Muon Detector for Muon Collider

R&D on MPGDs: GEM, Micromegas, μRWell, PICOSEC, …. and other ongoing developments

overview and perspectives

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Muon Collider Physics and Detector Workshop, 3rd June 2021

Let me start with disclaimers

- **I'll try to present a large picture of MPGD, but I apologize that, this is so large family that a good summary is almost impossible (please look to the backup slides for very wide view of existing MPGD technologies) moreover, I'm sure that I'm biased by my personal experience…**

- **The intent is to present some MPGD technologies for application in Muon Collider Detector, but absolutely not with the idea to sell any technology in favors of others (again mostly biased by my personal experience)**

- **Muon Detectors still nowadays the only way to instrument large volume at moderate cost and limited material budget, *MicroPattern Gas Detectors (MPGD)* are ideal tools for present and future large-scale use at LHC and behind**

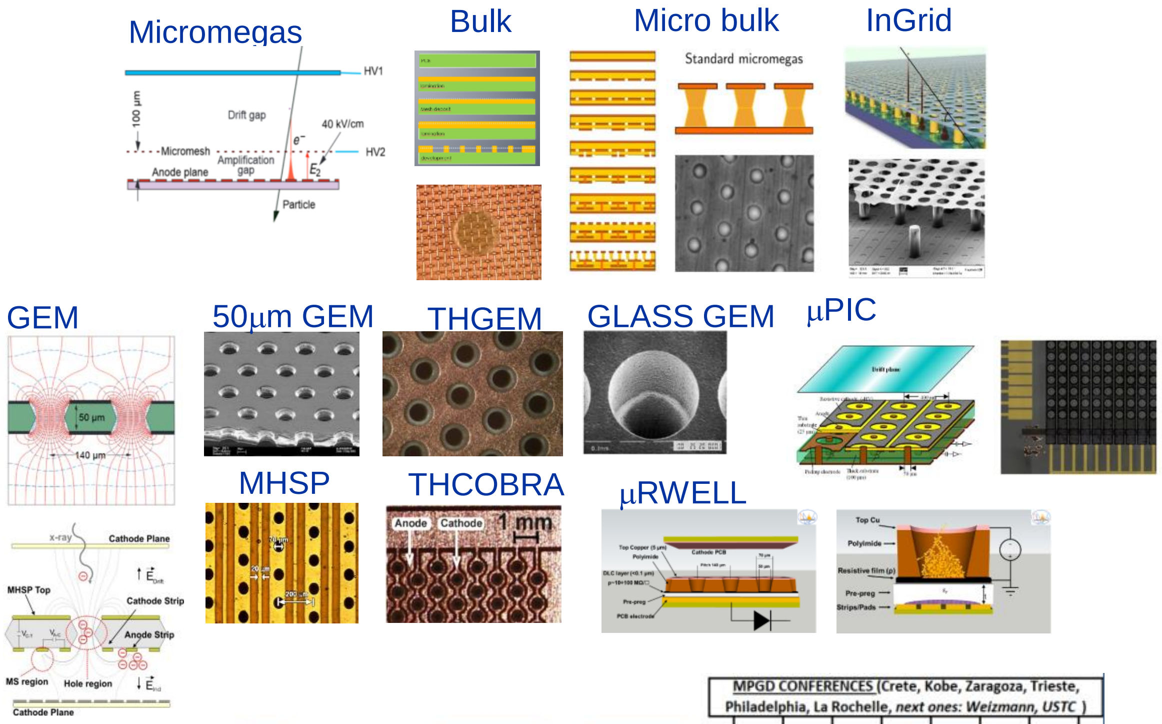
MPGD @ Muon Collider: which requirements?

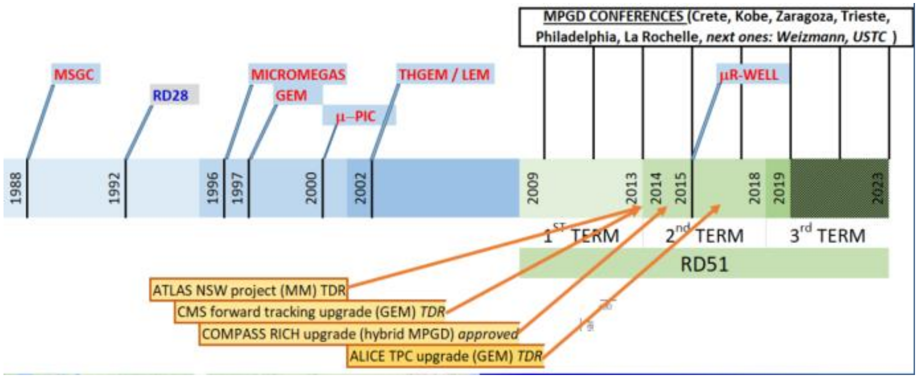
- **Time resolution?**
- **Space resolution?**
- **Energy Resolution?**
- **Material budget ?**
- **…….**

First of all, define the requirements than look to the technology as possible best solution for the use case.

.. again, as specified in the disclaimer the intent is not to suggest any specific technology, (some are more mature of others, some look more interesting for timing, rate capability, …)

Micro Pattern Gas Detector Family



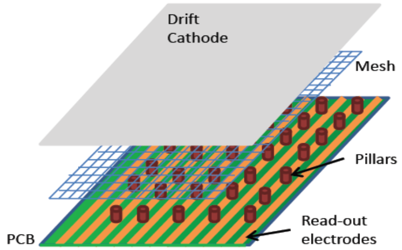


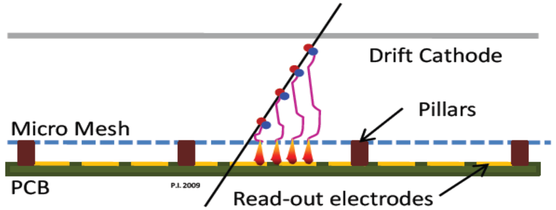
High Rate Capability	Up to MHz/mm^2 (MIP)
High Gain	Up to 10^5 - 10^6
High Space Resolution	<100µm
Good Time Resolution	In general few ns , sub-ns in specific configuration
Good Energy Resolution	10-20% FWHM @ soft X-Ray (6KeV)
Excellent Radiation Hardness	
Good Ageing Properties	
Ion Backflow Reduction	% level sort of easy, below % in particular configuration
Photon Feedback Reduction	
Large size	m^2
Low material budget	
Low cost	
…	

All subjects illustrated by examples:
A fully comprehensive review is impossible!
Technology share-point R&D51

MPDG as Tracking Detector

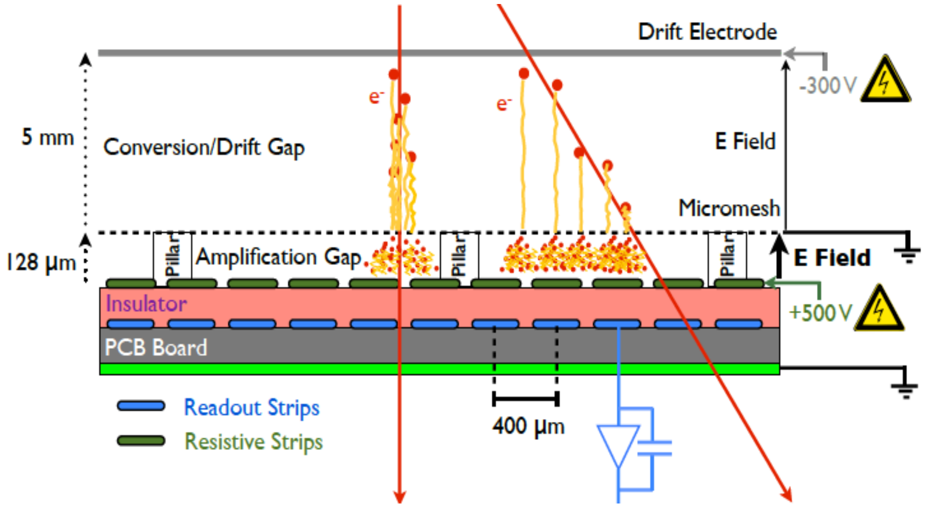
MicroMegas MM



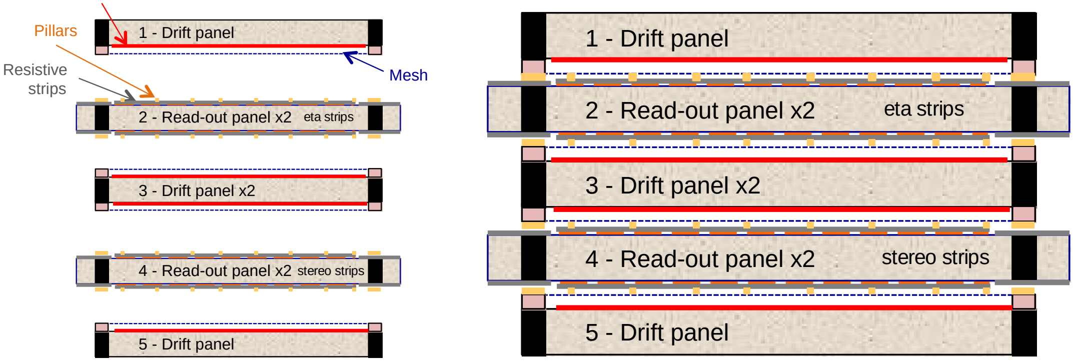


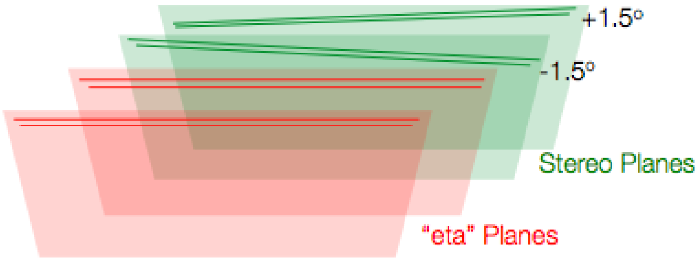
- **Micromegas (I. Giomataris et al., NIM A 376 (1996) 29)** are parallel-plate chambers where the amplification takes place in a thin gap, separated from the conversion region by a fine metallic mesh.

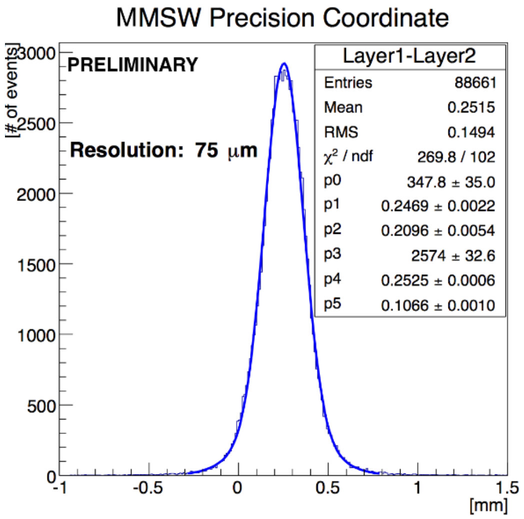
ATLAS MM
- Drift region: 5 mm
- Grounded mesh (stainless steel, 325 lines/inch)
- Floating Mesh (Not bulked detector)
- Amplification region: thin gap (128 μm)
- High electric field, fast ions evacuation and high rate tolerance
- e^- drift towards the mesh (95%transparent)
- Resistive strips for spark-protection
- Capacitive coupling of the resistive strips with readout strips
- The detector becomes spark tolerant by adding a layer of resistive strips(5-20MOhm/cm)
- Operated with an Ar/CO2 93/7 mixture



