverable with ToF)

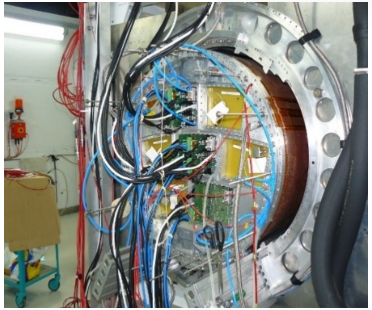


TPC at electron colliders

- 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.





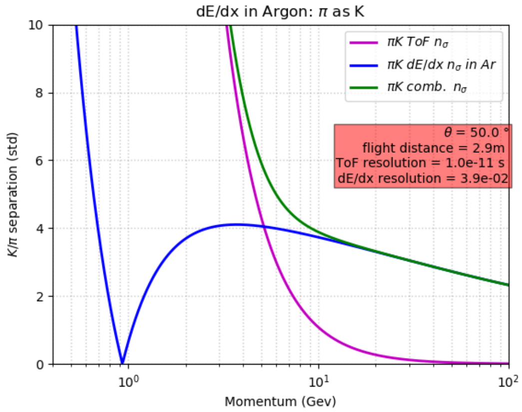


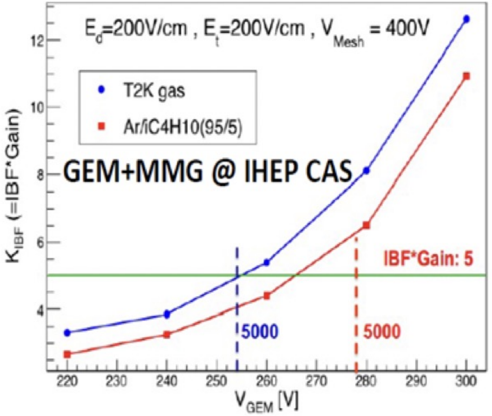
First development of large scale GridPix detector

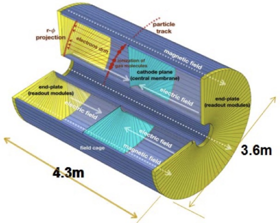
~10 m2 detector surface. Three option under study: Micromegas / GEM / GridPix

TPC at electron colliders

- The ILD collaboration is considering to adapt the TPC concept to a circular collider
- Baseline gas (same as T2K): Ar:CF4:Isobutane 95:3:2
  → excellent dE/dx
- For cluster counting He is needed (larger cluster separation)







CEPC TPC

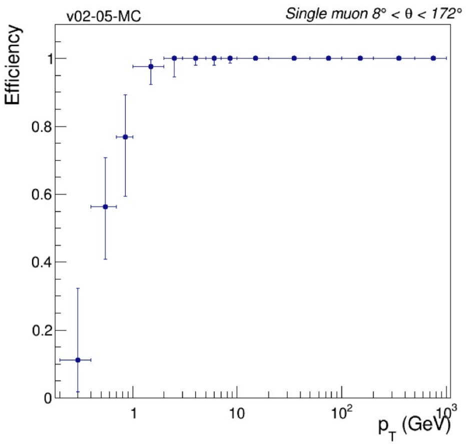
- Running a TPC @ Z pole @ 2. 1036 cm-2 s-1 is not trivial
- The ion backflow is an issue
- The positive ions of 22 000 Zs will accumulate in the TPC volume
- Continuous DAQ and tracking needed for real-time corrections for space point distortions
- The experience from ALICE at LHC (50 kHz Pb-Pb collisions) will be crucial

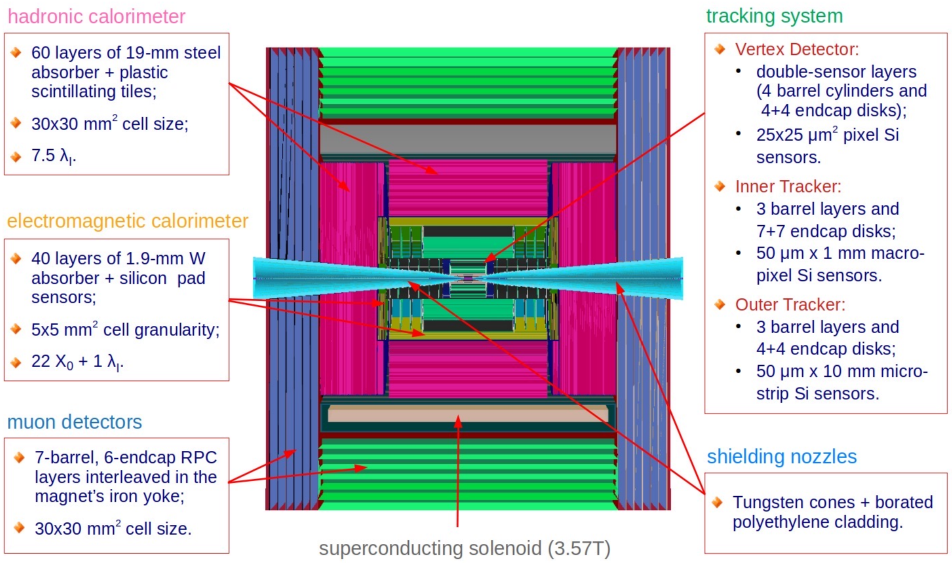
TPC for CEPC: promising results in IBF suppression for hybrid GEM+MM technology (tested by ALICE in the past)

Muon Collider

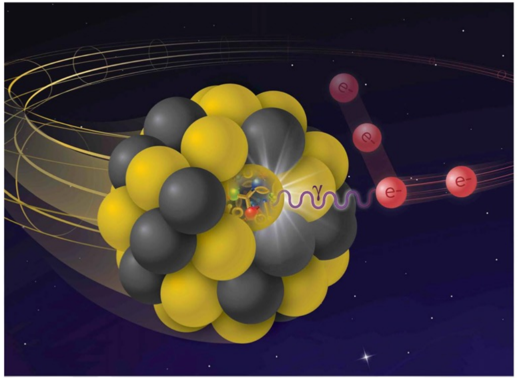
- Gaseous detectors (RPC) considered for Muon system, interleaved in an iron yoke

- Targets 100 um space and 1 ns time resolutions
- High number of hits in the forward disks due to the beam induced background
- Good efficiency observed throughout the momentum and rapidity range, further improvements in progress





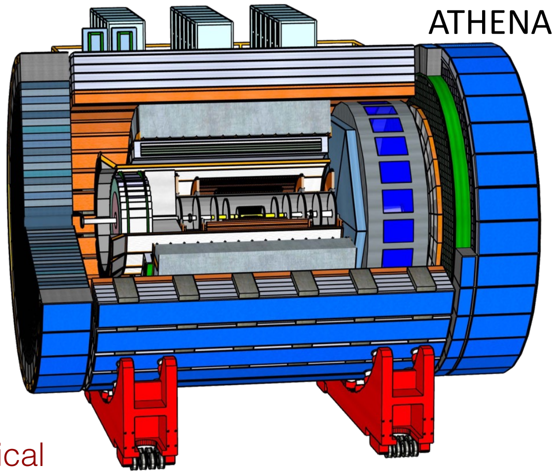
- Very high energy muon momentum reconstruction in 10 TeV collisions remain challenging
- Future R&D directions: better timing and resolution: GEM, Micromegas, mRPC, PicoSec...

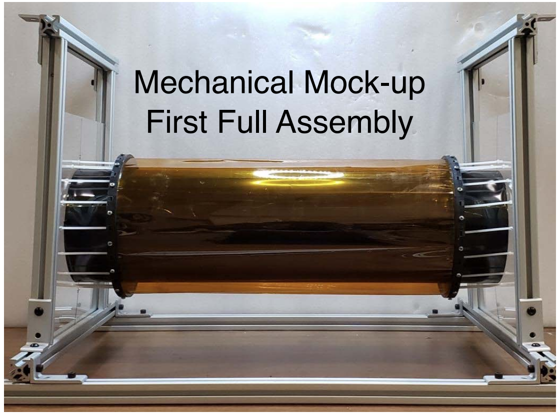


Electron-Ion Collider

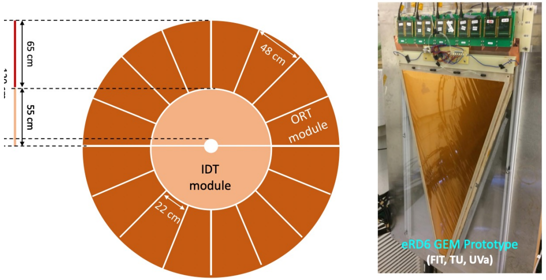
EIC Trackers

- 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

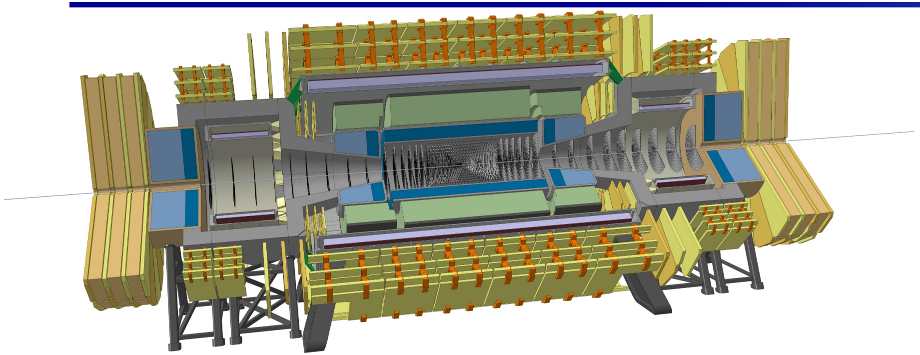




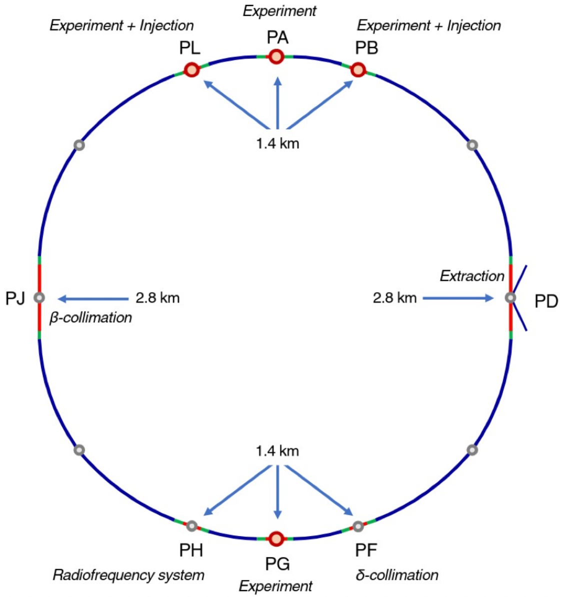
- Outer barrel tracker uses cylindrical Micromegas
- Endcap tracker uses planar u-RWELL
- Envision capacitive-sharing pad readout: Vertical stack of pads layers → reduce readout channels
- GEM or uRWELL proposed as forward tracker in CORE as well



