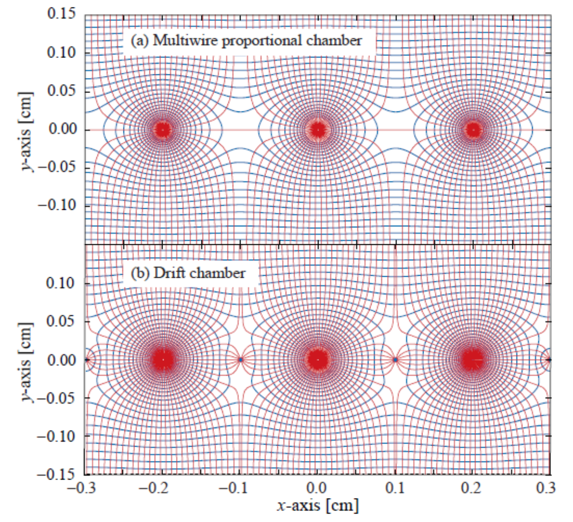

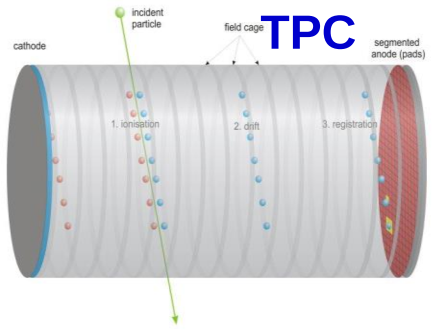

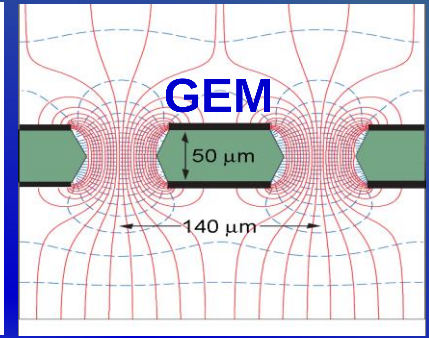

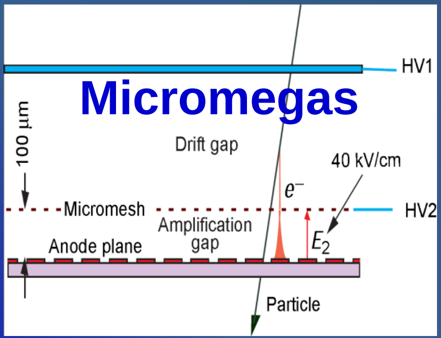

From (very) Basic Ideas to Rather Complex Gaseous Detector Systems

Maxim Titov, CEA Saclay, Irfu, France

The 8th International Conference on Micro-Pattern Gaseous Detectors
Oct.14th - Oct.18th 2024
University of Science and Technology of China, Hefei, China

MPGD2024:

The MPGD2024 conference program will comprise a series of plenary sessions for invited and contributed talks for new results and developments in the MPGD field around the world. A poster session will also be organised.

Topics covered in the conference program:

- ☑ MPGD technologies
- ☑ Detector physics
- ☑ Detector performance
- ☑ Simulation and software
- ☑ Applications
- ☑ Electronics
- ☑ Production techniques
- ☑ Future perspectives

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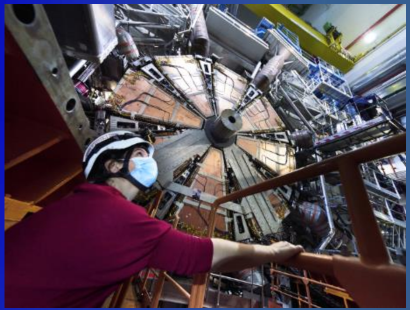
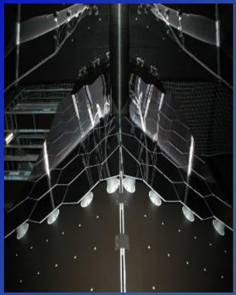
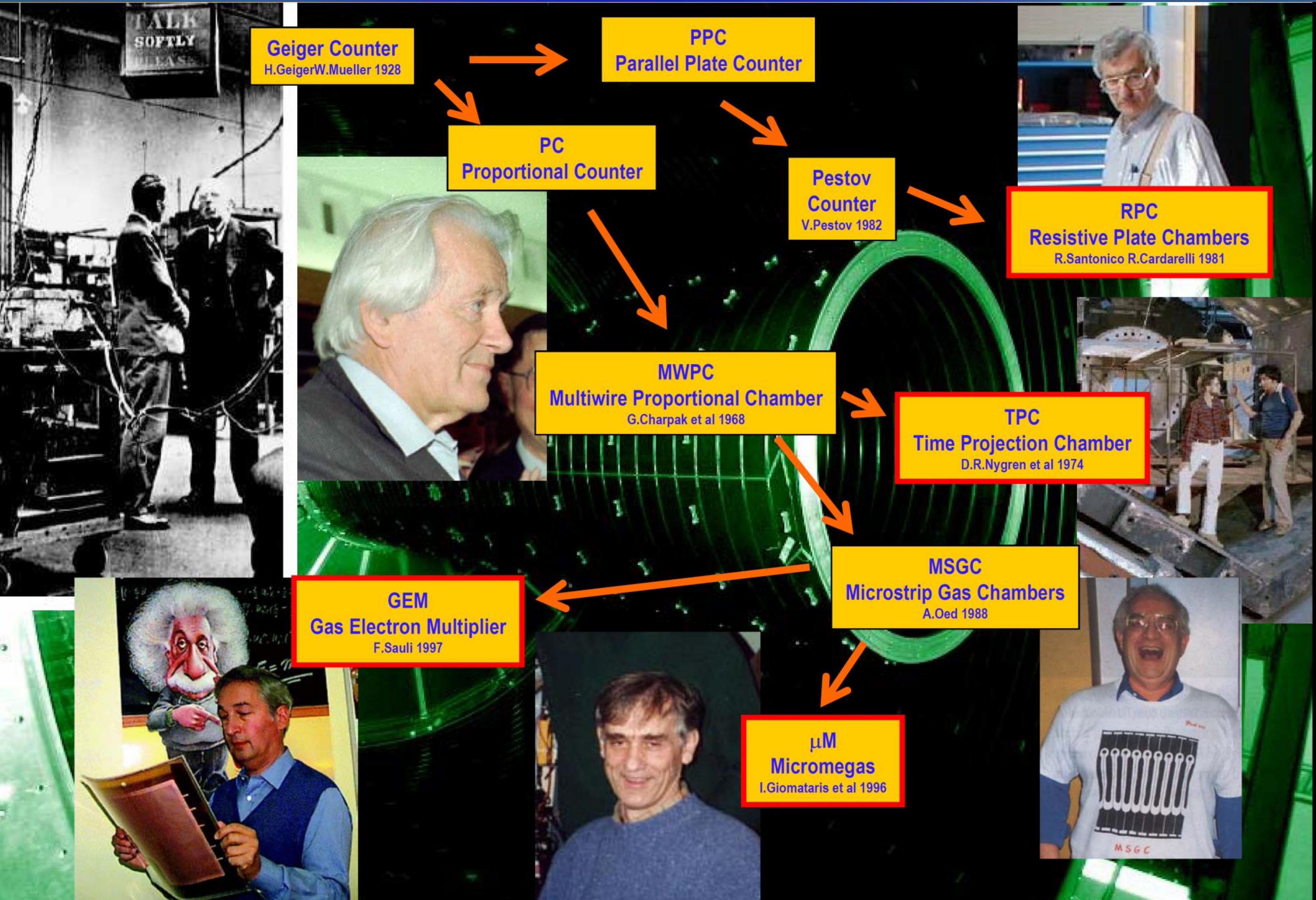







8th International Conference on Micro-Pattern Gaseous Detectors, University of Science and Technology of China, Hefei, China, Oct, 14-18, 2024

Gaseous Detectors: A Brief History



Geiger Counter
H.GeigerW.Mueller 1928

PPC
Parallel Plate Counter

PC
Proportional Counter

Pestov Counter
V.Pestov 1982

RPC
Resistive Plate Chambers
R.Santonico R.Cardarelli 1981

MWPC
Multiwire Proportional Chamber
G.Charpak et al 1968

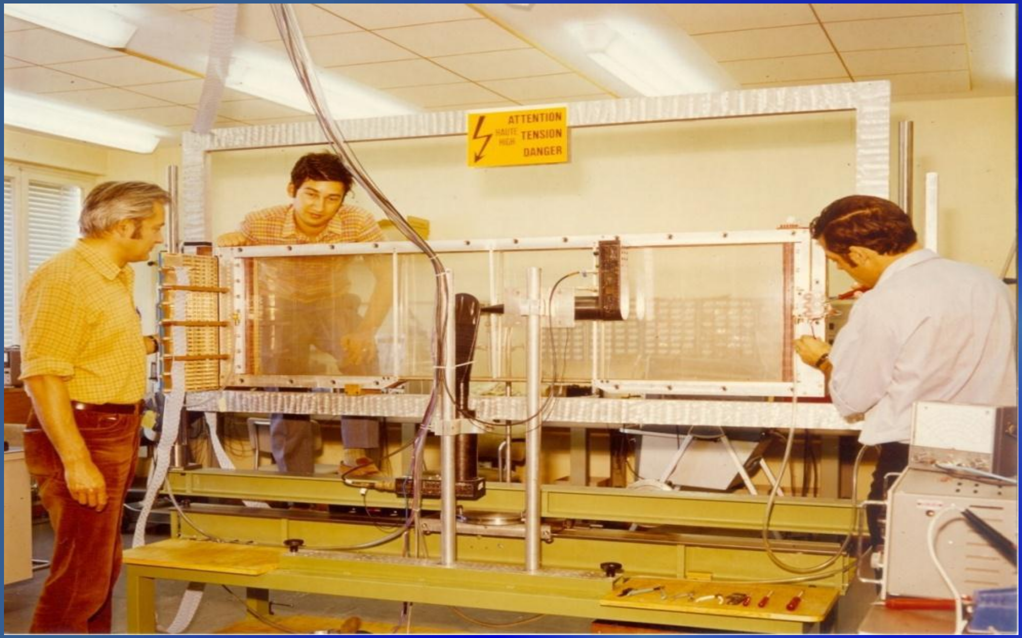
TPC
Time Projection Chamber
D.R.Nygren et al 1974

MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997

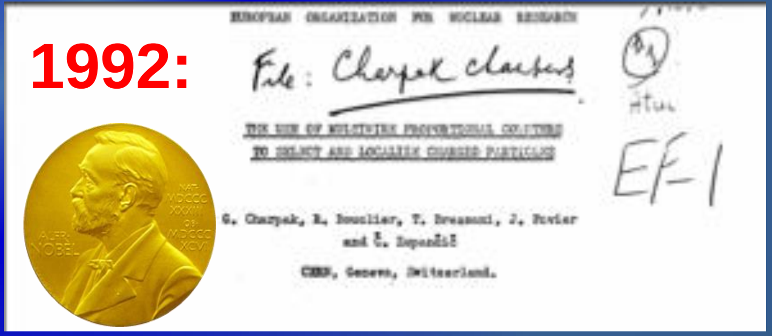
µM
Micromegas
I.Giomataris et al 1996

1968: MWPC – Revolutionising the Way Particle Physics is Done



The progress in experimental particle physics is driven by the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies:

1968: George Charpak developed the MultiWire Proportional Chamber, which revolutionized particle detection and HEP - which passed from the manual to the electronic era.



1992:

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

File: Charpak chambers

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

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

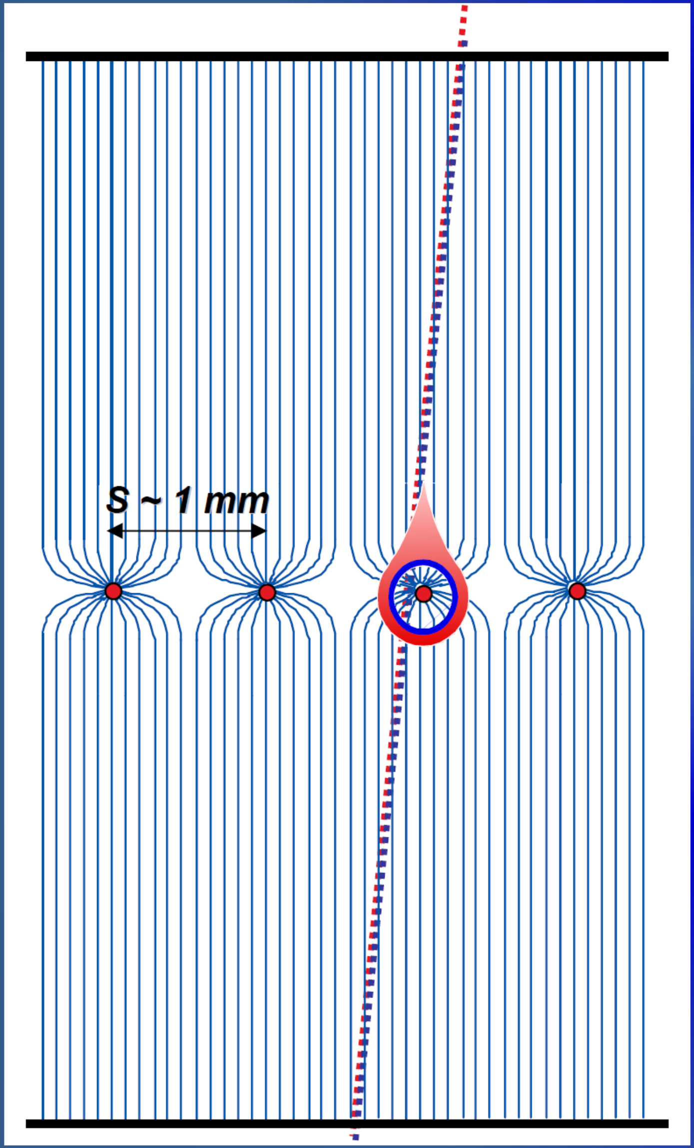
CERN, Geneva, Switzerland.

EF-1

Electronic particle track
detection is now standard
in all particle detectors

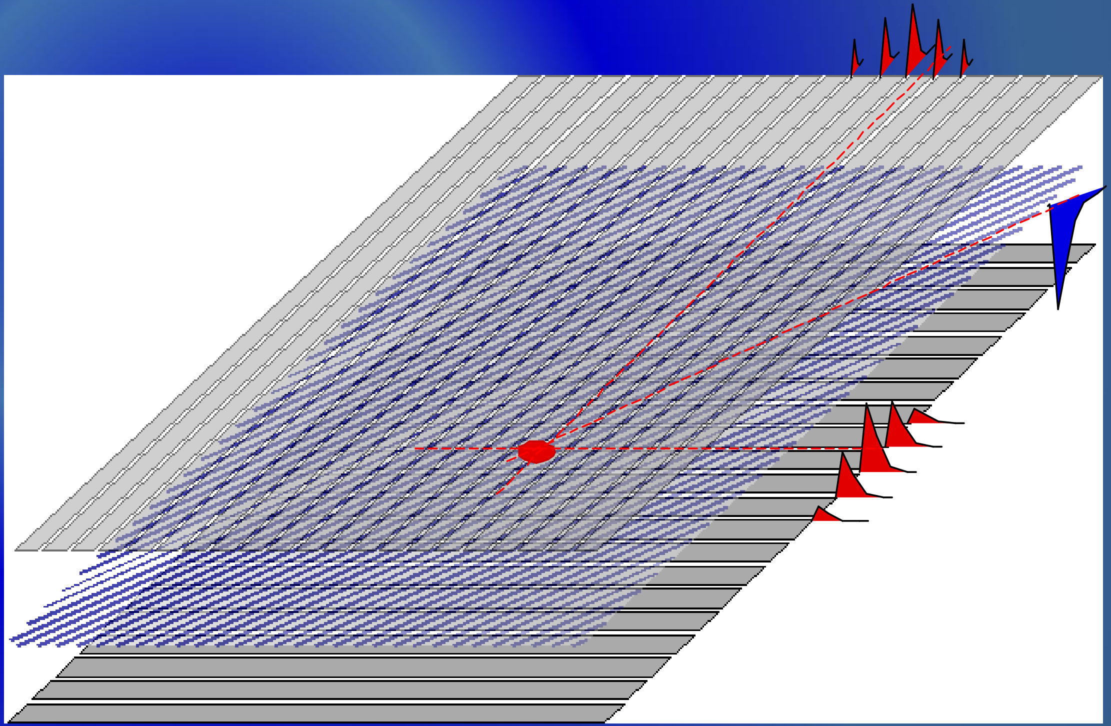
Multi-Wire Proportional Chamber (MWPC)

Simple idea to multiply SWPC cell → First electronic device allowing high statistics experiments !!



High-rate MWPC with digital readout:
Spatial resolution is limited to s_x ~ s/sqrt(12) ~ 300 μm

TWO-DIMENSIONAL MWPC READOUT CATHODE INDUCED CHARGE (Charpak and Sauli, 1973)



Spatial resolution determined by: Signal / Noise Ratio
Typical (i.e. 'very good') values: S ~ 20000 e: noise ~ 1000e
Space resolution < 100 μm

Multi-Wire Proportional Chamber (MWPC): Wire Displacements

Resolution of MWPCs limited by wire spacing
better resolution → shorter wire spacing → more (and more) wires...

- ✓ **Small wire displacements reduce field quality**

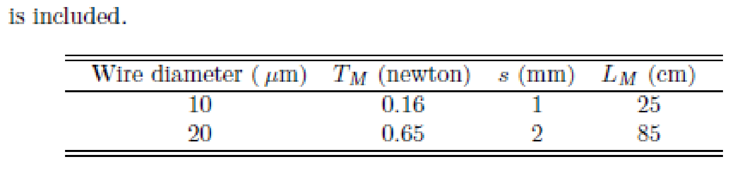
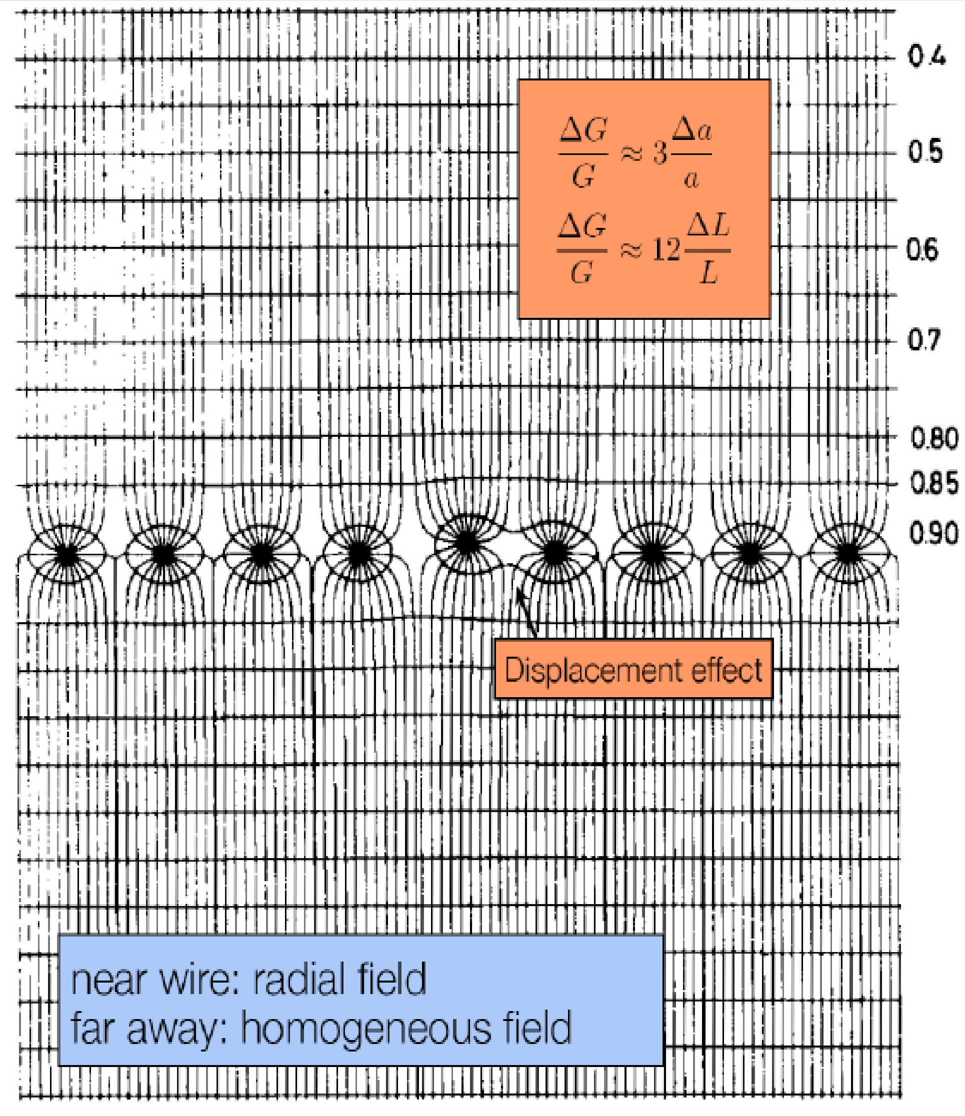


Table 35.1: Maximum tension T_M and stable unsupported length L_M for tungsten wires with spacing s, operated at $V_0 = 5$ kV. No safety factor is included.