MicroMegas

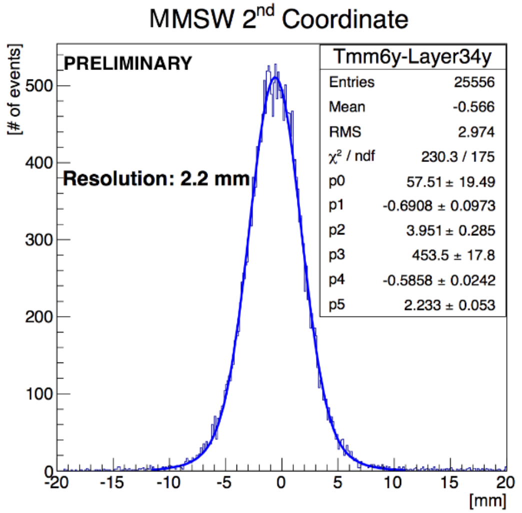






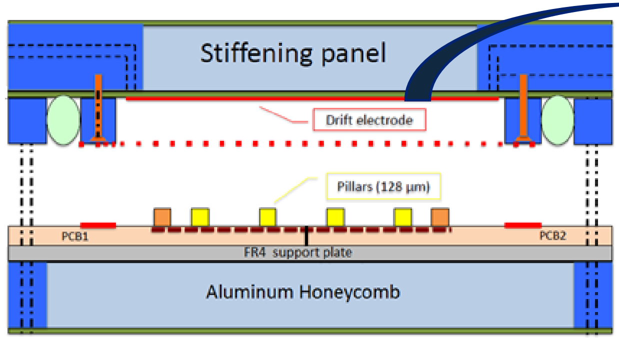
MM Performances:

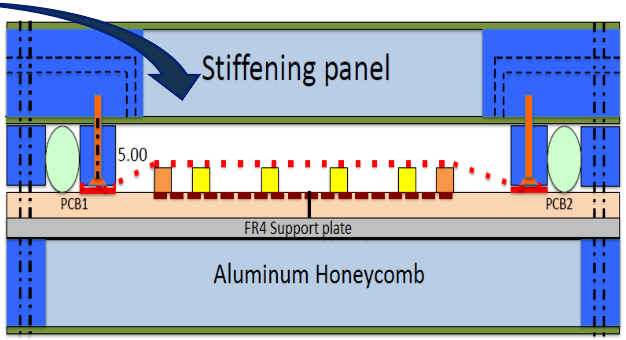
- Space resolution : ~ 80 um (10.1109/NSSMIC.2014.7431235)
- Time resolution : 7-9 ns (NIMA 577 (2007) 455)
- Gain
  - COMPASS: G ~ 6400 (NIMA 469 (2001) 133)
  - T2K TPC: G ~ 1500 (NIMA 637 (2011) 25)
- Rate capability ATLAS-NSW resistive, lin. up to 100kHz/cm

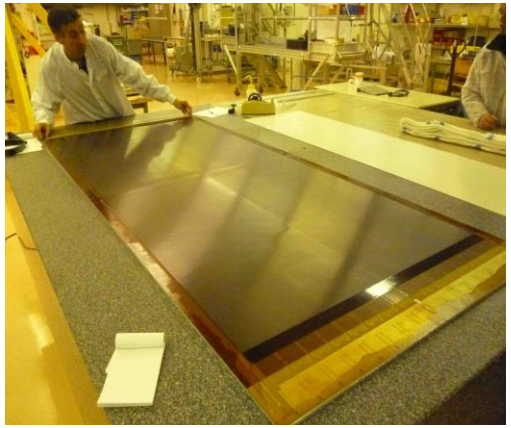


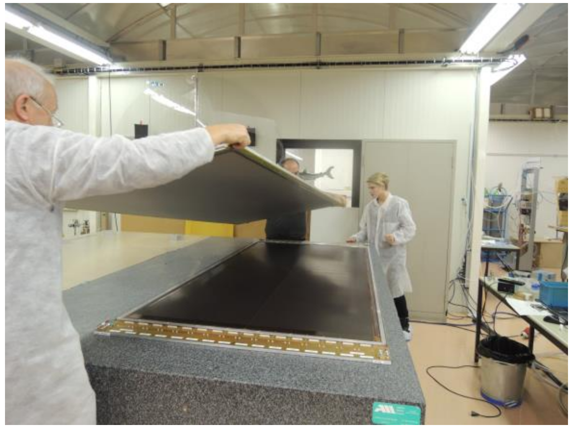
MicroMegas

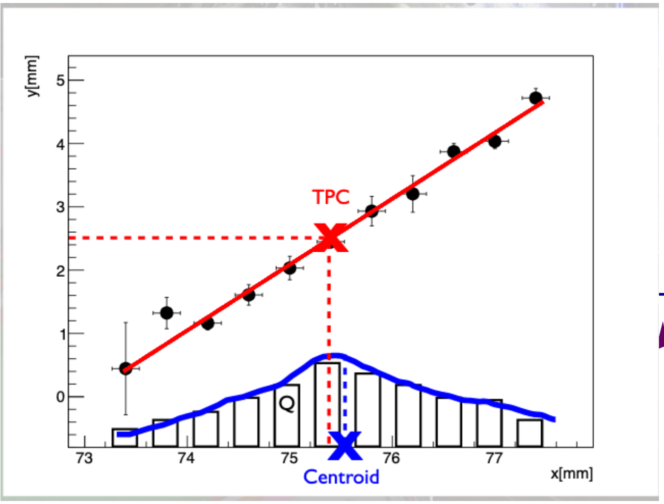
Non-bulk technique (**floating mesh**) that uses also pillars to keep the mesh at a defined distance from the board, the mesh is integrated with the drift-electrode panel and placed on the pillars when the chamber is closed. This allows us to build very large chambers using standard printed circuit boards (PCB) .

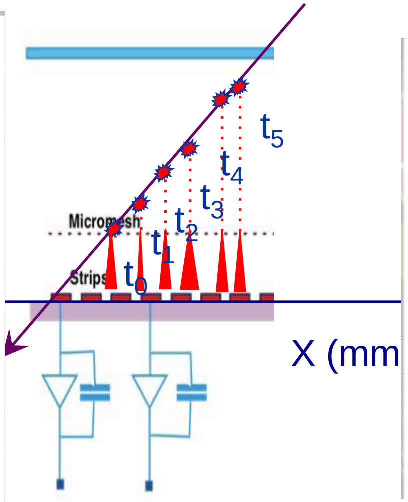


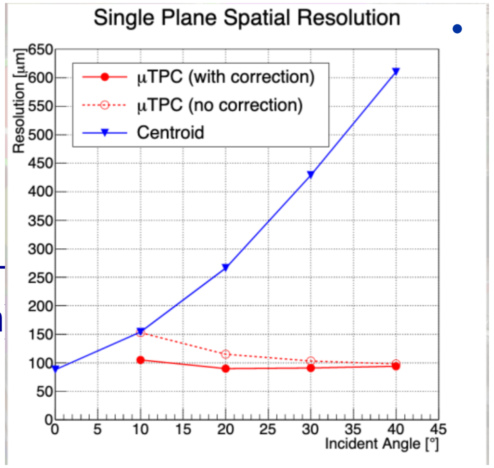












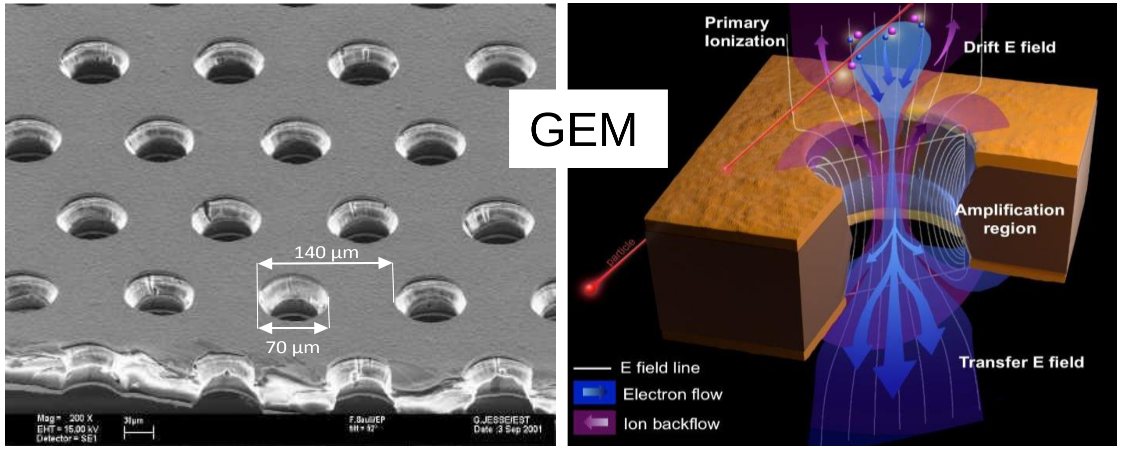
- **Hit & Track reconstruction**
  - ***Using charge amplitude (Centroid hit)***
    - Accuracy rapidly decreasing for larger track angles
  - ***Using time information (uTPC segment)***
    - Performance improving with increasing cluster size

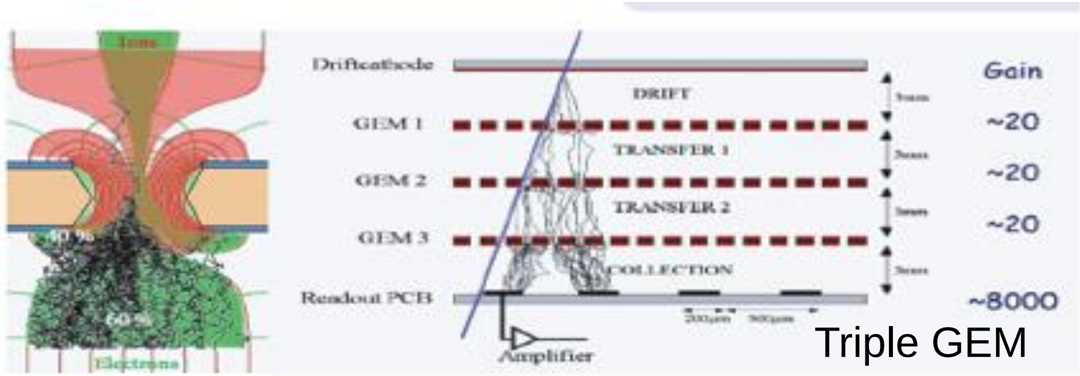
K. Nteakas ATL-MUON-PROC-2014-011
10.1109/NSSMIC.2014.7431235
Jinst10 (2015) C02026

Gas Electron Multipliers (GEM)

CMS GEM

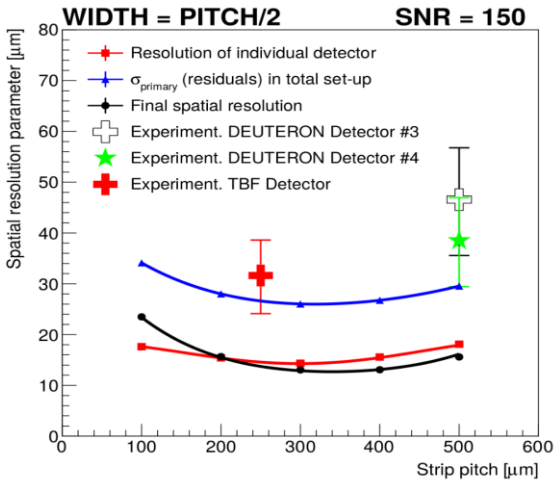
- Triple GEM detector 3/1/2/1 mm
- Drift region: 3 mm
- Maximum geometric acceptance within the given CMS envelope
- Rate capabilities up to 100’s kHz/cm2
- Gain uniformity of 10% or better across a chamber and between chambers
- High spatial and good time resolution
- Operated with an Ar/CO2 93/7 mixture