CORE EIC GEM prototype
U-V srtrip redout



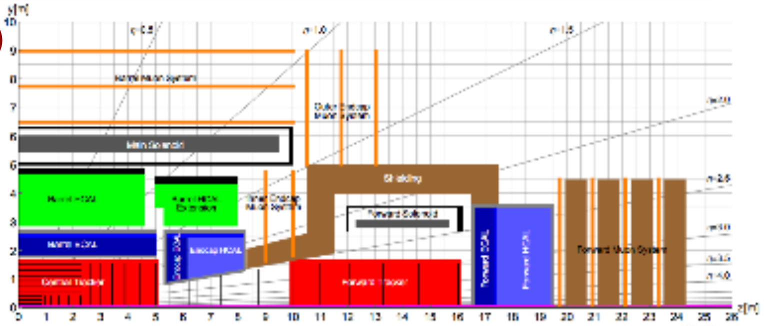
FCC-hh

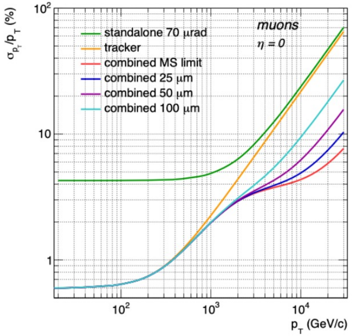


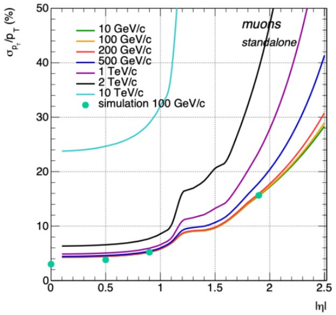
Experiment
Experiment + Injection
Experiment + Injection
PL
PA
PB
1.4 km
Extraction
PJ
2.8 km
2.8 km
PD
β-collimation
1.4 km
PH
PG
PF
Radiofrequency system
Experiment
δ-collimation

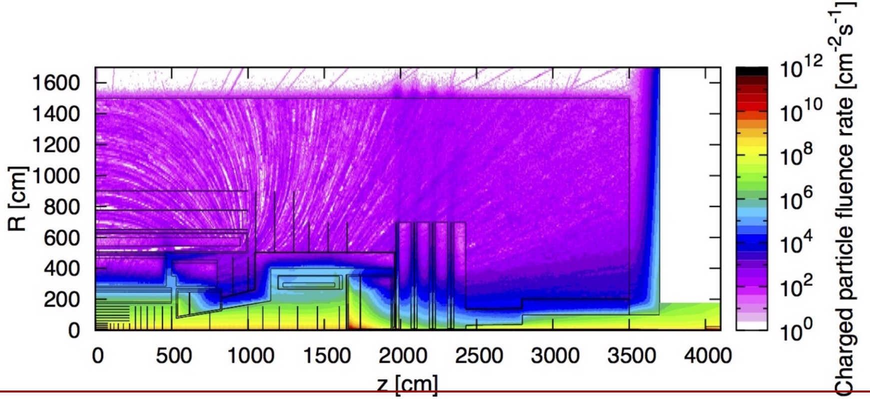
Gaseous Detectors at FCC-hh

- **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 $\eta = 0$.
- 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 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.

(Selected) Recent trends and R&D on gaseous detectors

RPC

Eco-friendly gas

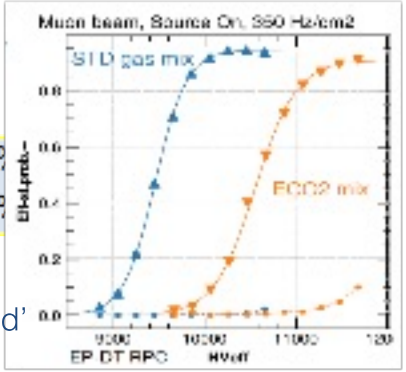
- RPC technology continuously improved, aiming at more and more challenging applications
- In HEP, typically operated in avalanche mode with the standard gas mixture: CH2FCF3 (> 90%)/ C4H10 / SF
- Need to investigate more eco-frindly gas: environmental ans cost reasons

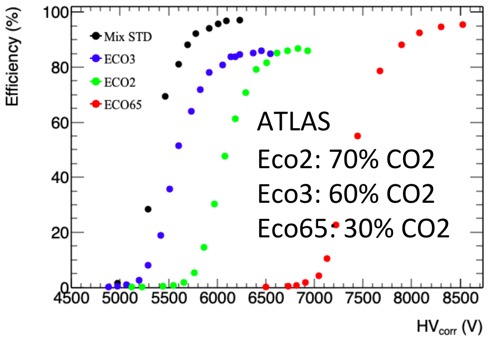
Gas	GWP* values 100-year time horizon
CO_2	1
CH_2FCF_3	1300
SF_6	23500

Tested several options. Promising results with:
HFO+CO2 replacing R134a (GWP reduced by 80%)

ECO2 $=CO_2/C_3H_2F_4/\text{i-}C_4H_{10}/SF_6$=(60/35/4/1)%

ECO3 $=CO_2/C_3H_2F_4/\text{i-}C_4H_{10}/SF_6$=(69/25/5/1)%





Search for optimal gas continuing in conjunction with development of new RPC for a new 'green and standard' mixture (larger CO2 content under investigation too)

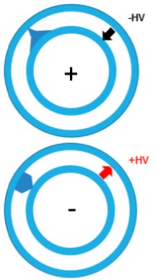
Similar performance but higher working point

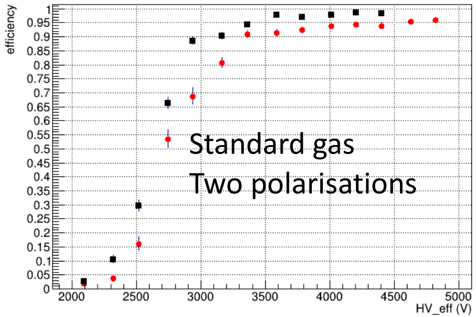
System aspect also relevant to reduce impact (and for cost saving): recirculation and recuperation largely used in LHC experiment are becoming more and more efficient

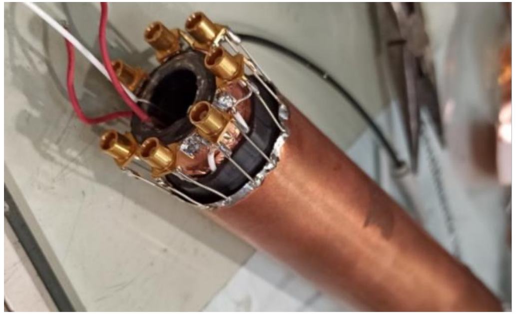
Cylindrical RPC

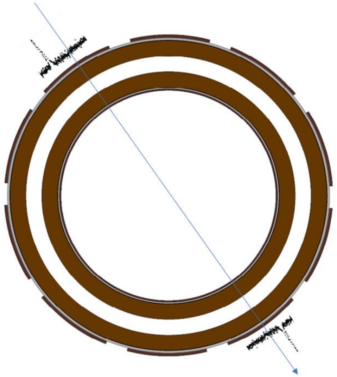
- Resistive Cylindrical Channel (RCC)
- Simple construction and solid mechanics, allowing gas pressurization : Increase the gas target density→ more primaries → light eco-friendly CO_2 based gas mixtures
- Double gap: Tracking capability Improvement in time resolution and efficiency

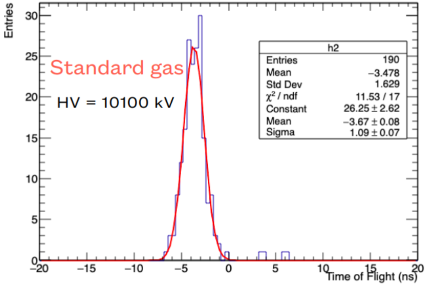
Gas-gap 1 mm



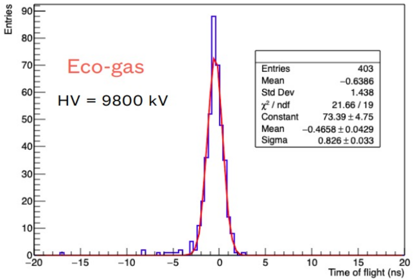


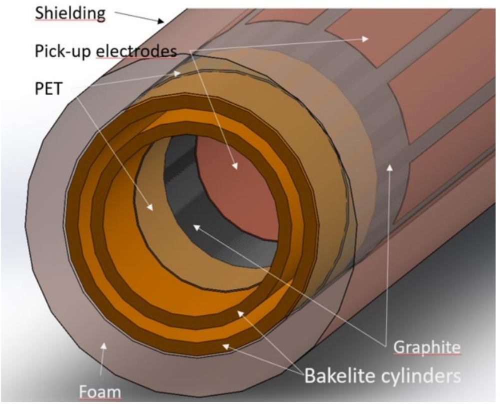






Test with pressurised gas





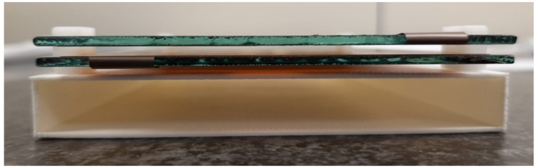
MPGD

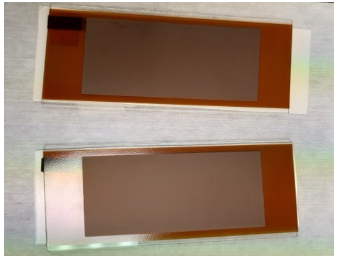
MPGD as RPC

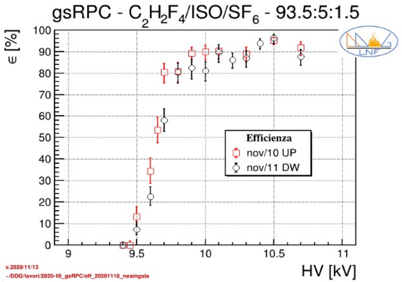
- The resistive coating of PCB allows to develop RPC-like structures for time resolution comparable to RPC (~ ns)
- Main difference with RPC: surface vs planar resistivity
  - Resistive pattern possible
  - Tuning of resistivity
- Some activities ongoing to explore the potential

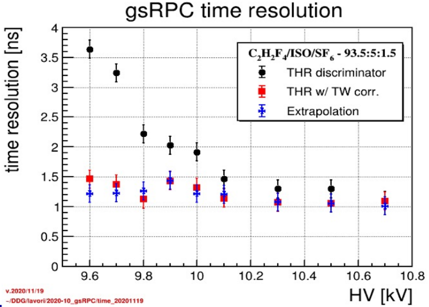
- RSD: Resistive Strip Detector
  - First prototype with screen-printed resistive strips
  - Good resistivity uniformity reached
  - Promising performance

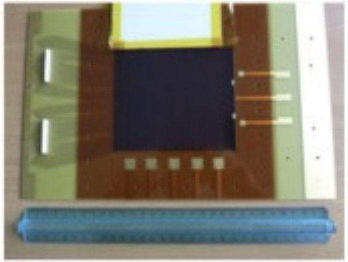
- sRPC: surface RPC
  - Standard DLC on substrate
  - σ_t = 1 ns reached

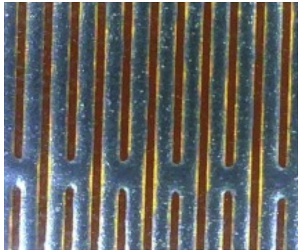


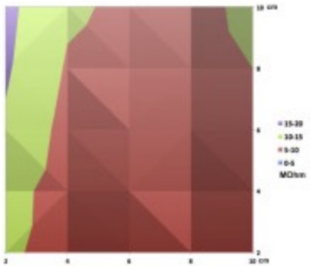


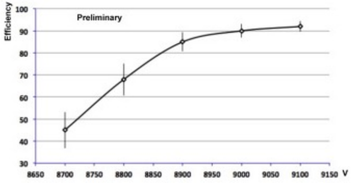






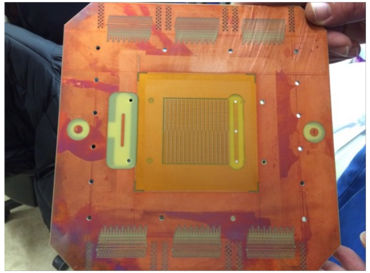


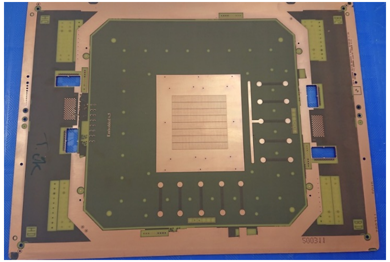




Resistive MPGD for high rate: Small-PAD Micromegas

- High-rate stable operation (>10 MHz/cm2) requires effective spark quenching mechanism → resistive material
- But resistivity limits the max attainable rate → charge evacuation path and voltage drop → fast evacuation path
- Low occupancy is required too → high granularity readout electrodes (pixel/pad readout; integrated electronics)