Wire diameter (μm)	T_M (newton)	s (mm)	L_M (cm)
10	0.16	1	25
20	0.65	2	85

- ✓ **Need high mechanical precision both for geometry and wire tension ... (electrostatic and gravitation, wire sag …)**
- ✓ Several simplifying assumptions are made in analytical calculations: electrostatic force acting on the wire does not change during wire movements, or varies linearly with the displacement, the wire shape is parabolic; only one wire moves at a time.
- ✓ The advantage of numerical integrations using Garfield++ program is to simulate the collective movement of all wires, which are difficult analytically, and to consider all forces acting on a wire: forces between anode wire and other electrodes (wires, cathode) & gravitational force



$$\frac{\Delta G}{G} \approx 3\frac{\Delta a}{a}$$

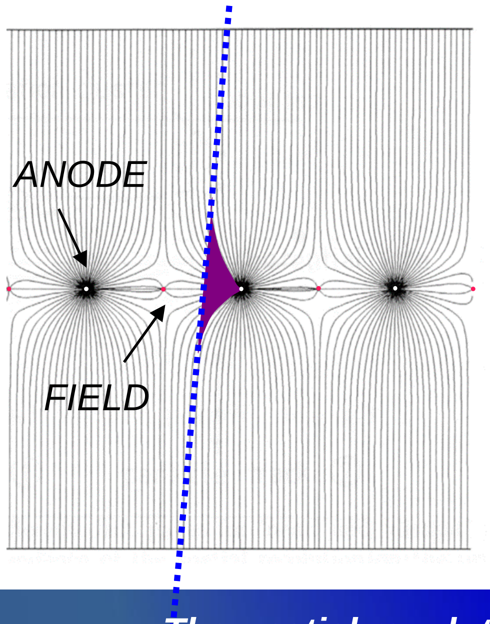
$$\frac{\Delta G}{G} \approx 12\frac{\Delta L}{L}$$

Displacement effect

near wire: radial field
far away: homogeneous field

Drift Chambers

FIRST DRIFT CHAMBER OPERATION (H. WALENTA ~ 1971);
HIGH ACCURACY DRIFT CHAMBERS (Charpak-Breskin-Sauli ~ 1973-75)



Choose drift gases with little dependence $v_D(E) \rightarrow$ linear space - time relation r(t)

Measure drift time t_D
[need to know t_0; fast scintillator, beam timing]

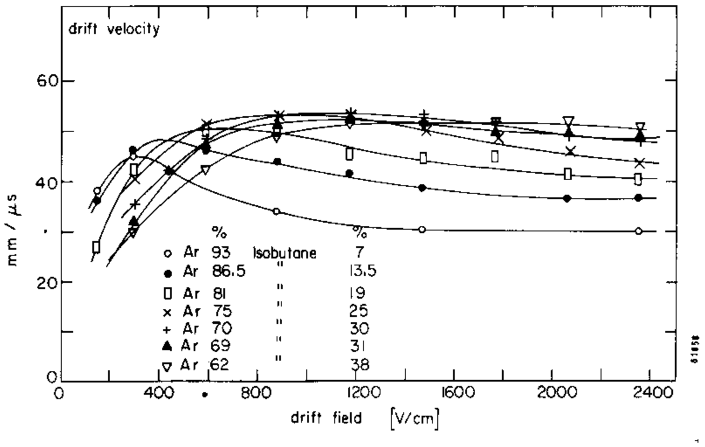
Determine location of original ionization:

$$x = x_0 \pm v_D \cdot t_D$$
$$y = y_0 \pm v_D \cdot t_D$$

If drift velocity changes along path:

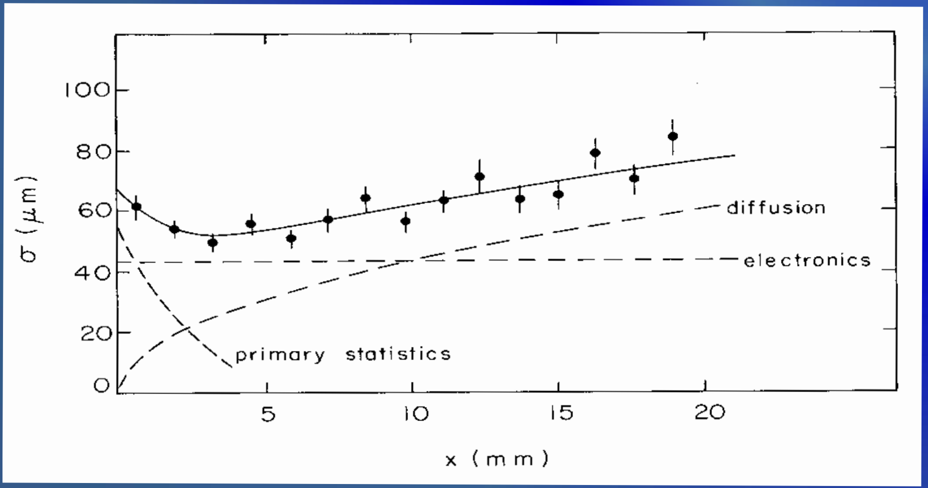
$$x = \int_0^{t_D} v_D \, dt$$

In any case:
Need well-defined drift field ...



$$\sigma_x^2 = \underbrace{\left(\frac{1}{64N^2}\right)\cdot\frac{1}{x^2}}_{\text{1st ionization statistics}} + \underbrace{\frac{2D}{v_d}\cdot x}_{\text{diffusion}} + \underbrace{\sigma^2_{\text{const}}}_{\text{electronics, δ-electrons}}$$

The spatial resolution is not limited to the cell size :



Typical single point resolutions of drift chambers:
50...150 µm depends on length of the drift path

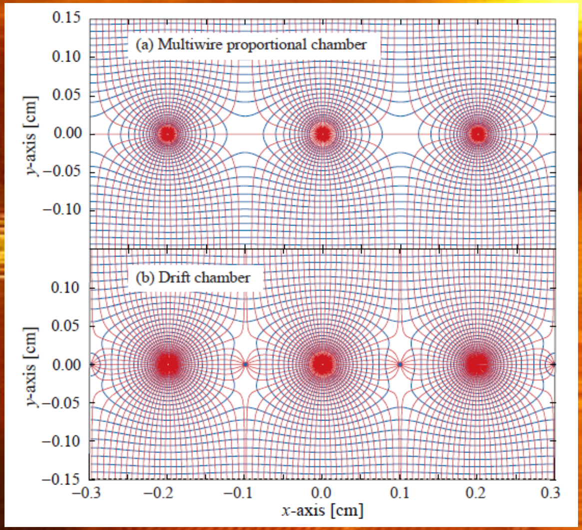
- ✓ *primary ionization statistics: how many ion pairs, ionization fluctuations dominates close to the wire*
- ✓ *diffusion of electrons in gas: dominates for large drift length*
- ✓ *electronics: noise, shaping characteristics constant contribution (drift length independent)*

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)

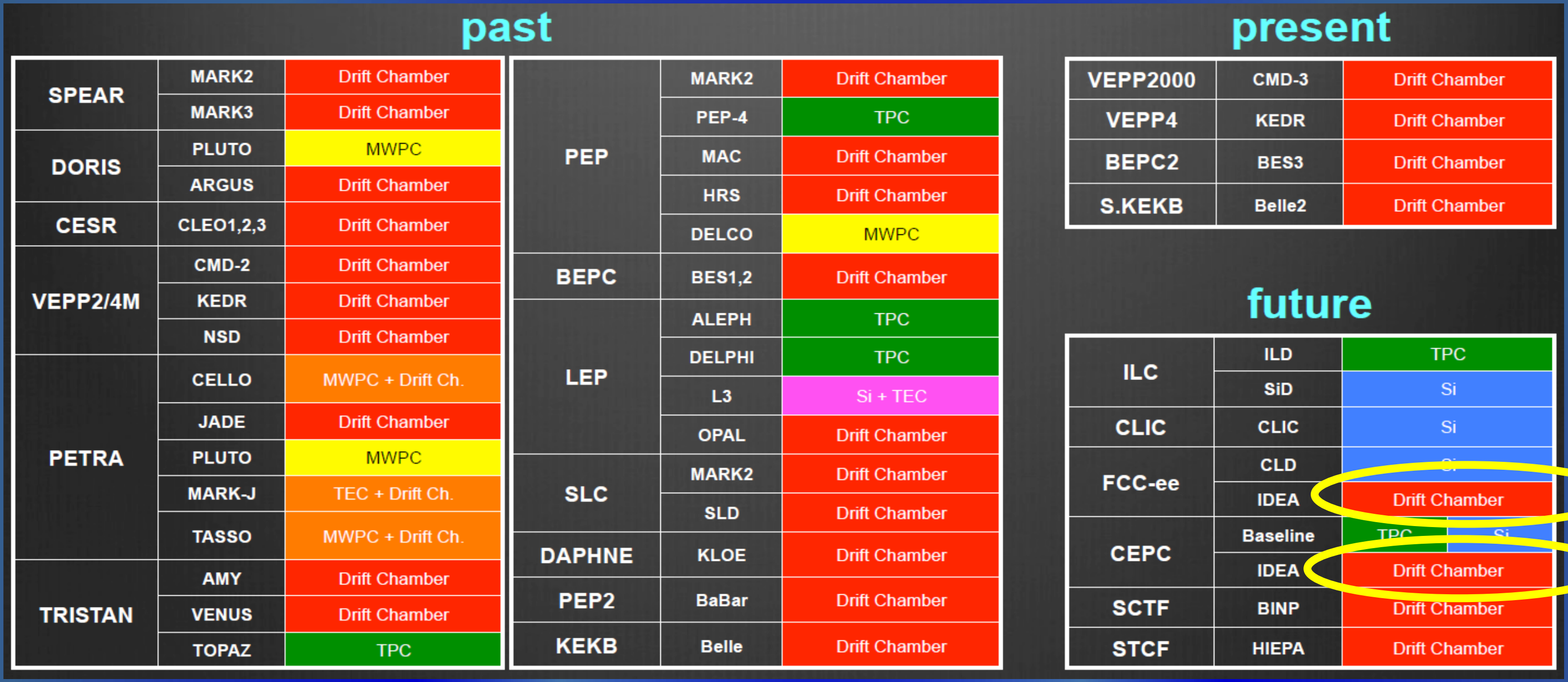
Discovery of W and Z bosons
C. Rubbia & S. Van der Meer,

1984:



Z → *ee* (white tracks) at UA1/CERN

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



past

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

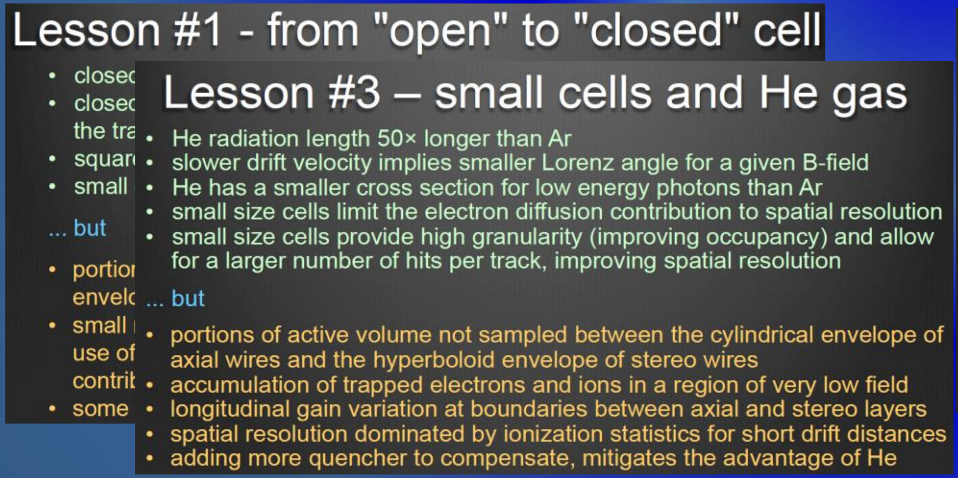
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

present

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

future

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



Lesson #1 - from "open" to "closed" cell

- close
- close
  the tra
- squar
- small

... but

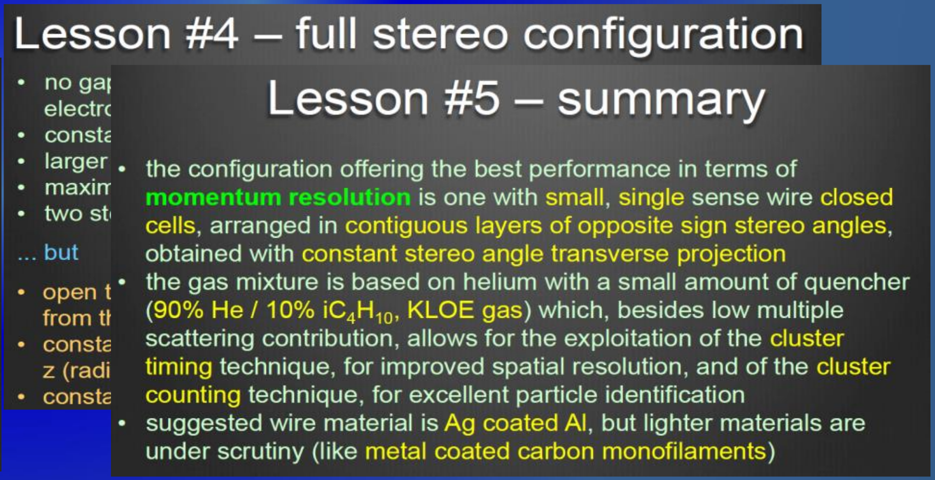
- portio
  envelo
- small
  use of
  contrib
- some

Lesson #3 – small cells and He gas

- He radiation length 50× longer than Ar
- slower drift velocity implies smaller Lorenz angle for a given B-field
- He has a smaller cross section for low energy photons than Ar
- small size cells limit the electron diffusion contribution to spatial resolution
- small size cells provide high granularity (improving occupancy) and allow for a larger number of hits per track, improving spatial resolution

... but

- portions of active volume not sampled between the cylindrical envelope of axial wires and the hyperboloid envelope of stereo wires
- accumulation of trapped electrons and ions in a region of very low field
- longitudinal gain variation at boundaries between axial and stereo layers
- spatial resolution dominated by ionization statistics for short drift distances
- adding more quencher to compensate, mitigates the advantage of He



Lesson #4 – full stereo configuration

- no gap
  electro
- consta
- larger
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  from th
- consta
  z (radi
- consta

Lesson #5 – summary

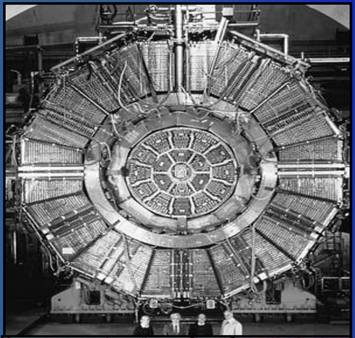
- the configuration offering the best performance in terms of **momentum resolution** is one with small, single sense wire closed cells, arranged in contiguous layers of opposite sign stereo angles, obtained with constant stereo angle transverse projection
- the gas mixture is based on helium with a small amount of quencher (90% He / 10% iC_4H_{10}, KLOE gas) which, besides low multiple scattering contribution, allows for the exploitation of the cluster timing technique, for improved spatial resolution, and of the cluster counting technique, for excellent particle identification
- suggested wire material is Ag coated Al, but lighter materials are under scrutiny (like metal coated carbon monofilaments)

An ultra-light drift chamber (IDEA concept) targetted for FCC-ee and CePC (100 km) was inspired by DAFNE KLOE Wire Chamber and by more recent version of it for MEG2 exp.

1974 - Now: Time Projection Chamber (TPC)

PEP4 (SLAC)

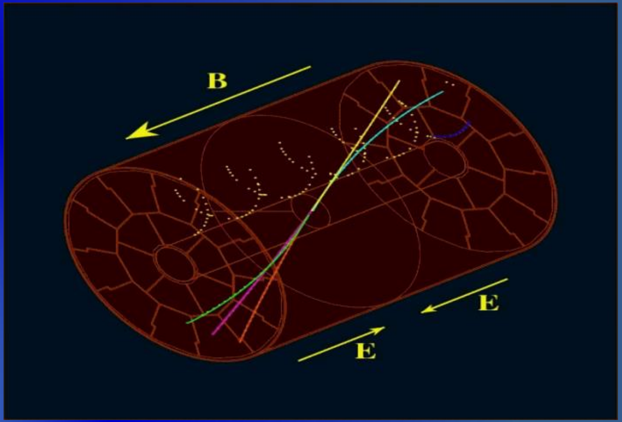
ALEPH (CERN)

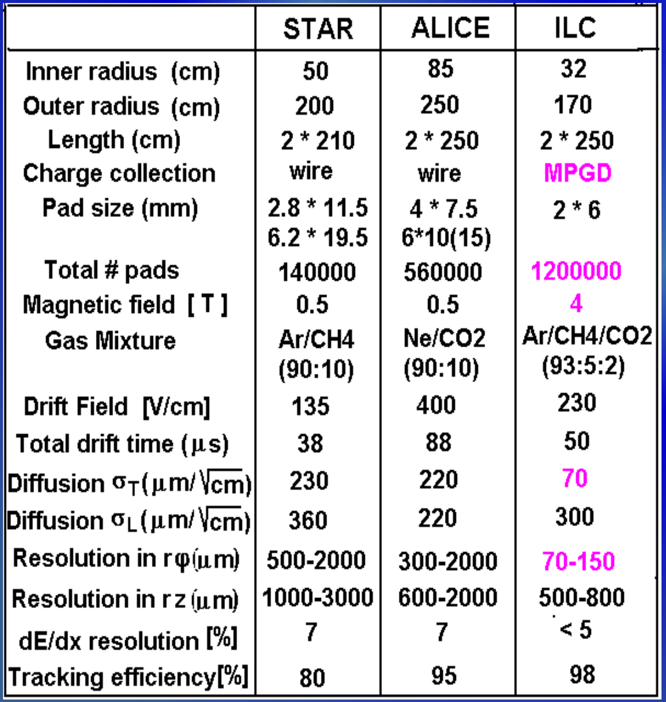


STAR (LBL)

- ✓ **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) TPCs were built, based on <u>MWPC readout</u>, a powerful tool for:**
  - **Lepton Colliders (LEP, Higgs Factories)**
  - **Modern heavy ion collisions**
  - **Liquid and high pressure TPCs for neutrino and dark matter searches**

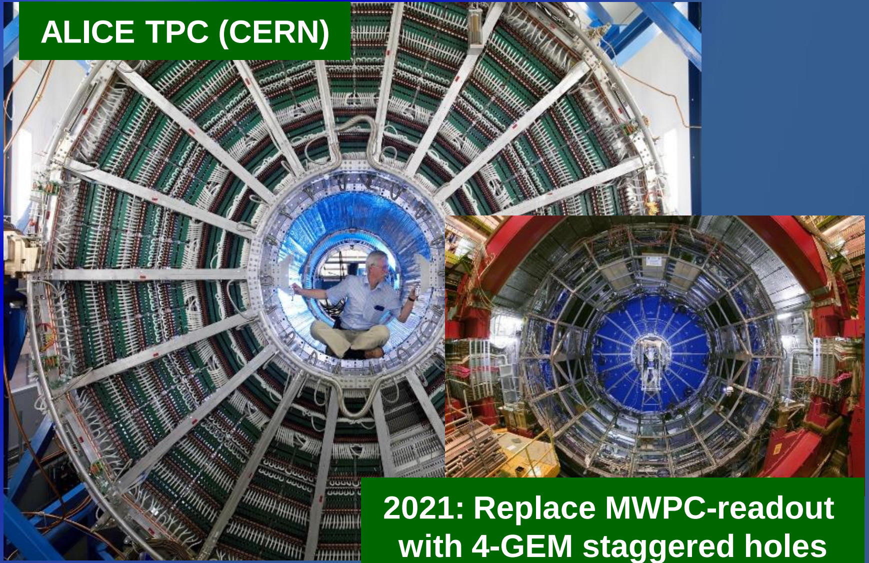
An ultimate drift chamber design is TPC concept - 3D precision tracking with low material budget & PID through differential energy loss dE/dx measurement and/or cluster counting dN_{cl}/dx tech.





	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 (μm/$\sqrt{cm}$)	230	220	70
Diffusion σ_L (μm/$\sqrt{cm}$)	360	220	300
Resolution in rφ (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

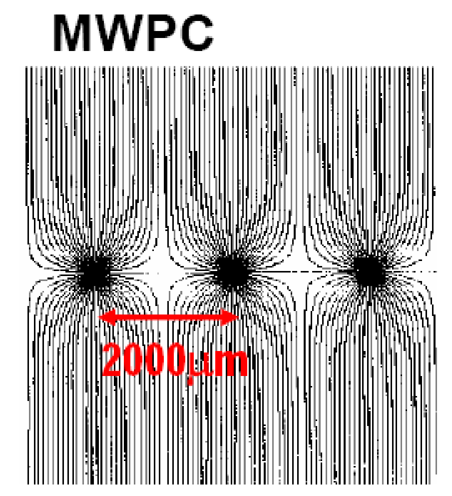
<u>New generation of TPCs use MPGD-based readout:</u> e.g. ALICE Upgrade, T2K, ILC, CepC



ALICE TPC (CERN)

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

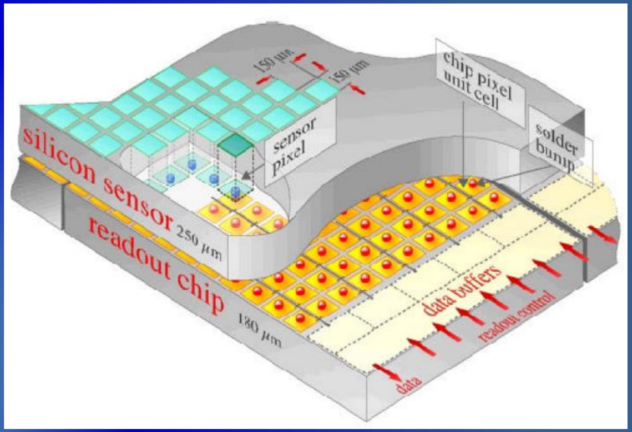
Micro-Pattern Gaseous Detectors: Bridging the Gap for Tracking between Wire Chambers and Silicon-based Devices



$\sigma \sim 100\ \mu m$

$\sigma < 10\ \mu m$

Pixel System:



Advantages of gas detectors:

- *low radiation length*
- *large areas at low price*
- *flexible geometry*
- *spatial, energy resolution …*

Problem:

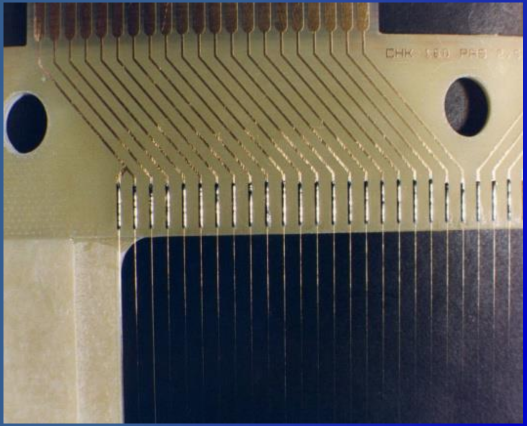
✓ *rate capability limited by space charge defined by the time of evacuation of positive ions*

Solution:

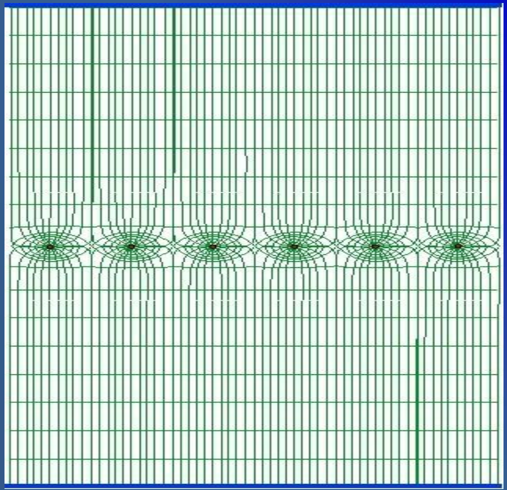
✓ ***reduction of the size** of the detecting cell (limitation of the length of the ion path) **using chemical etching and photo-lithographique techniques** developed for microelectronics and keeping at same time similar field shape.*

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

Multi-Wire Proportional Chamber (MWPC)

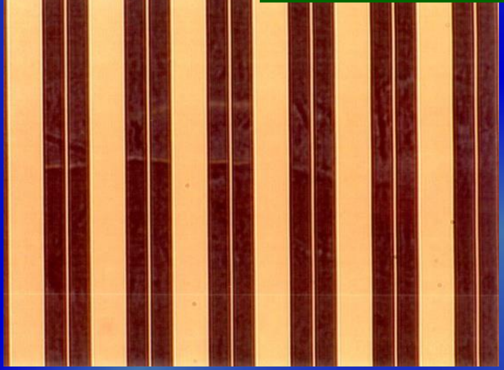


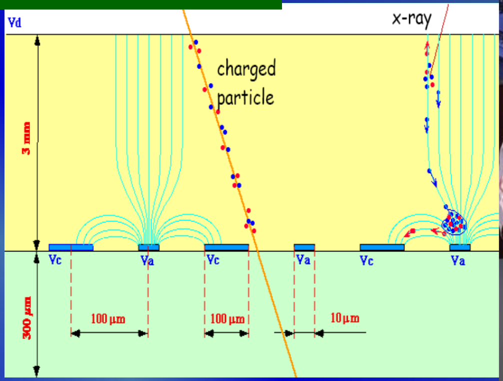
Typical distance between wires limited to ~1 mm due to mechanical and electrostatic forces

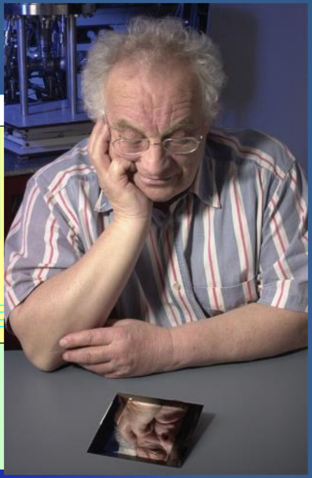


Micro-Strip Gas Chamber (MSGC)

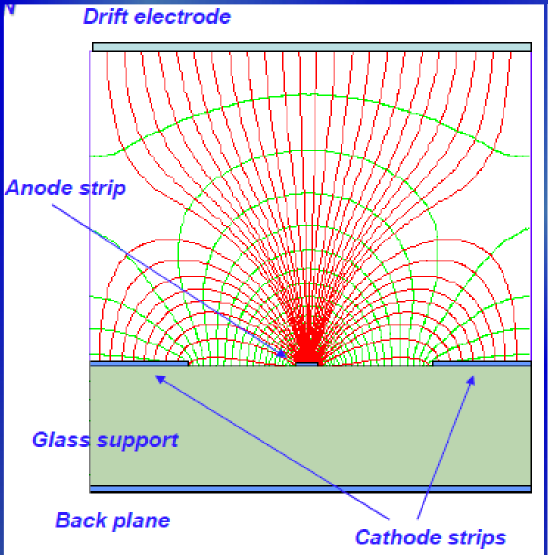
A. Oed, NIMA263 (1988) 351





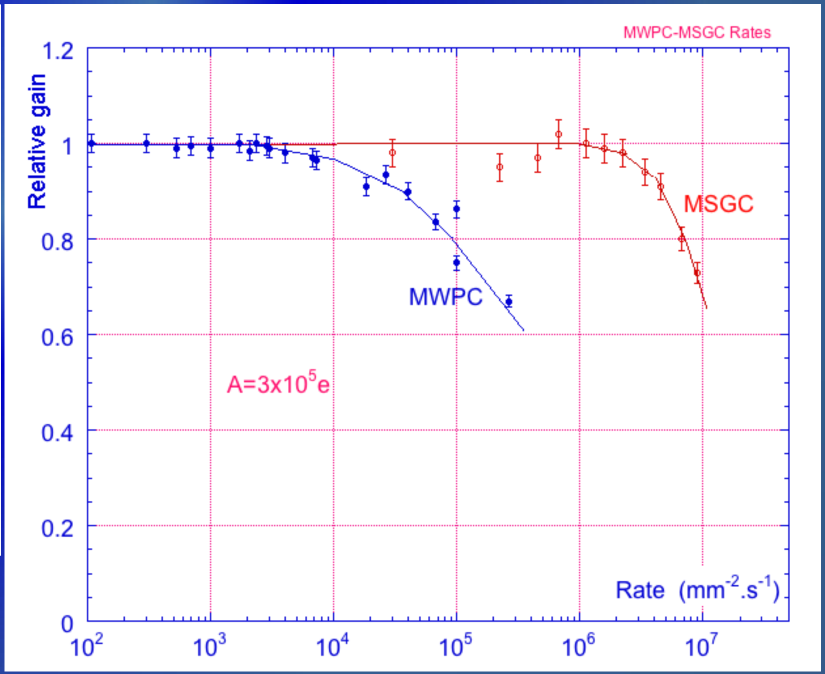


Excellent spatial resolution



Typical distance between electrodes ~100 μm

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



HERA-B Crisis(1998): Aging Effects in High-Rate Gas Detectors

Why 'Gas Micro Strip' chambers ?

- particle flux too high for conventional wire chambers (pitch > mm) (too high occupancy)
- area too large for Silicon Micro Strips (pitch 50 µm) (expensive, too many channels, large capacity…)

Novel technology ⇒Six years of struggle …

1994 : start with 'conventional' MSGC on bare glass

Unstable in intense radiation fields
(not well defined surface resistivity)

1995 : 'diamond coating' cures the problem (Sauli (CERN), Ze

1996 : induced discharges in hadronic beams
(test at PSI proton/pion beam)

INTENSE R & D

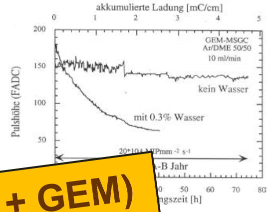
Damage of electrode structure
Only ~ days lifetime in HERA-B

WINTER 96 /97 **CRISIS**

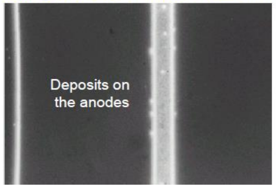
Inner Tracker: MSGC (MSGC + GEM)

MSGC-GEM Detector for HERA-B Inner Tracker System

Water admixture 0.3 % improves running stability, but massive anode aging…



Severe aging effects with Ar/CO2 & Ar/DME



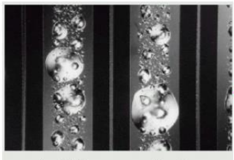
% H2O, MSGC discharges at low voltages - modification of substrate's dielectric rigidity

Use of MSGC with Al electrodes:

Easy to manufacture
more robust against gas
discharges than gold

↓

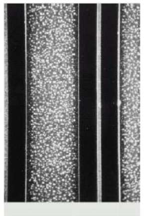
Rapid pulse-height reduction
for both Ar/CO2 & Ar/DME



bubbles on cathodes

Ar/CO2 (70:30)
2.7 mC/cm

Ar/DME(50:50)
+ 0.3% H2O
0.8 mC/cm



crates on cathodes

DESY/HERA-B PRC (1998)

Aging Studies for the HERA-B Outer Tracker

!!! Strong aging dependence from particle type:

Chambers with non-coated Pokalon-C cathode:

X-rays setup:
Small area honeycomb chambers had shown no aging effects up to 4.5 C/cm of integrated radiation dose

HERA-B high-rate environment:
Persistent Malter currents in full size prototype honeycomb chambers after ~ 0.5 mC/cm of accumulated charge

R&D to resemble HERA-B conditions:

Facility Radiation Type	Radiation Density	Radiation Density	Irradiation area	Gas Mixture	Effect seen?
Zeuthen X-Ray Mo (35 keV)	5 C/cm	1.5 µA/cm	~1x3 cm²	CF_4/CH_4	NO*
Dubna X-Ray Cu (8 keV)	6 C/cm	5 µA/cm	~0.5x1 cm²	$Ar/CF_4/CO_2$	NO*
HMI Electron 2.5 MeV	10 mC/cm	0.1-3 µA/cm	~100x 30 cm²	$Ar/CF_4/CH_4$	NO*
HD X-Ray Cu (8 keV)	~ mC/cm	~0.1 µA/cm	~46x 30 cm²	$Ar/CF_4/CH_4$	NO*

Facility Radiation Type	Radiation Density	Radiation Density	Irradiation area	Gas Mixture	Effect seen?
Rossendorf Protons 13 MeV/c	5 mC/cm	0.3 µA/cm	~9x9 cm²	$Ar/CF_4/CH_4$	NO
Rossendorf α-part, 28 MeV/c	3 mC/cm	0.6 µA/cm	~1x3 cm²	Ar/CF [illegible]	[illegible]
PSI p [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PS [illegible] π/p [illegible]	[illegible]	[illegible]	[illegible]	$_4/CH_4$	YES
Ka [illegible] α-part, 100 MeV/c	~ mC/cm	0.02 µA/cm	~7x7 cm²	$Ar/CF_4/CH_4$	YES
HERA-B P(920 GeV)-N	~ mC/cm	0.03 µA/cm	100x30 cm²	All gas mixures	YES

X-rays or e- can not trigger Malter effect independently of their energy or radiation intensity

Hadrons above certain energy produce Malter effect at ~mC/cm as in HERA-B
(Irradiation area above certain limit is necessary for ignition of Malter effect)

Outer Tracker: wire-type honeycomb

Aging Studies for the HERA-B Outer Tracker

Intense R&D program:

All building materials (glues, plastics, wires) and technique were tested and validated

Problems observed:

- Indications that the foils is responsible of Malter effect (related to conductivity)
- Araldit
- Fast anode aging is due to A F4/CH4

→

Solutions:

- Coat 1200 foils with 40 nm Cu (good adhesion to plastics)+ 40 nm Au (gas contact)
- New glue (Stycast)
- Change of gas Ar/CF4/CO2

Chamber would not operate in HERA-B longer than 10 hours

↓

Stable gain for more than 2 HERA-B years (~ 1C/cm)

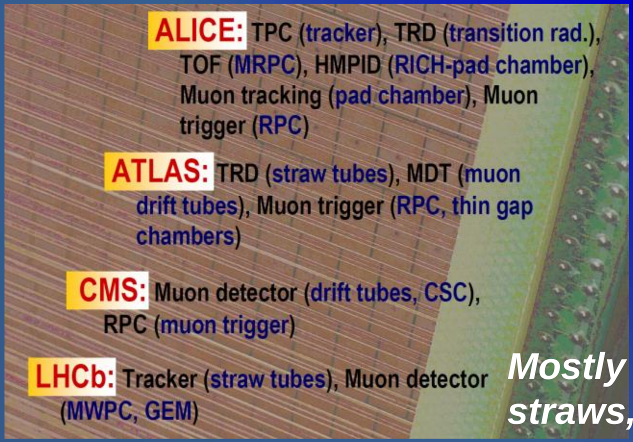
BUT, operating with Ar/CF4/CO2 (65:30:5):

- Permanent dark currents after 0.3 C/cm in the presence of ~1000 ppm H2O (FR4-strips become conductive)
- Wire etching after 0.6 C/cm (gold peels off) if H2O concentration is < 50 ppm

→ Carefull control the gas water content (100-500 ppm)

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***

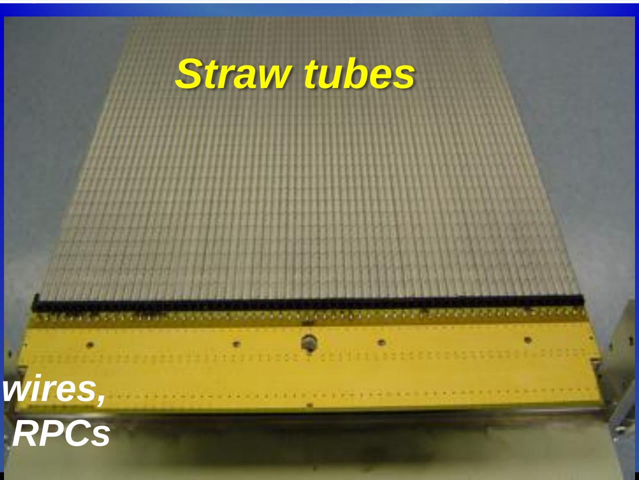


ALICE: TPC (tracker), TRD (transition rad.), TOF (MRPC), HMPID (RICH-pad chamber), Muon tracking (pad chamber), Muon trigger (RPC)

ATLAS: TRD (straw tubes), MDT (muon drift tubes), Muon trigger (RPC, thin gap chambers)

CMS: Muon detector (drift tubes, CSC), RPC (muon trigger)

LHCb: Tracker (straw tubes), Muon detector (MWPC, GEM)



Straw tubes

Mostly wires, straws, RPCs

CMS CSC

ATLAS MDT: Resolution Limits of High-Rate Wire Chambers

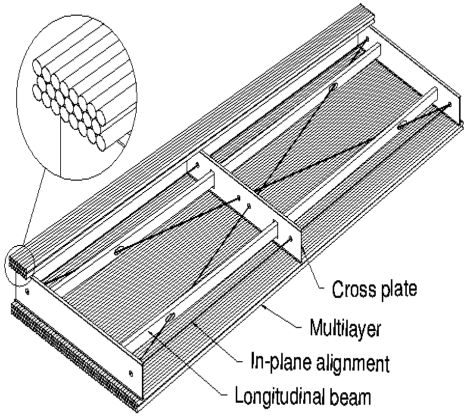
L3 Muon Spectrometer (LEP):

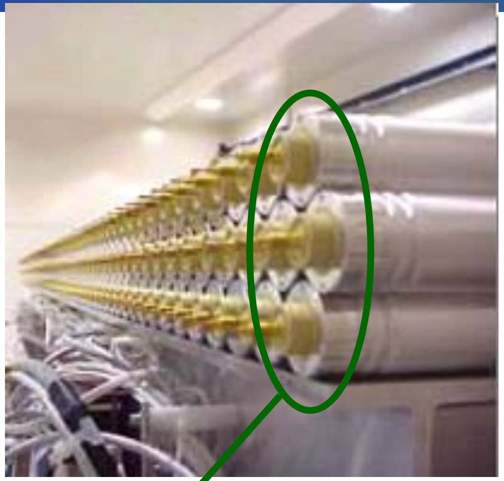
~ 40000 chan. ; σ (chamber) < 200 μm

ATLAS Muon Drift Tubes (LHC):

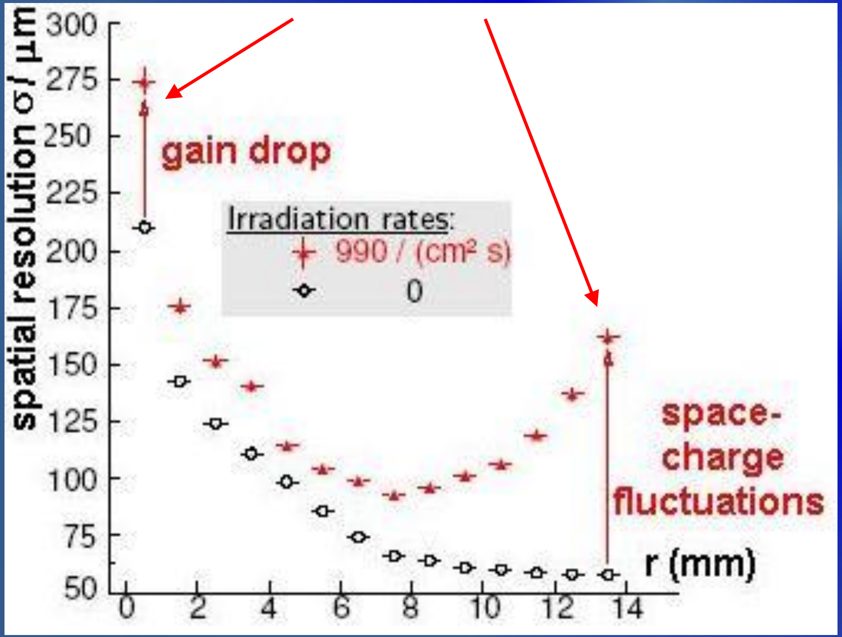
~ 1200 chambers, σ (chamber) ~ 50 μm

- *370000 tubes, 740000 end-plugs*
- *12000 CCD for optical alignment*



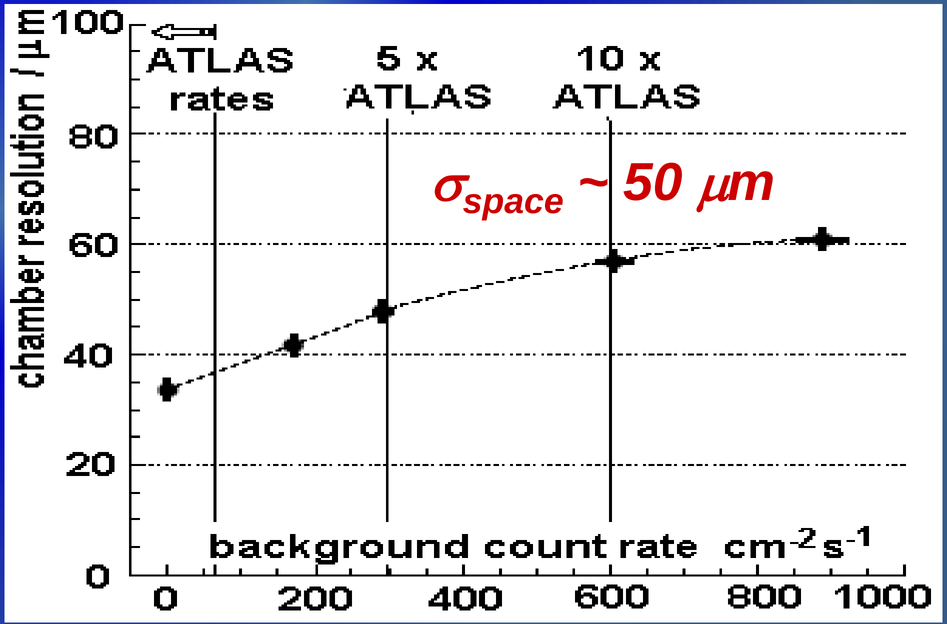


Intrinsic limitation of wire chambers: (resolution degradation at high rates):

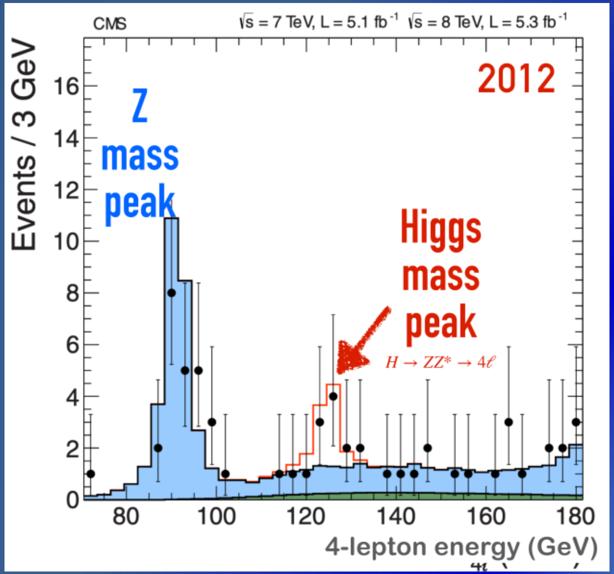


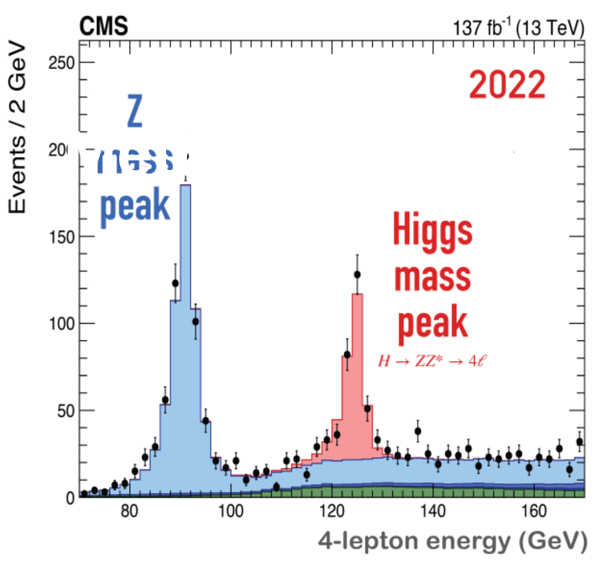
1 chamber → 2 layers of 3 drift tubes

Spatial resolution /chamber (2 layers of 3 drift tubes)



The Higgs at 10: An Experimental Retrospective





2013 Nobel Prize in Physics for Higgs Boson Discovery

AUTHOR INFORMATION

IMPACT FACTOR 3.148*

JINST
an IOP and SISSA journal

Journal of Instrumentation

jinst.sissa.it | iopscience.org/jinst

SISSA International School for Advanced Studies
IOP Publishing

Higgs Candidates @ LHC Muon gaseous detectors:

H → ZZ → 4 muons

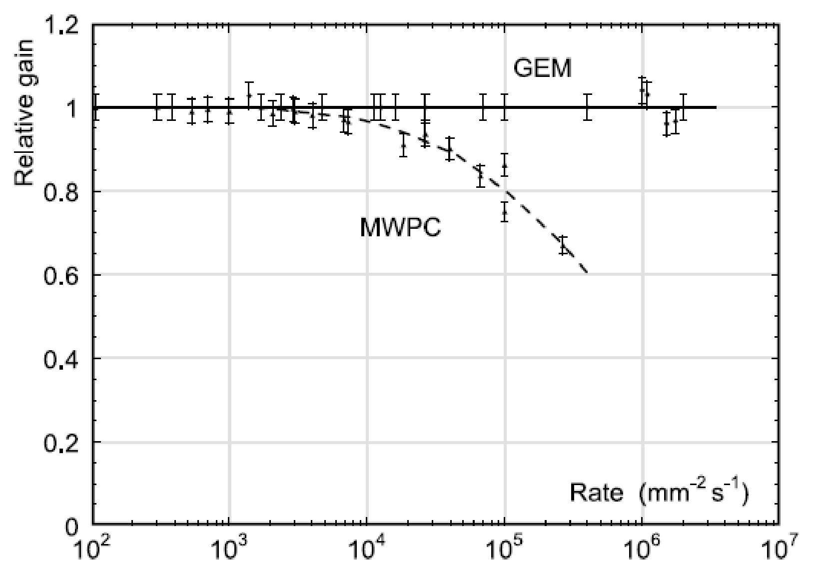
(2 Di-Z Boson candidate events decaying into 4 muons in CMS and ATLAS)