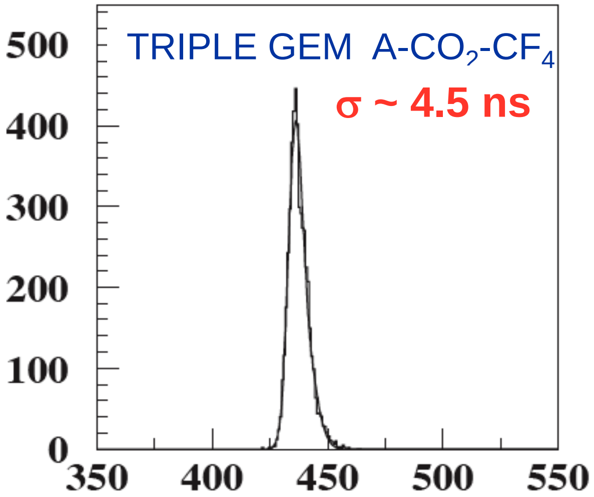


F. Sauli, *GEM: A new concept for electron amplification in gas detectors*, **NIMA386 (1997) 531**.

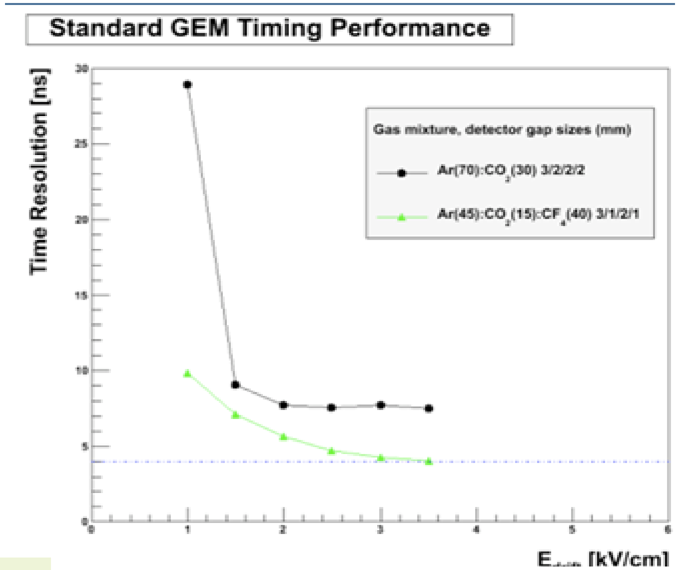
Gas Electron Multipliers (GEM)



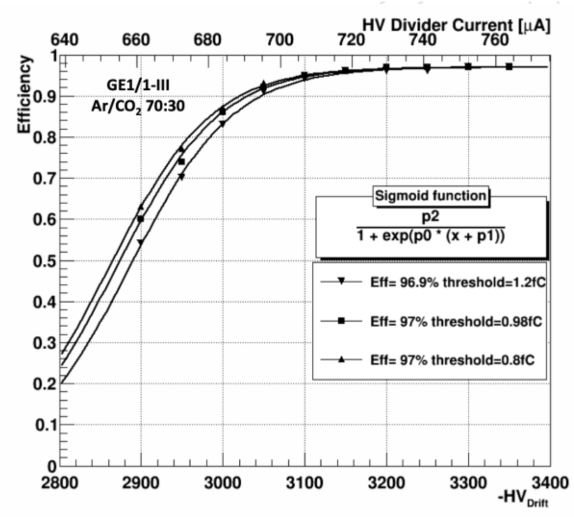
V.N. Kudryavtsev et al 2020 JINST15 C05018



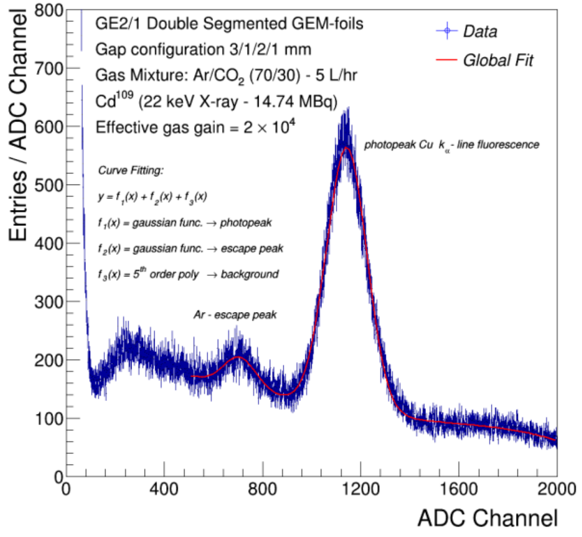
M. Alfonsi et al, Nucl. Instr. and Meth. A535(2004)319



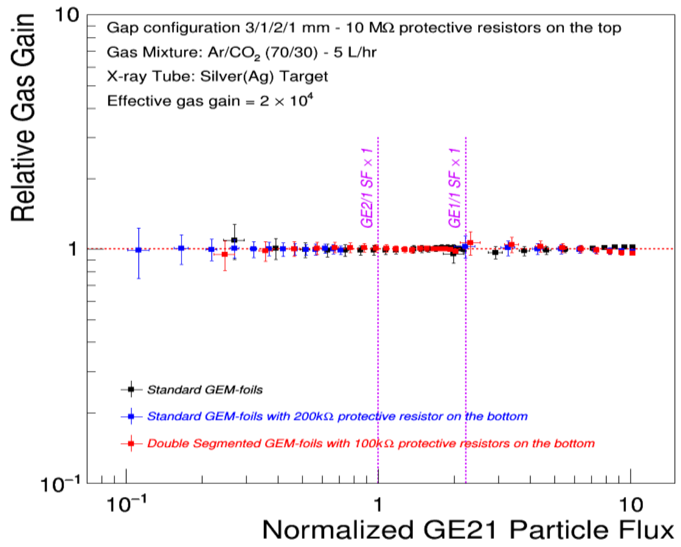
CMS TECHNICAL DESIGN REPORT FOR THE MUON ENDCAP GEM UPGRADE
CMS-TDR-013



CMS-TDR-013

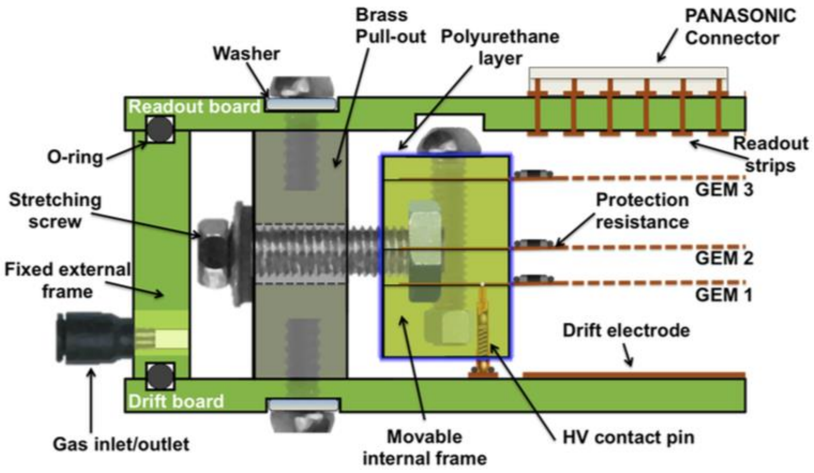


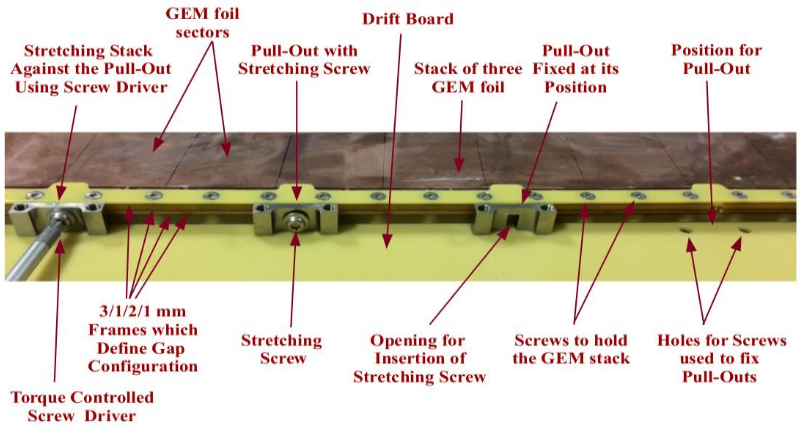
M. Bianco 2020 *JINST* **15** C09045

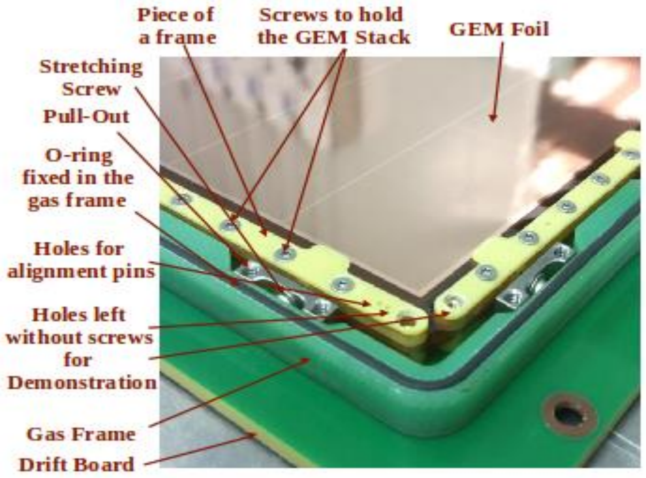


M. Bianco 2020 *JINST* **15** C09045

Gas Electron Multipliers (GEM)



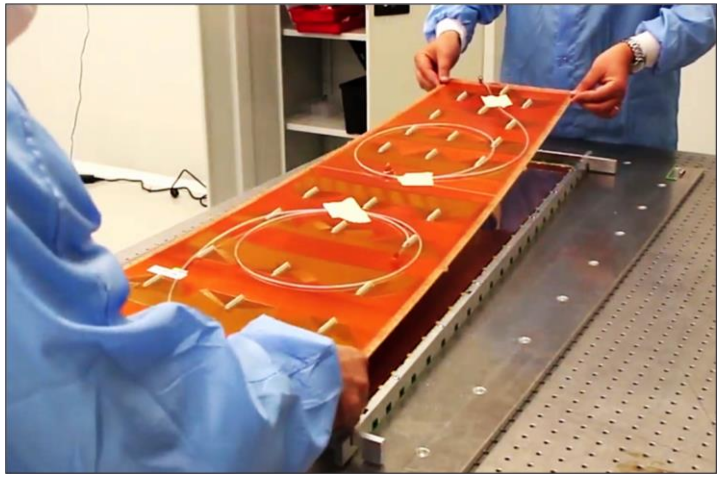




GEM Performances:

- Space resolution : ~ 40 um (JINST 15 CO5018)
- Time resolution : 4-9 ns (NIMA 535 (2004) 319)
- Gain
    - CMS up to 4*10^4 (and more) (JINST 15 C09045)

- Rate capability CMS GE1/1 configuration 20 kHz/cm2 (strongly dependent on spark protection resistances)



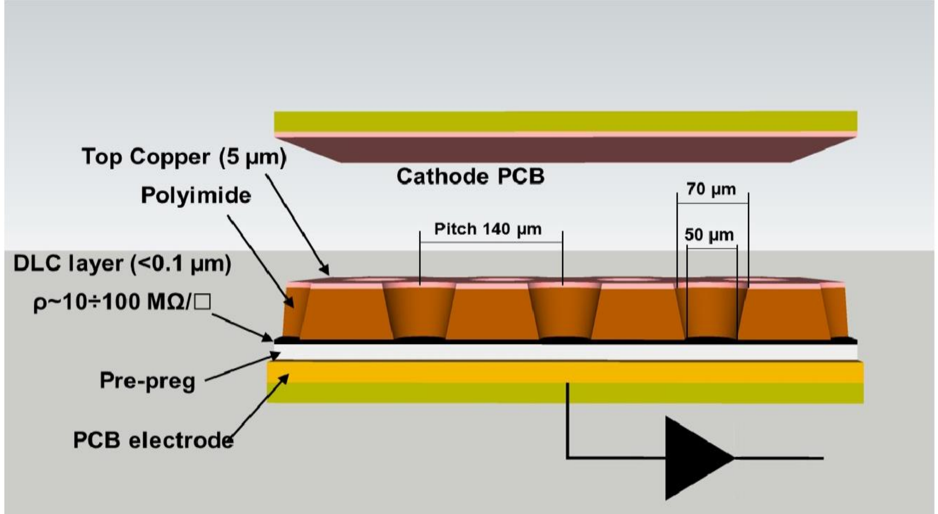
The µ-RWELL technology

The device is composed of two elements:

- µ-RWELL_PCB
- drift/cathode PCB defining the gas gap

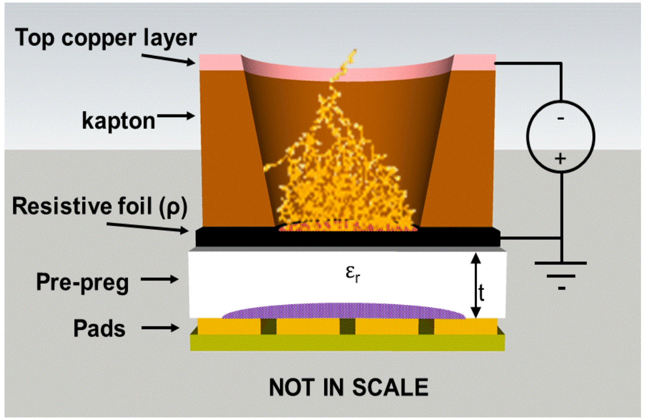
µ-RWELL_PCB = amplification-stage ⊕ resistive stage ⊕ readout PCB

large area & flexible geometry



- The "WELL" acts as a multiplication channel for the ionization produced in the gas of the drift gap
- The charge induced on the resistive layer is spread with a time constant, $\tau \sim \rho \times C$

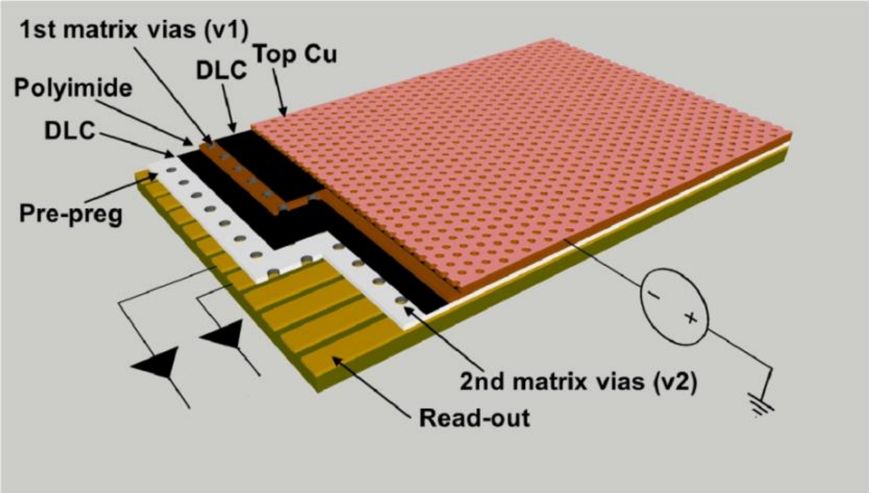
$$C = \varepsilon_0 \times \varepsilon_r \times \frac{S}{t} = 35\, pF \times S(cm^2)$$



µ-RWELL High-Rate Layout

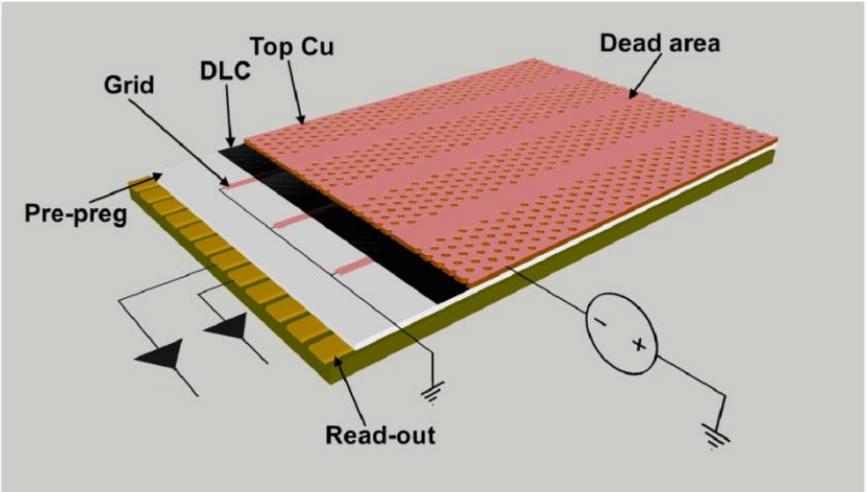
The purpose of these HR versions is to reduce the distance to be “travelled” by the charge towards the ground

Double Resistive layer (DRL)



- 3-D grounding
- Double DLC layers connected through matrices of conductive vias to the readout electrodes (density 1/cm2)

Silver Grid (SG)

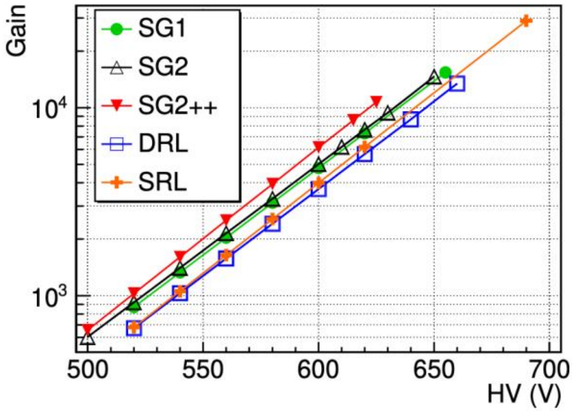


- 2-D grounding
- Single DLC layer grounded by means conductive strip lines realized on the DLC layer (density 1/cm)

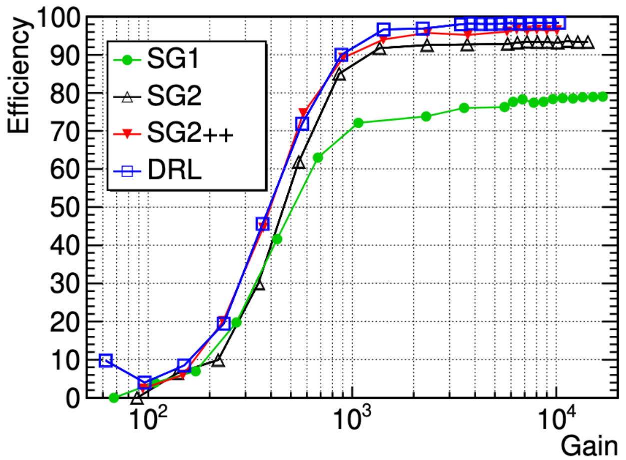
Silver Grid design introduced to simplify the e technology transfer, since the TT of the DRL industrial production is difficult, The new design, is based on the simple single-resistive layout with a suitable surface current evacuation scheme, the Grid layout (to avoid sparks) introduce dead area which reduce the geometrical acceptance

μ-RWELL Performances

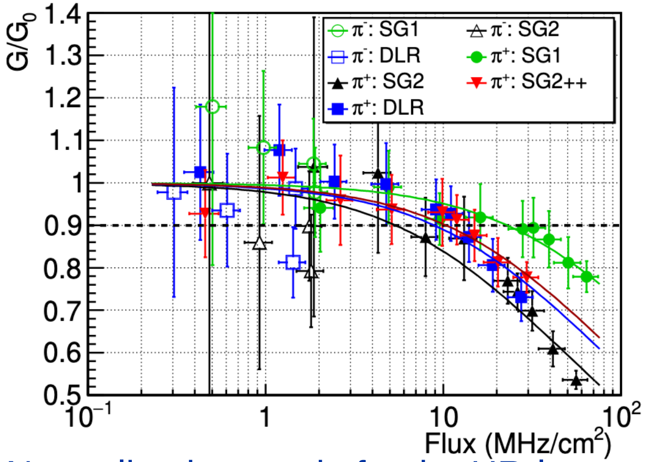
G. Bencivenni et al 2019 JINST14 P05014



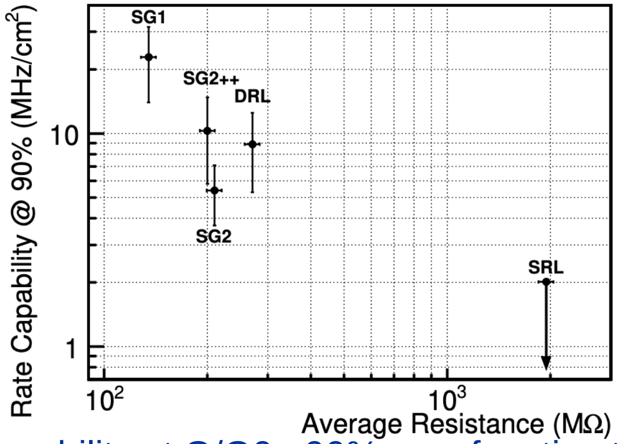
Gas gain of the uRwell (different HR layout) characterized at PSI



Efficiency as a function of the gas gain for the HR layouts (SG1 affected by geometrical acceptance)



Normalized gas gain for the HR-layouts as a function of the pion flux in PSI beam tests



Rate capability at G/G0= 90% as a function the effective resistance Ωeff. For the SRL, an upper limit of its rate capability is given

Thanks to the resistive plane:

- **very reliable**
- **very low discharge rate**
- **adequate for high particle rates O(1MHz/cm2)**

- **gain ≥10^4**
- **space resolution < 60 μm**
- **time resolution < 6 ns**

Perspectives

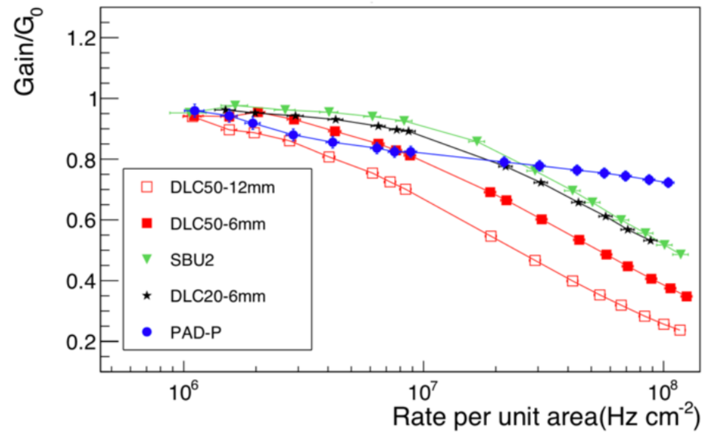
Single resistive layer (Moderate rate):

- **Quick progressing toward large size**
- **TT ongoing**
- **Industrial Partner ELTOS, MDT**

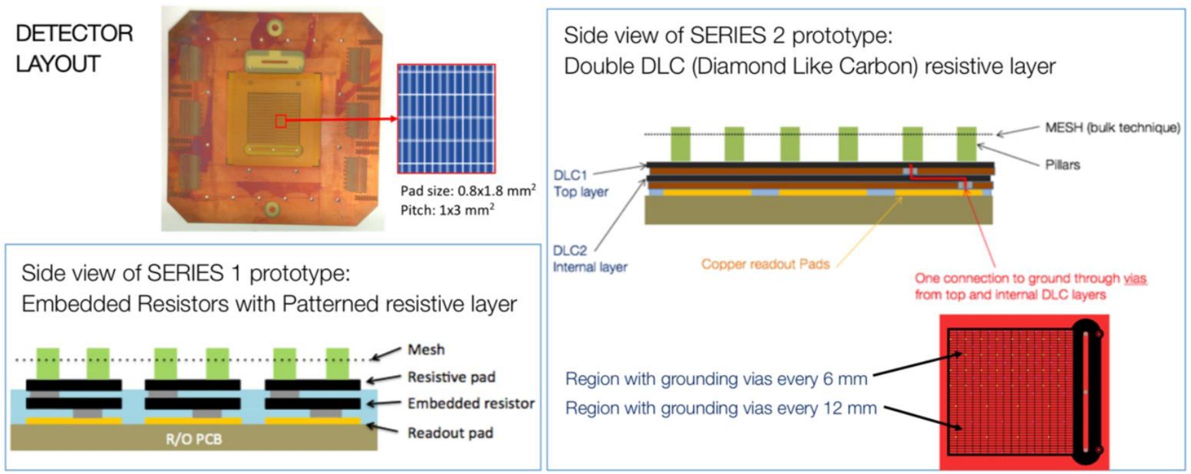
Small-PAD Resistive MM

MPGD for very high-rate application

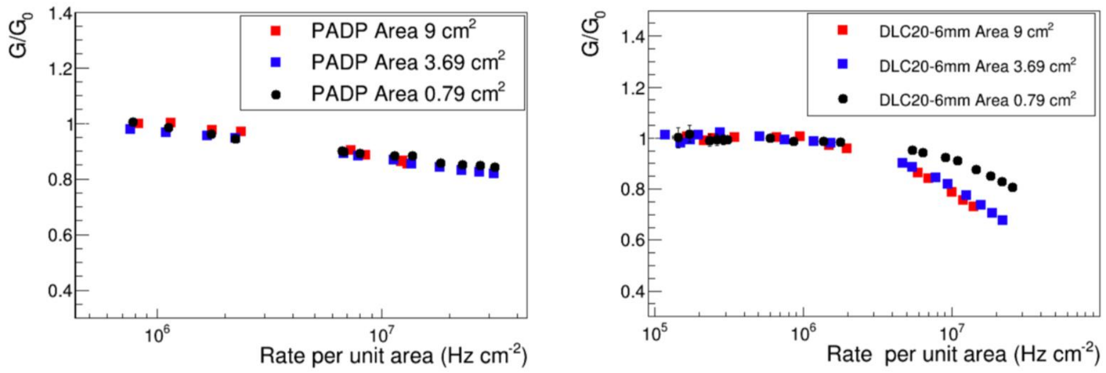
M. Iodice *et al* 2020 *JINST* **15** C09043