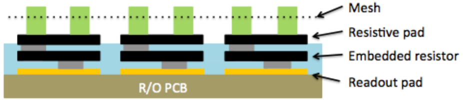




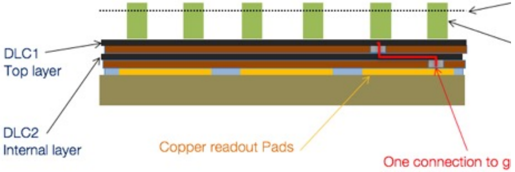
Prototype with integrated elx

Keep sufficient local surface resistivity to quench discharges with low resistance to ground

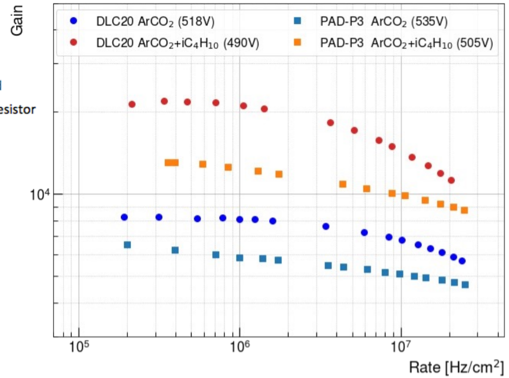
Several construction techniques



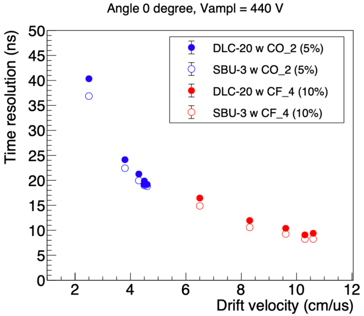
Pad-patterned

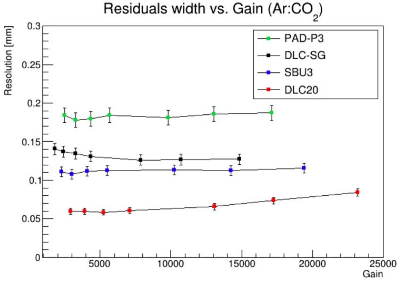


Double DLC



Rate capability ~5-10 MHz/cm^2 at Gain ~2x10^4



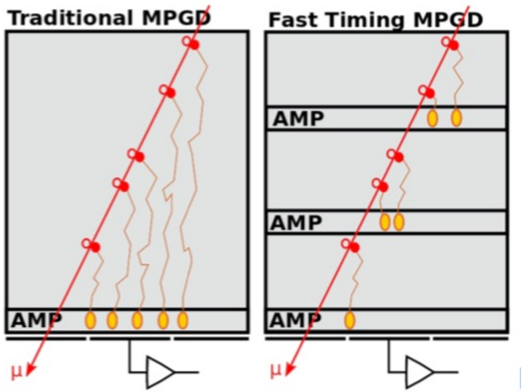


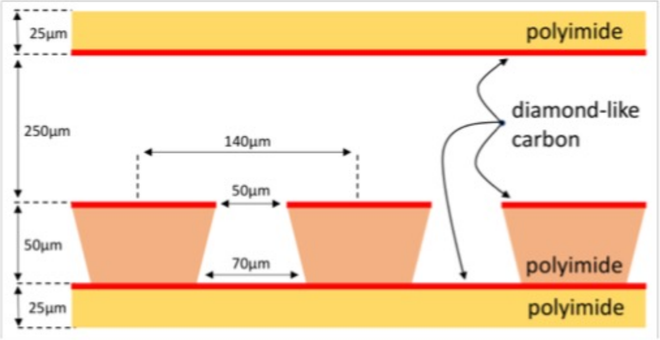
Few ns time resolution O(100um) space resolution with 1 mm pads (dependence on resistivity

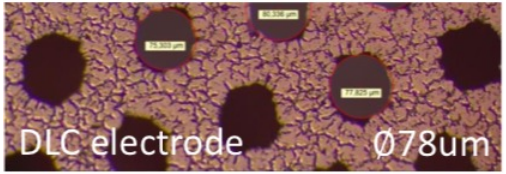
Timing MPGD

Fast Timing MPGD

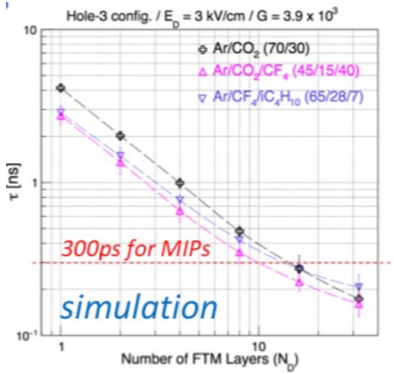
- **Fast Timing MPGD (FTM): Principle, similar to mRPC**
  - Divide drift in multiple layers, each with amplification stage
  - Resistive electrodes → Electrode Transparency
  - Signal induced in External pick-up strips
  - Closest primary electron → Fastest Signal
  - Time Resolution $\sigma_t = 1/(\lambda \cdot vdrift \cdot N)$, where N = layers
  - Measured 2 ns with 2-layer detector



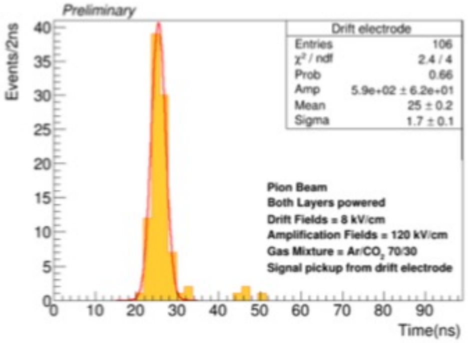




R&D to develop resistive GEM

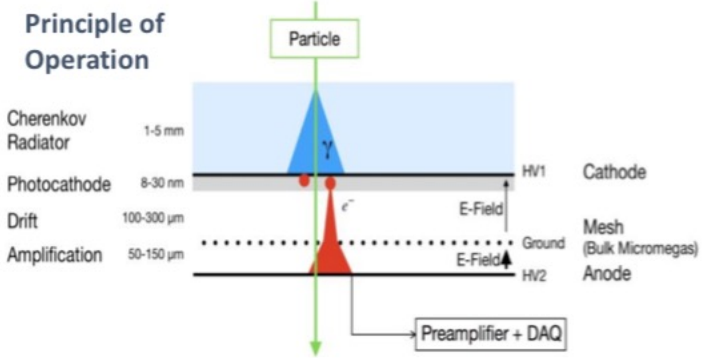


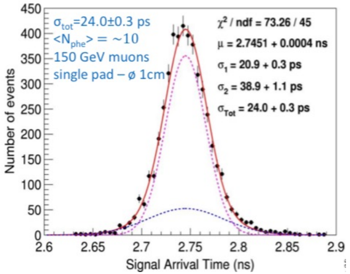
Test Beam Results (2 layers)

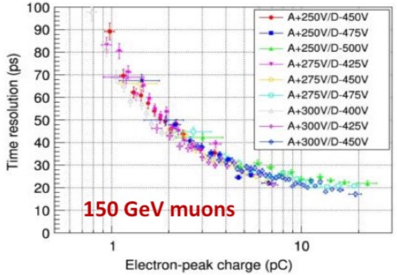


Picosec

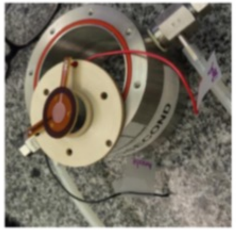
- Pushing MPGD to ps time resolution
- Operation principle:
  - (Cherenkov radiator + Photocathode) to get rid of intrinsic fluctuation in primary ionisation + Micromegas amplification and readout stage
- Nominal configuration:
  - Radiator: 3 mm MgF_2 + 5.5 nm Cr substrate; Photocathode:18 nm CsI
  - Bulk MicroMegas 200 μm drift + 128 μm amplification gap
  - Gas: Ne:C_2H_6:CF_4 (80:10:10) → gain of few 10^5-10^6
- Other configurations tested:
  - Different bulk MM: Thin Mesh, Resistive, Floating Pads
  - Different Photo Cathodes: CsI , Cr, Al, DLC, B_4C, B, doped DLC



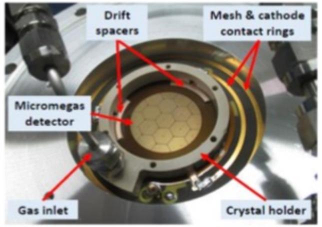




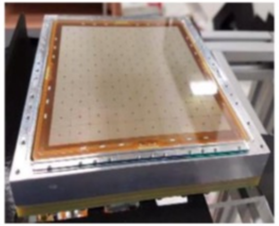
σ_t=24 ps for 150 GeV muons (N_{pe} = 10)



Single pad PICOSEC detector



Multi-pad PICOSEC: 19 hex pads ø 1cm



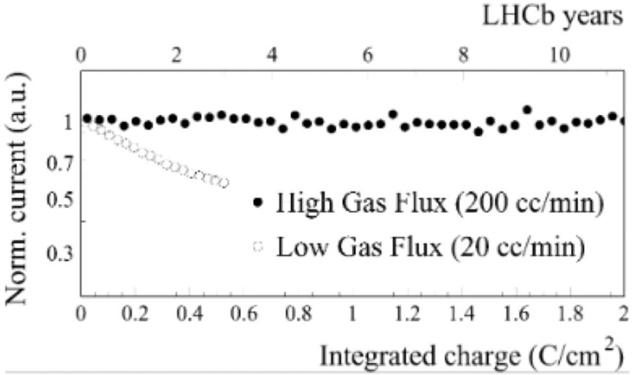
10x10 pad PICOSEC module with :

First prototype with single small (ø 1cm) readout plane
Larger prototypes built and tested

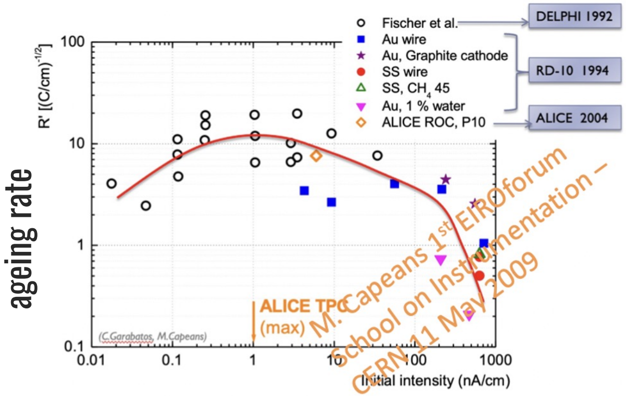
Photocathode optimisation studies ongoing
DLC is rad hard and allowed to reach σ_t < 50 ps

Gaseous detector longevity

- Ageing phenomena in gaseous detectors can be the subject of a dedicated conference (was in the past; the 3rd edition will be this fall). Here only few hints