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)*

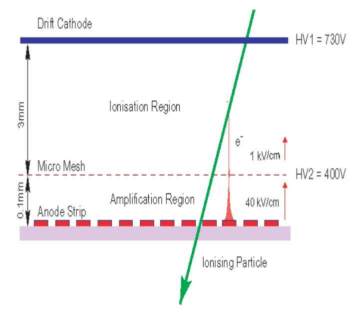
Rate Capability: MWPC vs GEM:

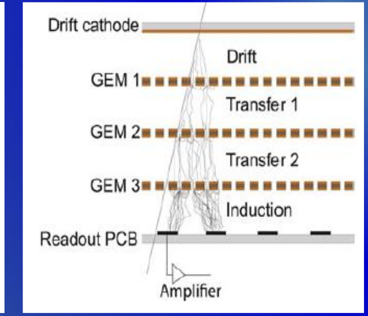


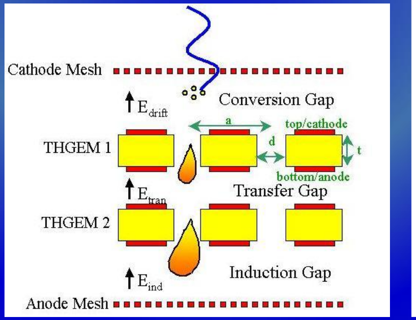
Micromegas

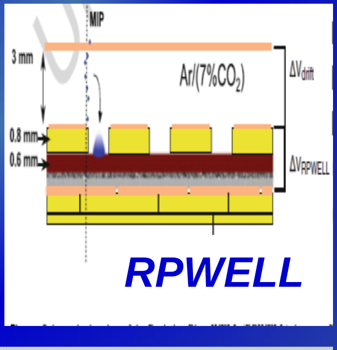
GEM

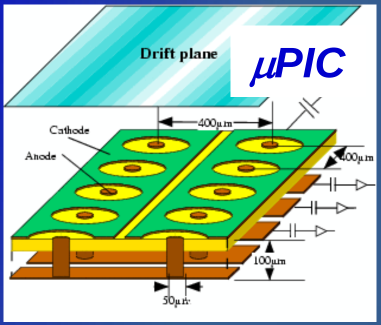
THGEM

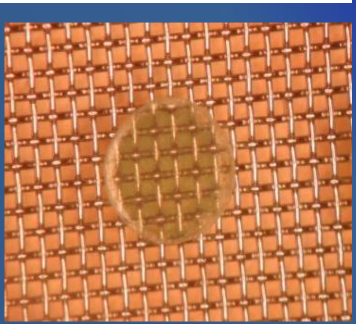


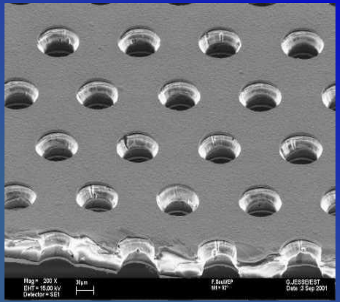


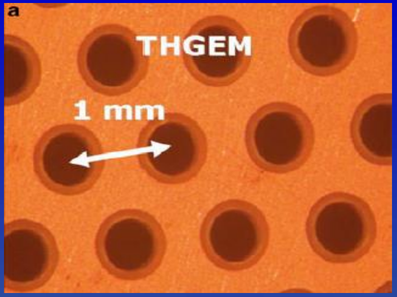


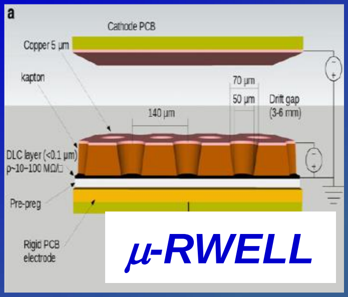


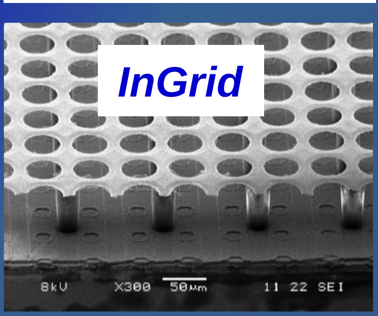










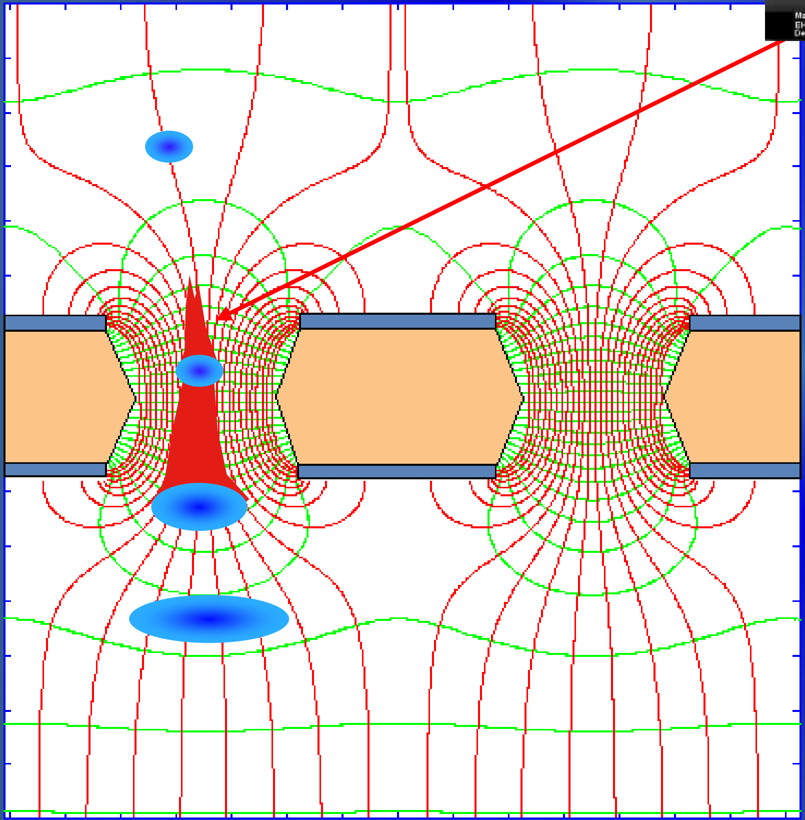


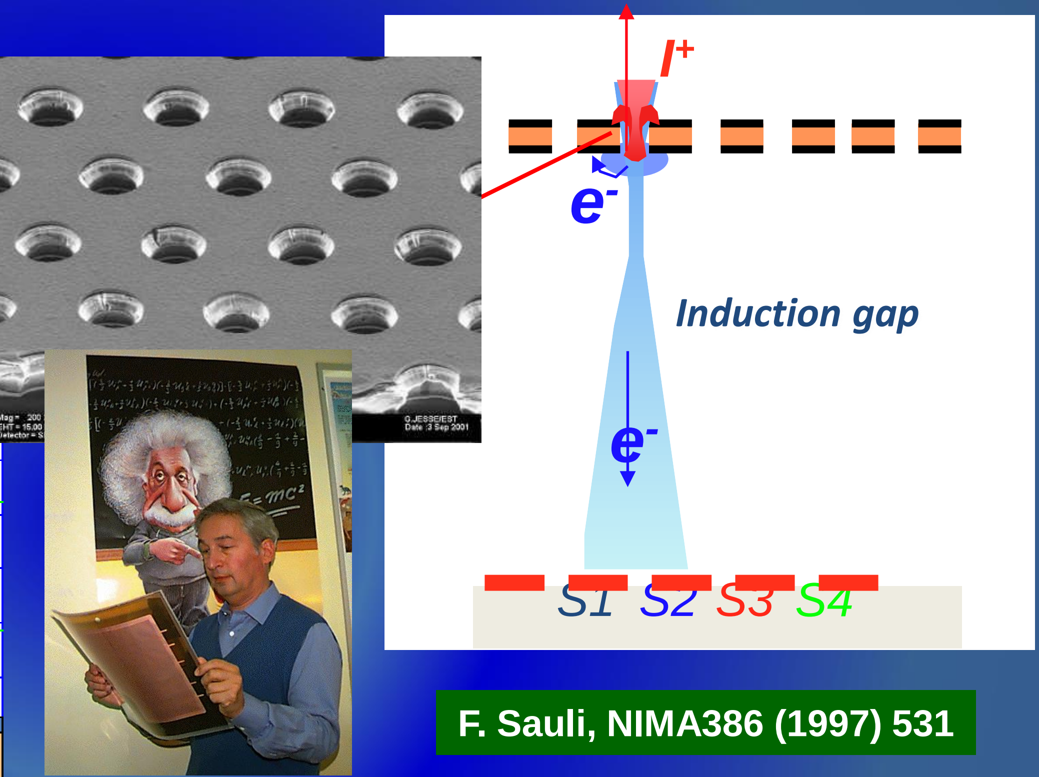
Gas Electron Multiplier (GEM)

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.





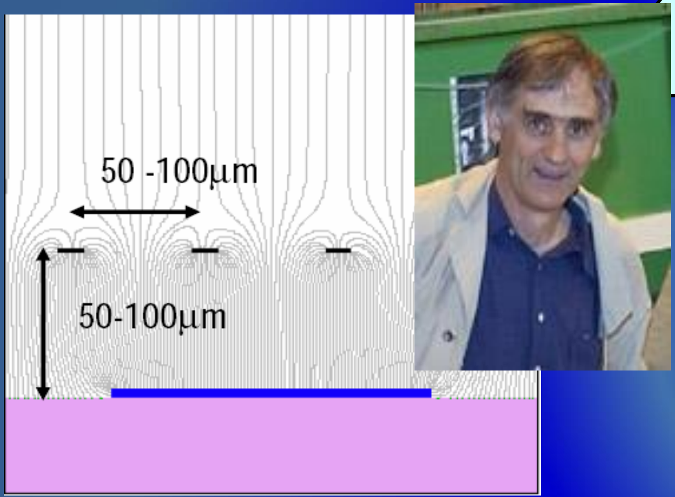
F. Sauli, NIMA386 (1997) 531

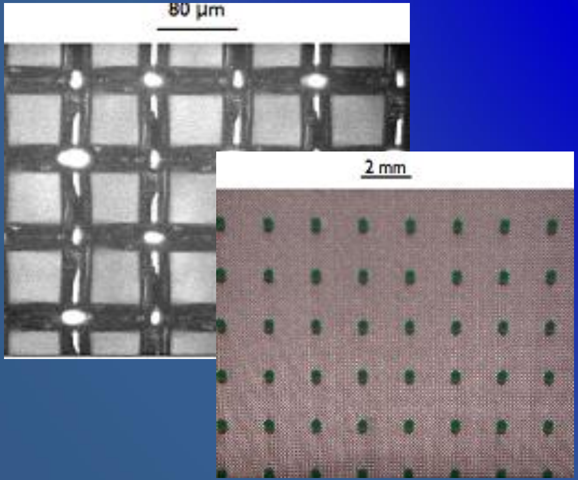
- ✓ Electrons are collected on patterned readout board.
- ✓ A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- ✓ All readout electrodes are at ground potential.
- ✓ Positive ions partially collected on GEM electrodes

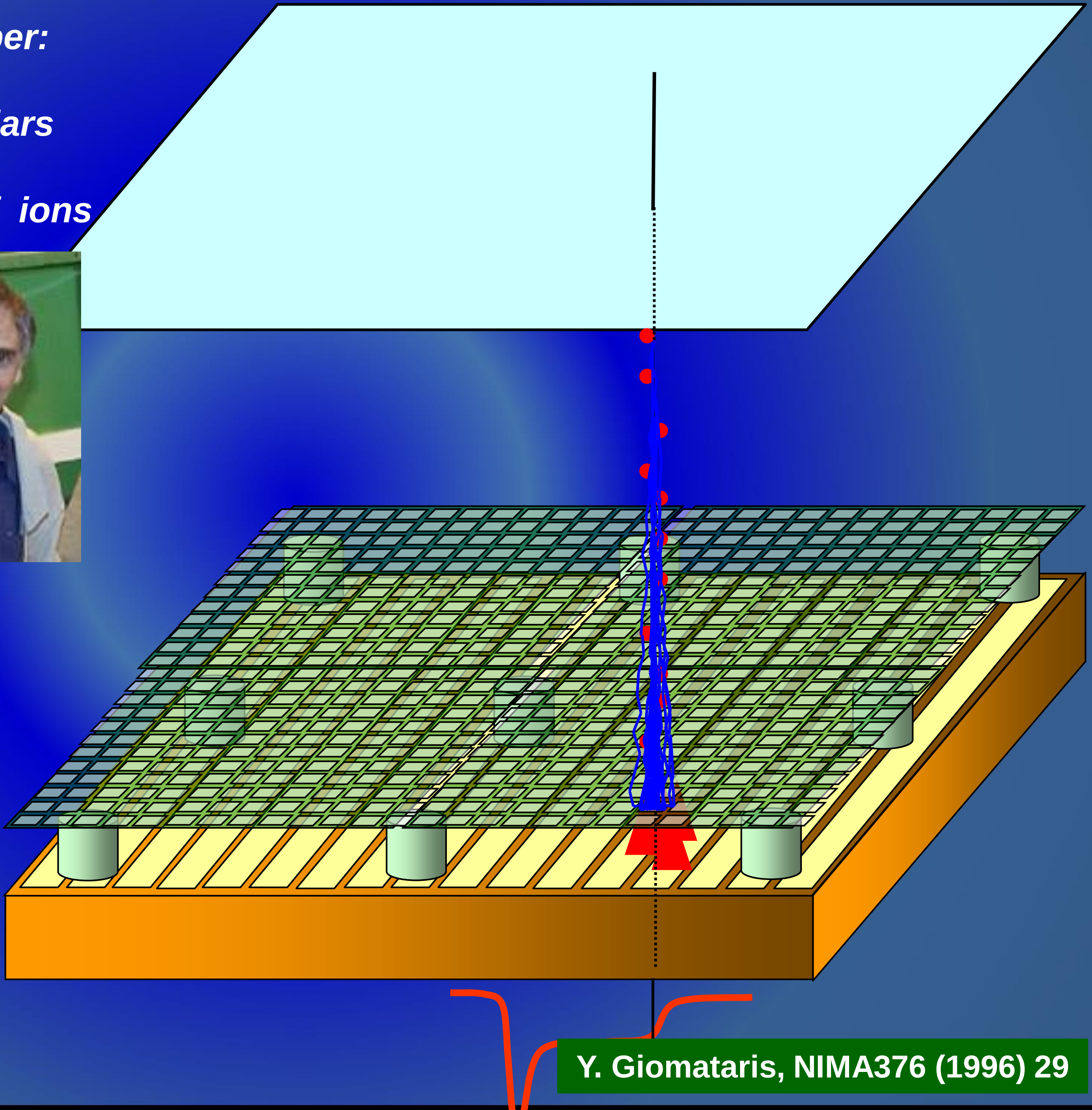
Micro Mesh Gaseous Structure (MICROMEGAS)

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

Small gap: fast collection of ions





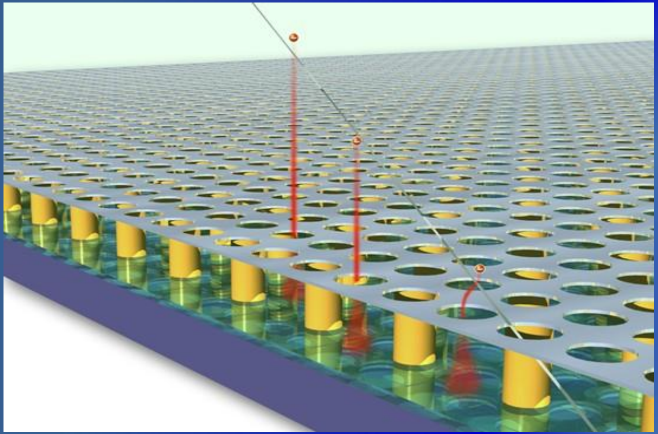


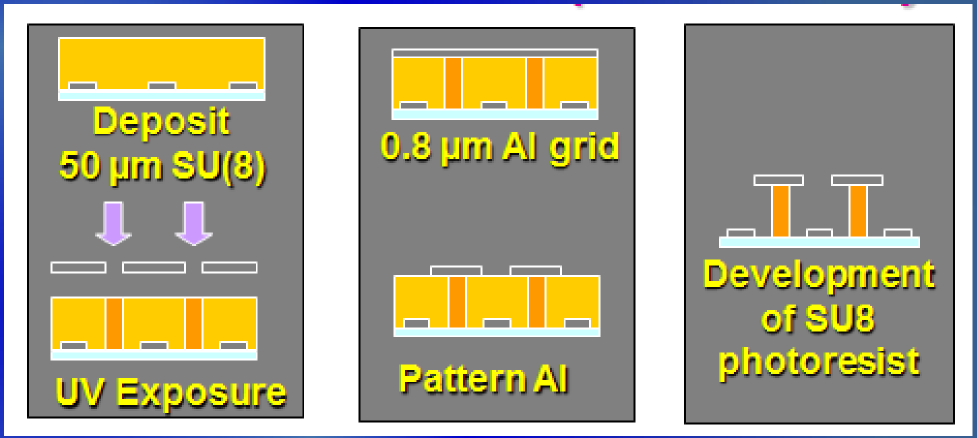
Y. Giomataris, NIMA376 (1996) 29

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)





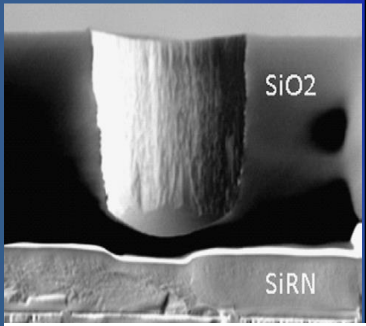
Deposit 50 µm SU(8)

UV Exposure

0.8 µm Al grid

Pattern Al

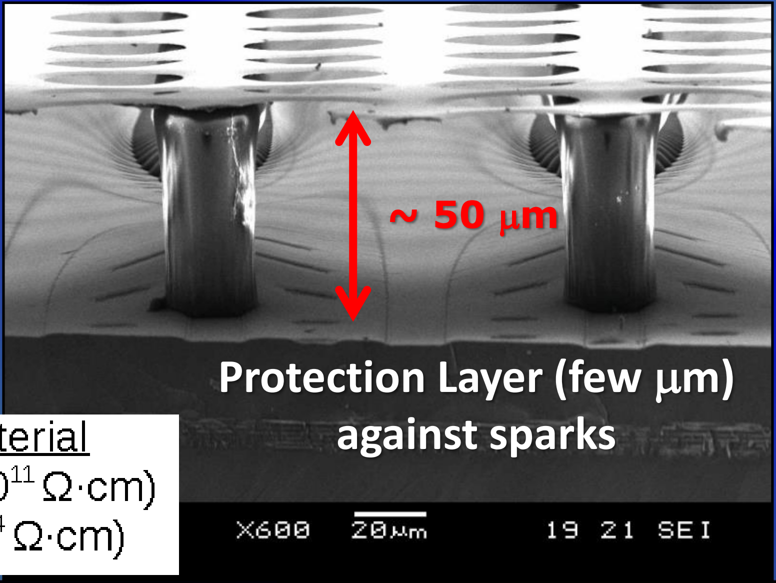
Development of SU8 photoresist



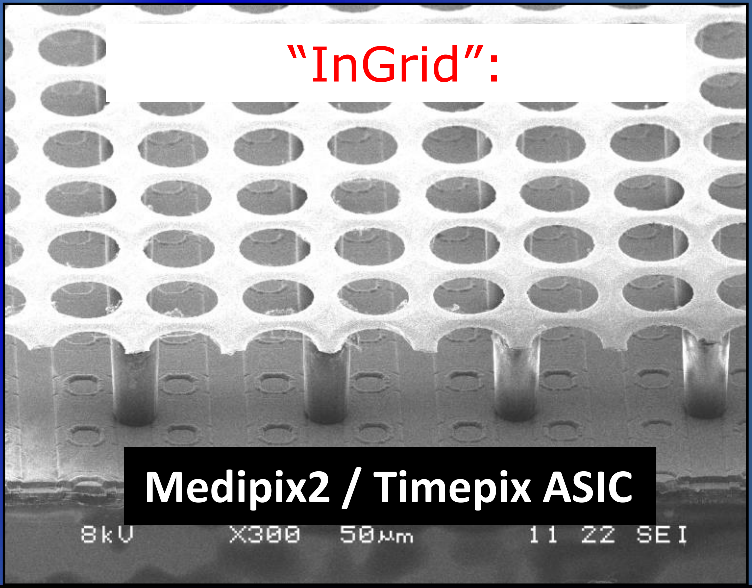
high resistive material

15 µm aSi:H (~10^{11} Ω·cm)

8 µm Si_XN_Y (~10^{14} Ω·cm)



Protection Layer (few µm) against sparks



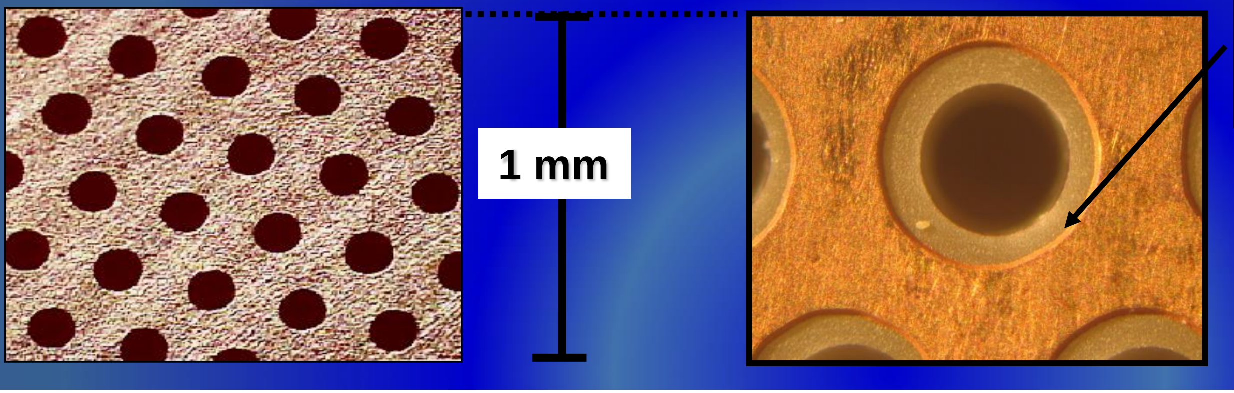
“InGrid”:

Medipix2 / Timepix ASIC

Other MPGDs Concepts: THGEM, μRWELL, RPWELL

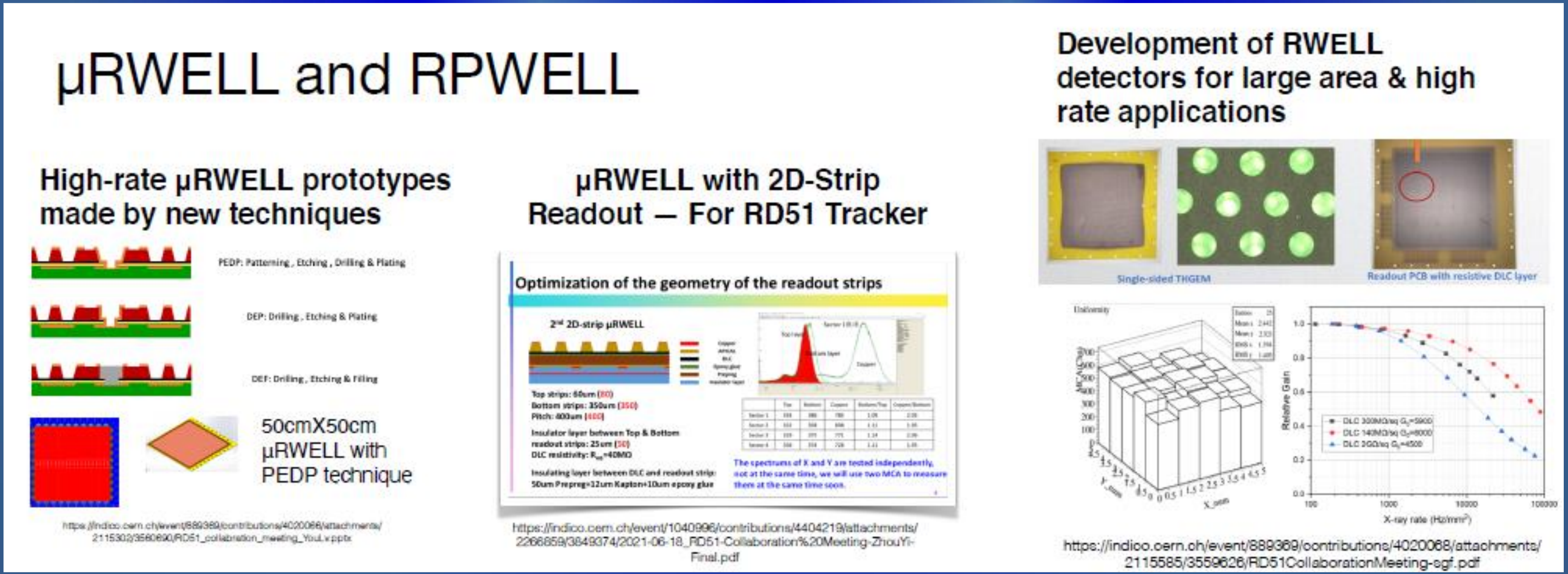
THGEM Manufactured by standard PCB techniques of precise drilling in G-10 (and other materials) and Cu etching

STANDARD GEM ***THGEM***



0.1 mm rim to prevent discharges

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



μRWELL and RPWELL

High-rate μRWELL prototypes made by new techniques

PEDP: Patterning , Etching , Drilling & Plating

DEP: Drilling , Etching & Plating

DEF: Drilling , Etching & Filling

50cmX50cm μRWELL with PEDP technique

https://indico.cern.ch/event/889369/contributions/4020066/attachments/2115302/3560690/RD51_collabration_meeting_YouLv.pptx

μRWELL with 2D-Strip Readout – For RD51 Tracker

Optimization of the geometry of the readout strips

2nd 2D-strip μRWELL

Top strips: 60um (80)
Bottom strips: 350um (350)
Pitch: 400um (400)

Insulator layer between Top & Bottom readout strips: 25um (50)
DLC resistivity: R_{sq}=40MΩ

Insulating layer between DLC and readout strip: 50um Prepreg=12um Kapton+10um epoxy glue

The spectrums of X and Y are tested independently, not at the same time, we will use two MCA to measure them at the same time soon.

https://indico.cern.ch/event/1040996/contributions/4404219/attachments/2266859/3849374/2021-06-18_RD51-Collaboration%20Meeting-ZhouYi-Final.pdf

Development of RWELL detectors for large area & high rate applications

Single-sided THGEM

Readout PCB with resistive DLC layer

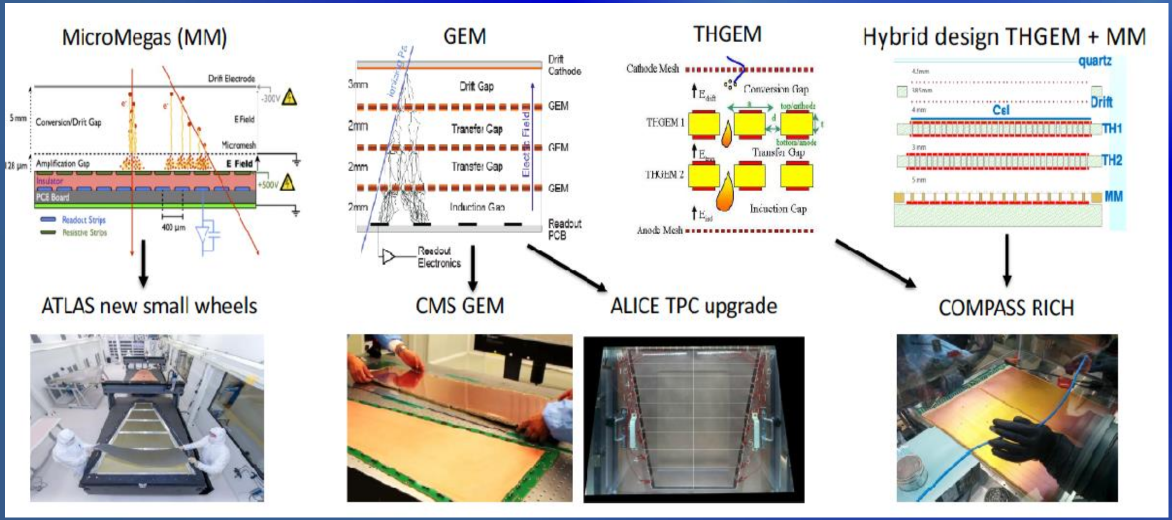
https://indico.cern.ch/event/889369/contributions/4020068/attachments/2115585/3559626/RD51CollaborationMeeting-sgf.pdf

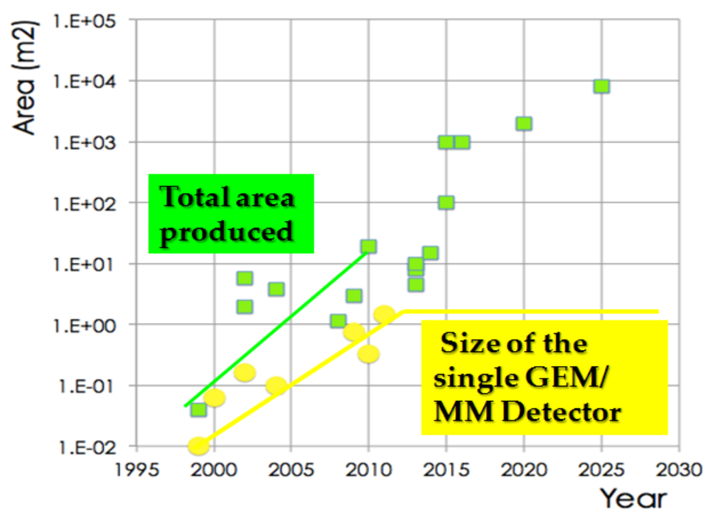
Success Story: MPGD Technologies @ CERN Experiments

- The integration of MPGDs in large experiments was not rapid, despite of the first large-scale application in COMPASS at SPS in the] 2000's

- Scaling up MPGD detectors, while preserving the typical properties of small prototypes, allowed their use in the LHC upgrades
  → Many emerged from the R&D studies within the CERN-RD51 Collaboration

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.:** 2500 mC/cm²	Required beam tracking (pixelized central / beam area)
TOTEM TRACKING: > 2009	Hadron Collider / Forward Physics ($5.3 \leq \lvert\eta\rvert \leq 6.5$)	3-GEM (semicircular shape)	Total area: ~ 4 m^2 Single unit detect: up to 0.03m^2	**Max.rate**:20 kHz/cm² **Spatial res.:** ~120µm **Time res.:** ~ 12 ns **Rad. Hard.:** ~ mC/cm²	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/cm² **Spatial res.:** ~ cm **Time res.:** ~ 3 ns **Rad. Hard.:** ~ C/cm²	Redundant triggering
COMPASS RICH UPGRADE > 2016	Fixed Target Experiment (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/cm² **Spatial res.:** <~ 2.5 mm **Time res.:** ~ 10 ns	Production of large area THGEM of sufficient quality
ATLAS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	Resistive Micromegas	Total area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**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
CMS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**:10 kHz/cm² **Spatial res.:** ~100µm **Time res.:** ~ 5-7 ns **Rad. Hard.:** ~ 0.5 C/cm²	Redundant tracking and triggering
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/cm² **Spatial res.:** ~300µm **Time res.:** ~ 100 ns **dE/dx:** 11 % **Rad. Hard.:** 50 mC/cm²	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution



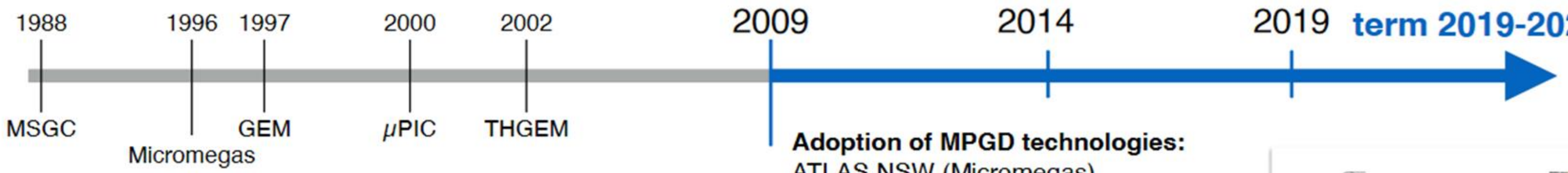


Legacy of the CERN-RD51 Collaboration: 2008-2023

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



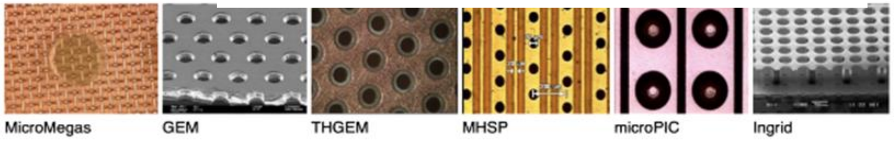
2008:

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:

May 2018

R&D PROPOSAL
RD51 EXTENSION BEYOND 2018

EDITORS:
S. Dalla Torre (INFN Trieste), E. Oliveri (CERN),
L. Ropelewski (CERN), M. Titov (CEA Saclay)

Abstract

arXiv:1806.09955v1 [physics.ins-det] 26 Jun 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***

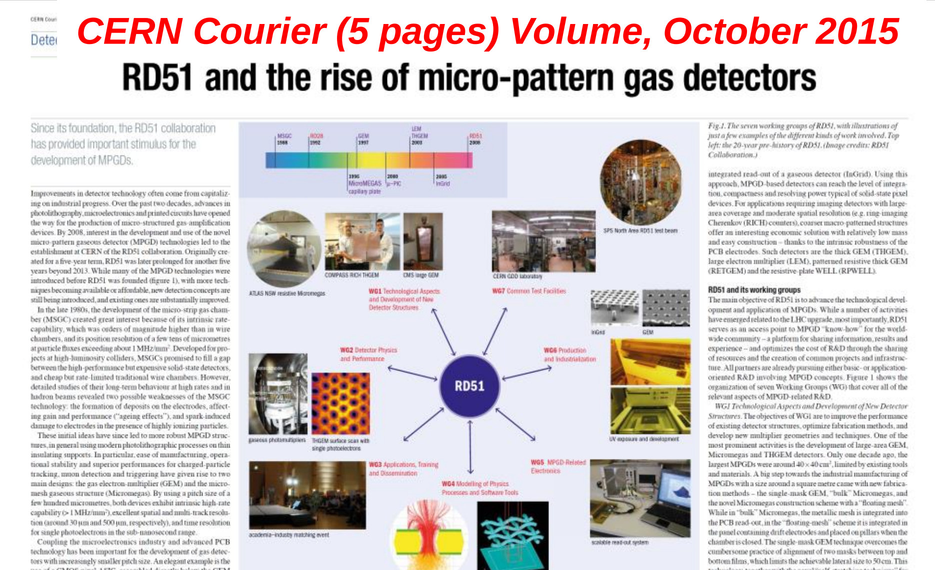
Legacy of the CERN-RD51 Collaboration:"RD51" Model

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

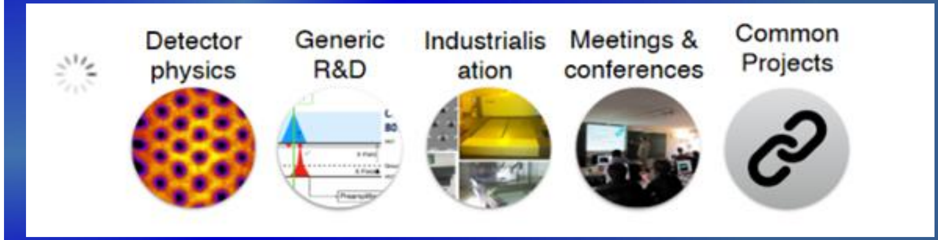
Since its foundation, the RD51 collaboration has provided important stimulus for the development of MPGDs.

RD51:

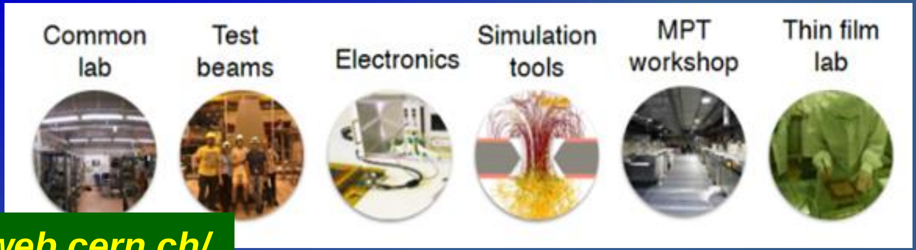
3 MAJOR ASSETS

Community and Expertize (RD51 Scientific Network)

MPGD Technology Development & Dissemination

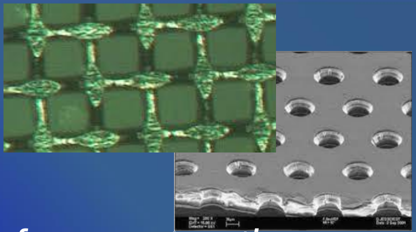


R&D Tools, Facilities and Infrastructure

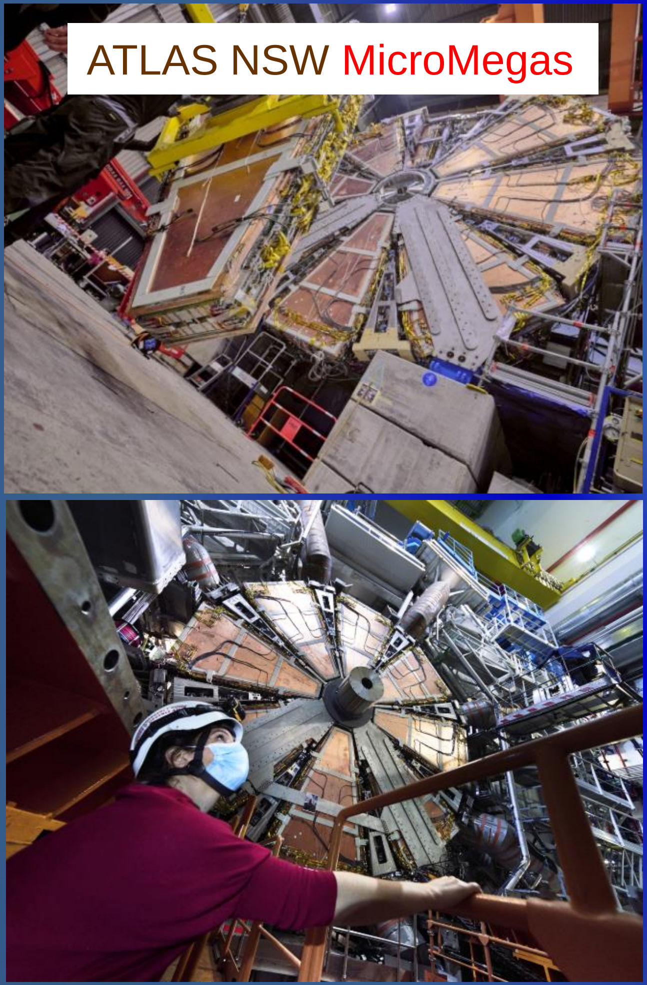


https://rd51-public.web.cern.ch/

2022: MPGDs for High Luminosity LHC Upgrades

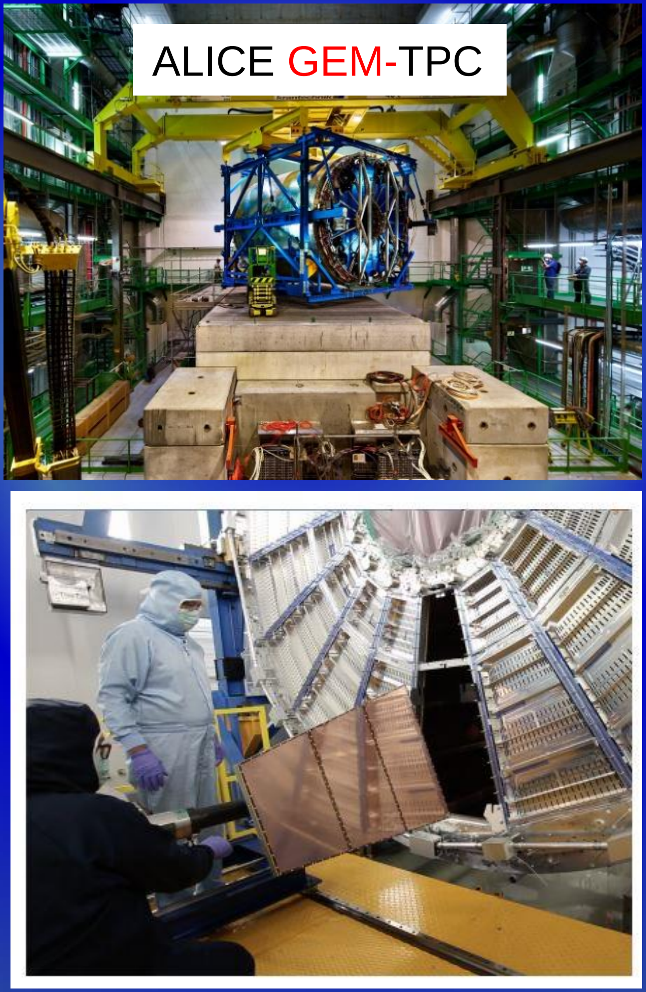


The successful implementation of MPGDs for relevant upgrades of CERN experiments indicates the degree of maturity of given detector technologies for constructing large-size detectors, the level of dissemination within the HEP community and their reliability



ATLAS NSW MicroMegas

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



ALICE GEM-TPC

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

CMS GEM muon endcaps

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

Large-Area MM / GEM Detectors for ATLAS / CMS Upgrade

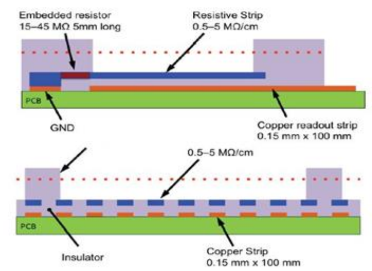
Resistive MM for ATLAS NSW Muon Upgrade:

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)

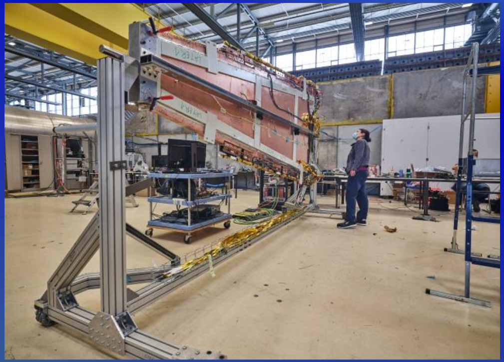


Still, main issue encountered: HV unstability

==> 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

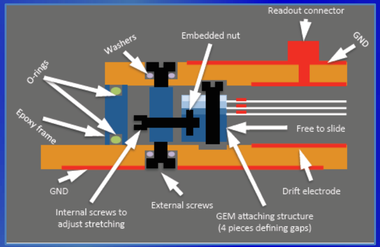
Production, sector integration (~1200m^2 resistive MM):



GEMs for CMS Muon System Upgrade:

- ➢ Single-mask GEM technology (instead of double-mask)
  → Reduces cost /allows production of large-area GEM

- ➢ Assembly optimization: self-stretching technique:
  → assembly time reduction to 1 day



September 2020: 144 GEM chambers installed

Breaking news:
GEM (GE1/1) installation completed last week.
First phase2 detector installed!