Dependence of the gains of the PAD-P, DLC and SBU detectors, normalized to their value at low rates, as a function of the X-Rays hit rates, in the range 1–100 MHz/cm . Irradiated area of 1 cm diameter (0.79 cm2). Gain about 6500 at 100 kHz/cm2 for all the detectors



Top-left: photo of the anode plane PCB with an expanded view of the pad structure; bottom- Left: side view sketch of the pad-patterned resistive scheme; right: side view sketch of the DLC detectors with a top view of the grounding vias layout.

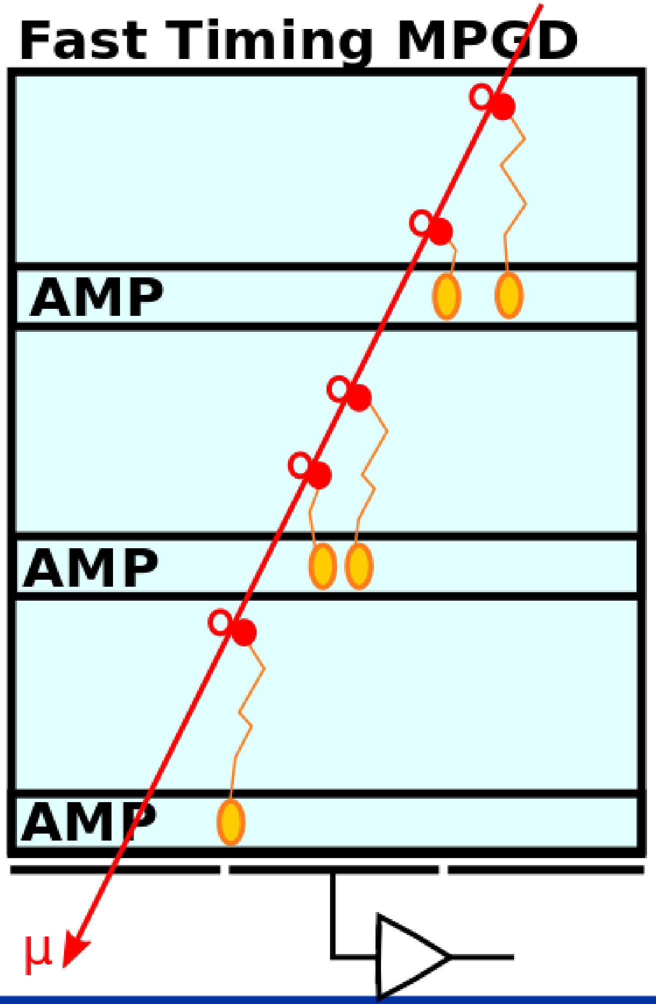


Dependence of the relative gain on the X-Rays hit rates for the PAD-P (left) and DLC-20-6mm (right) detectors for three different areas of exposure: 0.79, 3.69, 9 cm^2

MPDG as Timing Detector

Fast Timing MPGD (FTM)

- Time resolution of <u>all</u> proportional gas detectors (GEM,MM,uRWELL,…) is limited to 5-10ns [1]
- Typical <u>fluctuation of closest primary electron</u> to amplification structure:
  $\lambda \sim 2.8\text{mm}^{-1} \rightarrow \langle d \rangle = 350\mu\text{m}$ @ $v_{drift} = 50\text{-}70\mu\text{m/ns} \rightarrow \sigma_t = 5\text{-}7$ ns time resolution [2]



Fast Timing MPGD: Working Principle

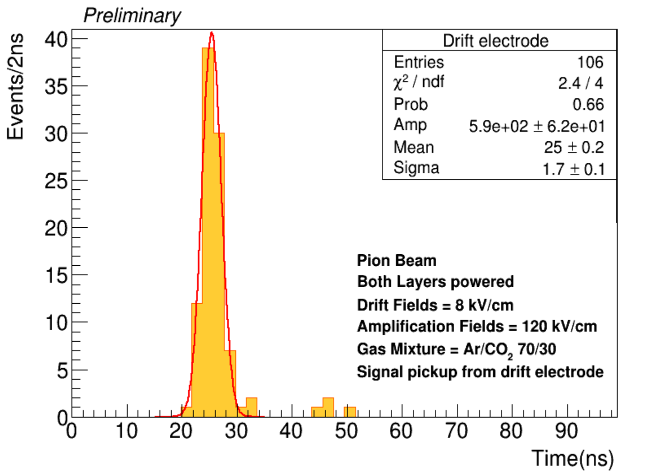
- Divide drift in multiple layers, each with Amplification
- Resistive electrodes => Electrode Transparency
- Closest primary electron => Fastest Signal
- Time Resolution $\sigma_t = 1/(\lambda \cdot v_{drift} \cdot N)$, where N = layers
- Observed: 2ns with 2 layer-detector [4] (→ OK)

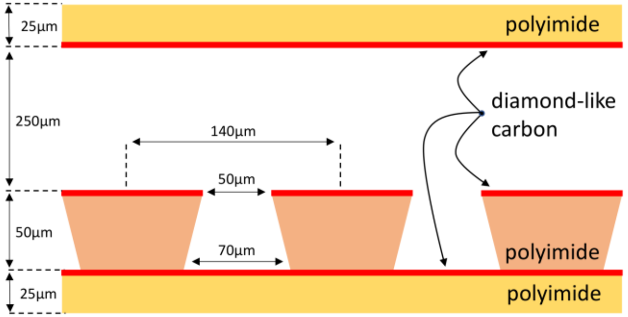
Fast Timing MPGD: Challenges

- Fully Resistive MPGD (no Copper, only DLC, resist. kapton)
- Detect single-electron (or single cluster) instead of many primary+secondary electrons created in drift gap
- **Requires High Gain Structures: G = 10^4 - 10^5**
- **Requires sensitive front-end** (< 1fC, few ns rise-time)

References:
[1] F.Sauli, Yellow Report, CERN-77-09 (1977)
[2] P.Verwilligen *et al.* J.Phys.Conf.Ser. 1498 (2020)
[3] M.Maggi *et al.* arXiv:1503.05330 (2015)
[4] I.Vai *et al.* NIM A 845 (2017) 313

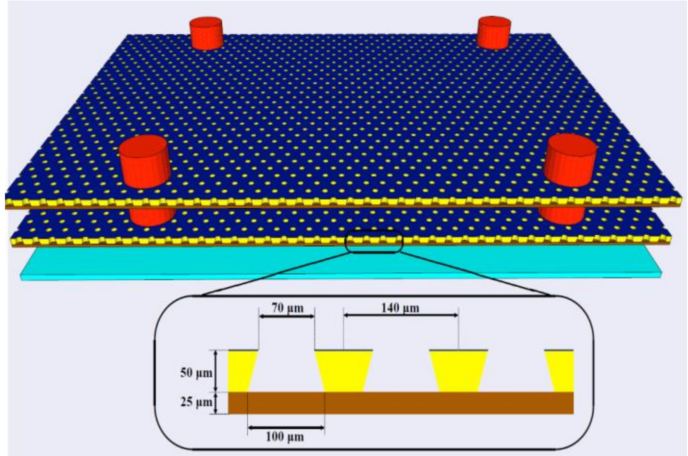
Test Beam Results (2 layers)





Design of single Layer:
Perforated GEM foil with DLC electrode

Fast Timing MPGD (FTM): Design



Single layer specifications:

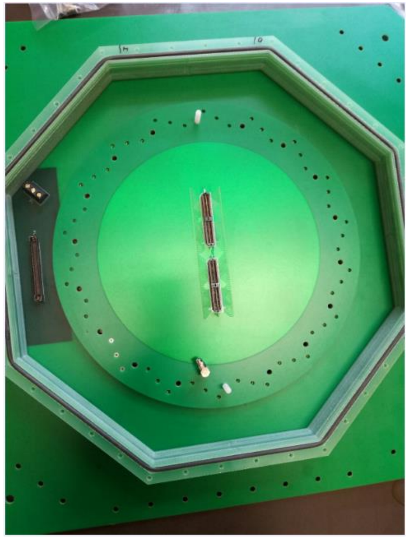
- Drift layer: 250µm drift layer *(Red: Dupont Coverlay spacers)*
- Gain layer: 50µm Kapton *(Yellow: GEM foil: 70µm hole, 140µm pitch)*
- Support Layer: 200µm *(Brown: Pre-Preg (glue) + FR4 PCB)*
- Resistive coating: 10–100 nm,~100 MΩ/☐ *(Blue: DLC)*

FTM requirements:

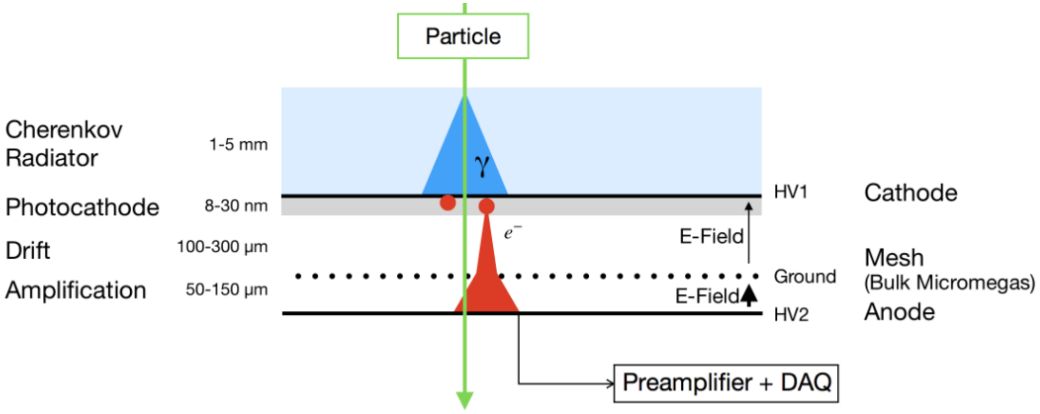
detection of single photo-e⁻(closest) instead of all e⁻ in drift (i.e. factor 10 reduction in charge)
detection with single amplification layer(Triple GEM has amplification divided in three stages)