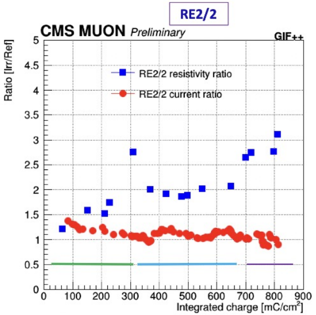


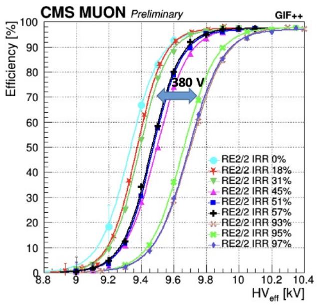
- Main source of classical ageing:
  - Degradation of material with integrated charge / time
  - Chemical effects of gas compounds
- Ageing is however a subtle phenomena, depending on many parameters (gas mixture, materials, operating conditions, rates…) and detector ageing must be studied for each specific 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 (well known from wire chambers)



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



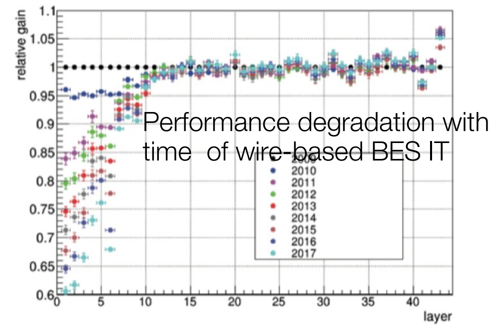


- Wire chambers
  - Deposits (whiskers) on the wire surface → distortion of pulse height spectra, gain loss, noise rate
    Mitigation: no hydrocarbons, no silicon material

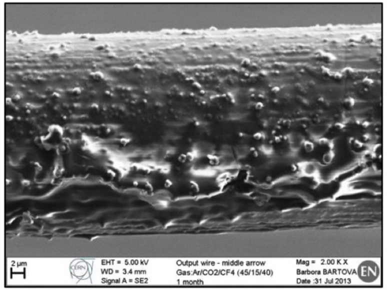
8. Conclusions on Gases

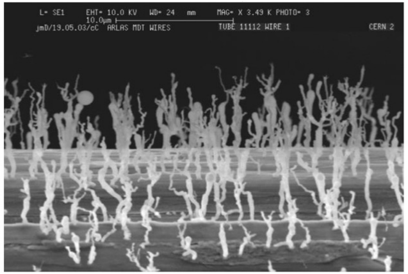
A. If we obtain regular purity gases, a basic conclusion of the workshop is that *Noble gas + hydrocarbon* mixture should not be trusted for more than[11,18,21,46] 0.01–0.05 C/cm. The Noble gas + CO_2 mixture appears to behave about ten times better.[11,21,46]

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



Performance degradation with time of wire-based BES IT



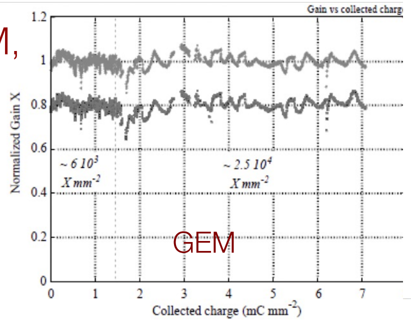


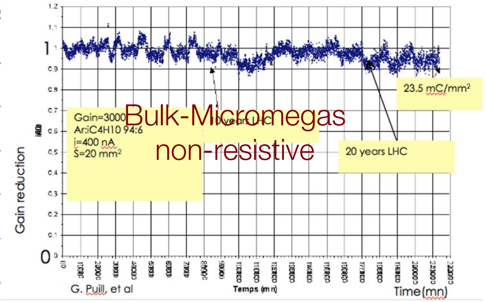
Typical aging phenomena on wire chambers

Gaseous detector longevity

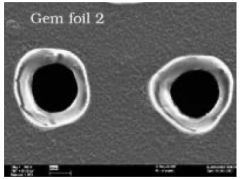
- MPGD better behavior compared with wire chambers
- Accelerated aging tests have been conducted on GEM, Micromegas and other MPGD with excellent results

  - 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

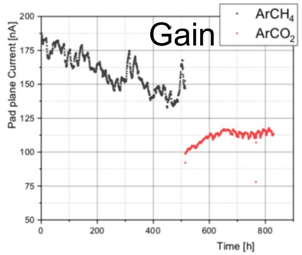


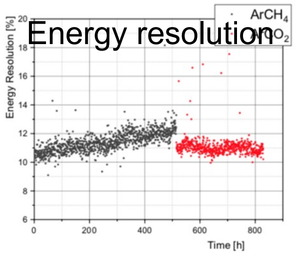


Resistive Micromegas (ATLAS-like): 3-years exposure at GIF++
Total collected charge ~0.3 C/cm^2 → No sign of aging in Ar:CO2

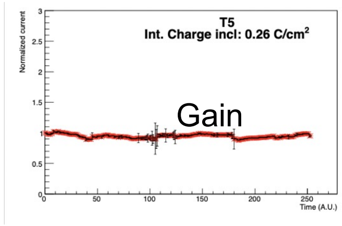


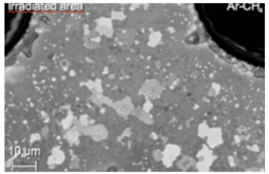
Etching effect on Triple-GEM operated with CF4-based mixture at low flow

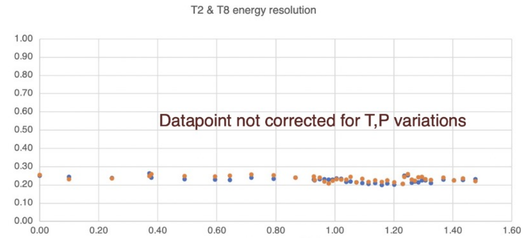




Aging in ALICE GEM prototype operated with hydrocarbons (CH4) in Ar 95% mixture. Aging stops when CH4 is replaced with CO2







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

Summary

- Gaseous detectors are still playing a central role for detector systems in present and future experiments, in spite of their age!
  - Unreplaceable to equip large system like Muon detectors
  - Low material budget for central trackers
  - TPC
- Community very active in developing new structures and proposing new ideas
  - Wire chambers and tubes widely used
  - RPC moving to high rates and eco-friendly gas
  - MPGD explosion boosted by resistive material

Gaseous detectors have a glorious past, a solid present and a brillant future!

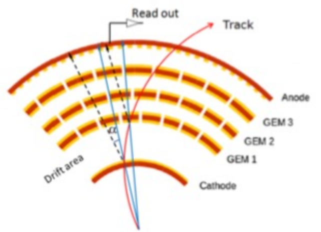
Thank you!

Additional Material

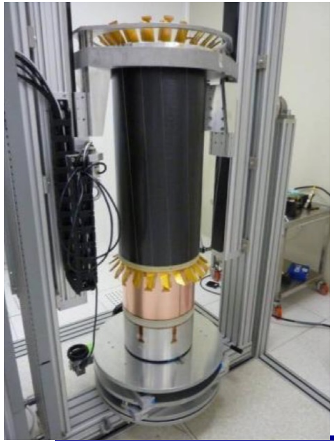
Inner Tracker with MPGD

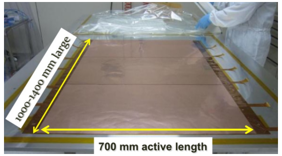
GEM Inner tracker

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

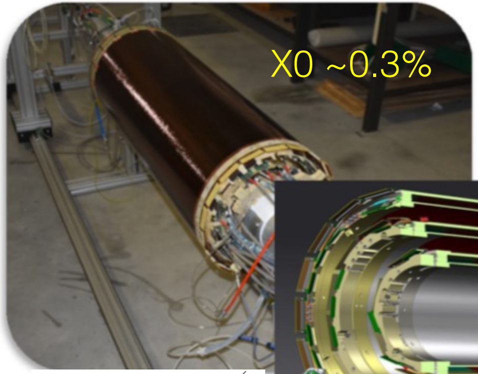


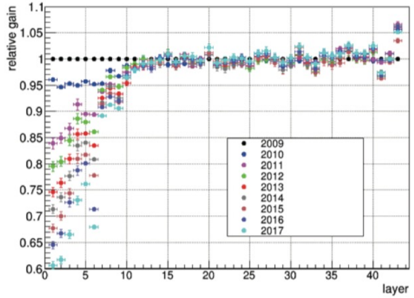
- KLOE2
- First development of cylindrical GEM
- Gas: Ar:iC_4H_{10} (90:10)



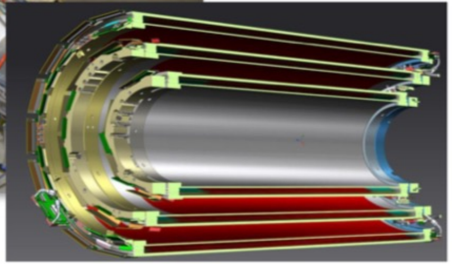


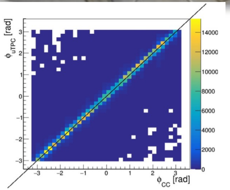
- BESIII
- Gas: Ar:iC_4H_{10} (90:10)





Performance degradation with time of wire-based BES IT (aging)





First μTPC event (cosmic)

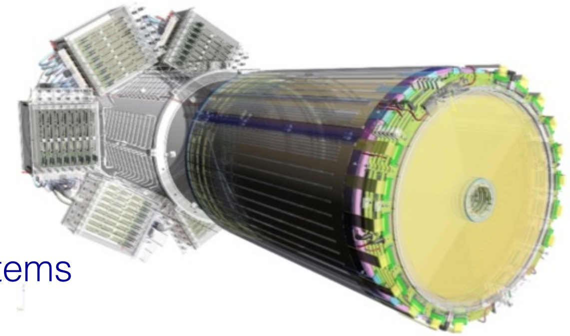
Table 1.1. List of requirements for the new inner tracker.

Value	Requirements
σ_{xy}	⩽130 μm
σ_z	⩽1 mm
dp/p for 1 GeV/c	0.5%
Material budget	⩽1.5% X_0
Angular Coverage	93%×4π
Hit Rate	10^4 Hz/cm^2
Minimum Radius	65.5 mm
Maximum Radius	180.7 mm

GEM-based IT fulfill all the requirements of the experiment

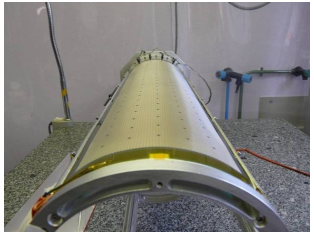
Cylindrical Micromegas

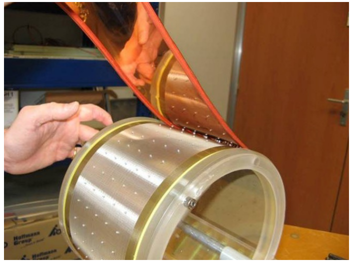
- CLAS12 @ JLAB
- Nuclear Physics/Hadron Spettroscopy/Deep Processes
- B=5 T magnet
- 11 GeV e- beam



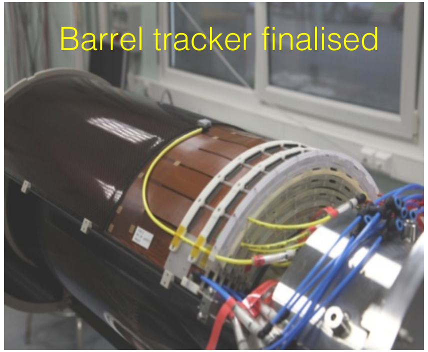
- Two Micromegas-based systems
- Barrel → cylindrical / A = 2.9 m2 / 18 units / Gas: Ar:iC_4H_{10} (90:10)
- Forward →
- Planar / A = 0.6 m2 / 6 units / Gas: Ar:iC_4H_{10}:CF_4 (80:10:10)
- 6 layers / X0 ~0.33/layer