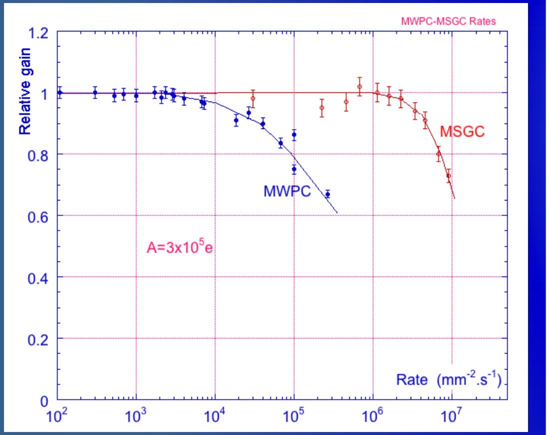
Important milestone for CMS collaboration as the first complete Phase II Upgrade detector, with a brand new detector technology, the GEMs, complementing the Muon system

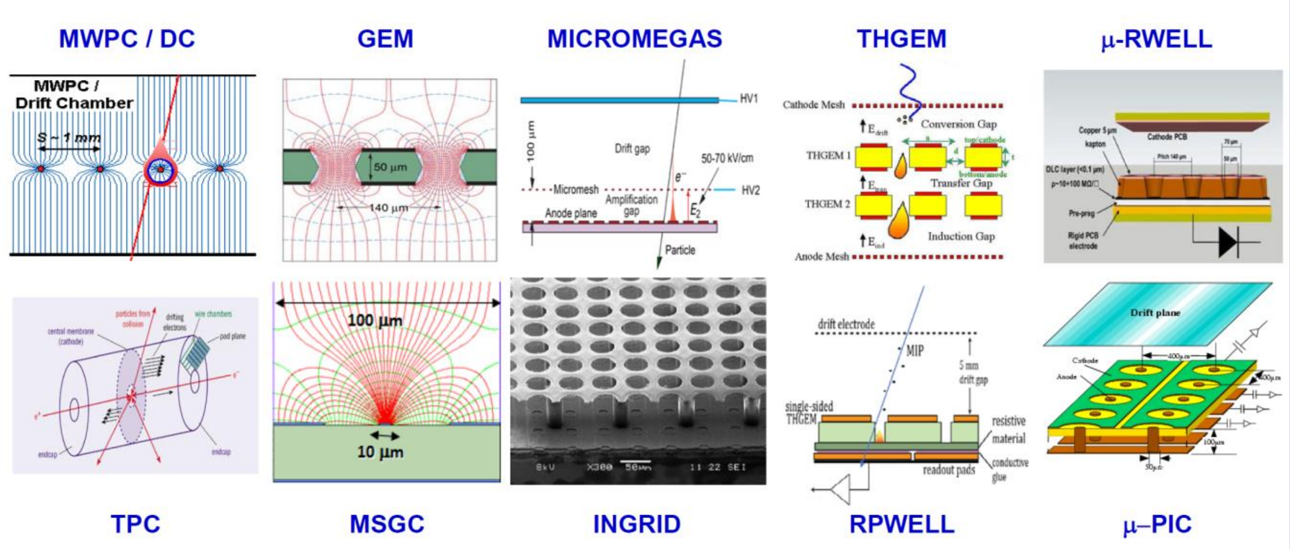
Gaseous Detectors: From Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

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





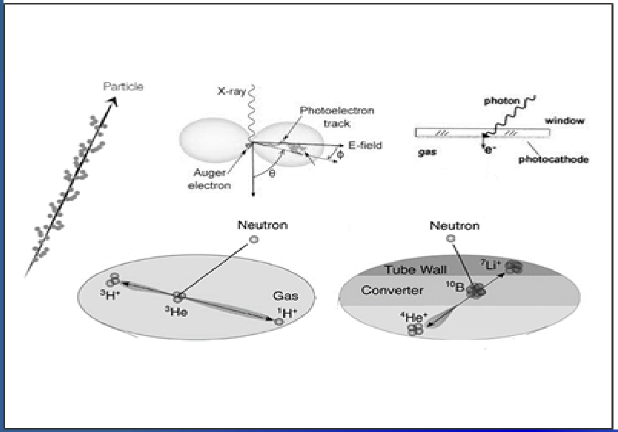
Examples of Gaseous Detectors for Future Colliders:

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)

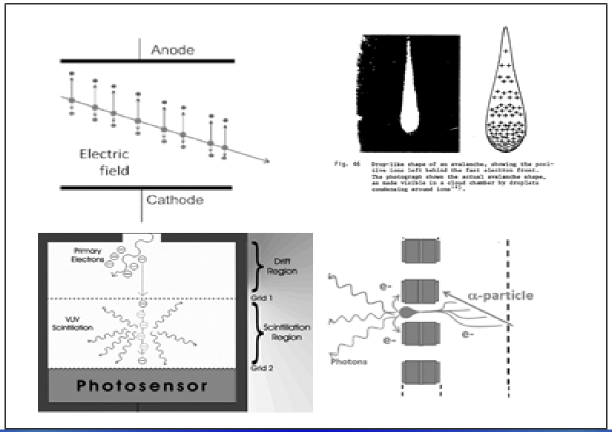
Future Election-Ion Collider: Tracking (GEM, μWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)

Gaseous Detector R&D: Common Issues

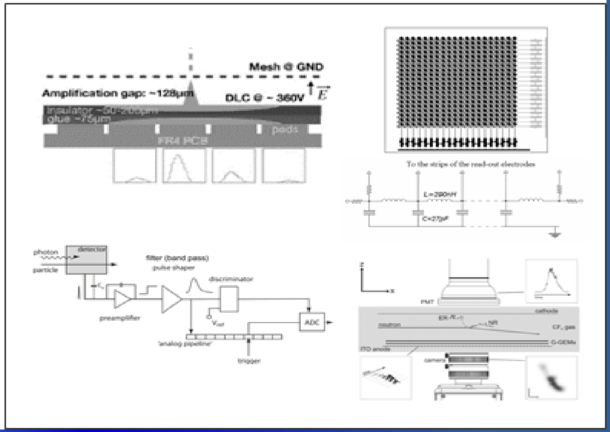
Ionization



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, picosecond-timing, optical readout**

- **RPC - focus stays on improving high-rate and precise timing capabilities, uniform detector response, and mechanical compactness, pico-second timing**

- **Straw tubes- requirements include extended length and smaller diameter, low material budget, and operation in a highly challenging radiation environment.**

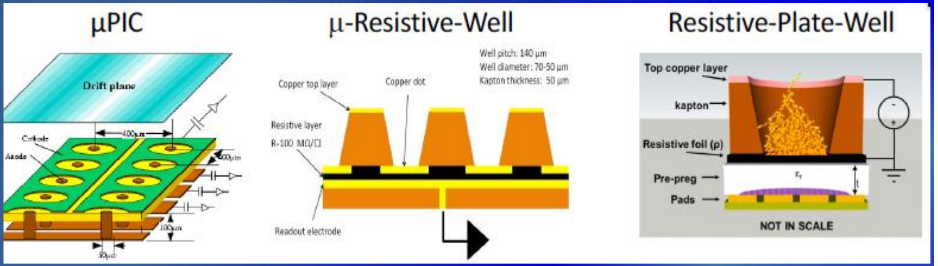
- **Large-volume Drift chamber with a reduced material budget in a high-rate environment requires searching for new materials. Avalanche-induced Ion Back Flow (IBF) remains the primary challenge for TPC applications in future facilities.**

Resistive MPGD Structures: Performance & Trends

SINGLE-STAGE DESIGNS with RESISTIVE MATERIALS and related detector architecture

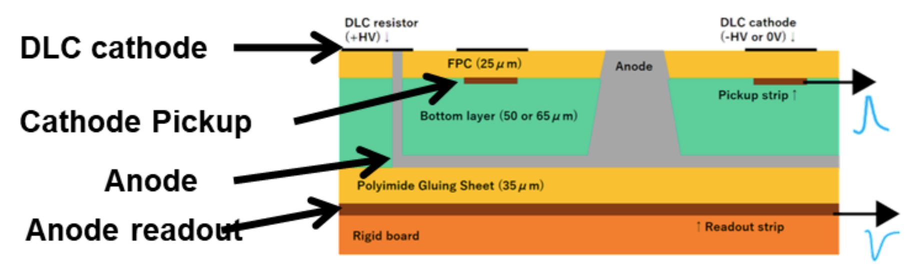
→ µPIC, µRWELL, small-pad res. MM (proposed for ATLAS HL-LHC Forward Muon Tagger), RPWELL

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



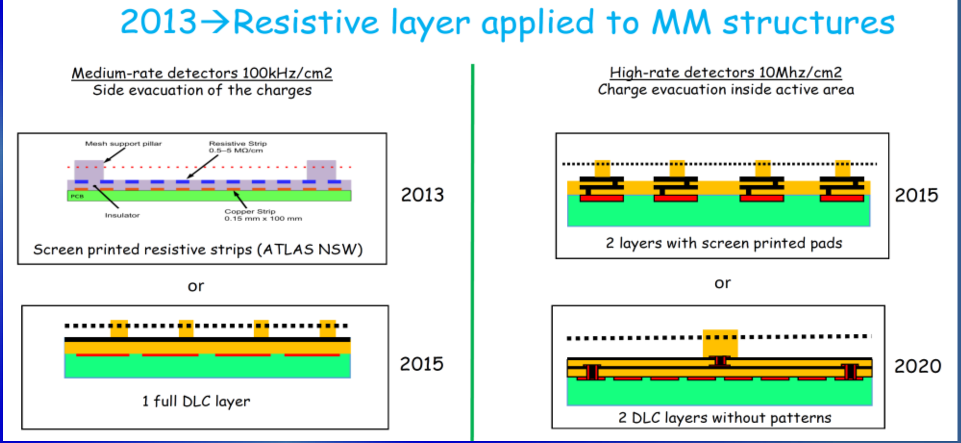
Diamond-like carbon (DLC) resistive layers :

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

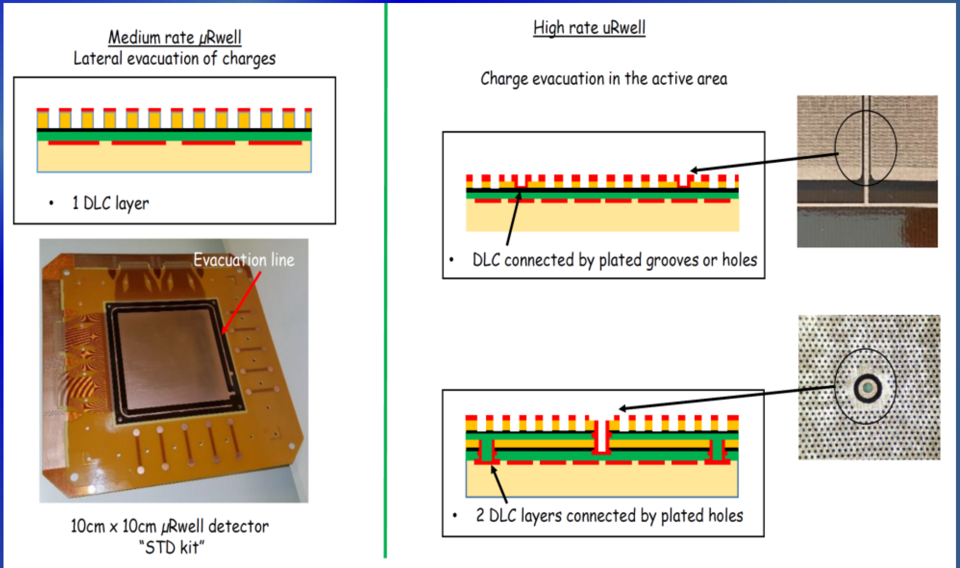


Future R&D Challenges:

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

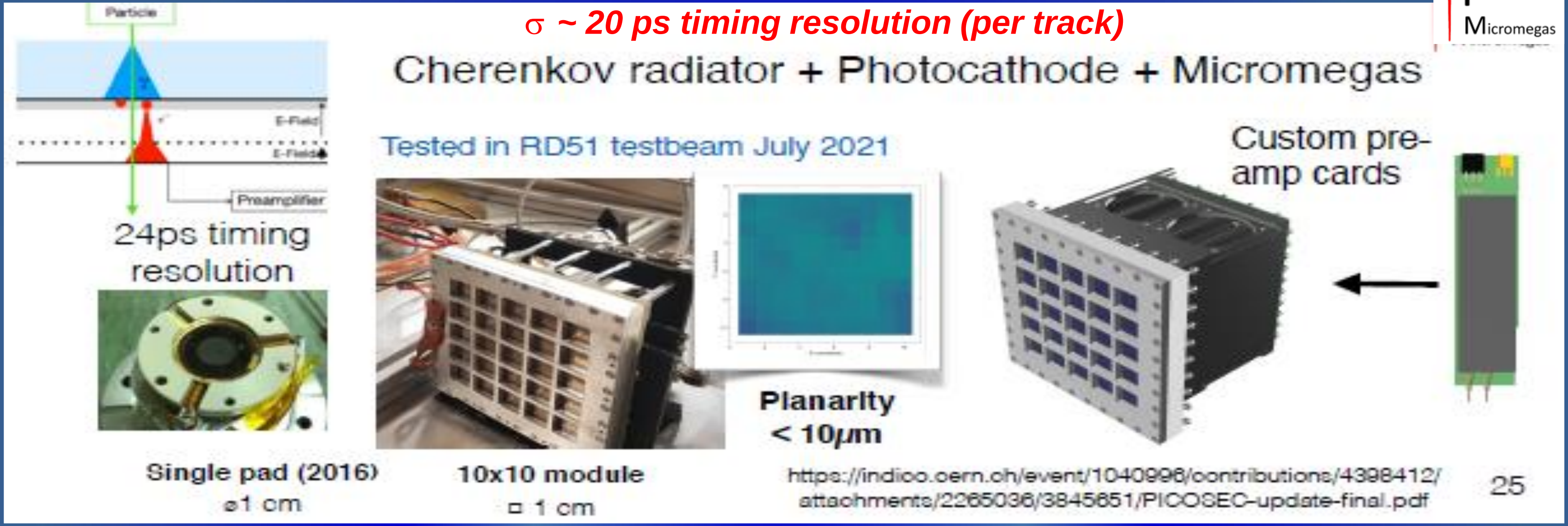


µRWELL High-Rate Layout O(Mhz/cm2) for LHCb Upgrade & Medium-Rate Layout for FCC-ee / CePC



Towards Large Area in Fast Timing GASEOUS DETECTORS

Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)



σ ~ 20 ps timing resolution (per track)

Cherenkov radiator + Photocathode + Micromegas

24ps timing resolution

Tested in RD51 testbeam July 2021

Custom pre-amp cards

Planarity < 10μm

Single pad (2016)
⌀1 cm

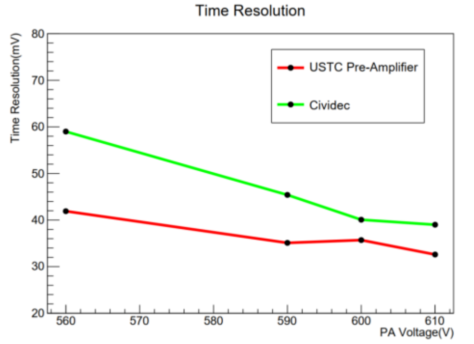
10x10 module
□ 1 cm

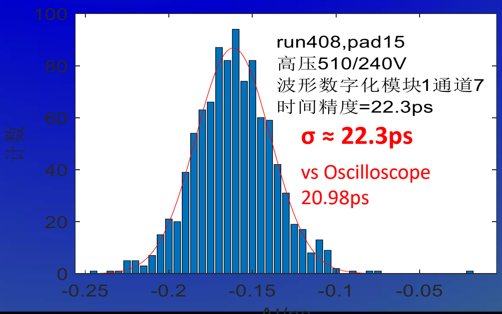
https://indico.cern.ch/event/1040996/contributions/4398412/attachments/2265036/3845651/PICOSEC-update-final.pdf

25

Your opportunity for MPGD R&D at the USTC:

Large area 4D Picosecond-timing tracker for high-rate experiments:

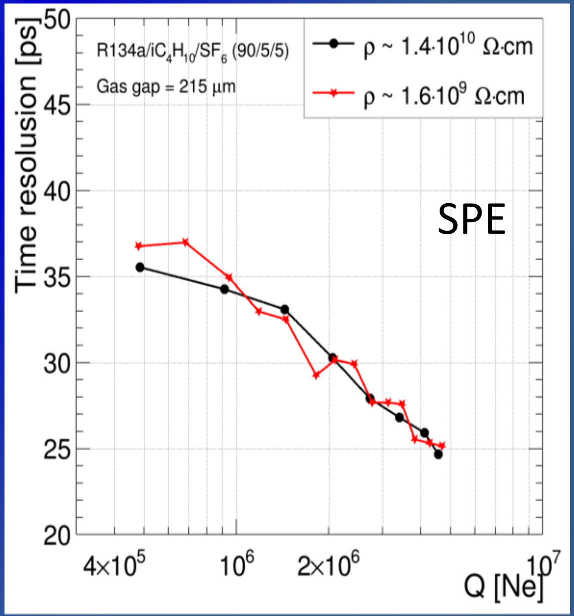




run408,pad15
高压510/240V
波形数字化模块1通道7
时间精度=22.3ps

σ ≈ 22.3ps

vs Oscilloscope 20.98ps



Optical Readout of MPGDs: Imaging Applications

Optical readout of gaseous detectors

Scintillation light emission Imaging sensors and optics

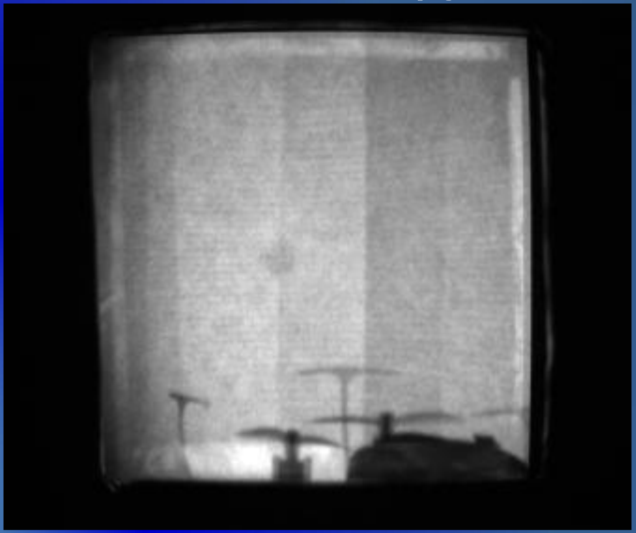
Applications of optical readout

Radiation imaging and fluorescence High spatial resolution imaging Optical TPCs Neutron imaging Beam monitoring and medical applications Optical readout for detector R&D

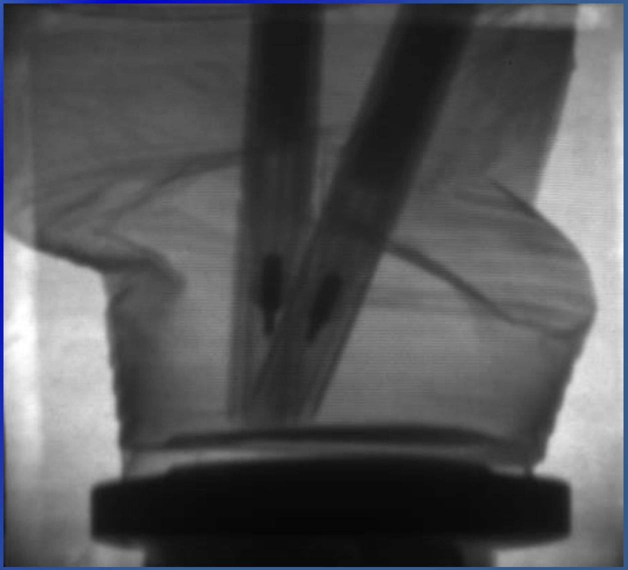
New developments

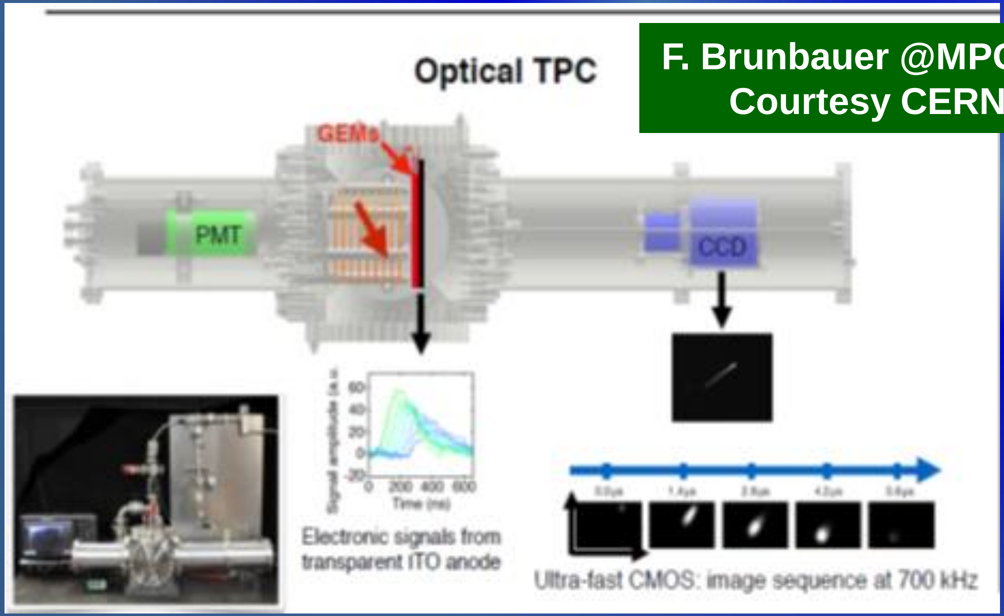
Alternative gases and wavelength shifters Ultra-fast imaging SiPM readout Optical readout of negative ion drift detectors

Fluoroscopy:



CT and 3 D Imaging:



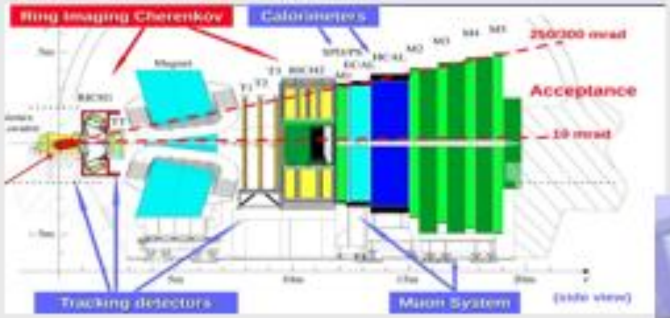


F. Brunbauer @MPGD2024 & Courtesy CERN GDD

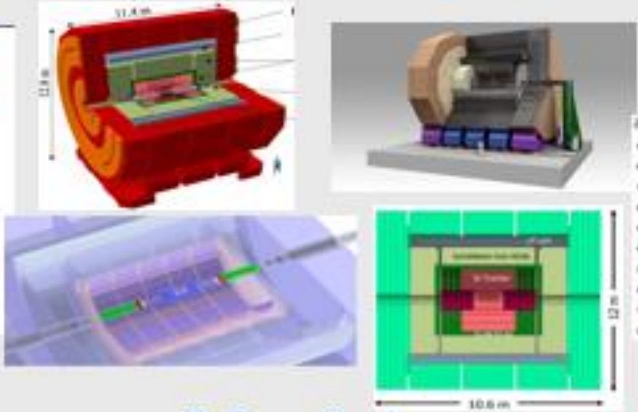
Steps Towards Long-Term Detector R&D Program

Main target projects of Gaseous Detector R&D

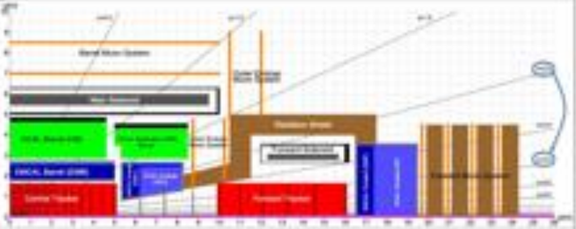
HL-LHC after LS4



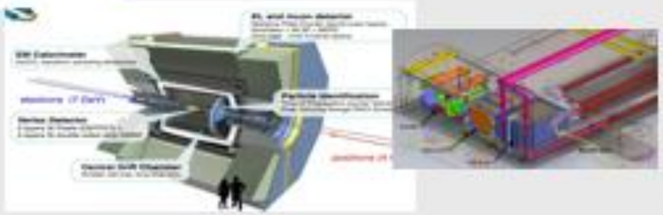
Higgs Factories



Future hadron colliders (FCC-hh/eh colliders)

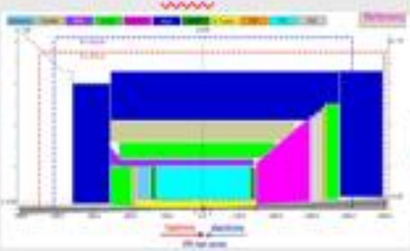


SuperKEKB, DUNE ND

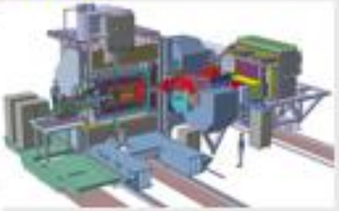


Hadron physics

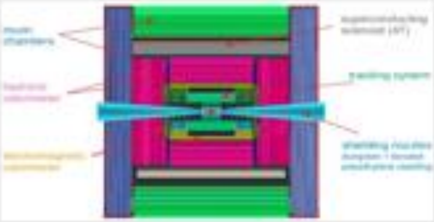
EiC



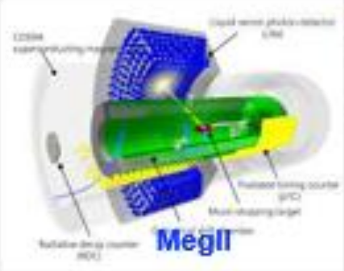
PANDA



Muon Collider

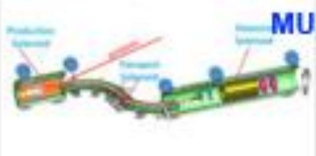


Rare event search, fixed target (LFV, Kaon physics)



MegII

HIKE



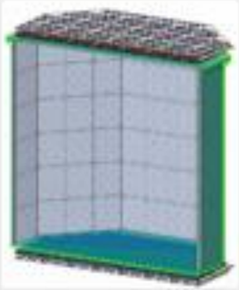
MU2E

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

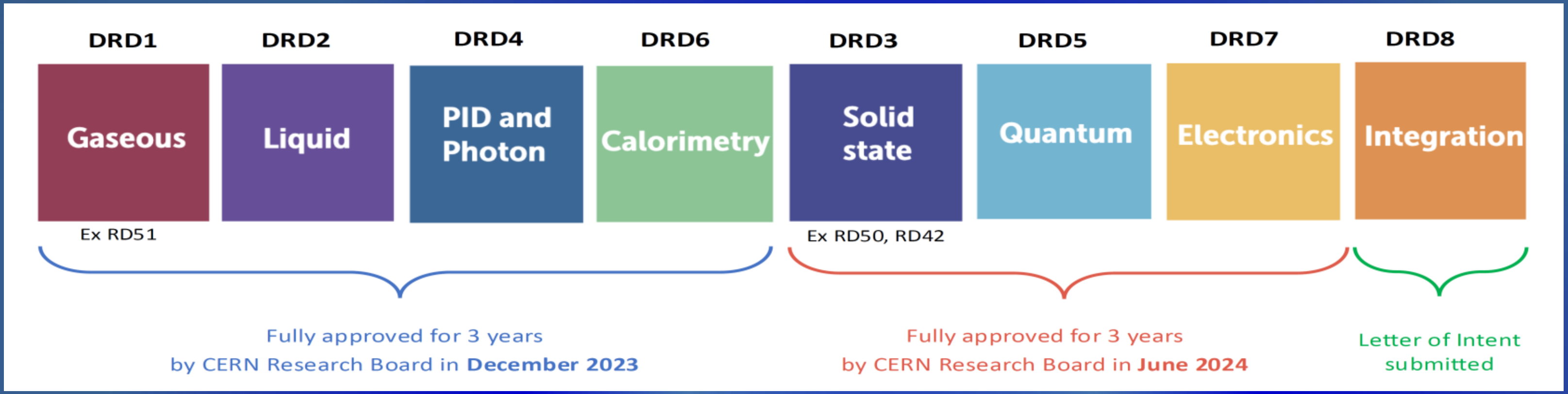
MIGDAL

Darksphere

Cygnus



> 2024: New DRD Collaborations @ CERN



DRD1	DRD2	DRD4	DRD6	DRD3	DRD5	DRD7	DRD8
Gaseous	Liquid	PID and Photon	Calorimetry	Solid state	Quantum	Electronics	Integration
Ex RD51				Ex RD50, RD42			

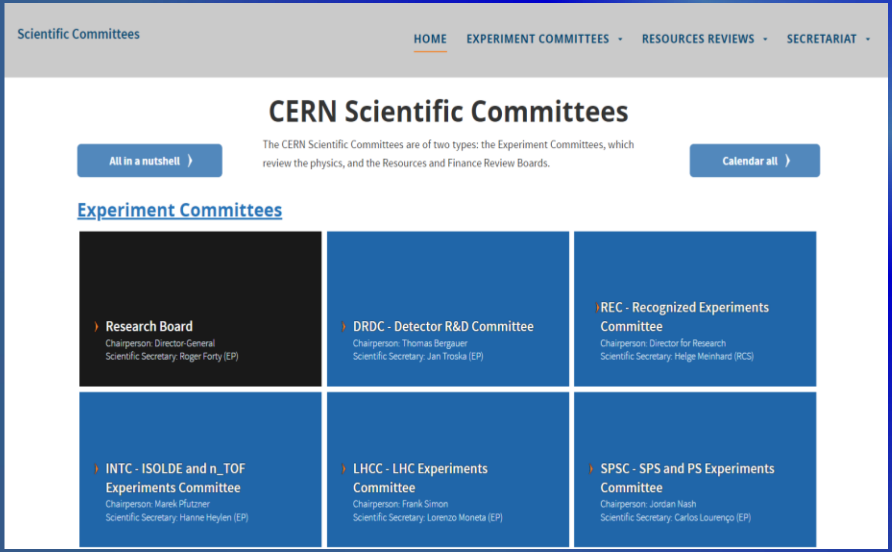
DRD1, DRD2, DRD4, DRD6: Fully approved for 3 years by CERN Research Board in **December 2023**

DRD3, DRD5, DRD7: Fully approved for 3 years by CERN Research Board in **June 2024**

DRD8: Letter of Intent submitted

DRD8 proposal expected by the end of 2024

- **DRD Reports** at open session of DRDC meetings: https://indico.cern.ch/event/1356910/
- **Indico Category: "Experiments / R&D":** https://indico.cern.ch/category/6805/
- **Full DRD proposals in CERN CDS:** https://cds.cern.ch/search?cc=DRDC+Public+Documents&sc=1&p=594__%3A%22Proposal%22
- **DRDC Committee:** https://committees.web.cern.ch/drdc (Chair – T. Bergauer HEPHY, Vienna)



CERN Scientific Committees

The CERN Scientific Committees are of two types: the Experiment Committees, which review the physics, and the Resources and Finance Review Boards.

Experiment Committees

Research Board
Chairperson: Director-General
Scientific Secretary: Roger Forty (EP)

DRDC - Detector R&D Committee
Chairperson: Thomas Bergauer
Scientific Secretary: Jan Troska (EP)

REC - Recognized Experiments Committee
Chairperson: Director for Research
Scientific Secretary: Helge Meinhard (RCS)

INTC - ISOLDE and n_TOF Experiments Committee
Chairperson: Marek Pfutzner
Scientific Secretary: Hanne Heylen (EP)

LHCC - LHC Experiments Committee
Chairperson: Frank Simon
Scientific Secretary: Lorenzo Moneta (EP)

SPSC - SPS and PS Experiments Committee
Chairperson: Jordan Nash
Scientific Secretary: Carlos Lourenço (EP)

✓ Proposals contain "**strategic" and "blue-sky" R&Ds,** definition of **Working Groups, Work Packages,** milestones, tasks & deliverables

✓ **Strategic funding** to be agreed with funding agencies/ institutions via Work Packages

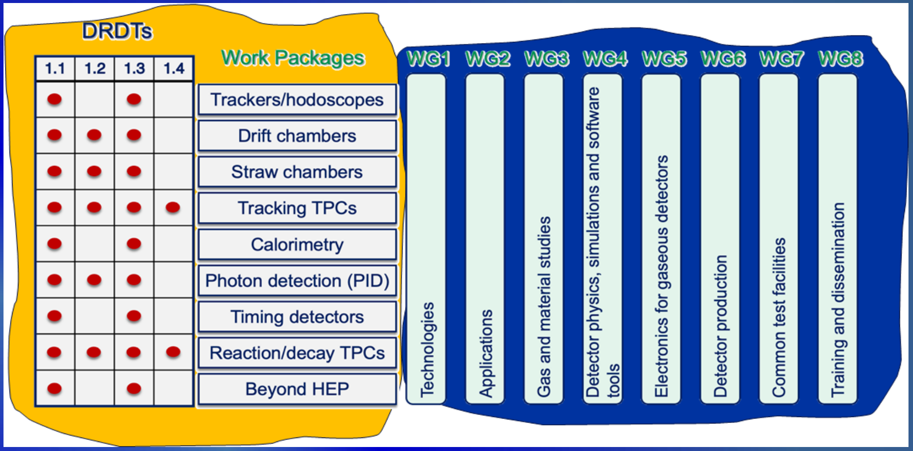
✓ **Next step** is to prepare and sign DRD **MoUs**

✓ **Progress** tracked by annual DRDC review
→ next meeting on Nov. 13, 2024:
https://indico.cern.ch/event/1424898/

DRD1 Collaboration Example: Gaseous Detectors

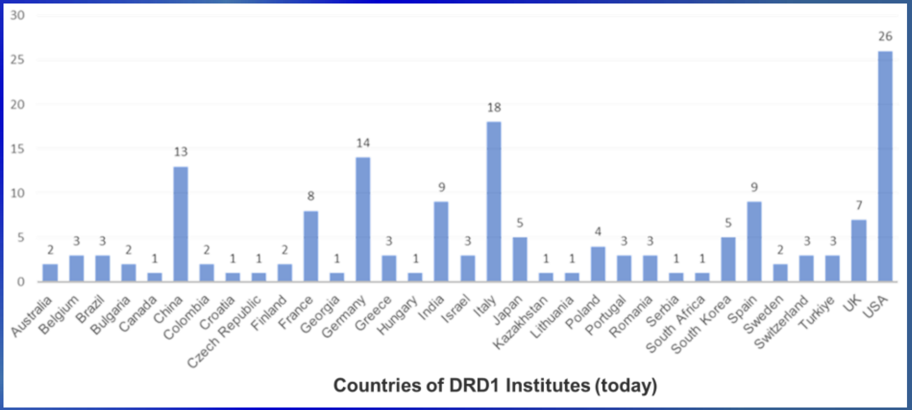
- ***Large community*** of 161 institutes, 700 members, 33 countries ***based on previous RD51 collaboration***

- ***R&D Framework organized based on:***
  - ***Working Groups (RD51 Legacy): serving as the backbone of R&D, distributed R&D Activities with Centralized Facilities***
  - ***Work Packages: will reflect the DRDTs → Strategic R&D and Long -Term Funding (Funding Agency Model)***
  - ***Common Projects: "blue sky" R&D (e.g. PICOSEC started as common project)***

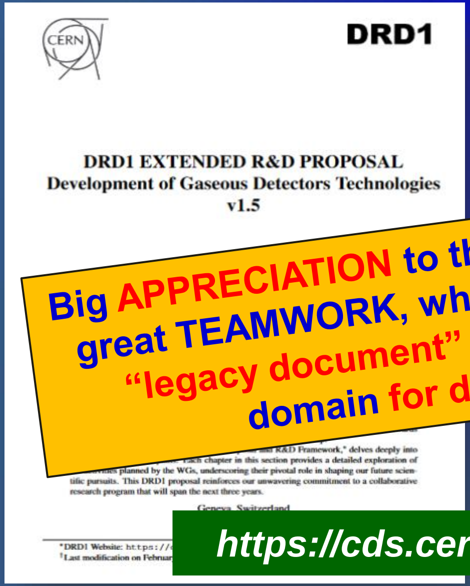


DRDTs 1.1	1.2	1.3	1.4	Work Packages
●		●		Trackers/hodoscopes
●	●	●		Drift chambers
●	●	●		Straw chambers
●	●	●	●	Tracking TPCs
●		●		Calorimetry
●	●	●		Photon detection (PID)
●		●		Timing detectors
●	●	●	●	Reaction/decay TPCs
●		●		Beyond HEP

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



Countries of DRD1 Institutes (today)



DRD1

DRD1 EXTENDED R&D PROPOSAL
Development of Gaseous Detectors Technologies
v1.5

R&D Framework," delves deeply into … Each chapter in this section provides a detailed exploration of … planned by the WGs, underscoring their pivotal role in shaping our future scientific pursuits. This DRD1 proposal reinforces our unwavering commitment to a collaborative research program that will span the next three years.

Geneva, Switzerland

*DRD1 Website: https://
†Last modification on February

I.7 DRD1 Implementation Team

I.7.1 Roles covered during the DRD1 Implementation Phase

In this section, the roles covered during the formation of the collaboration are listed.

Task Force Conveners
Anna Colaleo, Leszek Ropelewski;

Implementation Team Florian Brunbauer , Silvia Dalla Torre , Klaus Dehmelt , Ingo Deppner , Esther Ferrer Ribas , Roberto Guida , Giuseppe Iaselli , Jochen Kaminski , Barbara Liberti , Beatrice Mandelli , Eraldo Oliveri , Marco Panareo , Francesco Renga ,

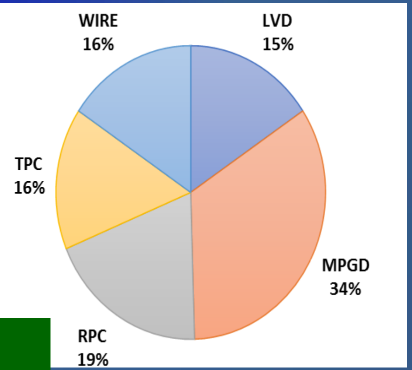
Proposal Review

T. Tsipolitis
M. Iodice, B. Liberti, A Paoloni

Work Package Coordinators
Overall Coordination: P. Gasik
WP1: G. Aielli, R. Farinelli, M. Iodice, A. Ochi, G. Pugliese
WP2: N. De Filippis, F. Grancagnolo
WP3: P. Wintz
WP4: D. Gonzalez Diaz, E. Ferrer Ribas, F. I. Garcia Fuentes, P. Gasik, J. Kaminski

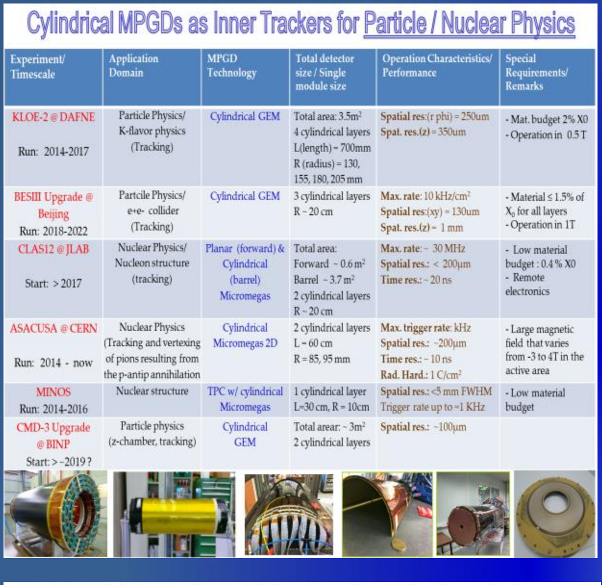
Big APPRECIATION to the DRD1 COMMUNITY for great TEAMWORK, which allowed to shape the "legacy document" for gaseous detectors domain for decades to come

https://cds.cern.ch/record/2885937



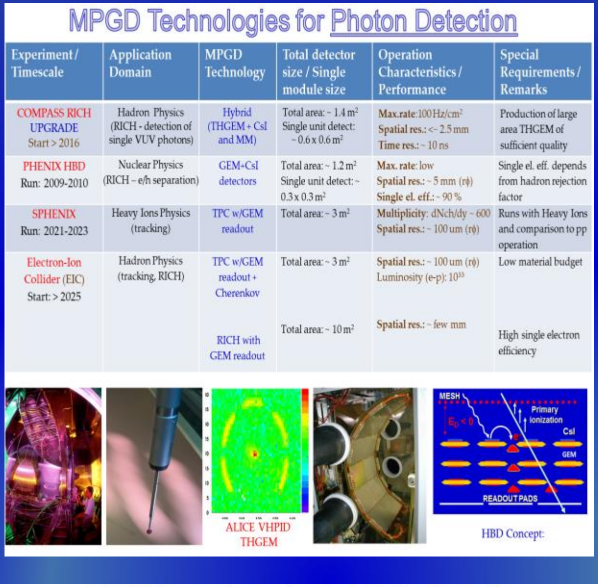
https://drd1.web.cern.ch

Dissemination of MPGD Applications in HEP & Beyond



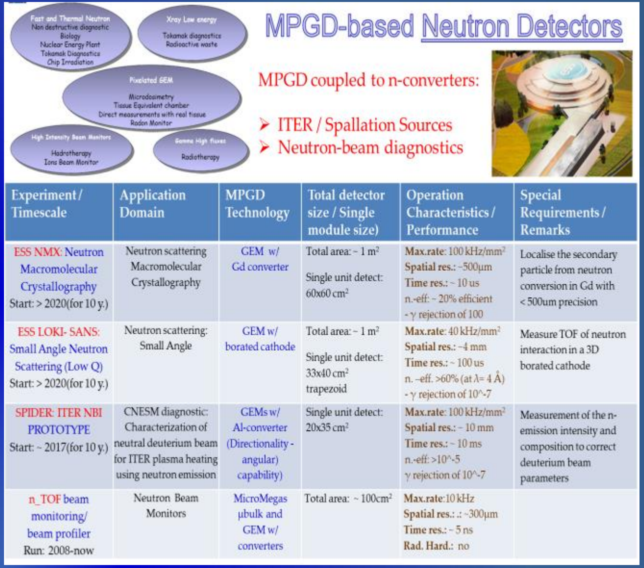
Cylindrical MPGDs as Inner Trackers for Particle / Nuclear Physics

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: 3.5m^2 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 0.5T
BESIII Upgrade @ Beijing Run: 2018-2022	Partcile Physics/ e+e- collider (Tracking)	Cylindrical GEM	3 cylindrical layers R ~ 20 cm	**Max. rate**: 10 kHz/cm^2 **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 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
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/cm^2	- 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: ~ 3m^2 2 cylindrical layers	**Spatial res.**: ~100µm	



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 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
PHENIX HBD Run: 2009-2010	Nuclear Physics (RICH – e/h separation)	GEM+CsI detectors	Total area: ~ 1.2 m^2 Single unit detect: ~ 0.3 x 0.3 m^2	**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 m^2	**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 m^2 Total area: ~ 10 m^2	**Spatial res.**: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} **Spatial res.**: ~ few mm	Low material budget High single electron efficiency

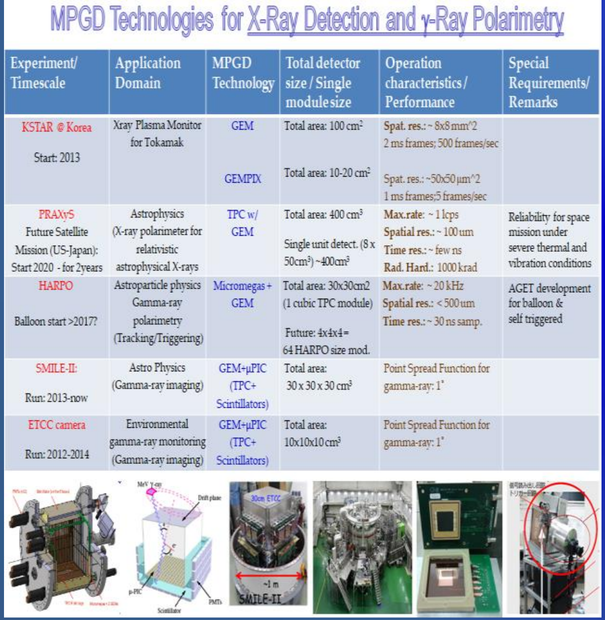


MPGD-based Neutron Detectors

MPGD coupled to n-converters:

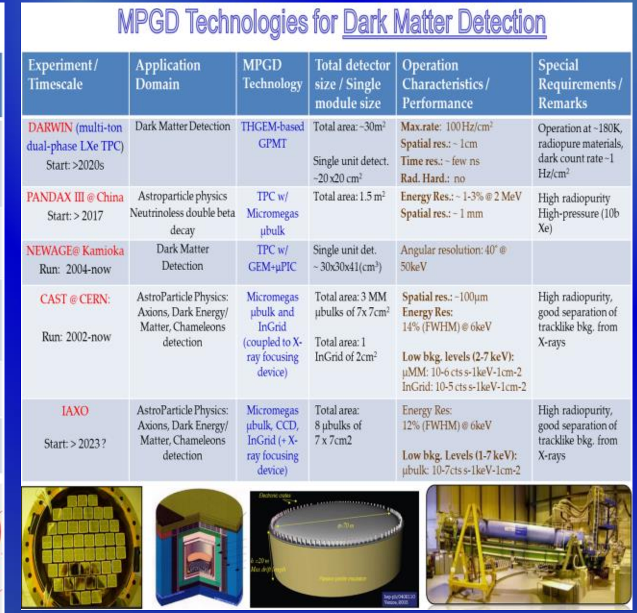
- ITER / Spallation Sources
- Neutron-beam diagnostics

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 m^2 Single unit detect: 60x60 cm^2	**Max.rate**: 100 kHz/mm^2 **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 m^2 Single unit detect: 33x40 cm^2 trapezoid	**Max.rate**: 40 kHz/mm^2 **Spatial res.**: ~4 mm **Time res.**: ~ 100 us n. –eff. >60% (at λ= 4 Å) - γ rejection of 10^-7	Measure TOF of neutron interaction in a 3D borated cathode
SPIDER: ITER NBI PROTOTYPE Start: ~ 2017(for 10 y.)	CNESM diagnostic: Characterization of neutral deuterium beam for ITER plasma heating using neutron emission	GEMs w/ Al-converter (Directionality - angular) capability)	Single unit detect: 20x35 cm^2	**Max.rate**: 100 kHz/mm^2 **Spatial res.**: ~ 10 mm **Time 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 monitoring/ beam profiler Run: 2008-now	Neutron Beam Monitors	MicroMegas µbulk and GEM w/ converters	Total area: ~ 100cm^2	**Max.rate**:10 kHz **Spatial res.**: .: ~300µm **Time res.**: ~ 5 ns **Rad. Hard.**: no	



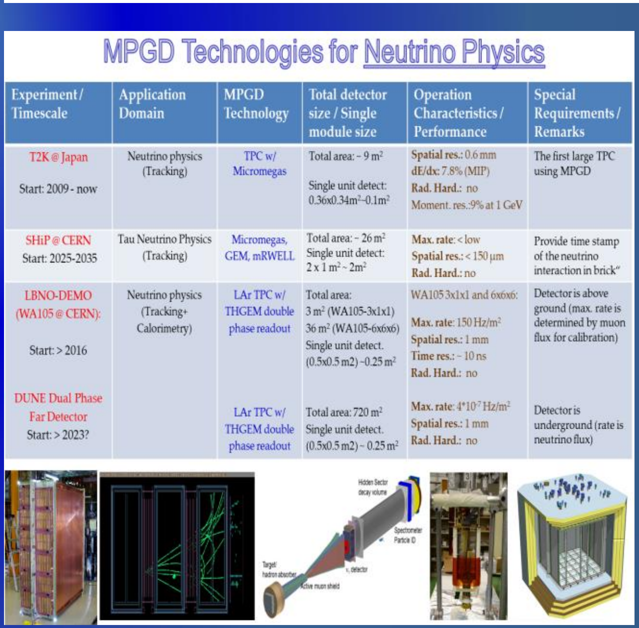
MPGD Technologies for X-Ray Detection and γ-Ray Polarimetry

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 cm^2 Total area: 10-20 cm^2	**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 cm^3 Single unit detect. (8 x 50cm^3) ~400cm^3	**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 cm^3	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 cm^3	Point Spread Function for gamma-ray: 1°	



MPGD Technologies for Dark Matter Detection

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: ~30m^2 Single unit detect. ~20 x20 cm^2	**Max.rate**: 100 Hz/cm^2 **Spatial res.**: ~ 1cm **Time res.**: ~ few ns **Rad. Hard.**: no	Operation at ~180K, radiopure materials, dark count rate ~1 Hz/cm^2
PANDAX III @ China Start: > 2017	Astroparticle physics Neutrinoless double beta decay	TPC w/ Micromegas µbulk	Total area: 1.5 m^2	**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(cm^3)	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 7cm^2 Total area: 1 InGrid of 2cm^2	**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



MPGD Technologies for Neutrino Physics

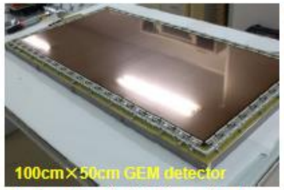
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
T2K @ Japan Start: 2009 - now	Neutrino physics (Tracking)	TPC w/ Micromegas	Total area: ~ 9 m^2 Single unit detect: 0.36x0.34m^2~0.1m^2	**Spatial res.**: 0.6 mm **dE/dx**: 7.8% (MIP) **Rad. Hard.**: no Moment. res.:9% at 1 GeV	The first large TPC using MPGD
SHiP @ CERN Start: 2025-2035	Tau Neutrino Physics (Tracking)	Micromegas, GEM, mRWELL	Total area: ~ 26 m^2 Single unit detect: 2 x 1 m^2 ~ 2m^2	**Max. rate**: < low **Spatial res.**: < 150 µm **Rad. Hard.**: no	Provide time stamp of the neutrino interaction in brick"
LBNO-DEMO (WA105 @ CERN): Start: > 2016	Neutrino physics (Tracking+ Calorimetry)	LAr TPC w/ THGEM double phase readout	Total area: 3 m^2 (WA105-3x1x1) 36 m^2 (WA105-6x6x6) Single unit detect. (0.5x0.5 m2) ~0.25 m^2	WA105 3x1x1 and 6x6x6: **Max. rate**: 150 Hz/m^2 **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 m^2 Single unit detect. (0.5x0.5 m2) ~ 0.25 m^2	**Max. rate**: 4*10^{-7} Hz/m^2 **Spatial res.**: 1 mm **Rad. Hard.**: no	Detector is underground (rate is neutrino flux)

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

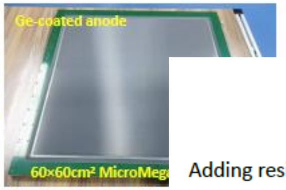
MPGD R&D @ USTC: Technology Advances

Large-area MPGD production

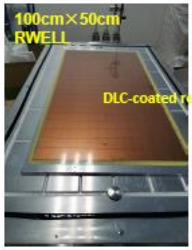
Gaseous detector features large-area, low-mass and cost-effective solution for particle detection. MPGD further enhances its high rate capability and spatial/temporal resolution for future particle and nuclear physics facilities.

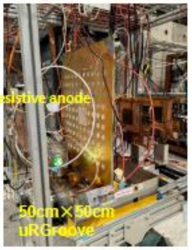


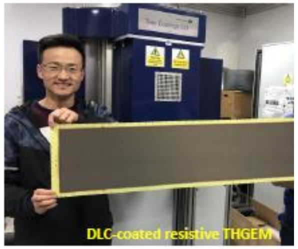
Produced by self-stretching method



Produced by thermal-bo



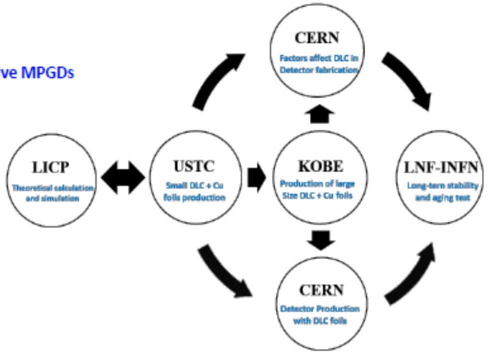




Resistive-layer coating

Adding resistive layer is essential to ensure stable operation of gaseous detector by effectively quenching the streamer/spark. New candidates, especially Diamond-Like Carbon (DLC), is very promising in developing many kinds of MPGDs.

RD51 Common Project
DLC based electrodes for resistive MPGDs



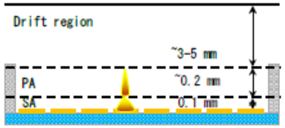
Goal of this project:

1. **Define a stable and well controlled DLC and DLC+Cu processing method for the production of MPGD electrodes**
2. **Studying the long-term stability under irradiation of DLC and DLC-based detectors.**

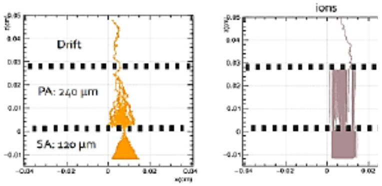
Low ion backflow (IBF)

Low ion backflow is preferred in applications involving high-rate and/or aging requirements. E.g., to suppress strong space-charge effect in TPC, or to improve life time for gaseous photomultiplier (GPM).

DMM : Double Micro-Mesh gaseous structure



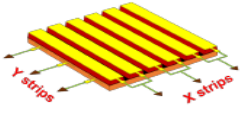
TMM : Triple Micro-Mesh gaseous structure



5×10^6 gain for single p
IBF ratio: down to 3×1

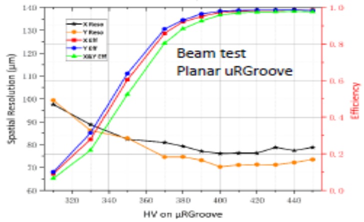
Novel MPGD structure - uRGroove

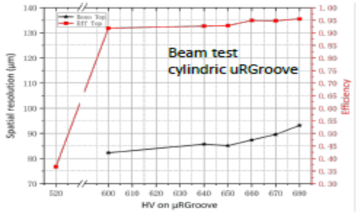
Similar to uRWELL, uRGroove provides compact and low-mass solution for large-area trackers. The intrinsic 2D structure is beneficial for higher signal gain and readout.
uRGroove is the optimal candidate for gaseous inner tracker at the Super Tau-Charm Facility (STCF).



μRGroove

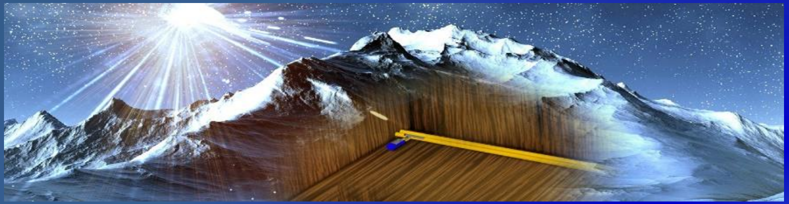
Cylindrical μRGroove for STCF
Material budget ~0.2%X_0/layer



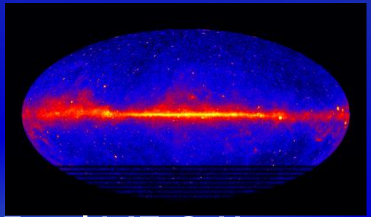


MPGD R&D @ USTC: Examples of Applications

Thermal bonding Micromegas for PandaX-III TPC， MIMAC， MeGaT

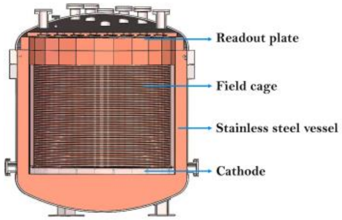


Jinping Deep Underground Dark Matter Laboratory



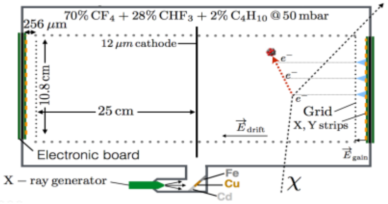
Fermi-LAT: GeV γ sources

PandaX-III: searching for neutrino-less double beta decay



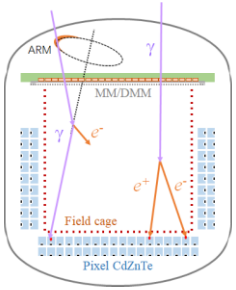
- High-pressure ^{136}Xe TPC
- Background suppression
- σ_E<3%@2.5MeV
- Ultra-low radiation level

MIMAC: Directional Dark Matter Detector



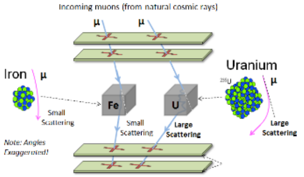
- Low-pressure nuclear-recoil TPC
- Complementary to existing techniques
- Precision measurements of neutrino cross-section

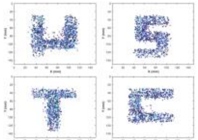
MeGaT: MeV Gamma rays Telescope



- High-pressure TPC+CZT
- High resolution
- High sensitivity
- γ polarization measurements

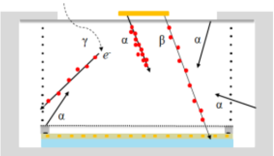
μSTC: μ scattering tomography and transmission imaging facility

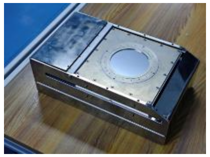




- Sensitive area ～ m^2
- Spatial resolution ～100um
- Efficiency >95% /layer
- Angular resolution <1 mrad

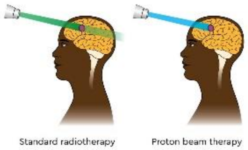
Ultra-low background α/β Counter and α Spectroscopy

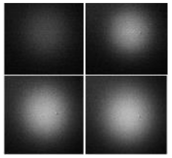




- Multi-dimensional information
- Ultra-low background
- Environmental α, β, γ discrimination
- Light-weighted

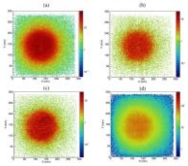
Medical Pencil Scanning Proton Beam monitoring





- >10^9 Hz/cm^2 proton
- Direct readout (camera)
- 30×40 cm^2 sensitive area
- Resolution <400 um

Micromegas-based neutron beam monitor for BNCT



- >10^9 Hz/cm^2 beam intensity
- ~Φ12 cm beam size
- High rate >1 MHz/cm^2
- Discrimination of thermal/fast neutron and γ

Development of radiation measurements and imaging facilities with novel detectors

Cutting Edge Science Relies on Cutting Edge Instrumentation

Standard Model

cessful for ever ??

Technicolor
New (strong) interactions produce EWSB
Extensions of the SM gauge group :
Little Higgs / GUTs / ...

For (most of) proposed solutions: new particles should appear at TeV scale → territory of the LHC

Supersymmetry
New particles at ≈ TeV scale, light Higgs
Unification of forces
Higgs mass stabilized
No new interactions

Extra Dimensions
New dimensions introduced
$m_{Gravity} \approx m_{EW}$ ⇒ Hierarchy problem solved
New particles at ≈ TeV scale

THE HIGGS BOSON
FINAL PIECE IN THE PUZZLE?

...but there must be a deeper relationship between Higgs / mass / gravity / dark energy

- ✓ The detrimental effect of the material budget and power consumption represents a very serious concern for a high-precision Si-vertex & tracking;
- ✓ CMOS sensors offers low mass and (potentially) radiation-hard technology for future colliders;
- ✓ ***MPGDs have become a well-established technique in the fertile field of gaseous detectors;***
- ✓ Several novel concepts of picosecond-timing detectors (LGAD, LAPPD) will have numerous powerful applications in PID & pile-up rejection:
- ✓ The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method (PFA);
- ✓ The integration of advanced electronics and data transmission functionalities plays an increasingly important role and needs to be addressed;
- ✓ Bringing the modern algorithmic advances from the field of machine learning from offline applications to online operations and trigger systems is another major challenge;

1) Our instrumentation represents both a towering achievement, and, in some cases, a scaled-up version of techniques used in the past. Recent discoveries of the Higgs boson and Gravitational Waves required increasingly sophisticated detectors and have created an exceptionally positive environment in society.

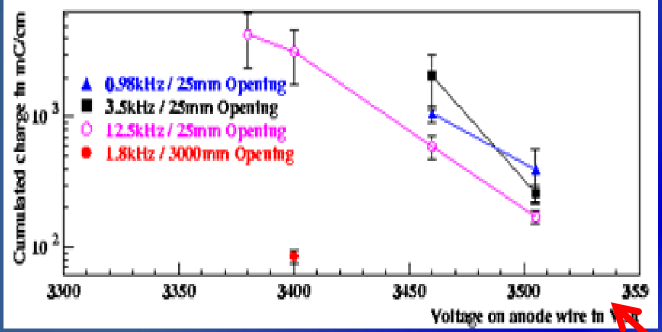
2) Key importance to keep an eye on new technologies, based on industry trends;

3) Encourage young scientists to do detector R&D; importance of recognition of excellence in instrumentation in careers at universities / RI;

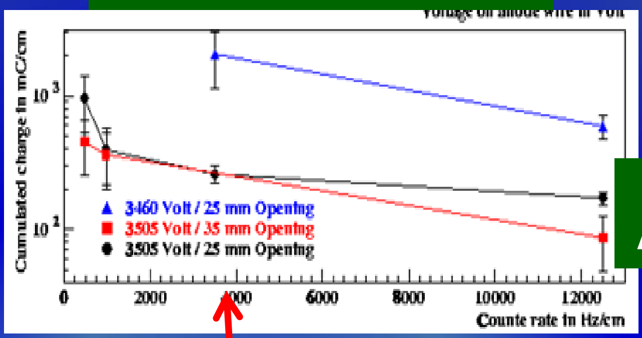
BACK-UP SLIDES

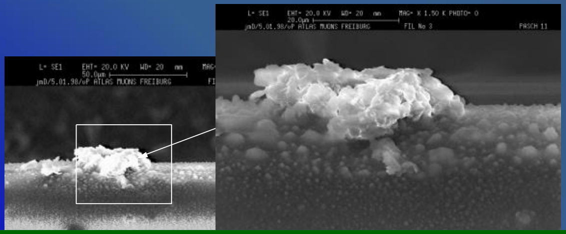
Aging Effects in Gas Detectors: “Non-Local” Phenomena

HIGH VOLTAGE:



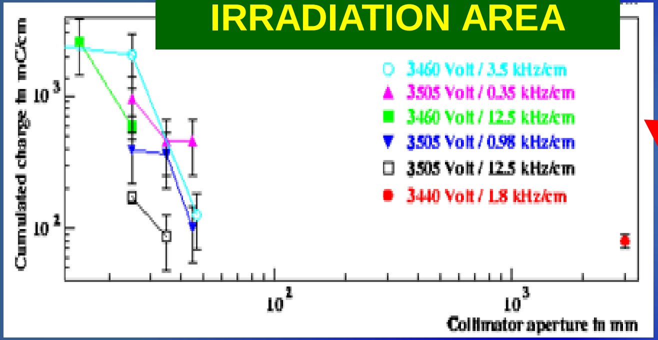
IRRADIATION RATE





M. Kollefrath, ATLAS MDT: ATLAS MUON-NOTE-012 (2001)

IRRADIATION AREA



ATLAS MDT - Ar/CH$_4$/N$_2$/CO$_2$ (94:3:2:1): Most likely polymerization of hydrocarbons (no indication that contamination caused aging

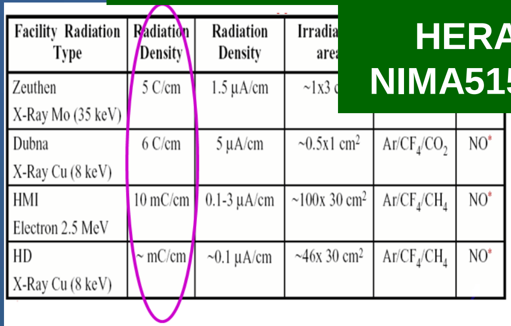
AGING RATE DEPENDS:

CLEAR EVIDENCE THAT AGING RATE DEPENDS ON:

- *Irradiation rate*
- *Ionization density*
- *High voltage (gas gain)*
- *Particle type & energy*
- *Gas exchange rate*

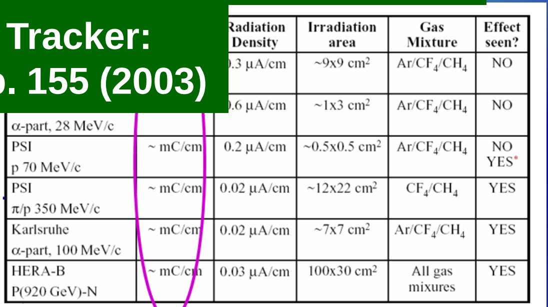
PARTICLE TYPE & ENERGY; IRRADIATION AREA

HERA-B Tracker: NIMA515, p. 155 (2003)



Facility Radiation Type	Radiation Density	Radiation Density	Irradia are		
Zeuthen X-Ray Mo (35 keV)	5 C/cm	1.5 µA/cm	~1x3		
Dubna X-Ray Cu (8 keV)	6 C/cm	5 µA/cm	~0.5x1 cm^2	Ar/CF$_4$/CO$_2$	NO*
HMI Electron 2.5 MeV	10 mC/cm	0.1-3 µA/cm	~100x 30 cm^2	Ar/CF$_4$/CH$_4$	NO*
HD X-Ray Cu (8 keV)	~ mC/cm	~0.1 µA/cm	~46x 30 cm^2	Ar/CF$_4$/CH$_4$	NO*

X-rays or e$^-$ can not trigger Malter effect independently of their energy or radiation intensity



		Radiation Density	Irradiation area	Gas Mixture	Effect seen?
		.3 µA/cm	~9x9 cm^2	Ar/CF$_4$/CH$_4$	NO
α-part, 28 MeV/c		.6 µA/cm	~1x3 cm^2	Ar/CF$_4$/CH$_4$	NO
PSI p 70 MeV/c	~ mC/cm	0.2 µA/cm	~0.5x0.5 cm^2	Ar/CF$_4$/CH$_4$	NO YES*
PSI π/p 350 MeV/c	~ mC/cm	0.02 µA/cm	~12x22 cm^2	CF$_4$/CH$_4$	YES
Karlsruhe α-part, 100 MeV/c	~ mC/cm	0.02 µA/cm	~7x7 cm^2	Ar/CF$_4$/CH$_4$	YES
HERA-B P(920 GeV)-N	~ mC/cm	0.03 µA/cm	100x30 cm^2	All gas mixures	YES

Hadrons above certain energy produce Malter effect at ~mC/cm as in HERA-B

(Irradiation area above certain limit is necessary for ignition of Malter effect)

GAS FLOW & IRRADIATION AREA

HERA-B Muon: NIMA515, p. 202 (2003)