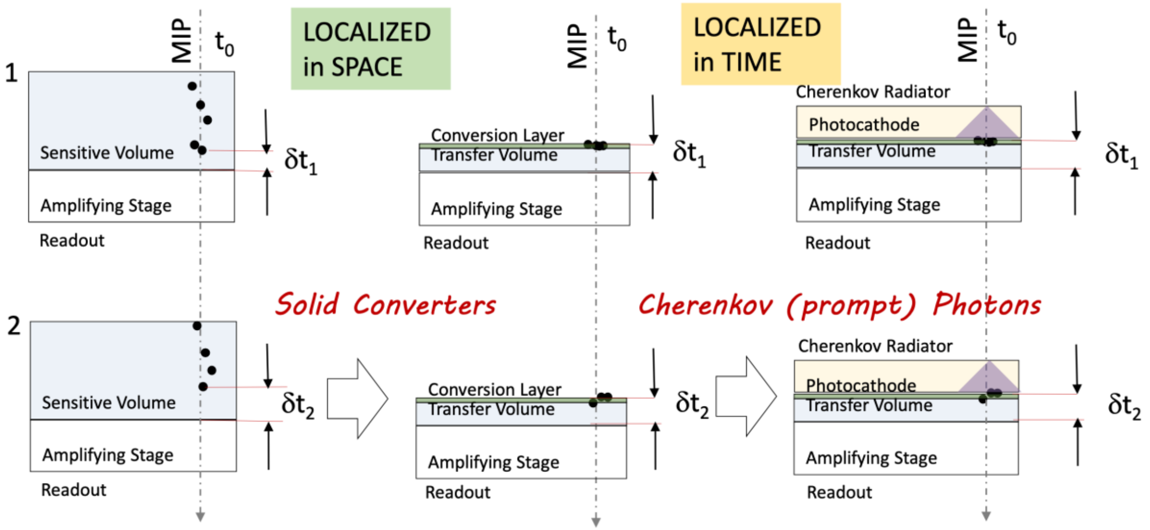
Therefore:

⇒need high gain structure, with low spark/discharge rate
⇒need low noise detector and low noise electronics
⇒need electronics that can process pulse with low charge ($10^4 e^- = 1.6$ fC)
⇒need electronics that can process and preserve a fast pulse



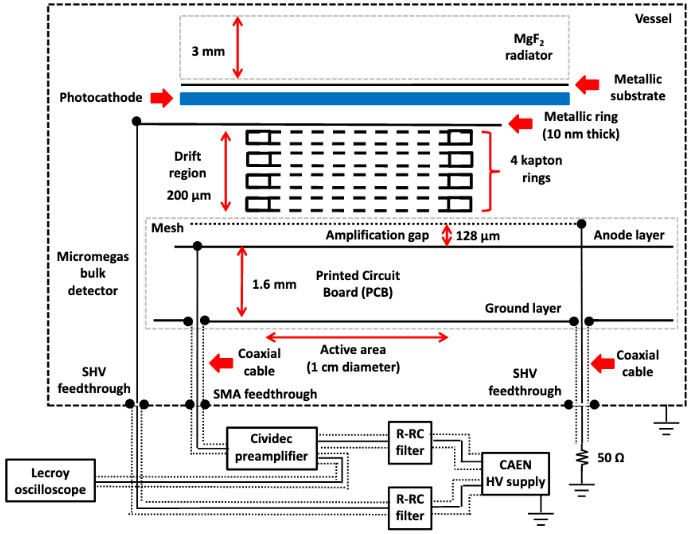
PICOSEC





Primary electrons at the same time in the same place

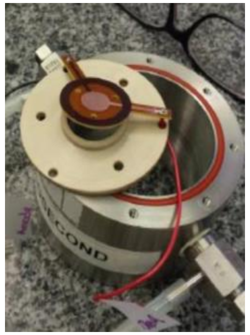
The PICOSEC detection concept
The passage of a charged particle through the Cherenkov radiator produces UV photons, which are then absorbed at the photocathode and partially converted into electrons. These electrons are subsequently preamplified and then amplified in the two high-field drift stages and induce a signal which is measured between the anode and the mesh.

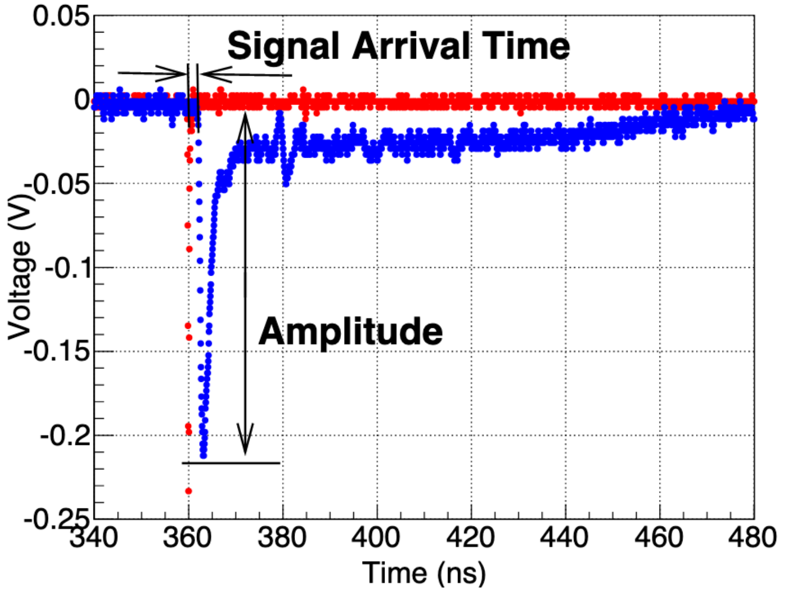


Sketch of the first prototype of the PICOSEC detector,

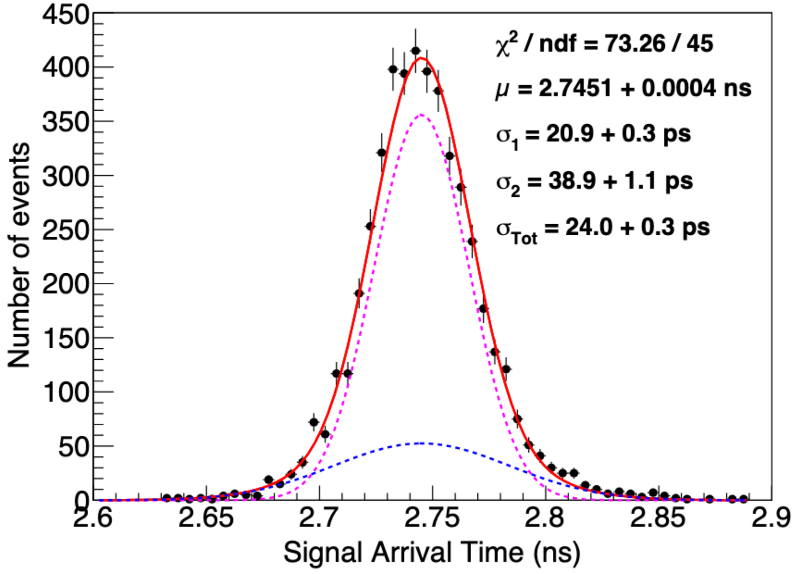
PICOSEC

https://arxiv.org/pdf/1712.05256.pdf

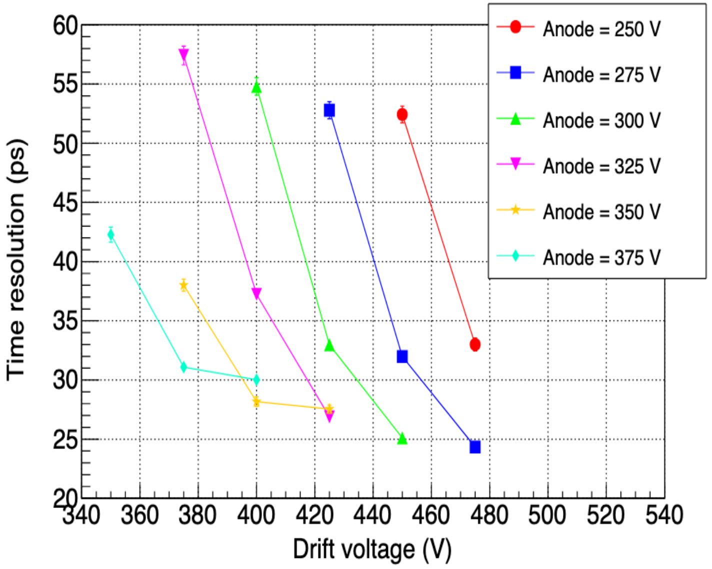




An example of an induced signal from the PICOSEC detector generated by 150 GeV muons (blue points), recorded together with the timing reference of the microchannel plate MCP signal (red points)



An example of the signal arrival time distribution for 150 GeV muons, and the superimposed fit with a two Gaussian function, for an anode and drift voltage of275 V and 475 V, respectively.



Dependence of the time resolution on the drift and anode voltage fora PICOSEC detector irradiated by 150 GeV muons.

R&D and Technological Transfer

Many R&D are ongoing, mostly within the R&D51 collaboration

- **Improving performances: rate, space resolution with limited number of channels, timing, high gain…**
- **Resistive layers/electrodes: stability, space resolution, simple/single stage…**
- **Material budget, minimized dead areas…**
- **Gas mixtures, New material, New manufacturing techniques for new structures and fast prototyping (etching, 3D,..)..**
- **Simplified structures with simplified production processes..**

The TT is a key point for future large production

- **TT Fundamental for Large Productions / Large Project (LP/LP)**
- **LP/LP (having responsibility for scientific aspects & related financial resources) have to identify resources and have cover the TT as well as the learning/training process**
- **Manpower from LP/LP is fundamental**

Summary

- **The MPGD is a brand-new family of gas detectors, many of them conceived and developed in the last 10 years.**
- **Some of them are quite mature technologies (LHC Phase2 is making large use of MPGD), others promising but still require not negligible R&D and developments,**
- **To highlight that the results achieved in the recent years are surprising and the rate of the speed with which new ideas/detectors are presented, implemented, tested is exceptional**
- **Critical point for the MPGD is the engineering and realization of large area detector (scaling up of surface may become very challenging for mechanical reasons/tolerances)**
- ***Personal comments***
  - ***Looking to the time scale of the Muon Collider project any technology (idea / detector model) selection looks to be premature, we cannot exclude that the correct technology will show up only in the incoming years; still enough time to develop/test/prove***
  - ***All R&D, on the base of the potential performance (not on the actual obtained results) should be sustained, technological development are so fast that good ideas have in front enough time to become good detectors***

Reference

- CERN EP Department - R&D on experimental technologies 1st WG2 Meeting https://indico.cern.ch/event/702148
- CERN EP Department - R&D on experimental technologies https://indico.cern.ch/event/696066/contributions/2927894/attachments/1618327/2573211/RDonGaseousDetectorTechnologies.pdf
- ECFA Detector R&D Roadmap Symposium of Task Force 1 Gaseous Detectors https://indico.cern.ch/event/999799/
- Mini-Workshop on gas transport parameters for present and future generation of experiments https://indico.cern.ch/event/1022051/timetable/?view=standard
- https://indico.desy.de/event/22513/contributions/46788/attachments/30337/38104/20200224-EDIT-GaseousDetectors.pdf
- https://detectors.fnal.gov/wp-content/uploads/2018/02/FNAL_dallatorre_13feb2018.pdf

Probably the most exhaustive list I know…

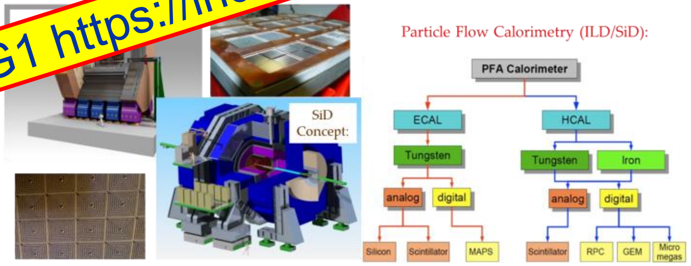
From Eraldo Oliveri ECFA Meeting WG1 https://indico.cern.ch/event/999799/