Curved MM bulk

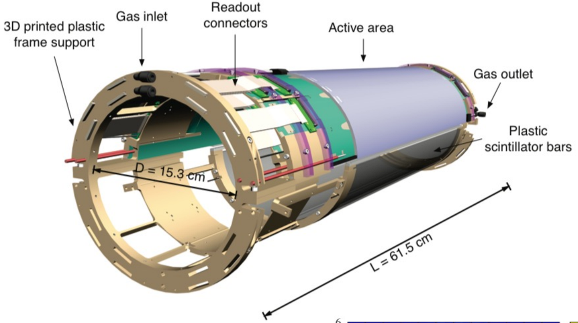




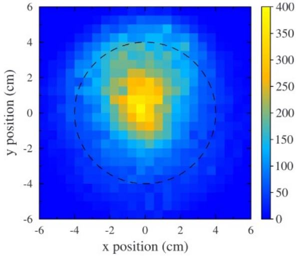
Drift electrode integration



- ASACUSA @ CERN
- Antimatter
- B=3-4 T magnet
- 2 Micromegas layers 413 mm long r_1 = 78.5 mm r_2 = 88.5 mm
- Gas: Ar:iC_4H_{10} (90:10)



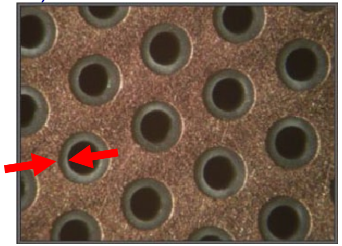
Antiproton annihilation event fully reconstructed with ASACUSA Miromegas

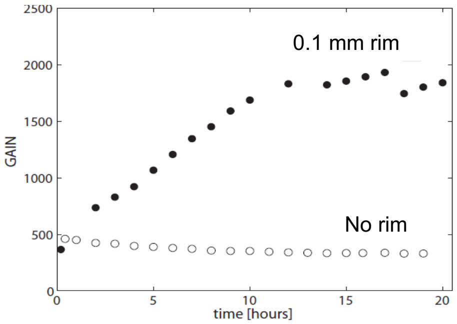


RICH & photon detection with MPGD

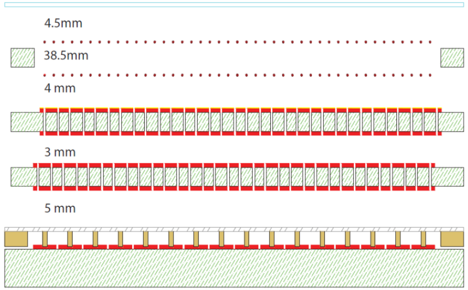
Thick GEM

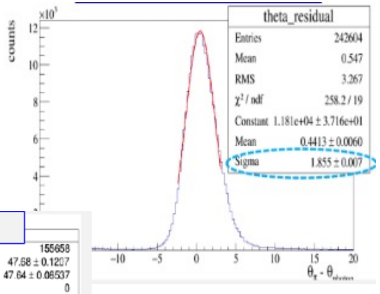
- THGEM: Same principle as GEM but with thick material (FR4)
    - PCB thickness ~ 0.4-3 mm
    - Hole – drilled - diameter ~ 0.2-1 mm
    - Pitch ~ 0.5-5 mm
- Industrial production for large size
- Mechanically self-supporting
- Robust

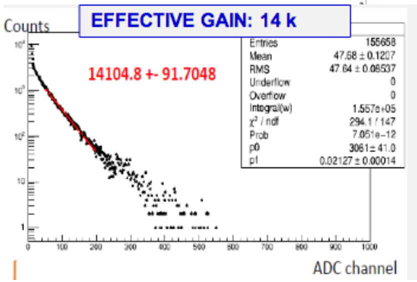


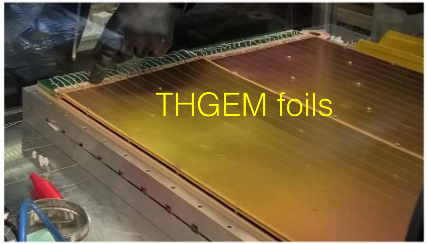


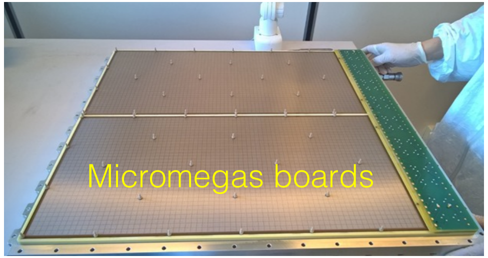
- Successfully used in COMPASS RICH-1 for single-photon detection
    - Hybrid configuration: THGEM+Micormegas; A = 1.4 m^2
    - eff. gain ~ 15000, gain stability ~5%
    - single γ angular res. 1.8 mrad
    - Gas: Ar:CH_4 50:50 →optimal photoelectron extraction from CsI to gas
    - IBF = 3%







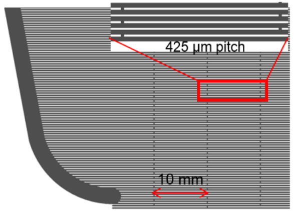


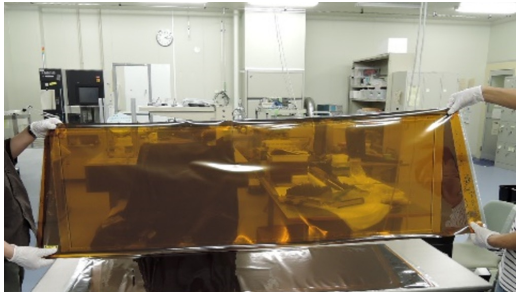


Resistive MPGD

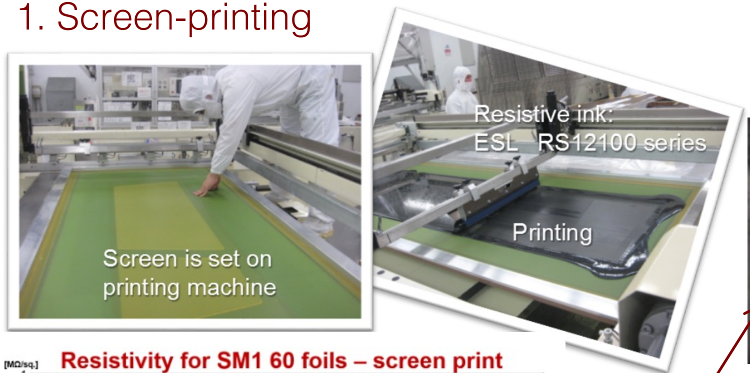
Resistive MPGD

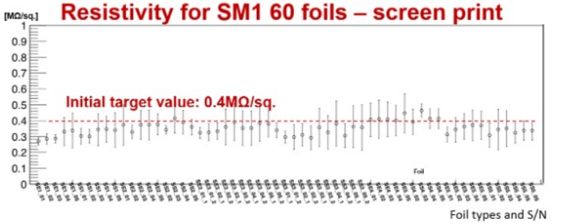
- The success of resistive Micromegas induced the development of many new resistive MPGD structures and the optimisation of the resistive coating
- During the R&D for ATLAS Micromegas to different coating techniques have been tested:



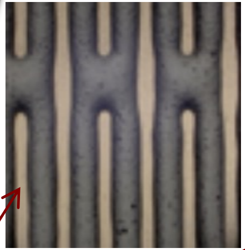


1. Screen-printing



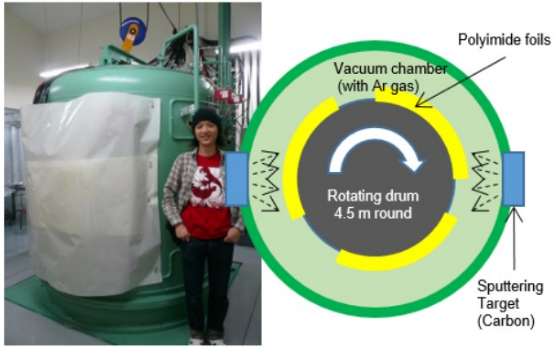


2. Carbon-dry sputtering (vacuum deposition) - DLC



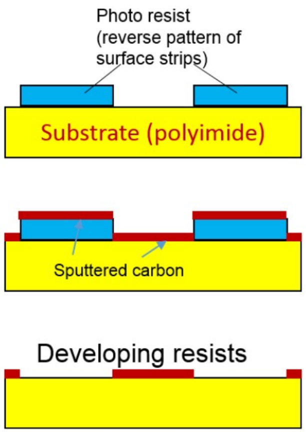
Printing: thick strips (~10-15 μm) slightly irregular edges
Sputtering: thin (~100 μm), regular shape

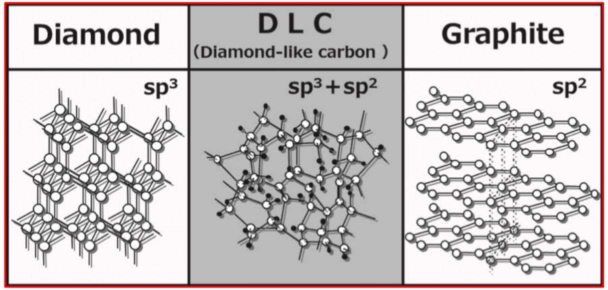
Sputtering machine (JP)



Diamond Like Carbon (DLC)

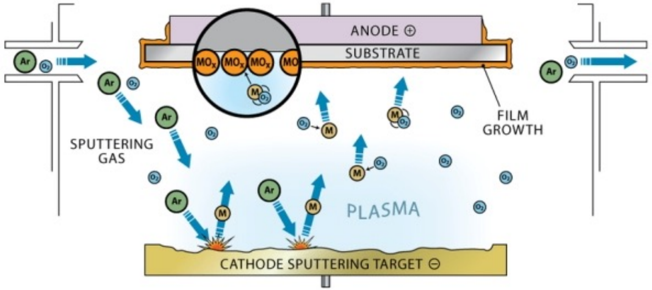
- Sputtering techniques uses carbon in 'Diamond Like', amorphous structure → carbon particles of molecular sizes
- Fine structure with given resistivity attainable





Random mixture of sp3 (diamond) and sp2 (graphite) carbon creates conductive paths of molecular size

Schematization of sputtering technique
Exposure time →
Thickness of deposited film →
Final resistivity



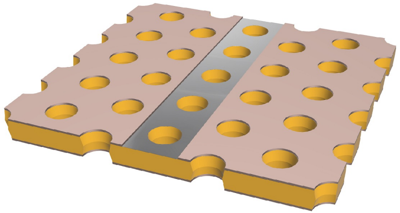
Carbon is sputtered uniformly on the substarte.
The lift-off method allows to create the desired pattern

- Diamond Like Carbon (DLC) coatings: stable and mechanically robust material
- Offers new possibilities to develop new detector structures

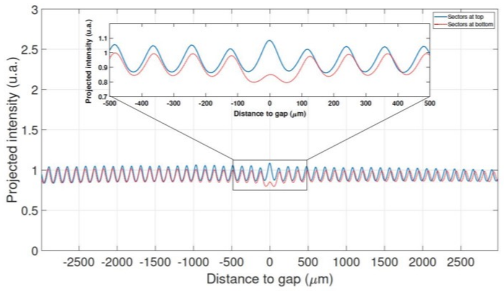
DLC GEM and THGEM

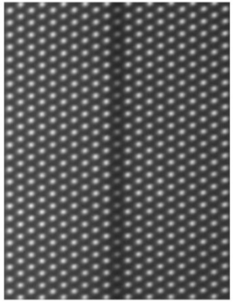
- Resistive DLC is being applied to several GEM and GEM-like detectors for different goals

- Maximum surface of GEM foil is limited to ~100 cm^2 to limit discharge energy
- Foils are thus segmented (O(100 μm) between sections) with the effect of a local field distortion and ~% efficiency loss

