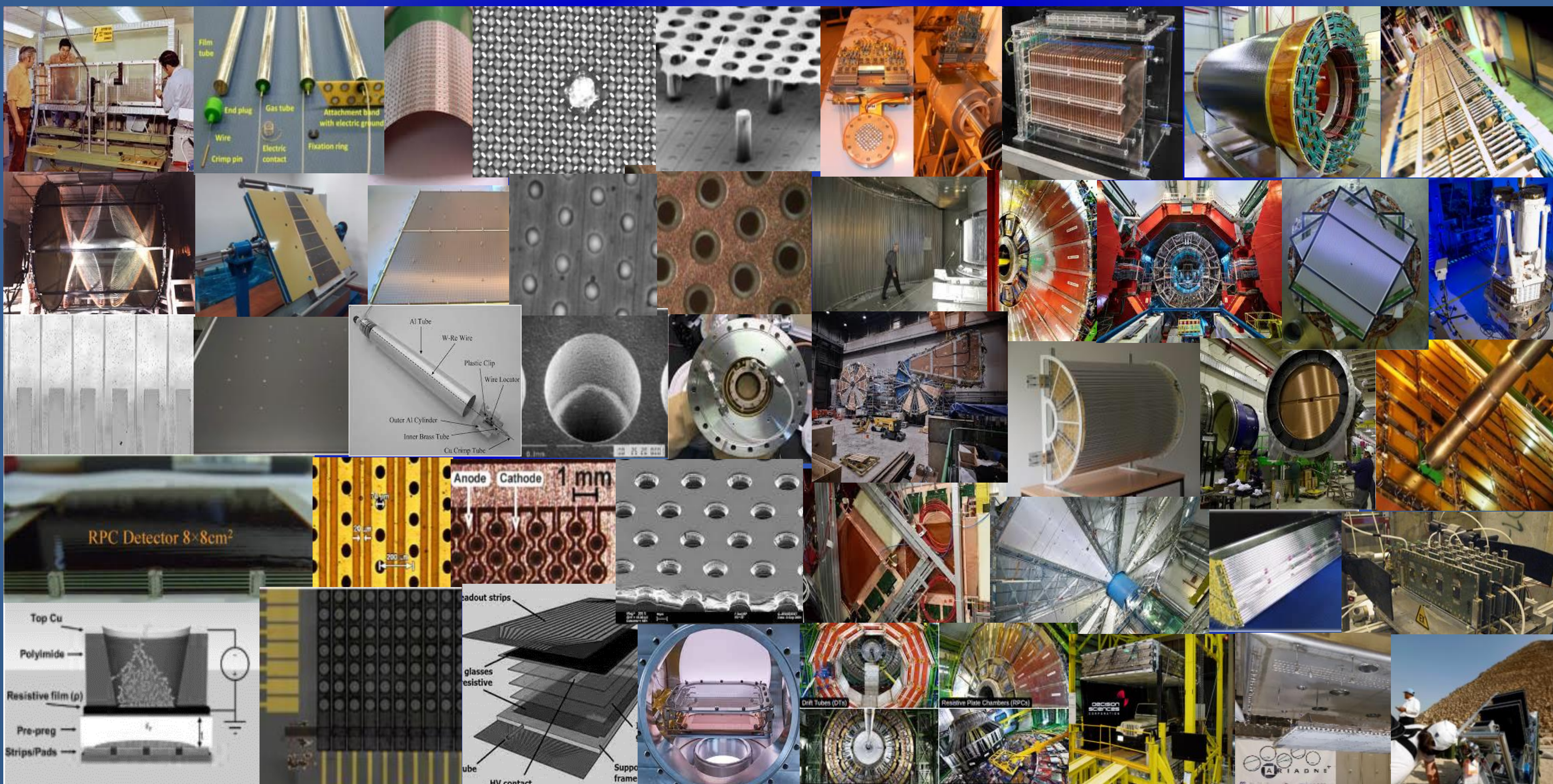
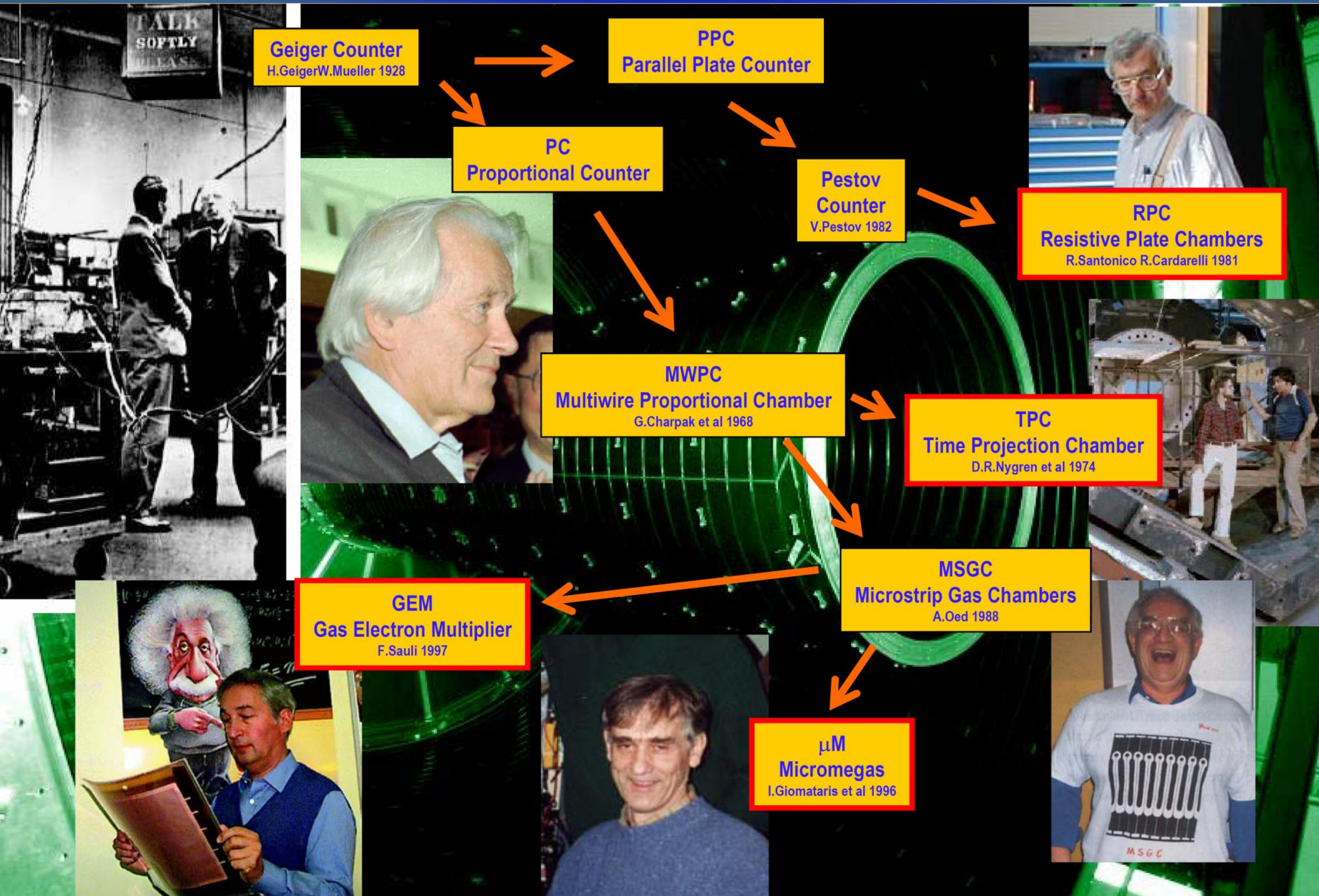
Gaseous Detector Technologies for Future Collider Experiments

Maxim Titov, CEA Saclay, Irfu, France

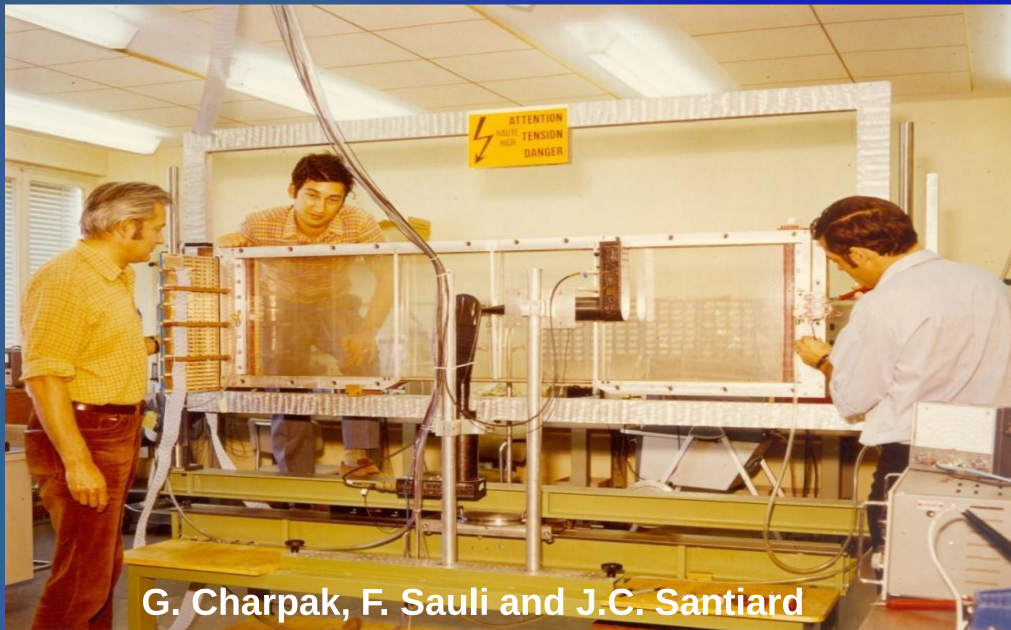


2nd Corfu Workshop on Future Accelerators (Corfu2024), Corfu, Greece, May 19-26, 2024

Gas-Based Detectors: A Brief History



1968: MWPC – Revolutionising the Way Particle Physics is Done

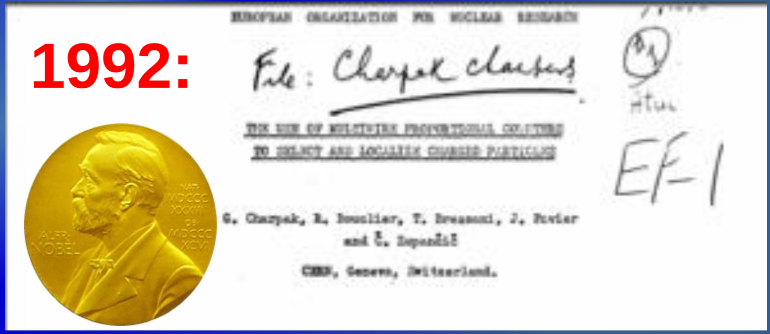


G. Charpak, F. Sauli and J.C. Santiard

Before MWPC: Detecting particles was a mainly a manual, tedious and labour intensive job – unsuited for rare particle decays

1968: George Charpak developed the MultiWire Proportional Chamber, (MWPC), which revolutionized particle detection & HEP, ***and marked transition from Manual to Electronics era***

1992:


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File: Charpak chambers

EF-1

THE USE OF MULTIWIRE PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

G. Charpak, R. Bouclier, T. Bressani, J. Favier and Č. Zupančič

CERN, Geneva, Switzerland.

"Image" & "Logic (electronics)" tradition combined into the "Electronics Image" detectors during the 1970ies

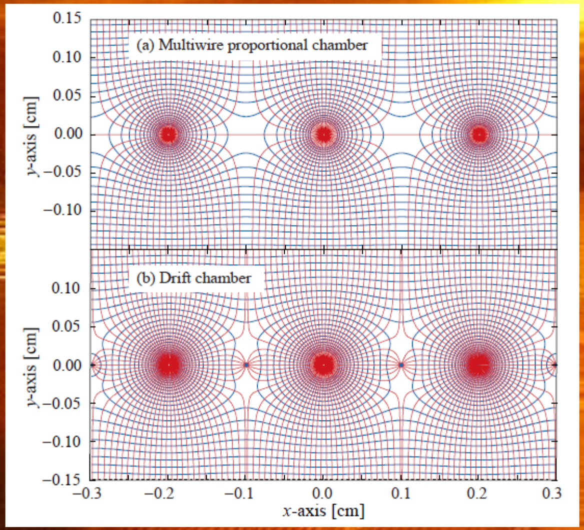
1983/1984: Discovery of W and Z Bosons at UA1/UA2

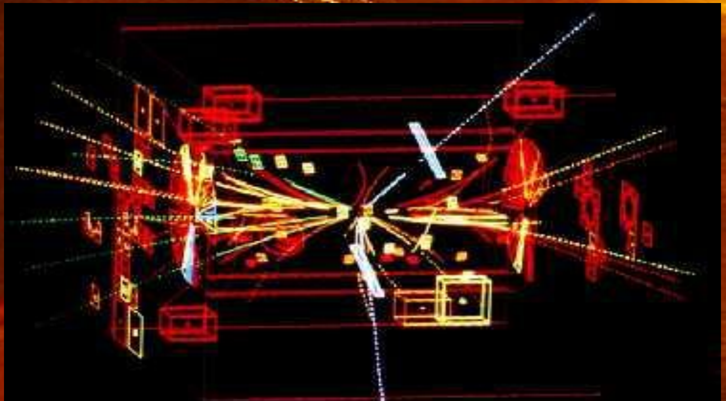
UA1 used the largest wire / drift chamber of its day (5.8 m long, 2.3 m in diameter)

It can be seen in the CERN Microcosm Exhibition

Discovery of W and Z bosons
C. Rubbia & S. Van der Meer,

1984:



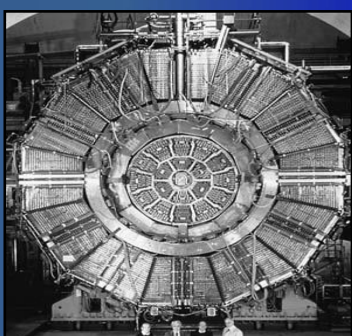


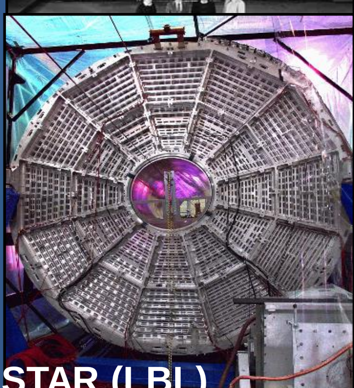
$Z \rightarrow ee$ (white tracks) at UA1/CERN

Time Projection Chamber (TPC) in Particle and Ion Physics

PEP4 (SLAC)

ALEPH (CERN)

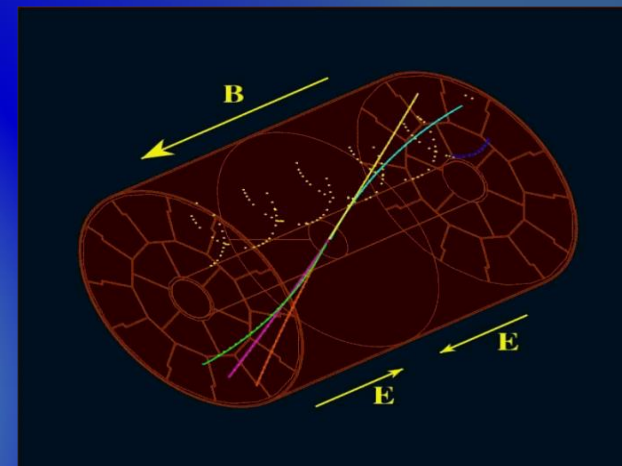




STAR (LBL)

- ✓ **Invented by David Nygren (Berkeley) in 1974**
- ✓ **Proposed as a central tracking device for the PEP-4 detector @ SLAC in 1976**
- ✓ **More (and even larger) were built, based on MWPC readout, serving as a powerful tool for:**
  - **Lepton Colliders (LEP, Higgs Factories)**
  - **Modern heavy ion collisions (RHIC, EIC)**
  - **Liquid and high pressure TPCs for neutrino and dark matter searches**

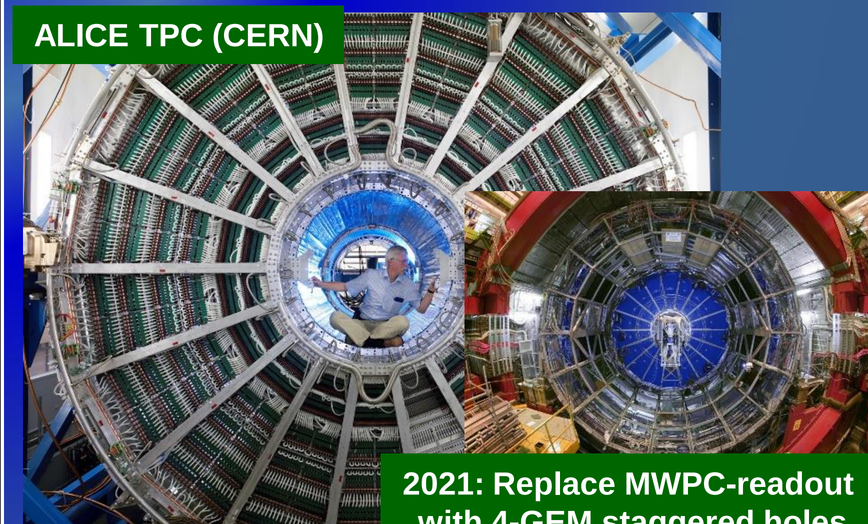
An ultimate drift chamber design is TPC concept - 3D precision tracking with low material budget & PID through differential energy loss dE/dx measurement and/or cluster counting dN_{cl}/dx tech.



	STAR	ALICE	ILC
Inner radius (cm)	50	85	32
Outer radius (cm)	200	250	170
Length (cm)	2 * 210	2 * 250	2 * 250
Charge collection	wire	wire	MPGD
Pad size (mm)	2.8 * 11.5 6.2 * 19.5	4 * 7.5 6*10(15)	2 * 6
Total # pads	140000	560000	1200000
Magnetic field [T]	0.5	0.5	4
Gas Mixture	Ar/CH4 (90:10)	Ne/CO2 (90:10)	Ar/CH4/CO2 (93:5:2)
Drift Field [V/cm]	135	400	230
Total drift time (μs)	38	88	50
Diffusion σ_T ($\mu m/\sqrt{cm}$)	230	220	70
Diffusion σ_L ($\mu m/\sqrt{cm}$)	360	220	300
Resolution in $r\varphi$ (μm)	500-2000	300-2000	70-150
Resolution in rz (μm)	1000-3000	600-2000	500-800
dE/dx resolution [%]	7	7	< 5
Tracking efficiency[%]	80	95	98

New generation of TPCs use MPGD-based readout: e.g. ALICE Upgrade, T2K, ILC, CepC

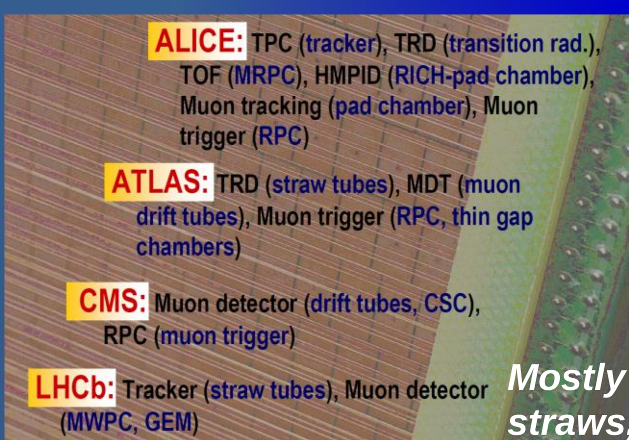
ALICE TPC (CERN)

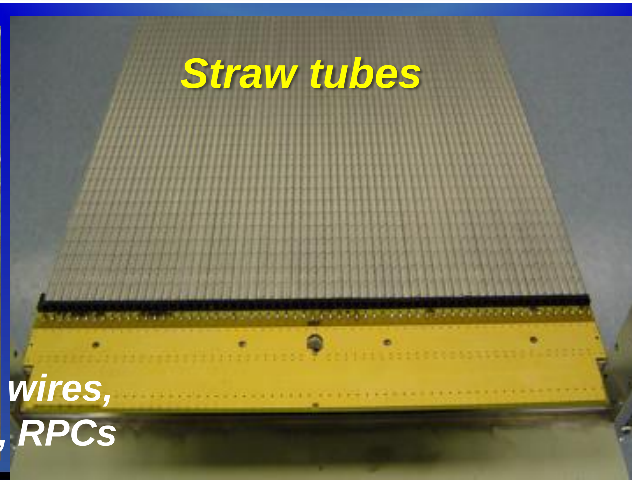


2021: Replace MWPC-readout with 4-GEM staggered holes

2008: Original Gaseous Detectors in LHC Experiments

	Vertex	*Inner Tracker*	*PID/ photo-detector*	*EM CALO*	*HAD CALO*	*MUON Track*	*MUON Trigger*
ATLAS	-	*TRD (straws)*	-	-	-	*MDT (drift tubes), CSC*	*RPC, TGC (thin gap chambers)*
CMS *-----* ***TOTEM***	-	*-* *--------* *GEM*	-	-	-	*Drift tubes, CSC*	*RPC, CSC*
LHCb	-	*Straw Tubes*	-	-	-	*MWPC*	*MWPC, GEM*
ALICE	-	*TPC (MWPC)*	*TOF (MRPC), HPMID (RICH-pad chamber), TRD (MWPC)*	-	-	*Muon pad chambers*	*RPC*