LHC

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ATLAS Muon System Upgrade: Start: 2019 (for 15 y.)	High Energy Physics (Tracking/Triggering)	Micromegas	Total area: 1200 m² Single unit detect: (2.2x1.4m²) – 2-3 m²	**Max. rate**: 15 kHz/cm² **Spatial res.**: <100μm **Time res.**: ~ 10 ns **Rad. Hard.**: ~ 0.5C/cm²	- Redundant tracking and triggering; Challenging constr. in mechanical precision:
ATLAS Muon Tagger Upgrade: Start: > 2023	High Energy Physics (Tracking/triggering)	μ-PIC	Total area: ~ 2m²	**Max.rate**: 100kHz/cm² **Spatial res.**: < 100μm	
CMS Muon System Upgrade: Start: > 2020	High Energy Physics (Tracking/Triggering)	GEM	Total area: ~ 143 m² Single unit detect: 0.3-0.4m²	**Max. rate**: 10 kHz/cm² **Spatial res.**: ~100μm **Time res.**: ~ 5-7 ns **Rad. Hard.**: ~ 0.5 C/cm²	- Redundant tracking and triggering
CMS Calorimetry (BE) Upgrade Start > 2023	High energy Physics (Calorimetry)	Micromegas, GEM	Total area: ~ 100 m² Single unit detect: 0.5m²	**Max. rate**: 100 MHz/cm² **Spatial res.**: ~ mm	Not main option; could be used with HGCAL (BE part)
ALICE Time Projection Chamber: Start: > 2020	Heavy-Ion Physics (Tracking + dE/dx)	GEM w/ TPC	Total area: ~ 32 m² Single unit detect: up to 0.3m²	**Max.rate**: 100 kHz/cm² **Spatial res.**: ~300μm **Time res.**: ~ 100 ns **dE/dx**: 12 % (Fe55) **Rad. Hard.**:	- 50 kHz Pb-Pb rate; - Continues TPC readout
TOTEM: Run: 2009-now	High Energy/ Forward Physics (5.3≤ |eta| ≤ 6.5)	GEM (semicircular shape)	Total area: ~ 4 m² Single	mC/cm²	collisions.
LHCb Muon System Run: 2010 - now	High Energy / B-flavor physics (muon		detect: 20-24 cm²	**Max.rate**: 500 kHz/cm² **Spatial res.**: ~ cm **Time res.**: ~ 3 ns **Rad. Hard.**: ~ C/cm²	- Redundant triggering
FCC	y/Muon)	THGEM Micromegas, μ-PIC, InGrid	Total area: 10.000 m² (for MPGDs around 1.000 m²)	**Max.rate**: 100 kHz/cm² **Spatial res.**: <100μm **Time res.**: ~ 1 ns	Maintenance free for decades

MPGD Technologies for the International Linear Collider

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ILC Time Projection Chamber for ILD: Start: > 2030	High Energy Physics (tracking)	Micromegas GEM (pads) InGrid (pixels)	Total area: ~ 20 m² Single unit detect: ~ 400 cm² (pads) ~ 130	**Max. rate**: < 1 kHz **Spatial**	Power-pulsing
ILC Hadronic (DHCAL) Calorimetry for ILD/SiD Start > 2030	High Energy Physics (calorimetry)		detect: 1 m²	**Max. rate**: 1 kHz/cm² **Spatial res.**: ~ 1cm **Time res.**: ~ 300 ns **Rad. Hard.**: no	Jet Energy resolution: 3-4 % Power-pulsing, self-triggering readout



MPGD Tracking Concepts for Hadron / Nuclear Physics

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS @ CERN Run: 2002 - now	Hadron Physics (Tracking)	GEM Micromegas w/ GEM preampl.	Total area: 2.6 m² Single unit detect: 0.31x0.31 m² Total area: ~ 2 m² Single unit detect: 0.4x0.4 m²	**Max.rate**: 10^7 Hz (~100kHz/mm²) **Spatial res.**: ~70-100 μm (strip), ~120μm (pixel) **Time res.**: ~ 8 ns **Rad. Hard.**: 2500 mC/cm²	Required beam tracking (pixelized central / beam area)
KEDR @ BINP Run: 2010-now	Particle Physics (Tracking)	GEM	Toral area: ~0.1 m²	**Max. rate**: 1 MHz/mm² **Spatial res.**: ~70μm	
SBS in Hall A @ JLAB Start: > 2017	Nuclear Physics (Tracking) nucleon form factors / struct.	GEM	Total area: 14 m² Single unit detect. 0.6x0.5m²	**Max. rate**: 400 kHz/cm² **Spatial res.**: ~70μm **Time res.**: ~ 15 ns **Rad. Hard.**: 0.1-1 kGy/y.	
pRad in Hall B @ JLAB Start: 2017	Nuclear Physics (Tracking) precision meas. of proton radius	GEM	Total area: 1.5m² Single unit detect. 1.2x0.6 m2	**Max. rate**: 5 kHz/cm² **Spatial res.**: ~70μm **Time res.**: ~ 15 ns **Rad. Hard.**: 10 kGy/y.	
SoLID in Hall A@ JLAB Start: ~ > 2020	Nuclear Physics (Tracking)	GEM	Total area: 40m² Single unit detect. 1.2x0.6 m2	**Max. rate**: 600 kHz/cm² **Spatial res.**: ~100μm **Time res.**: ~ 15 ns **Rad. Hard.**: 0.8-1 kGy/y.	
E42 and E45 @JPARC Start: ~2020	Hadron Physics (Tracking)	TPC w/ GEM, gating grid	Total area: 0.26m² 0.52m(diameter) x0.5m(drift length)	**Max. rate**: 10⁶ kHz/cm² **Spatial res.**: 0.2-0.4 mm	Gating grid operation ~ 1kHz
ACTAR TPC Start: ~2020 for 10 y.	Nuclear physics Nuclear structure Reaction processes	TPC w/ Micromegas (amp. gap -220 μm)	2 detectors: 25*25 cm2 and 12.5*50cm2	Counting rate < 10^4 nuclei but higher if some beam masks are used.	Work with various gas (He mixture, iC4H10, D2…)

Cylindrical MPGDs as Inner Trackers for Particle / Nuclear Physics

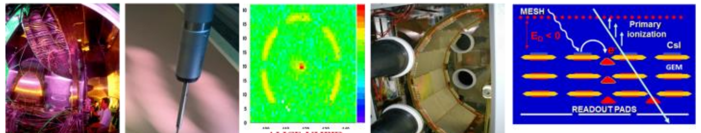
Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
KLOE-2 @ DAFNE Run: 2014-2017	Particle Physics/ K-flavor physics (Tracking)	Cylindrical GEM	Total area: 3.5m² 4 cylindrical layers L(length) = 700mm R (radius) = 130, 155, 180, 205 mm	**Spatial res**:(r phi) ~ 250um **Spat. res.(z)** ~ 350um	- Mat. budget 2% X0 - Operation in 0.5 T
BESIII Upgrade @ Beijing Run: 2018-2022	Partcile Physics/ e+e- collider (Tracking)	Cylindrical GEM	3 cylindrical layers R ~ 20 cm	**Max. rate**: 10 kHz/cm² **Spatial res**:(xy) ~ 130um **Spat. res.(z)** ~ 1 mm	- Material ≤ 1.5% of X_0 for all layers - Operation in 1T
CLAS12 @ JLAB Start: > 2017	Nuclear Physics/ Nucleon structure (tracking)	Planar (forward) & Cylindrical (barrel) Micromegas	Total area: Forward ~ 0.6 m² Barrel ~ 3.7 m² 2 cylindrical layers R ~ 20 cm	**Max. rate**: ~ 30 MHz **Spatial res.**: < 200μm **Time res.**: ~ 20 ns	- Low material budget : 0.4 % X0 - Remote electronics
ASACUSA @ CERN Run: 2014 - now	Nuclear Physics (Tracking and vertexing of pions resulting from the p-antip annihilation	Cylindrical Micromegas 2D	2 cylindrical layers L = 60 cm R = 85, 95 mm	**Max. trigger rate**: kHz **Spatial res.**: ~200μm **Time res.**: ~ 10 ns **Rad. Hard.**: 1 C/cm²	- Large magnetic field that varies from -3 to 4T in the active area
MINOS Run: 2014-2016	Nuclear structure	TPC w/ cylindrical Micromegas	1 cylindrical layer L=30 cm, R = 10cm	**Spatial res.**: <5 mm FWHM Trigger rate up to ~1 KHz	- Low material budget
CMD-3 Upgrade @ BINP Start: > ~2019 ?	Particle physics (z-chamber, tracking)	Cylindrical GEM	Total arear: ~ 3m² 2 cylindrical layers	**Spatial res.**: ~100μm	

MPGD Tracking for Heavy Ion / Nuclear Physics

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
STAR Forward GEM Tracker @ RHIC Run: 2012-present	Heavy Ion Physics (tracking)	GEM	Total area: ~ 3 m² Single unit detect: ~ 0.4 x 0.4 m²	**Spatial res.**: 60-100 μm	Low material budget:: < 1% X0 per tracking layer
Nuclotron BM@N @ NICA/JINR Start: > 2017	Heavy Ions Physics (tracking)	GEM	Total area: ~ 12 m² Single unit detect: ~ 0.9 m²	**Max. rate**: ~ 300 MHz **Spatial res.**: ~ 200μm	Magnetic field 0.5T orthogonal to electric field
SuperFRS @ FAIR Run: 2018-2022	Heavy Ion Physics (tracking/diagnostics at the In-Fly Super Fragment Separator)	TPC w/ GEMs	Total area:~ few m² Single unit detect: Type I : 50 x 9 cm² Type II: 50 x 16 cm²	**Max. rate**:~ 10^7 Hz/spill **Spatial res.**: < 1 mm	High dynamic range Particle detection from p to Uranium
PANDA @FAIR Start > 2020	Nuclear physics p - anti-p (tracking)	Micromegas/ GEMs	Total area: ~ 50 m² Single unit detect: ~ 1.5 m²	**Max. rate**: < 140kHz/cm² **Spatial res.**: ~ 150μm	Continuous-wave operation: 10^{11} interaction/s
CBM @ FAIR: Start: > 2020	Nuclear Physics (Muon System)	GEM	Total area: 9m² Single unit detect: 0.8x0.5m²–0.4m²	**Spatial res.**: < 1 mm **Max. rate**: 0.4 MHz/cm² **Time res.**: ~ 15ns **Rad hard.**: 10^{13} n.eq./cm²/year	Self-triggered electronics
Electron-Ion Collider (EIC) Start: > 2025	Hadron Physics (tracking, RICH)	TPC w/GEM readout Large area GEM planar tracking detectors	Total area: ~ 3 m² Total area: ~ 25 m²	**Spatial res.**: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} **Spatial res.**: ~ 50- 100 um **Max. rate**: ~ MHz/cm²	Low material budget Low material budget

MPGD Technologies for Photon Detection

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS RICH UPGRADE Start > 2016	Hadron Physics (RICH - detection of single VUV photons)	Hybrid (THGEM + CsI and MM)	Total area: ~ 1.4 m² Single unit detect: ~ 0.6 x 0.6 m²	**Max.rate**: 100 Hz/cm² **Spatial res.**: <~ 2.5 mm **Time res.**: ~ 10 ns	Production of large area THGEM of sufficient quality
PHENIX HBD Run: 2009-2010	Nuclear Physics (RICH – e/h separation)	GEM+CsI detectors	Total area: ~ 1.2 m² Single unit detect: ~ 0.3 x 0.3 m²	**Max. rate**: low **Spatial res.**: ~ 5 mm (rϕ) **Single el. eff.**: ~ 90 %	Single el. eff. depends from hadron rejection factor
SPHENIX Run: 2021-2023	Heavy Ions Physics (tracking)	TPC w/GEM readout	Total area: ~ 3 m²	**Multiplicity**: dNch/dy ~ 600 **Spatial res.**: ~ 100 um (rϕ)	Runs with Heavy Ions and comparison to pp operation
Electron-Ion Collider (EIC) Start: > 2025	Hadron Physics (tracking, RICH)	TPC w/GEM readout + Cherenkov RICH with GEM readout	Total area: ~ 3 m² Total area: ~ 10 m²	**Spatial res.**: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} **Spatial res.**: ~ few mm	Low material budget High single electron efficiency