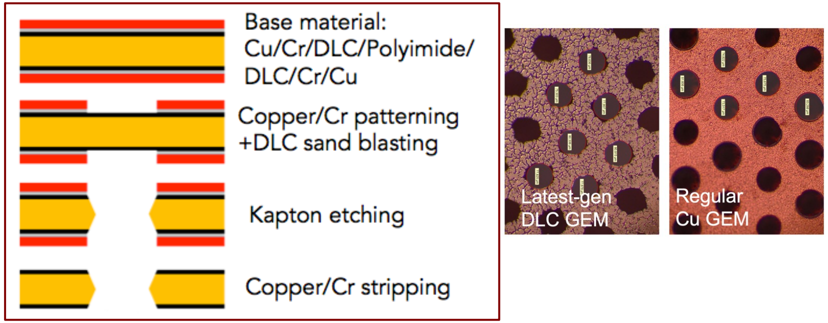


Promising results have been obtained with segmentation of GEM manufactured on DLC polymer foils

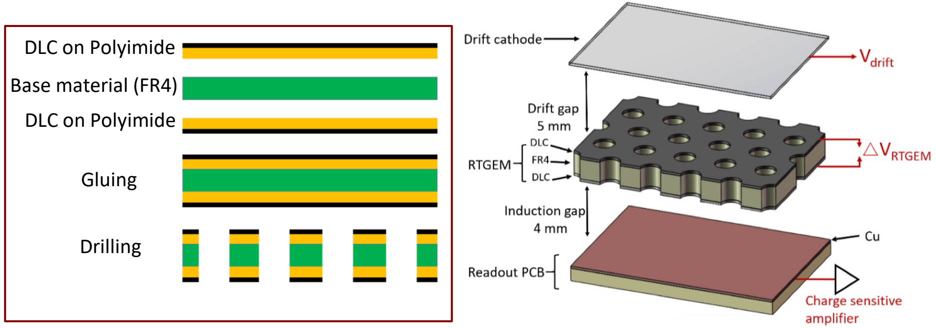




Resistive GEM under development

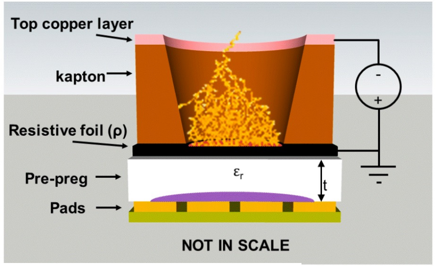


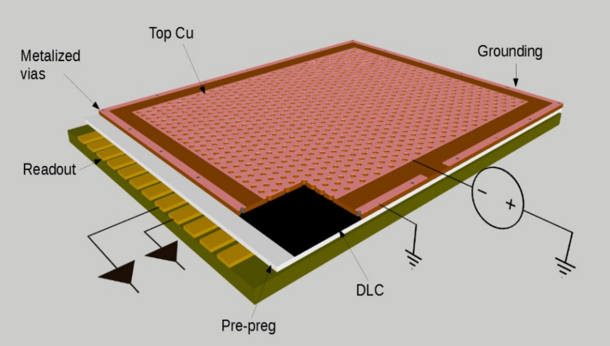
Resistive THGEM



μ-RWELL and μ-PIC

- μ-RWELL: full DLC-based detector with 3 elements:
  - WELL patterned Kapton foil acting as amplification stage (GEM-like)
  - resistive DLC layer
  - standard readout PCB
- Single layer device with good stability

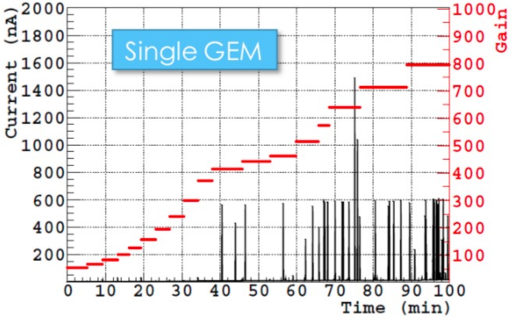


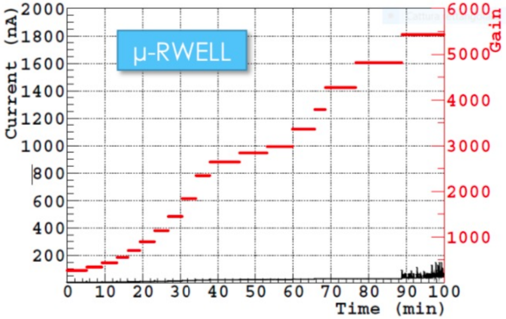


Single Resistive Layer (SRL)

Comparison of single GEM and uRWELL

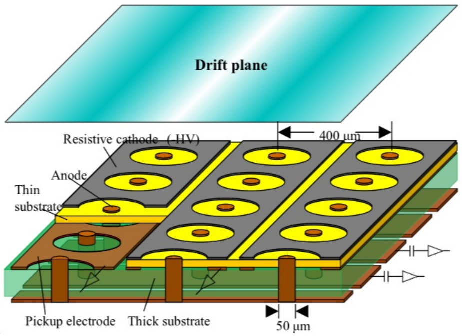
Single GEM: discharges of ~500 nA @ G~1k
uRWELL: discharges of ~50 nA @ G~5k

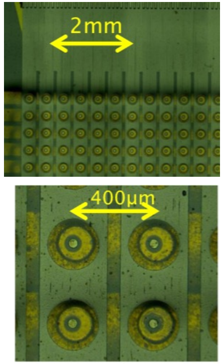




Limitation for large area: the signal amplitude depends on the particle incident point: electrons are evacuated on the side of the structure
→ limited rate capability - O(10 kHz/cm^2)

μ-PIC: radial electric field. Now resistive variant



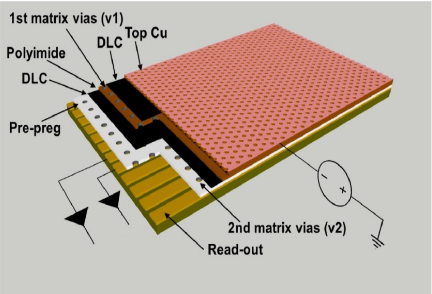


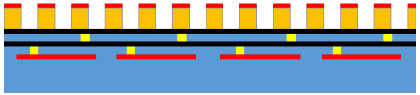
Resistive MPGD for high rate

- High-rate stable operation (>10 MHz/cm^2) requires effective spark quenching mechanism → resistive material
- But resistivity limits the max attainable rate → charge evacuation path and voltage drop → fast evacuation path
- Low occupancy is required too → high granularity readout electrodes (pixel/pad readout; integrated electronics)

Keep sufficient local surface resistivity to quench discharges with low resistance to ground

Double DLC μRWELL: conductive vias every few mm





Concept of the Double DLC layer with conductive vias to ground every few mm

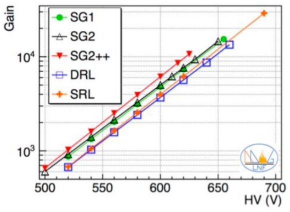
Several construction techniques under study

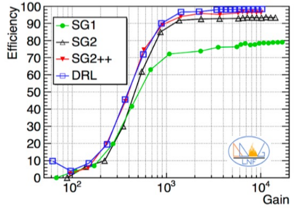
- 1"DLC+" with Silver or Cu evacuation Grid

- 1 "DLC" with Drill and fill method

- 2 "DLC+" Sequential Build Up

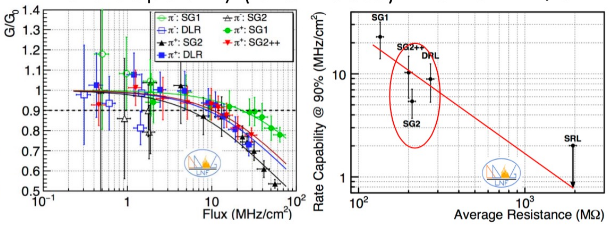
Gain up to ~ 10^4

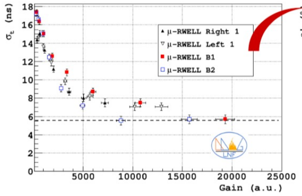




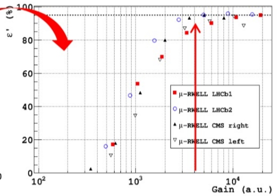
Efficiency ~ 98%

Rate capability (@ G = 5000) ~ 5-10 MHz/cm^2





σ_t ~ 5-6 ns



Efficiency in 25 ns

Optical Readout

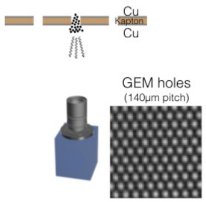
Optical readout

- During the multiplication process, photons are produced along with e-
  → light can be detected instead of (or together with) an electric signal
- Take advantage of the state-of-the art imaging sensors and readout ASICS
- Image immediately available, no need for reconstruction
- Three declinations:
  - Pure optical readout with imaging sensors
  - Hybrid readout (optical+electronic)
  - Pixellated readout with ASICs

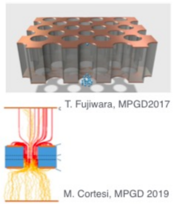
Micromegas on Timepix ASIC
- Bump-bond pads used for charge collection
- CMOS-ASIC designed by the Medipix collaboration
- GridPix based on Timepix 3:
  - 256 × 256 pixels with 55 × 55 μm² per pixel
  - Charge (ToT) and time (ToA) information with 1.56ns time resolution

Different MPGD technologies have been used with optical readout for maximising spatial resolution
Integration on transparent substrate (coated glass) for optical light transmission
High gain (light yield) amplification matched with pixel size of imaging sensor

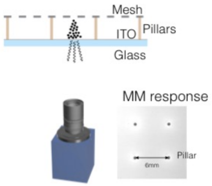
GEMs
Open structure inherently suited for optical readout
High gain in multi-GEM stacks



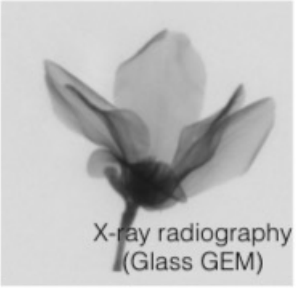
THGEMs
Long amplification region for e.g. low pressure operation
Variants: GlassGEM, MM,THGEM, …

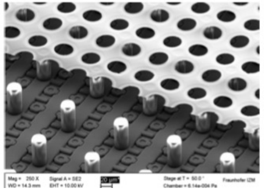


Glass Micromegas
High single stage gain, uniform amplification region and high energy resolution



Glass substrates → other MPGDs

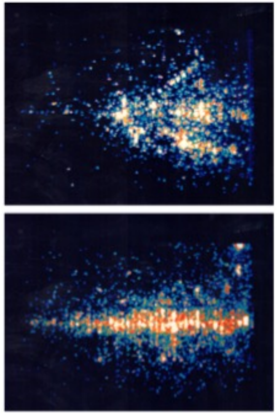




GridPix

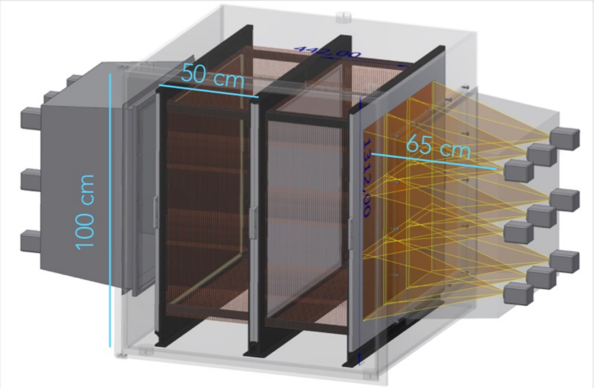
Optical TPC

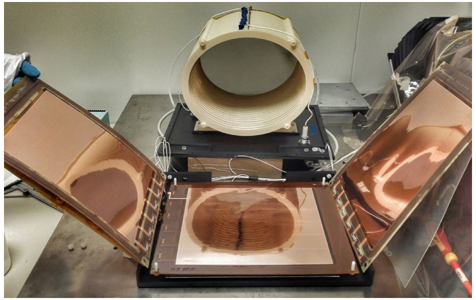
- Optically readout TPC have a long history
- Modern imaging techniques allow to exploit OTPC
- Detailed 2D projection → auxiliary timing for 3D reconstruction is needed
- Proposed in several experiments, particularly suited for DM searches



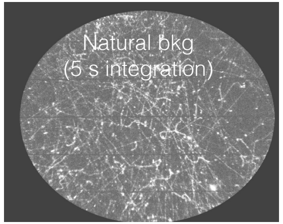
Fonte P., Breskin A., Charpak G., Dominik W. & Sauli F. (1989) NIM A. 283, 3, p. 658-664.