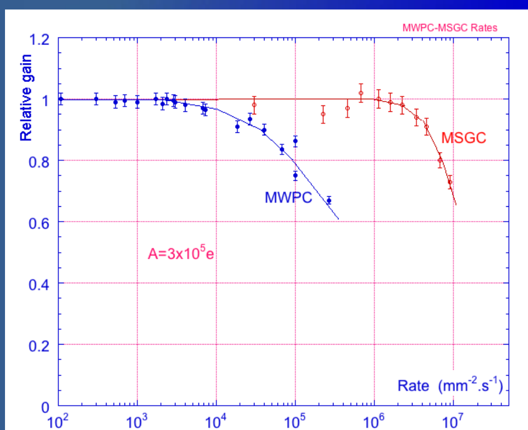
Mostly wires, straws, RPCs

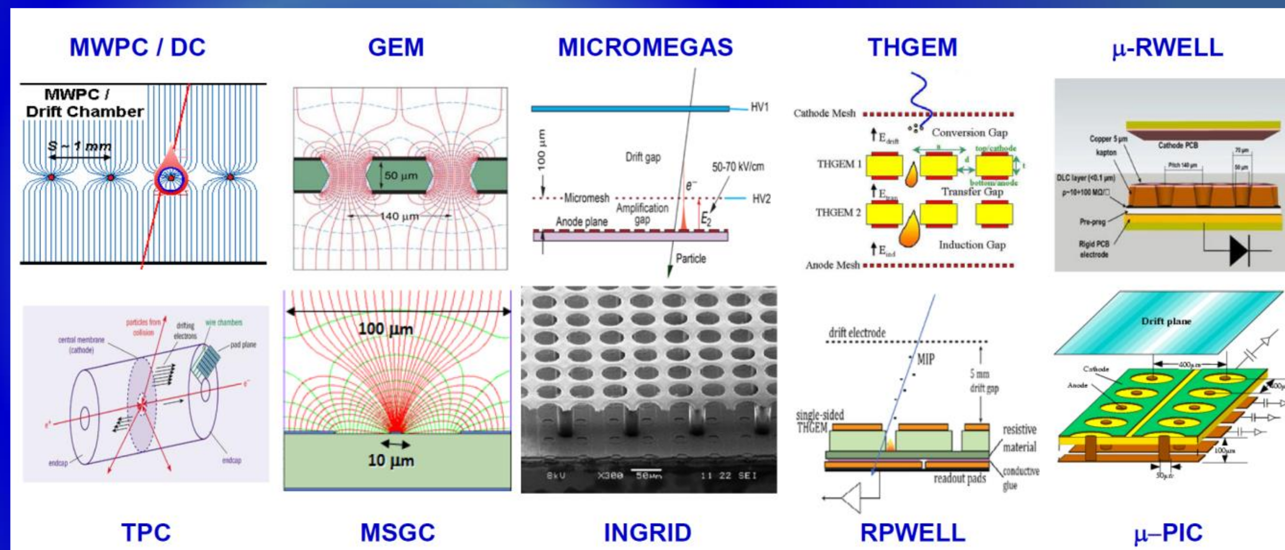
Gaseous Detectors: From Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

Primary choice for large-area coverage with low material-budget (+ dE/dx measurement)

1990's: Industrial advances in photolithography has favoured the invention of novel micro-structured gas amplification devices (MSGC, GEM, Micromegas, …)

Rate Capability:
MWPC vs MSGC





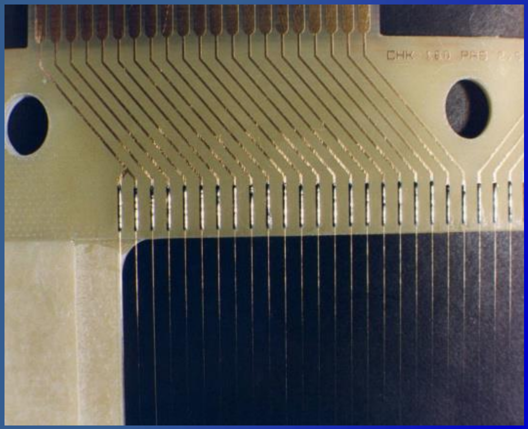
Examples of Gaseous Detectors for Future Colliders:

HL-LHC Upgrades: Tracking (ALICE TPC/MPGD); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;
Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, rates are comparable with HL-LHC)
Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (OK)

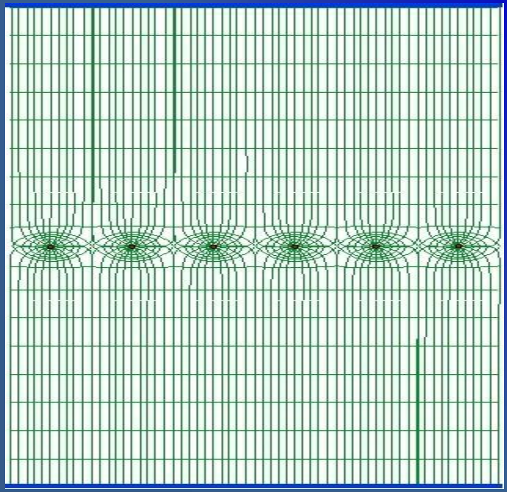
Future Election-Ion Collider: Tracking (GEM, μWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)

Micro-Strip Gas Chamber (MSGC): An Early MPGD

Multi-Wire Proportional Chamber (MWPC)

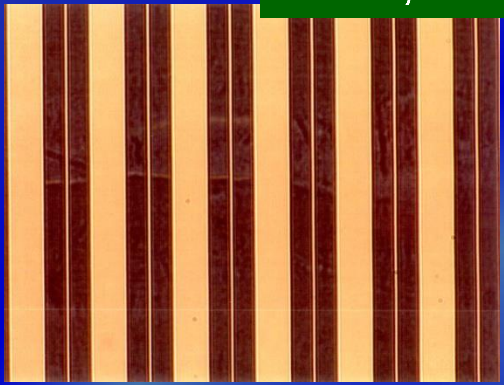


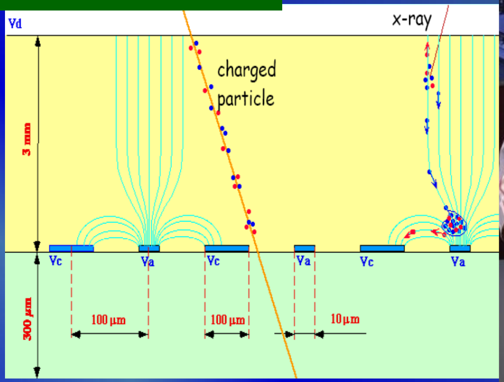
Typical distance between wires limited to ~1 mm due to mechanical and electrostatic forces

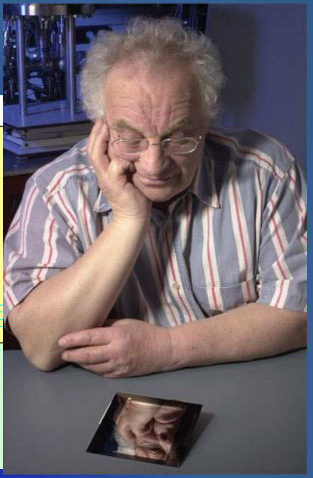


Micro-Strip Gas Chamber (MSGC)

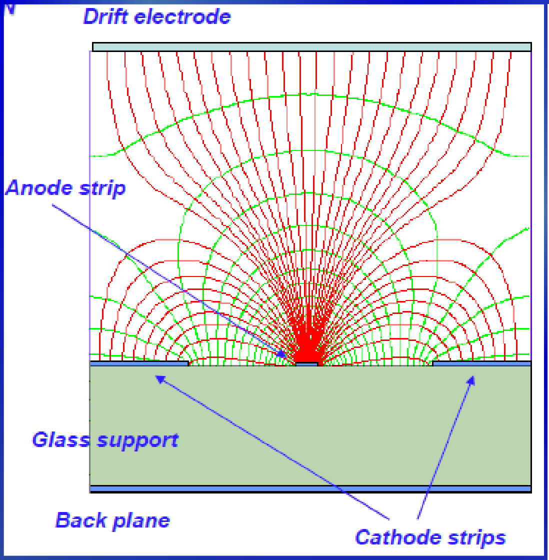
A. Oed, NIMA263 (1988) 351





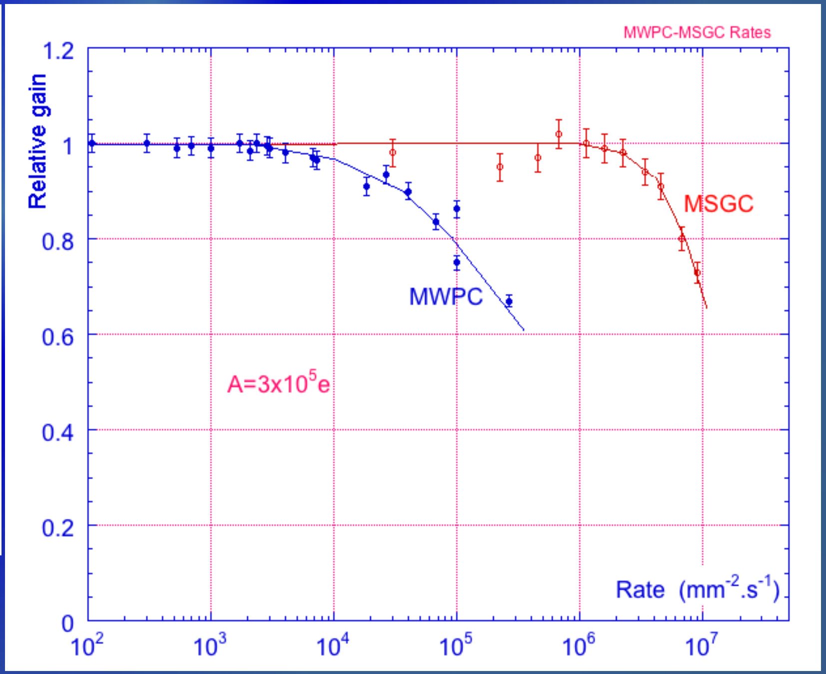


Excellent spatial resolution



Typical distance between electrodes ~100 µm

MSGC significantly improves rate capability due to fast removal of positive ions

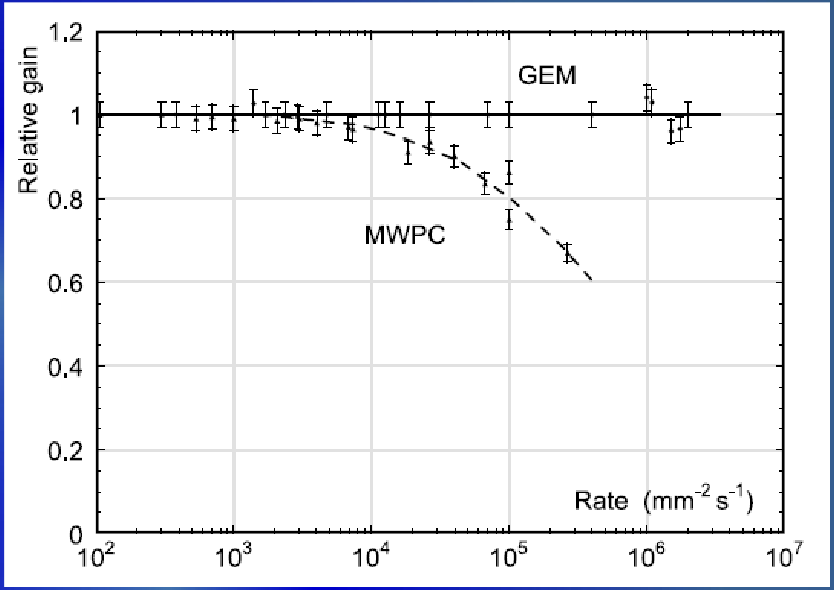


Micro-Pattern Gaseous Detector Technologies (MPGD)

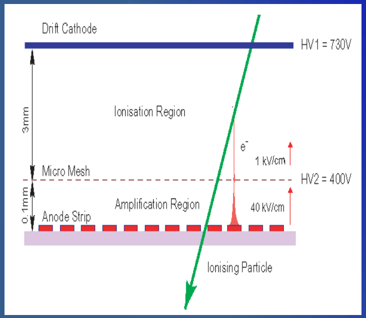
- ✓ *Micromegas*
- ✓ *Gas Electron Multiplier (GEM)*
- ✓ *Thick-GEM (LEM), Hole-Type & RETGEM*
- ✓ *MPDG with CMOS pixel ASICs ("GridPix")*

- ✓ *Micro-Pixel Chamber (μ–PIC)*
- ✓ *μ–Resistive WELL (μ-RWELL)*
- ✓ *Resistive-Plate WELL (RPWELL)*

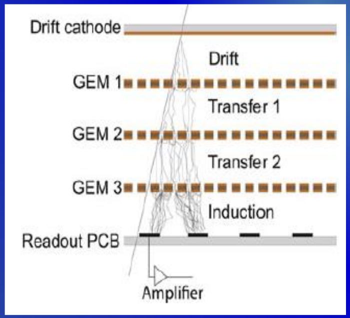
Rate Capability: MWPC vs GEM:



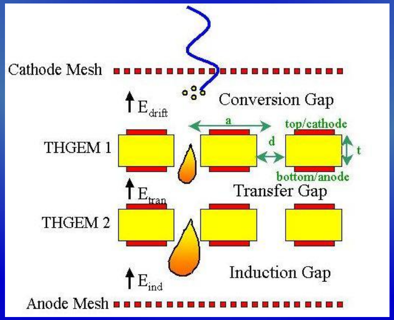
Micromegas

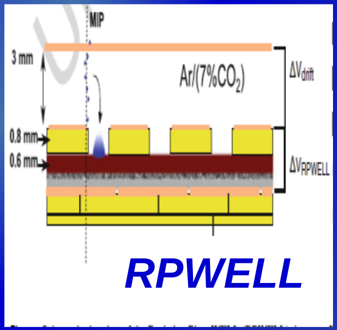


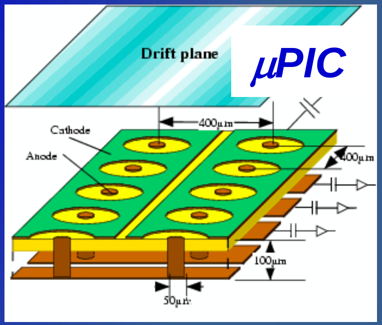
GEM

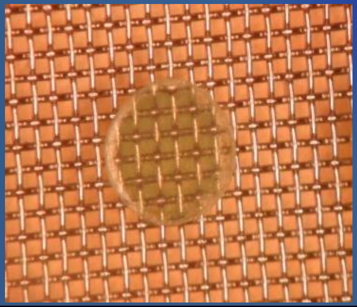


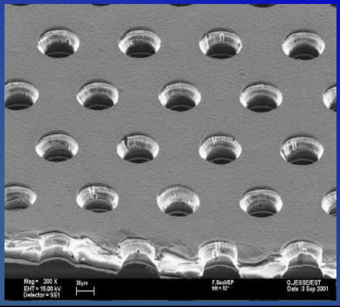
THGEM

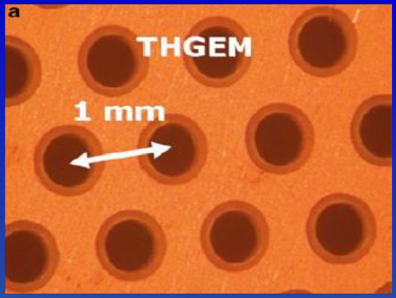


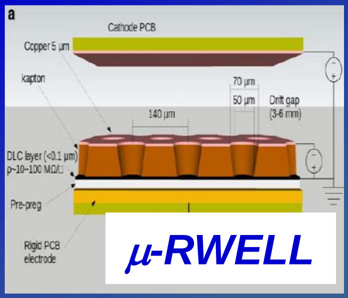


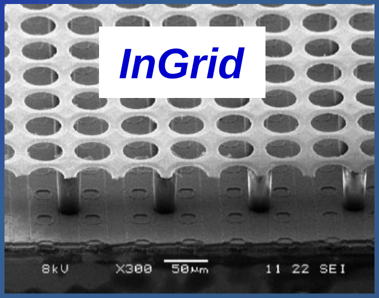










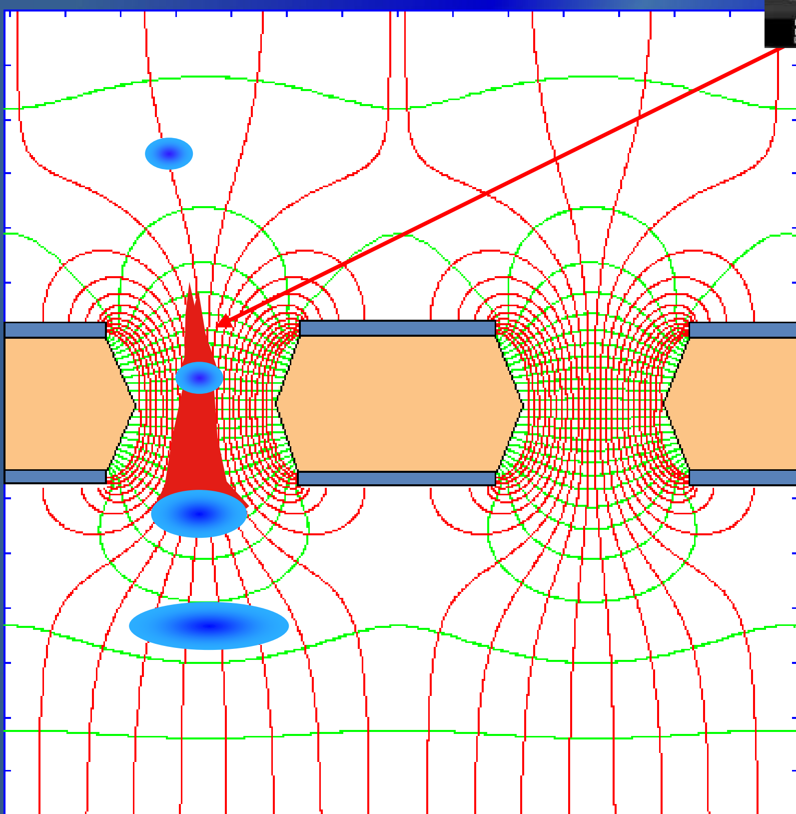


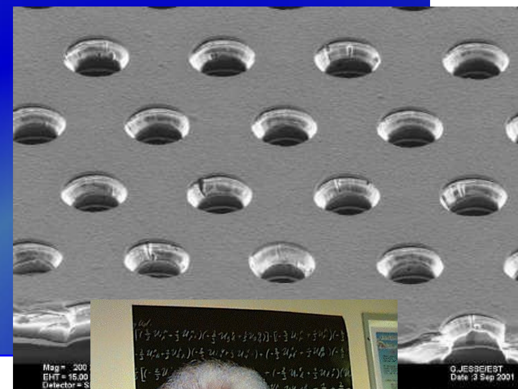
Gas Electron Multiplier (GEM)

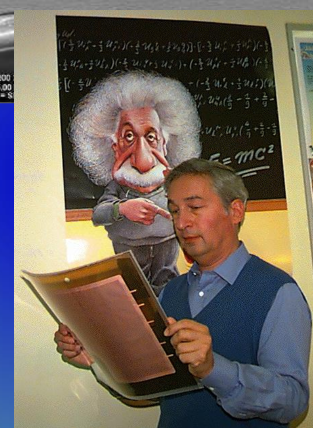
Thin metal-coated polymer foil chemically pierced by a high density of holes

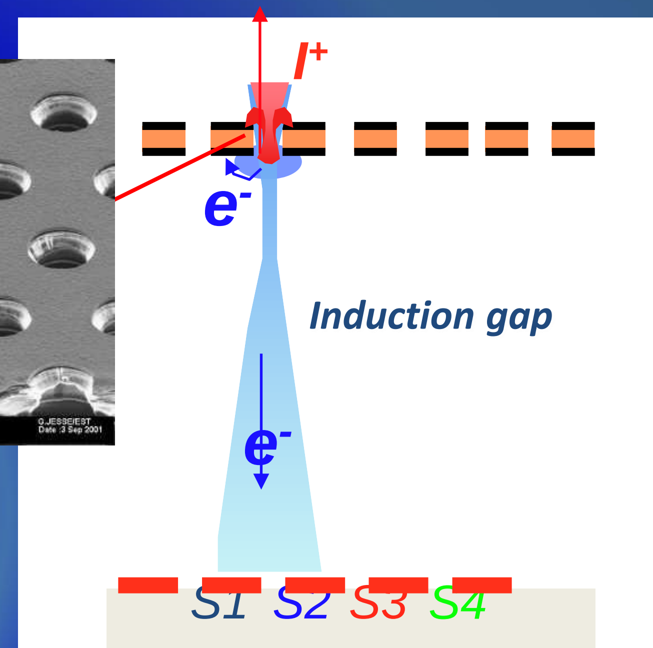
A difference of potentials of ~ 500V is applied between the two GEM electrodes.

→ the primary electrons released by the ionizing particle, drift towards the holes where the high electric field triggers the electron multiplication process.