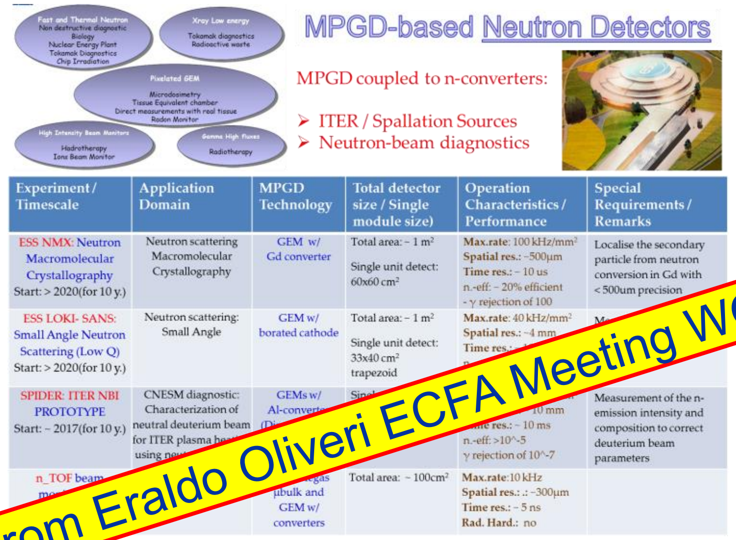
ALICE VHPID THGEM

HBD Concept:

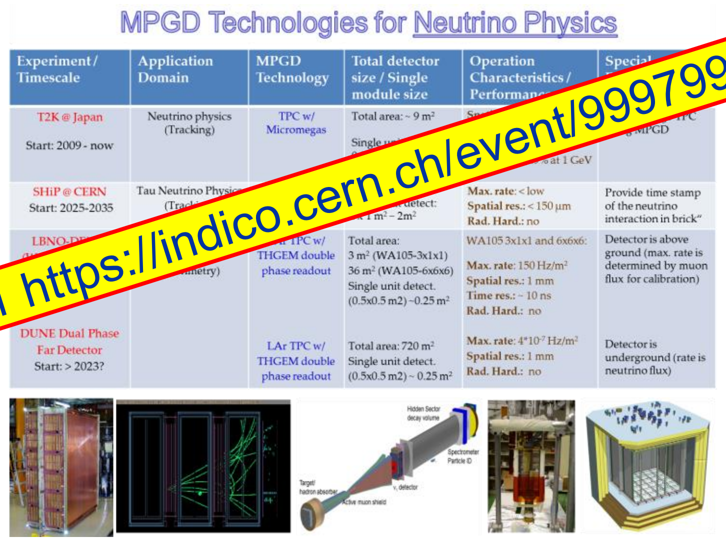
Maksym Titov, Conference Summary, 5th International Conference on Micro-Pattern Gas Detectors (MPGD2017), Temple University, Philadelphia,

Probably the most exhaustive list I know…

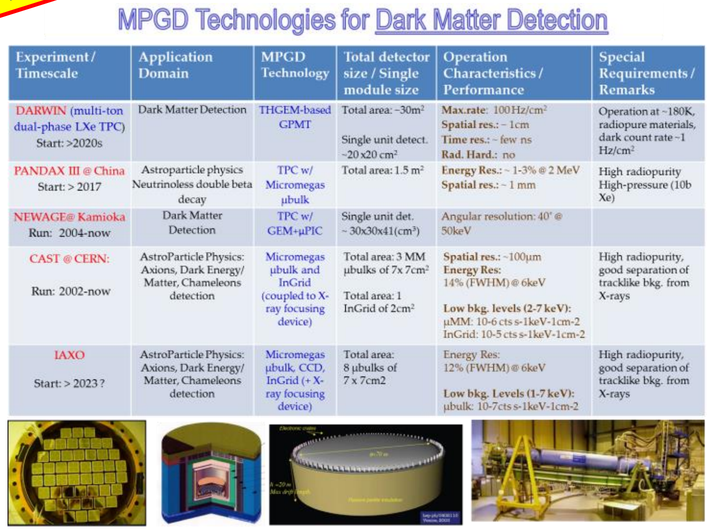
From Eraldo Oliveri ECFA Meeting WG1 https://indico.cern.ch/event/999799/



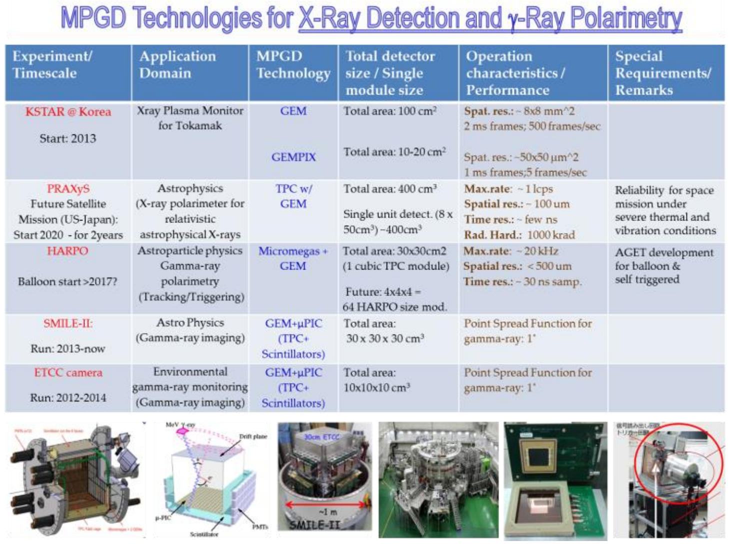
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size)	Operation Characteristics / Performance	Special Requirements / Remarks
ESS NMX: Neutron Macromolecular Crystallography Start: > 2020(for 10 y.)	Neutron scattering Macromolecular Crystallography	GEM w/ Gd converter	Total area: ~ 1 m² Single unit detect: 60x60 cm²	Max.rate: 100 kHz/mm² Spatial res.: ~500μm Time res.: ~ 10 us n.-eff: ~ 20% efficient - γ rejection of 100	Localise the secondary particle from neutron conversion in Gd with < 500um precision
ESS LOKI- SANS: Small Angle Neutron Scattering (Low Q) Start: > 2020(for 10 y.)	Neutron scattering: Small Angle	GEM w/ borated cathode	Total area: ~ 1 m² Single unit detect: 33x40 cm² trapezoid	Max.rate: 40 kHz/mm² Spatial res.: ~4 mm Time res…	…
SPIDER: ITER NBI PROTOTYPE Start: ~ 2017(for 10 y.)	CNESM diagnostic: Characterization of neutral deuterium beam for ITER plasma hea… using ne…	GEMs w/ Al-converte…	…	… 10 mm …me res.: ~ 10 ms n.-eff: >10^-5 γ rejection of 10^-7	Measurement of the n-emission intensity and composition to correct deuterium beam parameters
n_TOF beam mo…	…	…egas μbulk and GEM w/ converters	Total area: ~ 100cm²	Max.rate:10 kHz Spatial res.: .: ~300μm Time res.: ~ 5 ns Rad. Hard.: no	



Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special …
T2K @ Japan Start: 2009 - now	Neutrino physics (Tracking)	TPC w/ Micromegas	Total area: ~ 9 m² Single u…	Sp… … at 1 GeV	…TPC …g MPGD
SHiP @ CERN Start: 2025-2035	Tau Neutrino Physic… (Track…)	…	…detect: …1 m² – 2m²	Max. rate: < low Spatial res.: < 150 μm Rad. Hard.: no	Provide time stamp of the neutrino interaction in brick"
LBNO-DE…	…metry)	…TPC w/ THGEM double phase readout	Total area: 3 m² (WA105-3x1x1) 36 m² (WA105-6x6x6) Single unit detect. (0.5x0.5 m2) ~0.25 m²	WA105 3x1x1 and 6x6x6: Max. rate: 150 Hz/m² Spatial res.: 1 mm Time res.: ~ 10 ns Rad. Hard.: no	Detector is above ground (max. rate is determined by muon flux for calibration)
DUNE Dual Phase Far Detector Start: > 2023?		LAr TPC w/ THGEM double phase readout	Total area: 720 m² Single unit detect. (0.5x0.5 m2) ~ 0.25 m²	Max. rate: 4*10^-7 Hz/m² Spatial res.: 1 mm Rad. Hard.: no	Detector is underground (rate is neutrino flux)



Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
DARWIN (multi-ton dual-phase LXe TPC) Start: >2020s	Dark Matter Detection	THGEM-based GPMT	Total area: ~30m² Single unit detect. ~20x20 cm²	Max.rate: 100 Hz/cm² Spatial res.: ~ 1cm Time res.: ~ few ns Rad. Hard.: no	Operation at ~180K, radiopure materials, dark count rate ~1 Hz/cm²
PANDAX III @ China Start: > 2017	Astroparticle physics Neutrinoless double beta decay	TPC w/ Micromegas μbulk	Total area: 1.5 m²	Energy Res.: ~ 1-3% @ 2 MeV Spatial res.: ~ 1 mm	High radiopurity High-pressure (10b Xe)
NEWAGE@ Kamioka Run: 2004-now	Dark Matter Detection	TPC w/ GEM+μPIC	Single unit det. ~ 30x30x41(cm³)	Angular resolution: 40° @ 50keV	
CAST @ CERN: Run: 2002-now	AstroParticle Physics: Axions, Dark Energy/ Matter, Chameleons detection	Micromegas μbulk and InGrid (coupled to X-ray focusing device)	Total area: 3 MM μbulks of 7x 7cm² Total area: 1 InGrid of 2cm²	Spatial res.: ~100μm Energy Res: 14% (FWHM) @ 6keV Low bkg. levels (2-7 keV): μMM: 10-6 cts s-1keV-1cm-2 InGrid: 10-5 cts s-1keV-1cm-2	High radiopurity, good separation of tracklike bkg. from X-rays
IAXO Start: > 2023 ?	AstroParticle Physics: Axions, Dark Energy/ Matter, Chameleons detection	Micromegas μbulk, CCD, InGrid (+ X-ray focusing device)	Total area: 8 μbulks of 7 x 7cm2	Energy Res: 12% (FWHM) @ 6keV Low bkg. Levels (1-7 keV): μbulk: 10-7cts s-1keV-1cm-2	High radiopurity, good separation of tracklike bkg. from X-rays



Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation characteristics / Performance	Special Requirements/ Remarks
KSTAR @ Korea Start: 2013	Xray Plasma Monitor for Tokamak	GEM GEMPIX	Total area: 100 cm² Total area: 10-20 cm²	Spat. res.: ~ 8x8 mm^2 2 ms frames; 500 frames/sec Spat. res.: ~50x50 μm^2 1 ms frames;5 frames/sec	
PRAXyS Future Satellite Mission (US-Japan): Start 2020 - for 2years	Astrophysics (X-ray polarimeter for relativistic astrophysical X-rays	TPC w/ GEM	Total area: 400 cm³ Single unit detect. (8 x 50cm³) ~400cm³	Max.rate: ~ 1 lcps Spatial res.: ~ 100 um Time res.: ~ few ns Rad. Hard.: 1000 krad	Reliability for space mission under severe thermal and vibration conditions
HARPO Balloon start >2017?	Astroparticle physics Gamma-ray polarimetry (Tracking/Triggering)	Micromegas + GEM	Total area: 30x30cm2 (1 cubic TPC module) Future: 4x4x4 = 64 HARPO size mod.	Max.rate: ~ 20 kHz Spatial res.: < 500 um Time res.: ~ 30 ns samp.	AGET development for balloon & self triggered
SMILE-II: Run: 2013-now	Astro Physics (Gamma-ray imaging)	GEM+μPIC (TPC+ Scintillators)	Total area: 30 x 30 x 30 cm³	Point Spread Function for gamma-ray: 1°	
ETCC camera Run: 2012-2014	Environmental gamma-ray monitoring (Gamma-ray imaging)	GEM+μPIC (TPC+ Scintillators)	Total area: 10x10x10 cm³	Point Spread Function for gamma-ray: 1°	

Maksym Titov, Conference Summary, 5th International Conference on Micro-Pattern Gas Detectors (MPGD2017), Temple University, Philadelphia

https://indico.cern.ch/event/581417/contributions/2558346/attachments/1465881/2266161/2017_05_Philadelphia_MPGD2017-ConferenceSummary_25052017_MS.pdf

Impressive compilation.
Thanks Maxim….
Some update needed (table ref. to 2017)
Please check if you are not there and send us the missing info

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