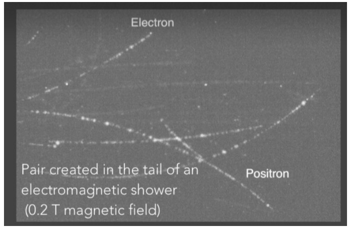
- The CYGNO Experiment
- Volume 1 m^3
- Gas: He:CF_4 (60:40) at P atm
- 3x3 Triple-GEM readout by a CMOS sensor from a transparent windows and a fast light detector (PMT or SiPM)
- Total of 72×10^6 readout 165x165 um^2 pixels

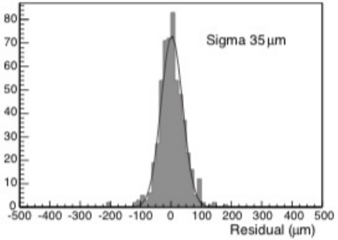




First prototype (LEMOn, 7l volume) successfully tested







Space resolution (x-y) 35 um
Energy resolution 18%

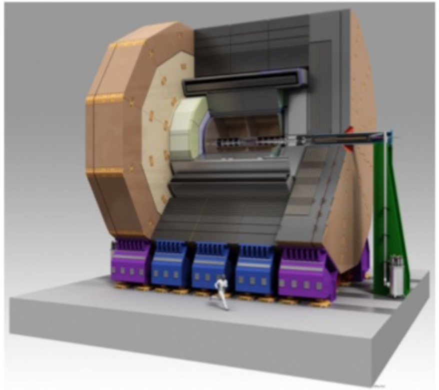
MPGD for future experiments

- MPDG are proposed for large future experiments.
- Here a shirt list for FCC and Muon collider

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

MPGD for future experiments: TPC for ILC

- TPC for ILC

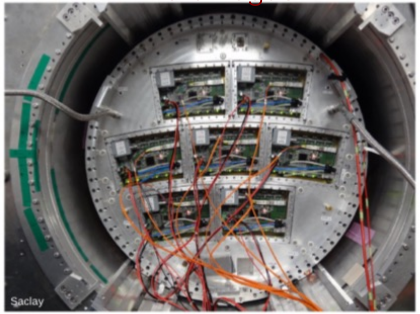


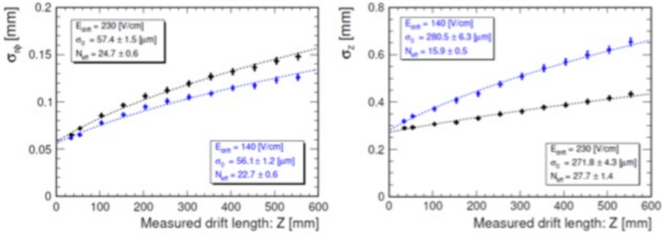
Parameter			
Geometrical parameters	r_{in}	r_{out}	z
	329 mm	1808 mm	± 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq 0.05$ X_0 including outer fieldcage in r		
	< 0.25 X_0 for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times$ 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 μm for zero drift, $<$ 100 μm 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

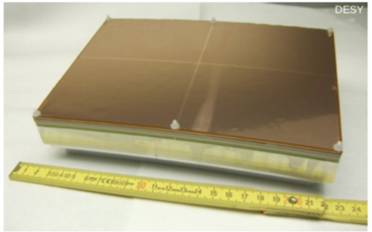
Micromegas

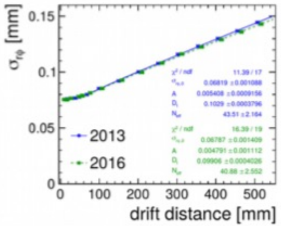


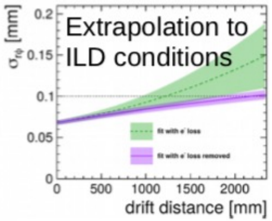


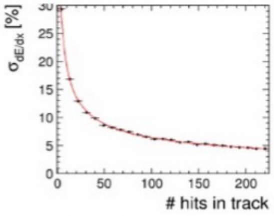
- Several options under study: GEM, Micromegas, GridPix

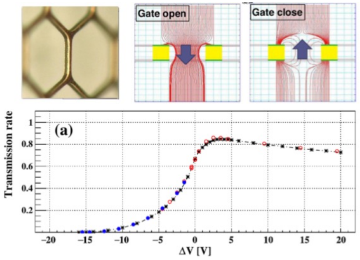
GEM





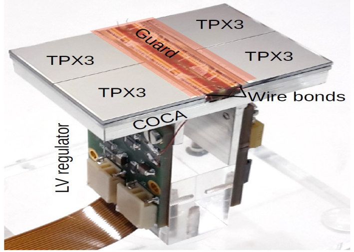


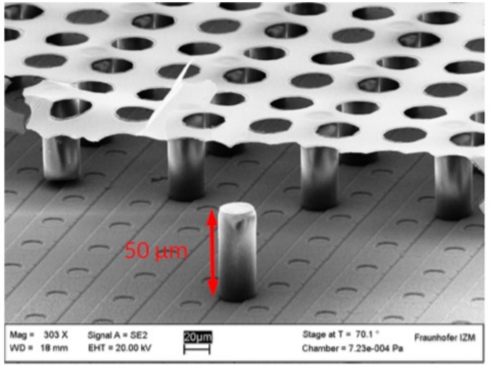


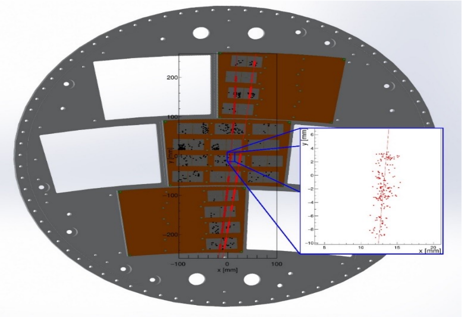


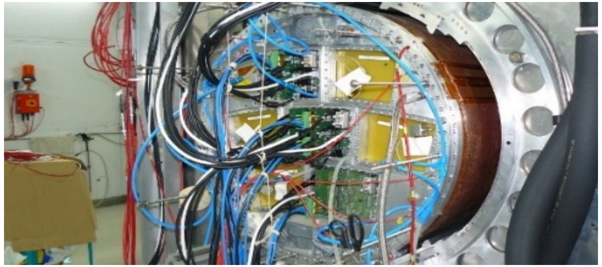
MPGD for future experiments: TPC for ILC

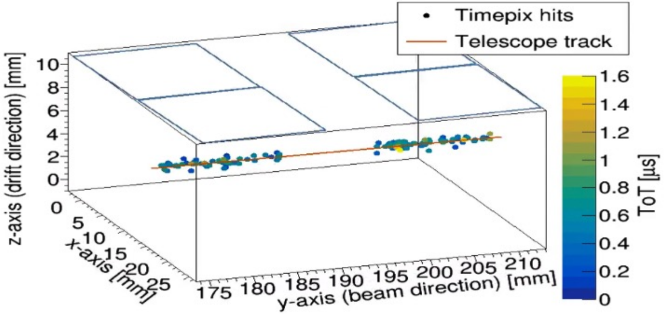
- Gridpix option → first large application
  - Bump bond pads are used as charge collection pads
- Offers:
  - Lower occupancy → easier track reco
  - Improved dE/dx (4% seems possible)
- Needs:
  - ~120 chips/module on 240 modules/endcap ($10m^2$)→ ~60k GridPixels
- Demonstrator of mass production: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





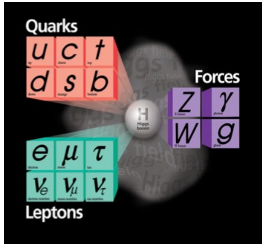




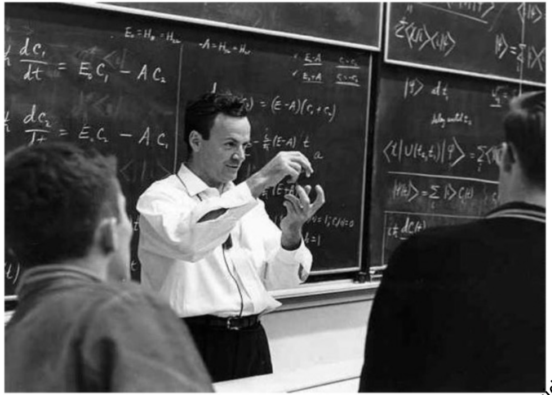


MPGD proposed for calorimetry at ILC too

- Higgs boson is turning 11 and we're desperately looking for something else...



- ...experiments at future colliders can do the job!



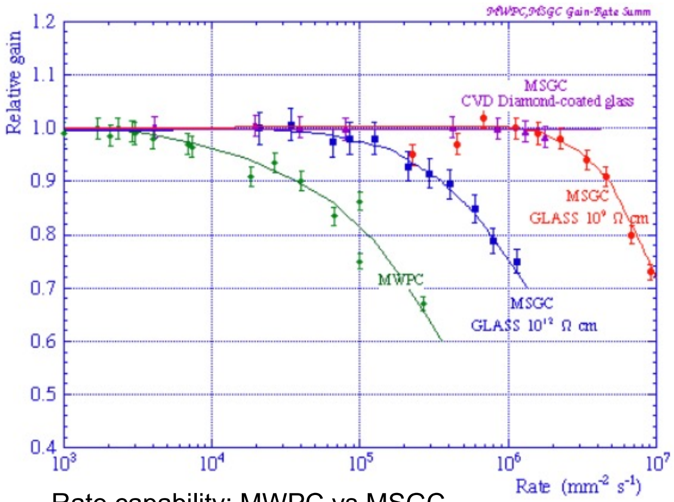
G. Isidori, ECFA meeting July 2022

"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]

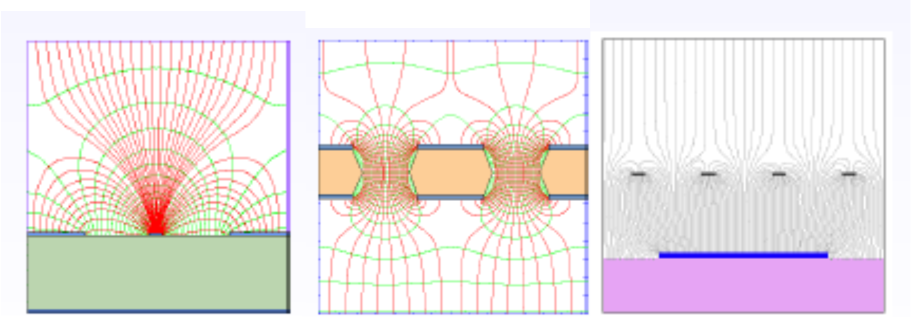
MPGD: increasing the rate capability

- 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



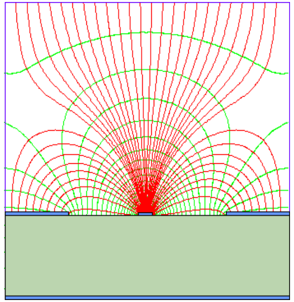
MSGC
A. Oed (1988)