F. Sauli, NIMA386 (1997) 531

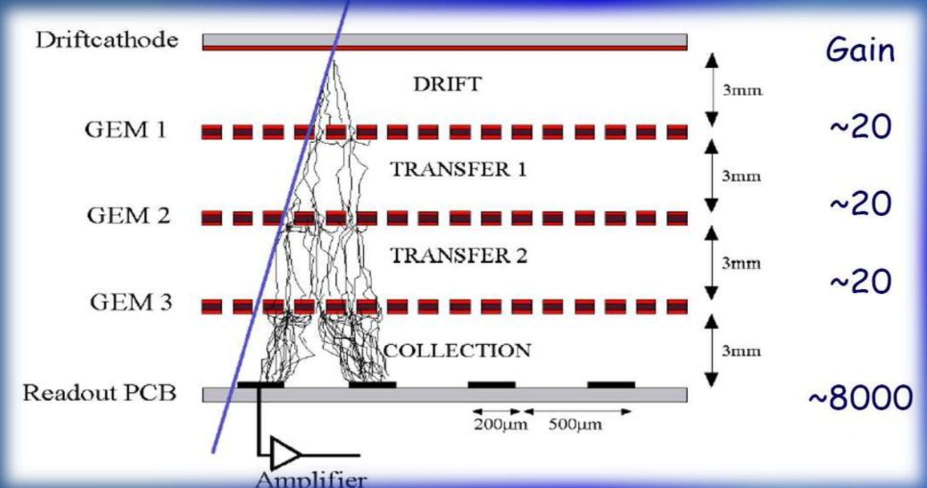
- ✓ Electrons are collected on patterned readout board.
- ✓ A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- ✓ All readout electrodes are at ground potential.
- ✓ Positive ions partially collected on GEM electrodes

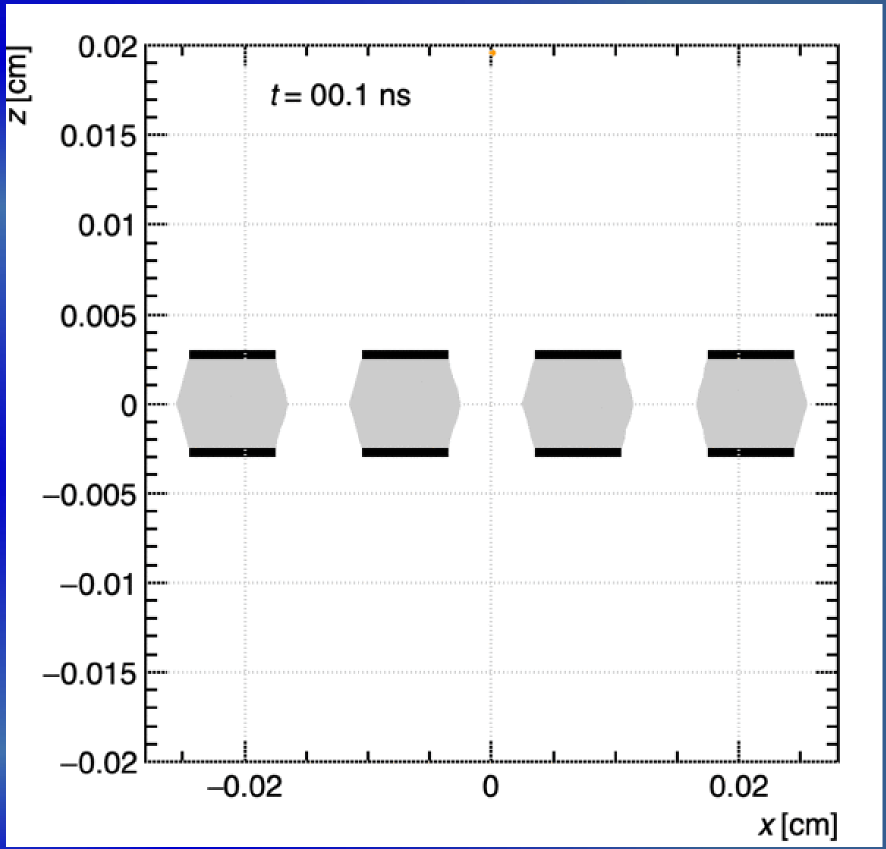
Avalanche Simulation in GEM & Triple-GEM Structures

Animation of the avalanche process (Garfield++): *monitor in ns-time electron/ ion drifting and multiplication in GEM*

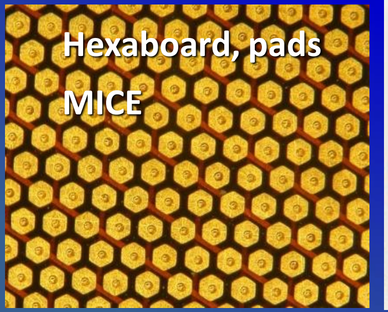
http://cern.ch/garfieldpp/examples/gemgain

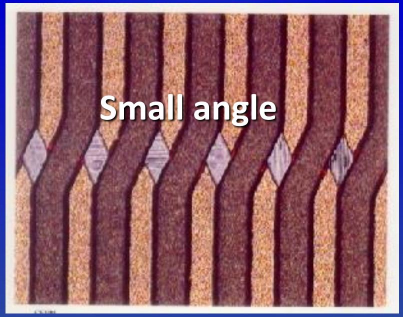
Full decoupling of amplification stage (GEM) and readout stage (PCB, anode)

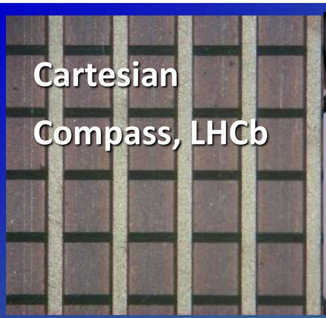


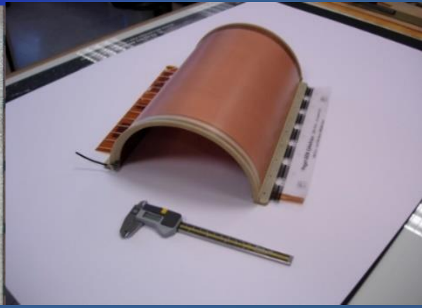


Amplification and readout structures can be optimized independently !





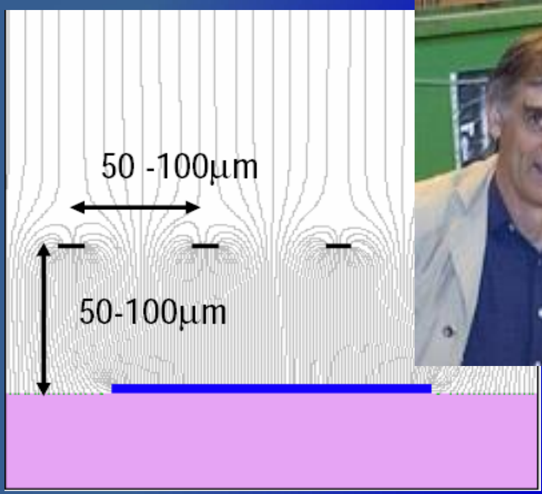


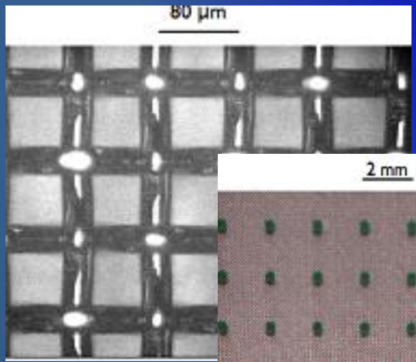


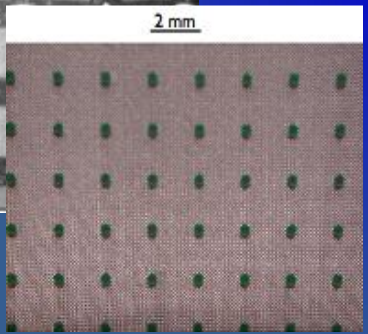
Micro Mesh Gaseous Structure (MICROMEGAS)

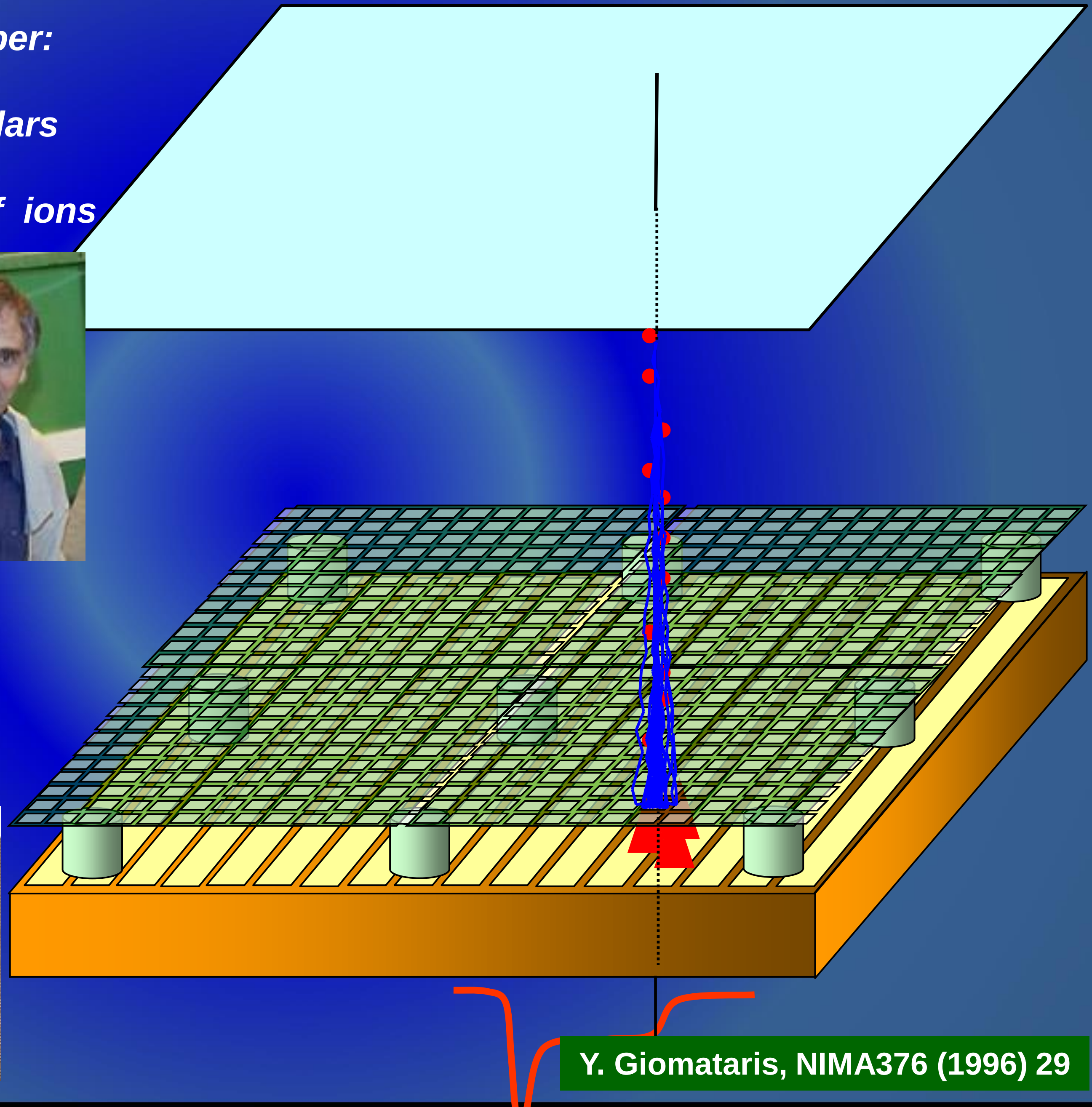
Micromesh Gaseous Chamber:
micromesh supported
by 50-100 mm insulating pillars

Small gap: fast collection of ions







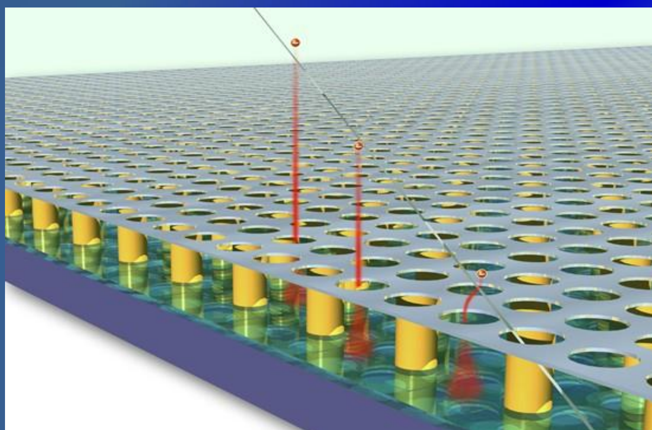


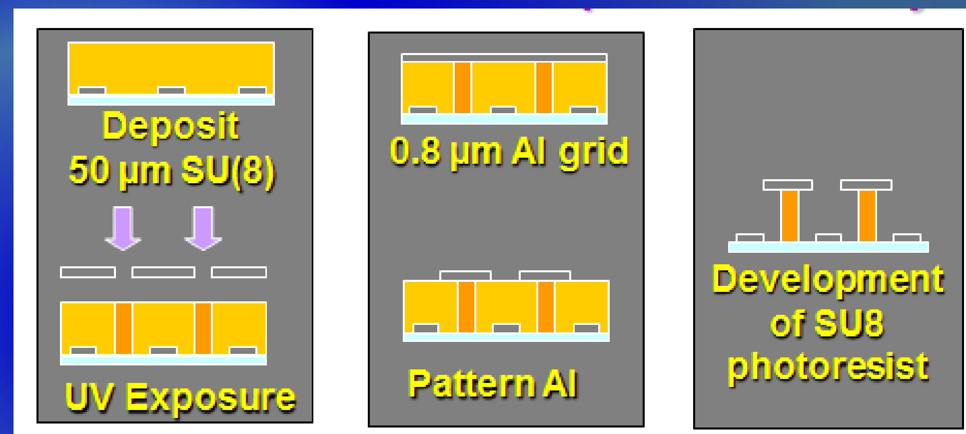
Y. Giomataris, NIMA376 (1996) 29

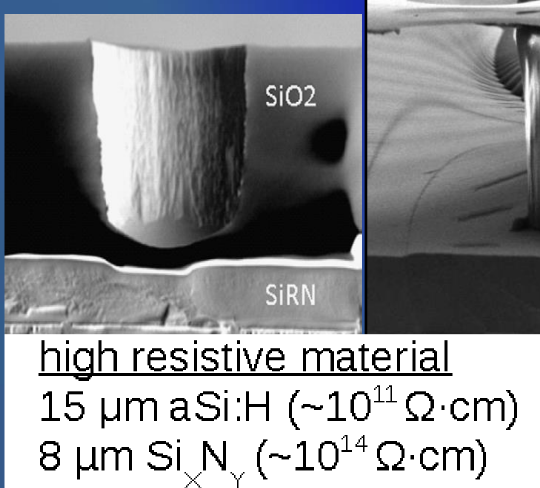
Pixel Readout of MPGDs: "GridPix" Concept

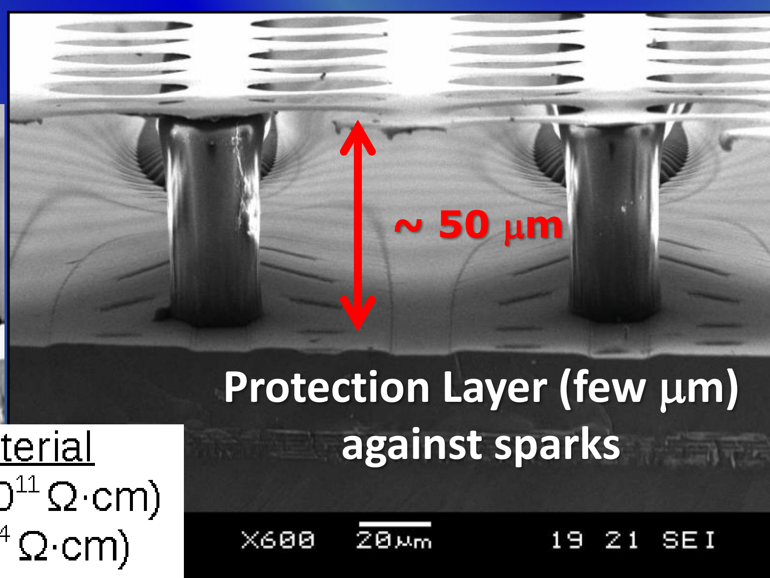
"InGrid" Concept: ***By means of advanced wafer processing-technology INTEGRATE MICROMEGAS amplification grid directly on top of TIMEPIX CMOS ASIC***

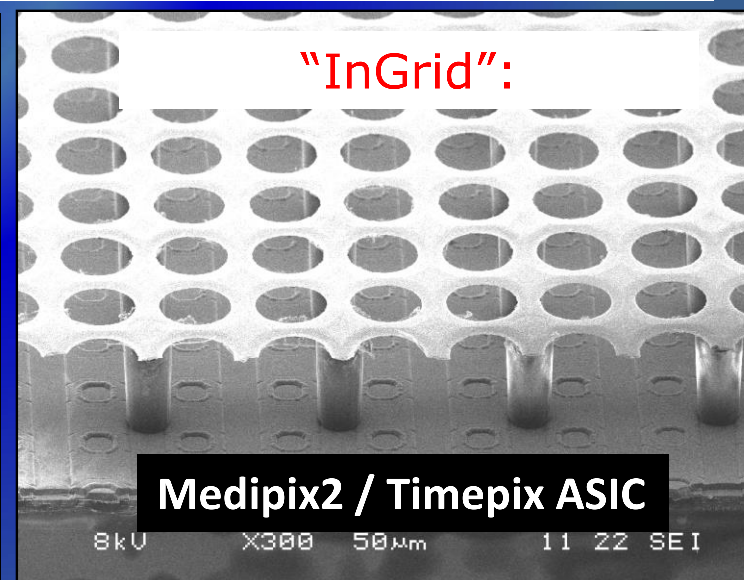
3D Gaseous Pixel Detector → 2D (pixel dimensions) x 1D (drift time)







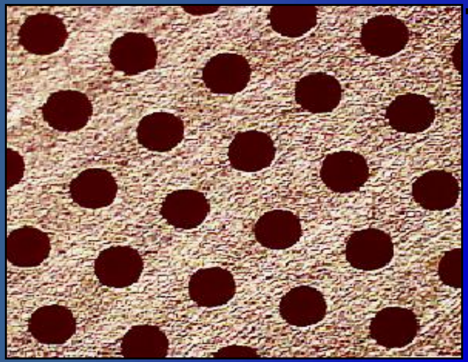


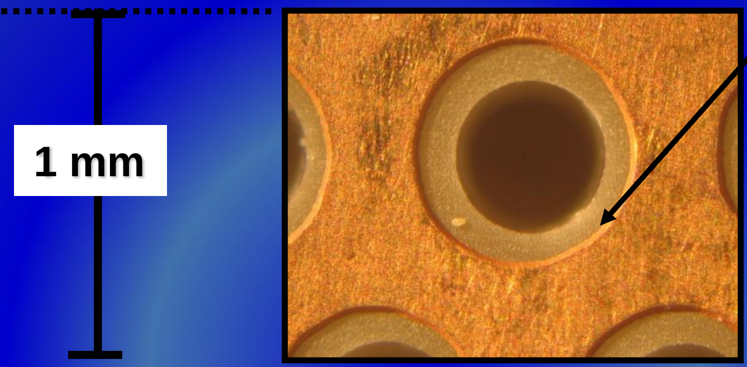


Other MPGDs Concepts: THGEM, µRWELL, RPWELL

THGEM Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching

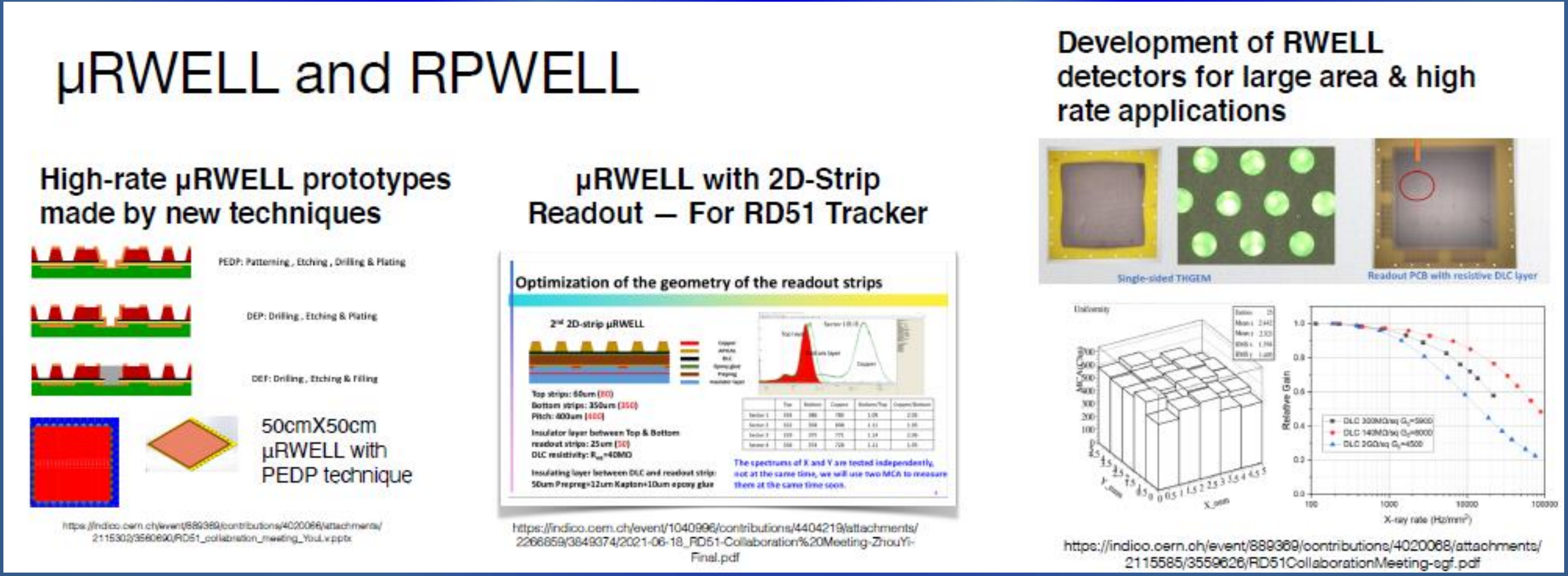
STANDARD GEM ***THGEM***





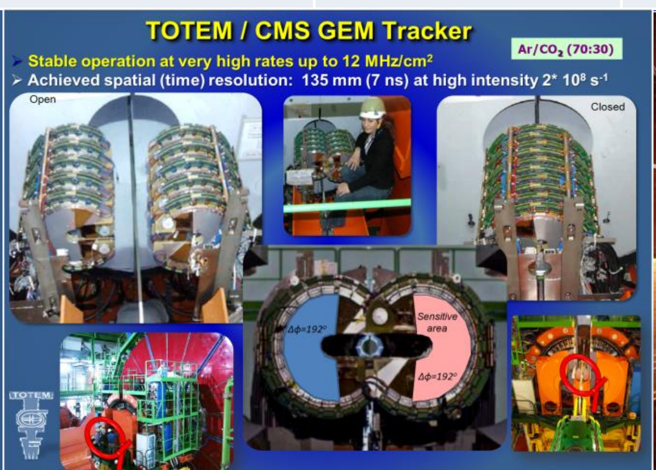
0.1 mm rim to prevent discharges

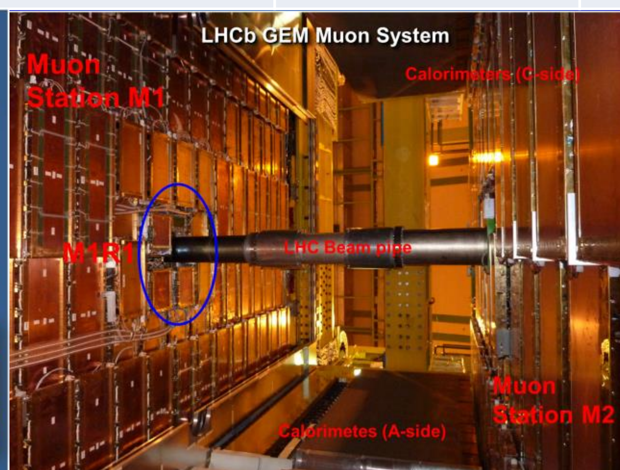
L. Periale, NIMA478 (2002) 377
LEM!: P. Jeanneret, PhD thesis, 2001