GEM
F Sauli (1997)

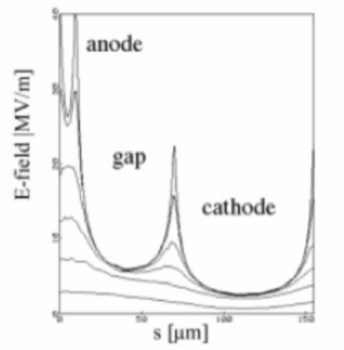
Micromegas
I. Giomataris,
G. Charpak (1997)

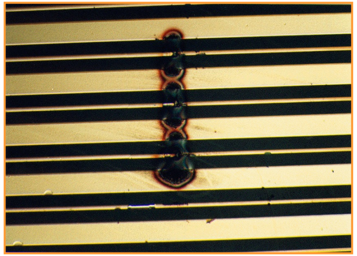
The first challenge: disruptive discharges

- 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

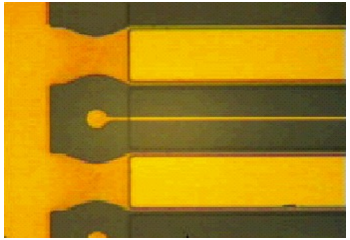


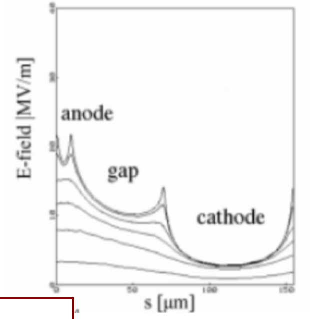
- Example: Gain ~ 10^4; Ionisation gap ~1 cm
  Avalanche size Q = # of e^- primaries x Gain
    - MIP: Q = 10^2 x 10^4 = 10^6 → OK
    - p of ~MeV: Q = 10^4 x 10^4 = 10^8 → discharge
    - Field emission from cathode strip: Q = 10^4 x 10^4 = 10^8 → discharge





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

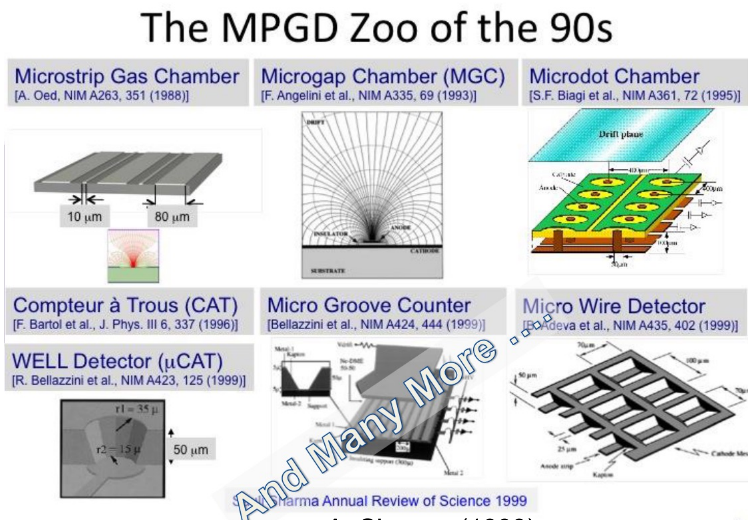




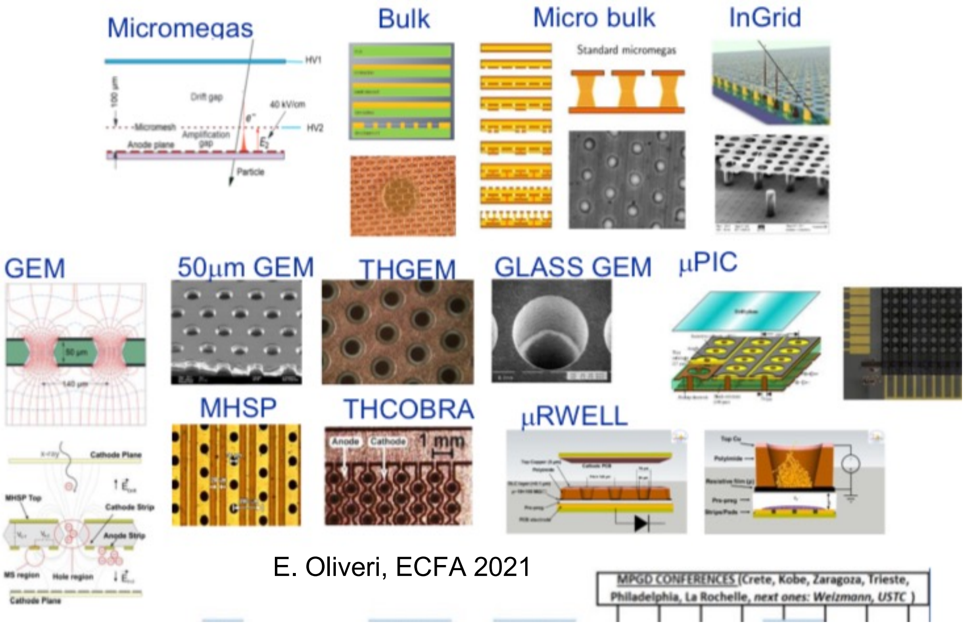
Other spark protection/reduction mechanisms adopted in other MPGD → more on that later

The MPGD 'explosion'

- Since the invention of the MSGC the gas detector community has introduced many other MPGD: some very promising, some somewhat less…



A. Sharma (1999)

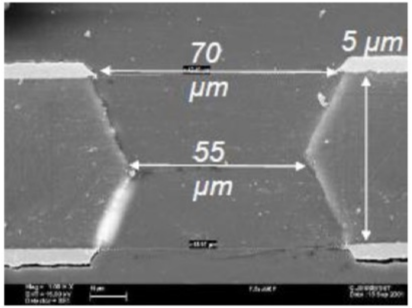


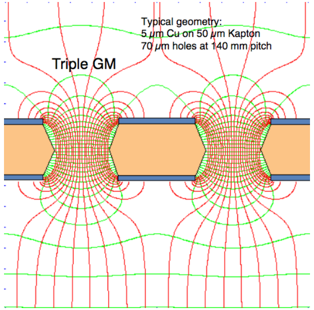
E. Oliveri, ECFA 2021

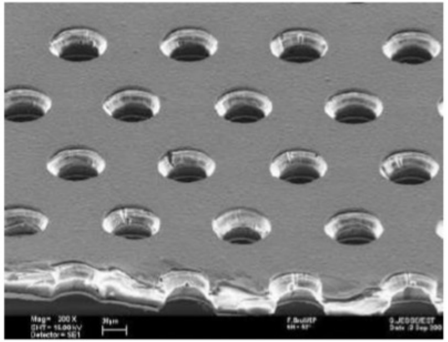
- Today the MPGD family includes a large number of detectors
  - Well established technologies adopted in HEP experiments
  - New ideas, R&D for future experiments or specific applications

Gas Electron Multipliers

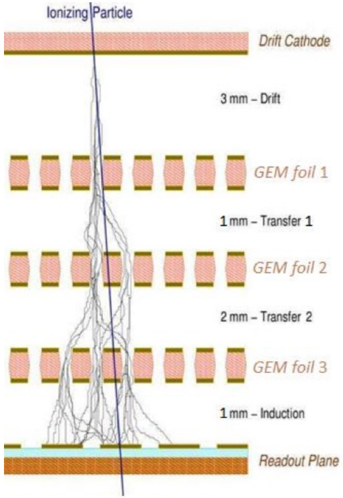
- GEM
- Thin (~50 μm) metal-clad polymer foil chemically perforated with high density of holes (~100/mm^2)
- Preamplification and charge transfer preserving the ionisation pattern

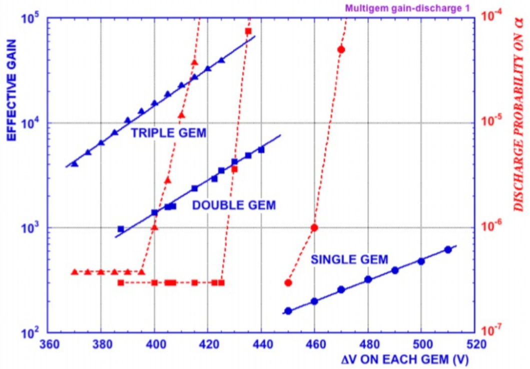






- GEM foils in cascade → high gain before discharges
- Multi-stage → triple GEM

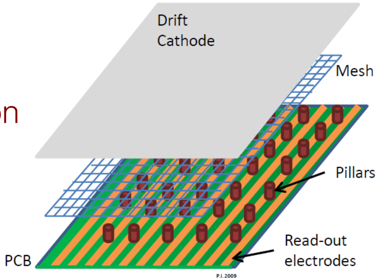


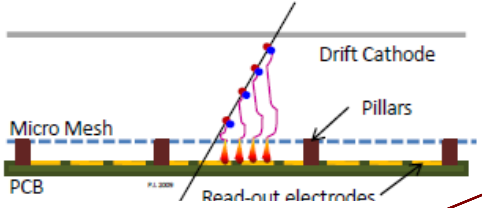


S. Bachmann et al, NIMA 479(2002)294

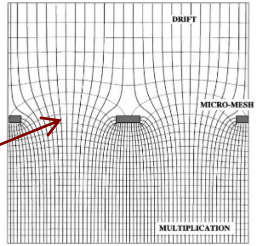
MICRO MEsh Gas Structure

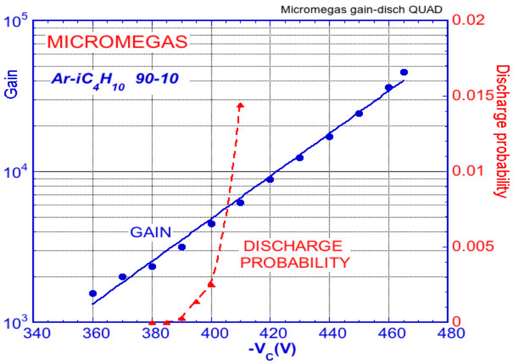
- Parallel-plate with small (~100 μm) amplification gap
- Thin metallic mesh separating the ionisation and amplification regions
- Rate capability and energy resolution of parallel plates



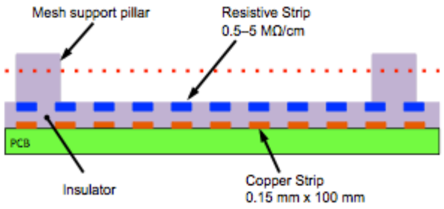


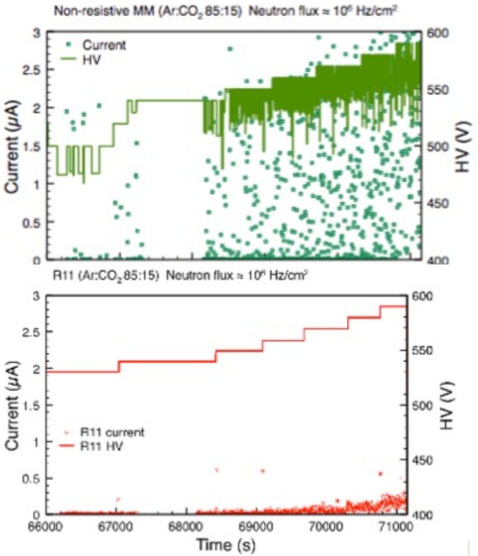
Funnel field lines:
high transparency to electrons





- 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