Early MPGD Detector Concepts @ CERN Experiments

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS TRACKING > 2002	Fixed Target Experiment (Tracking)	3-GEM Micromegas w/ GEM preampl.	Total area: 2.6 m^2 Single unit detect: 0.31x0.31 m^2 Total area: ~ 2 m^2 Single unit detect: 0.4x0.4 m^2	**Max.rate**: ~100kHz/mm² **Spatial res.:** ~70-100μm (strip), ~120μm (pixel) **Time res.:** ~ 8 ns **Rad. Hard.:** 2.5 C/cm^2	Required beam tracking (pixelized central / beam area)
TOTEM TRACKING: > 2009	Hadron Collider / Forward Physics (5.3≤|h| ≤ 6.5)	3-GEM (semicircular shape)	Total area: ~ 4 m^2 Single unit detect: up to 0.03m^2	**Max.rate**:20 kHz/cm^2 **Spatial res.:** ~120μm **Time res.:** ~ 12 ns **Rad. Hard.:** ~ mC/cm^2	Operation in pp, pA and AA collisions.
LHCb MUON DETECTOR > 2010	Hadron Collider / B-physics (triggering)	3-GEM	Total area: ~ 0.6 m^2 Single unit detect: 20-24 cm^2	**Max.rate**:500 kHz/cm^2 **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:**~ 0.5 C/cm^2	Redundant triggering
COMPASS RICH UPGRADE > 2016	Fixed Target (RICH - detection of single VUV photons)	Hybrid (THGEM + CsI and MM)	Total area: ~ 1.4 m^2 Single unit detect: ~ 0.6 x 0.6 m^2	**Max.rate**:100 Hz/cm^2 **Spatial res.:** <~ 2.5 mm **Time res.:** ~ 10 ns	Production of large area THGEM of sufficient quality



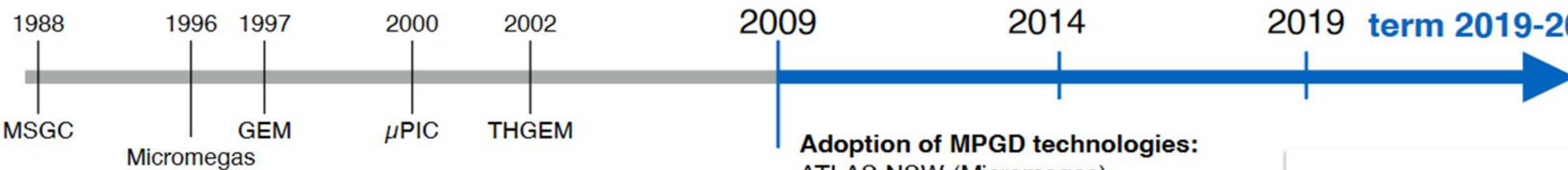


Legacy of the CERN-RD51 Collaboration: 2008-2023

***RD51* CERN-based *"TECHNOLOGY - DRIVEN R&D COLLABORATION"* was established to advance MPGD concepts and associated electronics readout systems**

RD51 community: ~ 90 institutes, 500 members RD51

renewed for 3rd term 2019-2023



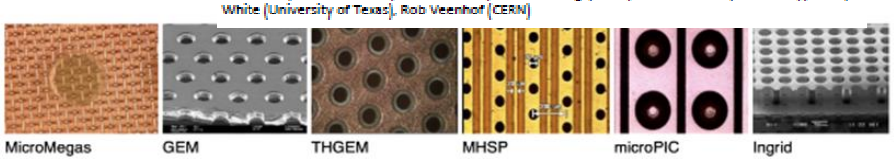
2008:

CERN-LHCC-2008-011 (LHCC-P-001)
RD51 2008-001
28 July 2008

R & D Proposal

Development of Micro-Pattern Gas Detectors Technologies

Editors: Matteo Alfonsi (CERN), Alain Bellerive (Carleton University), Amos Breskin (Weizmann Institute), Erik Van der Bij (CERN), Michael Campbell (CERN), Mar Capeans (CERN), Paul Colas (CEA Saclay), Silvia Dalla Torre (INFN Trieste), Klaus Desch (Bonn University), Ioannis Giomataris (CEA Saclay), Harry van der Graaf (NIKHEF), Lucie Linssen (CERN), Rui de Oliveira (CERN), Vladimir Peskov (St Etienne), Werner Riegler (CERN), Leszek Ropelewski (CERN), Fabio Sauli (TERA Foundation), Frank Simon (MPI Munchen), Hans Taureg (CERN), Maxim Titov (CEA Saclay), Andy White (University of Texas), Rob Veenhof (CERN)



Adoption of MPGD technologies:
ATLAS NSW (Micromegas)
CMS forward tracking update (GEM)
COMPASS RICH upgrade (hybrid MPGD)
ALICE TPC upgrade (GEM)
KLOE2 & BESIII (GEM)
LBNO-DEMO (THGEM)
T2K/ND280 TPC (Micromegas)
n-detection at ESS (GEM)
Muon radiography (Micromegas)

RD51 Spokespersons:
L. Ropelewski (2008-2022)
M. Titov (2008-2015, 2023)
S. Dalla Torre (2016-2022)
E. Oliveri (2023)

2018:

arXiv:1806.09955

- ✓ ***Many of the MPGD Technologies were introduced before the RD51 was founded***
- ✓ ***With more techniques becoming available, new detection concepts were introduced and the existing ones were substantially improved during the RD51 period (2008-2023)***
- ✓ ***Beyond 2023, RD51 served as a nuclei for the new DRD1 ("all gas detectors") collaboration, anchored at CERN, as part of the ECFA Detector R&D Roadmap***

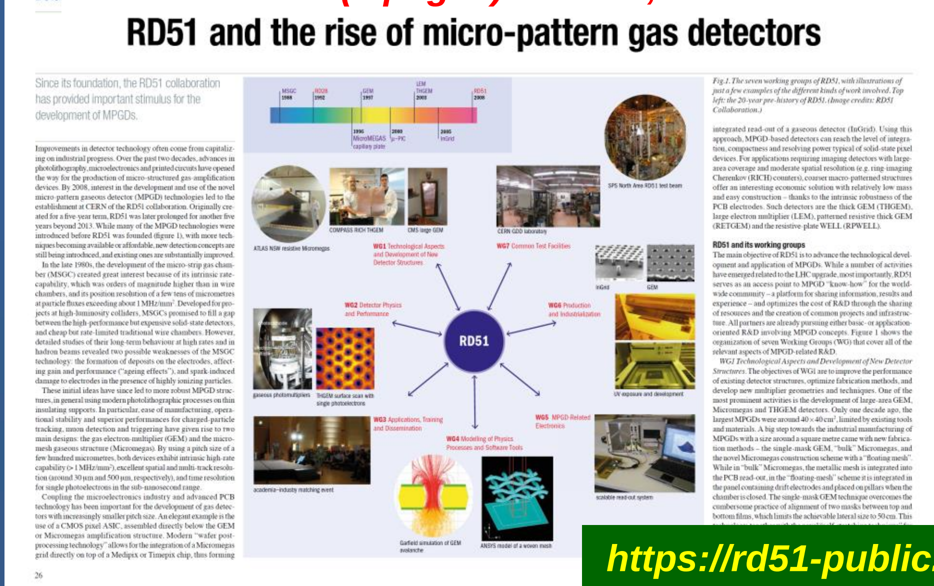
Legacy of the CERN-RD51 Collaboration:“RD51” Model

The success of the RD51 is related to the “RD51 model” inperforming R&D: combination of generic and focused R&D with bottom-up decision processes, full sharing of experience, “know-how”, and common infrastructure, which allows to build community with continuity and institutional memory and enhances the training of younger generation instrumentalists.

Scientific organisation in 7 working groups

- **WG1:** New structures and technologies
- **WG2:** Detector physics and performance
- **WG3:** Training and dissemination
- **WG4:** Software & Simulation Tools
- **WG5:** Readout Electronics (RD51 SRS)
- **WG6:** MPGD Production & Industrialization
- **WG7:** Common test facilities

CERN Courier (5 pages) Volume, October 2015


RD51 and the rise of micro-pattern gas detectors

Since its foundation, the RD51 collaboration has provided important stimulus for the development of MPGDs.

RD51: 3 MAJOR ASSETS

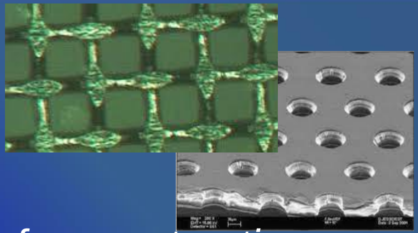
Community and Expertize (RD51 Scientific Network)

MPGD Technology Development & Dissemination

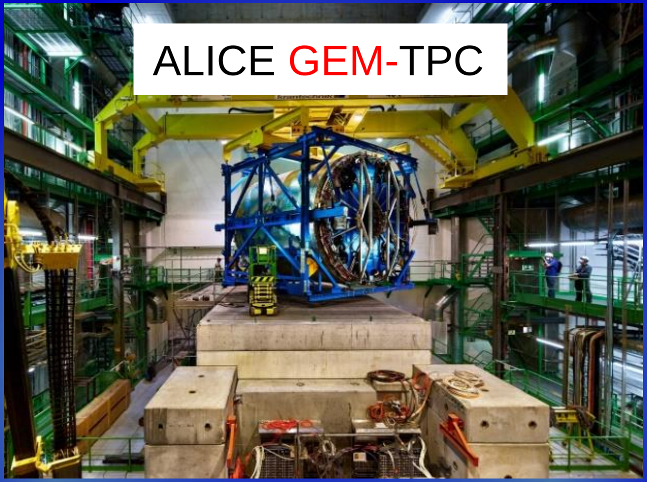
R&D Tools, Facilities and Infrastructure

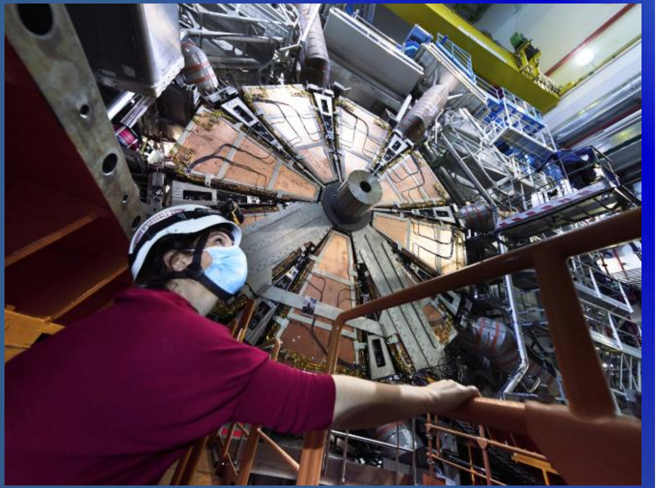
https://rd51-public.web.cern.ch/

2022: MPGDs for High Luminosity LHC Upgrades



The <u>successful implementation of MPGDs for relevant upgrades of CERN</u> experiments indicates the degree of maturity of given detector technologies for constructing large-size detectors, the level of dissemination within the HEP community and their reliability





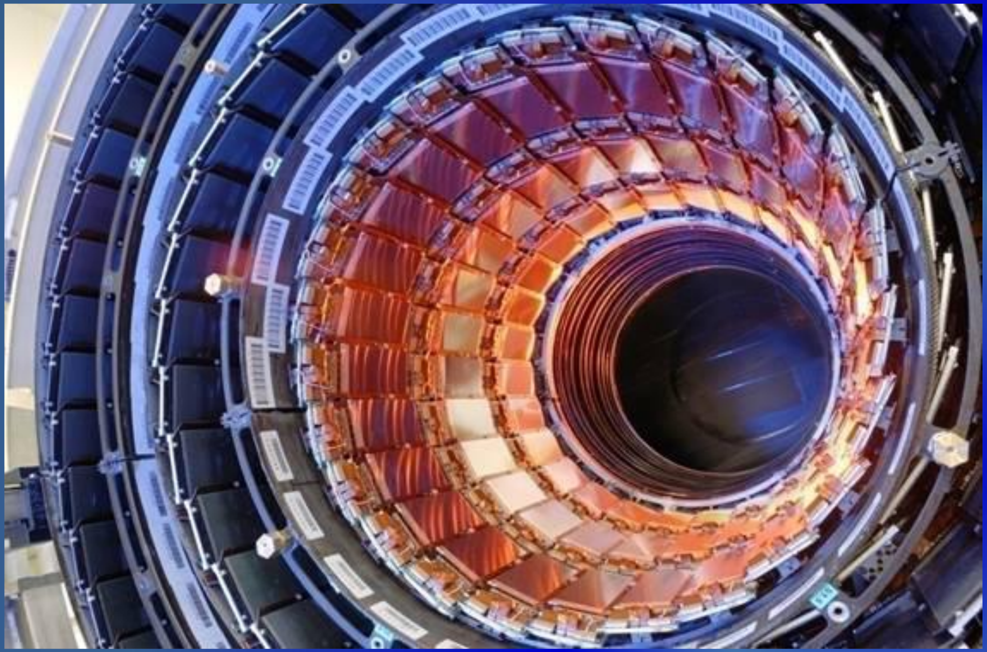
https://ep-news.web.cern.ch/content/atlas-new-small-wheel-upgrade-advances-0

https://ep-news.web.cern.ch/upgraded-alice-tpc

https://ep-news.web.cern.ch/content/demonstrating-capabilities-new-gem

State-of-the-Art in Tracking Detectors: 3 Major Technologies

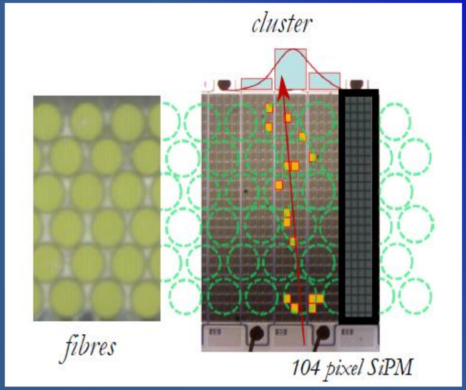
Silicon Tracking (strips, pixels, 3D, CMOS, MAPS)

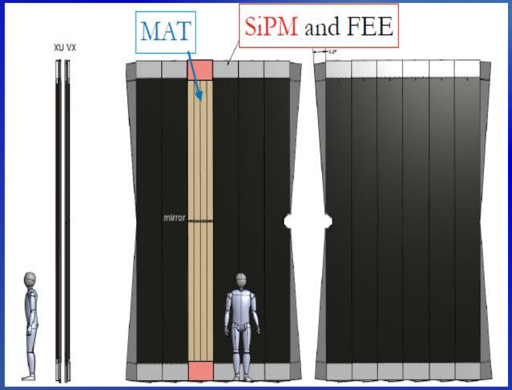


Gaseous Tracking (MPGD, RPC, TPC, Wire and Drift Chambers)

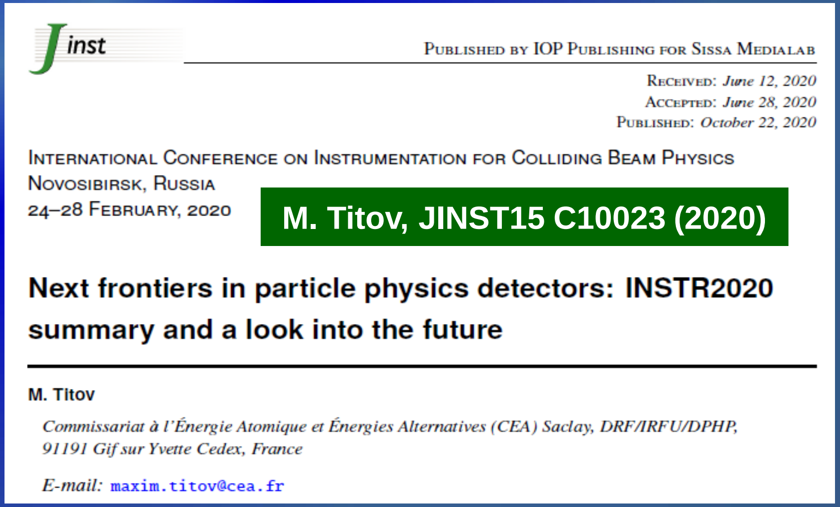
→ Core of CERN-DRD1 Collaboration

Fiber Trackers:





E.g: LHCb Tracker Upgrade (Sci-fibers with SiPM readout):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NOVOSIBIRSK, RUSSIA
24–28 FEBRUARY, 2020

M. Titov, JINST15 C10023 (2020)

Next frontiers in particle physics detectors: INSTR2020 summary and a look into the future

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Gaseous Tracking (Drift Chambers, TPC, MPGD) @ Future Colliders

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm^2 **Spatial res.:** ~300µm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
ILC TPC DETECTOR: STARTt: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm^2 (pixels)	**Max. rate**: < 1 kHz **Spatial res.:** <150µm **Time res.:** ~ 15 ns **dE/dx:** 5 %	Si + TPC Momentum resolution : dp/p < 9*10^{-5} 1/GeV Power-pulsing
CEPC TPC DETECTOR START: > 2035	e+e- Collider Tracking + dE/dx	MM, GEM (pads) InGrid (pixels)	Total area: ~ 2x10 m^2 Single unit detect: up to 0.04 m^2	**Max.rate**:>100 kHz/cm^2 **Spatial res.:** ~100µm **Time res.:** ~ 100 ns **dE/dx:** <5%	- Higgs run - Z pole run - Continues readout - Low IBF and dE/dx
FCC-ee and/or CEPC IDEA CENTRAL TRACKER START: >2035	e+e- Collider Tracking/ Triggering	He based Drift Chamber	Total volume: 50 m^3 Single unit detect: (12 m^2 X 4 m)	**Max. rate:** <1 MHz/cm^2 **Spatial res.:** <100 µm **Time res.:** 1 ns **Rad. Hard.:** NA	Particle sepration with cluster counting at 2% level
SUPER-CHARM TAU FACTORY START: > 2030	e+e- Collider Main Tracker	Drift Chamber	Total volume: ~ 3.6 m^3	**Max. rate**: 1 kHz/cm^2 **Spatial res.:** ~100 µm **Time res.:** ~ 100 ns **Rad. Hard.:** ~ 1 C/cm	
SUPER-CHARM TAU FACTORY START: > 2030	e+e- Collider Inner Tracker	Inner Tracker / (cylindrical µRWELL, or TPC / MPDG read.	Total area: ~ 2 - 4 m^2 Single unit detect: 0.5 m^2	**Max. rate**: 50-100 kHz/cm^2 **Spatial res.:** ~<100 µm **Time res.:** ~ 5 -10 ns **Rad. Hard.:** ~ 0.1-1 C/cm^2	Challenging mechanics & mat. budget < 1% X0

The Evolution of Drift Chambers & Future e+e- Colliders

past

Collider	Experiment	Tracker
SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC

Collider	Experiment	Tracker
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

present

Collider	Experiment	Tracker
VEPP2000	CMD-3	Drift Chamber
VEPP4	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber

future

Collider	Experiment	Tracker
ILC	ILD	TPC
	SiD	Si
CLIC	CLIC	Si
FCC-ee	CLD	Si
	IDEA	Drift Chamber
CEPC	Baseline	TPC / Si
	IDEA	Drift Chamber
SCTF	BINP	Drift Chamber
STCF	HIEPA	Drift Chamber

An ultra-light drift chamber (IDEA concept) targetted for FCC-ee and CePC was inspired by DAFNE KLOE Wire Chamber and by more recent version of it for MEG2 experiment

IDEA: full stereo, high resolution, ultra-light drift chamber

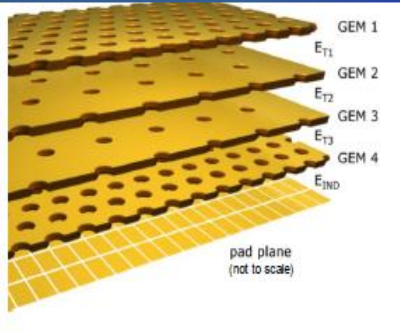
- **4000 mm length**, **350-2000 mm radius in ~ 2T solenoid B-field**
- **14 SL × 8 layers**, 24 φ-sectors
- **56k sense wires**, 20 μm diameter W (-Au)
- ~290k field and guard wires, 40/50 μm diameter Al(-Ag))
- He(90%) + i-C_4H_{10}
- X/X0 ~ 0.1 % (end plate incl. FEE with X/X0 ~ few %)
- Spatial resolution: σ ~ 100μm, mom. resolution: σ(pt)/pt < 0.3 %

Future R&D Challenges:

- *Aging studies for new modular DC designs (smaller size drift cells & higher fields, higher gain for cluster counting?)*
- *New wire materials- new alloy metallized carbon wire*
  → specific topics: wire corrosion, coating quality, …
- *Operation with hydrocarbon-free gas mixtures*

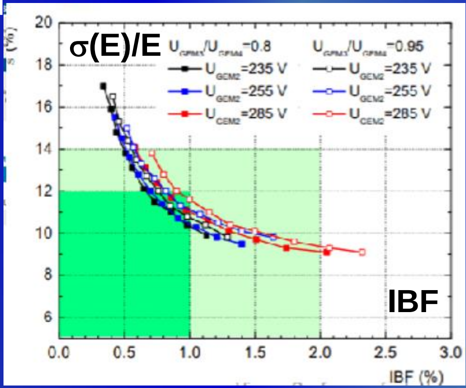
TPC with MPGD Readout for ALICE Upgrade and ILC

ALICE TPC → replace MWPC with 4-GEM staggered holes (to limit space-charge effects)

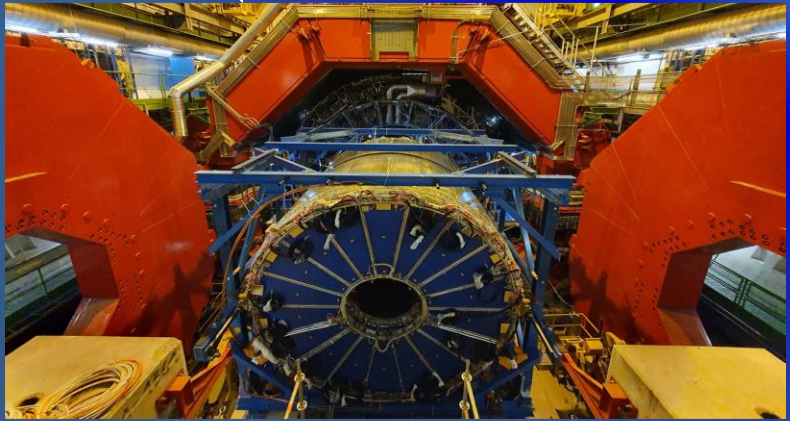


- Upgrade for continuous TPC readout @ 50 kHz Pb-Pb collisions

- Phys. requirements:
  IBF < 1%,
  Energy res. σ(E)E < 12%



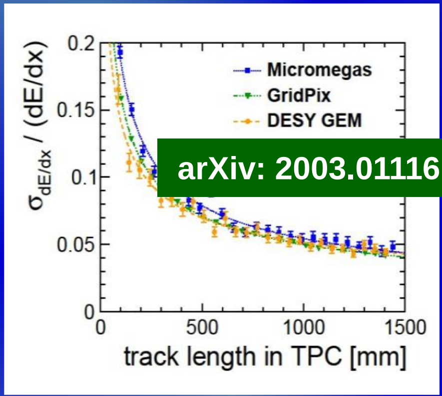
TPC reinstallation in the ALICE cavern (August 2020)

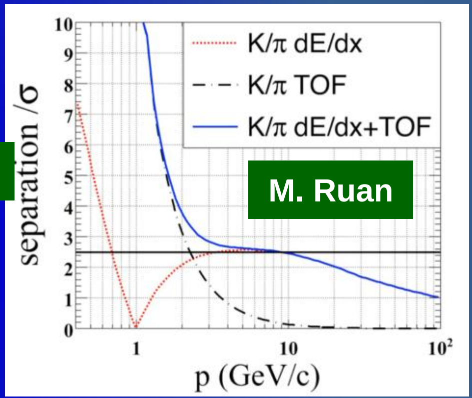


ILC –TPC with MPGD-based Readout

Target requirement of a spatial resolution of 100 um in transverse plane and dE/dx resolution < 5% have been reached with all technologies (GEM, MM and GridPix)

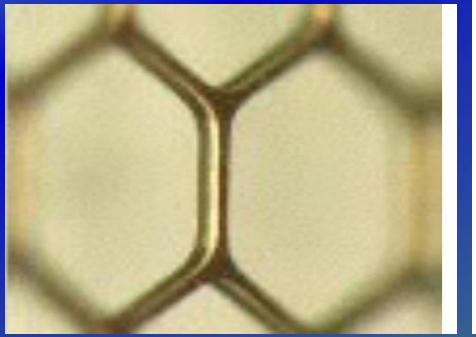
If dE/dx combined with ToF using SiECAL,
P < 10GeV region for pion-K separation covered

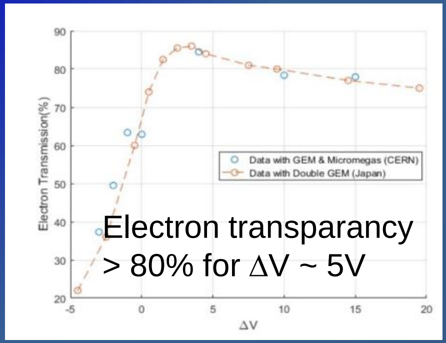




ILC: gating scheme, based on large-aperture GEM

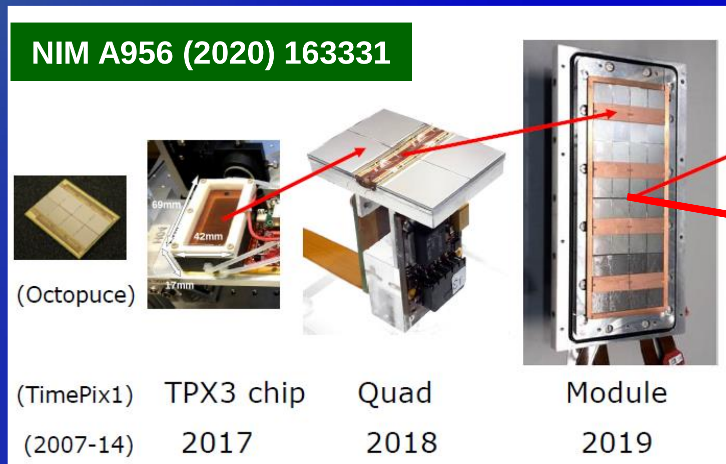
→ Machine-induced background and ions from gas amplific.
→ Exploit ILC bunch structure (gate opens 50 us before the first bunch and closes 50 us after the last bunch)





Towards Large-Scale Pixel "GridPix" TPC

Testbeams with GridPixes:
160 GridPixes (Timepix) & 32 GridPixes (Timepix3)



A PIXEL TPC IS REALISTIC!

Crucial considerations for
FCC-ee / CEPC @ Z pole running:
- primary ionization of the gas & backgrounds
- ions from the gas amplification stage;
- power consumption (no power pulsing);
- operation at 2 T during the Z-peak running;

Pixelated readout TPC has been formally chosen as the BASELINE TRACK DETECTOR in the CEPC Physics and Detector TDR document

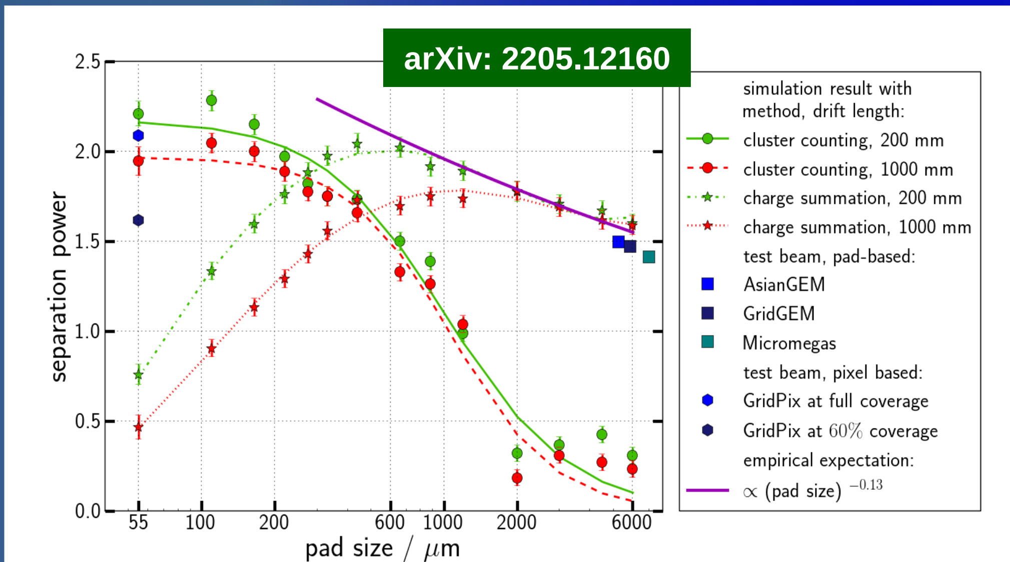
3 modules for LP TPC @ DESY: 160 (1 x 96 & 2 x 32) GridPixs
320 cm² active area, 10,5 M. channels, new SRS Readout system

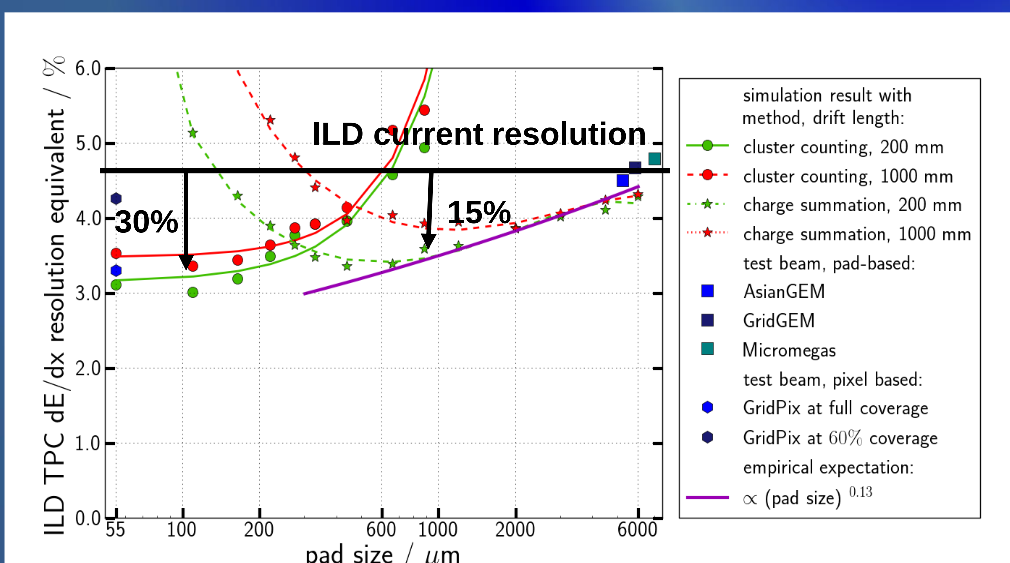
Future R&D Challenges:

- ***Optimal pad size to improve track resolution: pixel size ~ 200 um → cost reduction***
- ***Ion backflow suppression (double grid, graphene coating)***
- ***Baseline gas Ar/CF4/iC4H10 operation to be verified (replacement of CF4 with ωt ~ 20 is difficult)***
- ***Reduction of resistive protection layer s → sparking & radiation hardness of Gridpix fragile structure***

Cluster Counting / Charge Summation / Granularity

Simulation of PID with gaseous tracking and timing in ILD Prototype





Current full ILD reconstruction:

- ✓ 6 mm pads → 4.6 % dE/dx resolution
- ✓ 6 mm → 1 mm: 15% improved resolution via charge summing (dE/dx)
- ✓ 6 mm → 0.1 mm: 30% improved res. via cluster counting (dN/dx)

✓ **Cluster Counting promises a few times better dE/dx resolution & separation power:**

→ in time (small drift cells): requires very fast electronics

→ in space (TPC + pixelated endplates): requires good cluster finding algorithm

✓ Cluster Counting ia an attractive option and is complementary to classical dE/dx by the spread charge

→ Some groups focus on it and ongoing for CEPC, FCC-ee…

Gaseous Tracking (MPGD) @ Nuclear Physics & EiC Collider

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
CLAS12 @ JLAB Start: > 2017	Nuclear Physics/ Nucleon structure (tracking)	Planar (forward) & Cylindrical (barrel) Micromegas	Total area: Forward ~ 0.6 m^2 Barrel ~ 3.7 m^2 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
SBS in Hall A @ JLAB Start: > 2017	Nuclear Physics (Tracking) nucleon form factors / struct.	GEM	Total area: 14 m^2 Single unit detect. 0.6x0.5m^2	**Max. rate**:400 kHz/cm^2 **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: 1.5m^2 Single unit detect. 1.2x0.6 m2	**Max. rate**:5 kHz/cm^2 **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: 40m^2 Single unit detect. 1.2x0.6 m2	**Max. rate**:600 kHz/cm^2 **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: 0.26m^2 0.52m(diameter) x0.5m(drift length)	**Max. rate**:10^6 kHz/cm^2 **Spatial res.**: 0.2-0.4 mm	Gating grid operation ~ 1kHz
Electron-Ion Collider (EIC) Start: > 2030	Hadron Physics (tracking, RICH)	TPC w/GEM; GEM, MM, Gridpix, m-PWELL planar & cylindrical detectors	Total area: ~ 3 m^2 Total area: ~ 25 m^2	**Spatial res.**: ~ 100 um (rf) Luminosity (e-p): 10^{33} **Spatial res.**: ~ 50- 100 um **Max. rate**: ~ MHz/cm^2	Low material budget Low material budget

MPGD Tracking @ Nuclear Physics Experiments

Hall B: MPGD technology: large µRWELL

Key Requirements:
- ❑ Low mass ⇒ reduce multiple scattering
- ❑ Large area 1500 mm x 1500 mm
- ❑ Moderate rate: ~20kHz / cm^2
- ❑ Timing performance < 10 ns

Applications: Tracking
- ❑ High Luminosity CLAS12 Upgrade: Forward R1 and central trackers
- ❑ Proton radius Exp: PRad-II trackers

CLAS12 High-Lumi R1 tracker segment

There is a major synergy & complementarity for MPGD R&D Needs between Energy Frontier Colliders and Nuclear Physics (NP) Experiments

→ often rate-capabilities for tracker needs are higher in NP experiments

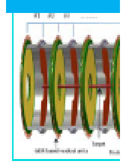
Hall A & C: MPGD technology: GEMs

Applications: Tracking
- ❑ SBS: Super Bigbite Spectrometer
- ❑ TDIS: multi-TPC proton recoil detector
- ❑ SoLID: Solenoid Intensity Device
- ❑ MOLLER
- ❑ LAD Experiment (Hall C)

Requirements are Challenging
- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale (Like RHIC)
- New Technologies
  - GEM's
  - Shashlyk Ecal
  - Pipeline DAQ

SoLID detector

TDIS mTPC

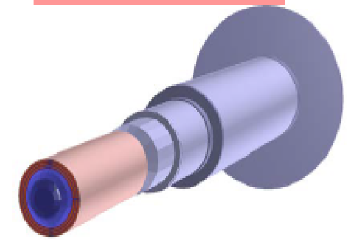


Hall D: MPGD technology: µRWELL / GEMs

Key Requirements:
- ❑ Low mass ⇒ reduce multiple scattering
- ❑ Large area 1500 mm x 1500 mm
- ❑ Low to moderate rate: ~20kHz / cm^2
- ❑ Timing performance < 10 ns

Applications: Tracking & PID
- ❑ MPGD-based Transition radiation Detectors
- ❑ GLUeX Inner Tracker: Cylindrical uRWELL layers

GLUeX cylindrical tracker

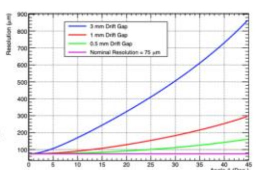


Proposed EIC concepts & their future upgrades feature a form of large MPGD detectors: Tracking (GEM, MM, uWELL), Tracking/PID (GridPix), TRD (GEM)

Jefferson Lab — FY22 Proposal: Generic Thin Gap MPGD Proposal — FLORIDA TECH

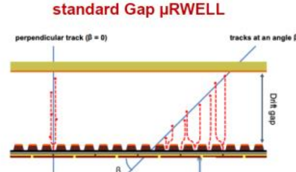
Challenges with standard (> 3-mm drift gap) MPGD
- ❖ Degradation of the spatial resolution with track angle .
- ❖ E × B in magnetic field negatively impact resolution

Development of Thin-gap MPGDs:
- ❖ Smaller drift gap to reduce the dependence of resolution
- ❖ Smaller gaps ➔ minimize E × B effect in magnetic field
- ❖ Improve the detector timing performance



parametrization from EPJ Web of Conferences 174 06005 (2018)

standard Gap µRWELL



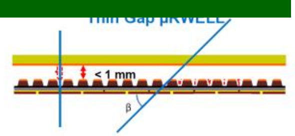
Development of Thin Gap MPGDs for EIC Trackers

K. Gnanvo[*1], S. Greene[4], H. Liyanage[2], N. Nguyen[2], M. Posik[3], N. Smirnov[5], B. Surrow[3], S. Tarafdar[4], and J. Velkovska[4]

[1]Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[2]University of Virginia, Department Of Physics, Charlottesville VA 22903, USA
[3]Temple University, Philadelphia, PA 23606, USA
[4]Vanderbilt University, Department of Physics and Astronomy, Nashville, TN 37240, USA
[5]Yale University, Physics Department, New Haven, CT 06520, USA

Thin-Gap MPGD for EiC

Thin Gap µRWELL



University of Virginia — Yale University — Vanderbilt University — Temple University

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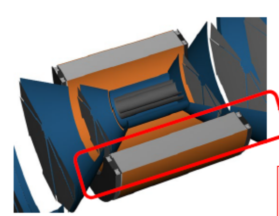
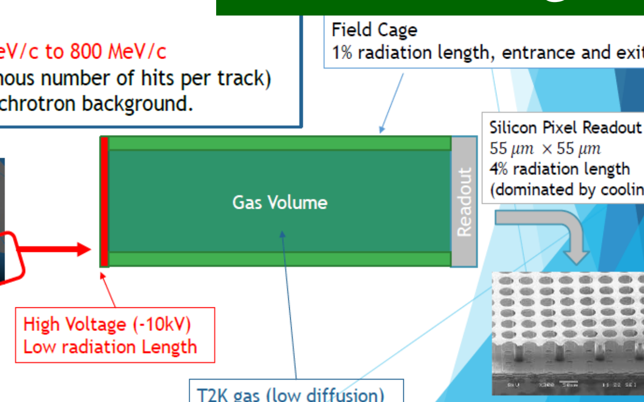
- Originally as "upgrade path" for ATHENA.
- Not discussed in current EPIC baseline.
- Ideally suited for Detector 2.
- Provides:
  - PID (pi-K-p) from 100 MeV/c to 800 MeV/c
  - ROBUST tracking (enormous number of hits per track)
  - Virtually immune to synchrotron background.

Tracking @ PID for GridPix detector @ EiC



ATHENA's Vision



Gaseous Detectors @ HL-LHC: ATLAS Muon System Upgrade

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ATLAS MUON UPGRADE CERN LS2 /	Hadron Collider (Tracking/Triggering)	Endcap: Res. Micromegas & sTGC	Endcap area: 1200 m^2 Single unit detect: ($2.2x1.4m^2$) ~ 2-3 m^2	**Max. rate**:20 kHz/cm^2 **Spatial res.:** <100 µm **Time res.:** ~ 10 ns **Rad. Hard.:** ~ 0.5 C/cm^2	Redundant tracking and triggering; Challenging constr. in mechanical precision
ATLAS MUON UPGRADE (BIS78 PILOT) CERN LS2	Hadron Collider (Tracking/Triggering)	Part of Inner Barrel: RPC + sMDT	Barrel area (3 layers): 140 m^2 Single unit det.: ~ m^2	**Max. rate**:1 kHz/cm^2 **Spatial res.:** ~ 7 mm **Time res.:** ~ 1 ns **Rad. Hard.:** 300 fb	Redundant tracking and triggering; 9 layers with 2D hit position + time
ATLAS MUON UPGRADE (BI PROJECT) CERN LS3	Hadron Collider (Tracking/Triggering	Inner Barrel: RPC	Barrel area: 1400 m^2 Single unit det.: ~ m^2	**Max. rate**:10 kHz/cm^2 **Spatial res.:** ~ (0.1 x 1) cm in (η , φ) **Time res.:** ~ 0.5 ns **Rad. Hard.:** 3000 fb	Redundant tracking and triggering; 9 layers with 2D hit position + time
ATLAS MUON UPGRADE (early proposal; not approved) CERN AFTER LS3	Hadron Collider (Tracking/Triggering) ($2.7 \le \|h\| \le 4.0$)	Forward region: Res MM, µWELL, µPIC	Total area: ~ 5 layers x1 m^2 Single unit detect: 0.1 m^2	**Max. rate**: 10 MHz/cm^2 **Spatial res.:** ~200 µm **Time res.:** ~ 5 ns **Rad. Hard.:** ~ 10 C/cm^2	Hit rates (given at 25 cm) falls rapidly with the distance from the beam axis. Miniaturization of readout elements.

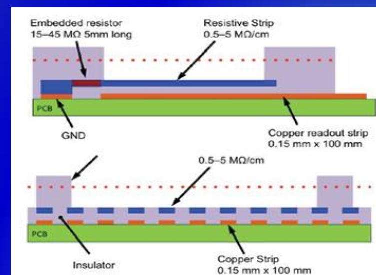
Large-Area Micromegas for ATLAS NSW Upgrade

Resistive MM for ATLAS NSW Muon Upgrade:

Standard Bulk MM suffers from limited efficiency at high rates due to discharges induced dead time
Solution: Resistive Micromegas technology:

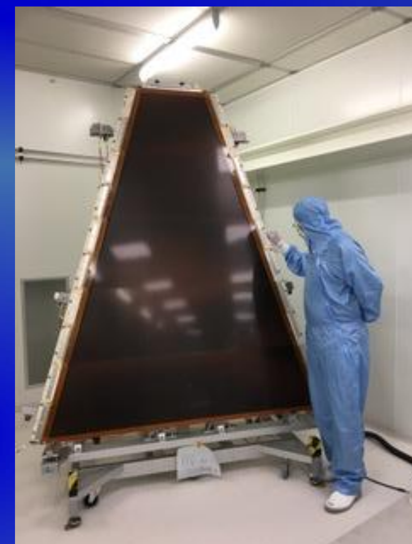
- Add a layer of resistive strips above the readout strips

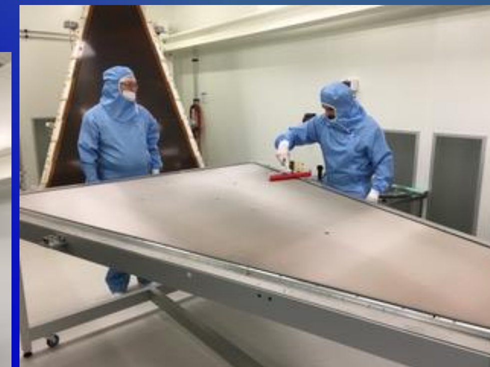
- Spark neutralization/suppression (sparks still occur, but become inoffensive)

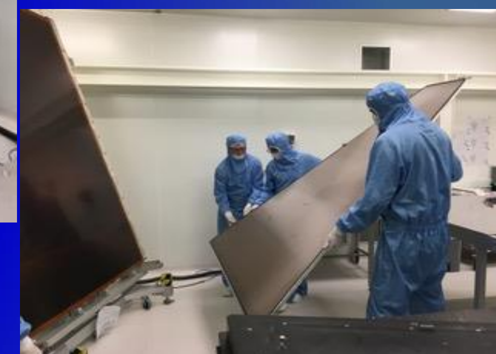


Still, main issue encountered: HV unstability
==> found to be correlated to low resistance of resistive strip anode
==> applied solutions + passivation in order to deactivate the region where R<0.8 MΩ

Mass-production (in collaboration with industry), sector integration of large-area (~1200m^2) MM:







- Changing from lab-sized detectors to large, mass producible detectors forced some changes that ended up reducing the MM performance and stability with the nominal gas mixture:

  → Replace Ar/CO2 with Ar-CO2-iC4H10 (93-5-2)

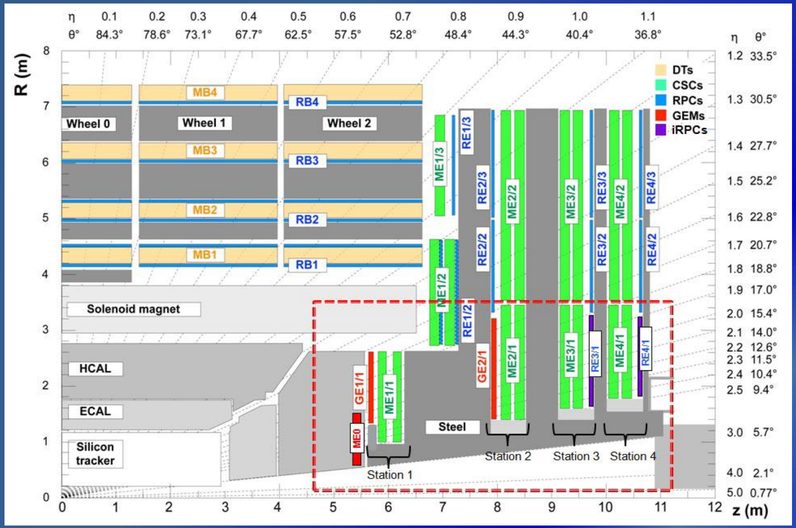
- **GIF++ tests and extrapolation to Run 3 conditions are convincing and validates the use of the new mixture**

- The decision of operating MM with isobutane in Run3 demands the parallel execution of a long-term test program

Gaseous Detectors @ HL-LHC: CMS and LHCb Muon System Upgrade

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
CMS MUON UPGRADE GE11 CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 50 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 5 kHz/cm^2 **Spatial res.:** 0.6 – 1.2mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 0.18 C/cm^2	Redundant tracking and triggering, improved pt resolution in trigger
CMS MUON UPGRADE GE21 CERN LS3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 105 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**: 1.5 kHz/cm^2 **Spatial res.:** 1.4 – 3.0mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 0.09 C/cm^2	Redundant tracking and triggering, displaced muon triggering
CMS MUON UPGRADE ME0 CERN LS3	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 65 m^2 Single unit detect: 0.3m^2	**Max. rate**:150 kHz/cm^2 **Spatial res.:** 0.6 – 1.3mm **Time res.:** ~ 7 ns **Rad. Hard.:** ~ 7.9 C/cm^2	Extension of the Muon System in pseudorapidity, installation behind HGCAL
CMS MUON UPGRADE RE3.1, RE 4.1 2023-24 (CERN L3)	Hadron Collider (Tracking/Triggering)	iRPC	Total area: ~ 140 m^2 Single unit detect: 2m^2	**Max.rate**: 2kHz/cm^2 **Spatial res.:** ~1-2cm **Time res.:** ~ 1 ns **Rad. Hard.:** 1 C/cm^2	Redundant tracking and triggering
LHCb MUON UPGRADE CERN LS4	Hadron Collider (triggering)	μ-RWELL	Total area: ~ 90 m^2 Single unit detector: From 0,4x0,3 m^2 To 0,8x0,3 m^2	**Max.rate**:900 kHz/cm^2 **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ 2 C/cm^2	About 600 detectors

CMS Large-Area GEMs (GE2/1, ME0) for HL-LHC Upgrade



GE21 Detector System

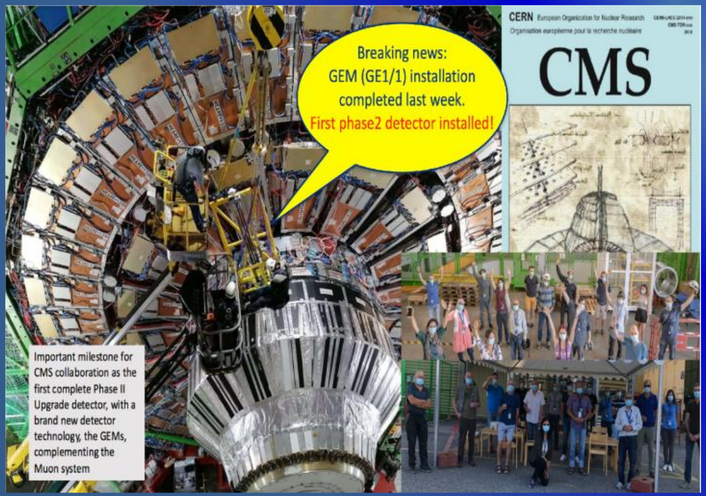
- 72 chambers arranged in 2 layers installed
- On-chamber and off-chamber
  - 4 triple GEM modules per chamber
- 20⁰ Chambers, layout similar to GE1/1, but covering much larger surface. (1.62<h<2.43)
- hit rate < 2 kHz/cm² (GE1/1 was up to 5 kHz/cm²)

ME0 Detector System

- 36 Stacks 6 layers each
- 20⁰ Stacks, Module Size comparable with GE1/1 chamber but covering high eta region (2<h<2.8)
- Background ~ 10² higher that GE2/1, very demanding from performance point of view

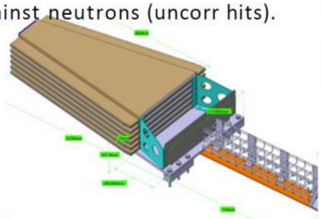
Triple GEM for HL-LHC in CMS: ME0

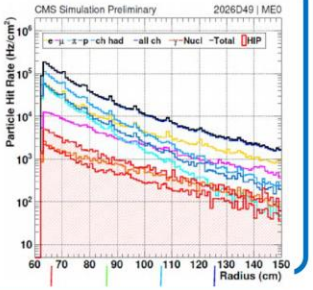
September 2020: 144 GEM GE1/1 chambers installed



Additional station GE2/1 and ME0 → **same technical solution successfully adopted for the GE1/1**

High granularity and spatial segmentation for for efficient matching of muon stubs to the offline pixel tracks.
Multi-layered structure to discriminate muon against neutrons (uncorr hits).





Detector requirements

- Rate-Capability: up to 150kHz/cm²
- Ageing: 7.9 C/cm² integrated charge in 10 yrs

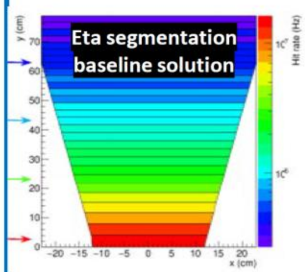
R&D needed to optimize the technology for operation of **large area detector** in very high rate environment

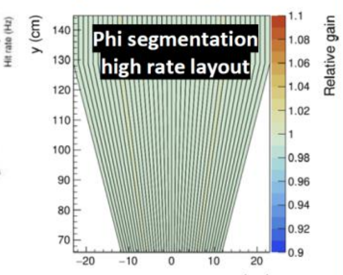
Discharge and x-talk mitigation strategy
GEM Foils Stack Design changes:

- GEM1 & GEM2 double segmented for discharge mitigation
- GEM3 single side (toward the Drift) segmented to reduce "cross-talk" effects

Aging test tests
No aging observed anywhere in Ar:CO_2 up to 1.5 C/cm² => 7,9 C/cm2 expected by 2023

Optimization of GEM foil layout for high rates



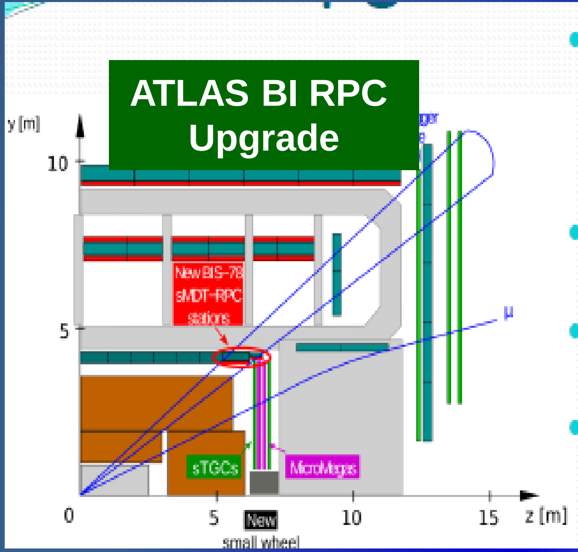


- Fine **foil segmentation** along phi direction → **reduced hit rate** per sector → **contained gain drop** due to voltage drops on protection resistors
- Segmentation independent of flux shape

ATLAS and CMS RPC Upgrades for HL-LHC

ATLAS BIS78 Upgrade – Pilot Project (LS2):

ATLAS BI RPC Upgrade



- The existing 32 BIS7 and BIS8 MDT will be replaced by 16 new muon stations made of:
  - one sMDT BIS7+8 chamber
  - two RPC triplets (BIS7 and BIS8)
- Selectivity in transition region improved by adding a new trigger layer
- 8 stations for one end cap (side A) to be installed in 2020
- BIS78 can be considered as a pilot project for the Phase II BI upgrade.

BIS7

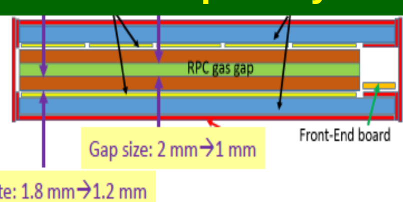
ATLAS BI RPC Upgrade (LS3):

	Standard RPC	BIS78 RPC	BI RPC
FEE			
Effective threshold	1mV	0.5mV	0.3mV
Power consumption	30 mW	6 mW	10 mW
Technology	GaAs	BJT Si + SiGe	Bi-CMOS SiGe
Discriminator	Embedded	Separated	Embedded
TDC embedded	No	No	Yes
Detector			
Gap Width	2 mm	1 mm	1 mm
Operating voltage	9600 V	5800 V	5400V
Electrode thickness	1.8 mm	1.2 mm	1.2 mm
Time resolution	1 ns	0.4 ns	0.4ns

ATLAS & CMS RPC Upgrades aim for rate capability ~ O(kHz/cm2)

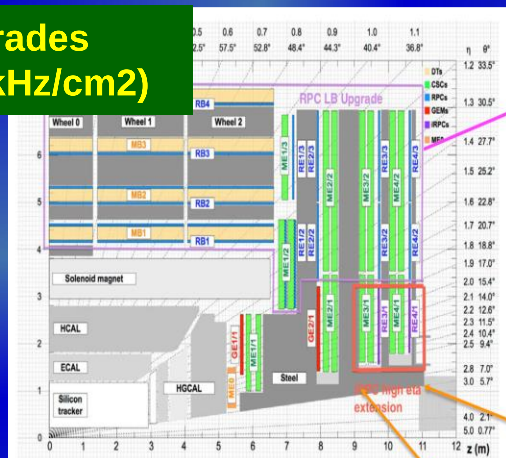
New generation of RPC

- Higher rate capability: → kHz/cm²
- Longer longevity: >10 years @ HL-LHC
- Higher spatial resolution: <1 cm
- Higher time resolution: ~ 0.5 ns

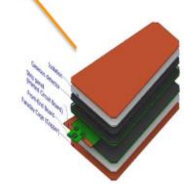


- Reduced bakelite thickness:
  - Less voltage loss in bakelite → improve the rate capability, larger induced signals
- Reduced gap size:
  - Less charge produced per event → improve longevity, l
  - Less high voltage applied but higher field → better tim
- New generation FE electronic:
  - Higher amplification factor and high S/N ratio to compensate the lost gas amplification.
- Improved readout panel and method
  - Better mechanics structure, better signal transmission and better spatial resolution.

ATLAS BI RPC Upgrade

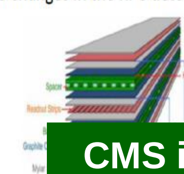


	iRPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap width	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10¹⁰	1 - 6 x 10¹⁰
Charge threshold	50 fC	150 fC
η segmentation	2D readout	3 η partitions



New LinkSystem (off-detector electronics):
- Increase readout frequency from 25 ns → 1.56 ns

No changes in the RPC detectors:



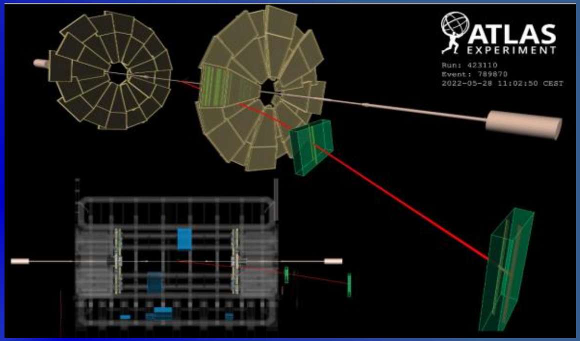
CMS iRPC Upgrade

New 72 RPC detectors will be installed in the two last endcap station RE3/1 and RE4/1 to extend RPC η coverage from 1.8 to 2.4.

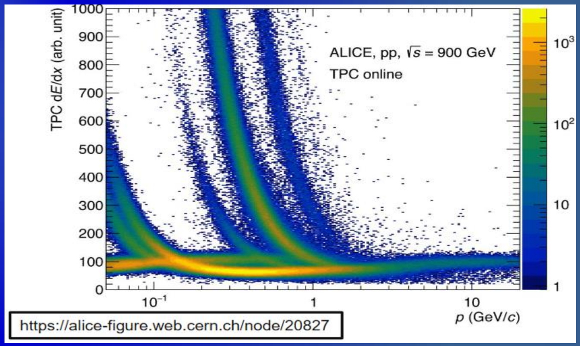
Improved RPCs:
- Improved hit position resolution along strips (≈2cm)
- Rate capability up to 2 kHz/cm²

CERN Detector Seminars in 2022: LS2 Upgrades

Major MPGDs developments for ATLAS, CMS, ALICE upgrades, towards establishing technology goals and technical requirements, and addressing engineering and integration challenges … and first results from Run 3 !!!

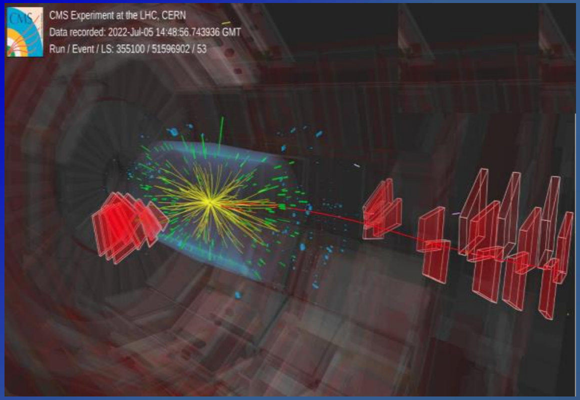


"The New Small Wheel project of ATLAS"
by Theodoros Vafeiadis (17 Jun 2022)
https://indico.cern.ch/event/1168778/



"Continuous data taking with the upgraded ALICE GEM-TPC"
by Robert Helmut Munzer (24 Jun 2022),
https://indico.cern.ch/event/1172978/

"The GEM detectors within the CMS Experiment"
Michele Bianco (08 Jul 2022)
https://indico.cern.ch/event/1175363/

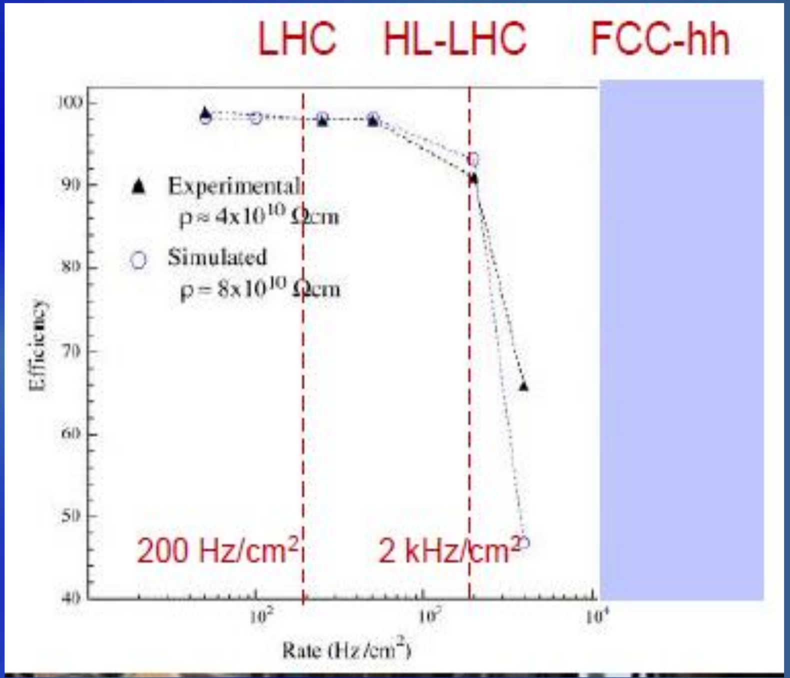


All three major LHC upgrades, incorporating MPGDs, started their R&D in close contact with RD51, using dedicated setups at GDD-RD51 Laboratory

Resistive Plate Chambers: Performance & Trends

Trigger and BX tagging at LHC / HL-LHC:

- ➢ Improve the rate capability
- ✓ from o(100 Hz/cm^2) --- LHC "now"
  - → o(1 kHz/cm^2) --- HL-LHC
  - → o(10 kHz/cm^2) --- FCC-hh



Future R&D Challenges:

- ***Will 10 kHz/cm2 be reachable and sustainably for 10-20 years of future collider operation?***
- ***What will be the trigger and aging performance with eco-friendly mixtures ?***
- ***MRPC challenges to produce large-areas of low resistivity glass***

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m^2) achieved time res. ~ 60 ps
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 µm-thick glass → down to 20 ps time resolution

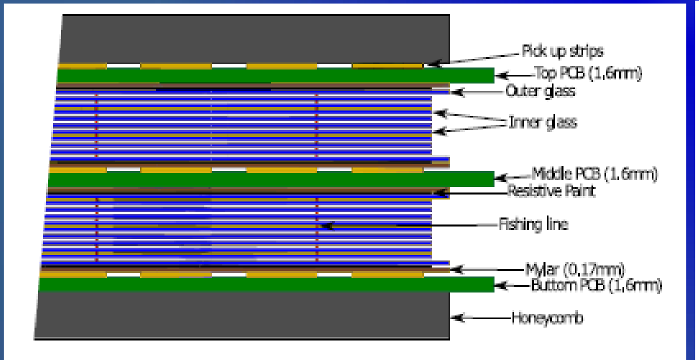
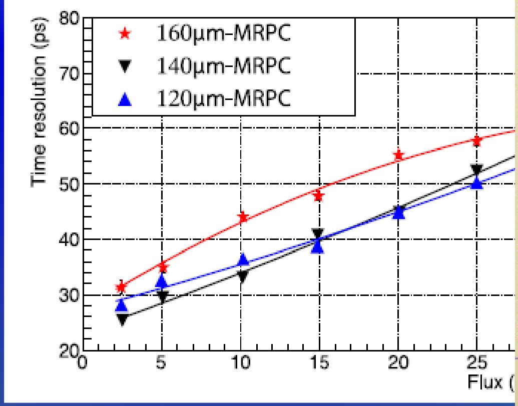
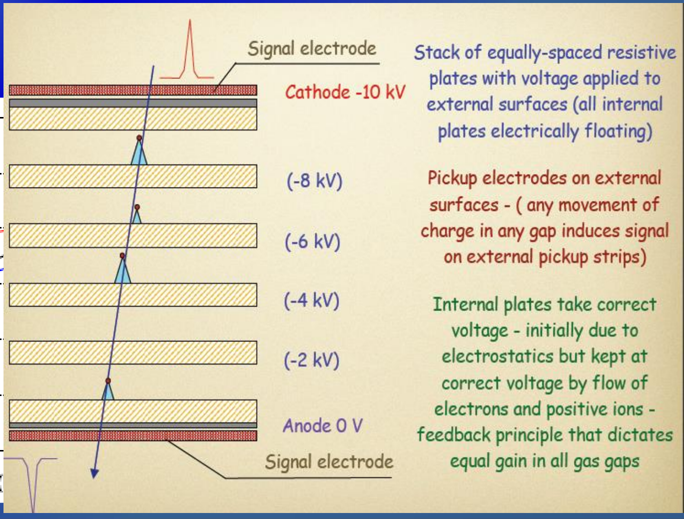


Fig. 1. Cross section of the double stack 20-gap MRPC.



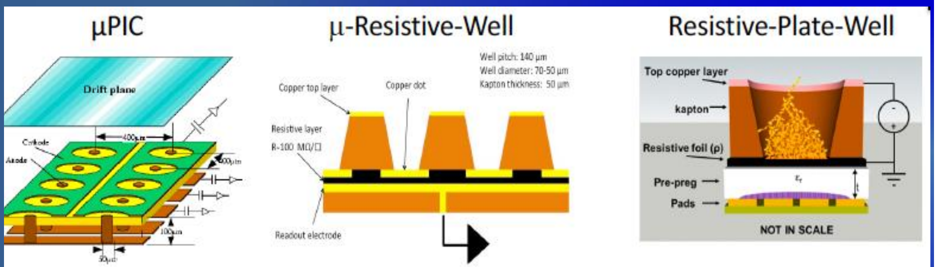


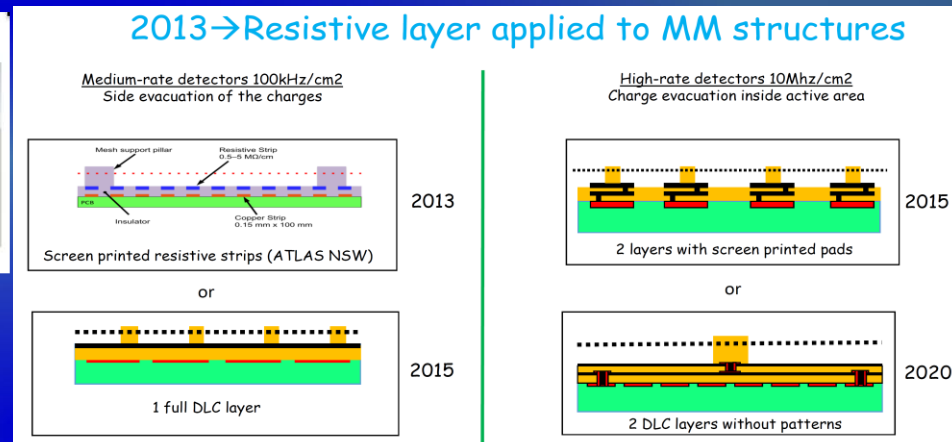
Resistive MPGD Structures: Performance & Trends

SINGLE-STAGE DESIGNS with RESISTIVE MATERIALS and related detector architecture

→ **µPIC, µRWELL, small-pad res. MM (proposed for ATLAS HL-LHC Forward Muon Tagger), RPWELL**

→ **improves detector stability; single-stage is advantage for assembly, mass production & cost**

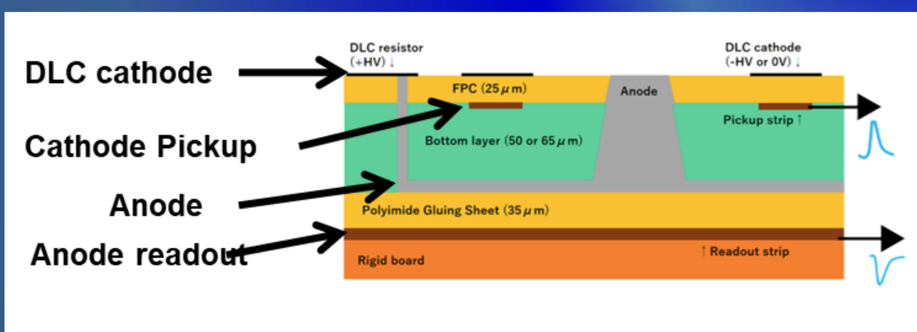


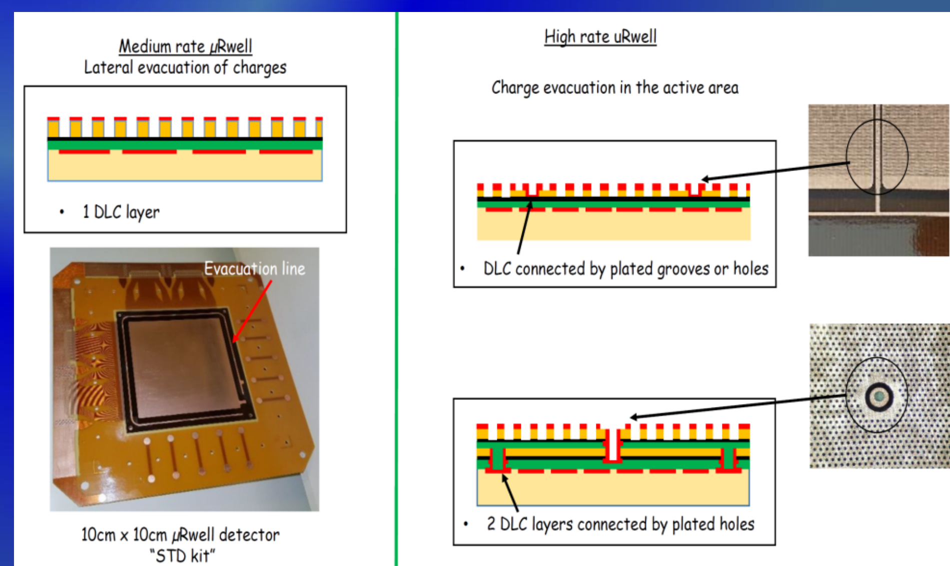


Diamond-like carbon (DLC) resistive layers :

- → Solutions to improve high-rate capability (≥ MHz)
- → Spark Protection
- → Resistive Spreading
- → Possibillity to make capacitive sharing

µRWELL High-Rate Layout O(Mhz/cm2) for LHCb Upgrade & Medium-Rate Layout for FCC-ee / CePC





Future R&D Challenges:

- ***Radiation-induced modification of surface resistivity after the very high radiation dose***

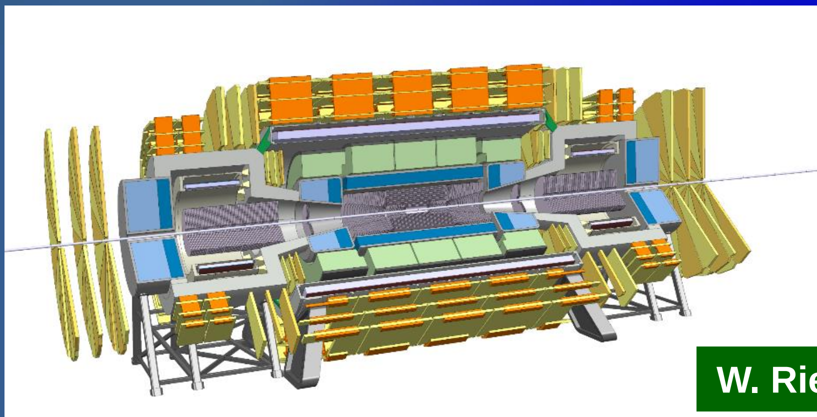
Muon Systems at Future Colliders (FCC, LHeC, Muon)

Experiment / Timescale	Application Domain	Gas Detector Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
LHeC COLLIDER MUON SYSTEM at HL-LHC	Electron – Proton Collider Tracking/Triggering	RPC / MDT	Total area ~ 400 m^2 Single unit detect: 2-5 m^2	**Max.rate**: 3 kHz/cm^2 **Time res.:** ~0.4 ns **Rad. Hard.:** 0.3 C/cm^2 **Spatial res.:** 1mm (RPC) 80 µm (MDT single tube)	
FCC-ee and/or CEPC IDEA PRESHOWER DETECTOR START: >2030	Lepton Collider Tracking	µ-RWELL	Total area: 225 m^2 Single unit detect: (0.5x0.5 $m^{2)}$ ~0.25 m^2	**Max. rate:** 10 kHz/cm^2 **Spatial res.:** ~60-80 µm **Time res.:** 5-7 ns **Rad. Hard.:** <100 mC/cm^2	
FCC-ee and/or CEPC IDEA MUON SYSTEM START: >2030	Lepton Collider Tracking/Triggering	µ-RWELL RPC	Total area: 3000 m^2 Single unit detect: ~0.25 m^2	**Max. rate:** <1 kHz/cm^2 **Spatial res.:** ~150 µm **Time res.:** 5-7 ns **Rad. Hard.:** <10 mC/cm^2	
FCC-hh COLLIDER MUON SYSTEM START: > 2050	Hadron Collider Tracking/Triggering	All HL-LHC technologies (MDT, RPC, MPGD, CSC)	Total area: 3000 m^2	**Max. rate**: < 500 kHz/cm^2 **Spatial res.:** <100 µm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ C/cm^2	Redundant tracking and triggering;
MUON COLLIDER MUON SYSTEM START: > 2050	Muon Collider	RPC or new generation fast Timing MPGD	Total area: ~ 3500m^2 Single unit detect: 0.3-0.4m^2	**Max.rate**: <100 kHz/cm^2 **Spatial res.:** ~100µm **Time res.:** <10 ns **Rad. Hard.:** < C/cm^2	Redundant tracking and triggering

- ✓ **Muon System at ILC: no challenges, same technology as for HCAL (RPC, MPGD)**
- ✓ **Muon System at LHeC: CDR update uses design similar to Phase 2 in ATLAS, and in particular, Barrel Muon - second generation RPC and small Monitored Drift Tubes:** 1 layer composed of a triplet of RPC 1mm gas-gaps and ~8 layers of MDT tubes assembled in station of ~ 2 m^2

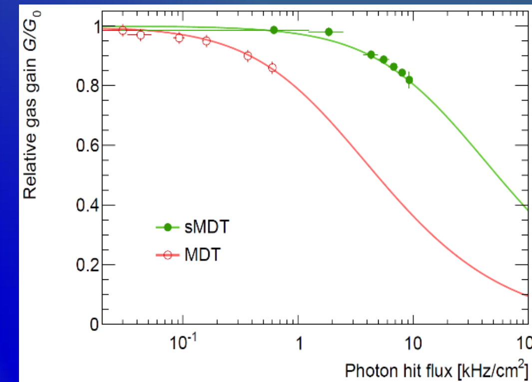
Muon System for the FCC-hh Collider

Barrel Muon system (2 layers) : 2000 m² total
Endcap Muon System (2 layers): 500 m² total
Forward Muon System: (4 layers): 320 m² total



W. Riegler

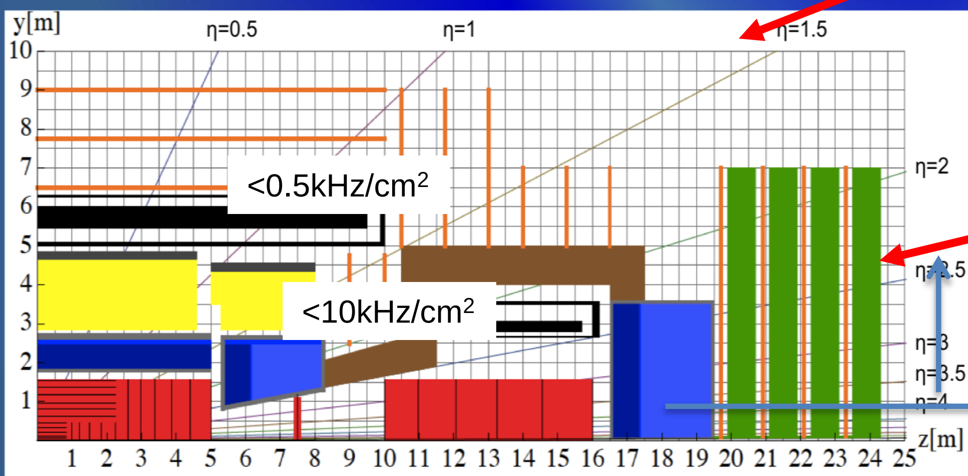
ATLAS MDT Drift Tubes:



ATLAS Muon System HL-LHC: (kHz/cm²):

- ✓ MDTs barrel: 0.28
- ✓ MDTs endcap: 0.42
- ✓ RPCs: 0.35
- ✓ TGCs: 2
- ✓ Micromegas und sTGCs: 9-10

HL-LHC muon system gas detector technology will work for most of the FCC detector area



LHCb Muon System (MWPC):

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} at a collision energy of 14 TeV. The values are averages, in kHz/cm², over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
M5R4	0.23 ± 0.03	2.1 ± 0.3	9.0 ± 1.3

Rad-hard design and hydrocarbon-free gas mixture studies will be needed for the very forward region ((R < 1m; Rate ~ 500 kHz/cm2)

Muon System for the Muon Collider

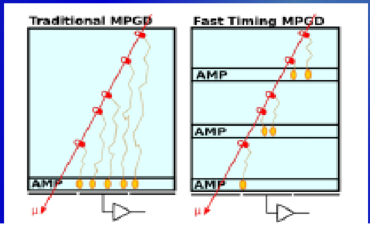
Muon system, based on CLIC, instruments the iron yoke plates with barrel/endcap (6/7 layers)

MPGDs / RPCs, ... for readout of high-granularity hadronic calorimeters and for muon detectors in high rate (e.g. endcaps, first station in barrel,…)

✓ Glass RPC cells of 30x30 mm2 to cover an area of 1942 (1547) m2 in barrel (endcaps)

C. Ilaria, C. Piccard N. Pastrone

✓ Fast Timing MPGDs:

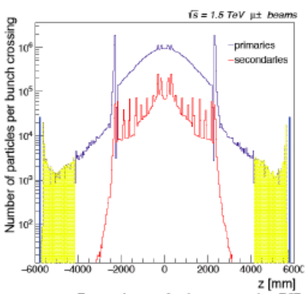


- Purpose of the fast timing MPGD (FTM): Improving on the time resolution of traditional MPGDs (~5ns) for MIP signals to ~500ps
- Jet energy resolution will scale 1/sqrt(number of jet particles)
- Working principle: Competition of arrival time of independent signals generated by fully decoupled drift+amplification layers

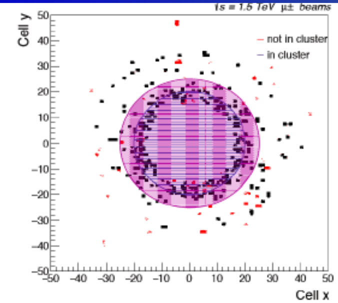
$$\sigma_{FTM} = \frac{\sigma_{layer}}{N_{layers}}$$

$N_{layers} = 12 \rightarrow \sigma \sim 400$ps

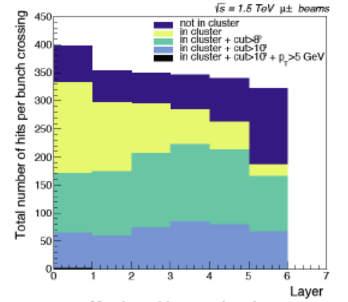
Beam Induced Background (BIB) due to the single bunch ($2\text{x}10^{12}\mu/bunch$) muon beams is dominant
→ affecting mostly the endcap region of the Muon detector



Z coordinate final position for BIB particles. The first and the last bin in solid blue are the integral of all particles escaping the detector. In yellow the position of the muon system endcaps.

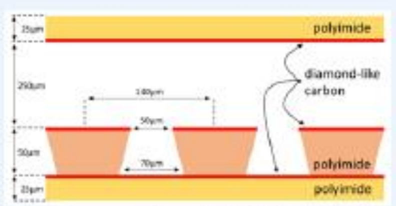


BIB muon hit spatial distribution in the first layer of the muon system endcap. In red the hits not associated to a cluster. The blue circle corresponds to region $\theta < 8°$, while the purple to $\theta < 10°$.



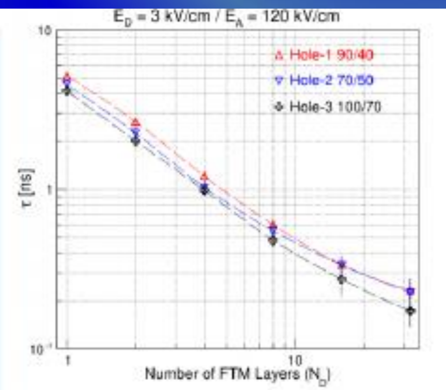
Number of hits per bunch crossing in each layer of the muon system. Different cuts are applied.

Signal pick-up by **external R/O electrodes**
→ **fully resistive** detector structure



Structure of a single FTM layer

Prototypes undergoing tests in Bari, Pavia (Italy), Ghent (Belgium)



Simulated FTM time resolution for different n. of layers

Glass RPC:

- σ_t < 100 ps
- Rate capability ~ 100-200 kHz/cm² , (but up to now only in small prototypes)
- ISSUE: gas mixture GWP

Alternatives: HPL-RPC:

- σ_t < 100 ps
  - also 50 ps in MRPC configuration
- σ_x ~ 1 x 1 cm²
- Rate capability ~ 1-2 kHz/cm²
- Large size

Some thoughts on technologies:

MPGD-based:

- σ_t > 10 ns
- σ_x ~ 100 um
- Rate capability ~ 100 kHz/cm²
- Large size

→ starting from MPDG technologies (ex. Triple-GEM) improve time resolution with alternative solution like PicoSec

Radiation Levels not Even Thought in '1980: from mC/cm → C/cm

'Low & Standard radiation levels' (LEP,HERA ep, BaBar/Belle,CDF/D0...)

- Basic rules for constructionare known and well tested
- Detectors are built and demonstrated to work
- Huge variety of gases are used
- If aging is nevertheless observed:
  - use oxygen-based (H20, alcohol) molecules to inhibit/relief/cure hydrocarbon polymerization (anode aging/Malter effect);
  - having identified the source of pollution, try to clean the gas system (e.g. operation with CF_4 decreases a risk of Si polymerization)

New classes of Igas detectors – straws, MSGC, MPGD, CsI, RPC with their own specific aging effects evolved

MPGDs are much less sensitive to radiation-induced aging, compared to MWPC

'High radiation levels' – enormous R&D done (RD10, RD28, RD6, HERA-B, LHC, NP Exp…)

- Some basic rules are found
- There are clearly a lot of 'bad' and some 'usable' materials → careful choice of construction materials: radiation hardness and outgassing properties are of a primary importance
- Only a few gases are attractive candidates (noble gases, CF_4, CO_2, O_2, H_2O, alcohols) at high rates:
  - Hydrocarbons are not trustable for high rate exper.
  - Operational issues can be aggravated by CO_2 as a quencher and by the very high aggressiveness of CF_4 dissociative products (e.g. glass etching)
- Adequate assembly procedures, maximal cleanliness for all processes andquality checks for all system parts → personnel training, no greasy fingers, no polluted tools, no spontaneously chosen materials installed in the detector or gas system in the last moment, before the start of real operation
- Careful control for any anomalous activity in the detector: dark currents, variation of anode current, remnant activity in the chamber when beam goes away.

https://indico.cern.ch/event/1237829

Gaseous Detectors: Software and Simulation Tools

Garfield, together with HEED, Degrad, Magboltz, SRIM, ANSYS, COMSOL, and neBEM software packages represent the core simulation tools for microscopic modelling of gaseous detector response.

MPGDs and the mean free path

- Recall:
  - Mean free path of electrons in Ar: 2.5 μm,
- Compare with:
  - Micromegas mesh pitch: 63.5 μm
  - GEM polyimide thickness: 50 μm
  - Micromegas wire thickness: 18 μm
  - GEM conductor thickness: 5 μm
- Hence:
  - mean free path approaches small structural elements;
  - such devices should be treated at a molecular level.
- In addition, MPGDs usually have structures for which no nearly-exact (e.g. 3d structures) fields are known.

✓ ***HEED* – energy loss, a photo-absorption and ionization model**

✓ ***DEGRAD* – electron transport, cluster size distribution**

✓ ***Magboltz* – electron transport properties: drift, diffusion, multiplication, attachment**

✓ ***ANSYS, COMSOL, neBEM* – electric field maps in 2D / 3D**

✓ ***Garfield* – fiedls, drift properties, signals (interfaced to above)**

Some recent highlights:

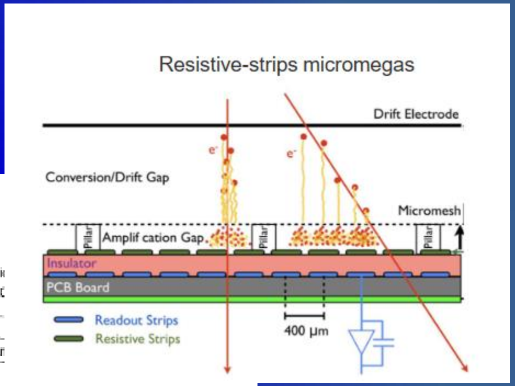
- ***Garfield++ et al.* (new development and maintenance of codes, documentation, examples)** **https://gitlab.cern.ch/garfield/garfieldpp**
- ***Garfield++ and delayed weighting fields in the calculation of the induced signal (resistive electrodes)***
- ***Greenhouse gases***
- ***Improving accuracy of the modelling and the detector physics understanding:* Penning transfer, Non equilibrium effect in gaseous detectors, Ions and cluster ions**

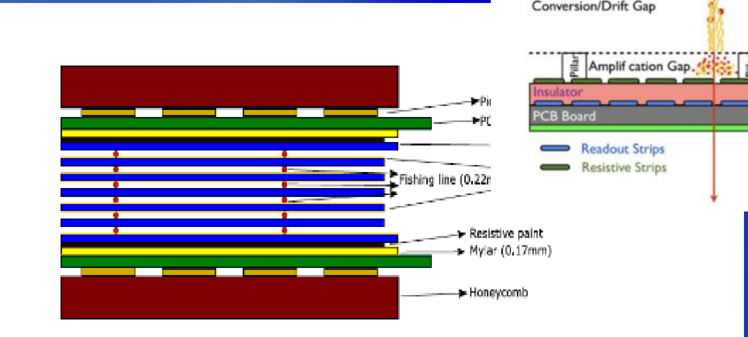
Signal Formation in Detectors with Resistive Elements

RD51 supported** ongoing efforts on **interfacing between different modeling tools** – to address properly involved processes at the microscopic level - **extending present simulation framework to other gaseous & Si-detectors

EP R&D SEMINAR, Signal formation in detectors with resistive elements by **Djunes Janssens:** https://indico.cern.ch/event/1167590/contributions/4903447/attachments/2460899/4219187/EPSeminar_DjunesJanssens.pdf

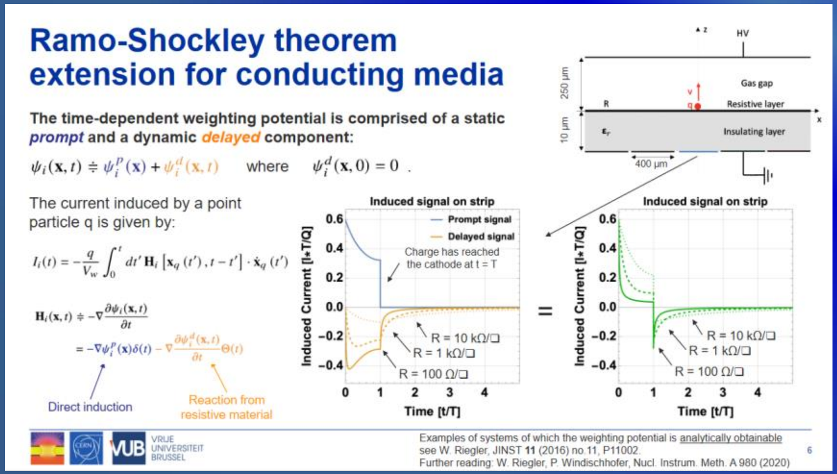
Gaseous (MPGD, RPC,..)

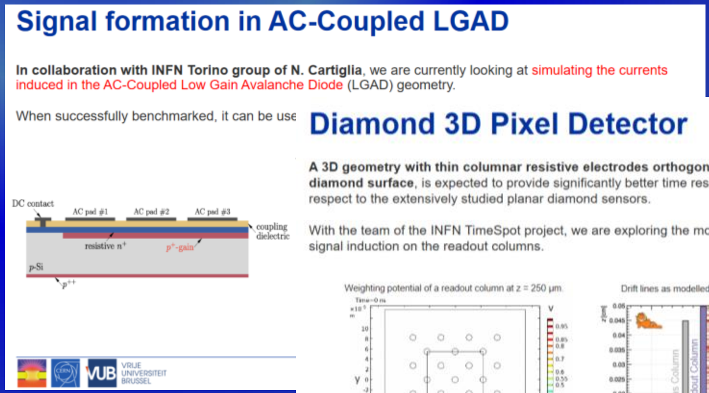


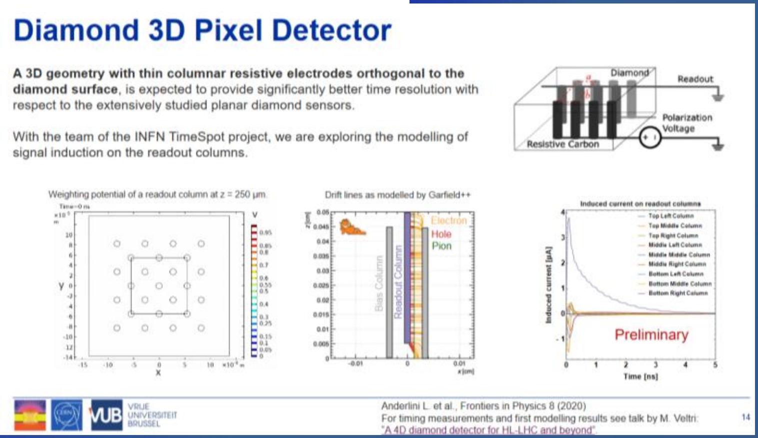


Garfield++ and COMSOL to model the **signal formation in detectors with resistive elements** by applying an extended form of the Ramo-Shockley theorem

Solid State (Silicon, Diamond,..)







Gaseous Detectors: DRD1 Successor and Extension of RD51

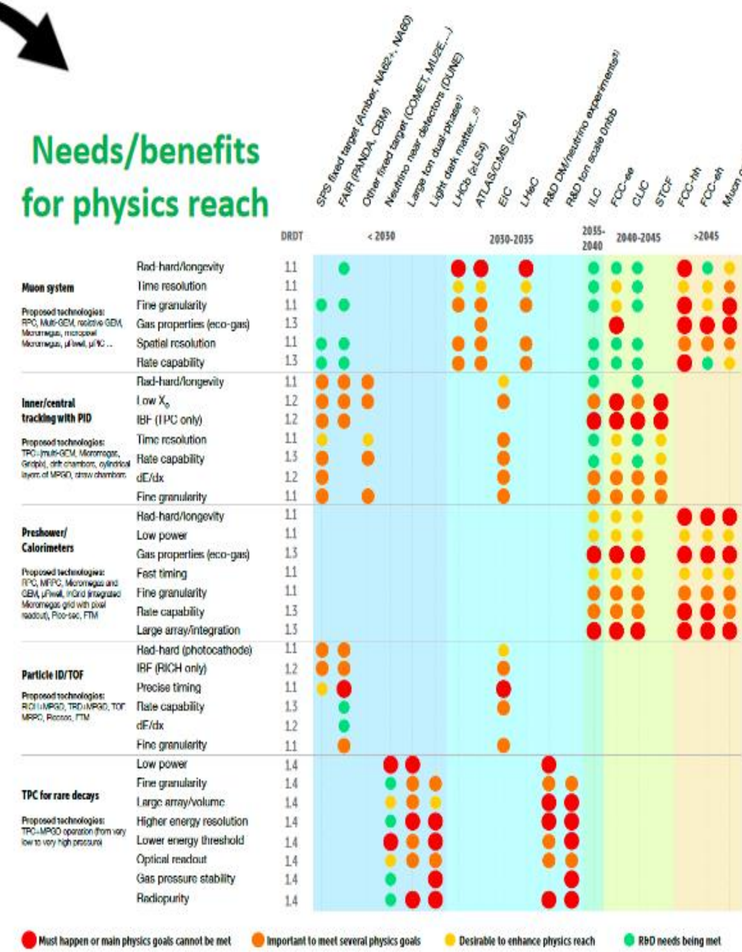
ECFA DETECTOR R&D ROADMAP CONTENT: TF1

Performance targets and main drivers from facilities

Facility	Technologies	Challenges	Most challenging requirements at the experiment
HL-LHC	RPC, Multi-GEM, resistive-GEM, Micromegas, micro-pixel Micromegas, μ-RWELL, μ-PIC	Ageing and radiation hard, large area, rate capability, space and time resolution, miniaturisation of readout, eco-gases, spark-free, low cost	**(LHCb)**: Max. rate: 900 kHz/cm^2 Spatial resolution: ~ cm Time resolution: O(ns) Radiation hardness: ~ 2 C/cm^2 (10 years)
Higgs-EW-Top Factories (ee) (ILC/FCC-ee/CepC/SCTF)	GEM, μ-RWELL, Micromegas, RPC	Stability, low cost, space resolution, large area, eco-gases	**(IDEA):** Max. rate: 10 kHz/cm^2 Spatial resolution: ~60-80 μm Time resolution: O(ns) Radiation hardness: <100 mC/cm^2
Muon collider	Triple-GEM, μ-RWELL, Micromegas, RPC, MRPC	High spatial resolution, fast/precise timing, large area, eco-gases, spark-free	Fluxes: > 2 MHz/cm^2 ($\theta<8^0$) < 2 kHz/cm^2 (for $\theta>12^0$) Spatial resolution: ~100μm Time resolution: sub-ns Radiation hardness: < C/cm^2
Hadron physics (EIC, AMBER, PANDA/CMB@FAIR, NA60+)	Micromegas, GEM, RPC	High rate capability, good spatial resolution, radiation hard, eco-gases, self-triggered front-end electronics	**(CBM@FAIR):** Max rate: <500 kHz/cm^2 Spatial resolution: < 1 mm Time resolution: ~ 15 ns Radiation hardness: 10^{11} neq/cm^2/year
FCC-hh (100 TeV hadron collider)	GEM, THGEM, μ-RWELL, Micromegas, RPC, FTM	Stability, ageing, large area, low cost, space resolution, eco-gases, spark-free, fast/precise timing	Max. rate 500 Hz/cm^2 Spatial resolution = 50 μm Angular resolution = 70 μrad (η=0) to get $\Delta p/p \leq 10\%$ up to 20 TeV/c

Example: Muon systems

Needs/benefits for physics reach



Detector R&D themes

DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)

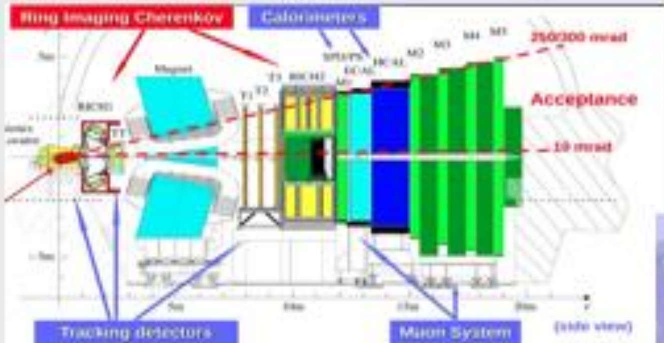
< 2030 | 2030-2035 | 2035-2040 | 2040-2045 | > 2045

Gaseous

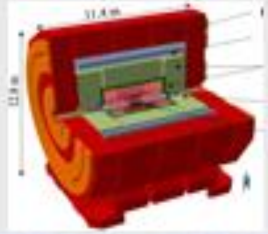
- **DRDT 1.1** Improve time and spatial resolution for gaseous detectors with long-term stability
- **DRDT 1.2** Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
- **DRDT 1.3** Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
- **DRDT 1.4** Achieve high sensitivity in both low and high-pressure TPCs

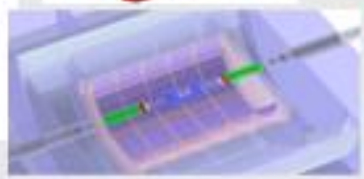
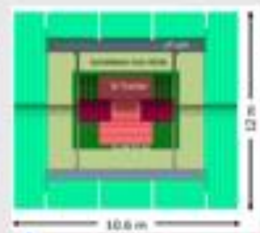
Main target projects of Gaseous Detector R&D

HL-LHC after LS4



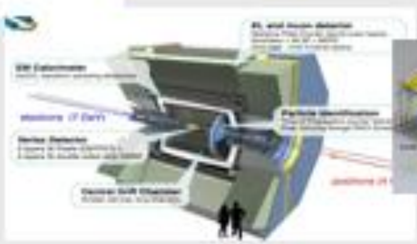
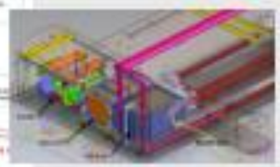
Higgs Factories



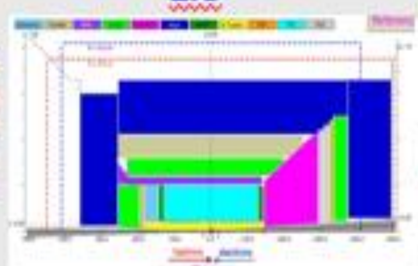
Future hadron colliders (FCC-hh/eh colliders)

SuperKEKB, DUNE ND

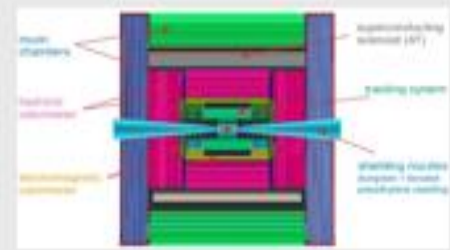
Hadron physics

EiC

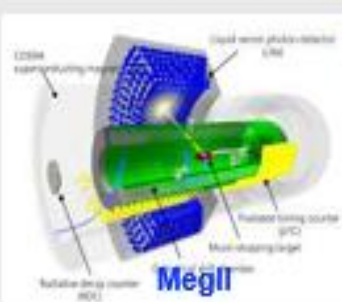


PANDA

Muon Collider

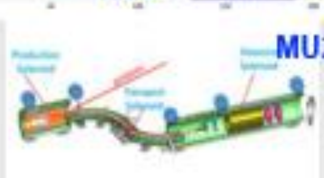


Rare event search, fixed target (LFV, Kaon physics)



MegII

HIKE



MU2E

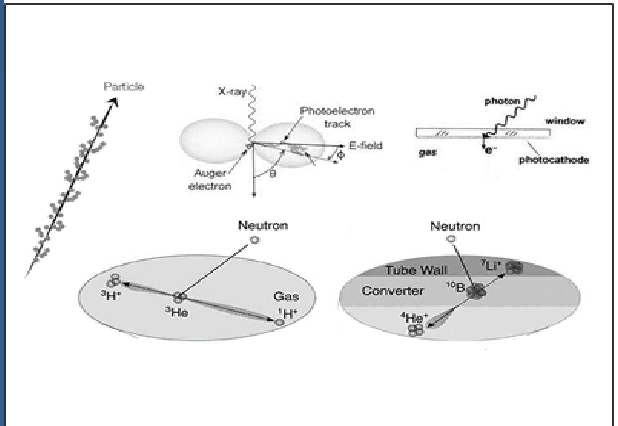
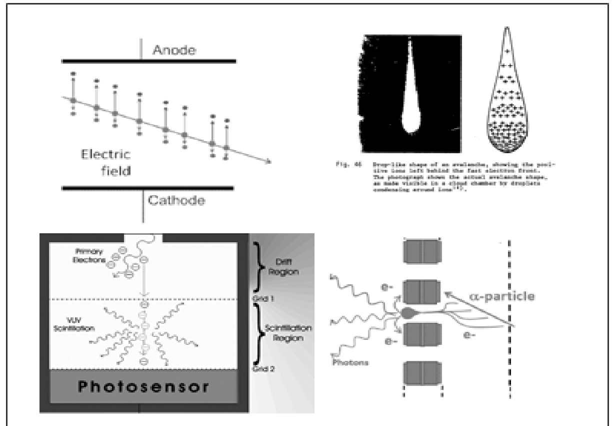
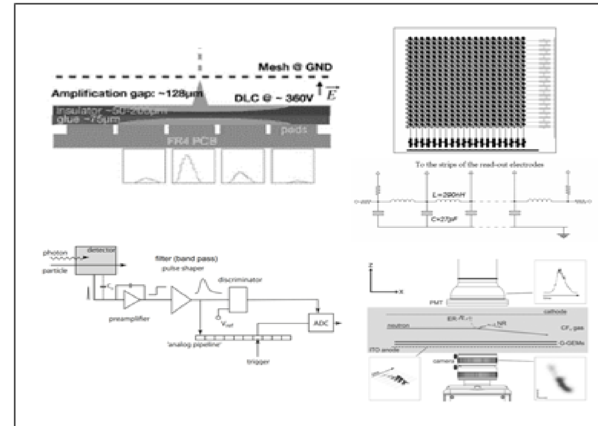
DM, solar axions, ββ0ν-decay, neutrino, nuclear, astroparicle

MIGDAL

Darksphere

Cygnus

Gaseous Detector R&D: Common Issues

Ionization	charge drifting and amplification	readout
		

Despite the different R&D requirements, there is **potential for overlapping in many aspects, allowing for a larger community of gaseous detectors to benefit.** The most straightforward example is the classic ageing issues, but many others can be mentioned:

- **MPGD-** the main challenges remain large areas, high rates, precise timing capabilities, and stable discharge-free operation
- **RPC -** focus stays on improving high-rate and precise timing capabilities, uniform detector response, and mechanical compactness.
- **Straw tubes-** requirements include extended length and smaller diameter, low material budget, and operation in a highly challenging radiation environment.
- **Large-volume Drift chamber** with a reduced material budget in a high-rate environment requires searching for new materials. Avalanche-induced Ion Back Flow (IBF) remains the primary challenge for **TPC applications** in future facilities.

DRD1 Scientific Organization

Gaseous		
	DRDT 1.1	Improve time and spatial resolution for gaseous detectors with long-term stability
	DRDT 1.2	Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes
	DRDT 1.3	Develop environmentally friendly gaseous detectors for very large areas with high-rate capability
	DRDT 1.4	Achieve high sensitivity in both low and high-pressure TPCs

ECFA Detector R&D Roadmap and General Recommendations are addressed with a scientific organization based on:

- ✓ **R&D Framework & Working Groups (RD51 Legacy)** → Distributed R&D Activities with Centralized Facilities.
- ✓ **Work Packages** → Strategic R&D and Long -Term Funding (Funding Agency)

DRDTs

1.1	1.2	1.3	1.4	Work Packages
●		●		Trackers/hodoscopes
●	●	●		Drift chambers
●	●	●		Straw chambers
●	●	●	●	Tracking TPCs
●		●		Calorimetry
●	●	●		Photon detection (PID)
●		●		Timing detectors
●	●	●	●	Reaction/decay TPCs
●		●		Beyond HEP

WG1	WG2	WG3	WG4	WG5	WG6	WG7	WG8
Technologies	Applications	Gas and material studies	Detector physics, simulations and software tools	Electronics for gaseous detectors	Detector production	Common test facilities	Training and dissemination

DRD1 Organization and Management

Approved during the Collaboration Board with Consensus

COLLABORATION BOARD

RESOURCE BOARD

MANAGEMENT BOARD

SPOKESPERSONS

SCIENTIFIC COORDINATION BOARD
(Working Groups, Work Packages, DRDs Liaisons, Common Projects

Simlar to the RD51 Structure + SCB

- DRD1 spokespersons and CB chair candidates, CV, statements and open presentations: https://indico.cern.ch/event/1352912/

- Wide consolations and nominations from whole community (about 160 institutes)
- Election procedure discussed & approved by the DRD1 Implementation Team and DRD1 CB
- About 110 instates casted votes:

Elections Results (2024 -2025)

- **2 Spokespersons: Eraldo Oliveri, Maxim Titov**
  CB Chair: Anna Colaleo

✓ **DRD1 implementation and organization: Community Driven with key role played by the Implementation Team (about 50 persons)**

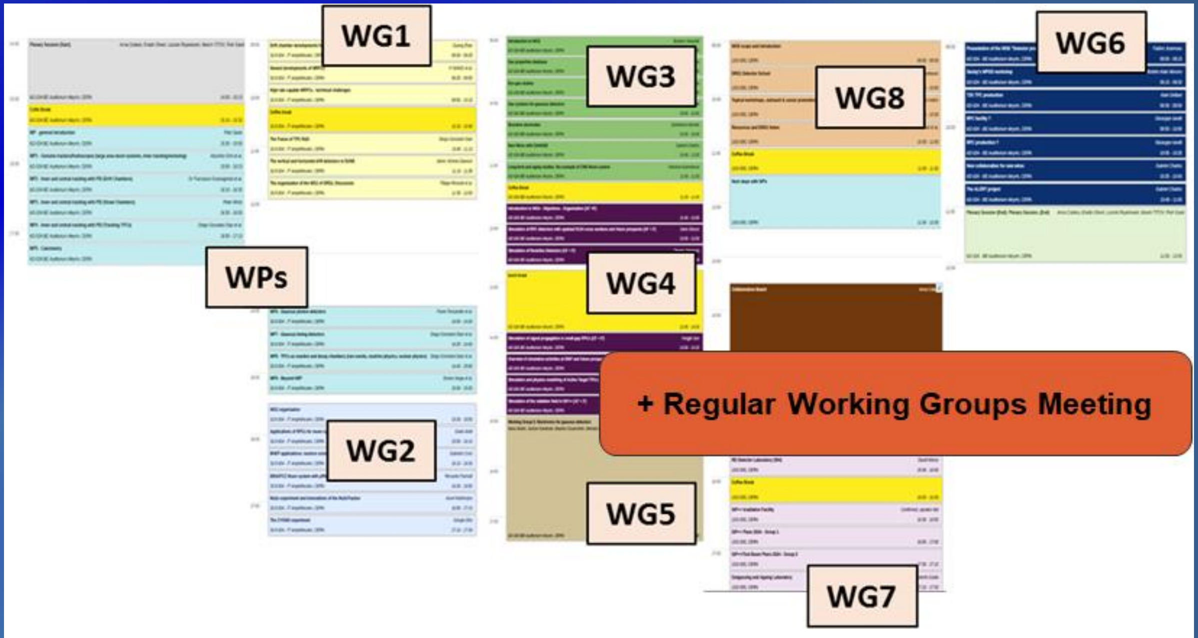
✓ **DRD1 Management Elections and Organization approved by CB. All roles will be approved by DRD1 Meting in June 2024**

✓ **DRD1 Activities started**

✓ **Prompt actions required to preserve and enhance the current momentum in the community**

DRD1 Collaboration & Future Events: JOIN US !!!

1st DRD Collaboration Meeting Agenda (Jan. 29 – Feb. 2)



1st Collaboration Meeting
Jan. 29-Feb. 2 (CERN):
https://indico.cern.ch/event/1360282/

2nd Collaboration Meeting
June 17-21 (CERN):
https://indico.cern.ch/event/1413681/

3rd Collaboration Meeting
December 9-13 (CERN)

More information on DRD1- related issues:
- Symposium of Task Force 1: https://indico.cern.ch/event/999799/
- ECFA Detector R&D Roadmap (chapter 1): https://cds.cern.ch/record/2784893
- DRD1 Proposal: https://cds.cern.ch/record/2885937
- DRD1 Website: https://drd1.web.cern.ch/
- Working Groups: https://drd1.web.cern.ch/working-groups
- Work Packages: https://drd1.web.cern.ch/wp

2024 Gaseous Detector Conferences & Schools:
- RPC2024 Conference, Santiago, 9-13 September: https://indico.cern.ch/event/1354736
- MPGD2024 Conference, Hefei, 14-18 October: https://mpgd2024.aconf.org
- DRD1 Gaseous Detector School, Nov. 27 – Dec. 6: https://indico.cern.ch/e/drd1school2024